Vector boson plus multijet production

Marek Schönherr

Institute for Particle Physics Phenomenology

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Contents

Motivation

V+jets as a background to top physics

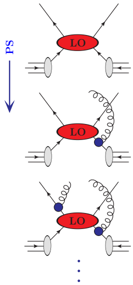
- W+jets:
  $pp \to \ell + \not{E}_T + \#$jets (irreducible in semileptonic ttbar production)
- Z+jets:
  $pp \to \ell\ell + \#$jets (reducible in all modes)

Need for higher accuracy

- (N)NLO calculations mandatory (QCD at large scales)
  - ⇒ stabilised cross sections, reliable differential distributions
- matching to parton showers (include QCD at low scales)
  - ⇒ hadron-level calculations
  - ⇒ reliable jet descriptions, leptons in jets, etc.
- multijet merging and inclusive description
  - ⇒ combine high-accuracy for different multiplicities
  - ⇒ resum multiscale logarithms

LO calculations and MePs merging

Complementary descriptions of multiparticle final states



LO $pp \to 2$ with parton showers vs. **LO $pp \to n$ matrix elements**

+ exponentiation of large IR logarithms	+ dominant terms for hard/wide angle rad.
− poor hard/wide angle emission pattern	− breakdown of α_s-expansion in log. region

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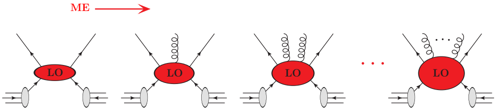

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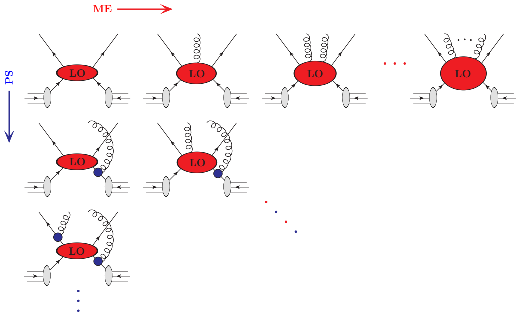

Consistent combination: MEPS-algorithms

- CKKW – phase space partition into two regimes emission by emission
  Catani et.al. JHEP11(2001)063, Lönnblad JHEP05(2002)046, Höche et.al. JHEP05(2009)053, Hamilton et.al. JHEP11(2009)038, Lönnblad, Prestel JHEP03(2012)019, ...
- MLM – phase space partition based on geometric reconstruction of jets
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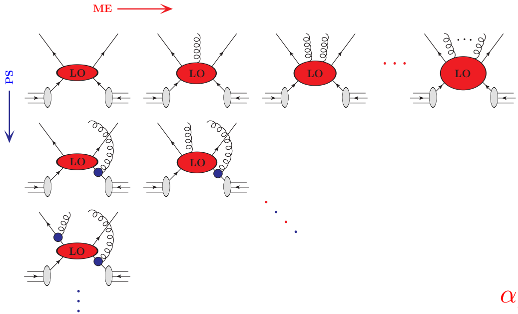
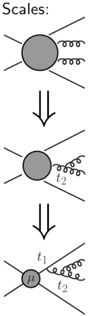
LO calculations and MEPs merging

Complementary descriptions of multiparticle final states





$$\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$

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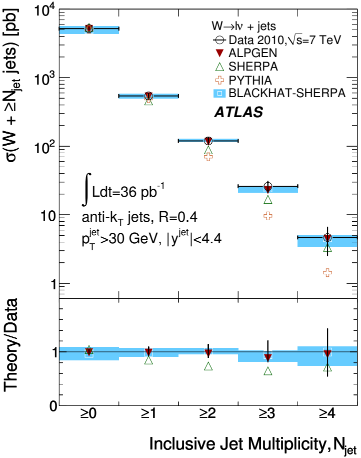
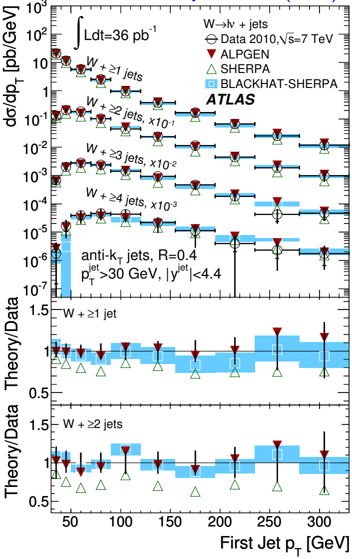
LO calculations and MEPS merging

