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Effective-theory approach to top quark production at hadron colliders

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outline

introduction
- background

Part I: off-shell effects $\leftrightarrow$ non-factorizable corrections

effective theory setup
- effective theory approach
- hard/soft modes, method of regions
- total cross section

single top production
- adapting ET approach to real corrections
- structure of fully differential NLO calculation
- results and comparison with complex-mass-scheme calculation

top pair production
- structure of fully differential NLO calculation
- results and impact on m_t determination

Part II: approximate NNLO fully differential cross sections

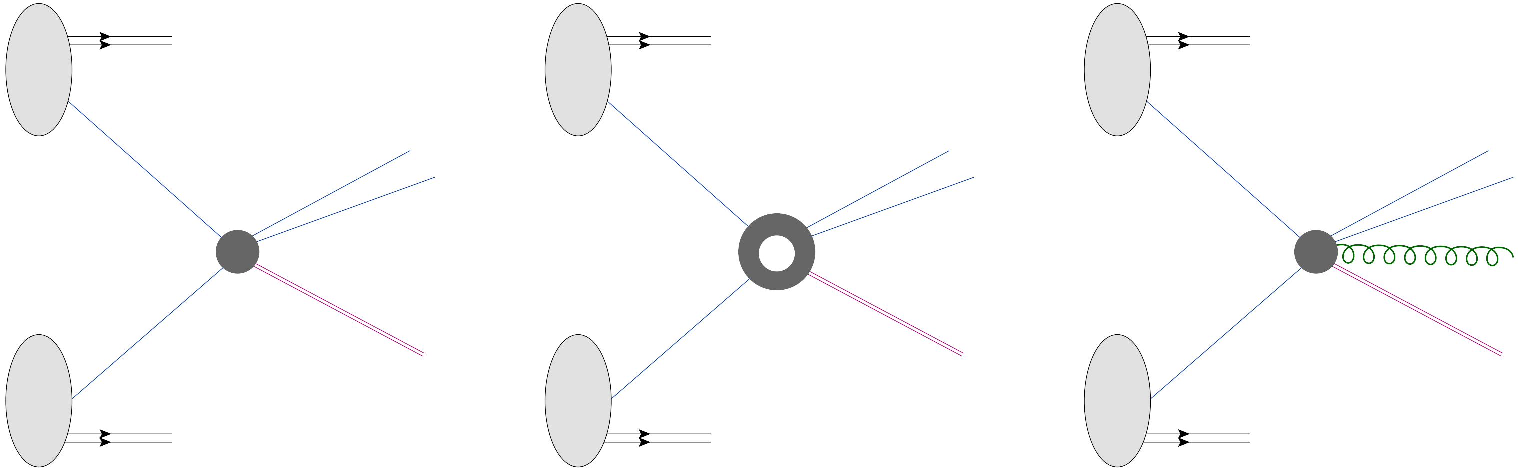
top pair production
- PIM and 1PI kinematics
- implementation and sample results

conclusions

background

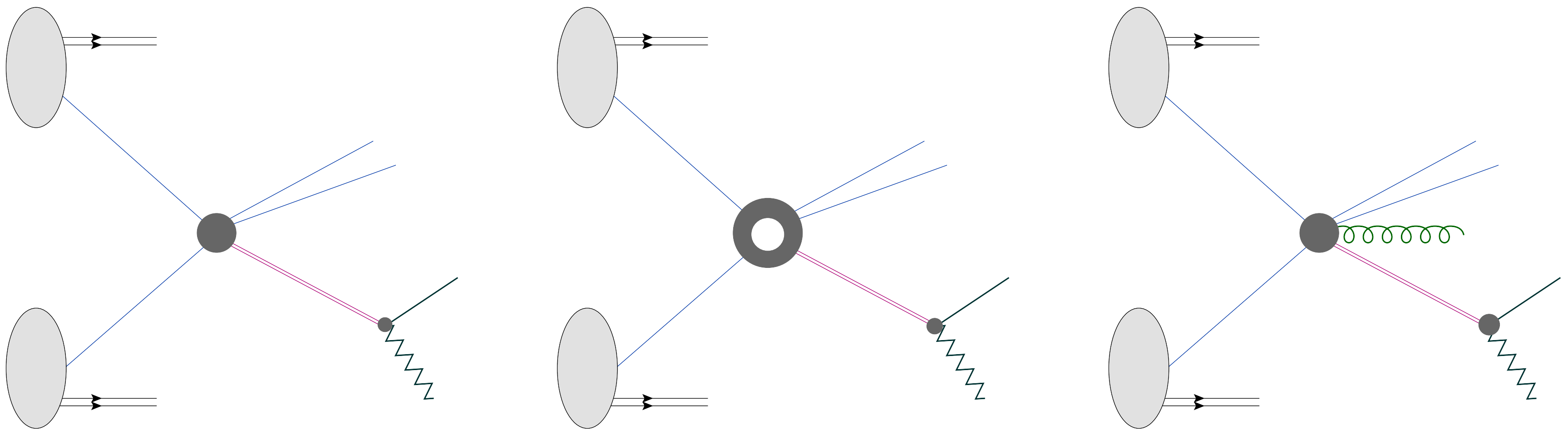
- most (all?) interesting phenomena at the LHC involve heavy unstable particles (SM: $W^\pm,\ Z,\ t,\ H$ and BSM $Z', X_{\rm susy} \ldots$)
- these particles are detected/studied through their decay products (neither the Tevatron nor the LHC has seen a single top quark!!)
- for realistic applications need to include the decay of these particles in theoretical description
- such particles are not proper external states in a QFT, but only intermediate states
- for most applications it is sufficient to ignore this and treat heavy particles as external but:
  - very precise determinations of observables (e.g. m_t) require to have full control of small effects
  - it is also an interesting problem in QFT

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

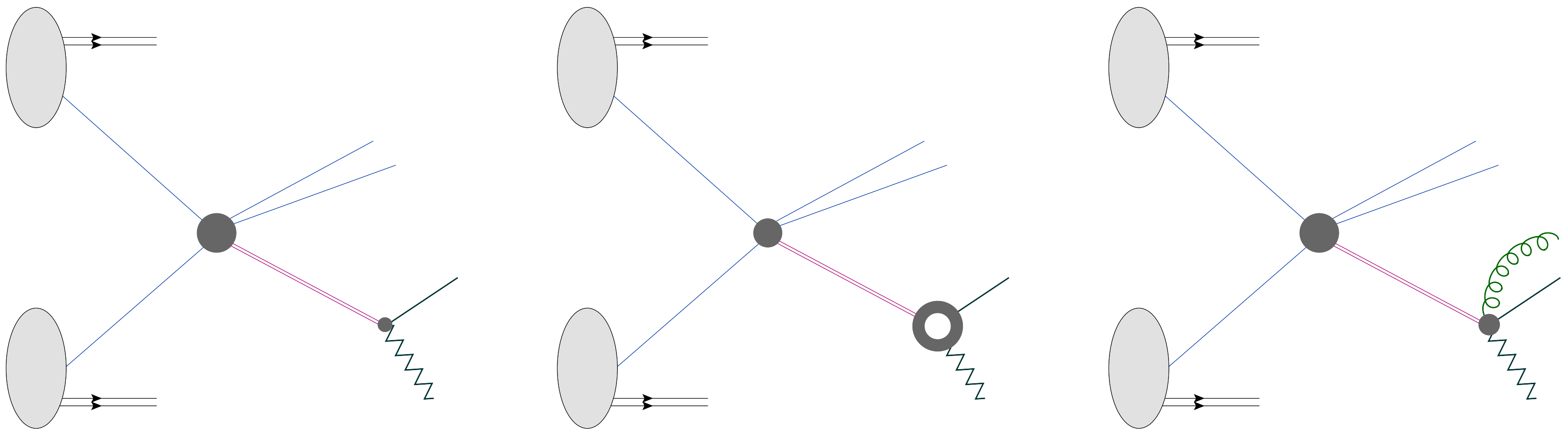
Production of an on-shell heavy (unstable) particle X, including decay: $p_X^2 = m_X^2$



