NLO merging with MiNLO and NNLOPS: VV and VH

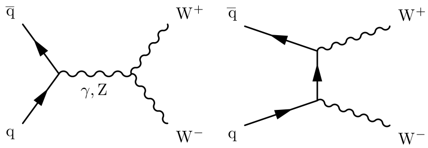
Emanuele Re

CERN & LAPTh Annecy

LoopFest XVI

Argonne National Laboratory, 31 May 2017

plan of the talk

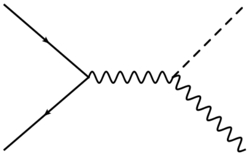


1. vector boson pair production

- access to anomalous gauge couplings
- background for several searches, for instance $H \to WW$
- NLO+PS merging of $pp \to WW$ and $pp \to WWj$ using MiNLO

2. associated Higgs production

- new-Physics in VVH vertex
- $H \to b\bar{b}$ decay (in boosted regime)
- NNLO+PS matching for $pp \to HW$



1. vector boson pair production

[Hamilton, Melia, Monni, ER, Zanderighi ’16]

Multiscale Improved NLO

[Hamilton,Nason,Zanderighi '12]

- original goal: method to a-priori choose scales in multijet NLO computation
- non-trivial task: hierarchy among scales can spoil accuracy (large logs can appear, without being resummed)
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

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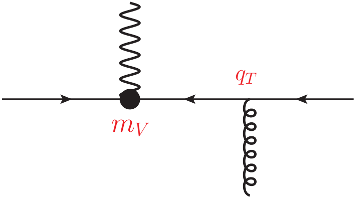

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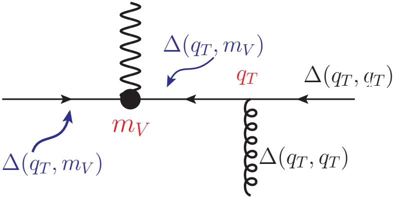

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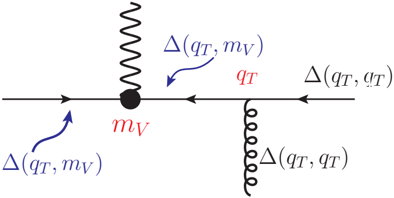

- $\bar{\mu}_R = q_T$
- $\log \Delta_{\rm f}(q_T, m_V) = -\int_{q_T^2}^{m_V^2} \frac{dq^2}{q^2}\frac{\alpha_{\rm S}(q^2)}{2\pi}\left[A_f \log\frac{m_V^2}{q^2} + B_f\right]$
- $\Delta_{\rm f}^{(1)}(q_T, m_V) = -\frac{\alpha_{\rm S}}{2\pi}\left[\frac{1}{2}A_{1,{\rm f}}\log^2\frac{m_V^2}{q_T^2} + B_{1,{\rm f}}\log\frac{m_V^2}{q_T^2}\right]$
- $\mu_F = q_T$

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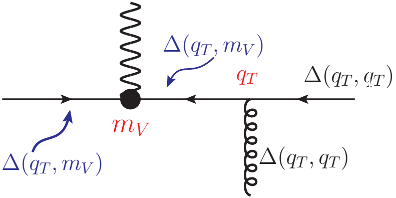

☞ Sudakov FF included on $V+j$ Born kinematics

- MiNLO-improved VJ yields finite results also when 1st jet is unresolved ($q_T \to 0$)
- $\bar{B}_{\rm MiNLO}$ allows extending the validity of VJ−POWHEG [called "VJ-MiNLO" hereafter]

MiNLO′

- formal accuracy of VJ−MiNLO for inclusive observables carefully investigated
  [Hamilton et al., 1212.4504]
- possible to improve VJ−MiNLO such that inclusive NLO is recovered (NLO$^{(0)}$), without spoiling NLO accuracy of V+j (NLO$^{(1)}$):

