Tools for precision and discovery physics with top quarks

Status of Single Top Cross Sections

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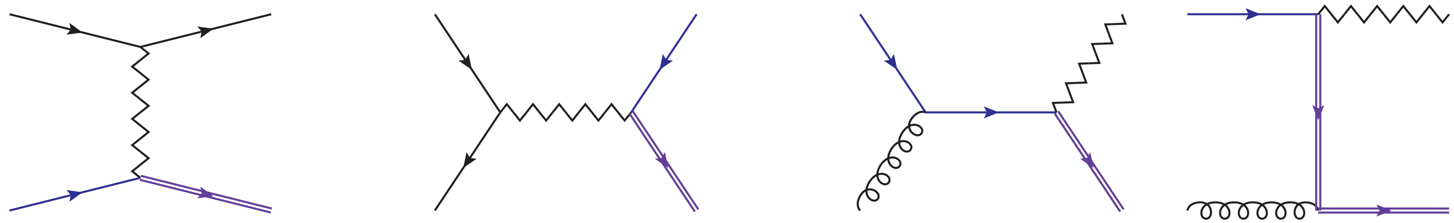
basic processes



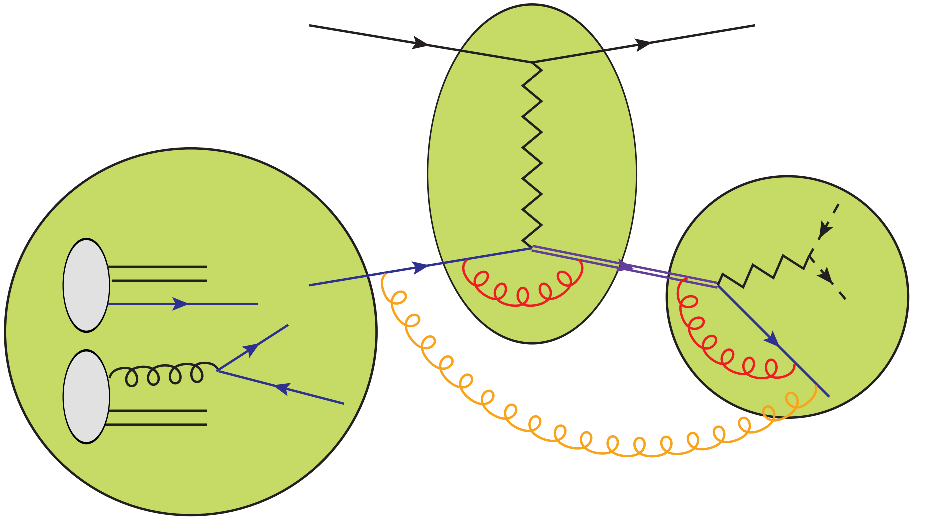
$t-$ channel $s-$ channel $W\,t$ (or $H^-\,t$) production

classification of physical processes is not that straightforward

approximate (!) expected / measured SM cross sections in pb

	Tevatron	7 TeV LHC	14 TeV LHC
$t\ (\bar{t})$ "t"-ch	1.2	40 (20)	150 (100)
$t\ (\bar{t})$ "s"-ch	0.55	2.5 (1.4)	7 (4)
$t\,W^-$	0.15	8	45

more detailed questions



- NLO corrections in production
- resummation of soft logs $\rightarrow$ "N"NLO corrections
- top decay, at LO/NLO, spin correlations
- off-shell effects / non-factorizable corrections
- initial b quark and m_b effects : 5 flavour scheme vs. 4-flavour scheme
- matching to parton showers

- fully differential NLO QCD corrections for t–, s–channel and Wt known [Harris et.al; Sullivan; Zhu . . .]
- resummation at NNLL of inclusive cross section [Kidonakis; Wang et.al.]
  $\rightarrow$ "poor man's" NNLO corrections
- top decay added, with NLO corrections in production and decay [Campbell et.al; Cao et.al]
  $\rightarrow$ issues with definition of channel
  $\rightarrow$ spin correlations
- EW corrections known in SM and MSSM [Beccaria et.al; Macorini et.al]
  effect small, a few %
- non-factorizable corrections known [Falgari et.al]
  $\rightarrow$ effects small, except at kinematic boundaries
- 4-flavour vs. 5-flavour scheme [Campbell et.al]
  $\rightarrow$ generally good agreement at NLO
- all channels (including $t\,H^-$) included in MC@NLO and POWHEG [Frixione,Frederix, Laenen, Motylinski, Alioli, Nason, Re, Webber, White . . . . . .]
- BSM effects (e.g. anomalous trilinear couplings) included in WHIZARD
  $\rightarrow$ interference with background diagrams on its way [Bach, Kilian, Ohl. . .]

