Matrix Elements + Parton Showers Reloaded
Matching vs Merging at NLO

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SLAC NAL

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Event generation for e^+e^- colliders

Three general-purpose tools with slightly different structure and emphasis

Herwig

- Originated in coherent shower studies → 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 → Lund string
- Leading in development of models for non-perturbative physics
- Pragmatic attitude to ME generation → 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⊗PS merging (at NLO)
- Automated framework for NLO calculations and MC@NLO

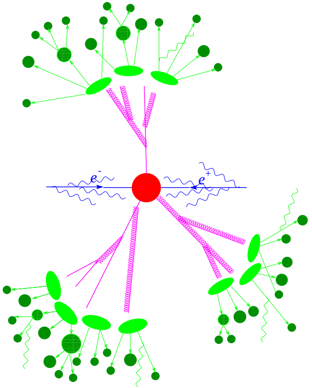
For more information, check out [Buckley et al.] arXiv:1101.2599
For updates and news, go to http://www.montecarlonet.org

Event generation for e^+e^- colliders

Structure of the simulation

- Hard interaction
- QCD evolution
- Hadronization
- Hadron decays
- Higher-order QED corrections

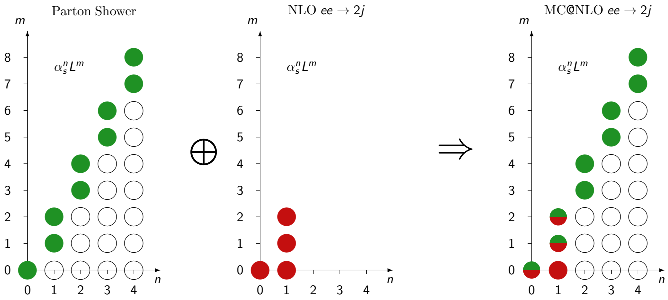
Much recent progress on hard QCD
Benefits from "NLO revolution"



Jets defined with some IR-safe algorithm (e.g. Durham k_T)
Measuring inclusive n-jet observable

Objectives

- NLO accurate prediction for inclusive n-jet process
- Logarithmic accuracy of LO+PS throughout



[Frixione,Webber] hep-ph/0204244

Differential event rate to $\mathcal{O}(\alpha_s)$ in LO+PS

$$\frac{\mathrm{d}\sigma_{\mathrm{PS}}}{\mathrm{d}\Phi} = \mathrm{B}\left[\Delta^{(\mathrm{K})}(t_c,\mu_Q^2) + \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1\,\mathrm{K}\,\Delta^{(\mathrm{K})}(t(\Phi_1),\mu_Q^2)\right]$$

K - sum of PS kernels for n-parton final state

Make this NLO-correct:

- Radiation pattern from ME corrected PS
  Correction weight $w = \mathrm{D}^{(\mathrm{A})}/\mathrm{BK}$, where $\mathrm{D}^{(\mathrm{A})} \to$ dipole term
- Add hard remainder function $\int \mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{A})}$, where $\mathrm{H}^{(\mathrm{A})} = \left[\,\mathrm{R} - \mathrm{D}^{(\mathrm{A})}\,\right]$
- Replace $\mathrm{B} \to \bar{\mathrm{B}}^{(\mathrm{A})} = \mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I} + \int \mathrm{d}\Phi_1 \left(\mathrm{D}^{(\mathrm{A})} - \mathrm{S}\right)$

Differential event rate to $\mathcal{O}(\alpha_s)$ in matched calculation

$$\frac{\mathrm{d}\sigma_{\mathrm{NLOPS}}}{\mathrm{d}\Phi} = \bar{\mathrm{B}}^{(\mathrm{A})}\left[\Delta^{(\mathrm{A})}(t_c) + \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1\,\frac{\mathrm{D}^{(\mathrm{A})}}{\mathrm{B}}\,\Delta^{(\mathrm{A})}(t(\Phi_1))\right] + \int \mathrm{d}\Phi_1\,\mathrm{H}^{(\mathrm{A})}$$

