Theoretical Tools for Collider Physics

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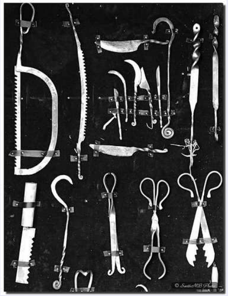
Outline

1. Which tools?
2. Parton level tools
3. Hadron level tools
4. Tuning & validation
5. Conclusions

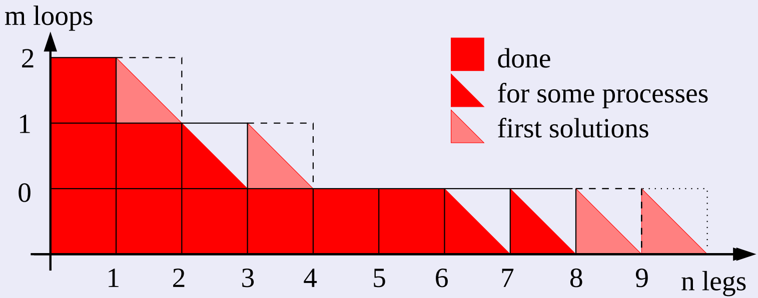
Introduction: The right choice of tools . . .

. . . helps getting the job done!



Parton level tools: Tree level & beyond

Availability of exact calculations



Fully automated solutions: Tree-level

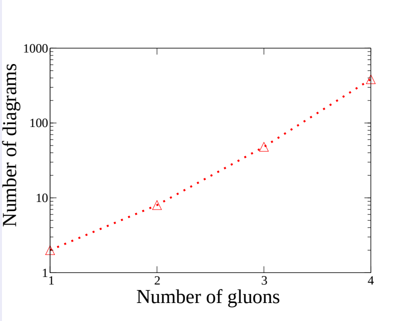
- Multi-particle final states for signals & backgrounds.
- Need to evaluate $\mathrm{d}\sigma_N$:

$$\int\limits_{\mathrm{cuts}} \left[\prod_{i=1}^{N} \frac{\mathrm{d}^3 q_i}{(2\pi)^3 2E_i}\right] \delta^4\left(p_1 + p_2 - \sum_i q_i\right) \left|\mathcal{M}_{p_1 p_2 \to N}\right|^2 .$$

- "Solved" problem $\Longrightarrow$ automated tools available
- Remaining tricky issues:
  - growth of number of amplitudes/colour configurations
  - efficient phase space integration
  - implementing new models

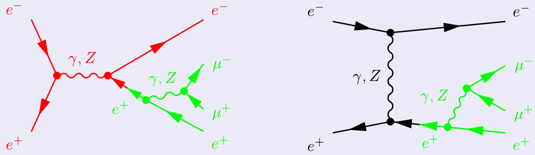
Factorial growth: $e^+e^- \longrightarrow q\bar{q} + ng$

n	$\#_{\text{diags}}$
0	1
1	2
2	8
3	48
4	384



Solution: helicity & recursive methods

- General: Calculate amplitudes as simple (spinor) products, depending on external d.o.f.'s.
- Feynman diagrams: Factorial growth remains. Improvements:
  - Re-using pieces: Calculate only once!
  - Factoring out: Reduce number of multiplications!



- Recursion relations - automatic recycling.
- But: Efficient treatment of colour remains difficult.

Colour-dressing: Fighting factorial growth in colour

- In principle: sampling over colours improves situation.

(But still, e.g. naively $\simeq (n-1)!$ permutations/colour-ordering for n external gluons).

- Improved scheme: colour dressing.

