Recent developments in POWHEG and MINLO

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LoopFest XII

Florida State University, 13 May 2013

*based mainly on Hamilton et al. [1206.3572,1212.4504]
+ many others for POWHEG improvements [POWHEG BOX homepage]

Outline

- Multiscale Improved NLO
- Merging of B at NLO and $B + 1j$ at NLO, and possible further developments
- (selected) new processes/improvements in `POWHEG BOX`

Scale choices in NLO computation

- scale often chosen a posteriori, requiring typically
  - NLO corrections to be small
  - sensitivity upon scale choice to be minimal ($\rightarrow$ plateau in $\sigma(\mu)$ vs. μ)
- Motivation: bad scale $\rightarrow$ large logs $\rightarrow$ potentially large K factors and large scale dependence
- However large NLO effects can be genuine: new channels (and gluon fluxes), Sudakov logarithms

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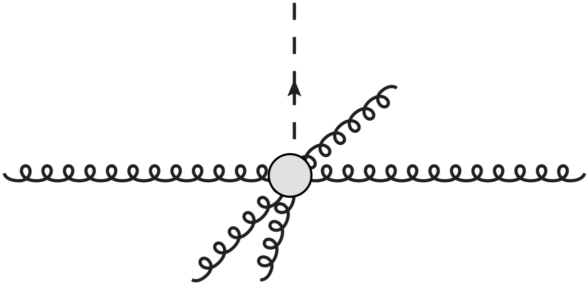
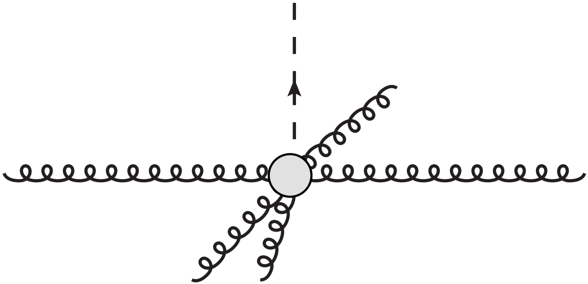
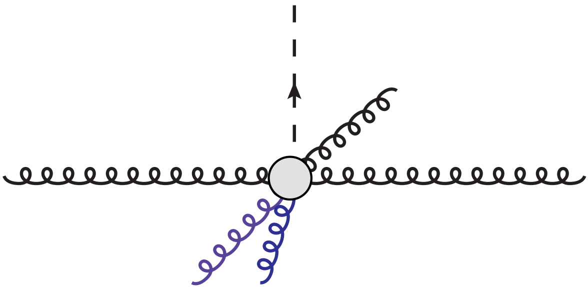
- Typically these issues show up when approaching PS regions with widely different scales (*e.g.* $B+$ jets).
- At LO, the CKKW procedure allows to take these effects into account, modifying the LO weight $B(\mathbf{\Phi}_n)$ obtained from ME in order to include LL effects.



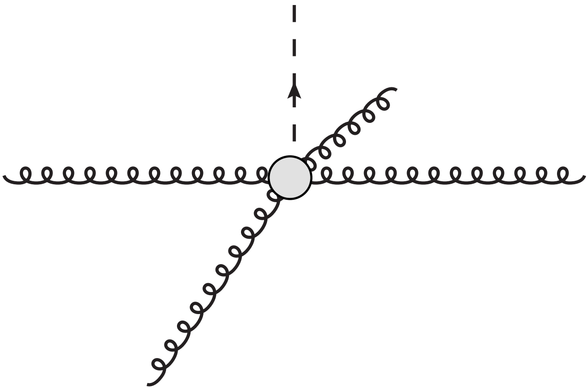
- start from ME weight $B(\mathbf{\Phi}_n)$



- find "most-likely" shower history (via k_T-algo)



- find “most-likely” shower history (via k_T-algo)
- clustering scale $q_1 = k_T$



