Parton Showers - Part III

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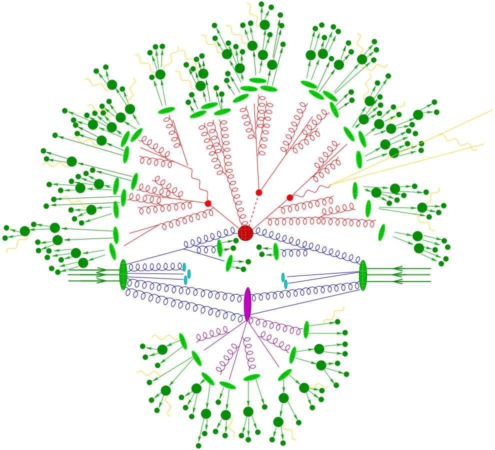
Outline of Lecture III

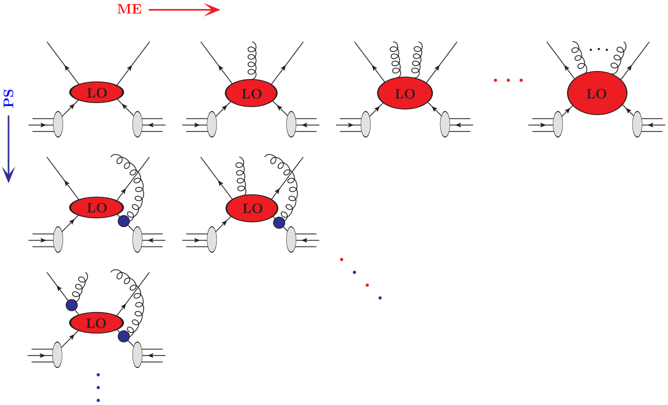
- Merging ME and PS at NLO
- Secondary hard interactions
- Hadronization & Decays

The structure of MC events

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



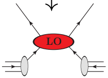
Recap: Merging matrix elements & parton showers



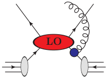
Recap: MEPS merging in MC@NLO notation

- Observable O to $\mathcal{O}(\alpha_s)$ given by

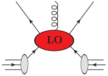
$$\langle O\rangle = \int \mathrm{d}\Phi_B \mathrm{B}(\Phi_B)\bigg[\, \Delta^{(\mathrm{K})}(t_c,\mu_Q^2)\, O(\Phi_B)$$



$$+ \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)\, \Delta^{(\mathrm{K})}(t(\Phi_1),\mu_Q^2)\, {\color{red}\Theta(Q_{\mathrm{cut}}-Q)}\, O(\Phi_R)\bigg]$$

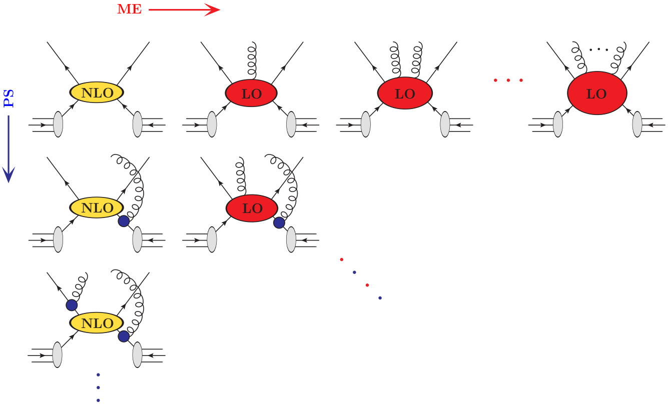


$$+ \int \mathrm{d}\Phi_R \mathrm{R}(\Phi_R)\, \Delta^{(\mathrm{K})}(t(\Phi_R),\mu_Q^2;{\color{red}>Q_{\mathrm{cut}}})\, {\color{blue}\Theta(Q-Q_{\mathrm{cut}})}\, O(\Phi_R)$$



- Jet veto in PS
- Jet cut on $n+1$-parton final state

Merging combined with matching (MENLOPS)

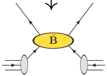


MENLOPS for POWHEG

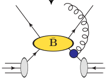
[Hamilton,Nason] arXiv:1004.1764
[SH,Krauss,Schönherr,Siegert] arXiv:1009.1127

- Increase accuracy below $Q_{\rm cut}$ to full NLO

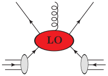
$$\langle O\rangle = \int \mathrm{d}\Phi_B \bar{\mathrm{B}}^{(\mathrm{R})}(\Phi_B)\bigg[\Delta^{(\mathrm{R})}(t_c, s_{\rm had})\,O(\Phi_B)$$



$$+\int_{t_c}^{s_{\rm had}} \mathrm{d}\Phi_1 \frac{\mathrm{R}(\Phi_R)}{\mathrm{B}(\Phi_B)}\Delta^{(\mathrm{R})}(t(\Phi_1), s_{\rm had})\Theta(Q_{\rm cut}-Q)\,O(\Phi_R)\bigg]$$



$$+\int \mathrm{d}\Phi_R\,\mathrm{k}^{(\mathrm{R})}(\Phi_R)\mathrm{R}(\Phi_R)\,\Delta^{(\mathrm{K})}(t(\Phi_R),\mu_Q^2;>Q_{\rm cut})\,\Theta(Q-Q_{\rm cut})\,O(\Phi_R)$$