s-channel: Kidonakis [1001.5034]

- resummation in moment space
- $s_4 \equiv (p_a + p_b - p_1)^2 - m_t^2 = s + t + u - m_t^2$ for $s_4 \to 0 \Rightarrow$

$$\alpha_s^n\, L^{2n-1} \equiv \alpha_s^n\, [\log^{2n-1}(s_4/m_t^2)/s_4]_+$$

- NLL $\to$ NNLO: $\alpha_s^2\, L^3$ and $\alpha_s^2\, L^2$ NLLO$_{\text{approx}}$/NLO $\sim$10% increase
  NNLL $\to$ NNLO: also $\alpha_s^2\, L^1$ and $\alpha_s^2\, L^0$ NLLO$_{\text{approx}}$/NLO further 3-4% increase
- soft limit good approximation for Tevatron and LHC
- damping factors (to limit soft gluon contributions away from threshold) improve soft approximation
- “best” predictions, MSTW2008 NNLO pdf:

Kidonakis $m_t = 173$ GeV	Zhu et.al. $m_t = 173.2$ GeV
$\sigma_{\text{TeV}} = 0.523^{+0.001+0.030}_{-0.005-0.028}$ pb	$\sigma_{\text{TeV}} = 0.467^{+0.01}_{-0.01}$ pb
$\sigma_{\text{LHC 7}} = 3.17^{+0.06+0.13}_{-0.06-0.10}$ pb	$\sigma_{\text{LHC 7}} = 2.81^{+0.16}_{-0.10}$ pb

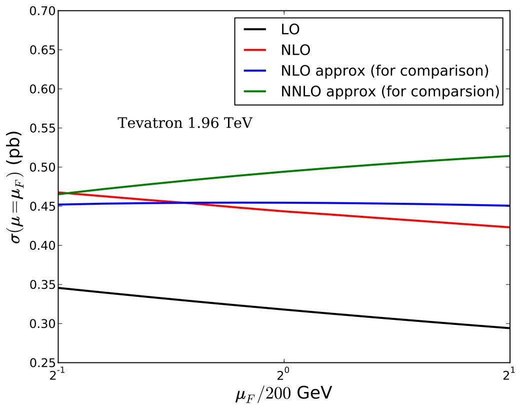
s-channel: Zhu, Li, Wang, Zhang [1006.0681]

- resummation via SCET
- different definition of resummation variable $q(p_1)\bar{q}(p_2) \to t(p_t)b(p_b)\{g(p_g)\}$

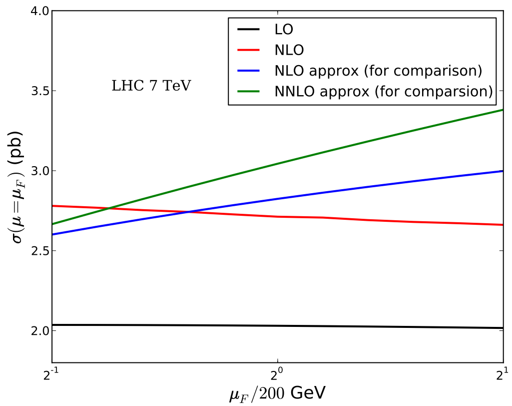
  Zhu et.al. $s_4 \equiv (p_1 + p_2 - p_t)^2$ $\quad s_4 \xrightarrow{p_g \| p_b} 0$

  Kidonakis $s_4^{\rm K} \equiv (p_1 + p_2 - p_b)^2 - m_t^2$ $\quad s_4^{\rm K} \overset{p_g \| p_b}{\not\longrightarrow} 0$

