Status of MC event generators

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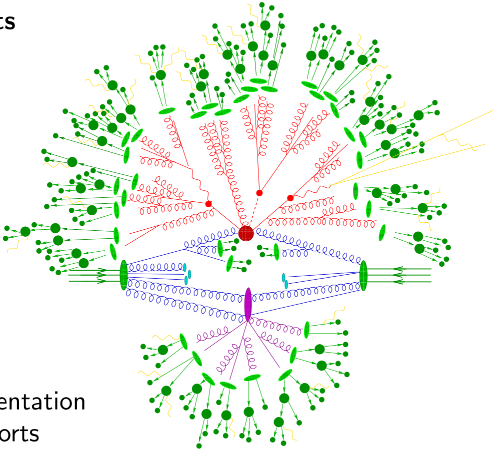
Physics at the LHC

Vancouver, 06/06/12

SLAC

Structure of simulated LHC events

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



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

Improved models for MPI and fragmentation
Combined with systematic tuning efforts

Event generators for LHC physics

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 multiple interaction models
- Pragmatic attitude to ME generation → external tools
- Extensive PS development and earliest ME⊗PS matching

Sherpa

- Started with PS generator APACIC++ & ME generator AMEGIC++
- Current MPI model and hadronization pragmatic add-ons
- Leading in development of automated ME⊗PS merging
- Automated framework for NLO calculations and MC@NLO

For more information, check out [Buckley et al.] Phys.Rept.504(2011)145
For updates and news, go to http://www.montecarlonet.org

Analysis and tuning tools

Rivet [Buckley et al.] arXiv:0103.0694

- LHC-successor to HZTool
  Collection of exp. data & matching analysis routines
- Spirit: "Right MC describes everything at the same time"

Professor [Buckley et al.] EPJC65(2010)331

- Tuning in multi-dimensional parameter space of MC
- Generate event samples at random parameter points
  Analyze them with Rivet
  Parametrize observables
  Minimize χ^2 and cross-check

Tune comparisons

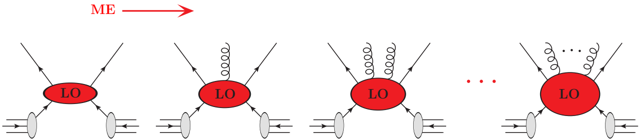
Deviation metrics per gen/tune and observable group:

Gen	Tune	UE	Dijets	Multijets	Jet shapes	W and Z	Fragmentation	B frag
AlpGen	HERWIG6	–	1.83	5.36	2.48	0.91	–	–
	PYTHIA6-AMBT1	–	1.55	2.80	0.61	0.53	–	–
	PYTHIA6-D6T	–	1.38	2.67	2.31	1.67	–	–
	PYTHIA6-P2010	–	1.09	2.65	2.03	1.48	–	–
	PYTHIA6-P2011	–	1.12	2.60	0.48	0.24	–	–
	PYTHIA6-Z2	–	1.48	2.63	0.55	0.48	–	–
	PYTHIA6-profQ2	–	1.16	2.65	1.43	1.29	–	–
HERWIG	AUET2-CTEQ6L1	0.43	0.55	0.77	0.35	0.58	22.80	2.38
	AUET2-LOxx	0.25	0.71	0.60	0.39	0.88	22.13	2.29
Herwig++	2.5.1-UE-EE-3-CTEQ6L1	0.27	0.87	0.78	0.51	0.98	10.58	1.32
	2.5.1-UE-EE-3-MRSTLOxx	0.23	1.05	0.78	0.50	0.65	10.58	1.32
PYTHIA6	AMBT1	0.39	1.20	0.54	0.77	0.27	0.93	1.65
	AUET2B-CTEQ6L1	0.16	0.92	0.44	0.59	0.74	0.67	1.29
	AUET2B-LOxx	0.13	1.33	0.55	0.58	1.15	0.67	1.30
	D6T	0.58	0.79	0.50	0.56	1.25	0.36	2.63
	DW	0.81	0.78	0.61	0.56	1.33	0.36	2.63
	P2010	0.30	0.93	0.82	1.07	0.30	0.44	1.75
	P2011	0.12	0.89	0.67	1.02	0.53	0.43	2.13
	ProfQ2	0.51	0.67	0.81	0.51	0.64	0.30	1.65
	Z2	0.18	0.94	0.73	0.80	0.30	0.95	2.78
Pythia8	4C	0.30	0.97	0.93	0.50	0.90	0.38	1.12
Sherpa	1.3.1	0.68	0.47	0.34	0.71	0.36	0.75	2.48