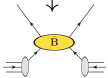


- Local K-factor for smooth merging

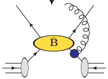
MENLOPS for MC@NLO

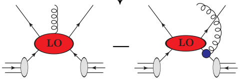
- Increase accuracy below Q_{cut} to full NLO

$$\langle O\rangle = \int \mathrm{d}\Phi_B \bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B)\Bigg[\Delta^{(\mathrm{K})}(t_c,\mu_Q^2)\,O(\Phi_B)$$

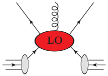


$$+\int_{t_c}^{\mu_Q^2}\mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)\Delta^{(\mathrm{K})}(t,\mu_Q^2)\Theta(Q_{\text{cut}}-Q)\,O(\Phi_R)\Bigg] + \int \mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{K})}(\Phi_R)\Theta(Q_{\text{cut}}-Q)O(\Phi_R)$$





$$+\int \mathrm{d}\Phi_R\,\mathrm{k}^{(\mathrm{K})}(\Phi_R)\mathrm{R}(\Phi_R)\,\Delta^{(\mathrm{K})}(t,\mu_Q^2;>Q_{\text{cut}})\,\Theta(Q-Q_{\text{cut}})\,O(\Phi_R)$$

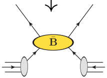


- Local K-factor for smooth merging

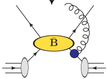
MENLOPS for MC@NLO

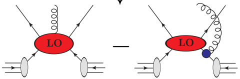
- Increase accuracy below Q_cut to full NLO

$$\langle O\rangle = \int \mathrm{d}\Phi_B \bar{\mathrm{B}}^{(\mathrm{D})}(\Phi_B)\Bigg[\Delta^{(\mathrm{D})}(t_c,\mu_Q^2)\,O(\Phi_B)$$

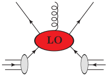


$$+\int_{t_c}^{\mu_Q^2}\mathrm{d}\Phi_1\,\frac{\mathrm{D}(\Phi_R)}{\mathrm{B}(\Phi_B)}\Delta^{(\mathrm{D})}(t,\mu_Q^2)\Theta(Q_\text{cut}-Q)\,O(\Phi_R)\Bigg] + \int \mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{D})}(\Phi_R)\Theta(Q_\text{cut}-Q)O(\Phi_R)$$



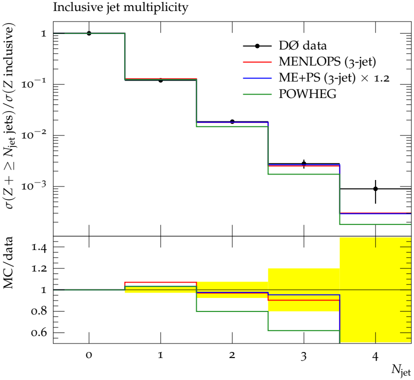


$$+\int \mathrm{d}\Phi_R\,\mathrm{k}^{(\mathrm{D})}(\Phi_R)\mathrm{R}(\Phi_R)\,\Delta^{(\mathrm{K})}(t,\mu_Q^2;>Q_\text{cut})\,\Theta(Q-Q_\text{cut})\,O(\Phi_R)$$



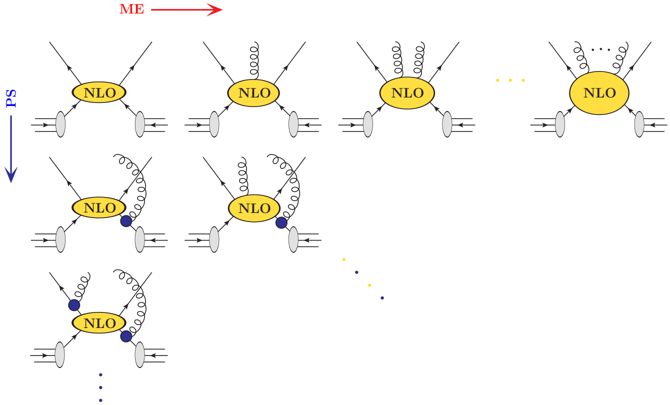
- Local K-factor for smooth merging

Z+jets at Tevatron



- Jet rates in MENLOPS improved over NLOPS
- Total cross section in MENLOPS improved over MEPS

Merging multiple matched calculations (MEPS@NLO)



Constructing MEPS@NLO

[Lavesson,Lönnblad,Prestel] arXiv:0811.2912 arXiv:1211.7278
[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031 arXiv:1207.5030
[Frederix,Frixione] arXiv:1209.6215

- MEPS for 0+1-jet in MC@NLO notation

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

- 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 MEPS@NLO

- Analyze exclusive contribution from k hard partons

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

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

Constructing MEPS@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 $\to$ dipole terms

Constructing MEPS@NLO

- Analyze exclusive contribution from k hard partons

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

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

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

Constructing MEPS@NLO

- Analyze exclusive contribution from k hard partons

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

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

$$+\int{\rm d}\Phi_{k+1}\,{\rm H}_k^{\rm (D)}\,\Delta_k^{\rm (K)}(t_k;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})\,\Theta(Q_{\rm cut}-Q_{k+1})\;O_{k+1}$$

- PS evolution kernels $\to$ dipole terms
- Born matrix element $\to$ NLO-weighted Born
- Add hard remainder function

