Electroweak corrections and off-shell effects in $t\bar{t}$ production and decay

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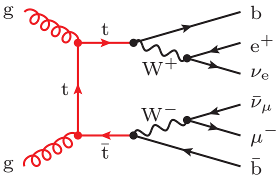
Precision and EW corrections

Motivation for high theoretical precision in $pp \to t\bar{t} \to WWb\bar{b}$

- precision PDF and m_t determinations
- small anomalies in top observables
- small signals with large top backgrounds



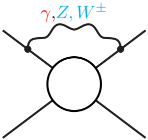
EW correction effects

- $\mathcal{O}(\alpha)$ corrections to on-shell $pp \to t\bar{t}$
- $\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right) = \mathcal{O}(\alpha)$ effects from off-shell $pp \to WWb\bar{b}$

both effects mostly small . . . but strongly enhanced in important kinematic regions

EW Sudakov logarithms at $Q \sim \mathrm{TeV} \gg M_W$

Soft/collinear logarithms from *virtual* EW bosons [Bauer, Becher, Ciafaloni, Comelli, Denner, Fadin, Kühn, Lipatov, Manohar Martin, Melles, Penin, S.P., Smirnov, ...]



- $Z, W^\pm$ bosons $\sim$ light particles at $\hat{s} \gg M^2_{W,Z}$

$\Rightarrow$ large logarithms of IR type

Universality and factorisation [Denner,S.P. '01]

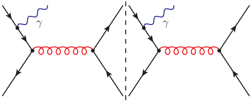
$$\delta\mathcal{M}^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

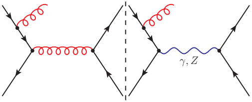
- large negative terms $\propto \alpha_w \ln^2(Q^2/M_W^2) \sim 25\% \gg \alpha_S$ in any TeV scale observable
- size depends on external EW charges: not very large for $gg \to t\bar{t}$

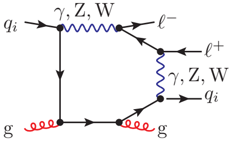
$\Rightarrow$ **EW corrections important for SM tests and BSM searches at TeV scale**

Nontrivial NLO EW features wrt NLO QCD (examples)

(1) QCD–EW "interference" (e.g. q/g bresstrahlung at NLO EW)

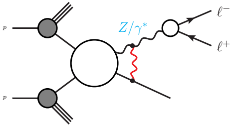


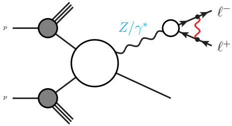


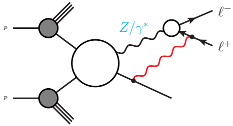


(2) Virtual EW corrections more involved than QCD ones (due to massive Z, W, H, b, t) and tend to dominate

(3) Leptons receive EW corrections and W, Z resonances require complex-mass scheme [Denner, Dittmaier]







(4) Protons and jets $\supset g, q, \gamma$ (IR safe photon–jet separation subtle)

First automated NLO QCD+EW tools and applications

NLO EW Tools	first results	
RECOLA+COLLIER	$pp \to \ell^+\ell^- jj$	[arXiv:1411.0916]
	$pp \to (t\bar{t}) \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$	[arXiv:1607.05571]
	$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$	[arXiv:1605.03419]
	$pp \to e^+e^-\mu^+\mu^-$	[arXiv:1601.07787]
OPENLOOPS+ MUNICH/SHERPA	$pp \to W + 1, 2, 3$ jets	[arXiv:1412.5156]
	$pp \to \ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets	[arXiv:1511.08692]
MADGRAPH5_AMC@NLO	$pp \to t\bar{t} + H/Z/W$	[arXiv:1504.03446]
	$pp \to t\bar{t}$	[arXiv:1606.01915]
GOSAM+ MADDIPOLE	$pp \to W + 2$ jets	[arXiv:1507.08579]

Benefits of automation

- NLO QCD+EW for multi-particle process, e.g. $pp \to WWb\bar{b}$ and $t\bar{t}+$ multijets
- NLO QCD+EW matching and mering with parton showers (still work in progress)

Outline

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3. Resonance aware NLO+PS matching for $pp \to W^+W^-b\bar{b}$
4. $t\bar{t} + 3\,$jets at NLO QCD

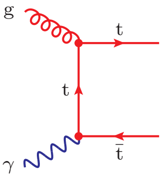
NLO EW corrections to on-shell $pp \to t\bar{t}$

Literature

- weak [Beenakker et al. '94; Kühn et al. '06–'13; Bernreuther et al. '06; Campbell et al. '16]
- QED [Hollik, Kollar '08]
- A_{FB} [Hollik, Pagani '11; Kühn, Rodrigo '12; Manohar, Trott '12; Bernreuther, Si '12]
- NLO EW with decays in NWA [Bernreuther, Si '10]

NLO QCD+EW [Pagani, Tsinikos, Zaro, 1606.01915]

channel	LO QCD $\mathcal{O}\left(\alpha_S^2\right)$	NLO QCD $\mathcal{O}\left(\alpha_S^3\right)$	LO EW $\mathcal{O}\left(\alpha_S\alpha\right)$	NLO EW $\mathcal{O}\left(\alpha_S^2\alpha\right)$
$q\bar{q} \to t\bar{t}$	x	x		x
$gg \to t\bar{t}$	x	x		x
$\gamma g \to t\bar{t}$			x	x
$\gamma q \to t\bar{t}$				x



In depth study of γ-induced contributions

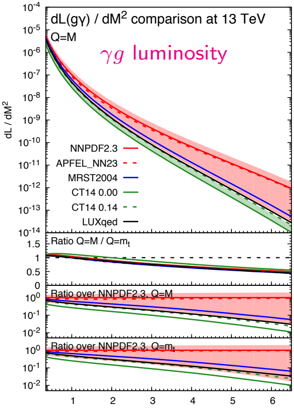
- dominated by $\gamma g \to t\bar{t}$ channel: included at $\mathcal{O}\left(\alpha_S\alpha\right)$ and $\mathcal{O}\left(\alpha_S^2\alpha\right)$

