Introduction to Sherpa

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ALCPG07, Fermilab, 23.10.2007

Outline

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).

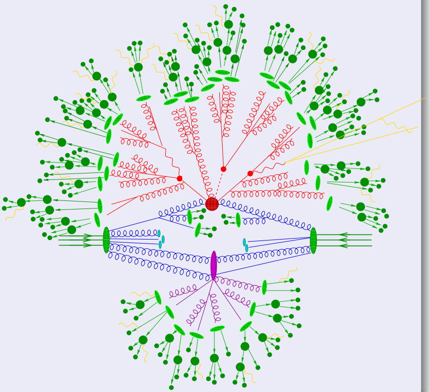
- Multiple interactions:

  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++

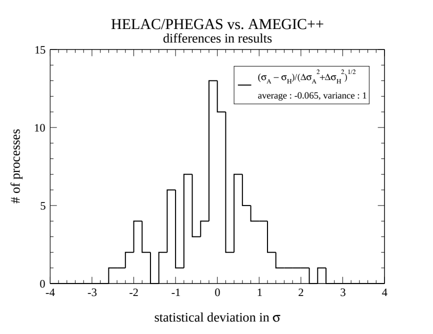
F.K., R.Kuhn, G.Soff, JHEP **0202** (2002) 044.

- 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, ...)

Standard Model @ Linear Collider

Consistency of HELAC/PHEGAS & AMEGIC++

T.Gleisberg, F.K., C.Papadopoulos, A.Schälicke and S.Schumann, Eur. Phys. J. C **34** (2004) 173



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

Integration

- HAAG (colour dipoles) + multichanneling + VEGAS

HAAG: A.v.Hameren, C.Ppapdopoulos EPJ**C25** (2002) 563

- Characteristic number for event generation:
  Unweighting eff. = average/maximal value of $\mathrm{d}\sigma$

Unweighting efficencies:

$gg \to ggg$	$jj \to jjj$	$gg \to gggg$	$jj \to jjjj$	$gg \to ggggg$	$jj \to jjjjj$
6.2514%	1.6213%	1.5692%	0.4944%	0.8631%	0.1908%

Comparison with other methods

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

$2 \longrightarrow n$ gluons, 10^4 phase space points
colour-ordered vs. colour-dressed, Berends-Giele, BCF vs. CSW

F.A.Berends, W.T.Giele NP**B306** (1988) 759
R.Britto, F.Cachazo, B.Feng PRL**94** (2005) 181602

n	BG, CO	BG, CD	CSW, CO	CSW, CD	BCF, CO	BCF, CD
2	0.24	0.28	0.31	0.26	0.28	0.33
4	1.2	1.04	1.63	1.75	0.84	1.32
6	14.2	7.19	27.8	30.6	11.9	59.1
8	276	82.1	919	1890	597	8690
10	7960	864	48900	-	64000	

From partons to hadrons

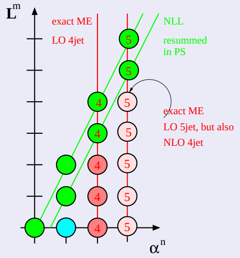
- Experimental definition of jets based on hadrons.
- But: Hadronization through phenomenological models

(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



From partons to hadrons

Parton showers

- Universal pattern of soft & collinear radiation:

$$\mathrm{d}\sigma_{N+1} \sim \mathrm{d}\sigma_N \sum_{a\in N} \frac{\mathrm{d}t_a}{t_a}\,\alpha_s\,\mathrm{d}z\,P_{a\to bc}(z)\,.$$

- Introduce "resolution of partons" (e.g. $p_\perp^{\min}$)
  $\Longrightarrow$ Large logarithms at each emission.
- Resummation of logs in Sudakov form factor:

$$\Delta_a(t,\,t_0) = \exp\left[-\int\limits_{t_0}^{t}\frac{\mathrm{d}t'}{t'}\int\limits_{z_-}^{z_+}\mathrm{d}z\,\alpha_s\,P_{a\to bc}(z)\right]\,.$$

- Interpretation: No-emission probability ($\to$ simulation).

