SM single-top production at hadron colliders

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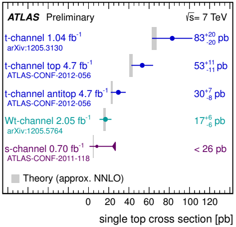
Why single-top production?

Electroweak single-top production rate competitive with QCD-mediated $t\bar{t}$ cross section

$$\text{LHC}(7\,\text{TeV}): \quad \sigma_{t\bar{t}} = 162.4\,\text{pb}$$
$$\sigma_t + \sigma_{\bar{t}} = 78.3\,\text{pb}$$

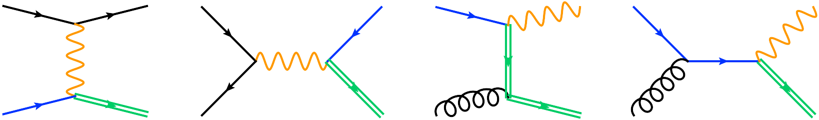


$\Rightarrow$ **complementary informations on top-quark properties!**

- sensitive to charged-current interactions of the top quark
  $\Rightarrow$ test $V-A$ nature of the Wtb vertex
- $\sigma \propto |V_{tb}|^2 \longrightarrow$ direct extraction of CKM matrix element V_{tb}
- probes bottom PDF inside the proton
- beside being an important signal, single-t production is background to Higgs production
- generally relevant to new physics searches (top anomalous couplings, 4^{th} generation searches, FCNC, charged-Higgs production,...)

Almost too good to be true! Unfortunately experimental extraction of the single-top signal much more challenging than top-pair measurements due to **large background from Wj and $t\bar{t}$**

Single-top production in the SM

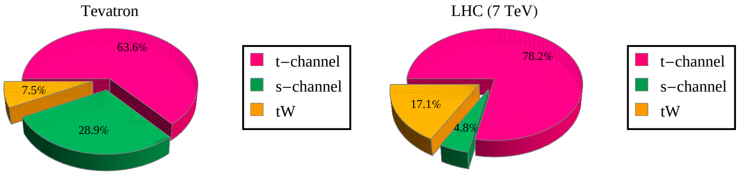


t–channel *s–channel* *associated W–t production*

In the SM **three production modes**:

- t-channel production ($k_W^2 < 0$)
- s-channel production ($k_W^2 > 0$)
- associated tW production ($k_W^2 \sim M_W^2$)

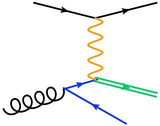
t-channel production is dominant channel at both Tevatron and LHC



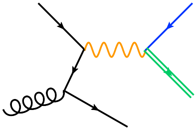
Different production channels?

Note that distinction into 3 production channels is somewhat ambiguous...

- t-channel and s-channel mix beyond LO (though no interf. at NLO due to colour)

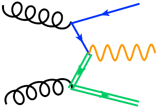


t–channel

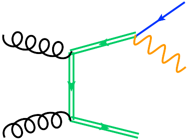


s–channel

- More seriously tW production mixes with (much bigger) $t\bar{t}$ production at NLO



associated tW production



tt production

$\Rightarrow$ from a theoretical point of view most satisfactory solution is fixing a specific **physical final state** (i.e. jets+leptons+$\not{E}_T$) and include the full **gauge-invariant set of relevant contributions**

Single-top production at NLO

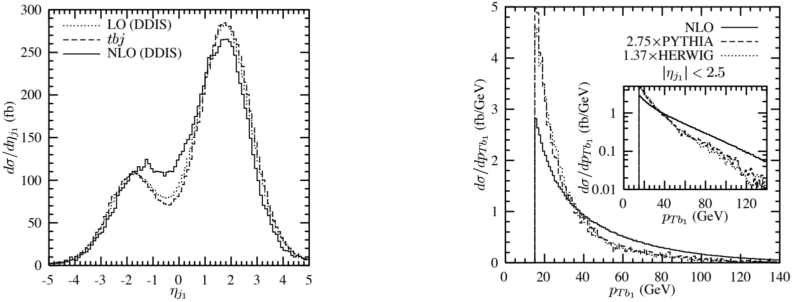
NLO QCD

$\mathcal{O}(\alpha_s)$ corrections to the tree-level **inclusive** cross sections have been known for a while:

