Deutsche Forschungsgemeinschaft

Project B1b: Top-Quark Physics

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Kick-off Meeting of the Collaborative Research Centre/Transregio 257
P³H – Particle Physics Phenomenology after the Higgs Discovery

Plan

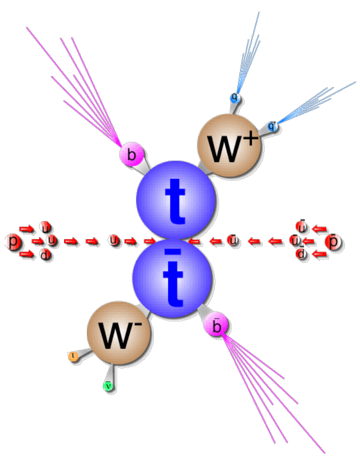
❖ Introduction

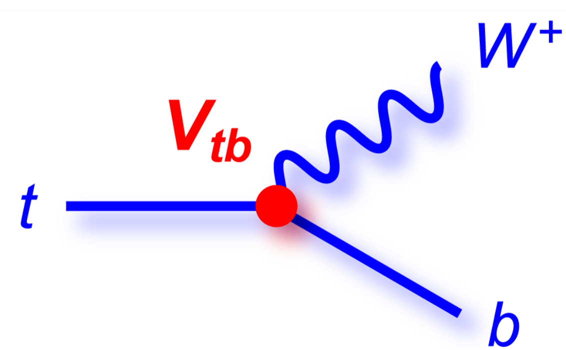
❖ Setting the stage…

❖ State-of-the-art NLO & NNLO results for top quark physics @ LHC

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

❖ Future projects within the CRC/TRR





Top-Quark Physics

Basic Facts about Top…

- Discovered at TeVatron in 1995
- Heaviest observed particle

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

World Combination '14
ATLAS, CDF, CMS, D0

- Yukawa coupling

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

- Short lifetime → Decay before bound states can be formed
- Can be measured directly via its decay products → ***b-jets, p_T^{miss}, $l^{\pm}$ & jets***

Why is it interesting ?

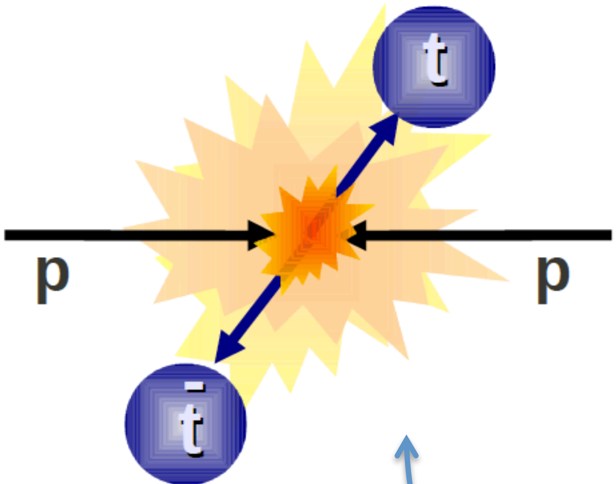
- Infrared structure of QCD
- Extract SM parameters: α_s & m_t
- Constraints on gluon PDFs
- Background process to various SM & BSM scenarios
- Window to New Physics

LHC Top-Quark Factory

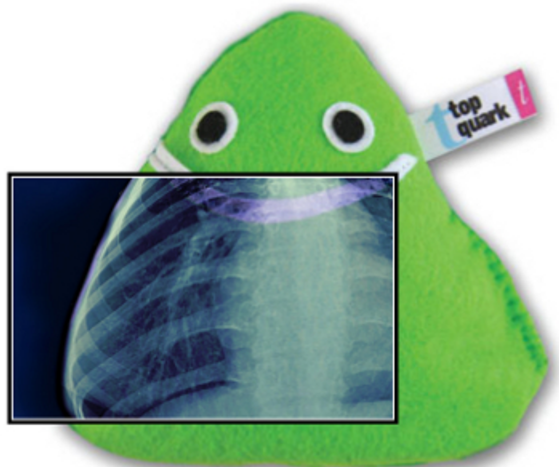
	Collider	$\sigma(tt)$ [pb]	L [fb^{-1}]	N_{event}
LHC Run 1	$LHC_{7\ TeV}$	180	5	9×10^5
	$LHC_{8\ TeV}$	256	20	5×10^6
LHC Run 2 →	$LHC_{13\ TeV}$	835	36	3×10^7
	$LHC_{14\ TeV}$	987	100	1×10^8
High Luminosity →	$HL\text{-}LHC_{14\ TeV}$	987	3000	3×10^9
High Energy →	$HE\text{-}LHC_{27\ TeV}$	3840	15000	6×10^{10}

Top quark pair production @ NNLO with TOP++
CT14 PDF, m_t =173.2 GeV

Czakon, Mitov '14

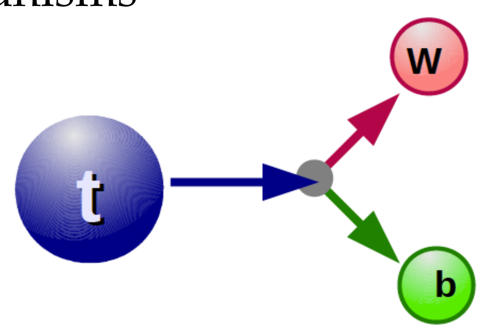


Intrinsic properties:
- Mass
- Charge
- Lifetime
- Width

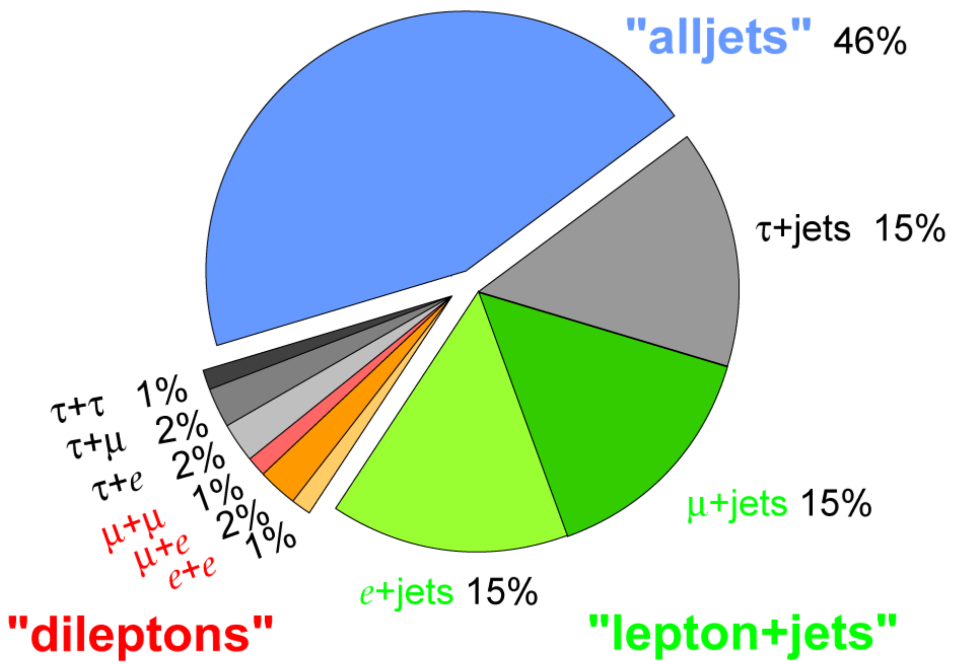


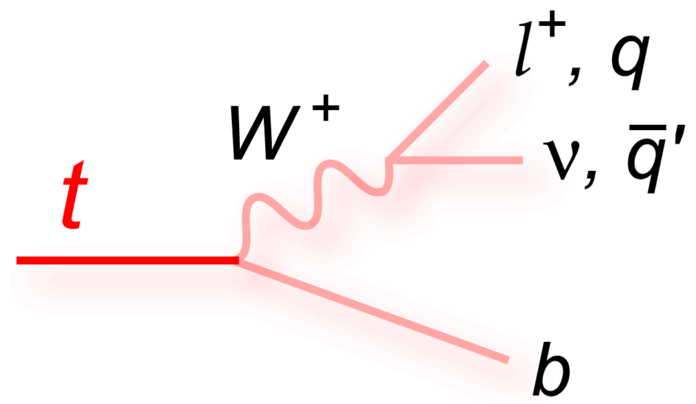
Production:
- Production rate
- Differential distributions
- New production mechanisms

