Top Pair-Production theory overview

TOP2017

17-22 September, Braga, Portugal

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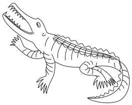
Science & Technology Facilities Council

UNIVERSITY OF CAMBRIDGE



Outline of talk

- Precision in production
  - news from NNLO-QCD
  - an application and a problem
- Towards the physical final states of $t\bar{t}$
  - toward NNLO production & decay in NWA
  - offshell and offshell + parton showers

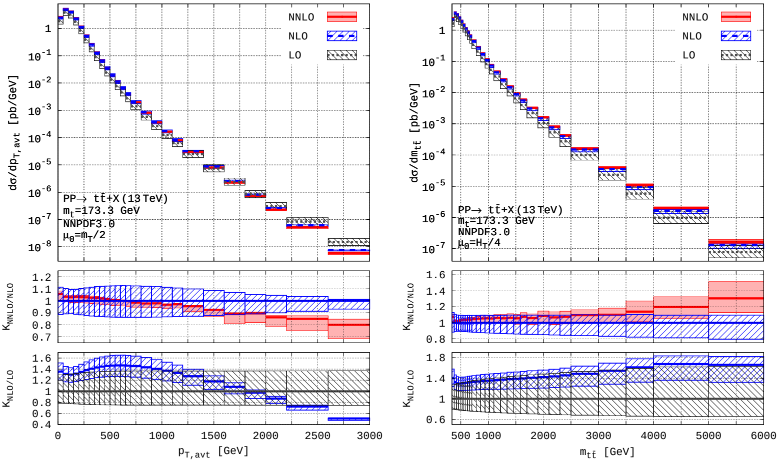
Apologies in advance for omissions in this talk.
I will talk about work done on $t\bar{t}$ mainly in the past year or so.
I will also not have time to cover $t\bar{t}$ with resummations: talk by A. Ferroglia today 16:00

Precision in Production

The state-of-the-art

- fully-differential NNLO-QCD predictions for $t\bar{t}$ production

[Czakon,Heymes,Mitov '16]



Precision in Production
The state-of-the-art

Important outcomes of [1606.03350] : [Czakon,Heymes,Mitov '16]

- detailed study of scale dependence through NNLO at fixed order
- dynamical scales crucial in multi-TeV regimes, however, how to pick dynamical scale? (typically large differences between choices)
- based on criterion of best (fastest) perturbative convergence, across full ranges of distributions, the following scales were found to be optimal

$$\mu = \begin{cases} M_T/2, & \text{for } p_T(t),\ p_T(\bar{t}),\ p_T(t)_{\text{ave}} \\ H_T/4, & \text{for all others studied } (y(t),\ m_{t\bar{t}},\ p_T(t\bar{t}), y_{t\bar{t}}) \end{cases}$$

- Note: $\sigma^{\text{NNLO}}(\mu = H_T/4) \simeq \sigma^{\text{NNLO+NNLL}}(\mu = m_t)$
- forms basis for scale choices in all NNLO studies that follow
- given scale uncertainty under control, in TeV-region leading uncertainty now comes from PDFs (different sets giving v. different results!)

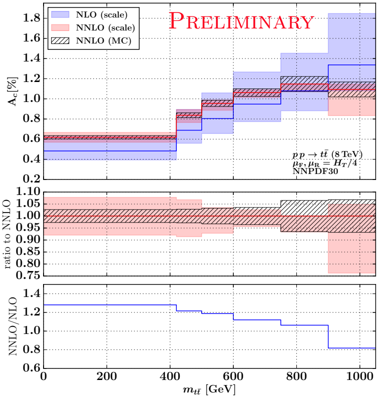
Precision in Production

New observables: LHC charge asymmetry, A_c

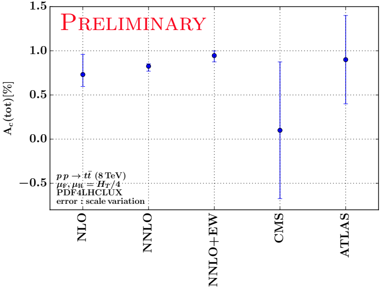
Thanks to D. Heymes for plots!

