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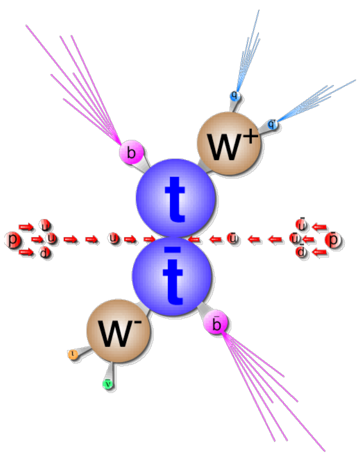
Top quark @ the LHC



Malgorzata Worek

Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

Seminarium IFJ PAN, Krakow, Poland, 21 January 2021

DFG Deutsche Forschungsgemeinschaft

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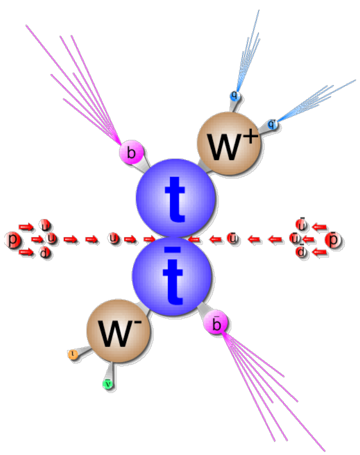
(Modelling of) Top quark @ the LHC



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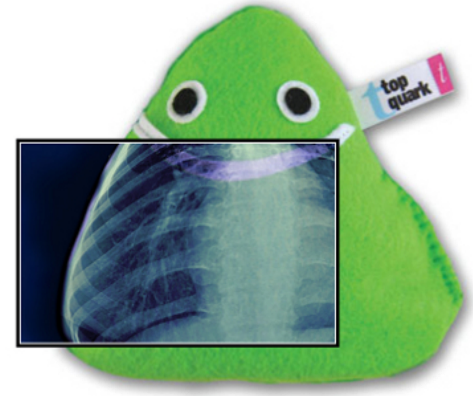
Outline



- What's so special about top quark physics ?
- Status of theoretical predictions ⇨ **QCD**
  - State-of-the-art theoretical predictions

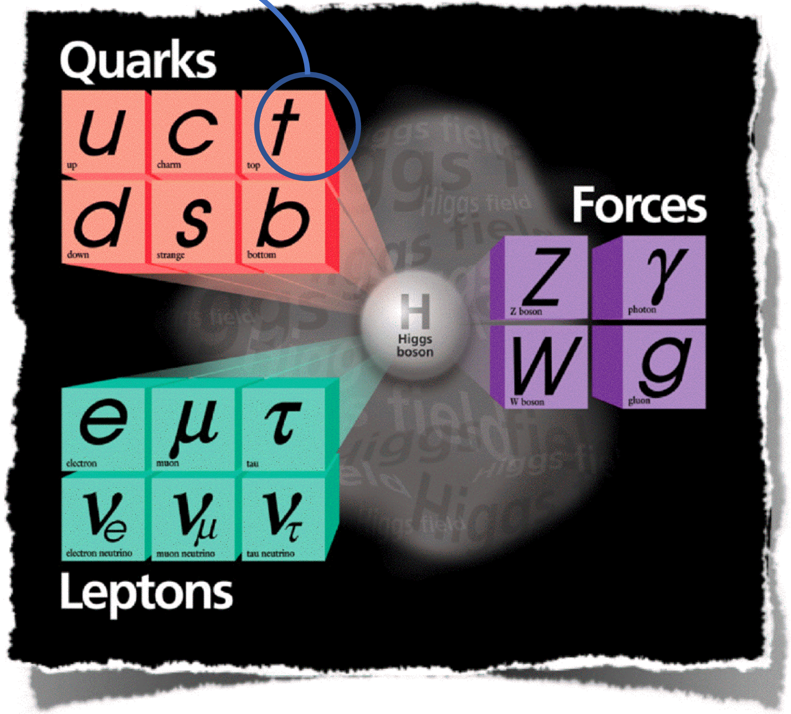
$$pp \to t\bar{t} \;\;\&\;\; pp \to t\bar{t}X\,,\;\; X = j, \gamma, W^{\pm}, Z(\to \nu\nu)$$

- Concentrate on modeling of top quark production & decays

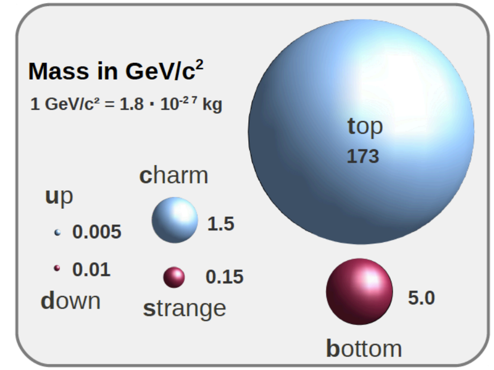
$$pp \to t\bar{t}\gamma$$ ← ***Testbed***

- ***Disclaimer***
  - Fixed order NNLO & NLO theoretical predictions @ $\mathrm{LHC}_{13\mathrm{TeV}}$
  - Top quark with off-shell effects versus NWA

Top Quark


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs
boson
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons

Unlike the other quarks



- Discovered at TeVatron in 1995
- Heaviest observed particle

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

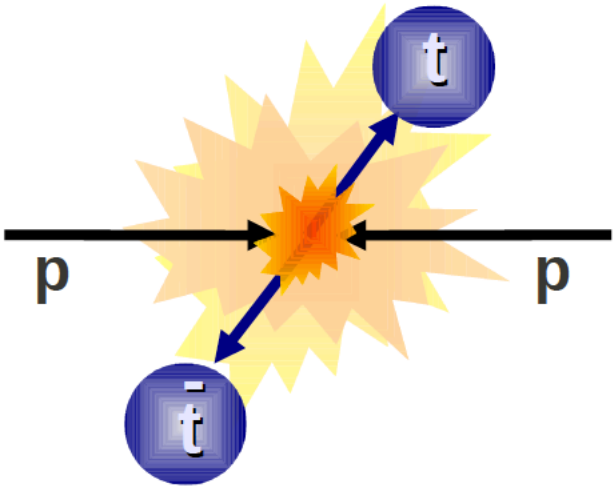
World Combination '14
ATLAS, CDF, CMS, D0

- Substantial Yukawa coupling ⇨ Special relation with the SM Higgs boson

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

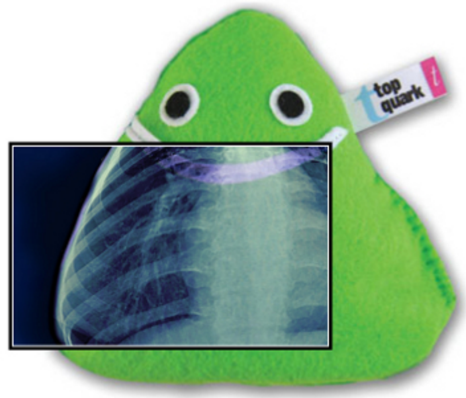
- Short lifetime $\tau \approx 5 \times 10^{-25}$ s ⇨ Decay before bound states can be formed
- Direct handle on top quark properties from decay products

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



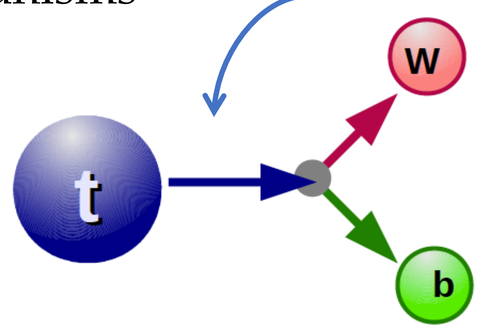
Intrinsic properties:

- Mass
- Charge
- Lifetime
- Width
- …



Production:

- Production rate
- Differential distributions
- New production mechanisms
- …

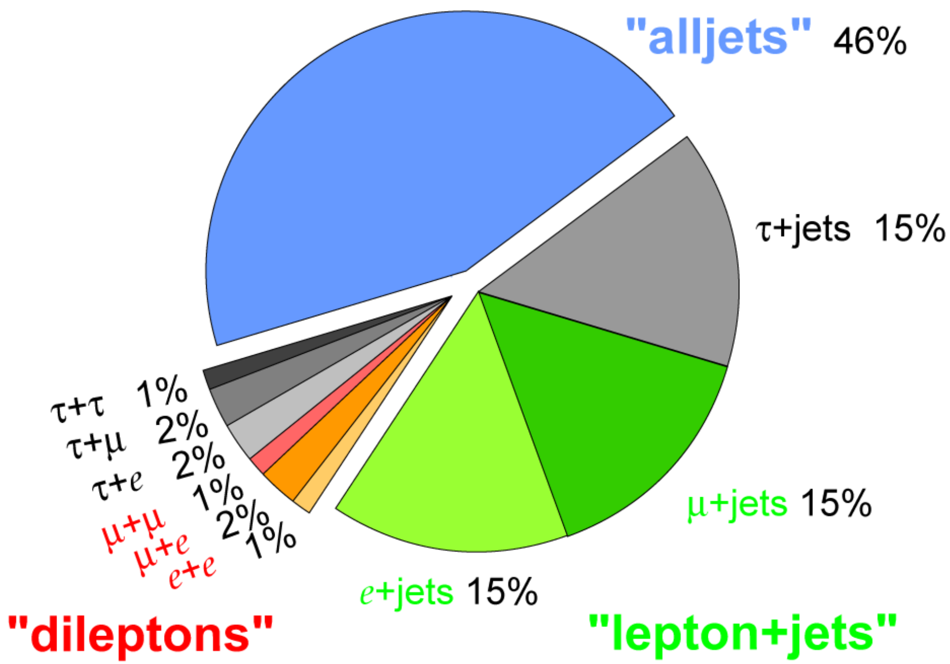


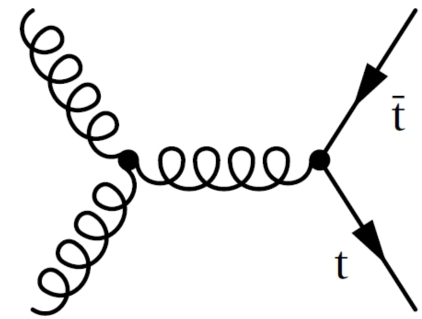
Decays:

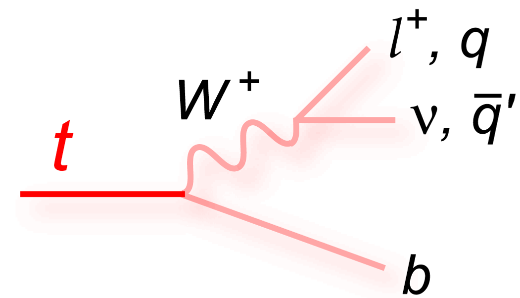
- Decay channels (SM & new)
- Couplings ***W, Z, γ & H***
- Spin correlations
- …

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)

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

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

Why top quark is special

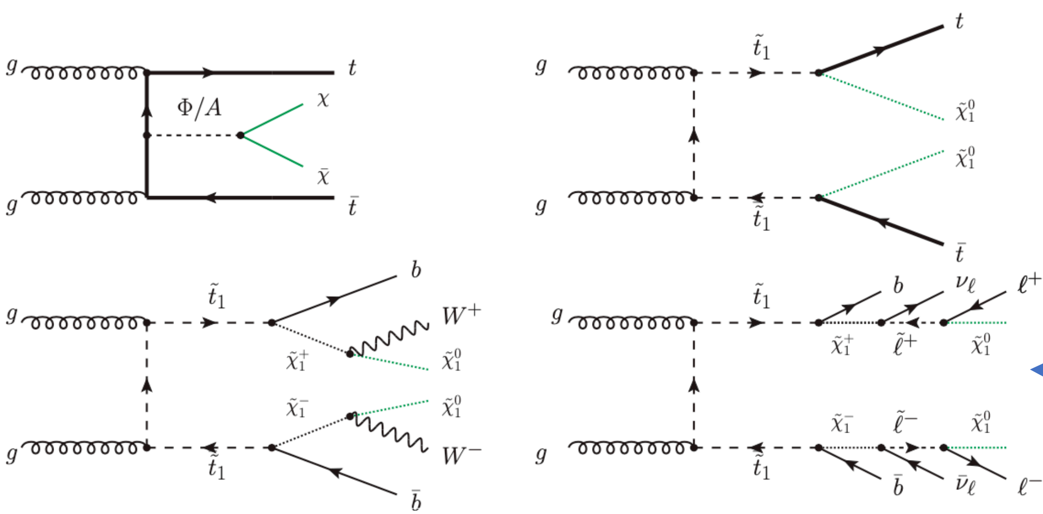
- ***Infrared structure of QCD*** ⇨ Precision physics
  - Extract SM parameters as precisely as possible ⇨ α_s & m_t
  - Constraining gluon PDFs
  - Verify couplings to other particles ⇨ $\gamma, H, Z, W^{\pm}$
  - Cross section ratios
    - More stable against radiative corrections
    - Reduced scale dependence ⇨ Various uncertainties cancel in ratio
    - Enhanced predictive power ⇨ Interesting to probe new physics @ LHC
  - Top quark charge ***asymmetry, differential top quark charge asymmetries***, …
  - Lepton charge asymmetry, …

Why top quark is special

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

- *Background process to various SM studies* ⇨ *Higgs boson*

- *Window to New Physics*
  - *Direct searches* ⇨ Main background to many BSM scenarios
  - *Indirect searches* ⇨ Precision tests of top quark production, decays & properties, rare decays, various top quark production modes



Bevilacqua, Hartanto, Kraus, Weber, Worek '19

Neutralino LSP

DM production and supersymmetric partners of top quarks

LHC as Top Quark Factory

Czakon, Mitov '14

	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	35.9	3×10^7
High Luminosity	$HL\text{-}LHC_{14\ TeV}$	987	3000	3×10^9
High Energy	$HE\text{-}LHC_{27\ TeV}$	3840	15000	6×10^{10}

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: **5% - 6%** & NNLO+NNLL: **3% - 4%***

Setting the stage …
… All that LO, NLO, NNLO & Jets

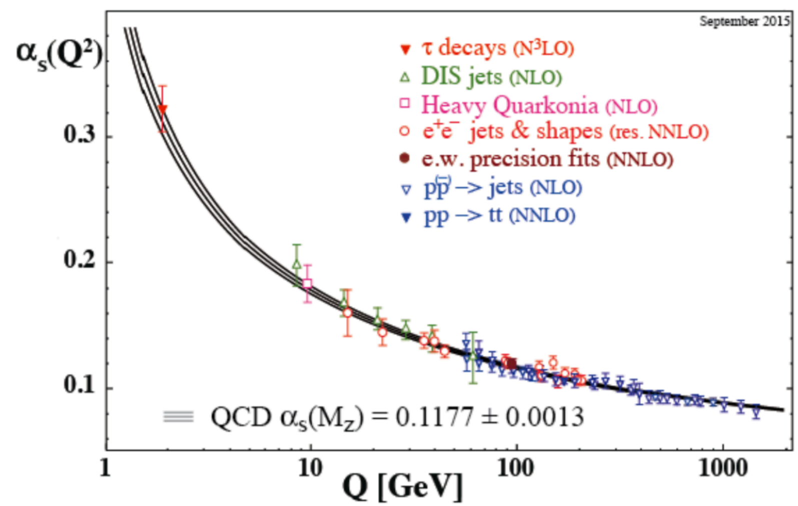
Cross Section for Hard Scattering Process Initiated by two Hadrons - Factorization Theorem -

Long distance (hadronic) physics absorbed into PDF $Q \approx M_{had}$

$$\sigma_{tot}(s) = \sum_{i,j} \int \hat{\sigma}_{part.}(\hat{s} = x_1 x_2\, s, \alpha_s, Q^2/\mu^2)\, f_i(x_1, \mu^2)\, f_j(x_2, \mu^2)\, dx_1\, dx_2\, d\Phi_{FS}$$