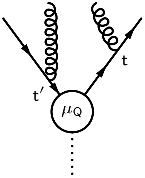
Constructing MEPS@NLO

- Analyze exclusive contribution from k hard partons

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

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

MEPS@NLO from a different perspective



- Define compound evolution kernel

$$\tilde{\mathrm{D}}_k(\Phi_{k+1}) = \mathrm{D}_k(\Phi_{k+1})\,\Theta(t_k - t_{k+1}) + \mathrm{B}_k(\Phi_k)\sum_{i=n}^{k-1}\mathrm{K}_i(\Phi_i)\,\Theta(t_i - t_{k+1})\Theta(t_{k+1} - t_{i+1})$$

- Extend MC@NLO modified subtraction

$$\tilde{\mathrm{B}}_k^{(\mathrm{D})}(\Phi_k) = \Big[\mathrm{B}_k(\Phi_k) + \tilde{\mathrm{V}}_k(\Phi_k) + \mathrm{I}_k(\Phi_k)\Big] + \int \mathrm{d}\Phi_1\Big[\tilde{\mathrm{D}}_k(\Phi_{k+1}) - \mathrm{S}_k(\Phi_{k+1})\Big]$$

$$\tilde{\mathrm{H}}_k^{(\mathrm{D})}(\Phi_{k+1}) = \mathrm{R}_k(\Phi_{k+1}) - \tilde{\mathrm{D}}_k(\Phi_{k+1})$$

MEPS@NLO from a different perspective

- Differential event rate for exclusive $n+k$-jet events

$$\langle O\rangle_k^{\text{excl}} = \int \mathrm{d}\Phi_k\,\tilde{\mathrm{B}}_k^{(\mathsf{D})}\,\Theta(Q_k-Q_{\text{cut}})$$

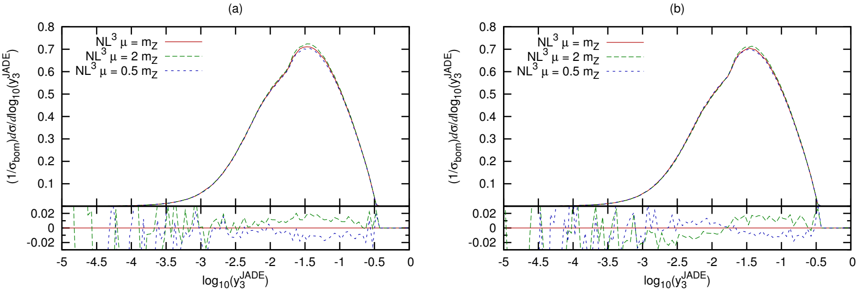
$$\times\left[\tilde{\Delta}_k^{(\mathsf{D})}(t_c,\mu_Q^2)\,O_k+\int_{t_c}^{\mu_Q^2}\mathrm{d}\Phi_1\,\frac{\tilde{\mathrm{D}}_k^{(\mathsf{D})}}{\mathrm{B}_k}\,\tilde{\Delta}_k^{(\mathsf{D})}(t,\mu_Q^2)\,\Theta(Q_{\mathsf{cut}}-Q_{k+1})\,O_{k+1}\right]$$

$$+\int \mathrm{d}\Phi_{k+1}\,\tilde{\mathrm{H}}_k^{(\mathrm{D})}\,\tilde{\Delta}_k^{(\mathrm{K})}(t_{k+1},\mu_Q^2;>Q_{\text{cut}})\,\Theta(Q_{\mathsf{cut}}-Q_{k+1})$$

- Structurally equivalent to MENLOPS!
- Truncated PS contributes at $\mathcal{O}(\alpha_s)$

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

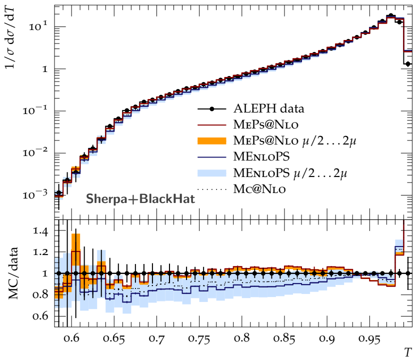
[Lavesson,Lönnblad] arXiv:0811.2912

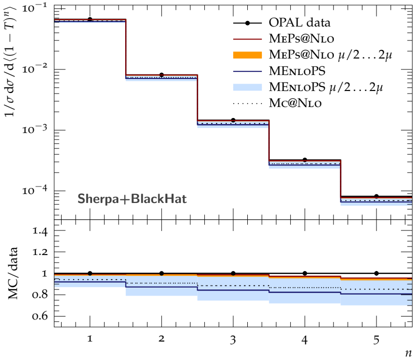


- Scale variations around 2%
- Agreement between 1- and 2-loop
  but no further reduction of uncertainty

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

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

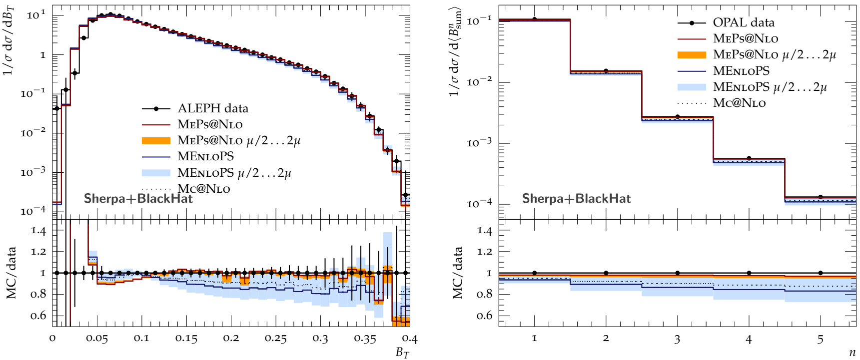




- Thrust & its moments
- MEPS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO vs MENLOPS with up to 6 jets at LO

