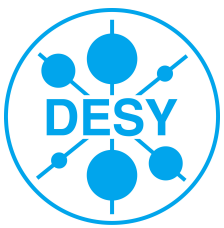
Theory Overview of recent Progress on Single Top

Andrew Papanastasiou

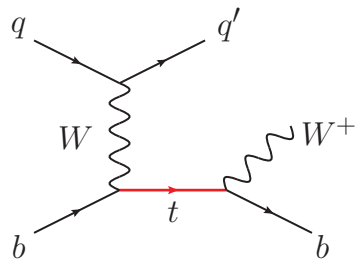


TOP2015 - International Workshop on Top Quark Physics

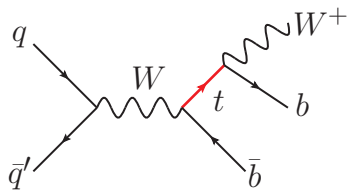
15th September 2015, Ischia

Big thank you to the local organising committee for their support!

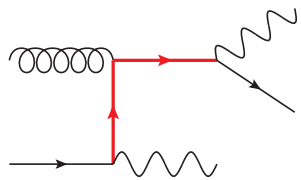
Splitting Up Single Top



t-channel



s-channel



Wt associated production

- split into 3 distinct channels 'ok' at LO in 5F scheme (*b*-PDF present) and for stable tops
- at higher orders, distinct split no longer strictly valid due to:
  - interferences between channels
  - corrections to different channels contribute to same physical final state

  (s&t channels) – ok
  - corrections to Born-level diagrams interfere with other processes

  Wt channel – serious
- including top decay: further care required (even at LO)
- focus on improvements in the description of single top – both in precision and in transition to realistic final-states (mainly 5F t-channel)

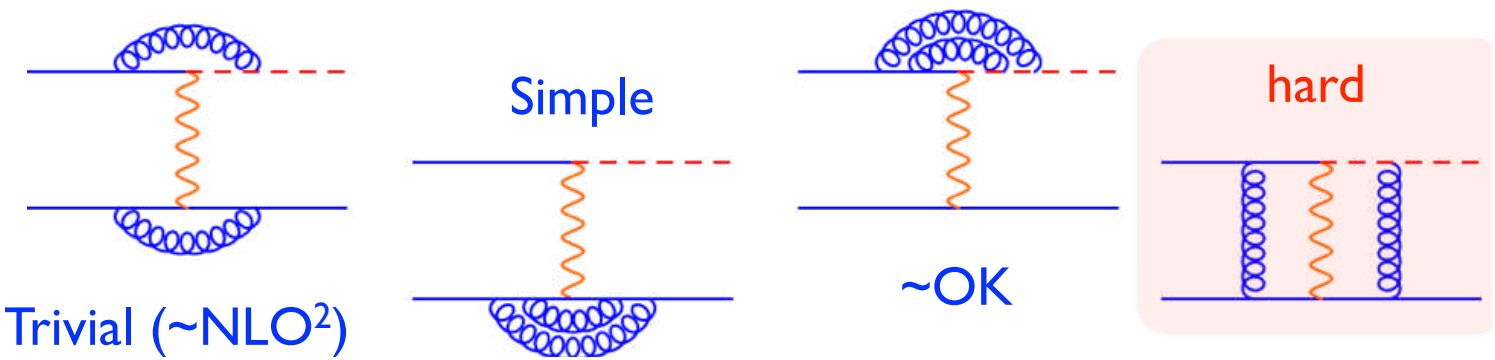
NNLO t-Channel Production

[Brucherseifer, Caola, Melnikov]

see also talk by F.Caola, TopWG meeting May '15

- big step in precision for single-top
- fully-differential NNLO predictions for t-channel process in 5F scheme
- made possible through very recent developments for NNLO [for top using Sector-Improved FKS: Czackon,Caola,Melnikov,Mitov,Brucherseifer,...but many more in general]

Two-loop amplitudes:

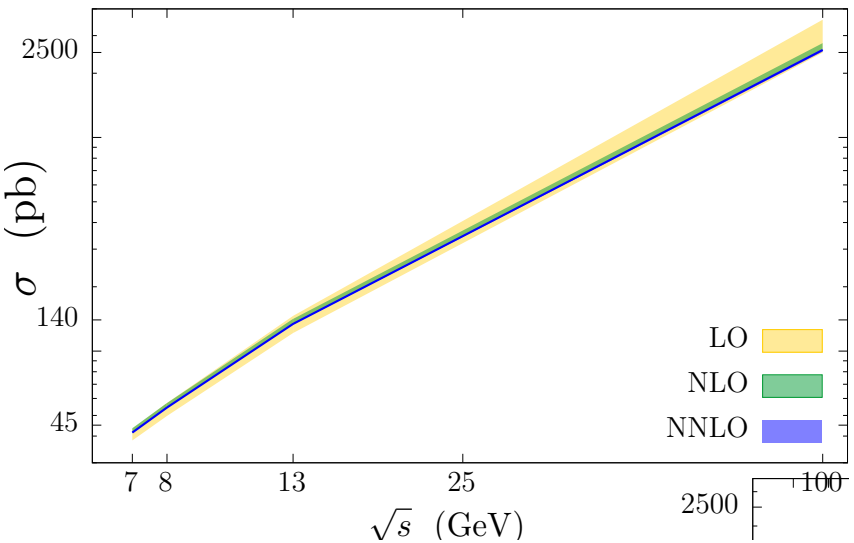


[F.Caola, TopWG meeting May '15]

- $1/N_c^2$-suppressed terms and t/s-channel interferences not included [work in this direction by P. Uwer]
- these missing pieces are expected give errors smaller than other uncertainties such as PDF, m_t etc

NNLO t-Channel Production

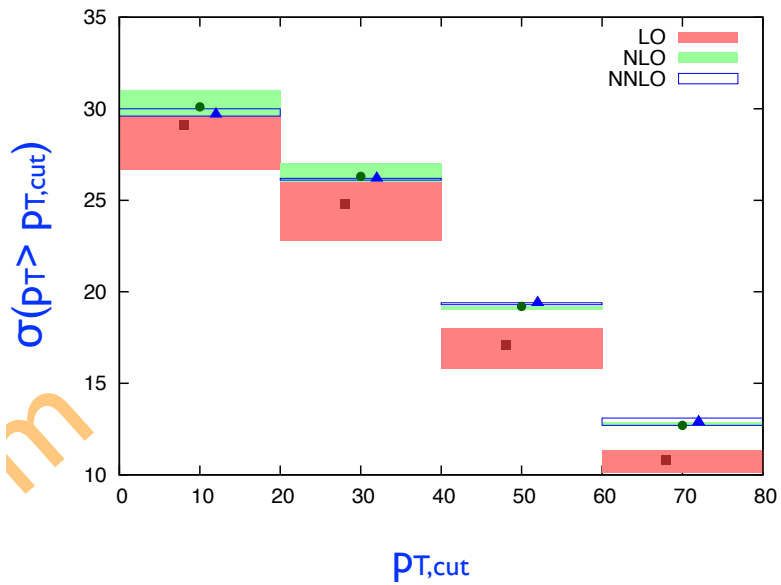
Plots & NNLO numbers from F.Caola's talk, TopWG meeting May '15



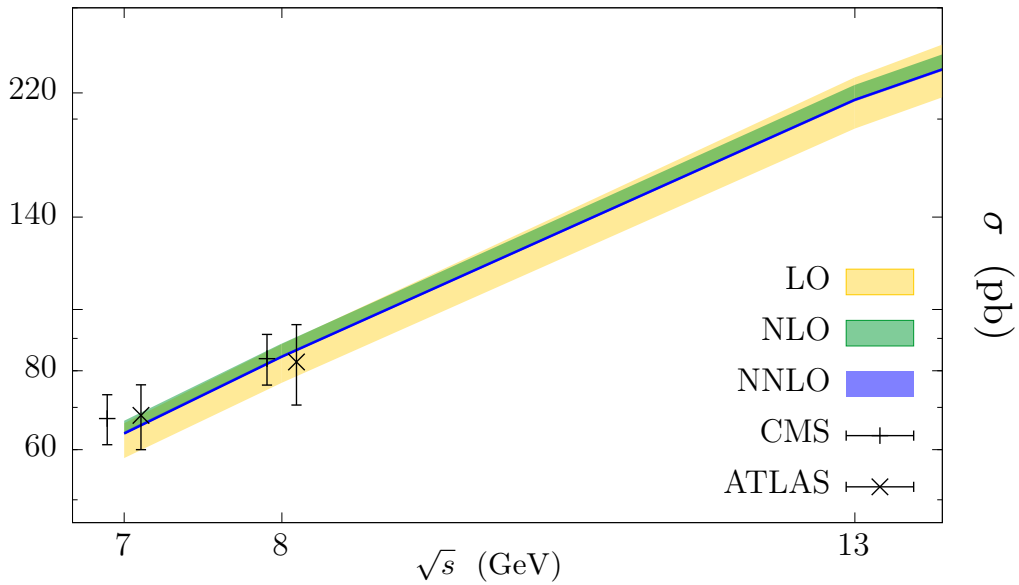
	NLO 4F
$\sigma_{t,\mathrm{NNLO}}(7\ \mathrm{TeV}) = 41.6^{+0.3}_{-0.1}\ \mathrm{pb}$	$38.0^{+2.2}_{-2.5}$ pb
$\sigma_{t,\mathrm{NNLO}}(8\ \mathrm{TeV}) = 54.4^{+0.4}_{-0.2}\ \mathrm{pb}$	$50.7^{+3.0}_{-3.1}$ pb
$\sigma_{t,\mathrm{NNLO}}(13\ \mathrm{TeV}) = 134.0^{+0.7}_{-0.6}\ \mathrm{pb}$	$127.3^{+7.1}_{-6.2}$ pb