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

$$\Delta|y| = |y(t)| - |y(\bar{t})|$$



[Czakon,Heymes,Mitov,Pagani,Tsinikos,Zaro - in preparation]



- unexpanded denominator
- NNLO-QCD corrections (& NLO-EW) increase total asymmetry (but not asymmetry in all bins of $m_{t\bar{t}}$)
- very challenging numerically due to large cancellations in numerator

Precision in Production

NNLO QCD + NLO EW

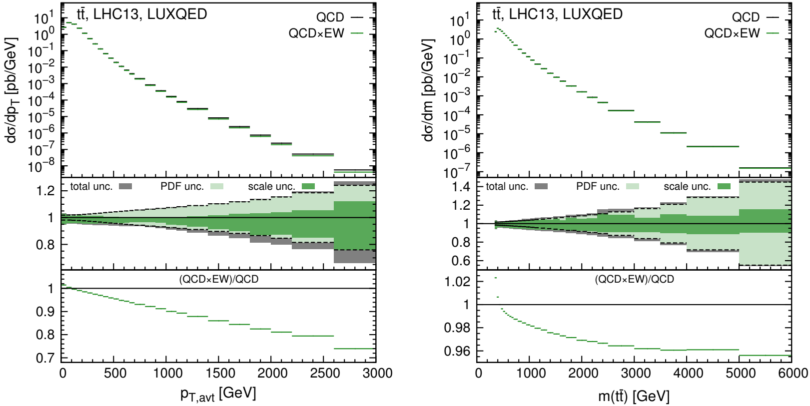
Dedicated talk by D. Pagani, tomorrow 16:30

- NLO-EW corrections tend to be small for total cross section, but
- large EW-Sudakov logarithms could have a large impact in tails of distributions, and in TeV-regime kinematics
- in [1705.04105] (see also [1606.01915]) [Czakon,Heymes,Mitov,Pagani,Tsinikos,Zaro '17; Pagani, Tsinikos, Zaro '16]
  - 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]



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

Precision in Production

Ease of use: fastNLO tables

[Czakon,Heymes,Mitov '17]

- 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 preferrable to re-running each time a new set is released
- applications such as PDF fitting, α_s or m_t extractions require results computed with $\mathcal{O}(10 - 1000)$ PDFs ...

$\Rightarrow$ require flexible storage format for fast evaluations

- fastNLO [Britzger et al.] has been interfaced to STRIPPER

✓ PDF and α_s independent storage $\Rightarrow$ fast, $\mathcal{O}(\text{seconds})$, recalculation of distributions

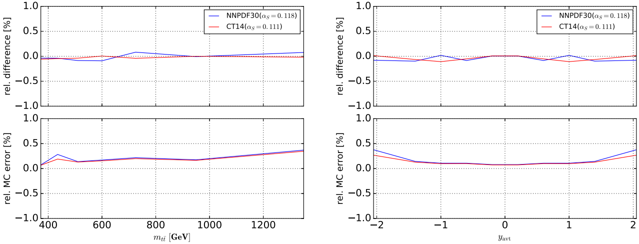
- fastNLO first tables produced for the central (dynamical) scale choice, as prescribed in [1606.03350]

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

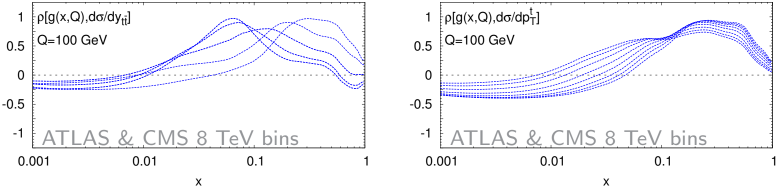


- tables for $p_T(t)$, $y(t)$, $y(t\bar{t})$, $M(t\bar{t})$ at 8 TeV (ATLAS & CMS binnings) available at: `www.precision.hep.phy.cam.ac.uk`
- tables for 13 TeV, 2D observables, different masses on the way!

