

Recent developments

in

Monte-Carlo Event Generators

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FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

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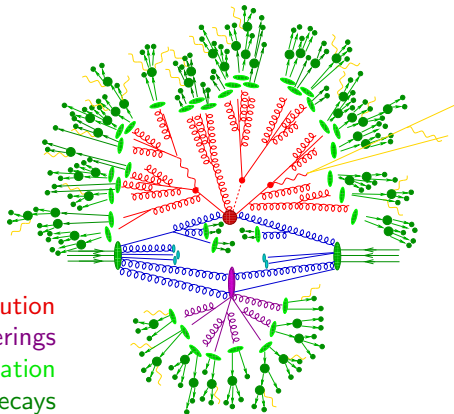
- 1 Parton shower developments
 - Higher precision in parton showers
 - Electroweak corrections in parton showers
- 2 Matching fixed order calculations to parton showers
 - Matching NLO calculations to parton showers
 - Matching NNLO calculations to parton showers
- 3 Multijet merging at higher accuracy
 - Merging multiple matched calculations of successive jet multiplicity
 - Examples

Introduction

Monte-Carlo event generators are the workhorses for collider physics analyses

- provide fully exclusive stable final state: e^\mp , μ^\mp , γ , π^\pm , K^\pm , K_L , p^\pm , n , ...
- factorise dynamics into event stages at different energy regimes and characteristic scales, roughly:

primary hard scattering and parton evolution
 secondary soft scatterings
 hadronisation
 hadron decays



Construction principle behind HERWIG++, PYTHIA8 and SHERPA

Introduction

Monte-Carlo event generators are the workhorses for collider physics analyses

- allows to be used as data stand-in
 - calculate realistic expectation values for measurable observables
 - extrapolate into unmeasurable regions
 - calculate signal/background composition
 - ...
- necessitates highest precision
 - focus in recent years has been on improving the perturbative accuracy of the hard scattering
 - very little to no development in non-perturbative regimes

State of the art a few years ago

NLOPS – MC@NLO, POWHEG

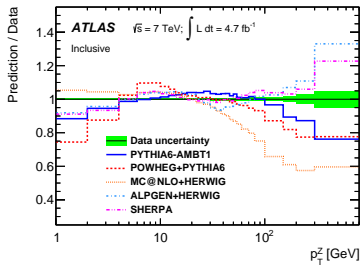
- one process/signature described at NLO
- matched to PS for further emissions

ATLAS arXiv:1406.3660

MEPs – CKKW, MLM

- simultaneously description of processes/signatures of successive jet multies at LO, e.g. $pp \rightarrow W + 1, 2, 3, \dots$ jets
- embeds them in parton shower evolution

⇒ **work well, but ideally combine approaches**



State of the art a few years ago

ATLAS arXiv:1304.7098

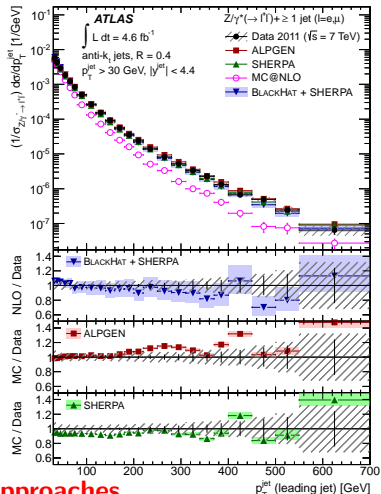
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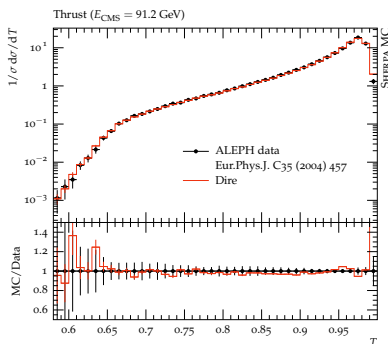
Improved analytical understanding

