General-purpose Monte Carlo in the LHC era

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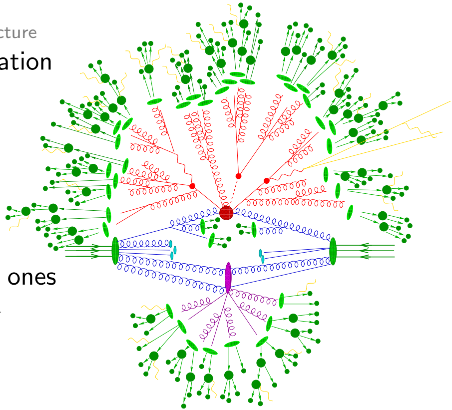
MC interpretation of QCD associated events

1. Hard matrix elements (ME) red blobs
   define "central" part of the event
2. Parton showers (PS) red & blue tree structure
   produce additional "hard" QCD radiation
3. Hard subprocesses (MPI) purple blob
   model additional QCD activity
4. Fragmentation models light green blobs
   hadronise 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



I will focus on the "hard" QCD part

i.e. ME / PS / MPI generation and their interplay

Matrix element generators

Tree-level ME-generator are easy to build and there are many options ...

- Diagrammatic techniques AMEGIC++, MADGRAPH, ...
- Recursive techniques Comix, HELAC, O'Mega, ...
- α-algorithm ALPGEN

Also varying handling of color & helicity sampling/summation

NLO ME-generators are more difficult and only recently available ...

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

S - subtraction term constructed such that IR singularities in R are removed

I - integrated subtraction term locally compensates $S \to 0 \stackrel{!}{=} I - \int \mathrm{d}\Phi_{(1)}\,S$

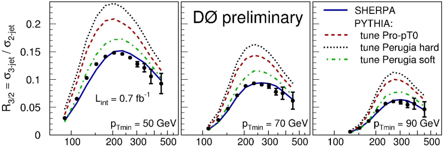
S and I are universal and "easy" to automate, V is tedious to compute

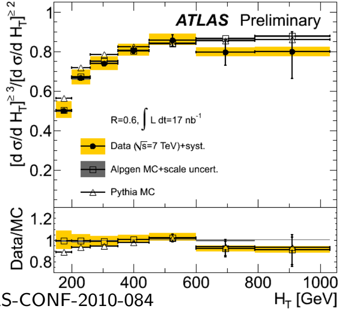
$\Rightarrow$ Two pieces combined using the Binoth Les Houches accord CPC181(2010)1612

- One-Loop-Engine (OLE) provides virtual piece BlackHat, Golem, ...
- MC takes care of Born, real emission, subtraction and phase space

Matrix element generators

Ratio of 3- & 2-jet rate DØ Note 6032-CONF



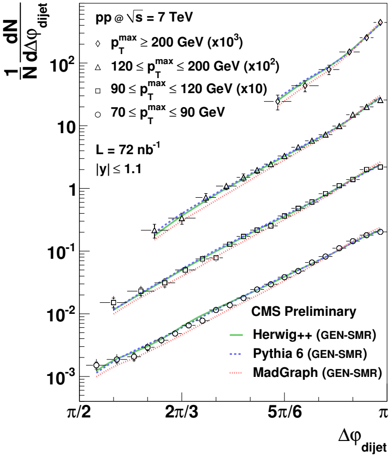


ATLAS-CONF-2010-084

Multi-leg ME⊗PS "standard" by now

Higher-order ME improve predictions for jet correlations & relative rates

Dijet decorrelation CMS PAS QCD-10-015



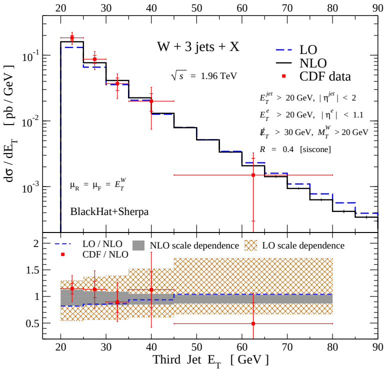
Matrix element generators

Full NLO multi-leg ME improve predictions for both, relative & absolute rates

But hard to combine with parton showers → most recent activity

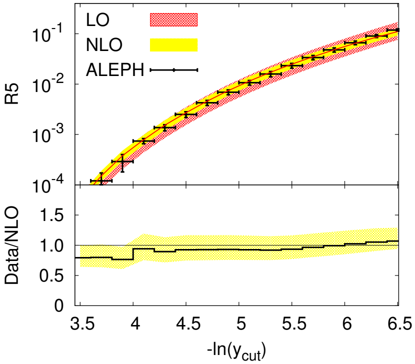
W+3 jets @ Tevatron

PRD80(2009)074036



$e^+e^- \to$ 5 jets @ LEP

arXiv:1008.5313 [hep-ph]



Want this to become the *new* standard !