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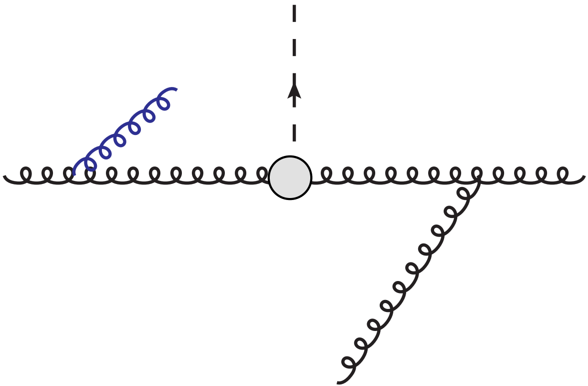
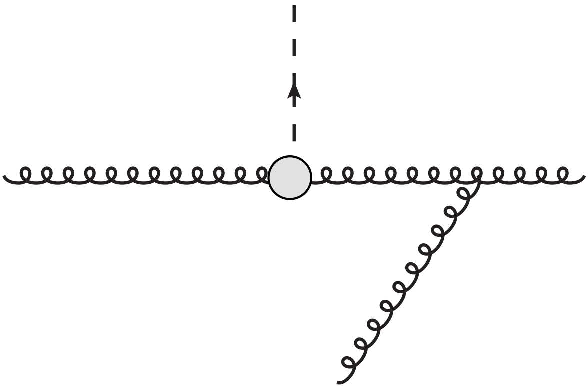
CKKW in a nutshell



- find “most-likely” shower history (via k_T-algo)
- clustering scale $q_2 = k_T$

CKKW in a nutshell



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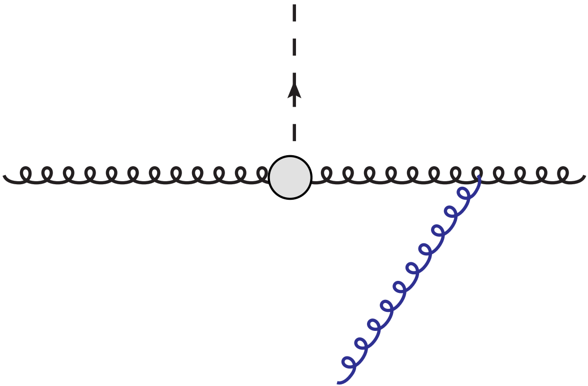
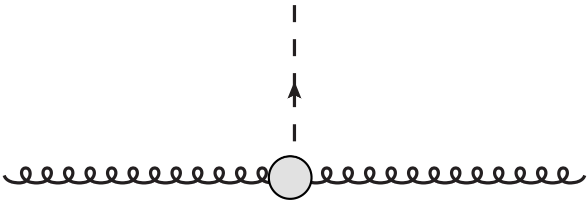
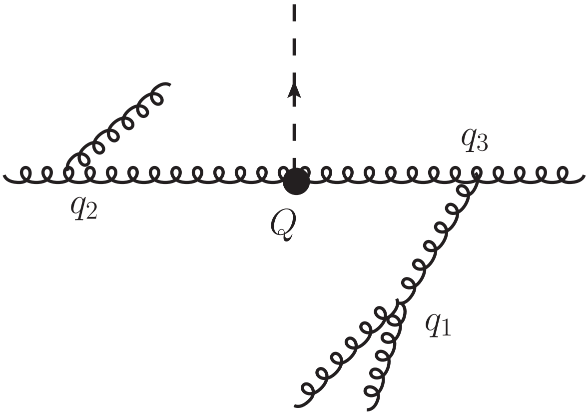


- find "most-likely" shower history (via k_T-algo)
- clustering scale $q_3 = k_T$

