

# Top-quark pair-production and decay at high precision



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# Top physics is alive and kicking @ LHC

A plethora of measurements of 'top quarks' from the ATLAS, CMS and LHCb experiments have and are being made at 7,8 & 13 TeV.

- ▶  $t\bar{t}$  is one of the most important backgrounds for other interesting physics searches
- ▶ uncertainties at the level of a **few %**

Impressive progress on theory side for stable tops:

- ▶  $t\bar{t}$  NNLO, fully-differential [Czakon,Fiedler,Heymes,Mitov '13-present]
- ▶ **important** applications:
  - ▶ steps towards understanding top  $p_T$  discrepancy
  - ▶ e.g. constraining high- $x$  gluon [Czakon et al '16]
  - ▶ NNLO QCD + NLO EW corrections understood [Czakon et al '17]

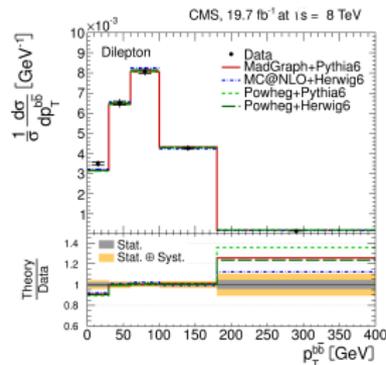
# The top quark is not stable

- ▶ due to its large width,  $\Gamma_t$ , top decays before hadronizing ...
- ▶ top quarks not directly measured – presence inferred through their decay products: **leptons, (b)jets, missing energy**

- ▶ To compare to stable top predictions, experiments have to
  - ▶ extrapolate their measurements from fiducial to inclusive
  - ▶ extrapolate/model from particle-level to top-quark partons

[ both of these steps currently use MCs which **treat top decay at LO** ]

Experiments already releasing measurements of  $t\bar{t}$  decay products in **fiducial regions**, via **decay products**: also at level of **few %** in uncertainty



# The top quark is not stable

**Serious** amount of work has gone into including top decay at NLO

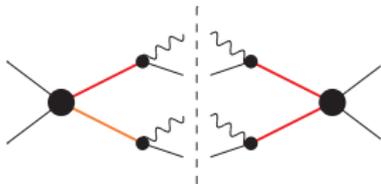
- ▶ narrow-width approx. (NWA) [Bernreuther et al; Melnikov, Schulze; Campell, Ellis]
  - ▶ Offshell [Bevilaqua et al, Denner et al, Falgari et al, Heinrich et al, Frederix et al]
  - ▶ NWA + PS [Campbell, Ellis, Nason, Re]
  - ▶ Offshell + PS [Jezo, Nason et al; Frederix et al]
- ▶ All of these MC codes are built from matrix-elements with **bs & leptons** in final state and consistently include higher order corrections in production & decay
- predictions closer to experimentally physical objects ←

**NEW HERE: going beyond NLO in NWA**

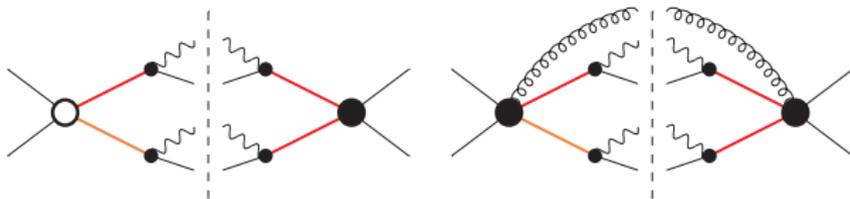
# Ingredients for production & decay in NWA

- ▶ in  $\Gamma_t \rightarrow 0$  limit amplitudes factorise into production and decay
- ▶ **polarized** production & decay amplitudes required

