New development in Monte Carlos for the LHC

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Outline

1. The next generation event generators
2. The new OO tools
3. Signals & backgrounds at the parton level
4. From parton level to exclusive studies at hadron level
5. Forthcoming attractions in Sherpa
6. Modelling hadron/tau decays
7. Conclusions

Why simulate events?

- Many interesting signals at the LHC:
  Higgs (or alternative EWSB), SUSY, ED's, ...
- But: Severe backgrounds in nearly all channels,
  (almost always with large influence of QCD)
  $\Longrightarrow$ depend on detailed understanding of QCD.
- Typically: Take backgrounds from data in some region, but extrapolate to signal region.
- Examples:
  - Central jet-veto in VBF (Higgs)
  - Multi-jet backgrounds for SUSY (e.g. Z+jets)
- Todays signals = tomorrows backgrounds.

Why does anyone write a new event generator?

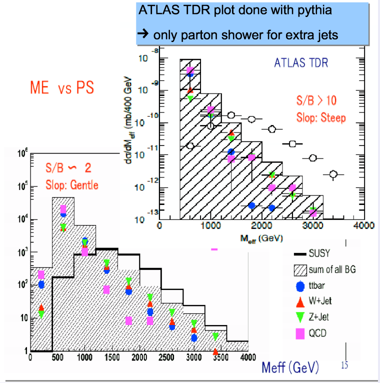
New tools on the market: Pythia8, Herwig++, Sherpa

Reflecting increased needs (precision, new physics, etc.):

- getting rid of old errors (having new ones)
- easier implementation of new physics models
- incorporate new, better methods!
- systematic inclusion of HO QCD

The impact of HO QCD

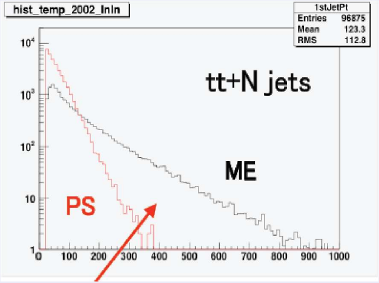
Example: SUSY searches (4 jets + $\not{E}_T$), observable: $M_{\rm eff}$



ATLAS TDR plot done with pythia

→ only parton shower for extra jets

ME vs PS



Simulation's paradigm

Basic strategy

Divide event into stages, separated by different scales.

- Signal/background:

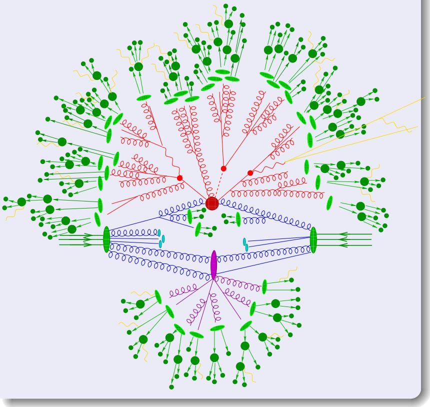
  Exact matrix elements.
- QCD-Bremsstrahlung:

  Parton showers (also in initial state).
- Multiple interactions:

  Beyond factorization: Modeling.
- Hadronization:

  Non-perturbative QCD: Modeling.

Sketch of an event



Introducing SHERPA

T.Gleisberg, S.Höche, F.K., A.Schälicke, S.Schumann and J.C.Winter, JHEP **0402** (2004) 056

- New event generator, written from scratch in `C++`.
- Fully automated matrix element generation,
- Parton shower implementation (similar to PYTHIA), new improved parton shower formulations in preparation,
- Unique feature: Multijet ME+PS merging,
- Cluster hadronization model (still to be tuned to data), also interface to string fragmentation of Pythia,
- Hadron and tau decays,
- spin correlations,
- Underlying event according to old Pythia model, new model based on BFKL evolution to be released.

PYTHIA 8

T.Sjostrand, S.Mrenna, and P.Skands, arXiv:0710.3820 [hep-ph]

- Rewrite of `Pythia 6.4` in `C++`.
- $2 \rightarrow 2$ matrix elements for some processes (limited w.r.t. old Fortran code), plus use of LHA input,
- $k_\perp$-ordered parton shower,
- Lund-string fragmentation,
- Hadron decays and link to external code,
- interleafed underlying event model.

Herwig++

M. Bahr *et al.*, arXiv:0804.3053 [hep-ph]

- Rewrite and improvement of `Herwig 6.5` in `C++`.
- 2 → 2 matrix elements for many processes (especially BSM), through a helicity-amplitude library, plus use of LHA input,
- new angle-ordered parton shower,
- first processes through PowHEG method,
- cluster fragmentation,
- Hadron and τ decays,
- spin correlations,
- improved eikonal underlying event model.

Parton level simulations

Stating the problem(s)

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

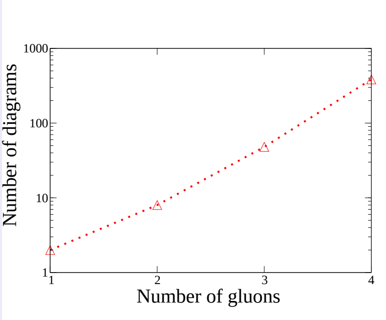
$$\int\limits_{\mathrm{cuts}} \left[\prod_{i=1}^{N} \frac{\mathrm{d}^3 q_i}{(2\pi)^3 2E_i}\right] \delta^4\left(p_1 + p_2 - \sum_i q_i\right) |\mathcal{M}_{p_1 p_2 \to N}|^2 .$$

- Problem 1: Factorial growth of number of amplitudes.
- Problem 2: Complicated phase-space structure.
- Solutions: Numerical methods.