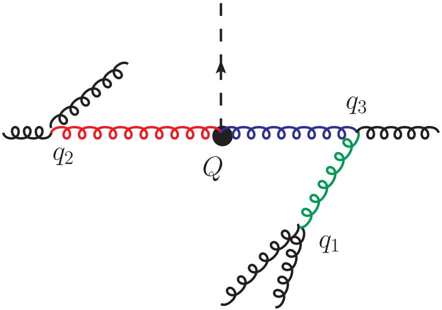
CKKW in a nutshell



- Hard process scale Q



- most-likely shower history



- New weight:

$$\alpha_S^5(Q)B(\mathbf{\Phi}_3) \quad \rightarrow \quad \alpha_S^2(Q)B(\mathbf{\Phi}_3)\frac{\Delta_g(Q_0,Q)}{\Delta_g(Q_0,q_2)}\frac{\Delta_g(Q_0,Q)}{\Delta_g(Q_0,q_3)}\frac{\Delta_g(Q_0,q_3)}{\Delta_g(Q_0,q_1)}$$
$$\Delta_g(Q_0,q_2)\Delta_g(Q_0,q_2)\Delta_g(Q_0,q_3)\Delta_g(Q_0,q_1)\Delta_g(Q_0,q_1)$$
$$\alpha_S(q_1)\alpha_S(q_2)\alpha_S(q_3)$$

where $Q > q_3 > q_2 > q_1 \equiv Q_0$ and, at LL,

$$\log \Delta_f(q_T, Q) = -\int_{q_T^2}^{Q^2} \frac{dq^2}{q^2}\frac{\alpha_S(q^2)}{2\pi}\left[A_{1,f}\log\frac{Q^2}{q^2} + B_{1,f}\right]$$

- Fill phase space below Q_0 with vetoed shower

MiNLO: Multiscale Improved NLO

[Hamilton,Nason,Zanderighi,1206.3572]

⇒ Use CKKW on top of NLO computation that potentially involves many scales.

✓ Scales assigned a priori

$$\alpha_S^n(Q) \Rightarrow \alpha_S(q_1)\alpha_S(q_2)...\alpha_S(q_n)$$

✓ include Sudakov FFs in internal and external lines ⇒ improved description of Sudakov regions

$$B(\mathbf{\Phi}_n) \Rightarrow B(\mathbf{\Phi}_n) \times \{\Delta(Q_0, Q)\Delta(Q_0, q_i)...\}$$

✓ $B+$ jets cross-section finite without generation cuts

Next-to-Leading Order accuracy needs to be preserved

1. Scale dependence shows up at NNLO [“scale compensation”]:

$$O(\mu') - O(\mu) = \mathcal{O}(\alpha_S^{n+2}) \quad \text{if} \quad O \sim \alpha_S^n \quad \text{at LO}$$

2. Away from soft-collinear regions, exact NLO recovered:

$$O_{\text{MiNLO}} = O_{\text{NLO}} + \mathcal{O}(\alpha_S^{n+2})$$

1. MiNLO: All α_S in Born term are chosen with CKKW (local) scales $q_1, ..., q_n$

$$\alpha_S^n(\mu_R)B \Rightarrow \alpha_S(q_1)\alpha_S(q_2)...\alpha_S(q_n)B$$

- Normal NLO structure ($\mu = \mu_R$):

$$\sigma(\mu) = \underbrace{\alpha_S^n(\mu)B}_{\text{Born}} + \underbrace{\alpha_S^{n+1}(\mu)\Big(C + nb_0\log(\mu^2/Q^2)B\Big)}_{\text{Virtual}} + \underbrace{\alpha_S^{n+1}(\mu)R}_{\text{Real}}$$

- Explicit μ dependence of virtual term as required by RG invariance:

$$\alpha_S^n(\mu')B = \Big[\alpha_S(\mu)\ -nb_0\alpha_S^{n+1}(\mu)\log(\mu'^2/\mu^2)\Big]B + \mathcal{O}(\alpha_S^{n+2})$$

$$\text{Virtual}(\mu') = \text{Virtual}(\mu)\ +\alpha_S^{n+1}(\mu)nb_0\log(\mu'^2/\mu^2)\ B + \mathcal{O}(\alpha_S^{n+2})$$