  MiNLO′ : NLO+PS merging, without merging scale

- accurate control of subleading small-p_T logarithms is needed:
  - include B_2 (NNLL) coefficient in MiNLO-Sudakov
  - set scales in R, V and subtraction terms equal to q_T (boson transverse momentum)
  - without the above requirements, spurious $\alpha_S^{3/2}$ terms show up in $\sigma_{\text{NLO}}^{(0)}$ upon integration over q_T

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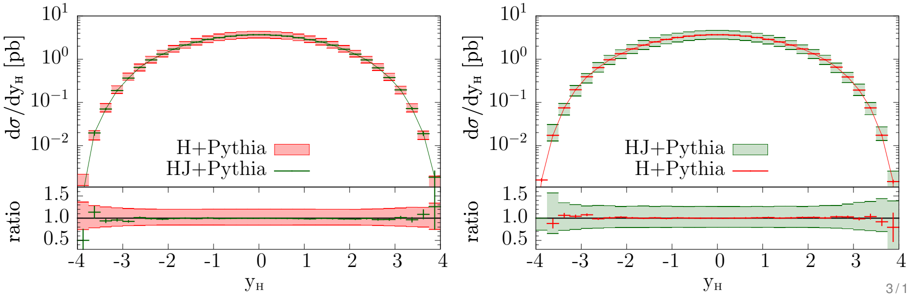


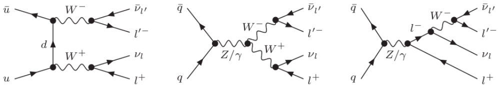
MiNLO′ : from Drell-Yan to WW

1606.07062: MiNLO′ generator that merges WW and WW + 1 jet at NLO+PS:

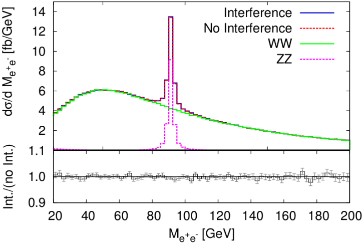
- POWHEG WWJ generator obtained ex-novo using interfaces to Madgraph and Gosam 2.0
  [Campbell et al. 1202.547; Luisoni et al. 1306.2542; Cullen et al. 1404.7096]
- starting from the Drell-Yan case, we extracted the $B_2^{\text{(WW)}}$ term from the virtual ($V^{\text{(WW)}}$) and Born ($B^{\text{(WW)}}$) contributions of $pp \to WW$
- for Drell-Yan, $V^{\text{(V)}}$ and $B^{\text{(V)}}$ are proportional, hence $B_2^{\text{(V)}}$ is just a number
- in $pp \to WW$, this is no longer true: $B_2^{\text{(WW)}} = B_2^{\text{(WW)}}(\Phi_{WW})$
  - for $q\bar{q}$-initiated color singlet production, B_2 has the form
    $$B_2 = -2\gamma^{(2)} + \beta_0 C_F \zeta_2 + 2(2C_F)^2\zeta_3 + \beta_0 H_1(\Phi)$$
  - from which
    $$B_2^{\text{(WW)}} = B_2^{\text{(V)}} - \beta_0 H_1^{\text{(V)}} + \beta_0 H_1^{\text{(WW)}}(\Phi_{WW})$$
- process-dependent part of B_2 extracted on an event-by-event basis: projection of Φ_{WWJ} onto Φ_{WW}, used FKS ISR mapping (smooth collinear limit)

WWJ-MiNLO′ : technical details and choices

- All off-shell and single-resonant diagrams included. Full matrix-element with leptonic decays.



- worked in the 4F scheme: no interference with Wt and $t\bar{t}$
- for same-family leptons, "$Z(\to \ell\bar{\ell})Z(\to \nu_\ell\bar{\nu}_\ell)$" not included:
  - will be part of ZZ generator
  - interference between WW and ZZ shown to be extremely small [Melia et al. 1107.5051]