Combining MEs & PS

Idea (Example: $e^+e^- \longrightarrow$ hadrons):

- Define $k_\perp$-jets with $Q^2_{\rm cut} = y_{\rm cut} Q^2$, $Q = E_{\rm c.m.}$
- Probabilistic interpretation of Sudakov form factor:

$$\begin{aligned}
\mathcal{R}_2(y_{\rm cut}) &= \Delta_q^2(Q, Q_{\rm cut}) \\
\mathcal{R}_3(y_{\rm cut}) &= 2\Delta_q(Q, Q_{\rm cut}) \\
&\int\limits_{Q_{\rm cut}}^{Q} {\rm d}q\, \frac{\Delta_q(Q, Q_{\rm cut})}{\Delta_q(q, Q_{\rm cut})} \Gamma_q(q,\, Q)\Delta_q(q, Q_{\rm cut})\Delta_g(q, Q_{\rm cut})
\end{aligned}$$

  - No emission off outgoing/internal lines.
  - Emission at q: Integrated splitting function $\Gamma_q(q,\, Q) = \frac{2C_F}{\pi}\frac{\alpha_s(q)}{q}\left[\log\frac{Q}{q} - \frac{3}{4}\right]$

- Obvious trick: replace Γ_q by full matrix element.

Combining MEs & PS: LO-Merging

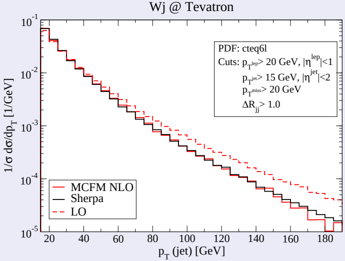
S.Catani, F.K., R.Kuhn and B.R.Webber, JHEP **0111** (2001) 063
F.K., JHEP **0208** (2002) 015

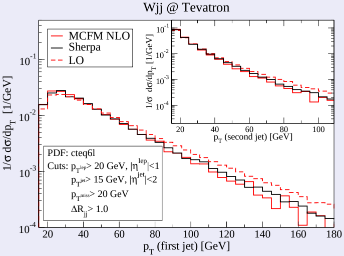
- Want:
  - All jet emissions correct at tree level + LL,
  - Soft emissions correctly resummed in PS
- Method:
  - Separate Jet-production/evolution by $Q_{\rm jet}$ ($k_\perp$ algorithm).
  - Produce jets according to LO matrix elements
  - re-weight with Sudakov form factor + running α_s weights,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

Algorithm as scale-setting prescription

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

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





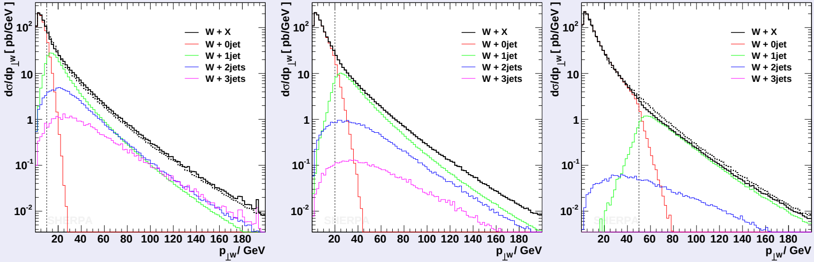
Sherpa = tree-level matrix elements with α_s scales and Sudakov form factors.

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

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

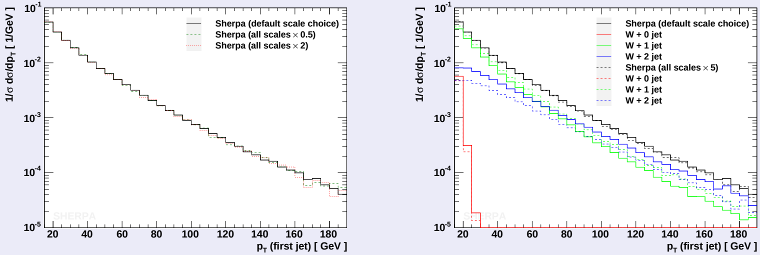
Example: $p_\perp$ of W in $p\bar{p} \to W + X$ @ Tevatron

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



Merging issues: Dependence on scales

$p_\perp$ distribution of 1st jet @ Tevatron

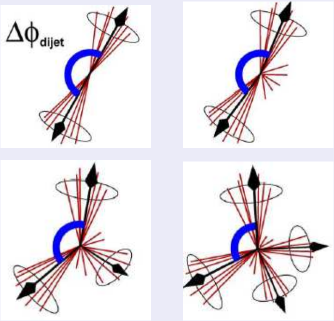


Azimuthal decorrelations of jets at the Tevatron

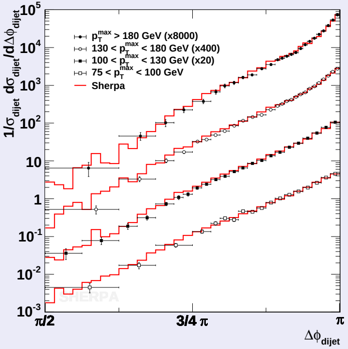
V.Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **94** (2005) 221801