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



Top Pair Branching Fractions





❖ Top quark produced via QCD interaction decay through weak interaction

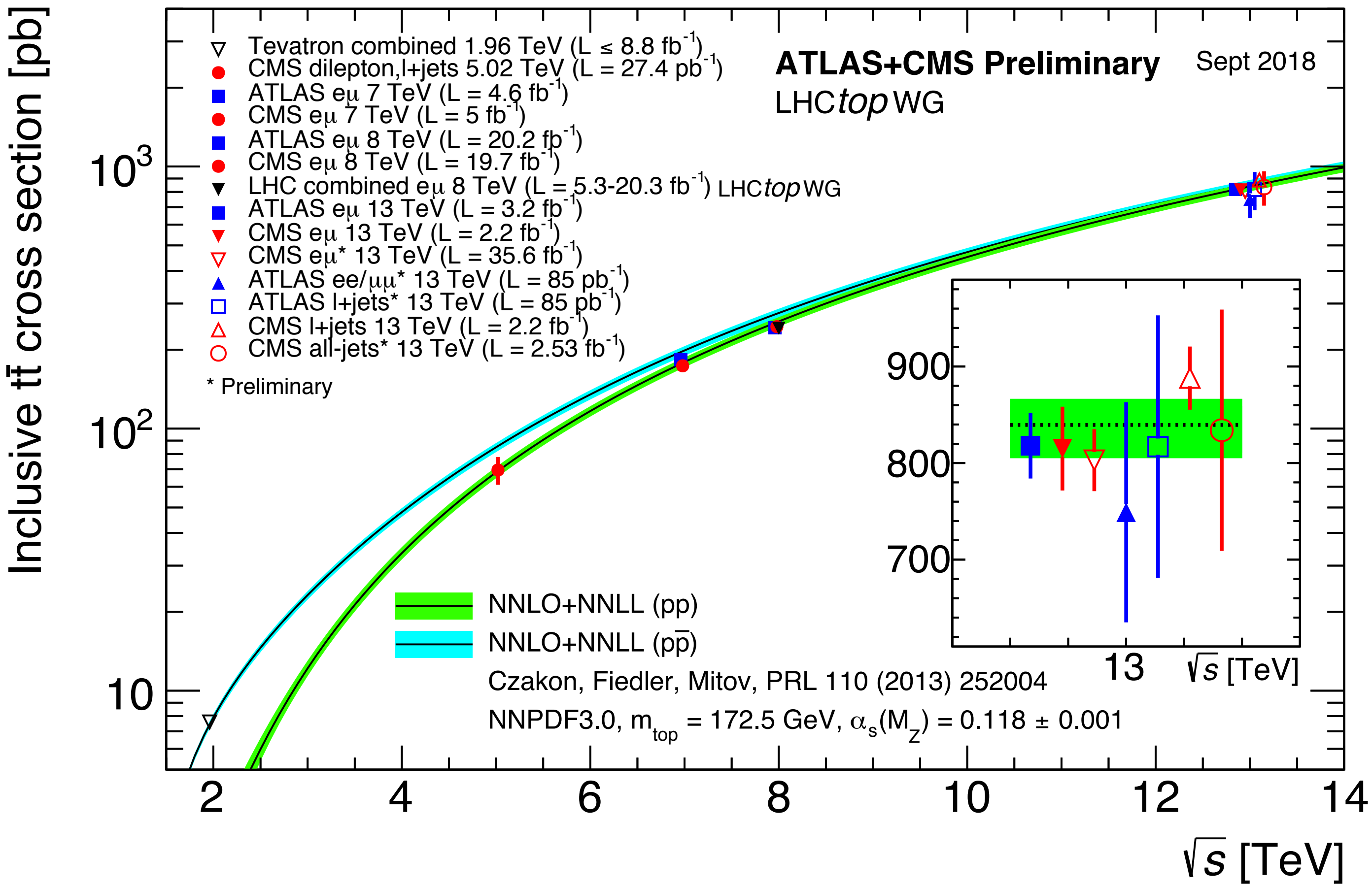
❖ Producing W-boson and a down-type quark (down, strange, or bottom)

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

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

Top-Quark Pair Production

On-shell Tops

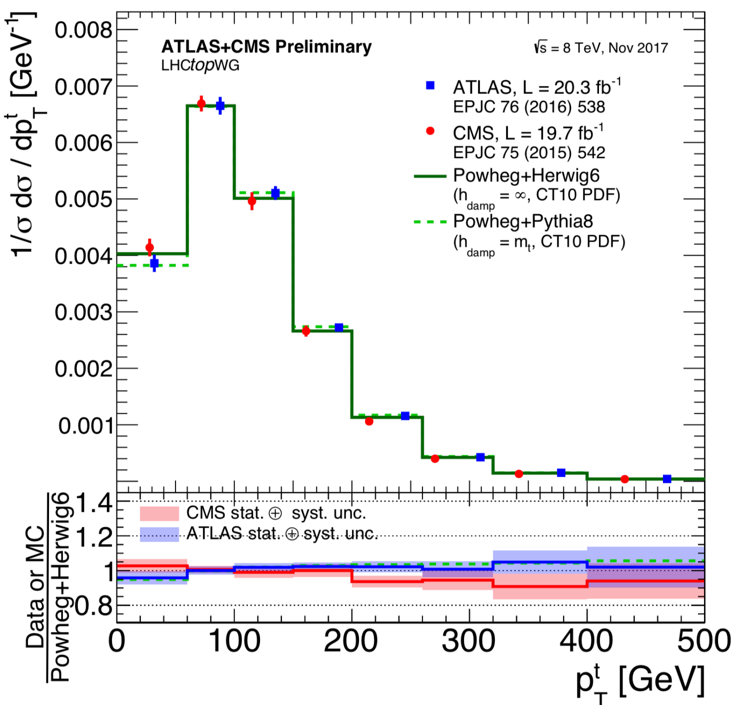


Summary of LHC and Tevatron measurements of tt cross-section compared to NNLO QCD calculation complemented with NNLL resummation - **TOP++**

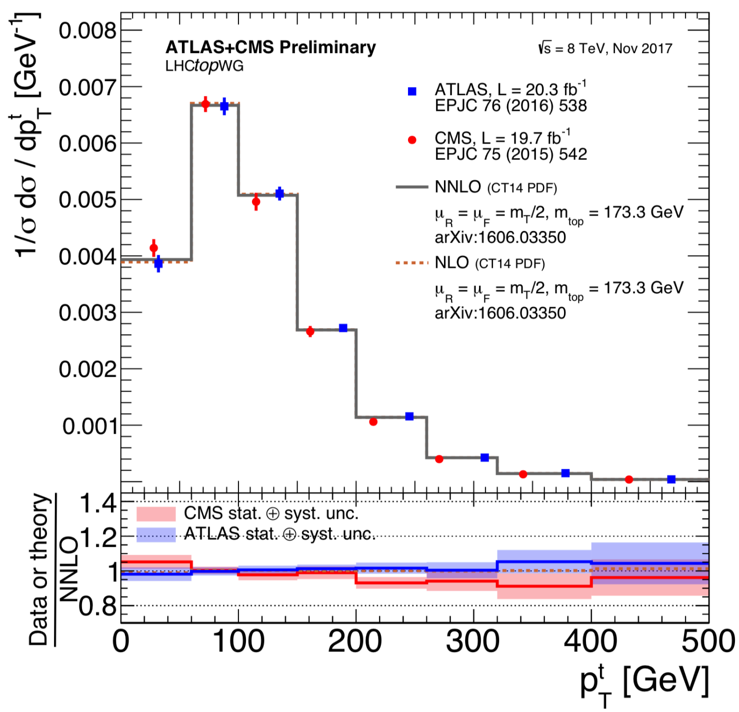
Top-Quark Pair Production

On-shell Tops

Full phase-space normalized differential tt cross-section as a function of $p_T(t)$



The CMS and ATLAS results are compared to Powheg+Herwig6 & Powheg+Pythia8 MC generators.



