Precision event generation for LHC physics

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SLAC NAL

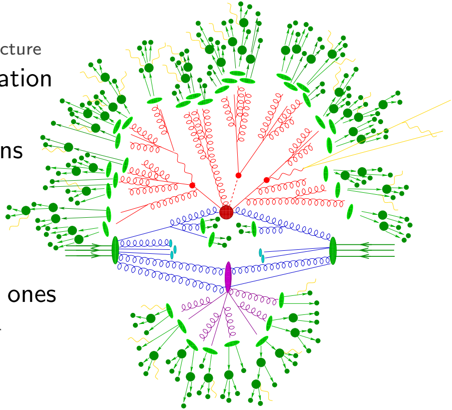
HEP Theory Seminar

IPMU, 05/29/13

[1] based on work with Zvi Bern, Lance Dixon, Fernando Febres Cordero, Thomas Gehrmann, Junwu Huang, Harald Ita, David Kosower, Frank Krauss, Gionata Luisoni, Daniel Maître, Kemal Ozeren, Laura Reina, Marek Schönherr, Frank Siegert, Jennifer Thompson, Doreen Wackeroth, Jan Winter

Event generation at hadron colliders

1. Matrix Element (ME) generators red blobs
   simulate "central" part of the event
2. Parton Showers (PS) red & blue tree structure
   produce additional "hard" QCD radiation
3. Multiple interaction models purple blob
   simulate "secondary hard" interactions
4. Fragmentation models light green blobs
   hadronize QCD partons
5. Hadron decay modules dark green blobs
   decay primary hadrons into observed ones
6. Photon emission generators yellow stuff
   simulate additional QED radiation



General-purpose event generators

Herwig

- Originated in coherent shower studies $\to$ angular ordered PS
- Front-runner in development of MC@NLO and POWHEG
- Simple in-house ME generator & spin-correlated decay chains
- Original framework for cluster fragmentation

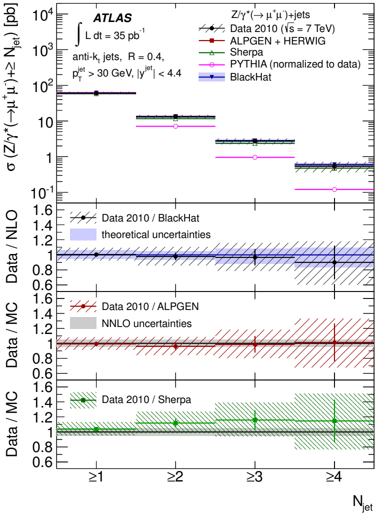
Pythia

- Originated in hadronization studies $\to$ Lund string
- Leading in development of models for non-perturbative physics
- Pragmatic attitude to ME generation $\to$ external tools
- Extensive PS development and earliest ME+PS matching

Sherpa

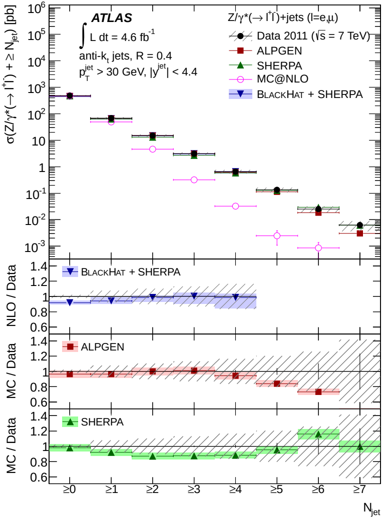
- Started with PS generator APACIC++ & ME generator AMEGIC++
- Hadronization pragmatic add-on, but extensive decay package
- Leading in development of automated ME$\oplus$PS merging (at NLO)
- Automated framework for NLO calculations and MC@NLO

Status of Z+Jets



[ATLAS] arXiv:1111.2690

$\Rightarrow$



[ATLAS] arXiv:1304.7098

Status of Z+Jets

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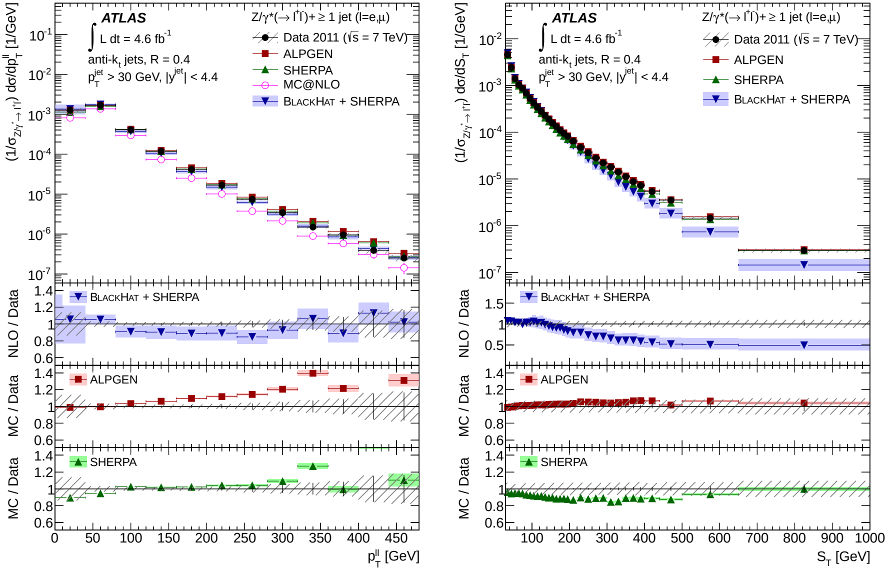


Outline

This talk:

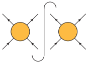
- Efficient automated NLO QCD calculations at parton level
- Matching NLO QCD calculations and parton showers
- Merging matched calculations for varying jet multiplicity

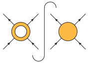
Aim:

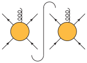
- Particle-level predictions with uncertainty estimates
- NLO-accurate simulations for $X+n$-jets with $n = 0, 1, 2, \ldots$ combined into inclusive sample for $X+$anything

