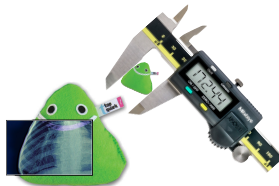


# Theoretical aspects of top-pair production cross sections



Top Quark Physics at the Precision Frontier  
16-17 January 2018, Fermilab

Andrew Papanastasiou  
Cavendish Laboratory, University of Cambridge



Science & Technology  
Facilities Council



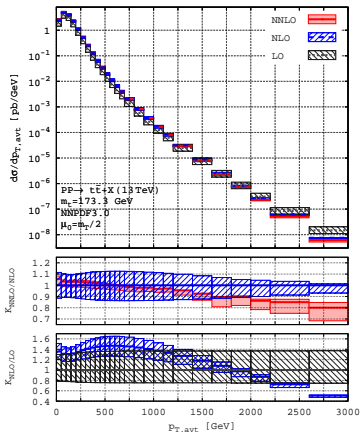
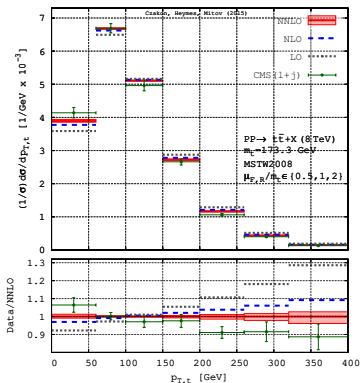
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- ▶  $t\bar{t}$  production at high precision (stable tops)
  - ▶ scale choices
  - ▶ fast evaluations of NNLO
  - ▶ NNLO-QCD+NLO-EW combinations
  - ▶ preliminary look at new observables
- ▶ Predictions for the physical final states of  $t\bar{t}$ 
  - ▶ NWA: toward NNLO production & decay
  - ▶ NLO predictions for offshell  $t\bar{t}$  and  $t\bar{t}j$
  - ▶ NLO+PS for offshell  $t\bar{t}$

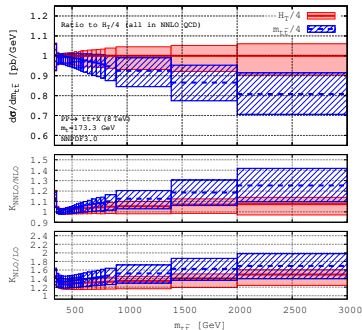
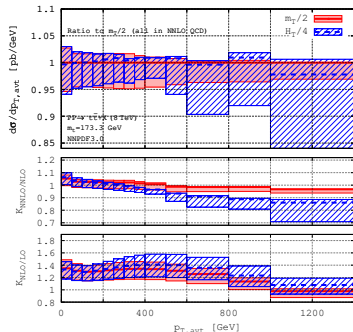
- ▶ fully-differential NNLO-QCD predictions for  $t\bar{t}$  production
- ▶ NNLO corrections often non-trivial in shape



- ▶ dynamical scales crucial in multi-TeV regimes, however, how to pick dynamical scale? (typically large differences between choices)
- ▶ choice of functional form for  $\mu_F, \mu_R$  scales is by no means unique, can vary from observable to observable
- ▶ 'optimal choice' is often subject of debate

Study of scale dependence [through NNLO \[1606.03350\]](#) :

- ▶ for a given distribution, decide on optimal scale based on criterion of best (fastest) perturbative convergence, i.e., pick scale that leads to smaller  $K$ -factors at NLO and NNLO, across full ranges of distributions.
- ▶ large number of choices considered
- ▶ scales picked according to this principle appear to lead to smallest scale uncertainties for  $t\bar{t}$
- ▶ 'optimal' choices used for NNLO studies that follow



- ▶ the following scales were found to be optimal:

$$\mu = \begin{cases} M_T/2, & \text{for } p_{T,t}, p_{T,\bar{t}}, p_{T,avt} \\ H_T/4, & \text{for all others studied } (y_t, m_{t\bar{t}}, p_{T,t\bar{t}}, y_{t\bar{t}}) \end{cases}$$

- ▶ given scale uncertainty under control, in TeV-region leading uncertainty now comes from PDFs (different sets giving v. different results!)