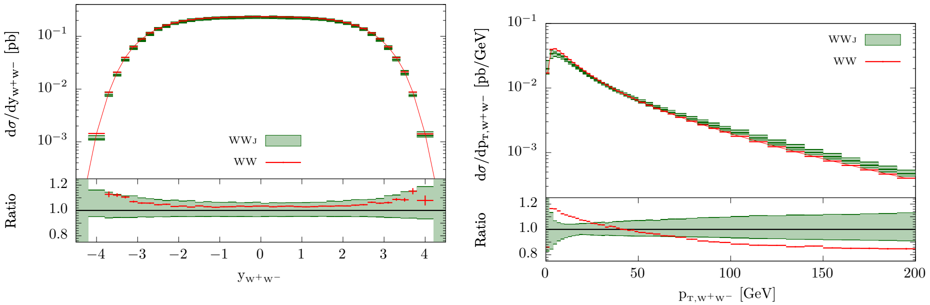


- option to include/exclude fermionic loop corrections (at most 1-2% difference in tails, x2 difference in speed)

WWJ−MiNLO′ : results I

[Hamilton,Melia,Monni,ER,Zanderighi '16]

WW generator vs. WWJ-MiNLO generator

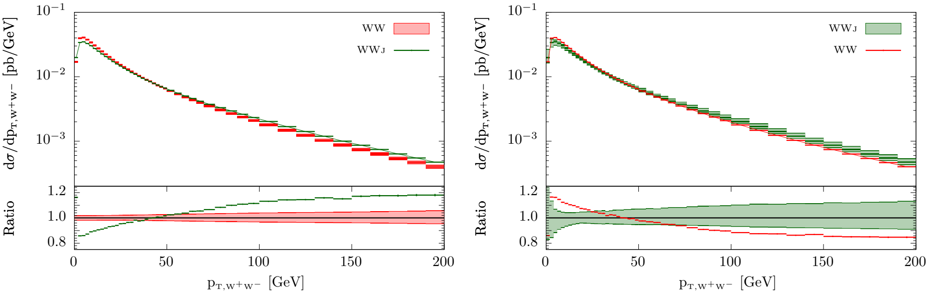


- total cross-section agrees at the level of 4% (although MiNLO uncertainty bands are wider than the WW ones)
- part of the shape difference in y_{WW} is correlated with the differences in the $p_{T,WW}$ spectrum

WWJ−MiNLO′ : results II

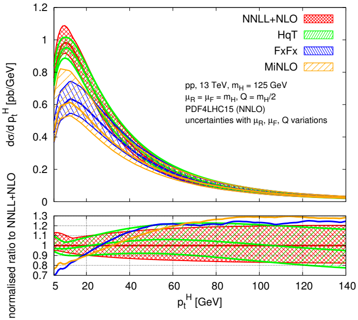
[Hamilton,Melia,Monni,ER,Zanderighi '16]

WW generator vs. WWJ-MiNLO generator

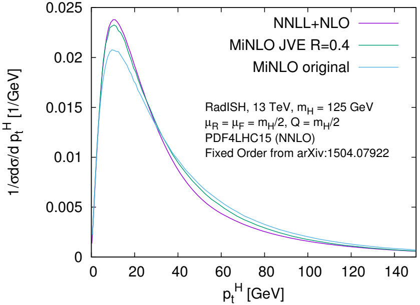


- NLO corrections sizeable in the spectrum
- small p_T region: different terms in the two approaches.
  - at small p_T, there's also a non-zero contribution from the two-emissions matrix element (missing in the WW case)
- underestimated WW uncertainty band

color-singlet p_T spectrum



[Monni,ER,Torrielli '16]



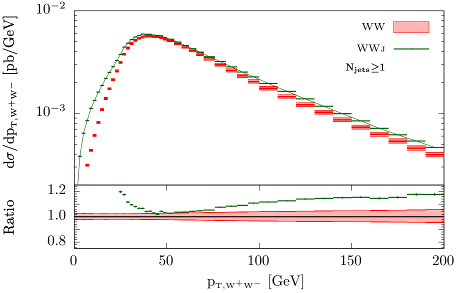
- to implement `MiNLO'`, possible also to use $(p_T^{j_1})$ as resolution variable (using Sudakov from "jet-veto" resummation)
- ongoing studies suggest that this would improve the shape at small p_T (at least qualitatively)
- probably related to scaling properties at small p_T
- *perhaps* some of the aforementioned differences are related to this...