- *t*-**channel** [Bordes, van Eijk '95; Stelzer, Sullivan, Willenbrock '97]: $\Delta\sigma^{\text{NLO}}/\sigma^{\text{LO}} \sim 10\%$
- *s*-**channel** [Smith, Willenbrock '96]: $\Delta\sigma^{\text{NLO}}/\sigma^{\text{LO}} \sim 40-50\%$
- tW **production** [Zhu '02; Cao '08]: $\Delta\sigma^{\text{NLO}}/\sigma^{\text{LO}} \sim 50\%$

and **differential** cross section computed by [Harris, Laenen, Phaf, Sullivan, Weinzierl '02; ZTOP '04]

***t*-channel**

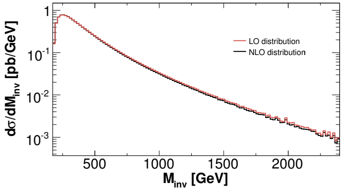


big differences between NLO calc. and LO showers ⇒ shows necessity of full NLO result!

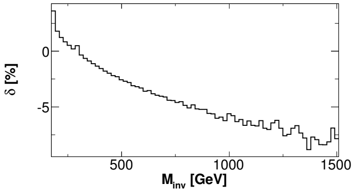
NLO EW/SUSY QCD

NLO EW corrections and SUSY QCD corrections also available for t-channel production and associated production [Beccaria, Carloni Calame, Mirabella, Piccinini, Renard, Verzegnassi '07/'08]

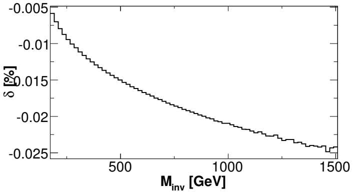
t-channel $[M_{inv}(t, j_1)]$



EW



SUSY-QCD

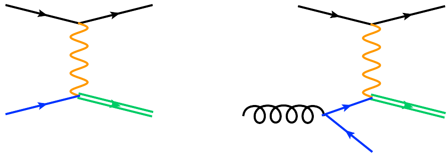


EW corrections small ($\lesssim 5\%$) and SUSY QCD corr. negligible ($< 1\%$ for mSUGRA SU1)

5-flavour vs 4-flavour scheme

t-chan. NLO results first computed in the 5-flavour scheme (5F). Recently NLO results in the 4-flavour scheme (4F) have also become available [Campbell, Frederix, Maltoni, Tramontano '09].

What are the main differences between the two schemes?



5–flavour scheme *4–flavour scheme*

5F: initial b from PDF inside proton

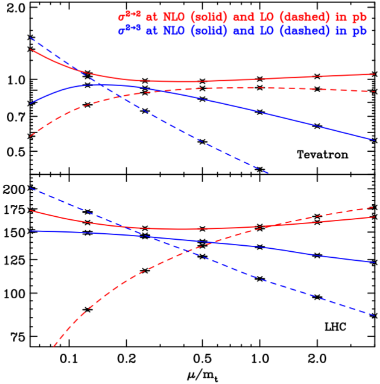
- large logs $\ln \mu^2/m_b^2$ resummed by bottom PDF evolution
- exact factorization of QCD corrections to heavy/light currents at NLO and simpler calculation
- m_b dependence and spectator b-jet only described from NLO onwards

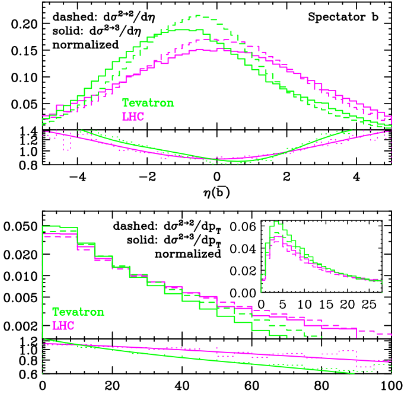
4F: initial b-quark from gluon splitting

- potentially large logs not resummed
- almost exact heavy/light currect factorization. More complicated calculation due to additional mass and additional external leg.
- spectator b-jet observables and m_b dependence already at LO

