Monte-Carlo Event Generators

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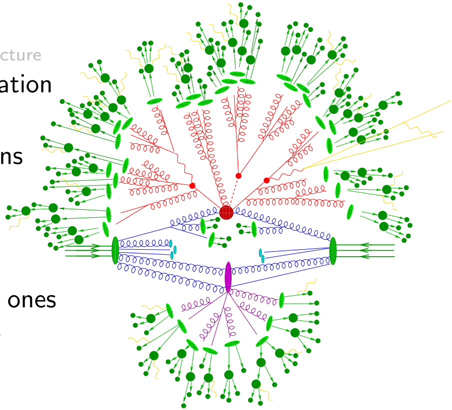
QCD at the LHC

St. Andrews, August 23, 2011

Event generation in standard Monte Carlo

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



Will focus on general-purpose MC plus NLO ME generators in this talk

Disclaimer: No attempt to present full status of the field

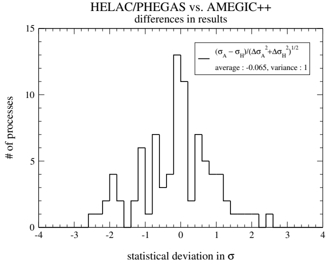
Find more in recently published review [Buckley et al.] Phys.Rept.504(2011)145

Matrix element generators

State of the art: Automated tree-level ME

Strategies for efficient computation:

- diagrams AMEGIC++, CompHEP, MADGRAPH, ...
- recursion Comix, HELAC, O'Mega, ...
- α-algorithm ALPGEN
- **phase-space integration using multi-channel**
- **color/helicity sampling**



[Gleisberg et al.] EPJC34(2004)173

New models via FeynRules generator-independent

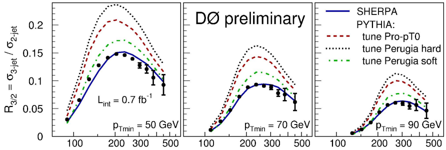
Most codes provide LHEF output to feed into external PS MC HERWIG++, PYTHIA
Some built into PS MC AMEGIC++, Comix

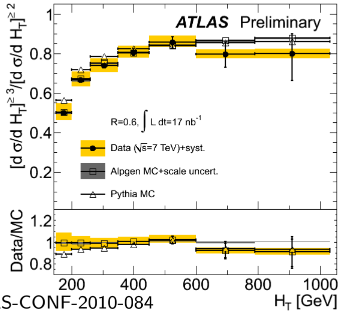
Performance example: $t\bar{t}$ + jets MC4LHC workshop 2004 and JHEP12(2008)039

σ [pb]	Number of jets						
$t\bar{t}$ + jets	0	1	2	3	4	5	6
ALPGEN	755.4(8)	748(2)	518(2)	310.9(8)	170.9(5)	87.6(3)	45.1(8)
AMEGIC	754.4(3)	747(1)	520(1)				
Comix	754.8(8)	745(1)	518(1)	309.8(8)	170.4(7)	89.2(4)	44.4(4)
CompHEP	757.8(8)	752(1)	519(1)				
HELAC	745(5)	711(7)	515(5)				
MadGraph	754(2)	749(2)	516(1)	306(1)			

Matrix element generators

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



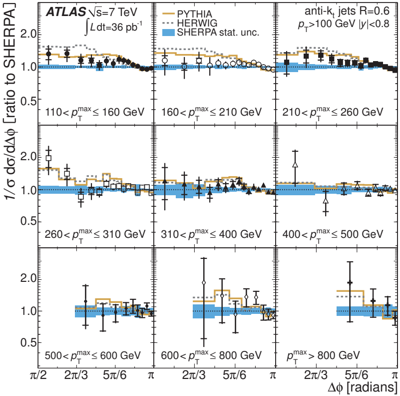


ATLAS-CONF-2010-084

Multi-leg ME⊗PS "standard" by now

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

Dijet decorrelation (MC vs. data)



[ATLAS] arXiv:1102.2696

Matrix element generators

Cutting edge: Automating multi-leg NLO calculations

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

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 universal and "easy" to automate, V tedious

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

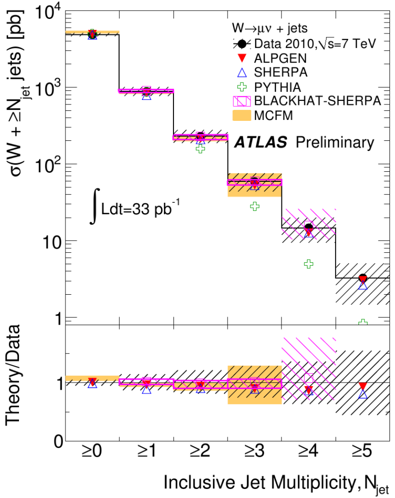
- One-Loop-Engine (OLE) $\to$ virtual piece
  BlackHat, GOLEM, HELAC, MADLOOP, MCFM, NLOJET++, Rocket, Samurai, ...
- MC $\to$ Born, real emission, subtraction and phase space
  SHERPA, HELAC, MADDIPOLE, MADFKS, ...

