Developments in (N)NLO + PS matching

Stefan Prestel

SLAC NATIONAL ACCELERATOR LABORATORY

DIS 2015

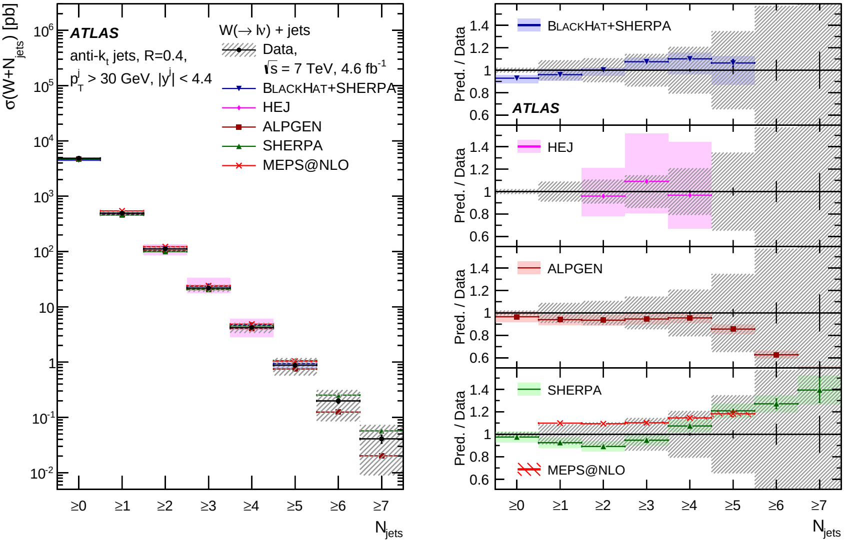
Dallas, April 28, 2015

(in collaboration with Stefan Höche and Ye Li)

Outline

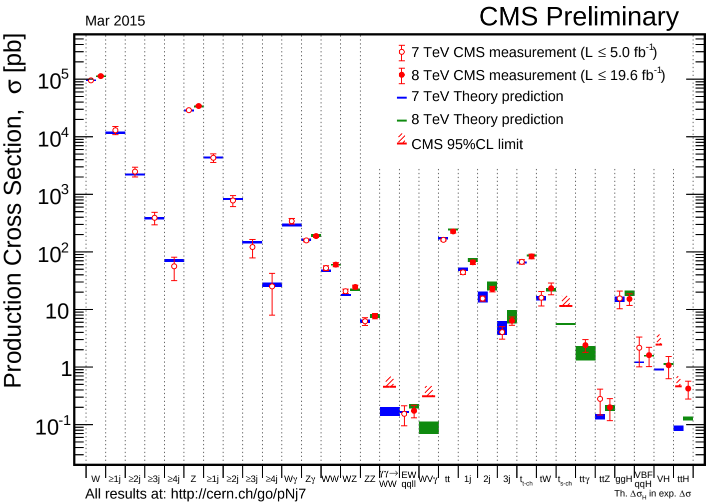
- Motivation / introduction
- NLO matching and LO merging (from a NNLO +PS viewpoint)
- NLO merging and NNLO matching
- Summary

How do event generators manage to describe this?



(Figure taken from EPJC 75 (2015) 2 82)

How can we get good accuracy for everything in this plot?



CMS summary (taken from https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined)

Task: Combine multiple fixed-order calculations with each other and with PS into a single *one-does-it-all* prediction.
Keep highest accuracy for inclusive n-jet cross sections.
Keep fixed-order + resummation goodies for exclusive n-jet cross sections.

$\Longrightarrow$ **Develop feasible, stable, generic and extendable methods embedded in a realistic event description.**

The current state-of-the-art is NLO merging.

Fixed order + Parton shower

Pen-and-paper: Add Born + Virtual + Real.

$$\langle \mathcal{O} \rangle^{\text{NLO}} \quad = \quad \int \mathrm{B}_n \mathcal{O}(\Phi_n) d\Phi_n + \int \mathrm{V}_n \mathcal{O}_n(\Phi_n) d\Phi_n + \int \mathrm{B}_{n+1} \mathcal{O}(\Phi_n) d\Phi_{n+1}$$

Next-to-leading order calculations

Pen-and-paper: Add Born + Virtual + Real.

$$\langle \mathcal{O} \rangle^{\mathsf{NLO}} = \int \mathrm{B}_n \mathcal{O}(\Phi_n) d\Phi_n + \int \mathrm{V}_n \mathcal{O}_n(\Phi_n) d\Phi_n + \int \mathrm{B}_{n+1} \mathcal{O}(\Phi_n) d\Phi_{n+1}$$

Reality: Phase space integral separately divergent $\Rightarrow$ Add zero!

$$\langle \mathcal{O} \rangle^{\mathsf{NLO}} = \int \left[\mathrm{B}_n + \mathrm{V}_n + \int \mathrm{D}_{n+1} \right] \mathcal{O}(\Phi_n) d\Phi_n + \int \left[\mathrm{B}_{n+1} \mathcal{O}(\Phi_{n+1}) - \mathrm{D}_{n+1} \mathcal{O}(\Phi_n') \right] d\Phi_{n+1}$$

Next-to-leading order calculations

Pen-and-paper: Add Born + Virtual + Real.

$$\langle\mathcal{O}\rangle^{\mathsf{NLO}} = \int \mathrm{B}_n\mathcal{O}(\Phi_n)d\Phi_n + \int \mathrm{V}_n\mathcal{O}_n(\Phi_n)d\Phi_n + \int \mathrm{B}_{n+1}\mathcal{O}(\Phi_n)d\Phi_{n+1}$$

Reality: Phase space integral separately divergent $\Rightarrow$ Add zero!

$$\langle\mathcal{O}\rangle^{\mathsf{NLO}} = \int \left[\mathrm{B}_n + \mathrm{V}_n + \int \mathrm{D}_{n+1}\right]\mathcal{O}(\Phi_n)d\Phi_n + \int \left[\mathrm{B}_{n+1}\mathcal{O}(\Phi_{n+1}) - \mathrm{D}_{n+1}\mathcal{O}(\Phi_n')\right]d\Phi_{n+1}$$

Real reality: States Φ_{n+1} and Φ_n' are correlated. $\Rightarrow$ Problematic, since further manipulations (e.g. hadronisation) can spoil the cancellations $\Rightarrow$ Add more zeros!

$$\begin{aligned}\langle\mathcal{O}\rangle^{\mathsf{NLO}} &= \int \left[\mathrm{B}_n + \mathrm{V}_n + \mathrm{I}_n + \int d\Phi_{\mathrm{rad}}\left(\mathrm{B}_{n+1}' - \mathrm{D}_{n+1}\right)\right]\mathcal{O}(\Phi_n)d\Phi_n \\ &+ \int \left(\mathrm{B}_{n+1} - \mathrm{B}_{n+1}'\right)\mathcal{O}(\Phi_{n+1}) \\ &+ \int \left(\mathrm{B}_{n+1}'\mathcal{O}(\Phi_{n+1}) - \mathrm{B}_{n+1}'\mathcal{O}(\Phi_n)\right) \longleftarrow \text{That's the } \mathcal{O}(\alpha_s) \text{ of a PS step!}\end{aligned}$$

NLO matching

For NLO matching, we start out with a seed cross section and Sudakov

$$\overline{\mathrm{B}}_n = \mathrm{B}_n + \mathrm{V}_n + \mathrm{I}_n + \int d\Phi_{\mathrm{rad}} \left(\mathrm{B}'_{n+1} - \mathrm{D}_{n+1}\right)$$

$$\Delta^B(t_0, t_{min}) = \exp\left(-\int^{t_0} d\Phi_{\mathrm{rad}} \frac{\mathrm{B}'_{n+1}}{\mathrm{B}_n}\right)$$

and perform a PS step on $\overline{\mathrm{B}}_n$[1]

$$\overline{\mathrm{B}}_n \Delta^B(t_0, t_{min}) \mathcal{O}_0(\Phi_n) + \int^{t_0} d\Phi_{\mathrm{rad}} \overline{\mathrm{B}}_n \frac{\mathrm{B}'_{n+1}}{\mathrm{B}_n} \Delta^B(t_0, t) \mathcal{O}_1(\Phi_{n+1}) + \left(\mathrm{B}_{n+1} - \mathrm{B}'_{n+1}\right) \mathcal{O}_1(\Phi_{n+1})$$

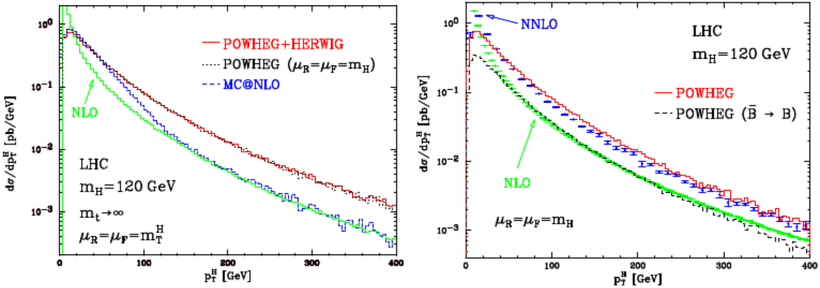
At $\mathcal{O}(\alpha_s^{n+1})$, this gives back the NLO cross section. Common schemes are

POWHEG: $\mathrm{B}'_{n+1} = \mathrm{B}_{n+1} \cdot \frac{h^2}{h^2 + p_\perp^2}$, $t_0 = s$

MC@NLO: $\mathrm{B}'_{n+1} = \mathrm{D}_{n+1} \cdot \Theta(\mu_Q - t(S_{+1}))$, $\mu_Q = kQ^2$

[1] Glossing over subtleties with the PS interface here.