NLO calculation in 4F scheme

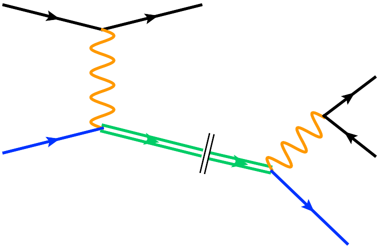
[Campbell, Frederix, Maltoni, Tramontano ’09]





- small differences between 4F and 5F results for total cross section ($\sim 6\%$, compatible with theory uncertainty)
- larger differences in distributions ($10 - 20\%$), especially for spectator *b*-jet (expected, since effectively LO in 5F calculation)

Top-quark decay



Precise description of the single top production requires consistent inclusion of top quark decay (theoretically a delicate business due to gauge-invariance issues...)

Decay commonly treated in **Narrow-Width Approximation** (**NWA**)

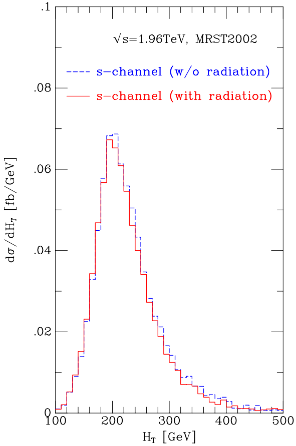
$$\frac{1}{|p^2 - m_t^2 + i m_t \Gamma_t|^2} = \frac{\pi}{\Gamma_t} \delta(p_t^2 - m_t^2) + \mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

- matrix element factorizes into production AND decay of an **on-shell** top ($p_t^2 = m_t^2$)
- preserves top-quark spin correlations between production and decay
- includes NLO corrections to production AND decay, but no production/decay interferences (expect effect $\sim \Gamma_t/m_t \sim 1\%$ on total cross section)
- off-shell effects are completely lost (again expect effect $\sim \Gamma_t/m_t$).

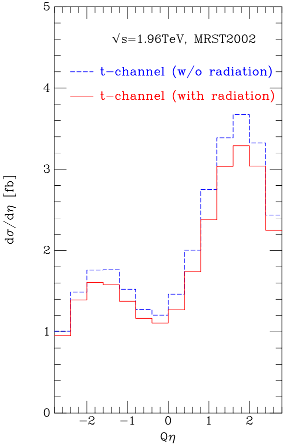
Single-top production and decay at NLO

[Campbell, Ellis, Tramontano ’04; MCFM; Cao, Schwienhorst, Yuan ’04+Benitez, Brock ’05]

H_T



$Q_l\eta(j_1)$



Decay corrections modify significantly the normalization (though shape is preserved...)

Beyond fixed-order on-shell NLO

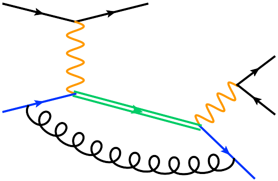
inclusion of off-shell effects and production/decay interferences

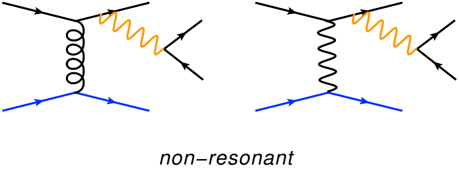
resummation of threshold logarithms

matching of fixed-order NLO results and MC parton showers

Production-decay interferences in single-top production

NWA only includes factorizable corrections to on-shell production and decay!
$\Rightarrow$ no information on off-shell effects ($p_t^2 \neq m_t^2$), non-factorizable corrections and non-resonant (background) diagrams





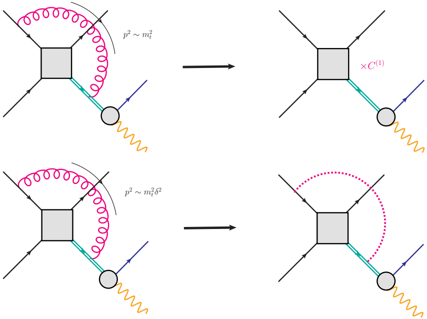
These effects are expected to be of order $\Gamma_t/m_t \sim 1\%$ (true for the **total cross section**).