$\Rightarrow \sigma(\mu') - \sigma(\mu) = \mathcal{O}(\alpha_S^{n+2})$

- In MiNLO "scale compensation" kept if

$$\Big(C + nb_0\log(\mu_R^2/Q^2)B\Big) \Rightarrow \Big(C + nb_0\log(\bar{\mu}_R^2/Q^2)B\Big)$$

with $\bar{\mu}_R^2 = (q_1 q_2 ... q_n)^{2/n}$

MiNLO and NLO accuracy (2)

2. MiNLO: internal and external lines of Born "skeleton" are assigned Sudakovs

$$B(\mathbf{\Phi}_n) \Rightarrow B(\mathbf{\Phi}_n) \times \{\Delta(Q_0, Q)\Delta(Q_0, q_i)...\}$$

- Expanded Sudakovs generate IR logs, that hit $\alpha_S^n B(\mathbf{\Phi}_n)$

$$\begin{aligned}\Delta_f(q', Q) &= 1 + \Delta_f^{(1)}(q', Q) + \mathcal{O}(\alpha_S^2) \\ \Delta_f^{(1)}(q', Q) &= -\frac{\alpha_S}{2\pi}\left[\frac{1}{2}A_{1,f}\log^2\frac{Q^2}{q'^2} + B_{1,f}\log\frac{Q^2}{q'^2}\right]\end{aligned}$$

- These terms are $\mathcal{O}(\alpha_S^{n+1})$, so already present in original NLO!
- Subtract them to keep NLO accuracy (but keep overall CKKW Sudakovs!):

$$B(\mathbf{\Phi}_n) \Rightarrow B(\mathbf{\Phi}_n)\Big(1 - \Delta^{(1)}(Q_0, Q) - \Delta^{(1)}(Q_0, q_i) + ...\Big)$$

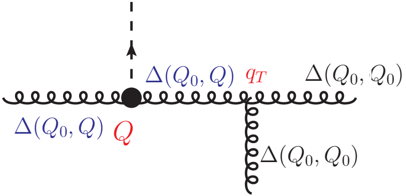
Example, in 1 line: $H+1$ jet

- Pure NLO:

$$\bar{B} = \alpha_S^3(\mu_R)\left[B + \alpha_S V(\mu_R) + \alpha_S \int d\Phi_{\mathrm{rad}} R\right]$$

- MiNLO:

$$\bar{B} = \alpha_S^2(M_H)\alpha_S(q_T)\Delta_g^2(q_T, M_H)\left[B\left(1 - 2\Delta_g^{(1)}(q_T, M_H)\right) + \alpha_S V(\bar{\mu}_R) + \alpha_S \int d\Phi_{\mathrm{rad}} R\right]$$



It can be shown that this corresponds to use $\alpha_S^3(q_T) B\left[1 - C_A \frac{\alpha_S}{2\pi}\log^2\frac{Q^2}{q_T^2}\right]$

MiNLO (2)

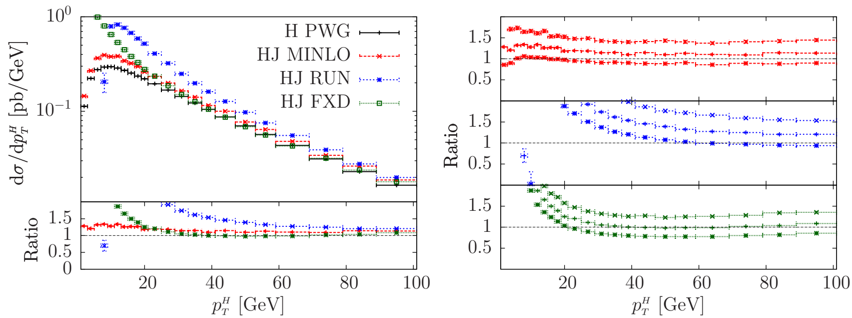
MiNLO+POWHEG

- $\bar{B}$ with MiNLO prescription can be used as starting point of POWHEG
- For $B + n$ jets, this modified $\bar{B}$ will be finite even if we are inclusive on radiation (also totally inclusive)
- MiNLO for $B + n$ jets improves description of observables made out of n jets, because Sudakov logs are taken into acccount
- (One can build observables s.t. MiNLO fails)
- POWHEG resums extra radiation in $\mathbf{\Phi}_{n+1}$, without spoiling $B + n$ jets NLO

$\Rightarrow$ Many benefits when combined!