Höche, Prestel arXiv:1506.05057

Premise: build parton shower with controlled resummation behaviour

- dipole shower for controlled collinear and soft limits
- fulfills all momentum and flavour sum rules
- correct anomalous dimensions
- data description also good

DIRE – dipole resummation



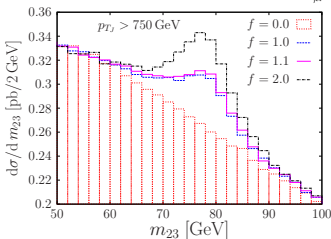
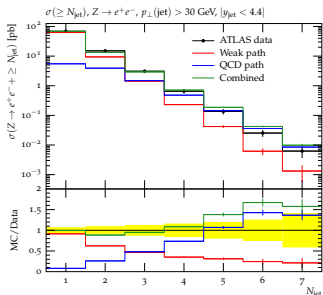


Parton shower developments

Electroweak corrections in parton showers

- add splitting functions for W^\pm , Z , problem: highly spin dependent
- ME to correct first emission
Christiansen, Sjöstrand arXiv:1401.5238
- $E_V \gg m_V$ limit with prefactors to account for spin composition
Krauss, Petrov, MS, Spannowsky arXiv:1402.XXXX
- interleaved evolution can lead to same signatures from different starting points, e.g. $pp \rightarrow Wjj$ from $pp \rightarrow W$ and 2 QCD emissions or $pp \rightarrow jj$ and W emission

No generic solution in spin-averaged parton shower



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NLOPs matching

- Two traditional schemes

MC@NLO

Frixione, Webber [hep-ph/0204244](#)

POWHEG

Nason [hep-ph/0409146](#), Frixione, Nason, Oleari [arXiv:0709.2092](#)

⇒ two sides of the same medal

Höche, Krauss, MS, Siegert [arXiv:1111.1220](#)

$$d\sigma = \bar{B}_0(\Phi_0) \overline{PS}_0(t_{\max}) + \left[R_0 - \overline{PS}_0^{(1)} \right] (\Phi_1) PS_1(t_1)$$

NLO correction smeared through resummation phase space

- A differing scheme

UNLOPS

Lönnblad, Prestel [arXiv:1211.7278](#)

$$d\sigma = B_0(\Phi_0) \overline{PS}_0(\mu_Q^2) + \left[R_0 - \overline{PS}_0^{(1)} \right] (\Phi_1) PS_1(t_1) \\ + \left[\bar{B}_0 - B_0 \right] (\Phi_0)$$

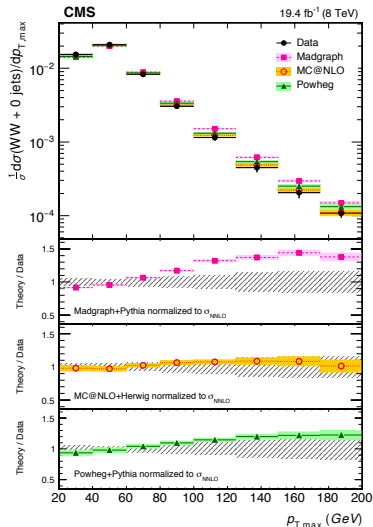
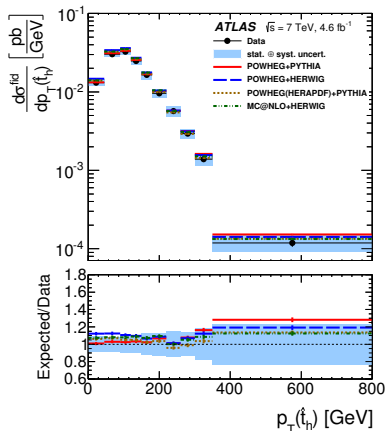
NLO correction localised in Born phase space, not showered