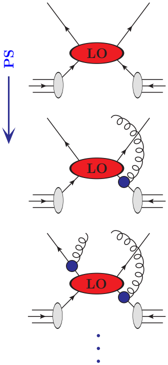
[LH'11 SM WG] arXiv:1203.6803 [hep-ph]

http://rivet.hepforge.org/tunecmp/

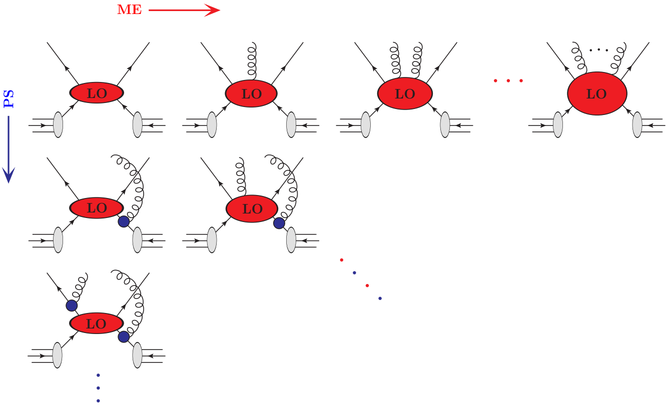
High-multiplicity LO matrix elements



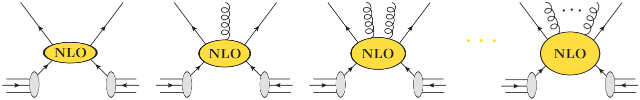
Parton showers



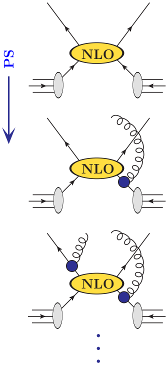
Matrix-element parton-shower merging (ME⊗PS)



High-multiplicity NLO matrix elements



NLO matrix-element parton-shower matching



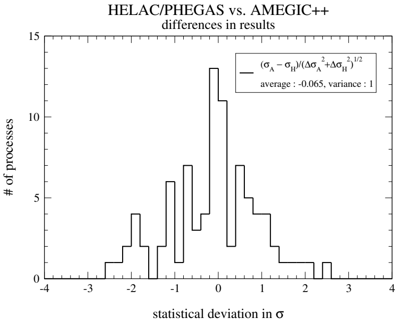
Plethora of tree-level tools on market

State of the art: Full automation

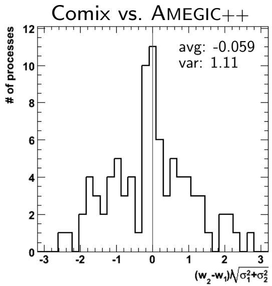
- **Feynman diagrams**
  - AMEGIC++ [Krauss et al.] JHEP02(2002)044
  - CompHEP [Boos et al.] NIMA534(2004)250
  - MADGRAPH [Alwall et al.] JHEP02(2011)128
- **Recursive techniques**
  - Comix [Gleisberg,SH] JHEP12(2008)039
  - HELAC [Kanaki,Papadopoulos] CPC132(2000)306
  - O'Mega [Moretti,Ohl,Reuter] hep-ph/0102195
- **α-algorithm**
  - ALPGEN [Mangano et al.] JHEP07(2001)003

LHEF output for passing events to external MC HERWIG++ & PYTHIA

Useful plugins for NLO calculation
$\rightarrow$ Born, real emission & subtraction



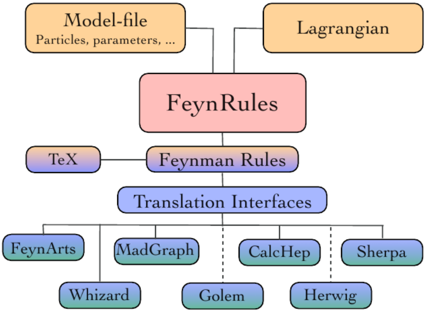
[Gleisberg et al.] EPJC34(2004)173



Tree-level ME generators suited for any physics model but implementing Feynman rules tedious and error-prone

Automated by FeynRules
[Christensen,Duhr] CPC180(2009)1614

- Extract vertices from Lagrangian based on minimal information about particle content
- Write ME-generator specific output $\to$ universality and cross-checks

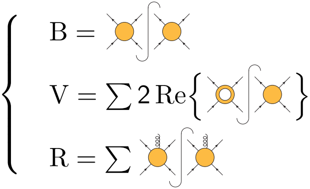


Recent developments include:

- UFO [Degrande,Duhr,Fuks,Grellscheid,Mattelaer,Reiter] CPC183(2012)1201
  Model files and Feynman rules $\to$ self-contained Python library
  ALOHA [deAquino,Link,Maltoni,Mattelaer,Stelzer] arXiv:1108.2041 $\to$ MadGraph
  Automated implementation of arbitrary higher-dimensional operators
- Spin-3/2 particles and superfield formalism
- Counterterms for NLO ME generators

Matrix element tools for NLO

NLO prediction



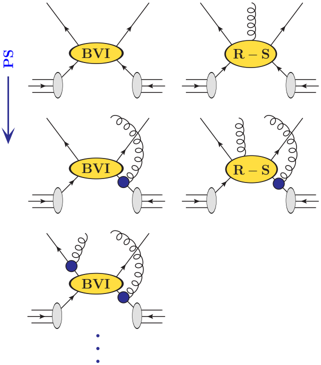
Singularities in V & R to be removed before MC-integration