Parton level simulations

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

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

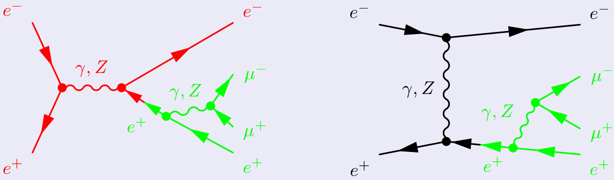


Parton level simulations

Taming the factorial growth in the helicity method

- Reusing pieces: Calculate only once!
- Factoring out: Reduce number of multiplications!

Implemented as a-posteriori manipulations of amplitudes.



Parton level simulations

Recursion methods (off-shell)

Basic idea: Recursively build one-particle off-shell currents (various versions of this: Berends-Giele, Alpha etc.).

"Classical" example: n-gluon amplitudes:

- Start with two on-shell gluons, represented by their polarization vectors, hence the currents associated with them are $J^\nu(k) = \varepsilon^\nu(k)$.
- Then the two-gluon current reads (no colors) $J^\mu(k = k_1 + k_2) = \frac{ig_3}{(k_1+k_2)^2} V^{\mu\nu\rho} J_\nu(k_1) J_\rho(k_2)$.
- From this, larger and larger currents can be built recursively.
- For quarks, the currents are given by spinors, and similar reasoning applies for the construction of the one-particle off-shell currents.
- Treatment of color: Color-ordering the amplitudes $\Longrightarrow \mathcal{C}^{(1,\,\dots,\,n)} = \mathrm{Tr}\,[T^{a_1}\,\dots\,T^{a_n}]$, where T^a are color matrices in fundamental representation.
- Problem: Need to sum over all allowed permutations.

Parton level simulations

Integration methods: Multi-channeling

Basic idea: Translate Feynman diagrams into channels

$\Longrightarrow$ decays, s- and t-channel props as building blocks.

R.Kleiss and R.Pittau, Comput. Phys. Commun. **83** (1994) 141

Integration methods: "Democratic" methods

- Rambo/Mambo: Flat & isotropic

  R.Kleiss, W.J.Stirling and S.D.Ellis, Comput. Phys. Commun. **40** (1986) 359;

- HAAG: Follows QCD antenna pattern

  A.van Hameren and C.G.Papadopoulos, Eur. Phys. J. C **25** (2002) 563.

Automated cross section calculation AMEGIC++

F.K., R.Kuhn, G.Soff, JHEP **0202** (2002) 044.

- Uses helicity/recursion methods;
- Helicity method supplemented with "factoring out" (taming the factorial growth)
- Phase space integration through multi-channeling (i.e. one phasespace mapping/Feynman diagram)
- Implemented & tested models: SM, SM+AGC, THDM, MSSM, ADD.
- Tested in > 1000 SM & > 500 MSSM channels.
- Still under development (towards higher multis, more models, . . .)

Implementing CSW recursion relations: A snaphot

F.Cachazo, P.Svrcek and E.Witten, JHEP **0409** (2004) 006

- Obtained summing over colours and helicities, sampling much better

Jet cross sections @ LHC, $k_\perp^{\mathrm{min}} = 20\mathrm{GeV}$

Process	helicity	MHV where possible	MHV only ($\leq$ 2 quark lines)
$jj \to jj$	745.85 μb$\pm$0.10% 57 s	745.85 μb$\pm$0.10% 44 s	
$jj \to jjj$	81.274 μb$\pm$0.20% 826 s	81.274 μb$\pm$0.20% 166 s	
$gg \to gggg$	10.112 μb$\pm$0.23% 1.5 ks	10.145 μb$\pm$0.23% 0.6 ks	
$jj \to jjjj$	23.23 μb$\pm$0.27% 35 ks	23.245 μb$\pm$0.26% 7.6 ks	23.208 μb$\pm$0.26% 5.8 ks
$gg \to ggggg$	2.6592 μb$\pm$0.16% 131 ks	2.6915 μb$\pm$0.15% 41 ks	
$jj \to jjjjj$	not possible	7.3829 μb$\pm$0.25% 970 ks	7.3294 μb$\pm$0.17% 295 ks

COMIX - a new matrix element generator for Sherpa

T.Gleisberg & S.Hoeche, in preparation

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

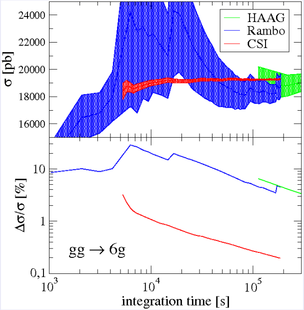
$gg \longrightarrow ng$	Cross section [pb]				
n $\sqrt{s}$ [GeV]	8 1500	9 2000	10 2500	11 3500	12 5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
Alpgen	0.719(19)				

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	4.780(5)	8.83(2)	1.826(8)	0.459(2)	0.1500(8)	0.0544(6)	0.023(2)
ALPGEN	4.760(6)	8.83(1)	1.822(9)	0.459(2)	0.150(2)	0.053(1)	0.0215(8)
AMEGIC++	4.730(4)	8.84(2)	1.817(6)				

COMIX - a new matrix element generator for Sherpa

T.Gleisberg & S.Hoeche, in preparation

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



Survey of public parton-level tools

Comparison of tree-level tools

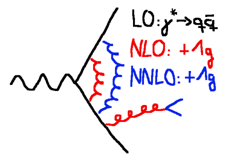
- Tools:

	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++
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
O'Mega	SM,MSSM,LH	$n = 8$	rec.	Multi	yes	O'Caml

- Typically fed into shower MC's through LHA, method then MLM.