Different $\gamma(x, Q^2)$ in PDF sets with LO QED evolution

PDF	initial condition	QED⊗QCD evol.	data	$\gamma_{\mathrm{elastic}}(x)$
MRSTW2004QED	$P_{\gamma q} \otimes q_{\mathrm{valence}}$	coupled	no	no
CT14QED	$P_{\gamma q} \otimes q_{\mathrm{valence}}$	coupled	DIS $ep \to e\gamma + X$	(CT14QED_inc)
NNPDF2.3 QED	unconstrained	decoupled	DIS + DY@LHC	fit $\gamma_{\mathrm{el+inel}}(x)$
APFEL_NN23	idem	coupled	idem	idem
LUXqed	from data		$F_{2,L}(x, Q^2)$	yes

$\gamma(x, Q^2)$ potentially relevant at very high x

- NNPDFs: very large $\gamma(x, Q^2)$ and uncertainty
  ⇔ agnostic Ansatz and poor sensitivity of data
- other PDFs: consistently lower $\gamma(x, Q^2)$ and smaller uncertainty
- LUXqed [Manohar, Nason, Salam, Zanderighi '16]: very small uncertainties ⇔ $\gamma(x, Q^2)$ from proton structure functions (i.e. data)

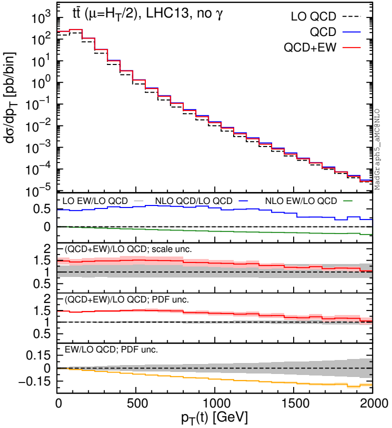


D. Pagani at QCD@LHC2016

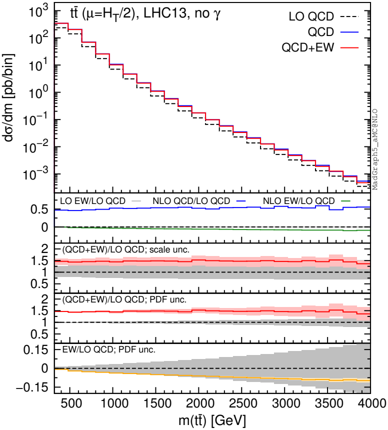
NLO QCD+EW corrections without $\gamma(x, Q^2)$

Typical Sudakov behaviour but moderate size (see lowest frame)

-20% at $p_{T,\mathrm{top}} \sim 2$ TeV

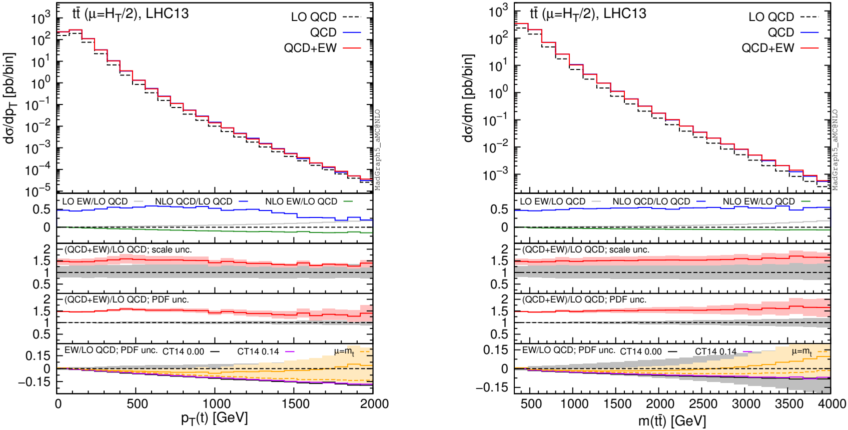


-10% at $m_{t\bar{t}} \sim 4$ TeV



Photon-induced contributions

- dominated by $g\gamma \to t\bar{t}$ at LO ($\gamma q \to t\bar{t}q$ negligible)
- overall effect up to $20\% \pm 20\%$ in NNPDF and negligible in CT14QED



Important to constrain NNPDFs with data sensitive to $\gamma(x, Q^2)$ at high-x

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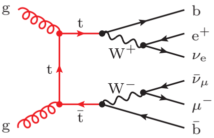
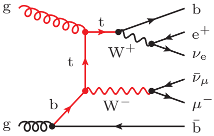
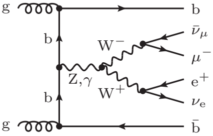
4. $t\bar{t} + 3$ jets at NLO QCD

$pp \to WWb\bar{b}$ at NLO QCD







On-shell $t\bar{t}$ production$\times$decay in NWA [Bernreuther et al. '04; Melnikov, Schulze '09]

$$\lim_{\Gamma_t \to 0} \left| \frac{1}{p_t^2 - m_t^2 + \mathrm{i}\Gamma_t m_t} \right|^2 = \frac{\pi}{\Gamma_t m_t} \delta(p_t^2 - m_t^2) \quad \Rightarrow$$ life much simpler beyond LO

Full calculations of $pp \to W^+W^-b\bar{b}$ [Denner et al. '10; Bevilacqua et al. '10; Heinrich et al. '13; Cascioli et al '13; Frederix'13] **and $WWb\bar{b}j$** [Bevilacqua et al,'15–'16]

- $t\bar{t}$ production *and* decays at NLO with off-shell effects
- $t\bar{t} + Wt$ and non-resonant channels with interferences
- 0- and 1-jet bins thanks to $m_b > 0$ [Cascioli et al '13; Frederix'13]

Deviations from naive NWA can be sizable

In inclusive $t\bar{t}$ observables (2 b-jets)