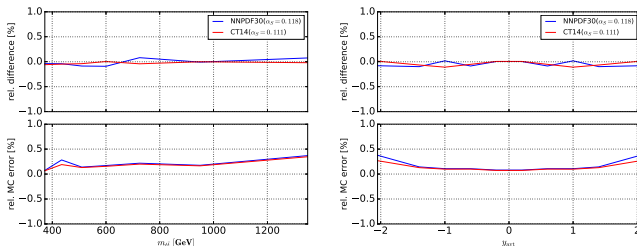
- ▶ typically  $\mathcal{O}(10^5)$  CPU hours for a single NNLO calculation (for fixed observables, scales,  $m_t$ , PDFs)
- ▶ option to compute distributions quickly with updated/improved PDF sets preferable to re-running each time a new set is released
- ▶ applications such as PDF fitting,  $\alpha_s$  or  $m_t$  extractions require results computed with  $\mathcal{O}(10 - 10^4)$  PDFs ...
  - ⇒ require flexible storage format for fast evaluations
- ▶ fastNLO [Britzger et al.] has been interfaced to STRIPPER
- ✓ PDF and  $\alpha_s$  independent storage ⇒ fast,  $\mathcal{O}(\text{seconds})$ , recalculation of distributions
- ▶ fastNLO first tables produced for the central (dynamical) scale choice, as prescribed in [1606.03350]

# Precision in Production

## Ease of use: fastNLO tables

Czakon, Heymes, Mitov '17

- ▶ same MC sample used for direct calculation and filling of tables
- ✓ interpolation error  $\lesssim 0.1\%$ , much smaller than MC error of NNLO calculation  $< 0.5\%$
- ✓ all results checked against statistically independent calculations



- ▶ repository of results & tables for  $p_{T,\text{avt}}$ ,  $y_{\text{avt}}$ ,  $y_{t\bar{t}}$ ,  $m_{t\bar{t}}$  :  
[www.precision.hep.phy.cam.ac.uk](http://www.precision.hep.phy.cam.ac.uk)
- ▶ soon: tables for different masses, 2D observables

# Precision in Production

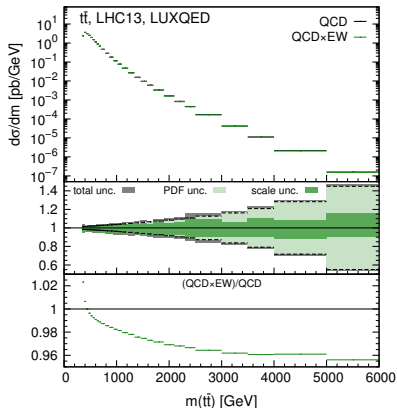
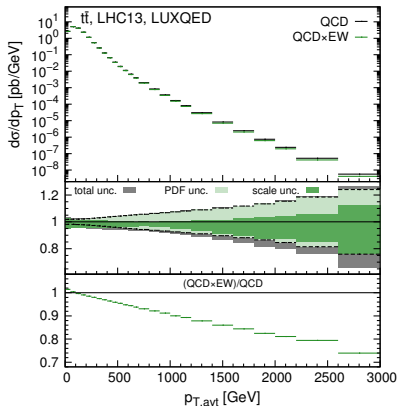
## NNLO QCD + NLO EW

- ▶ until recently no consistent combination of NNLO QCD with EW corrections
- ▶ EW-corrections naively of same order of magnitude as NNLO-QCD:  $\alpha_s^2 \sim \alpha$
- ▶ NLO-EW corrections tend to be small for total cross section
- ▶ large EW-Sudakov logarithms could have a large impact in tails of distributions, and in TeV-regime kinematics
- ▶ work of [\[1705.04105\]](#) [Czakon,Heymes,Mitov,Pagani,Tsinikos,Zaro ]
  - ▶ ‘Complete’ NLO ( $\mathcal{O}(\alpha_s^3, \alpha_s^2\alpha, \alpha_s\alpha^2, \alpha^3)$ ) contributions combined with NNLO-QCD ( $\mathcal{O}(\alpha_s^4)$ ) corrections
  - ▶ assessment of overall size of EW corrections to  $p_{T,t}, m_{t\bar{t}}, y_t, y_{t\bar{t}}$  for LHC 13 TeV
  - ▶ study effects of different photon PDFs