MEPS: LO+(N)LL accuracy
$\rightarrow$ good agreement with data,
but large uncertainties (not shown)

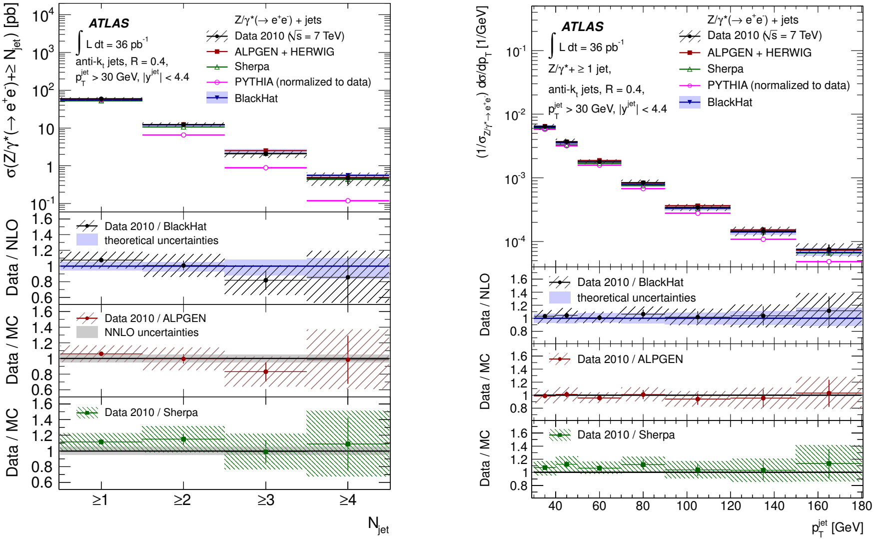


ATLAS Phys.Rev.D85(2012)092002



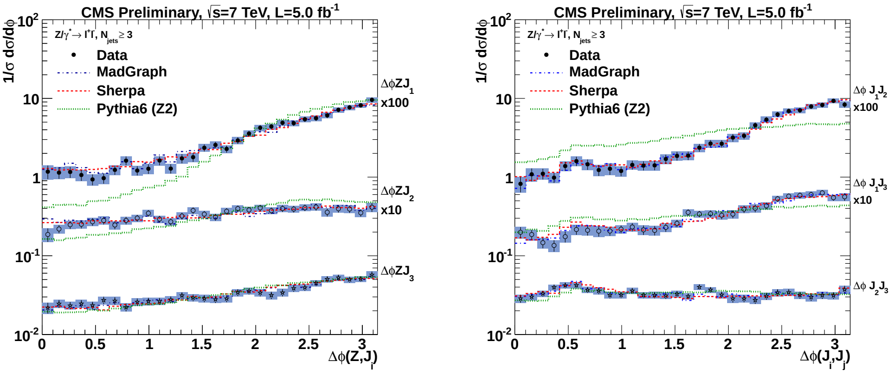
LO calculations and MePs merging

ATLAS Phys.Rev.D85(2012)032009



LO calculations and MEPS merging

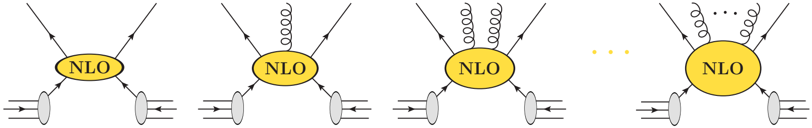
CMS-PAS-EWK-11-021



CMS measurement of correlations in Z+jets

- $Z+\geq 3$ jets
- good description of shapes by MEPS methods, norm from data

NLO calculations



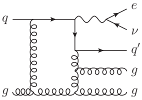
$$\mathbf{pp \to W/Z + n\ jets}$$

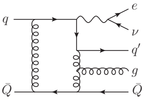
NLO calculations

- a lot of progress in recent years

$pp \to W + n$ jets

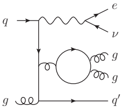
n	groups
2	Campbell, Ellis Phys.Rev.D65(2002)113007
3	Ellis et.al. JHEP04(2009)077; Berger et.al. Phys.Rev.Lett.102(2009)222001
4	Berger et.al. Phys.Rev.Lett.106(2011)092001
5	BLACKHAT in preparation