MC@NLO and POWHEG differ in choice of $\mathrm{D}^{(\mathrm{A})}$ and μ_Q^2

Method 1 [Frixione,Webber] hep-ph/0204244

- Original algorithm formulated such that $\mathrm{D}^{(\mathrm{A})} \to \mathrm{D}^{(\mathrm{K})} = \mathrm{BK}$,
  i.e. modified subtraction carried out with parton-shower approximation
- Exact only in collinear region
  Missing subleading color terms in single-logarithmic divergences
- Solved by smoothly fading out real-emission correction in singly-soft region
  Need to correct for mismatch, but only affects unresolved gluons anyhow

Method 2 [Krauss,Schönherr,Siegert,SH] arXiv:1111.1220

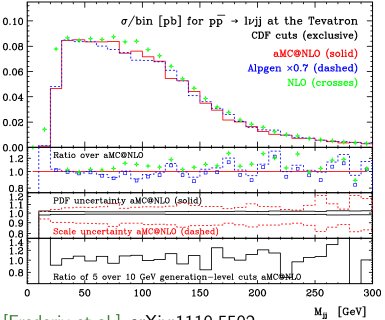
- Alternative solution employs $\mathrm{D}^{(\mathrm{A})} \to \mathrm{D}^{(\mathrm{S})} = \mathrm{S}$
  i.e. parton-shower evolution performed with NLO subtraction terms
- Leads to non-probabilistic Sudakov factor $\Delta^{(\mathrm{S})}$
  Requires modification of veto algorithm
- Exact cancellation of all divergences without additional smoothing
  Equivalent to one-step full col-our parton shower algorithm

Method 1 automated in aMC@NLO

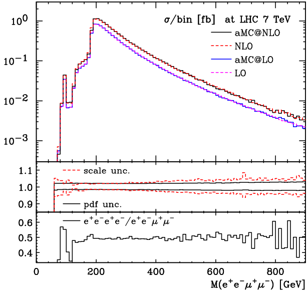
Using MADFKS subtraction and external PS from fHERWIG/ PYTHIA

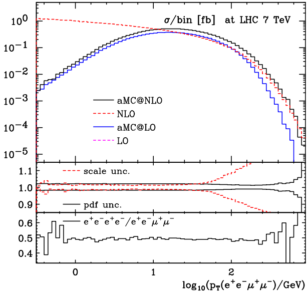
Framework for uncertainty estimates

- $t\bar{t}h$ arXiv:1104.5613
- 4 leptons arXiv:1110.4738
- $W^{\pm}$+2 jets arXiv:1110.5502



[Frederix et al.] arXiv:1110.5502



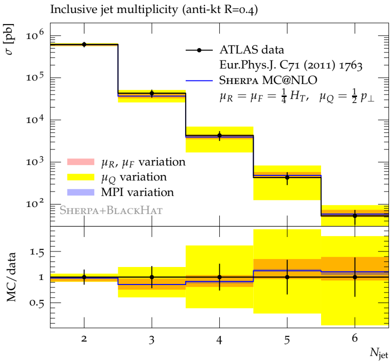


[Frederix et al.] arXiv:1110.4738

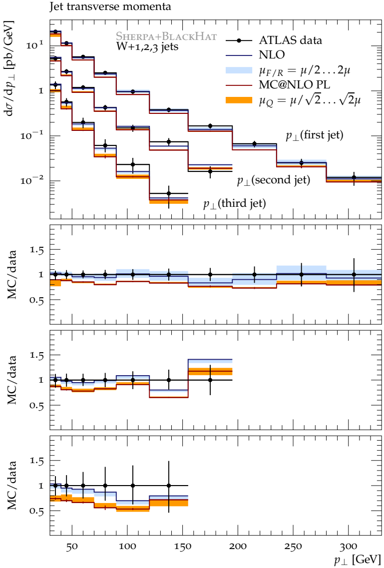
Method 2 automated in SHERPA

Allows to determine fixed-order and resummation scale uncertainty

- QCD dijets arXiv:1208.2815
- $W^{\pm} + \leq 3$ jets arXiv:12012.5882



[Schönherr,SH] arXiv:1208.2815



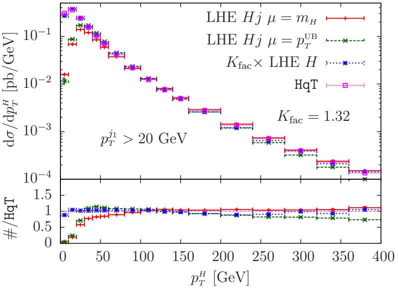
[Krauss,Schönherr,Siegert,SH] arXiv:1201.5882

