Workshop on Heavy Particles at the LHC

Resonant Single Top Production at Hadron Colliders

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IN COLLABORATION WITH

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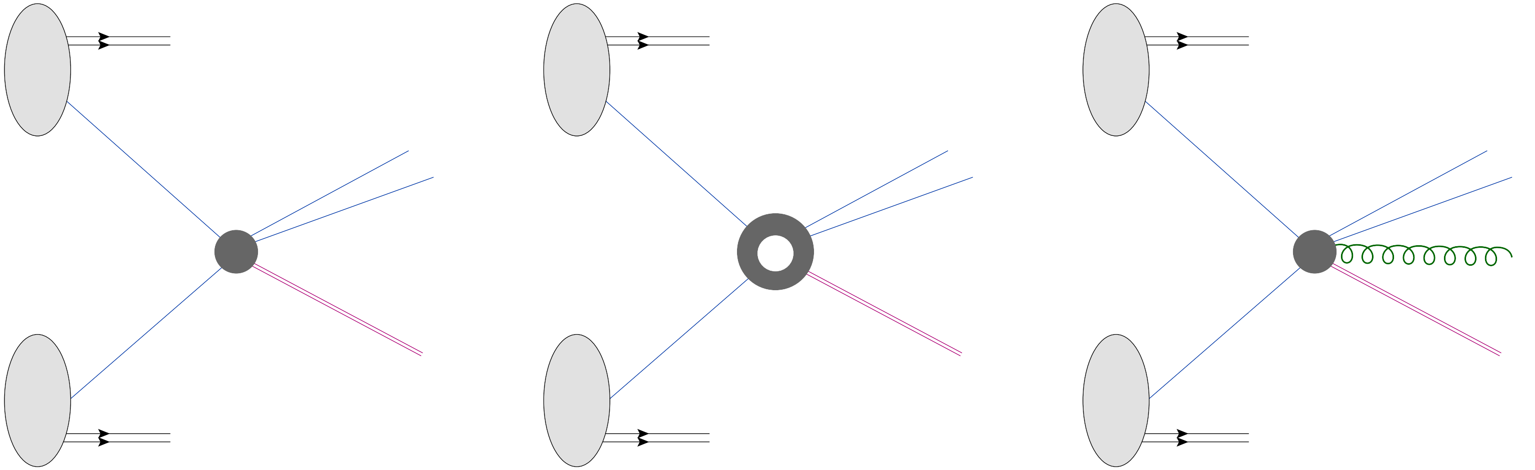
5.–7. JANUARY 2011, ZURICH, SWITZERLAND

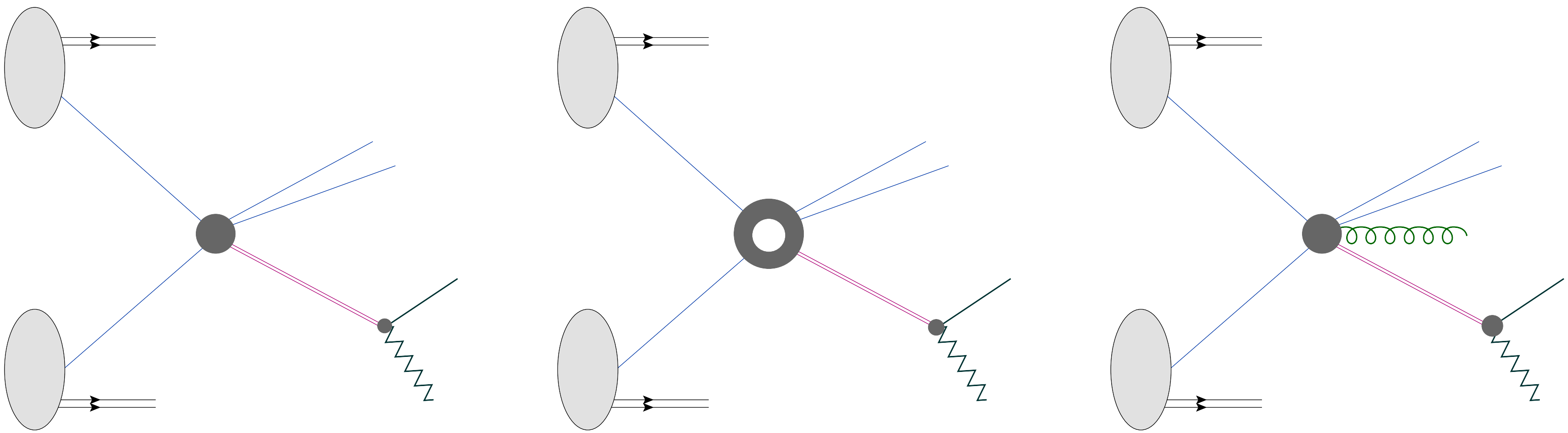
introduction	• background • non-factorizable corrections
method	• effective theory approach • virtual corrections • real corrections
application	• overview single-top 't' and 's'-channel • tree level, virtual corrections, real corrections
results	• 't'-channel LHC • 's'-channel LHC • 't' and 's'-channel Tevatron
conclusions	• outlook

Production of an on-shell heavy (unstable) particle X: $p_X^2 = m_X^2$



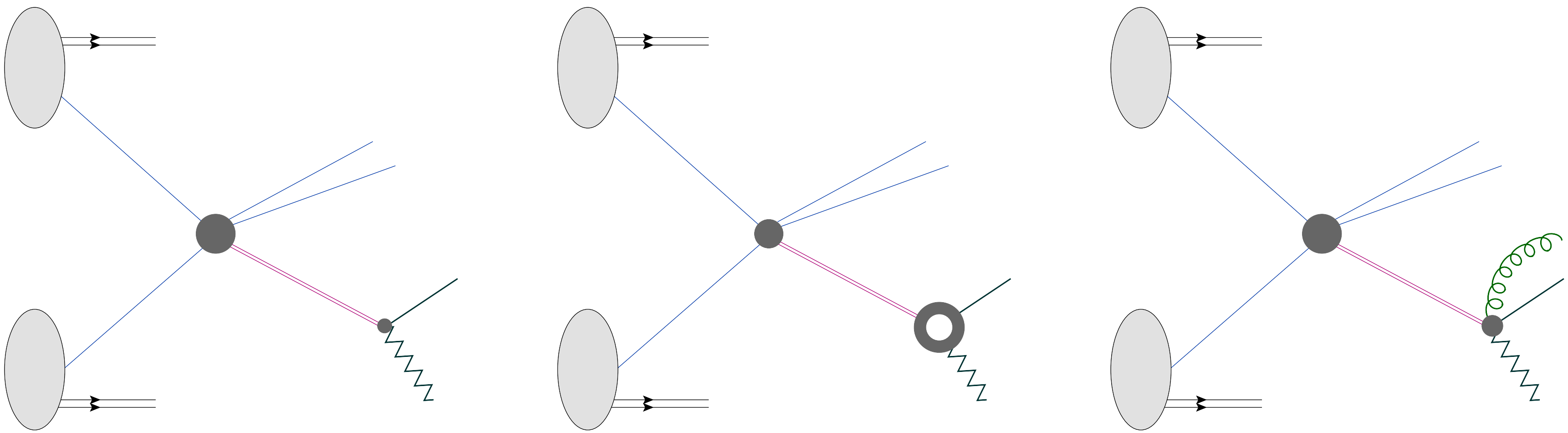
- often this is a reasonable approximation but
- cuts on decay products not possible
- off-shell effects of X not taken into account

Production of an on-shell heavy (unstable) particle X, including decay: $p_X^2 = m_X^2$