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

Commonly used subtraction techniques:

- **Dipole method** [Catani,Seymour] NPB485(1997)291 [Catani,Dittmaier,Seymour,Trocsanyi] NPB627(2002)189, implemented in
  - AMEGIC++ [Gleisberg,Krauss] EPJC53(2008)501, Comix [SH] colorful
  - HELAC/PHEGAS [Czakon,Papadopoulos,Worek] JHEP08(2009)085 polarized
  - MADDIPOLE [Frederix,Gehrmann,Greiner] JHEP09(2008)122, JHEP06(2010)096
- **FKS method** [Frixione,Kunszt,Signer] NPB467(1996)399, implemented in
  - MADFKS [Frederix,Frixione,Maltoni,Stelzer] JHEP10(2003)009

Several other implementations, which are not part of automated tree-level tools


PS
BVI
R – S
BVI
R – S
BVI

Assume parton shower with same structure as NLO-subtraction method

Expectation value of observable O to $\mathcal{O}(\alpha_s)$ in PS approximation:

$$\langle O\rangle = \sum\int \mathrm{d}\Phi_B\,\mathrm{B}\left[\Delta^{(\mathrm{PS})}(t_0)\,O(\Phi_B) + \sum_i\int_{t_0}^{Q^2}\mathrm{d}\Phi^i_{R|B}\,\mathrm{K}_i\,\Delta^{(\mathrm{PS})}(t(\Phi_{R|B}))\,O(\Phi_R)\right]$$

where $\Delta_i^{(\mathrm{PS})}(t) = \exp\left\{-\int_t^{Q^2}\mathrm{d}\Phi^i_{R|B}\,\mathrm{K}_i\right\}$

Make this NLO-correct:

- Radiation pattern of R from ME correction
  Correction weight $w = \mathrm{D}_i^{(\mathrm{A})}/\mathrm{B}\mathrm{K}_i$, where $\mathrm{D}_i^{(\mathrm{A})} \to$ dipole term
- Replace $\mathrm{B} \to \bar{\mathrm{B}}^{(\mathrm{A})} = \mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I}^{(\mathrm{S})} + \sum_i\int\mathrm{d}\Phi^i_{R|B}\left[\mathrm{D}_i^{(\mathrm{A})} - \mathrm{D}_i^{(\mathrm{S})}\right]$
- Add hard remainder function $\int\mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{A})}$, where $\mathrm{H}^{(\mathrm{A})} = \left[R - \sum_i \mathrm{D}_i^{(\mathrm{A})}\right]$

Defines MC@NLO algorithm [Frixione,Webber] JHEP06(2002)029

$$\langle O\rangle = \sum\int\mathrm{d}\Phi_B\,\bar{\mathrm{B}}^{(\mathrm{A})}\left[\bar{\Delta}^{(\mathrm{A})}(t_0)\,O(\Phi_B) + \sum_i\int_{t_0}^{Q^2}\mathrm{d}\Phi^i_{R|B}\,\frac{\mathrm{D}_i^{(\mathrm{A})}}{\mathrm{B}}\,\bar{\Delta}^{(\mathrm{A})}(t(\Phi_{R|B}))\,O(\Phi_R)\right] + \int\mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{A})}\,O(\Phi_R)$$

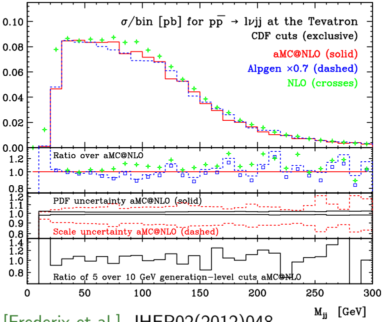
Standard method to combine NLO with MC   POWHEG almost identical

Automated in aMC@NLO

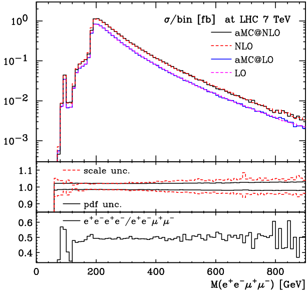
Using MADFKS subtraction and fHERWIG PS

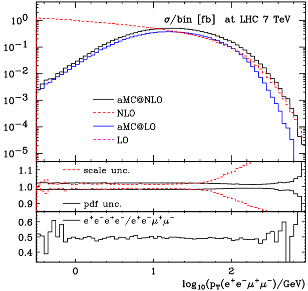
Framework for convenient uncertainty estimate

- $t\bar{t}h$ PLB701(2011)427
- $W^{\pm}/Z + b\bar{b}$ JHEP09(2011)061
- 4 leptons JHEP02(2012)099
- $W^{\pm}$+2 jets JHEP02(2012)048