...a cautionary tale



ME+PS methods can show large differences. Even striking differences can be consistent with higher order effects.

NLO matching: Differences

POWHEG and MC@NLO exhibit differences:

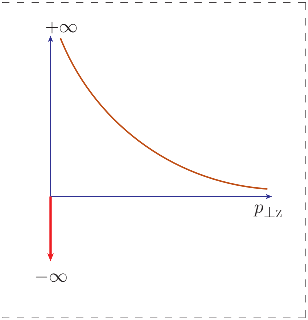
...in exponentiation

...in treatment of (smearing of NLO K-factor into) real emission

The differences are in shower-driven or "beyond LO" regions.
$\Rightarrow$ Improving on multi-jet patterns should (naively) help.
$\Rightarrow$ Upgrade with multiple fixed-order calculations $\rightarrow$ Merging.

Taking KLN literally

An NLO calculation is "subtract what we have added" – up to (crucial) $\delta(p_\perp)$ and $p_\perp/Q^2$ terms.
This does not give a very physical prediction of real-emission observables (like "full" NLO)

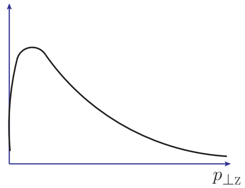


$$\mathrm{B}_0\mathcal{O}_0 - \int_1 \mathrm{B}_1\mathcal{O}_0 \qquad + \int_1 \mathrm{B}_1\mathcal{O}_1$$

Taking KLN literally

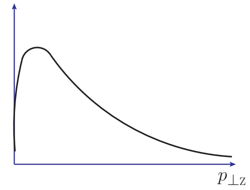
The divergence in B_1 can be regularized by resummtion, i.e. attaching a Sudakov factor.

...this will only give reasonable inclusive observables if we subtract what we have added!



$$\mathrm{B}_0\mathcal{O}_0 \;-\; \int_1 \mathrm{B}_1\mathcal{O}_0\Pi_{S_{+0}} \;+\; \int_1 \mathrm{B}_1\mathcal{O}_1\Pi_{S_{+0}}$$

Now assuming $\Pi_{S_{+0}} = \exp\left\{-\int_1 \mathrm{B}_1/\mathrm{B}_0\right\}$ we get the shower approximation when showering B_0



$$\mathrm{B}_0\mathcal{O}_0 - \int_1 \mathrm{B}_1\mathcal{O}_0\Pi_{S_{+0}} + \int_1 \mathrm{B}_1\mathcal{O}_1\Pi_{S_{+0}}$$

$$= \mathrm{B}_0\mathcal{O}_0\Pi_{S_{+0}} + \int_1 \mathrm{B}_1\mathcal{O}_1\Pi_{S_{+0}} = \mathrm{B}_0\left[\mathcal{O}_0\Pi_{S_{+0}} + \int_1 \frac{\mathrm{B}_1}{\mathrm{B}_0}\mathcal{O}_1\Pi_{S_{+0}}\right]$$

Now assuming $\Pi_{S_{+0}} = \exp\left\{-\int_1 \mathrm{B}_1/\mathrm{B}_0\right\}$ we get

Take-home: The inclusive cross section is preserved if we
a) subtract what we add, or
b) exponentiate the full radiation pattern.

Both are just different ways of addressing

$$P_{no\ emission} = 1 - P_{emission}$$

$$= \mathrm{B}_0\mathcal{O}_0\Pi_{S_{+0}} + \int_1 \mathrm{B}_1\mathcal{O}_1\Pi_{S_{+0}} = \mathrm{B}_0\left[\mathcal{O}_0\Pi_{S_{+0}} + \int_1 \frac{\mathrm{B}_1}{\mathrm{B}_0}\mathcal{O}_1\Pi_{S_{+0}}\right]$$

We could equally well have started from a one-jet calculation B_1.

The argument will then go through, except that we would also want to regularise the "starting point" by attaching Sudakovs.

...but the first part is just the real correction of the previous calculation!

$$\mathrm{B}_1\mathcal{O}_1 \;\longrightarrow\; \Pi_{S_{+0}}\mathrm{B}_1\mathcal{O}_1 \;-\; \int_1 \mathrm{B}_2\mathcal{O}_1\Pi_{S_{+0}}\Pi_{S_{+1}} \;+\; \int_1 \mathrm{B}_2\mathcal{O}_2\Pi_{S_{+0}}\Pi_{S_{+1}}$$

Going to higher multiplicities

We could equally well have started from a one-jet calculation B_1.

The argument will then go through, except that we would also want to regularise the "starting point" by attaching Sudakovs.

Now we can replace the previous real emission contribution and iterate

$$
\begin{aligned}
& \mathrm{B}_0\mathcal{O}_0 \\
\to\ & \mathrm{B}_0\mathcal{O}_0 - \int_1 \mathrm{B}_1\mathcal{O}_0\Pi_{S_{+0}} + \int_1 \mathrm{B}_1\mathcal{O}_1\Pi_{S_{+0}} \\
& - \int_2 \mathrm{B}_2\mathcal{O}_1\Pi_{S_{+0}}\Pi_{S_{+1}} + \int_2 \mathrm{B}_2\mathcal{O}_2\Pi_{S_{+0}}\Pi_{S_{+1}}
\end{aligned}
$$

Glossing over some subtleties with higher-multiplicities here.

We could equally well have started from a one-jet calculation B_1.

The argument will then go through, except that we would also want to regularise the "starting point" by attaching Sudakovs.

Take-home message: Can add as many tree-level calculations as desired if we consistently subtract.

Can we get rid of positive-negative weight cancellations?

$$\to \mathrm{B}_0\mathcal{O}_0 - \int_1 \mathrm{B}_1\mathcal{O}_0\Pi_{S_{+0}} + \int_1 \mathrm{B}_1\mathcal{O}_1\Pi_{S_{+0}}$$

$$- \int_2 \mathrm{B}_2\mathcal{O}_1\Pi_{S_{+0}}\Pi_{S_{+1}} + \int_2 \mathrm{B}_2\mathcal{O}_2\Pi_{S_{+0}}\Pi_{S_{+1}}$$

Q: Can we simplify this?

Now assuming $\Pi_{S_{+i}} = \exp\left\{-\int_1 \frac{\mathrm{B}_{i+1}}{\mathrm{B}_i}\right\}$ we would get

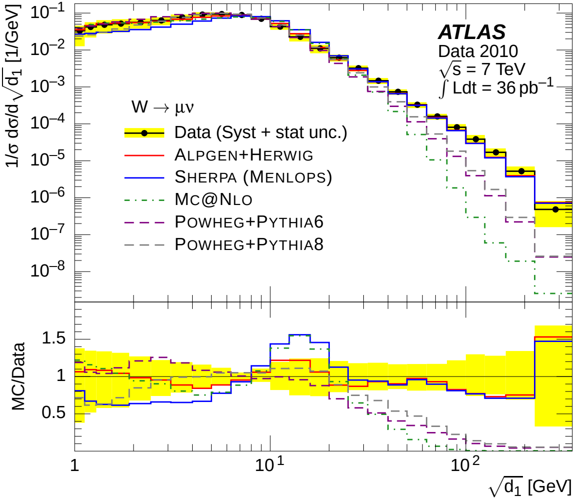
$$\mathrm{B}_0\mathcal{O}_0 \to \mathrm{B}_0\mathcal{O}_0\Pi_{S_{+0}} \;+\; \int_1 \mathrm{B}_1\mathcal{O}_1\Pi_{S_{+0}}\Pi_{S_{+1}} \;+\; \int_2 \mathrm{B}_2\mathcal{O}_2\Pi_{S_{+0}}\Pi_{S_{+1}}$$

Comments:

- The assumption is (almost?) impossible in all generality.
  $\Rightarrow$ Sudakovs can't regularise MEs
  $\Rightarrow$ Additional regularisation cut (merging scale) needed.
  $\Rightarrow$ Produces holes in phase space that need to be filled.
  $\Rightarrow$ Use PS below merging scale, ME above ($\to$ CKKW)
  $\Rightarrow$ Non-cancellation of reals and virtuals.
  $\Rightarrow$ Inclusive cross section changed.
- If the inclusive cross section were preserved, we could trivially upgrade to NLO.

