Recent developments in Sherpa

Frank Krauss

IPPP Durham

Loops & Legs 08, Sondershausen, 21.4.2008

Outline

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.
- Examples:
  - Central jet-veto in VBF (Higgs)
  - Multi-jet backgrounds for SUSY (e.g. Z+jets)
- Todays signals = tomorrows backgrounds.

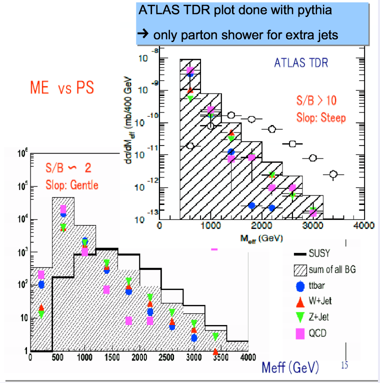
Why does anyone write a new event generator?

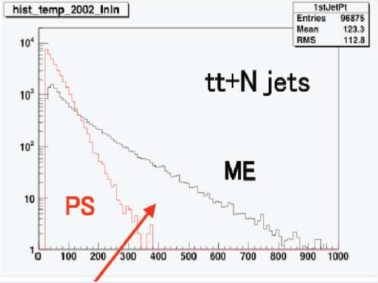
New tools on the market: Pythia8, Herwig++, Sherpa
Reflecting increased needs (precision, new physics, etc.):

- 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: $M_{\rm eff}$





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).

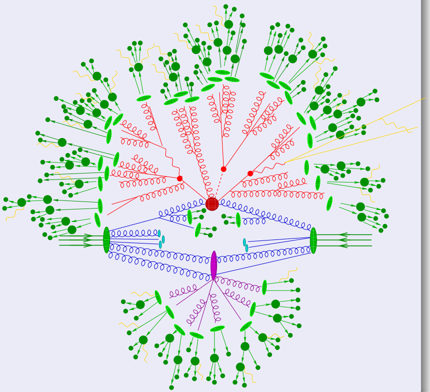
- Multiple interactions:

  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,
- Underlying event according to old Pythia model, new model based on BFKL evolution to be released.

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, $k_\perp^{\rm min} = 20$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):

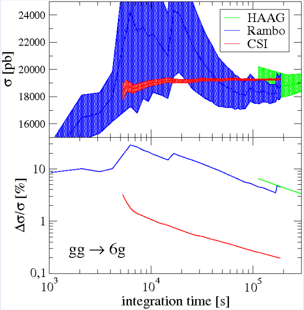
$gg \longrightarrow ng$	Cross section [pb]				
n	8	9	10	11	12
$\sqrt{s}$ [GeV]	1500	2000	2500	3500	5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
Alpgen	0.719(19)				

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	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):



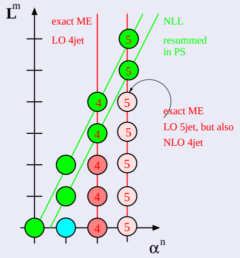
From partons to hadrons

- Experimental definition of jets based on hadrons.
- But: Hadronization through phenomenological models (need to be tuned to data).

ME vs. PS

- MEs: hard, large-angle emissions; interferences.
- PS: soft, collinear emissions; resumation of large logarithms.
- Combine both, avoid double-counting.

α_s vs. Log



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

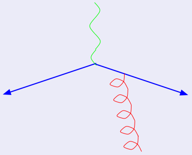
At NLL-Accuracy

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

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

Sudakov weights

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



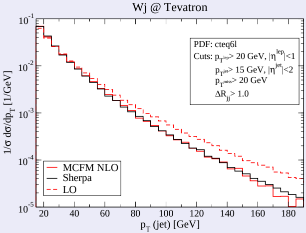
$$\mathcal{W}_{\rm Sud} = \frac{\alpha_s(q)}{\alpha_s(Q_{\rm jet})} \cdot \Delta_q(E_{\rm c.m.}, Q_{\rm jet}) \frac{\Delta_q(E_{\rm c.m.}, Q_{\rm jet})}{\Delta_q(q, Q_{\rm jet})} \Delta_q(q, Q_{\rm jet})\Delta_g(q, Q_{\rm jet})$$

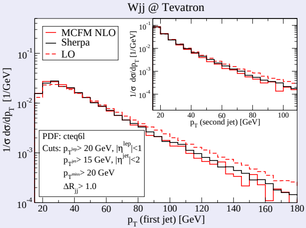
Combining MEs & PS

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

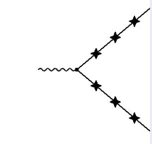




Sherpa = tree-level matrix elements with α_s scales and Sudakov form factors.