Short distance (partonic) physics $Q \gg M_{had}$

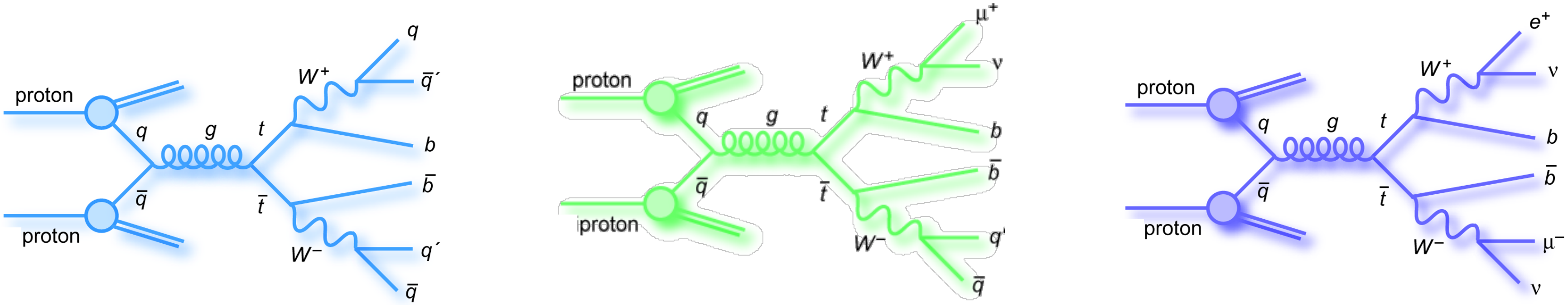
arXiv:1512.05194 [hep-ph]



energy scale Q in GeV

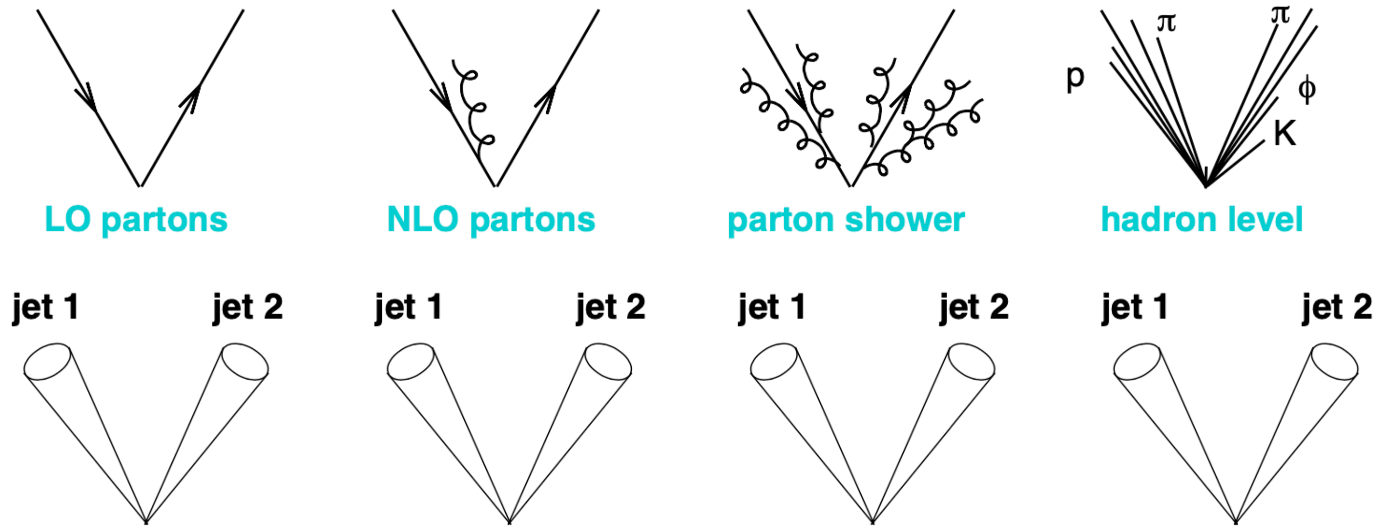
- Factorization is not exact ⇨ $\mathcal{O}(M_{had}/Q)$
- Asymptotic freedom ⇨ α_s small at high Q
- $\hat{\sigma}_{part.}$ ⇨ Perturbation series in α_s

$$\hat{\sigma}_{part.} = \sigma_{LO} + \alpha_s \sigma_{NLO} + \alpha_s^2 \sigma_{NNLO} + \ldots$$



Various top quark decay channels

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



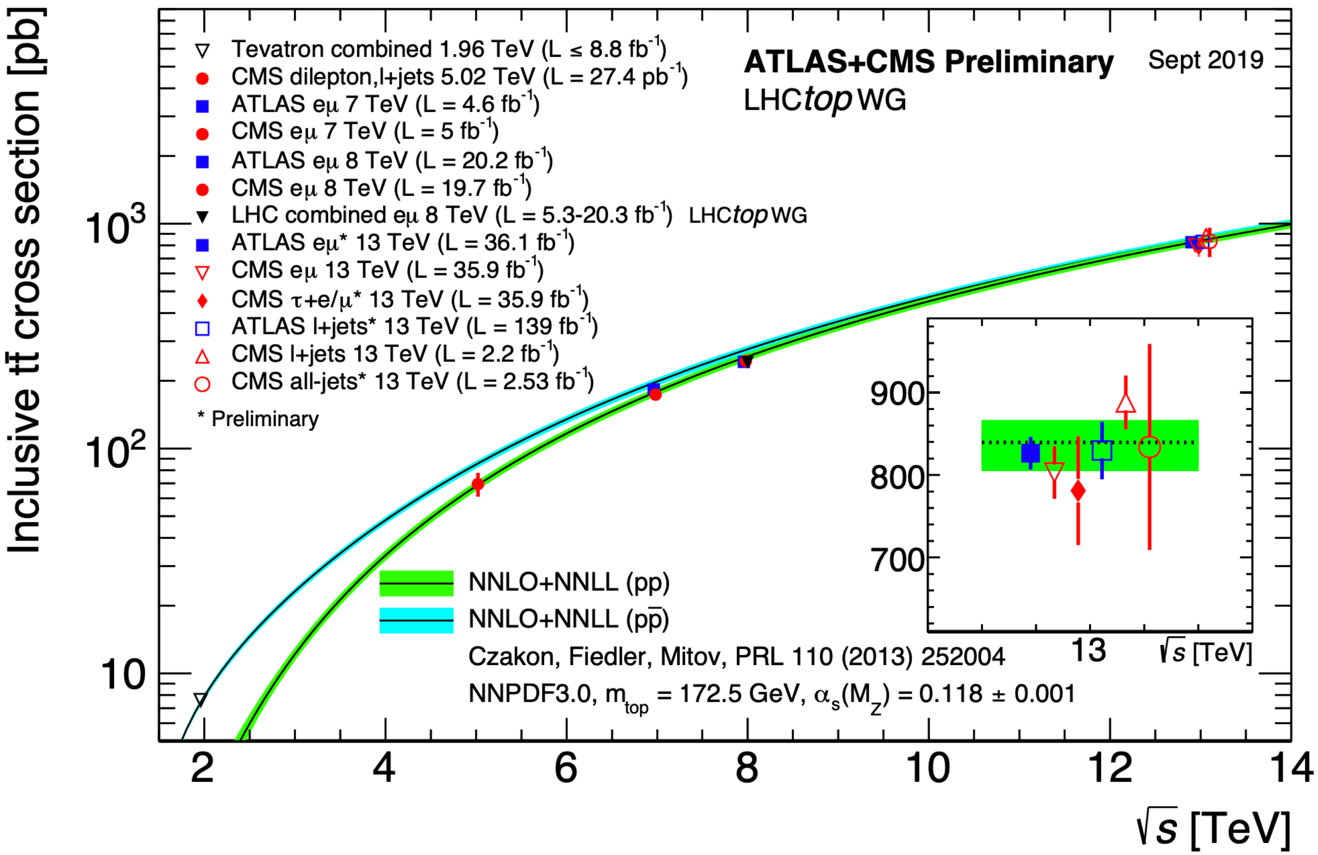
"A good jet definition can be applied to experimental measurements, to the output of parton-showering Monte Carlo and to partonic calculations, and the resulting jets provide a common representation of all these different kinds of events"

"Projection to jets should be resilient to QCD effects"

Gavin P. Salam, Towards Jetography '10

State-of-the-art NNLO QCD results for tt @LHC

Top-Quark Pair Production



Summary of LHC and Tevatron measurements of tt cross-section compared to NNLO QCD calculation complemented with NNLL resummation - **TOP++**

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

Stable top quarks

Normalization:

Czakon, Fiedler, Mitov '13

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

Fully differential:

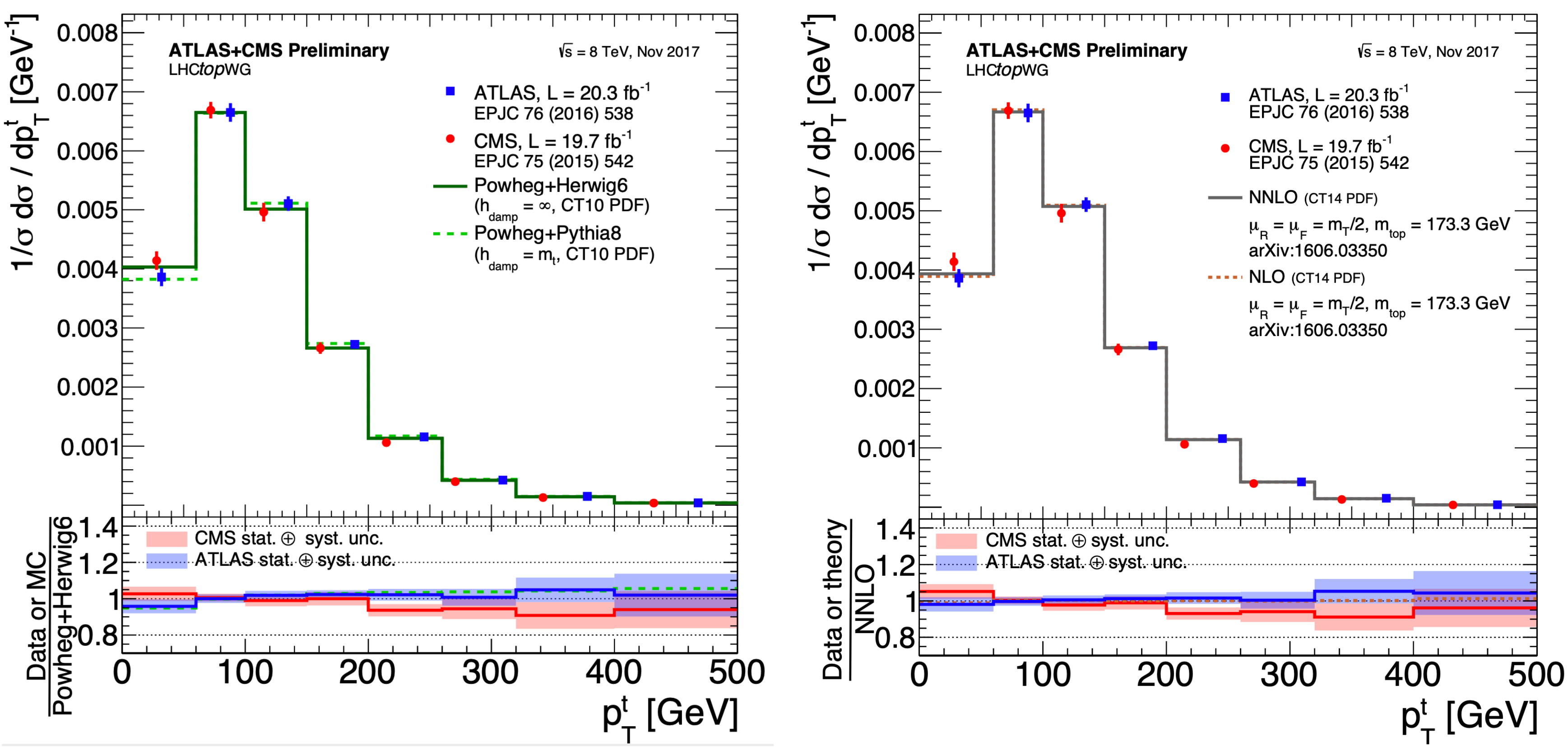
Czakon, Heymes, Mitov '16

Catani, Devoto, Grazzini, Kallweit, Mazzitelli '19

Top-Quark Pair Production

Stable top quarks

Full phase-space normalized differential tt cross-section → $p_T(t)$

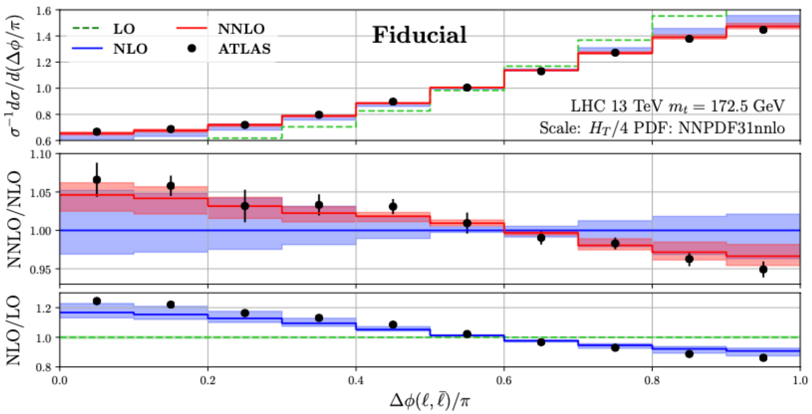


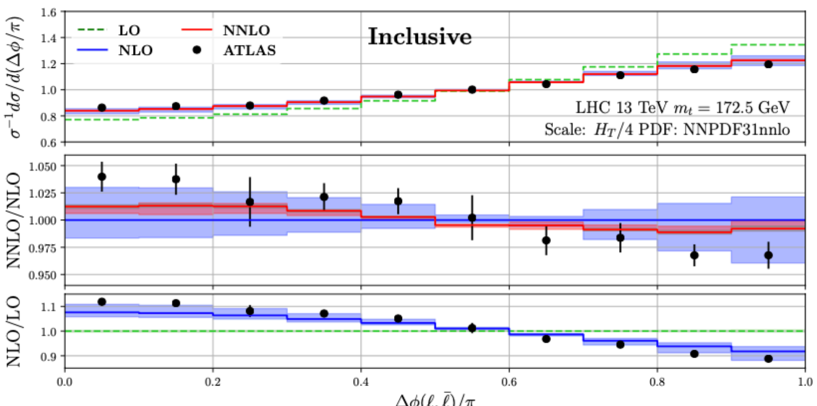
The CMS and ATLAS results are compared to Powheg+Herwig6 and Powheg+Pythia8 MC generators as well as the NLO & NNLO calculations

Top-Quark Pair Production & Decays

Normalized differential tt cross-section ⇰ azimuthal opening angle between two leptons

agreement





tension

Top quarks in NWA di-lepton channel

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

Inclusive ⇰ does not assume any selection cuts

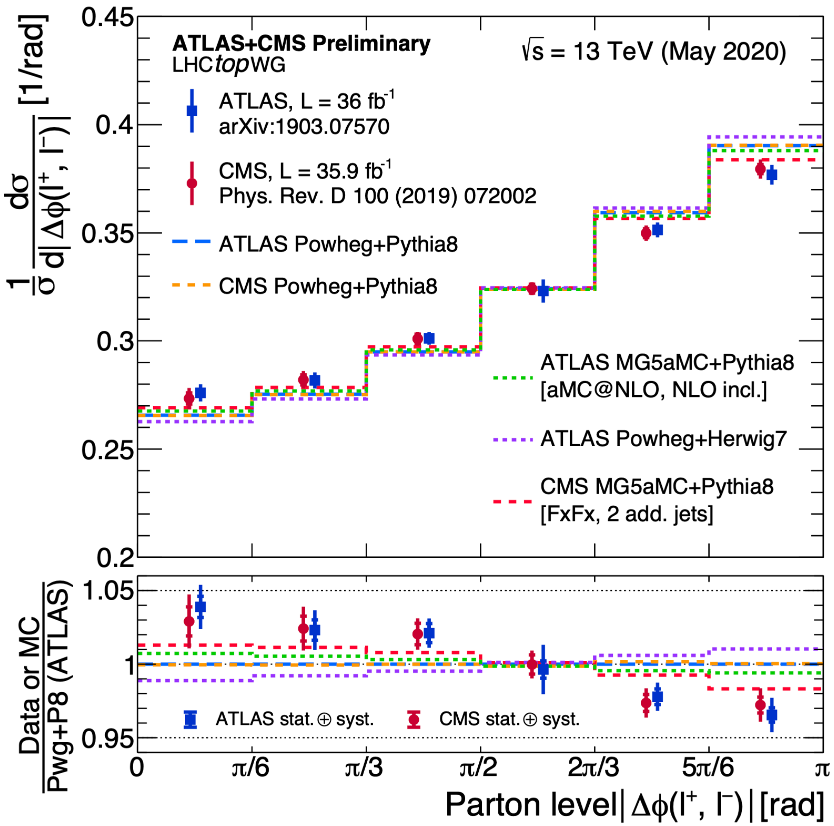
Fiducial ⇰ based on the ATLAS selection cuts