A: No, unless we upgrade Sudakovs. Else, keep add-subtract scheme.

Merged predictions



Merged predictions are employed in many LHC analyses. And they perform as expected: Well-separated jets are described consistently. Plot from EPJC, 73 5 (2013) 2432.

Differences merging/matching

- NLO matching is NLO-correct. Showers assumed exchangeable.
- Merging can be used to combine "any number" of LO calculations. Shower details deemed crucial.

Comments

- If an NLO matched calculation describes too exclusive data (i.e. beyond the real-emission jet), the choices were lucky.
  If merged calculations describes normalisations, the choices were lucky.
- Luck $=$ Tuning $\neq$ Precision.

$\Rightarrow$ Both strategies are incomplete and need to be combined for a satisfactory result.

Observation: If a LO merged calculation leads to a well-defined zero-jet inclusive cross section, it is easy to upgrade this cross section to NLO.

The road to NLO merging

Any leading-order method **X** only ever contains approximate virtual corrections.

We want to use the full NLO results whenever possible.

The road to NLO merging

Any leading-order method **X** only ever contains approximate virtual corrections.

We want to use the full NLO results whenever possible.

To do NLO multi-jet merging for your preferred LO scheme **X**, do:

- Subtract approximate **X** $\mathcal{O}(\alpha_s)$-terms, add multiple NLO calculations.
- Make sure fixed-order calculations do not overlap by cutting, vetoing events and/or vetoing emissions.
- Adjust higher orders to suit other needs.

$\Rightarrow$ **X**@NLO

The road to NLO merging

Any leading-order method **X** only ever contains approximate virtual corrections.

We want to use the full NLO results whenever possible.

To do NLO multi-jet merging for your preferred LO scheme **X**, do:

- Subtract approximate **X** $\mathcal{O}(\alpha_s)$-terms, add multiple NLO calculations.
- Make sure fixed-order calculations do not overlap by cutting, vetoing events and/or vetoing emissions.
- Adjust higher orders to suit other needs.

$\Rightarrow$ **X**@NLO

After this, the inclusive cross section will be accurate at NLO, and any issues are pushed to $\mathcal{O}(\alpha_s^2)$.

LHC Run II+ era theory predictions (H+jets)

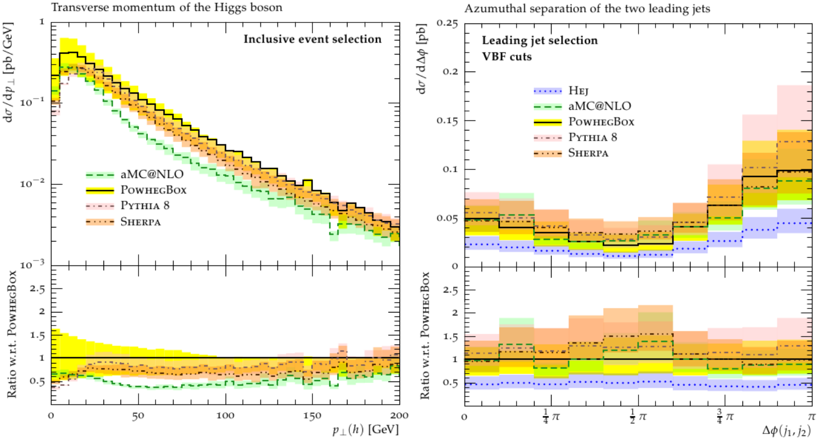
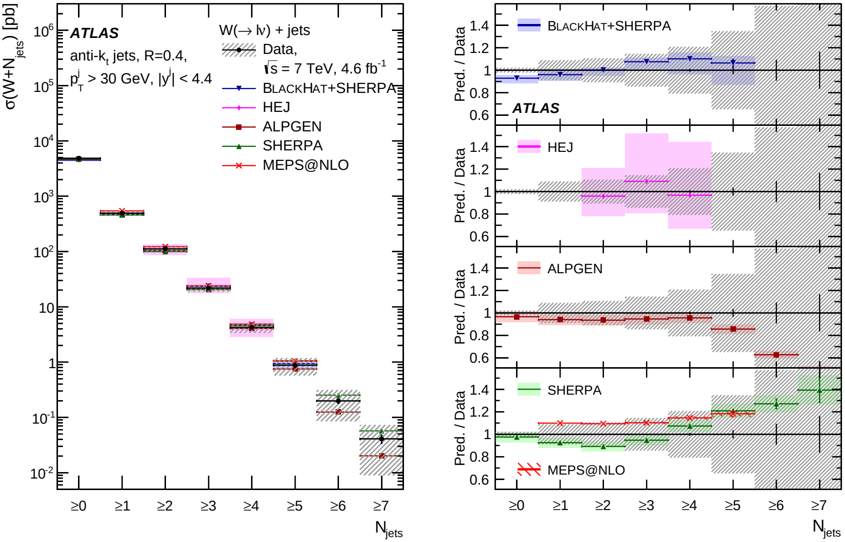


Figure: $p_{\perp,H}$ and $\Delta\phi_{12}$ for gg→H after merging (H+0)@NLO, (H+1)@NLO, (H+2)@NLO, (H+3)@LO, compared to other generators.

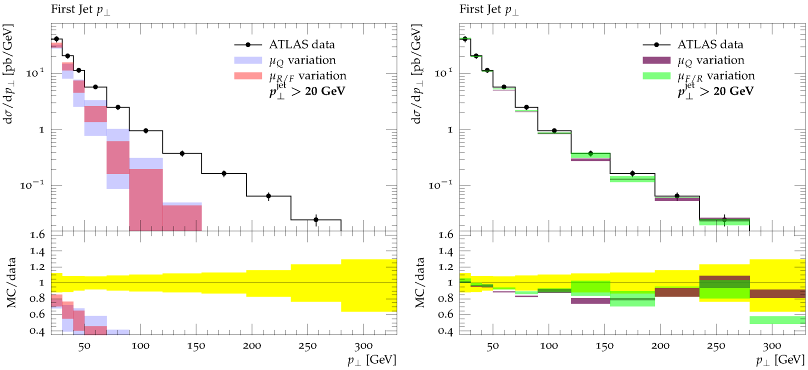
⇒ The generators come closer together if enough fixed-order matrix elements are employed. The uncertainties after cuts are still very large.

NLO merged results: The end of a 10-year journey



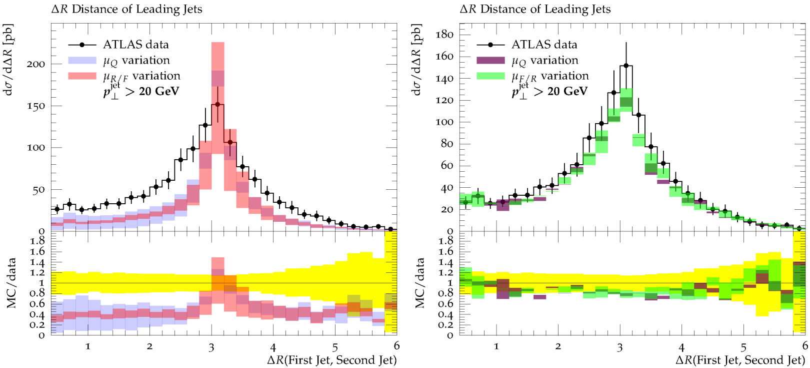
…but theory uncertainties decrease (from EPJC 75 (2015) 2 82)

NLO merged results: The end of a 10-year journey



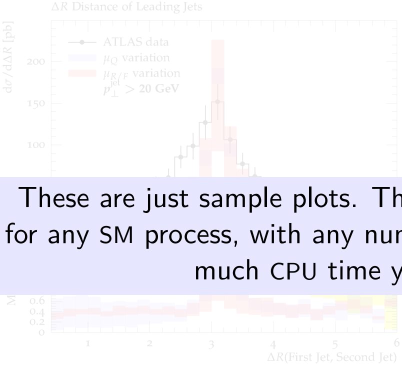
W(+jets) production at ATLAS (PRD 85 (2012) 092002) in PYTHIA8 UNLOPS.

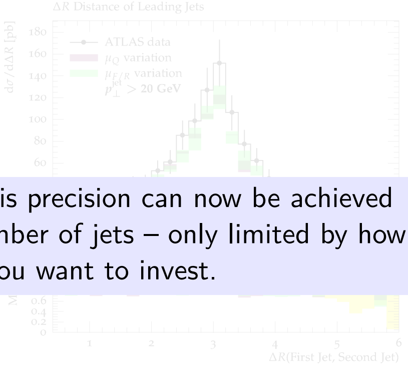
NLO merged results: The end of a 10-year journey



W(+jets) production at ATLAS (PRD 85 (2012) 092002) in PYTHIA8 UNLOPS.