$D^{(A)} \to R \Rightarrow$ MC@NLO $\to$ POWHEG
[Frixione,Nason,Oleari] arXiv:0709.2092

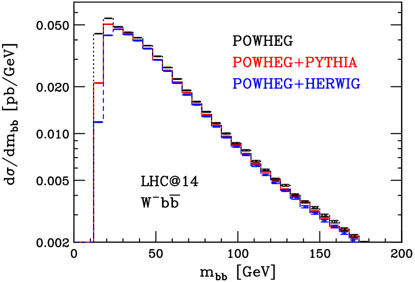
Automated in POWHEGBOX
[Alioli,Oleari,Nason,Re] arXiv:1002.2581

- FKS subtraction
- PYTHIA/fHERWIG PS

Extensive list of processes implemented



[Campbell et al.] arXiv:1202.5475



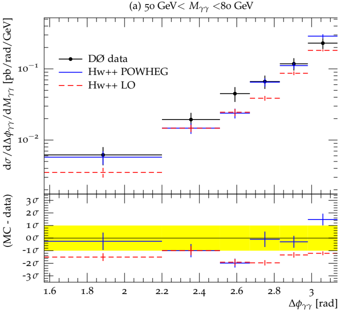
[Oleari,Reina] arXiv:1105.4488

POWHEGBOX originally aimed at providing framework only $\Rightarrow$ many contributors & rapid growth

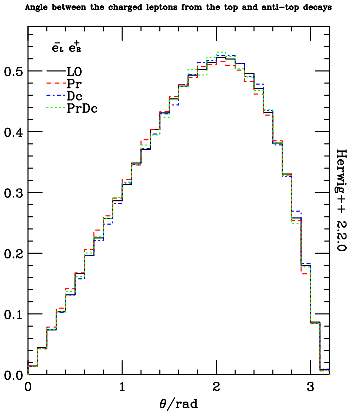
[Barzè,Bernaciak,Bagnaschi,Campbell,Ellis, Frederix,deGrassi,Jäger,Klasen,Kovarik,Melia, Moch,Montagna,Nicrosini,Piccinini,Reina,Ridolfi, Rontsch,Slavich,Uwer,Vicini,Wackeroth,Weydert, Williams,Zanderighi,...]

Implementation in HERWIG++

- $e^+e^- \to$jets hep-ph/0612281
- $e^+e^- \to t\bar{t}$ arXiv:0806.4560
- Drell-Yan arXiv:0806.0290
- W/Z+Higgs arXiv:0903.4135
- Higgs in GF arXiv:0903.4345
- DIS & VBF arXiv:1106.2983
- Diphoton arXiv:1106.3939



[D'Errico,Richardson] arXiv:1106.3939



[Latunde-Dada] arXiv:0806.4560

Truncated PS always included!

Neglected in POWHEGBOX
but necessary to fill complete
phase space [Nason] hep-ph/0409146

Parton shower issues

McNlo and Powheg both rely on general-purpose MC for subsequent showering

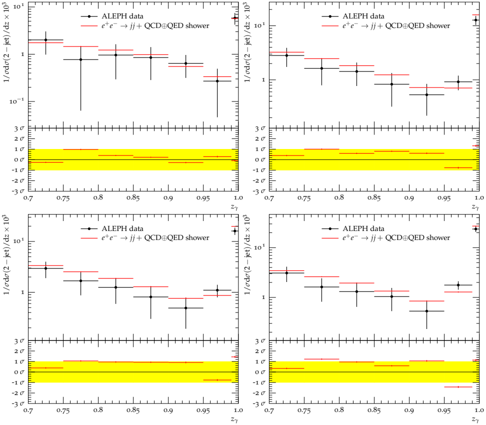
Kinematic effects & scale choices play a role → PS model affects accuracy of matched NLO result

Need improved parton showers as part of general-purpose MC

Various new implementations but few public codes on market

PS & Hadronization linked → combined tuning necessary!