[Frederix et al.] JHEP02(2012)048





[Frederix et al.] JHEP02(2012)099

MC@NLO

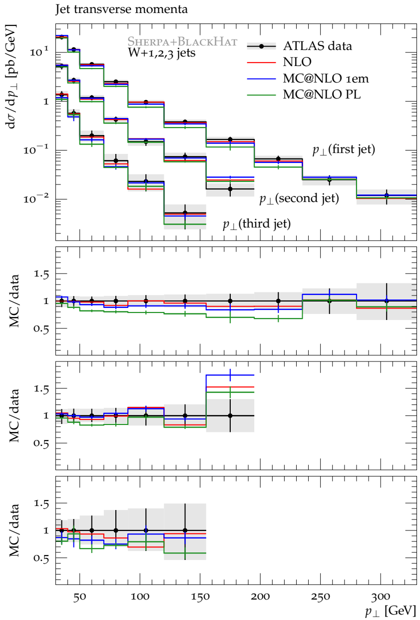
Substantial simplification of MC@NLO
if $\mathrm{D}^{(\mathrm{A})} \to \mathrm{D}^{(\mathrm{S})} \Rightarrow$ zero integral in $\bar{\mathrm{B}}^{(\mathrm{A})}$

Works well for $W+\leq 3$ jets $\to$

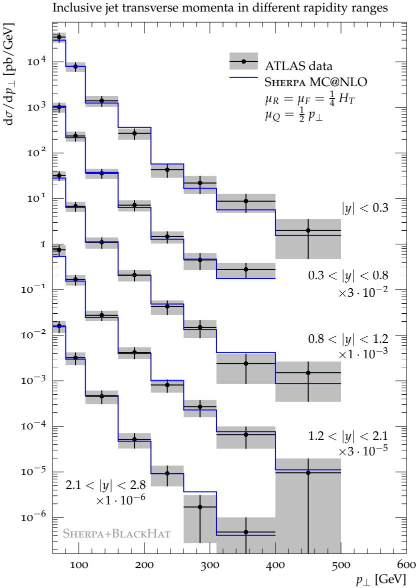
or inclusive QCD jets ($\nearrow$ next slide)

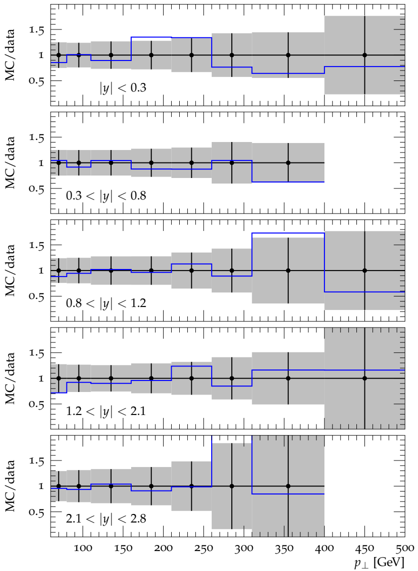
Automated for light partons
Released with Sherpa 1.4.0

Resummation scale defined by α_{cut}
will be changed to k_T in next version



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





Inclusive jet cross sections at 7 TeV

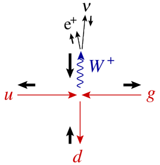
Exp data: [ATLAS] EPJC71(2011)1512

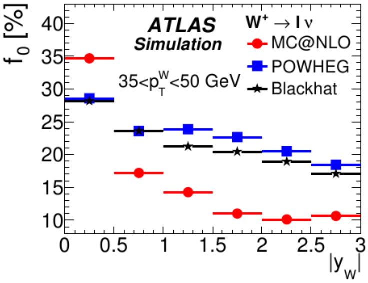
Appropriate predictions, please!

Example: MC@NLO ↔ POWHEG

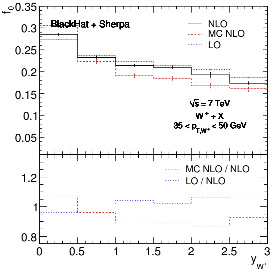
in W-polarization measurement

[ATLAS] arXiv:1203.2165

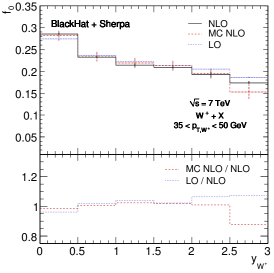




W+0j MC@NLO ✗



W+1j MC@NLO ✓



Originally $\mathrm{D}^{(\mathrm{A})}$ defined by PS kernels
+ soft suppression function (subleading color)

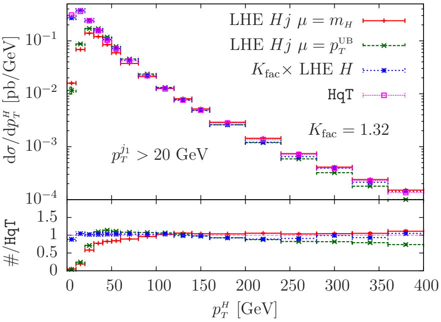
Use instead $\mathrm{R}_i^{(\mathrm{A})} = \mathrm{D}_i^{(\mathrm{S})} / \sum \mathrm{D}^{(\mathrm{S})}\ \mathrm{R}$