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

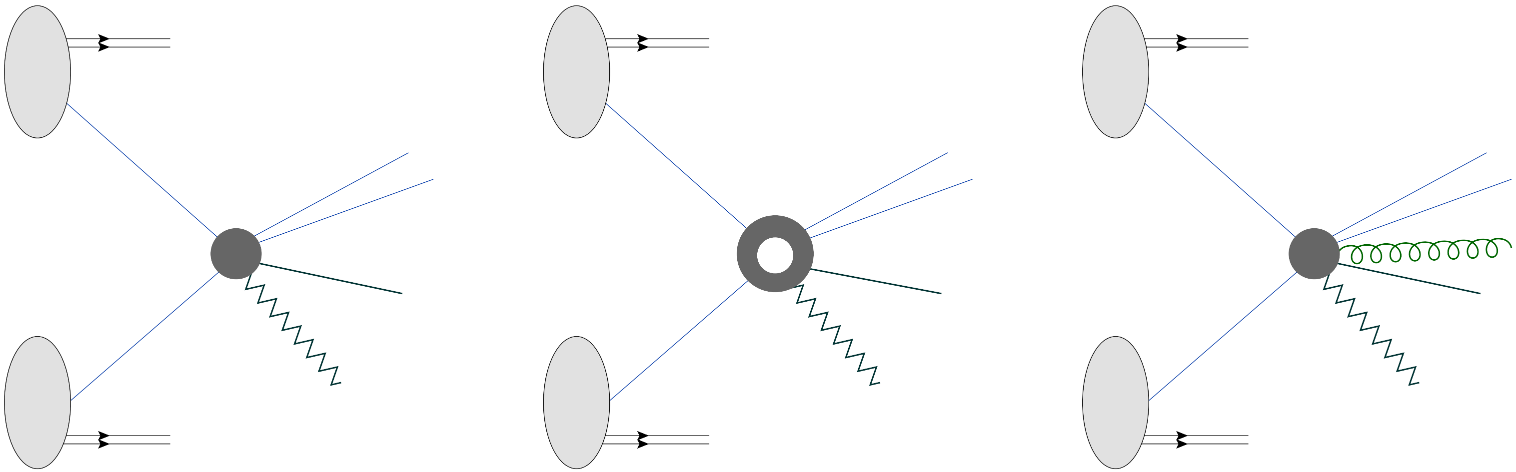
background

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



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

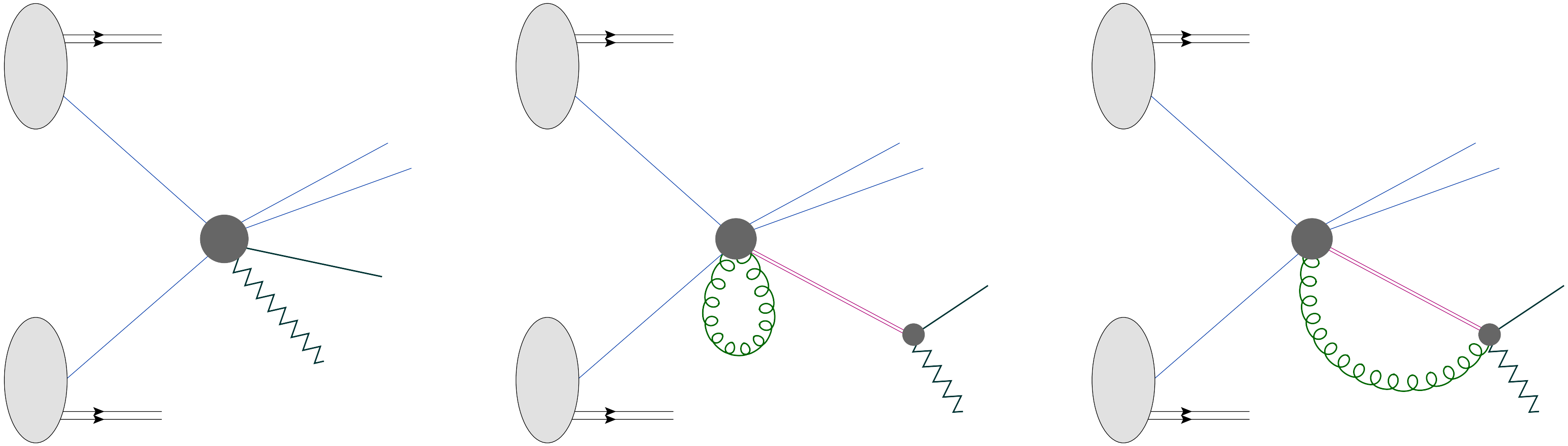
Production of an off-shell heavy (unstable) particle X, including decay: $p_X^2 \neq m_X^2$



- 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 (e.g. complex-mass scheme)

background

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
- valid for $p_X^2 \sim m_X^2$, off-shell effects of X are taken into account, calculation simplified

off-shell effects

non-factorizable corrections have been extensively studied
[Fadin et al; Melnikov et al; Beenakker et al; Denner et al; Bevilacqua 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 $\to$ non-resonant propagator unless $E \lesssim \Gamma$ is small (soft)
  - cancellations for "inclusive" observables [Fadin, Khoze, Martin]

purpose of this work (part I):

- do not neglect non-factorizable corrections
- consistently combine with propagator corrections
- try to obtain an efficient way to identify and compute minimal amount required
- do this for fully differential cross section

effective theory approach

- the feature: hierarchy of scales, exploit via effective theory (ET) approach
  - hard $k \sim m_X$
  - soft: $k \sim (p_X^2 - m_X^2)/m_X \sim \delta\, m_X \ll m_X$
- expand in all small parameters α and $\delta = (p_X^2 - m_X^2)/m_X^2 \longrightarrow$ power counting:

  $\alpha \sim \dfrac{p_X^2 - m_X^2}{m_X^2} \sim \dfrac{\Gamma_X}{m_X} \sim \delta \ll 1$ for top: $\alpha \equiv \alpha_{ew} \sim \alpha_s^2$
- integrate out hard modes: $\mathcal{L}(\phi, A, \psi) \longrightarrow \mathcal{L}_{\rm eff}(c_i, \phi_s, A_s, A_c, \psi_s, \psi_c)$
  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:
    $e^+e^- \longrightarrow t\bar{t}$ near threshold [Hoang et al; Beneke et al; Melnikov et al; ...]
    "Higgs" production in toy model [Beneke et al.]
    $e^+e^- \longrightarrow W^+W^-$ near threshold [Beneke et al.]
- arbitrary real corrections problematic (new scales from definition of observable)

method of region: an example

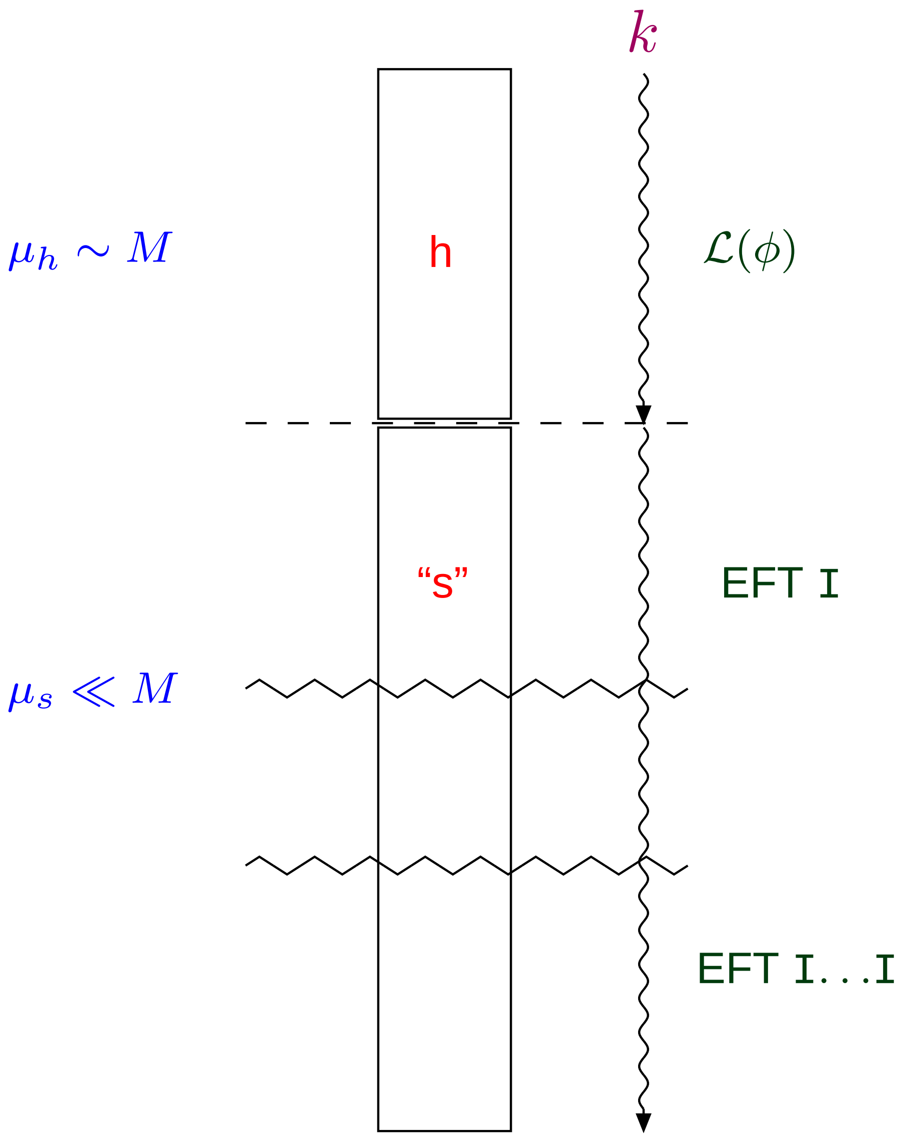
Let $p^2 \ll M^2$ and assume we want to compute (the first few terms in an expansion in $p^2/M^2 \ll 1$ of) the integral

$$\int \frac{d^d k}{(k^2 - p^2)(k^2 - M^2)}$$

$$= \underbrace{\int \frac{d^d k}{(k^2 - p^2)} \sum_n \frac{(k^2)^n}{(M^2)^{n+1}}}_{\text{soft}} + \underbrace{\int \frac{d^d k}{(k^2 - M^2)} \sum_n \frac{(p^2)^n}{(k^2)^{n+1}}}_{\text{hard}}$$

- identify modes: soft $(k \sim p)$ and hard $(k \sim M)$
  (in general there are other modes, e.g. potential, collinear . . .)
- expand integrand in each region to whatever order required
- each term has a well-defined scaling in $p^2/M^2 \;\rightarrow\;$ power counting
- no explicit cutoff needed (dimensional regularization is important)
- the soft part generates UV singularities, the hard part generates IR singularites

structure of effective theory



underlying theory

$$\mathcal{L}(\partial,\phi) = \mathcal{L}(\phi_h,\phi_s,\ldots)$$

effective theory I

$$\mathcal{L} = \sum_i c_i(h,\mu_h)\, O_i(\phi_s,\ldots,\{\mu_s\})$$

- UV divergences due to operators O_i are compensated by IR singularities in matching coefficients c_i
- anomalous dimensions of O_i $\longrightarrow$ resummation of $\ln \mu_h/\mu_s$
- outside region of validity of EFT match to underlying theory

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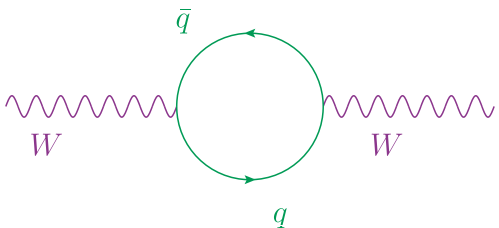
virtual corrections

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

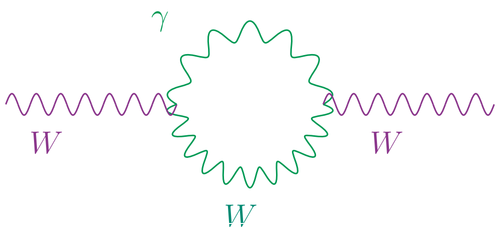
- hard corrections $\ell \sim m_X$ (= factorizable corrections)
- soft corrections $\ell \sim m_X\, \delta$ (= non-factorizable corrections)



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

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

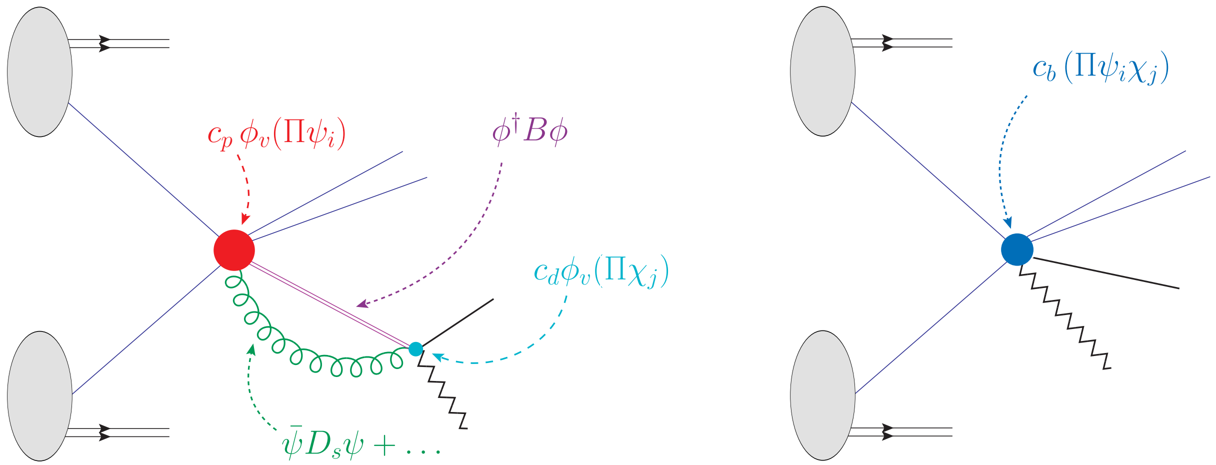
$$\mathcal{L}_{\rm eff} = 2m_X\,\phi_s^\dagger\left(iv\cdot\partial - \frac{c_{\phi\phi}}{2}\right)\phi_s + \ldots$$