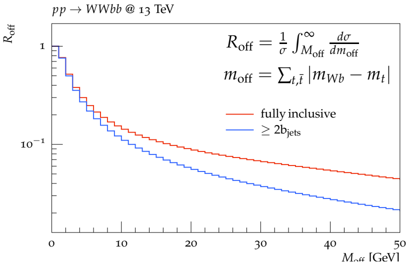
- formally or EW order

$$\frac{\Gamma_t}{m_t} \simeq \alpha \simeq 10^{-2}$$

and typically strongly suppressed

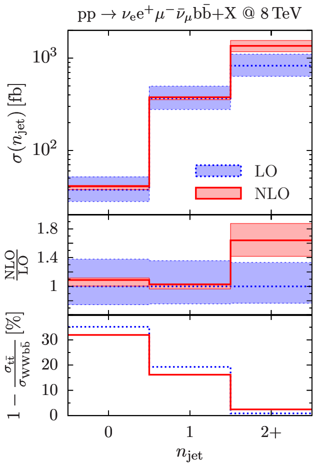
In off-shell regions

- 10% of $\sigma_{t\bar{t}}$ with off-shellness $> 10\,\text{GeV}$



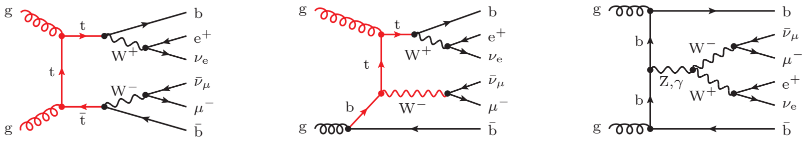
In presence of jet vetoes

- beyond 30% Wt contributions



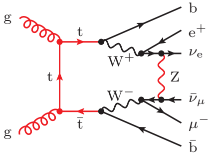
[Cascioli et al;'13]

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ at NLO EW [Denner and Pellen '16]



Exact $2 \to 6$ NLO EW calculation

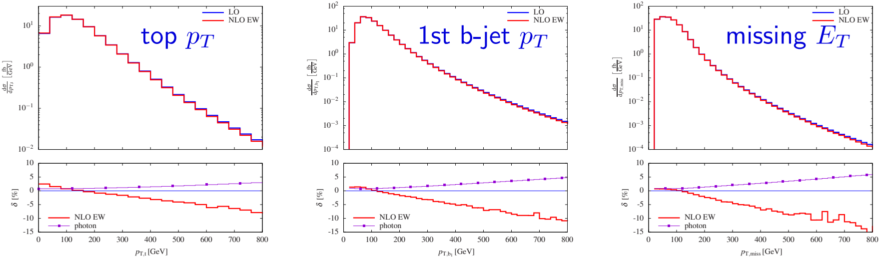
- fully differential 6-particle final state
- NLO EW top decays
- off-shell $t\bar{t}$ + Wt + non-resonant contributions



Applicable only with $t\bar{t}$ type cuts ($m_b = 0 \Rightarrow$ no unresolved b-quarks)

- 2 b-jets ($p_T > 25$ GeV, $|\eta| < 2.5$)
- 2 charged leptons ($p_T > 20$ GeV, $|\eta| < 2.5$) and missing $E_T > 20$ GeV

NLO EW corrections and γg contributions [Denner and Pellen '16]



NLO EW corrections

- up to -10-15% at $p_T \sim 800$ GeV
- qualitatively consistent with [Pagani et al '16] for reconstructed top p_T

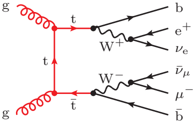
γ-induced contributions (γg at LO and γq at NLO EW included)

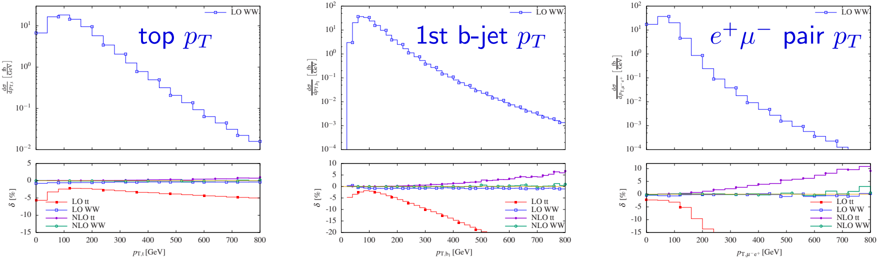
- 5–6% at $p_T \sim 800$ GeV
- smaller wrt [Pagani et al '16] due to fixed $\mu_F = m_t$

Exact $pp \to b\bar{b} + 4\ell$ vs double-pole approximation

Double-pole approximation (similar to $t\bar{t}$ MC generators!)

- on-shell $t\bar{t} \to b\bar{b} + 4\ell$ matrix elements
- approx. off-shell effects via $1/[(p^2 - m_t^2)^2 + \Gamma_t^2 m_t^2]$ distributions





Genuine off-shell and Wt effects (see deviations wrt LO $t\bar{t}$)

- $+3\%$ for σ_{tot} and $+5\%$ in tail of reconstructed top p_T
- beyond 20–30% in p_T-tails of individual top-decay products

$\Rightarrow$ **NLO EW and $\mathcal{O}(\Gamma_t/m_t)$ effects madatory for precision at high p_T**

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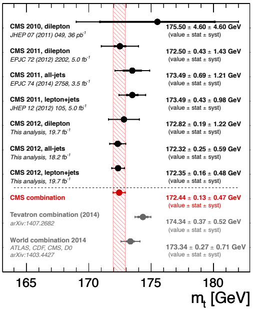
Precision m_t determination



Direct and indirect m_t determinations

- $\Delta m_t^{(\mathrm{exp})} \sim 0.5\,\mathrm{GeV}$ but spread around 2 GeV
- EW precision fit ($m_t = 177 \pm 2.1$ GeV) 1.6σ above world average

Kinematic m_t^{pole} determinations

- excellent experimental systematics
- require accurate theory understanding of

  $m_t^{\overline{\mathrm{MS}}} \quad \leftrightarrow \quad m_t^{\mathrm{pole}} \quad \leftrightarrow$ observables