γ-fragmentation function arXiv:0912.3501



[Schumann,Siegert,SH] arXiv:0912.3501

Most promising progress with dipole-like parton showers
[Schumann,Krauss] arXiv:0709.1027, [Plätzer,Gieseke] arXiv:0909.5593

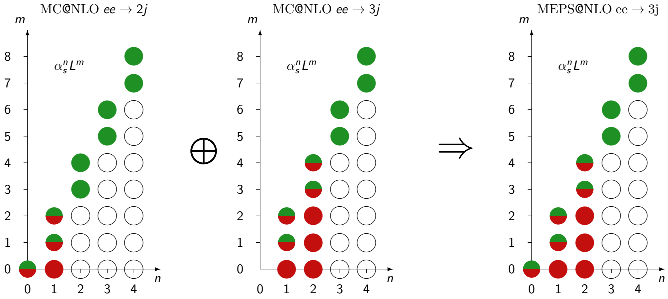
Sector showers interesting new alternative
[Giele,Kosower,Skands] arXiv:1102.2126, [Larkoski,Peskin] arXiv:0908.2450

ME⊗PS merging

Jets defined with some IR-safe algorithm (e.g. Durham k_T)
Measuring n-jet observables for varying n simultaneously

Objectives

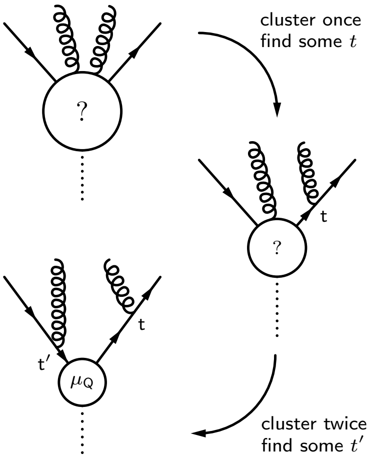
- Fixed-order accurate prediction for $k_T > k_{T,\mathrm{cut}}$
- Logarithmic accuracy of PS throughout



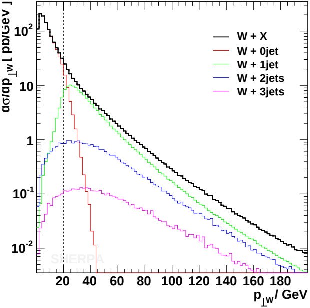
Prerequisite: Parton-shower histories

[André,Sjöstrand] hep-ph/9708390

- 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
- If we want to match ME & PS the correct clustering algorithm suggests itself
  - Identify most likely splitting according to PS emission probability
  - Combine partons into mother according to PS kinematics
  - Continue until core process



ME⊗PS merging



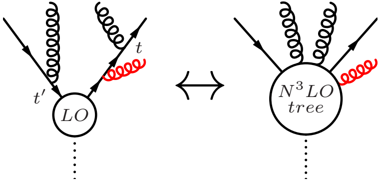
[Catani,Krauss,Kuhn,Webber] hep-ph/0109231

Basic idea of Merging

- Jet criterion Q ($\sim k_T$) identifies hardness
  $\rightarrow$ $Q_{\rm cut}$ separates phase space
- Matrix elements populate hard domain
- Parton shower populates soft domain

Method

- Start PS from core process
- Evolve until predefined branching
  $\leftrightarrow$ truncated parton shower
- Veto emissions at $Q > Q_{\rm cut}$



$$\Delta^{(K)}(t,\mu_Q^2;>Q_{\rm cut}) \;=\; \exp\left\{-\int_t^{\mu_Q^2} {\rm d}\Phi_1\, K(\Phi_1)\,\Theta(Q-Q_{cut})\right\}$$

Need control of PS to do things correctly → only two techniques with

- Exact correspondence between clustering & PS evolution
- Sudakov form factors as defined in parton shower

[Lönnblad] hep-ph/0112284
[Lönnblad,Prestel] arXiv:1109.4829

CKKW-L (**Pythia 8**)

- Truncated showers generate suppression, but no emissions
- Jet criterion dynamically redefined during PS evolution
- Simple and easy to implement

[Krauss,Schumann,Siegert,SH] arXiv:0903.1219
[Hamilton,Richardson,Tully] arXiv:0905.3072

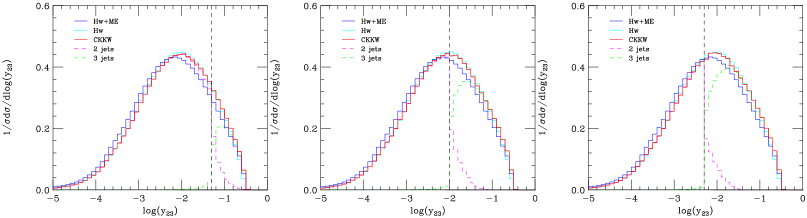
METS (**Herwig++** & **Sherpa**)