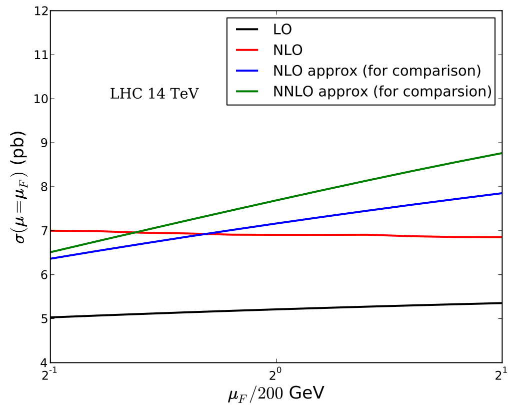
  contrary to $s_4^{\rm K}$ with s_4 hard-collinear logarithms are also included
- soft/coll limit good approximation for Tevatron, not very good for LHC



Tevatron



LHC @ 7 TeV



LHC @ 14 TeV

t-channel: Kidonakis [1103.2792] vs Wang, Li, Zhu, Zhang [1010.4509]

- similar technical (moments vs SCET) and physical (resummation kinematics and virtual contribution) differences as for s-channel
- soft gluon approximation not considered reliable
- results for $m_t = 173$ GeV and MSTW2008 NNLO pdf

Kidonakis	Wang et.al.
$\sigma_{\rm TeV} = 1.04^{+0.00}_{-0.02} \pm 0.06 \text{ pb}$	$\sigma_{\rm TeV} = 0.982 \text{ pb}$
$\sigma_{\rm LHC\ 7} = 41.7^{+1.6}_{-0.2} \pm 0.8 \text{ pb}$	$\sigma_{\rm LHC\ 7} = 40.9^{+0.1}_{-0.1} \text{ pb}$
$\sigma_{\rm LHC\ 14} = 151^{+4}_{-1} \pm 3 \text{ pb}$	$\sigma_{\rm LHC\ 7} = 152.4^{+0.4}_{-1.0} \text{ pb}$

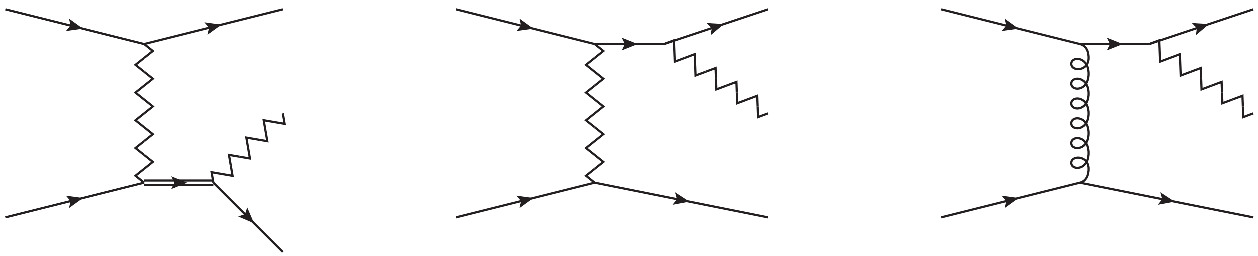
- better numerical agreement than for s-channel
- resummation effects decrease scale dependence

$W\,t$ and $H^-\,t$: Kidonakis [1005.4451]

- resummed cross section re-expanded: $\sigma^{(2)} = \sigma^{(0)}\alpha_s^2 \left(\underbrace{c_3 L^3 + c_2 L^2}_{\mathrm{NLL}} + \underbrace{c_1 L^1 + c_0 L^0}_{\mathrm{NNLL}} \right)$
- soft gluons claimed to be dominant
- damping factors applied
- NLO $\to$ 'N'NLO: 8% increase at 7 TeV LHC
- $m_t = 173$ GeV, MSTW2008 NNLO pdf: $\sigma(t\,W^-) = 7.8 \pm 0.2^{+0.5}_{-0.6}$ pb
- scale variation error < pdf error
- similar analysis for $H^-\,t$: corrections NLO $\to$ 'N'NLO: 15-20%, depending on m_H

adding top decay

- new issue: definition of process, e.g t-channel

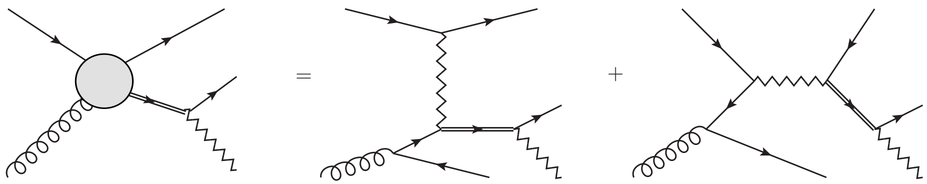


$\mathcal{A}_{\rm res}$ $\qquad$ $\mathcal{A}_{\rm EWbg}$ $\qquad$ $\mathcal{A}_{\rm QCDbg}$