NLO merged results: The end of a 10-year journey





These are just sample plots. This precision can now be achieved for any SM process, with any number of jets – only limited by how much CPU time you want to invest.

W(+jets) production at ATLAS (PRD 85 (2012) 092002) in PYTHIA8 UNLOPS.

Comparison of NLO merging schemes

FxFx: Restricts the range of merging scales. Cross section changes thus numerically small.
Probably fewest counter events.

MEPS@NLO: Improved, colour-correct Sudakov of MC@NLO for the first emission. Larger t_{MS} range.
Smaller cross section changes.
Improved resummation in process-independent way.

UNLOPS: Inclusive observables strictly NLO correct. Further shower improvements also directly improve the results.
Many counter events if done naively.

MiNLO: applies analytical (N)NLL Sudakov factors, which cancel problematic logs, only merging two multiplicities.
Was moulded into an NNLO matching.

Warning

- Fixed-order calculations and parton showers can be combined in many ways.
- A general construction principle is:

  1. Decide on the fixed-order and logarithmic accuracy of the method (and decide what to *call* “logarithm”).
  2. Go for it.
  3. Fix higher orders by personal taste/experience.

  This gives highly biased methods. Almost always, not all choices are considered as uncertainty.
- Personal bias can be minimised by going to higher accuracy.

The next step(s): Matching @ NNLO

Aim: For important processes – lumi monitors like Drell-Yan, precision studies (ggH, ZH, WBF,...) – reduce uncertainties and remove personal bias. But make sure all other improvements stay intact!

Observation: If an NLO merged calculation leads to a well-defined zero-jet inclusive cross section, it is easy to upgrade this cross section to NNLO.

$\Longrightarrow$ Fulfilled by MiNLO and UNLOPS

Ways to matching @ NNLO

$$\mathrm{B}_0\left[\mathcal{O}_0\Pi_{S_{+0}} + \int\limits_1 \frac{\mathrm{B}_1}{\mathrm{B}_0}\mathcal{O}_1\Pi_{S_{+0}}\right] \sim \mathrm{B}_0\mathcal{O}_0 - \int\limits_1 \mathrm{B}_1\mathcal{O}_0\Pi_{S_{+0}} + \int\limits_1 \mathrm{B}_1\mathcal{O}_1\Pi_{S_{+0}}$$

Upgrade Sudakov factor
Analytically $\rightarrow$ MiNLO

Match integral of $q_\perp$ resummation onto 0-jet incl. cross section!

Pro: Should capture all-order structure of theory. Analytic control over probability of 1st emission.

Con: Current incarnation MiNLO-NNLOPS is process-dependent, relies on tabulated differential K-factors.

Subtract what you add
$\rightarrow$ Unitarisation

Reassess which 0-jet inclusive cross section to unitarise to!

Pro: Easy PS implementation, process-independent. Improving PS automatically improves scheme.

Con: Current incarnation UN²LOPS does not shower $\alpha_s^2\delta(p_\perp)$ terms, or only showers a subset – i.e. has bin edges.

- HJ−MiNLO* differential cross section $(d\sigma/dy)_{\mathrm{HJ-MiNLO}}$ is NLO accurate

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

- thus, reweighting each event with this factor, we get NNLO+PS
  * obvious for y_H, by construction
  * α_S^4 accuracy of HJ−MiNLO* in 1-jet region not spoiled, because $W(y) = 1 + \mathcal{O}(\alpha_S^2)$
  * if we had $\mathrm{NLO}^{(0)} + \mathcal{O}(\alpha_S^{2+3/2})$, 1-jet region spoiled because

$$[\mathrm{NLO}^{(1)}]_{\mathrm{NNLOPS}} = \mathrm{NLO}^{(1)} + \mathcal{O}(\alpha_S^{4.5})$$

---

* Variants for W are possible:

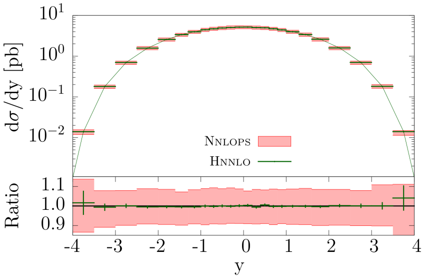
$$W(y, p_T) = h(p_T)\frac{\int d\sigma_A^{\mathrm{NNLO}}\delta(y - y(\mathbf{\Phi}))}{\int d\sigma_A^{\mathrm{MiNLO}}\delta(y - y(\mathbf{\Phi}))} + (1 - h(p_T))$$

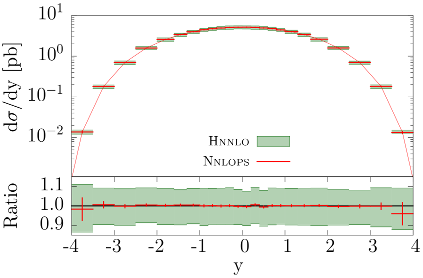
$$d\sigma_A = d\sigma\ h(p_T), \qquad d\sigma_B = d\sigma\ (1 - h(p_T)), \qquad h = \frac{(\beta m_H)^2}{(\beta m_H)^2 + p_T^2}$$

* $h(p_T)$ controls where the NNLO/NLO K-factor is spread
* with above W, we get $(d\sigma/dy)_{\mathrm{NNLOPS}} = (d\sigma_A/dy)_{\mathrm{NNLO}} + (d\sigma_B/dy)_{\mathrm{HJ-MiNLO}}$

Slide taken from Emanuele Re, Talk given at ZPW 2014

- NNLO with $\mu = m_H/2$, `HJ-MiNLO` "core scale" m_H [NNLO from `HNNLO`, Catani,Grazzini]
- $(7_{\mathrm{Mi}} \times 3_{\mathrm{NN}})$ pts scale var. in `NNLOPS`, 7pts in NNLO

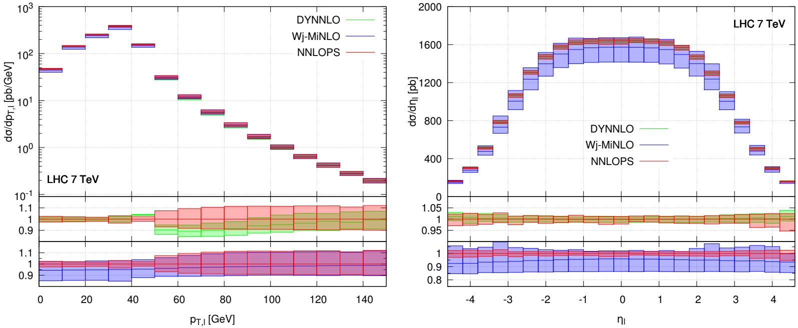




☞ Notice: band is 10%

[Until and including $\mathcal{O}(\alpha_S^4)$, PS effects don't affect y_H (first 2 emissions controlled properly at $\mathcal{O}(\alpha_S^4)$ by MiNLO+POWHEG)]

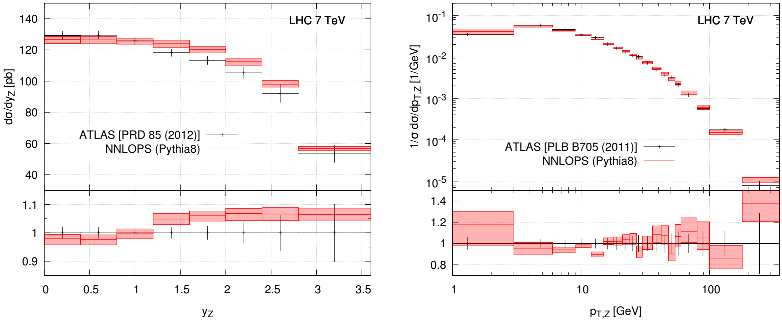
MiNLO charged current Drell-Yan



Transverse momentum and pseudoradidity of the lepton in charged current Drell-Yan.

Plot taken from arXiv:1407.2940

MiNLO neutral current Drell-Yan



Rapidity and transverse momentum of the Drell-Yan pair. Plot taken from arXiv:1407.2940

UN^{2}LOPS matching

Aim: Start from NLO merging of two calculations, improve, then upgrade to NNLO directly.

Statistical convergence of unitarised NLO+PS method is expected to be slow for vanishing merging scales (which we want!) – because of deliberate choices.

Revisit choices and refine the UNLOPS method!
Need Sudakov factors for one-jet virtuals and subtractions.
Issue $\Rightarrow$ Damping will induce non-PS higher orders.
Issue $\Rightarrow$ Careful not to count universal (PS) higher-order corrections twice!
Issue $\Rightarrow$ Theoretically more sensible than previous version.