Proper modeling of top-quark production & decay essential

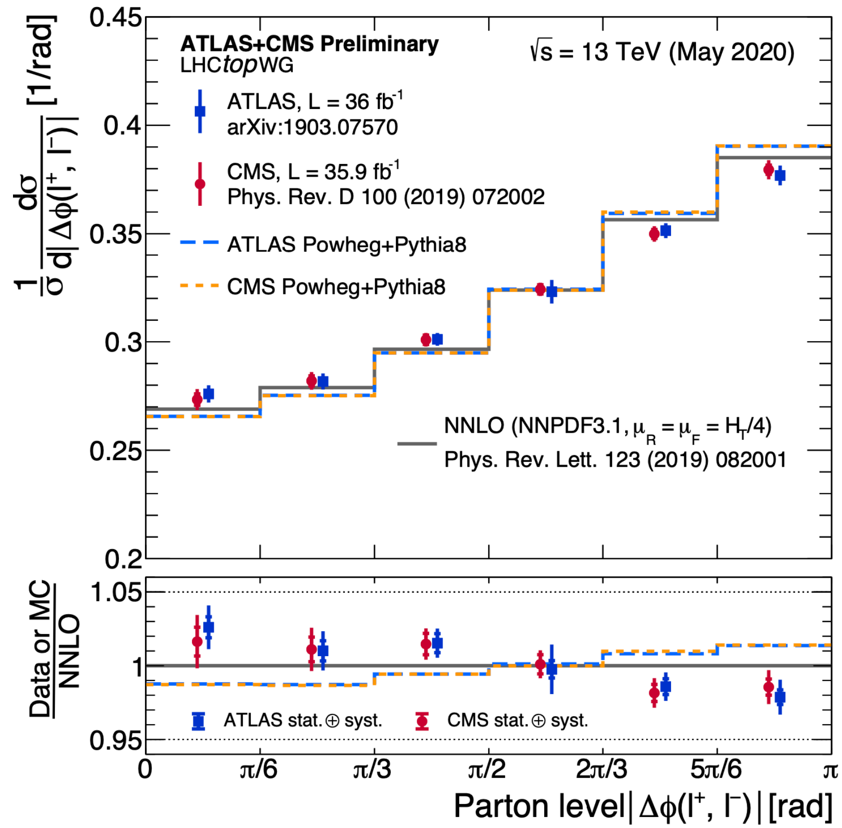
Top-Quark Pair Production & Decays

Normalized differential tt cross-section
→ *azimuthal opening angle between two leptons*

LHCtopWG



Comparison to Powheg & Mad-Graph5_aMC@NLO



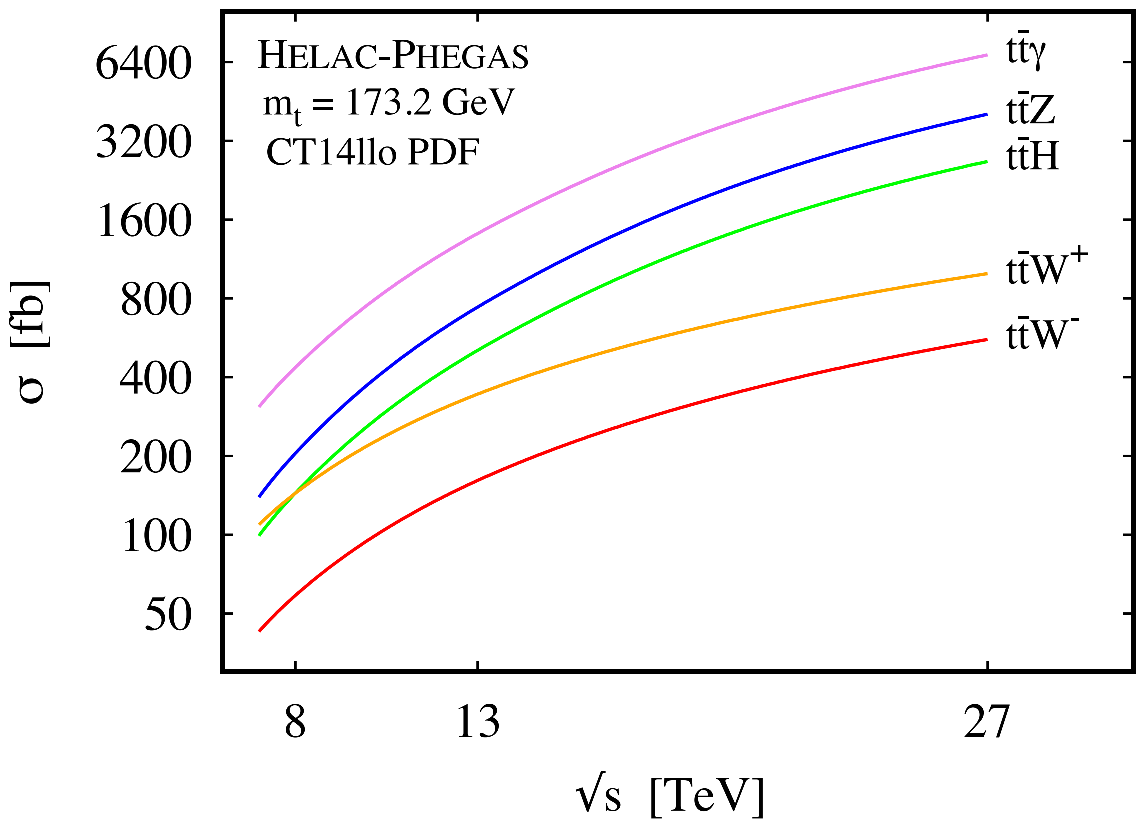
Comparison to NNLO QCD predictions in the NWA

More exclusive final states

What about other processes ?

- NNLO theoretical predictions only for ***tt*** ⇨ di-lepton channel
- Besides ***tt*** more exclusive final states can be accessed @ LHC

$t\bar{t}\gamma, t\bar{t}Z, t\bar{t}H, t\bar{t}W^+, t\bar{t}W^-$ @LHC



Stable top quarks

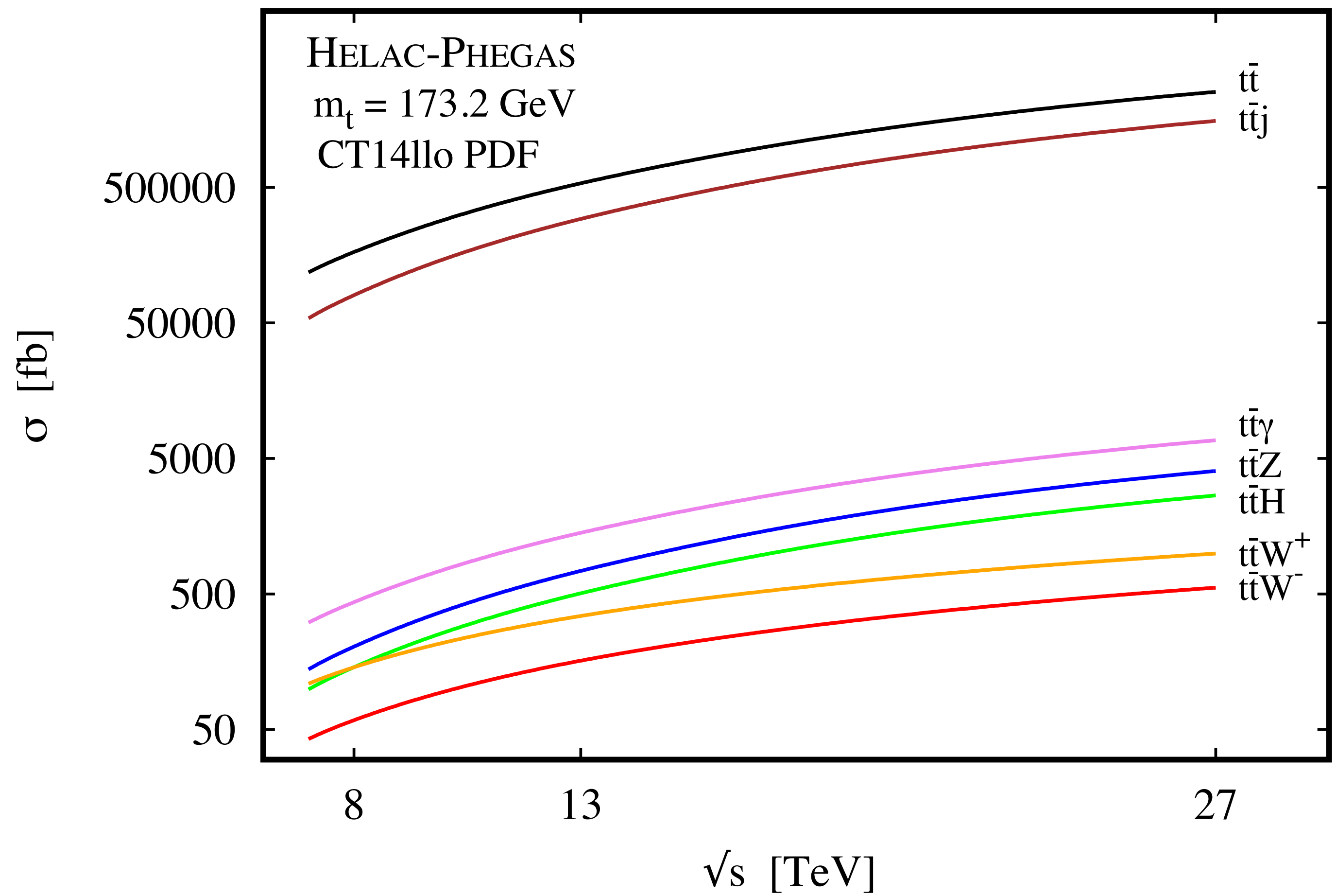
HELAC-PHEGAS

Cafarella, Papadopoulos, Worek '09

What about other processes ?

Stable top quarks

tt, ttj, ttγ, ttZ, ttH, ttW⁺, ttW⁻ @ LHC



HELAC-PHEGAS

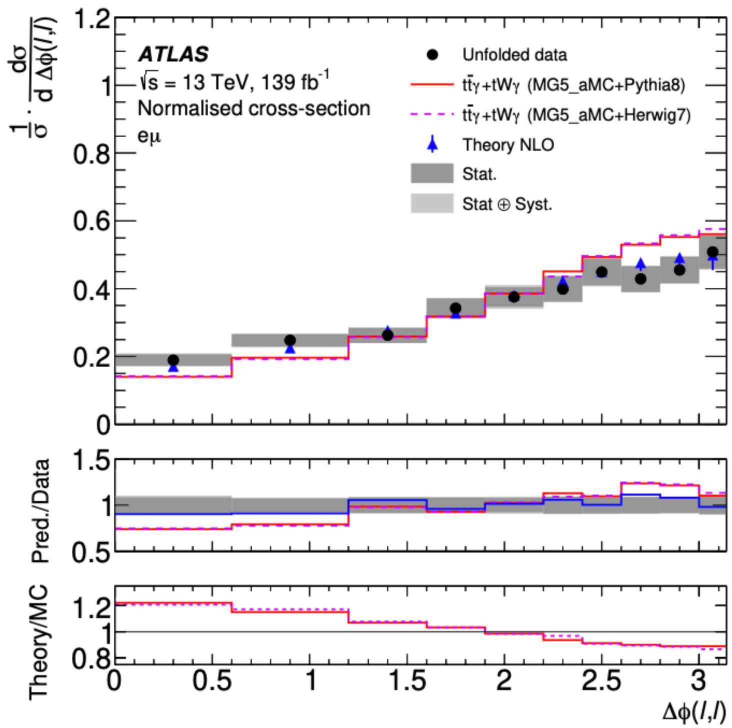
Cafarella, Papadopoulos, Worek '09

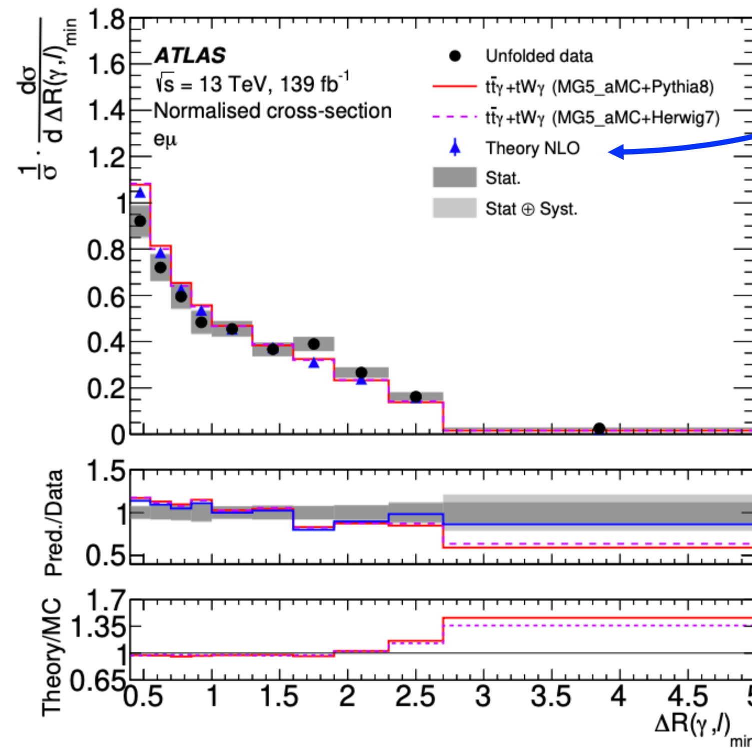
Combined $t\bar{t}\gamma + tW\gamma$ production

eμ channel

ATLAS Collaboration '20
JHEP 09 (2020) 049

HELAC-NLO





Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\|\eta(\gamma)\|$ χ^2/ndf	$\|\eta(\gamma)\|$ 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	$\|\Delta\eta(\ell,\ell)\|$ χ^2/ndf	$\|\Delta\eta(\ell,\ell)\|$ 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

State-of-the-art NLO QCD results with off-shell top quarks

NWA & Off-Shell Effects

Complete off-shell effects

- Off-shell top quarks are described by Breit-Wigner propagators
- Double-, single- as well as non-resonant top-quark contributions are included
- All interference effects consistently incorporated at the matrix element level

NWA

- Works in the limit ⇨ $\boldsymbol{\Gamma_t/m_t \to 0}$

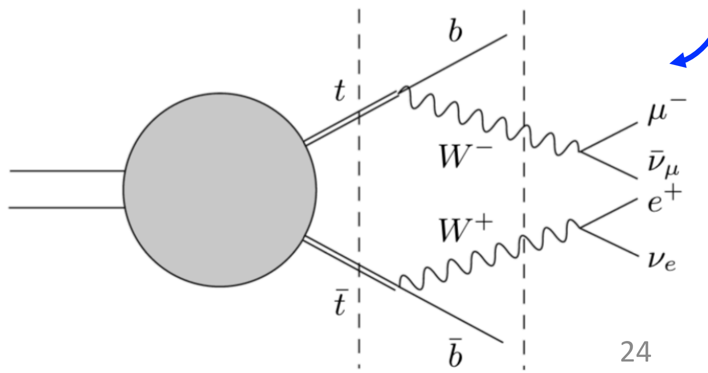
$$\boldsymbol{\Gamma_t = 1.35159 \text{ GeV}, \; m_t = 173.2 \, \text{GeV}, \; \Gamma_t/m_t \approx 0.008}$$

- Incorporates only double resonant contributions
- Restricts the unstable top quarks (W gauge bosons) to on-shell states