$pp \to Z + n$ jets

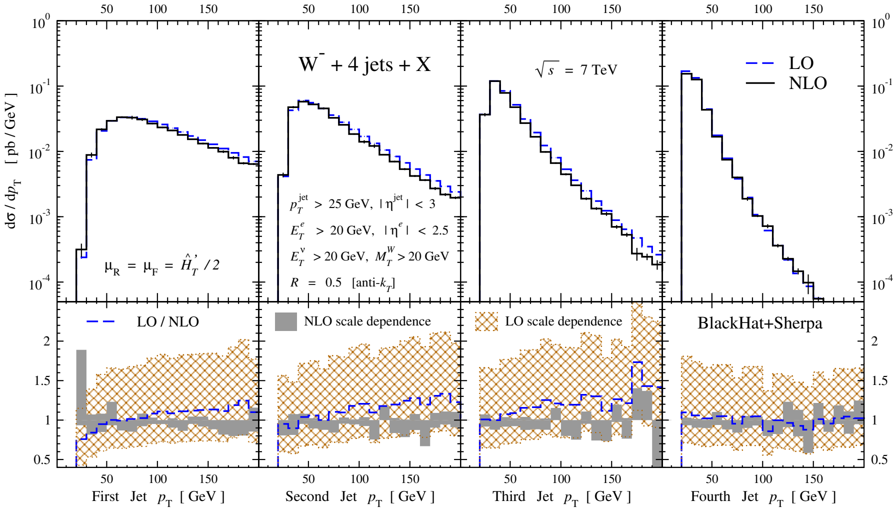
n	groups
2	Campbell, Ellis Phys.Rev.D65(2002)113007
3	Berger et.al Phys.Rev.D82(2010)074002
4	Ita et.al. Phys.Rev.D85(2012)031501



- $W/Z+ \leq 2$ jets various public implementations
- $W/Z+ \geq 3$ no completely public implementation/n-tuples
  - ROCKET+MCFM: generalised D-dim. unitarity
  - BLACKHAT+SHERPA: unitarity based, on-shell methods

NLO state of the art

Berger et.al. Phys.Rev.Lett.106(2011)092001



NLO state of the art

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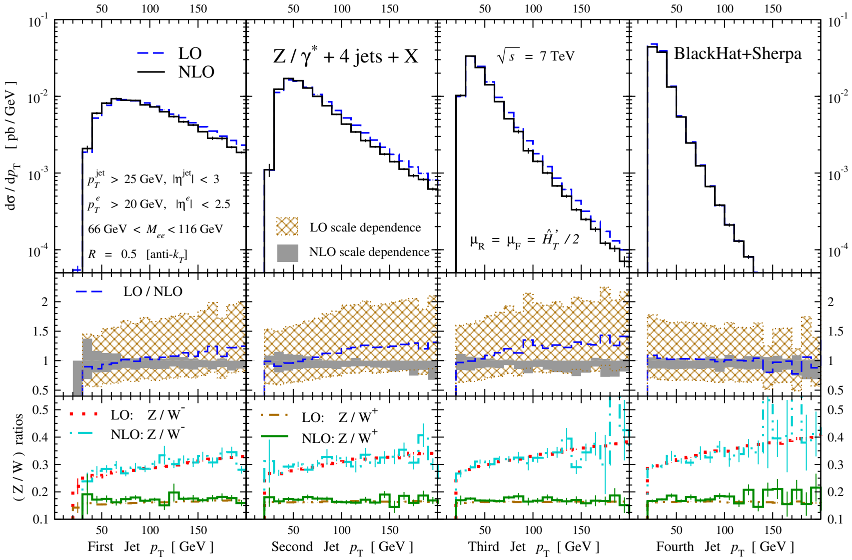
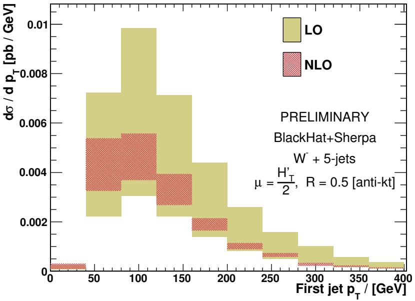
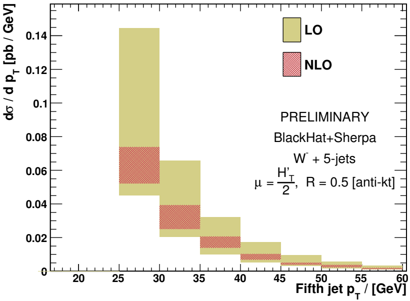