Construction of a general-purpose NLO ME generator

NLO prediction

$$\mathrm{B} =$$ 

$$\mathrm{V} = \sum 2\,\mathrm{Re}\Big\{$$  $$\Big\}$$

$$\mathrm{R} = \sum$$ 

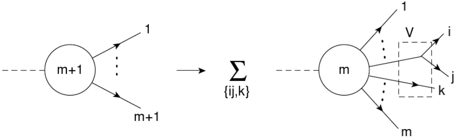
Singularities in V & R to be removed before MC-integration

$$\sigma^{NLO} = \int \mathrm{d}\Phi_B \left(\mathrm{B} + \tilde{\mathrm{V}}\right) + \int \mathrm{d}\Phi_R\, \mathrm{R} = \int \mathrm{d}\Phi_B \left[\left(\mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I}\right) + \int \mathrm{d}\Phi_{R|B}\, (\mathrm{R} - \mathrm{S})\right]$$

Generic scheme given by dipole subtraction method

[Catani,Seymour] hep-ph/9605323 [Catani,Dittmaier,Seymour,Trocsanyi] hep-ph/0201036

Schematically: $\mathrm{S} \to \sum_{\{i,j\}} \sum_{k \neq i,j} D_{ij,k}$



$D_{ij,k} = \mathrm{B}_{\widetilde{ij},k} \otimes V_{ij,k}$ - dipole terms

$V_{ij,k}$ - process-independent dipole functions

Virtual contribution

Share the workload

$$\sigma_{\mathrm{NLO}} = \int \mathrm{d}\Phi_{\mathrm{B}} \sum \left(\mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I}\right) + \int \mathrm{d}\Phi_{R} \sum \left(\mathrm{R} - \mathrm{S}\right)$$

Standardized interface → Binoth Les Houches accord [Binoth et al.] arXiv:1001.1307

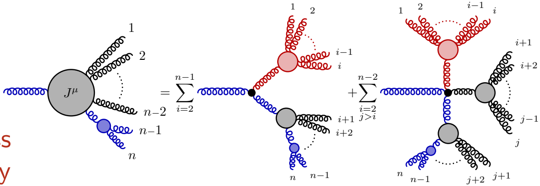
- One-Loop Engines (OLEs) provide virtual piece
- ME generator takes care of Born, real emission, subtraction phase-space integration and event generation

First successfully used for computing W+3 jets with BlackHat and SHERPA

Real contribution

One-Loop codes capable of computing very high multiplicity processes
$\rightarrow$ need to compute real-radiation & infrared subtraction terms efficiently

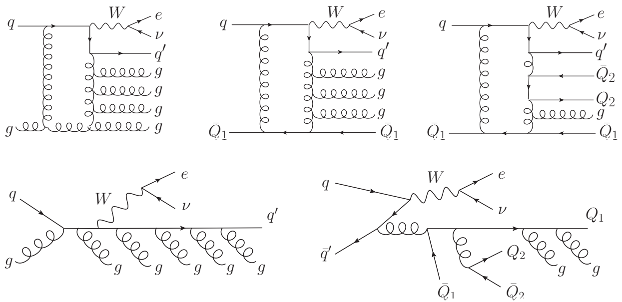
- Naively computational effort in dipole subtraction method grows like N^3 with number of external QCD particles, N
- Can be reduced by recursive computation similar to Berends-Giele technique at LO [SH] to appear
- Fix spectator parton as "final" leg in amplitude
- Recycle subamplitudes from real-radiation process and dipoles simultaneously



- Implemented in matrix element generator Comix [Gleisberg,SH] arXiv:0808.3674

W+5jets at the LHC

- First $2 \rightarrow 6$ NLO calculation (plus decay $W \rightarrow l\nu$)
- Will be measured with good precision at LHC $\rightarrow$ test of SM
- Can be used to understand jet scaling patterns $\rightarrow$ BSM searches

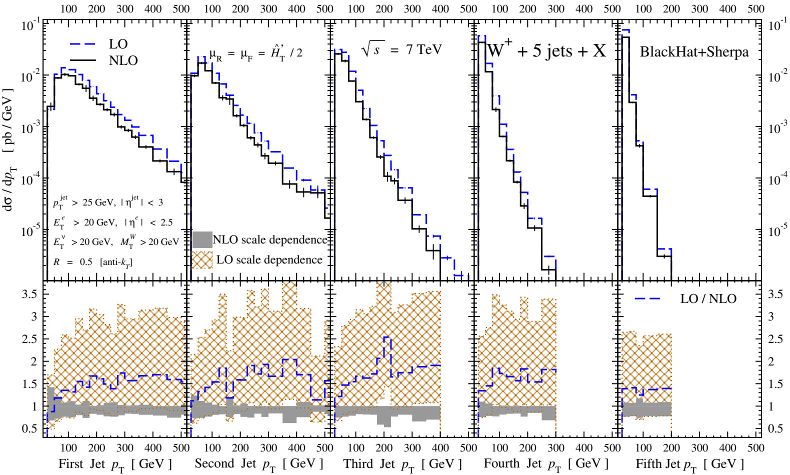


Approximations:

- Leading color in virtual piece (estimated $< 3\%$ correction)
- No real corrections with 8 quark lines ($< 1\%$ correction)

W+5jets at the LHC

[BlackHat] arXiv:1304.1253



Jet ratio scaling patterns

- Consider "core" process (e.g. W-production) plus n jets
- Cross section ratios
$$R_{(n+1)/n} = \frac{\sigma_{n+1}^{\mathrm{excl}}}{\sigma_n^{\mathrm{excl}}}$$
$\sim$ stable against QCD corrections [Gerwick et al.] JHEP10(2012)162

- **Staircase Scaling**:
$$R_{(n+1)/n} = \mathrm{const} \quad \left(\sigma_n = \sigma_0\, R^n\right)$$
- First predicted for W/Z+jets
[Berends,Giele,Kuijf] NPB321(1989)39
- Induced by democratic jet cuts
[Gerwick et al.] JHEP10(2012)162

- **Poisson Scaling**:
$$R_{(n+1)/n} = \frac{\bar{n}}{n+1} \quad \left(\sigma_n = \frac{\bar{n}^n e^{-\bar{n}}}{n!}\right)$$
- Independent emission picture (like soft γ radiation in QED)
- Driven by large emission probability
[Gerwick et al.] JHEP10(2012)162

NLO predictions

[BlackHat] arXiv:1304.1253

- W+jets at 7 TeV, $E_T^e > 20\ \text{GeV}\,,\quad |\eta^e| < 2.5\,,\quad \not{E}_T > 20\ \text{GeV}$
  $p_T^j > 25\ \text{GeV}\,,\quad |\eta^j| < 3\,,\quad M_T^W > 20\ \text{GeV}$