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

$$\frac{1}{\left(p_t^2 - m_t^2\right)^2 + m_t^2\Gamma_t^2} \xrightarrow{\Gamma_t/m_t \to 0} \frac{\pi}{m_t\Gamma_t}\,\delta\left(p_t^2 - m_t^2\right) + \mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

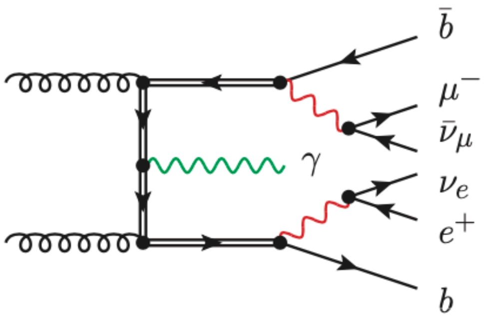
$$d\sigma_{t\bar{t}}^{\text{NWA}} = d\sigma_{t\bar{t}}\, d\mathcal{B}_{t \to be^+\nu_e}\, d\mathcal{B}_{\bar{t} \to \bar{b}\mu^-\bar{\nu}_\mu}$$



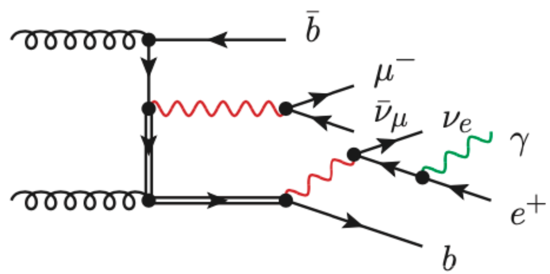
NWA & Off-Shell Effects

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

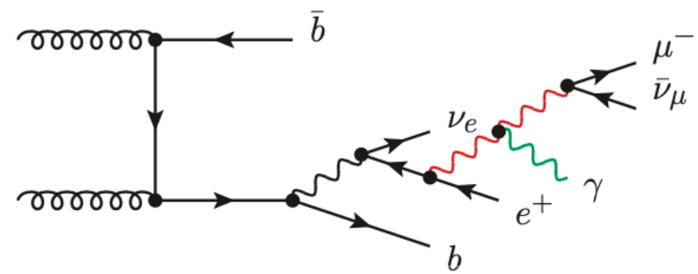
- Feynman Diagrams ⇨ *628* @ LO for gg channel versus *38* in NWA
- *8* diagrams with photon in production and *30* in decay stage



two top-quark resonances



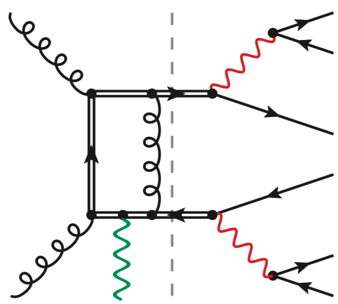
one top-quark resonance

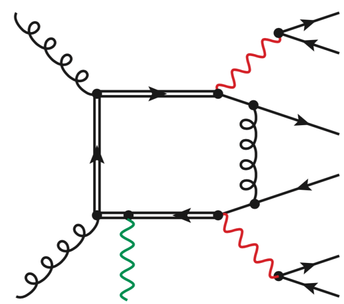


no top-quark resonances

- NLO ⇨ *4348* real emission *& 36032* @ 1-loop for gg channel
- Most complicated ⇨ *90* heptagons *& 958* hexagons

ttγ in NWA
up to pentagons





ttγ full
up to heptagons

$pp \to t\bar{t}\gamma + X$ @ $\mathcal{O}(\alpha_s^3\alpha^5)$

Top-Quark Resonances

- Putting simply $\Gamma_t \neq 0$ violates gauge invariance
- Gauge-invariant treatment ⇨ ***Complex Mass Scheme***
- In the amplitude the substitution is performed for top quark

$$(\not{p} - m_t + i\epsilon)^{-1} \longrightarrow (\not{p} - \mu_t + i\epsilon)^{-1}$$

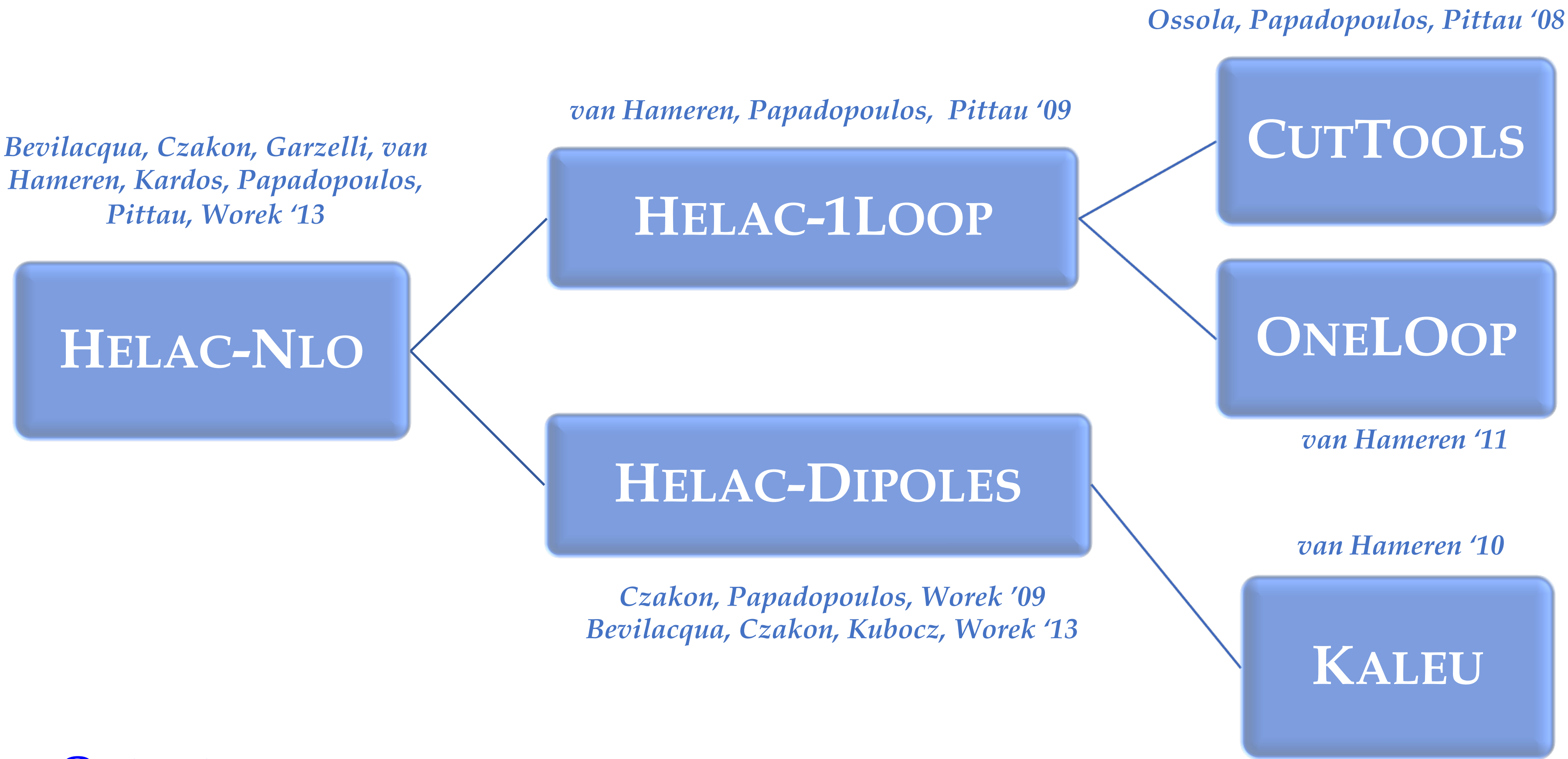
$$\mu_t^2 = m_t^2 - i\, m_t \Gamma_t$$

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

- All matrix elements evaluated using complex masses
- Another non trivial aspect ⇨ Evaluation of one-loop scalar integrals
- Scalar integrals with complex masses ⇨ Supported e.g. by **ONELOOP**

van Hameren '11

HELAC-NLO



- **Output:**
  - Theoretical predictions are stored in the form of the **Ntuples Files** and modified **Les Houches & ROOT Files**
  - Kinematical cuts can be changed
  - New observables can be defined
  - Renormalization or factorization scales & PDF sets can be changed

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

How Good Is the NWA ?

- Should be accurate for sufficiently inclusive observables $\mathcal{O}(\Gamma_t/m_t) \approx 0.8\%$
- Off-shell effects for integrated fiducial σ_{tt} ⇨ ***at few % level*** @ NLO in QCD

• ***tt*** *(di-lepton)*	*Denner, Dittmaier, Kallweit, Pozzorini '11 '12* *Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11* *Frederix '14* *Heinrich, Maier, Nisius, Schlenk, Winter '14* *Denner, Pellen '16 (EW+QCD)* *Jezo, Lindert, Nason, Oleari, Pozzorini '16 (PS)*
• ***ttH*** *(di-lepton)*	*Denner, Feger '15* *Denner, Lang, Pellen, Uccirati '17 (EW+QCD)*
• ***ttj*** *(di-lepton)*	*Bevilacqua, Hartanto, Kraus, Worek '16 '18*
• $tt\gamma$ *(di-lepton)*	*Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20*
• $ttZ,\ Z \to \nu_l \nu_l$ *(di-lepton)*	*Bevilacqua, Hartanto, Kraus, Weber, Worek '19*
• $ttW^{\pm}$ *(di-lepton)*	*Bevilacqua, Bi, Hartanto, Kraus, Worek '20* *Denner, Pellicciioli '20*
• ***ttbb*** *(di-lepton)*	*Denner, Lang, Pellen '20*

ttγ production @ LHC

Questions:

- Size of NLO QCD corrections ⇨ $\sigma_{t\bar{t}\gamma}$, $d\sigma_{t\bar{t}\gamma}/dX$
- Reduction of theoretical Uncertainties ⇨ $t\bar{t}\gamma/t\bar{t}$
- Applicability of the NWA ⇨ ***Importance of off-shell effects***

$t\bar{t}\gamma$ with dynamical scale ¼ H_T

HELAC-NLO

$$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma \text{ @ LHC}_{13\text{TeV}}$$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

PDF	$p_{T,b}$	$\sigma^{\rm LO}$ [fb]	δ_{scale}	$\sigma^{\rm NLO}$ [fb]	δ_{scale}	$\delta_{\rm PDF}$	$\mathcal{K} = \frac{NLO}{LO}$
CT	25	10.68	+3.54 (33%) −2.49 (23%)	11.19	+0.16 (1%) −0.54 (5%)	+0.32 (3%) −0.35 (3%)	1.05
	30	9.58	+3.18 (33%) −2.24 (23%)	9.93	+0.14 (1%) −0.54 (5%)	+0.28 (3%) −0.31 (3%)	1.04
	35	8.44	+2.80 (33%) −1.97 (23%)	8.69	+0.12 (1%) −0.50 (6%)	+0.25 (3%) −0.27 (3%)	1.03
	40	7.32	+2.45 (33%) −1.71 (23%)	7.50	+0.11 (1%) −0.45 (6%)	+0.22 (3%) −0.23 (3%)	1.02
MMHT	25	11.59	+4.22 (36%) −2.88 (25%)	11.29	+0.16 (1%) −0.57 (5%)	+0.24 (2%) −0.22 (2%)	0.97
	30	10.38	+3.78 (36%) −2.58 (25%)	10.02	+0.13 (1%) −0.58 (6%)	+0.22 (2%) −0.19 (2%)	0.97
	35	9.12	+3.33 (36%) −2.26 (25%)	8.77	+0.11 (1%) −0.54 (6%)	+0.19 (2%) −0.17 (2%)	0.96
	40	7.90	+2.89 (37%) −1.96 (25%)	7.57	+0.09 (1%) −0.48 (6%)	+0.16 (2%) −0.15 (2%)	0.96
NNPDF	25	10.78	+3.82 (35%) −2.62 (24%)	11.62	+0.17 (1%) −0.58 (5%)	+0.16 (1%) −0.16 (1%)	1.08
	30	9.65	+3.42 (35%) −2.34 (24%)	10.31	+0.14 (1%) −0.58 (6%)	+0.14 (1%) −0.14 (1%)	1.07
	35	8.48	+3.01 (35%) −2.05 (24%)	9.02	+0.12 (1%) −0.53 (6%)	+0.12 (1%) −0.12 (1%)	1.06
	40	7.34	+2.61 (36%) −1.78 (24%)	7.79	+0.10 (1%) −0.48 (6%)	+0.11 (1%) −0.11 (1%)	1.06

Stability w.r.t. $p_{T,b}$ cut

- NLO QCD corrections stable against $p_{T,b}$ cut
- CT14 PDF uncertainties similar/smaller than difference between various PDF sets (also at the differential level)
- Similar results for $p_{T,\gamma}$ *cut*

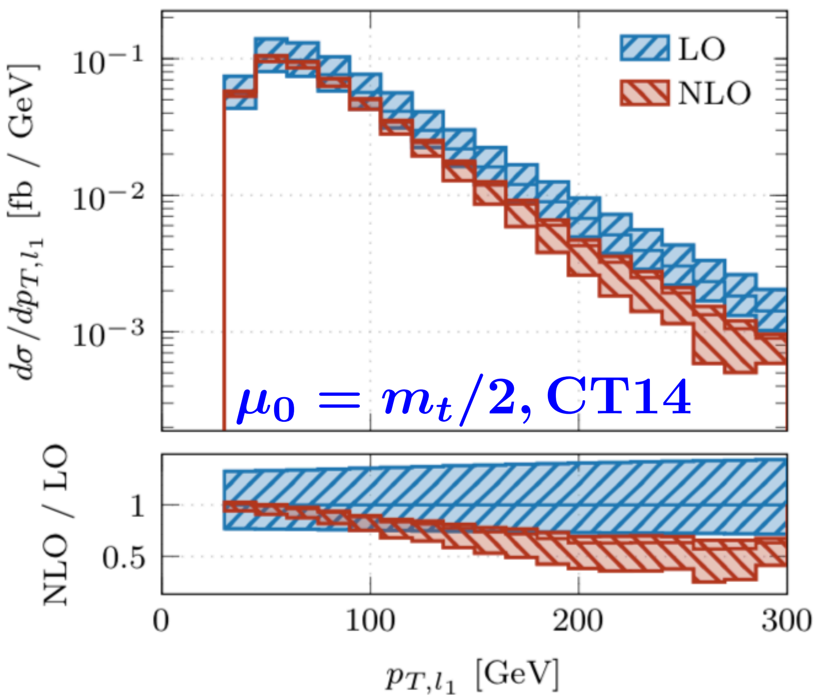
$$H_T = p_{T,\,e^+} + p_{T,\,\mu^-} + p_{T,\,j_b} + p_{T,\,j_b} + p_T^{miss} + p_{T,\,\gamma}$$

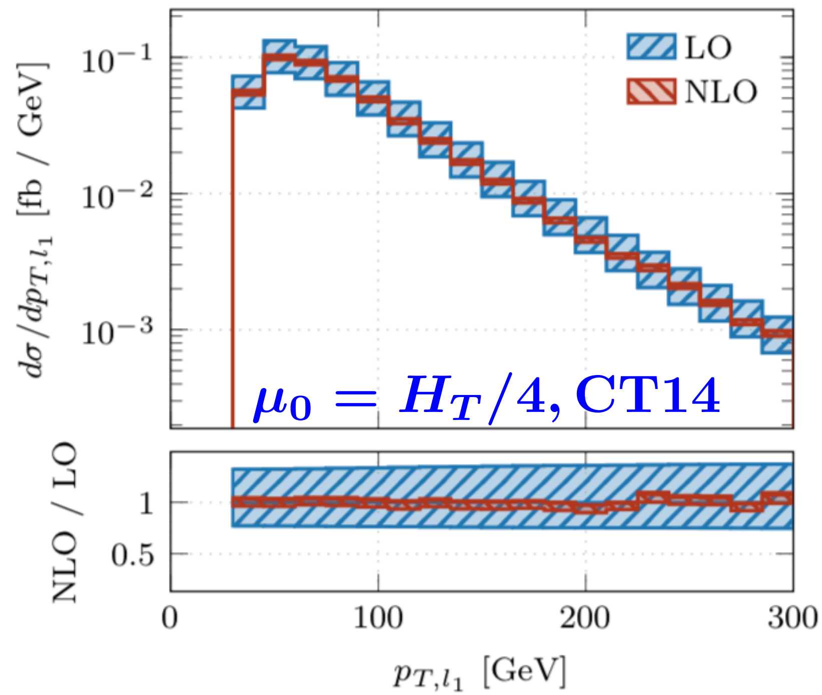
$t\bar{t}\gamma$ with dynamical scale H_T

HELAC-NLO

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

$$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma \text{ @ LHC}_{13\text{TeV}}$$





- NLO Corrections up to *- 43%*
- Theoretical uncertainties up to *± 56%*

- NLO Corrections up to *+ 8%*
- Error reduced down to *± 7%*

Dynamical scale very effective in stabilizing perturbative convergence !
Provides smaller theoretical error !