NLO state of the art

BLACKHAT in preparation

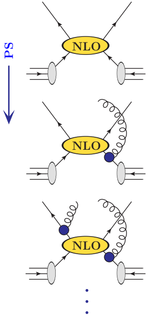




- 1^{st} and 5^{th} jet transverse momentum in $pp \to W + 5$ jet events
- BLACKHAT supplies virtual matrix elements, COMIX supplies born and real emission matrix elements, CS subtraction and phase space integration

NLOPS matching

NLO calculations inclusive wrt. higher orders, therefore matching to parton showers mandatory to achieve fully exclusive description of final state.



- attach parton showers to NLO calculations
- remove overlap of real emission contribution and parton shower emission, and Sudakov and virtual correction
- retain respective accuracies ⇒ NLO+(N)LL

NLOPs matching

NLO calculations inclusive wrt. higher orders, therefore matching to parton showers mandatory to achieve fully exclusive description of final state.

Methods:

- MC@NLO — Frixione, Webber JHEP06(2002)029
  (variants of) method implemented in:
  - MC@NLO v4.0 ($V+0$ jets) — Frixione, Webber arXiv:1010.0819
  - aMC@NLO ($V+\leq 2$ jets) — Frederix et.al. JHEP02(2012)048
  - SHERPA ($V+\leq 3$ jets) — Höche, Krauss, MS, Siegert arXiv:1201.5882
- POWHEG — Nason JHEP11(2004)040; Frixione, Nason, Oleari JHEP11(2007)070
  method implemented in:
  - POWHEG-BOX ($V+\leq 2$ jets) — Alioli, Nason, Oleari, Re JHEP01(2011)095; Re arXiv:1204.5433
  - HERWIG++ ($V+0$ jets) — Hamilton, Richardson, Tully JHEP10(2008)015
  - SHERPA ($V+0$ jets) — Höche, Krauss, MS, Siegert JHEP04(2011)024

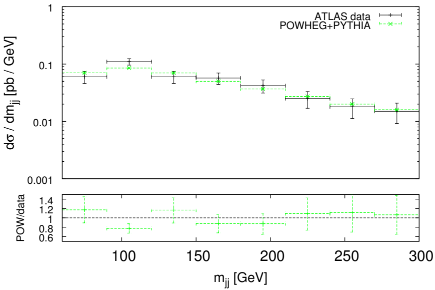
Both methods intimatly related — Höche, Krauss, MS, Siegert arXiv:1111.1220; Nason, Webber arXiv:1202.1251