F.Maltoni, K.Paul, T.Stelzer & S.Willenbrock Phys. Rev. **D67** (2003) 014026

- Works very well with Berends-Giele recursions:

C.Duhr, S.Hoche & F.Maltoni, JHEP **0608** (2006) 062

Final State	BG		BCF		CSW	
	CO	CD	CO	CD	CO	CD
$2g$	0.24	0.28	0.28	0.33	0.31	0.26
$3g$	0.45	0.48	0.42	0.51	0.57	0.55
$4g$	1.20	1.04	0.84	1.32	1.63	1.75
$5g$	3.78	2.69	2.59	7.26	5.95	5.96
$6g$	14.2	7.19	11.9	59.1	27.8	30.6
$7g$	58.5	23.7	73.6	646	146	195
$8g$	276	82.1	597	8690	919	1890
$9g$	1450	270	5900	127000	6310	29700
$10g$	7960	864	64000	-	48900	-

Time [s] for the evaluation of 10^4 phase space points, sampled over helicities & colour.

Efficient phase space integration

("Amateurs study strategy, professionals study logistics")

- Democratic, process-blind integration methods:
  - Rambo/Mambo: Flat & isotropic

    R.Kleiss, W.J.Stirling & S.D.Ellis, Comput. Phys. Commun. **40** (1986) 359;
  - HAAG/Sarge: Follows QCD antenna pattern

    A.van Hameren & C.G.Papadopoulos, Eur. Phys. J. C **25** (2002) 563.
- Multi-channeling: Each Feynman diagram related to a phase space mapping (= "channel"), optimise their relative weights.

  R.Kleiss & R.Pittau, Comput. Phys. Commun. **83** (1994) 141.
- Main problem: practical only up to $\mathcal{O}(10\mathrm{k})$ channels.

COMIX- a new matrix element generator for SHERPA

T.Gleisberg & S.Hoeche, JHEP **0812** (2008) 039

- Colour-dressed Berends-Giele amplitudes in the SM.
- Fully recursive phase space generation.
- Example results (cross sections):

$gg \longrightarrow ng$	Cross section [pb]				
n	8	9	10	11	12
$\sqrt{s}$ [GeV]	1500	2000	2500	3500	5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
Alpgen	0.719(19)				

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	470.8(5)	8.83(2)	1.826(8)	0.459(2)	0.1500(8)	0.0544(6)	0.023(2)
ALPGEN	470.6(6)	8.83(1)	1.822(9)	0.459(2)	0.150(2)	0.053(1)	0.0215(8)
AMEGIC++	470.3(4)	8.84(2)	1.817(6)				

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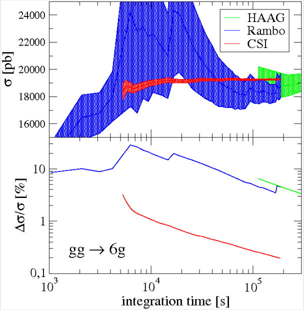
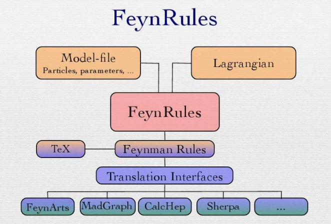


FeynRules: Implementing new models made easy

Aim

- Portable, transparent & reproducible implementation of (nearly arbitrary) new physics models.
- In most codes: New models given by new particles, their properties & interactions.
- Output to standard ME generators enabled (MadGraph, Sherpa, . . .)



- Various models already implemented & validated for a list: http://feynrules.phys.ucl.ac.be

Survey of existing parton-level tools

Comparison of tree-level tools

	Models	$2 \longrightarrow n$	Ampl.	Integ.	public?	lang.
ALPGEN	SM	$n = 8$	rec.	Multi	yes	Fortran
AMEGIC++	SM,MSSM,ADD	$n = 6$	hel.	Multi	yes	C++
COMIX	SM	$n = 8$	rec.	Multi	yes	C++
COMPHEP	SM,MSSM	$n = 4$	trace	1Channel	yes	C
HELAC	SM	$n = 8$	rec.	Multi	yes	Fortran
MADEVENT	SM,MSSM,UED	$n = 6$	hel.	Multi	yes	Fortran
WHIZARD	SM,MSSM,LH	$n = 8$	rec.	Multi	yes	O'Caml

Parton level tools: Loop level

Specific solutions

- Currently only process-specific codes/calculations, e.g.:
  - NLOJET++ (jets only),
  - MCFM (the interesting rest)

  Common to both: Reach so far to $2 \to 3$ processes.
- Bottleneck so far: virtual contributions
  $\Longrightarrow$ a general solution is in sight (see G.Zanderighi's talk)
- Major nuisance: real contributions & subtraction
  $\Longrightarrow$ has been "solved", i.e. automated.