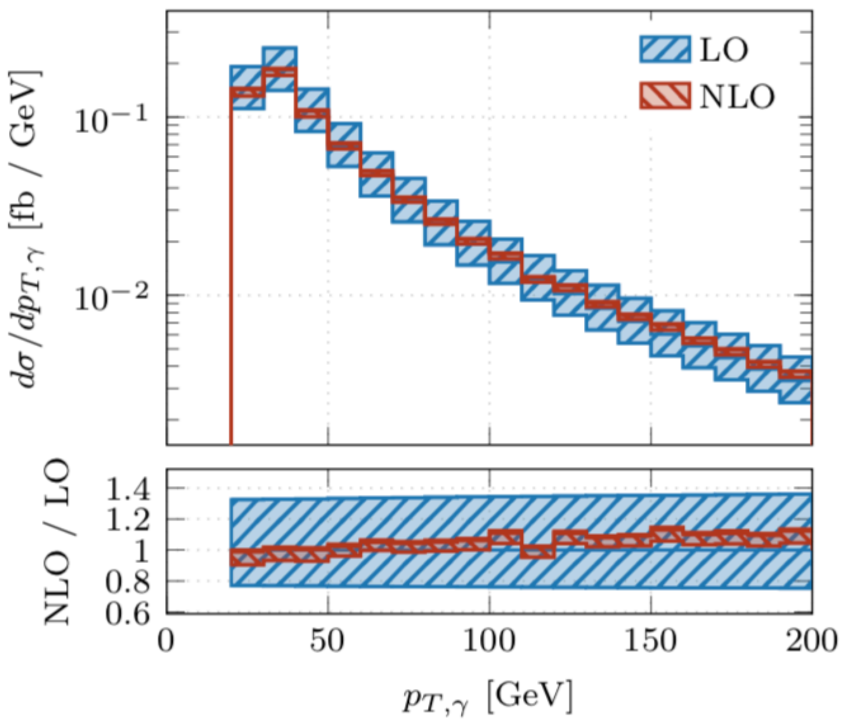
ttγ with dynamical scale H_T

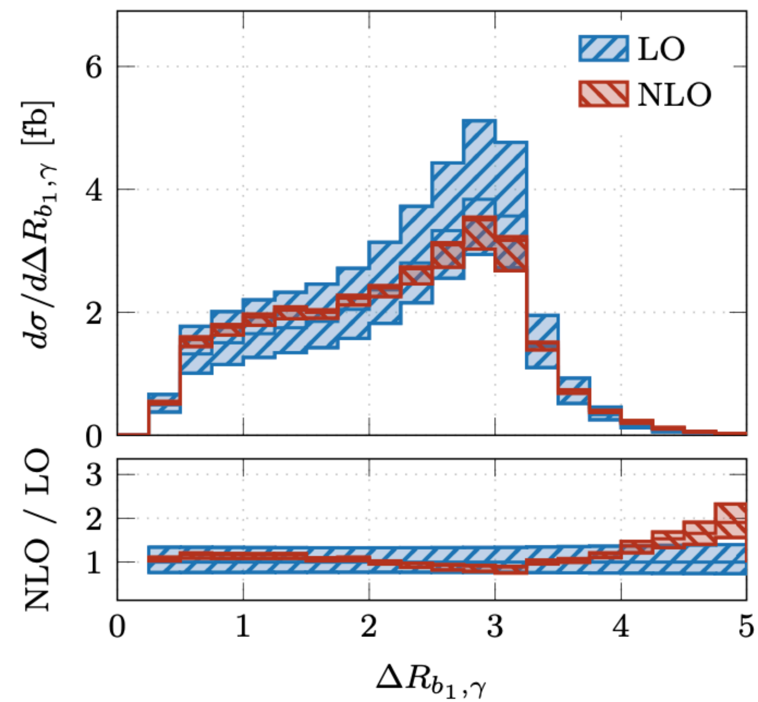
HELAC-NLO

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC}_{13\mathrm{TeV}}$

$\mu_0 = H_T/4, \mathrm{CT14}$





- *Positive NLO corrections up to 13%*
- NLO error bands within LO
- Theoretical error up to ± *8%*

Not all differential K-factors are flat even with μ_0 = ¼ H_T !

$t\bar{t}\gamma/t\bar{t}$

- Fiducial integrated $\sigma_{t\bar{t}\gamma}$ with dynamical scale ⇨ theoretical error of ± *6%*
- Fiducial differential $d\sigma_{t\bar{t}\gamma}/dX$ ⇨ theoretical error ± *(10% - 30%)*
- Can we decrease theoretical error even further for $t\bar{t}\gamma$ without going to NNLO ?
- ***Answer is yes !***

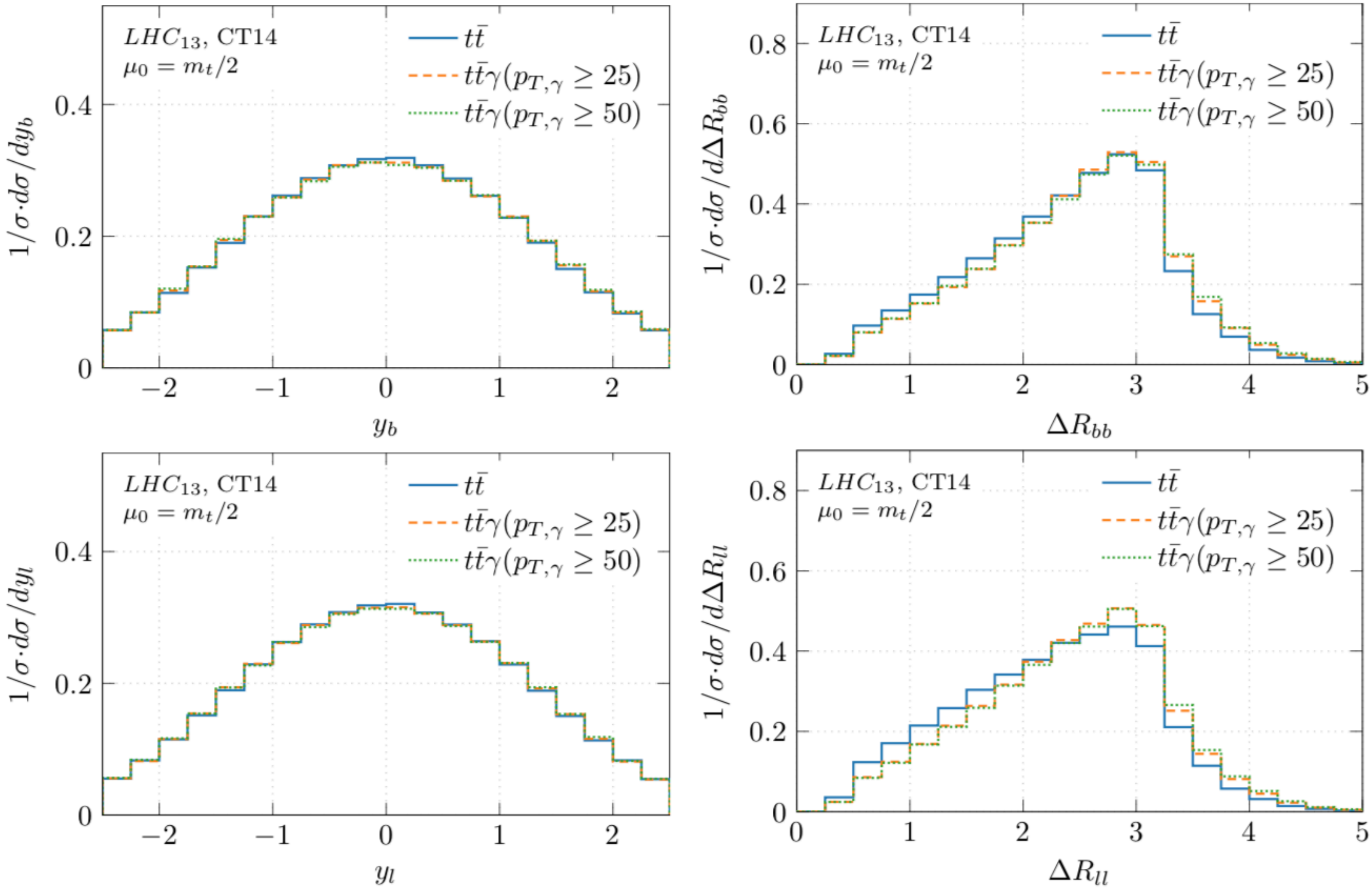
$\mathcal{R} = \dfrac{\sigma^{\rm NLO}_{t\bar{t}\gamma}(\mu_1)}{\sigma^{\rm NLO}_{t\bar{t}}(\mu_2)}$	$\mathcal{R}_X = \left(\dfrac{d\sigma^{\rm NLO}_{t\bar{t}\gamma}(\mu_1)}{dX}\right)\left(\dfrac{d\sigma^{\rm NLO}_{t\bar{t}}(\mu_2)}{dX}\right)^{-1}$

- $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$ we have ± *(1% - 3%)* ⇨ Differential cross section ratios ± *(1% - 6%)*
- ***High precision comparable to NNLO QCD results for top quark physics !***
- Processes need to be correlated ⇨ top quark pair production excellent candidate
- Similar dynamical scale choice need to be implemented for μ_1 & μ_2 !

$tt\gamma$ & tt

HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathbf{LHC_{13TeV}}$



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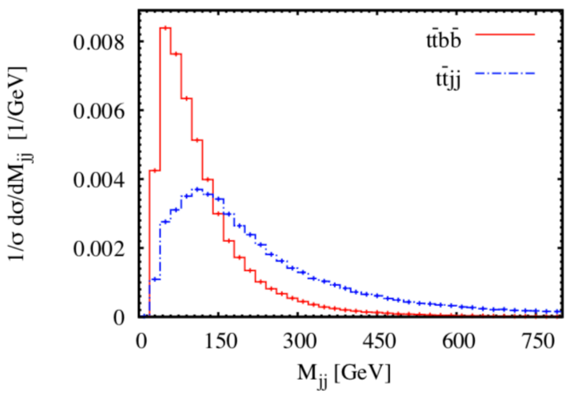
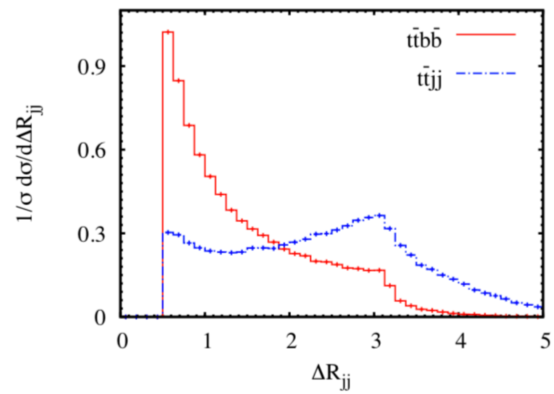
ttbb & ttjj

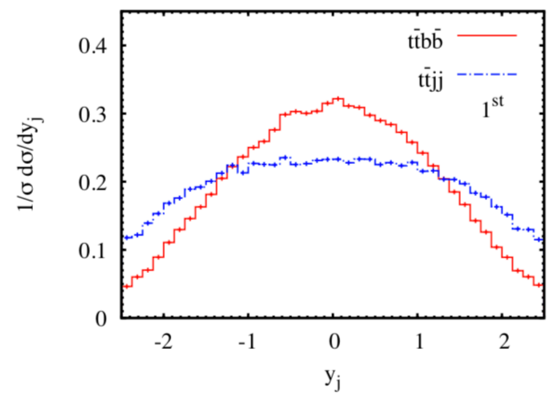
Stable top quarks

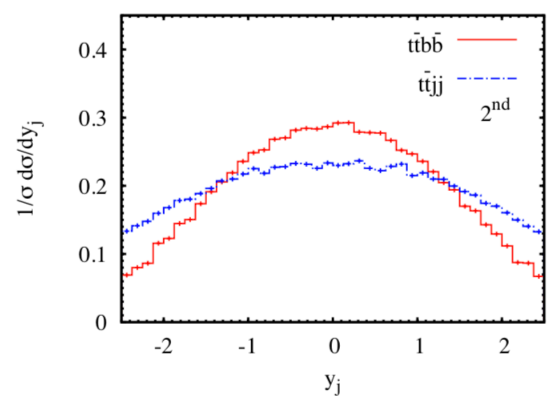
$t\bar{t}b\bar{b}$ & $t\bar{t}jj$ @ $\mathrm{LHC}_{8\mathrm{TeV}}$

HELAC-NLO









- Different jet kinematics makes the *ttbb* and *ttjj* processes uncorrelated in several observables
- Scale uncertainty is not significantly reduced when taking ratio of cross sections

Bevilacqua, Worek '14

$t\bar{t}\gamma/t\bar{t}$

$$\mathcal{R} = \frac{\sigma^{\rm NLO}_{t\bar{t}\gamma}(\mu_1)}{\sigma^{\rm NLO}_{t\bar{t}}(\mu_2)}$$

HELAC-NLO

$$\mathcal{R}\,(\mu_0 = m_t/2, {\rm CT14}, p_{T,\gamma} > 25\,{\rm GeV}) = (4.56 \pm 0.25)\cdot 10^{-3}\,(5\%)\,,$$

$$\mathcal{R}\,(\mu_0 = H_T/4, {\rm CT14}, p_{T,\gamma} > 25\,{\rm GeV}) = (4.62 \pm 0.06)\cdot 10^{-3}\,(1\%)\,,$$

$$\mathcal{R}(\mu_0 = m_t/2, {\rm CT14}, p_{T,\gamma} > 50\,{\rm GeV}) = (1.89 \pm 0.16)\cdot 10^{-3}\,(8\%)\,,$$

$$\mathcal{R}(\mu_0 = H_T/4, {\rm CT14}, p_{T,\gamma} > 50\,{\rm GeV}) = (1.93 \pm 0.06)\cdot 10^{-3}\,(3\%)\,.$$

- ***Uncertainties stable against $p_{T,\gamma}$ cut ⇨ 25 GeV increased to 50 GeV***
- Our best NLO QCD predictions with dynamical scale choice:

$$\mathcal{R}\,(\mu_0 = H_T/4, {\rm CT14}, p_{T,\gamma} > 25\,{\rm GeV}) = (4.62 \pm 0.06\,[{\rm scales}] \pm 0.02\,[{\rm PDFs}])\cdot 10^{-3}$$