However: small effect is partly due to **large cancellations** between virtual and real non-factorizable corrections $\Rightarrow$ off-shell and non-factorizable effects could be larger for arbitrary kinematical distributions

Effective-theory approach to single t production

[PF, Giannuzzi, Mellor, Signer '10, '11]

Consider a resonant unstable top (rather than on-shell) and use the small virtuality of t as an expansion parameter, $\delta \equiv (p_t^2 - m_t^2)/m_t^2 \ll 1$



- **Hard region** $(q^2 \sim m_t^2)$
  $\Rightarrow$ **factorizable corrections**
  ($\Leftrightarrow$ corrections in the NWA)
- **Soft region** $(q^2 \sim m_t^2\delta^2)$
  $\Rightarrow$ **non-factorizable corrections**
  ($\Leftrightarrow$ off-shell effects and production/decay interferences)

Effective-theory expansion resums **finite-width effects**, includes leading **non-factorizable corrections** and preserves **gauge invariance**

+ much simpler than full 1-loop calculation in the Complex Mass Scheme!

Integrated cross section ($m_t = 172\,\text{GeV}$, $\mu_{F/R} = m_t/2$)

$pp \to J_b J_l e^+ \not{E}_T + X$	$pp \to J_b J_{\bar{b}} e^+ \not{E}_T + X$
$p_T(J_b) > 20$ GeV	$p_T(J_b) > 20$ GeV
$p_T(\text{hardest } J_l) > 20$ GeV	$p_T(J_{\bar{b}}) > 30$ GeV
$p_T(\text{extra } J_{\bar{b}}) < 15$ GeV	$p_T(\text{extra } J_l) < 15$ GeV
$\not{E}_T + p_T(e) > 60$ GeV	$\not{E}_T + p_T(e) > 60$ GeV

LHC@7TeV

$pp \to J_b J_l e^+ \not{E}_T + X$ (∼ *t*-channel)		**Eff. Theory**	**NWA**
	LO[pb]	$3.460^{+0.278}_{-0.403}$	3.505
	NLO[pb]	$1.609^{+0.303}_{-0.240}$	1.642
$pp \to J_b J_{\bar{b}} e^+ \not{E}_T + X$ (∼ *s*-channel)		**Eff. Theory**	**NWA**
	LO[pb]	$0.1654^{+0.0001}_{-0.0010}$	0.1677
	NLO[pb]	$0.1618^{+0.0021}_{-0.0005}$	0.1635

Differences between effective-theory calculation and NWA $\sim 2\%$

$\Rightarrow$ consistent with expectation $\sim \Gamma_t/m_t$...

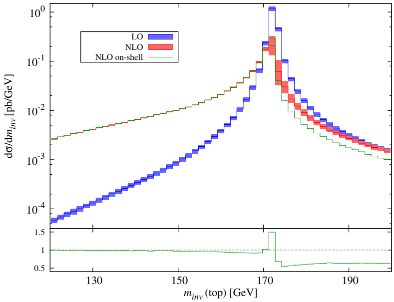
Similar effects found in $t\bar{t}$ production [Bevilacqua et al. '10, Denner et al. '10]

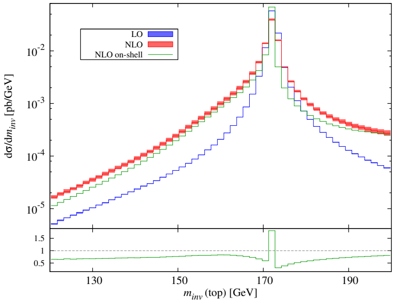
Invariant-mass distribution

LHC@7TeV

$pp \to J_b J_l e^+ \not{E}_T + X$ $\sim$**t**$-$*channel*

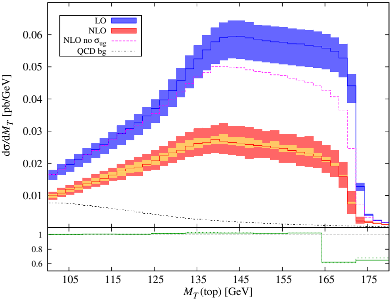
$pp \to J_b J_{\bar{b}} e^+ \not{E}_T + X$ $\sim$**s**$-$*channel*

