Recent developments

in

Monte-Carlo Event Generators

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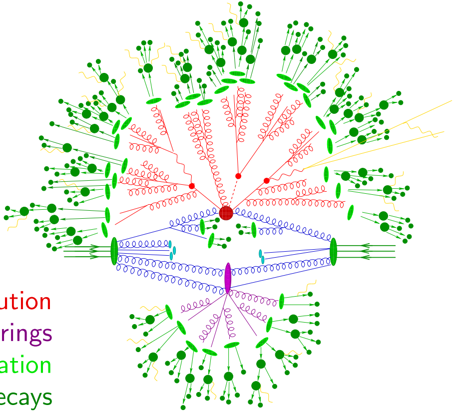
Contents

Introduction

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

- provide fully exclusive stable final state: $e^{\mp}$, $\mu^{\mp}$, γ, $\pi^{\pm}$, $K^{\pm}$, 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

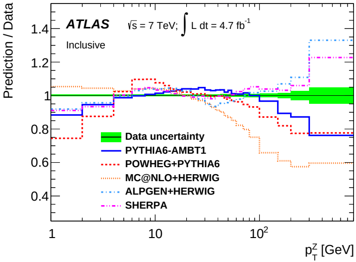
- allows to be used as data stand-in
  $\rightarrow$ calculate realistic expectation values for measurable observables
  $\rightarrow$ extrapolate into unmeasurable regions
  $\rightarrow$ calculate signal/background composition
  $\rightarrow$ ...
- necessitates highest precision
  $\rightarrow$ focus in recent years has been on improving the perturbative accuracy of the hard scattering
  $\rightarrow$ 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. $pp \to W + 1, 2, 3, \ldots$ jets
- embeds them in parton shower evolution

$\Rightarrow$ **work well, but ideally combine approaches**

State of the art a few years ago

ATLAS arXiv:1304.7098

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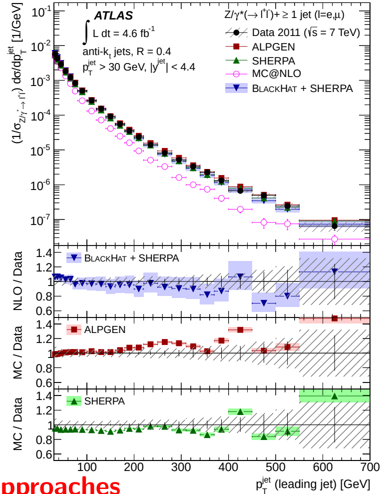


⇒ work well, but ideally combine approaches

Contents

Higher precision in parton showers

Parton showers operate in leading colour spin-avaraged approximation

Improved colour treatment

- full-colour first emission

  Höche, Krauss, MS, Siegert arXiv:1111.1220

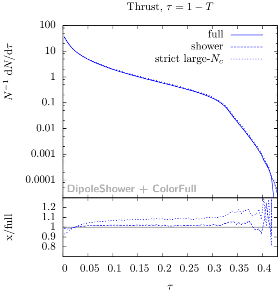
- diagonalised full colour evolution

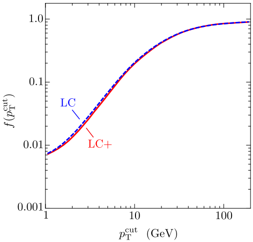
  Plätzer, Sjödahl arXiv:1201.0260

- LC+ approximation

  Nagy, Soper arXiv:1401.6364

⇒ **small effects for most observables**





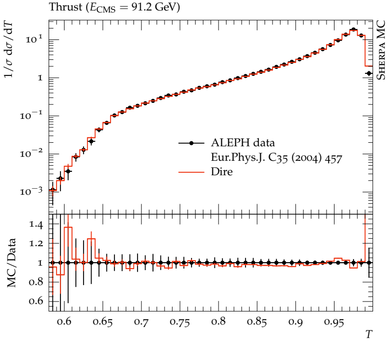
Improved analytical understanding

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

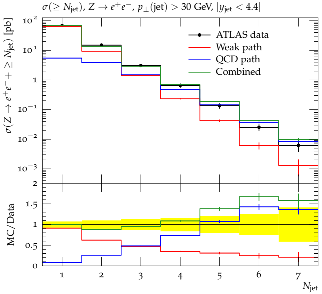
Christiansen, Sjöstrand arXiv:1401.5238

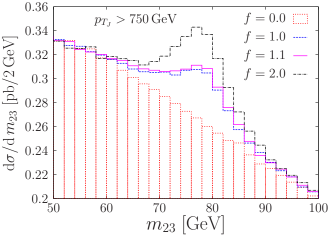
- $E_V \gg m_V$ limit with prefactors to account for spin composition