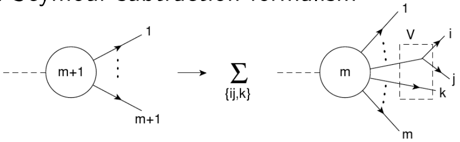
Dipole-like parton showers

New PS developments based on Catani-Seymour subtraction formalism

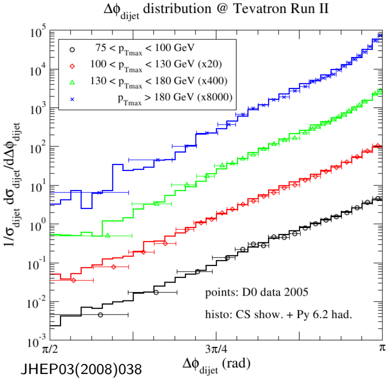
Schematically: $S \to \sum_{ij,k} B \otimes V_{ij,k}$

$V_{ij,k}$ - spin & color dependent dipoles

here: large-N_C limit, spin-averaged

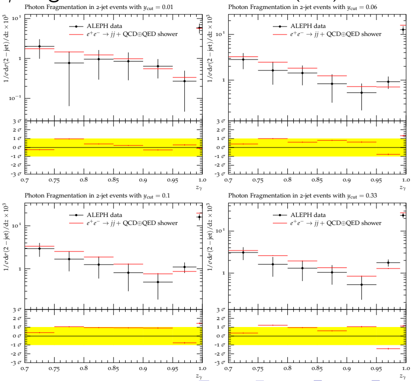


Few model ambiguities, excellent approximation of higher-order real ME



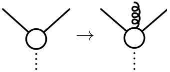
JHEP03(2008)038

γ-fragmentation function PRD81(2010)034026



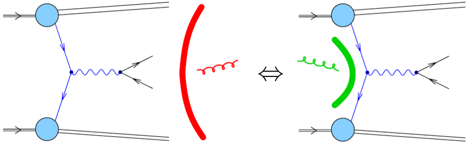
Dipole showers

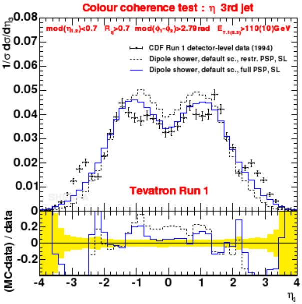
PS's consider $1 \to 2$ parton splittings eventually including spectator
can consider $2 \to 3$ *dipole* splittings as well

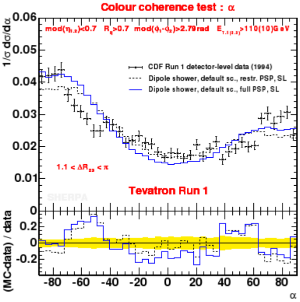


Novel dipole showers use perturbative picture in initial-state evolution

Original dipole showers reinterpret IS-evolution as restricted FS-evolution of beam remnant $\to$ non-perturbative

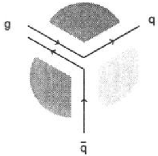






Promising results e.g. for CDF color coherence analysis

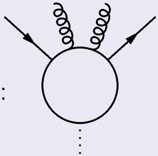
JHEP07(2008)040



ME⊗PS at tree-level

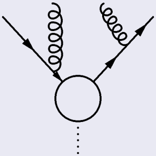
As we have both, automated ME & PS generators, get the best of them !

ME:



$\leftrightarrow$

PS:



- σ from coherent sum of all Feynman graphs
- No resummation

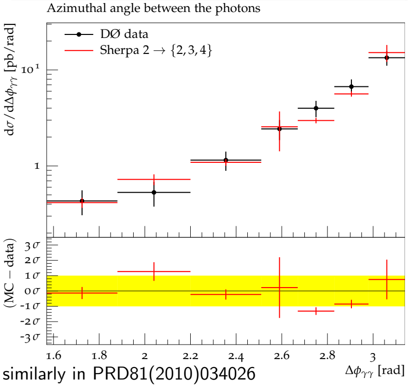
- σ from LO ME & PS splittings
- Proper resummation in parts of phase space

How do we run a parton shower on a N^{x}LO tree-level matrix element ?