Nomenclature

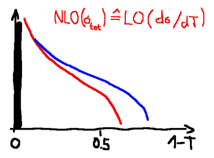
Specifying higher-order corrections: $\gamma^* \rightarrow$ hadrons



- In general: N^{n}LO $\leftrightarrow$ $\mathcal{O}(\alpha_s^n)$
- But: only for inclusive quantities

(e.g.: total xsecs like γ^* $\rightarrow$hadrons).

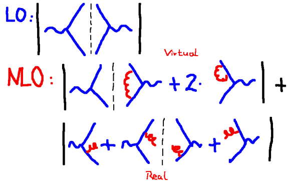
Counter-example: thrust distribution



- In general, distributions are HO.
- Distinguish real & virtual emissions: Real emissions $\longrightarrow$ mainly distributions, virtual emissions $\longrightarrow$ mainly normalization.

Nomenclature

Anatomy of HO calculations: Virtual and real corrections



NLO corrections: $\mathcal{O}(\alpha_s)$

Virtual corrections = extra loops

Real corrections = extra legs

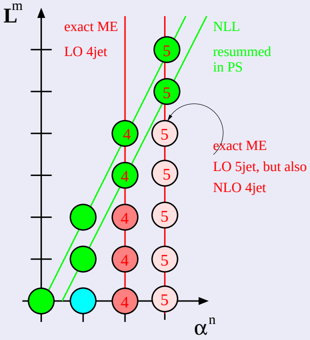
- UV-divergences in virtual graphs → renormalization
- But also: IR-divergences in real & virtual contributions
  Must cancel each other, non-trivial to see:
  N vs. $N+1$ particle FS, divergence in PS vs. loop

Orders in ME and PS

ME vs. PS

- Matrix elements good for: hard, large-angle emissions; take care of interferences.
- Parton shower good for: soft, collinear emissions; resums large logarithms.
- Want to combine both! Avoid double-counting.

α_s vs. Log

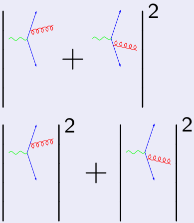


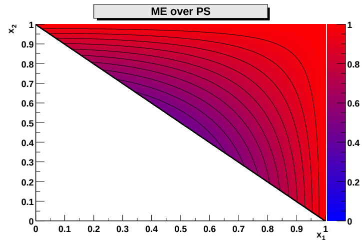
Correcting the parton shower

Example: $e^+e^- \longrightarrow q\bar{q}g$

ME :

PS :





Correcting the parton shower

Practicalities of ME-corrections

- Obviously, $ME < PS$ is not always fulfilled.
- Could enhance PS expression by a (large) factor.
  Question: Efficiency of the approach?
- Therefore: realized in few processes only:
  Best-known: $ee \longrightarrow q\bar{q}$, $q\bar{q} \longrightarrow V$, $t \longrightarrow bW$

Correcting the parton shower

Power shower

Can use ME corrections for "power shower":

This is the evil empire of MC event generators!

- In $q\bar{q} \to V$, start parton shower @ $s_{\rm pp}$.
- Re-weight first emissions on both legs with ME.
- Effect: More hard radiation through showering.

MC@NLO

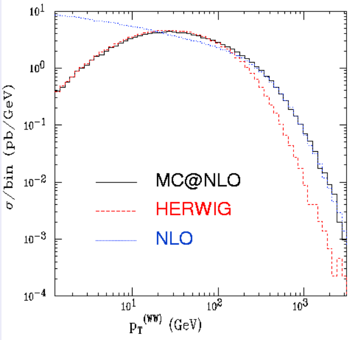
S.Frixione, B.R.Webber, JHEP **0206** (2002) 029
S.Frixione, P.Nason, B.R.Webber, JHEP **0308** (2003) 007

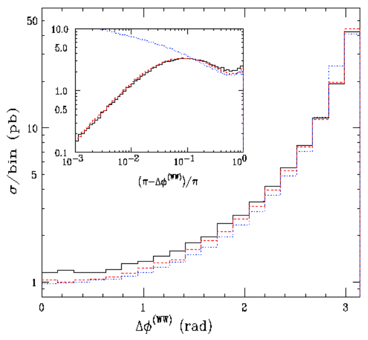
Basic principles

- Want:
    - NLO-Normalization and 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





Combining MEs & PS: LO-Merging

S.Catani, F.K., R.Kuhn and 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.