$\Rightarrow$ UN^{2}LOPS: Self-contained process-independent NNLO+PS matching, based on new fully differential NNLO code in SHERPA.

arXiv:1405.3607 + Phys.Rev. D90 (2014) 5 (Höche, Li, SP)

UN²LOPS in SHERPA includes new fully differential NNLO generators,

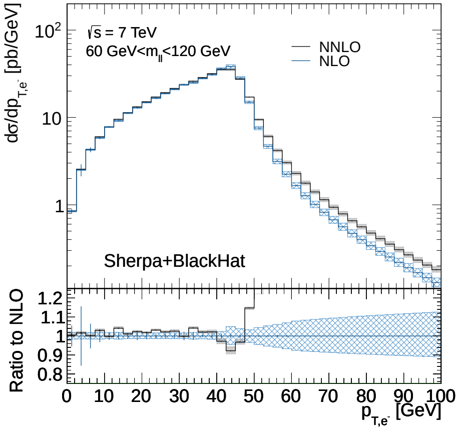
- based on $q_\perp$ subtraction, numerically stable, reasonably fast
- produce event output (HEPMC)
  $\rightarrow$ Easy analysis with standard tools like RIVET
- combined with the parton shower
- combined with QED effects, remnants, MPI, hadronisation...
- can be used as fixed-order code, fixed-order+resummed calculation, or comprehensive event generator.

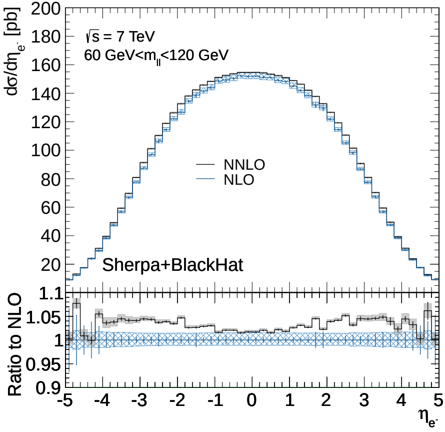
Note: Any PS improvements immediately improve the calculation.

Sherpa plugin code and sample plots available from

`http://www.slac.stanford.edu/~shoeche/pub/nnlo/`

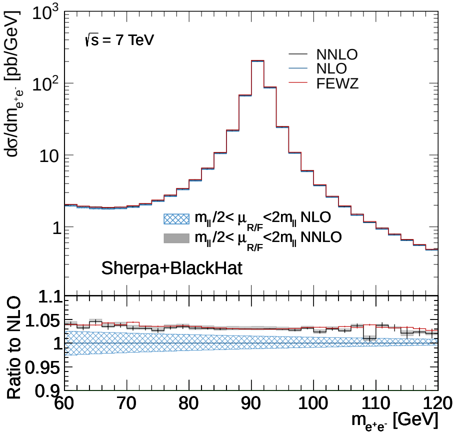
UN^{2}LOPS (neutral current Drell-Yan)

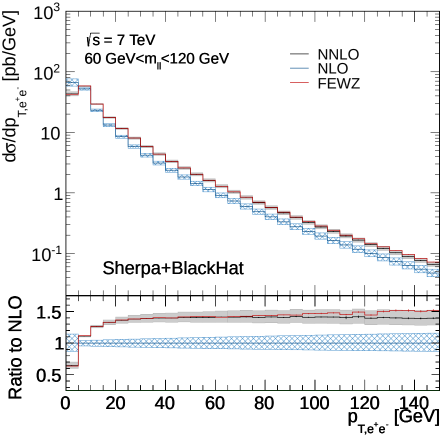




New NNLO calculation is working as expected.

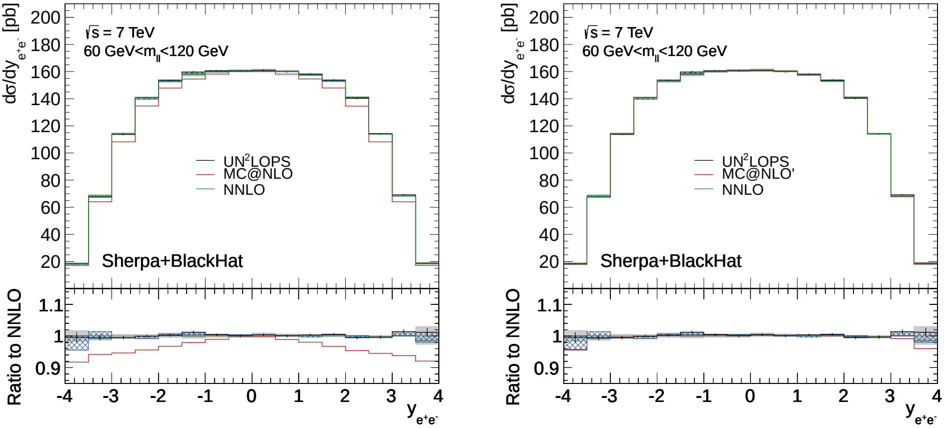
UN^{2}LOPS (neutral current Drell-Yan)





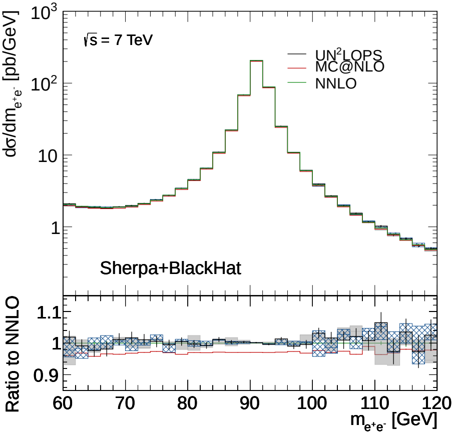
New NNLO calculation is working as expected.

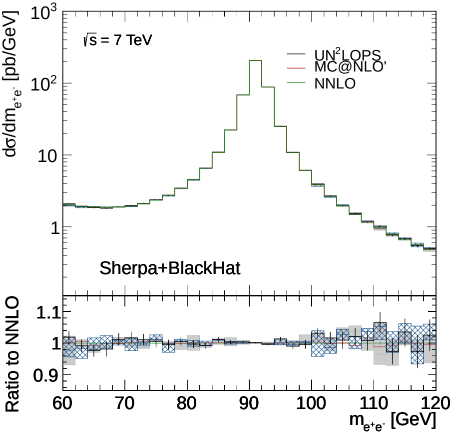
UN^{2}LOPS (neutral current Drell-Yan)



The PDF fitter's secret: NLO calculation with NNLO PDFs reproduces full NNLO.

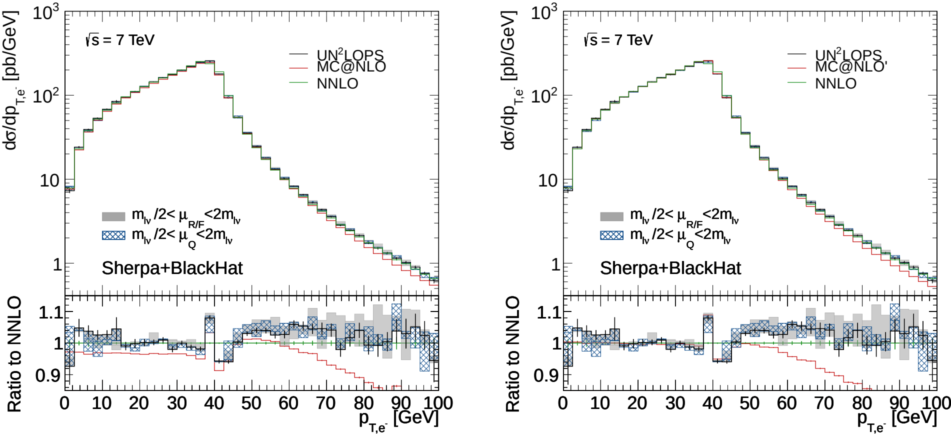
UN^{2}LOPS (neutral current Drell-Yan)





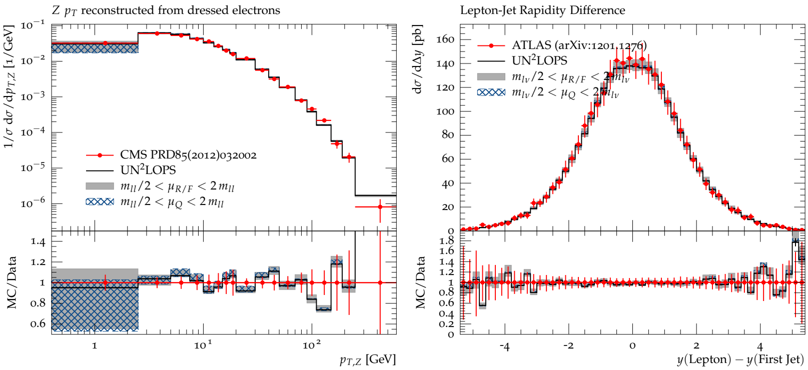
The PDF fitter's secret: NLO calculation with NNLO PDFs reproduces full NNLO.