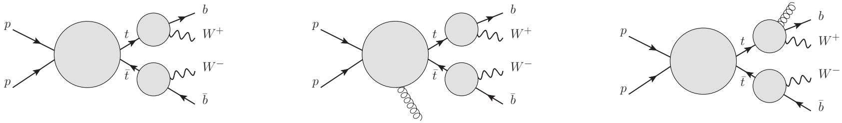
Non-perturbative (renormalon) ambiguity in $m_t^{\overline{\mathrm{MS}}} \leftrightarrow m_t^{\mathrm{pole}}$

- intrinsic $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ ambiguity of pole mass much smaller than previously expected: $\Delta m_t^{\mathrm{pole}} \sim 70$ MeV [Beneke et al, 1605.03609]

Monte Carlo simulations with higher-order $pp \to WWb\bar{b}$ matrix elements

- well defined m_t^{pole} input (no MC mass!)
- systematic precision improvements in $m_t^{\mathrm{pole}} \leftrightarrow$ observables

Resonance aware NLO+PS matching method



Long-standing problem: NLO+PS for resonant $pp \to WWb\bar{b}$ MEs

- uncontrolled M_{Wb} shifts from resonance unaware first emission and showering

⇒ highy inefficient event generation

⇒ unphysical order $\alpha_S^2 m_t/\Gamma_t \sim 1$ distortion of top line shape and related observables

Resonance aware Powheg matching [Jezo and Nason, 1509.09071]

- **guiding principle:** respects on-shellness and all-order factorisation of top production×decay for $\Gamma_t \to 0$

⇒ assign radiation to top production or decays consistent with $\Gamma_t \to 0$ limit

⇒ modified NLO+PS approach to preserve resonance virtualities at all stages

see analogous approach in MC@NLO [Frederix et al, 1603.01178]

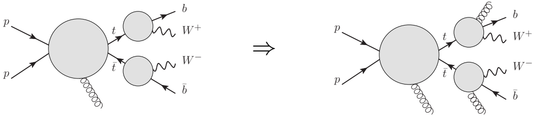
$pp \to b\bar{b} + 4\ell$ resonance aware NLO+PS generator

[Jezo, Lindert, Nason, Oleari, S.P., 1607.04538] http://powhegbox.mib.infn.it

based on POWHEG+OPENLOOPS

Precision improvements wrt standard $t\bar{t}$ NLO+PS generators

- full $pp \to t\bar{t} + Wt \to b\bar{b} + 4\ell$ process with $t\bar{t}$–tW interference
- well defined $M_t^{(\mathrm{OS})}$ with quantum corrections to top propagators
- applicable to observables with unresolved b quarks (jet vetoes) thanks to $m_b > 0$
- NLO+PS top production *and* decay with multi-radiation scheme [Campbell, Ellis, Nason, Re '15]



Potentially very useful for

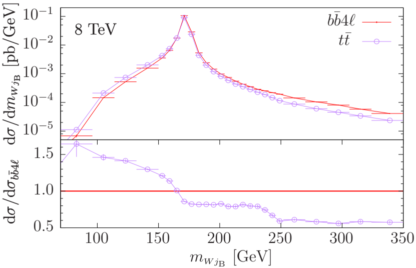
- m_t determinations
- Wt measurements and top backgrounds with jet vetoes or high p_T/missing E_T

$pp \to b\bar{b}4\ell$ vs traditional Powheg $t\bar{t}$ generator I

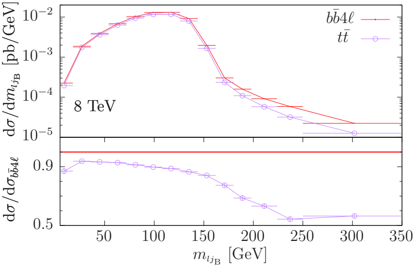
$b\bar{b}4\ell$: NLO+PS $pp \to e^+\mu^-\nu_e\bar{\nu}_\mu b\bar{b}$ [Jezo et al, 1607.04538]

$t\bar{t}$: NLO+PS $pp \to t\bar{t}$ with LO+PS decays (hvq) [Frixione, Nason, Ridolfi, '07]

Reconstructed top mass



b-jet–lepton mass

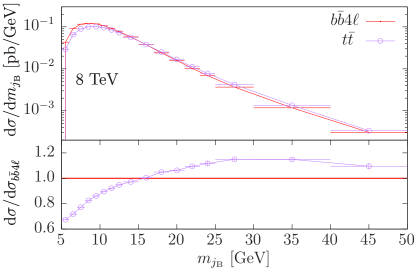


Significant effects for m_t determination

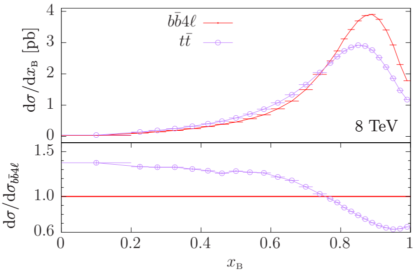
- asymmetric shape distortion around the resonance
- average $M_{W j_B}$ roughly 0.5 GeV higher (within ± 30 GeV around m_t) in $b\bar{b}4\ell$
- 20–30% effects around the $M_{\ell j_B}$ edge

$pp \to b\bar{b}4\ell$ vs traditional Powheg $t\bar{t}$ generator II

b-jet mass



B-hadron fragmentation function



Significant effects in b-jet properties

- narrower b-jets and harder B-fragmentation
- due to reduced radiation from b-quarks in $b\bar{b}4\ell$ generator

calls for detailed studies of realistic LHC observables

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$t\bar{t} + 3$ jets at NLO [Moretti, Höche, S.P., Maierhöfer, Siegert, ArXiv:1607.06934]

Motivations for $t\bar{t}$+multijet precision

- benchmark for perturbative QCD and tools
- large background systematics in $t\bar{t}H(b\bar{b})$ and BSM searches