→ MC@NLO becomes POWHEG
[Frixione,Nason,Oleari] JHEP11(2007)070

Partially automated in POWHEGBOX
[Alioli,Oleari,Nason,Re] JHEP06(2010)043

- FKS subtraction
- PYTHIA/fHERWIG PS

Extensive list of processes implemented
Recent example: h+2 jets in GF



[Campbell,Ellis,Frederix,Nason,Oleari,Williams]
arXiv:1202.5475 [hep-ph]

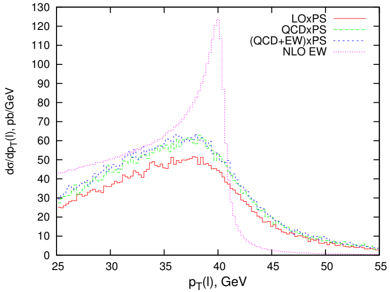
POWHEGBOX originally aimed at providing framework only
→ many contributors and rapid development
[Barzè,Bernaciak,Bagnaschi,Campbell,Ellis,Frederix,deGrassi,Jäger,Klasen,Kovarik,Melia,Moch,Montagna, Nicrosini,Piccinini,Reina,Ridolfi,Rontsch,Slavich,Uwer,Vicini,Wackeroth,Weydert,Williams,Zanderighi]

Now heading towards full automation using MADGRAPH & GOSAM

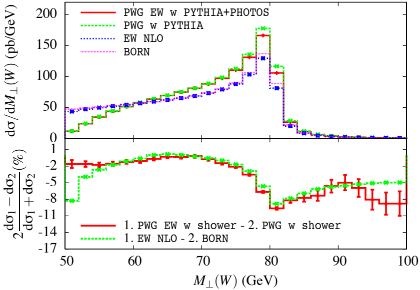
EW corrections in the POWHEGBOX

Single vector boson production → two different implementations:

- NLO QCD+EW ⊗ QCD PS [Bernaciak,Wackeroth] arXiv:1201.4804 [hep-ph]
- NLO QCD+EW ⊗ QCD+QED PS [Barzè et al.] JHEP04(2012)037



[Bernaciak,Wackeroth]
arXiv:1201.4804 [hep-ph]



[Barzè,Montagna,Nason,Nicrosini,Piccinini]
JHEP04(2012)037

Some in-house implementations of **POWHEG in HERWIG++**

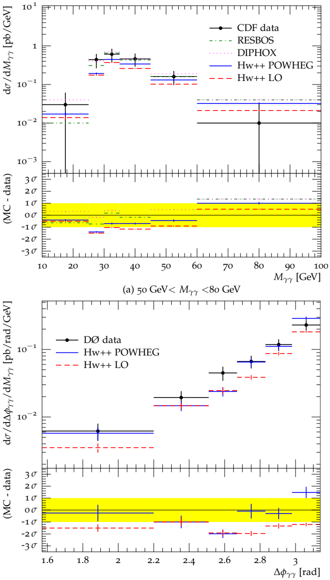
- Drell-Yan JHEP10(2008)015
- W/Z+Higgs JHEP05(2009)112
- Higgs in GF JHEP04(2009)116
- DIS & VBF arXiv:1106.2983 [hep-ph]
- Diphoton JHEP02(2012)130

Truncated PS always included!

While argued that necessary in principle truncated PS is **neglected** in POWHEGBOX

Elegant solution for diphoton production: Split real-emission ME into QCD & QED parts using respective subtraction terms

$$\mathrm{R}^{(\mathrm{A})}_{\mathrm{QCD}} = \mathrm{R} \frac{\sum \mathrm{D}^{(\mathrm{A})}_{\mathrm{QCD}}}{\sum \mathrm{D}^{(\mathrm{A})}_{\mathrm{QCD}} + \sum \mathrm{D}^{(\mathrm{A})}_{\mathrm{QED}}}$$



[d'Errico,Richardson] JHEP02(2012)130

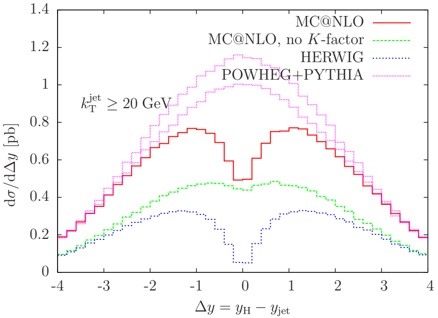
Controversial issue: What is resummed in POWHEG / MC@NLO?