# Precision in Production

## NNLO QCD + NLO EW

Czakon, Heymes, Mitov,  
Pagani, Tsinikos, Zaro '17

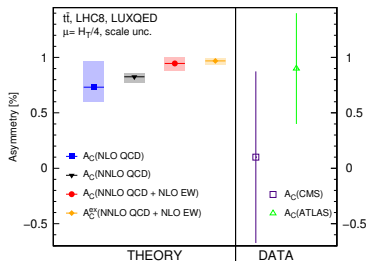


- ▶  $p_{T,t\bar{t}}$ : EW corrections grow from +2%  $\rightarrow$  -25% in range  $[0, 3]$  TeV
- ▶  $p_{T,t\bar{t}}$ : EW corrections as significant as NNLO-QCD scale uncertainty
- ▶ smaller effects for  $m_{t\bar{t}}$

# Precision in Production

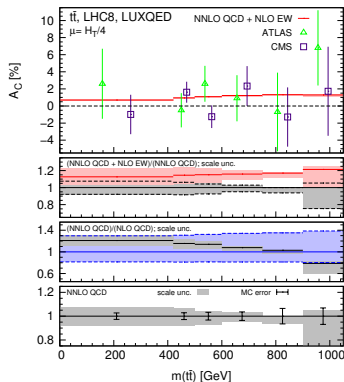
## NNLO-QCD+NLO-EW: asymmetries

Czakon, Heymes, Mitov,  
Pagani, Tsinikos, Zaro '17

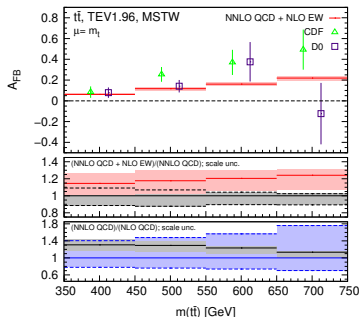
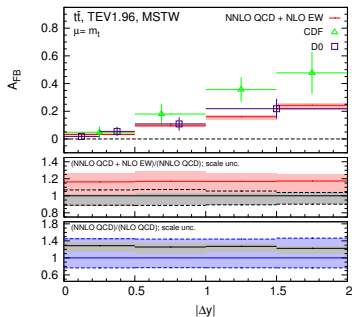


$$A_c = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



- ▶ NNLO-QCD corrections significant, increasing total asymmetry, and asymmetry in most bins of  $m_{t\bar{t}}$
- ▶ EW corrections: positive, increasing  $A_c^{\text{NNLO}}$  by  $\sim 13\text{--}20\%$  differentially
- ▶ very challenging numerically due to large cancellations in numerator



$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

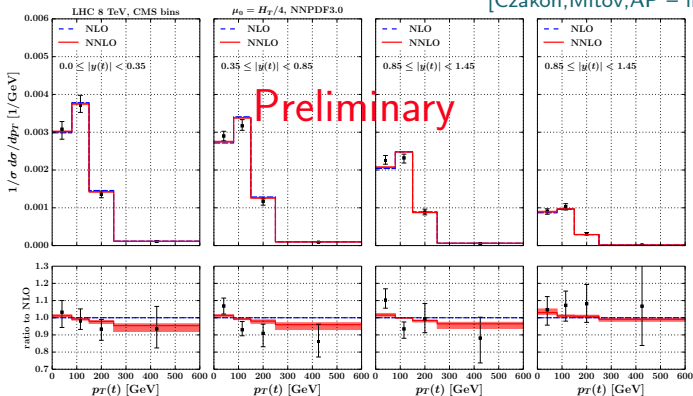
- ▶ NNLO-QCD: positive 10–30% corrections
- ▶ EW corrections: positive, increasing  $A_{FB}^{\text{NNLO}}$  by  $\sim 15\text{--}20\%$  differentially
- ▶ EW corrections: slightly increase size of scale uncertainty

# Precision in Production

## NNLO-QCD: double-differential predictions

- ▶ CMS recently published double-differential 8TeV measurements [\[1703.01630\]](#)
- ▶ stress-test theory predictions and modelling
- ▶ **preliminary**: NNLO predictions for distributions for CMS bins, 8 TeV
- ▶  $\mu = H_T/4$ , produced fastNNLO tables