Jets	$\frac{W^- + (n+1)}{W^- + n}$		$\frac{W^+ + (n+1)}{W^+ + n}$	
	LO	NLO	LO	NLO
1	0.2949(0.0003)	0.238(0.001)	0.3119(0.0005)	0.242(0.002)
2	0.2511(0.0005)	0.220(0.001)	0.2671(0.0004)	0.235(0.002)
3	0.2345(0.0008)	0.211(0.003)	0.2490(0.0005)	0.225(0.003)
4	0.218(0.001)	0.200(0.006)	0.2319(0.0008)	0.218(0.006)

- Fit to straight line for $W + n$ jets gives $(n \geq 2)$

$$R_{n/(n-1)}^{\text{NLO},\,W^-} = 0.248 \pm 0.008 - (0.009 \pm 0.002)\,n$$

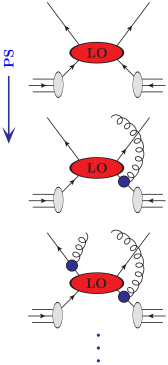
$$R_{n/(n-1)}^{\text{NLO},\,W^+} = 0.263 \pm 0.009 - (0.009 \pm 0.003)\,n$$

- Extrapolate to six jets

$W^- + 6$ jets : 0.15 ± 0.01 pb

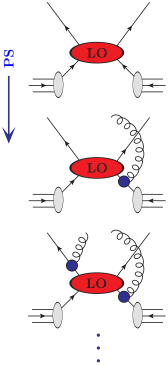
$W^+ + 6$ jets : 0.30 ± 0.03 pb

Parton showers



$$\sigma^{\text{incl}}_{2\to 2}\,\mathcal{F}_{\text{MC}}(\mu_Q^2)$$

Parton showers



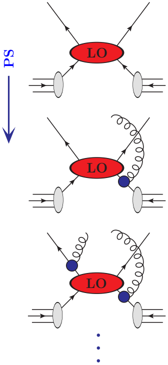
$$\sigma_{2\to 2}^{\mathrm{incl}} \Bigg[\Delta(t_c, \mu_Q^2)$$

$$+ \int_{t_c} \frac{\mathrm{d}t}{t} \mathrm{d}z \frac{\alpha_s}{2\pi} P(z) \Delta(t, \mu_Q^2)$$

$$+ \frac{1}{2} \left(\int_{t_c} \frac{\mathrm{d}t}{t} \mathrm{d}z \frac{\alpha_s}{2\pi} P(z) \Delta(t, \mu_Q^2) \right)^2$$

$$+ \ldots$$

Parton showers



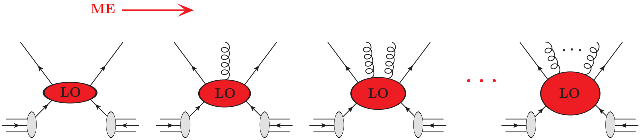
$$\sigma^{\mathrm{excl}}_{2\to2}$$

$$+\,\sigma^{\mathrm{excl}}_{2\to3}$$

$$+\,\sigma^{\mathrm{excl}}_{2\to4}$$

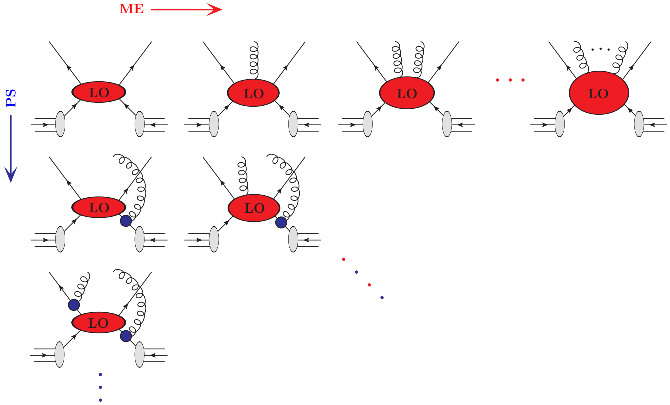
$$+\,\ldots$$

Matrix elements

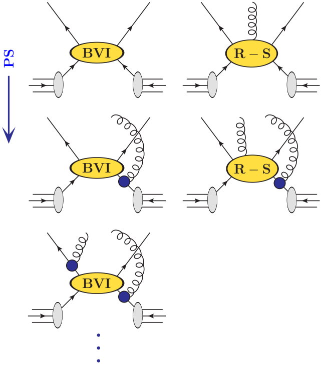


$\sigma^{\text{incl}}_{2\to 2}$ $\quad$ $\sigma^{\text{incl}}_{2\to 3}$ $\quad$ $\sigma^{\text{incl}}_{2\to 4}$ $\quad \ldots \quad$ $\sigma^{\text{incl}}_{2\to \text{N}}$

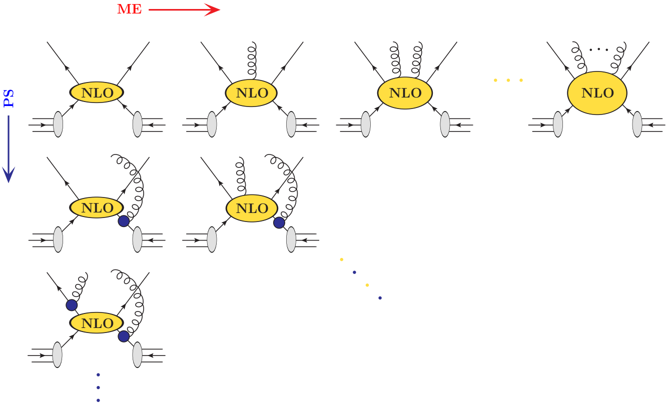
Merging at leading order



Matching NLO calculations and parton showers



Merging at next-to-leading order



Evolution of matching and merging methods

Incomplete and personally biased, just to give a flavor of things

- Matrix-element corrections to parton showers
  [Bengtsson,Sjöstrand] PLB185(1987)435, [Seymour] CPC90(1995)95
- ME↔PS correspondence, truncated PS [André,Sjöstrand] PRD57(1998)5767
- CKKW merging [Catani,Krauss,Kuhn,Webber] JHEP11(2001)063 JHEP08(2002)015
  Combines LO calculations of varying parton multiplicity
- MC@NLO [Frixione,Webber] JHEP06(2002)029
  Modified subtraction to remove overlap between ME & PS at NLO
- POWHEG [Nason] JHEP11(2004)040, [Frixione,Nason,Oleari] JHEP11(2007)070
  Combination of MC@NLO and ME-corrected parton shower
- NL^{3}SP [Lavesson,Lönnblad] JHEP12(2008)070, [Lönnblad,Prestel] JHEP03(2013)166
  Combines NLO calculations of varying jet multiplicity, explicit subtraction
- MENLOPS [Hamilton,Nason] JHEP06(2010)039 [Krauss,Schönherr,Siegert,SH] JHEP08(2011)123
  Combines lowest multiplicity NLO with higher-multiplicity LO
- ME⊕PS@NLO [Gehrmann,Krauss,Schönherr,Siegert,SH] JHEP01(2013)144 JHEP04(2013)027
  Combines NLO calculations of varying jet multiplicity, implicit subtraction