- 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

structure of effective theory

integrate out hard modes $\longrightarrow$ effective Lagrangian

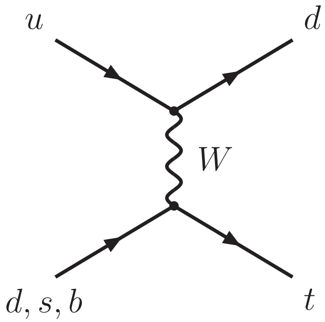
$$\mathcal{L} = \phi^\dagger B \phi + c_p\, \phi(\Pi\psi_i) + c_d \phi(\Pi\chi_j) + c_b\, (\Pi\psi_i\chi_j) + \bar{\psi} D_s \psi + \ldots$$

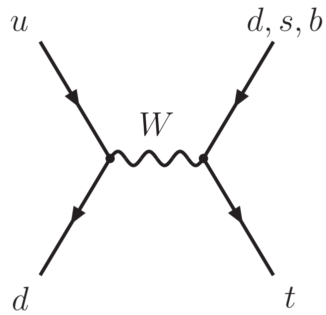


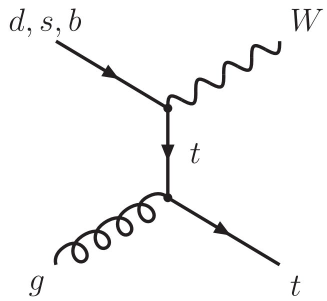
- matching coefficients c_i contain effects of hard modes
- matching done on shell, $p_X^2 = \bar{s} = m_X^2 + \mathcal{O}(\delta)$, with $\bar{s}$ the complex position of pole
- soft (and collinear . . .) d.o.f. still dynamical
- can be combined with further resummations (e.g. non-relativistic $\longrightarrow$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

single top

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.]
- full NLO calculation of $p\bar{p} \to W\,J_b\,J_q$ in complex mass scheme [Papanastasiou et al.]

- consider t channel (i.e. $p\bar{p} \to W J_b J_q$)
- final state $W (= \ell\nu)$ (treated in improved narrow-width approximation)

  require J_b and J_q, apply whatever cuts

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

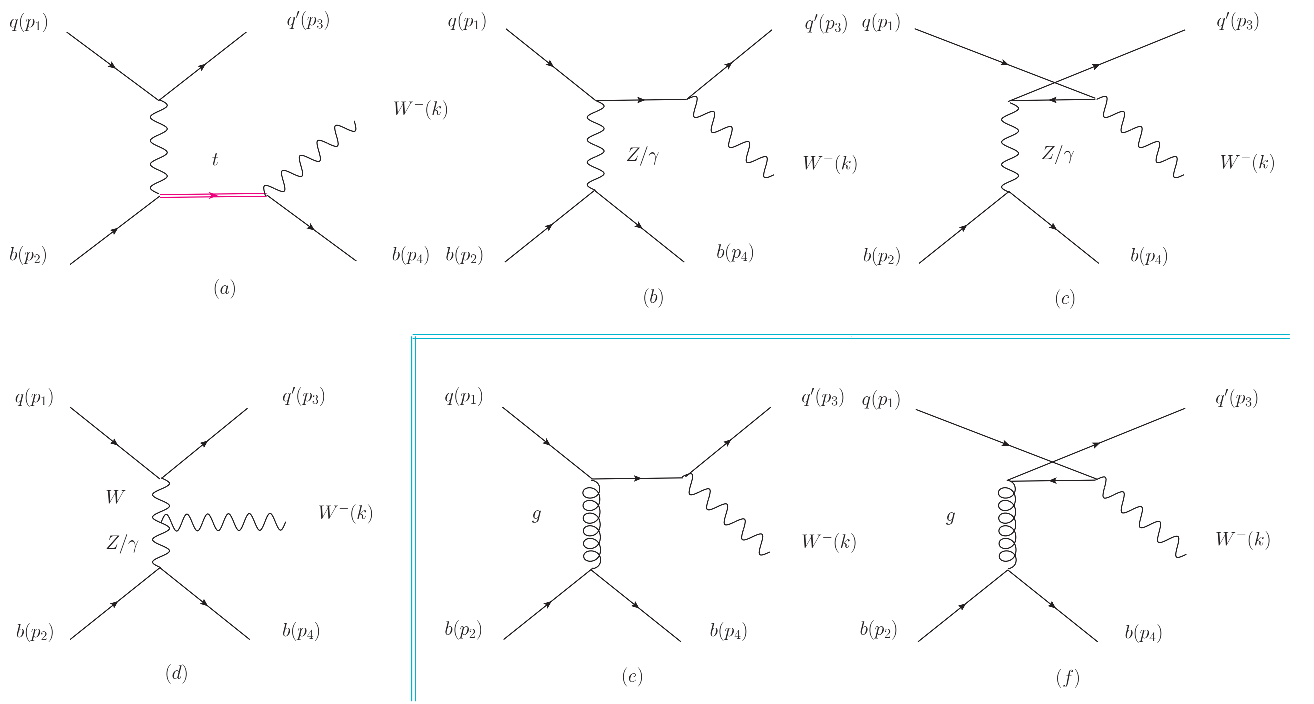
- small parameter: $\delta \sim \dfrac{s_{Wb} - m_t^2}{m_t^2} \equiv \dfrac{D}{m_t^2}$; counting: $\alpha_s^2 \sim \alpha_{ew} \sim \dfrac{\Gamma_t}{m_t} \sim \delta \ll 1$
- use 5 flavour scheme, $m_b = 0$, and “fixed” order, i.e. no parton shower etc.
- resummation of “self-energies” is resummation of hard part of two-point function in scheme X (operator $\phi^\dagger B \phi$)

$$\mathcal{L}_{\text{EFT}}^{\text{kin}} = 2\hat{m}_X\, \phi_X^\dagger \left(iv \cdot \partial - \frac{\Omega_X}{2} \right) \phi_X + \ldots$$

- matching coefficient $\Omega_X = (\bar{s} - \hat{m}_X^2)/(2\hat{m}_X)$, in pole scheme $\Omega_{\text{pole}} = -i\,\Gamma_t$ but can take any scheme X as long as $\Omega_X \sim \delta$
- propagator in ET $\dfrac{1}{s_{Wb} - m_t^2} = \dfrac{1}{D} \Rightarrow \dfrac{1}{s_{Wb} - m_t^2 + i m_t \Gamma_t} = \dfrac{1}{\Delta_t}$

single top

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

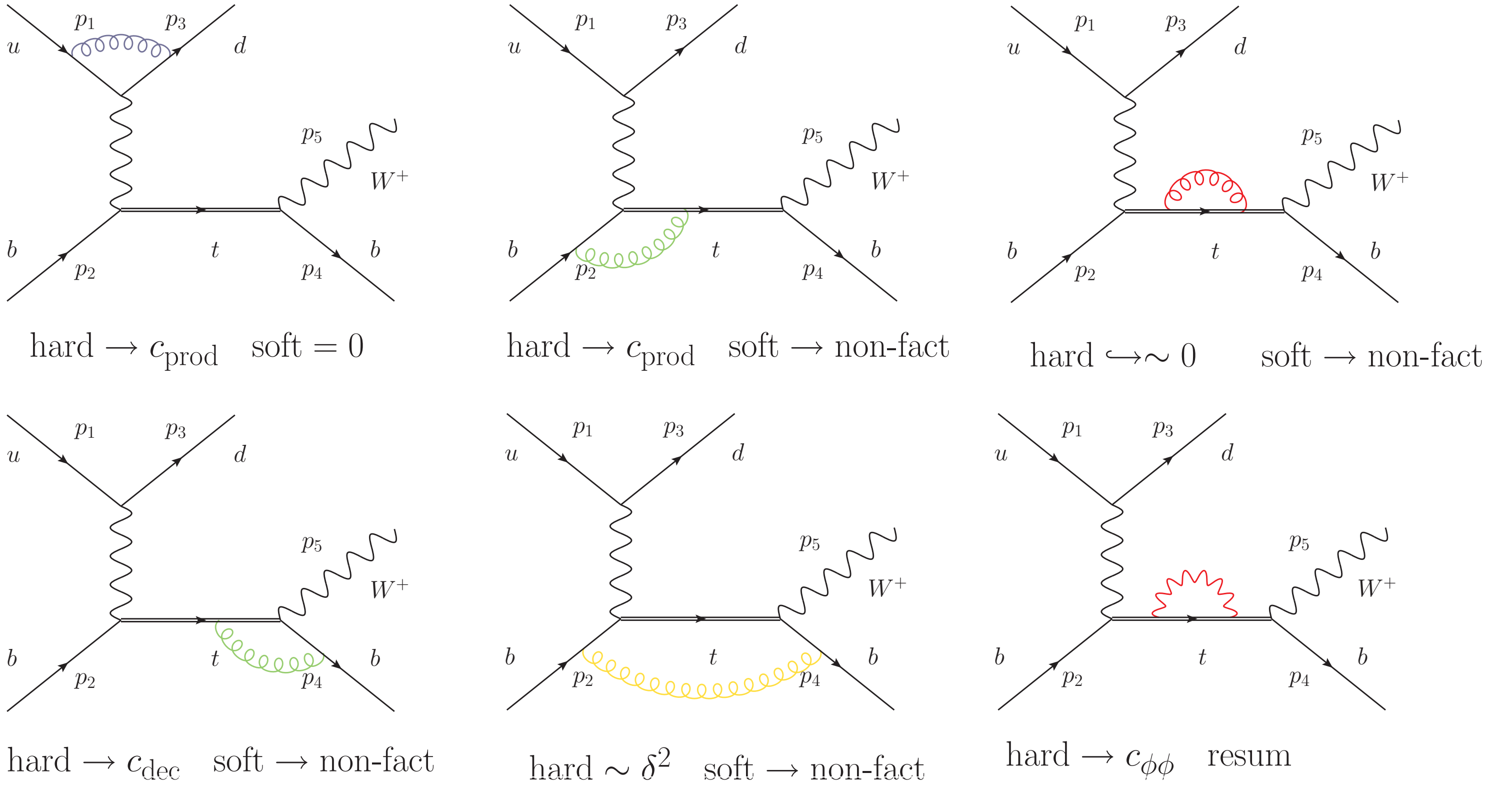


amplitude squared: (no interference due to colour $\to$ no $\delta^{3/2}$ term)