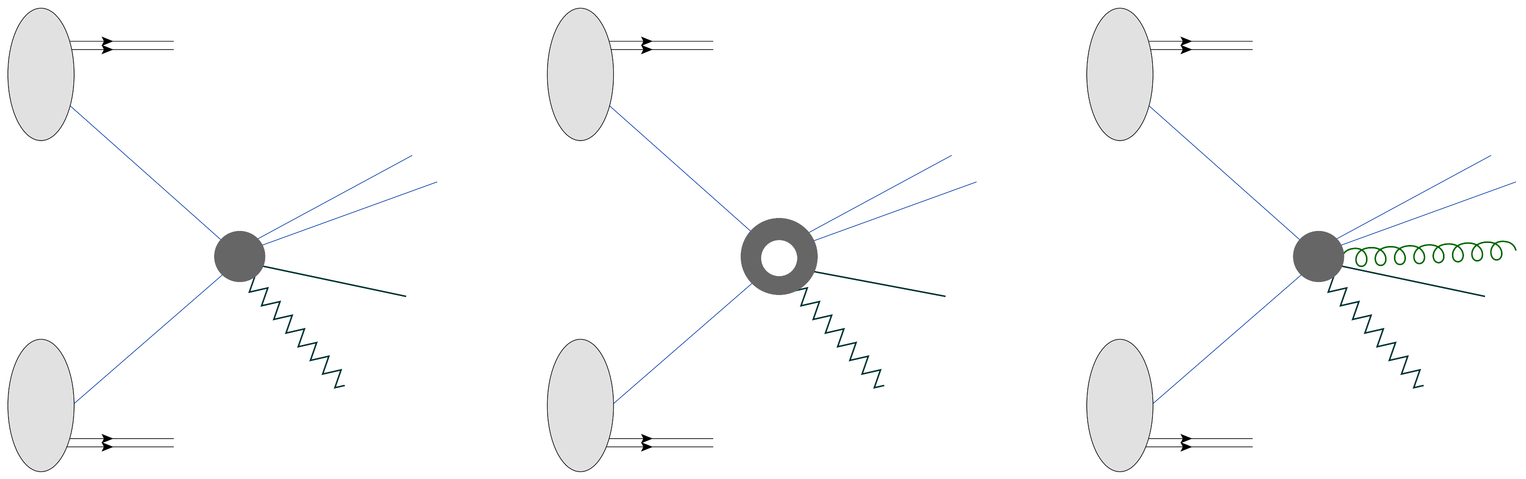
- (improved) narrow width approximation, $M_{\mathrm{decay}}^2 = m_X^2$
- NLO correction of production and decay included
- cuts on decay products possible but off-shell effects of X not taken into account

Production of an on-shell heavy (unstable) particle X, including decay: $p_X^2 = m_X^2$



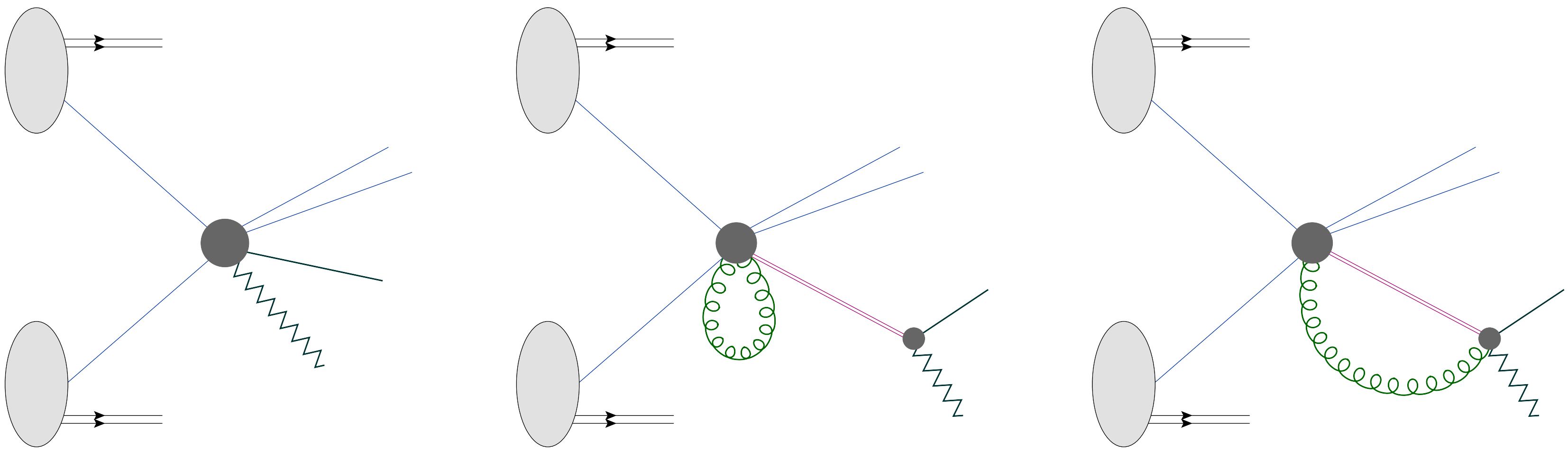
- (improved) narrow width approximation, $M^2_{\text{decay}} = m_X^2$
- NLO correction of production and decay included
- cuts on decay products possible but off-shell effects of X not taken into account

Production of an off-shell heavy (unstable) particle X, including decay: $p_X^2 \neq m_X^2$



- tree-level background diagrams (no particle X, but same final state)
- virtual and real background diagrams
- valid for any p_X^2, (off-shell effects taken into account) but calculation complicated

Production of a resonant heavy (unstable) particle X, including decay: $p_X^2 \sim m_X^2$



- tree-level background diagrams (no particle X, but same final state)
- use pole approximation (at one loop)
  - factorizable corrections
  - non-factorizable corrections

  } gauge invariant separation
- real background diagrams
- off-shell effects of X are taken into account, calculation simplified

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

- they seem to be more difficult to compute (not really)
- they are generally small [Beenakker et.al; Pittau]
  - resonant $\rightarrow$ non-resonant propagator unless $E \lesssim \Gamma$ is small (soft)
  - cancellations for “inclusive” observables [Fadin, Khoze, Martin]

purpose of this work:

- do not neglect non-factorizable corrections
- try to obtain an efficient way to identify and compute minimal amount required

in this talk I will not consider many other (sometimes related) issues such as

- (soft) connection of unstable particle to beam remnant
- issues related to using pole mass for unstable particle $\delta m_t \simeq \Lambda_{\rm QCD}$??

ET and normal approach

- small scale $(p_X^2 - m_X^2)/m_X^2 \sim \delta \ll 1 \rightarrow$ effective theory (ET) approach
- expand in all small parameters α and $(p_X^2 - m_X^2)/m_X^2 \rightarrow$ power counting:

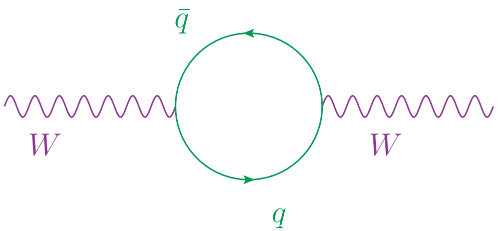
$$\alpha \sim \frac{p_X^2 - m_X^2}{m_X^2} \equiv \frac{\Delta}{m_X^2} \sim \frac{\Gamma_X}{m_X} \sim \delta \ll 1$$

- integrate out hard modes: $\mathcal{L}(\phi, A, \psi) \rightarrow \mathcal{L}_{\rm eff}(c_i, \phi_s, A_s, A_c, \psi_s, \psi_c)$
  UPET is nothing but a mix between SCET and H'Q'ET
- virtual corrections and total cross section
  - expand integrand, method of regions [Beneke, Smirnov]
  - new identification [Chapovsky, Khoze, AS, Stirling]
    factorizable corrections = hard corrections (ET)
    non-factorizable corrections = soft corrections (ET)
  - applications for total cross section:
    $e^+e^- \rightarrow t\bar{t}$ near threshold [Hoang et.al; Beneke et.al; Melnikov et.al; . . .]
    $e^+e^- \rightarrow W^+W^-$ near threshold [Beneke et.al.]
- arbitrary real corrections problematic (new scales from definition of observable)
- follow fixed-order approach, but expand $d\sigma^{\rm real}$ to match IR singularities of $d\sigma^{\rm virt}$

virtual corrections

use method of regions [Beneke, Smirnov] and expand integrand (in principle to any order):