Automated real subtraction algorithms

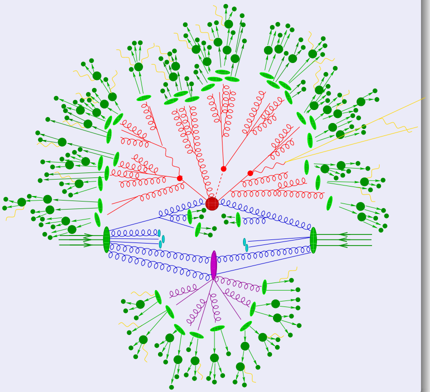
- In principle: simple ("only" tree-level) & general (process-independent subtraction schemes).
- A problem that begs for automation.
- Status by now:
  - Various implementations documented in different stages, all building on Catani-Seymour subtraction.
  - Only one fully public version (MADDIPOLE), but lacks integrated dipoles.
  - Advert: The SHERPA implementation will go public in next weeks, proved to be useful in $W+3$ jets (from BLACKHAT + SHERPA, see G.Zanderighi's talk)

Hadron level tools

Full event generators

- Signal/background:
  Fixed-order perturbation theory
- QCD-Bremsstrahlung:
  Leading log resummation
- Multiple interactions:
  Modelling beyond factorisation
- Hadronisation:
  Modelling with plausibility guidance
- Hadron decays:
  Encoding the PDG

Sketch of an event



“New” event generators

- Why not keep the old ones?
  - Increased needs (precision, new physics, etc.):
    $\longrightarrow$ getting rid of old errors (having new ones)
    $\longrightarrow$ incorporate new, better methods!
  - Enhanced flexibility, modularity, capability:
    $\longrightarrow$ improved maintenance
  - Object-orientation, the new paradigm
    $\longrightarrow$ “industrial” relevance of education
- New tools on the market:
  PYTHIA 8 (PYTHIA 7 died), HERWIG++, SHERPA

Status of new event generators

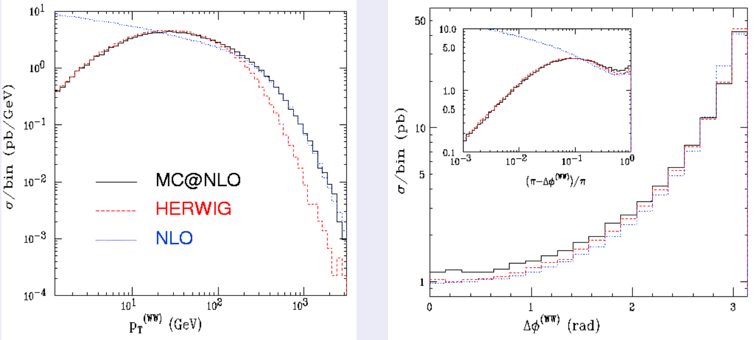
- PYTHIA 8: (arXiv:0809.0303)
  - Interleaved $p_\perp$-ordered MI+ISR+FSR evolution;
  - Improved UE model (more processes);
  - Two hard interactions in the same event.
- HERWIG++: (arXiv:0812.0529)
  - New (angular-ordered) shower (improved mass treatment);
  - POWHEG-methods (see later) being implemented;
  - MPI model for UE;
  - Spin correlations & width treatment in all decays.
- SHERPA: (arXiv:0811.4622)
  - Matching with MEs (see later) fully integrated;
  - Now fully independent of Fortran-PYTHIA;
  - Moving towards new $p_\perp$-ordered showers based on CS dipole;
  - Embedding a new matrix element generator (AMEGIC++ $\longrightarrow$ COMIX).