Combining MEs & PS

n-jet rates @ NLL

S.Catani *et al.* Phys. Lett. **B269** (1991) 432

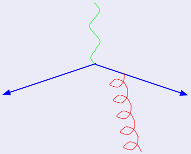
At NLL-Accuracy

$$\mathcal{R}_2(Q_{\rm jet}) = \left[\Delta_q(E_{\rm c.m.},\,Q_{\rm jet})\right]^2$$

$$\begin{aligned}\mathcal{R}_3(Q_{\rm jet}) &= 2\Delta_q(E_{\rm c.m.},\,Q_{\rm jet})\\ &\cdot \int {\rm d}q\left[\alpha_s(q)\Gamma_q(E_{\rm c.m.},\,q)\,\frac{\Delta_q(E_{\rm c.m.},\,Q_{\rm jet})}{\Delta_q(q,\,Q_{\rm jet})}\right.\\ &\left.\Delta_q(q,\,Q_{\rm jet})\Delta_g(q,\,Q_{\rm jet})\right]\end{aligned}$$

Sudakov weights

Example: $\gamma^* \to q\bar{q}g$



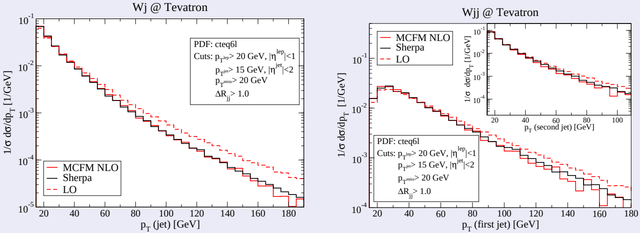
$$\mathcal{W}_{\rm Sud} = \frac{\alpha_s(q)}{\alpha_s(Q_{\rm jet})}\cdot\Delta_q(E_{\rm c.m.},\,Q_{\rm jet})\,\frac{\Delta_q(E_{\rm c.m.},\,Q_{\rm jet})}{\Delta_q(q,\,Q_{\rm jet})}\Delta_q(q,\,Q_{\rm jet})\Delta_g(q,\,Q_{\rm jet})$$

Combining MEs & PS

Algorithm as scale-setting prescription

- Example: $p_\perp$ distribution of jets @ Tevatron
- Consider exclusive $W+1$- and $W+2$-jet production

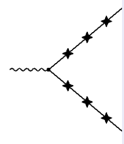
Comparison with MCFM; J.Campbell and R.K.Ellis, Phys. Rev. D **65** (2002) 113007
in : F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009



Sherpa = tree-level matrix elements with α_s scales and Sudakov form factors.

Combining MEs & PS

Vetoing the shower



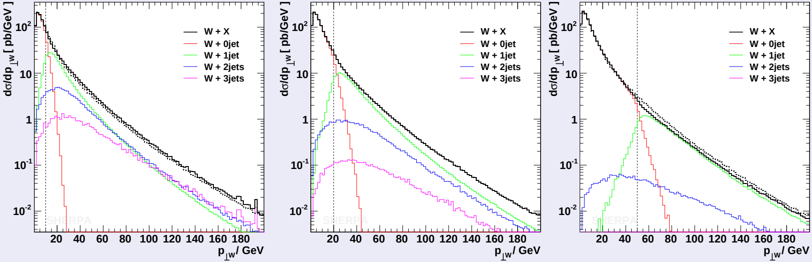
$$\begin{aligned}\mathcal{W}_{\rm Veto} &= \left\{1 + \int_{Q_{\rm jet}}^{E_{\rm c.m.}} dq\,\Gamma_q(E_{\rm c.m.}, q) + \int_{Q_{\rm jet}}^{E_{\rm c.m.}} dq\,\Gamma_q(E_{\rm c.m.}, q) \int_{Q_{\rm jet}}^{q} dq'\,\Gamma_q(E_{\rm c.m.} q') + \cdots\right\}^2 \\ &= \left\{\exp\left(\int_{Q_{\rm jet}}^{E_{\rm c.m.}} dq\,\Gamma_q(E_{\rm c.m.}, q)\right)\right\}^2 = \Delta_q^{-2}(E_{\rm c.m.}, Q_{\rm jet})\end{aligned}$$

$\Longrightarrow$ Cancels dependence on $Q_{\rm jet}$.

Combining MEs & PS: Independence on Q_{jet}

F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009

Example: $p_\perp$ of W in $p\bar{p} \to W + X$ @ Tevatron

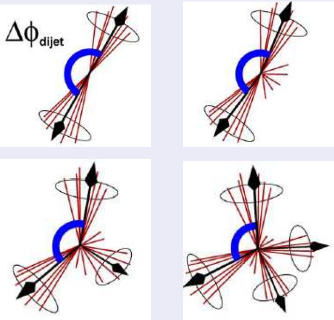


$Q_{\mathrm{jet}} = 10\,\mathrm{GeV}$ $Q_{\mathrm{jet}} = 30\,\mathrm{GeV}$ $Q_{\mathrm{jet}} = 50\,\mathrm{GeV}$

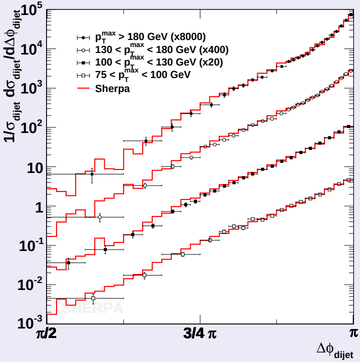
Data: Azimuthal decorrelations of jets at the Tevatron

Idea

- Check QCD radiation pattern

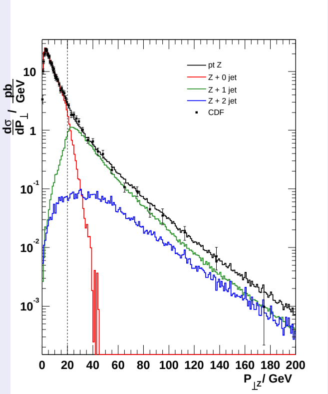


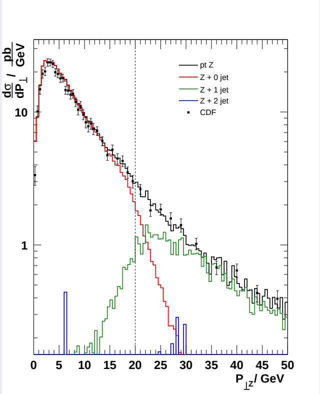
$\Delta\Phi_{12}$ @ Run II (D0)