LO

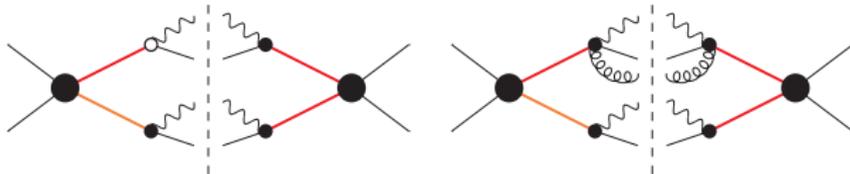


NLO  
production



[Bernreuther, Si;  
Melnikov, Schulze;  
Badger et al;  
Campbell, Ellis]

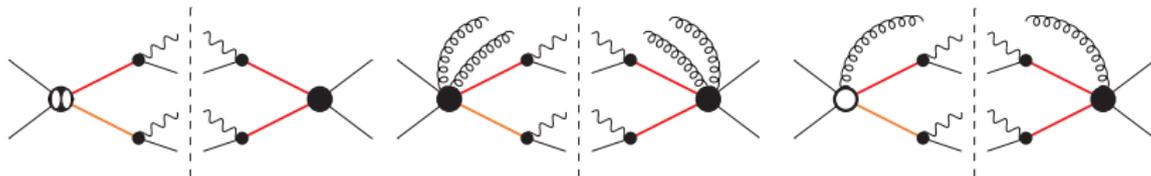
NLO  
decay



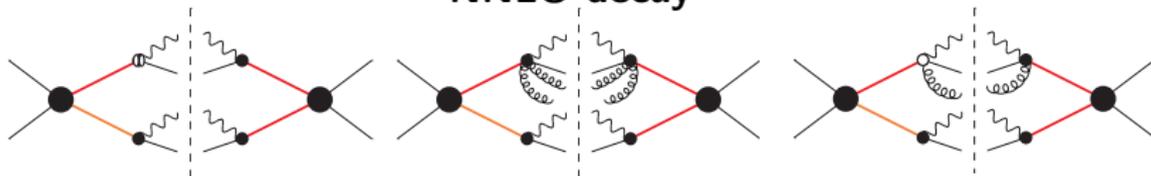
[Bernreuther et al;  
Campbell et al;  
Melnikov, Schulze ...]