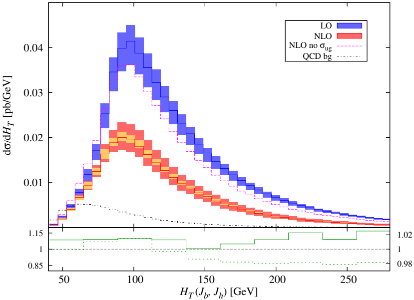


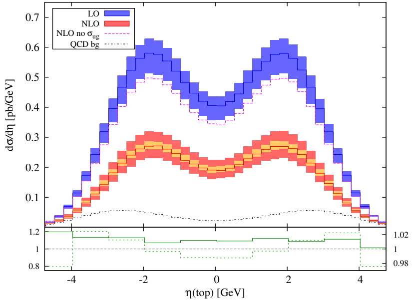


- large off-shell effects (up to 50%) close to the peak
- non-factorizable corrections change sign around the peak
  $\Leftrightarrow$ **explains small effect on the total cross section**

$pp \to J_b J_l e^+ \not{E}_T + X$ (LHC @ 7 TeV)







- off-shell and non-factorizable effects **generally small** ($\sim 2\%$) due to averaging effect over m_{inv}
- **sizeable corrections** (up to 40%) close to kinematics edges, e.g. $M_T \sim m_t$ (relevant for m_t extraction)

Threshold resummation

Single-top cross sections affected by potentially large corrections related to suppression of soft emission near kinematical thresholds

$$p_1 p_2 \to t(p_t) q(k) + X(p_X)$$

$$\sigma^{\mathrm{N}^n\mathrm{LO}} \sim \alpha_s^n \left[\frac{\ln^m s_4}{s_4}\right]_+ \qquad m \leq 2n-1 \qquad s_4 = (p_t + p_X)^2 - m_t^2$$

partonic cross section kinematically enhanced when $s_4 \to 0$
⇒ **all-order resummation of the enhanced terms is desirable!**
(leads to accurate normalization of the cross section and reduced theoretical uncertainties)

State of the art for single-top is NNLL resummation (i.e. $m = 2n-1,\ 2n-2,\ 2n-3$)

- NNLL resummation performed recently by two independent groups with different formalims (Mellin space VS SCET) [Kidonakis '10, '11; Li, Wang, Zhang, Zhu '10]
- NNLL resummed results usually re-expanded to obtain approximated fixed-order NNLO cross section (more convenient for numerical implementation...)

Threshold resummation

Resummation based on factorization of different relevant scales [Kidonakis, Sterman '97].
In Mellin space:

$$\hat{\sigma}^{res}(N) = \overbrace{\exp\left[\sum_{i=1,2} E(N_i) + E'(N')\right]}^{\text{soft-coll. radiation from external massless p.}} \overbrace{\exp\left[\sum_{i=1,2} 2\int_{\mu_F}^{\sqrt{s}} \frac{d\mu}{\mu}\, \gamma_{q/q}\left(\tilde{N}_i, \alpha_s(\mu)\right)\right]}^{\text{scale dep. from PDFs}}$$
$$\times \mathrm{Tr}\left\{ \underbrace{H\left(\alpha_s(\sqrt{s})\right)}_{\text{hard scatt.}} \underbrace{\exp\left[\int_{\sqrt{s}}^{\sqrt{s}/\tilde{N}'} \frac{d\mu}{\mu}\, \Gamma_S^\dagger\left(\alpha_s(\mu)\right)\right] S\left(\alpha_s(\sqrt{s}/\tilde{N}')\right) \exp\left[\int_{\sqrt{s}}^{\sqrt{s}/\tilde{N}'} \frac{d\mu}{\mu}\, \Gamma_S\left(\alpha_s(\mu)\right)\right]}_{\text{large-angle soft radiation}} \right\}$$

- H, S, Γ_S are matrices in colour-state space!
- NNLL resummation requires recently-computed two-loop Γ_S [Neubert, Becher '09; Kidonakis '10]

Analogous factorization in SCET: $\sigma \sim f \otimes f \otimes Tr[H \times S] \otimes J$ [Li, Wang, Zhang, Zhu '10]
+ resummation in momentum space via RG evolution equations.