Precision in Production
An application: probing high-x gluon

[Czakon,Hartland,Mitov,Nocera,Rojo '16]

- 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 (all 8TeV, l+jets channel)
  - ATLAS normalized y_t distribution
  - CMS normalized $y_{t\bar{t}}$ distribution
  - ATLAS & CMS measurement of $\sigma_{t\bar{t}}$

Precision in Production

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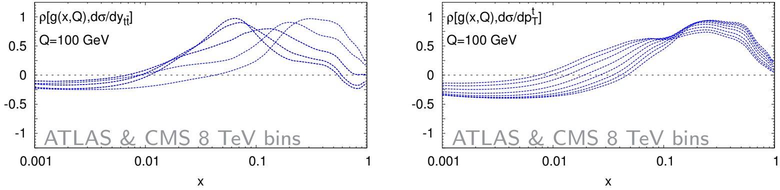

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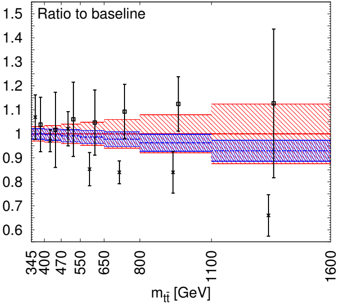
  } ✓small dependence on m_t uncertainty
  ✓low BSM sensitivity

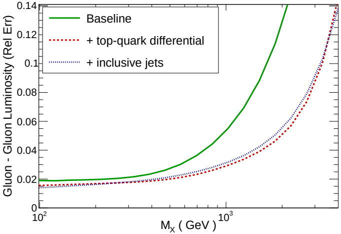
Precision in Production

Application: probing high-x gluon – outcomes

[Czakon,Hartland,Mitov,Nocera,Rojo '16]



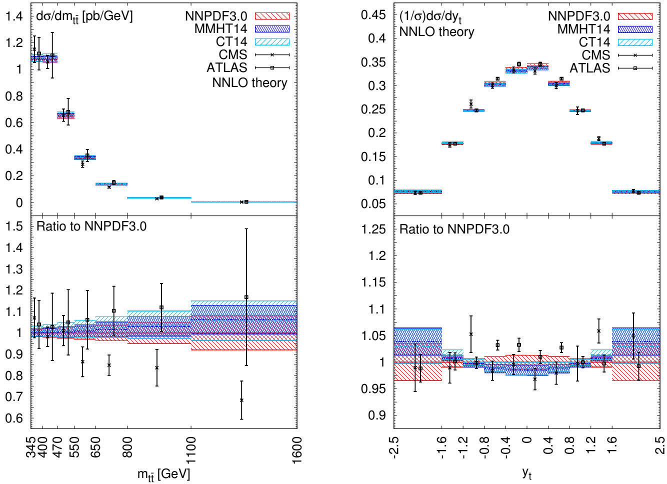
- red: baseline-fit PDFs (NNPDF)
  blue: PDFs after select top data included
- ✓ bands: PDF uncertainties → reduction by factor 2!
- description of obs. included in fit improves, but little/no improvement of distributions not included in fit



- 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
- surely one of the big motivations for $t\bar{t}$?

[Czakon,Hartland,Mitov,Nocera,Rojo '16]

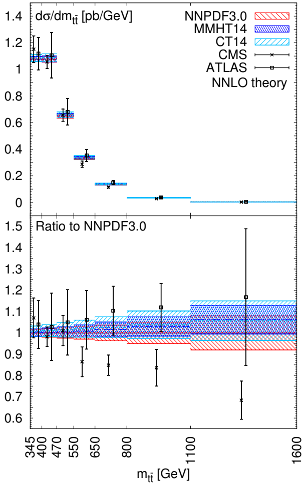
Two examples of 'tension' between measurements:



Precision in Production

Some unsettling observations

[Czakon,Hartland,Mitov,Nocera,Rojo '16]



- very difficult to get a good description of both ATLAS and CMS (l+jets 8TeV) data, particularly for normalized y_t, $p_T(t)$ and $m_{t\bar{t}}$
- for best fit quality authors had use a different observable from each experiment
  (multiple distributions from each exp. not possible due to lack of correlations b/w distributions)
- to maximize benefit of NNLO predictions, such discrepancies must be resolved
- has there been any understanding to the reasons behind discrepancies?
  - are we missing/underestimating some systematic uncertainty?
  - are ATLAS and CMS presenting exactly the same 'stable-top' quantities?