Combining MEs & PS

Vetoing the shower



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

$$= \left\{\exp\left(\int_{Q_{\rm jet}}^{E_{\rm c.m.}} dq\,\Gamma_q(E_{\rm c.m.}, q)\right)\right\}^2 = \Delta_q^{-2}(E_{\rm c.m.}, Q_{\rm jet})$$

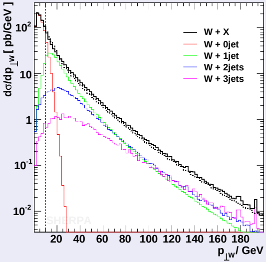
$\Longrightarrow$ Cancels dependence on $Q_{\rm jet}$.

Combining MEs & PS: Independence on $Q_{\rm jet}$

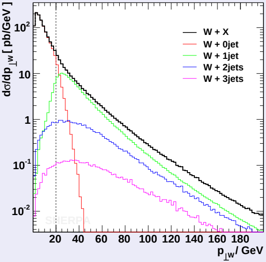
F.K., A.Schälicke, S.Schumann and G.Soff, Phys. Rev. D **70** (2004) 114009

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

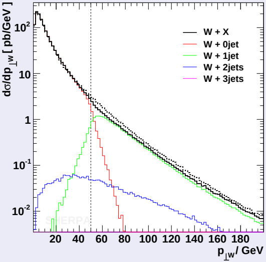
$Q_{\rm jet} = 10\,{\rm GeV}$



$Q_{\rm jet} = 30\,{\rm GeV}$



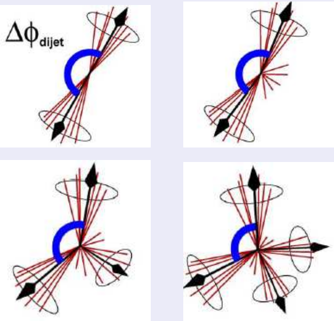
$Q_{\rm jet} = 50\,{\rm GeV}$



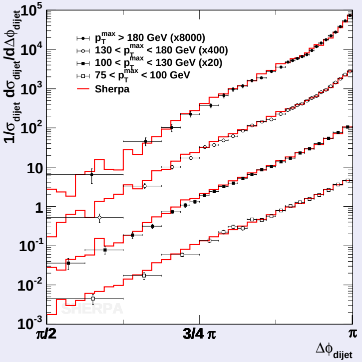
Azimuthal decorrelations of jets at the Tevatron

Idea

- Check QCD radiation pattern

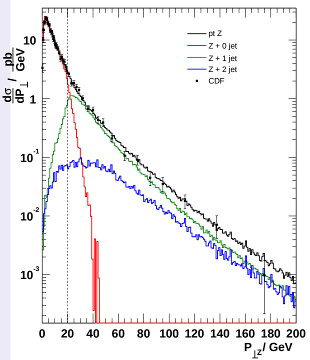


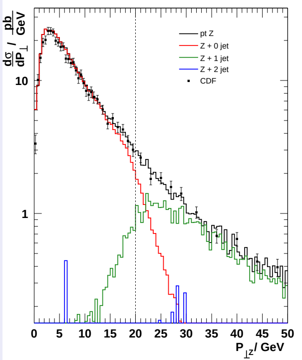
$\Delta\Phi_{12}$ @ Run II (D0)