Basics of NLO+PS matching

- Leading-order calculation for observable O

$$\langle O \rangle = \int \mathrm{d}\Phi_B \, \mathrm{B}(\Phi_B) \, O(\Phi_B)$$

- NLO calculation for same observable

$$\langle O \rangle = \int \mathrm{d}\Phi_B \left\{ \mathrm{B}(\Phi_B) + \tilde{V}(\Phi_B) \right\} O(\Phi_B) + \int \mathrm{d}\Phi_R \, \mathrm{R}(\Phi_R) \, O(\Phi_R)$$

- Parton-shower result

$$\langle O \rangle = \int \mathrm{d}\Phi_B \, \mathrm{B}(\Phi_B) \, \mathcal{F}_{\mathrm{MC}}(\mu_Q^2, O)$$

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- NLO calculation for same observable

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- Parton-shower result

$$\langle O\rangle = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left[\Delta^{(\mathrm{K})}(t_c)\,O(\Phi_B) + \int_{t_c} \mathrm{d}\Phi_1\,\mathrm{K}(\Phi_1)\,\Delta^{(\mathrm{K})}(t(\Phi_1))\,O(\Phi_R) + \ldots\right]$$

Phase space: $\mathrm{d}\Phi_1 = \mathrm{d}t\,\mathrm{d}z\,\mathrm{d}\phi\,J(t,z,\phi)$
Splitting functions: $\mathrm{K}(t,z) \to \alpha_s/(2\pi t)\sum \mathrm{P}(z)\,\Theta(\mu_Q^2 - t)$
Sudakov factors: $\Delta^{(\mathrm{K})}(t) = \exp\left\{-\int_t \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)\right\}$

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- Parton-shower result

$$\langle O\rangle = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left[\Delta^{(\mathrm{K})}(t_c)\,O(\Phi_B)+\int_{t_c}\mathrm{d}\Phi_1\,\mathrm{K}(\Phi_1)\,\Delta^{(\mathrm{K})}(t(\Phi_1))\,O(\Phi_R)+\ldots\right]$$

$$\overset{\mathcal{O}(\alpha_s)}{\to}\int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left\{1-\int_{t_c}\mathrm{d}\Phi_1\mathrm{K}(\Phi_1)\right\}O(\Phi_B)+\int_{t_c}\mathrm{d}\Phi_B\mathrm{d}\Phi_1\,\mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1)\,O(\Phi_R)$$

Phase space: $\mathrm{d}\Phi_1 = \mathrm{d}t\,\mathrm{d}z\,\mathrm{d}\phi\,J(t,z,\phi)$
Splitting functions: $\mathrm{K}(t,z)\to\alpha_s/(2\pi t)\sum\mathrm{P}(z)\,\Theta(\mu_Q^2-t)$
Sudakov factors: $\Delta^{(\mathrm{K})}(t)=\exp\left\{-\int_t\mathrm{d}\Phi_1\mathrm{K}(\Phi_1)\right\}$

Basics of NLO+PS matching

- Subtract $\mathcal{O}(\alpha_s)$ PS terms from NLO result ($t_c \to 0$)

$$\langle O\rangle = \int \mathrm{d}\Phi_B \left\{ \mathrm{B}(\Phi_B) + \tilde{\mathrm{V}}(\Phi_B) + \mathrm{B}(\Phi_B) \int \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1) \right\} O(\Phi_B)$$
$$+ \int \mathrm{d}\Phi_R \left\{ \mathrm{R}(\Phi_R) - \mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1) \right\} O(\Phi_R)$$

- In DLL approximation both terms finite $\to$
  MC events in two categories, $\mathbb{S}$tandard and $\mathbb{H}$ard

$$\mathbb{S} \;\to\; \bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B) = \mathrm{B}(\Phi_B) + \tilde{\mathrm{V}}(\Phi_B) + \mathrm{B}(\Phi_B) \int \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)$$
$$\mathbb{H} \;\to\; \mathrm{H}^{(\mathrm{K})} = \mathrm{R}(\Phi_R) - \mathrm{B}(\Phi_B)\mathrm{K}(\Phi_1)$$

- Full QCD has color & spin correlations $\to$ NLO subtraction needed
  $1/N_c$ corrections faded out in soft region by smoothing function

$$\bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B) = \mathrm{B}(\Phi_B) + \tilde{\mathrm{V}}(\Phi_B) + \mathrm{I}(\Phi_B) + \int \mathrm{d}\Phi_1 \Big[\mathrm{S}(\Phi_R) - \mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1) \Big] f(\Phi_1)$$
$$\mathrm{H}^{(\mathrm{K})}(\Phi_R) = \Big[\mathrm{R}(\Phi_R) - \mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1) \Big] f(\Phi_1)$$

MC@NLO

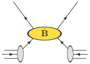
[Frixione,Webber] hep-ph/0204244

- Add parton shower, described by generating functional $\mathcal{F}_{\rm MC}$

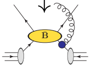
$$\langle O\rangle = \int \mathrm{d}\Phi_B\,\bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B)\,\mathcal{F}^{(0)}_{\rm MC}(\mu_Q^2,O) + \int \mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{K})}(\Phi_R)\,\mathcal{F}^{(1)}_{\rm MC}(t(\Phi_R),O)$$

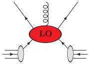
  Probability conservation $\leftrightarrow$ $\mathcal{F}_{\rm MC}(t,1)=1$
- Expansion of matched result until first emission

$$\langle O\rangle = \int \mathrm{d}\Phi_B\bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B)\bigg[\Delta^{(\mathrm{K})}(t_c)\,O(\Phi_B) \quad\leftrightarrow$$



$$+\int_{t_c}\mathrm{d}\Phi_1\mathrm{K}(\Phi_1)\Delta^{(\mathrm{K})}(t(\Phi_1))\,O(\Phi_r)\bigg] + \int \mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{K})}(\Phi_{n+1})\,O(\Phi_R)$$