Moving towards physical final states

The top quark is not stable

- due to its large width, Γ_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
  - each MC generator has a different shower & (potentially) way of attaching the decay

    $\Rightarrow$ is the top 'parton' one arrives at is a MC-dependent object?
  - these steps currently use MCs that treat top decay at LO

    $\Rightarrow$ no reliable estimate of uncertainty on shape & normalization due to higher order corrections to decay

Moving towards physical final states

Predictions (fixed order)

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

- Narrow-width approximation (NWA), $p(t)^2 = m_t^2$, $\Gamma_t \to 0$ limit
  - NLO: [Bernreuther, Si; Melnikov, Schulze; Campbell, Ellis (MCFM)]
  - 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, $p(t)^2 \neq m_t^2$
  - NLO: [Bevilaqua et al, Denner et al, Falgari et al, Heinrich et al, Frederix, Cascioli et al]
  - 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!

Key features:

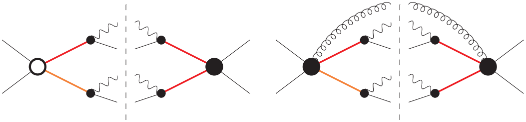
- predictions built from matrix-elements with **bs & leptons** in final state
- consistently include higher order corrections in production & decay

Measurements can be directly compared to predictions from these codes!

Moving towards physical final states

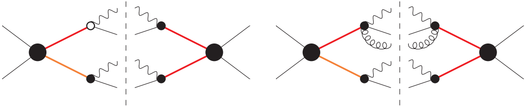
Narrow-width approximation (NWA)

NLO production



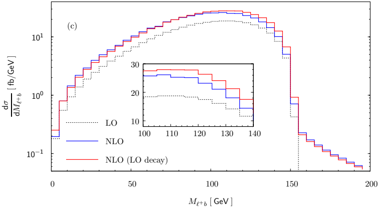
[Bernreuther,Si; Melnikov, Schulze; Badger et al; Campbell, Ellis]

NLO decay



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

[Melnikov,Schulze '09]

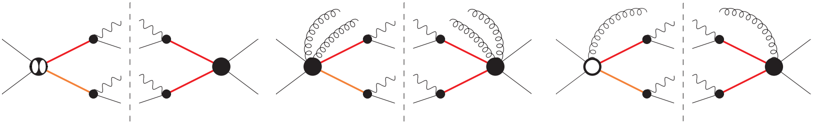


- NLO corrections to decay, in general, change normalization and shape
- decay corrections enhanced when cuts imposed on top-quark decay products

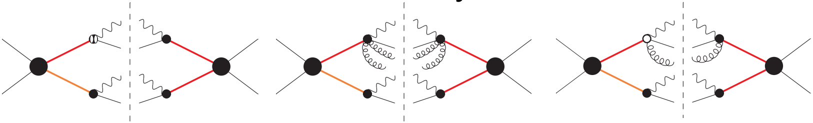
Moving towards physical final states

Narrow-width approximation (NWA)