Idea

- Check QCD radiation pattern



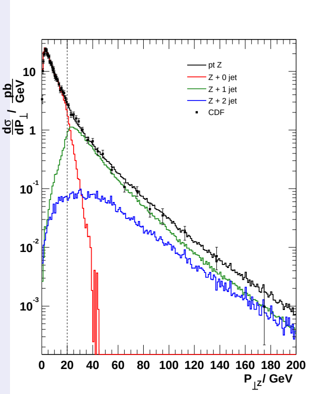
Distributions @ Run II (D0)

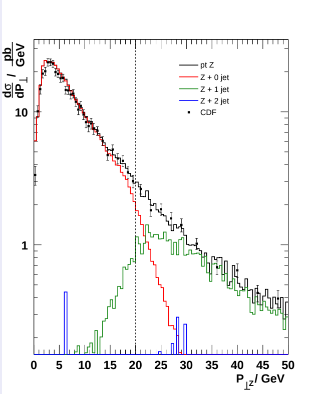


Comparison with data from Tevatron

$p_\perp$ of Z-bosons

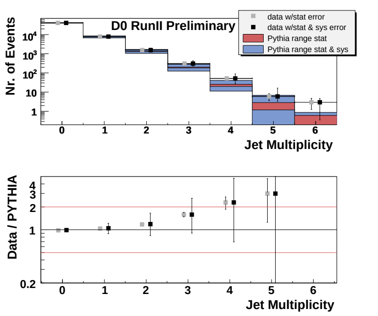
A. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **84** (2000) 845.

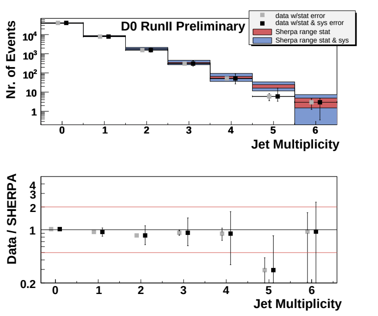




Comparison with RunII $Z + X$ data: Jet multis

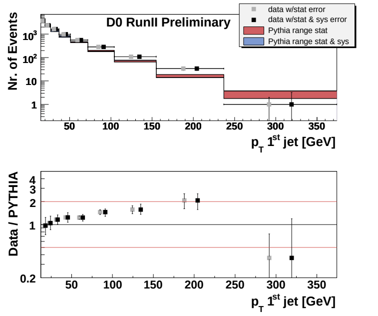
(D0-Note 5066)

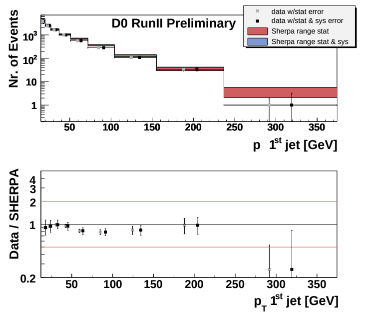




Comparison with RunII $Z + X$ data: $p_\perp^{j_1}$

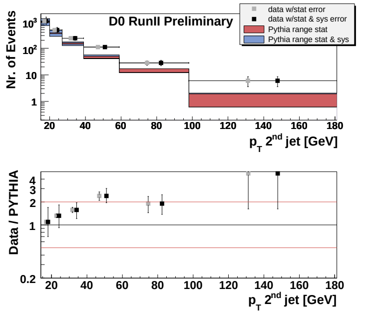
(D0-Note 5066)

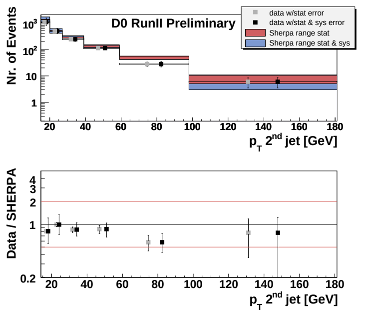




Comparison with RunII $Z + X$ data: $p_\perp^{j_2}$

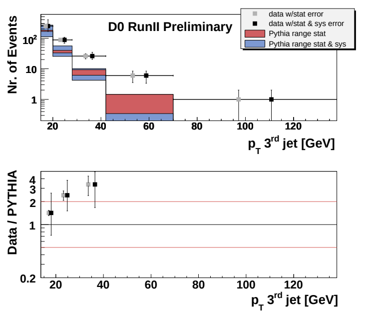
(D0-Note 5066)