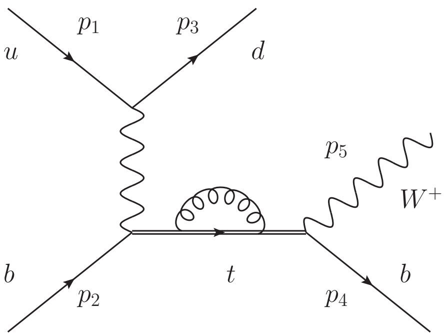
$$|M|^2 = \underbrace{g_{ew}^6\, N_c^2\, \left|A^{(3,0)}_{(-1)}\right|^2}_{\delta} + \underbrace{g_{ew}^6\, N_c^2\, 2\,{\rm Re}\left(A^{(3,0)}_{(-1)}\,[A^{(3,0)}_{(0)}]^*\right)}_{\delta^2} + \underbrace{g_{ew}^2 g_s^4\, N_c\, C_F/2 \left|A^{(1,2)}\right|^2}_{\delta^2} + \ldots$$

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)



QCD self energy



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

- 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
- can use another scheme, as long as this cancellation holds up to $\mathcal{O}(\delta)$
- soft and subleading hard part of QCD self-energy is NLO, i.e. $\mathcal{O}(\delta^{3/2})$ for $|M|^2$
- hard part of EW self-energy is leading, i.e. $\mathcal{O}(\delta^{1/2})\to$ resum

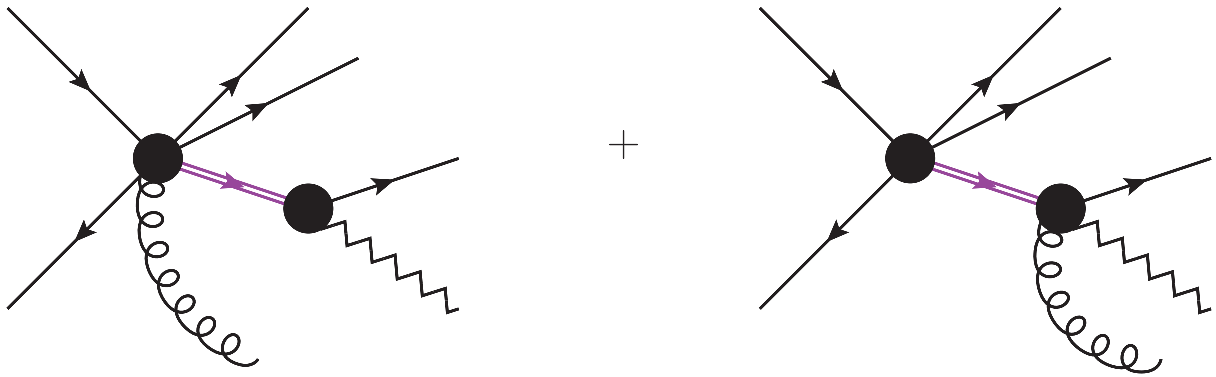
real corrections

- real corrections for “arbitrary” differential cross section cannot be done in a strict ET approach
- it is not even clear what the proper expansion parameter is (where is the gluon attached?)
- ET relies on the fact that all scales are explicit, but observable can introduce new small scale $\longrightarrow$ change of structure of ET
- aim: compute real corrections for “arbitrary” observable with the implicit assumption no new small scale is introduced (e.g. for a p_t distribution result is unreliable for small p_t)
- if there is a new small scale $\longrightarrow$ large logs $\longrightarrow$ resummation $\longrightarrow$ requires dedicated ET (or other) calculation
- expand real amplitude in δ and α under the assumption that there is no further small scale (compare to parton showers)

$$\mathcal{A}_{\rm real} = \mathcal{A}^{g}_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^{0}_{\rm dec} + \mathcal{A}^{0}_{\rm prod} \otimes \mathcal{P} \otimes \mathcal{A}^{g}_{\rm dec}$$

- the restriction to no new small scales is generic for fixed-order calculations

real corrections



$$\mathcal{A}^{g}_{\mathrm{prod}} \otimes \mathcal{P} \otimes \mathcal{A}^{0}_{\mathrm{dec}} \quad + \quad \mathcal{A}^{0}_{\mathrm{prod}} \otimes \mathcal{P} \otimes \mathcal{A}^{g}_{\mathrm{dec}}$$

corrections to production (soft and coll singularities):

$\int d\Phi_{n+1} \left| \mathcal{A}^{g}_{\mathrm{prod}} \otimes \mathcal{P} \otimes \mathcal{A}^{0}_{\mathrm{dec}} \right|^2$ combined with (hard) Wilson coeff. for production is IR finite

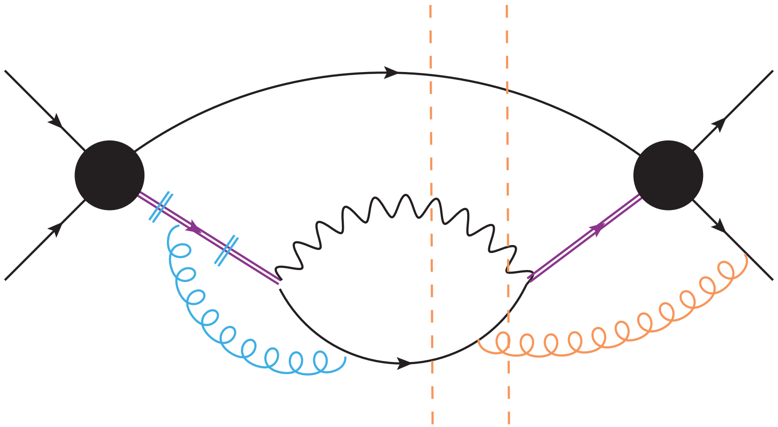
corrections to decay (soft and coll singularities):

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

non-factorizable corrections (soft singularities only):

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

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, $m_t/4 \le \mu \le m_t$

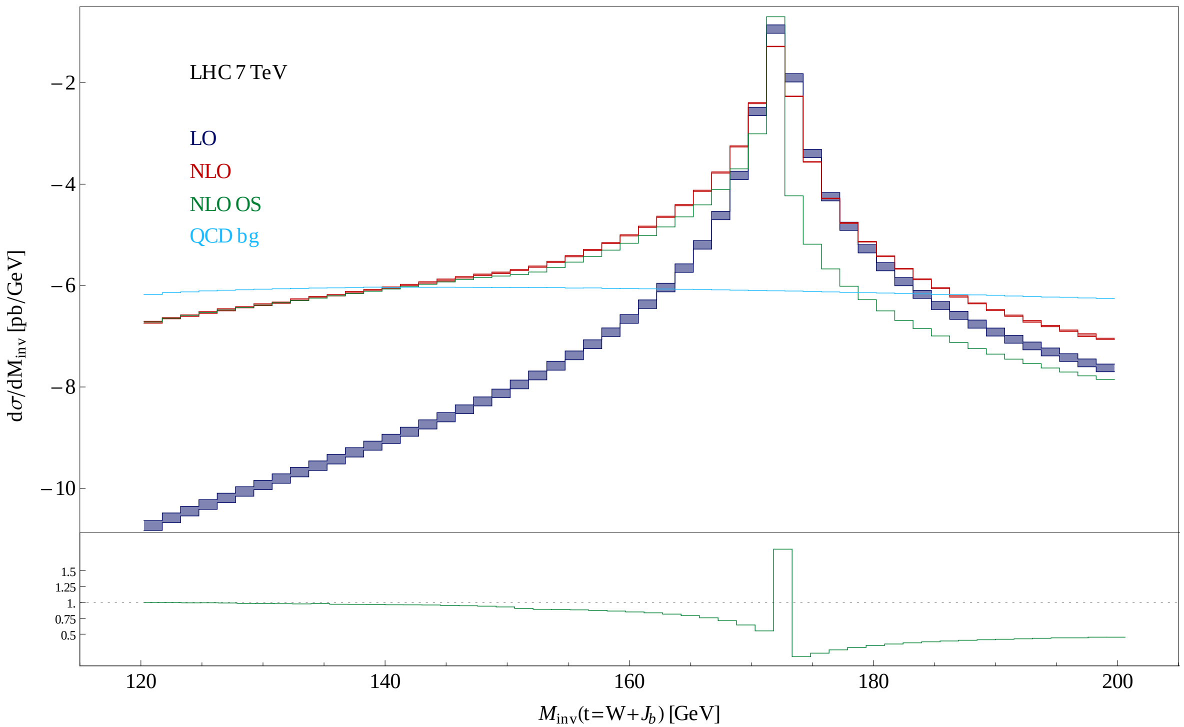
define jets: $k_\perp$ cluster algorithm $\Rightarrow$ cuts on $p_\perp(J_b)$, $p_\perp(J_q)$, $\not{E}_\perp$, $p_\perp(\ell)$

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

invariant mass of 'top'

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

effects large around the peak, but small for observables inclusive enough in $M_{\rm inv}$



7 TeV LHC ’t’-channel:

$m_t = 171.3$ GeV, MSTW 2008 NLO pdf, $m_t/4 \le \mu \le m_t$

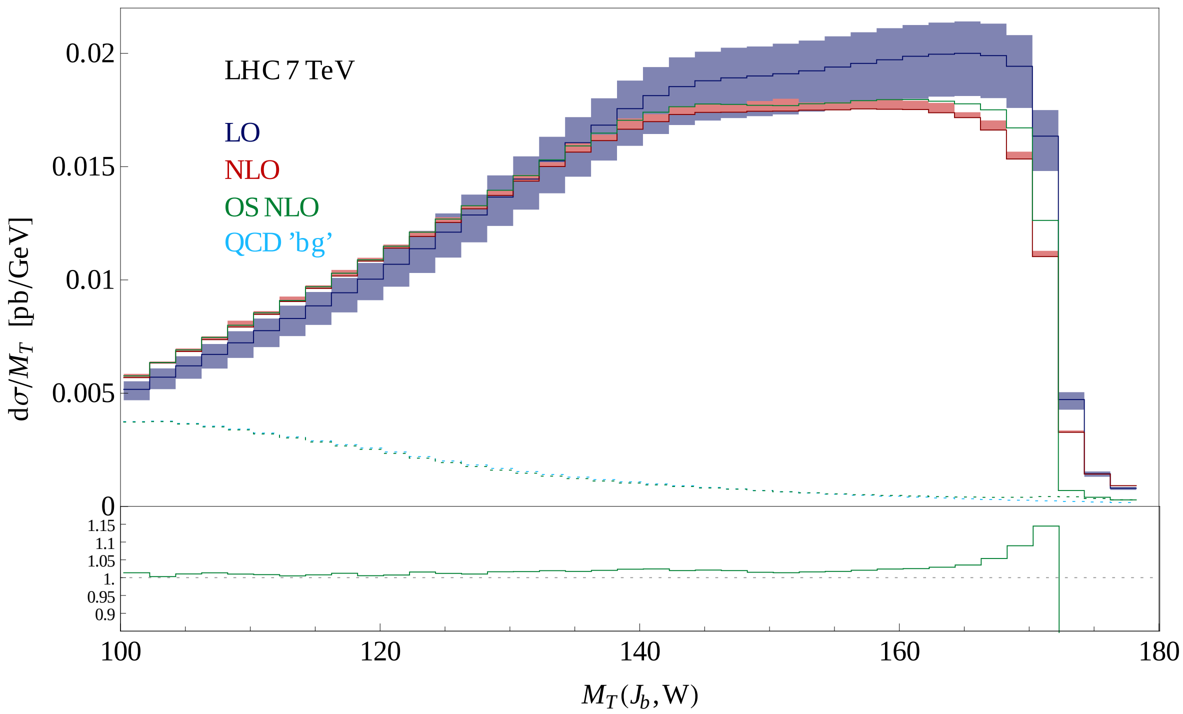
define jets: $k_\perp$ cluster algorithm $\Rightarrow$ cuts on $p_\perp(J_b)$, $p_\perp(J_q)$, $\not{E}_\perp$, $p_\perp(\ell)$