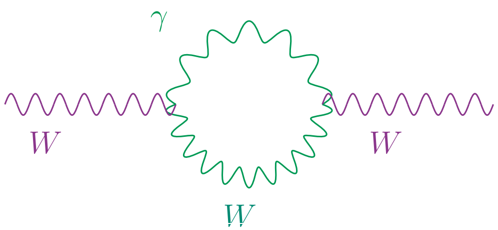
- hard corrections $\ell \sim m_X$ (= factorizable corrections)
- soft corrections $\ell \sim m_X\,\delta$ (= non-factorizable corrections)



$$\int \frac{d^d\ell}{(p+\ell)^2\ell^2}$$

hard: full

soft: $$\int \frac{d^d\ell\,(2p\cdot\ell)}{p^2\ell^2} = 0$$



$$\int \frac{d^d\ell}{(\ell^2+2p\cdot\ell+\Delta)\ell^2}$$

hard: $$\int \frac{d^d\ell}{\ell^2(\ell^2+2p\cdot\ell)} \neq 0$$

soft: $$\int \frac{d^d\ell}{\ell^2(2p\cdot\ell+\Delta)} \neq 0$$

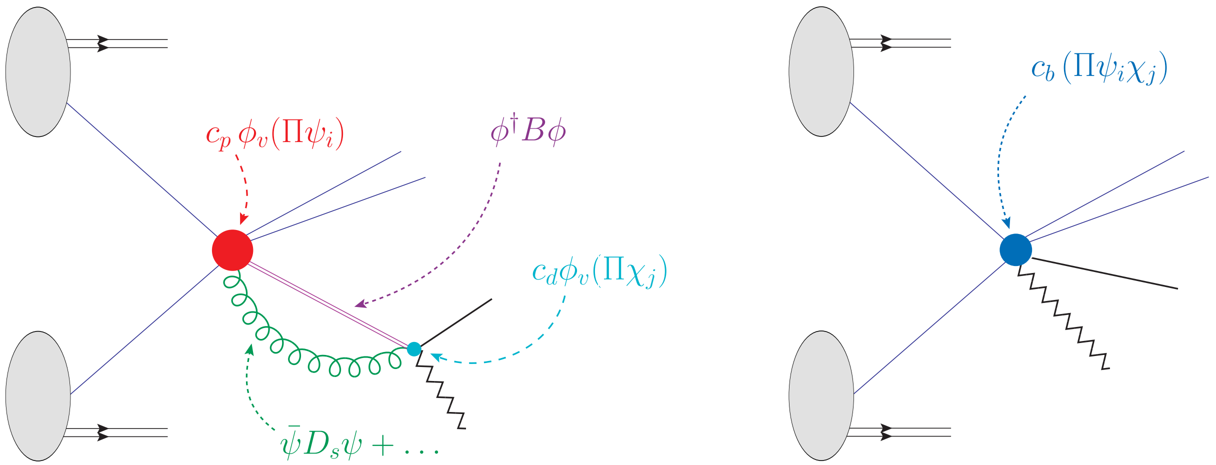
- leads to resummation of hard part (= leading part in Δ) of self-energy insertions

$$\mathcal{L}_{\rm eff} = 2m_X\,\phi_s^\dagger\left(iv\cdot\partial - \frac{c_{\phi\phi}}{2}\right)\phi_s + \ldots$$

- matching coefficients are gauge invariant ($c_{\phi\phi} = -i\Gamma$ in pole scheme)
  full result is gauge invariant at each order in δ, but gauge invariance is not an input

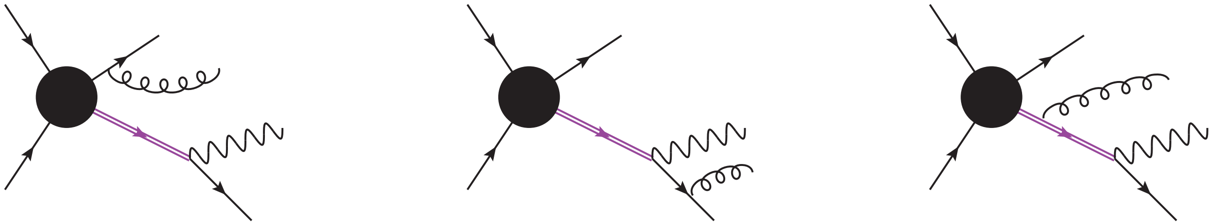
integrate out hard modes $\longrightarrow$ effective Lagrangian

$$\mathcal{L} = \phi^\dagger B\phi + c_p\,\phi(\Pi\psi_i) + c_d\phi(\Pi\chi_j) + c_b\,(\Pi\psi_i\chi_j) + \bar\psi D_s\psi + \ldots$$



- matching coefficients c_i contain effects of hard modes
- matching done on shell, $p_X^2 = \bar{s} = m_X^2 + \mathcal{O}(\Delta)$, with $\bar{s}$ the complex position of pole
- soft (and collinear . . .) d.o.f. still dynamical
- can be combined with further resummations (e.g. non-relativistic $\longrightarrow$ ET has more complicated structure)
- direct link to anomalous couplings via $\mathcal{L}_{\text{eff}}$

- for arbitrary observable it is not clear what expansion parameter is

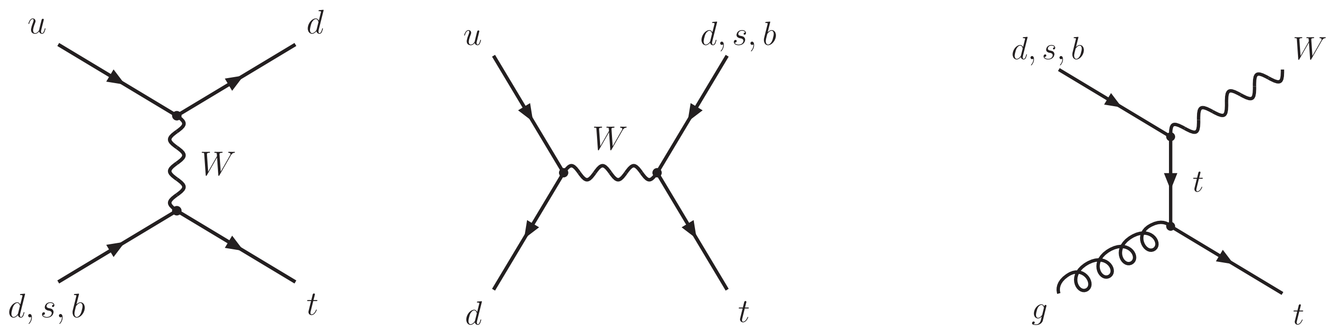


- observable can introduce new scales $\longrightarrow$ change in structure of ET
- take full real matrix element and apply (say) subtraction method

$$\begin{aligned}\int d\Phi_{n+1}|M_{n+1}|^2 &= \int d\Phi_{n+1}\left(|M_{n+1}|^2 - |M^{\rm sing}_{n(+1)}|^2\right) + \int d\Phi_{n+1}|M^{\rm sing}_{n(+1)}|^2 \\ &\simeq \int d\Phi_{n+1}\left(|M_{n+1}|^2 - |M^{\rm sing}_{n(+1)}|^2\right) + \int d\Phi_{n+1}|M^{\rm sing\ exp}_{n(+1)}|^2\end{aligned}$$

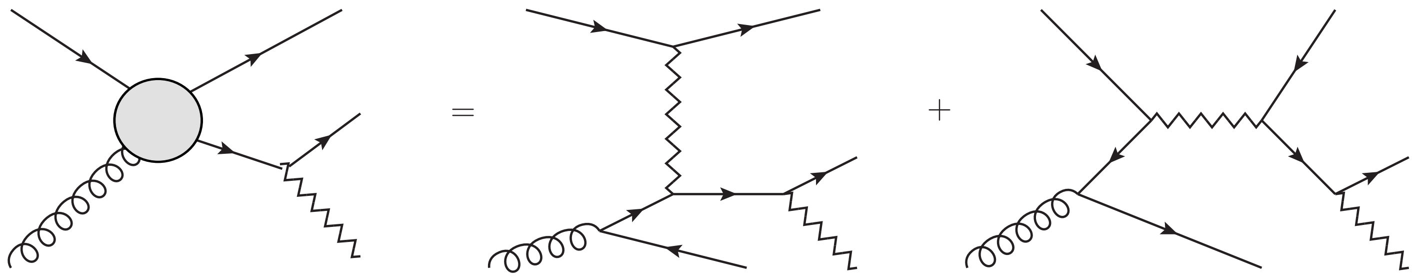
- $\int d\Phi_{n+1}|M^{\rm sing}_{n(+1)}|^2$ matches singularity structure of full virtual correction $\int d\Phi_n|M^{\rm v}_n|^2$
- $\int d\Phi_{n+1}|M^{\rm sing\ exp}_{n(+1)}|^2$ matches singularity structure of virtual term $\int d\Phi_n|M^{\rm v\ exp}_n|^2$
- we subtract something and add back something different, but difference is higher order in δ
- expansion only required for n parton kinematics

single top: t-channel s-channel ($W\,t$ not considered here)