⇒ **same formal accuracy, differ at $O(\alpha_s^2)$**

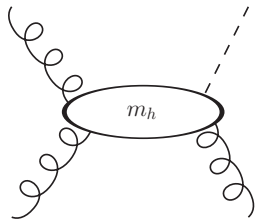
MC@NLO and POWHEG

CMS arXiv:1507.03268

ATLAS arXiv:1502.05923

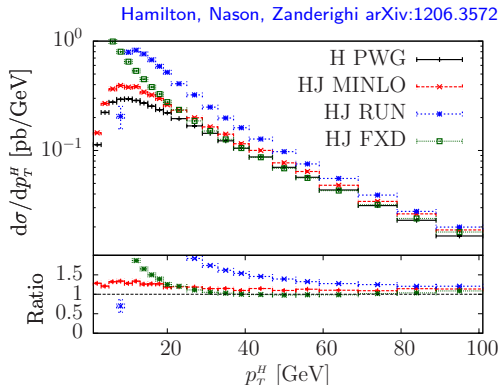


CKKW/MiNLO



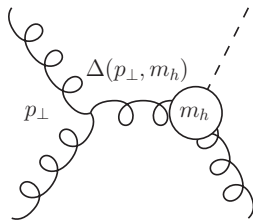
Example $pp \rightarrow h + j$:

$$\alpha_s^3(\mu_R) = \alpha_s^3(m_h)$$



- Sudakov resums $p_{\perp}(j)$ in $pp \rightarrow hj$ wrt. $pp \rightarrow h$
- local scale choice resums logs associated with emission
- ⇒ embeds first emission in evolution off $pp \rightarrow h$ process
- necessary for MEPS merging, improves NLOs with $\langle n \rangle > 1$ jet in Φ_0

CKKW/MiNLO

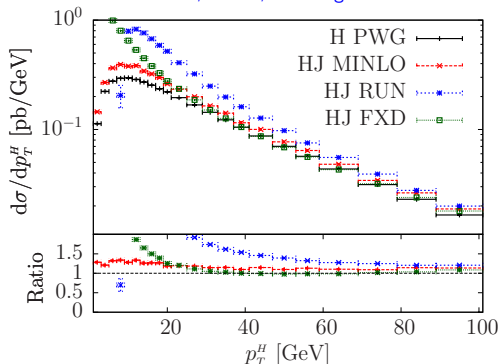


Example $pp \rightarrow h + j$:

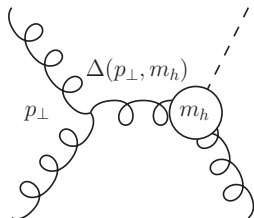
$$\alpha_s^3(\tilde{\mu}_R) = \alpha_s^2(m_h)\alpha_s(p_\perp)$$

- Sudakov resums $p_\perp(j)$ in $pp \rightarrow hj$ wrt. $pp \rightarrow h$
 - local scale choice resums logs associated with emission
- ⇒ embeds first emission in evolution off $pp \rightarrow h$ process
- necessary for MEPS merging, improves NLOPS with ≥ 1 jet in Φ_0

Hamilton, Nason, Zanderighi arXiv:1206.3572



MiNLO

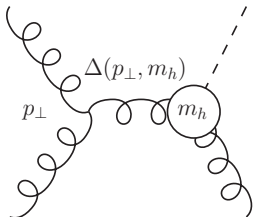


Example $pp \rightarrow h + j$:

$$\alpha_s^3(\tilde{\mu}_R) = \alpha_s^2(m_h)\alpha_s(p_\perp)$$

- inclusion of Sudakov of appropriate logarithmic accuracy leads to finite result as $p_\perp(j) \rightarrow 0$
 - inclusion of process dependent coefficients in Sudakov reaches NLO accuracy for $pp \rightarrow h$ as $p_\perp(j) \rightarrow 0$
- ⇒ simultaneous NLO accurate description of $pp \rightarrow h$ and $pp \rightarrow h + j$