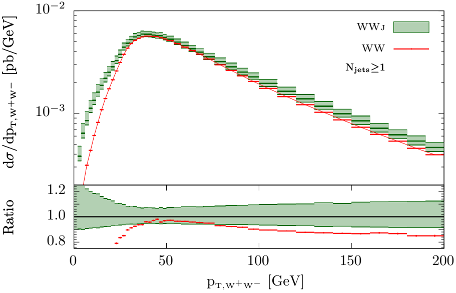
WWJ−MiNLO′ : results III

[Hamilton,Melia,Monni,ER,Zanderighi '16]

WW generator vs. WWJ-MiNLO generator

here explicit jet requirement: 25 GeV, R=0.4



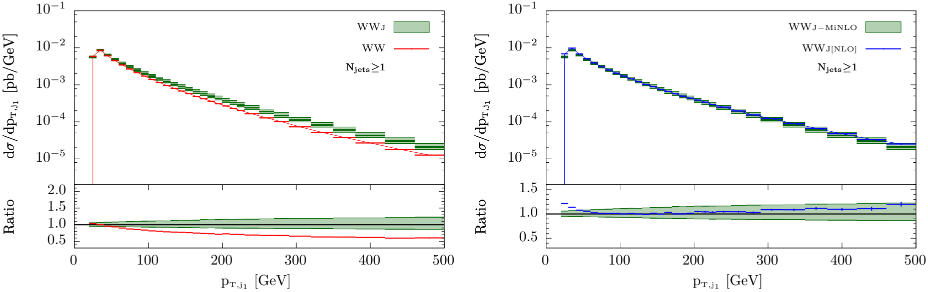


- below 25 GeV, at least 2 QCD emissions needed: only PS for WW, LO matrix elements for WWJ-MiNLO
- NLO K-factor visible throughout
- notice WWJ uncertainty bands: WWJ is NLO accurate for $p_{T,WW} > 25$ GeV, whereas WW is only LO.

[Hamilton,Melia,Monni,ER,Zanderighi ’16]

WW generator vs. WWJ-MiNLO generator (WW+j at NLO, partonic)

here explicit jet requirement: 25 GeV, R=0.4



- right plot shows that MiNLO mantains the formal NLO accuracy in the “1-jet” region
- small differences: Sudakov effects, different scale choices ($\mu_{\text{NLO}} = 2m_W$ vs. μ_{MiNLO})

2. VH @ NNLO+PS

[Astill, Bizon, ER, Zanderighi '16]

NNLO+PS for color-singlet production

- starting from a `MiNLO′` generator, it's possible to match a PS simulation to NNLO
- `XJ−MiNLO′` (+`POWHEG`) generator gives X-XJ @ NLOPS

	X (inclusive)	X+j (inclusive)	X+2j (inclusive)
✓ X-XJ @ NLOPS	NLO	NLO	LO
X @ NNLOPS	NNLO	NLO	LO

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- reweighting (differential on Φ_B) of "MiNLO-generated" events:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm XJ-MiNLO'}}$$

  - by construction NNLO accuracy on fully inclusive observables [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of XJ−MiNLO in 1-jet region [ ]

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$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\rm XJ-MiNLO'}} = \frac{c_0 + c_1\alpha_S + c_2\alpha_S^2}{c_0 + c_1\alpha_S + d_2\alpha_S^2} \simeq 1 + \frac{c_2 - d_2}{c_0}\alpha_S^2 + \mathcal{O}(\alpha_S^3)$$

  - by construction NNLO accuracy on fully inclusive observables [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of `XJ−MiNLO` in 1-jet region [✓]
  - notice: formally works because no spurious $\mathcal{O}(\alpha_S^{1.5})$ terms in X-XJ @ NLOPS (relative to σ_X)