UN^{2}LOPS (charged current Drell-Yan)



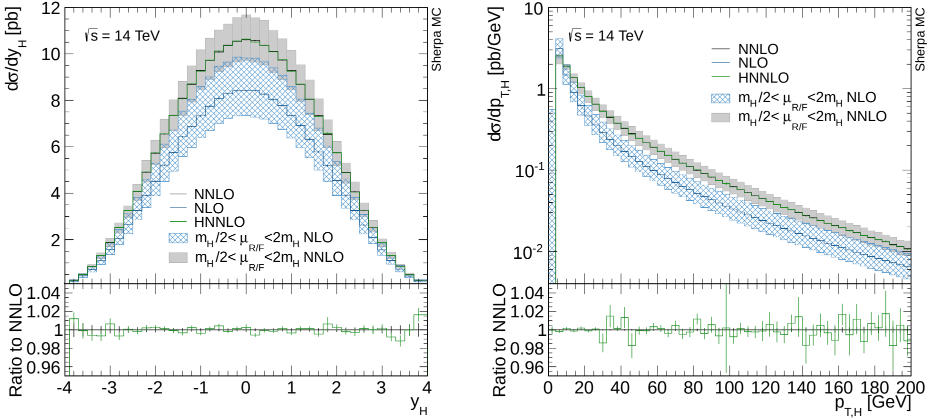
The PDF fitter's secret: NLO calculation with NNLO PDFs reproduces full NNLO... but not everywhere.

UN^{2}LOPS (Drell-Yan)



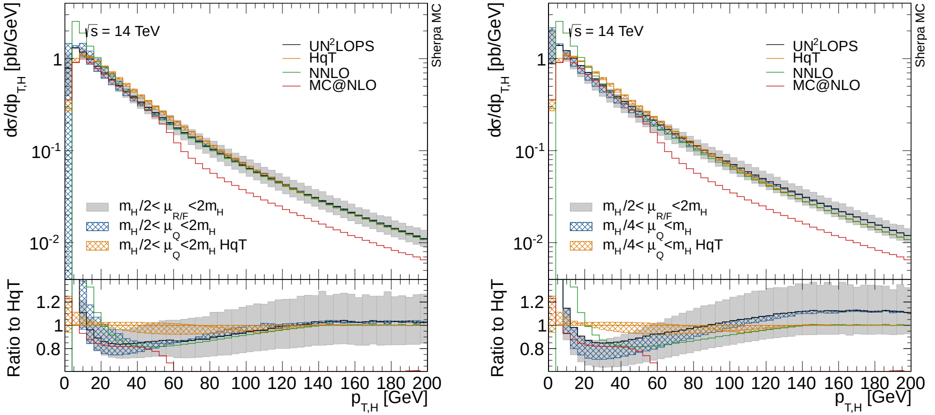
CMS data for Z-boson $p_\perp$. UN^{2}LOPS does quite well. Large band at low $p_\perp$ reflects log scale and shower modelling. ATLAS data for charged current well described.

UN^{2}LOPS (Higgs production)



Rapidity and $p_\perp$ of the Higgs-boson, comparing SHERPA-NNLO and HNNLO. Our independent NNLO calculation works nicely.

UN²LOPS (Higgs production)



$p_\perp$ of the Higgs-boson for two different matching schemes in UN²LOPS – mimicing the philosophical differences between common NLO matching schemes. Might want to improve shower.

Summary

- Fixed-order + parton shower continues to be an active field.
- We can combine multiple LO calculations, or multiple NLO calculations, or match $pp \to colour\ singlett$ at NNLO +PS.
- Two NNLO +PS strategies have been implemented[1]:
  MiNLO-NNLOPS relies on analytic Sudakov factors.
  UN^{2}LOPS relies on unitarisation.
- Ever better measurements need ever better predictions.

  ...we always want better QCD showers
  ...need to think about other enhancement structures
  ...should eventually upgrade to "SM" showers...

Thanks for your time!

[1] A theoretical introduction has been given by the GENEVA collaboration (arXiv:1311.0286).

Back-up supplement

References

POWHEG
JHEP 0411 (2004) 040 JHEP 0711 (2007) 070 POWHEG-BOX (JHEP 1006 (2010) 043)

MC@NLO
Original (JHEP 0206 (2002) 029) Herwig++ (Eur.Phys.J. C72 (2012) 2187)
Sherpa (JHEP 1209 (2012) 049) aMC@NLO (arXiv:1405.0301)

NLO matching results and comparisons
Plots taken from Ann.Rev.Nucl.Part.Sci. 62 (2012) 187 Plots taken from JHEP 0904 (2009) 002

Tree-level merging MLM (Mangano, http://www-cpd.fnal.gov/personal/mrenna/tuning/nov2002/mlm.pdf. Talk presented at the Fermilab ME/MC Tuning Workshop, Oct 4, 2002, Mangano et al. JHEP 0701 (2007) 013)
Pseudoshower (JHEP 0405 (2004) 040)
CKKW (JHEP 0111 (2001) 063, JHEP 0208 (2002) 015)
CKKW-L (JHEP 0205 (2002) 046, JHEP 0507 (2005) 054, JHEP 1203 (2012) 019)
METS (JHEP 0911 (2009) 038, JHEP 0905 (2009) 053)

Unitarised merging
Pythia (JHEP 1302 (2013) 094) Herwig (JHEP 1308 (2013) 114) Sherpa (arXiv:1405.3607)

FxFx: Jet matching @ NLO: JHEP 1212 (2012) 061

MEPS@NLO
JHEP 1304 (2013) 027 JHEP 1301 (2013) 144 Plots taken from arXiv:1401.7971

UNLOPS JHEP 1303 (2013) 166 arXiv:1405.1067

MiNLO: Original (JHEP 1210 (2012) 155) Improved (JHEP 1305 (2013) 082)

MiNLO-NNLOPS: JHEP 1310 (2013) 222 arXiv:1407.2940
arXiv:1501.04637

UN^{2}LOPS: arXiv:1405.3607 arXiv:1407.3773

Parton showers are **unitary** all-order operators:

$$\mathbf{PS}\left[\sigma^{\mathsf{ME}}_{+0}\right]$$

Parton showers are **unitary** all-order operators:

$$\mathbf{PS}\left[\sigma_{+0}^{\mathsf{ME}}\right] = \sigma_{+0}^{\mathsf{PS}} +$$

$$= \sigma_{+0}^{\mathsf{ME}}\Pi_{S_{+0}}\left(\rho_0, \rho_{\mathsf{min}}\right)$$

$$+$$

$\longleftarrow$ 0 emissions in $[\rho_0, \rho_{\mathsf{min}}]$

Parton shower basics

Parton showers are **unitary** all-order operators:

$$
\begin{aligned}
\mathbf{PS}\left[\sigma_{+0}^{\mathsf{ME}}\right] &= \sigma_{+0}^{\mathsf{PS}} + \sigma_{+1}^{\mathsf{PS}} + \\
&= \sigma_{+0}^{\mathsf{ME}}\Pi_{S_{+0}}\left(\rho_0, \rho_{\mathsf{min}}\right) && \longleftarrow \text{0 emissions in } [\rho_0, \rho_{\mathsf{min}}] \\
&+ \sigma_{+0}^{\mathsf{ME}}\Pi_{S_{+0}}\left(\rho_0, \rho_1\right)\alpha_s w_f^0 P_0 \Pi_{S_{+1}}\left(\rho_1, \rho_{\mathsf{min}}\right) && \longleftarrow \text{1 emission in } [\rho_0, \rho_{\mathsf{min}}] \\
&+
\end{aligned}
$$

Parton showers are **unitary** all-order operators:

$$\mathbf{PS}\left[\sigma_{+0}^{\mathsf{ME}}\right] = \sigma_{+0}^{\mathsf{PS}} + \sigma_{+1}^{\mathsf{PS}} + \sigma_{+\geq 2}$$

$$= \sigma_{+0}^{\mathsf{ME}}\Pi_{S_{+0}}(\rho_0, \rho_{\mathrm{min}}) \longleftarrow \text{0 emissions in } [\rho_0, \rho_{\mathrm{min}}]$$

$$+ \sigma_{+0}^{\mathsf{ME}}\Pi_{S_{+0}}(\rho_0, \rho_1)\,\alpha_s w_f^0 P_0 \Pi_{S_{+1}}(\rho_1, \rho_{\mathrm{min}}) \longleftarrow \text{1 emission in } [\rho_0, \rho_{\mathrm{min}}]$$

$$+ \sigma_{+0}^{\mathsf{ME}}\Pi_{S_{+0}}(\rho_0, \rho_1)\,\alpha_s w_f^0 P_0 \Pi_{S_{+1}}(\rho_1, \rho_2)\,\alpha_s w_f^1 P_1 \left[\Pi_{S_{+2}}(\rho_2, \rho_{\mathrm{min}}) + \ldots\right]$$