Embedding higher orders: MC@NLO

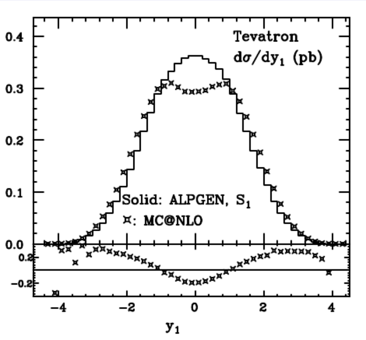
S.Frixione, B.R.Webber, JHEP **0206** (2002) 029
S.Frixione, P.Nason, B.R.Webber, JHEP **0308** (2003) 007

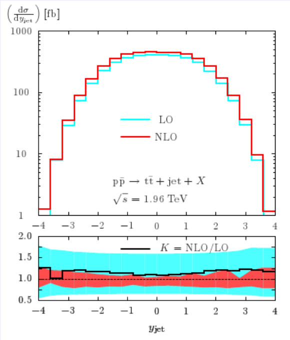
- Want:
  - NLO-Normalisation & first (hard) emission correct,
  - Soft emissions correctly resummed in PS.
- Method:
  - Modify subtraction terms for real infrared divergences,
  - use first order parton shower-expression,
  - this is process-dependent!
- In practise much more complicated.
- Implemented for DY, W-pairs, $gg \longrightarrow H$, Q-pairs.

MC@NLO example results: W-pairs @ Tevatron



A problem: $t\bar{t}$ at Tevatron





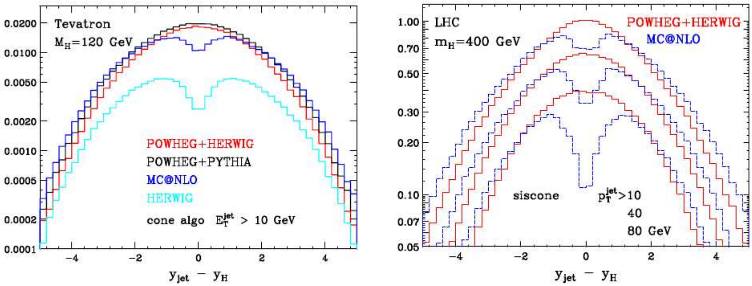
An alternative formulation: POWHEG

S.Frixione, P.Nason, C.Oleari, JHEP **0711** (2007) 070

- Occurrence of negative weights in MC@NLO.
- Improved matching scheme avoiding negative weights:
  - Generate process with LO kinematics & NLO weight
  - Generate hardest emission according to real-emission ME:
    $\sim \exp\left[-\int \mathrm{d}\Phi_1 \sigma_{n+1}(\Phi_{n+1})/\sigma_n(\Phi_n)\right]$
  - Effect: Replacing the approximation (splitting function) with exact result
- Reproduces rate & first emission at NLO accuracy.
- Shower-independent: The method of choice.

POWHEG vs. MC@NLO (stolen from C.Oleari)

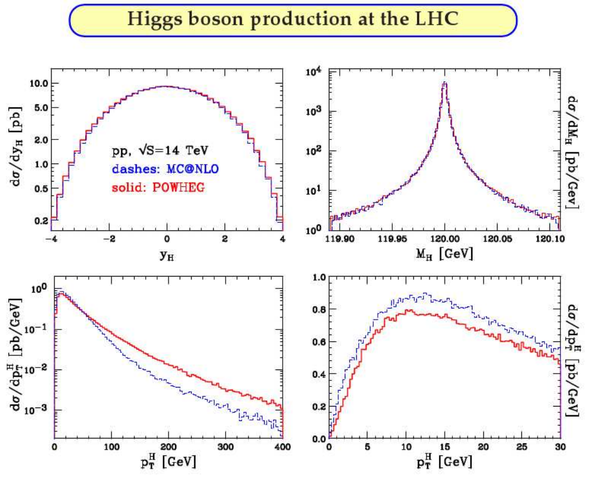
Higgs boson rapidity distribution at Tevatron and LHC