- it is an “irrelevant coincidence” at LO that

$$|\mathcal{A}_{\rm res} + \mathcal{A}_{\rm EWbg} + \mathcal{A}_{\rm QCDbg}|^2 = |\mathcal{A}_{\rm res} + \mathcal{A}_{\rm EWbg}|^2 + |\mathcal{A}_{\rm QCDbg}|^2$$

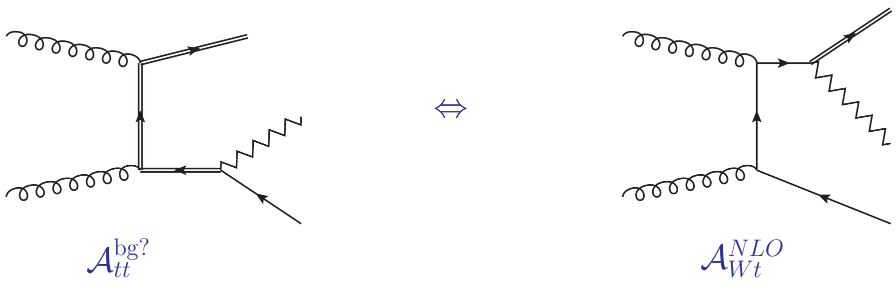
- shouldn’t we define a proper observable (to which $\mathcal{A}_{\rm QCDbg}$ contributes) with proper final states (e.g. b-jets), rather than try to subtract $|\mathcal{A}_{\rm QCDbg}|^2$?
- similar comment regarding distinction between s-channel and t-channel



t − channel $\qquad$ s − channel

- mixing but no interference at NLO (another “irrelevant coincidence”), beyond NLO there is interference

- this issue is particularly acute for $W\,t$ and has been studied extensively [Kersevan et.al; Tait; Belyaev et.al; Campbell et.al; Frixione et.al]



- possible remedies
  - invariant mass (anti-) cut $|M_{Wb} - m_t| \gg \Gamma_t$
  - $p_T^b < p_T^{\rm veto}$ (hard b tend to come from t decay)
  - Diagram removal $\mathcal{A}_{(Wt)} + \mathcal{A}_{(tt)} \to \mathcal{A}_{(Wt)}$
  - Diagram subtraction

    $$|\mathcal{A}_{(Wt)} + \mathcal{A}_{(tt)}|^2 \to |\mathcal{A}_{(Wt)}|^2 + 2{\rm Re}(\mathcal{A}_{(Wt)}\mathcal{A}^*_{(tt)}) + |\mathcal{A}_{(tt)}|^2 - |\widetilde{\mathcal{A}_{(tt)}}|^2$$
- using b-jet rather than b-parton allows to define (at least theoretically) clean observables

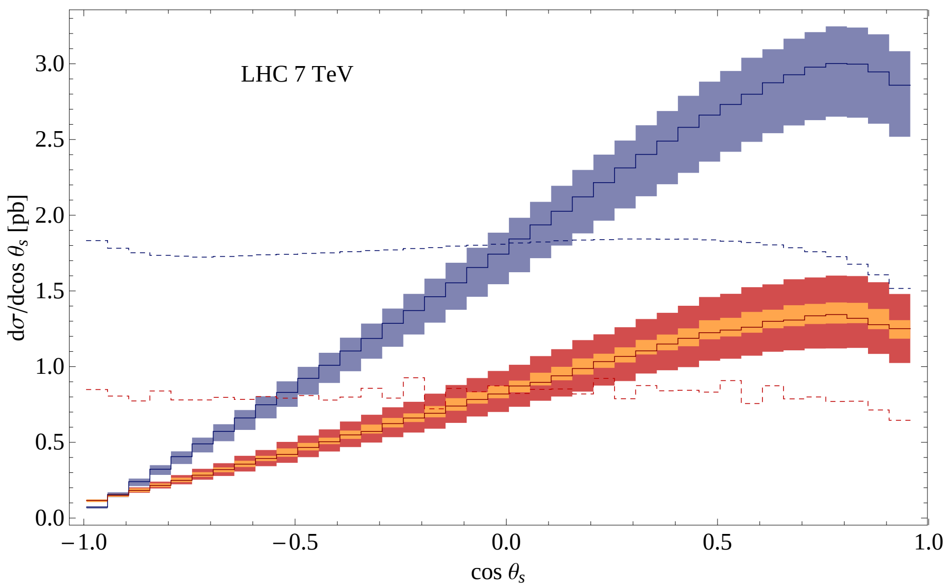
politically incorrect comment about gauge invariance:

- diagram removal induces gauge invariance, is this a disaster?
- if gauge dependence is suppressed w.r.t. accuracy of calculation, this is the same as μ dependence
- ideally introduce counting in small kinematic variable δ
  if we compute at order δ^n, it is ok to end up with residual gauge dependence at order δ^{n+1}.
- if no counting available, check numerically, e.g. DR vs DS
- this is completely analogous to renormalization/factorization scale/scheme dependence.

what value for ξ ?	what value for μ ?	formally: any
$\xi \sim 1$ (parameter in $\mathcal{L}$)	$\mu \sim s_{ij}$	avoid large coefficients
setting $\xi = 10^{10}$	setting $\mu = M_{\rm Planck}$	simply stupid !!
variation of ξ	variation of μ	estimate of h.o. corrections ??

- cross check possible e.g. with WHIZARD

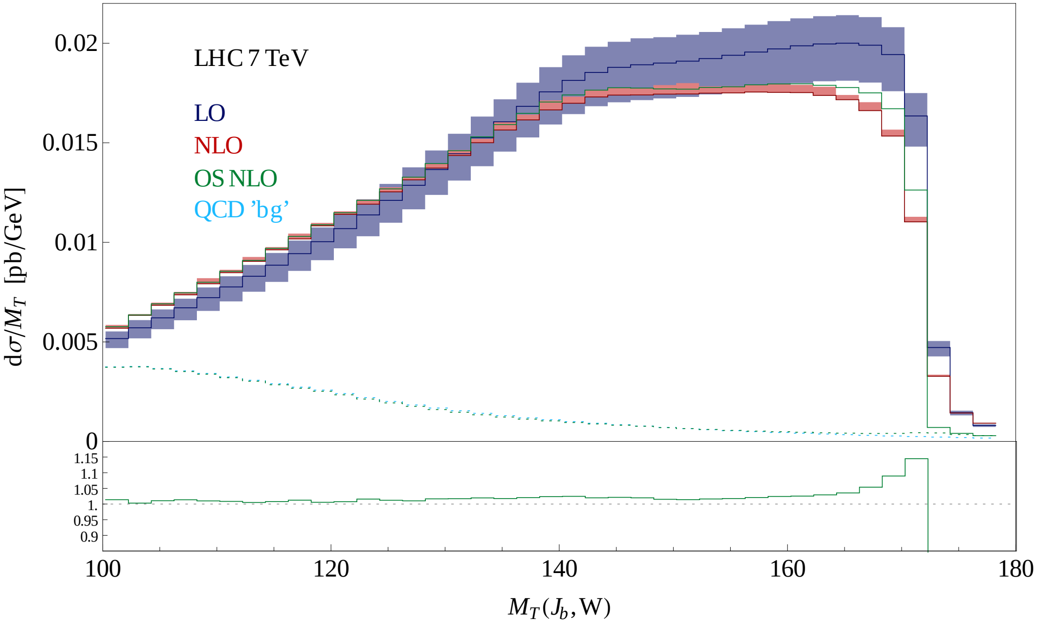
- $\Gamma_t > \Lambda_{\rm QCD} \Longrightarrow$ top quark decays before QCD blurs spin information [Mahlon, Parke; Bernreuther et.al; Motylinski; Cao et.al; Melnikov, Schulze, . . .]
- detailed test of $t \to Wb \to \ell\nu b$ possible
- details depend on process (top pair production / single top), collider (Tevatron / LHC) and kinematic regime (invariant mass)
- find observable that strongly depends on spin correlation, e.g: $\cos(\vec{p}^{\,*}_{\rm spec} \cdot \vec{p}^{\,*}_{\ell})$ [Cao et.al]
  $\to$ relatively insensitive to higher-order corrections