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

transverse mass of ’top’

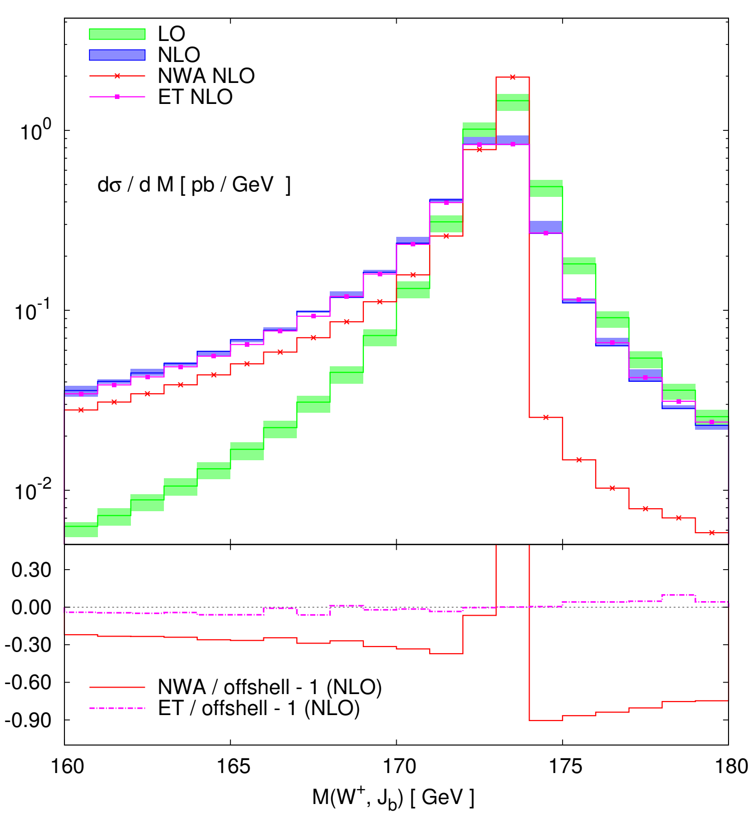
$$M_T^2 = (\sum E_T)^2 - (\sum \vec{p}_T)^2$$

effects tiny except at edges of distributions

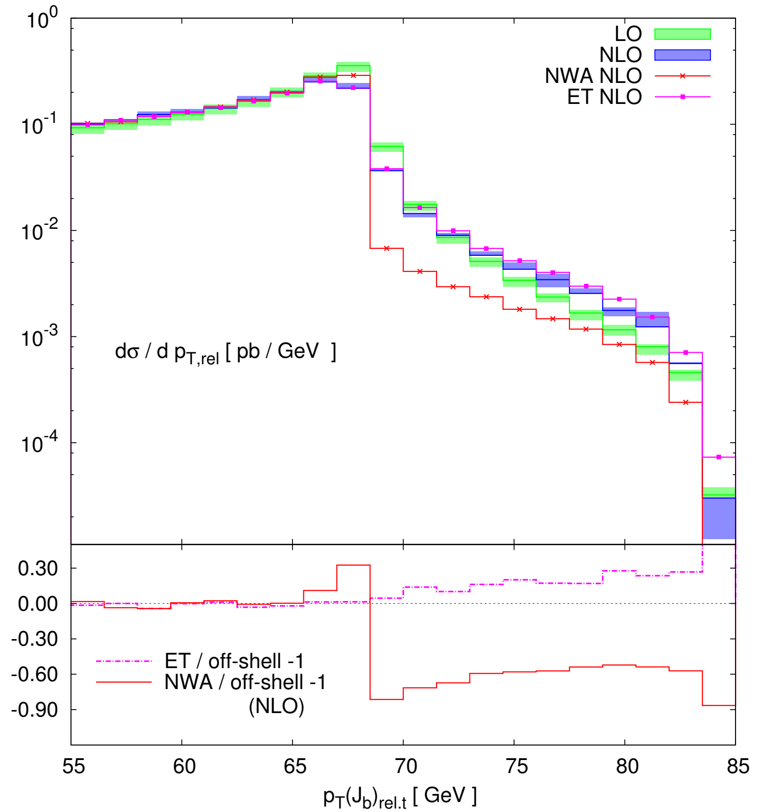


comparison EFT approch vs complex mass scheme calculation $\Rightarrow$ good agreement
[Papanastasiou et al. 1305.7088]

invariant mass



relative transverse b-jet momentum



SM $t\,\bar{t}$ theory status

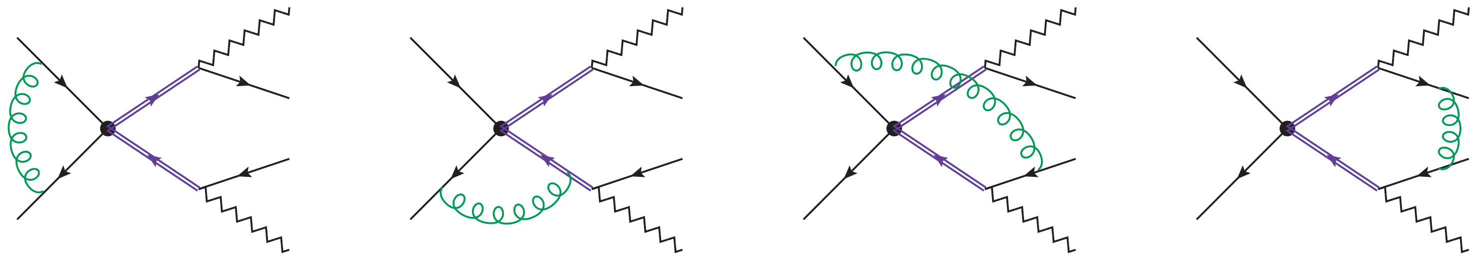
- fully exclusive known at $\sim$ one-loop

  electroweak corrections known [Bernreuther et al., Kuhn et al.]
  spin correlations included [Bernreuther et al., Melnikov et al.]
  full one-loop $2 \longrightarrow 4$ computed [Denner et al., Bevilacqua et al.]
  included in MC@NLO and POWHEG [Frixione, Nason, Webber . . . . . .]
  two-loop corrections on their way . . .

- inclusive cross section(s) known at $\sim$ two-loop

  two-loop known [Czakon et al.]
  bound-state effects computed [Hagiwara et al., Kiyo et al.]
  non-factorizable corrections computed [Beenakker et al.]
  resummation of logs under control [Ahrens et al, Beneke et al . . .]

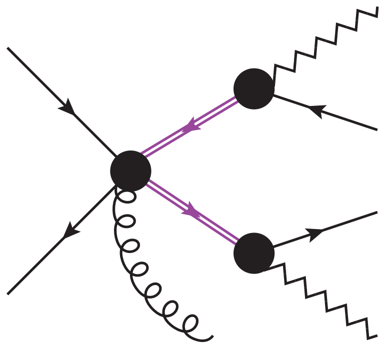
virtual correction $q\bar{q} \to W^+\bar{b}W^-b$



hard only | hard and soft | soft only | soft only

- hard parts $\Rightarrow$ matching coefficients
- soft parts $\Rightarrow$ explicit diagrams in ET
- integrals with more than 4 legs only needed in soft approximation
- hard integrals: $\left(\frac{\mu^2}{s}\right)^\epsilon$ $\Rightarrow$ hard scale
- soft integrals: $\left(\frac{\mu^2}{\Delta_t\, m_t}\right)^\epsilon$ $\Rightarrow$ soft scale

top pair production: structure of real amplitude



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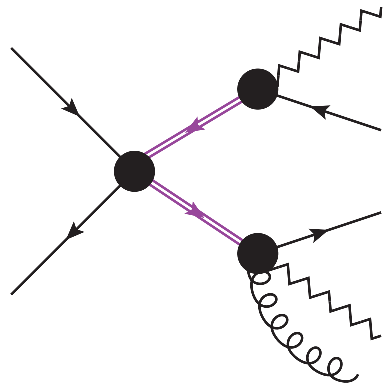

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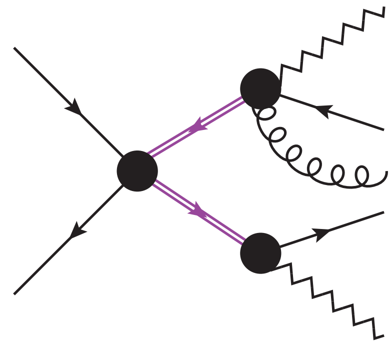


$$\mathcal{A}^g_{\text{prod}} \otimes \mathcal{P}_t \otimes \mathcal{P}_{\bar{t}} \otimes \mathcal{A}^0_t \otimes \mathcal{A}^0_{\bar{t}} \quad + \quad \mathcal{A}^0_{\text{prod}} \otimes \mathcal{P}_t \otimes \mathcal{P}_{\bar{t}} \otimes \mathcal{A}^g_t \otimes \mathcal{A}^0_{\bar{t}} \quad + \quad \mathcal{A}^0_{\text{prod}} \otimes \mathcal{P}_t \otimes \mathcal{P}_{\bar{t}} \otimes \mathcal{A}^0_t \otimes \mathcal{A}^g_{\bar{t}}$$

corrections to production

$$\int d\Phi_{n+1} \left| \mathcal{A}^g_{\text{prod}} \otimes \mathcal{P}_t \otimes \mathcal{A}^0_t \otimes \mathcal{P}_{\bar{t}} \otimes \mathcal{A}^0_{\bar{t}} \right|^2$$ (finite if combined with virtual corr. to production)