Example: Z+4 jets with BlackHat [Ita et al.] arXiv:1108.2229 [hep-ph]

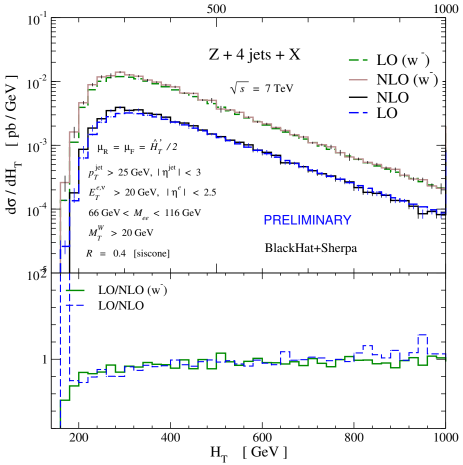
no. jets	Z LO	Z NLO	Z/W^+ LO	Z/W^+ NLO	$Zn/(n-1)$ LO	$Zn/(n-1)$ NLO
0	$323.1(0.1)^{+39.3}_{-44.3}$	$457.2(0.3)^{+5.7}_{-3.4}$	0.1209(0.0001)	0.1393(0.0003)	—	—
1	$66.69(0.04)^{+5.59}_{-5.30}$	$82.1(0.1)^{+3.3}_{-2.6}$	0.1674(0.0002)	0.166(0.001)	0.2064(0.0001)	0.1795(0.0003)
2	$19.10(0.02)^{+5.32}_{-3.82}$	$20.25(0.07)^{+0.31}_{-1.02}$	0.1636(0.0003)	0.166(0.002)	0.2864(0.0003)	0.247(0.001)
3	$4.76(0.01)^{+2.18}_{-1.35}$	$4.73(0.03)^{+0.05}_{-0.35}$	0.1634(0.0004)	0.169(0.002)	0.2494(0.0004)	0.234(0.002)
4	$1.116(0.002)^{+0.695}_{-0.390}$	$1.06(0.01)^{+0.05}_{-0.14}$	0.1618(0.0003)	0.172(0.002)	0.2343(0.0005)	0.223(0.002)

Matrix element generators

Synergy between OLE and MC allows to attack e.g. W+3/4 jets, Z+3/4 jets



[Atlas] ATLAS-CONF-2011-060



[BlackHat] arXiv:1108.2229 [hep-ph]

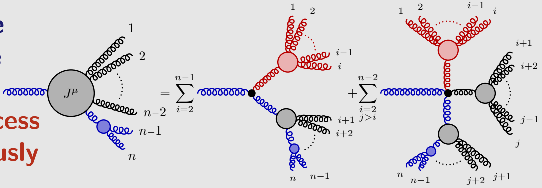
Matrix element generators

OLEs attacks higher and higher jet multiplicity

$\rightarrow$ need to compute real-radiation & infrared subtraction terms efficiently

Tree-level $\Rightarrow$ Use color-dressed Berends-Giele recursion [Duhr,Maltoni,SH] hep-ph/0607057

- **Let spectator parton be "final" leg in amplitude**
- **Recycle subamplitudes from real-radiation process and dipoles simultaneously**



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

Similar technique to be applied to integrated subtraction terms

Example: $pp \rightarrow e^+\nu_e$+jets (7 TeV) real-radiation & subtraction only

σ_{R-S} [pb]	Number of jets					
n k_T-jets	0	1 $\alpha_c = 0.1$	2 $\alpha_c = 0.03$	3 $\alpha_c = 0.01$	4 $\alpha_c = 0.003$	5 $\alpha_c = 0.001$
AMEGIC++/BlackHat	-200(1)	297(3)	576(6)	342(2)		
Comix	-198(1)	297(3)	586(6)	**343(1)**	**143(1)**	**31.7(6)**
Speedup	0.4	0.9	0.6	**3.39**	–	–

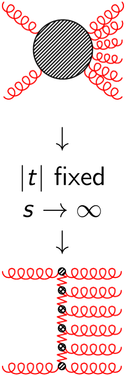
Matrix element generators

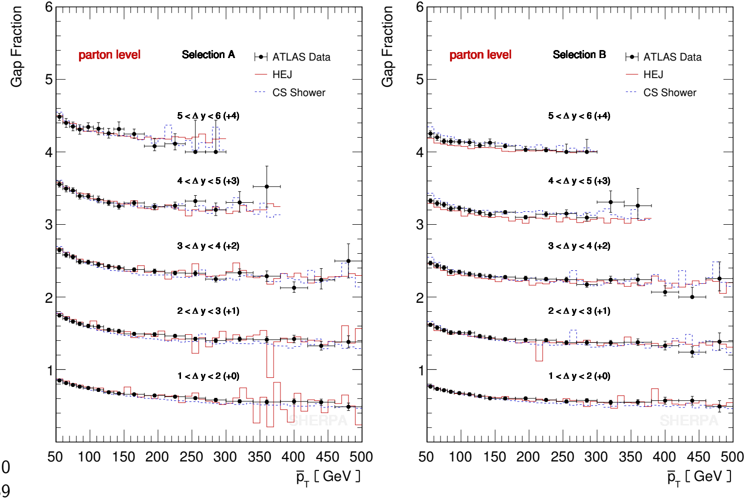
MadLoop → fully automated NLO predictions [Hirschi et al.] JHEP 1105(2011)044

	Process	μ	n_{lf}	LO	NLO
a.1	$pp \to t\bar{t}$	m_t	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_t	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_t	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_t/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_t/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^- j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^- jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_t$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_t$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_t$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^- j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+ jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+ j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_t + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

High Energy Jets (HEJ)

All-order corrections to multi-jet rates from the high-energy limit





[Andersen,Smillie]
JHEP 06(2011)010
JHEP 01(2010)039

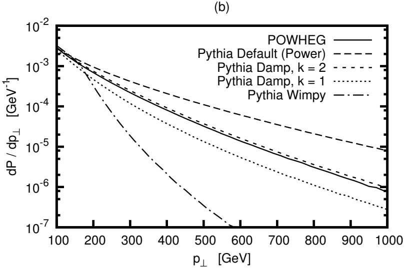
Resummation only. Exp. data: [Atlas] arXiv:1107.1641 [hep-ph]