NNLO+PS for color-singlet production

- Variants for reweighting $W(\Phi_B)$ are also possible:

$$W(\Phi_B, p_T) = h(p_T)\frac{\int d\sigma_A^{\rm NNLO}\delta(\Phi_B - \Phi_B(\mathbf{\Phi}))}{\int d\sigma_A^{\rm MiNLO}\delta(\Phi_B - \Phi_B(\mathbf{\Phi}))} + (1 - h(p_T))$$

$$d\sigma_A = d\sigma\, h(p_T), \qquad d\sigma_B = d\sigma\,(1 - h(p_T)), \qquad h(p_T) = \frac{(\beta M)^2}{(\beta M)^2 + p_T^2}$$

- freedom to distribute "NNLO/NLO K-factor" only over medium-small p_T region
  - $h(p_T)$ controls where the NNLO/NLO K-factor is distributed
    (in the high-p_T region, there is no improvement in including it)
  - β cannot be too small, otherwise resummation spoiled:
    for Higgs, chosen $\beta = 1/2$; for DY and HW, $\beta = 1$

- in practice, we used

$$W(\Phi_B, p_T) = h(p_T)\frac{\int d\sigma^{\rm NNLO}\delta(\Phi_B - \Phi_B(\mathbf{\Phi})) - \int d\sigma_B^{\rm MiNLO}\delta(\Phi_B - \Phi_B(\mathbf{\Phi}))}{\int d\sigma_A^{\rm MiNLO}\delta(\Phi_B - \Phi_B(\mathbf{\Phi}))} + (1 - h(p_T))$$

  - one gets exactly $(d\sigma/d\Phi_B)_{\rm NNLOPS} = (d\sigma/d\Phi_B)_{\rm NNLO}$
  - chosen $h(p_T^{j_1})$

WH @ NNLOPS: technical details and choices

- started from existing HWJ-`MiNLO'` generator [Luisoni et al. 1306.2542]
- NNLO input from `HVNNLO` by [Ferrera et al. '11]

- to compute the $W(\Phi_B)$ function, $(d\sigma_{\rm NNLO}/d\Phi_B)$ needed!

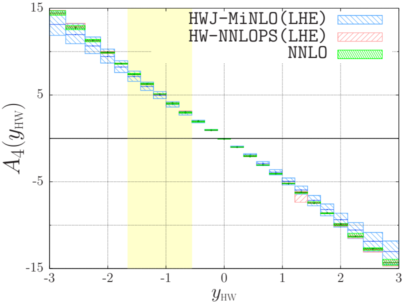
  $\Rightarrow$ albeit conceptually simple, in practice it gets quickly complicated
- Higgs and Drell-Yan production: extracted $(d\sigma_{\rm NNLO}/d\Phi_B)$ numerically as a (multi-dimensional) histogram: 25 bins/dimension
- not possible for $W(\to \ell\nu)H$ [at least using brute-force approach]

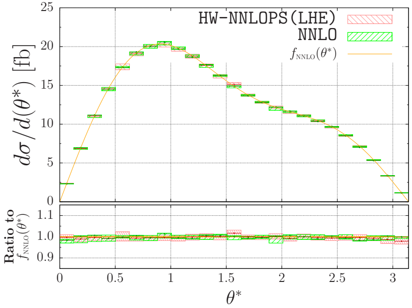
- used properties of final state: $(y_{\rm HW}, \Delta y_{\rm HW}, p_{t,\rm H})$ + Collins-Soper angles

$$\begin{aligned}\frac{d\sigma}{d\Phi_B} &= \frac{d\sigma}{dy_{\rm HW}\, d\Delta y_{\rm HW}\, dp_{t,\rm H}\, d\cos\theta^* d\phi^*}\\ &= \frac{3}{16\pi}\left(\frac{d\sigma}{d\Phi_{\rm HW^*}}(1+\cos^2\theta^*)+\sum_{i=0}^{7}A_i(\Phi_{\rm HW^*})f_i(\theta^*,\phi^*)\right)\end{aligned}$$

- moreover verified that reweighting factor is independent from lepton pair invariant mass
- $(25)^5$ bins $\to$ 9 $\times$ 3-d histograms (still tough, but manageable)