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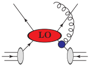


- Parametrically $\mathcal{O}(\alpha_s)$ correct
- Preserves logarithmic accuracy of PS

Handling soft singularities in MC@NLO

Method 1 [Frixione,Webber] JHEP06(2002)029

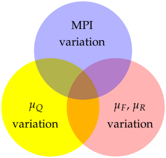
- $f(\Phi_1) \to 0$ in soft-gluon limit
- Full NLO only in hard / collinear region
  Missing subleading color terms in soft domain
- Only affects unresolved gluons $\to$ no need to correct

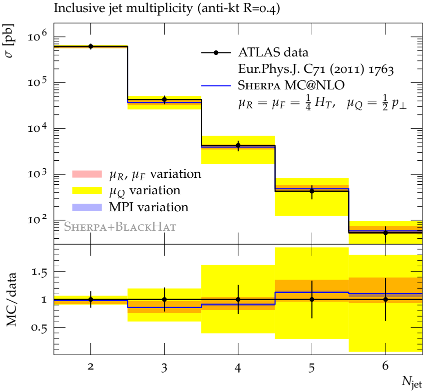
Method 2 [Krauss,Schönherr,Siegert,SH] JHEP09(2012)049

- Replace $\mathrm{B}(\Phi_B)\mathrm{K}(\Phi_1) \to \mathrm{S}(\Phi_R)$, i.e. include color & spin correlations
- May lead to non-probabilistic Sudakov factor $\Delta^{(\mathrm{S})}(t)$
  Requires modification of veto algorithm
- Exact cancellation of all divergences without additional smoothing
  Equivalent to one-step full colour parton shower algorithm

MC@NLO in Sherpa

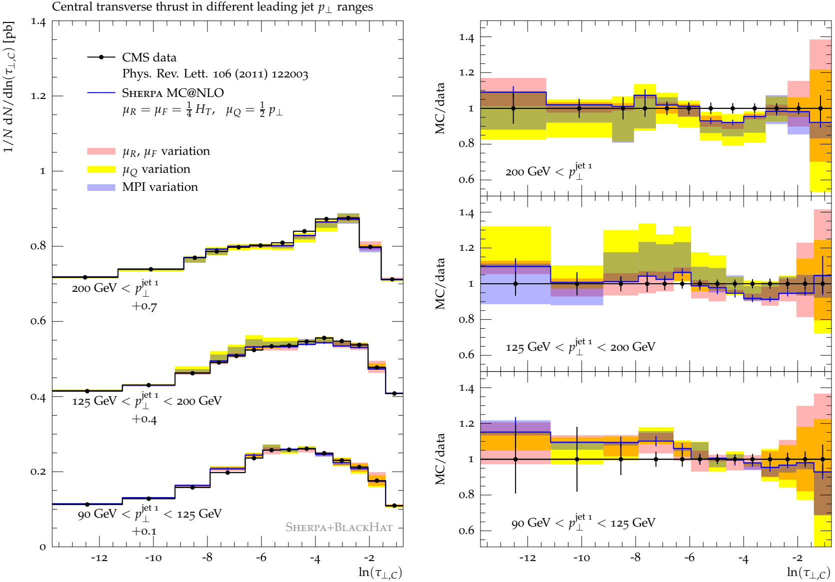
- Full-color MC@NLO automated in SHERPA using CS subtraction
  [Catani,Seymour] NPB485(1997)291
  [Gleisberg,Krauss] EPJC53(2008)501
  [Schumann,Krauss] JHEP03(2008)038
- Validated in QCD jets production
  - CT10, $\alpha_s(M_Z) = 0.118$
  - Full hadron level, incl. MPI
  - Virtual corrections $\rightarrow$ BlackHat
    [Berger et al.] PRD78(2008)036003
    [Giele,Glover,Kosower] NPB403(1993)633
  - $p_{T,j1} > 20$ GeV, $p_{T,j2} > 10$ GeV
  - $\mu_{R/F} = H_T/4$, $\mu_Q = p_T/2$
- Implementation allows to assess renormalization/factorization and resummation scale uncertainty