[Czakon,Mitov,AP – in preparation]

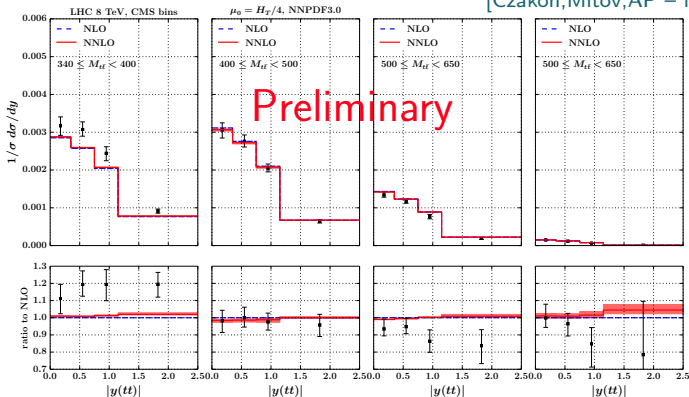


# Precision in Production

## NNLO-QCD: double-differential predictions

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[Czakon,Mitov,AP – in preparation]



# Moving towards physical final states

## The top quark is not stable

- ▶ due to its large width,  $\Gamma_t$ , top quark decays before hadronizing ...
- ▶ top quarks not directly measured – presence always 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
- ▶ this back-modelling depends on Monte Carlo
  - ▶ these steps currently use MCs that **treat top decay at LO**
    - ⇒ no reliable estimate of uncertainty on shape & normalization due to higher order corrections to decay
  - ▶ each MC generator has a different shower
    - ⇒ is the top ‘parton’ one arrives at is a **MC-dependent** object?

# Predictions for physical final states

## Including the top quark decay

Two mainstream ways of calculating, when top decay is included:

- ▶ Narrow-width approximation (NWA),  $p(t)^2 = m_t^2$ ,  $\Gamma_t \rightarrow 0$  limit
  - ▶ production / decay of onshell tops completely factorize
  - ▶ compute higher-order corrections to prod. & decay separately
  - ▶ for large class of observables NWA is an excellent approx (error  $\sim \mathcal{O}(\Gamma_t/m_t)$ )
- ▶ Offshell,  $p(t)^2 \neq m_t^2$ 
  - ▶ diagrams involving top quarks only form a subset of all required contributions
  - ▶ since there are both resonant and non-resonant contributions, notion of a physical, onshell top-quark parton loses meaning
  - ▶ finite-width effects vital in certain regions of phase space, e.g. edge of  $M_{bl}$  distribution!

# Predictions for physical final states

## Predictions (fixed order)

Key features:

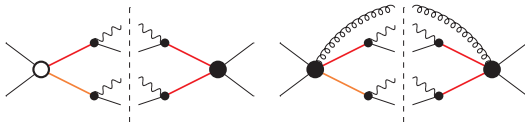
- ▶ predictions built from matrix-elements with **bs & leptons** in final state
- ▶ consistently include higher order corrections in production & decay

Measurements can be directly compared to predictions from these codes!

# Predictions for physical final states

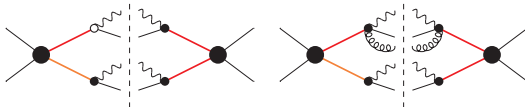
## Narrow-width approximation (NWA)

NLO  
production



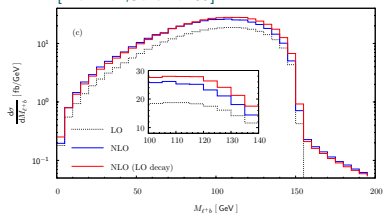
[Bernreuther, Si;  
Melnikov, Schulze;  
Badger et al;  
Campbell, Ellis]

NLO  
decay



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

[Melnikov, Schulze '09]

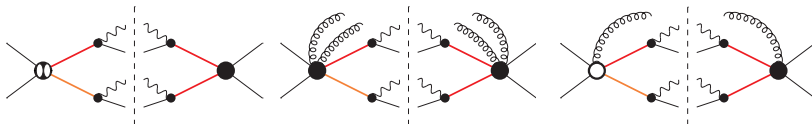


- NLO corrections to decay, in general, change **normalization** and **shape**
- decay corrections **enhanced** when cuts imposed on top-quark decay products