$D^{(A)}$ / $H^{(A)}$ can be adjusted in functional form & active phase space

MC@NLO → a-priori choice / POWHEG → tuneable damping parameter h

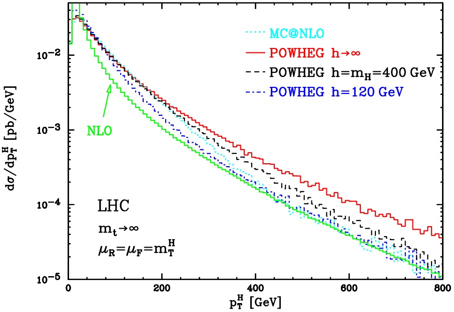
Why important? Two examples:

Limited phase-space coverage of PS → dead zones appear as "MC@NLO dip"



[Nason,Webber] arXiv:1202.1251 [hep-ph]

h not defined by resummation scale → disagreement with NLO in high-p_T tails



[Nason,Webber] arXiv:1202.1251 [hep-ph]

Parton shower issues

MC@NLO and POWHEG both rely on general-purpose MC for subsequent showering

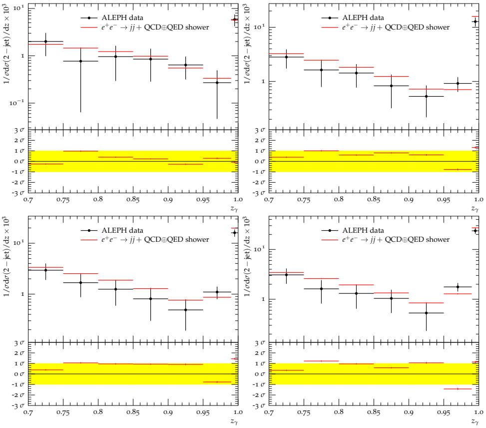
Kinematic effects & scale choices play a role → PS model affects accuracy of matched NLO result

Need improved parton showers as part of general-purpose MC

Various new implementations but few public codes on market

PS, Hadronization, & MPI linked → combined tuning necessary!

γ-fragmentation function PRD81(2010)034026

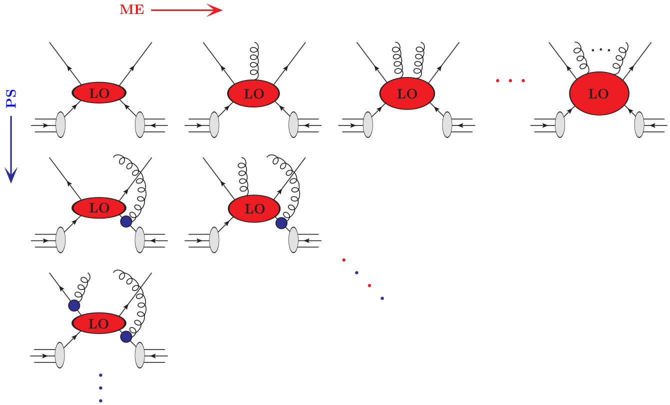


[Schumann,Siegert,SH] PRD81(2010)034026

Most promising progress from dipole-like parton showers
[Schumann,Krauss] JHEP03(2008)038, [Plätzer,Gieseke] JHEP01(2011)024

Sector showers interesting new alternative, but no IS shower yet
[Giele,Kosower,Skands] PRD84(2011)054003, [Larkoski,Peskin] PRD81(2010)054010

ME⊗PS merging

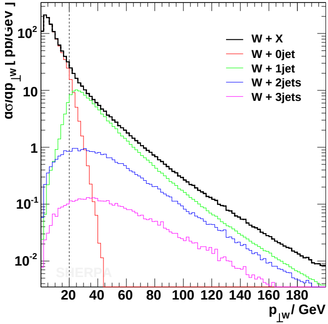


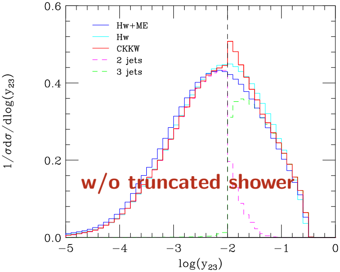
Separate radiation into “hard” & “soft”
[Catani,Krauss,Kuhn,Webber] JHEP11(2001)063
[Krauss,Schumann,Siegert,SH] JHEP05(2009)053

- Real-emission ME in hard domain
- PS approximation in soft domain

need measure for “hard” & “soft”
→ above / below critical value in
Jet criterion Q e.g. k_T-jet measure

↔





[Hamilton,Richardson,Tully] JHEP11(2009)038

If Q different from evolution variable truncated showers needed to maintain logarithmic accuracy of original PS

Only two implementations so far

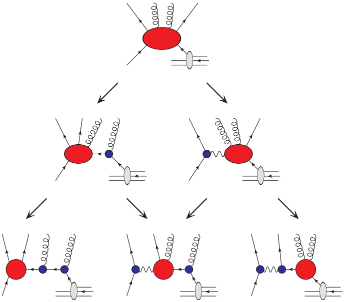
- SHERPA JHEP05(2009)053
- HERWIG++ JHEP11(2009)038