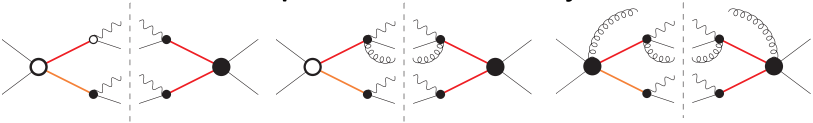
NNLO production



NNLO decay

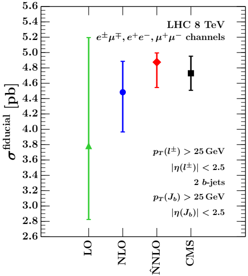


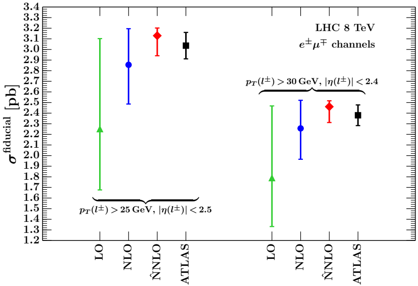
NLO-production x NLO-decay



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

- exact NNLO not yet available: ongoing work within `Stripper`
- recent work: approx-NNLO prod. [Broggio,AP,Signer '14] with exact NNLO in decay [Gao,Li,Zhu '12] (& exact interferences): **N̂NLO** [Gao,AP '17]





- significant improvement in agreement of theory with measurements
- to see good agreement for both ATLAS and CMS fiducial volumes, must include corrections in prod. & decay – including no corrections in decay $\Rightarrow$ cross section $\sim 8\%$ larger than full result, for CMS volume

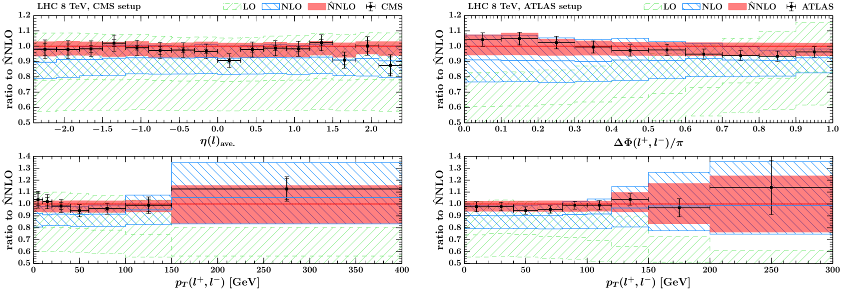
Moving towards physical final states
Towards NNLO production & decay

[Gao,AP '17]

Comparisons also made differentially:

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

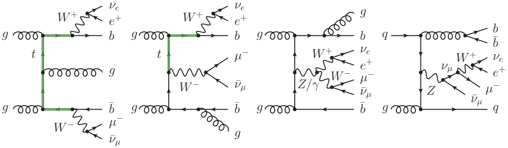
$m_t = 173.3$ GeV
$\mu \in [m_t/2, 2m_t]$
MMHT2014 PDFs



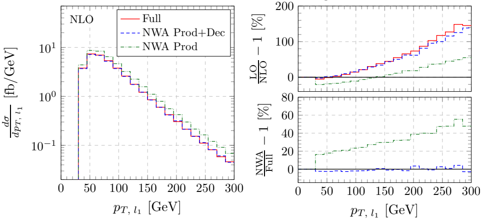
- good agreement in norm. & shape with N̂NLO predictions
- start exploiting these for applications, e.g. m_t^{pole}-extraction from $\sigma^{\text{fid.}}$

Moving towards physical final states
Offshell state-of-the-art

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



From B. Hartando's talk @ QCD@LHC2017



[Bevilaqua,Hartando,Krauss,Schulze,Worek – in preparation]

- offshell & nonresonant effects very 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 & norm.)

Moving towards physical final states
Offshell state-of-the-art

- NLO corrections to $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}+X$ known [5FS: Bevilaqua et al, Denner et al, Heinrich et al 4FS: Frederix, Cascioli et al]
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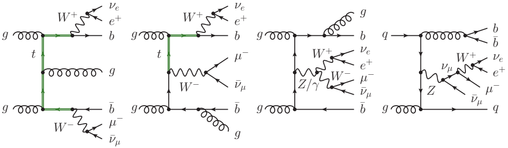

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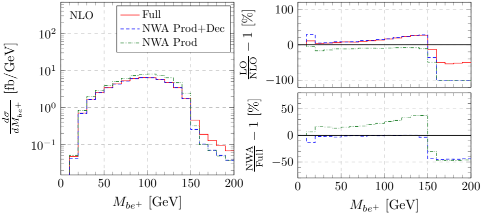


