

Theoretical Tools for Collider Physics

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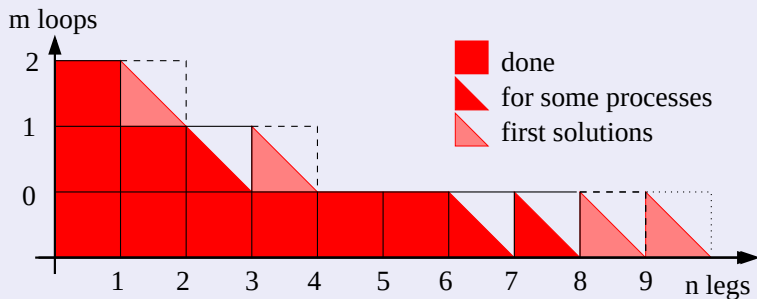
Pheno 2009, 13.5.2009

Outline

- 1 Parton level tools
- 2 Hadron level tools
- 3 Tuning & validation
- 4 Conclusions

Parton level tools: Tree level & beyond

Availability of exact calculations



Fully automated solutions: Tree-level

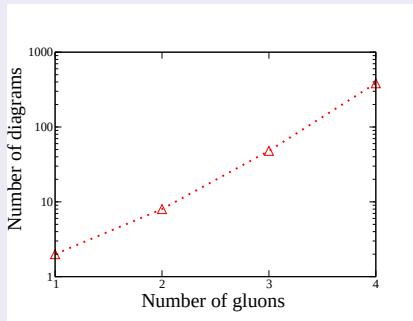
- Multi-particle final states for signals & backgrounds.
- Need to evaluate $d\sigma_N$:

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

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

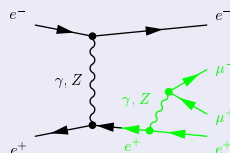
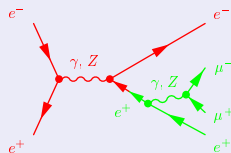
Factorial growth: $e^+e^- \rightarrow q\bar{q} + ng$

n	#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 $\mathcal{O}(10k)$ 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):

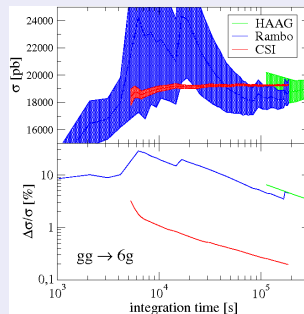
$gg \rightarrow ng$	Cross section [pb]				
n	8	9	10	11	12
$\sqrt{s}$ [GeV]	1500	2000	2500	3500	5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
Alpgen	0.719(19)				

σ [μb]	Number of jets						
$b\bar{b} + \text{QCD jets}$	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)				

COMIX- a new matrix element generator for Sherpa

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

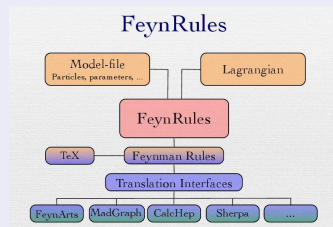
- Colour-dressed Berends-Giele amplitudes in the SM.
- Fully recursive phase space generation.
- Example results (phase space performance):



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	$2 \rightarrow n$	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 $2 \rightarrow 3$ processes.

- Bottleneck so far: virtual contributions
 $\implies$ a general solution is in sight (see G.Zanderighi's talk)
- Major nuisance: real contributions & subtraction
 $\implies$ 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

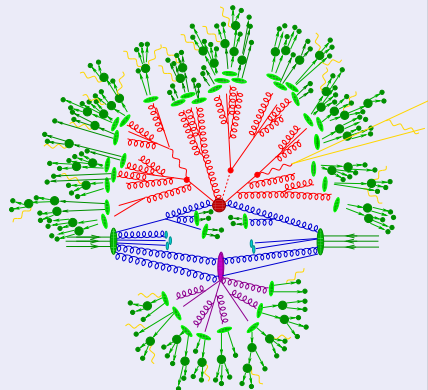
- **Hadronisation:**

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.):
 - getting rid of old errors (having new ones)
 - **incorporate new, better methods!**
 - Enhanced flexibility, modularity, capability:
 - **improved maintenance**
 - Object-orientation, the new paradigm
 - “industrial” relevance of education
- New tools on the market:
Pythia8 (Pythia7 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++ $\rightarrow$ COMIX).