→ differ only in choice of resummation kernel and res. phase space

NLOPs matching

POWHEG $Z+2$ jets at LHC

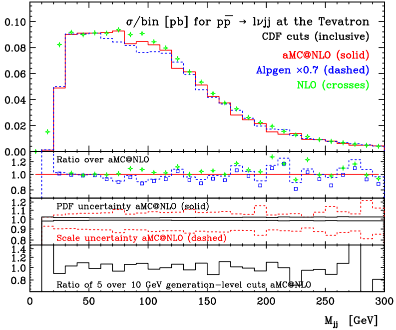
Re arXiv:1204.5433



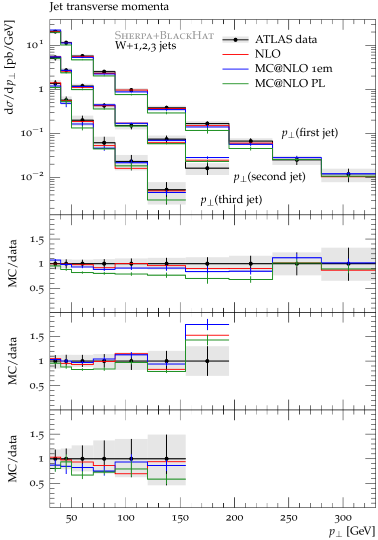
Data: ATLAS Phys.Rev.D85(2012)032009

aMC@NLO $W+2$ jets at Tevatron

Frederix et.al. JHEP02(2012)048



NLOPs matching



Höche, Krauss, MS, Siegert arXiv:1201.5882

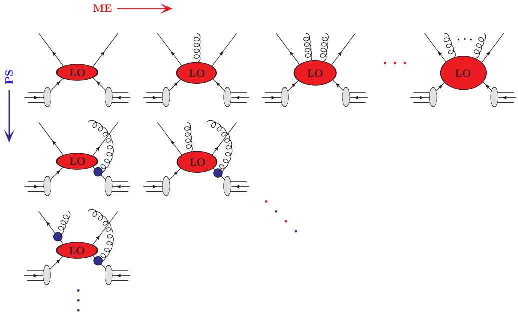
$pp \to W + 1, 2, 3$ jets with MC@NLO-type matching

- 3 separate samples/calculations
- NLO accuracy for inclusive observables of respective jet multiplicity
- resummation of softest/LO jet, i.e. 4th jet in $pp \to W + 3$ jets
- no resummation of sample-defining jet multiplicity, i.e. first 3 jets in $pp \to W + 3$ jets
- nonetheless good description of data

Data: ATLAS Phys.Rev.D85(2012)092002

MEPS@NLO merging

Promote MEPS to higher accuracy:



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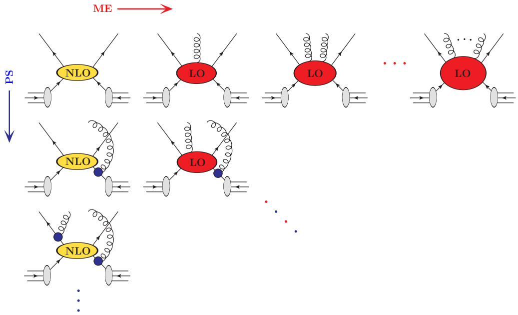

- promote lowest multiplicity to NLO:
  merge one NLOPS with MEPS ⇒ MENLOPS

Bauer, Tackmann, Thaler JHEP12(2008)010
Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123
Höche, Krauss, MS, Siegert arXiv:1207.5031

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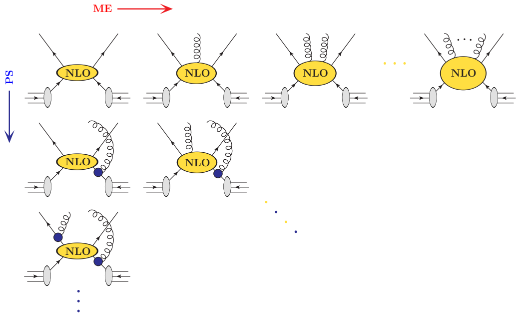

- promote all multiplicities up to n_{max} to NLO: merge NLOPs of successive multiplicity, i.e. elevate MePs to NLO ⇒ MePs@Nlo

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert arXiv:1207.5030
Höche, Krauss, MS, Siegert arXiv:1207.5031

- overlap of Sudakovs and NLO corrections spoils NLO accuracy
  → corrected for by modified truncated parton shower

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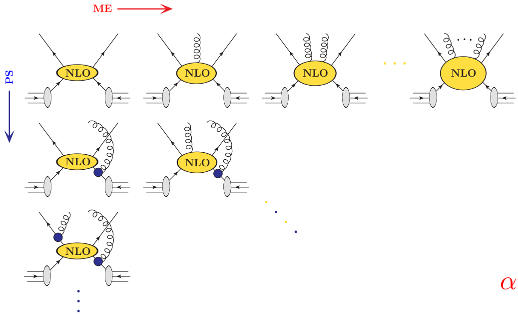

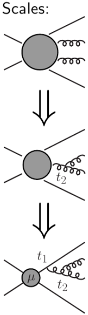

$$\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$

defined on respective LO configurations

- promote all multiplicities up to n_{max} to NLO: merge NLOPS of successive multiplicity, i.e. elevate MEPS to NLO ⇒ MEPS@NLO