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

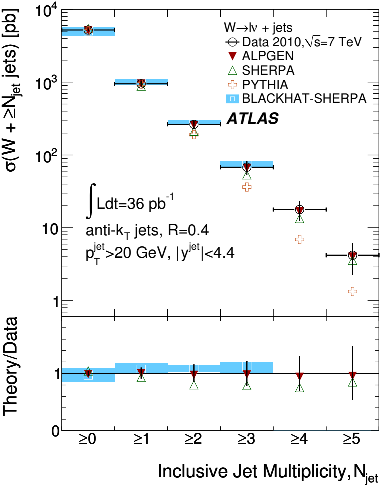
[Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031

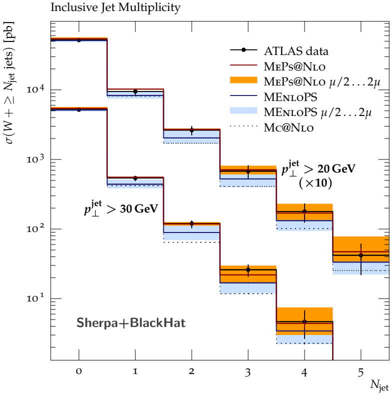


- Total jet broadening & its moments
- MEPS@NLO with 2,3&4 jet PL at NLO plus 5&6 jet PL at LO vs MENLOPS with up to 6 jets at LO

W+jets production at the LHC

[ATLAS] arXiv:1201.1276
[SH,Krauss,Schönherr,Siegert] arXiv:1207.5030

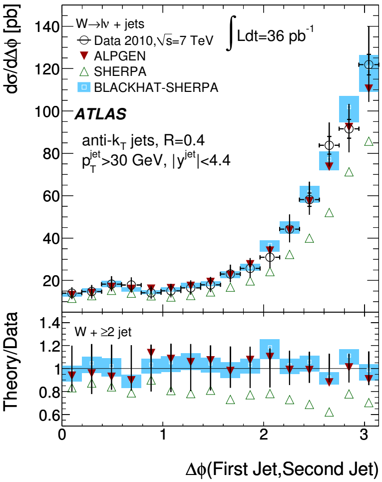


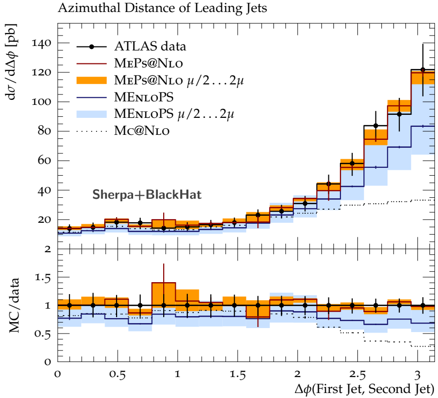


- MEPS@NLO with 0,1&2 jet PL at NLO plus 3&4 jet PL at LO
- MENLOPS with up to 4 jets at LO

W+jets production at the LHC

[ATLAS] arXiv:1201.1276
[SH,Krauss,Schönherr,Siegert] arXiv:1207.5030

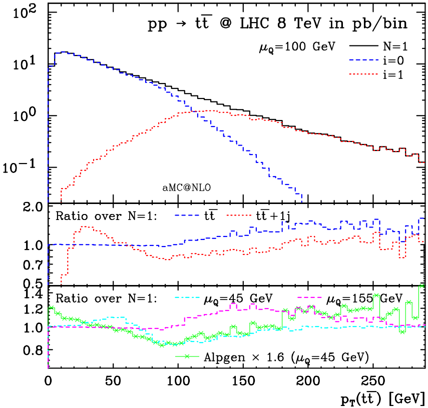


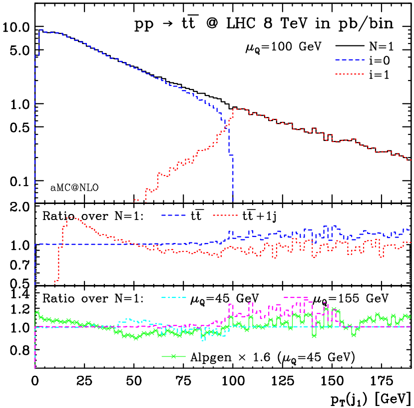


- MEPS@NLO with 0,1&2 jet PL at NLO plus 3&4 jet PL at LO
- MENLOPS with up to 4 jets at LO