- Truncated parton showers generate emissions and suppression
- Accounts for mismatch between jet criterion and evolution variable
- Requires intimate knowledge of PS

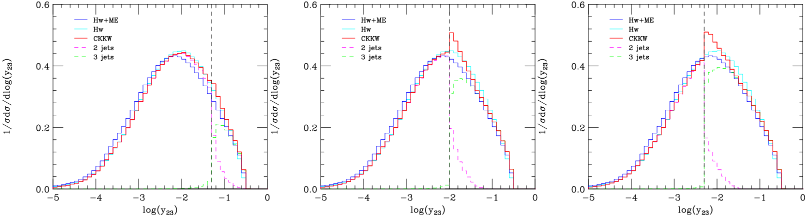
[Hamilton,Richardson,Tully] arXiv:0905.3072

Effect of truncated showers in $e^+e^- \to$ hadrons

truncated shower on



truncated shower off

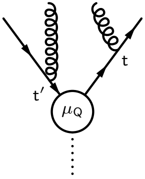


[Lavesson,Lönnblad] arXiv:0811.2912 [Lönnblad,Prestel] in preparation
[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5030, arXiv:1207.5031

Prerequisite: MC@NLO for higher parton multiplicity

Compound PS evolution kernel for $n+k$-particle final state

$$\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k} = \mathrm{D}^{(\mathrm{A})}_{n+k}\,\Theta(t_{n+k} - t_{n+k+1}) + \mathrm{B}_{n+k} \sum_{i=n}^{n+k-1} \mathrm{K}_i\,\Theta(t_i - t_{n+k+1})\Theta(t_{n+k+1} - t_{i+1})$$



t_i - nodal scales of parton emission in corresponding PS history

Extended modified subtraction, including $\mathcal{O}(\alpha_s)$ terms of truncated PS

$$\tilde{\mathrm{B}}^{(\mathrm{A})}_{n+k} = \left(\mathrm{B}_{n+k} + \tilde{\mathrm{V}}_{n+k} + \mathrm{I}_{n+k}\right) + \int \mathrm{d}\Phi_1 \left(\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k} - \mathrm{S}_{n+k}\right)$$

$$\tilde{\mathrm{H}}^{(\mathrm{A})}_{n+k} = \mathrm{R}_{n+k} - \tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k}$$

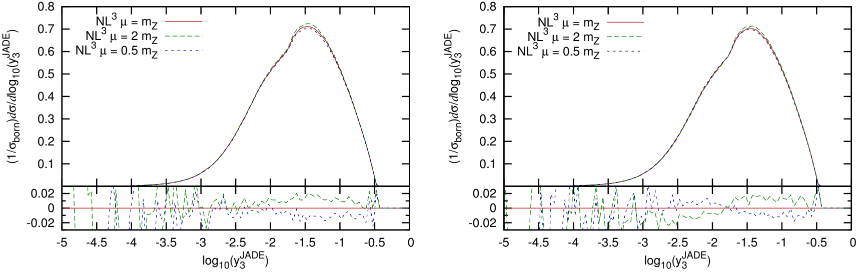
Otherwise arguments for ME⊗PS merging at LO go straight through!

Currently two techniques

- Explicit subtraction (**Pythia 8**)
- Shower veto (**SHERPA**)

ME⊗PS merging at NLO

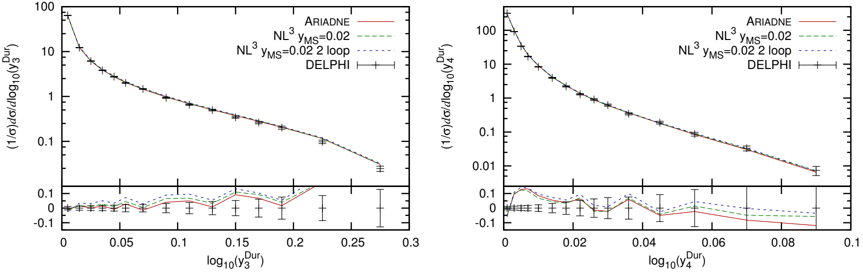
[Lavesson,Lönnblad] arXiv:0811.2912



- Jade jet resolution in $e^+e^- \to$hadrons at LEP
- MEPS@NLO with 2&3 jet PL at NLO / 2 jet PL at NNLO & 3 jet PL at NLO