- test against SM and BSM predictions

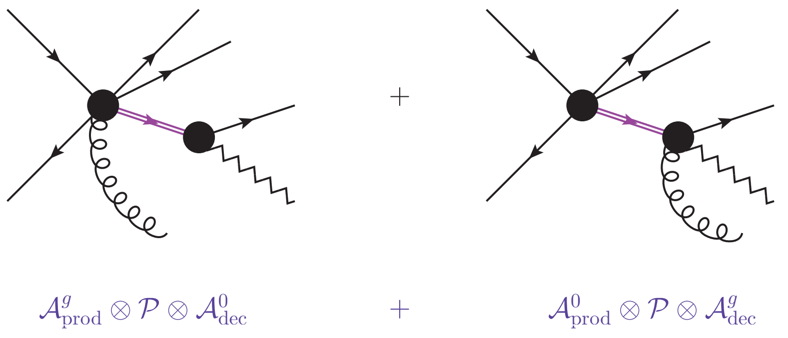
non-factorizable corrections have been extensively studied [Fadin et.al; Melnikov et.al; Beenakker et.al; Denner et.al.; Jadach et.al; . . .] but usually neglected at hadron colliders:

- they seem to be more difficult to compute (not really)
- they are generally small [Beenakker et.al; Pittau]
  - resonant $\to$ non-resonant propagator unless $E \lesssim \Gamma$ is small (soft)
  - cancellations for "inclusive" observables [Fadin, Khoze, Martin]
- include off-shell effects: consistently combine non-factorizable with propagator corrections: [Falgari et.al] e.g. transverse mass: $M_T = \sum_{J_b,\ell,\nu} |p_T|^2 - (\sum_{J_b,\ell,\nu} \vec{p}_T)^2$



effective-theory inspired calculation (hard/soft through method of region)

real amplitude:



corrections to production (soft and coll singularities):

$\int d\Phi_{n+1} \left| \mathcal{A}^g_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^0_{\rm dec} \right|^2$ plus (hard) virtual corrections for t-production is IR finite

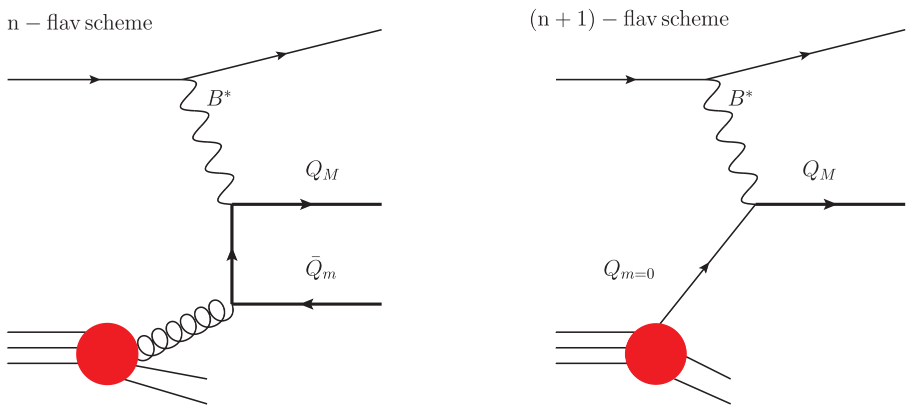
corrections to decay (soft and coll singularities):

$\int d\Phi_{n+1} \left| \mathcal{A}^0_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^g_{\rm dec} \right|^2$ combined with (hard) virtual correction for decay is IR finite

non-factorizable corrections (soft singularities only):

$\int d\Phi_{n+1}\, 2\,{\rm Re} \left(\mathcal{A}^0_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^{\rm g}_{\rm dec} \right) \left(\mathcal{A}^{\rm g}_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^0_{\rm dec} \right)^*$ plus soft virtual is IR finite

4-flavour scheme vs. 5-flavour scheme

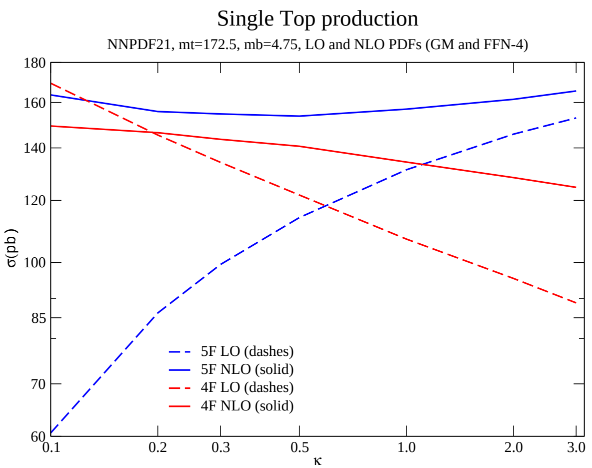


$b \notin p$: 4 flavour scheme	$b \in p$: 5 flavour scheme
$\exists \bar{b}$ @ LO	$\nexists \bar{b}$ @ LO
only 1 $\log \mu_f^2/m_b^2$ @ NLO	$\log \mu_f^2/m_b^2$ resummed
m_b effects can be included	$m_b = 0$ for initial state