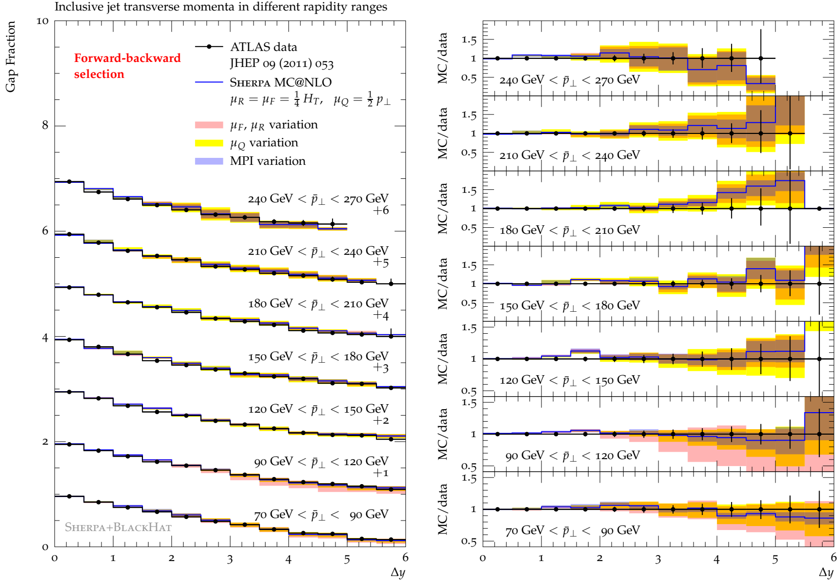


[Schönherr,SH] PRD86(2012)094042

Inclusive jet production at the LHC

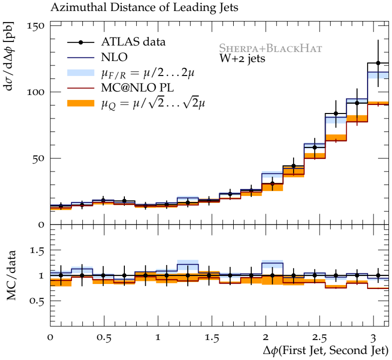


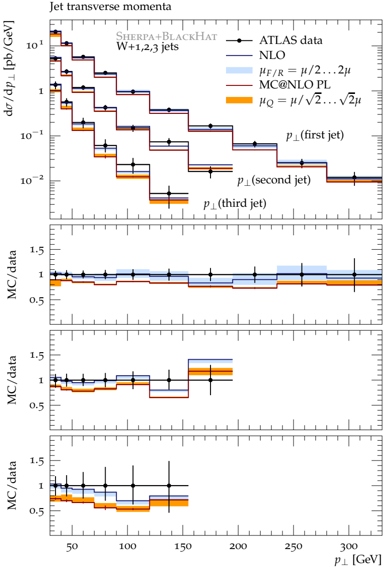
Dijet production with a jet veto



$W + n$ jet production at the LHC

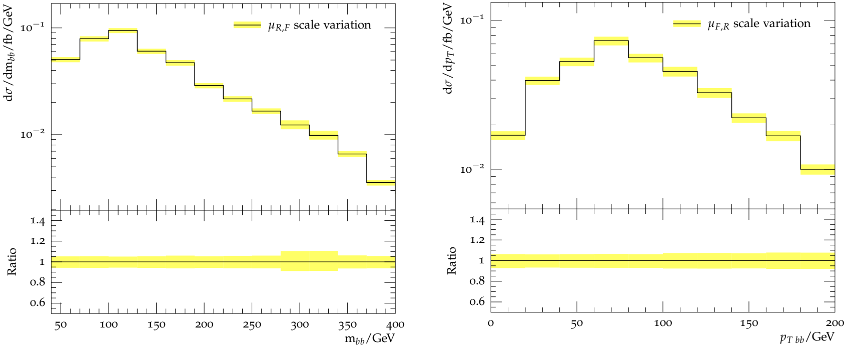
- $p_{T,l} > 20$ GeV, $|\eta_l| < 2.5$, $\not{E}_T > 25$ GeV, $M_T > 40$ GeV
- $p_{T,j} > 30$ GeV, $|y_j| < 2.8$
- Virtual corrections from BlackHat
  [Berger et al.] PRD78(2008)036003





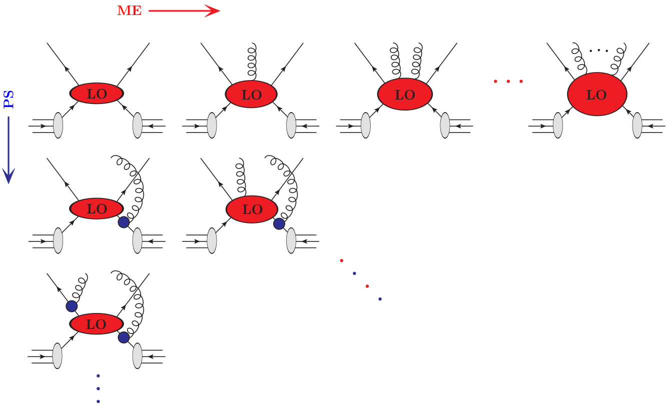
[Krauss,Schönherr,Siegert,SH] PRL110(2013)052001

$t\bar{t}h$ production at the LHC



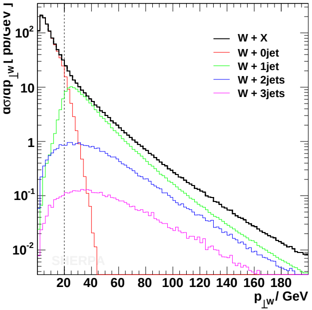
- Invariant mass and p_T of b-jets not associated with top decay
- Virtual ME from [Dawson,Jackson,Orr,Reina,Wackeroth]
  PRD68(2003)034022 PRD67(2003)071503 PRL87(2001)201804

Merging at leading and next-to-leading order



Basic idea of ME⊕PS merging

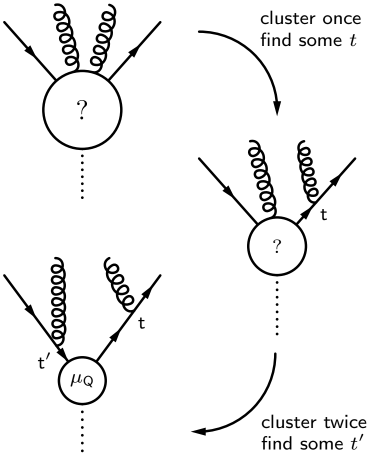
- Separate phase space into "hard" and "soft" region
- Matrix elements populate hard domain
- Parton shower populates soft domain
- Need criterion to define "hard" & "soft" $\rightarrow$ jet measure Q and corresponding cut, Q_{cut}



Parton-shower histories

[André,Sjöstrand] PRD57(1998)5767

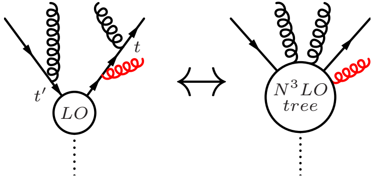
- Start with some "core" process
  for example $e^+e^- \to q\bar{q}$
- This process is considered inclusive
  It sets the resummation scale μ_Q^2
- Higher-multiplicity ME can be reduced to core by clustering
- Clustering algorithm uniquely defined by requiring exact correspondence between ME & PS
  - Identify most likely splitting according to PS emission probability
  - Combine partons into mother according to PS kinematics
  - Continue until core process



Truncated & vetoed parton showers

[Catani,Krauss,Kuhn,Webber] JHEP11(2001)063
[Lönnblad] JHEP05(2002)046

- Higher-multiplicity MEs that can be reduced to core process are included in core's inclusive cross section (unitarity of PS)
- Sudakov suppression factors needed to make inclusive MEs exclusive
- Most efficiently computed with pseudo-showers
  - Start PS from core process
  - Evolve until predefined branching $\leftrightarrow$ truncated parton shower
  - Emissions producing additional hard jets lead to event veto



$$\Delta_n^{(\mathrm{K})}(t;>Q_{\mathrm{cut}}) = \exp\left\{ -\int_t \mathrm{d}\Phi_1\, \mathrm{K}_n(\Phi_1)\, \Theta(Q-Q_{cut}) \right\}$$