Top pair production at the LHC

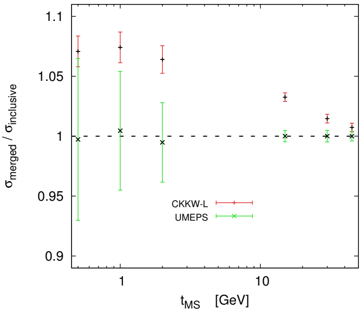
[Frederix,Frixione] JHEP12(2012)061





Unitarized ME+PS merging

[Lönnblad,Prestel] JHEP02(2013)094



- Unitarity condition of PS:

$$1 = \Delta^{(\mathrm{K})}(t_c) + \int_{t_c} \mathrm{d}\Phi_1\, \mathrm{K}(\Phi_1)\, \Delta^{(\mathrm{K})}(t)$$

- CKKW-like merging violates PS unitarity as ME ratio replaces splitting kernels in emission terms, but not in Sudakovs

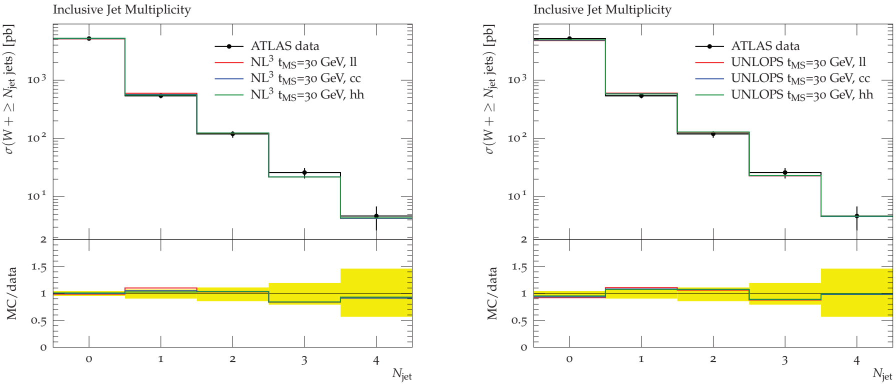
$$\mathrm{K}(\Phi_1) \to \frac{\mathrm{R}(\Phi_1, \Phi_B)}{\mathrm{B}(\Phi_B)}$$

- Mismatch removed by explicit subtraction

$$1 = \underbrace{\left\{ \Delta^{(\mathrm{K})}(t_c) + \int_{t_c} \mathrm{d}\Phi_1 \left[\mathrm{K}(\Phi_1) - \frac{\mathrm{R}(\Phi_1, \Phi_B)}{\mathrm{B}(\Phi_B)} \right] \Theta(Q - Q_{\text{cut}})\, \Delta^{(\mathrm{K})}(t) \right\}}_{\text{unresolved emission / virtual correction}}$$

$$+ \underbrace{\int_{t_c} \mathrm{d}\Phi_1 \left[\mathrm{K}(\Phi_1)\Theta(Q_{\text{cut}} - Q) + \frac{\mathrm{R}(\Phi_1, \Phi_B)}{\mathrm{B}(\Phi_B)} \Theta(Q - Q_{\text{cut}}) \right] \Delta^{(\mathrm{K})}(t)}_{\text{resolved emission}}$$

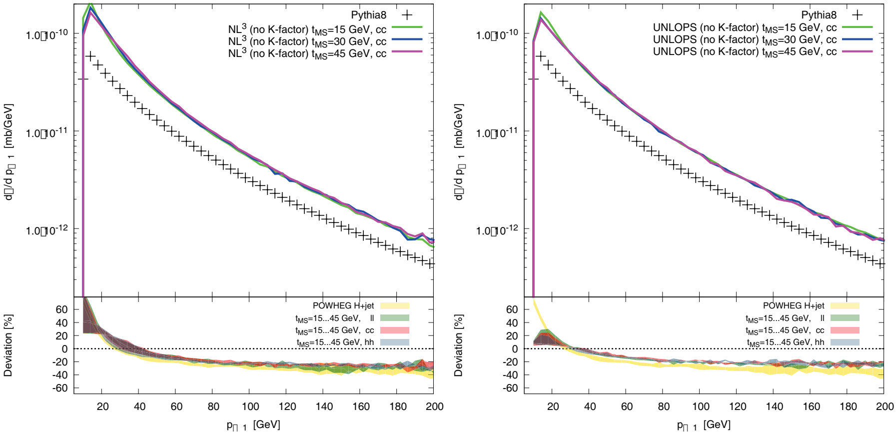
Z+jets production at the LHC



- Compare NL^3 with UNLOPS merging
- Both parametrically $\mathcal{O}(\alpha_s)$ correct!

Higgs+jets production at the LHC

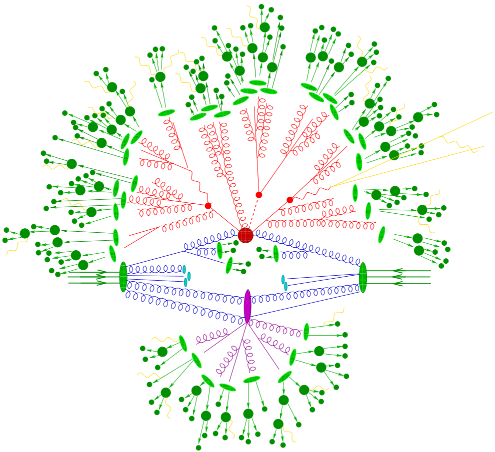
[Lönnblad,Prestel] JHEP03(2013)166



- Compare NL^3 with UNLOPS merging
- Both parametrically $\mathcal{O}(\alpha_s)$ correct!