Parton showers

Pythia: Aim at better PS at large p_T
bridge gap between “power” and “wimpy”

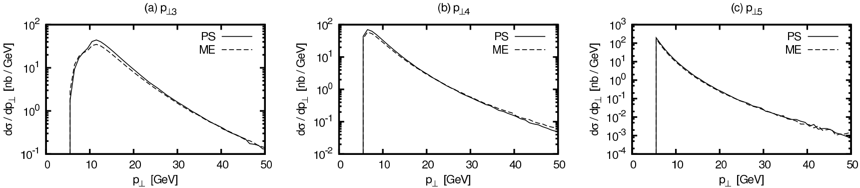
Introduce dampening $k^2\mu^2/(k^2\mu^2 + p_T^2)$
for colored massive final states only

Improved default PS alleviates matching to NLO simulation MC@NLO, POWHEG



$t\bar{t}$+jets from [Corke,Sjöstrand] EPJC69(2010)1

Study of PS emission pattern in pure QCD yields good agreement with ME
large region of phase space usually well described → reduced systematics in NLO merging



[Corke,Sjöstrand] JHEP03(2011)032

Parton showers

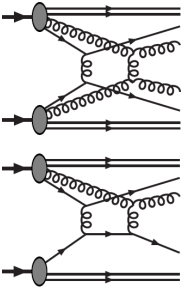
PYTHIA: Same evolution variable, k_T, for ISR/FSR and MPI

Interleave PS & MPI to arrive at more inclusive picture
[Sjöstrand,Skands] EPJC39(2005)129, [Corke,Sjöstrand] JHEP01(2010)035

$$\frac{\mathrm{d}P}{\mathrm{d}p_T} = \frac{\mathrm{d}}{\mathrm{d}p_T} \exp\left\{ - \int_{p_T} \mathrm{d}\bar{p}_T \left(\frac{\mathrm{d}\mathcal{P}_{PS}}{\mathrm{d}\bar{p}_T} + \frac{\mathrm{d}\mathcal{P}_{MPI}}{\mathrm{d}\bar{p}_T} \right) \right\}$$

Rescattering effects important at higher energies

	Tevatron		LHC	
	Min Bias	QCD Jets	Min Bias	QCD Jets
Normal scattering	2.81	5.09	5.19	12.19
Single rescatterings	0.41	1.32	1.03	4.10
Double rescatterings	0.01	0.04	0.03	0.15

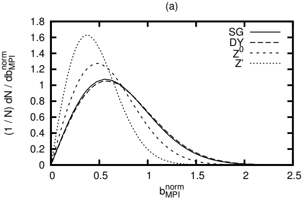


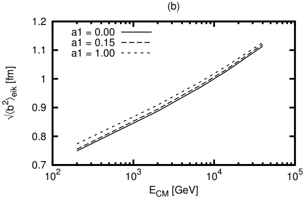
[Corke,Sjöstrand] JHEP01(2010)035

Also: New MPI model:
x-dependent proton size

intuitive picture of protons spreading out to lower x
$\rightarrow$ large x implies small b

[Corke,Sjöstrand]JHEP05(2011)009





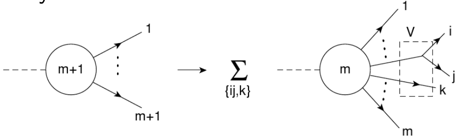
Parton showers

New PS developments based on Catani-Seymour subtraction formalism

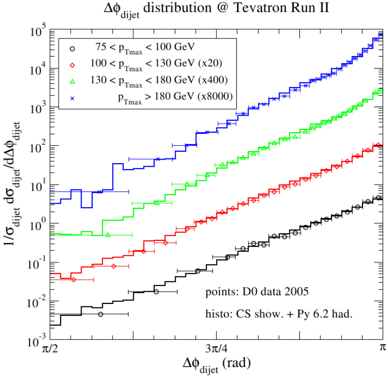
Schematically: $S \rightarrow \sum_{ij,k} B \otimes V_{ij,k}$

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

here: large-N_C limit, spin-averaged

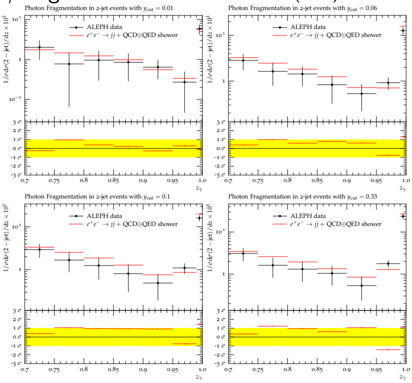


Few model ambiguities, excellent approximation of higher-order real ME



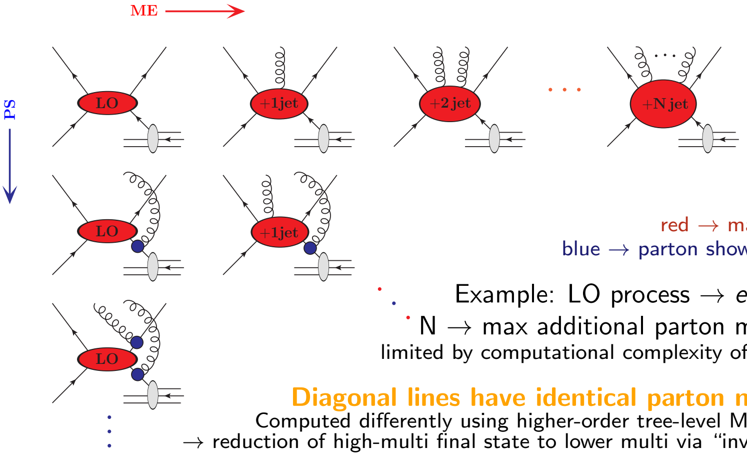
[Krauss,Schumann] JHEP03(2008)038

γ-fragmentation function PRD81(2010)034026



Connecting ME and PS

Chance and challenge: ME and PS can simulate the same thing!