Technical challenge addressed with Sherpa+OpenLoops

- fully coloured $2 \to 5$ process with heavy quarks

partonic channel \ N	0	1	2	3
$gg \to t\bar{t} + N\, g$	47	630	9'438	152'070
$u\bar{u} \to t\bar{t} + N\, g$	12	122	1'608	23'835
$u\bar{u} \to t\bar{t}u\bar{u} + (N-2)\, g$	–	–	506	6'642
$u\bar{u} \to t\bar{t}d\bar{d} + (N-2)\, g$	–	–	252	3'321

number of 1-loop diagrams

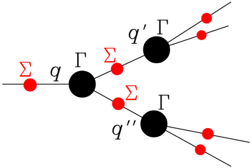
Study of scale choices and uncertainties for non-trivial multi-scale process

- hard global scale $\mu = H_T/2$: good convergence for V+multijets [Blackhat+Sherpa]
- MINLO method [Hamilton, Nason, Zanderighi '12]: **improved convergence for multi-scale processes** through NLO+NLL CKKW resummation

MINLO automation in Sherpa [Höche et al, ArXiv:1607.06934]

Interpretation of $t\bar{t} + N$ jet events throught k_T-jet clustering

- $t\bar{t} + M$ jet core process with $0 \leq M < N$ and $\mu_{\text{core}} = H_T/2$
- $N - M$ ordered jet emissions at $q_1 < q_2 < \ldots q_{\tilde{N}} < \mu_{\text{core}}$



CKKW scale choice + Sudakov FFs for ext & int lines

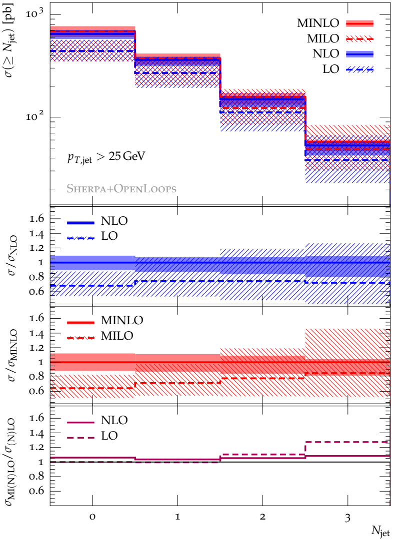
$$[\alpha_S(\mu_R)]^{N+2} = [\alpha_S(\mu_{\text{core}})]^{2+M} \prod_{i=1}^{\tilde{N}} \alpha_S(q_i),$$

$$\Delta_a(q_{\min}, q_i) \quad \text{and} \quad \Sigma(q_k, q_l) = \frac{\Delta_a(q_{\min}, q_l)}{\Delta_a(q_{\min}, q_k)}$$

Matched to $t\bar{t} + N$ jet NLO calculations

- $\mathcal{O}(\alpha_S)$ amputation of Sudakov FFs

$t\bar{t} + 0, 1, 2, 3$ jet cross sections at 13 TeV



Setup

- stable tops and anti-k_T jets
- $R = 0.4$, $p_{T,j} > 25$ GeV, $|\eta_j| < 2/5$
- Ntuples allow decays & showering

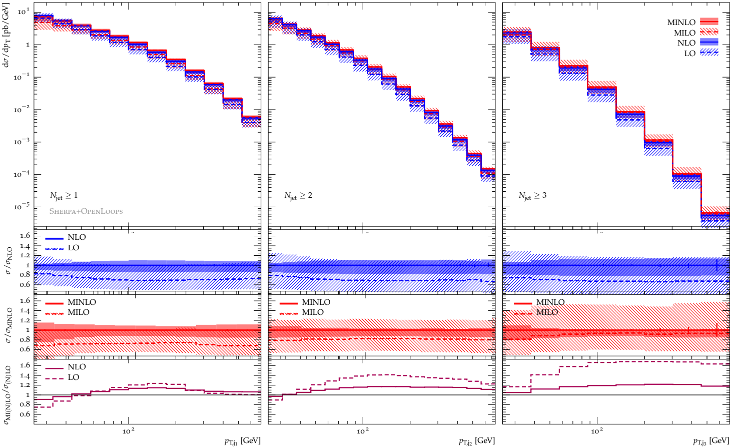
Plotted predictions and ratios

- LO/NLO at $\mu = H_T/2$
- MILO/MINLO
- MINLO/NLO

NLO corrections and uncertainties

- MINLO convergence better at large N_{jets} (also for larger $p_{T,j}$)
- $\sim$10% factor-2 variations in (MI)NLO
- 4–8% MINLO/NLO agreement!

n-th jet p_T for $pp \to t\bar{t} + n$ jets with $n = 1, 2, 3$



- **large NLO/LO but excellent MINLO convergence** at large N_{jets} and p_T
- In general: very good MINLO/NLO agreement and factor-2 scale variations consistent with TH uncertainty $\lesssim 10\%$

Summary

NLO EW corrections to on-shell $t\bar{t}$ production

- Sudakov EW effects around -15% for $p_{T,\mathrm{top}} \sim$ TeV
- $\gamma g \to t\bar{t}$ can be similarly large (with NNPDFs) or negligible (other PDFs)

Off-shell $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ production at NLO EW

- NLO EW predictions for fully differential final state
- sizeable off-shell and Wt effects at large p_T and missing E_T

First $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ NLO+PS generator (resonance-aware matching method)

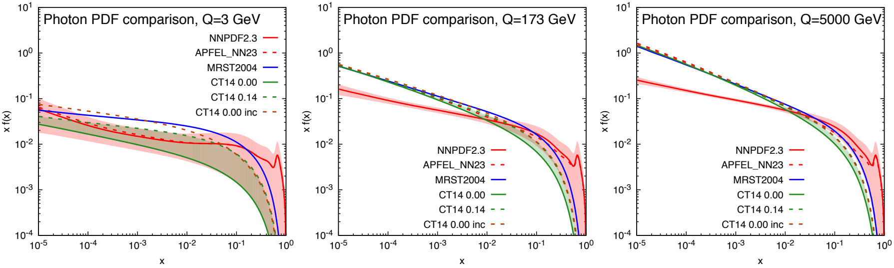
- new wrt standard NLO+PS: NLO decays, off-shell effects, $t\bar{t} + Wt$, ...
- potential shift $\Delta m_t \sim 0.5\,\mathrm{GeV}$ in kinematic m_t determinations

$t\bar{t} + 0, 1, 2, 3$ jets at NLO

- $t\bar{t}$+multijets at 10% precision level
- important for $t\bar{t}H(b\bar{b})$ and BSM backgrounds

Backup Slides

The different photon PDFs ...