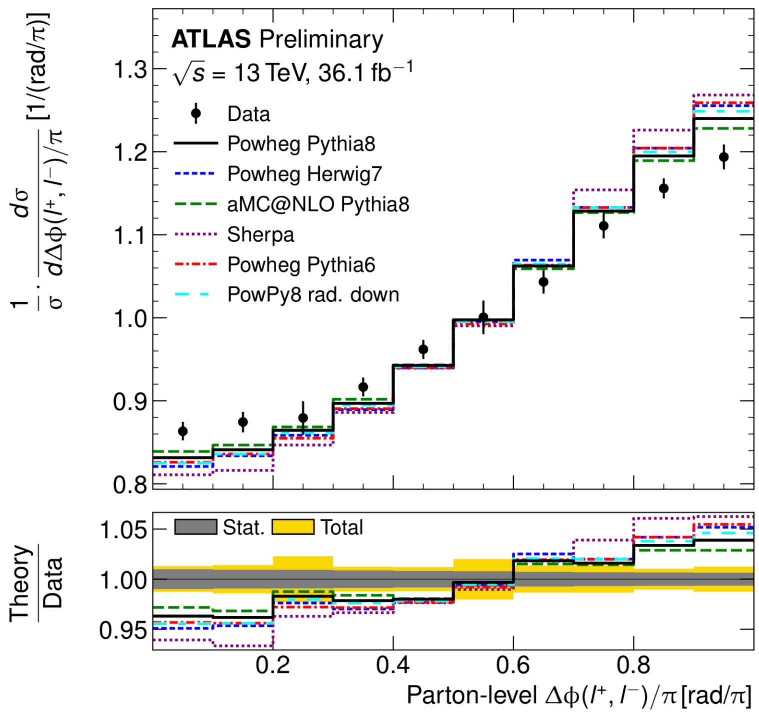
The CMS and ATLAS results are compared to the NLO & NNLO calculations.

Czakon, Heymes, Mitov '17

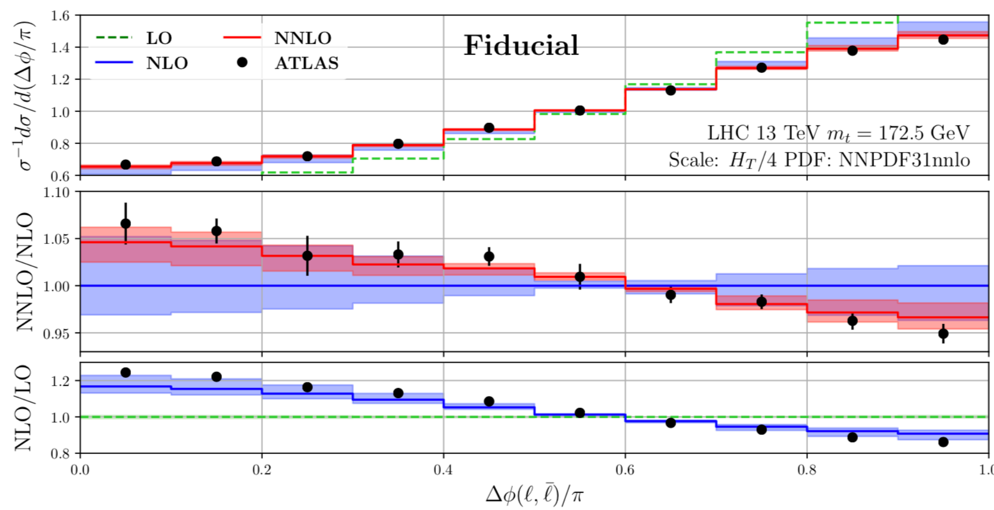
Top-Quark Production & Decays

Normalized differential tt cross-section as a function of azimuthal opening angle between two leptons

Tops in NWA



ATLAS-CONF-2018-027



Behring, Czakon, Mitov, Papanastasiou, Poncelet '19

Comparison to NNLO QCD predictions in NWA

Comparison to Powheg, Mad-Graph5_aMC@NLO & Sherpa

tt & tt+X @ LHC

- ***Proper modeling of top decays essential already in presence of inclusive cuts:***
  - Higher order QCD corrections → Corrections to production & decays
  - Full NWA or complete off-shell effects for top quarks
  - ***tt*** spin correlations
  - Possibility of using kinematic-dependent μ_R & μ_F scales

- ***Even more important for:***
  - High luminosity & Exclusive cuts
  - New Physics searches & SM parameter extraction

- ***tt & tt +X status:***
  - NNLO QCD predictions for ***pp → tt*** in NWA (di-lepton)
  - NLO QCD with off-shell effects: ***pp → tt, pp → ttγ, pp → ttj, pp → ttH***
  - NLO QCD in NWA: ***pp → ttZ & pp → ttW$^{\pm}$***

Röntsch, Schulze '14
Campbell, Ellis '12

  - NLO QCD with on-shell tops: ***pp → ttbb, pp → ttjj, pp → tttt***

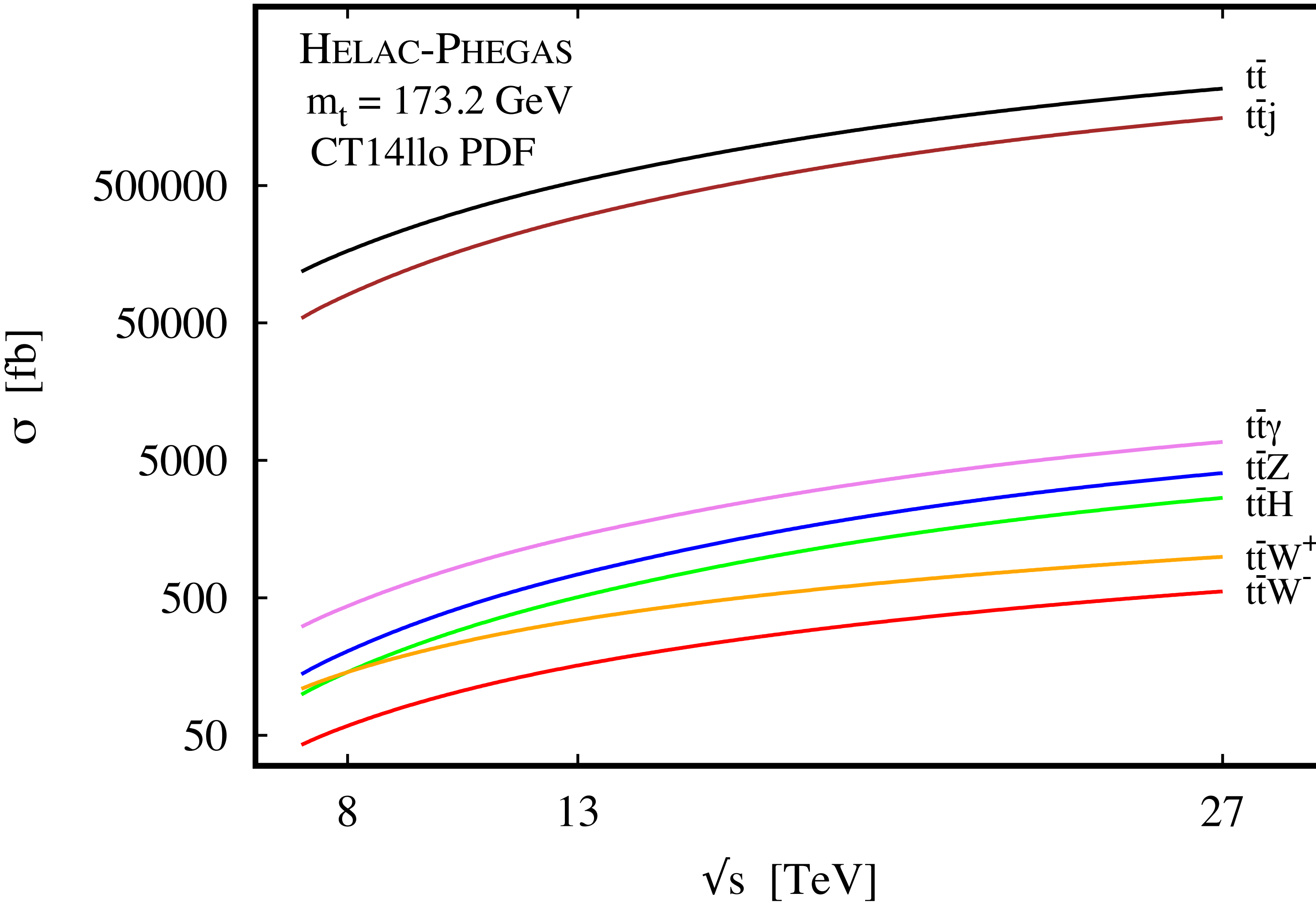
We plan to improve predictions for all these processes !