red → matrix element
blue → parton shower branching

Example: LO process → $e^{\pm}q \rightarrow e^{\pm}q$
N → max additional parton multi in ME
limited by computational complexity of the problem

Diagonal lines have identical parton multiplicity
Computed differently using higher-order tree-level ME or/and PS
→ reduction of high-multi final state to lower multi via "inverse" shower

ME⊗PS idea: Use ME/PS in regime of their respective strengths

ME → hard emissions / PS → soft/collinear regime JHEP11(2001)063, JHEP05(2009)053

Connecting ME and PS

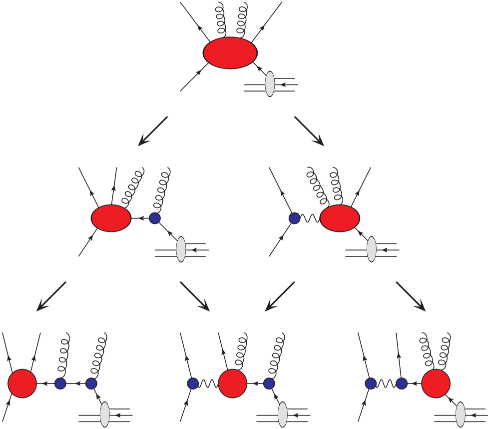
Matrix elements can have very different PS equivalents depending on kinematics

Must reduce full high-multi ME to either of these configurations in order to start PS

Radiation effects off intermediate legs must be modeled to account for Sudakov suppression → truncated PS

Method: PRD57(1998)5767, JHEP05(2009)053

- Probability to identify splitting given by PS's branching eqns
- Reduced ME configuration defined by "inverted" PS splitting kinematics
- **Continue until** $2 \to 2$ **"core"**



Core processes set the hardness scale of events $\to \mu_F$

i.e. no scale should be larger than this PRD70(2004)114009, JHEP05(2009)053

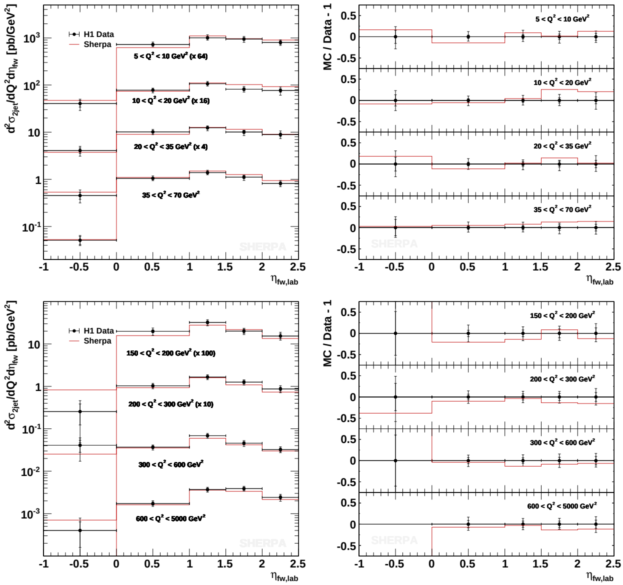
Connecting ME and PS

Must define ME regime and compute no-emission weights → methods differ

- Truncated shower scheme SHERPA, HERWIG++ JHEP05(2009)053, JHEP11(2009)038
  flexible phase-space separation criterion
  Sudakov suppression via truncated vetoed shower
- CKKW-L scheme ARIADNE JHEP05(2002)046, JHEP07(2005)054
  phase-space separation in terms of shower evolution variable ⇒ no truncated PS
  Sudakov suppression via vetoed shower
  Dipole shower including low-x effects
- MLM scheme ALPGEN NPB632(2002)343, JHEP01(2007)013
  phase-space separation via cone-like algorithm
  Sudakov suppression via "jet matching"
  Geometrical picture, no truncated shower would be needed!
- CKKW scheme SHERPA before v1.2.0 JHEP11(2001)063, JHEP08(2002)015
  phase-space separation via k_T-algorithm
  Sudakov suppression via weight from NLL formalism
  NLL ↔ PS mismatch, no truncated shower would be needed!
- mixed schemes MADGRAPH, HELAC JHEP02(2009)017
  employing techniques similar to MLM / CKKW

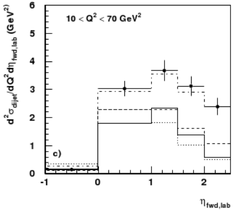
Predictions mostly agree hep-ph/0602031, EPJC53(2008)473 & arXiv:1003.1643 [hep-ph]

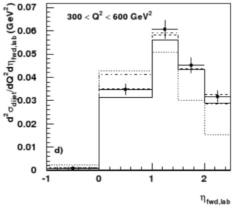
Tree-level ME⊗PS for DIS di-jets



Compare to LO⊗PS results

→ MC status 1999 vs. 2010





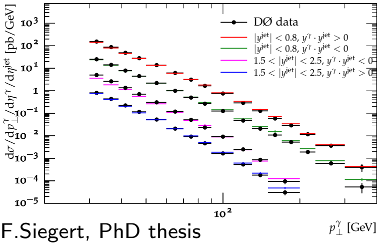
[Carli,Gehrmann,SH]