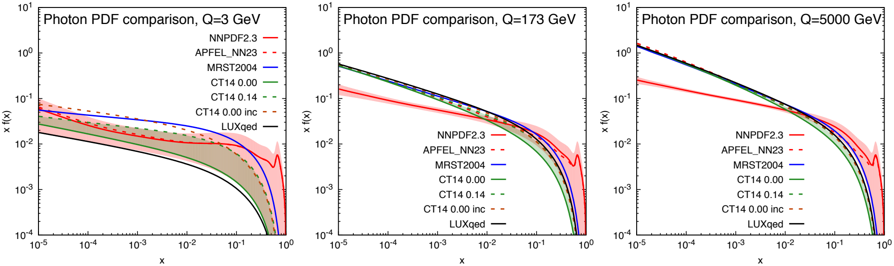


- **APFEL_NN23** (*Bertone, Carrazza, DP, Zaro '15*) is at the initial scale equivalent to **NNPDF2.3QED** for all the PDFs. But, the DGLAP QCD and QED running is consistent (similar to **NNPDF3.0QED**, where also quark and gluons have been updated to **NNPDF3.0**).

- At small Q: **APFEL_NN23** is like **NNPDF2.3QED.** At large Q: it is like **CTEQ14QED** at small x, while it is like **NNPDF2.3QED** at large x.

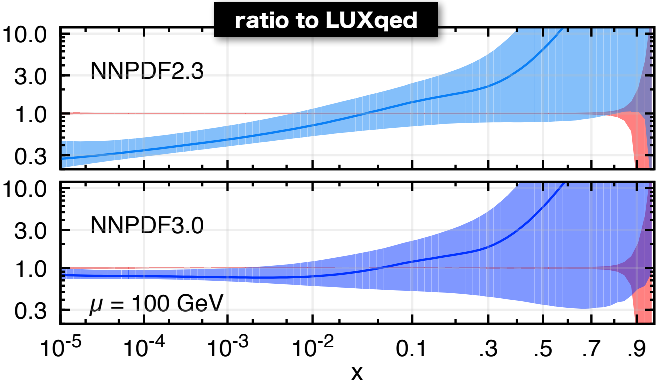
- **CTEQ14QED** is close to the upper edge of the **CTEQ14QEDinc** band.

The different photon PDFs ...



- **LUXQED** is close to the upper edge of the **CTEQ14QED** band and to **CTEQ14QEDinc**

other PDFs v. LUXqed



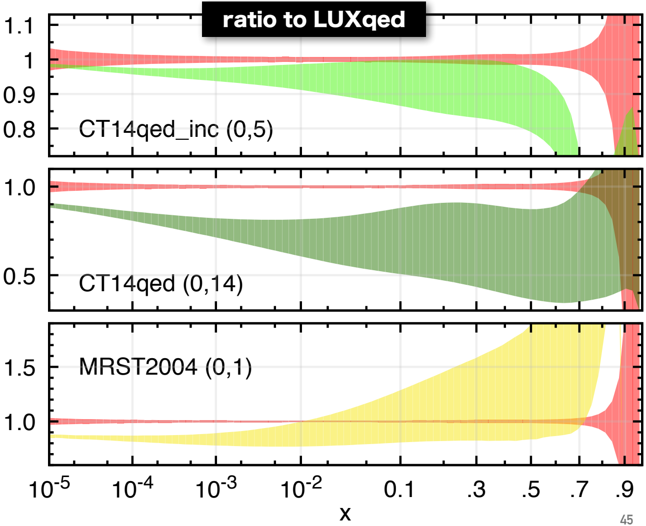
central NNPDF result much higher at large x (but consistent within errors)

at small x, with corrected evolution (NNPDF30), about 20% smaller

other PDFs v. LUXqed

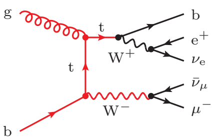
Others are numerically closer

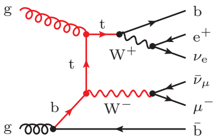
Error bands don't always overlap with LUXqed, but within ~10-20%



45

Wt production in 5F scheme [Demartin et al, 1607.05862]





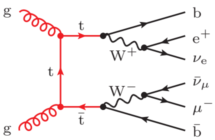
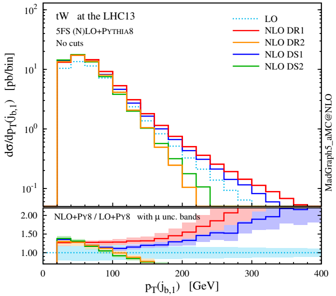


Diagram removal (DR) and subtraction (DS) for $t\bar{t}$ contamination at NLO

[Frixione et al '08] [Hollik et al '13]

scheme	$t\bar{t}$ subtraction	$t\bar{t}$–Wt interf.
DR1	full	subtr.
DR2	full	included
DS1	gauge-inv CT	included
DS2	improved gauge-inv CT	included

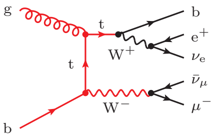


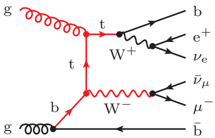
Sizable ambiguities at large p_{T,b_1} (no cuts!)

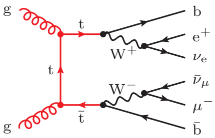
- $t\bar{t}$–Wt interference
- naive Breit-Wigner modelling of off-shell $t\bar{t}$ effects (used also in standard MCs!)