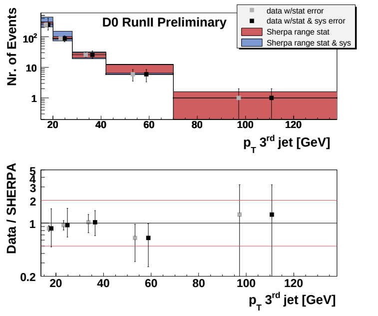




Comparison with RunII $Z + X$ data: $p_\perp^{j_3}$

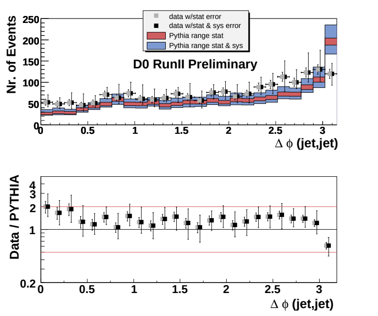
(D0-Note 5066)

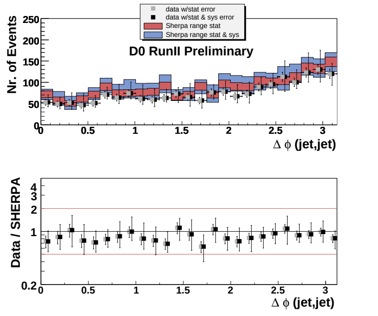




Comparison with RunII $Z + X$ data: $\Delta\phi^{j_1 j_2}$

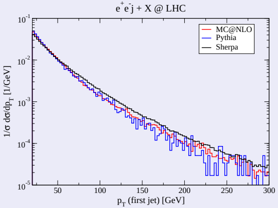
(D0-Note 5066)

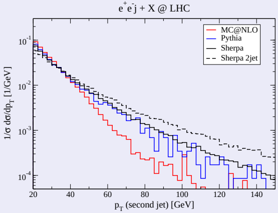


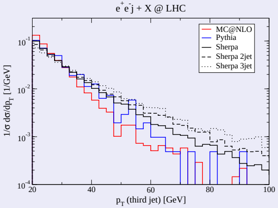


Extrapolation to LHC : $p_\perp$ of jets in inclusive Z+jets

- Influence of more jets.
- Displayed here: x-sections.
- Difference in shape & x-sec.







Further developments of parton showers

Shower based on Catani-Seymour splitting kernels

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

Implemented in: S.Schumann and F.K., arXiv:0709.1027 [hep-ph];

M.Dinsdale, M.Ternick and S.Weinzierl, arXiv:0709.1026 [hep-ph]

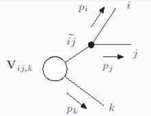
- Catani-Seymour dipole subtraction terms as universal framework for QCD NLO calculations.
- Factorization formulae for real emission process:
- Full phase space coverage & good approx. to ME.

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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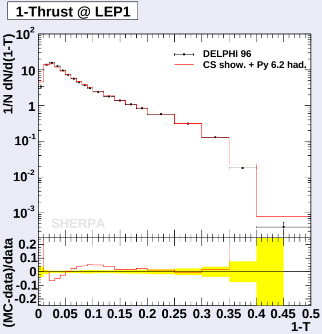
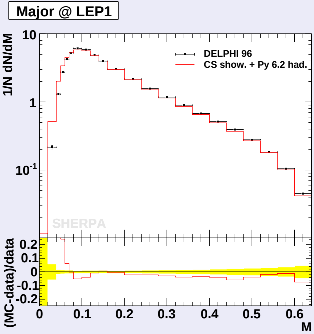
P.Abreu *et al.* [DELPHI Collaboration], Z. Phys. C **59** (1993) 357

Results for $e^+e^- \longrightarrow$ hadrons





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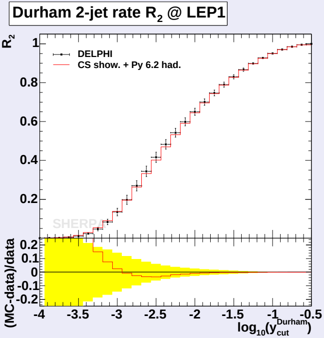

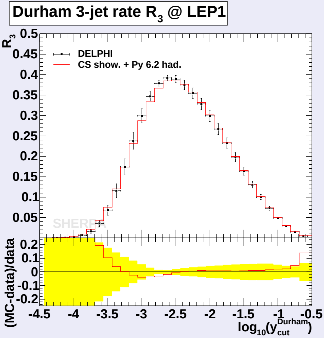

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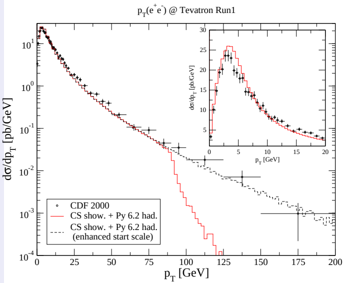
A. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **84** (2000) 845