MiNLO

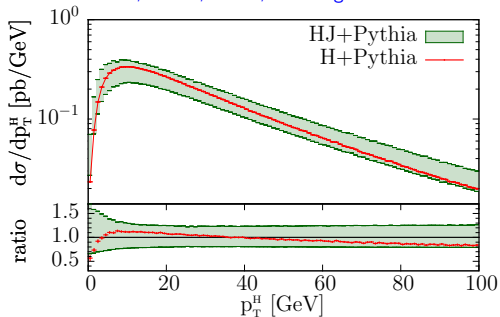


Example $pp \rightarrow h + j$:

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- inclusion of Sudakov of appropriate logarithmic accuracy leads to finite result as $p_\perp(j) \rightarrow 0$
 - inclusion of process dependent coefficients in Sudakov reaches NLO accuracy for $pp \rightarrow h$ as $p_\perp(j) \rightarrow 0$
- ⇒ simultaneous NLO accurate description of $pp \rightarrow h$ and $pp \rightarrow h + j$

Hamilton, Nason, Oleari, Zanderighi arXiv:1212.4504



NNLOPs

Two approaches

- POWHEG/MiNLO + reweighting

$$pp \rightarrow h \quad \text{Hamilton, Nason, Re, Zanderighi arXiv:1309.0017}$$

$$pp \rightarrow \ell^+ \ell^- \quad \text{Karlberg, Re, Zanderighi arXiv:1407.2940}$$

- S-MC@NLO + UNLOPs + q_\perp -slicing

$$pp \rightarrow \ell^+ \ell^- \quad \text{Höche, Li, Prestel arXiv:1405.3607}$$

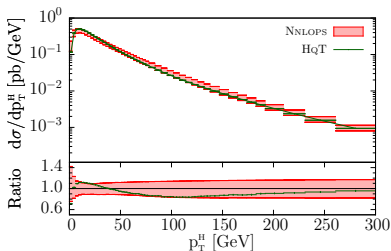
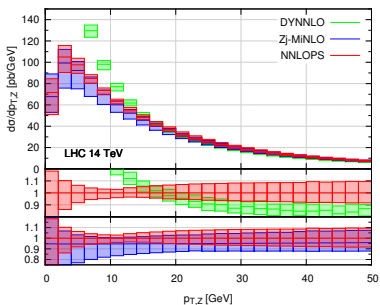
$$pp \rightarrow h \quad \text{Höche, Li, Prestel arXiv:1407.3773}$$

both are not “proper” NNLOPs matchings but rather exploit the simplified structure of logarithms and NNLO correction in singlet production

NNLOs with POWHEG/MinLO + reweighting

Hamilton, Nason, Re, Zanderighi arXiv:1309.0017, Karlberg, Re, Zanderighi arXiv:1407.2940

A simulation that is accurate to NLO in both Φ_0 and Φ_1 can be reweighted differentially in Φ_0 to NNLO.

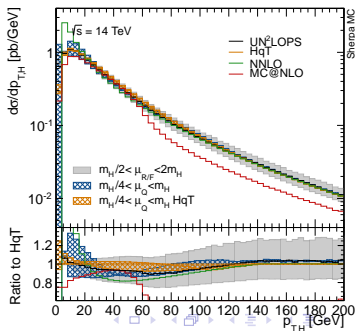
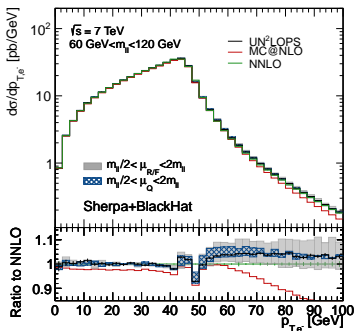




NNLOs with S-Mc@NLO + UNLOs + q_{\perp} -slicing

Höche, Li, Prestel arXiv:1405.3607, arXiv:1407.3773

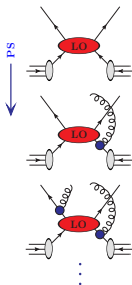
Φ_0 is localised at $q_{\perp} = 0$. For $q_{\perp} > q_{\perp, \text{cut}}$ ($q_{\perp, \text{cut}} < t_c$) a S-Mc@NLO calculation in Φ_1 can be used to complement an exclusive NNLO calculation at zero q_{\perp} . Overlaps of the Sudakov form factor and the NNLO calculation have to be subtracted, e.g. UNLOs-style.