- total rate and distributions for on-shell top quarks at NLO known [Bordes et.al; Stelzer et.al; Harris et.al; Campbell et.al; Cao et.al; . . .]
- implemented in MC@NLO [Frixione et.al.] and POWHEG [Alioli et.al.]
- comparison 5-flavour scheme vs. 4-flavour scheme [Campbell et.al.]
- EW corrections [Beccaria et.al.]
- effects of BSM operators [Willenbrock et.al.]
- resummation of threshold logs [Kidonakis, Wang et.al.]

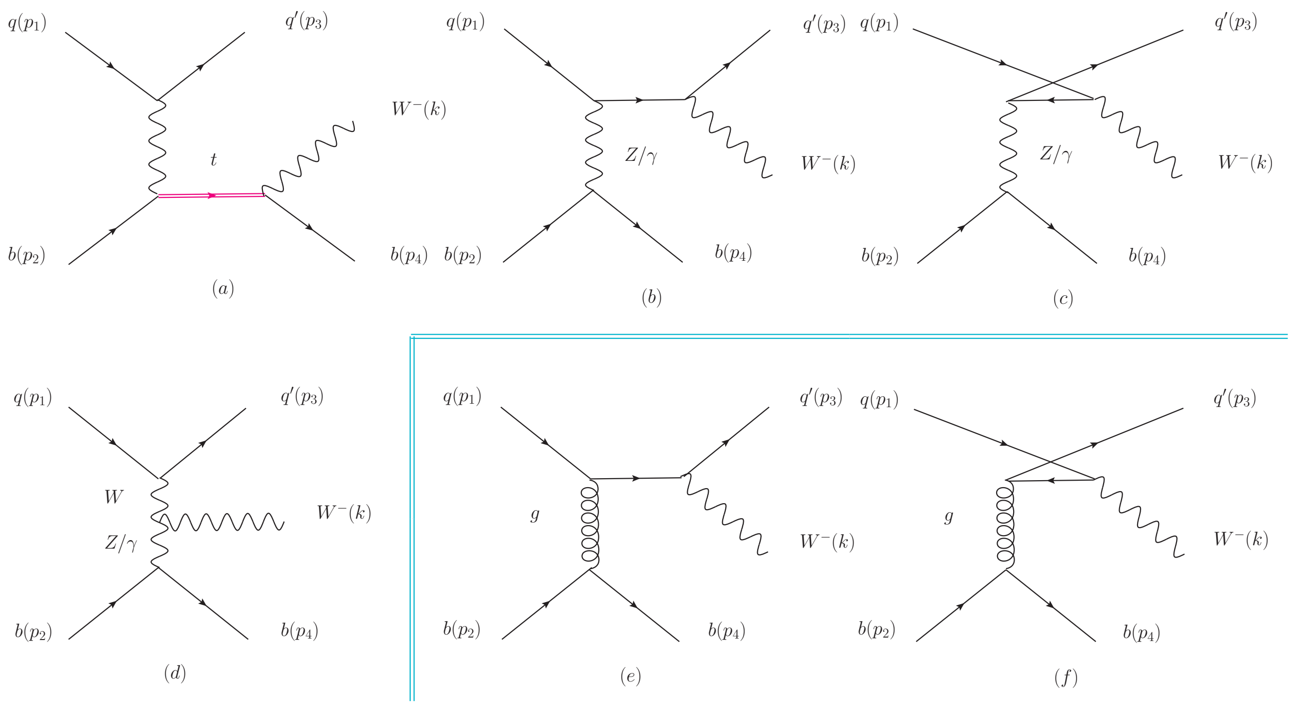
- s and t channel mix (beyond LO)
  $\longrightarrow$ more appropriate to talk about (tJ), (tb) (and (tW)) cross sections



$t-$channel $\qquad$ $s-$channel

- final state $W(=\ell\nu), J_b, J$ for 't'-channel and $W(=\ell\nu), J_b, J_{\bar{b}}$ for 's'-channel
- signal for top is $W J_b$ pair with invariant mass $(p_W + p_{J_b})^2 \equiv s_{Wb} \sim m_t^2$
- small parameter: $\delta \sim \frac{s_{Wb} - m_t^2}{m_t^2} \equiv \frac{\Delta}{m_t^2}$; counting: $\alpha_s^2 \sim \alpha_{ew} \sim \frac{\Gamma_t}{m_t} \sim \delta \ll 1$
- use (improved) narrow width for W decay
- use 5 flavour scheme, $m_b = 0$, and "fixed" order, i.e. no parton shower etc.

amplitude: $\mathcal{A}^{\text{tree}} = \delta_{31}\delta_{42}\Big(\underbrace{g_{ew}^3\, A^{(3,0)}_{(-1)}}_{\delta^{1/2}} + \underbrace{g_{ew}^3\, A^{(3,0)}_{(0)}}_{\delta^{3/2}} + \dots\Big) + \underbrace{T^a_{31} T^a_{42}\, g_{ew} g_s^2\, A^{(1,2)}}_{\delta \quad \text{signal!}}$

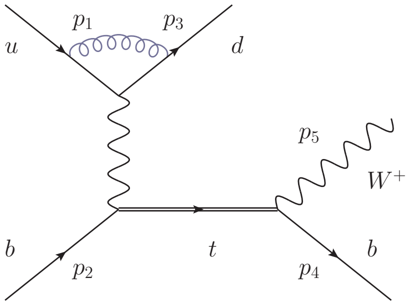


amplitude squared: (no inteference due to colour → no $\delta^{3/2}$ term)

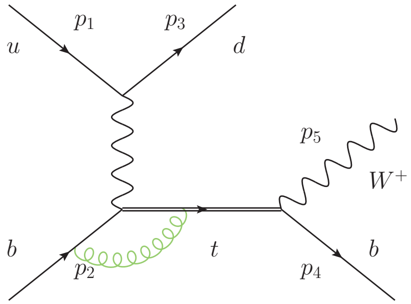
$$|M|^2 = \underbrace{g_{ew}^6\, N_c^2\, \left|A^{(3,0)}_{(-1)}\right|^2}_{\delta} + \underbrace{g_{ew}^6\, N_c^2\, 2\,\mathrm{Re}\left(A^{(3,0)}_{(-1)}\,[A^{(3,0)}_{(0)}]^*\right)}_{\delta^2} + \underbrace{g_{ew}^2 g_s^4\, N_c\, C_F/2 \left|A^{(1,2)}\right|^2}_{\delta^2} + \dots$$

tree-level (squared) $\sim \delta$, compute all $\sim \delta^{3/2}$ contributions to $|M|^2$ ($\sim \mathcal{O}(\alpha_s)$ corrections)

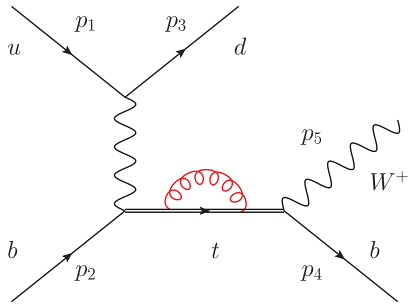
consider subset of resonant virtual diagrams (before expansion in δ this is gauge dependent)