The structure of MC events

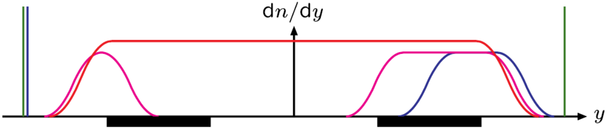
- Hard interaction
- QCD evolution
- Secondary hard interactions
- Hadronization
- Hadron decays
- Higher-order QED corrections



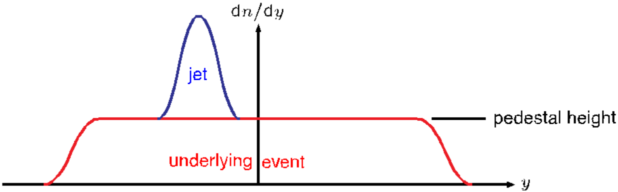
What is what

- Soft inclusive collision

$$\sigma_{\mathrm{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{single diffractive}} + \sigma_{\text{double diffractive}} + \sigma_{\text{non-diffractive}}$$

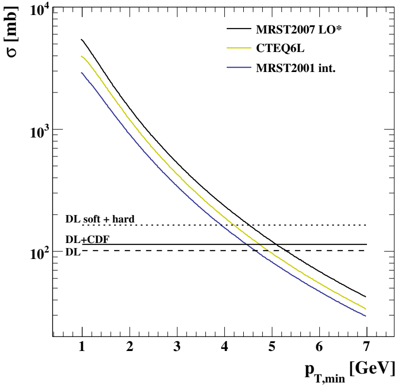


- Underlying event



Modeling the pedestal

[Sjöstrand,Zijl] PRD36(1987)2019

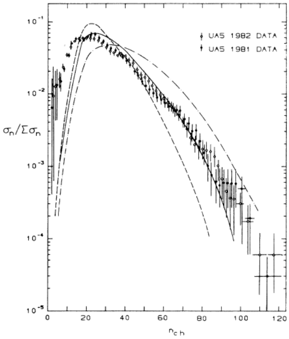


- Partonic cross sections diverge roughly like $\mathrm{d}p_T^2/p_T^4$
- Total cross section at LHC exceeded for $p_T \approx$ 2-5 GeV
- Interpretation as possibility for multiple hard scatters with

$$\langle n \rangle = \frac{\sigma_{\text{hard}}}{\sigma_{\text{non-diffractive}}}$$

- Main free parameter is $p_{T,\min}$
  Determines size of σ_{hard}

Modeling the pedestal

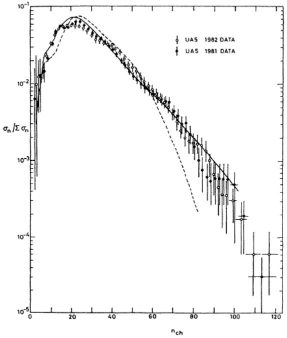


- Despite MPI wrong charged multi distribution
  Impact parameter dependent model needed
- Various hadron shape models in b-space
  (Exponential, Gaussian, double Gaussian)

$$\langle n \rangle = \frac{\sigma_{\text{hard}}}{\sigma_{\text{non-diffractive}}}$$

$$\downarrow$$

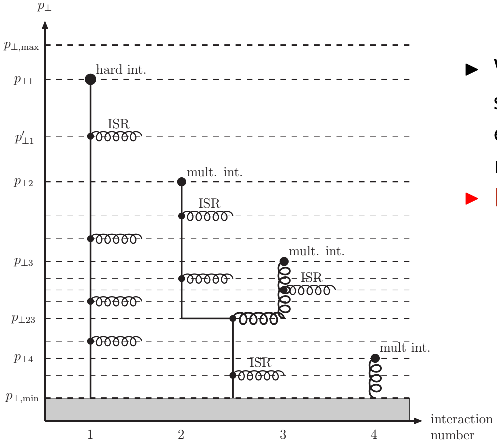
$$\langle \tilde{n}(b) \rangle = f_c f(b) \frac{\sigma_{\text{hard}}}{\sigma_{\text{non-diffractive}}}$$



- Hardness of the collision determines overlap
  Collisions with large overlap in turn
  have more secondary interactions

Combination with the parton shower

[Sjöstrand,Skands] hep-ph/0408302

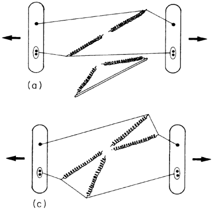


- When attaching IS shower to secondary scattering can ask at each point whether emission or new interaction is more likely
- New evolution equation

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_T} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_T} + \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_T}\right) \times \exp\left\{-\int_{p_T} \mathrm{d}p'_T \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_T} + \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_T}\right)\right\}$$

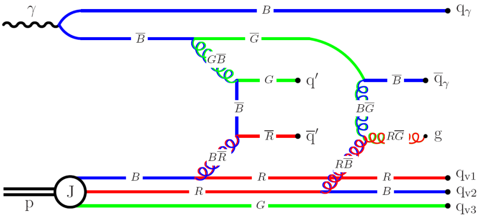
Color connections and beam remnants

[Sjöstrand,Skands] hep-ph/0402078



- Secondary scatterings need to be color-connected to something
- Simplest model would decouple them from proton remnants
- Next-to-simplest model would put all scatters on one color string

- New models embed scatters into existing color topology
- Three different options for string drawing
  - At random
  - Rapidity ordered
  - String length optimized