Krauss, Petrov, MS, Spannowsky arXiv:1402.XXXX

- interleaved evolution can lead to same signatures from different starting points, e.g. $pp \to Wjj$ from $pp \to W$ and 2 QCD emissions or $pp \to jj$ and W emission

No generic solution in spin-avaraged parton shower





Contents

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

$$\mathrm{d}\sigma = \bar{\mathrm{B}}_0(\Phi_0)\,\overline{\mathrm{PS}}_0(t_{\max}) + \left[\mathrm{R}_0 - \overline{\mathrm{PS}}_0^{(1)}\right](\Phi_1)\,\mathrm{PS}_1(t_1)$$

  NLO correction smeared through resummation phase space

- A differing scheme
  UNLOPS — Lönnblad, Prestel arXiv:1211.7278

$$\mathrm{d}\sigma = \mathrm{B}_0(\Phi_0)\,\overline{\mathrm{PS}}_0(\mu_Q^2) + \left[\mathrm{R}_0 - \overline{\mathrm{PS}}_0^{(1)}\right](\Phi_1)\,\mathrm{PS}_1(t_1) + \left[\bar{\mathrm{B}}_0 - \mathrm{B}_0\right](\Phi_0)$$

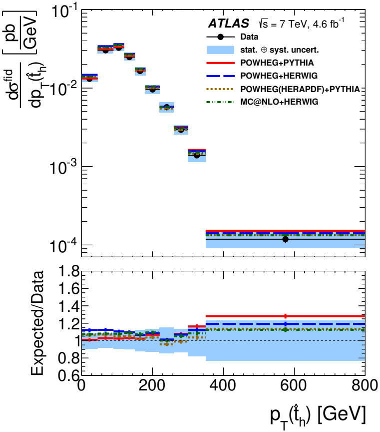
  NLO correction localised in Born phase space, not showered

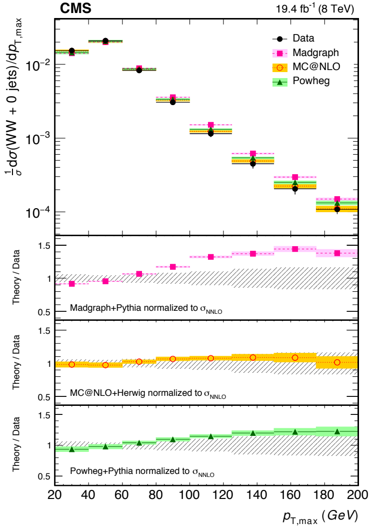
⇒ **same formal accuracy, differ at $O(\alpha_s^2)$**

MC@NLO and POWHEG

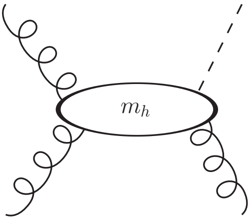
CMS arXiv:1507.03268

ATLAS arXiv:1502.05923





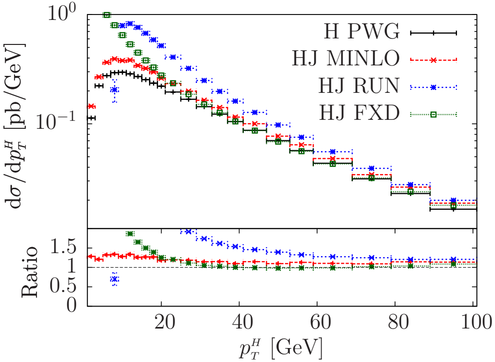
CKKW/MiNLO



Example $pp \to h + j$:

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

Hamilton, Nason, Zanderighi arXiv:1206.3572

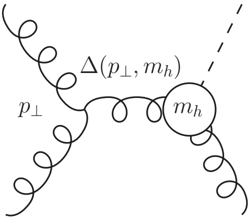


- Sudakov resums $p_\perp(j)$ in $pp \to hj$ wrt. $pp \to h$
- local scale choice resums logs associated with emission