Bredenstein, Denner, Dittmaier, Pozzorini '09
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09
Bevilacqua, Czakon, Papadopoulos, Worek '10 '11
Bevilacqua, Worek '12

tt & tt+X @ LHC

On-shell Tops

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



How Good Is NWA ?

Off-shell Tops

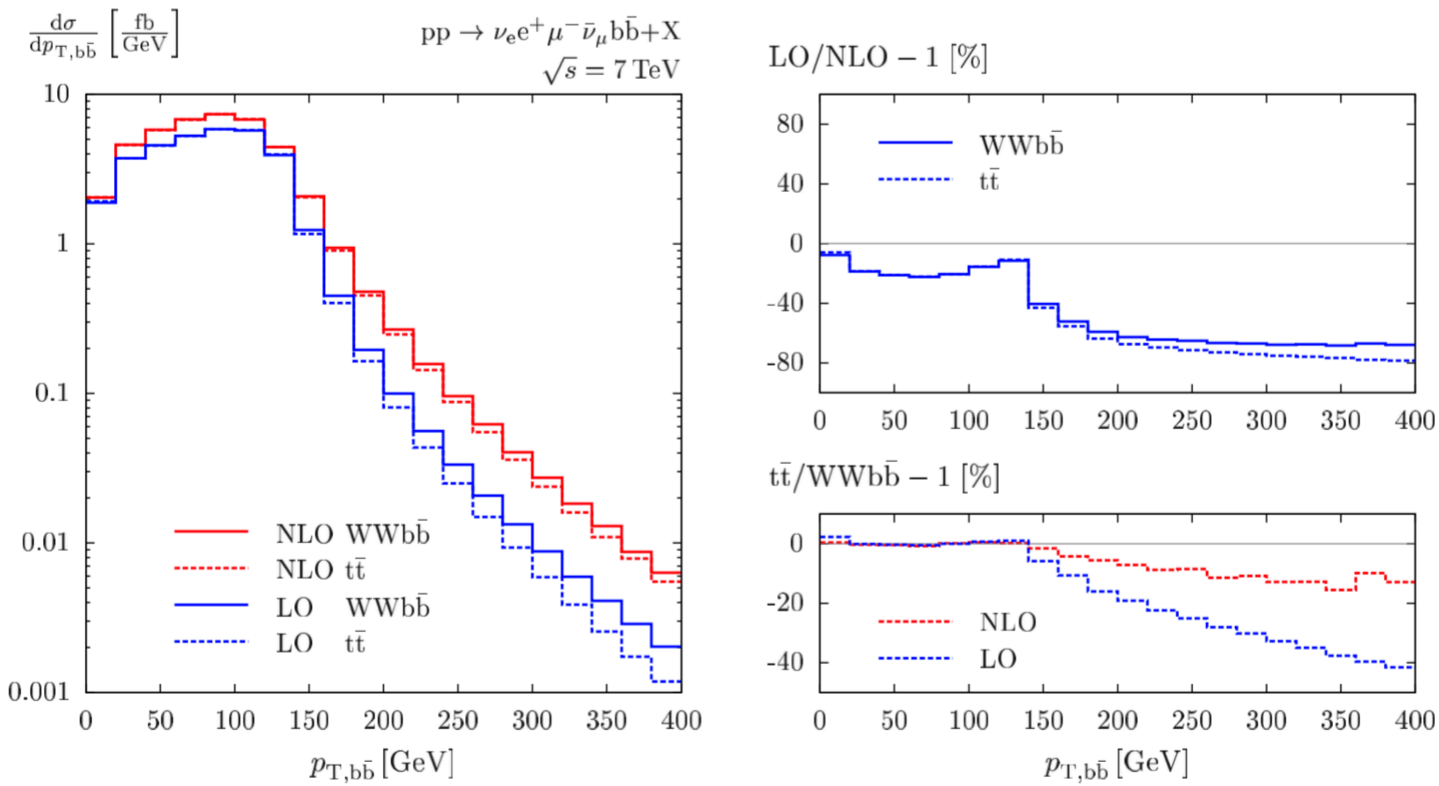
- In NWA tops are restricted to on-shell states
- Approximation is controlled by the ratio $\Gamma_t / m_t \approx 0.8\%$
- Should be accurate for sufficiently inclusive observables
- ***Off-shell effects for integrated σ_{tt} at few % level @ NLO in QCD***

tt (di-lepton)	*Denner, Dittmaier, Kallweit, Pozzorini '11 '12* *Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11* *Denner, Pellen '16 (EW)* *Jezo, Lindert, Nason, Oleari, Pozzorini '16 (PS)*
tt (semi-leptonic)	*Denner, Pellen '18*
ttH (di-lepton)	*Denner, Feger '15* *Denner, Lang, Pellen, Uccirati '17 (EW+QCD)*
ttj (di-lepton)	*Bevilacqua, Hartanto, Kraus, Worek '16 '18*
ttγ (di-lepton)	*Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19*

NWA & Off-Shell Effects

Off-shell Tops

- Off-shell results vs. results with (spin-correlated) NWA
- *Tens of per cent* in phase-space regions where *tt* suppressed as signal
- Important as background to *Higgs & BSM searches*



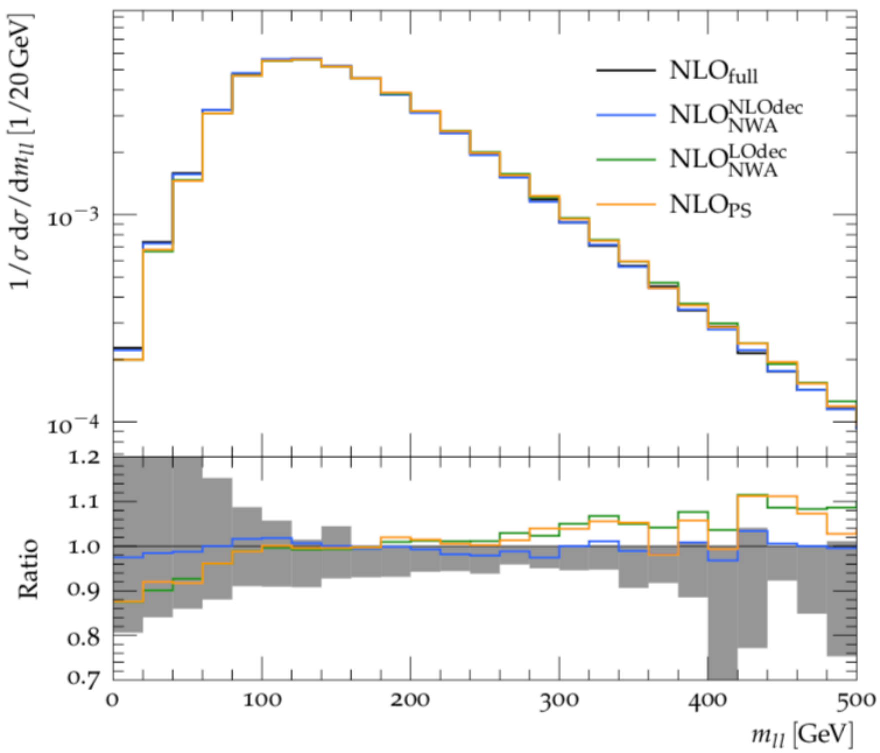
Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12