Comparison with data from Tevatron

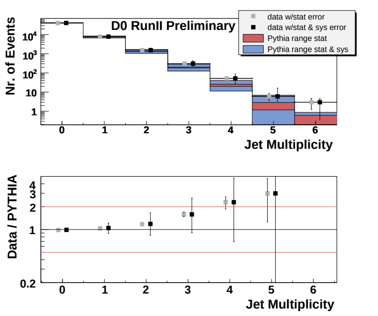
$p_\perp$ of Z-bosons

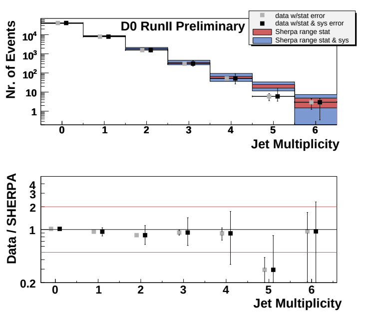




Comparison with RunII $Z + X$ data: Jet multis

(D0-Note 5066)



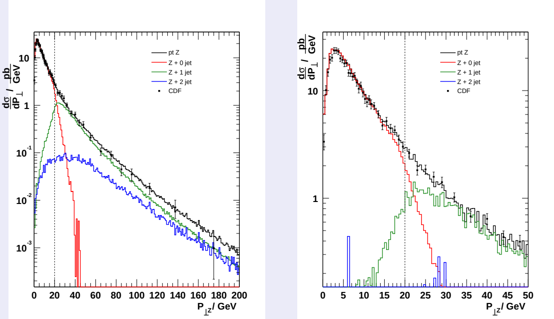


Combining MEs & PS

Comparison with data from Tevatron

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

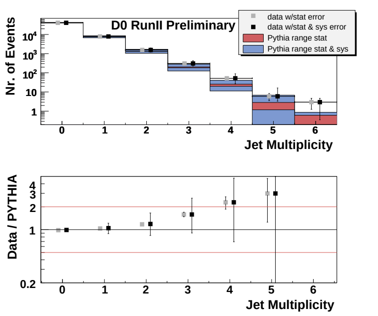
Data from CDF, Phys. Rev. Lett. 84 (2000) 845

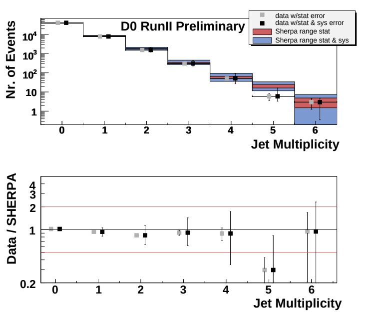


Combining MEs & PS

Comparison with data from Tevatron

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

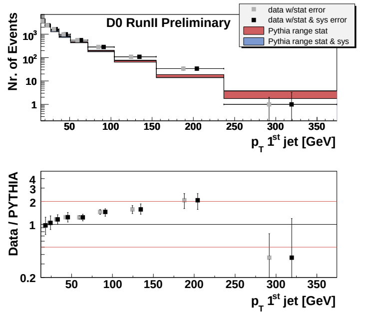


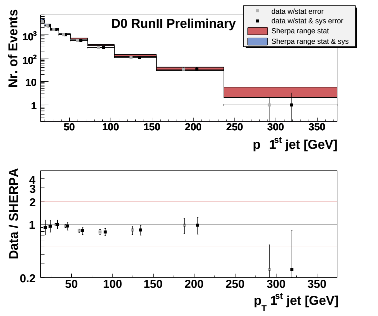


Combining MEs & PS

Comparison with data from Tevatron

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

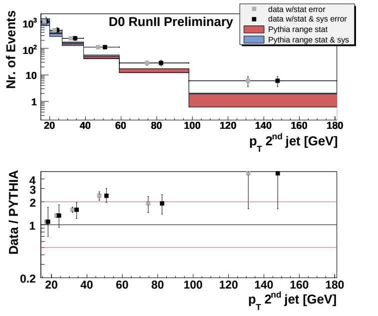


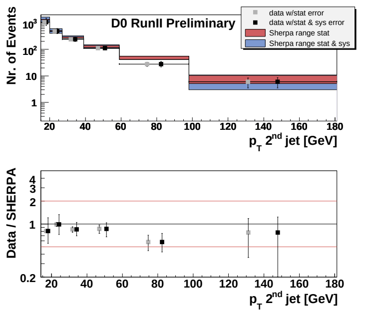


Combining MEs & PS

Comparison with data from Tevatron

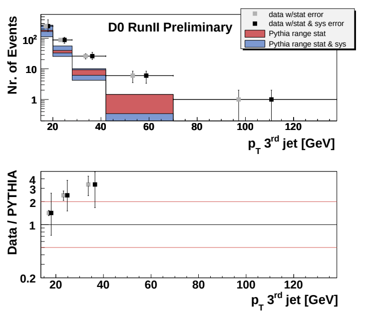
Jet spectra (2nd jet) in $p\bar{p} \longrightarrow Z + X$ (D0-Note 5066)