$\Rightarrow$ embeds first emission in evolution off $pp \to h$ process

- necessary for MEPs merging, improves NLOPs with ≥ 1 jet in Φ_0

CKKW/MiNLO



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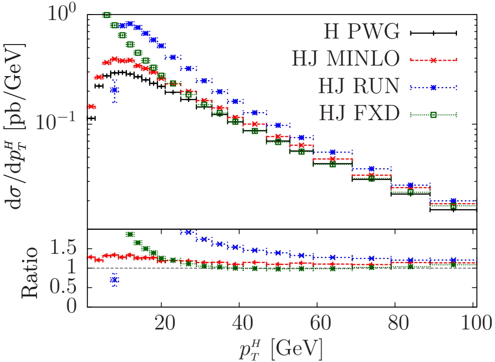

Example $pp \to h + j$:

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

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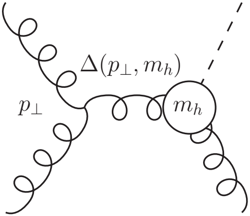
MiNLO



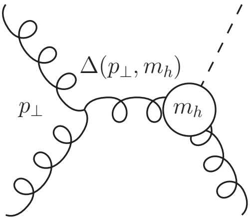
Example $pp \to h + j$:

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

- inclusion of Sudakov of appropriate logarithmic accuracy leads to finite result as $p_\perp(j) \to 0$
- inclusion of process dependent coefficients in Sudakov reaches NLO accuracy fo $pp \to h$ as $p_\perp(j) \to 0$

$\Rightarrow$ simultaneous NLO accurate description of $pp \to h$ and $pp \to h + j$

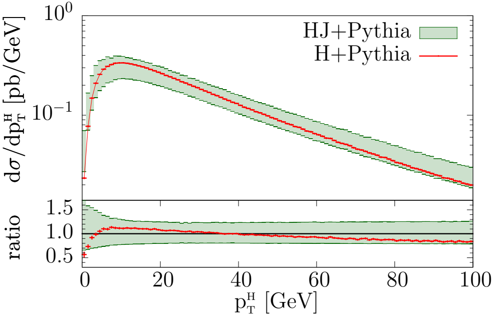
MiNLO



Example $pp \to h + j$:

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

Hamilton, Nason, Oleari, Zanderighi arXiv:1212.4504



- inclusion of Sudakov of appropriate logarithmic accuracy leads to finite result as $p_\perp(j) \to 0$
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$\Rightarrow$ simultaneous NLO accurate description of $pp \to h$ and $pp \to h + j$

NNLOPS

Two approaches

- POWHEG/MiNLO + reweighting
  $pp \to h$ Hamilton, Nason, Re, Zanderighi arXiv:1309.0017
  $pp \to \ell^+\ell^-$ Karlberg, Re, Zanderighi arXiv:1407.2940

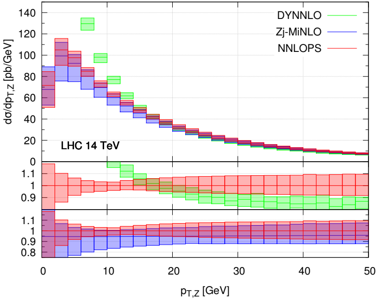
- S-MC@NLO + UNLOPS + $q_\perp$-slicing
  $pp \to \ell^+\ell^-$ Höche, Li, Prestel arXiv:1405.3607
  $pp \to h$ Höche, Li, Prestel arXiv:1407.3773

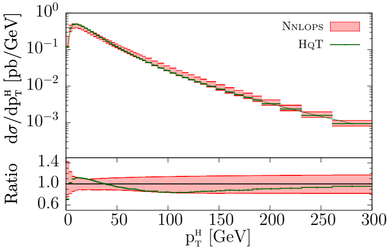
both are not "proper" NNLOPS matchings but rather exploit the simplified structure of logarithms and NNLO correction in singlet production

NNLOPs 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.

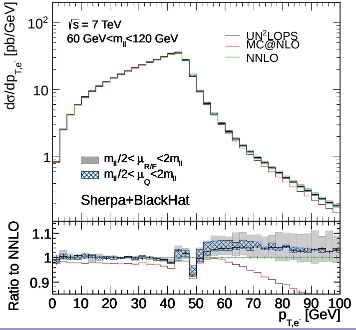


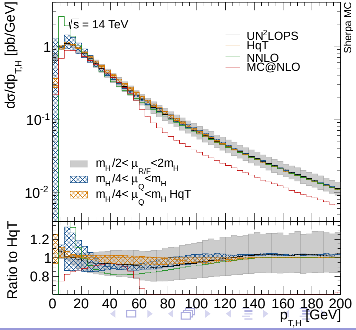


NNLOPs with S-MC@NLO + UNLOPs + $q_\perp$-slicing

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

Φ_0 is localised at $q_\perp = 0$. For $q_\perp > q_{\perp,\mathrm{cut}}$ ($q_{\perp,\mathrm{cut}} < t_c$) 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. UNLOPs-style.





