Developments in Monte Carlo simulation

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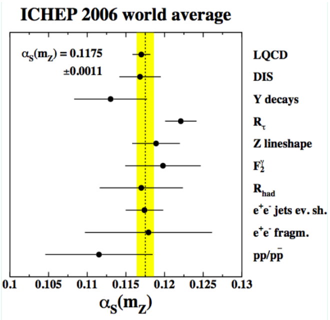
Precision MC

MC events are the only “data” from the LHC so far! Some people don’t like it when they change!

Most MC events are showered & hadronised. . . usually by Fortran Pythia or Herwig MC. Effect is to take a leading order matrix element (with IR ME correction) and resum logs in collinear approximation via QCD (& QED) radiation. Then hadronise & decay. . .

QCD is centrally important:
α_s is sufficiently large —
$\alpha_s(M_Z) = 0.1175 \pm 0.0011$ —
that $\mathcal{O}(10\%)$ errors not unusual at LO.
LHC will demand higher precision MC.



In this talk…

- Parton level events at LO & NLO
- Shower/hadronization gens:
  - matching: MC@NLO & POWHEG
  - merging: CKKW & friends
  - new showers: C-S, dipole
- C++ generators
- Tuning

I'm just here to start the discussion!

ME calculations

First, developments in leading order ME calculations. No loops, just trees — but lots of legs.

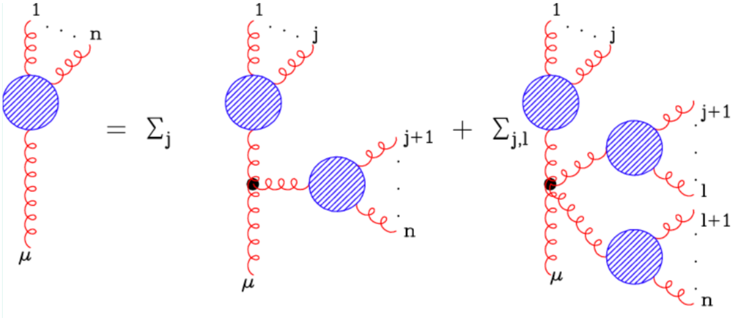
Important to understand multi-jet backgrounds to BSM processes. At tree level, several algorithmic approaches exist:

Berends–Giele recursion	off-shell recursion
MadGraph/HELAS	helicity amplitudes
MHV/BCFW recursion	on-shell recursion

Plus phase space sampling & colour

Recursion methods

Berends–Giele recursion: $t \propto N_{\text{legs}}^4$



Efficient despite evaluating all Feynman diagrams, due to recursion.
Colour sampling reqd. [Duhr, Hoeche, Maltoni]

Recursion methods (ctd.)

MHV rules: express helicity configuration amplitudes in a simple form. On-shell ⇒ gauge cancellation ⇒ many fewer terms.

Event gen times (s) at leading colour (planar first term in $1/N_c$):

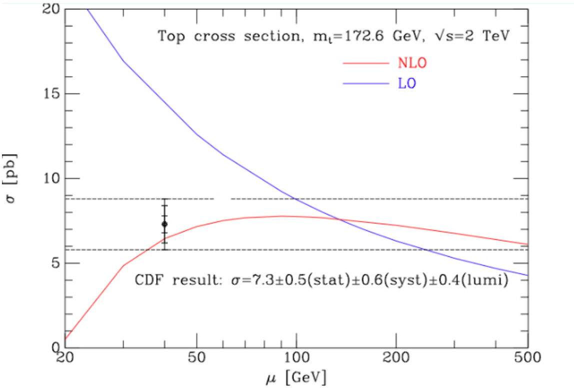
	n							
	5	6	7	8	9	10	11	12
BG	0.00023	0.0009	0.003	0.011	0.030	0.09	0.27	0.7
Scalar	0.00046	0.0018	0.006	0.019	0.057	0.16	0.40	1
MHV	0.00040	0.0042	0.033	0.240	1.770	13	81	–
BCFW	0.00007	0.0003	0.001	0.006	0.037	0.19	0.97	5.5

Once colour dressing included, BG wins anyway. [Duhr, Hoeche, Maltoni]. Implementation in COMIX

NLO matrix elements

A lot of recent activity on semi-automated NLO calculations, largely driven by resurgence of interest in generalised unitarity.

Reduces unphysical fixed-order dependence on renormalisation scale



NLO matrix elements (ctd.)