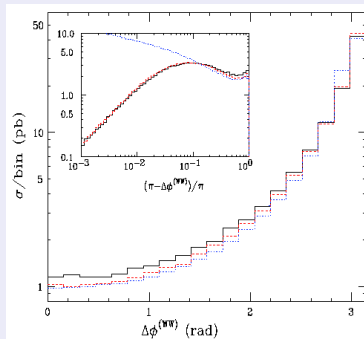
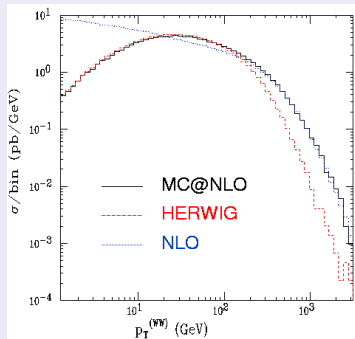
Embedding higher orders: MC@NLO

S.Frixione, B.R.Webber, JHEP **0206** (2002) 029

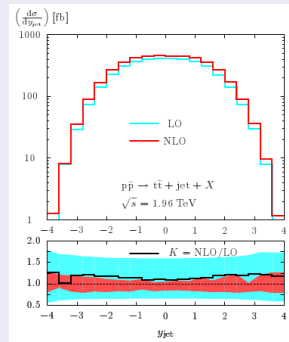
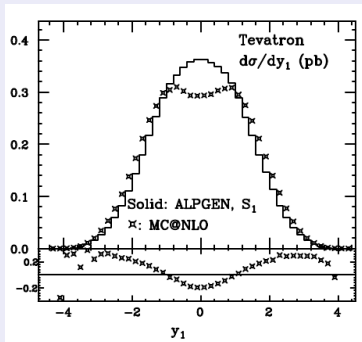
S.Frixione, P.Nason, B.R.Webber, JHEP **0308** (2003) 007

- 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, $gg \rightarrow H$, Q -pairs.

MC@NLO example results: W -pairs @ Tevatron



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



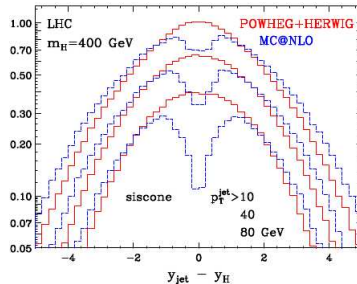
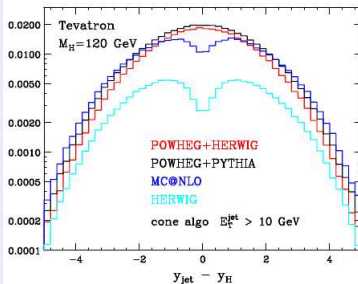
An alternative formulation: PowHEG

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:
 $\sim \exp \left[- \int d\Phi_1 \sigma_{n+1}(\Phi_{n+1}) / \sigma_n(\Phi_n) \right]$
 - 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

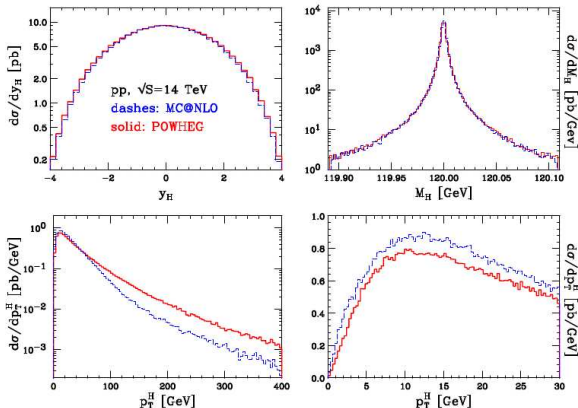


Dip **inherited** from the **even-deeper dip** of **HERWIG**. MC@NLO fills partially the dip.