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Multijet merging at LO

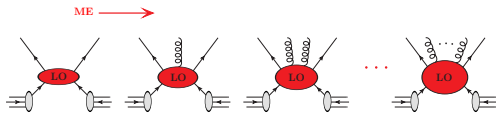


Parton showers

resummation of (soft-)collinear limit
→ intrajet evolution

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- multiplicities are defined using resolution criterion → merging cut

Multijet merging at LO



Matrix elements

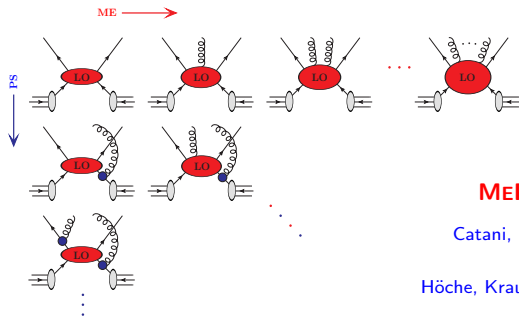
fixed-order in α_s

→ hard wide-angle emissions

→ interference terms

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
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Multijet merging at LO



MEPS (CKKW, MLM)

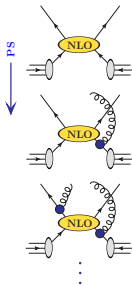
Catani, Krauss, Kuhn, Webber JHEP11(2001)063

Lönnblad JHEP05(2002)046

Höche, Krauss, Schumann, Siebert JHEP05(2009)053

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
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Multijet merging at NLO



NLOs (Mc@NLO, POWHEG)

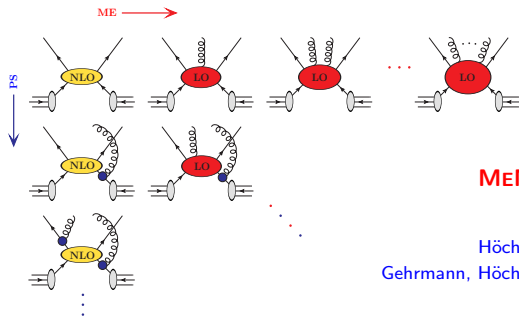
Frixione, Webber JHEP06(2002)029

Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070

Höche, Krauss, MS, Siegert JHEP09(2012)049

- NLOs elevate LOPs to NLO accuracy
- MENLOs supplements core NLOs with higher multiplicities LOPs
- MEPS@NLO combines multiple NLOs – keeping either accuracy
- all methods need resolution criterion separating n and $n + 1$ jet calculations

Multijet merging at NLO



MENLOPS

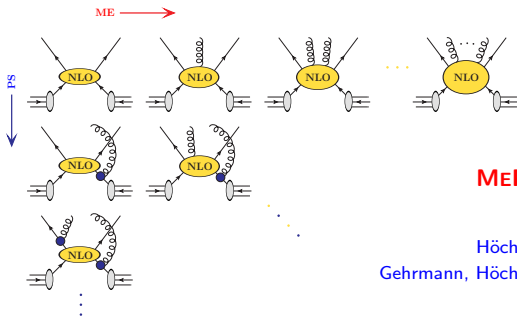
Hamilton, Nason JHEP06(2010)039

Höche, Krauss, MS, Siebert JHEP08(2011)123

Gehrmann, Höche, Krauss, MS, Siebert JHEP01(2013)144

- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
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Multijet merging at NLO