EPJC67(2010)73

Photon p_T spectra PLB666(2008)435

in regions of jet rapidity/orientation

scaled by 5, 1, 0.3 and 0.1 top to bottom



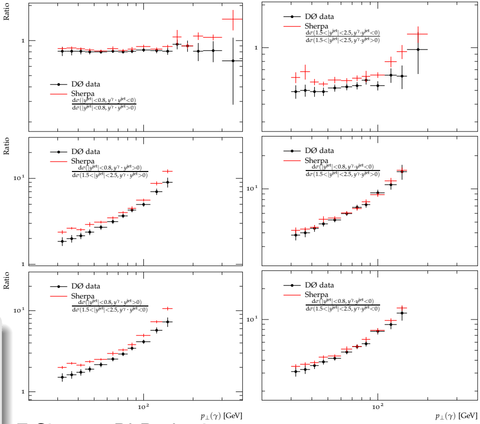
F.Siegert, PhD thesis

"Democratic" model ZPC62(1994)311

- Treat partons and γ equally
- Combine ME of various parton/γ multiplicity with
- Interleaved QCD⊕QED PS

Ratio of photon p_T spectra PLB666(2008)435

compare regions of jet rapidity/orientation

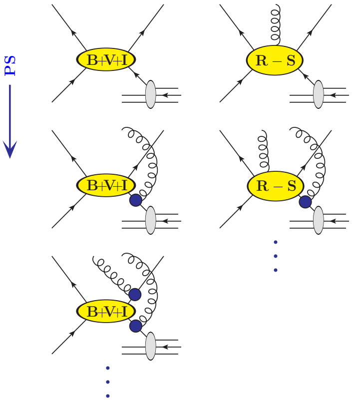


F.Siegert, PhD thesis

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

Combining NLO and PS

NLO challenge: B-, V-, I- and S-terms kinematically different from R



Requirements for NLO⊗PS:

- Preserve resummation as in PS
- Implement $\mathcal{O}(\alpha_s)$ accuracy from ME

Problems much like for ME⊗PS:

- **Real-emission term and PS populate same phase-space region**
- **Naively adding PS on top of ME leads to double-counting**

Unlike for ME⊗PS one cannot simply divide up the phase space !

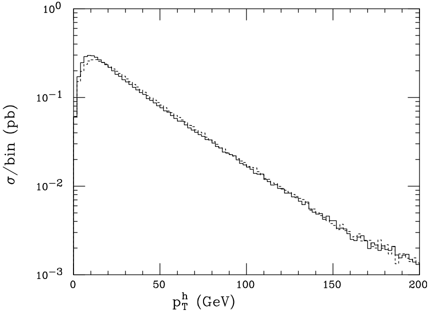
Combining NLO and PS

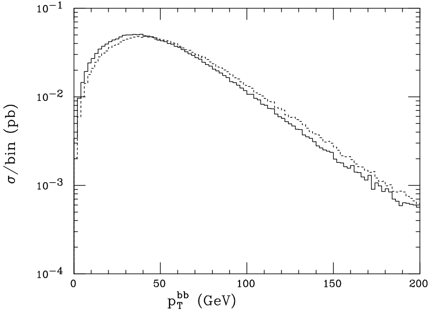
McNlo → first general solution to NLO ME ⊗ PS [Frixione,Webber] JHEP06(2002)029

- Subtraction terms used to regularize NLO ME based on PS
- Finite remainder of NLO correction added explicitly on top of PS

Explicitly PS dependent need MC subtraction terms in ME calculation
Currently implemented for fHERWIG, HERWIG++ and PYTHIA

Example: fHERWIG vs. HERWIG++ for $pp \to h + X$ / $pp \to t\bar{t} + X$





[Frixione,Stöckli,Torrielli,Webber] JHEP01(2011)053

Combining NLO and PS

Extensive list of available processes

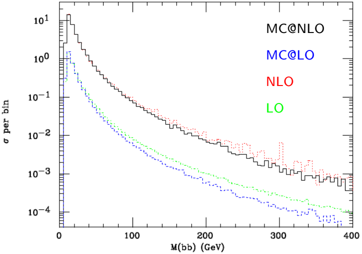
IPROC	IV	IL_1	IL_2	Spin	Process
−1350−IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL} l_{IL} + X$
−1360−IL				✓	$H_1H_2 \to (Z \to) l_{IL} l_{IL} + X$
−1370−IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL} l_{IL} + X$
−1460−IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL} \nu_{IL} + X$
−1470−IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL} \bar{\nu}_{IL} + X$
−1396				×	$H_1H_2 \to \gamma^* (\to \sum_i f_i f_i) + X$
−1397				×	$H_1H_2 \to Z^0 + X$
−1497				×	$H_1H_2 \to W^+ + X$
−1498				×	$H_1H_2 \to W^- + X$
−1600−ID					$H_1H_2 \to H^0 + X$
−1705					$H_1H_2 \to bb + X$
−1706		7	7	×	$H_1H_2 \to t\bar{t} + X$
−2000−IC		7		×	$H_1H_2 \to t/\bar{t} + X$
−2001−IC		7		×	$H_1H_2 \to \bar{t} + X$
−2004−IC		7		×	$H_1H_2 \to t + X$
−2030		7	7	×	$H_1H_2 \to tW^- / \bar{t}W^+ + X$
−2031		7	7	×	$H_1H_2 \to \bar{t}W^+ + X$
−2034		7	7	×	$H_1H_2 \to tW^- + X$
−2040		7	7	×	$H_1H_2 \to tH^- / \bar{t}H^+ + X$
−2041		7	7	×	$H_1H_2 \to \bar{t}H^+ + X$
−2044		7	7	×	$H_1H_2 \to tH^- + X$
−2600−ID	1	7		×	$H_1H_2 \to H^0 W^+ + X$
−2600−ID	1	i		✓	$H_1H_2 \to H^0 (W^+ \to) l^+_i \nu_i + X$
−2600−ID	-1	7		×	$H_1H_2 \to H^0 W^- + X$
−2600−ID	-1	i		✓	$H_1H_2 \to H^0 (W^- \to) l^-_i \bar{\nu}_i + X$
−2700−ID	0	7		×	$H_1H_2 \to H^0 Z + X$
−2700−ID	0	i		✓	$H_1H_2 \to H^0 (Z \to) l_i \bar{l}_i + X$
−2850		7	7	×	$H_1H_2 \to W^+ W^- + X$
−2860		7	7	×	$H_1H_2 \to Z^0 Z^0 + X$
−2870		7	7	×	$H_1H_2 \to W^+ Z^0 + X$
−2880		7	7	×	$H_1H_2 \to W^- Z^0 + X$