$\Rightarrow$ calls for $pp \to WWb\bar{b}$ at NLO

Wt production in 5F scheme [Demartin et al, 1607.05862]







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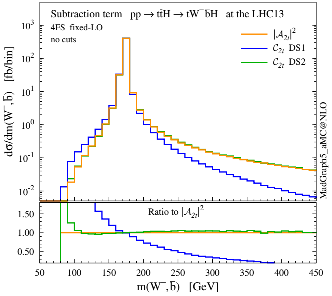
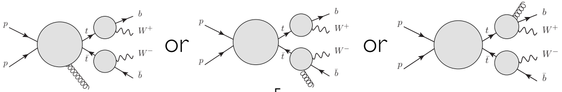


DS1-DS2 = different Breit-Wigner modelling of off-shell $t\bar{t}$ effects

Multiple-radiation scheme

- In traditional approach only hardest radiation is generated by POWHEG:

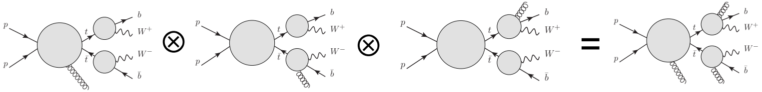


$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_{\rm B})\, d\Phi_{\rm B} \left[\Delta(q_{\rm cut}) + \sum_{\alpha} \Delta(k_T^{\alpha}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_{\rm B}, \Phi_{\rm rad}))}{B(\Phi_{\rm B})}\, d\Phi_{\rm rad} \right]$$

BUT: for top-pair (or single-top) production and decay, emission from production is almost always the hardest.

➡ emission off decays are mostly generated by the shower.

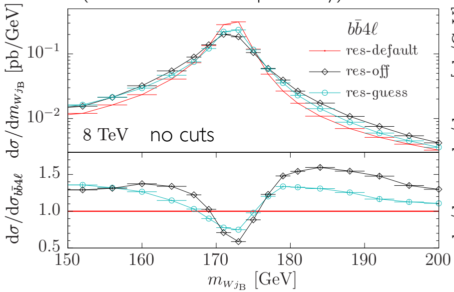
- **Multiple-radiation scheme**: . *introduced in [Campbell, Ellis, Nason, Re; '15]*
  - keep hardest emission from all resonance histories.
  - merge emissions into a single radiation event with several radiated partons

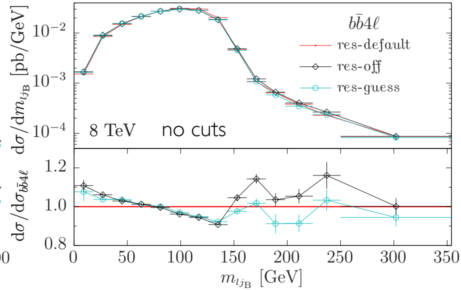


$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_{\rm B})\, d\Phi_{\rm B} \prod_{\alpha=\alpha_b, \alpha_{\bar{b}}, \alpha_{\rm ISR}} \left[\Delta_{\alpha}(q_{\rm cut}) + \Delta_{\alpha}(k_T^{\alpha}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_{\rm B}, \Phi_{\rm rad}^{\alpha}))}{B(\Phi_{\rm B})}\, d\Phi_{\rm rad}^{\alpha} \right]$$

Results: top-resonance

- default: resonance aware matching & multiple-radiation scheme
- off: resonance unaware matching
- guess: resonance unaware matching but kinematic guess off resonance structure before PS (based on kinematic proximity)



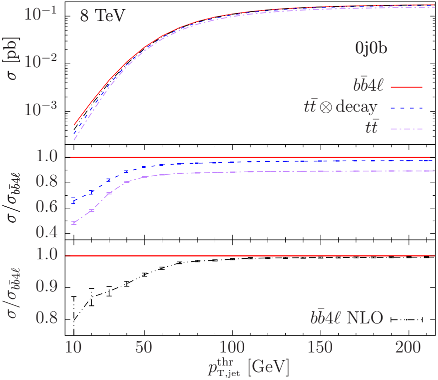


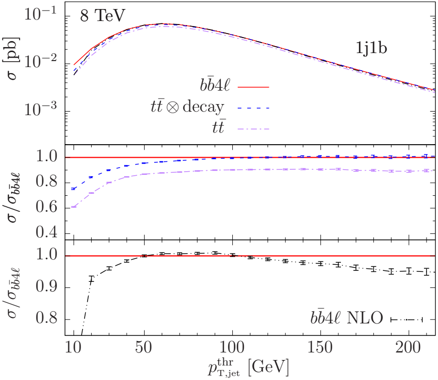
$\Longrightarrow$ resonance unaware matching yields distortions of important kinematic shapes

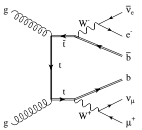
$\Longrightarrow$ control of these shapes crucial for **precise top-mass measurements!**

$\Longrightarrow$ resonance assignment based on kinematic proximity with standard matching not sufficient

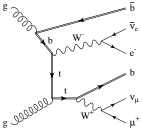
jet vetoes and single-top enriched observables





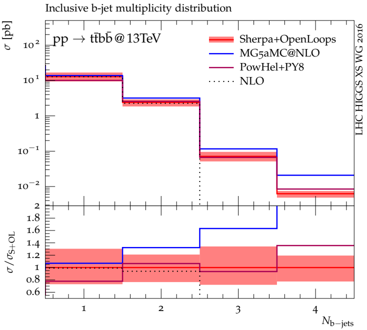


VS.