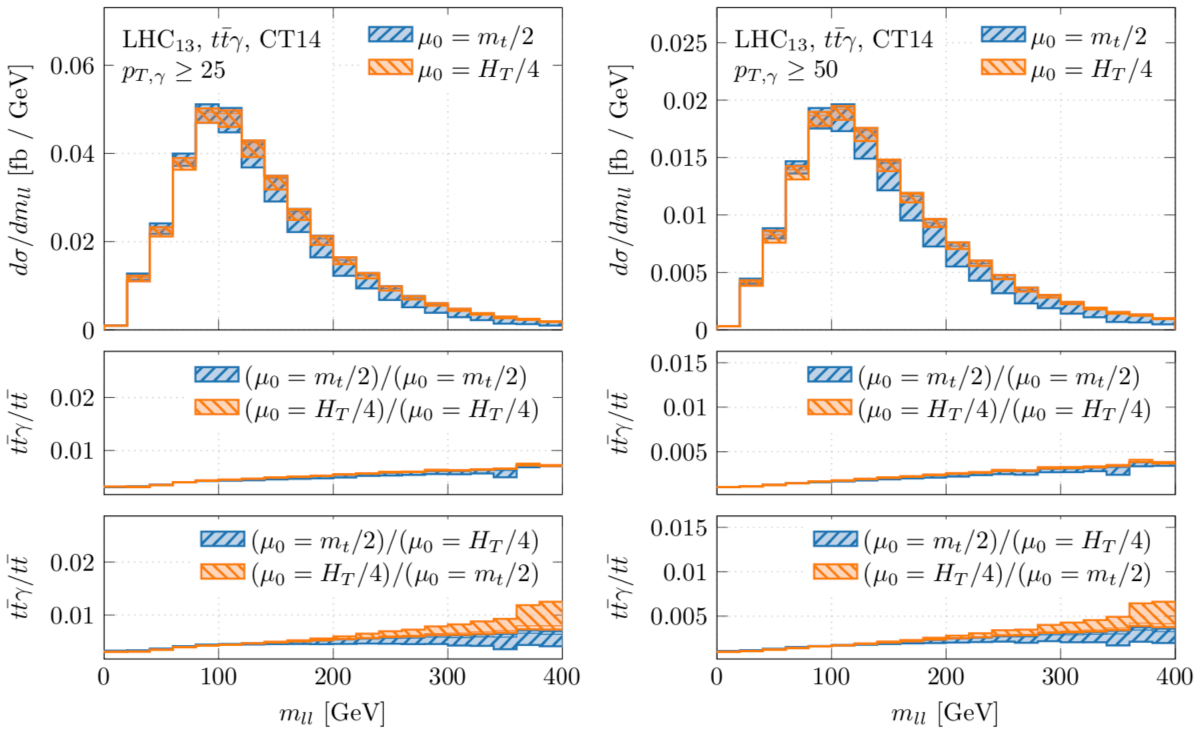
$$\mathcal{R}(\mu_0 = H_T/4, {\rm CT14}, p_{T,\gamma} > 50\,{\rm GeV}) = (1.93 \pm 0.06\,[{\rm scales}] \pm 0.02\,[{\rm PDFs}])\cdot 10^{-3}\,,$$

Bevilacqua, Hartanto, Kraus, Weber, Worek '19

Differential Cross Section Ratio

Bevilacqua, Hartanto, Kraus, Weber, Worek '19

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC_{13TeV}}$



HELAC-NLO

Theoretical uncertainties:

± (1% – 4%) dynamical scale

± (20% – 25%) fixed scale

- Should be compared to uncertainties for absolute differential cross section
  - *up to ± 10% for $\mu_0 = H_T/4$ & up to ± 50% for $\mu_0 = m_t/2$*
- When different scales are used in numerator and denominator *up to ± 60%*

Fiducial Cross Section for $t\bar{t}\gamma$

HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC_{13TeV}}$

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

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

Various approaches for the modelling of top quark production & decays

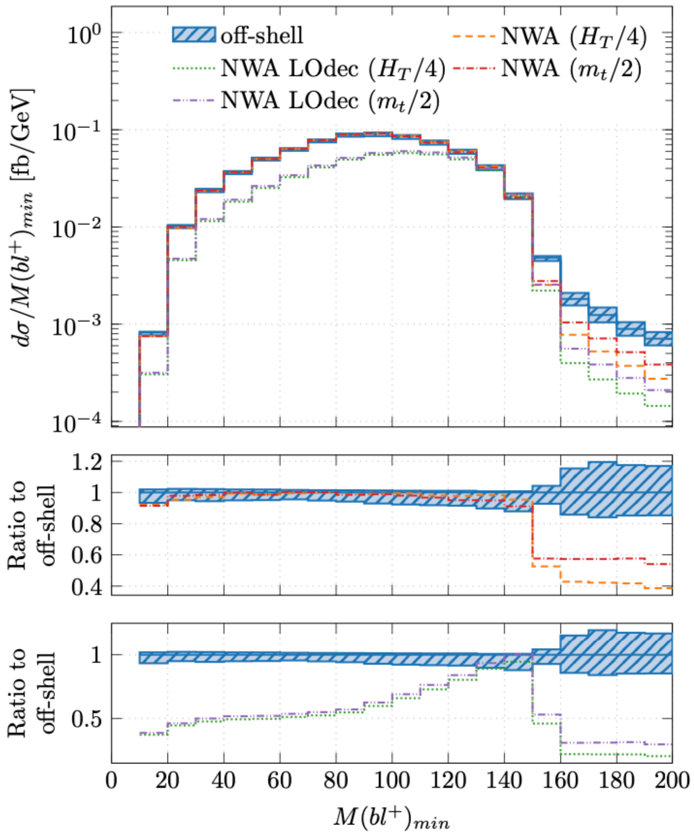
- Off-shell effects *3%*
- Consistent with $\Gamma_t/m_t \approx 0.8\%$
- *57%* ⇨ γ emitted in production
- *43%* ⇨ γ emitted in decay stage
- For $p_{T,b} > 25$ GeV it is *50%-50%*
- NLO QCD corrections to top quark decays are negative and not small
- *17%* ⇨ $\mu_0 = ½\, m_t$
- *12%* ⇨ $\mu_0 = ¼\, H_T$
- Theoretical uncertainties not underestimated for the full NWA
- They increase for $\mathrm{NWA}_{\mathrm{LOdecay}}$

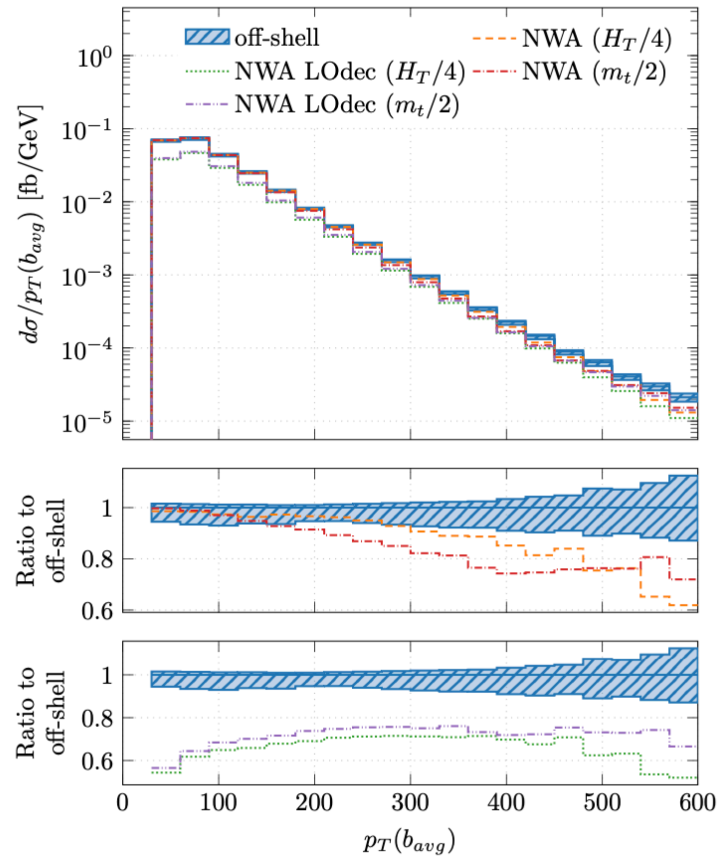
How Good Is the NWA ?

HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathbf{LHC_{13TeV}}$

- Dimensionful observables are sensitive to non-factorizable top quark corrections ⇨ *Tens of per cent* in specific phase-space regions
- *Kinematical thresholds / edges & high p_T regions*





Bevilacqua, Hartanto, Kraus, Weber, Worek '20

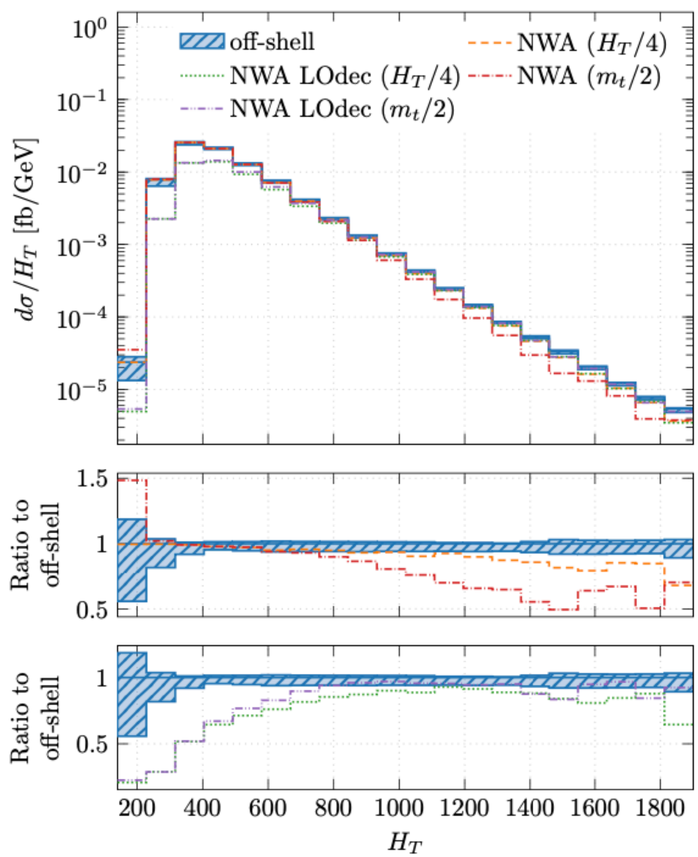
How Good Is the NWA ?

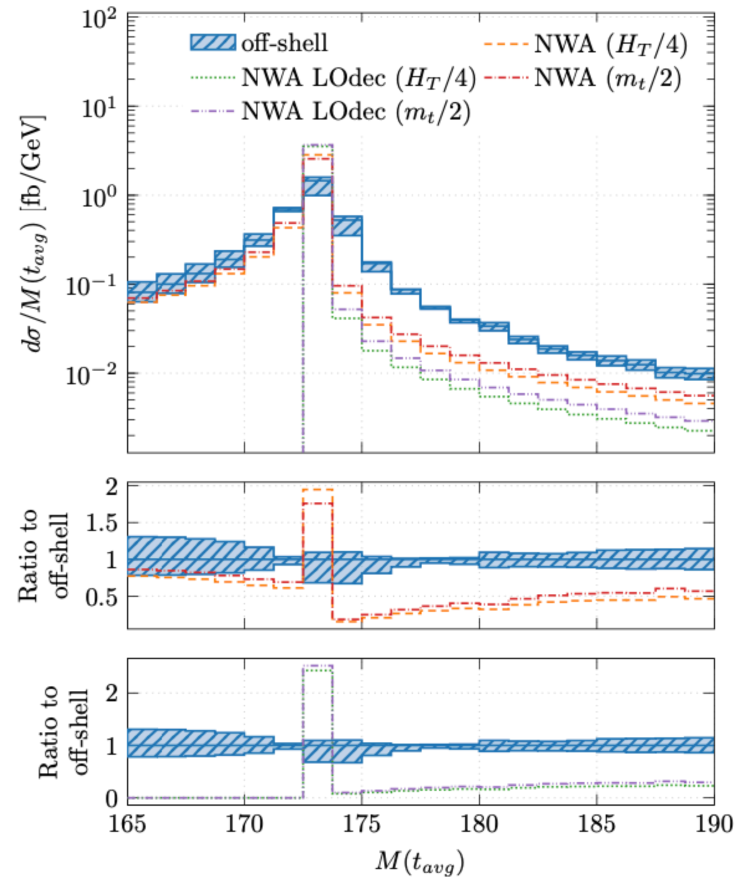
HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC_{13TeV}}$

- *Dimensionful* observables are sensitive to non-factorizable top quark corrections ⇨ *Tens of per cent* in specific phase-space regions
- *Kinematical edges & high p_T regions*