Effects of threshold resummation

Results for t- and s-channel available in both formalisms

[Kidonakis '10, '11; Li, Wang, Zhang, Zhu '10]

For t-channel small NNLO effects in both approaches (few percents at both Tevatron and LHC) but large discrepancies for s-channel production...

s-channel	SCET	Mellin sp.
Tevatron	$0.463^{+0.002}_{-0.004}(+5\%)$	$0.523^{+0.001}_{-0.005}(+15\%)$
LHC@7	$2.82^{+0.06}_{-0.07}(+4\%)$	$3.17^{+0.06}_{-0.06}(+13\%)$
LHC@14	$7.17^{+0.20}_{-0.25}(+4\%)$	$7.93^{+0.14}_{-0.14}(+13\%)$

What's the source of the discrepancy?

- two formalisms resum different logs

$$s_{4,\mathrm{Mellin}} = (p_t + p_X)^2 - m_t^2 \qquad s_{4,\mathrm{SCET}} = (k + p_X)^2$$

  formally equivalent for the total cross section, but power-suppressed terms can be large.

- is one parameterization better than the other? Not completely clear...
- estimate of theory uncertainty by scale variation only is probably too optimistic

NLO/parton shower matching

One of most recent developments in single-top physics is matching of fixed-order NLO cross section with Monte Carlo parton shower (MCPS)

- **NLO:** $d\sigma = d\Phi_n \left\{ \underbrace{B(\Phi_n)}_{\text{LO}} + \frac{\alpha_s}{2\pi} \left[\underbrace{V(\Phi_n)}_{\text{virt.}} + \underbrace{R(\Phi_{n+1})}_{\text{real}} d\Phi_r \right] \right\}$
  - normalization of the cross section correct to order $\mathcal{O}(\alpha_s)$
  - reduced renormalization and factorization scale dependence
  - correct description of wide-angle radiation
- **MCPS:** $d\sigma = d\Phi_n \underbrace{B(\Phi_n)}_{\text{LO}} \left\{ \overbrace{\Delta(t_m, t_0)}^{\text{Sudakov}} + \Delta(t_m, t) \underbrace{\frac{\alpha_s}{2\pi} \frac{1}{t} P(z) d\Phi_r}_{\text{coll.}} \right\}$
  - $\Delta(t_m, t) = \exp\left[-\frac{\alpha_s}{2\pi} \int_t^{t_m} d\Phi_r' \frac{P(z')}{t'} \right]$
  - correctly describes multiple collinear emission at low p_T
  - can be used to generate events down to the hadronic level

...ideal solution is clearly to combine the two approaches!
Issue: how to avoid double-counting in the collinear region?

POWHEG vs MC@NLO

Two different frameworks have been tested: **POWHEG and MC@NLO**

POWHEG:[Nason '04; Frixione, Nason, Oleari '07; ...]
Modifies Sudakov factor for hardest emission such that collinear limit is preserved and expansion in α_s of matched result reproduces exact NLO

$$d\sigma_{\text{POWHEG}} = d\Phi_n \overline{B}(\Phi_n)\left\{ \overbrace{\Delta(\Phi_n, k_T^{min})}^{\text{POWHEG Sudakov}} + \Delta(\Phi_n, k_T)\frac{\alpha_s}{2\pi}\frac{R(\Phi_{n+1})}{B(\Phi_n)}d\Phi_r \right\}$$

$$\overline{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R(\Phi_{n+1})d\Phi_r\right]$$

$$\Delta(\Phi_n, k_T) = \exp\left[-\frac{\alpha_s}{2\pi}\int d\Phi_r \frac{R(\Phi_{n+1})}{B(\Phi_n)}\theta(k_T' - k_T)\right]$$

MC@NLO:[Frixione, Webber '02; Frixione, Nason, Webber '03; ....]
Subtract hardest collinear emission from exact NLO matrix element and then shower

$$d\sigma_{\text{MC@NLO}} = d\Phi_n \overline{B}(\Phi_n)\left\{\Delta(t_m, t_0) + \Delta(t_m, t)\frac{\alpha_s}{2\pi}\frac{P(z)}{t}d\Phi_r\right\} + d\Phi_n d\Phi_r\left[R(\Phi_{n+1}) - R_{MCS}(\Phi_{n+1})\right]$$

$$\overline{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R_{MCS}(\Phi_{n+1})d\Phi_r\right]$$