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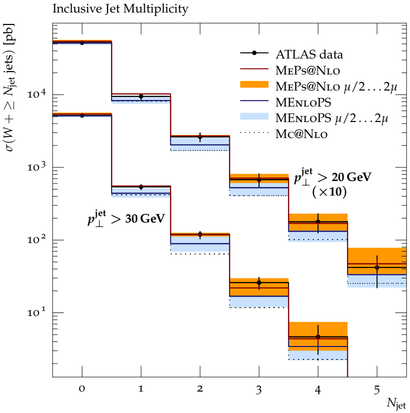


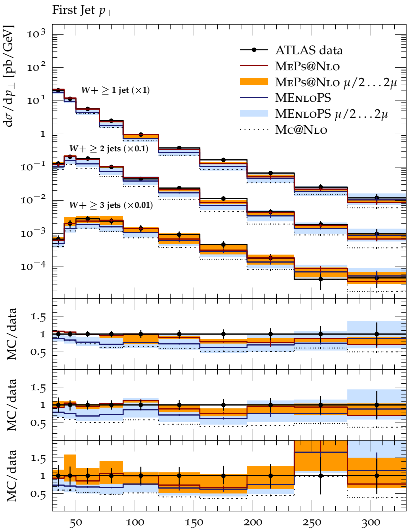
Höche, Krauss, MS, Siegert arXiv:1207.5030

$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

- NLO+(N)LL accuracy for $pp \to W$+0,1,2 jets
  LO+(N)LL accuracy for $pp \to W$+3,4 jets
- all jet emissions are resummed wrt. inclusive W production with $\mu_Q = m_W$
- simultaneous description of different jet multiplicities

Data: ATLAS Phys.Rev.D85(2012)092002

MEPS@NLO merging



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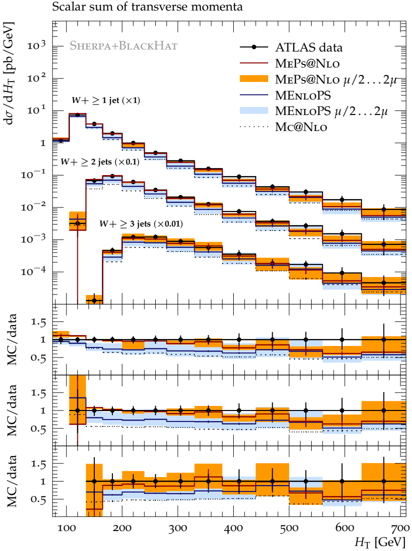

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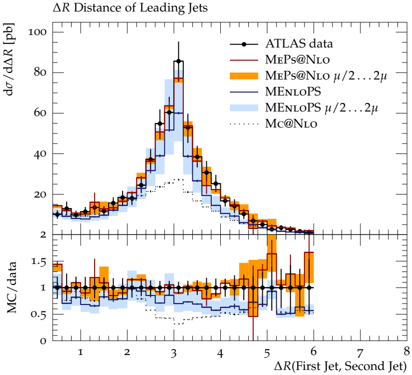
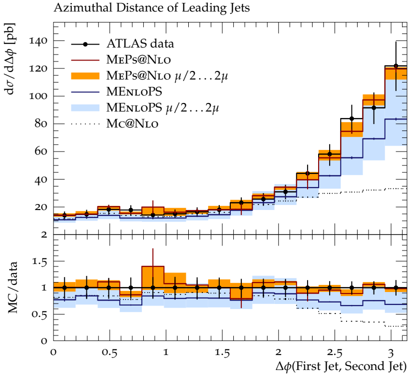




Data: ATLAS data Phys.Rev.D85(2012)092002

NNLO calculations

NNLO QCD inclusive cross sections Hamberg, van Neerven, Matsuura Nucl.Phys.B359(1991)343405

Fully differential NNLO QCD to inclusive W, Z production

- FEWZ Melnikov, Petrielle Phys.Rev.Lett.96(2006)231803
  recently included NLO EW corrections Li, Petriello arXiv:1208.5967
- DYNNLO Catani, Cieri, Ferrera, de Florian, Grazzini Phys.Rev.Lett.103(2009)082001

(N)NLO+(N)NLL resummation

- e.g. Becher, Neubert Eur.Phys.J.C71(2011)1665, Banfi; Salam, Zanderighi JHEP06(2012)159; Banfi, Dasgupta, Marzani, Tomlinson JHEP01(2012)044, ...
- observable specific resummation for inclusive production