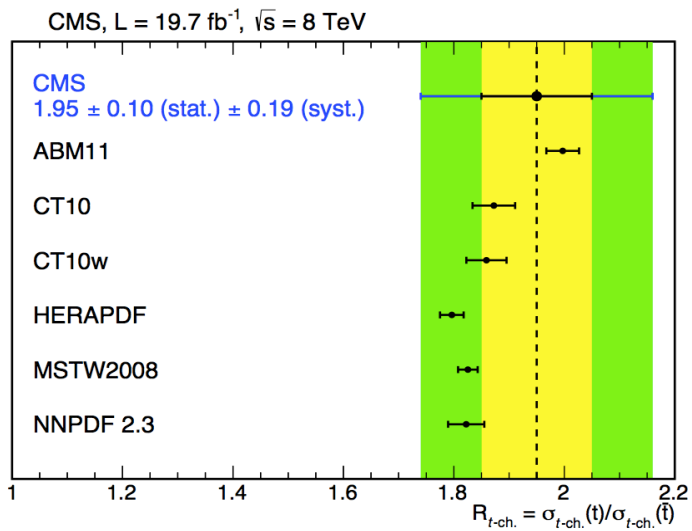
(barely any overlap in 5F/4F errors)

- small NNLO corrections in inclusive case
- significant reduction in scale uncert.
- errors include scale uncertainties, but not yet PDF, m_t, α_s etc



NNLO t-Channel Production





- very good agreement of data with theory for inclusive cross section
- ratio of $t/\bar{t}$ cross sections stable wrt higher orders (& consistent between schemes)

$$\sigma_{t,\mathrm{NLO}}/\sigma_{\bar{t},\mathrm{NLO}} = 1.83$$

$$\sigma_{t,\mathrm{NNLO}}/\sigma_{\bar{t},\mathrm{NNLO}} = 1.83$$

$$\left(\sigma^{\mathrm{4F}}_{t,\mathrm{NLO}}/\sigma^{\mathrm{4F}}_{\bar{t},\mathrm{NLO}} = 1.84\right)$$

NNLO t-Channel Production: impact

At inclusive level the NLO corrections are small, $\sim 2\%$ and NLO central value is very close to the NNLO (& for $\sigma(p_T > x)$) $\rightarrow$ is NNLO needed for single top?

1. small NLO corrections come about via a large cancellation between corrections to Born-level and those due to new channels opening up at NLO.
   $\rightarrow$ given NLO corrections typically an order of magnitude larger, may be unwise to blindly trust central value
   $\rightarrow$ with NNLO, perturbative uncertainties are controlled at the % level
   $\rightarrow$ errors due to PDF, m_t now on par or larger than scale uncertainties
2. discriminating between PDF sets (& heavy-quark schemes), once theory error budget compiled [in progress by Caola et al.] and once exp. uncertainties shrink
3. smaller theory errors at NNLO could have implications in constraining Wtb anomalous couplings, V_{tb} [e.g. Cao, Yan et al.] $\rightarrow$ M. Schultze's talk

Curious to see comparison of data vs NNLO $p_T(t)$-distribution!