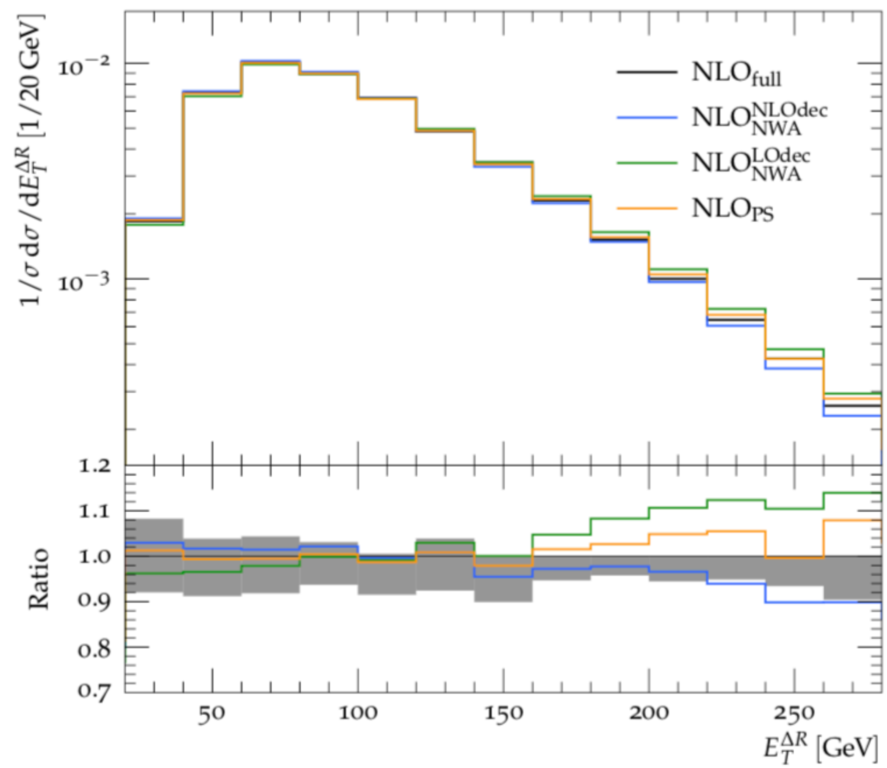
NWA & Off-Shell Effects

❖ Observables used for a recent top quark mass determination

Off-shell, NWA, PS

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





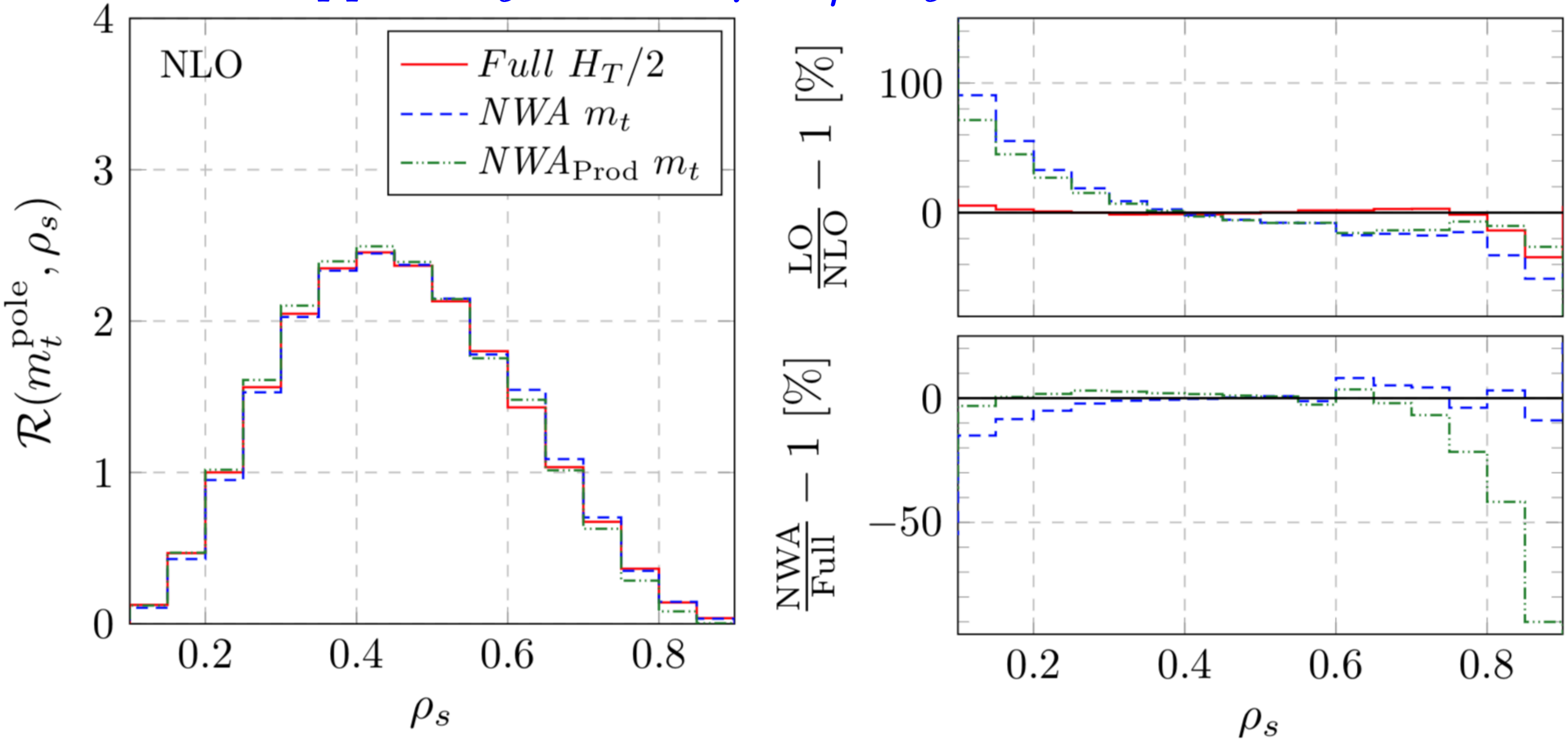
Heinrich, Maier, Nisius, Schlenk, Schulze, Scyboz, Winter '18

NWA & Off-Shell Effects

❖ Observable used for a recent top quark mass determination

Off-shell, NWA

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



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

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

Bevilacqua, Hartanto, Kraus, Schulze, Worek ‘18

NWA & Off-Shell Effects

2.5 fb^{-1}

$pp \to t\bar{t}j \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,j$ **@ 13 TeV LHC**

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, $\mu_0 = H_T/2$	173.38 ± 1.34	1.04	0.40 (0.8σ)	−0.18
Full, $\mu_0 = E_T/2$	172.84 ± 1.33	1.05	0.39 (0.9σ)	+0.36
Full, $\mu_0 = m_t$	174.11 ± 1.39	1.07	0.37 (0.9σ)	−0.91
NWA, $\mu_0 = m_t$	175.70 ± 0.96	1.17	0.24 (1.2σ)	−2.50
$NWA_{\text{Prod.}}$, $\mu_0 = m_t$	169.93 ± 0.98	1.20	0.20 (1.3σ)	+3.27
5 bins				
Full, $\mu_0 = H_T/2$	173.15 ± 1.32	0.93	0.44 (0.8σ)	+0.05
Full, $\mu_0 = E_T/2$	172.55 ± 1.18	1.07	0.37 (0.9σ)	+0.65
Full, $\mu_0 = m_t$	173.92 ± 1.38	1.48	0.20 (1.3σ)	−0.72
NWA, $\mu_0 = m_t$	175.54 ± 0.97	1.38	0.24 (1.2σ)	−2.34
$NWA_{\text{Prod.}}$, $\mu_0 = m_t$	169.37 ± 1.43	1.16	0.33 (1.0σ)	+3.83

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

NWA & Off-Shell Effects

25 fb^{-1}

$pp \to t\bar{t}j \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, b\bar{b}\, j$ **@ 13 TeV LHC**