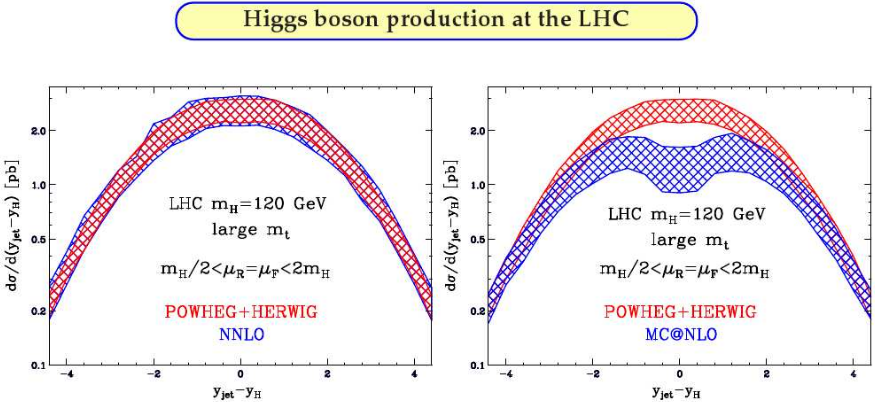
Dip inherited from the even-deeper dip of HERWIG. MC@NLO fills partially the dip.

The dip in the MC@NLO result is compatible with an effect beyond NLO.

POWHEG vs. MC@NLO (stolen from C.Oleari)



POWHEG vs. MC@NLO (stolen from C.Oleari)



NNLO result obtained with HNNLO by Catani & Grazzini

Combining MEs & PS: LO-Merging

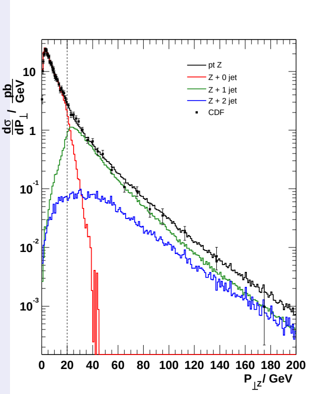
S.Catani, F.K., R.Kuhn & B.R.Webber, JHEP **0111** (2001) 063
F.K., JHEP **0208** (2002) 015

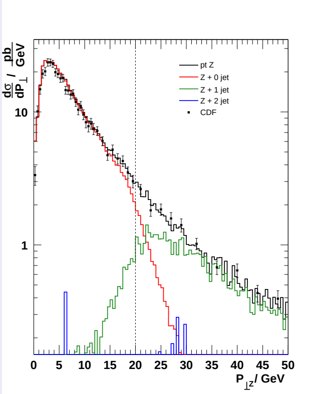
- Want:
  - All jet emissions correct at tree level + LL,
  - Soft emissions correctly resummed in PS
- Method:
  - Separate Jet-production/evolution by $Q_{\rm jet}$ ($k_\perp$ algorithm).
  - Produce jets according to LO matrix elements
  - re-weight with Sudakov form factor + running α_s weights,
  - veto jet production in parton shower.
- Process-independent implementation.

Comparison with data from Tevatron

$p_\perp$ of Z-bosons

CDF, Phys. Rev. Lett. **84** (2000) 845





Improving the algorithm

Using the shower

- Two problems in the description so far:
  - Typically jet variable & ordering variable in parton shower not identical $\longrightarrow$ mismatches.
  - Sudakov form factors in parton shower & rejection weight not identical - equivalent at (N)LL only.
- Solutions:
  - Cluster matrix element configurations with shower kinematics. Possible only, if shower partons always, at each step on-shell.
  - Use parton shower to generate rejection weight: start at relevant scales & veto event if a jet was generated.