- for small jet thresholds Wt single-top reaches 40-50%
- tt⊗decay includes Wt only at LO and treats tops on-shell at NLO ⟹ overestimates radiation in Wt region
- 10-20% jet veto resummation effects
- important for any $t\bar{t}$ background with jet vetoes (e.g. $H \rightarrow W^+W^-$)

Inclusive $t\bar{t} + b$-jet multiplicity distribution



- S-MC@NLO (Sherpa+OpenLoops) with $\mu_{R,F}$ variations
- MG5_aMC@NLO+PY8 w.o. variations
- Powhel+PY8 w.o. variations

NLO vs NLO+PS

- decent agreement in NLO accurate bins with ≥ 1 and ≥ 2 b-jets

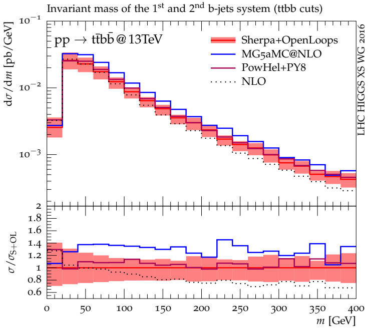
S-MC@NLO vs PowHel+PY8

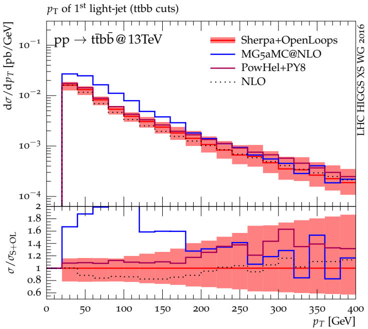
- good overall agreement in spite of differences in matching method, parton shower, N_f-scheme and ad-hoc cuts in Powhel

S-MC@NLO vs MG5aMC@NLO

- good agreement only for $\geq 1\, b$-jets despite similar matching method and same N_f

$t\bar{t}b\bar{b}$ distributions with $\geq 2b$-jets





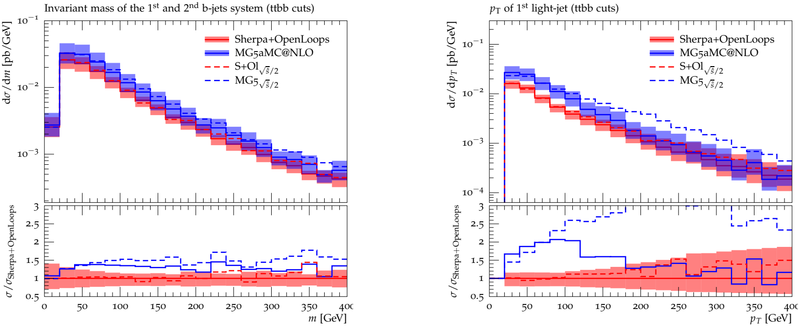
S-MC@NLO vs PowHel+PY8

- well consistent also in observables that receive significant shower corrections
- confirmation of "double-splitting effects" (see e.g. m_{bb})

S-MC@NLO vs MG5aMC@NLO

- 40% enhancement of $t\bar{t} + 2$b XS & sizable differences in NLO radiation pattern
- related to strong sensitivity to resummation scale (shower starting scale) in MG5 . . .

Dependence on resummation scale μ_Q

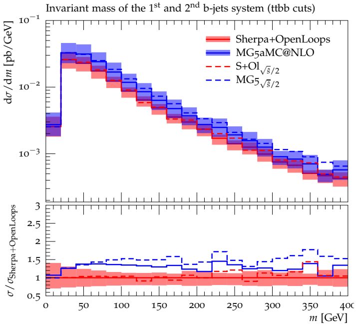


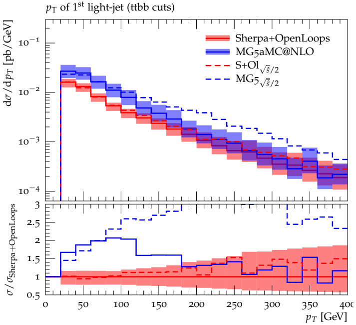
Nominal MG5_aMC and Sherpa+OpenLoops predictions in YR4

- MG5_aMC supports only $\mu_Q = f(\xi)\sqrt{\hat{s}}$ $\Rightarrow$ smearing function restricted to $0.1 < f(\xi) < 0.25$ to mimic recommended $\mu_Q = H_T/2$ implemented in Sherpa

New: μ_Q variations enhance the discrepancy

- $\mu_Q = \sqrt{\hat{s}}/2$ in Sherpa to mimic MG5_aMC default choice $0.1 < f(\xi) < 1$
- strong μ_Q-sensitivity of MG5_aMC $\Rightarrow$ much more pronounced deviations



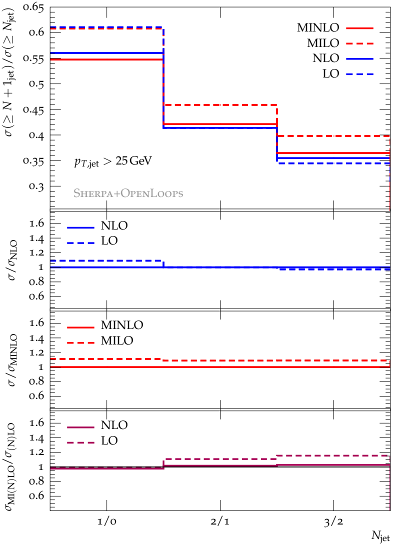


General aspects and relevance of the problem

- understanding of c- and b-jet production via $g \to Q\bar{Q}$ splittings
- how to describe multi-scale process $(M_{tt} \sim 100 M_b)$ in NLO+PS framework (MC@NLO) with single scale μ_Q for 1st emission?
- relevant for various BSM searches and $Hc\bar{c}$ and $Hb\bar{b}$ production

$\Rightarrow$ **motivates $pp \to t\bar{t} + 3$ jets at NLO!**

Multijet scaling: $\sigma(t\bar{t}+n\,\text{jets})/\sigma(t\bar{t}+n-1\,\text{jets})$



Motivation

- insights into multi-jet emission pattern
- cancellations of TH and EXP uncertainties

No clear scaling for $t\bar{t}+0,1,2,3\,$jets

- similar to V+jets (scaling onset beyond 3 jets)
- related to delayed opening of qg and qq channels

Perturbative convergence

- NLO/LO and MINLO/MILO corrections of order 10%
- MINLO/NLO agreement of order 1%

$\Rightarrow$ benchmarks for precision tests!