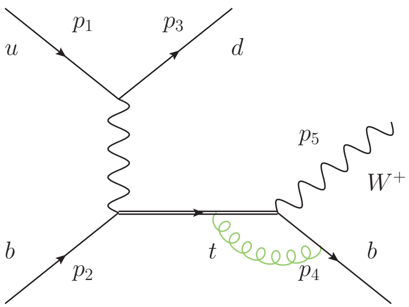


hard $\longrightarrow c_{\rm prod}$ soft $= 0$

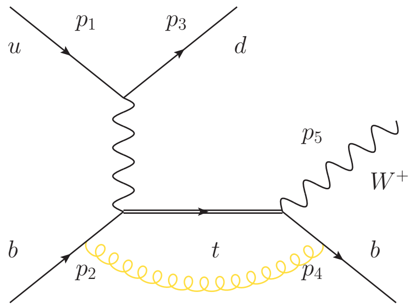


hard $\longrightarrow c_{\rm prod}$ soft $\longrightarrow$ non-fact

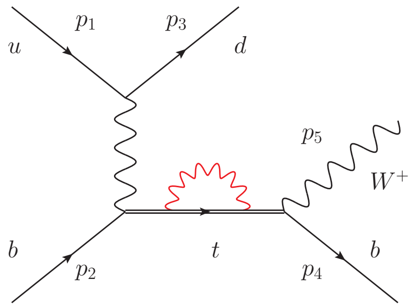




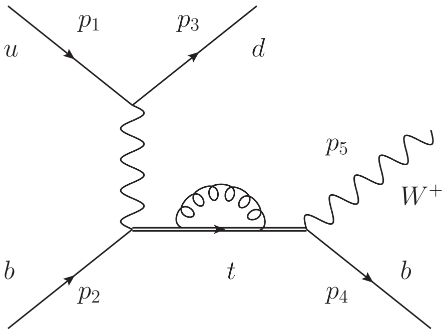
hard $\longrightarrow c_{\rm dec}$ soft $\longrightarrow$ non-fact



hard $\sim \delta^2$ soft $\longrightarrow$ non-fact

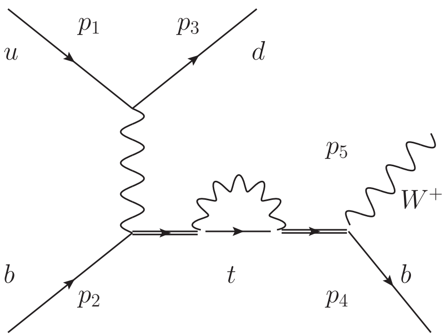


hard $\longrightarrow c_{\phi\phi}$ soft $\longrightarrow$ non-fact



denominator	$\Delta^2\,\ell^2\,[(p_t-\ell)^2-m_t^2]$	
hard	$\Delta^2\,\ell^2\,[\ell^2-2\ell\cdot p_t]$	$\sim \dfrac{g_{ew}^3\cdot\alpha_s\cdot 1}{\delta^2\cdot 1\cdot 1}\sim 1$
soft	$\Delta^2\,\ell^2\,[-2\ell\cdot p_t+\Delta]$	$\sim \dfrac{g_{ew}^3\cdot\alpha_s\cdot \delta^4}{\delta^2\cdot \delta^2\cdot \delta}\sim \delta$

hard part of QCD self-energy is superleading, i.e. $\mathcal{O}(1)$ with LO amplitude $\sim\delta^{1/2}$
but in pole scheme the leading hard part is precisely cancelled by counter term
soft and subleading hard part of QCD self-energy is NLO, i.e. $\mathcal{O}(\delta^{3/2})$ for $|M|^2$



denominator	$\Delta^2\,\ell^2\,[(p_t-\ell)^2-m_t^2]$	
hard	$\Delta^2\,\ell^2\,[\ell^2-2\ell\cdot p_t]$	$\sim \dfrac{g_{ew}^3\cdot\alpha_{ew}\cdot 1}{\delta^2\cdot 1\cdot 1}\sim \delta^{1/2}$
soft	$\Delta^2\,\ell^2\,[-2\ell\cdot p_t+\Delta]$	$\sim \dfrac{g_{ew}^3\cdot\alpha_{ew}\cdot \delta^4}{\delta^2\cdot \delta^2\cdot \delta}\sim \delta^{3/2}$

hard part of EW self-energy is leading, i.e. $\mathcal{O}(\delta^{1/2})\longrightarrow$ resum
soft part of EW self-energy is beyond NLO, i.e. $\mathcal{O}(\delta^2)$ for $|M|^2$

explicit calculations and results are very simple!

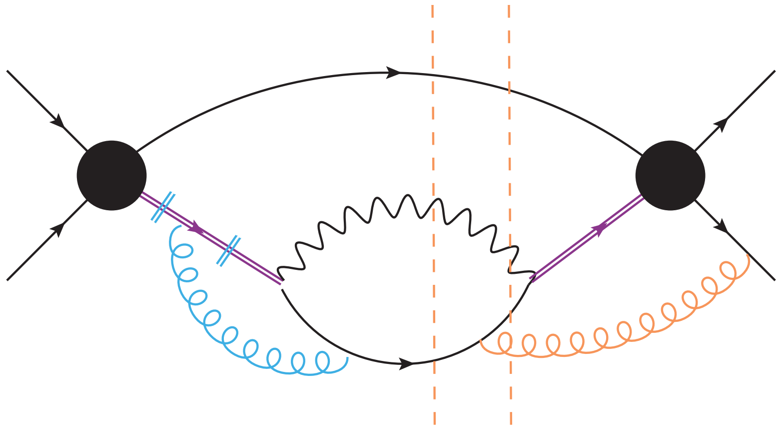
$$\mathcal{A}^{(1),\mathrm{soft}} = \mathcal{A}^{(0)}\delta V^{\mathrm{soft}}$$

$$\delta V^{\mathrm{soft}} = \frac{\alpha_s C_F}{2\pi}\left(-\frac{\Delta}{\mu m_t}\right)^{-2\epsilon}\left[\frac{1}{\epsilon}\left(1-\ln\frac{s_{2t}s_{4t}}{m_t^2\, s_{24}}\right)+2+\mathrm{Li}_2\left(1-\frac{s_{2t}s_{4t}}{m_t^2\, s_{24}}\right)\right]$$

$$\mathcal{A}^{\mathrm{hard},(b)} = \mathcal{A}^{(0)}\delta V^{\mathrm{hard},(b)} + \frac{\alpha_s C_F}{2\pi}\,\frac{-ig_{ew}^4\langle 46\rangle\langle 3|2|1\rangle[25]}{(s_{13}+M_W^2)\,\Delta}\,\frac{m_t^2}{m_t^2-s_{2t}}\ln\frac{s_{2t}}{m_t^2}$$

$$\begin{aligned}\delta V^{\mathrm{hard},(b)} = \frac{\alpha_s C_F}{2\pi}\Bigg[& -\frac{1}{2\epsilon^2}+\frac{1}{\epsilon}\left(\ln\frac{s_{2t}}{m_t\mu}-\frac{1}{2}\right)+\mathrm{Li}_2\left(1-\frac{m_t^2}{s_{2t}}\right)-2-\frac{\pi^2}{24}\\ & -\frac{1}{2}\ln^2\frac{s_{2t}}{m_t\mu}+\frac{1}{8}\ln^2\frac{m_t^2}{\mu^2}+\frac{s_{2t}}{4(m_t^2-s_{2t})}\ln\frac{m_t^2}{\mu^2}\\ & +\frac{1}{2}\ln\frac{s_{2t}}{m_t\mu}\left(2-\frac{s_{2t}}{m_t^2-s_{2t}}-\ln\frac{m_t^2}{\mu^2}\right)\Bigg]\end{aligned}$$

Comparison between (ET) and earlier (non-ET) NLO calculations [Campbell et.al, Yuan et.al.]