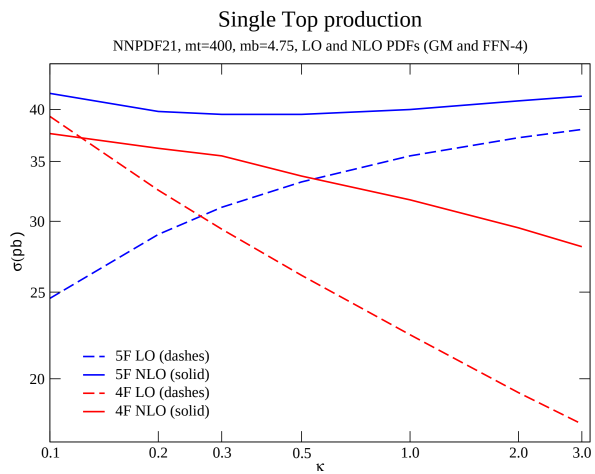
- Comparison 4F vs 5F for single top at NLO [Campbell et.al]:
- Generally good agreement already at NLO
- A detailed single-top analysis POWHEG vs aMC@NLO in 4F (and 4F vs 5F including parton showers) is under way [Frederix, Re, Torrielli]

4-flavour scheme vs. 5-flavour scheme

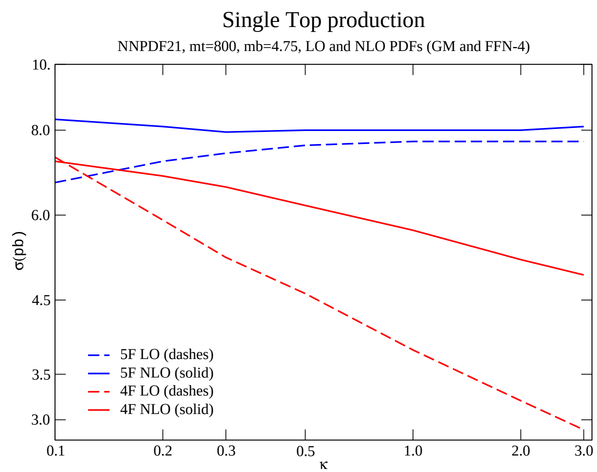
- general analysis 4F vs 5F [Maltoni, Ridolfi, Ubiali (1203.6393)]
- resummation of $\log \mu_f^2/m_x^2$ numerically not very important (except for x large)
- scale in $\log$ suppressed through phase space



$m_t = 172.5$ GeV



$m_t = 400$ GeV



$m_t = 800$ GeV

tools (no claim for completeness!)

- resummed total cross sections available
  - for s- and t-channel by two groups
  - for $W\,t$, $H\,t$ by one group
- several fixed-order NLO calculations (including decay and spin correlations) available
- off-shell effects at NLO available
- all channels (s-, t-, $W\,t$, $H\,t$) implemented in POWHEG and MC@NLO
- t-channel in 4 flavour scheme (very soon) available in POWHEG and (a)MC@NLO
- all channels (s-, t-, $W\,t$, $H\,t$) available in WHIZARD
  - up to 6 final state partons at LO
  - including “background” diagrams
  - BSM models implemented
  - including interface to shower

- open issues for NNLL resummed cross section
  - impact of collinear logs has to be clarified
- parton-shower compatible definition of single-top processes
  - is a $p_T(J_b) < p_T^{\rm veto}$ or a $|M_{W\,J_b} - m_t| \gg \Gamma_t$ cut a viable way to suppress $t\bar{t}$ contributions to $W\,t$ production?
- is there any point in doing NNLO calculation? (apart from being a nice technical exercise)
- BSM: anomalous couplings vs. effective theory
- will single-top ever be more than simply a test?
  - how far can we go with V_{tb}
  - can we measure m_t via single top
  - can we learn something about pdf
    - from comparing single top vs. single anti-top cross sections
    - using (∆ pdf) > (∆ scale) for resummed cross sections