Moreover MiNLO+POWHEG is the starting point to merge NLO B with NLO $B + j$ (without a merging scale).

MiNLO results 1



- "H PWG": POWHEG ($gg \to H$) + PYTHIA (PS level)
- "HJ RUN(FXD)": NLO Hj with $\mu = p_{T,H}(M_H)$ (7pt envelopes)

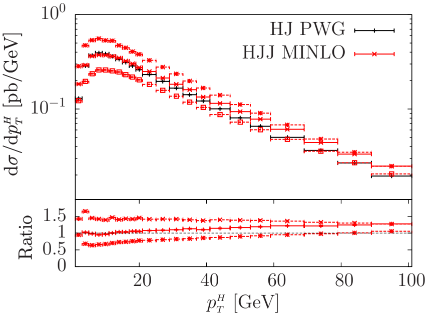
✗ NLO's band don't overlap if $p_{T,H} < 30$ GeV

✓ At small p_T, MiNLO is finite and $\sim$ H PWG (both include Sudakov)

✓ At large p_T, MiNLO $\sim Hj$ NLO

- HJ FXD higher scale "compensate" for absence of Sudakov (more than HJ RUN, that misses it)

MiNLO results 2

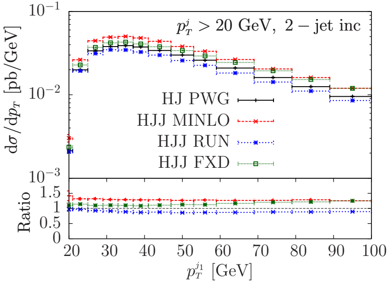


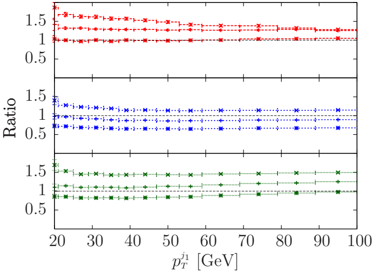
LEFT:

- "HJ PWG": `HJ POWHEG` (w MiNLO) + `PYTHIA` (PS level)
- "HJJ MINLO": finite even if fully inclusive + compatible with `POWHEG` down to very low p_T

BOTTOM:

- All results predictive (2 jets required)
- "HJJ MINLO" $\sim$ "HJJ RUN" seems to support running scale H_T; for $H_T/2$, MINLO and RUN would overlap even better





MiNLO & merging

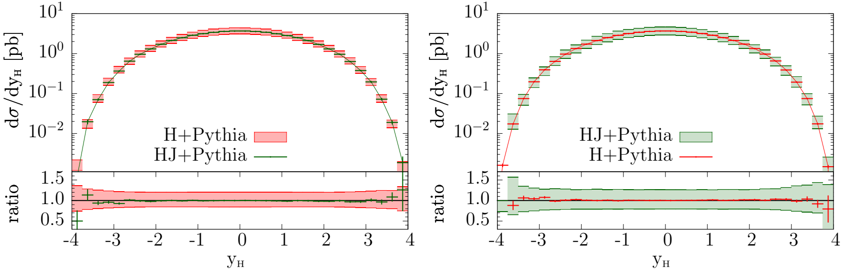
- Accuracy of BJ+MiNLO for inclusive observables carefully investigated in arXiv:1212.4504 (Hamilton,Nason,Oleari,Zanderighi)
- BJ+MiNLO describes inclusive boson observables at relative order α_S wrt $B + 0j$ at LO
- However, to reach genuine NLO, higher terms must be order α_S^2, *i.e.*

$$O_{\mathrm{VJ+MiNLO}} = O_{\mathrm{V@NLO}} + \mathcal{O}(\alpha_S^2)$$

  if O is inclusive. "Original MiNLO" contains ambiguous $\mathcal{O}(\alpha_S^{3/2})$ terms
- Possible to modify BJ+MiNLO such that NLO $B + 0j$ is recovered, without spoiling NLO accuracy for $B + 1j$.
  - proof based on careful comparisons of general resummation formula with MiNLO
  - need to include B_2 in Sudakovs
  - need to evaluate ${\alpha_S}^{(\mathrm{NLO})}$ in BJ+MiNLO at scale q_T

In the end is like if we merged NLO$^{(0)}$ and NLO$^{(1)}$ samples, without merging different samples (no merging scale used).