- ET virtual: hard part vanishes (at this order), soft part contributes and is included
- ET real: interference between production and decay radiation included
  after expansion this cancels corresponding virtual IR singularities
- non-ET real and virtual: not included
- ET: both top quarks can be off-shell, hard and soft part contribute
- non-ET: one top is always on-shell

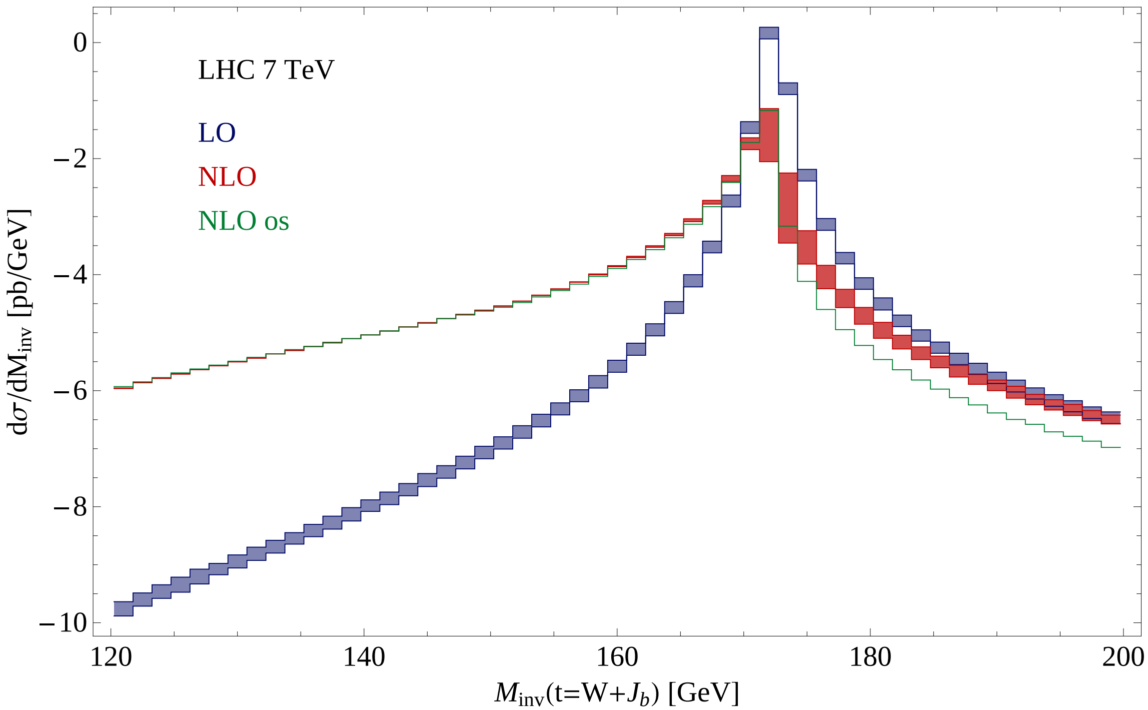
7 TeV LHC 't'-channel: $m_t = 171.3$ GeV, MSTW 2008 NLO pdf, $m_t/4 \le \mu \le m_t$

define jets: $k_\perp$ cluster algorithm $\Rightarrow$
J_b with $p_\perp(J_b) > 20$ GeV
J_q with $p_\perp(J_q) > 20$ GeV
no further $J_{\bar{b}}$ with $p_\perp(J_{\bar{b}}) > 15$ GeV
$\not{E}_\perp + p_\perp(\ell) > 60$ GeV,

top window: $150\ \text{GeV} < \sqrt{(p(J_b) + p(\ell) + p(\nu))^2} < 200\ \text{GeV}$

invariant mass of 'top'

$M^2_{\text{inv}} \equiv (p(J_b) + p(W))^2$



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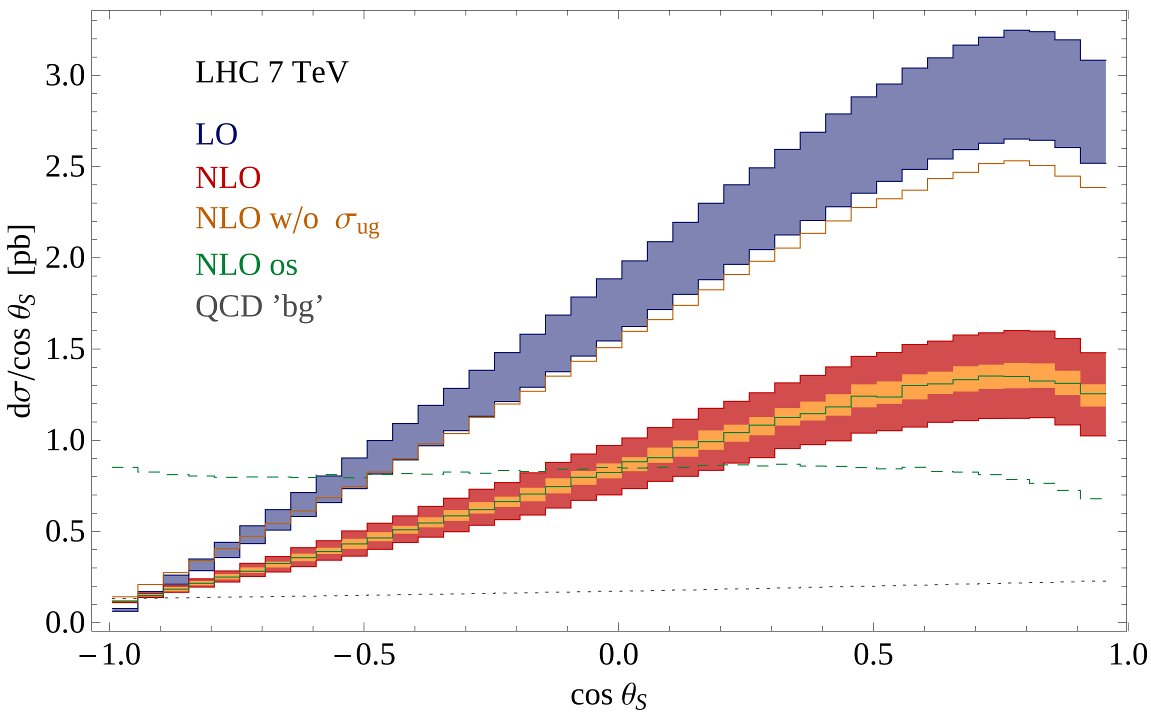
spin correlation

$$\cos\theta_{\rm spec} \equiv \frac{\vec{p}_q^{\,*}\cdot\vec{p}_\ell^{\,*}}{|\vec{p}_q^{\,*}|\,|\vec{p}_\ell^{\,*}|}$$



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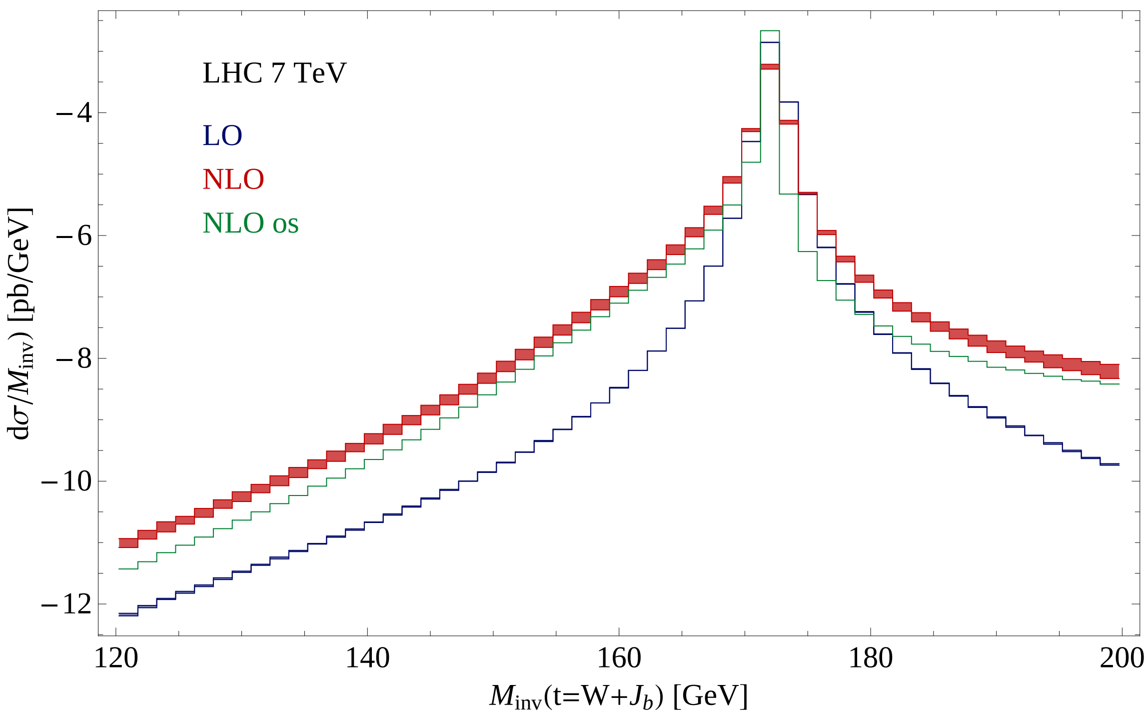
$$M^2_{\rm inv} \equiv (p(J_b) + p(W))^2$$