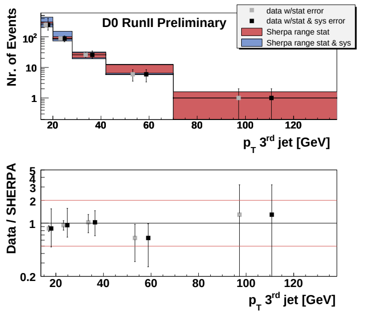




Comparison with RunII $Z+X$ data: $p_\perp^{j_3}$

(D0-Note 5066)

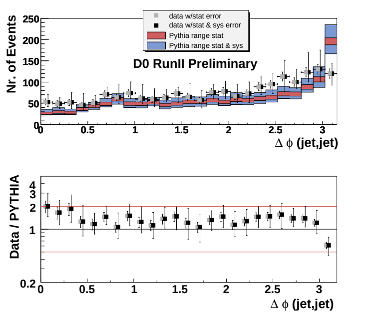


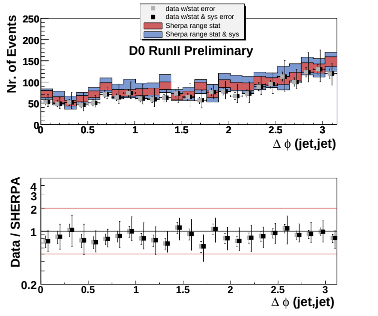


Combining MEs & PS

Comparison with data from Tevatron

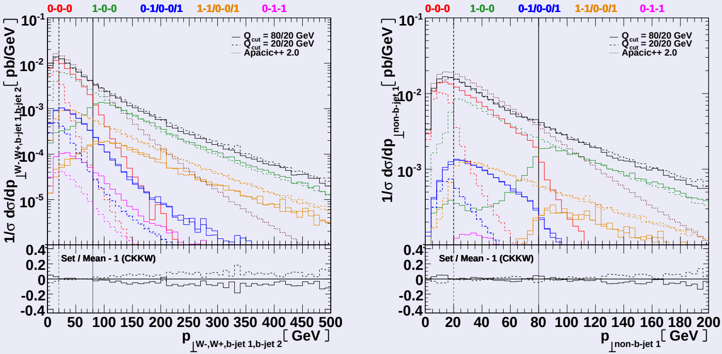
Azimuthal correlation $(\angle_{1.\mathrm{jet},2.\mathrm{jet}})$ in $p\bar{p} \to Z + X$ (D0-Note 5066)





A new feature: Merging in decay chains

Example: top-pair production @ LHC

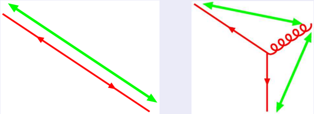


Dipole shower

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

Upshot

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

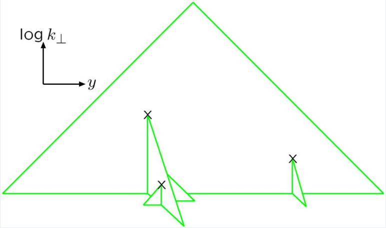


- Quantum coherence on similar grounds for angular and k_T-ordering.