Comparison with data from Tevatron

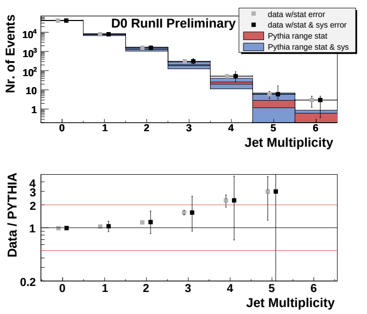
$p_\perp$ of Z-bosons

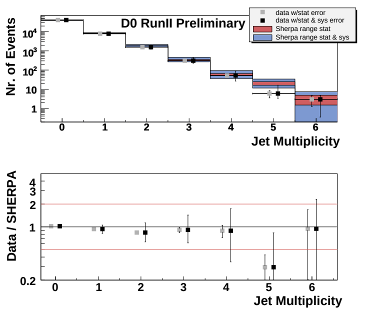




Comparison with RunII $Z + X$ data: Jet multis

(D0-Note 5066)



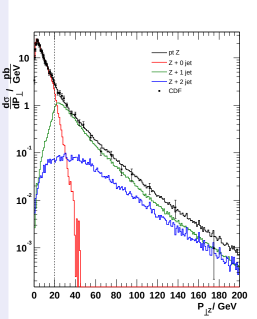


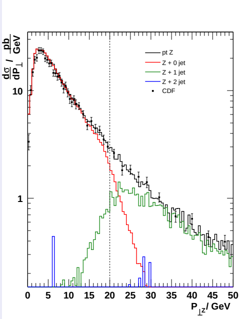
Combining MEs & PS

Comparison with data from Tevatron

$p_\perp$ of Z-bosons in $p\bar{p} \longrightarrow Z + X$

Data from CDF, Phys. Rev. Lett. 84 (2000) 845

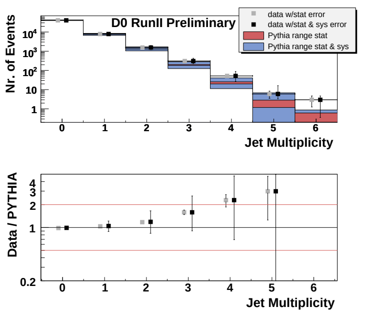


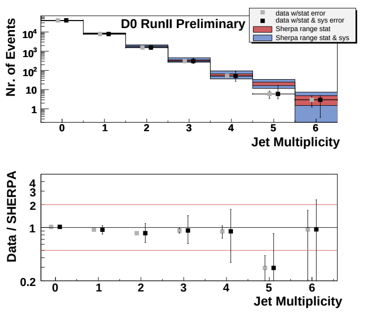


Combining MEs & PS

Comparison with data from Tevatron

Jet rates in $p\bar{p} \to Z + X$ (D0-Note 5066)

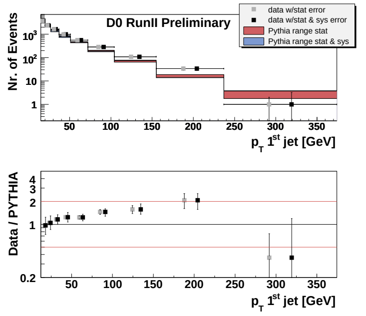


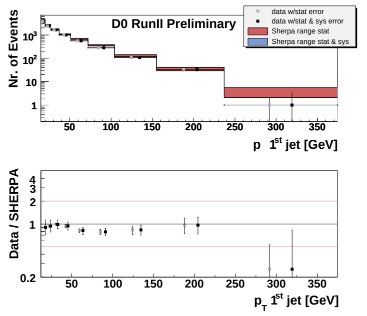


Combining MEs & PS

Comparison with data from Tevatron

Jet spectra (1st jet) in $p\bar{p} \longrightarrow Z + X$ (D0-Note 5066)

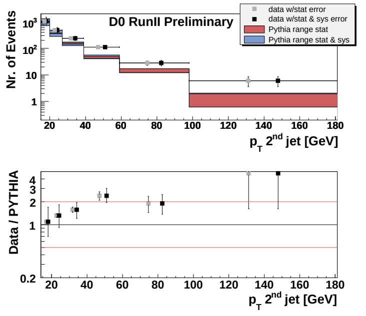


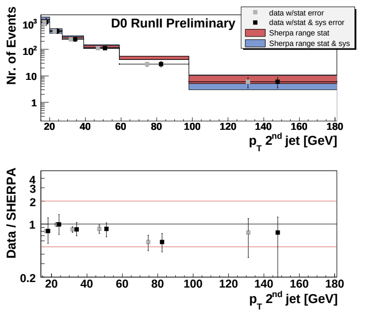


Combining MEs & PS

Comparison with data from Tevatron

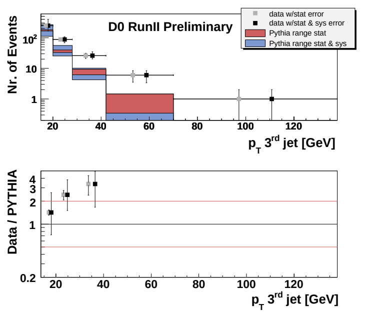
Jet spectra (2nd jet) in $p\bar{p} \longrightarrow Z + X$ (D0-Note 5066)