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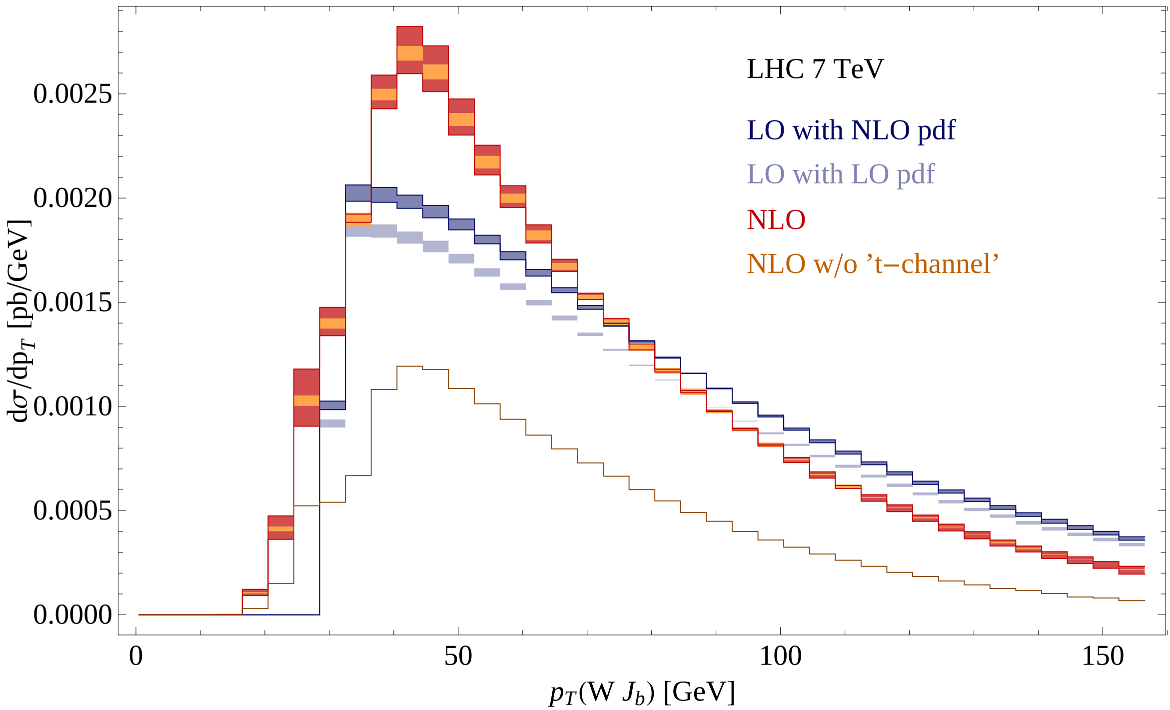
transverse momentum 'top'

$p_T(t = J_b + W)$



Tevatron 't'-channel: $m_t = 171.3\ \text{GeV}$, MSTW 2008 NLO pdf, $m_t/4 \le \mu \le m_t$

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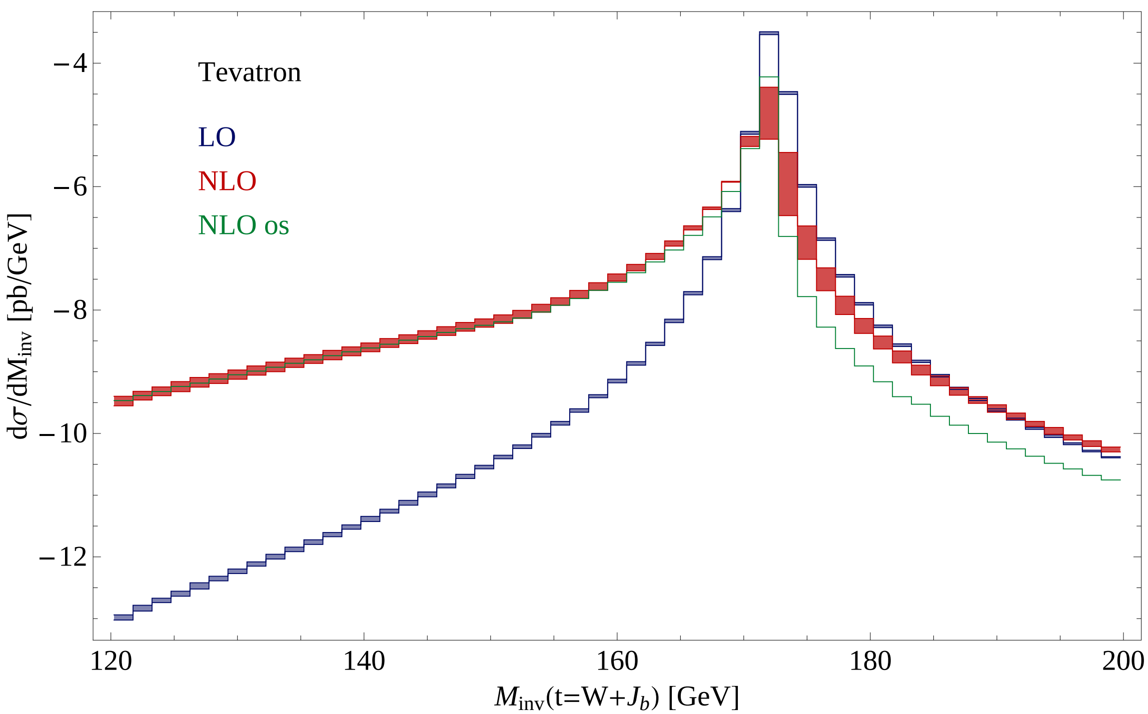
invariant mass of 'top'

$$M^2_{\text{inv}} \equiv (p(J_b)+p(W))^2$$



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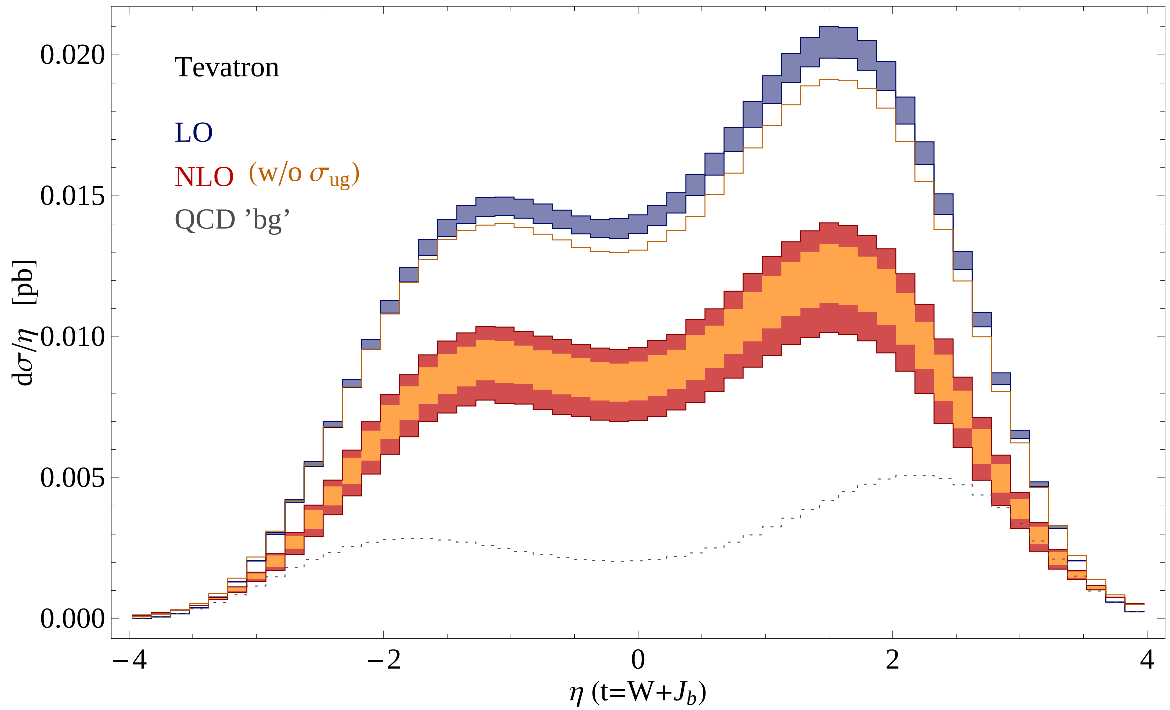
rapidity of top