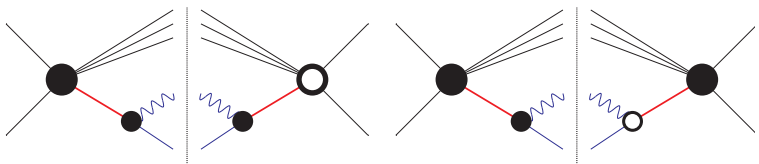
Improving fixed-order generators: Top Decay and Offshellness

$1/\Gamma_t < \tau_{\text{hadr.}}$ so top quark has no chance to form stable bound states

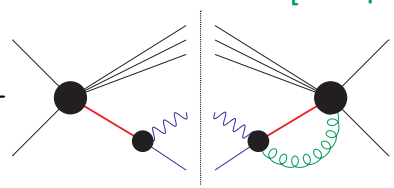
- top decay $t \to W^+ b$
- measurements are of b-jets, light jets, leptons, $\not{E}_T$, not top quarks!
- $M(J_b, l^+, \nu_l) \neq m_t$!

Onshell fixed-order generators are improved by including top decay at amplitude-level. Achieved via a series of more realistic (and complicated) approximations:

- narrow-width approx (NWA): top produced and decayed onshell $p_t^2 \equiv \left(p(W^+) + p(b)\right)^2 = m_t^2$
- pole expansion / effective theory (ET): valid when $M(W^+, b) \sim m_t$
- complex-mass scheme: process considered is that after decay, so $M(W^+, b)$ can be arbitrary

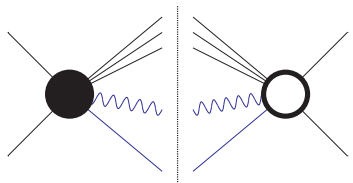


[Campbell et al. (MCFM); Cao et al.]



[Falgari et al. (s&t-channels,private codes)]

(only 5F)

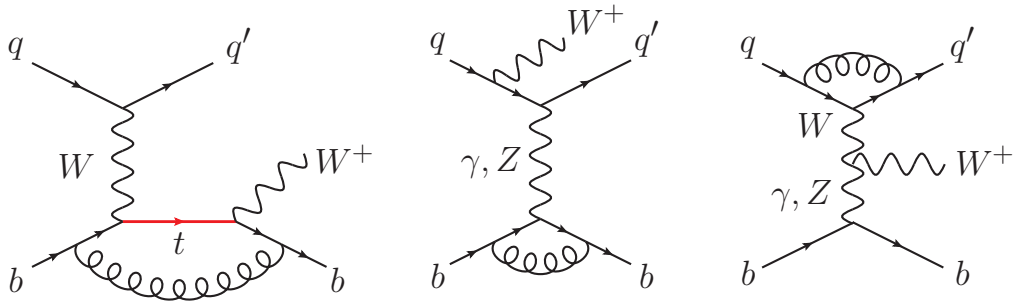


[AP,Frederix,Frixione,Hirschi ,Maltoni (t-ch.,mg5_aMC@NLO)]

(only 5F)

t-Channel with offshell and nonresonant effects

[AP, Frederix, Frixione, Hirschi, Maltoni; mg5_aMC@NLO]



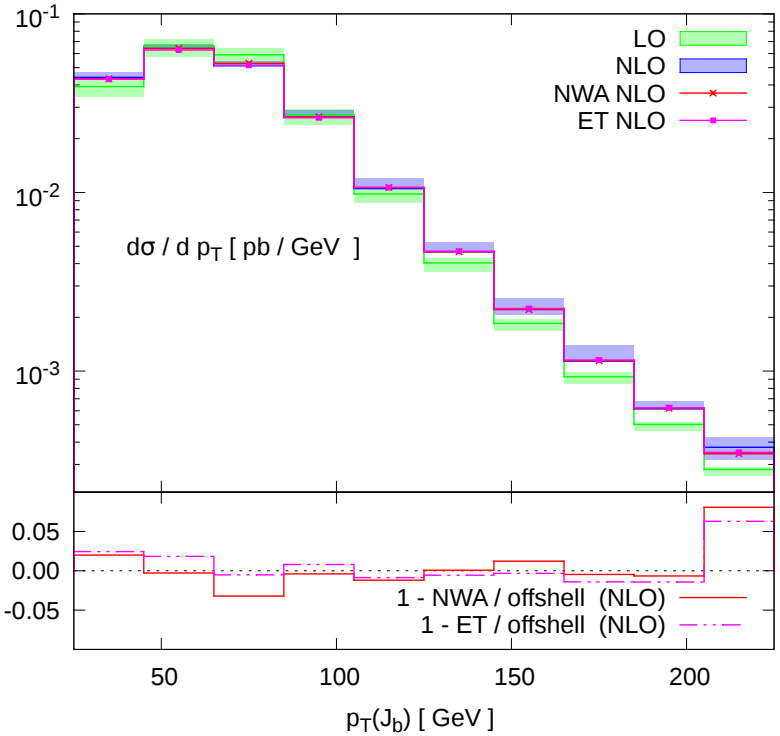
$$p\,p \to W^+ J_b J_{\text{light}} + X$$