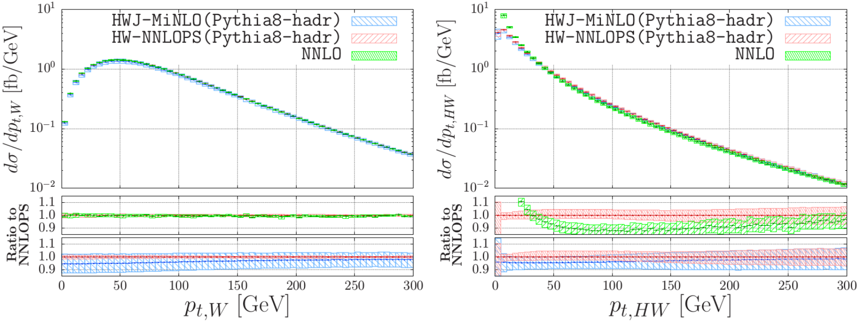
WH @ NNLOPS: validation





- left: CS coefficient A_4 as a function of y_{HW}. NNLOPS agrees with NNLO
- right: θ^* distribution in a y_{HW} window.
  - very good agreement between NNLOPS, the NNLO result, and the differential NNLO cross section reconstructed from the CS parametrization.

WH @ NNLOPS: results I



- left: inclusive observable → NNLO+PS is NNLO accurate, and displays non-flat K-factor w.r.t. NLO+PS
- right: p_t of color-singlet: standard observable to visualize Sudakov resummation.
  - p_t dependence of NNLO reweighting visible
  - NNLO+PS approach NLO+PS at large p_t

conclusions

- presented a recent non-trivial application of the "improved" MiNLO method:
  - aside from applying it to processes of the same class ($pp \to VV$), one obvious avenue to be explored is NNLOPS simulations for $2 \to 2$ processes.
    - in principle, for color singlet (as VV production), all ingredients are there.
  - including the gg-initiated channels at NLO+PS can also be studied

    results for $gg \to ZZ$: [Alioli et al. 1609.09719]
- presented NNLO+PS results for $pp \to HW$:
  - the HZ case is straightforward
  - boosted regime will become increasingly important: possible to include also $H \to b\bar{b}$ at NLO (techniques developed for resonance-aware NLO+PS)
- variants of the MiNLO method might allow better resummation properties for the final results

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Thank you for your attention!

Extra slides

“Improved” MiNLO & NLOPS merging: details

- Resummation formula can be written as

$$\frac{d\sigma}{dq_T^2 dy} = \sigma_0 \frac{d}{dq_T^2}\Big\{[C_{ga}\otimes f_a](x_A,q_T)\times[C_{gb}\otimes f_b](x_B,q_T)\times \exp S(q_T,Q)\Big\} + R_f$$

$$S(q_T,Q) = -2\int_{q_T^2}^{Q^2}\frac{dq^2}{q^2}\frac{\alpha_S(q^2)}{2\pi}\left[A_f \log\frac{Q^2}{q^2} + B_f\right]$$

- If $C_{ij}^{(1)}$ included and R_f is LO$^{(1)}$, then upon integration we get NLO$^{(0)}$
- `MiNLO` formula is not written as a total derivative: “expand” the above expression, then compare with `MiNLO` :

$$\sim \sigma_0 \frac{1}{q_T^2}[\alpha_S, \boxed{\alpha_S^2}, \alpha_S^3, \alpha_S^4, \alpha_S L, \alpha_S^2 L, \alpha_S^3 L, \alpha_S^4 L]\exp S(q_T,Q) + R_f \qquad L = \log(Q^2/q_T^2)$$

- highlighted terms are needed to reach NLO$^{(0)}$:

$$\int^{Q^2}\frac{dq_T^2}{q_T^2} L^m {\alpha_S}^n(q_T)\exp S \sim \left(\alpha_S(Q^2)\right)^{n-(m+1)/2}$$

(scaling in low-p_T region is $\alpha_S L^2 \sim 1$!)

- if I don’t include B_2 in `MiNLO` Δ_g, I miss a term $(1/q_T^2)\ \boxed{\alpha_S^2}\ B_2 \exp S$
- upon integration, violate NLO$^{(0)}$ by a term of <u>relative</u> $\mathcal{O}(\alpha_S^{3/2})$