Subtraction method for finiteness:

$$\sigma = \sigma^{\mathrm{LO}} + \sigma^{\mathrm{NLO}}$$

$$\sigma^{\mathrm{NLO}} = \int_{m+1} \left[\mathrm{d}\sigma^{\mathrm{R}} - \mathrm{d}\sigma^{\mathrm{A}} \right] + \int_{m+1} \mathrm{d}\sigma^{\mathrm{A}} + \int_{m} \mathrm{d}\sigma^{\mathrm{V}}$$

$\mathrm{d}\sigma^{\mathrm{A(pprox)}}$ has same singularity structure as $\mathrm{d}\sigma^{\mathrm{R}}$, e.g. CS kernels

Dimensionality of spacetime ⇒ all one loop integrals can be reduced to linear sums of scalar "master integrals": boxes, triangles & tadpoles.

Full basis set of basis integrals with vanishing internal masses calculated by Ellis & Zanderighi. **http://qcdloop.fnal.gov** SOLVED!

Generalised unitarity

Any one-loop amplitude can be written as:

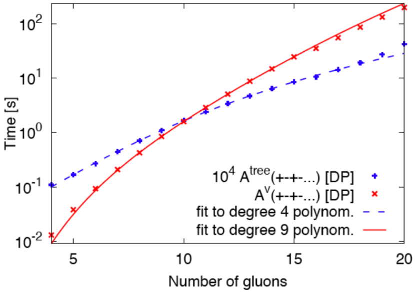
$$A^{\text{1-loop}}(p) = \int \frac{\mathrm{d}^D l}{(2\pi)^D} \frac{N_D(l,p)}{\prod d_i} = \sum c_j I_j$$

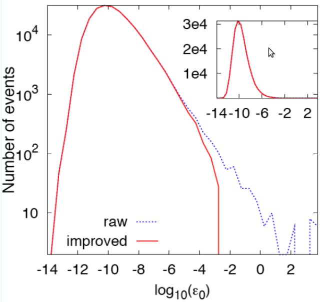
OPP method to get c_j by setting d_i to zero. Equivalent to setting propagators on-shell $\equiv$ unitarity cuts

In D dimensions, also need to compute a left-over "rational part". Linearly extrapolate from two integer dimensions $D > 4$ to get finite result at $D > 4$ [Giele, Kunst, Melnikov]

NLO amplitudes

Pure gluonic:
$t \propto N_{\text{legs}}^{9}$
Giele & Zanderighi, 2008





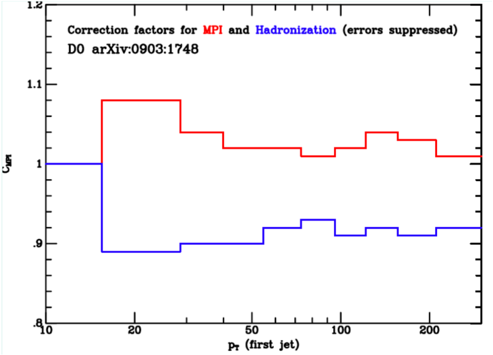
Since extended to fermions and vectors.
Error reduction by heuristic use of quad precision

Processes at NLO

Rocket, CutTools, BlackHat, Golem…

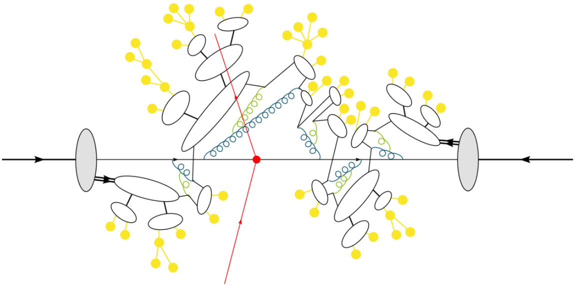
Rocket: N gluons; $qq + N$ gluons; W + 2,4 quarks + gluon(s), etc. Partial full result on W + 3 jets at NLO.

Parton level, but UE/hadronisation systematics cancel to some extent. LHC studies (that I've seen) not keen on parton level MC.



Shower & hadronisation generators

In SHGs, the same two issues — loops and legs — recur. Problem is double counting: naïvely the shower will be doing some of the extra emission that comes from the high-multiplicity/NLO ME.



You have a choice between 1 extra jet at NLO (MC@NLO, POWHEG), or many extra jets at LO (CKKW, MLM, . . . ; implementations in Sherpa, Herwig++, AlpGen)

1-loop matching schemes

Matching schemes will get the full NLO normalisation (i.e. includes virtual contribution) with shape from one extra emission.