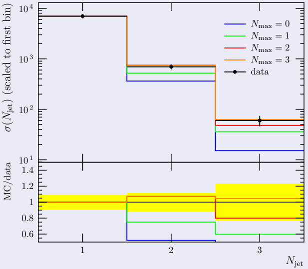
COMIX +CS shower in SHERPA

Results for $Z+$ jets at Tevatron

S.Hoeche, F.K., S.Schumann & F.Siegert, arXiv::0903.1219

- Again stable total cross sections (vs. $Q_{\rm cut}$ & $N_{\rm max}$)

$Q_{\rm cut}$	$N_{\rm max}$						
	0	1	2	3	4	5	6
20 GeV	192.6(1)	191.0(3)	190.5(4)	189.0(5)	189.4(7)	188.2(8)	189.9(10)
30 GeV		192.3(2)	192.7(2)	192.6(3)	192.9(3)	192.7(3)	193.2(3)
45 GeV		193.6(1)	194.4(1)	194.3(1)	194.4(1)	194.6(2)	194.4(1)



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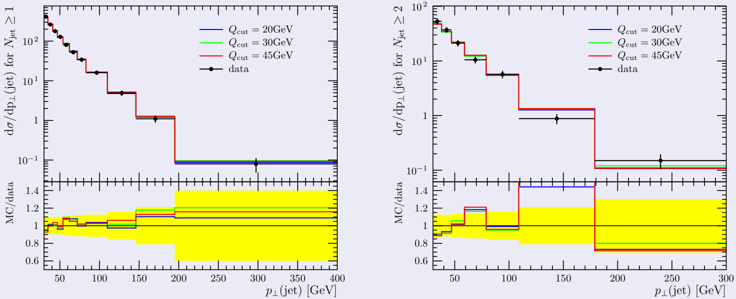
Jet-$p_\perp$ for first jet in $N \geq 1$, 2 jets.



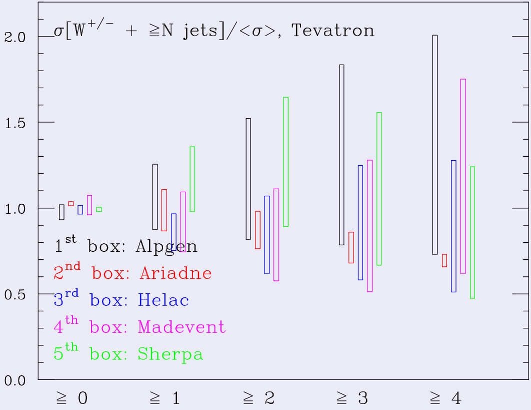
Other prescriptions

- CKKW-L — L.Lönnblad, JHEP **0205** (2002) 046
  - Start with ME, jets defined with $k_\perp$ algorithm,
  - Cluster backwards with shower-specific $k_\perp$,
  - Use "PS-history" to fix starting conditions for shower,
  - Use first trial emission to reject/accept event
  - Run shower below jet scale.
- MLM — M.Mangano *et al.*, Nucl. Phys. **B632** (2002) 343
  - Start with ME, jets defined with cones,
  - Feed configuration into shower, through LHA interface,
  - Match cone jets before hadronisation with partons, reject event in case of mismatch.
- Theory: CKKW & CKKW-L equivalent, MLM not.

Comparison with other merging algorithms

J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

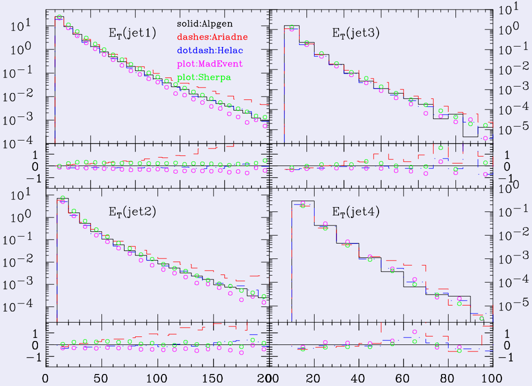
Jet rates in inclusive W+jets at Tevatron