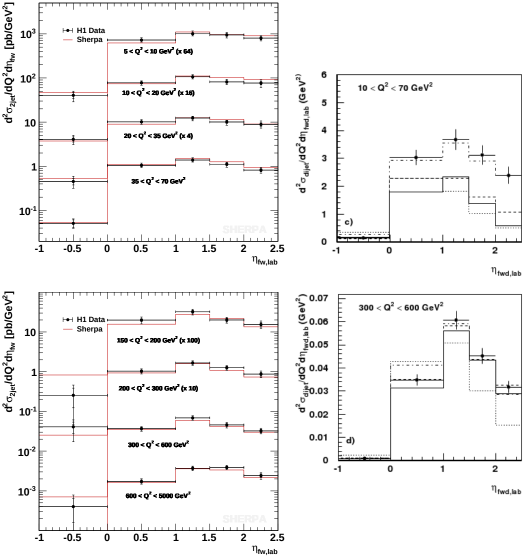
Requires intimate knowledge of PS

ME⊗PS merging

Lessons from DIS @ HERA:
Simulation often too focused on resonant contributions

Sometimes need be inclusive e.g. for low-mass Drell-Yan or photon & diphoton events



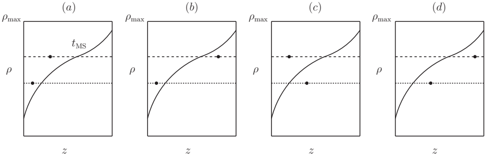


[Carli,Gehrmann,SH] EPJC67(2010)73

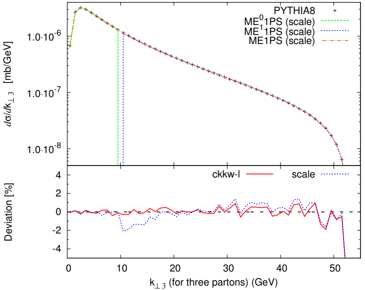
ME$\otimes$PS merging

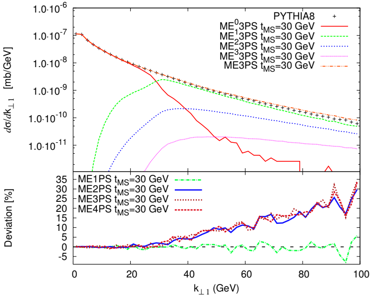
New, promising merging approach
in Pythia 8 [Lönnblad,Prestel] JHEP03(2012)019

- CKKW-L like [Lönnblad] JHEP05(2002)046
  Works for interleaved showers
- Based on recasting jet criterion into hybrid of Q and PS evolution variable
- Alternative solution to truncated PS
  same formal accuracy in most regions
- Difficult to disentangle effects of phase-space separation analytically
  most likely not an issue in practice



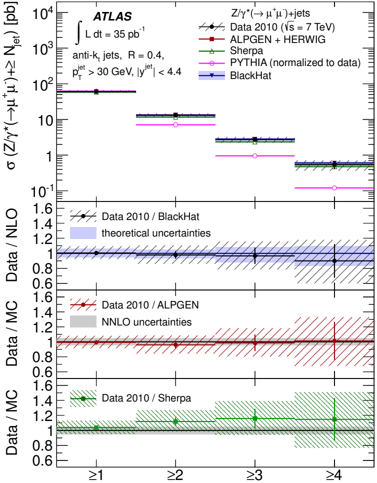
Formal improvement over MLM method and suitable for all PS algorithms



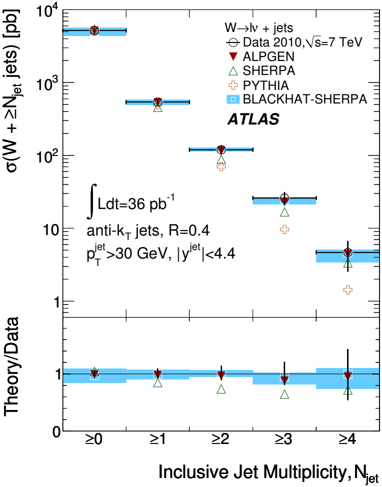


[Lönnblad,Prestel] JHEP03(2012)019

Often good description of data with one approach (or one tool)
but not so good with another → **need systematic study of differences**



[ATLAS] EPJC72(2012)1910



[ATLAS] arXiv:1201.1276 [hep-ex]

Need more systematic quantification of hadronization & MPI uncertainties

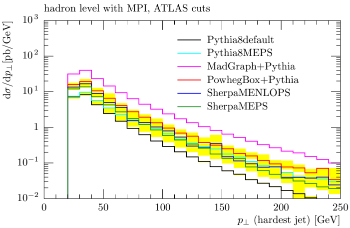
Instead of many different tunes, provide “error tunes”? like PDF

→ Joint effort of theory and experiment

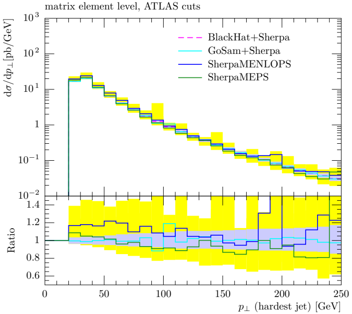
Need MC comparison at different levels and including full uncertainties