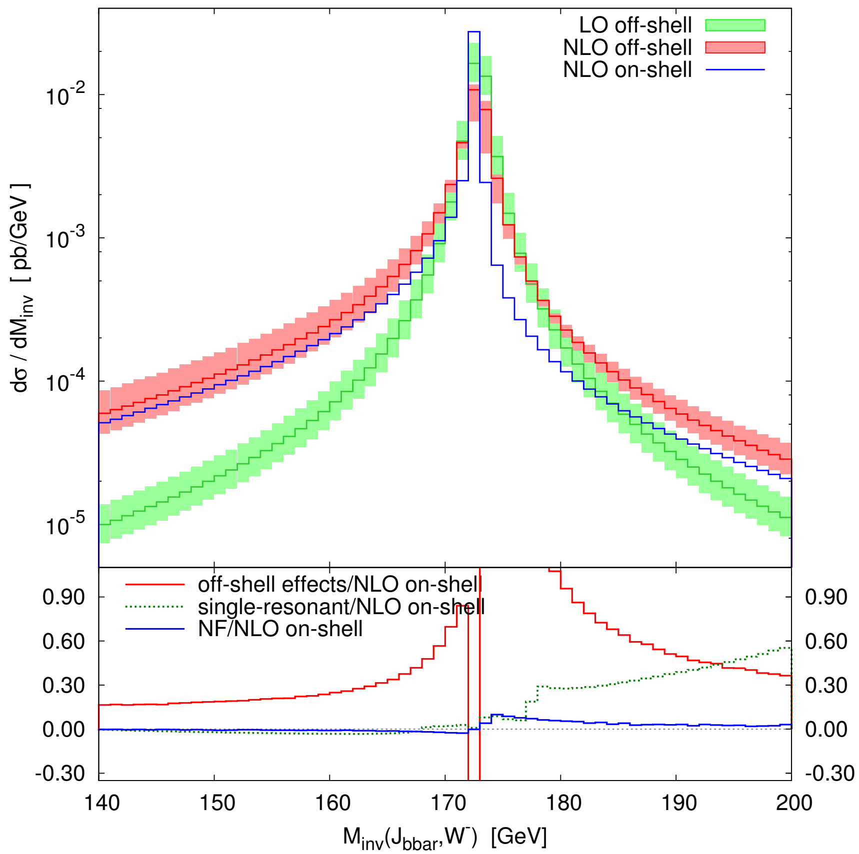
and corrections to decay

$$\int d\Phi_{n+1} \left| \mathcal{A}^0_{\text{prod}} \otimes \mathcal{P}_t \otimes \mathcal{A}^g_t \otimes \mathcal{P}_{\bar{t}} \otimes \mathcal{A}^0_{\bar{t}} \right|^2$$ (finite if combined with virtual corr. to top decay)

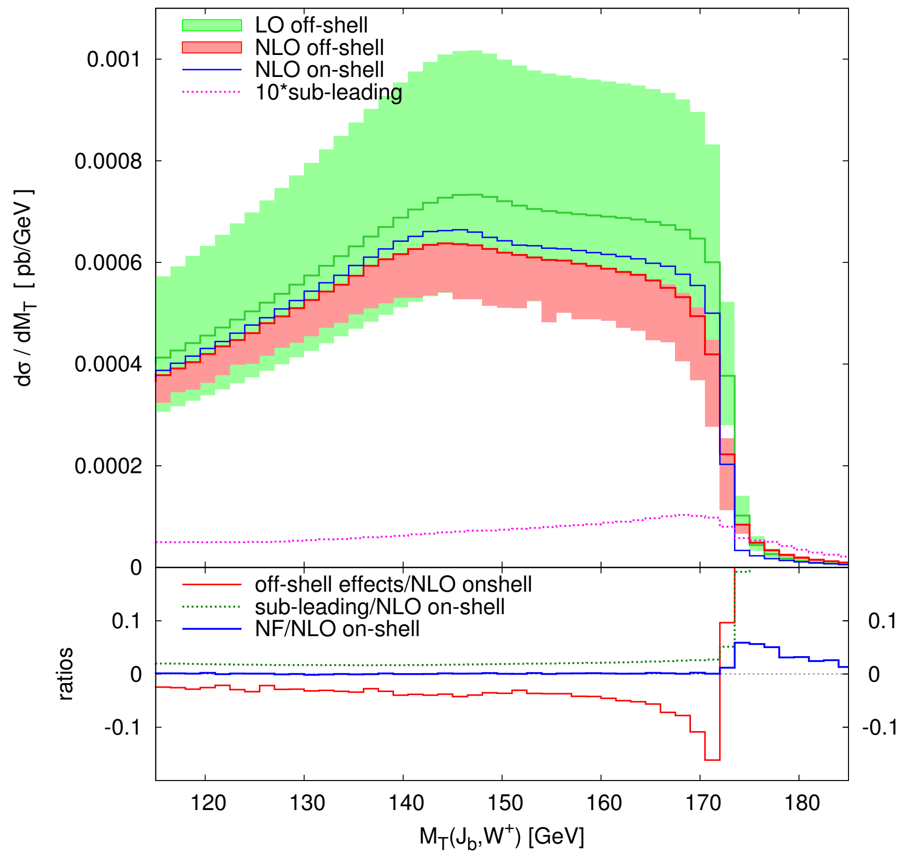
routinely taken into account [Bernreuther et al; Melnikov et al; Campbell et al;]

real interference contributions combined with soft virtual corrections are separately IR finite generally small, but study e.g. impact on m_t measurement [Falgari, Papanastasiou, AS] sample results for Tevatron, $q\bar{q} \to t\bar{t}$ only

invariant mass of 'top'



transverse mass of 'top'



again, effects small except at kinematic boundaries

extraction of top mass from invariant mass

- consider mass scheme different from pole mass m_t
  - check scheme dependence
  - avoid infrared sensitivity of pole mass (renormalons)
- many possible choices
- example used here: potential subtracted mass $m_{\rm PS}$ [Beneke]

$$m_{\rm PS}(\mu_{\rm PS}) = m_t + \frac{1}{2}\int\limits_{q<\mu_{\rm PS}} \frac{d^3\vec{q}}{(2\pi)^3} V_{\rm coul}(q) \quad \text{with} \quad \mu_{\rm PS} \sim m\,\alpha_s \sim \delta^{1/2}$$

- express everything in terms of $m_{\rm PS}$

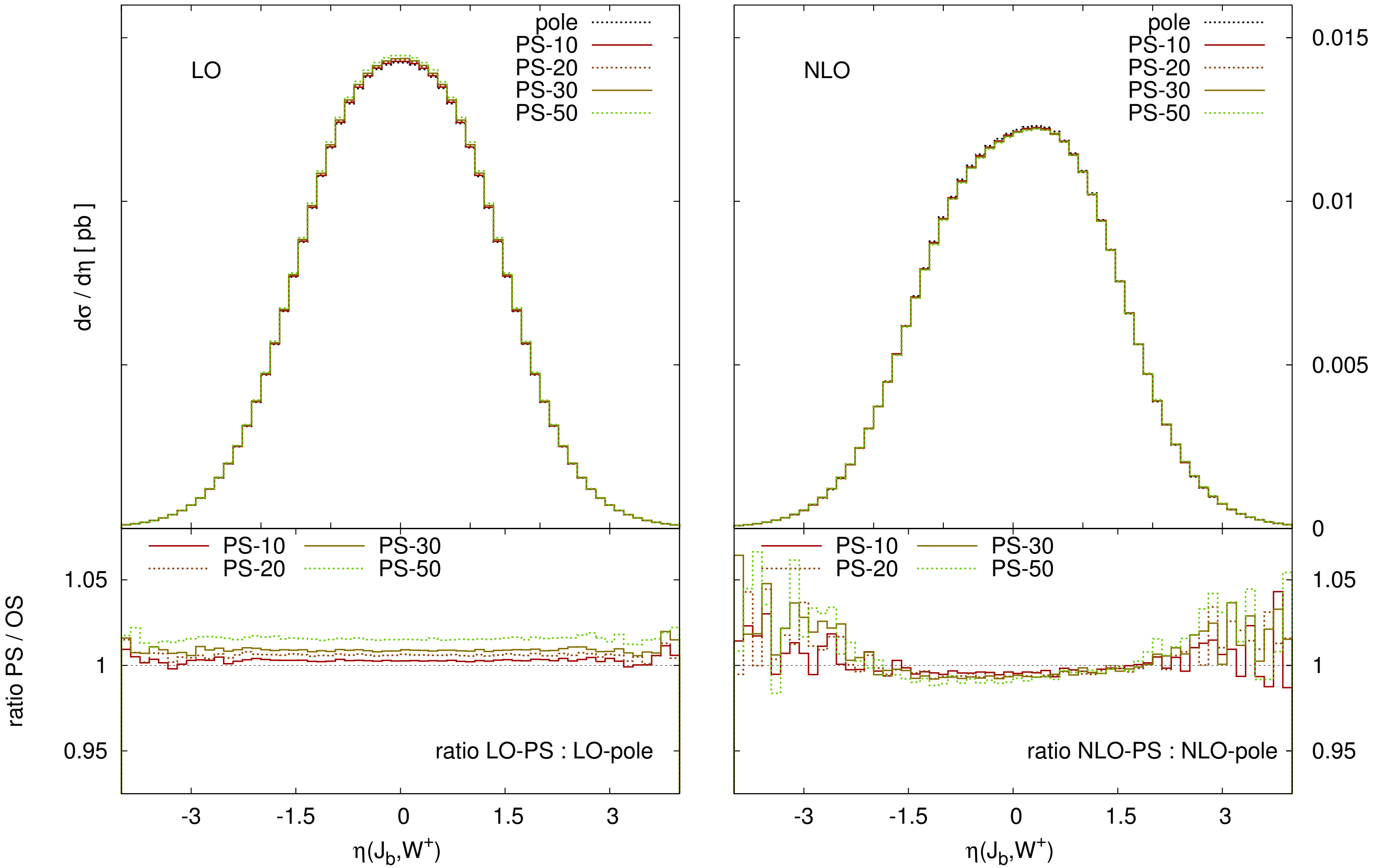
$$m_t = m_{\rm PS}(\mu_{\rm PS}) + \mu_{\rm PS}\left[\frac{\alpha_s}{2\pi}\delta_1 + \frac{\alpha_s^2}{(2\pi)^2}\delta_2 + \dots\right]$$

- (inverse of) propagator:

$$\underbrace{p^2 - m_{\rm PS}^2 + i m_{\rm PS}\Gamma}_{\sim\delta} - \underbrace{\frac{\alpha_s}{\pi}\,\delta_1 \mu_{\rm PS}\, m_{\rm PS}}_{\sim\delta} - \underbrace{\frac{\alpha_s^2}{2\pi^2}\,\delta_2 \mu_{\rm PS}\, m_{\rm PS}}_{\sim\delta^{3/2}} + \dots$$