Comparison with other merging algorithms

J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

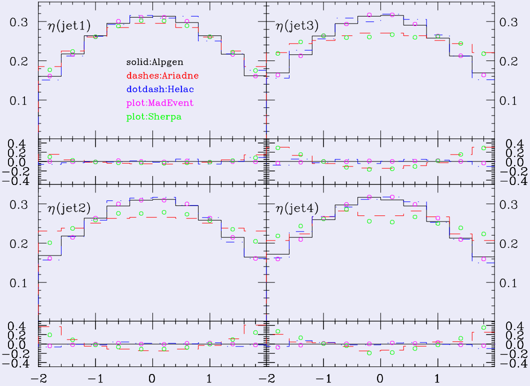
$p_\perp$ of jets in inclusive W+jets at Tevatron



Comparison with other merging algorithms

J.Alwall *et al.* Eur. Phys. J. **C53** (2008) 473

η of jets in inclusive W+jets at Tevatron



Tuning & validation of event generators

The tools: PROFESSOR & RIVET

(Transparencies stolen from H.Hoeth)

Professor and Rivet

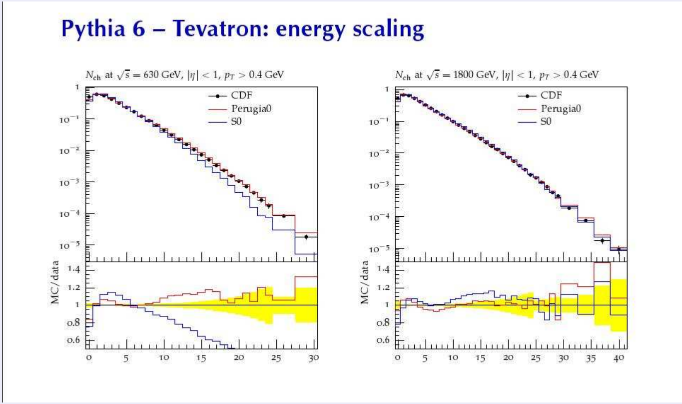
Tools for MC tuning have been developed and tested as part of the MCnet programme.

Rivet/(Rivetgun): A general tool to steer different MC generators in a common way and to run analyses on generator level. Lots of published analyses are implemented, direct data/MC comparison is very easy. (http://projects.hepforge.org/rivet/)

Professor: Implementation of the tuning procedure. Uses Rivet to fill histograms. (http://projects.hepforge.org/professor/)

Example: Underlying event for PYTHIA 6

(Transparencies stolen from H.Hoeth)



Perugia = PROFESSOR-tune, S0 = standard tune

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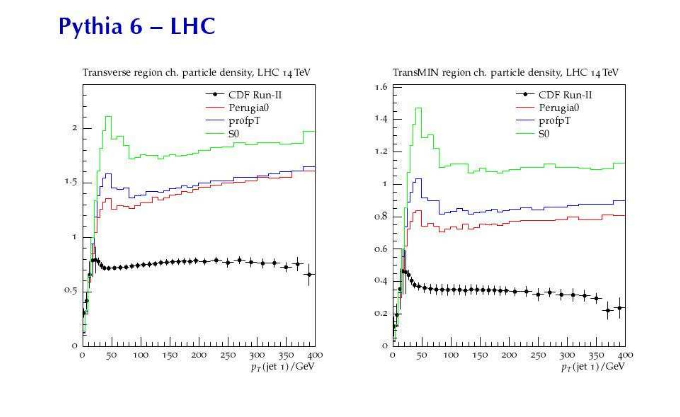
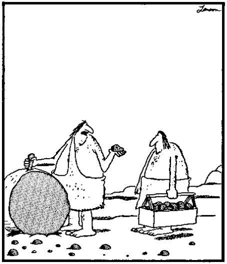


Perugia = PROFESSOR-tune, S0 = standard tune

Conclusion

- Astonishing change of paradigm in MC generators: Pushing towards precision (matching & merging)
- Development of tools ongoing:
  - Improved automated parton level tools (NLO seems in reach);
  - Better parton showers (merging/matching simplified);
  - Systematic inclusion of higher orders into shower Monte Carlo algorithms (by now a matured technology).



- Extremely powerful if used wisely & in combination!
- Validation & training needed.
- MCnet: European network for Monte Carlos offers short-term studentships for training/development.