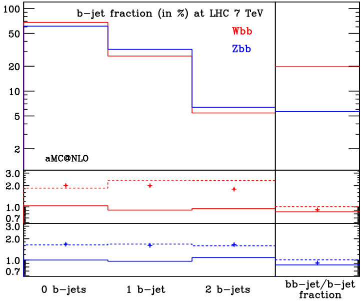
... and more, full list available at

http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO

Many contributors

Automated using MadLoop





$Wb\bar{b}$+X [Frederix et al.] arXiv:1106.6019 [hep-ph]

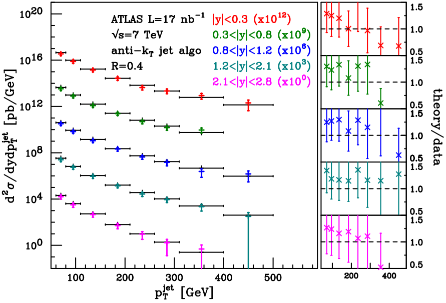
Combining NLO and PS

POWHEG $\rightarrow$ NLO ME $\otimes$ PS with positive weights [Nason] JHEP11(2004)040

- PS for 1^{st} emission based on exponentiated NLO real correction
- Subsequent emissions from PS $\rightarrow$ truncated showers potentially needed

MC independent technique hardest emission decoupled from PS

Cutting edge: POWHEG for di-jets

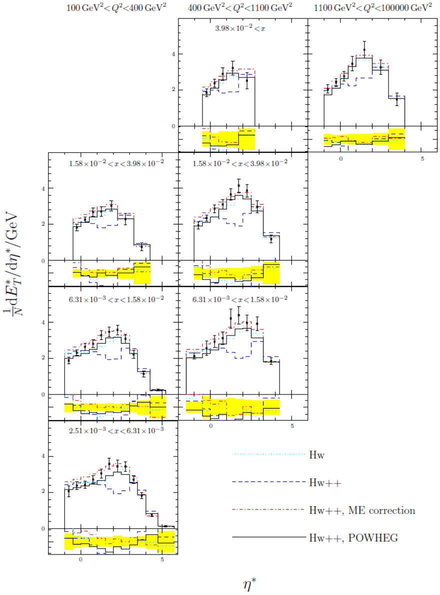


[Alioli et al.] JHEP 1104(2011)081

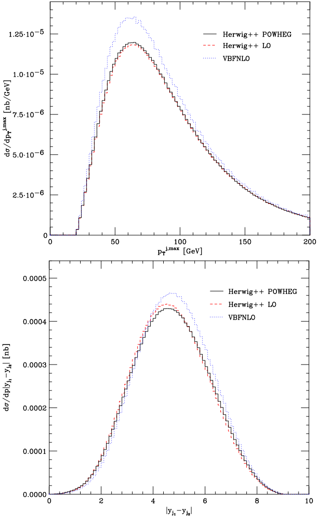
Available POWHEG implementations SM

Process	POWHEGBOX	HERWIG++	SHERPA
$e^+e^- \rightarrow jj$	X	✓	✓
DIS	X	✓	✓
$pp \rightarrow W/Z$	✓	✓	✓
$pp \rightarrow H$ (GF)	✓	✓	✓
$pp \rightarrow V+H$	X	✓	✓
$pp \rightarrow VV$	X	✓	✓
VBF	✓	✓	in prep.
$pp \rightarrow Q\bar{Q}$	✓	X	X
$pp \rightarrow Q\bar{Q}+j$	✓	X	X
single-top	✓	X	X
$pp \rightarrow V+j$	✓	X	in prep.
$pp \rightarrow V+jj$	in prep.	X	in prep.
$pp \rightarrow H+j$ (GF)	X	X	in prep.
$pp \rightarrow H+t\bar{t}$	✓	X	X
$pp \rightarrow W^+W^+jj$	✓	X	X
$pp \rightarrow V+b\bar{b}$	✓	X	in prep.
diphotons	?	✓	in prep.
dijets	✓	X	in prep.