MEPs@NLO

Lavesson, Lönnblad JHEP12(2008)070

Höche, Krauss, MS, Siebert JHEP04(2013)027

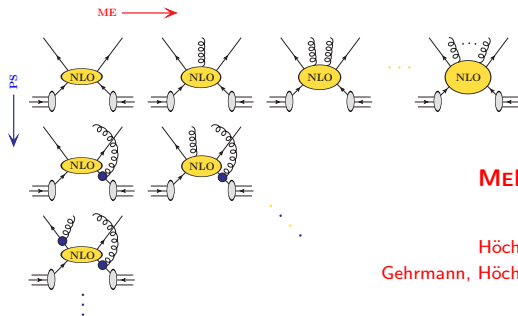
Gehrmann, Höche, Krauss, MS, Siebert JHEP01(2013)144

Lönnblad, Prestel JHEP03(2013)166

Plätzer JHEP08(2013)114

- NLOPS elevate LOPS to NLO accuracy
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Multijet merging at NLO



MEPs@NLO

Lavesson, Lönnblad JHEP12(2008)070

Höche, Krauss, MS, Siebert JHEP04(2013)027

Gehrmann, Höche, Krauss, MS, Siebert JHEP01(2013)144

Lönnblad, Prestel JHEP03(2013)166

Plätzer JHEP08(2013)114

- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
- **MEPs@NLO combines multiple NLOPS – keeping either accuracy**
- all methods need resolution criterion separating n and $n + 1$ jet calculations

Multijet merging at NLO

MEPS@NLO

Höche, Krauss, MS, Siegert [arXiv:1207.5030](https://arxiv.org/abs/1207.5030)

Gehrmann, Höche, Krauss, MS, Siegert [arXiv:1207.5031](https://arxiv.org/abs/1207.5031)

- generalisation of CKKW to NLO accuracy, proof along the same lines
- merges NLOPS (S-Mc@NLO) instead of LOPS for each multiplicity

FxFx

Frederix, Frixione [arXiv:1209.6215](https://arxiv.org/abs/1209.6215)

- generalisation of MLM to NLO accuracy, as at LO proof not provided yet

UNLOPS

Lavesson, Lönnblad [arXiv:0811.2912](https://arxiv.org/abs/0811.2912)

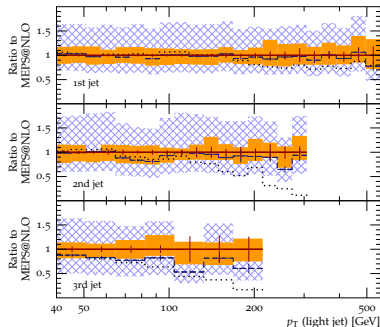
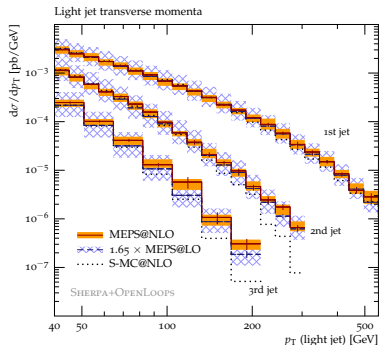
Lönnblad, Prestel [arXiv:1211.7278](https://arxiv.org/abs/1211.7278)

- generalisation of CKKW-L to NLO accuracy, proof along same lines
- merges NLOPS (UNLOPS) for each multiplicity

MEPS@NLO

 $pp \rightarrow t\bar{t} + \text{jets}$

Höche, Krauss, Maierhöfer, Pozzorini, MS, Siegert in arXiv:1401.7971

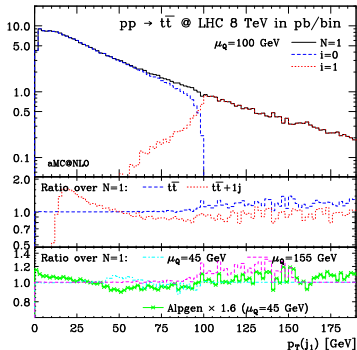
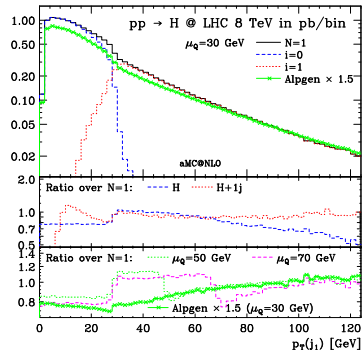