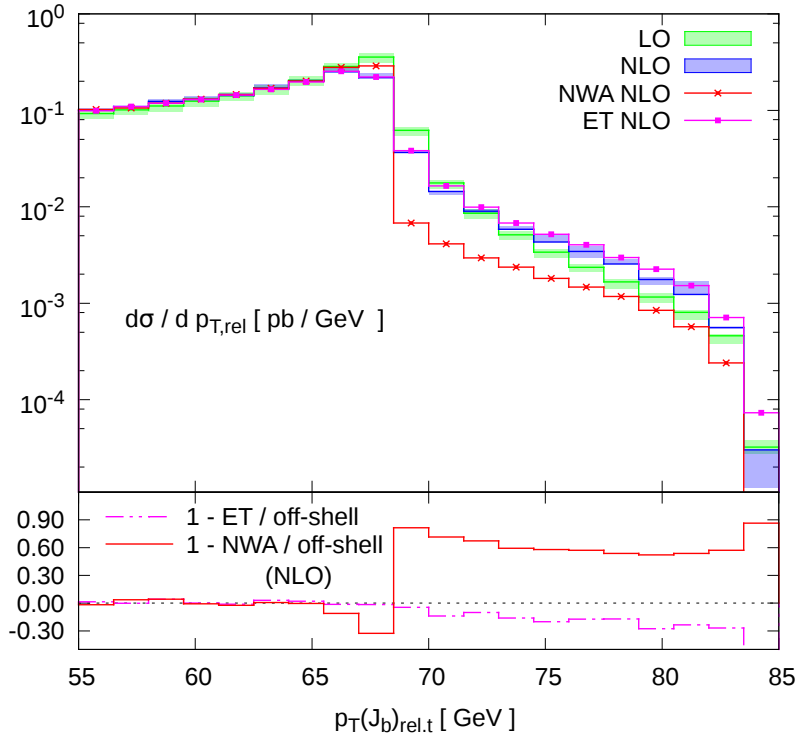
- complex-mass scheme [Denner et al] to compute full set of diagrams at NLO
- t-channel topologies can be consistently identified
- cut on p_T of jet containing b-quark, J_b, required for consistent definition of process
- diagonal CKM matrix also required to ensure no further b-quarks present at Born-level

- typical cuts are applied to J_b, J_{light}, $M(W^+, J_b)$ for results presented next

NWA vs ET vs Full

Full set of results allows us to better understand structure of cross section and to assess approximations



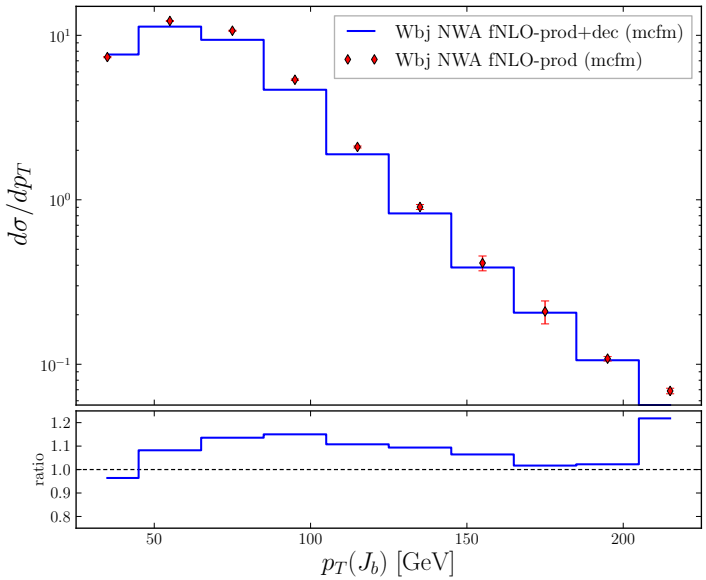


✓ NWA & offshell approaches agree very well for variables inclusive over $M(W^+, J_b)$ [cancelling out of offshell effects]