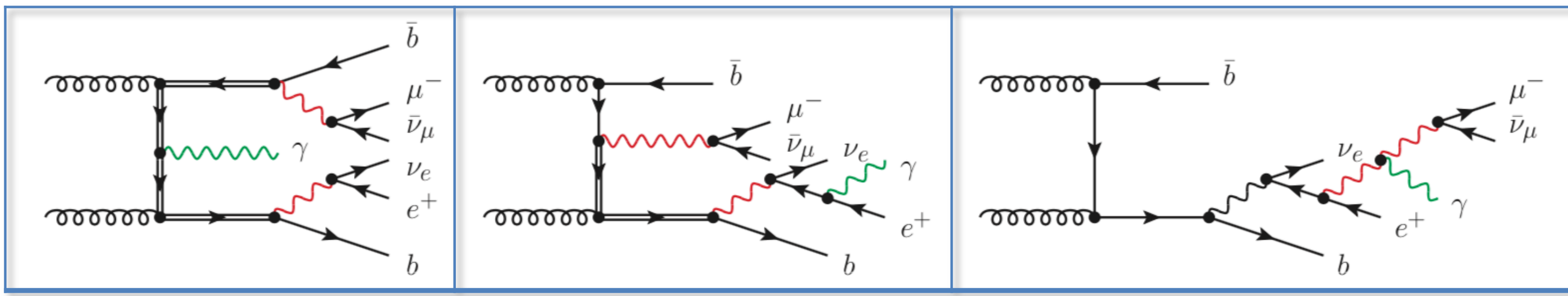
Theory, NLO QCD CT14 PDF	$m_t^{\rm out} \pm \delta m_t^{\rm out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{\rm in} - m_t^{\rm out}$ [GeV]
		31 bins		
Full, $\mu_0 = H_T/2$	173.09 ± 0.42	1.04	0.41 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.45 ± 0.39	1.12	0.30 (1.0σ)	+0.75
Full, $\mu_0 = m_t$	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
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	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
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	169.39 ± 0.47	3.42	$8 \cdot 10^{-3}$ (2.6σ)	+3.81

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

NWA & Off-Shell Effects

- Feynman Diagrams → *628 @ LO for gg channel*

$t\bar{t}\gamma + X$ @ $\mathcal{O}(\alpha_s^2\alpha^5)$

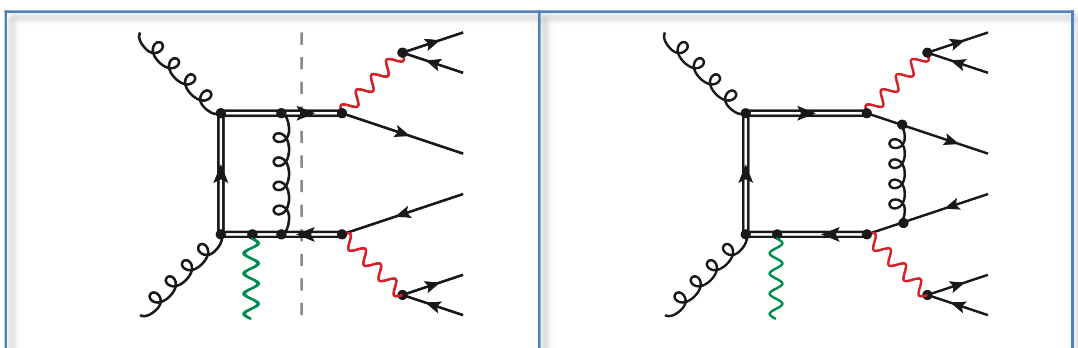


- NLO → *4348 real emission & 36032 @ 1-loop for gg channel*

- Most complicated → *90 heptagons & 958 hexagons*

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

ttγ in NWA
up to pentagons



ttγ full
up to heptagons

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

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

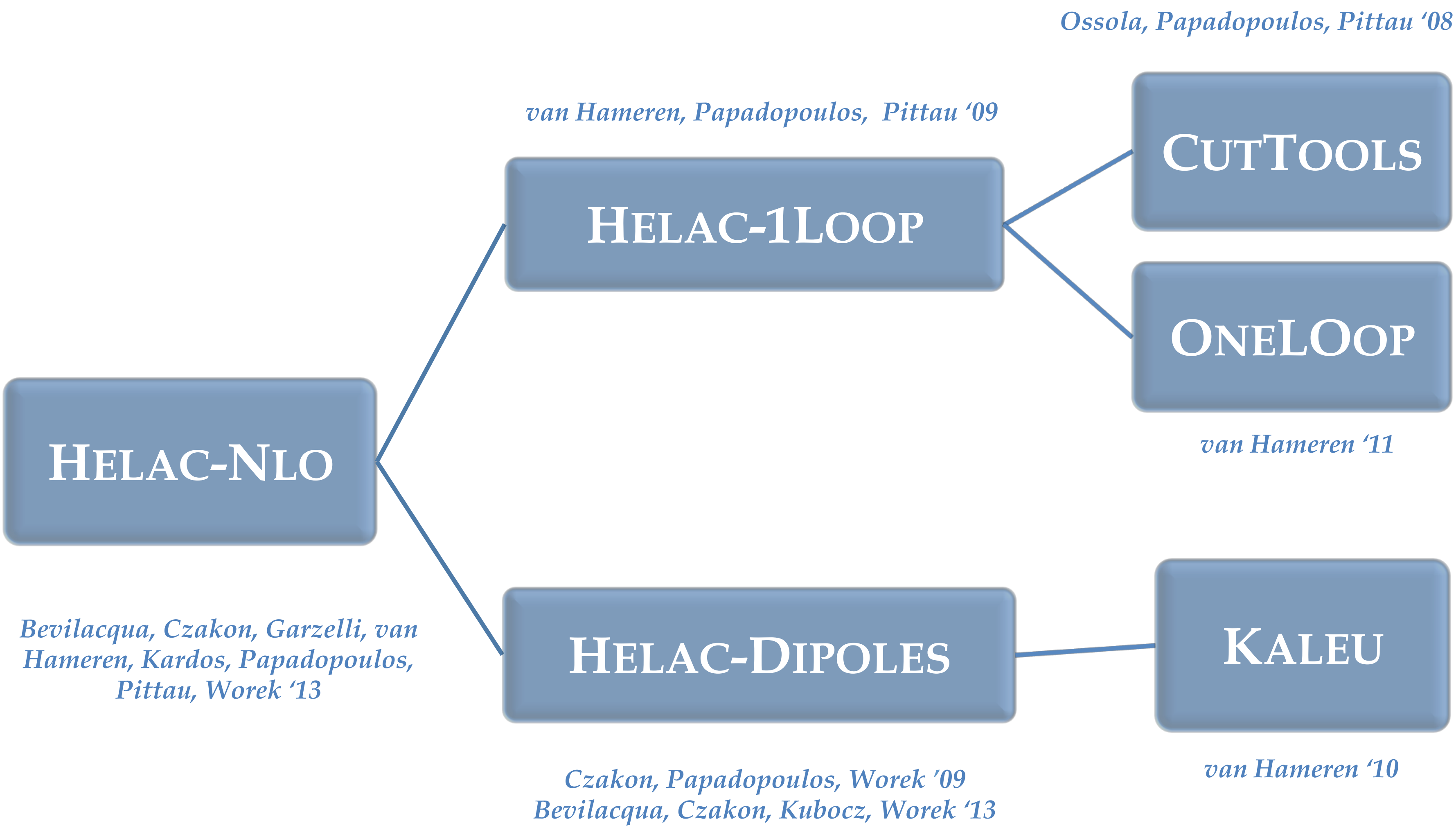
$$\mu_t^2 = m_t^2 - i\, m_t \Gamma_t$$

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

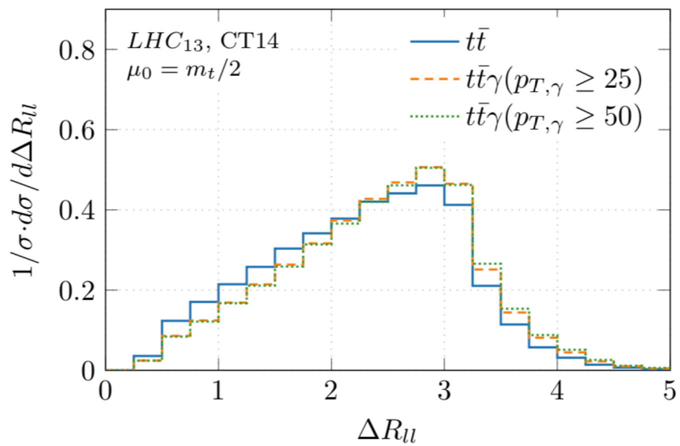

Ossola, Papadopoulos, Pittau '08
van Hameren, Papadopoulos, Pittau '09
CUTTOOLS
HELAC-1LOOP
ONELOOP
van Hameren '11
HELAC-NLO
Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek '13
HELAC-DIPOLES
KALEU
van Hameren '10
Czakon, Papadopoulos, Worek '09
Bevilacqua, Czakon, Kubocz, Worek '13