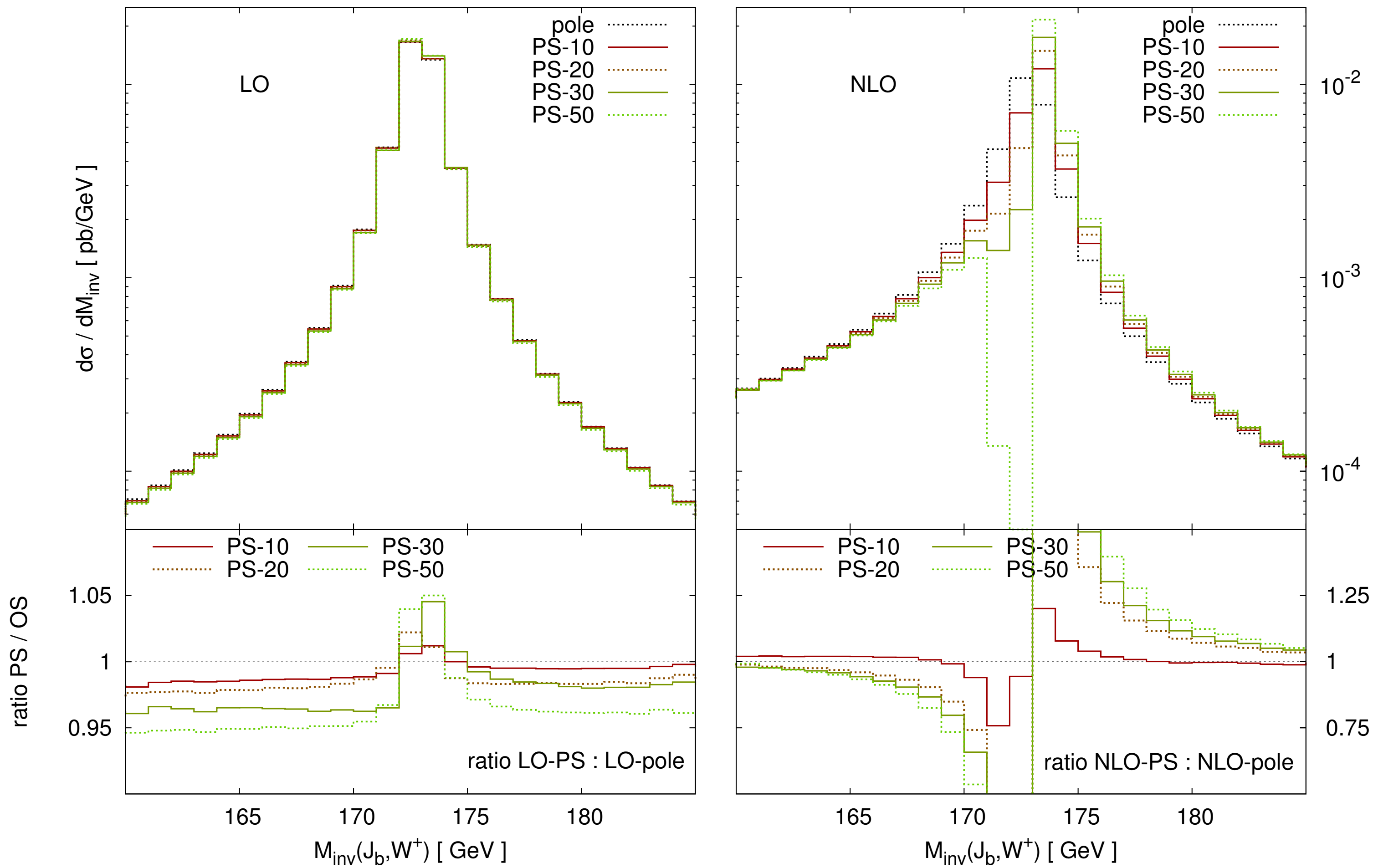
results in PS scheme $\mu_{\rm PS} \in \{0, 10, 20, 30, 50\}$ GeV

example of non-sensitive observable (pseudo-rapidity of ’top’)



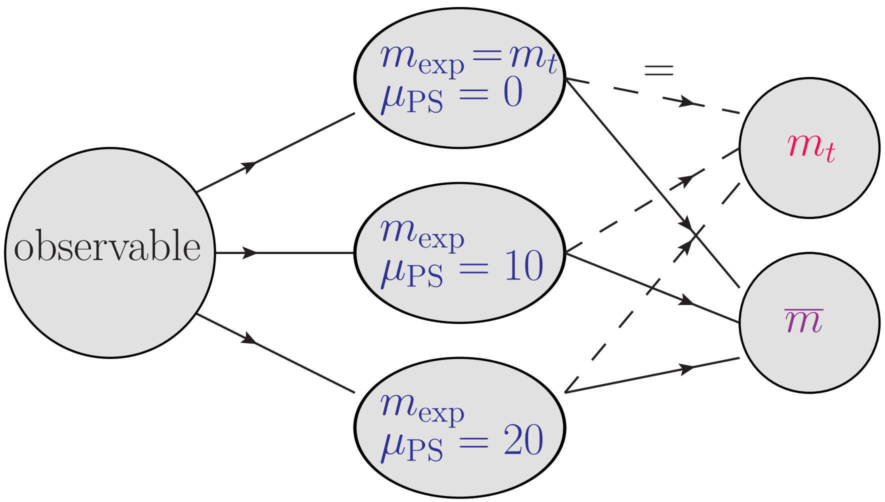
results in PS scheme $\mu_{\rm PS} \in \{0, 10, 20, 30, 50\}$ GeV

example of sensitive observable (invariant mass of 'top') $\Rightarrow \mu_{\rm PS} \lesssim 20$ GeV



consider scheme dependence of mass extraction

μ_{PS}	LO m_{exp}	LO $\overline{m}$	LO m_t	NLO m_{exp}	NLO $\overline{m}$	NLO m_t
0	172.9	162.2	172.9	172.9	162.2	172.9
10	172.4	162.7	173.5	172.2	162.4	173.3
20	172.0	163.0	173.8	171.5	162.5	173.4



- conversion at NNNLO [Melnikov, Ritbergen] (+ Pade approximation)
- scheme ambiguity $\sim 500 - 900$ MeV at LO
- scheme ambiguity $\sim 400 - 500$ MeV at NLO
- $\overline{\text{MS}}$ scheme somewhat more stable

Part II: approximate NNLO for fully differential $t\bar{t}$ production, including decay

- NNLL renormalization-group improved calculations for total cross section, $d\sigma/(dM_{t\bar{t}}\, d\cos\theta)$ and $d\sigma/(dp_T\, dy)$ available [Kidonakis et al, Ahrens et al. . . .]
- resummation can reproduce dominant (??) terms of fixed-order approach
- generalize resummed cross section to include decay of top quarks
- obtain approximate NNLO corrections to the production part of $q\bar{q} \to t\bar{t} \to W^+ b\, W^- \bar{b}$ and $gg \to t\bar{t} \to W^+ b\, W^- \bar{b}$ through expansion of resummed results
- implement these and match to fixed-order NLO to obtain 'improved' weight for parton-level Monte Carlo

$$d\sigma^{\text{approx NNLO}} = d\sigma^{\text{NLO}} + \alpha_s^2\, d\sigma_2^{\text{resum}}$$

- not a strict approach, not a unique approach
  attempt to include most important features of fully differential NNLO corrections

approx NNLO

pair-invariant mass (PIM) kinematics

- $h_1(P_1)\, h_2(P_2) \to (t+\bar{t})(p_3+p_4) + X(p_X)$
- soft limit $z = (p_3+p_4)^2/\hat{s} \to 1$
- factorization of cross section [Ahrens et al.]

$$\frac{d\sigma}{dM_{t\bar{t}}\, d\cos\theta} \simeq \sum_{ij} \int \frac{dz}{z} \int \frac{dx}{x} f_{i/h_1}(x) f_{j/h_2}(\tau/(zx)) \left(\mathrm{Tr}\left[\mathbf{H_{ij}} \cdot \mathbf{S_{ij}}\right] + \mathcal{O}(1-z) \right)$$

- plus distribution $P_n(z) = \left[\frac{\ln^n(1-z)}{1-z}\right]_+$

one-particle inclusive (1PI) kinematics

- $h_1(P_1)\, h_2(P_2) \to t(p_3) + (\bar{t}+X)(p_4+p_X)$
- soft limit $s_4 = (p_4+p_X)^2 - m_t^2 \to 0$
- factorization of cross section [Ahrens et al.]

$$\frac{d\sigma}{dp_T\, dy} \simeq \sum_{ij} \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} f_{i/h_1}(x_1) f_{j/h_2}(x_2) \left(\mathrm{Tr}\left[\mathbf{H_{ij}} \cdot \mathbf{S_{ij}}\right] + \mathcal{O}(s_4) \right)$$

- plus distribution $P_n(s_4) = \left[\frac{1}{s_4} \ln^n\left(\frac{s_4}{m_t^2}\right)\right]_+$

approx NNLO

parton-level Monte Carlo, including top decay

- compute modified hard function including top decay (in narrow-width approximation)
- soft functions and structure of renormalization group equations not affected
- obtain approximate NLO (for consistency checks only) and NNLO corrections by expansion in $\alpha_s \to$ coefficients of plus distributions
- e.g. for PIM @ NNLL $\to$ NNLO:

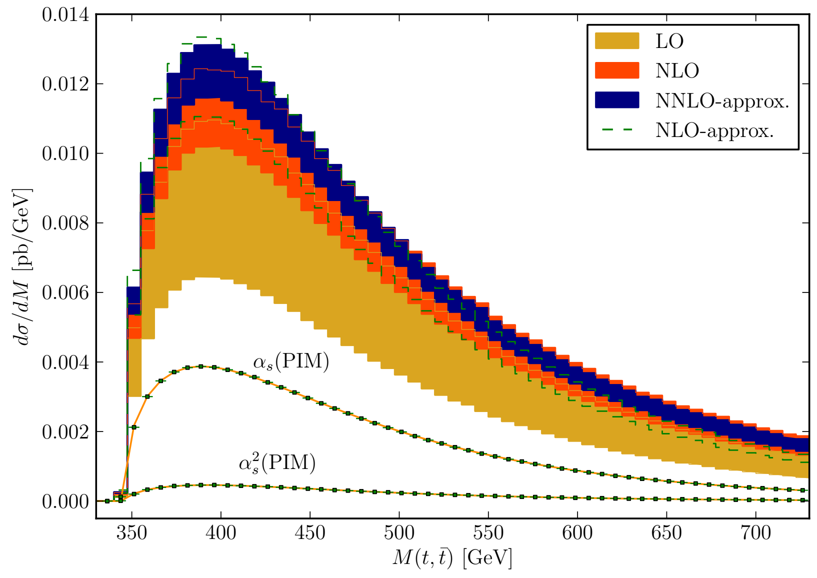
$$\left[\mathbf{H_{ij}} \cdot \mathbf{S_{ij}}\right] \sim D_3\, P_3(z) + D_2\, P_2(z) + D_1\, P_1(z) + D_0\, P_0(z) + C_0\, \delta(1-z) + R(z)$$