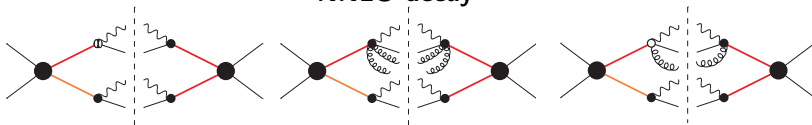
# Predictions for physical final states

## Narrow-width approximation (NWA)

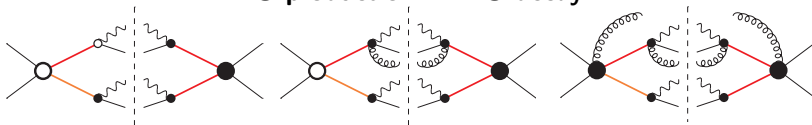
### NNLO production



### NNLO decay



### NLO-production x NLO-decay



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

# Predictions for physical final states

## NWA: towards NNLO, di-lepton channel

- ▶  $t\bar{t}$  production and decay [Gao, AP '17]
  - ▶ NNLO-decay [Gao, Li, Zhu; Caola Melnikov '12] included exactly
  - ▶ NLO-prod  $\times$  NLO-dec included exactly [Gao, AP '17]
  - ▶ NNLO-prod: soft-gluon approx. [Broggio, AP, Signer '14]  
(approximation compares well against differential LHC8 exact NNLO results of [Czakon et al.] )

Code to produce results is a parton-level Monte Carlo, which produces results at LO, NLO and  $\hat{\text{NNLO}}$ .

So far, only (direct) leptonic decays of  $W$ -bosons included.

Predictions for any IR-safe observable constructed from final state leptons and ( $b$ )jets, in fiducial regions, can be made.

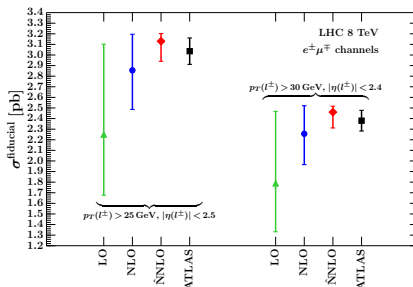
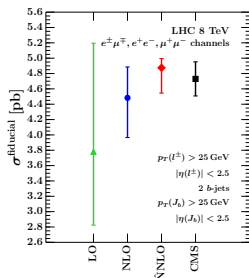
# Predictions for physical final states

## Fiducial cross sections: di-lepton channel

Gao, AP '17

Two different fiducial volumes investigated:

- ▶ CMS (8 TeV): require 2  $b$ jets,  $p_T(J_b) > 25$  GeV,  $|\eta(J_b)| < 2.5$ ,  
 $p_T(l^\pm) > 25$  GeV,  $|\eta(l^\pm)| < 2.5$
- ▶ ATLAS (8 TeV):  $p_T(l^\pm) > 25(30)$  GeV,  $|\eta(l^\pm)| < 2.5(2.4)$



- ▶ corrections beyond NLO important
- ✓ improvement in agreement between theory and measurements

## Fiducial cross sections: decay corrections vary with cuts

Look at breakdown of higher-order corrections in decay (as % of fid xs):

ATLAS:

$$\blacktriangleright \delta_{\text{dec}}^{(1)} = -0.25\%$$

$$\blacktriangleright \delta_{\text{dec}}^{(2)} = -0.10\%$$

$$\blacktriangleright \delta_{\text{prod} \times \text{dec}}^{(2)} = +0.05\%$$

CMS:

$$\blacktriangleright \delta_{\text{dec}}^{(1)} = -7.4\% \quad \in \text{NLO}$$

$$\blacktriangleright \delta_{\text{dec}}^{(2)} = -2.9\% \quad \in \text{NNLO}$$

$$\blacktriangleright \delta_{\text{prod} \times \text{dec}}^{(2)} = +1.6\% \quad \in \text{NNLO}$$

(Note:  $\delta_{\text{prod}}^{(1)} \sim +20\%$ ,  $\delta_{\text{prod}}^{(2)} \sim +10\%$ )

What we learn:

- ▶ including higher-orders in decay generally reduces fid. cross section
- ▶ size/impact of corrections in decay depend on cuts on final states  
(for good theory/data agreement in both ATLAS and CMS fiducial volumes, must include corrections in **production & decay**)
- ▶ NNLO-decay + NLO-prod  $\times$  NLO-decay corrections, are small (large cancellation in sum)

# Predictions for physical final states

## Towards NNLO production & decay

Gao, AP '17

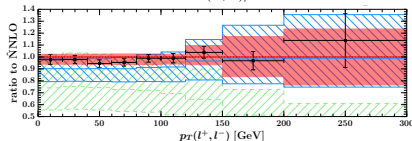
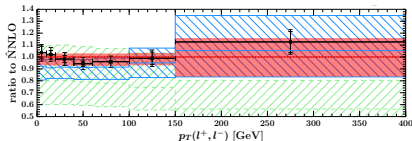
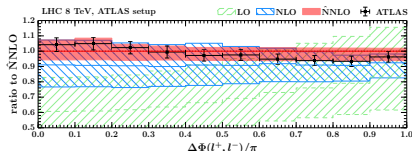
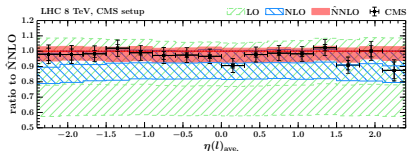
Comparisons also made differentially:

- ▶ CMS 8 TeV: [1505.04480,1510.03072]
- ▶ ATLAS 8 TeV: [ATLAS-CONF-2017-044]

$$m_t = 173.3 \text{ GeV}$$

$$\mu \in [m_t/2, 2m_t]$$

MMHT2014 PDFs

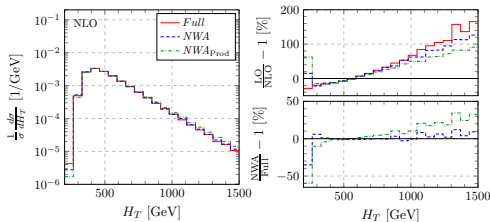
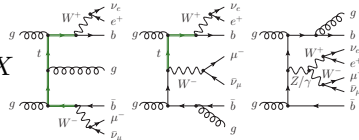


- ▶ good agreement in norm. & shape with  $\hat{\text{NNLO}}$  predictions
- ▶ exploit these for applications, e.g.  $m_t^{\text{pole}}$ -extraction from  $\sigma^{\text{fid.}}$

# Predictions for physical final states

## Offshell state-of-the-art: di-lepton

- ▶ NLO-QCD corrections to  $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$  [5FS: Bevilacqua et al, Denner et al, Heinrich et al  
4FS: Frederix, Cascioli et al]
- ▶ NLO-EW corrections to  $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$  [Denner,Pellen '17]
- ▶ NLO-QCD corrections to  $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$  [Bevilacqua,Hartando,Krauss,Worek '15,16']



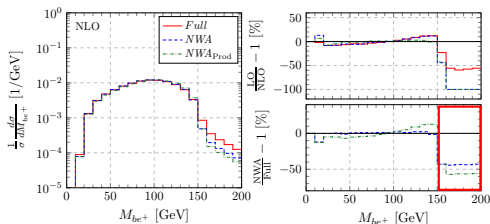
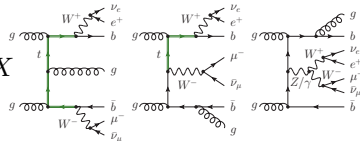
[Bevilacqua,Hartando,Krauss,Schulze,Worek '17]

- ▶ offshell & nonresonant effects small for large class of obs.
- ▶ excellent performance of NWA, when NLO corrections to prod & decay included
- ▶ Notice: NLO-production with LO-decay not a good approx. of full result (shape)

# Predictions for physical final states

## Offshell state-of-the-art: di-lepton

- ▶ NLO-QCD corrections to  $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$  [5FS: Bevilacqua et al, Denner et al, Heinrich et al  
4FS: Frederix, Cascioli et al]
- ▶ NLO-EW corrections to  $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$  [Denner,Pellen '17]
- ▶ NLO-QCD corrections to  $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}j + X$  [Bevilacqua,Hartando,Krauss,Worek '15,16']