[Bevilaqua,Hartando,Krauss,Schulze,Worek – in preparation]

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

Moving towards physical final states

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

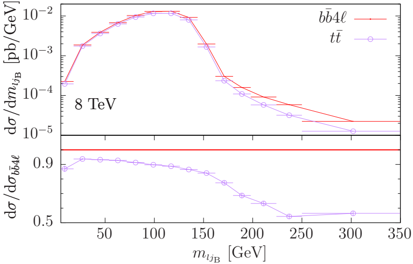
See also talk by T. Ježo → tomorrow 11:50

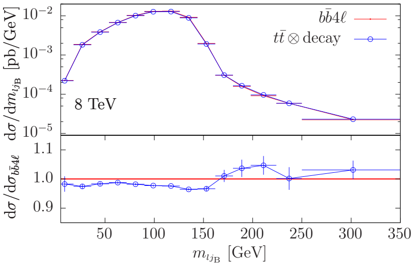
- Aim: to match $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}+X$ to parton showers
- despite top quarks not being a final state in the matrix elements, an 'intermediate top' must be written in event file if one wants the PS to preserve the resonance mass
- resonance-aware matching to parton showers for $t\bar{t}$ (NWA & offshell) have been developed in the `POWHEG` framework over last couple of years
- two state-of-the-art generators:
  - "$t\bar{t}\otimes\mathrm{decay}$": NWA, NLO corrections in prod. & decay, and LO approximation of finite-width effects [Campbell,Ellis,Nason,Re '14]
  - "$b\bar{b}4l$": 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):
  - "$t\bar{t}$ ": NWA, NLO corrections in production only

Moving towards physical final states

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

[POWHEG;NWA: Campbell, Ellis, Nason, Re '14; offshell: Ježo, Nason '15; Ježo, Lindert, Nason, Oleari, Pozzorini '16]





- sizeable differences in shape (10-50%) and normalization (∼10%) between $b\bar{b}4l$ and $t\bar{t}$ generators
- much milder differences between $b\bar{b}4l$ and $t\bar{t} \otimes \mathrm{decay}$ generators
- these features are repeated for a number of observables
- even though offshell effects are modelled (∼LO) in $t\bar{t}$ and $t\bar{t} \otimes \mathrm{decay}$ generators, it clear that to get close to full result when using an onshell approx., it is imperative to include corrections in decay

Moving towards physical final states

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

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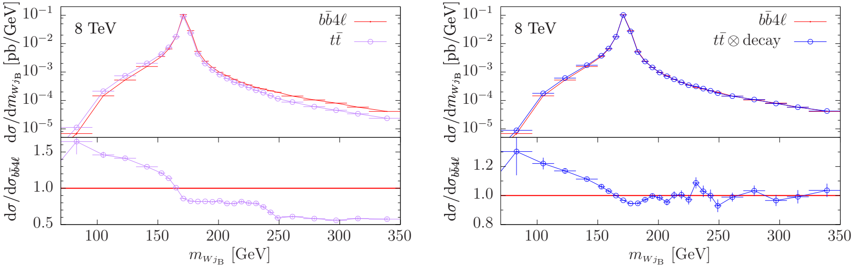

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Summary & Outlook

- It is clear that 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!
- Fast re-evaluations of differential observables now possible via `fastNLO` interface, and there is an ongoing 'production line' of new runs, observables, K-factors, tables... all of which will be available at

  `www.precision.hep.phy.cam.ac.uk`
- Also clear, that certain unsettling aspects such as p_T-discrepancy (not fully gone away) & consistency b/w measurements still remain.
- To benefit maximally from precision stable-top theory (e.g. for PDF fits) such issues/features must be understood.

- Given non-trivial nature of higher-order corrections in decay, their effect on extrapolations to 'parton level' ought to be accounted for (this is a systematic error we currently don't have an estimate for).
- The tools to do this at high precision are already available.

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Obrigado!