Dipole shower

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

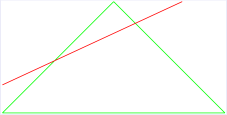
Radiation pattern



IS Radiation

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

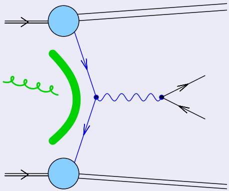
  Thus, no real Dipole Shower for *pp* collisions.
- Cut FS phase space of remnants:



Dipole shower: New developments

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

Initial state dipole showers



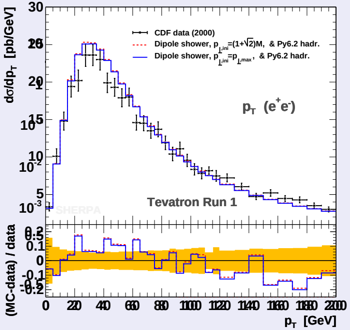
- Complete perturbative formulation.
- Dipoles and their radiation associated to **IS-IS**, **IS-FS** and **FS-FS** colour lines.
- Beam remnants kept outside evolution.
- Onshell kinematics, evolution in $k_\perp$.

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.

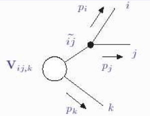
- Catani-Seymour dipole subtraction terms as universal framework for QCD NLO calculations.
- Factorization formulae for real emission process:
- Full phase space coverage & good approx. to ME.

Example: final-state final-state dipoles

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

variables: $y_{ij,k} = \frac{p_i p_j}{p_i p_j + p_i p_k + p_j p_k}$, $z_i = \frac{p_i p_k}{p_i p_k + p_j p_k}$

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



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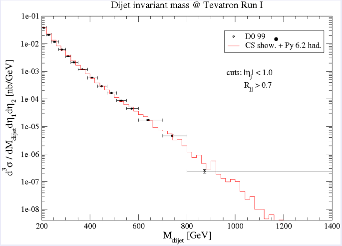

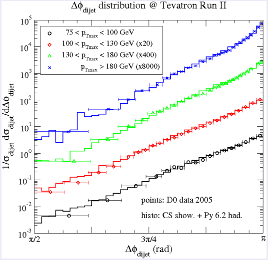

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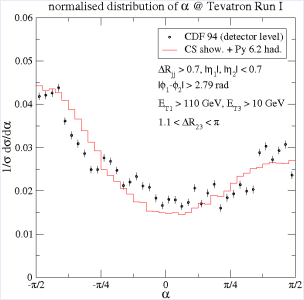
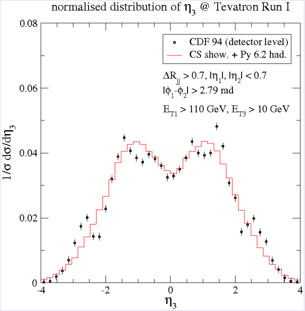
and S.Schumann& F.K., JHEP **0803** (2008) 038.