[Bevilacqua,Hartando,Krauss,Schulze,Worek '17]

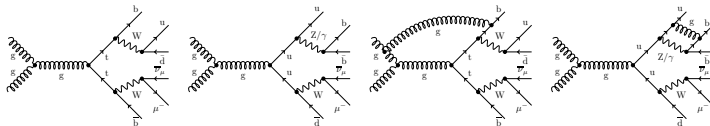
- ▶ near kinematic thresholds / edges of distributions, offshell effects become crucial
- ▶ good description of these phase space regions relies on top kept offshell  
⇒ NWA fails (not designed to capture these effects)

# Predictions for physical final states

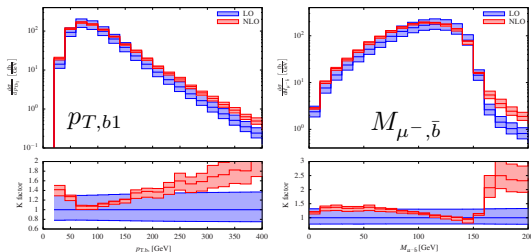
## Offshell state-of-the-art: lepton+jets

Denner, Pellen '17

- ▶ NLO-QCD corrections to  $\mu^- \bar{\nu}_\mu b \bar{b} j j + X$  recently computed



- ▶ final state: 2 light jets, 2  $b$  jets, charged lepton,  $\cancel{E}_T$  (“resolved” topology)



- ▶  $K$ -factors can be non-trivial & large (& different to di-lepton channel in general)
- ▶ size of NLO corrections sensitive on event selection (particularly treatment of light jets)

- ▶ a comparison with NWA results [Melnikov,Schulze; Campbell, Ellis (MCFM)] would be very useful at this point

# Predictions for physical final states

## NWA & Offshell $t\bar{t}$ matched to parton showers

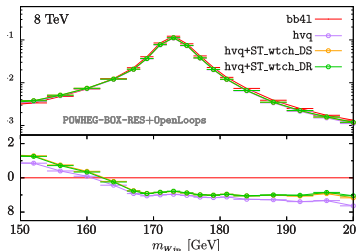
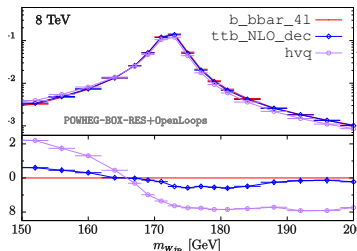
- ▶ Aim: match NLO matrix elements for  $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$  to parton showers
- ▶ despite top quarks not being a final state in the matrix elements, an ‘intermediate top’ must be written in event file if one wants the PS to preserve the resonance mass
- ▶ resonance-aware matching to parton showers for  $t\bar{t}$  (NWA & offshell) have been developed in the POWHEG framework over last couple of years
- ▶ two state-of-the-art generators:
  - ▶ “ttb\_NLO\_dec”: NWA, NLO corrections in prod. & decay, and LO approximation of finite-width effects [Campbell,Ellis,Nason,Re '14]
  - ▶ “bb4l”: fully offshell, NLO corrections to resonant & nonresonant contributions [Ježo, Nason '15; Ježo, Lindert, Nason, Oleari, Pozzorini '16]
- ▶ study differences between these and the older (but routinely used today):
  - ▶ “hvvq”: NWA, NLO corrections in production only [Frixione,Nason,Ridolfi '07]

# Predictions for physical final states

## NWA & Offshell $t\bar{t}$ matched to parton showers

Ježo, Lindert, Nason,  
Oleari, Pozzorini '16

Taken from T. Ježo's talk @ Top2017



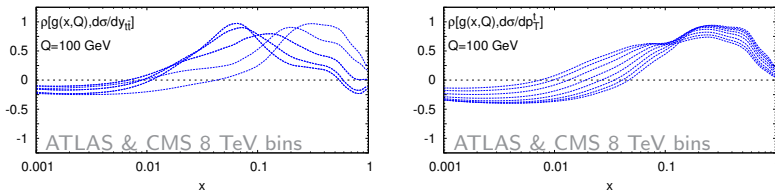
- ▶ sizeable differences in shape (10-50%) and normalization ( $\sim 10\%$ ) between  $bb41$  and  $h\nu q$  generators
- ▶ milder differences between  $bb41$  and  $t\bar{t}b_{\text{NLO\_dec}}$  generators
- ▶ even though offshell effects are modelled ( $\sim \text{LO}$ ) in  $h\nu q$  and  $t\bar{t}b_{\text{NLO\_dec}}$  generators, to get close to full result when using an onshell approx., it is **imperative** to include corrections in decay
- ▶ radiative corrections in decay impact  $b$ jet dynamics