MC@NLO [Frixione, Webber] based on same subtraction idea as before for ME. Attempt to also subtract effect of the shower algorithm. Very shower/process specific. Negative weights: efficiency/technical problem.

POWHEG [Nason] designed to avoid negative weights, using a modified Sudakov form factor for 1st emission and a "hardest emission first" ordering. Also not shower-specific — MC@NLO is hard-wired to subtract the Herwig shower. Implementations by Frixione, Nason & Oleari, and in Herwig++.

Merging schemes

Merging schemes aim to include multi-leg tree-level MEs into shower at leading log accuracy. Effectively do so by replacing approximate splitting kernels in shower evolution with ME.

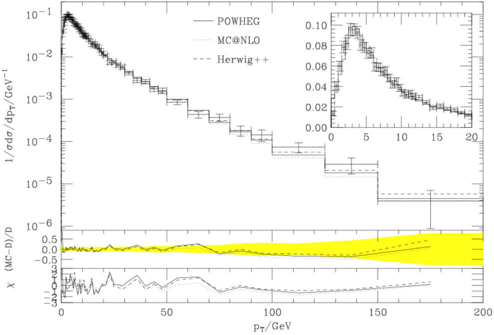
CKKW and MLM are most established. Based on backward clustering to “core process”, and appropriate use of $\mathrm{ME}_{n+1}/\mathrm{ME}_n$ ratios and Sudakov factors.

Also CKKW-L defined using an Ariadne-type dipole shower [Lavesson, Lonnblad].
Recent work on defining general merging algorithm formalism with emphasis on truncated shower & phase space treatment. [Hoeche, Krauss, Schumann, Siegert]
Work towards NLO merging [Lavesson, Lonnblad]

Herwig++
POWHEG

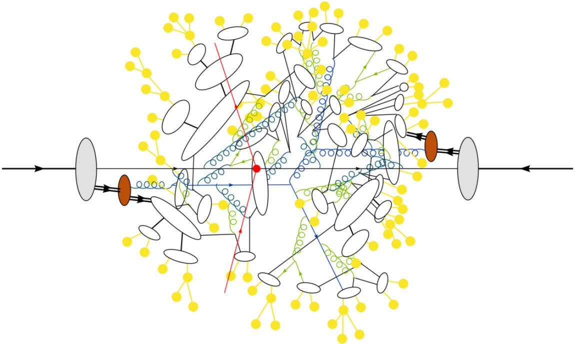
Showered NLO for pp $\rightarrow \{\mathrm{H}, \mathrm{ZH}, \mathrm{WH}, \mathrm{W} \rightarrow f\bar{f}, \gamma/\mathrm{Z} \rightarrow f\bar{f}\}$
Not yet vector pair, heavy quark pair, lepton pair & single top (+ W) cf. MC@NLO

Construction of POWHEG more complex for H++ angular ordered shower than for $p_\perp$-ordered shower.
Use truncated shower, cf. new Sherpa merging, to add in soft, wide-angle emissions.



Herwig++

Underlying event

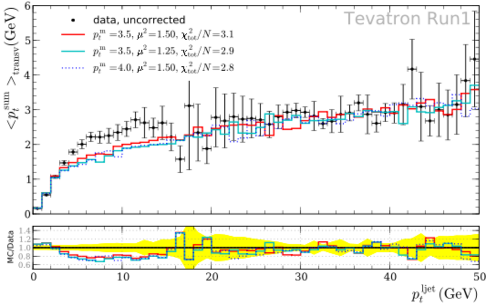


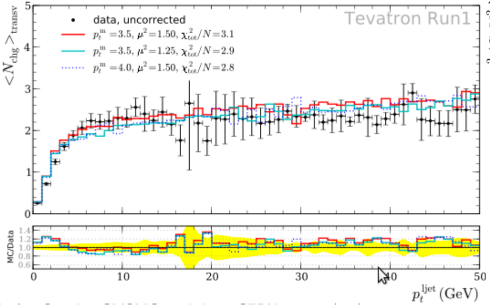
New eikonal MPI model with regularised small $p_\perp$ cross-section, sim to Pythia

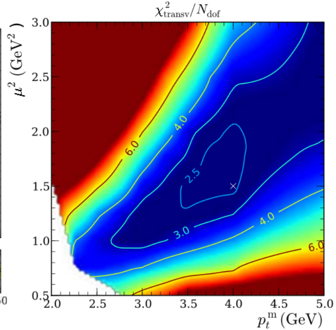
Hot-spot model: different matter distributions for different scales [Bähr, Seymour]