- Shapes are generally stable
- Uncertainties are much smaller

Examples

FxFx

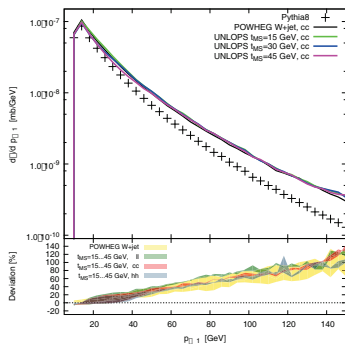
Frederix, Frixione arXiv:1209.6215

 $pp \rightarrow t\bar{t} + \text{jets}$  $pp \rightarrow h + \text{jets}$

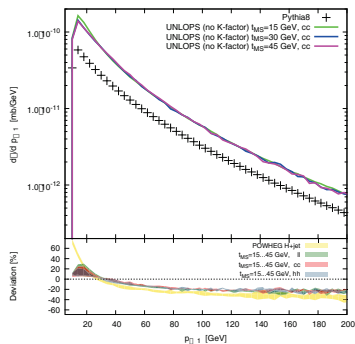


UNLOPs

Lönnblad, Prestel arXiv:1211.7278



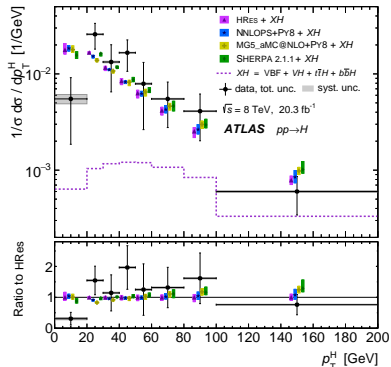
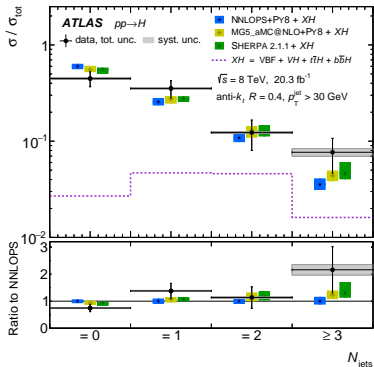
$pp \rightarrow W + \text{jets}$



$pp \rightarrow h + \text{jets}$

Use of state-of-the-art generators

ATLAS arXiv:1504.05833



Conclusion

- there has been tremendous progress in increasing the theoretical precision in the perturbative description
 - increasingly precise calculation of observables sensitive to large momentum transfers (high p_{\perp} , m_{inv} , etc)
- theoretical precision in describing observables sensitive to small scales remains basically unchanged:
 - many described by phenomenological models with unclear uncertainties
 - central value nonetheless gives good description
 - well-tuned models with enough parameters

Stress testing the new prediction

Approaches aim at describing all observables of one process class with one calculation.

As the uncertainty bands collapse with the recent developments, the limits of the inherent approximations need to be tested.

- measure observables that are sensitive to different characteristic scales simultaneously
- examples:
 - select events with 3 comparably hard jets in Mercedes star configuration in transverse plane, where does a much softer fourth jet go?
 - select event with $\ell^+\ell^-$ -pair and 3 jets of comparable energy in tetrahedral configuration, where is the additional hadronic activity concentrated
 - select events with $\ell^+\ell^-$ -pair and 2 hard back-to-back jets, measure ΔR between jet and $\ell^+\ell^-$ -pair

→ also new challenges for experiments

Thank you for your attention!