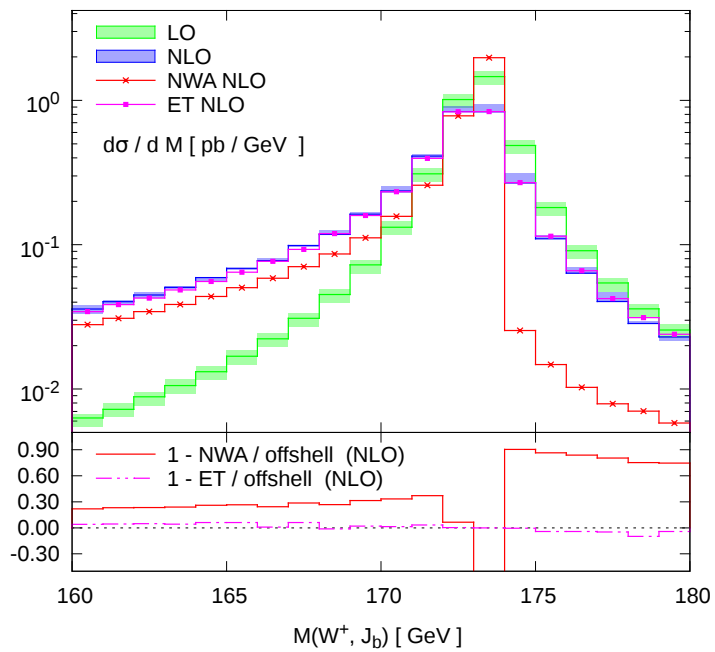
- large differences in regions phase space sensitive at LO to offshellness, i.e. beyond edge in $p_{T,rel.}(J_b)$ (expected)
- subleading-Γ_t/nonresonant effects grow away from resonance structures

Impact of improved predictions

- corrections in top-decay subprocess affect normalization and can alter shapes of observables sensitive to decay products



- offshell and nonresonant effects important for good description of many m_t-sensitive observables: $M(W^+, J_b)$, $M(J_b, l^+)$, etc
- resonance structure dominated by top contributions (see ET result)



- PSMC for single top currently do not include NLO corrections in decay or full offshell effects

NLO+PS – including top decay and offshellness

Ongoing work with R.Frederix, S.Frixione, S.Prestel & P.Torrielli
(See also work by Campbell, Ellis, Nason, Re for NWA $t\bar{t}$ → talk by E. Re)

- NLO+PS in Powheg and MC@NLO for onshell single top has been available for a few years in both 4F and 5F schemes [Alioli et al; Frixione et al; Frederix,Torrielli,Re]
- working towards translating progress made at fixed-order to NLO+PS, i.e. matching process where top is decayed at amplitude-level to PS
- focus on matching of full t-channel process (W^+bj) to PS (within framework of `mg5_aMC@NLO`)

In principle, given that the final state is W^+bj could simply generate LH-events with no intermediate top-quarks and pass to the shower. However,

- after showering do not recover limit $\Gamma_t \to 0$ (result should tend to NWA)
- fixed-order comparison of full vs ET calculation tells us that near resonance cross-section is dominated by amplitudes involving top
- not writing intermediate top quarks means PS radiates without preserving resonance structure

NLO+PS – intermediate tops

Deciding whether or not an event contains an intermediate top quark is somewhat arbitrary (each evt weight contains some nonresonant contribution).

Procedure followed here:

$$\text{if } \min\left(\left|\sqrt{(p_W+p_b)^2}-m_t\right|,\left|\sqrt{(p_W+p_b+p_g)^2}-m_t\right|\right) < x_{\text{cut}}\Gamma_t$$

$$\Rightarrow \text{write intermediate top in LH event}$$
(else no top written)