$\eta(t = W + J_b)$



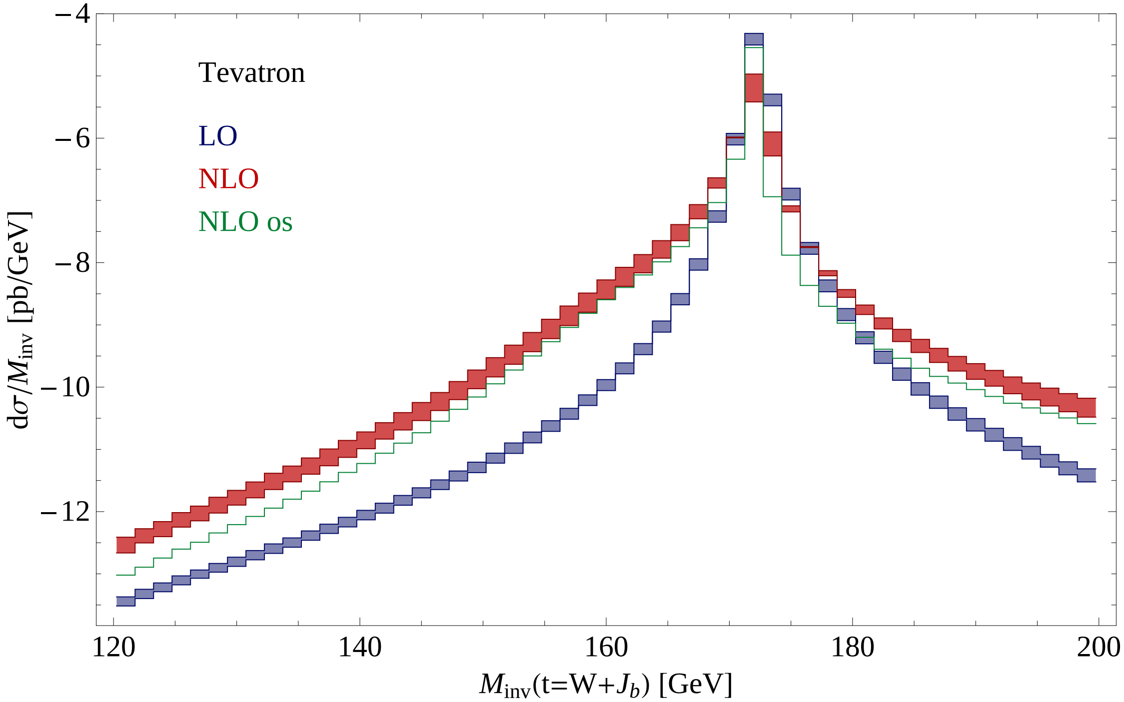
Tevatron 's'-channel: $m_t = 171.3$ GeV, MSTW 2008 NLO pdf, $m_t/4 \le \mu \le m_t$

define jets: $k_\perp$ cluster algorithm $\Rightarrow$
- J_b with $p_\perp(J_b) > 20$ GeV
- J_q with $p_\perp(J_q) > 20$ GeV
- no further $J_{\bar{b}}$ with $p_\perp(J_{\bar{b}}) > 15$ GeV
- $\not{E}_\perp + p_\perp(\ell) > 30$ GeV,

top window: $150 \text{ GeV} < \sqrt{(p(J_b) + p(\ell) + p(\nu))^2} < 200 \text{ GeV}$

invariant mass of 'top'

$$M_{\rm inv}^2 \equiv (p(J_b) + p(W))^2$$



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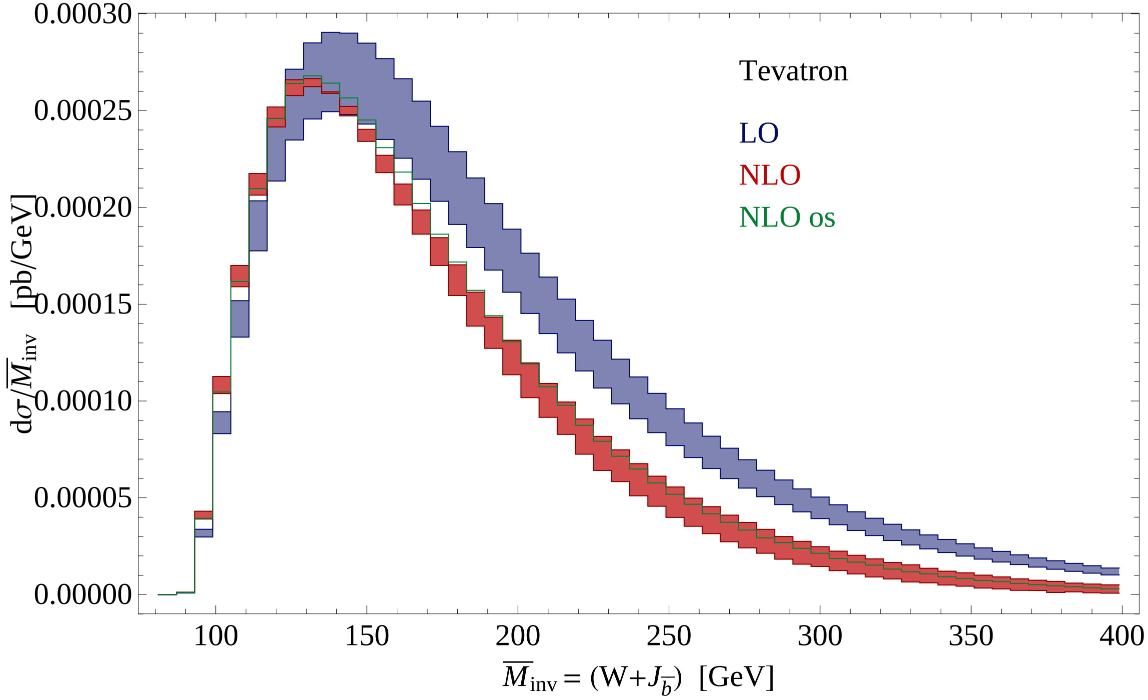
'wrong' invariant mass

$$\bar{M}^2_{\rm inv} \equiv (p(J_{\bar{b}}) + p(W))^2$$



- using ET inspired approach, the computational effort to include off-shell effects at NLO for unstable particles is very modest
  - amounts to inclusion of non-factorizable (= soft) corrections (and all spin correlation effects)
  - combined with “standard” (= hard) corrections for production and decay
- can be extended beyond NLO, well defined power counting to identify minimal amount of computation required for a certain precision
- applicable to unstable fermions, gauge bosons and scalars
- example single top:
  - off-shell effects $\mathcal{O}(\alpha_s\,\delta)$ are small for total cross section and most observables off-shell effects seem to be smeared by ’reconstruction effects’
  - higher order contributions in Δ are not too difficult to compute and can be numerically important (e.g. QCD “background”)
  - full calculation beyond $\mathcal{O}(\delta^{3/2})$ for $|M|^2$ would require two-loop matching coefficient