Towards ME⊕PS@NLO

- ME⊕PS for 0+1-jet in MC@NLO notation

$$\langle O\rangle = \int \mathrm{d}\Phi_B \mathrm{B}(\Phi_B)\left[\Delta^{(\mathrm{K})}(t_c)\,O(\Phi_B) + \int_{t_c} \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)\,\Delta^{(\mathrm{K})}(t)\,\Theta(Q_\mathrm{cut}-Q)\,O(\Phi_R)\right]$$
$$+ \int \mathrm{d}\Phi_R\,\mathrm{R}(\Phi_R)\,\Delta^{(\mathrm{K})}(t(\Phi_R);>Q_\mathrm{cut})\,\Theta(Q-Q_\mathrm{cut})\,O(\Phi_R) + \ldots$$

- Reorder by parton multiplicity k, change notation $\mathrm{R}_k \to \mathrm{B}_{k+1}$
- Analyze exclusive contribution from k hard partons only $(t_0 = \mu_Q^2)$

$$\langle O\rangle_k^\mathrm{excl} = \int \mathrm{d}\Phi_k\,\mathrm{B}_k \prod_{i=0}^{k-1} \Delta_i^{(\mathrm{K})}(t_{i+1}, t_i;>Q_\mathrm{cut})\,\Theta(Q_k - Q_\mathrm{cut})$$
$$\times \left[\Delta_k^{(\mathrm{K})}(t_c, t_k)\,O_k + \int_{t_c}^{t_k} \mathrm{d}\Phi_1\,\mathrm{K}_k\,\Delta_k^{(\mathrm{K})}(t_{k+1}, t_k)\,\Theta(Q_\mathrm{cut} - Q_{k+1})\,O_{k+1}\right]$$

Constructing ME⊕PS@NLO

- Analyze exclusive contribution from k hard partons

$$\langle O\rangle_k^{\rm excl} = \int {\rm d}\Phi_k\,{\rm B}_k\,\prod_{i=0}^{k-1}\Delta_i^{\rm (K)}(t_{i+1},t_i;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})$$

$$\times\left[\Delta_k^{\rm (K)}(t_c,t_k)\,O_k + \int_{t_c}^{t_k}{\rm d}\Phi_1\,{\rm K}_k\,\Delta_k^{\rm (K)}(t_{k+1},t_k)\,\Theta(Q_{\rm cut}-Q_{k+1})\,O_{k+1}\right]$$

Constructing ME⊕PS@NLO

- Analyze exclusive contribution from k hard partons

$$\langle O\rangle_k^{\rm excl} = \int {\rm d}\Phi_k\,{\rm B}_k \prod_{i=0}^{k-1}\Delta_i^{\rm (K)}(t_{i+1},t_i;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})$$

$$\times\left[\Delta_k^{\rm (D)}(t_c,t_k)\,O_k + \int_{t_c}^{t_k}{\rm d}\Phi_1\,\frac{\rm D_k}{\rm B_k}\,\Delta_k^{\rm (D)}(t_{k+1},t_k)\,\Theta(Q_{\rm cut}-Q_{k+1})\,O_{k+1}\right]$$

- PS evolution kernels $\rightarrow$ dipole terms

Constructing ME$\oplus$PS@NLO

- Analyze exclusive contribution from k hard partons

$$\langle O\rangle_k^{\rm excl} = \int {\rm d}\Phi_k\,\bar{\rm B}_k^{\rm (K)}\prod_{i=0}^{k-1}\Delta_i^{\rm (K)}(t_{i+1},t_i;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})$$

$$\times\left[\Delta_k^{\rm (D)}(t_c,t_k)\,O_k + \int_{t_c}^{t_k}{\rm d}\Phi_1\,\frac{\rm D_k}{\rm B_k}\,\Delta_k^{\rm (D)}(t_{k+1},t_k)\,\Theta(Q_{\rm cut}-Q_{k+1})\,O_{k+1}\right]$$

- PS evolution kernels $\rightarrow$ dipole terms
- Born matrix element $\rightarrow$ NLO-weighted Born

Constructing ME⊕PS@NLO

- Analyze exclusive contribution from k hard partons

$$\langle O\rangle_k^{\rm excl} = \int {\rm d}\Phi_k\,\bar{\rm B}_k^{\rm (K)}\prod_{i=0}^{k-1}\Delta_i^{\rm (K)}(t_{i+1},t_i;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})$$

$$\times\left[\Delta_k^{\rm (D)}(t_c,t_k)\,O_k+\int_{t_c}^{t_k}{\rm d}\Phi_1\,\frac{\rm D_k}{\rm B_k}\,\Delta_k^{\rm (D)}(t_{k+1},t_k)\,\Theta(Q_{\rm cut}-Q_{k+1})\,O_{k+1}\right]$$
$$+\int{\rm d}\Phi_{k+1}\,{\rm H}_k^{\rm (D)}\,\Delta_k^{\rm (K)}(t_k;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})\,\Theta(Q_{\rm cut}-Q_{k+1})\,O_{k+1}$$

- PS evolution kernels → dipole terms
- Born matrix element → NLO-weighted Born
- Add hard remainder function

Constructing ME⊕PS@NLO

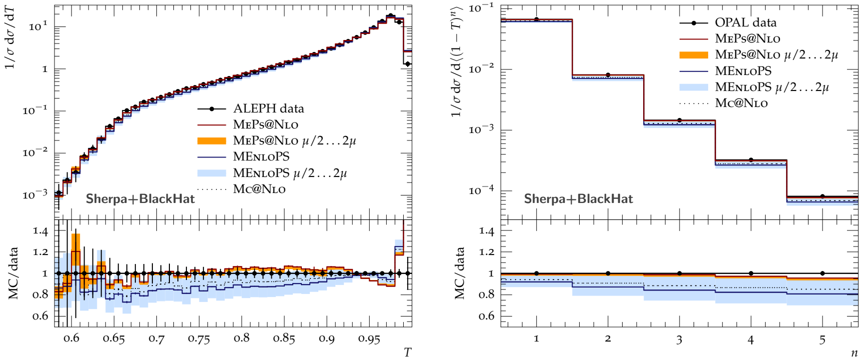
- Analyze exclusive contribution from k hard partons

$$
\begin{aligned}
\langle O\rangle_k^{\rm excl} =& \int {\rm d}\Phi_k\,\bar{\rm B}_k^{\rm (K)}\,\prod_{i=0}^{k-1}\Delta_i^{\rm (K)}(t_{i+1},t_i;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})\\
&\times\prod_{i=0}^{k-1}\left(1+\int_{t_{i+1}}^{t_i}{\rm d}\Phi_1{\rm K}_i\,\Theta(Q_i-Q_{\rm cut})\right)F_i(t_{i+1},t_i;\mu_F^2)\\
&\times\left[\Delta_k^{\rm (D)}(t_c,t_k)\,O_k\;+\int_{t_c}^{t_k}{\rm d}\Phi_1\,\frac{\rm D_k}{\rm B_k}\,\Delta_k^{\rm (D)}(t_{k+1},t_k)\,\Theta(Q_{\rm cut}-Q_{k+1})\,O_{k+1}\right]\\
&+\int{\rm d}\Phi_{k+1}\,{\rm H}_k^{\rm (D)}\,\Delta_k^{\rm (K)}(t_k;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})\,\Theta(Q_{\rm cut}-Q_{k+1})\;O_{k+1}
\end{aligned}
$$