POWHEG vs MC@NLO

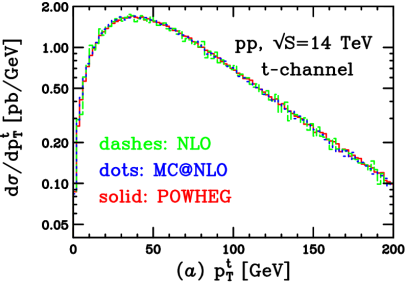
Similarities and differences between MC@NLO and POWHEG:

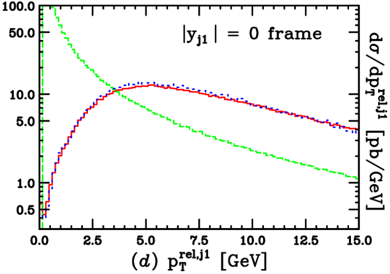
- in both frameworks double-counting is avoided
- exact NLO result reproduced upon expansion in α_s
- in MC@NLO matching depends on the MCPS used
- positive weights in POWHEG, while small number of negative-weighted events appear in MC@NLO (theoretically not a problem...)

How do POWHEG and MC@NLO numerically compare to each other (and to NLO)?

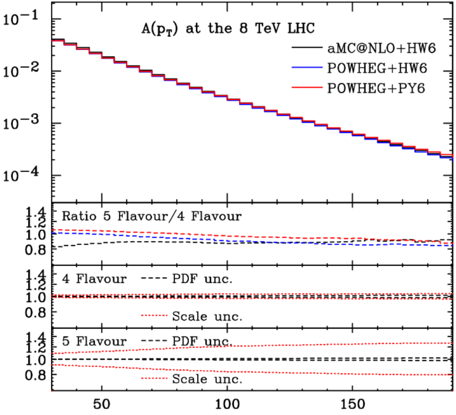
POWHEG vs MC@NLO: t-channel production

5F:[Alioli, Nason, Oleari, Re ’09]; **4F:**[Frederix, Re, Torrielli ’12]



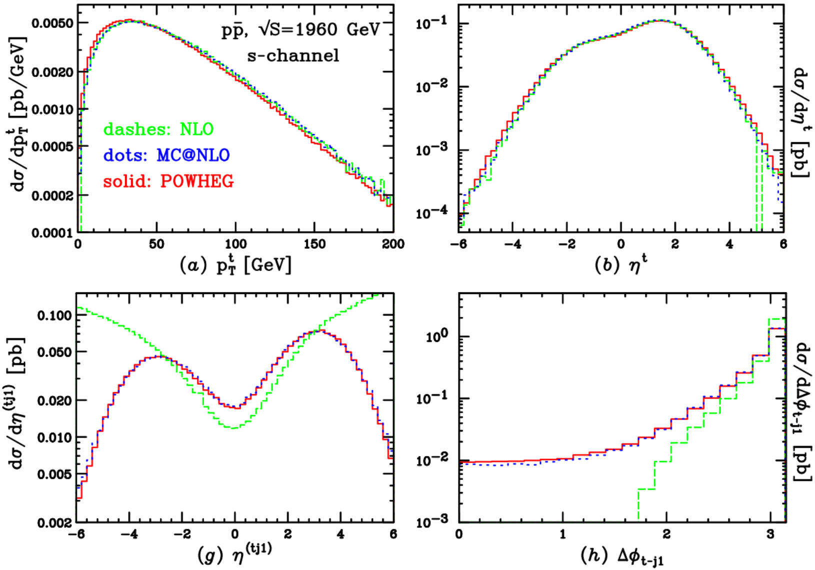


$$A(p_T) = \frac{1}{\sigma} \int_{p_T}^{\infty} dp_T^{(j_b,2)} \frac{d\sigma}{dp_T^{(j_b,2)}}$$



POWHEG vs MC@NLO: s-channel production

[Alioli, Nason, Oleari, Re ’09]