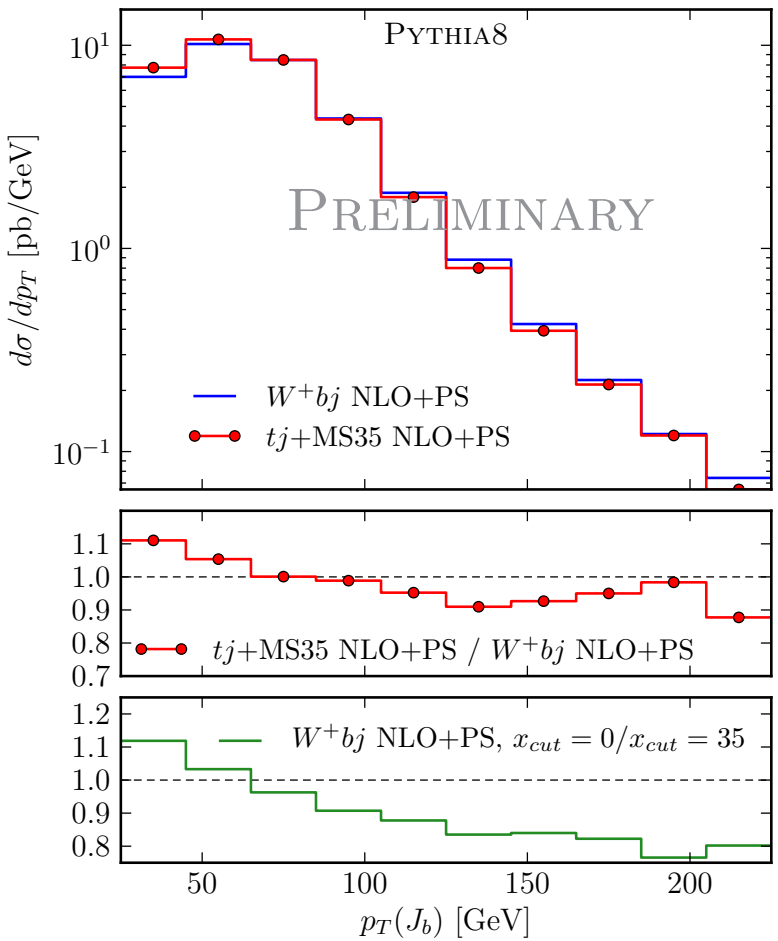
This gives rise to a potential double-counting problem in offshell case:

- full NLO amplitude contains effects of radiation off intermediate top. However, this particular gluon emission is finite (soft singularity screened by Γ_t), so no MC subtraction required.
- allowing PS to shower off intermediate tops (default behaviour) therefore leads to counting twice such emissions
- get around this by disallowing PS to radiate off intermediate tops

When writing top in LH-event, to maintain NLO accuracy after showering, same recoil must be used in MC-counterterm and in 1st emission by PS

NLO+PS – results for Pythia8

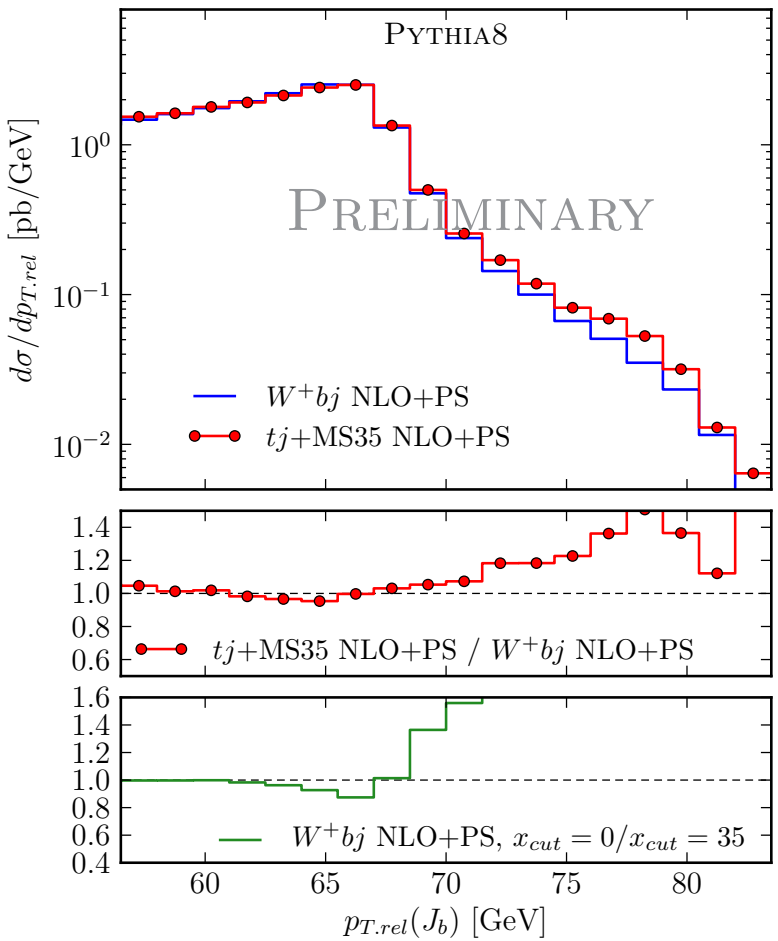
- same setup and analysis as for fixed-order case
- MC truth used to identify correct b-jet
- also compare to onshell single top sample (tj), where tops are decayed using MadSpin (spin-correlated LO decay + LO offshell effects)