# The power of tops

## Application: probing high- $x$ gluon

Czakon, Hartland, Mitov,  
Nocera, Rojo '16

- ▶ differential top-pair production data sensitive to large- $x$  gluon PDF

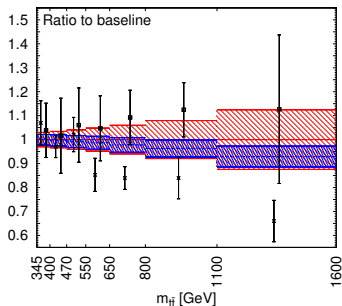


- ▶ [1611.08609] performed a global fit (in NNPDF framework) using NNLO  $t\bar{t}$  predictions to study impact of diff. top data on PDF fit
- ▶ baseline fit data:  $\sim$  NNPDF3.0, *without*  $\sigma_{t\bar{t}}$  & *inclusive-jet* data
- ▶ fit with top data: included (8TeV,  $l$ +jets channel)
  - ▶ ATLAS normalized  $y_t$  distribution
  - ▶ CMS normalized  $y_{t\bar{t}}$  distribution
  - ▶ ATLAS & CMS measurement of  $\sigma_{t\bar{t}}$

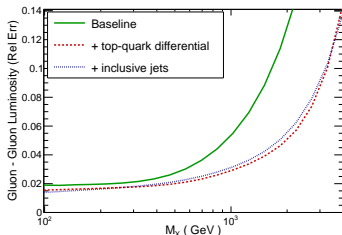
# The power of tops

## Application: probing high- $x$ gluon

Czakon, Hartland, Mitov,  
Nocera, Rojo '16



- ▶ red: baseline-fit PDFs (NNPDF)
- ▶ blue: PDFs after select top data included
- ✓ bands: PDF uncertainties  $\rightarrow$  reduction by factor 2!
- ▶ description of obs. included in fit improves, but little/no improvement of distributions not included in fit

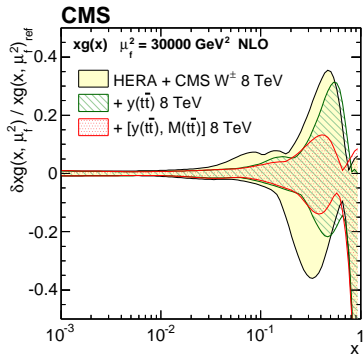


- ▶ Relative uncertainty on gluon-gluon lumi at high  $M_X$  shows remarkable reduction, with inclusion of just 17 data points!
- ▶ differential top data is very constraining and perhaps can compete with jets

# The power of tops

## Application: constraining PDFs with 2D-distributions

CMS '17



- ▶ CMS perform a PDF fit using their recent  $t\bar{t}$  2D measurements
- ▶ measurements of double-differential distributions seem to be more constraining than the 1-dim.

- ▶ presently: study performed at NLO, but soon this could be done at NNLO
- ✓ very encouraging prospects

# Summary & Outlook

- ▶ at the stable-top level, theory for  $t\bar{t}$  is at a high level of precision: NNLO-QCD, +NLO-EW, +resummation, and its potential for **impactful** applications using LHC data is **huge**!
- ▶ ongoing production line for NNLO results & tables, in particular new observables and, variations of  $m_t$  will appear:  
[www.precision.hep.phy.cam.ac.uk](http://www.precision.hep.phy.cam.ac.uk)
- ▶ To benefit maximally from precision stable-top theory (e.g. for PDF fits), systematics arising from e.g. particle-to-parton level extrapolations, higher-order corrections in decay must be understood **thoroughly**.
- ▶ new high-precision tools & predictions at level of top decay products show non-trivial top-decay effects on observables
- ▶ comparisons with these new tools is **the way** to truly exploit progress on stable-top side

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**Thank you for your attention!**