- PS evolution kernels → dipole terms
- Born matrix element → NLO-weighted Born
- Add hard remainder function
- Subtract $\mathcal{O}(\alpha_s)$ terms from truncated vetoed PS

$e^+e^- \to$hadrons at LEP

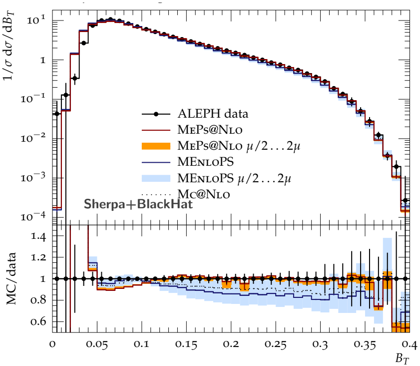
[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031

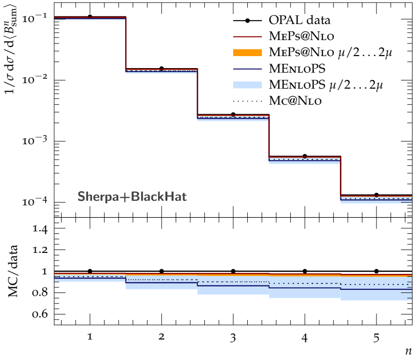


- Thrust & its moments
- ME⊕PS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO vs 2 jet PL at NLO plus up to 6 jets at LO

$e^+e^- \rightarrow$hadrons at LEP

[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031

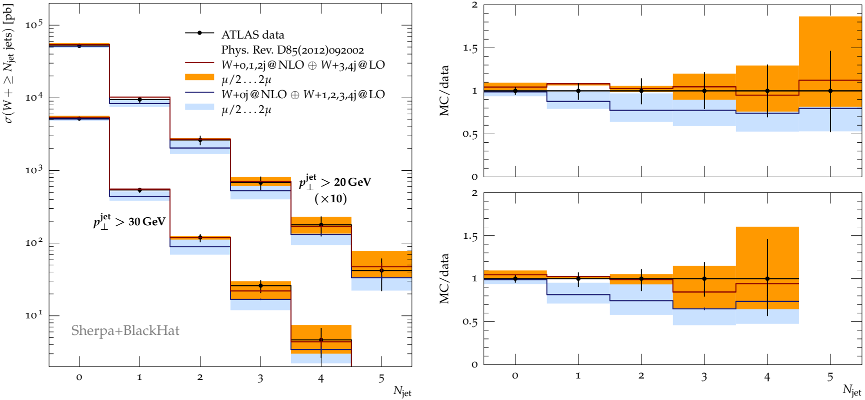




- Total jet broadening & its moments
- ME⊕PS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO vs 2 jet PL at NLO plus up to 6 jets at LO

$W+$jets production at the LHC

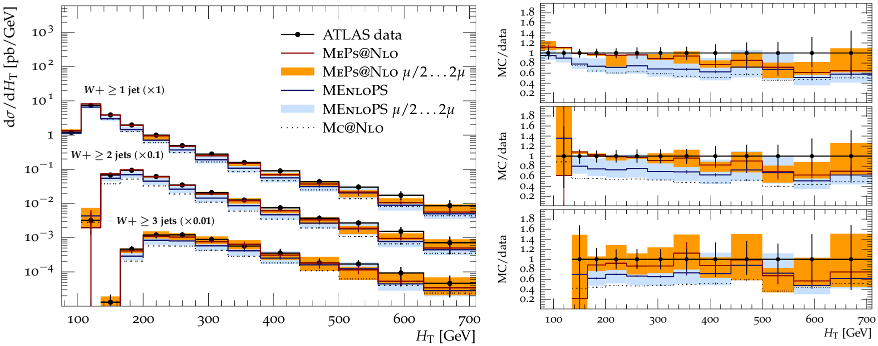
[SH,Krauss,Schönherr,Siegert] arXiv:1207.5030



- ME⊕PS@NLO with 0,1&2 jet PL at NLO plus 3&4 jet PL at LO
- vs 0 jet PL at NLO plus up to 4 jets at LO

W+jets production at the LHC

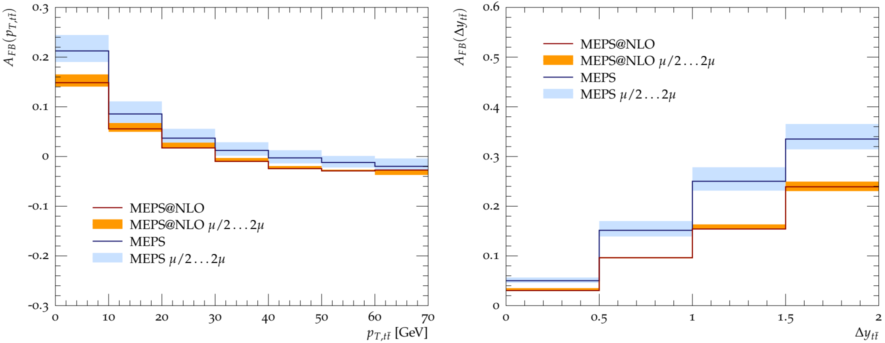
[SH,Krauss,Schönherr,Siegert] arXiv:1207.5030



- ME⊕PS@NLO with 0,1&2 jet PL at NLO plus 3&4 jet PL at LO
- vs 0 jet PL at NLO plus up to 4 jets at LO

Top pair production at the Tevatron

[Huang,Luisoni,Schönherr,Winter,SH] to appear



- ME⊕PS@NLO with 0&1 jet PL at NLO
- ME⊕PS with up to 1 jet at LO

Summary

- NLO calculations, matching and merging automated
- Improved precision of MC event generators (LO $\to$ NLO)
- Full exploitation of a wealth of NLO calculations
- Assessment of fixed-order scale uncertainties