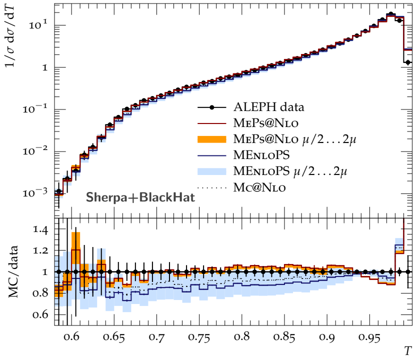
ME⊗PS merging at NLO

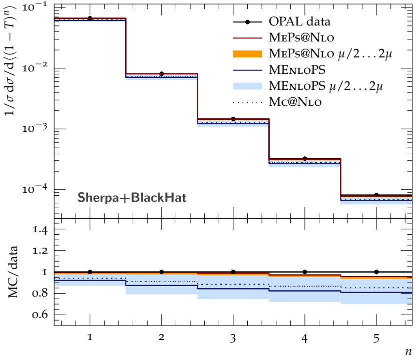
[Lavesson,Lönnblad] arXiv:0811.2912



- Durham k_T-jet resolution in e^+e^- →hadrons at LEP
- MEPS@NLO with 2&3 jet PL at NLO /
  2 jet PL at NNLO & 3 jet PL at NLO

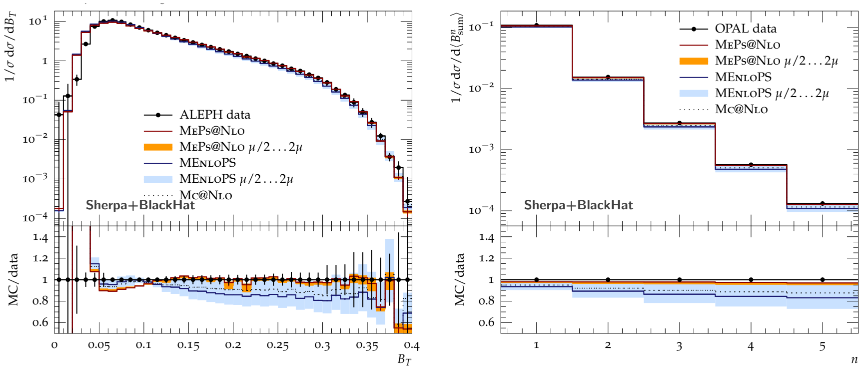
[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031





- Thrust & its moments
- MEPS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO vs MENLOPS with 2-6 jet PL at LO

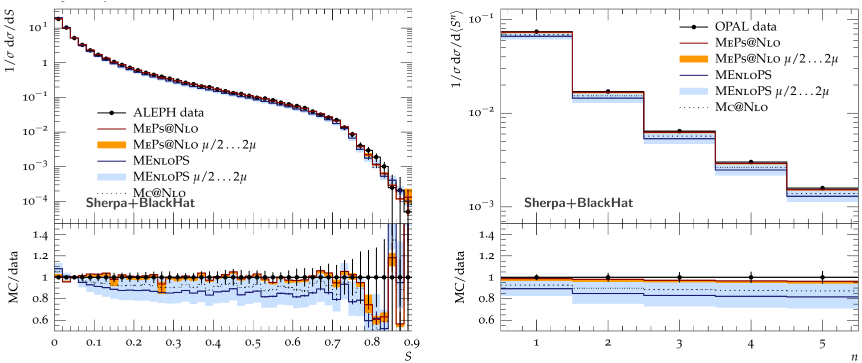
[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031



- Total jet broadening & its moments
- MEPS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO vs MENLOPS with 2-6 jet PL at LO

ME⊗PS merging at NLO

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



- Sphericity & its moments
- MEPS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO vs MENLOPS with 2-6 jet PL at LO

Summary

- Lots of progress to combine NLO tools with general-purpose MC
- Combination of multiple NLO calculations into inclusive event samples

- More systematic uncertainty studies needed
- Improved resummation needed if accuracy to be increased further
- Need to improve simulation of EW effects & e^+e^- ISR