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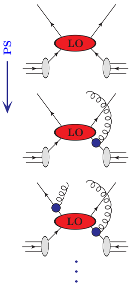
Multijet merging at LO

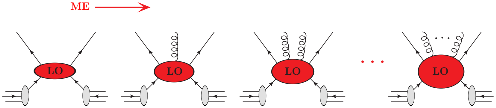


Parton showers

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

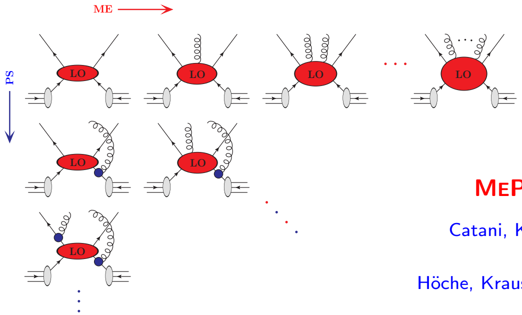


Matrix elements

fixed-order in α_s
$\rightarrow$ hard wide-angle emissions
$\rightarrow$ interference terms

- 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 $\rightarrow$ merging cut

Multijet merging at LO



MEPS (CKKW,MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053

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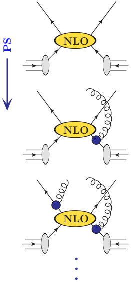
Multijet merging at NLO

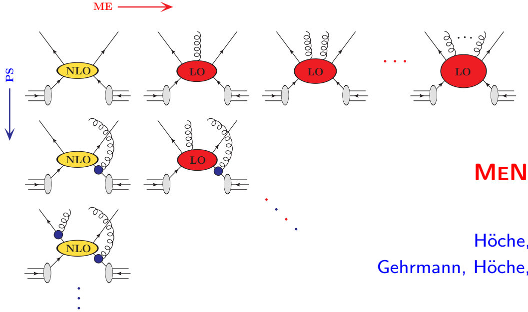


NLOPS (MC@NLO,POWHEG)

Frixione, Webber JHEP06(2002)029
Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070
Höche, Krauss, MS, Siegert JHEP09(2012)049

- 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

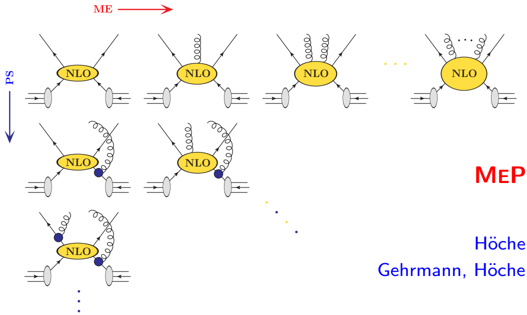


MeNloPs

Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

- 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

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
Lönnblad, Prestel JHEP03(2013)166
Plätzer JHEP08(2013)114

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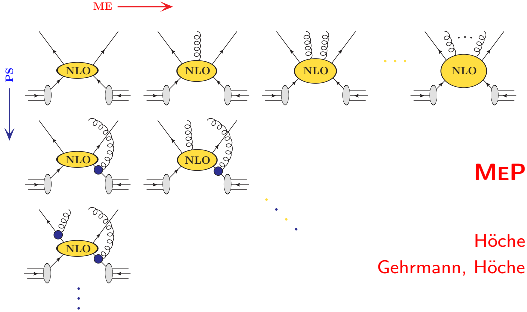

MEPS@NLO

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Plätzer JHEP08(2013)114

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- **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
Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031