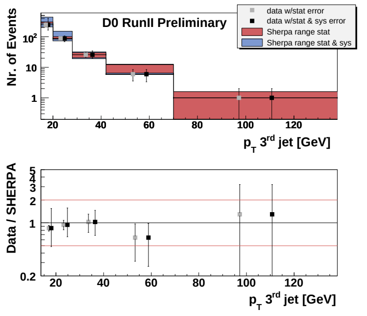




Comparison with RunII $Z + X$ data: $p_\perp^{j_3}$

(D0-Note 5066)

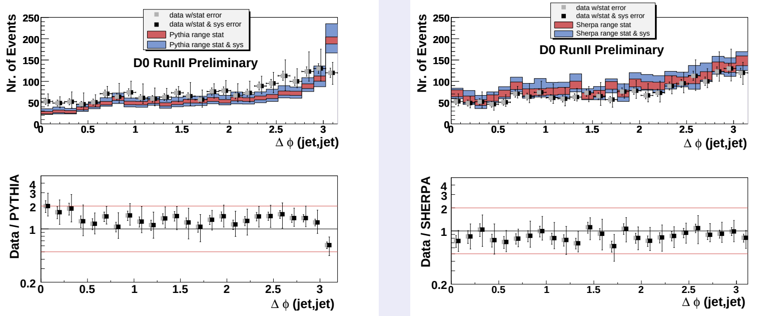




Combining MEs & PS

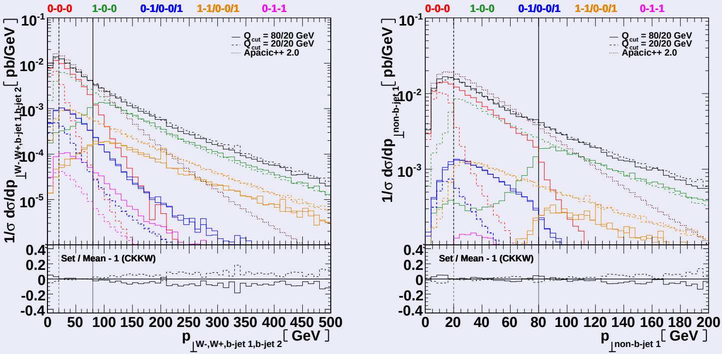
Comparison with data from Tevatron

Azimuthal correlation $(\angle_{1.\mathrm{jet},2.\mathrm{jet}})$ in $p\bar{p} \rightarrow Z + X$ (D0-Note 5066)



A new feature: Merging in decay chains

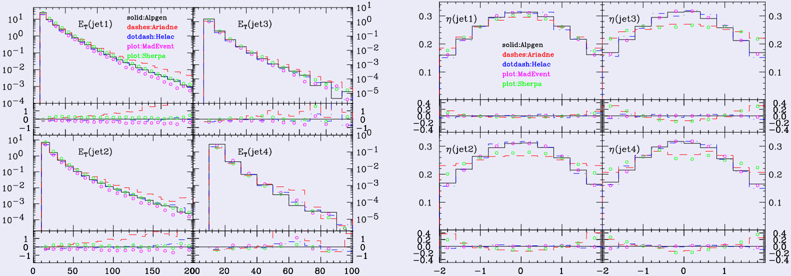
Example: top-pair production @ LHC



Combining MEs & PS

Comparison with other merging algorithms: MLM

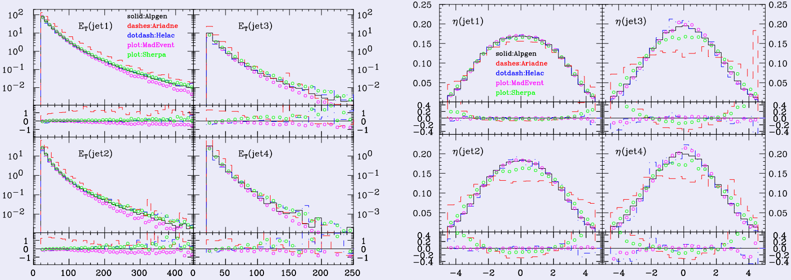
$p_\perp$ of jets in inclusive W+jets at Tevatron



Combining MEs & PS

Comparison with other merging algorithms: MLM

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

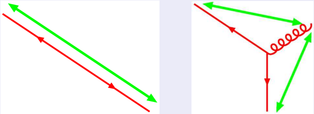


Dipole shower

Implemented in Ariadne (L.Lonnblad, Comput. Phys. Commun. **71**, 15 (1992)).

Upshot

- Expansion around soft logs, particles always on-shell
$$\mathrm{d}\sigma = \sigma_0 \frac{C_F\alpha_s(k_\perp^2)}{2\pi}\frac{\mathrm{d}k_\perp^2}{k_\perp^2}\mathrm{d}y.$$
- Always color-connected partners (recoil of emission)
$\Longrightarrow$ emission: 1 dipole → 2 dipoles.

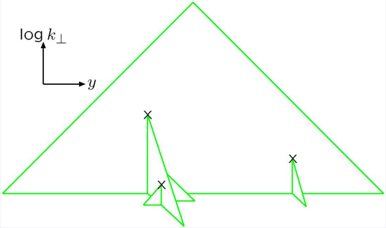


- Quantum coherence on similar grounds for angular and k_T-ordering.

Dipole shower

Implemented in Ariadne (L.Lonnblad, Comput. Phys. Commun. **71**, 15 (1992)).