# Ingredients for production & decay in NWA

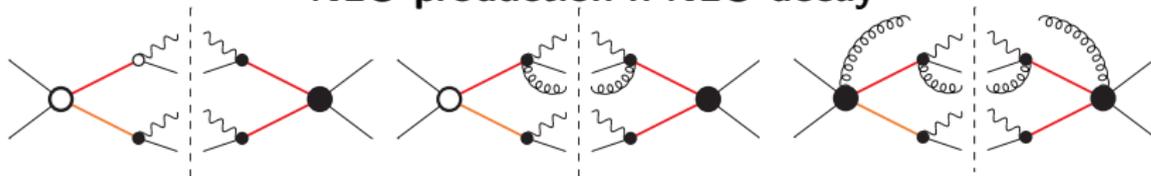
## NNLO production



## NNLO decay



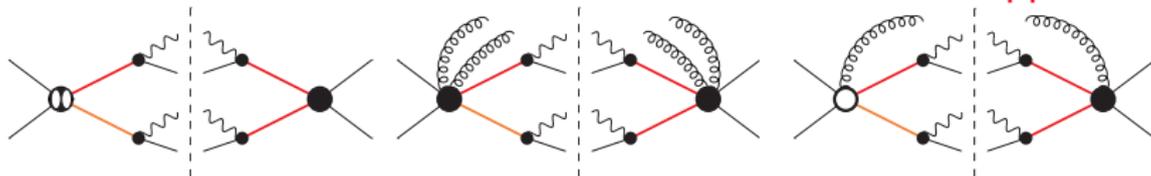
## NLO-production x NLO-decay



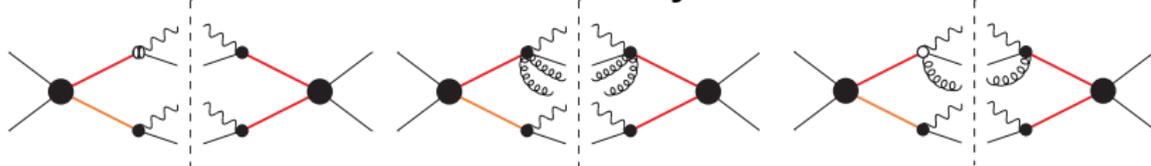
(also: NLO- $t$ decay x NLO- $\bar{t}$ decay)

# Ingredients for production & decay in NWA

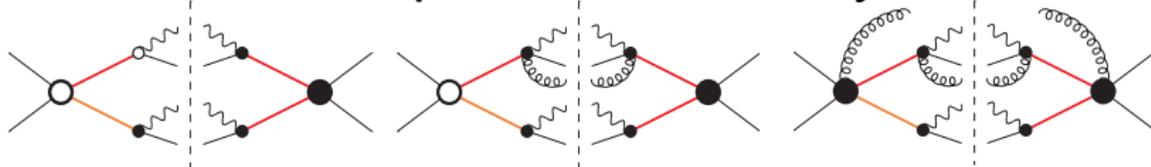
**NNLO production** → include approx.



**NNLO decay** → exact

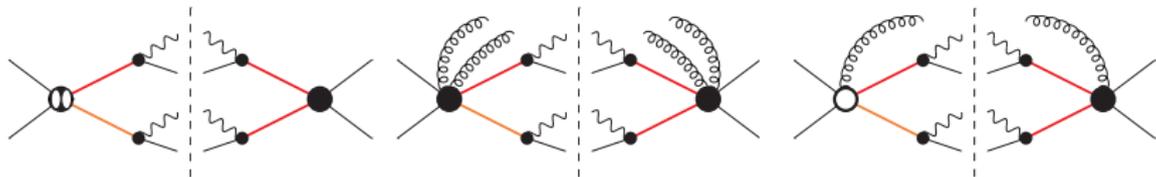


**NLO-production x NLO-decay** → exact



(also: NLO- $t$ decay x NLO- $\bar{t}$ decay)

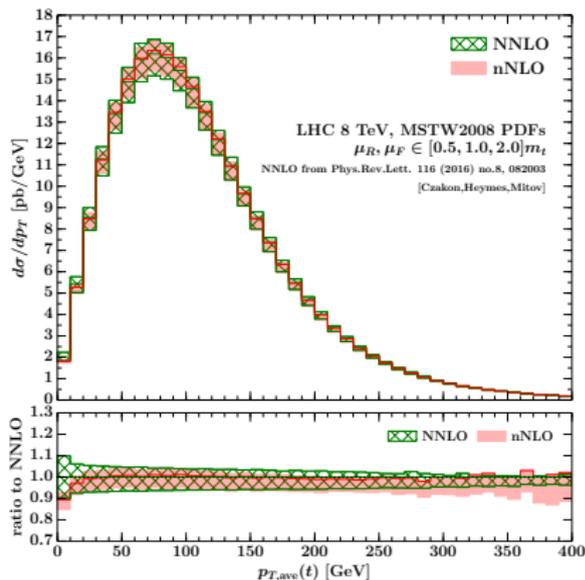
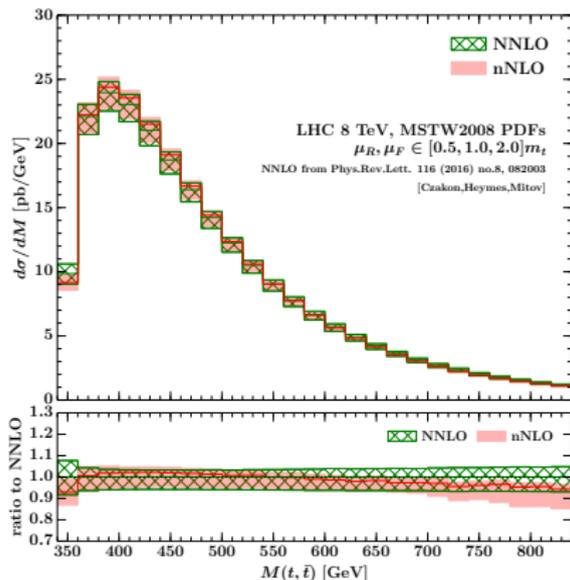
# Approximate NNLO in production