2 or more emissions in $[\rho_0, \rho_{\mathrm{min}}]$

$$\stackrel{!}{=} \sigma_{+0}^{\mathsf{ME}}$$

Parton shower basics

Parton showers are **unitary** all-order operators:

$$
\begin{aligned}
\mathbf{PS}\left[\sigma^{\mathsf{ME}}_{+0}\right] &= \sigma^{\mathsf{PS}}_{+0} + \sigma^{\mathsf{PS}}_{+1} + \sigma_{+\geq 2} \\
&= \sigma^{\mathsf{ME}}_{+0}\Pi_{S_{+0}}(\rho_0, \rho_{\mathsf{min}}) \quad \longleftarrow \boxed{\text{0 emissions in } [\rho_0, \rho_{\mathsf{min}}]} \\
&+ \sigma^{\mathsf{ME}}_{+0}\Pi_{S_{+0}}(\rho_0, \rho_1)\,\alpha_s w_f^0 P_0 \Pi_{S_{+1}}(\rho_1, \rho_{\mathsf{min}}) \quad \longleftarrow \boxed{\text{1 emission in } [\rho_0, \rho_{\mathsf{min}}]} \\
&+ \sigma^{\mathsf{ME}}_{+0}\Pi_{S_{+0}}(\rho_0, \rho_1)\,\alpha_s w_f^0 P_0 \Pi_{S_{+1}}(\rho_1, \rho_2)\,\alpha_s w_f^1 P_1 \left[\Pi_{S_{+2}}(\rho_2, \rho_{\mathsf{min}}) + \ldots\right]
\end{aligned}
$$

$$\boxed{\text{2 or more emissions in } [\rho_0, \rho_{\mathsf{min}}]}$$

$$\stackrel{!}{=} \sigma^{\mathsf{ME}}_{+0}$$

The no-emission probabilities

$$\Pi_{S_{+i}}(\rho_1, \rho_2) = \exp\left\{-\int_{\rho_2}^{\rho_1} d\rho\, \alpha_s w_f^i P_i\right\}$$

define *exclusive* cross sections and remove the overlap between samples!

CKKW(-L)

Aim: Combine multiple tree-level calculations with each other and (PS) resummation. Fill in soft and collinear regions with parton shower.

$$
\begin{aligned}
\langle\mathcal{O}\rangle \quad &= \mathrm{B}_0\mathcal{O}(S_{+0j}) \\
&\qquad\qquad - \int d\rho\ \mathrm{B}_0 P_0(\rho)\Theta_{>}^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0,\rho)\mathcal{O}(S_{+0j}) \\
&+ \int \mathrm{B}_1\Theta_{>}^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0,\rho)\mathcal{O}(S_{+1j}) \\
&\qquad\qquad - \int d\rho\ \mathrm{B}_1 P_1(\rho)\Theta_{>}^{(2)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0,\rho_1)\Pi_{S_{+1}}(\rho_1,\rho)\mathcal{O}(S_{+1j}) \\
&+ \int \mathrm{B}_2\Theta_{>}^{(2)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0,\rho_1)\Pi_{S_{+1}}(\rho_1,\rho)\mathcal{O}(S_{+2j})
\end{aligned}
$$

Changes inclusive cross sections

$\Longrightarrow$ Can contain numerically large (sub-leading) logs.

$\Longrightarrow$ Needs fixing!

Bug vs. Feature in CKKW(-L)

The ME includes terms that are not compensated by the PS approximate virtual corrections (i.e. Sudakov factors).

These are the improvements that we need to describe multiple hard jets!

If we simply add samples, the "improvements" will degrade the inclusive cross section: σ_{inc} will contain $\ln(t_{\mathrm{MS}})$ terms.

THE INCLUSIVE CROSS SECTION DOES NOT CONTAIN LOGS RELATED TO CUTS ON HIGHER MULTIPLICITIES.

Traditional approach: Don't use a too small merging scale.

$\rightarrow$ Uncancelled terms numerically not important.

Unitary approach[1]:

Use a (PS) unitarity inspired approach exactly cancel the dependence of the inclusive cross section on t_{MS}.

[1] JHEP1302(2013)094 (Leif Lönnblad, SP), JHEP1308(2013)114 (Simon Plätzer)

Unitarised ME+PS

Aim: If you add too much, then subtract what you add!

$$
\begin{aligned}
\langle \mathcal{O} \rangle \quad &= \mathrm{B}_0 \mathcal{O}(S_{+0j}) \\
&\quad - \int d\rho\ \mathrm{B}_1 \Theta_>^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho) \mathcal{O}(S_{+0j}) - \int d\rho\ \mathrm{B}_2 \Theta_>^{(2)} \Theta_<^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho) \mathcal{O}(S_{+0j}) \\
&+ \int \mathrm{B}_1 \Theta_>^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho) \mathcal{O}(S_{+1j}) \\
&\quad - \int d\rho\ \mathrm{B}_2 \Theta_>^{(2)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho_1) \Pi_{S_{+1}}(\rho_1, \rho) \mathcal{O}(S_{+1j}) \\
&+ \int \mathrm{B}_2 \Theta_>^{(2)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho_1) \Pi_{S_{+1}}(\rho_1, \rho) \mathcal{O}(S_{+2j}) + \int \mathrm{B}_2 \Theta_>^{(2)} \Theta_<^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho_1) \mathcal{O}(S_{+
\end{aligned}
$$

Inclusive cross sections preserved by construction.
Cancellation between different "jet bins".
$\Rightarrow$ Statistics needs fixing.

NLO matching with MC@NLO

Aim: Achieve NLO for inclusive +0-jet, and LO for inclusive +1-jet observables and attach PS resummation.

To get there, remember that the (regularised) NLO cross section is

$$\begin{aligned}
\mathrm{B}_{\mathrm{NLO}} &= \left[\mathrm{B}_n + \mathrm{V}_n + \mathrm{I}_n\right]\mathcal{O}_0 + \int d\Phi_{\mathrm{rad}}\left(\mathrm{B}_{n+1}\mathcal{O}_1 - \mathrm{D}_{n+1}\mathcal{O}_0\right) \\
&= \left[\mathrm{B}_n + \mathrm{V}_n + \mathrm{I}_n\right]\mathcal{O}_0 + \int d\Phi_{\mathrm{rad}}\left(\mathrm{S}_{n+1}\mathcal{O}_0 - \mathrm{D}_{n+1}\mathcal{O}_0\right) \\
&\quad + \int d\Phi_{\mathrm{rad}}\left(\mathrm{S}_{n+1}\mathcal{O}_1 - \mathrm{S}_{n+1}\mathcal{O}_0\right) + \int d\Phi_{\mathrm{rad}}\left(\mathrm{B}_{n+1}\mathcal{O}_1 - \mathrm{S}_{n+1}\mathcal{O}_1\right)
\end{aligned}$$

where S_{n+1} are some additional "transfer functions", e.g. the PS kernels.

Red term is the $\mathcal{O}(\alpha_s)$ part of a shower from B_n. $\Rightarrow$ Discard from $\mathrm{B}_{\mathrm{NLO}}$.

Thus, we have the seed cross section

$$\widehat{\mathrm{B}}_{\mathrm{NLO}} = \left[\mathrm{B}_n + \mathrm{V}_n + \mathrm{I}_n + \int d\Phi_{\mathrm{rad}}\left(\mathrm{S}_{n+1} - \mathrm{D}_{n+1}\right)\right]\mathcal{O}_0 + \int d\Phi_{\mathrm{rad}}\left(\mathrm{B}_{n+1} - \mathrm{S}_{n+1}\right)\mathcal{O}_1$$

This is not the NLO result…but showering the $\mathcal{O}_0$-part will restore this!

UMEPS, MC@NLO-style (Plätzer)

Aim: Combine multiple tree-level calculations with each other and (PS) resummation. Fill in soft and collinear regions with parton shower.

$$
\begin{aligned}
\langle \mathcal{O} \rangle \quad &= \mathrm{B}_0 \Pi_{S_{+0}}(\rho_0, \rho_{\mathrm{MS}}) \mathcal{O}(S_{+0j}) \\
&\quad - \int d\rho \; [\mathrm{B}_1 - \mathrm{B}_0 P_0(\rho)] \, \Theta_{>}^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho) \mathcal{O}(S_{+0j}) \\
&+ \int \mathrm{B}_1 \Theta_{>}^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho) \Pi_{S_{+1}}(\rho, \rho_{\mathrm{MS}}) \mathcal{O}(S_{+1j}) \\
&\quad - \int d\rho \; [\mathrm{B}_2 - \mathrm{B}_1 P_1(\rho)] \, \Theta_{>}^{(2)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho_1) \Pi_{S_{+1}}(\rho_1, \rho) \mathcal{O}(S_{+1j}) \\
&+ \int \mathrm{B}_2 \Theta_{>}^{(2)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho_1) \Pi_{S_{+1}}(\rho_1, \rho) \mathcal{O}(S_{+2j}) \; + \int \mathrm{B}_2 \Theta_{>}^{(2)} \Theta_{<}^{(1)} w_f w_{\alpha_s} \Pi_{S_{+0}}(\rho_0, \rho_1) \mathcal{O}(S_{+2
\end{aligned}
$$

Inclusive cross sections preserved by construction.
Less cancellation between different "jet bins" fixed.
$\Longrightarrow$ Statistics okay.