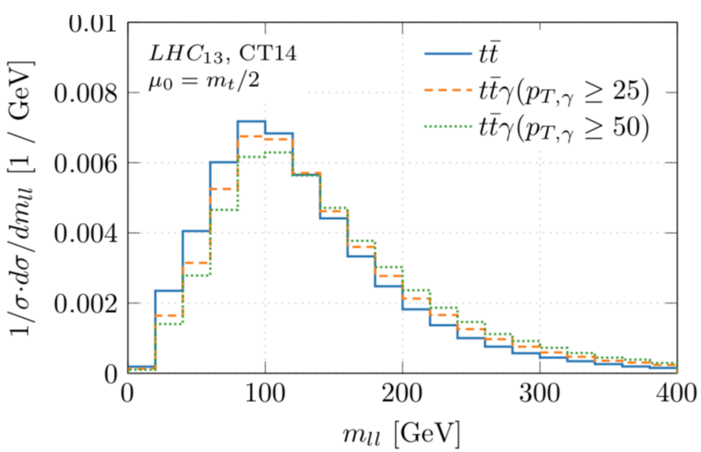
Cross Section Ratios: ttγ/ tt

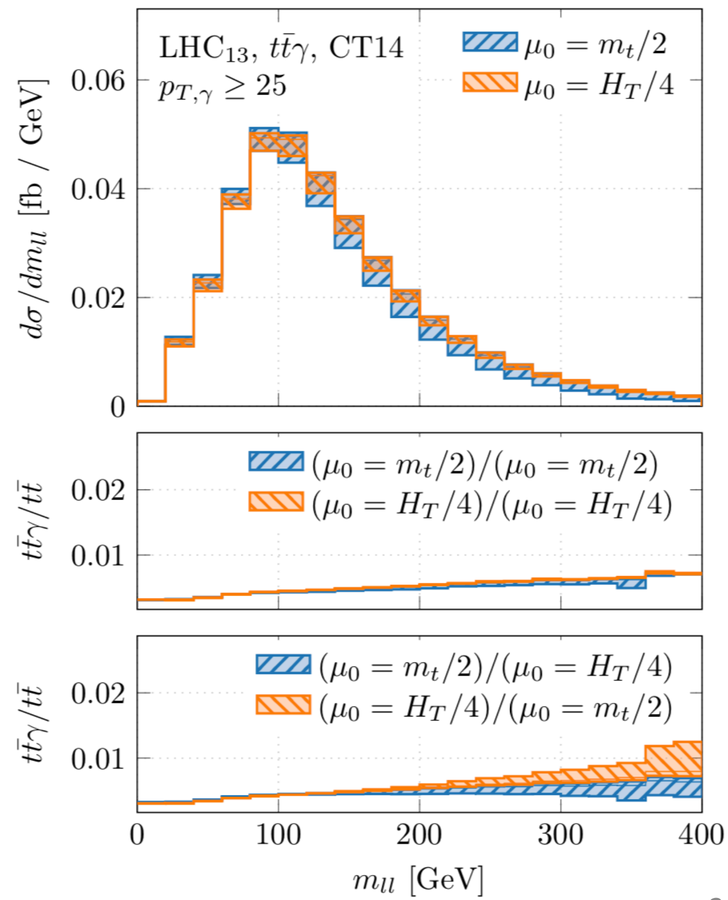
- ***1% −3%*** precision for ***Integrated Cross Section Ratios***
- ***Differential Ratios*** with ***1% −6%*** precision:
- Such high precision has only been reserved till now for NNLO !

Off-shell Tops

$M_{b\bar{b}}$, $M_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, p_{T,ℓ_1}



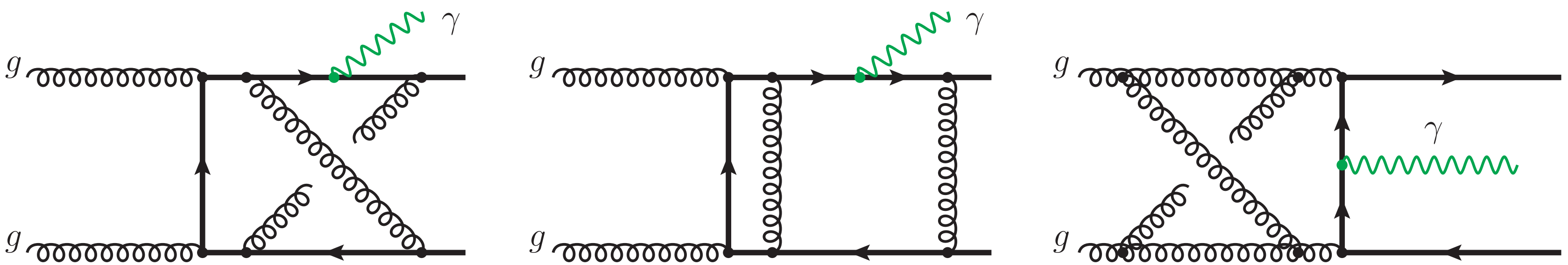




Bevilacqua, Hartanto, Kraus, Weber, Worek '19

NNLO & Open Questions

- NNLO QCD to on-shell ***pp → ttγ***
  - 2-loop virtual amplitude ☒



  - Double-real radiation @ NNLO: sector-improved residue subtraction scheme with **STRIPPER** ☑

Czakon '10 '11 & Czakon, Heymes '14

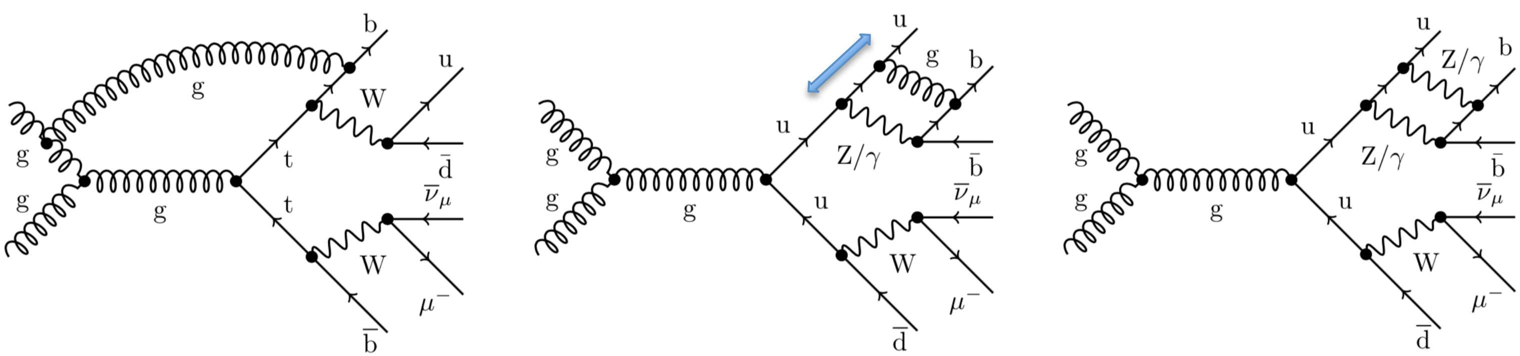
- Phenomenological applications for ***ttγ & ttγ/tt***
  - Measuring top quark charge, various asymmetries
  - Constraining exotic physics scenarios
  - Probing strength & structure of ***ttγ*** vertex, …