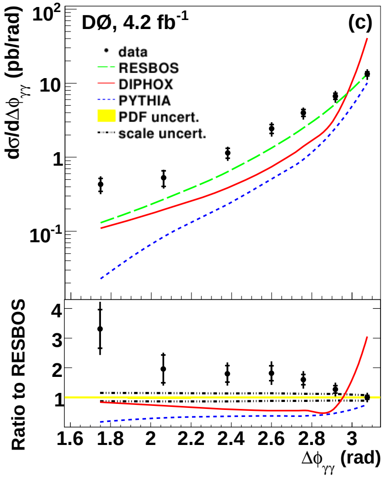
1. Find suitable starting conditions for the parton shower
   i.e. find a tree-structure corresponding to the full ME
   which can be used by the parton shower as a branching history
2. Make sure not to double-count or miss out emissions
   i.e. eventually populate the whole available real emission
   phase space with *either* matrix elements *or* the parton shower

ME⊗PS results: Diphoton production PLB690(2010)108

$E_T^{\gamma 1} > 21$ GeV, $E_T^{\gamma 1} > 20$ GeV,
$|\eta^\gamma| < 0.9$, $E_T^{R=0.4} - E_T^\gamma < 2.5$ GeV



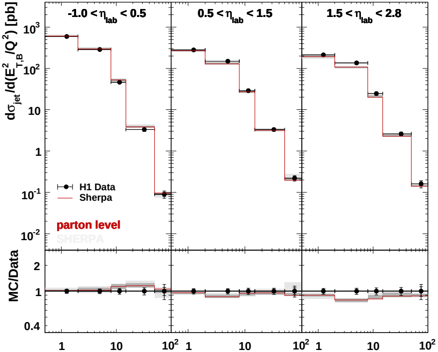
similarly in PRD81(2010)034026



SHERPA prediction: Merged 2→{2,3,4}-jet/γ plus $gg \to \gamma\gamma$ box

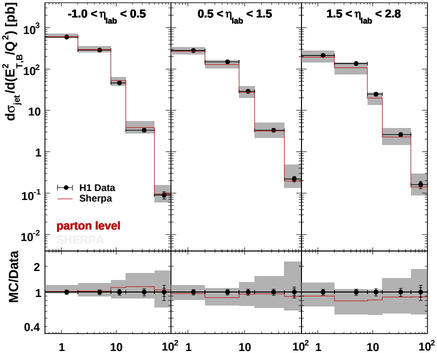
ME⊗PS results: Inclusive jets in DIS PLB542(2002)193

$5\,\mathrm{GeV}^2 < Q^2 < 100\,\mathrm{GeV}^2$, $E_{T,B} > 5$ GeV, $-1 < \eta_{\rm lab} < 2.8$



EPJC67(2010)73

Variation of ME⊗PS parameters



EPJC67(2010)73

Scale variations $\mu_F = \mu_R$

SHERPA prediction: Merged 2→{0,2,3,4,5}-jet

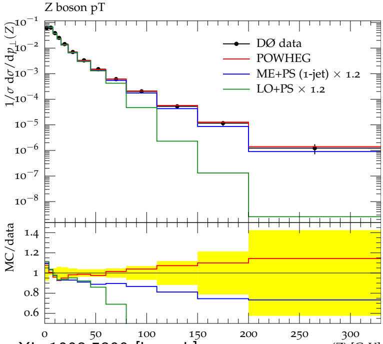
Merging NLO with parton showers

The POWHEG master formula JHEP11(2004)040, JHEP11(2007)070, …

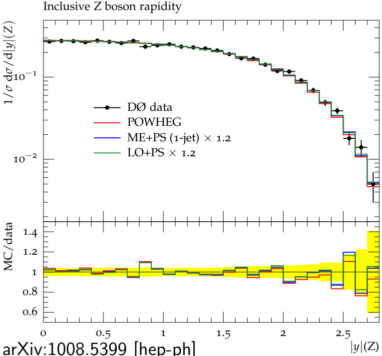
$$\mathrm{d}\sigma_{\mathrm{NLO}} = \mathrm{d}\Phi_B\, \bar{B}(\Phi_B) \left[\bar{\Delta}(k_{T,0}) + \sum \int_{k_{T,0}} \mathrm{d}\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \bar{\Delta}(k_T) \right]$$

with the NLO differential cross section $\bar{B} = B + V + I + \mathrm{d}\Phi_{R|B}\,[R - S]$

and the POWHEG-Sudakov $\bar{\Delta}(k_T) = \exp\left\{ -\sum \int_{k_T} \mathrm{d}\Phi_{R|B} \frac{R(\Phi_R)}{B(\Phi_B)} \right\}$



arXiv:1008.5399 [hep-ph]



arXiv:1008.5399 [hep-ph]

Hot topic: Combining ME⊗PS with full NLO

- Currently we can merge "arbitrary" tree-level ME's with PS's
  Several automated codes on the market e.g. in hep-ph/0602031, EPJC53(2008)473
- Automation of 1-loop QCD corrections seems feasible
  (Semi-)automated codes now emerging PRD78(2008)036003, CPC180(2009)2317, ...