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

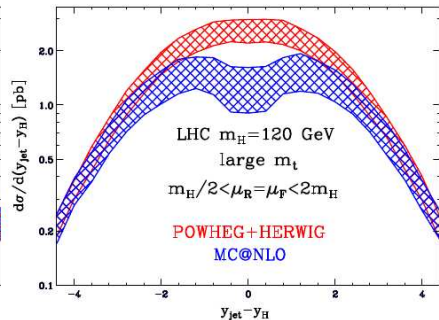
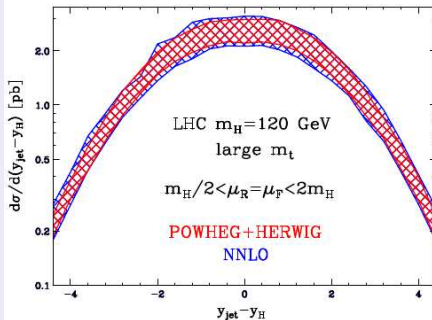
PowHEG vs. MC@NLO (stolen from C.Oleari)

Higgs boson production at the LHC



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

Higgs boson production at the LHC



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

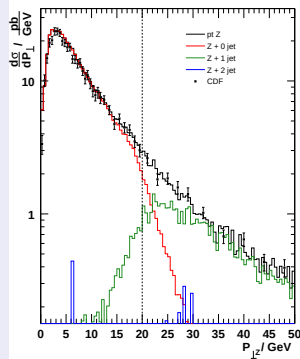
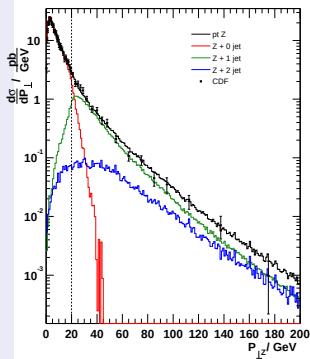
F.K., JHEP **0208** (2002) 015

- Want:
 - All jet emissions correct at tree level + LL,
 - Soft emissions correctly resummed in PS
- Method:
 - Separate Jet-production/evolution by Q_{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 $\rightarrow$ 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.

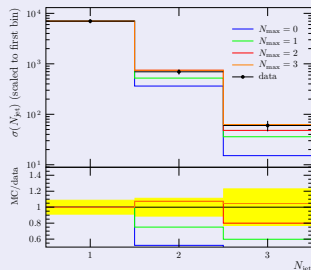
COMIX +CS shower in SHERPA

Results for $Z + \text{jets}$ at Tevatron

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

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

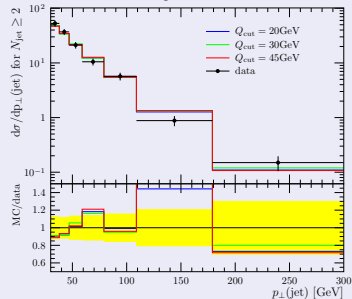
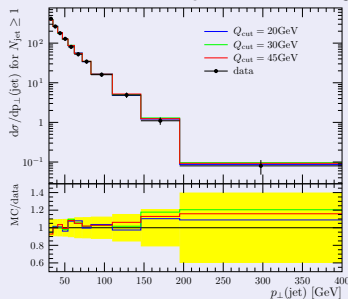
Q_{cut}	N_{max}						
	0	1	2	3	4	5	6
20 GeV	192.6(1)	191.0(3)	190.5(4)	189.0(5)	189.4(7)	188.2(8)	189.9(10)
30 GeV		192.3(2)	192.7(2)	192.6(3)	192.9(3)	192.7(3)	193.2(3)
45 GeV		193.6(1)	194.4(1)	194.3(1)	194.4(1)	194.6(2)	194.4(1)