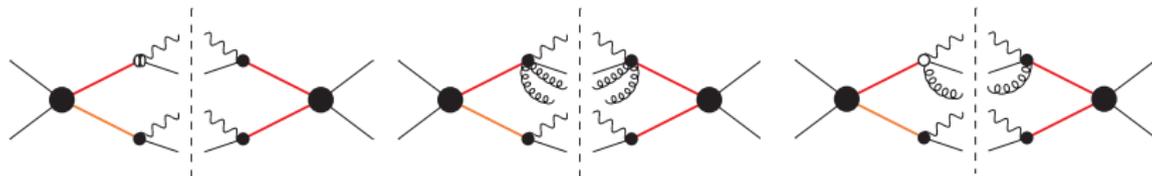
- ▶ based on work with **A. Broggio** and **A. Signer** [1407.2532] : fully differential approx. NNLO, (top decay included at NLO)
- ▶ in the soft-gluon limit  $z = \frac{M_{t\bar{t}}}{\hat{s}} \rightarrow 1$  production cross section factorizes as:
$$\frac{d\sigma}{dM_{t\bar{t}}d\cos\theta} \sim f_{i/h_1} f_{j/h_2} \cdot (\text{Tr}[\mathbf{H}_{ij} \cdot \mathbf{S}_{ij}] + \mathcal{O}(1-z))$$
- ▶ RG-improved cross section in SCET framework [Ahrens, Ferroglia et al] expanded to fixed-order to construct approximation to exact fixed-order (here NNLO)
- ▶ use approx.-NNLO kernels to improve the weights of an NLO fully-differential parton-level Monte Carlo

# Approximate NNLO in production

- ▶ validate against NNLO stable  $t\bar{t}$  predictions [Czakon,Heymes,Mitov]
- ✓ overall very good approximation of shape and error bands



# Exact NNLO in decay



- ▶ based on results of **Gao, Li, Zhu** [1210.2808], modified to include tree-level  $t\bar{t}$  production helicity amplitudes
- ▶ defining  $\tau = (p_b + p_X)^2/m_t$ , then in  $\tau \rightarrow 0$  limit radiation is constrained to being either soft, or collinear to  $b$ -quark and width factorizes as  $\frac{d\Gamma_t}{d\tau} \sim H^{\text{dec}} \cdot J \cdot S^{\text{dec}} + \text{nonsingular}$
- ▶ slicing method to split up NNLO calculation of width:

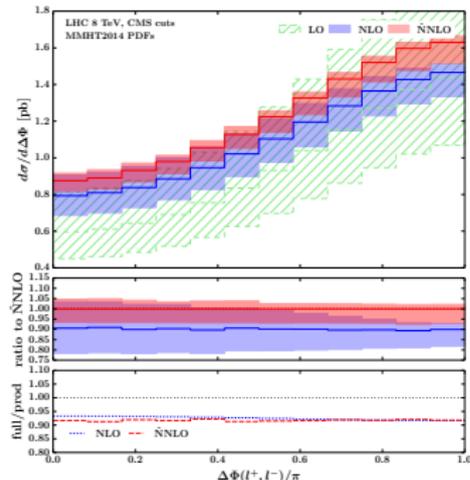
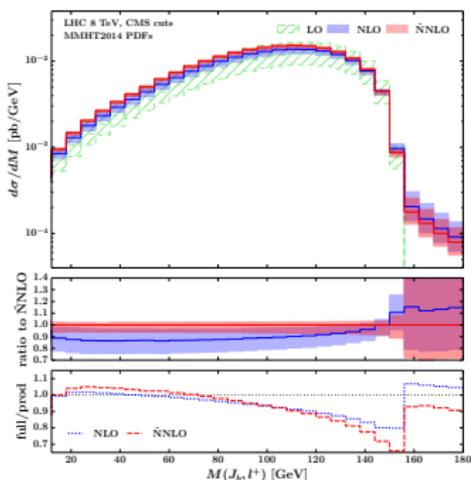
$$\Gamma_t = \underbrace{\int_0^{\tau_0} d\tau \frac{d\Gamma_t}{d\tau}}_{\text{use fact. formula}} + \underbrace{\int_{\tau_0}^{\tau_{\max}} d\tau \frac{d\Gamma_t}{d\tau}}_{\text{use } t \rightarrow W^+ b + j @ \text{ NLO}}$$

# Fully differential results at $\hat{\text{N}}\text{NLO}$ (examples)

[Gao, AP 1705.08903]

- ▶ best predictions:  $\hat{\text{N}}\text{NLO}$  (approx. NNLO prod.)
- ▶ all corrections implemented in a parton-level Monte Carlo program
- ▶ currently can provide predictions for arbitrary IR-safe observables in di-lepton channel (cuts on leptons,  $\cancel{E}_T$ ,  $b$ -jets)

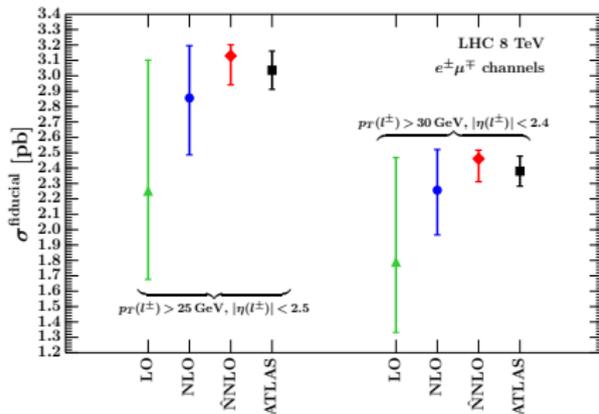
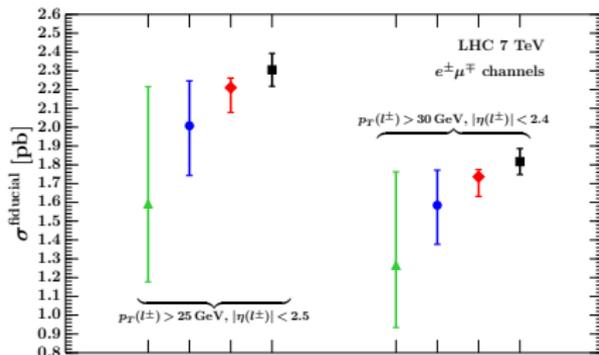
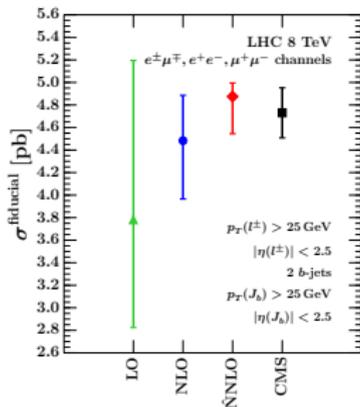
( $m_t = 173.3$  GeV,  $\mu_F = \mu_R \in [0.5, 1.0, 2.0]m_t$ , MMHT2014 PDFs)



# Comparison to data: fiducial cross sections

[Gao, AP 1705.08903]