Problems

- no matching methods to parton showers, no hadron level calculations
- does not reach jet multiplicity relevant for top physics

$\Rightarrow$ can be used to renorm inclusive MEPS calculations

Conclusions

- highly active field
- traditional MEPS works fine for prediction of shapes, but large uncertainties (everything is LO at best)
- NLO calculations have reached final state multiplicities interesting for top physics backgrounds
- NLOPS matching techniques extended/generalised
  have been shown to also work with large final state multiplicities and complicated colour structures
- multijet-merging techniques have been promoted to NLO accuracy recently
- NNLO can be used for normalisation of inclusive calculations

Thank you for your attention!

Backup: MEPs merging – Scales

Divide phase space using jet measure Q_{cut}:

$\rightarrow$ emissions with $Q > Q_{\text{cut}}$ by ME

$\rightarrow$ emissions with $Q < Q_{\text{cut}}$ by PS

Shower on top of higher order ME:

Problem: ME only gives final state, no history as PS input

Solution: Backward clustering (inverted probabilistic PS splittings)

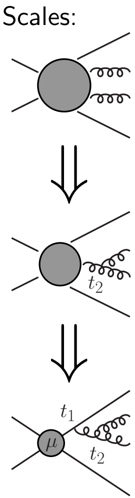
$\Rightarrow$ **ME final state with branching history and PS starting scale μ and branching scales t_i**

$$\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$

Veto PS emissions with $Q > Q_{\text{cut}}$

$\rightarrow$ Reject event $\rightarrow$ Sudokov suppression

If $t \neq Q^2$ then truncated shower necessary



Backup: MEPS@NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

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

$\langle O \rangle^{\text{MEPS@NLO}}$

$$= \int \mathrm{d}\Phi_n \, \bar{\mathrm{B}}_n^{(\mathrm{A})} \left[\Delta_n^{(\mathrm{A})}(t_0, \mu_Q^2) \, O_n + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1 \, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n} \, \Delta_n^{(\mathrm{A})}(t_{n+1}, \mu_Q^2) \, \Theta(Q_{\text{cut}} - Q) \, O_{n+1} \right]$$

$$+ \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathrm{A})} \right] \Theta(Q_{\text{cut}} - Q) \, \Delta_n^{(\mathrm{PS})}(t_{n+1}, \mu_Q^2) \, O_{n+1}$$

Backup: MePs@Nlo merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

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

$$
\begin{aligned}
\langle O\rangle^{\text{MePs@Nlo}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \Bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n \\
&\qquad\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\Bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1}
\end{aligned}
$$

Backup: MePs@Nlo merging

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$$\langle O\rangle^{\text{MePs@Nlo}}$$

$$= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \Bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1} \Bigg]$$

$$+ \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1}$$

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$$
\begin{aligned}
\langle O\rangle^{\text{MEPS@NLO}} \\
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})}\Bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\,O_n \\
&\qquad + \int_{t_0}^{\mu_Q^2}\mathrm{d}\Phi_1\,\frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\,\Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\,\Theta(Q_{\mathsf{cut}}-Q)\,O_{n+1}\Bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1}\left[\mathrm{R}_n-\mathrm{D}_n^{(\mathsf{A})}\right]\Theta(Q_{\mathsf{cut}}-Q)\,\Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\,O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\,\bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}\left[1+\frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}}\int_{t_{n+1}}^{\mu_Q^2}\mathrm{d}\Phi_1\,\mathrm{K}_n\right]\Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\,\Theta(Q-Q_{\mathsf{cut}}) \\
&\qquad \times\left[\Delta_{n+1}^{(\mathsf{A})}(t_0,t_{n+1})\,O_{n+1}+\int_{t_0}^{t_{n+1}}\mathrm{d}\Phi_1\,\frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\,\Delta_{n+1}^{(\mathsf{A})}(t_{n+2},t_{n+1})\,O_{n+2}\right] \\
&\quad + \int \mathrm{d}\Phi_{n+2}\left[\mathrm{R}_{n+1}-\mathrm{D}_{n+1}^{(\mathsf{A})}\right]\Delta_{n+1}^{(\mathsf{PS})}(t_{n+2},t_{n+1})\,\Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\,\Theta(Q-Q_{\mathsf{cut}})\,O_{n+2}
\end{aligned}
$$