We should make use of both and **automate ME⊗PS at 1-loop**

- Process NLO parton-level events with PS's
  using MC@NLO or POWHEG method JHEP06(2002)029, JHEP11(2004)040, ...
- Supplement with higher-order ME⊗PS
  using standard merging technique JHEP05(2009)053, JHEP11(2009)038

Ansatz: MENLOPS JHEP06(2010)039

Combine POWHEG and ME⊗PS via phase-space slicing
ME⊗PS rescaled to "correct" norm by global K-factor cut dependent

MENLOPS results JHEP06(2010)039

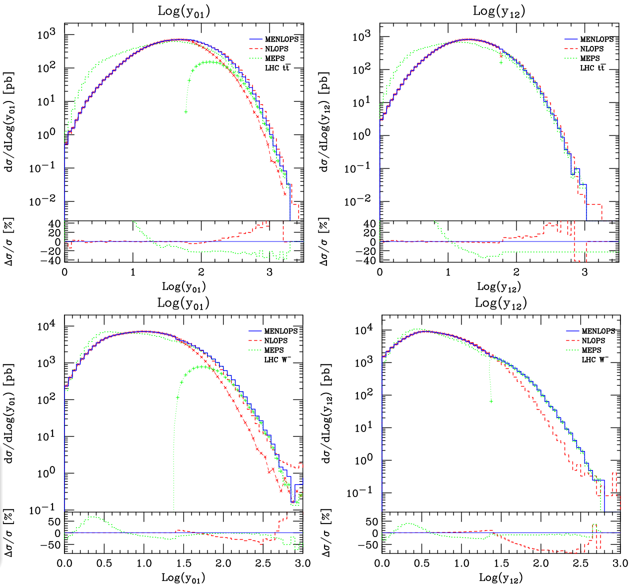
Differential jet rates in $t\bar{t}$+jets production

Compare:

- ME⊗PS 0+1-jet
- POWHEG
- MENLOPS 0+1-jet

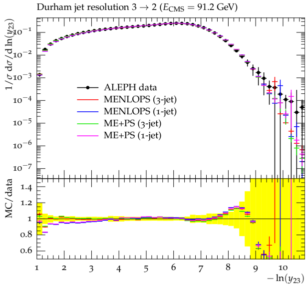
$pp \to t\bar{t}$ @ NLO

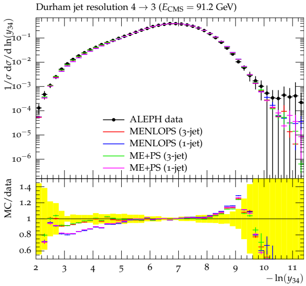
Differential jet rates in $W[\to l\nu]$+jets



MENLOPS likely to become new standard for high-multiplicity MC simulations

MENLOPS results SHERPA, in preparation

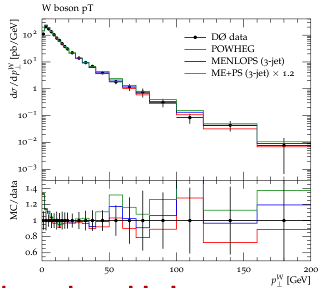


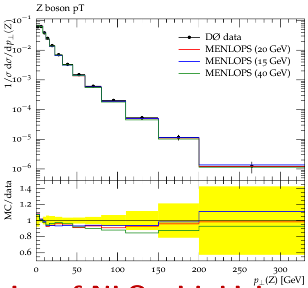


Jet rates and event shapes in $e^+e^- \to$jets

Compare:

- ME⊗PS 2+3[+4+5]-jet
- MENLOPS 2+3[+4+5]-jet 2 jets @ NLO





W/Z-boson p_T

Compare:

- ME⊗PS 0+1+2+3-jet
- MENLOPS 0+1+2+3-jet 0 jets @ NLO

Note that this is not a merging of NLO with higher multi NLO ! yet ...

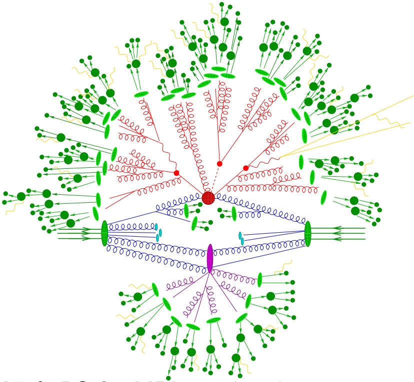
What are Multiple Parton Interactions ?