The UNLOPS method

Start with UMEPS:

$$\langle \mathcal{O} \rangle = \int d\phi_0 \left\{ \mathcal{O}(S_{+0j}) \left(\mathrm{B}_0 + \qquad - \int \widehat{\mathrm{B}}_{1\to 0} \qquad - \int \widehat{\mathrm{B}}_{2\to 0} \right) \right.$$
$$\left. + \int \mathcal{O}(S_{+1j}) \left(\qquad \widehat{\mathrm{B}}_1 \qquad - \int \widehat{\mathrm{B}}_{2\to 1} \qquad \right) + \int\!\!\int \mathcal{O}(S_{+2j}) \widehat{\mathrm{B}}_2 \right\}$$

Remove all unwanted $\mathcal{O}(\alpha_s^n)$- and $\mathcal{O}(\alpha_s^{n+1})$-terms:

$$\langle\mathcal{O}\rangle = \int d\phi_0 \Bigg\{ \mathcal{O}(S_{+0j}) \Bigg(- \left[\int \widehat{\mathrm{B}}_{1\to 0}\right]_{-1,2} - \int \widehat{\mathrm{B}}_{2\to 0} \Bigg) + \int \mathcal{O}(S_{+1j}) \Bigg(\left[\widehat{\mathrm{B}}_1\right]_{-1,2} - \left[\int \widehat{\mathrm{B}}_{2\to 1}\right]_{-2} \Bigg) + \int\!\!\int \mathcal{O}(S_{+2j})\widehat{\mathrm{B}}_2 \Bigg\}$$

Add full NLO results:

$$\langle\mathcal{O}\rangle = \int d\phi_0 \Bigg\{ \mathcal{O}(S_{+0j}) \Bigg(\widetilde{\mathrm{B}}_0 - \left[\int \widehat{\mathrm{B}}_{1\to0} \right]_{-1,2} - \int \widehat{\mathrm{B}}_{2\to0} \Bigg) + \int \mathcal{O}(S_{+1j}) \Bigg(\widetilde{\mathrm{B}}_1 + \left[\widehat{\mathrm{B}}_1 \right]_{-1,2} - \left[\int \widehat{\mathrm{B}}_{2\to1} \right]_{-2} \Bigg) + \int\!\!\int \mathcal{O}(S_{+2j}) \widehat{\mathrm{B}}_2 \Bigg\}$$

Unitarise:

$$\langle\mathcal{O}\rangle = \int d\phi_0 \Bigg\{ \mathcal{O}(S_{+0j}) \Bigg(\widetilde{\mathrm{B}}_0 - \int_s \widetilde{\mathrm{B}}_{1\to 0} + \int_s \mathrm{B}_{1\to 0} - \left[\int \widehat{\mathrm{B}}_{1\to 0} \right]_{-1,2} - \int_s \mathrm{B}^{\uparrow}_{2\to 0} - \int \widehat{\mathrm{B}}_{2\to 0} \Bigg)$$

$$+ \int \mathcal{O}(S_{+1j}) \left(\widetilde{\mathrm{B}}_1 + \left[\widehat{\mathrm{B}}_1 \right]_{-1,2} - \left[\int \widehat{\mathrm{B}}_{2\to 1} \right]_{-2} \right) + \int\!\!\int \mathcal{O}(S_{+2j}) \widehat{\mathrm{B}}_2 \Bigg\}$$

Deriving an UN²LOPS matching

We basically follow a "merging strategy":

- Pick calculations to combine (two MC@NLOs) with each other *and* with the PS resummation.
- Remove kinematic overlaps between the two MC@NLOs by dividing the one-jet phase space.
- Reweight one-jet MC@NLO (*to make it exclusive* $\leftrightarrow$ *want to describe hardest jet with this*),
  remove all undesired terms at $\mathcal{O}(\alpha_s^{1+1})$
  and make sure that the whole thing is numerically stable.
  Reweight subtractions with $\Pi_{S_{+0}}$ to be able to group them with virtuals.
- Add and subtract reweighted one-jet MC@NLO, ($\rightarrow$ unitarise) to ensure inclusive zero-jet cross section is unchanged w.r.t. NLO.
- Remove all terms up to $\mathcal{O}(\alpha_s^2)$ in the zero-jet contribution, replace by NNLO jet-vetoed cross section.

Aim: Combine just two NLO calculations, then upgrade to NNLO directly.

Work with Stefan Höche and Ye Li.

UN^{2}LOPS matching

Aim: Combine just two NLO calculations, then upgrade to NNLO directly.

Start over again, now combining MC@NLO's because those are resonably stable. Thus:

- ◇ Use 0-jet matched (MC@NLO $_0$) and 1-jet matched calculation (MC@NLO $_1$).
- ◇ Remove hard ($q_T > \rho_{\rm MS}$) reals in MC@NLO $_0$.
- ◇ Reweight B_1 of MC@NLO $_1$ with "zero-jet Sudakov" factor $\Pi_{S_{+0}}/\alpha_s$ running.
- ◇ Reweight NLO part $\widetilde{\mathrm{B}}_1^{\mathrm{R}}$ of MC@NLO $_1$ with "zero-jet Sudakov" factor.
- ◇ Subtract erroneous $\mathcal{O}(\alpha_s^{+1})$ terms multiplying B_1.
- ◇ Reweight subtractions with $\Pi_{S_{+0}}$ to be able to group them with $\widetilde{\mathrm{B}}_1^{\mathrm{R}}$.
- ◇ Put $\rho_{\rm MS} \to \rho_c < 1$GeV. ($\to$ MC@NLO $_0$ becomes exclusive NLO)
- ◇ Unitarise by subtracting the processed MC@NLO $'_1$ from the "zero-q_T bin".
- ◇ Remove all terms up to α_s^2 from the "zero-q_T bin" and add the q_T-vetoed NNLO cross section.

$\Rightarrow$ $\sigma_{inclusive}$ @ NNLO, resummation as accurate as Sudakov, stats fine.
NNLO logarithmic parts from q_T-vetoed TMDs (EFT calculation),
hard coefficients from q_T-subtraction (i.e. DYNNLO, HNNLO),
power corrections from MC@NLO $_1$.

Work with Stefan Höche and Ye Li.

UN^{2}LOPS matching

$$
\begin{aligned}
\mathcal{O}^{(\mathrm{UN^2LOPS})} = &\int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_{T,\mathrm{cut}}}(\Phi_0)\, O(\Phi_0) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1(\Phi_1)\, O(\Phi_0) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1,O) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1,O) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_2 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \Pi_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2,O) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2,O)
\end{aligned}
$$

$$\mathcal{O}^{(\mathrm{UN^2LOPS})} = \int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_{T,\mathrm{cut}}}(\Phi_0)\, O(\Phi_0)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1(\Phi_1)\, O(\Phi_0)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_2 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \Pi_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2, O)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2, O)$$

Note that this is just an extention of the old Sudakov veto algorithm:
Run trial shower on the reconstructed zero-jet state,
If trial shower produces an emission, keep zero-jet kinematics and stop;
else start PS off one-jet state.

$$
\begin{aligned}
\mathcal{O}^{(\mathrm{UN^2LOPS})} = & \int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_{T,\mathrm{cut}}}(\Phi_0)\, O(\Phi_0) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1(\Phi_1)\, O(\Phi_0) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1,O) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1,O) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_2 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \Pi_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2,O) \\
& + \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2,O)
\end{aligned}
$$

Note: $\left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}$ etc. comes from using q_T-vetoed cross sections.

UN^{2}LOPS matching

$$\mathcal{O}^{(\mathrm{UN^2LOPS})} = \int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_{T,\mathrm{cut}}}(\Phi_0)\, O(\Phi_0)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1(\Phi_1)\, O(\Phi_0)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_2 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \Pi_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2, O)$$

$$+ \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2, O)$$

$$\bar{\bar{\mathrm{B}}}_0^{q_{T,\mathrm{cut}}} + \tilde{\mathrm{B}}_1^{\mathrm{R}} + \mathrm{H}_1^{\mathrm{R}} + \mathrm{H}_1^{\mathrm{E}} = \mathrm{B}_{\mathrm{NNLO}}$$

Other terms drop out in inclusive observables.

UN²LOPS matching

$$
\begin{aligned}
\mathcal{O}^{(\mathrm{UN^2LOPS})} = &\int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_{T,\mathrm{cut}}}(\Phi_0)\, O(\Phi_0) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1(\Phi_1)\, O(\Phi_0) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_2 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, O(\Phi_0) + \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \Pi_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2, O) \\
&+ \int_{q_{T,\mathrm{cut}}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2, O)
\end{aligned}
$$

Orange terms do not contain any universal α_s corrections present in the PS.
H_1 do not contribute in the soft/collinear limit.
$\Longrightarrow$ PS accuracy is preserved.