A model for minimum bias collisions

[Butterworth,Forshaw,Seymour] hep-ph/9601371
[Borozan,Seymour] hep-ph/0207283

- Assume parton distribution within beam hadron is

$$\frac{\mathrm{d}n_a(x,\mathbf{b})}{\mathrm{d}^2\mathbf{b}\mathrm{d}x} = f_a(x)\,G(\mathbf{b})$$

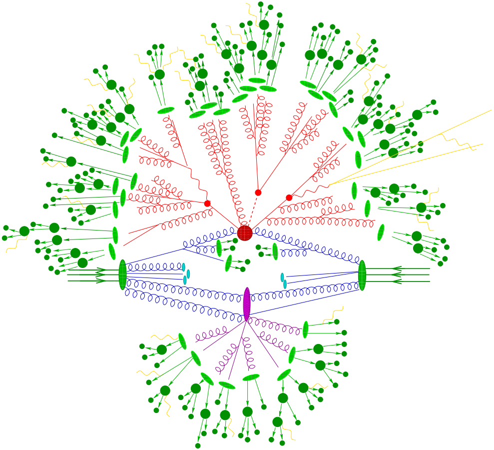
- Use electromagnetic form factor

$$G(\mathbf{b}) = \int \frac{\mathrm{d}^2\mathbf{k}}{(2\pi)^2}\,\frac{\exp(\mathbf{k}\cdot\mathbf{b})}{(1+\mathbf{k^2}/\mu^\mathbf{2})^\mathbf{2}}$$

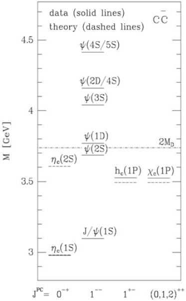
- EM measurements indicate $\mu_P = 0.71$ GeV
  μ is however left free in model $\rightarrow$ tuning
- Continue model below $p_{T,\mathrm{min}}$ with same b-space parametrization
  but cross section as Gaussian in p_T $\rightarrow$ inclusive non-diffractive events

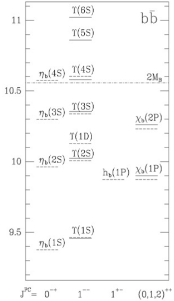
The structure of MC events

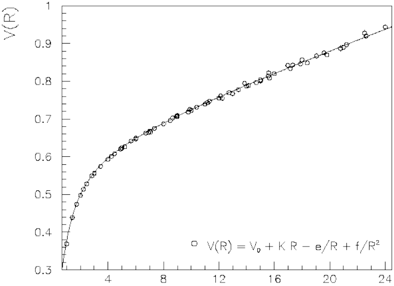
- Hard interaction
- QCD evolution
- Secondary hard interactions
- Hadronization
- Hadron decays
- Higher-order QED corrections



The inter-quark potential



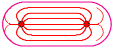




- Measure QCD potential from quarkonia masses
- Or compute using lattice QCD
- Approximately linear potential $\leftrightarrow$ QCD flux tube

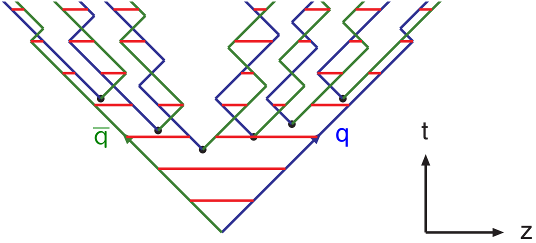
The Lund string model

[Andersson,Gustafson,Ingelman,Sjöstrand] PR97(1983)31

- Start with example $e^+e^- \to q\bar{q}$
- QCD flux tube with constant energy per unit rapidity $\leftrightarrow$ 
- New $q\bar{q}$-pairs created by tunneling (κ - string tension)

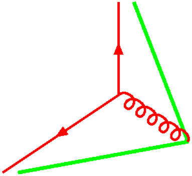
$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}x\mathrm{d}t} = \exp\left\{-\frac{\pi^2 m_q^2}{\kappa}\right\}$$

- Expanding string breaks into hadrons, then yo-yo modes
- Baryons modeled as quark-diquark pairs

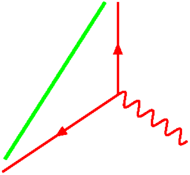


The Lund string model

- String model very well motivated, but many parameters
- But also gives genuine prediction of “string effect”
- Gluons are kinks on string
  String accelerated in direction of gluon
- Infrared safe matching to parton showers
  Gluons with $k_T \lesssim 1/\kappa$ irrelevant



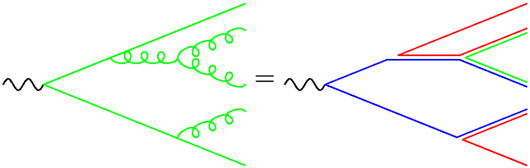
vs.