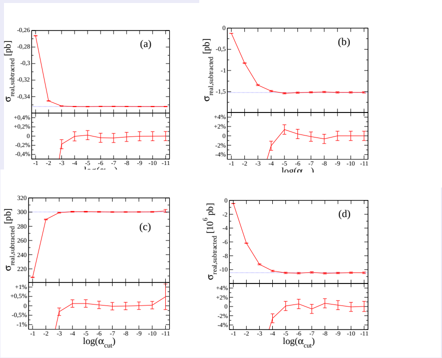




First steps towards NLO

Automated Catani-Seymour subtraction

T.Gleisberg& F.K., eprint 0709.2881



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

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

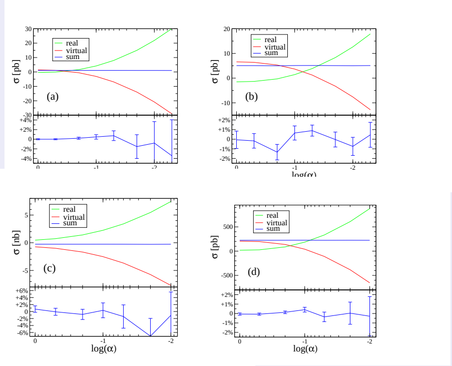
(c) $ep \longrightarrow e +$ 1jet

(d) $pp \longrightarrow$ 2jets

First steps towards NLO

Automated Catani-Seymour subtraction

T.Gleisberg& F.K., eprint 0709.2881



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

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

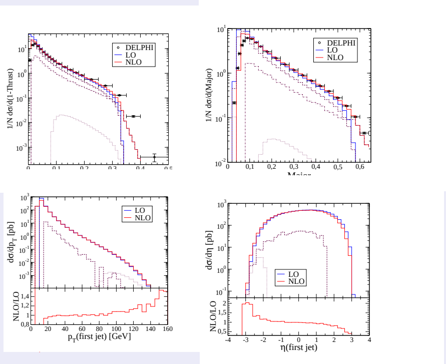
(c) $ep \longrightarrow e +$ 1jet

(d) $pp \longrightarrow W$

First steps towards NLO

Automated Catani-Seymour subtraction

T.Gleisberg& F.K., eprint 0709.2881

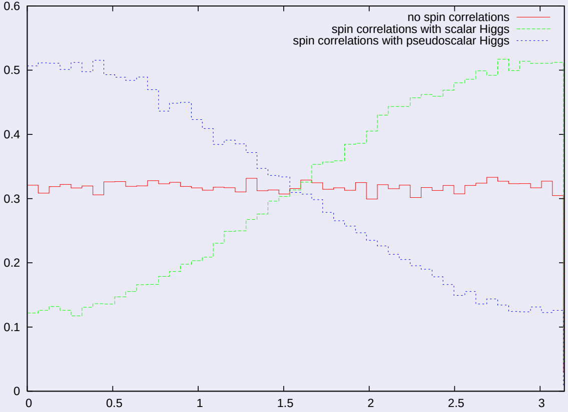


Soft physics simulation in Sherpa

- 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.

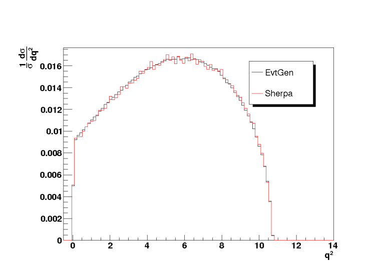
Example (1): Spin correlations in $H \to \tau^+\tau^-$

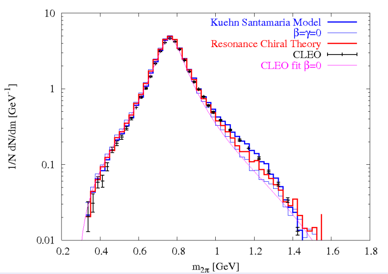
Angle of planes of decay products ($pi\nu$) in c.m.s



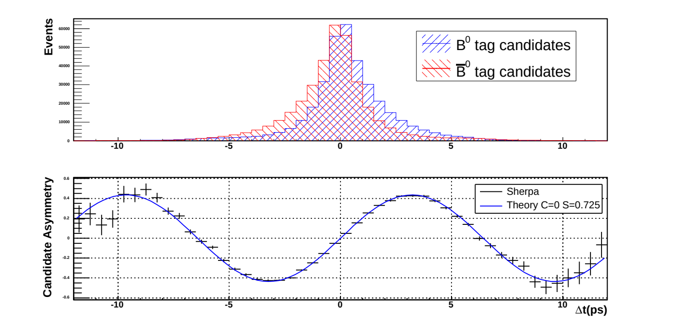
Example (2): Form factors in decays

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

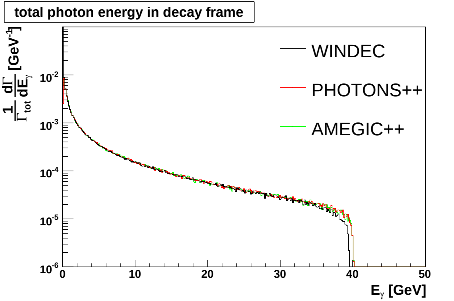




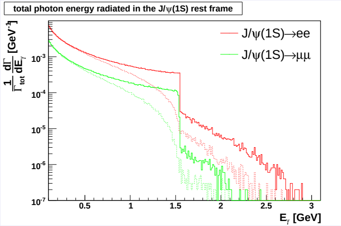
Example (3): $B\bar{B}$-mixing and decay into $J/\Psi K_S$

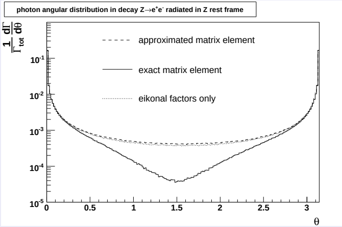


Example (4): Photon radiation in $W \to \ell\nu$



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.