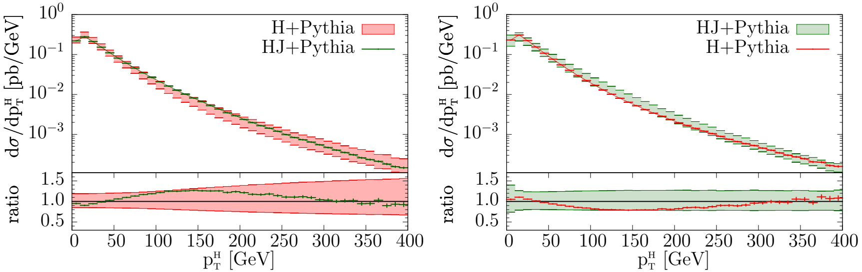
MiNLO merging: results 1



- "H+Pythia": standalone POWHEG ($gg \to H$) + PYTHIA (PS level) [7pts band]
- "HJ+Pythia": HJ−MiNLO* + PYTHIA (PS level) [7pts band]

✓ very good agreement (both value and band)

MiNLO merging: results 2



- Good agreement
- At high p_T, bands as expected (LO vs NLO)
- Low p_T shape difference: different NNLL terms in MiNLO Sudakovs
- Bands at low p_T: “H+Pythia” band spurious (S-events, i.e. inherit property of full $\bar{B}$)
  “HJ+Pythia” widens as expected (strong coupling regime)

Possible further improvements

- NNLO+PS
  - `HJ-MiNLO`* differential cross section $(d\sigma/dy)_{\rm HJ-MiNLO}$ is NLO accurate

$$\frac{\left(\frac{d\sigma}{dy}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{dy}\right)_{\rm HJ-MiNLO}} = \frac{c_2\alpha_S^2 + c_3\alpha_S^3 + c_4\alpha_S^4}{c_2\alpha_S^2 + c_3\alpha_S^3 + d_4\alpha_S^4} \simeq 1 + \frac{c_4 - d_4}{c_2}\alpha_S^2 + \mathcal{O}(\alpha_S^3)$$

  - thus, reweighting with this factor, we get NNLO+PS
  - notice that α_S^4 accuracy of `HJ-MiNLO`* in 1-jet region not spoiled
  - variants possible

- merging for higher multiplicity needs more study

Automation:

- Interface to MadGraph 4 (Frederix): automatically builds subprocesses list, B, B_{ij}, $B^{\mu\nu}$, R and large-N Born color structures.
  - Used to build the code for Hj and Hjj (Campbell, Ellis, Frederix, Nason, Oleari), with virtuals from MCFM.
- Work is in progress (Luisoni, Nason, Oleari, Tramontano) to build an interface to GoSam, to automatically write the code for 1-loop amplitudes

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Complicated processes & parallelization:

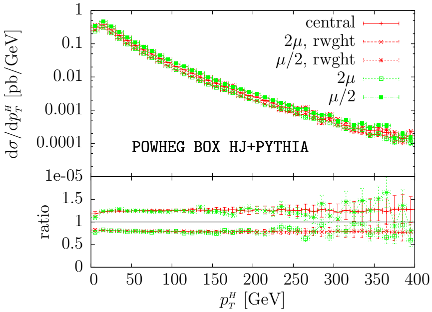
- Possible to run POWHEG BOX in parallel. Not only event generation, but also grid computation.
- details in repository [Parallel-grids]

PDF and scale uncertainties:

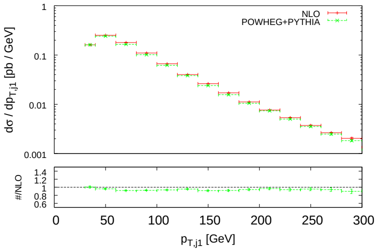
- Generate MC samples for different scale choices, and, even more, for different PDFs, is very time consuming
- Primitive reweighting facility now superseded by new mechanism (Hamilton,Nason,ER):

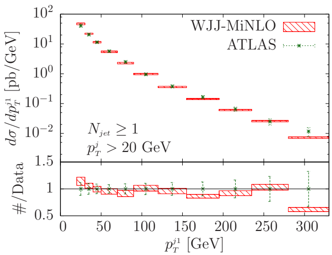
- instead of tracking coefficients of μ logs, for each event save random number seeds associated to PS point and value of $\tilde{B}$ (+ some extra info)
- for each event in already existing LH file, use stored random number seeds to generate the same PS points, and compute new value of $\tilde{B}$ with new scales and/or pdf
- append new weight, rescaling with

$$w' = w \times (\text{new integrand}/\text{old integrand})$$

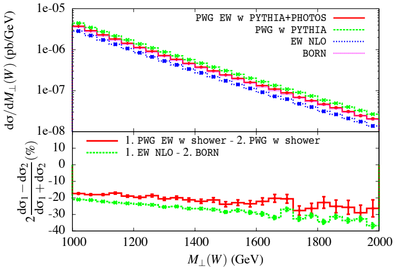


- Zjj (ER, '12), Vjj-MiNLO (Campbell,Ellis,Nason,Zanderighi '13)





- NLO QCD and NLO EW, for DY (Bernaciak,Wackeroth'12 - Barze et al'12-'13)



Conclusions

1. MiNLO:
   - assign scales and Sudakov FF in $B+n$ jets NLO computations
   - well-behaved in Sudakov regions
   - NLO away from Sudakov regions
   - ideal as starting point for `POWHEG`
2. Improved MiNLO:
   - $B+1$ jet improved MiNLO allows to merge NLO$^{(0)}$ and NLO$^{(1)}$ samples, without merging (no merging scale used)
   - seems possible to reach NNLO+PS
   - merging for higher multiplicity requires further study
3. Progress in POWHEG:
   - list of processes steadily increasing
   - automation
   - keep up with theoretical and experimental needs
   - ...
   - ongoing work on angular correlations in heavy-quark decays
   - ...other talks here !

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Thanks for your attention!

Backup (1)

Few technicalities for MiNLO:

- $\mu_F = Q_0$ (as in CKKW)
- Cluster with CKKW also V and R kinematics
  - Actual implementation uses FKS mapping for first cluster of $\mathbf{\Phi}_{n+1}$
  - Ignore CKKW Sudakov for 1^{st} clustering of $\mathbf{\Phi}_{n+1}$ (inclusive on extra radiation)
- Some freedom in choice of $\alpha_{\mathrm{S}}{}^{(n+1)}$ (entering V, R and $\Delta^{(1)}$) (not free for MiNLO merging)
- Used full NLL Sudakovs

Backup (2)

Improved MiNLO:

- Resummation formula

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

- NLO$^{(0)}$ if $C_{ij}^{(1)}$ included and R_f is LO$^{(1)}$
- Take derivative:

$$\sim \sigma_0 \frac{1}{q_T^2}[\alpha_S, \alpha_S^2, \alpha_S^3, \alpha_S^4, \alpha_S L, \alpha_S^2 L, \alpha_S^3 L, \alpha_S^4 L]\exp S(q_T,Q)$$

- can be shown that

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

- if I drop B_2 in MiNLO, I miss a term $(1/q_T^2)\alpha_S^2 B_2 \exp S$
- upon integration, violate NLO$^{(0)}$ by a term $\mathcal{O}(\alpha_S^{3/2})$
- wrong scale in NLO α_S in MiNLO produces again same error

More “analytic” proof with all details also available in the paper.