POWHEG vs MC@NLO: tW production

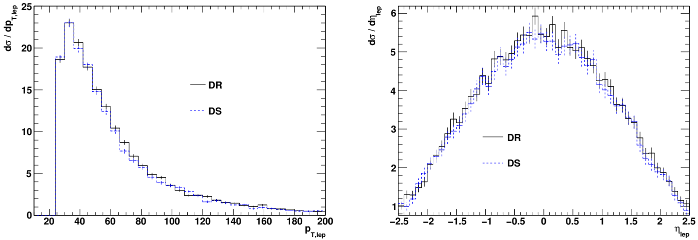
Unambiguous theoretical definition of tW production is difficult due to **interference with $t\bar{t}$ production at NLO**

$$\mathcal{A}_{WWbb} = \overbrace{\mathcal{A}_{WWbb,tW}}^{\text{NLO single t prod.}} + \overbrace{\mathcal{A}_{WWbb,t\bar{t}}}^{\text{LO top-pair prod.}}$$

One can still try to define the tW signal subject to a certain set of kinematical cuts.
Two schemes implemented in MC@NLO and POWHEG [Frixione, Laenen, Motylinski, Webber, White '08; White, Frixione, Laenen, Maltoni '09]

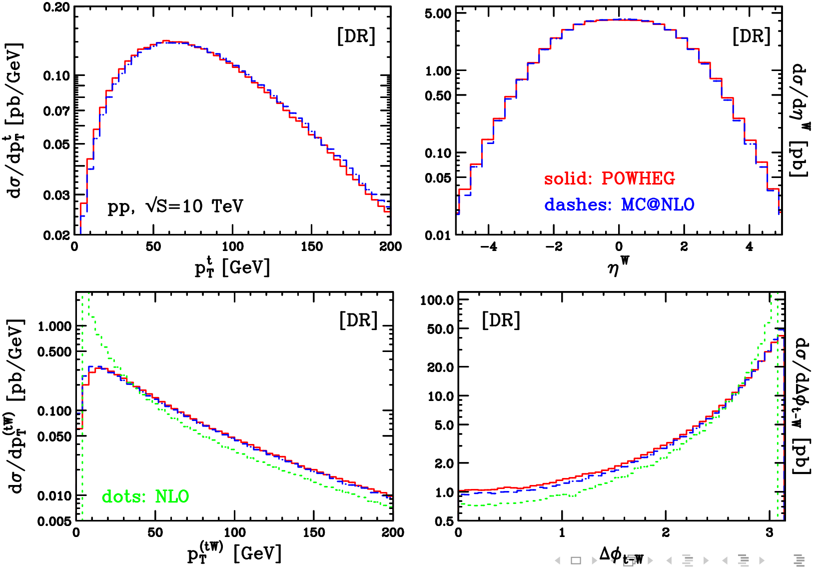
- **Diagram removal** (DR): $d\sigma_{tW}^{\rm NLO} = d\phi_n |\mathcal{A}_{WWbb,tW}|^2$
- **Diagram subtraction** (DS): $d\sigma_{tW}^{\rm NLO} = d\phi_n \left(|\mathcal{A}_{WWbb,tW} + \mathcal{A}_{WWbb,t\bar{t}}|^2 - \mathcal{M}_{subt.} \right)$

$$\mathcal{M}_{subt.} \to |\mathcal{A}_{WWbb,t\bar{t}}|^2 \text{ when } m_{bW} \to m_t$$



POWHEG vs MC@NLO: tW production

[Re '10]



Conclusions

Theoretical understanding and modelling of single-top production in the SM has progressed significantly in the last few years!

⇒ NLO results for the 3 production channels matched to MC parton shower (MC@NLO and POWHEG)

⇒ (matched) results in the 4F scheme have also become available
→ precise (NLO) modelling of spectator-b jet observables

⇒ contribution of off-shell and non-factorizable corrections has been assessed
→ generally small, but can be locally large (up to 40%) near kinematical edges

⇒ some additional information on higher-order corrections might be inferred from soft resummation, though some discrepancies have to be clarified first...

In this talk we focused only on the SM. However **beyond-SM single-top production** has also been studied

⇒ anomalous couplings

⇒ associated $H^- t$ production

⇒ ...