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

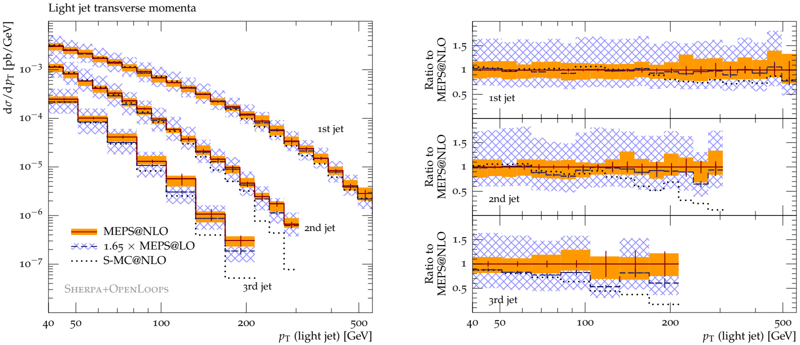
FxFx Frederix, Frixione arXiv:1209.6215

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

UNLOPS Lavesson, Lönnblad arXiv:0811.2912
Lönnblad, Prestel arXiv:1211.7278

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

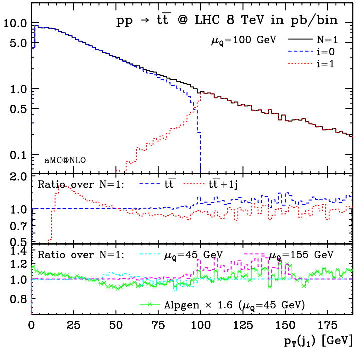
MEPS@NLO – pp → $t\bar{t}$+jets



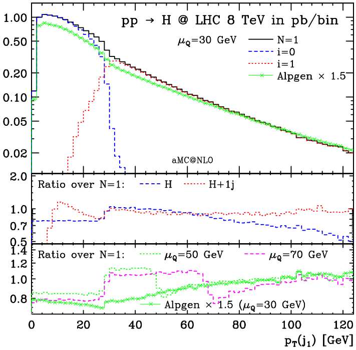
- Shapes are generally stable
- Uncertainties are much smaller

FxFx

Frederix, Frixione arXiv:1209.6215



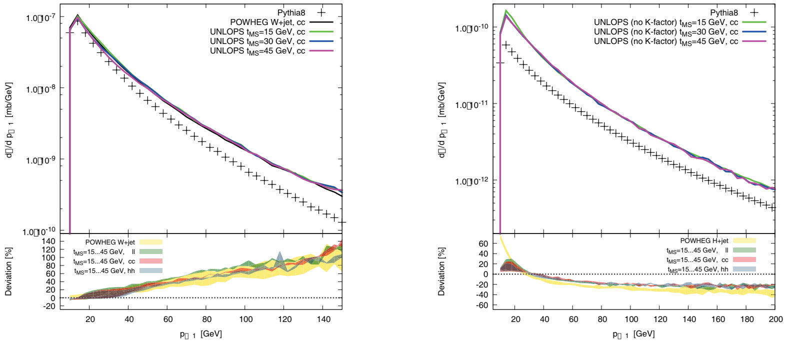
$pp \to t\bar{t} +$ jets



$pp \to h +$ jets

UNLOPS

Lönnblad, Prestel arXiv:1211.7278

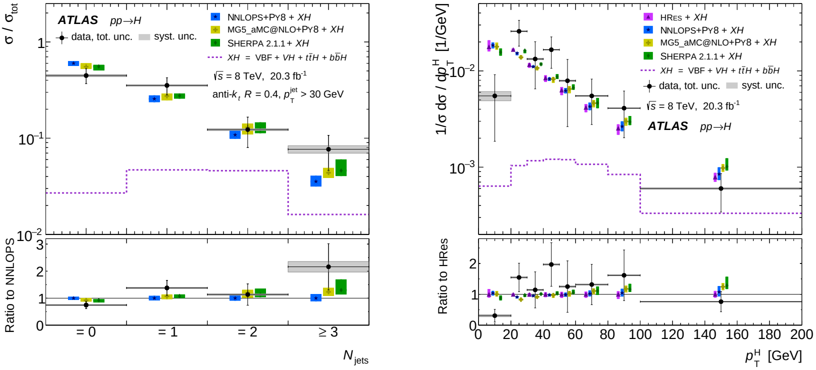


$pp \to W +$ jets

$pp \to h +$ 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
  $\rightarrow$ increasingly precise calculation of observables senstive to large momentum transfers (high $p_\perp$, m_{inv}, etc)
- theoretical precision in describing observables sensitive to small scales remains basically unchanged:
  $\rightarrow$ many described by phenomenolgical models with unclear uncertainties
  $\rightarrow$ 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 collaps 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

$\rightarrow$ also new challenges for experiments

Thank you for your attention!