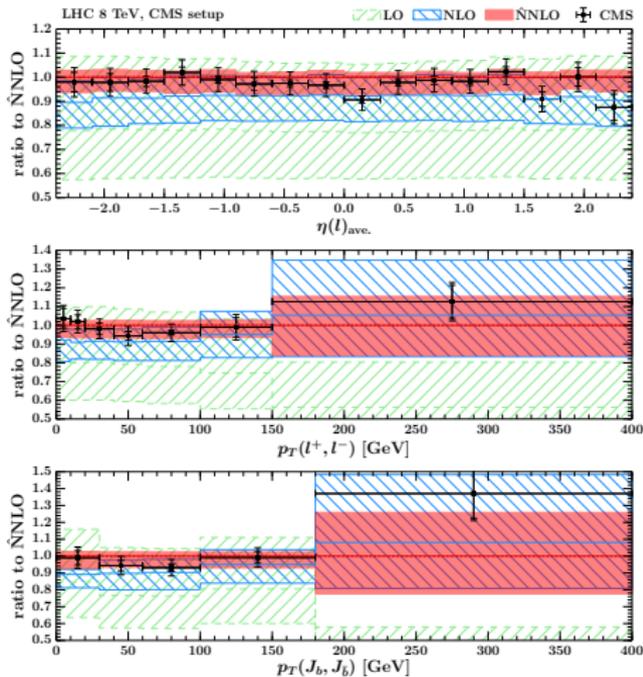
- ▶ ATLAS: measure  $e^\pm\mu^\mp$  channel in fiducial volume defined through cuts on leptons [1406.5375]
- ▶ CMS: measure  $l^\pm l'^\mp$  ( $l, l' = e, \mu$ ) fiducial volume defined through cuts on leptons and  $b$ -jets [1510.03072, 1505.04480]



# Comparison to data: distributions (examples)

[Gao, AP 1705.08903]

- ▶ CMS have released results for lepton and  $b$ -jet distributions  
[1505.04480,1510.03072]
- ▶  $p_T(l^\pm) > 25$  GeV,  $|\eta(l^\pm)| < 2.5$ ,  
anti- $k_t$  jets,  $R = 0.5$ ,  
 $p_T(J_b) > 25$  GeV,  $|\eta(J_b)| < 2.5$
- ▶  $\hat{\text{NNLO}}$ : improved agreement with measurements overall in both normalization and shape



# Conclusions & Outlook

- ▶ **high precision** experiment/theory comparisons at level of **top-quark decay** products can & should be made!
- ▶ calculation for fully-differential  $t\bar{t}$  production and decay, including
  - ▶ good approximation of NNLO in production
  - ▶ exact NNLO corrections in decay
  - ▶ exact NLO $\times$ NLO corrections (decay-decay, prod-decay)
- ▶ NNLO corrections are **significant** (normalisation & shape), reduction in scale uncertainties by  $\sim$  factor 1/2
- ▶  $\hat{\text{N}}\text{NLO}$  predictions bring improved agreement with fiducial ATLAS & CMS cross sections and distributions
- ▶ only true if **production and decay** corrections are included

- ▶ 13 TeV runs & dynamical scales (important at high- $p_T$ )
- ▶ applications:
  - ▶  $m_t^{\text{pole}}$ -extraction from  $\sigma^{\text{fiducial}}$
  - ▶ effects of NNLO corrections on  $m_t^{\text{pole}}$ -extraction from  $M_{bl}$ ,  $E(J_b)$  distributions (for NLO see [Heinrich et al '14, Agashe et al. '16] )
- ▶ NNLO top decay into STRIPPER framework [Czakon,Heymes,Mitov] : ongoing work with Czakon,Heymes,Lim,Mitov

Where possible every effort should be made to compare the **physical objects** in **fiducial volumes** that experiments are actually sensitive to, to reduce or remove the reliance on extrapolations.

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**Grazie per la vostra attenzione!**