- restore dependence on final-state particles $\to$ weight of events in Monte Carlo

$$D_i(M_{t\bar{t}}, \cos\theta) \to \; D_i(\{p_i\})$$

- different resummation (PIM and 1PI) and different implementations due to treatment of subleading terms (e.g. in phase-space integration)
- take scale variation and variation over various implementations for estimate of theory error (take known NNLO total cross section as cross check of procedure)

approx NNLO, cross checks, LHC 8TeV



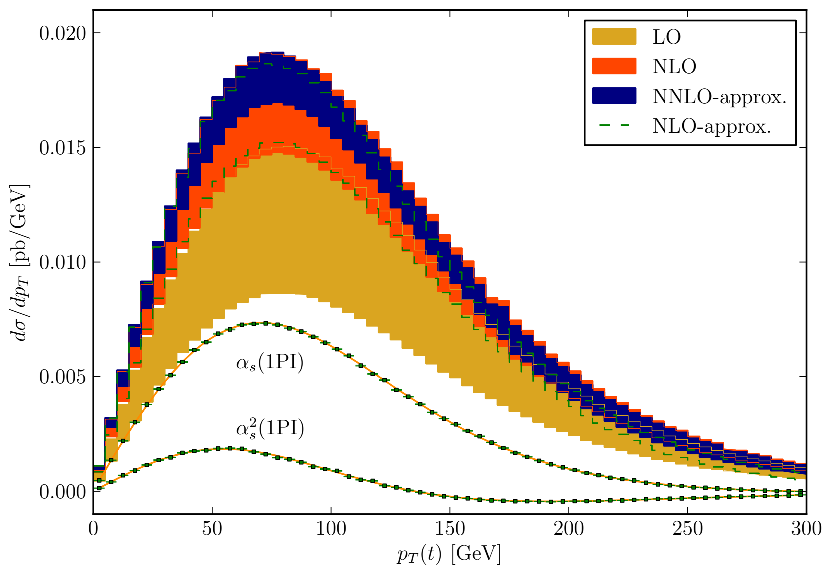
compare $M_{t\bar{t}}$ with [Ahrens et al.]

cluster final state partons into jets

reconstruct top $t \doteq J_b + \ell + \nu$

here: no cuts whatsoever

recover total cross section



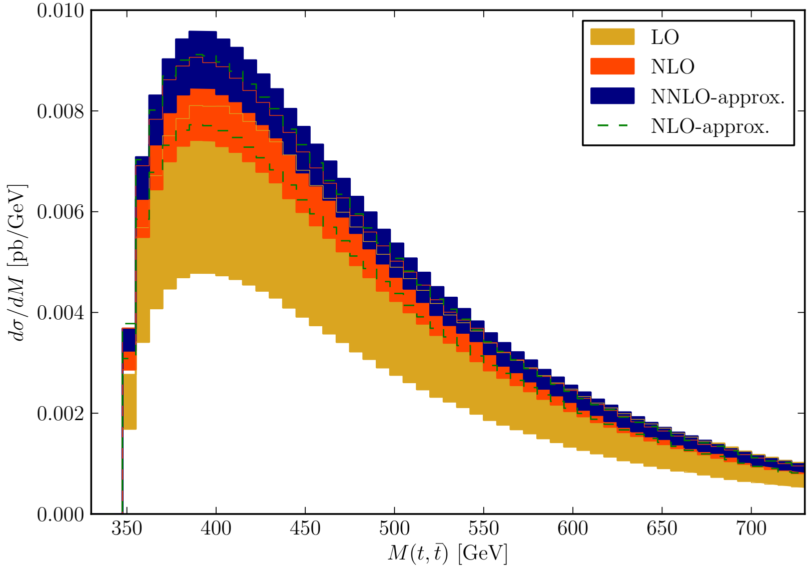
compare $p_T(t)$ with [Ahrens et al.]

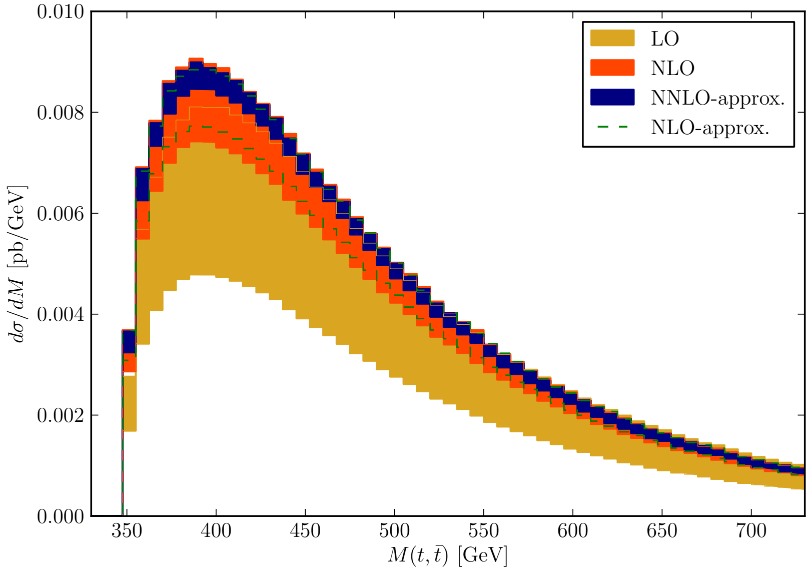
stable perturbative behaviour

pdf: mstw08nlo (!)

theory error band: envelope of scale variation and phase-space implementations

realistic $M_{t\bar{t}}$ distribution with (standard) cuts





cluster final state partons into jets

reconstruct top $t \doteq J_b + \ell + \nu$

apply (whatever) cuts

compute $M_{t\bar{t}}$ distribution

note: no improvement in treatment of decay (strict NLO)

theory error band: $\{$1PI, PIM$\}_{\rm impl}$

less conservative error estimate:

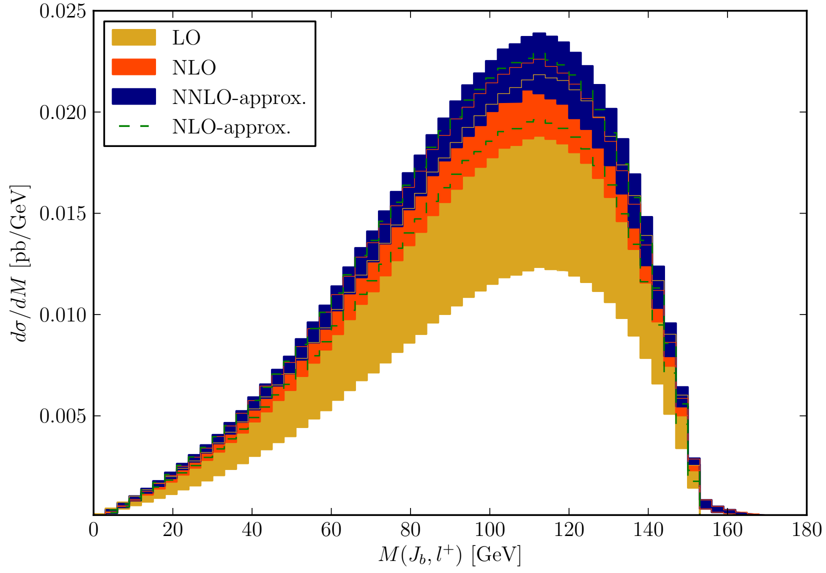
theory error band: $\{$1PI, PIM$\}$

“wrong” resummation (1PI) gives remarkably consistent results with “correct” resummation (PIM)

pdf: mstw08nlo (!)

approx NNLO

'go crazy' and compute other distributions with realistic cuts, e.g. $M(J_b, \ell^+)$



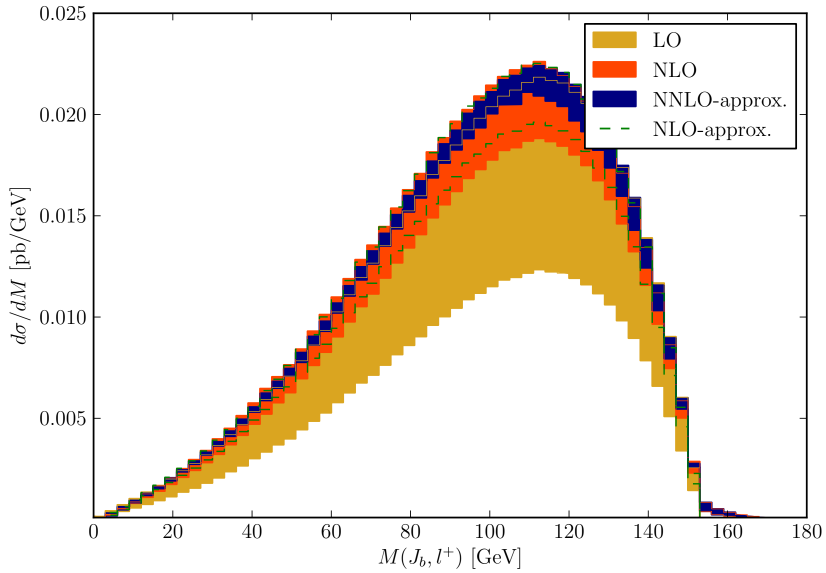
apply (whatever) cuts

compute $M(J_b, \ell^+)$ @ approx NNLO

note: no improvement in treatment of decay (strict NLO)

pdf: mstw08nlo (!), approx NNLO band is lower for mstw08nnlo

theory error band: $\{$1PI, PIM$\}_{\rm impl}$



less conservative error estimate:

theory error band: $\{$1PI, PIM$\}$

both resummations (1PI) and (PIM) give remarkably consistent results

- include off-shell effects at NLO for unstable particles using ET inspired approach
  - amounts to inclusion of non-factorizable (= soft) corrections (and all spin correlation effects)
  - combined with “standard” (= hard) corrections for production and decay
- applicable to unstable fermions, gauge bosons and scalars
- example single top:
  - off-shell effects $\mathcal{O}(\alpha_s\,\delta)$ are small $1-2\%$ for most observables
  - can be larger at kinematic end points
  - excellent agreement between ET and complex mass scheme calculations
- example top pair production:
  - off-shell effects small except for kinematic edges
  - impact on m_t determination needs to be under control for $\delta m_t/m_t < 1\%$
- approximate NNLO for fully differential top pair cross section, including the decay
  - PIM and 1PI implemented in fully differential parton-level Monte Carlo
  - decay only at NLO