Backup: MePs@Nlo merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

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

$$
\begin{aligned}
\langle O\rangle^{\text{MePs@Nlo}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \Bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n \\
&\qquad\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1} \Bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathsf{A})} \left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n\right] \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \\
&\qquad\qquad \times \left[\Delta_{n+1}^{(\mathsf{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathsf{A})}(t_{n+2},t_{n+1})\, O_{n+2} \right] \\
&\quad + \int \mathrm{d}\Phi_{n+2} \left[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathsf{A})}\right] \Delta_{n+1}^{(\mathsf{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\, O_{n+2}
\end{aligned}
$$

Backup: MEPS@NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

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

$$
\begin{aligned}
\langle O\rangle^{\text{MEPS@NLO}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathrm{A})} \left[\Delta_n^{(\mathrm{A})}(t_0,\mu_Q^2)\, O_n \right.\\
&\qquad \left. + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathrm{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\right]\\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathrm{A})}\right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1}\\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathrm{A})} \left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n\right] \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\\
&\qquad \times \left[\Delta_{n+1}^{(\mathrm{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathrm{A})}(t_{n+2},t_{n+1})\, O_{n+2}\right]\\
&\quad + \int \mathrm{d}\Phi_{n+2} \left[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathrm{A})}\right] \Delta_{n+1}^{(\mathrm{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\, O_{n+2}
\end{aligned}
$$

Backup: MePs@Nlo merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

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

$$\langle O\rangle^{\textsf{MePs@Nlo}}$$

$$
\begin{aligned}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n \\
&\qquad\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\mathsf{cut}}-Q)\, O_{n+1}\bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1} \Big[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\Big]\, \Theta(Q_{\mathsf{cut}}-Q)\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathsf{A})} \bigg[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n\bigg]\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\mathsf{cut}}) \\
&\qquad\qquad \times \bigg[\Delta_{n+1}^{(\mathsf{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathsf{A})}(t_{n+2},t_{n+1})\, O_{n+2}\bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+2} \Big[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathsf{A})}\Big]\, \Delta_{n+1}^{(\mathsf{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\mathsf{cut}})\, O_{n+2}
\end{aligned}
$$

Backup: MePs@Nlo merging – MC counterterm

$$\left[1+\frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}}\int_{t_{n+1}}^{\mu_Q^2}\mathrm{d}\Phi_1\,\mathrm{K}_n\right]$$

- same form as exponent of Sudakov form factor $\Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)$
- truncated parton shower on n-parton configuration underlying $n+1$-parton event
  1. no emission $\rightarrow$ retain $n+1$-parton event as is
  2. first emission at t' with $Q > Q_{\text{cut}}$, multiply event weight with $\mathrm{B}_{n+1}/\bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}$, restart evolution at t', do not apply emission kinematics
  3. treat every subsequent emission as in standard truncated vetoed shower
- generates

$$\left[1+\frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}}\int_{t_{n+1}}^{\mu_Q^2}\mathrm{d}\Phi_1\,\mathrm{K}_n\right]\Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)$$

$\Rightarrow$ **identify $\mathcal{O}(\alpha_s)$ counterterm with the emitted emission**

Backup: MEPS@NLO merging – scale variations

Renormalisation scales:

- determined by clustering using PS probabilities and taking the respective nodal values t_i

$$\alpha_s(\mu_R^2)^k = \prod_{i=1}^{k} \alpha_s(t_i)$$

- change of scales $\mu_R \to \tilde{\mu}_R$ in MEs necessitates one-loop counter term

$$\alpha_s(\tilde{\mu}_R^2)^k \left(1 - \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\, \beta_0 \sum_{i=1}^{k} \ln \frac{t_i}{\tilde{\mu}_R^2}\right)$$

Factorisation scale:

- μ_F determined from core n-jet process
- change of scales $\mu_F \to \tilde{\mu}_F$ in MEs necessitates one-loop counter term

$$\mathrm{B}_n(\Phi_n)\, \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\, \log \frac{\mu_F^2}{\tilde{\mu}_F^2} \left(\sum_{c=q,g}^{n} \int_{x_a}^{1} \frac{\mathrm{d}z}{z}\, P_{ac}(z)\, f_c(x_a/z, \tilde{\mu}_F^2) + \ldots \right)$$