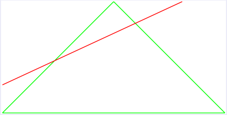
Radiation pattern



IS Radiation

- There is none!
  Treat radiation in DIS as FS radiation between remnant & quark

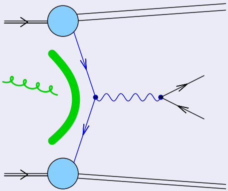
  Thus, no real Dipole Shower for *pp* collisions.
- Cut FS phase space of remnants:



Dipole shower: New developments

J.Winter & F.K., arXiv:0712.3913 [hep-ph]

Initial state dipole showers



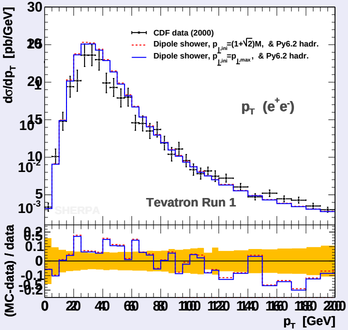
- Complete perturbative formulation.
- Dipoles and their radiation associated to **IS-IS**, **IS-FS** and **FS-FS** colour lines.
- Beam remnants kept outside evolution.
- Onshell kinematics, evolution in $k_\perp$.

Dipole shower: New developments

J.Winter & F.K., arXiv:0712.3913 [hep-ph]

Initial state dipole showers

- Testbed: DY production.
- P_T spectrum of Z^0 boson.
- Mainly recoils vs. 1st emission: by construction: ME-corrected.



A new parton shower approach

Using Catani-Seymour splitting kernels

First discussed in: Z.Nagy and D.E.Soper, JHEP **0510** (2005) 024;

Implemented by M.Dinsdale, M.Ternick, S.Weinzierl Phys.Rev.**D76** (2007) 094003,

and S.Schumann& F.K., JHEP **0803** (2008) 038.

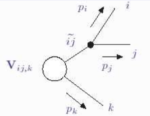
- Catani-Seymour dipole subtraction terms as universal framework for QCD NLO calculations.
- Factorization formulae for real emission process:
- Full phase space coverage & good approx. to ME.

Example: final-state final-state dipoles

splitting: $\tilde{p}_{ij} + \tilde{p}_k \longrightarrow p_i + p_j + p_k$

variables: $y_{ij,k} = \frac{p_ip_j}{p_ip_j+p_ip_k+p_jp_k}\,, \quad z_i = \frac{p_ip_k}{p_ip_k+p_jp_k}$

consider $\mathrm{q}_{ij} \longrightarrow \mathrm{q}_i\mathrm{g}_j$: $\langle V_{\mathrm{q}_i\mathrm{g}_j,k}(\tilde{z}_i, y_{ij,k})\rangle = C_F\left\{\frac{2}{1-\tilde{z}_i+\tilde{z}_iy_{ij,k}} - (1+\tilde{z}_i)\right\}$



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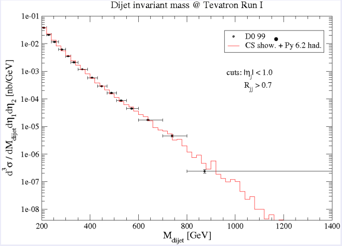

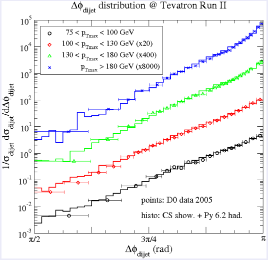

A new parton shower approach

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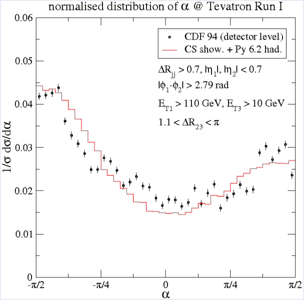
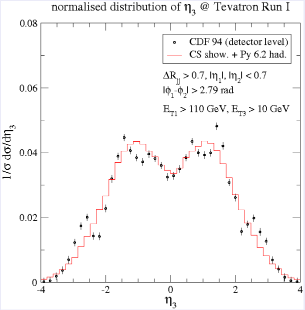
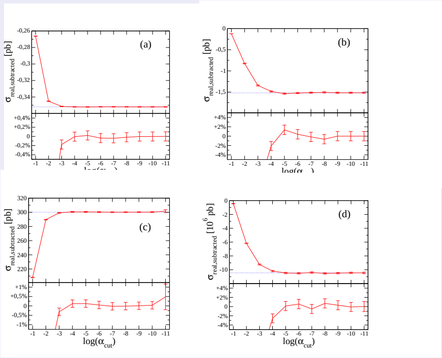




First steps towards NLO

Automated Catani-Seymour subtraction

T.Gleisberg& F.K., eprint 0709.2881



(a) $e^+e^- \longrightarrow$ 2jets

(b) $e^+e^- \longrightarrow$ 3jets

(c) $ep \longrightarrow e +$ 1jet

(d) $pp \longrightarrow$ 2jets

First steps towards NLO

Automated Catani-Seymour subtraction

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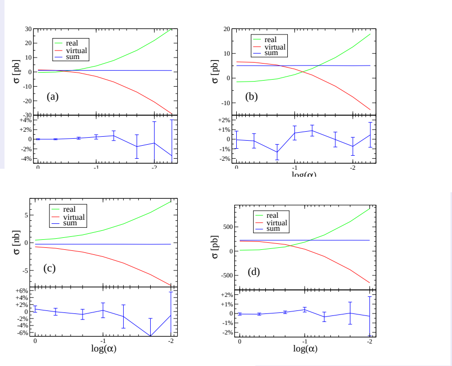