Herwig++

Underlying event







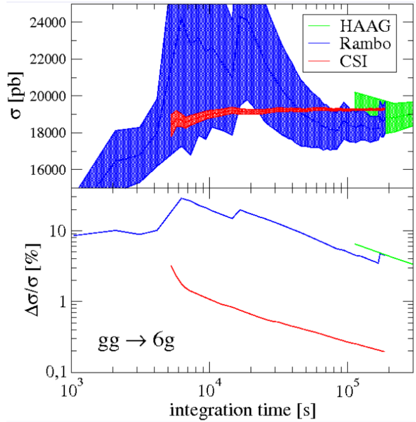
Sherpa

COMIX ME generator

COMIX: BG-based ME integrator. [Gleisberg, Hoeche]

Breaks down 4-vertices to 3-vertices for speed. Colour sampling. Recursive phase space sampling.

Up to 6 jets now painless. No more writing out / compiling / linking libraries



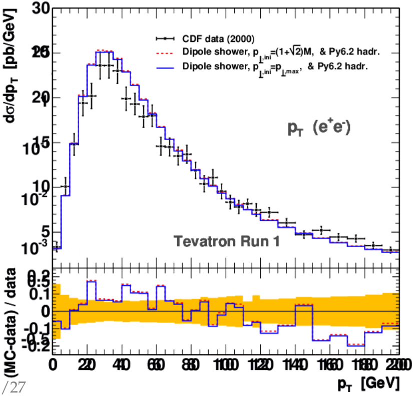
Sherpa

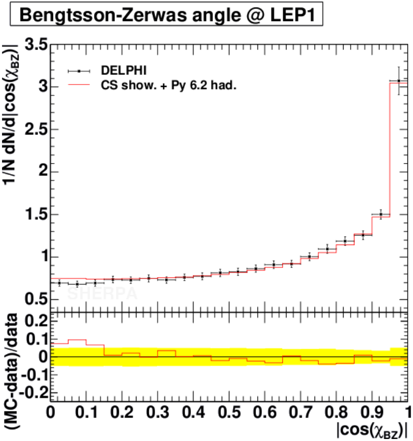
New showers

CSSHOWER: CS kernels, $2 \to 3$ allows on-shell treatment w/o reshuffling. NLO compat.

[Nagy, Soper], [Krauss, Schumann],

[Dinsdale, Ternick, Weinzierl]



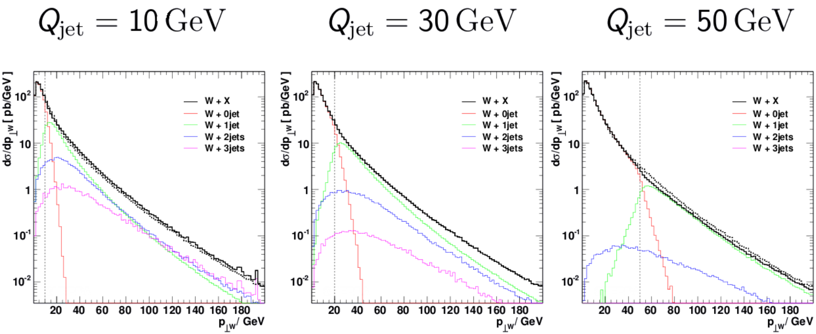


ADICIC++: Ariadne type dipole, including ISR [Krauss, Winter]

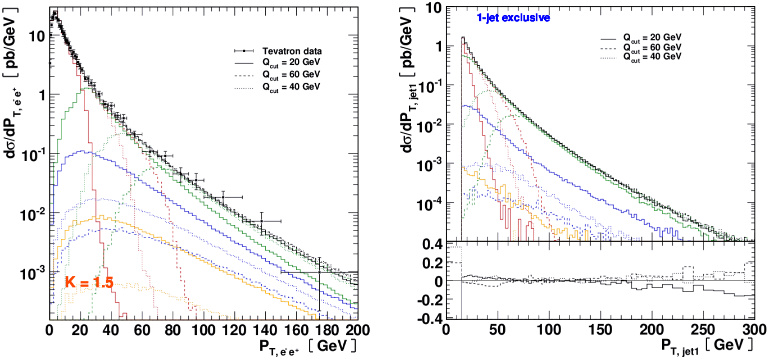
Sherpa

ME/PS merging

CKKW is/was key feature of Sherpa.