Results for $Z + \text{jets}$ at Tevatron

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

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

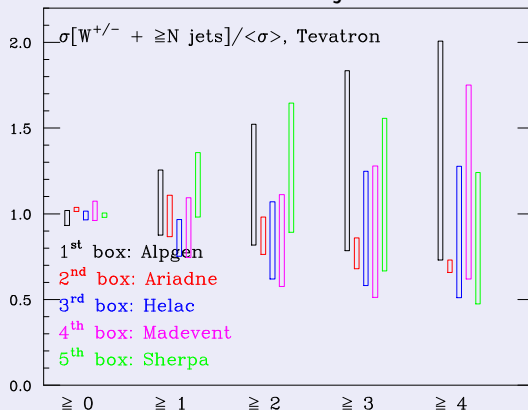
- Start with ME, jets defined with cones,
- Feed configuration into shower, through LHA interface,
- Match cone jets before hadronisation with partons, reject event in case of mismatch.

• Theory: CKKW & CKKW-L equivalent, MLM not.

Comparison with other merging algorithms

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

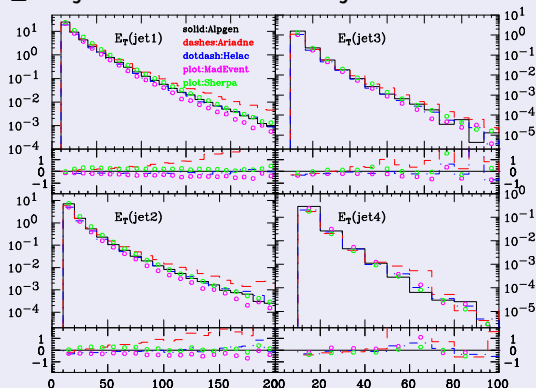
Jet rates in inclusive W +jets at Tevatron



Comparison with other merging algorithms

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

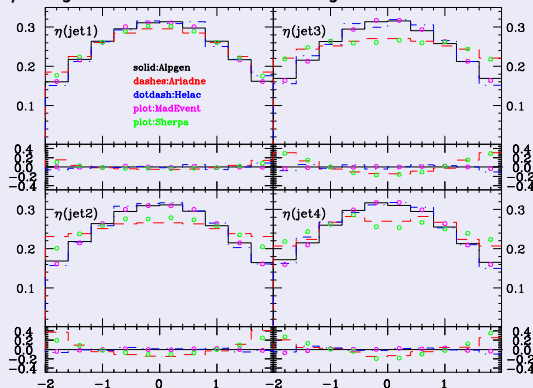
$p_{\perp}$ of jets in inclusive W +jets at Tevatron



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/>)

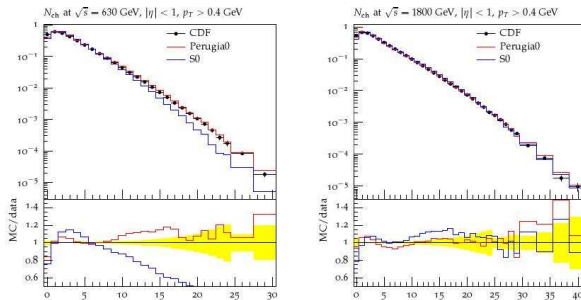
Professor: Implementation of the tuning procedure. Uses Rivet to fill histograms. (<http://projects.hepforge.org/professor/>)



Example: Underlying event for PYTHIA 6

(Transparencies stolen from H.Hoeth)

Pythia 6 – Tevatron: energy scaling

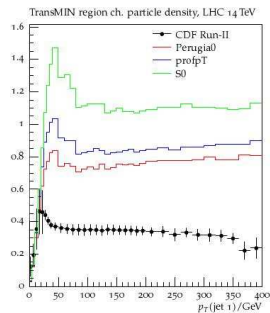
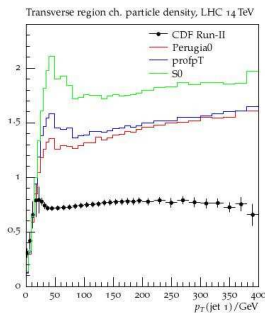


Perugia = PROFESSOR-tune, S0 = standard tune

Example: Underlying event for PYTHIA 6

(Transparencies stolen from H.Hoeth)

Pythia 6 – LHC



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.