- ***Long term goal*** → NNLO QCD to ***ttγ & ttH*** in NWA - ***di-lepton*** channel
  - Polarized 2-loop virtual amplitudes for ***ttγ & ttH*** ☒

NLO & Open Questions

- Top off-shell effects @ NLO QCD ***pp→ tt & pp → tt + X*** for ***lepton+jets*** channel
  - **HELAC-DIPOLES** → Dipole subtraction method for both **QCD** ☑ & **QED** ☒
    → Soft or collinear photon emission *Dittmaier '00*
  - **HELAC-1LOOP** → W, Z, γ in 1-loop diagrams, rational parts, … ☒

QCD correction ***Mixed correction*** ***EW correction***



One-loop Feynman diagrams contributing to $gg \to \mu^-\bar{\nu}_\mu\, b\bar{b}\, jj$ @ $\mathcal{O}(\alpha_s^3\alpha^4)$

Denner, Pellen '18

- ***Long term goal*** → EW + QCD for ***tt, ttγ, ttH, ttj, ttZ, ttW±***

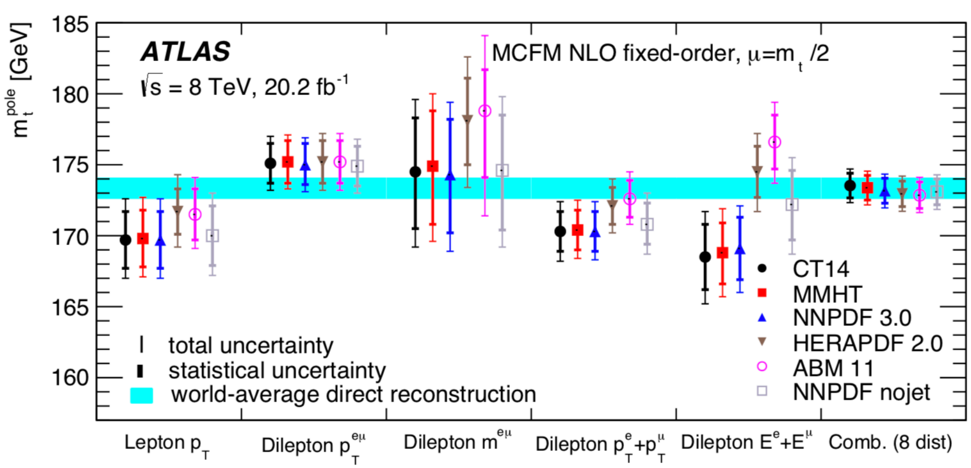
NNLO-NLO & Open Questions

- Merging off-shell top quark effects @ NLO in QCD with NNLO QCD top quark predictions for ***pp → tt*** in ***di-lepton*** channel

- Determination of the top quark mass from leptonic observables → Fiducial σ_{tt}

$$p_T^{\ell^+}\,,p_T^{\ell\ell}\,,M_{\ell\ell}\,,(E^{\ell^+}+E^{\ell^-})\,,(p_T^{\ell^+}+p_T^{\ell^-})\,,\eta^{\ell^+}\,,\eta^{\ell\ell}\,,\Delta\phi_{\ell\ell}$$

$$m_t = 172.2 \pm 0.9\,(\text{stat.}) \pm 0.8\,(\text{syst.}) \pm 1.2\,(\text{th.})\ \text{GeV}$$



CERN-EP-2017-200
TOP2018 Workshop

- Various tt NLO generators interfaced to PS used

- ***$d\sigma_{tt}/dX$*** modeled poorly by NLO+PS

- The most precise result obtained from fixed-order NLO predictions

- ***Measurements limited by theory uncertainties stemming from modeling of top quark decays !***

NLO & Open Questions

- Effects of New Physics at high scale ***Λ*** described by effective Lagrangian

$$\mathcal{L}_{\mathrm{SM}}^{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \dots$$

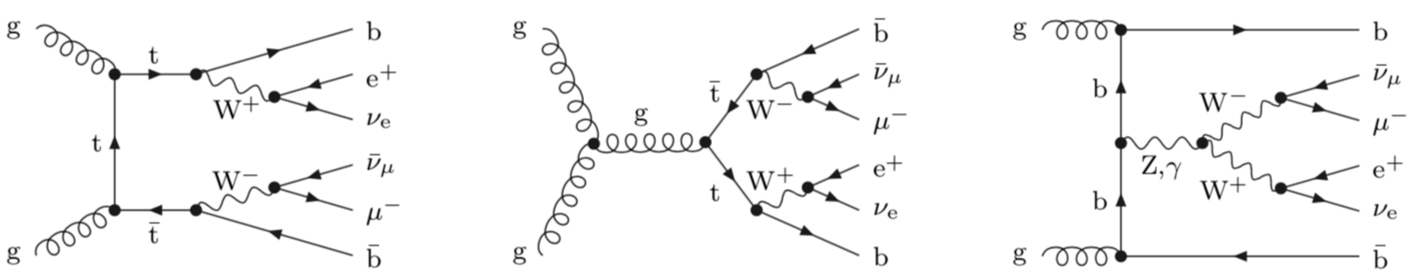
O_i – effective operators
C_i – Wilson coefficients

- Minimal set of top anomalous couplings → *Aguilar-Saavedra '09*

- ***ttγ*** vertex with contributions from dim-6 effective operators parameterized as

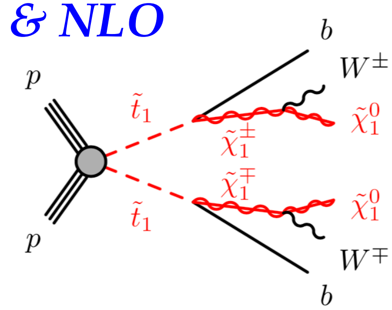
$$\mathcal{L}_{t\bar{t}\gamma} = -eQ_t\bar{t}\gamma^\mu t A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}(p_t - p_{\bar{t}})_\nu}{m_t}\,(d_V^\gamma + i d_A^\gamma \gamma_5)\, t A_\mu$$

- **HELAC-NLO** → Top anomalous couplings ***Wtb, Ztt, ttγ, ttH & gtt*** ☒
- **HELAC-NLO** → NWA ☒
- How meaningful is this approach when top off-shell effects are included ? ☒

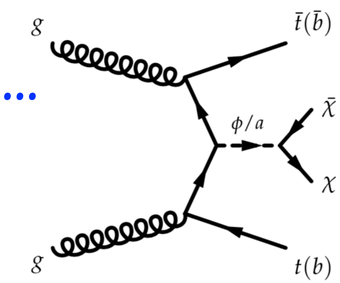


Summary

- ***Very ambition program for top-quark physics at NNLO & NLO***



- ***Modeling of top quark decays crucial***
  - Full NWA or complete top quark off-shell effects
  - ***tt*** spin correlations
  - Possibility of using kinematic-dependent scales

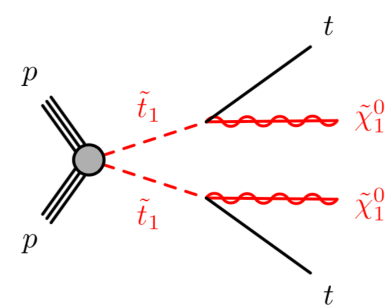


- Improving predictions for: ***pp → tt+X, X=γ, Z, W±, H, j, bb, jj, tt, …***

- ***di-lepton & lepton + jets*** top-quark decay channels

- Plethora of phenomenological applications

- ***Important input for New Physics searches***



- ***Simplified top-philic dark matter & SUSY models***
  - Signal: ***pp → ttχχ → tt*** p_T^{miss}
  - Dominant reducible SM background: ***pp → tt***
  - Irreducible SM background: ***pp → ttZ → tt***$\upsilon_l\upsilon_l$ ***→ tt*** p_T^{miss}