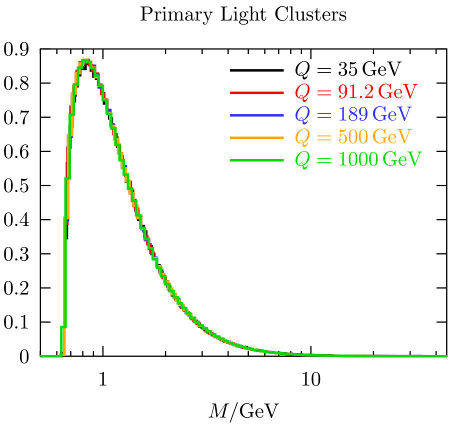
The cluster model

[Webber] NPB238(1984)492

- Underlying idea: Preconfinement
- Follow color structure of parton showers: color singlets end up close in phase space
- Mass of color singlets peaked at low scales ($\approx t_c$)



The cluster model



- Mass spectrum of primordial clusters independent of cm energy

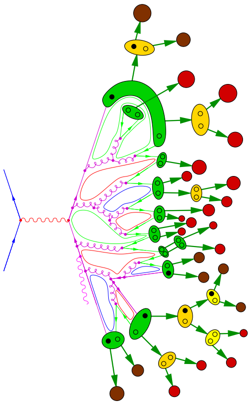
The cluster model

Naïve model

- Split gluons into $q\bar{q}$-pairs
- Color-adjacent pairs form primordial clusters
- Clusters decay into hadrons according to phase space $\rightarrow$ baryon & heavy quark production suppressed

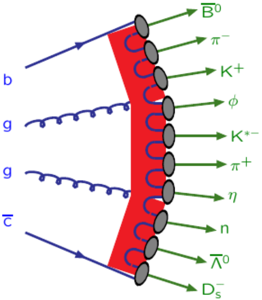
Improved model

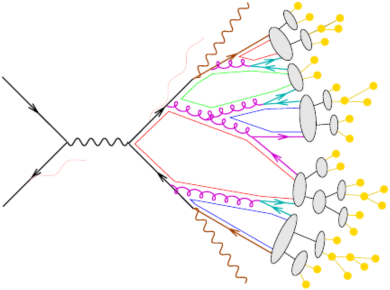
- Heavy clusters decay into lighter ones
- Three options: C$\rightarrow$CC, C$\rightarrow$CH & C$\rightarrow$HH
- Leading particle effects



String vs Cluster

[T.Sjöstrand, Durham'09]





program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

"There ain't no such thing as a parameter-free *good* description"

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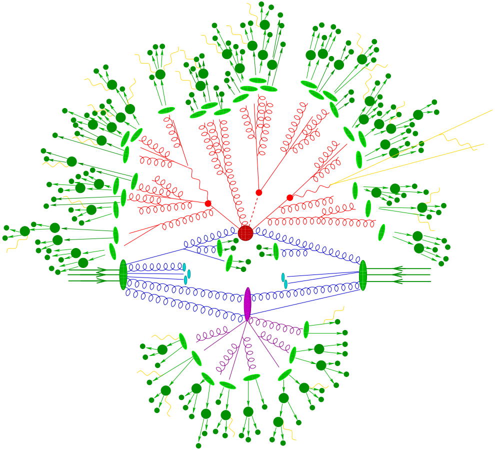
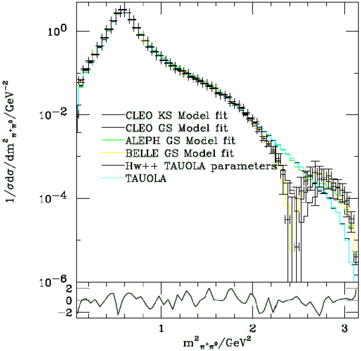


Secondary particle decays

- String and clusters decay to some stable hadrons
  but main outcome are unstable resonances
- These decay further according to the PDG decay tables
- Many hadron decays according to phase space
  but also a large variety of form factors known
- Not all branching ratios known precisely
  plus many BR's in PDG tables do not add up to one
- Significant effect on hadronization yields,
  hadronization corrections to event shapes, etc.

Secondary particle decays & photon radiation

- Previous generations of generators relied on external decay packages Tauola (τ-decays) & EvtGen (B-decays)
- New generation programs Herwig++ & Sherpa contain at least as complete a description
- Spin correlations and B-mixing built in
- No interfacing issues



- Previous generations of generators relied on external package Photos to simulate QED radiation
- New generation programs Herwig++ & Sherpa have simulation of QED radiation built in

Summary

- NL^{3}SP, MEPS@NLO & FxFx allow to merge NLO-matched simulations of anything+jets
- UNLOPS unitarises entire simulation
- Underlying event typically simulated by MPI can be combined with PS in common evolution
- Two models (string & cluster) for parton to hadron fragmentation

Strong couplings and PDFs

- PS dictates choice of renormalization scale (n - order α_s in Born)

$$\Big[\alpha_s(\mu_R^2)\Big]^{n+k} = \Big[\alpha_s(\mu_{\rm core}^2)\Big]^n \prod_{i=0}^{k} \alpha_s(b\, k_T^2(t_i, z_i))\,, \qquad b = \text{const}$$

- Monotonicity of strong coupling allows to solve for μ_R
- PS also dictates choice of factorization scales (DGLAP evolution)
- Introduces collinear counterterms due to constrained evolution

$$F_i(t, t'; \mu_F^2) = 1 - \frac{\alpha_s(\mu_R^2)}{2\pi} \log\frac{t'}{t} \sum_{b=q,g} \int_{x_i}^{1} \frac{{\rm d}z}{z}\, P_{ba}(z)\, \frac{f_b(x_i/z, \mu_F^2)}{f_a(x_i, \mu_F^2)}$$