$t \to be^+\nu_e$ & $\bar{t} \to \bar{b}\mu^-\bar{\nu}_\mu$



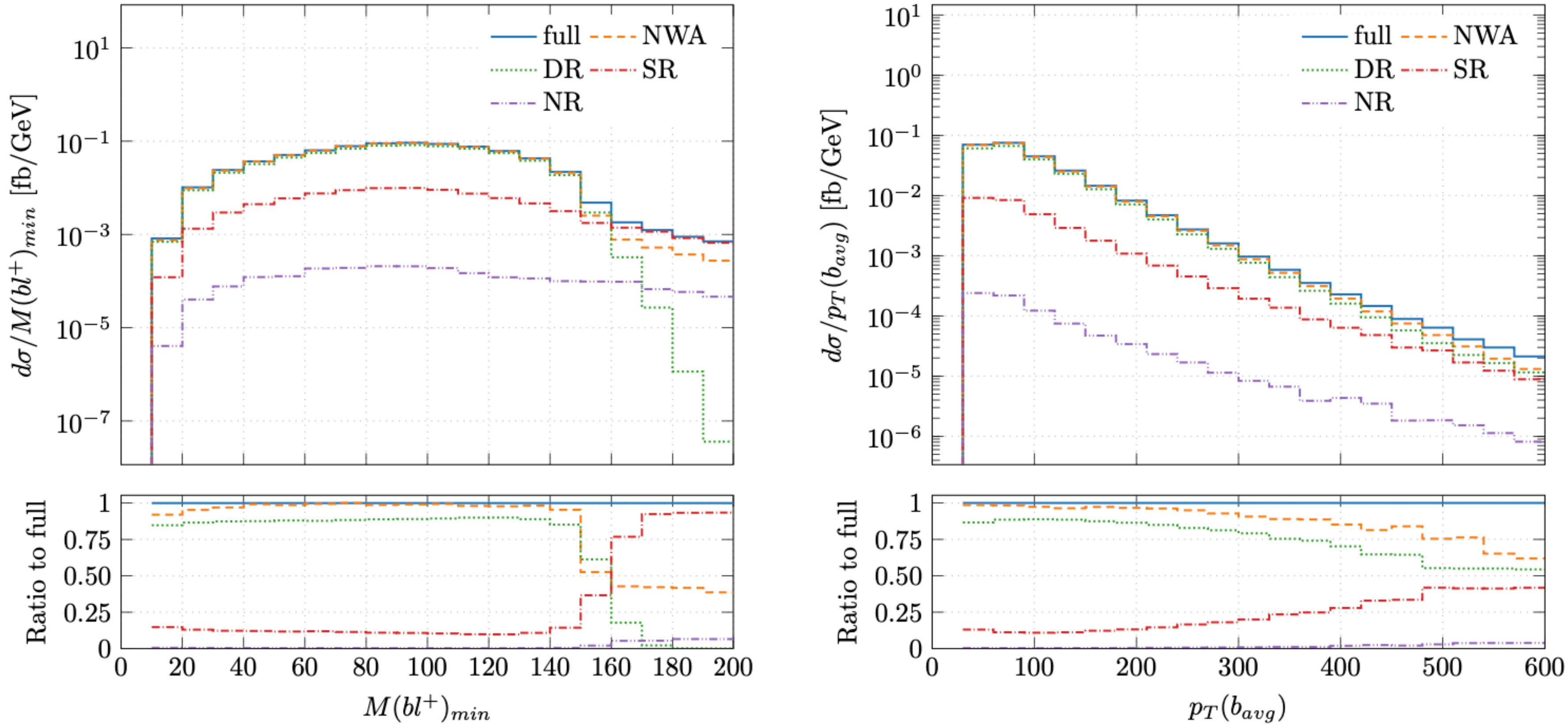


Bevilacqua, Hartanto, Kraus, Weber, Worek '20

Various Phase-space Regions

HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC}_{13\mathrm{TeV}}$

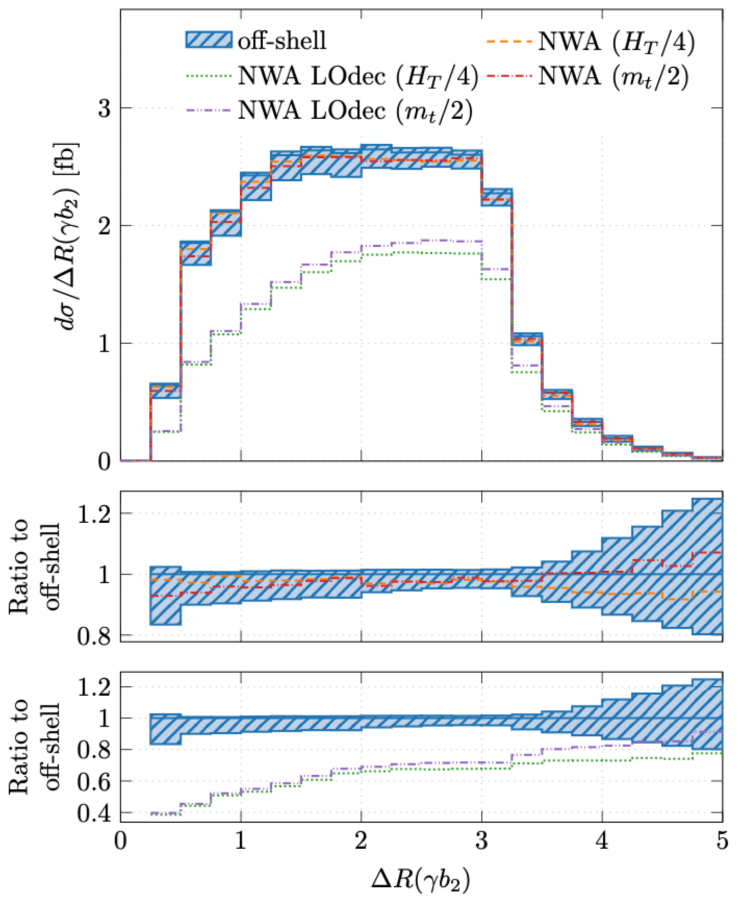


Bevilacqua, Hartanto, Kraus, Weber, Worek '20

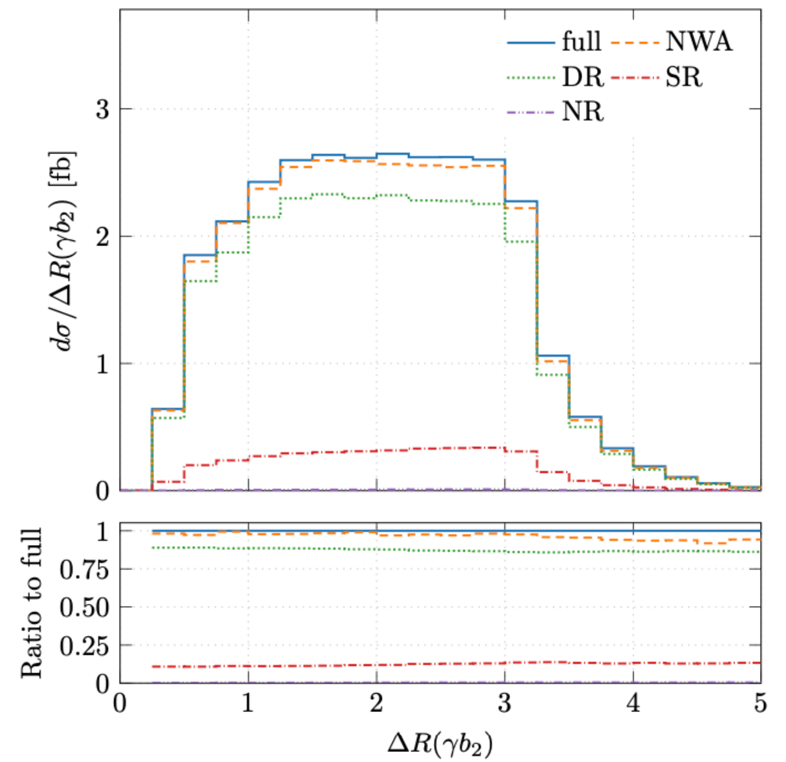
- ***Off-shell effects:***
  - High p_T region of various dimensionful observables
  - Vicinity of kinematical edges
  - Contribute up to ***50% – 60%***

Various Phase-space Regions

HELAC-NLO



$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ LHC$_{13\text{TeV}}$



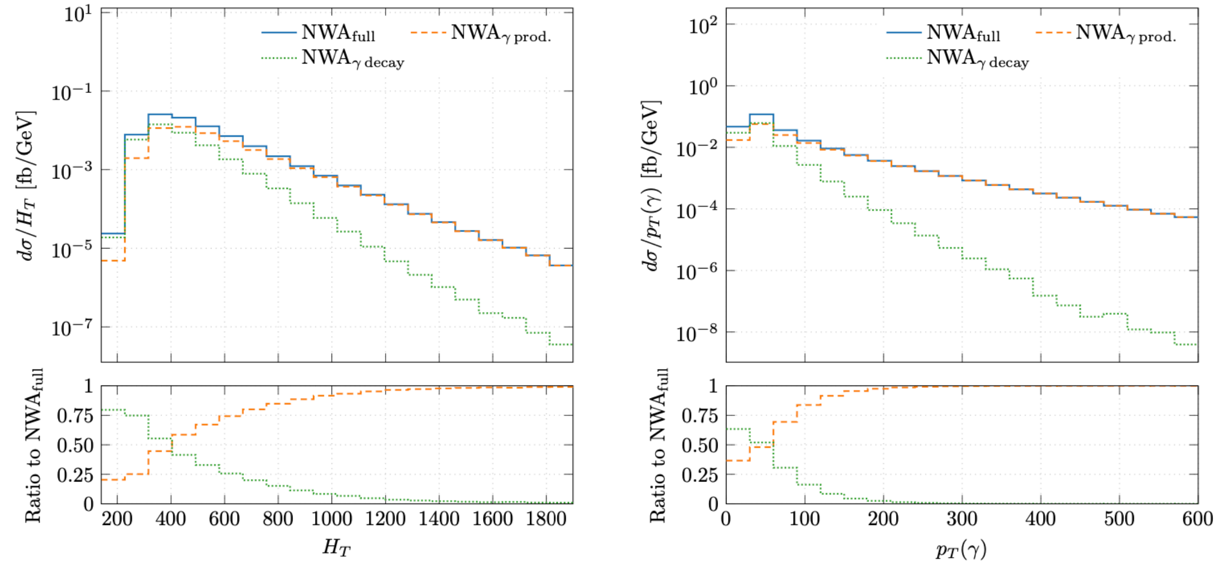
Bevilacqua, Hartanto, Kraus, Weber, Worek '20

- Observables sensitive to top quark off-shell effects ⇨ Substantial contributions from single top quark process

- ***Dimensionless observables rather insensitive to top quark off-shell effects***

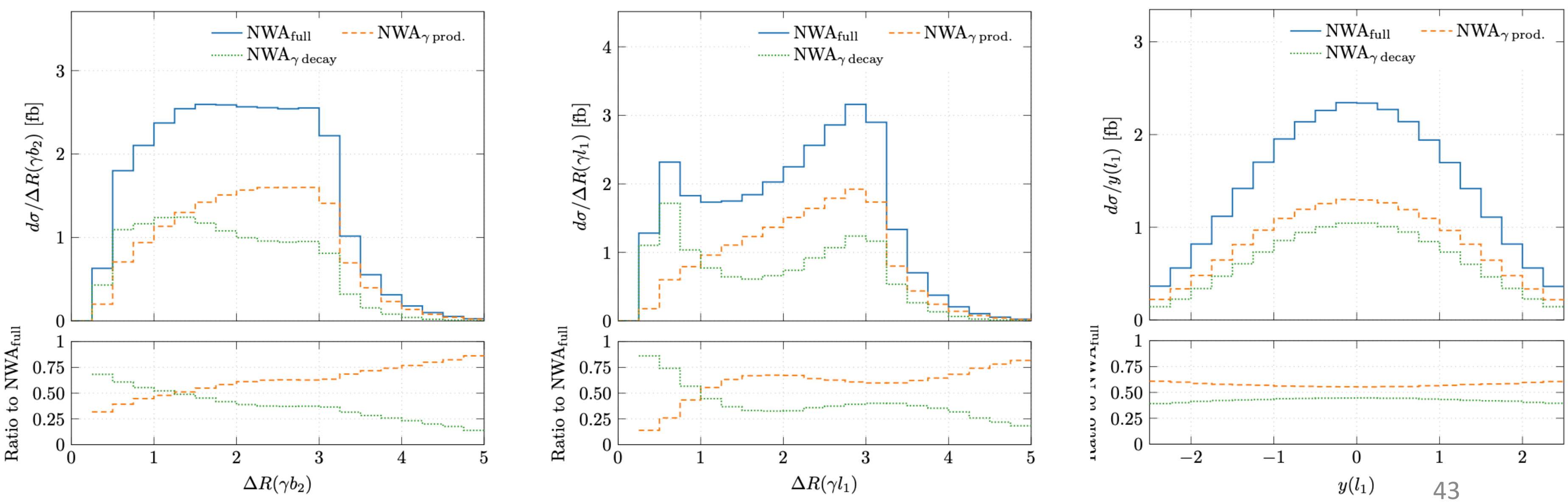
γ in Production & Decays ⇨ Differential Level

Bevilacqua, Hartanto, Kraus, Weber, Worek '20



HELAC-NLO

- Diverse picture
- Photon emission in decays can be reduced
  - $H_T > 400$ GeV
  - $p_T(\gamma) > 50$ GeV



$ttW^{\pm}$ *production @ LHC*

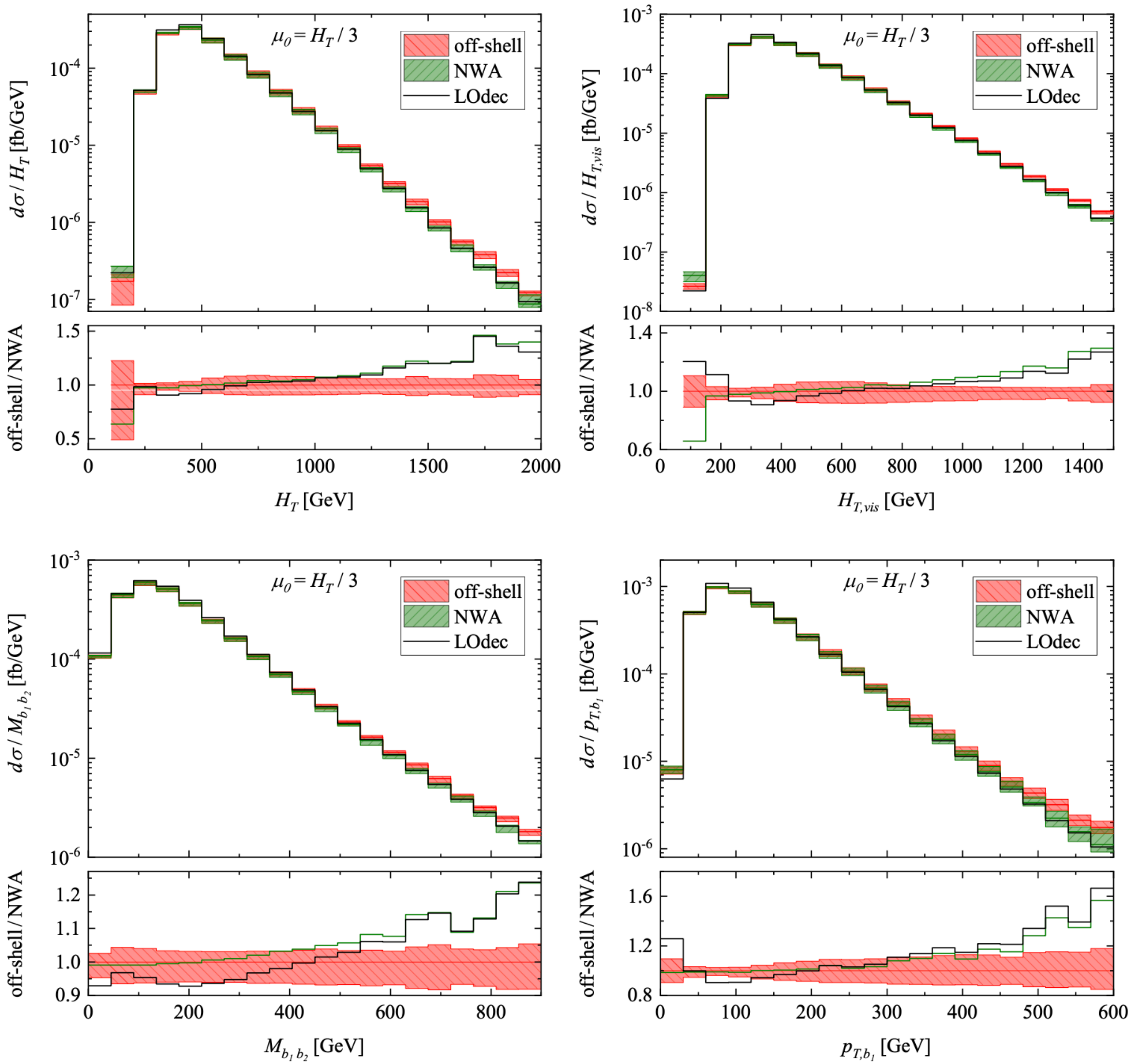
- Background process for ***ttH*** ⇨ Multi-lepton final state
- Higher normalization for ***ttW*** when compared to SM predictions given by multipurpose MC programs ⇨ ***30%−70%***
- Problems with modeling of the final states in the phase space regions dominated by ***ttW***

ATLAS-CONF-2019-045

ttW with dynamical scale

HELAC-NLO

$$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, b\bar{b}\, e^+\nu_e @\ \mathrm{LHC_{13TeV}}$$



Bevilacqua, Bi, Hartanto, Kraus, Worek '20

- Top-quark off-shell effects ***30% − 70%***
- Large discrepancies between full NWA description & $\mathrm{NWA_{LOdecay}}$
- Differences also in regions currently scrutinised by ATLAS & CMS experiments

ttZ production @ LHC

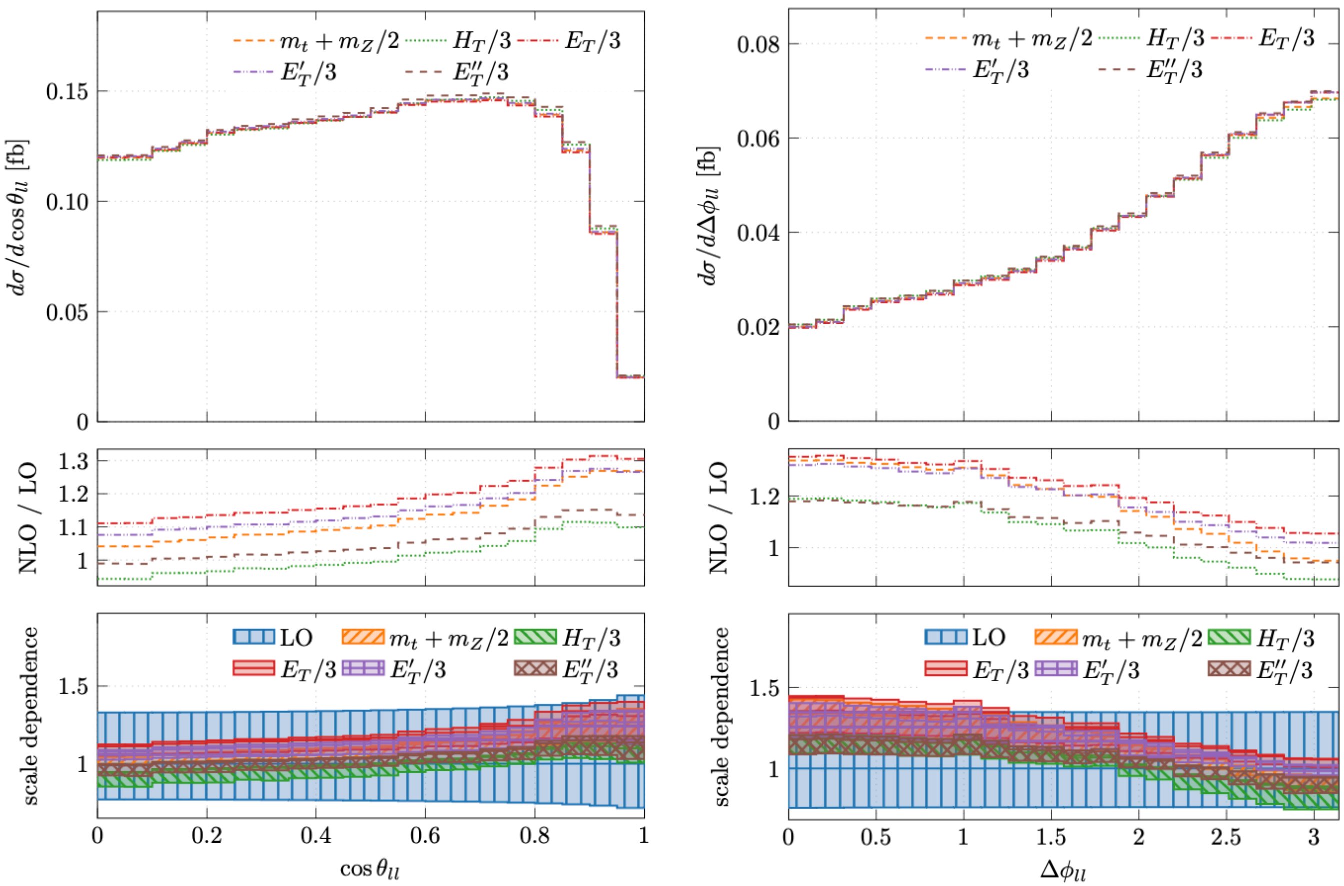
- Irreducible background process for $t\bar{t} + p_T^{miss}$

ttZ (Z → νν) with dynamical scale

HELAC-NLO

- Searches of new physics ⇨ $t\bar{t} + p_T^{miss}$
- New physics observables ⇨ p_T^{miss}, $\cos_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta y_{\ell\ell}$, H_T, E_T

$$e^{+}\nu_e\, \mu^{-}\bar{\nu}_\mu\, b\bar{b}\, \bar{\nu}_\tau \nu_\tau @\ \mathrm{LHC}_{13\mathrm{TeV}}$$