Transverse energy flow in DIS



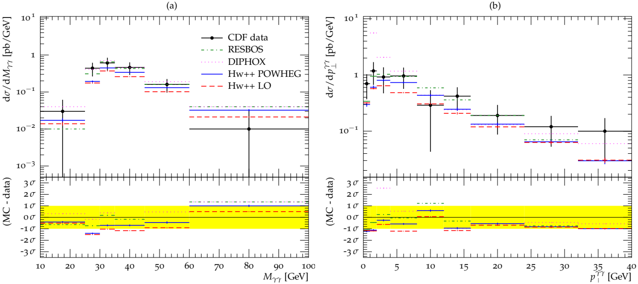
Jet transverse momentum and rapidity separation in VBF



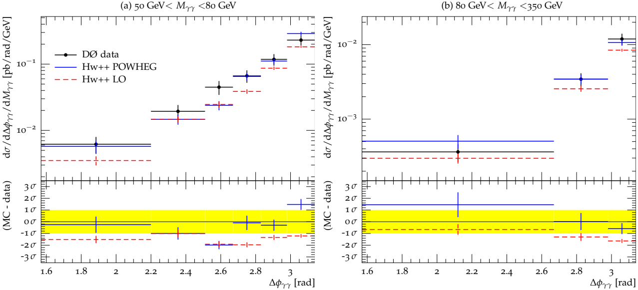
[D'Errico,Richardson] arXiv:1106.2983 [hep-ph]

Combining NLO and PS

$m_{\gamma\gamma}$ and $p_{T\,\gamma\gamma}$ in di-photon events at the Tevatron



$\Delta\phi_{\gamma\gamma}$ in di-photon events at Tevatron



[D'Errico,Richardson]

arXiv:1106.3939 [hep-ph]

Combining NLO and PS

Cutting edge: POWHEG for non-trivial color flow

Problems:

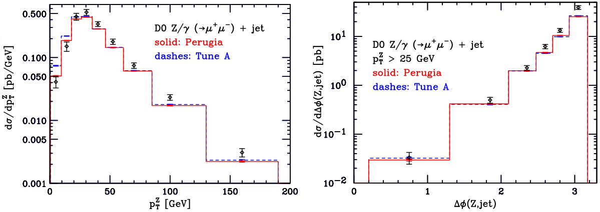
- divergent Born ME
- phase-space maps
- **efficiency**

Efforts to automate:

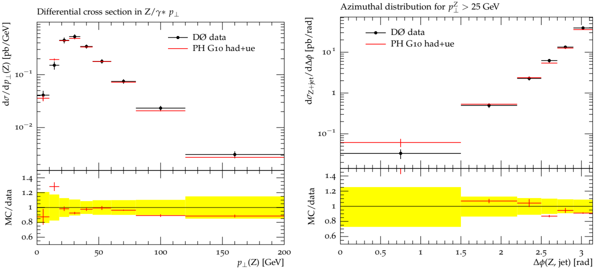
POWHEGBOX [Alioli et al.]
JHEP06(2010)043
needs colour-correlated Born ME
LO phase space and NLO ME

SHERPA [Krauss et al.]
JHEP04(2011)024
needs virtual correction only

Example: Z/W+j+X

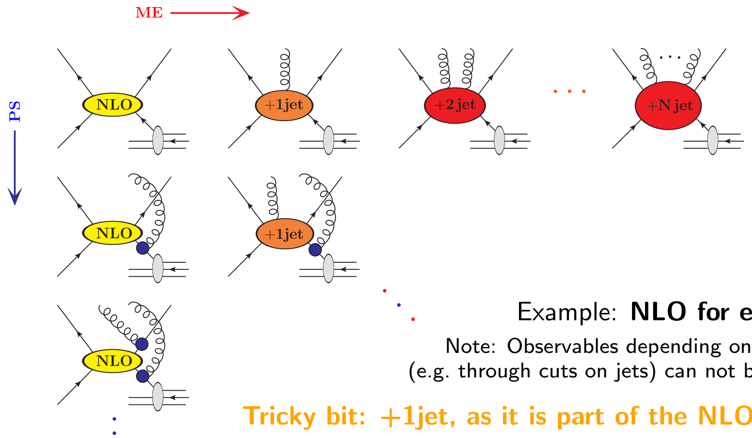


[Alioli,Nason,Oleari,Re] arXiv:1009.5594 [hep-ph]



[Krauss,Schönherr,Siegert,SH] leading colour

Promoting ME⊗PS to NLO accuracy for the "core process"
[Hamilton,Nason] JHEP06(2010)039, [Krauss,Schönherr,Siegert,SH] arXiv:1009.1127 [hep-ph]



Example: **NLO for $e^{\pm}q \to e^{\pm}q$**

Note: Observables depending on higher multi (e.g. through cuts on jets) can not be improved !

Tricky bit: +1jet, as it is part of the NLO core, too

Note that we don't merge NLO with higher-multi NLO yet !

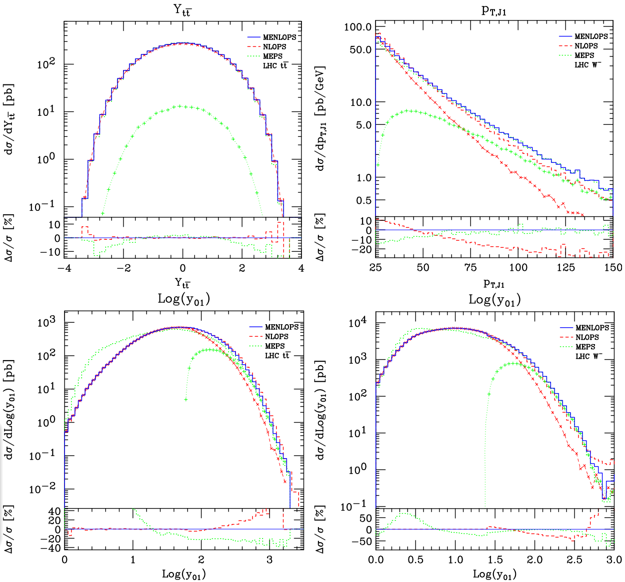
MENLOPS predictions

$t\bar{t}$-rapidity in $t\bar{t}$+jets

$p_{T,j1}$ in $W[\to l\nu]$+jets

Compare:

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

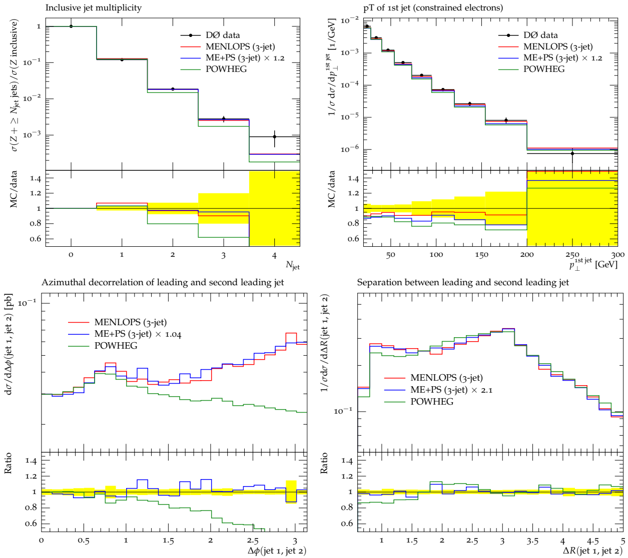


Differential jet rates in $t\bar{t}$+jets and $W[\to l\nu]$+jets

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

[Hamilton,Nason] JHEP06(2010)039

MENLOPS predictions



Jet multiplicity / $p_{T,j1}$ in Z+jets
Compare:

- ME⊗PS 0+1+2+3-jet
- MENLOPS 0+1+2+3-jet

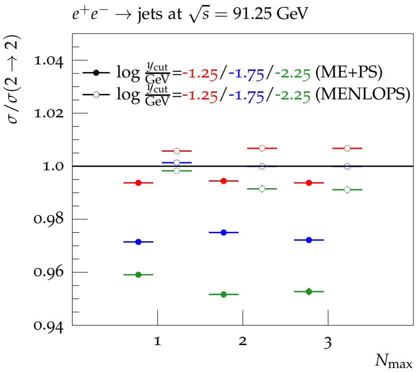
$\Delta\phi_{jj}$ / ΔR_{jj} in WW+jets / h+jets
Compare:

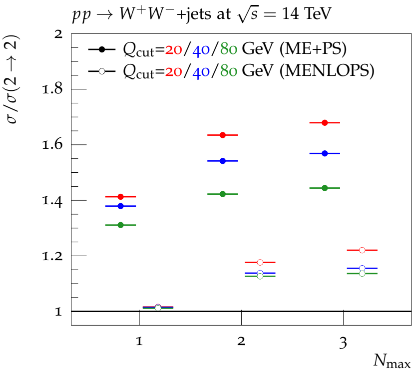
- ME⊗PS 0+1+2+3-jet
- MENLOPS 0+1+2+3-jet

[Krauss,Schönherr,Siegert,SH] arXiv:1009.1127 [hep-ph]

MENLOPS predictions

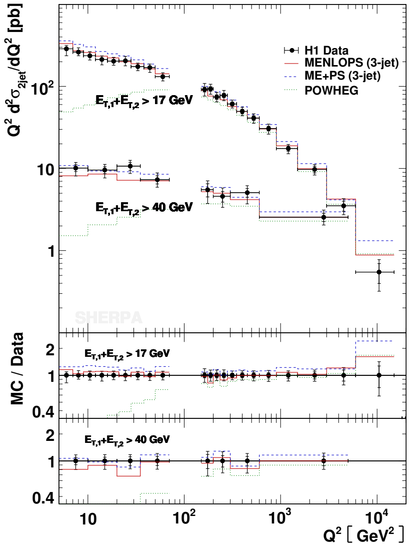
ME⊗PS/ MENLOPS cross sections compared to 2 → 2 LO / NLO





Large "unitarity violations" in ME⊗PS reduced by MENLOPS arXiv:1009.1127 [hep-ph]

MENLOPS predictions



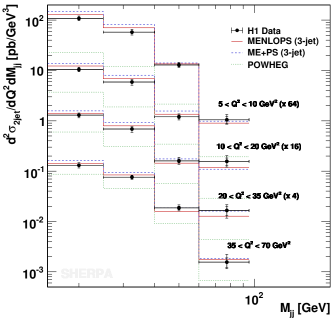
Can we improve over ME⊗PS?

Not always !

$Q^2 < \bar{E}_{T,B}$ is unlikely in POWHEG

→ same scale uncertainty from MENLOPS

Need inclusive MENLOPS ...



[Krauss,Schönherr,Siegert,SH] arXiv:1009.1127 [hep-ph], H1 data: EPJC19(2001)289

Summary

Monte-Carlo event generators have improved:

- Reduced uncertainty due to fully/partially automated NLO MEs
- Largely reduced systematics with ME$\otimes$PS, POWHEG & MC@NLO
- Reliable predictions for LEP, HERA, Tevatron and LHC
- ME$\otimes$PS and MENLOPS fully automated, to become new standard

More and more higher-order pQCD built into MC event generators!

Models only where necessary mostly for non-perturbative aspects