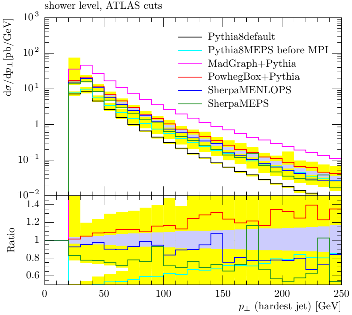
Pinpoint where tools could look alike and why they don’t

→ Joint effort of theory and theory



[LH’11 SM WG] arXiv:1203.6803 [hep-ph]





Minimum Bias

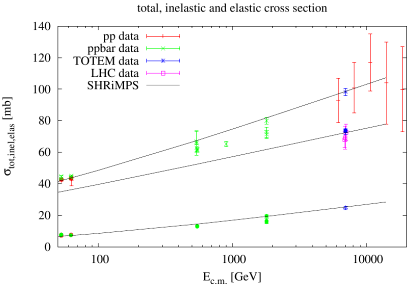
New min bias generator based on KMR model in Sherpa 1.4.0

Optical theorem relates σ_{tot} to elastic forward scattering (Pomeron)

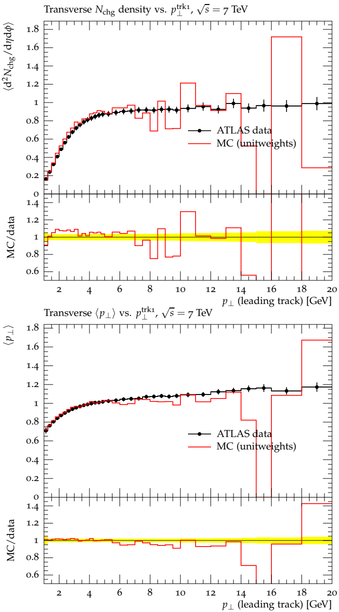
Elastic bare Pomeron exchange simulated as rapidity evolution

Rescattering in high density & strong coupling regime

Proton FF $\leftrightarrow$ diffractive Eigenstates



[Hoeth,Khoze,Krauss,Martin,Ryskin,Zapp] SM@LHC'12



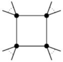
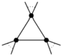
Exp. data: [ATLAS] PRD83(2011)112001

Summary

- HERWIG++, PYTHIA & SHERPA $\rightarrow$ frameworks for LHC event simulation
- Lots of progress to combine NLO tools with these general-purpose MC
- Systematic uncertainty studies should enhance physics capabilities

Automated NLO calculations

Multi-particle cuts and generalized unitarity simplify loop integration:

$A_{loop} = \sum d_i$  $+ \sum c_i$  $+ \sum b_i$  $+ R + \mathcal{O}(\epsilon)$

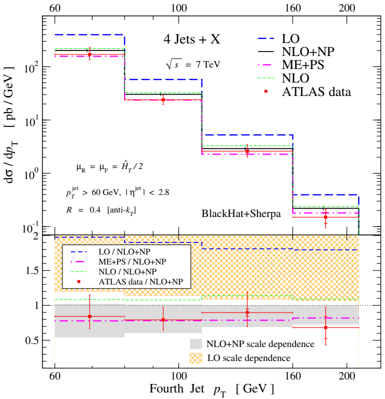
Cut-constructible part of virtual amplitude reduced to scalar integrals at integrand level → determine coefficients from tree amplitudes
[Ossola,Papadopoulos,Pittau] NPB763(2007)147, [Forde] PRD75(2007)125019

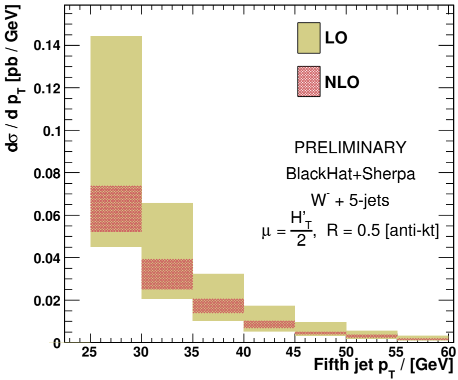
Various (semi-)automated codes:

- BlackHat [Bern,Dixon,Febres-Cordero,Höche,Ita,Kosower,Maître,Ozeren]
- GoSam [Cullen,Greiner,Heinrich,Luisoni,Mastrolia,Ossola,Reiter,Tramontano]
- Helac-NLO [Bevilacqua,Czakon,Garzelli,van Hameren,Malamos,Papadopoulos,Pittau,Worek]
- MadLoop [Hirschi,Frederix,Frixione,Garzelli,Maltoni,Pittau]
- OpenLoops [Cascioli,Maierhöfer,Pozzorini]
- Rocket [Ellis,Giele,Kunszt,Melnikov,Zanderighi]
- & others [Badger,Lazopoulos,Giele,Kunszt, Winter,...]

Standalone programs, but also "loop engines" for MC@NLO & POWHEG
Anticipate symbiotic relationship with tree-level tools → Binoth LH interface

Example: BlackHat ⊕ Comix





Four-jet production at 7 TeV LHC

[BlackHat] arXiv:1112.3940 [hep-ph]

First results for W+5 jets

Highly preliminary! [BlackHat]