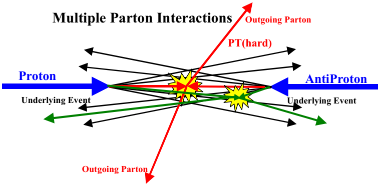
Our picture of collider events is inspired by Q^2-factorisation (DGLAP-evolution):

- Matrix elements $\otimes$ parton showers
- Secondary hard interactions $\Rightarrow$ MPI
- Hadronisation $\otimes$ Hadron decays

So what is MPI simulation then about ?

- Matrix elements & parton showers
- Connection to the hard collision





- Ideally ME & PS for MPI simulated along the same lines as primary collision $\Rightarrow$ guideline for models (consistency) !
- Beam remnant assignment and colour handling are nontrivial ! Various scenarios at large N_C

When using ME$\otimes$PS, merging with primary collision is nontrivial

What can we learn from early LHC data?

MPI models usually contain several free parameters

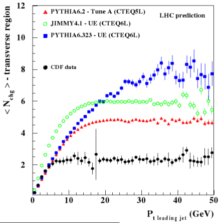
Biggest problem before LHC was energy extrapolation

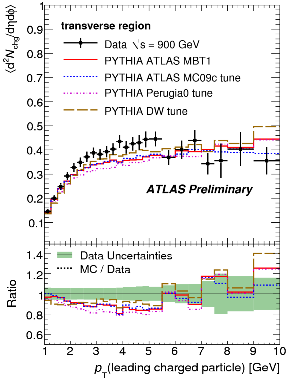
Define cms-energy dependent regulator paramter $p_{\perp,\min}$ to limit σ_{QCD}

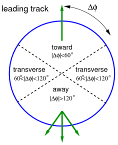
Interplay with soft UE & soft/hard transition still unclear

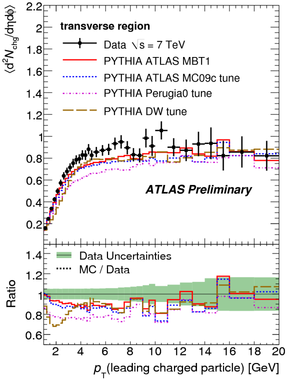
$\Rightarrow$ **LHC data essential to constrain models**

colour string/cluster topology, freeze-out of α_s, primordial k_T, ...









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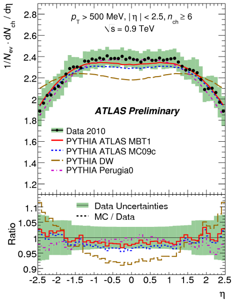
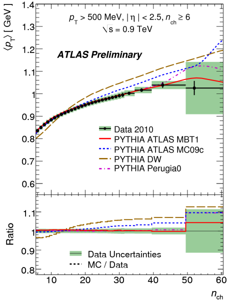
What can we learn from early LHC data?





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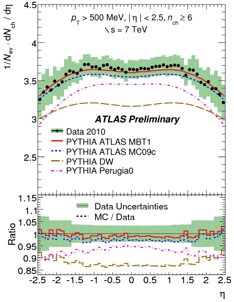
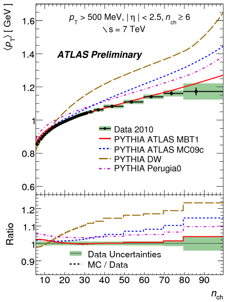
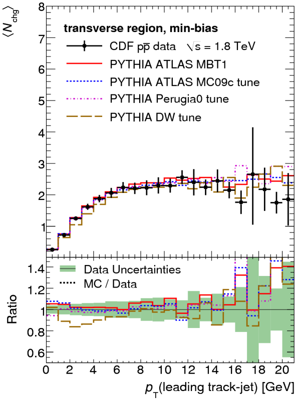
- models *can* be constrained
- don't forget "old" data sets
- don't take models for physics







Summary

ME, PS and ME⊗PS perturbative QCD

- Automation of NLO ME generation within reach
- Improved PS generators, merging with NLO ME through POWHEG
- ME⊗PS at tree-level new standard, ME⊗PS at 1-loop under way

MPI (non-)perturbative QCD

- Various models on the market
- Large tuning efforts with encouraging results

Other topics

- Alternative MPI models e.g. BFKL-like
- BSM ME-generators and showers
- EW NLO corrections
- ...

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