Improved treatment [Hoeche, Krauss, Schumann, Siegert]



Merging in decay chains

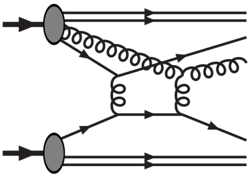
Automated CS subtraction for NLO [Gleisberg, Krauss]

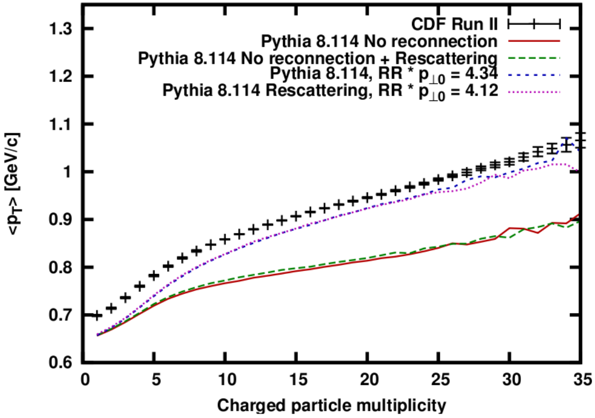
Lots coming in 1.2.0

Also hadron & tau decays, YFS QED, hadronisation, Pythia-like MPI model (Stefan will talk tomorrow about extending this)

Pythia 8

Rescattering: perturbative connections between multiple scatterings. Suppressed, but maybe reduces need for intrinsic $k_\perp$ / colour reconnections?

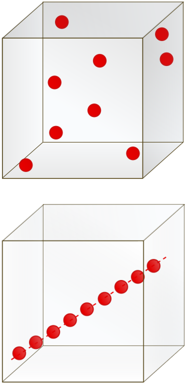


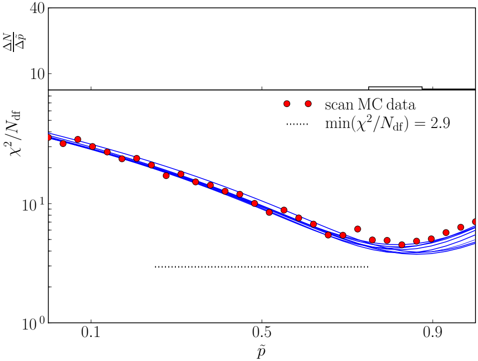


Not really!

Tuning

Rivet: gen indep analysis framework based on HepMC;
Professor: SVD-based parameterisation/optimisation system



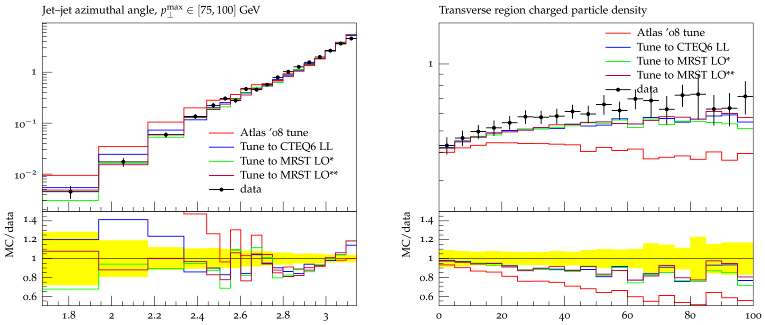


Py6 UE tunes, mLO tunes successful so far.

MCnet C++ gens next, esp. Pythia 8 since totally untuned so far

Example Prof tune plots

e.g. DØ azimuthal angular decorrelation & preliminary CDF 2008 Drell-Yan



From Pythia 6 with $\sim$300 sampled param points for each PDF, in 10 dims.

Summary

Much work in parton level calculations recently; tree level a "solved problem", particularly in the colour-sampled COMIX implementation (in Sherpa)

NLO matrix element calculations also progressing towards semi-automation. MCFM, BlackHat, CutTools, Golem…at parton level. Some amazing breakthroughs.

S&H gens: active development of the "big 3" is all in C++ now. Only reason not to move is inertia, e.g. physics and tune superior in Hw++ w.r.t. FHw. Pythia 8: the usual tune/production chicken/egg…

Summary (ctd.)

New showers & active work on merging in Sherpa. Hw++ with POWHEG is now effectively $\sim$MC@NLO + Photos + Tauola in one package. Truncated showers appearing useful in both merging and matching approaches: unifying idea?

MCnet tuning programme established. Good learning experience and results with Pythia 6, now progressing to other gens. Can be used for updating UE tunes with early data.