(a) $e^+e^- \longrightarrow$ 2jets

(b) $e^+e^- \longrightarrow$ 3jets

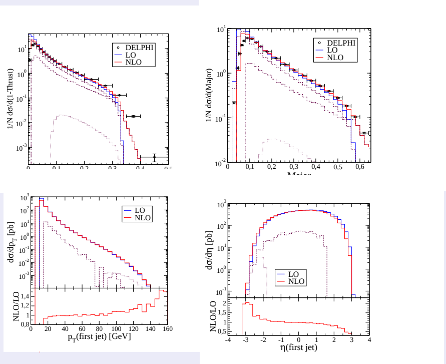
(c) $ep \longrightarrow e + 1$jet

(d) $pp \longrightarrow W$

First steps towards NLO

Automated Catani-Seymour subtraction

T.Gleisberg& F.K., eprint 0709.2881

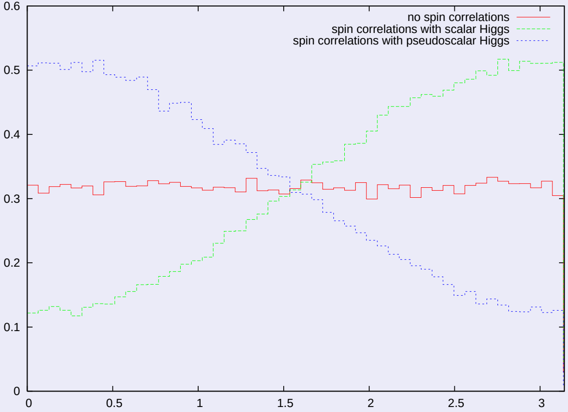


Soft physics simulation in Sherpa

- Implemented a new version of the cluster fragmentation model;
- a new module for the simulation of hadron and τ decays (special emphasis on τ, B and D decays, including mixing, CP-violation etc.);
- a new module for the simulation of photon radiation in hadron decays based on the YFS approach;
- all in current, new release, Sherpa 1.1.

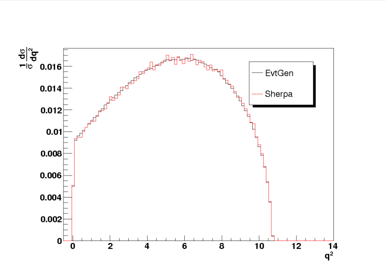
Example (1): Spin correlations in $H \to \tau^+\tau^-$

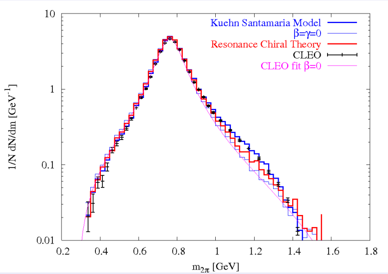
Angle of planes of decay products ($pi\nu$) in c.m.s



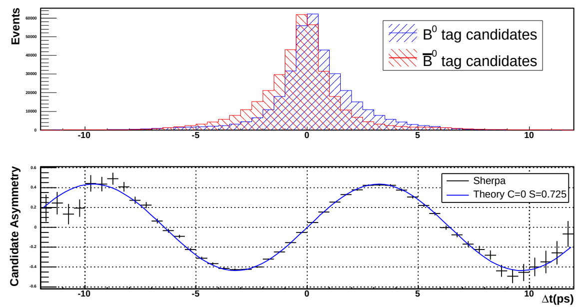
Example (2): Form factors in decays

$B \longrightarrow D^* \ell \nu$ $\tau \longrightarrow \pi \pi \nu$

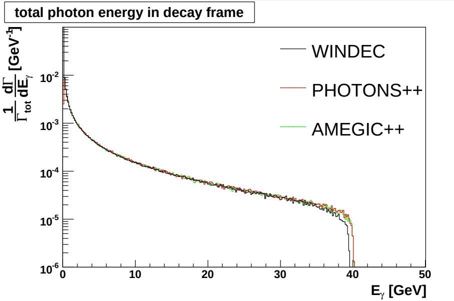




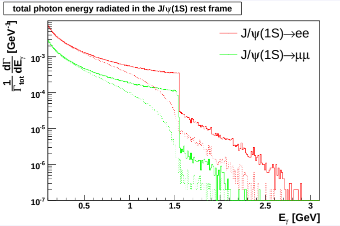
Example (3): $B\bar{B}$-mixing and decay into $J/\Psi K_S$

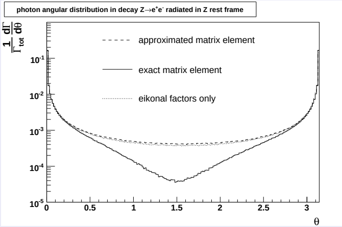


Example (4): Photon radiation in $W \to \ell\nu$



Example (5): Photon radiation in $J/\psi \to \ell\bar{\ell}$





Summary & outlook

- Many interesting signals at LHC "spoiled" by QCD.
- Simulation tools mandatory for success of LHC
- Various new OO-projects in C++.
- New methods of merging of ME& PS extremely powerful (Complementary to MC@NLO)
- Sherpa a versatile tool - new features becoming available: higher ME multis, new showers, new Underlying Event model (based on $k_\perp$-factorization), more BSM models.
- Plan: Go to NLO
    - automatic dipole subtraction implemented and tested
    - build library of virtual corrections.