Bevilacqua, Hartanto, Kraus, Weber, Worek '19

- Uncertainties reduced when going from LO to NLO
- Substantial non-flat K-factors

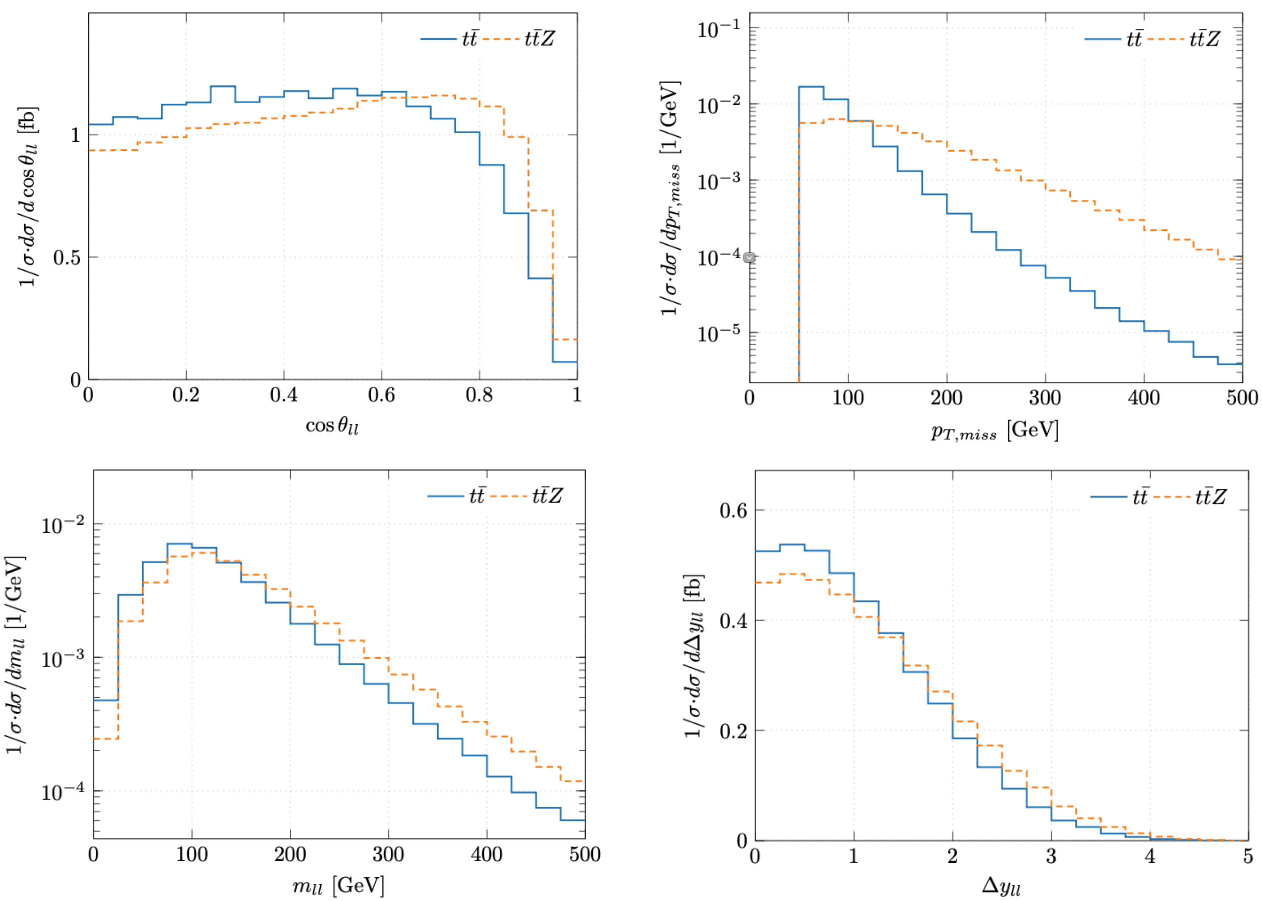
ttZ ($Z \rightarrow \nu\nu$) with dynamical scale

HELAC-NLO

- Searches of new physics ⇨ $t\bar{t} + p_T^{miss}$
- New physics observables ⇨ p_T^{miss}, $\cos_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta y_{\ell\ell}$, H_T, E_T

$$e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,\bar{\nu}_\tau\nu_\tau @\ \mathrm{LHC}_{13\mathrm{TeV}}$$

Bevilacqua, Hartanto, Kraus, Weber, Worek '19



- Reducible and irreducible backgrounds
- tt production process does not exhibit long enough tails in p_T^{miss}
- Might impact exclusion limits

Theoretical Predictions For ttV

- 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 electroweak***

- For more realistic studies decays are needed:

    - ***NLO QCD for ttV + PS*** ⇨ Corrections to production & Top decays in parton shower approximation & omitting even LO ***tt*** spin correlations

    - ***NLO QCD for ttV + LO decays + PS*** ⇨ Top decays @ LO before matched to parton shower programs & LO ***tt*** spin correlations

    - ***NLO QCD in NWA*** ⇨ NLO QCD corrections to top production & decays & NLO ***tt*** spin correlations

    - ***NLO QCD complete off-shell effects of top quarks*** ⇨ Additionally to the previous point ⇨ Resonant & non-resonant diagrams & Interference effects & Off-shell top quarks described by Breit-Wigner propagators

Summary

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

- NLO QCD corrections to ***ttV***
  - At least full NWA or better yet complete off-shell effects for top quarks
    1. Corrections to production & decays ⇨ NLO ***tt*** spin correlations
    2. Possibility of using kinematic-dependent μ_R & μ_F scales
    3. Complete off-shell effects for top quarks

- ***Even more important for:***
  - Exclusive cuts & High luminosity measurements
  - New Physics searches & Might impact 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***

- Our full off-shell results for ***tt, ttj, ttγ, ttZ,*** $ttW^{\pm}$
  - Stored ⇨ ***Ntuples Files*** ⇨ ***Les Houches & ROOT Files***
  - ***ttγ*** ⇨ Used by ATLAS Collaboration ⇨ ***JHEP 09 (2020) 049***

Backup

Various Phase-space Regions

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC}_{13\mathrm{TeV}}$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

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

- Compute for each history Q and pick the one that minimises the Q value

$$Q = |M(t) - m_t| + |M(\bar{t}) - m_t|$$

- *Double-resonant (DR):* $|M(t) - m_t| < n\,\Gamma_t\,,$ and $|M(\bar{t}) - m_t| < n\,\Gamma_t$

- *Two single-resonant regions (SR):*

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

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

- *Non-resonant region (NR):*

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

Various Phase-space Regions

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathbf{LHC_{13TeV}}$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

- ***n* = 15** ⇨ Boundaries outside which effects of Γ_t in BW propagator < 1%
- DR region is set to for m_t = ***173.2 GeV***

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

- Contributions at the integrated cross section level for these 3 regions

$\sigma^{\rm NLO}_{\rm DR} = 6.57$ fb ,	$\sigma^{\rm NLO}_{\rm SR} = 0.91$ fb ,	$\sigma^{\rm NLO}_{\rm NR} = 0.02$ fb

- DR contribution to full $\sigma_{t\bar{t}\gamma}$ ⇨ ***88%*** ⇨ SR comprises ***12%*** ⇨ NR only ***0.5%***
- Should we instead use ***n* = 5**

$$\sigma^{\rm NLO}_{\rm DR} = 4.82 \text{ fb}, \ \sigma^{\rm NLO}_{\rm SR} = 2.50 \text{ fb and } \sigma^{\rm NLO}_{\rm NR} = 0.18 \text{ fb}$$

- DR = 64%, SR = 33%, NR = 3%

$t\bar{t}\gamma$

- Cuts on the transverse momenta and the rapidity of two recombined b-jets, which we assume to be always tagged ⇨ ***Anti-k_T with R = 0.4***

$p_T(b) > 40$ GeV,	$\lvert y(b)\rvert < 2.5,$	$\Delta R(bb) > 0.4$

- Isolated hard photon

$p_T(\gamma) > 25$ GeV	$\lvert y(\gamma)\rvert < 2.5$

- Basic selection cuts for charged leptons to ensure that they are observed inside the detector and well separated from each other

$p_T(\ell) > 30$ GeV ,	$\Delta R(\ell\ell) > 0.4\,,$	$\lvert y(\ell)\rvert < 2.5$

- Charged leptons are well separated from the isolated photon and from b-jets

$\Delta R(\ell b) > 0.4\,,$	$\Delta R(\ell\gamma) > 0.4\,,$	$\Delta R(b\gamma) > 0.4$

$t\bar{t}\gamma$

- Different lequipment lepton generations

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC}_{13\mathrm{TeV}}$

- Interference effects neglected ⇨ ***Per-mille level @ LO***
- Contribution from b quarks in the initial state neglected ⇨ ***Effect < 0.1% @ LO***
- ***2 b-jets, one photon, two charged leptons & p_T^{miss}***
- Photon: $p_T(\gamma) > 25~\mathrm{GeV}, |y_\gamma| < 2.5$
- Isolation condition for photon ⇨ Reject event if $R \leq R_{\gamma j}$ with $R_{\gamma j} = 0.4$

Frixione '98

$$\sum_i E_{T,i}\,\Theta(R - R_{\gamma i}) \leq E_{T,\gamma}\left(\frac{1-\cos(R)}{1-\cos(R_{\gamma j})}\right)$$

- For hard photon $\alpha = \alpha(0) = 1/137$ ⇨ ***Predictions decreased by 3%***
- Electroweak coupling in the G_μ scheme ⇨ Account for some electroweak effects
- Kinematics-independent & kinematic-dependent scale: $\mu_0 = m_t/2, H_T/4$

ttW with dynamical & fixed scale

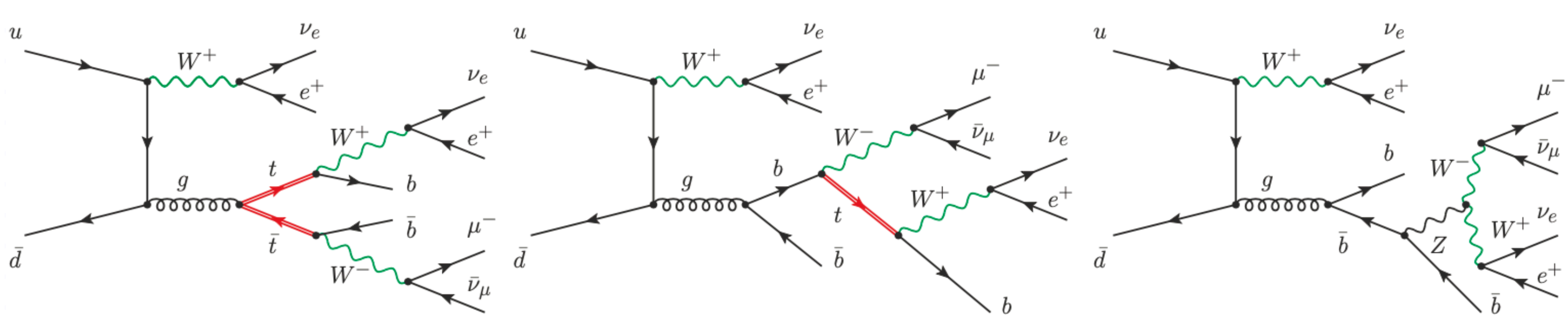
HELAC-NLO

Bevilacqua, Bi, Hartanto, Kraus, Worek '20

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

Results for various approaches for modelling of top quark production and decays

- Complete top-quark off-shell effects ⇨ ***0.2%***
- NLO QCD corrections to top-quark decays ⇨ ***3%*** for fixed scale ⇨ ***5%*** for dynamical scale
- Theoretical uncertainties are similar for off-shell case and NWA ⇨ ***6% − 7%***
- For $\rm NWA_{LOdecay}$ ⇨ Rise up to ***10% − 11%***



Top Quark Width

- Finite W width contributions included in matrix elements & in top quark width
- *Top width for unstable W bosons, neglecting bottom quark mass @ LO & NLO*

$$\Gamma_{\rm t}^{\rm LO} = \frac{G_\mu m_{\rm t}^5}{16\sqrt{2}\pi^2 M_{\rm W}^2} \int_0^1 \frac{{\rm d}y\, \gamma_{\rm W}}{(1-y/\bar{y})^2+\gamma_{\rm W}^2} F_0(y)$$

M. Jezabek, J. H. Kühn '89
A. Denner, et al. '12

$$\gamma_{\rm W} = \Gamma_{\rm W}/M_{\rm W},\ \bar{y} = (M_{\rm W}/m_{\rm t})^2 \qquad F_0(y) = 2(1-y)^2(1+2y)$$

$$\Gamma_{\rm t}^{\rm NLO} = \frac{G_\mu m_{\rm t}^5}{16\sqrt{2}\pi^2 M_{\rm W}^2} \int_0^1 \frac{{\rm d}y\, \gamma_{\rm W}}{(1-y/\bar{y})^2+\gamma_{\rm W}^2} \left[F_0(y) - \frac{2\alpha_{\rm s}}{3\pi} F_1(y)\right]$$

$$\begin{aligned} F_1(y) = {} & 2(1-y)^2(1+2y)\left[\pi^2 + 2\,{\rm Li}_2(y) - 2\,{\rm Li}_2(1-y)\right] \\ & + 4y(1-y-2y^2)\ln(y) + 2(1-y)^2(5+4y)\ln(1-y) \\ & - (1-y)(5+9y-6y^2). \end{aligned}$$

- In the limit $\gamma_W \longrightarrow 0$

$$\frac{\gamma_{\rm W}}{(1-y/\bar{y})^2+\gamma_{\rm W}^2} \to \pi\bar{y}\,\delta(y-\bar{y}).$$

Top Quark Width

m_t [GeV]	$\Gamma_{\rm t}^{\rm LO}$ [GeV]	$\Gamma_{\rm tW}^{\rm LO}$ [GeV]	$\Gamma_{\rm t}^{\rm NLO}$ [GeV]	$\Gamma_{\rm tW}^{\rm NLO}$ [GeV]
168.2	1.33273	1.35426	1.21823	1.23792
170.7	1.40449	1.4269	1.28389	1.30438
173.2	1.47834	1.50162	1.35146	1.37276
175.7	1.55429	1.57847	1.42097	1.44309
178.2	1.63237	1.65746	1.49243	1.51538

$\Gamma_{\rm t}$	top quark width with W gauge boson off-shell effects included
$\Gamma_{\rm tW}$	top-quark width with the on-shell W gauge boson