- $x_{\text{cut}} = 35$ used for W^+bj NLO+PS
- tj+MadSpin includes spin correlated decay, NLO corrections in production, but no NLO corrections in decay
- hard corrections in top-decay subprocess can lead to visible effects (roughly pattern seen for fixed order)
- writing or not an intermediate top in LH events makes a sizeable difference (shower radiating without resonance constraints)

NLO+PS – results for Pythia8

- same setup and analysis as for fixed-order case
- MC truth used to identify correct b-jet
- also compare to onshell single top sample (tj), where tops are decayed using MadSpin (spin-correlated LO decay + LO offshell effects)



- $x_{\text{cut}} = 35$ used for W^+bj NLO+PS
- offshell and nonresonant contributions important away from sharp edge
- similar large effects will generically be present for $M(W^+, J_b)$, $M(J_b, l^+)$ etc
- writing or not an intermediate top in LH events makes a sizeable difference beyond edge (shower radiating without resonance constraints)

Outlook

To look forward to:

NNLO t-channel

- full error budget (m_b,m_t,PDFs,etc) and further distributions (e.g. $p_T(t)$) [in progress by Caola et al.]
- addition of NNLO top decay [Gao,Zhu; Brucherseifer,Caola,Melnikov]
  $\rightarrow$ allowing for comparisons to data in fiducial region!

Top decay and offshellness at fixed-order

- process $p\,p \rightarrow l^+\nu_l J_b J_{\text{light}} + X$ at NLO (s&t-channels and including effects of Γ_W)
- EW corrections using automated tools `mg5_aMC@NLO, Sherpa+OpenLoops`

NLO+PS with decay and offshell effects

- completion of work of W^+bj matched to parton showers
- keep an eye out for related work by Nason et al.
- study systematics of m_t-extractions using full process or approximations

Outlook

To look forward to:

NNLO t-channel

- full error budget (m_b,m_t,PDFs,etc) and further distributions (e.g. $p_T(t)$) [in progress by Caola et al.]
- addition of NNLO top decay [Gao,Zhu; Brucherseifer,Caola,Melnikov]
  $\rightarrow$ allowing for comparisons to data in fiducial region!

Top decay and offshellness at fixed-order

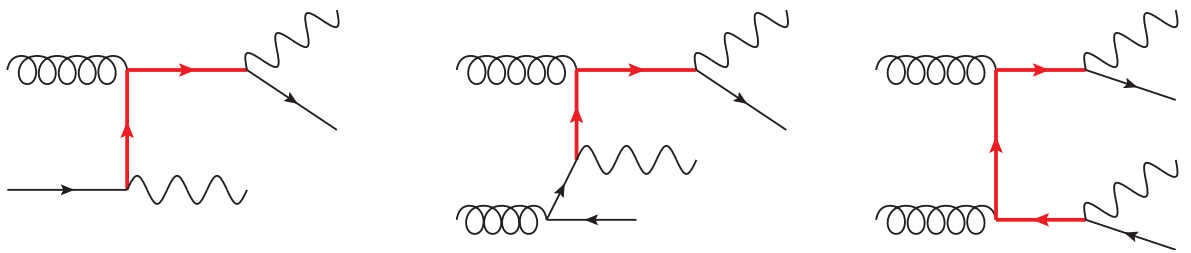
- process $p\,p \rightarrow l^+\nu_l J_b J_{\text{light}} + X$ at NLO (s&t-channels and including effects of Γ_W)
- EW corrections using automated tools `mg5_aMC@NLO`, `Sherpa+OpenLoops`

NLO+PS with decay and offshell effects

- completion of work of W^+bj matched to parton showers
- keep an eye out for related work by Nason et al.
- study systematics of m_t-extractions using full process or approximations

Thank you for your attention

The Wt-channel



LO NLO: interference of Wt with $t\bar{t}$

- problem comes from thinking about Wt-channel in 5F scheme at LO: appears to be well defined
- in 4F scheme, immediately recognise that Wt-channel is actually one (of many) contributions to $W^+bW^-\bar{b}$ production
- $W^+bW^-\bar{b}$ in 4F scheme at NLO: [Frederix; Cascioli et al]
  $\Rightarrow$ now these results are available, more correct to consider Wt as single resonant component of $W^+bW^-\bar{b}$, which can be enhanced from the latter via suitable analysis cuts