Results for $p\bar{p} \longrightarrow \ell^+\ell^-$



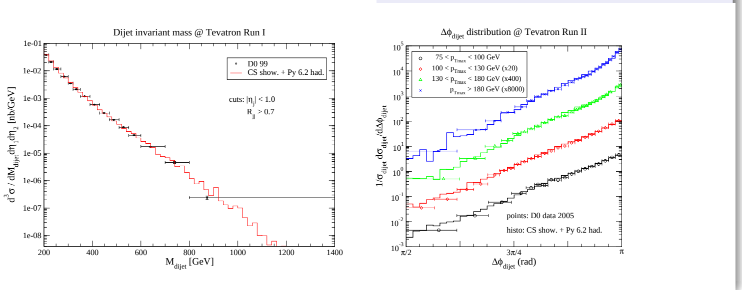
Further developments of parton showers

Shower based on Catani-Seymour splitting kernels

B.Abbott *et al.* [D0 Collaboration], Phys. Rev. Lett. **82** (1999) 2457

V.Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **94** (2005) 221801

Results for $p\bar{p} \longrightarrow$ jets

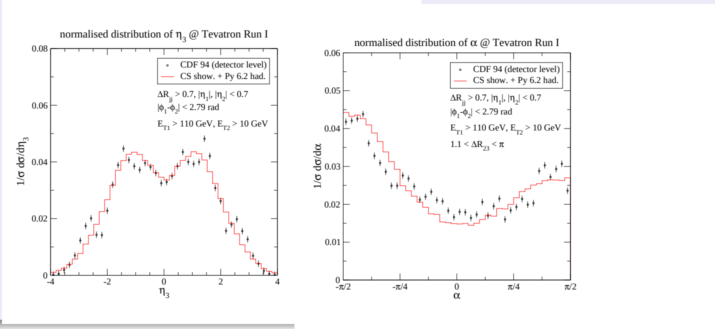


Further developments of parton showers

Shower based on Catani-Seymour splitting kernels

F.Abe *et al.* [CDF Collaboration], Phys. Rev. D **50** (1994) 5562

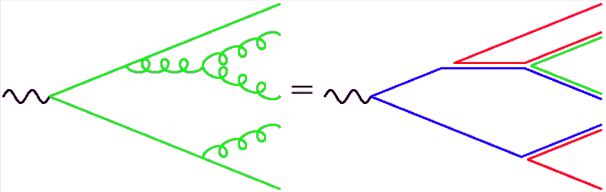
Results for $p\bar{p} \longrightarrow$ jets



Hadronization

Preconfinement

- Underlying: Large N_c-limit (planar graphs).
- Follows evolution of color in parton showers: at the end of shower color singlets close in phase space.
- Mass of singlets: peaked at low scales $\approx Q_0^2$.

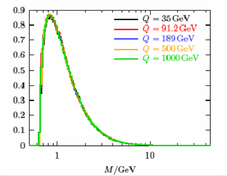


Hadronization

Cluster model

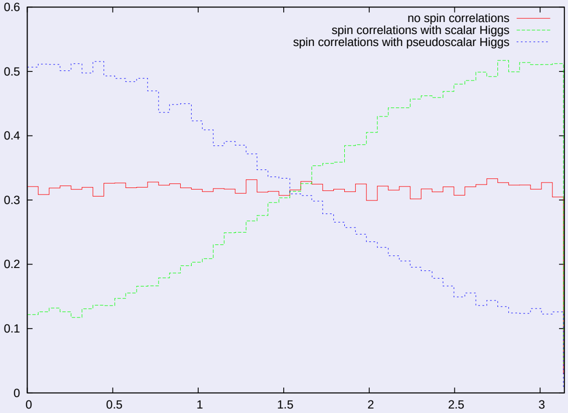
B.R.Webber, Nucl. Phys. B **238** (1984) 492
J.Winter, F.Krauss, and G.Soff, Eur. Phys. J. **C36** (2004) 381

- Split gluons into $q\bar{q}$ pairs, form singlet clusters:
  $\Longrightarrow$ continuum of meson resonances.
- Decay heavy clusters into lighter ones;
  (here, many improvements to ensure leading hadron spectrum hard enough, overall effect: cluster model becomes more string-like);
- if light enough, clusters $\longrightarrow$ hadrons.
- Naively: spin information washed out, decay determined through phase space only $\longrightarrow$ heavy hadrons suppressed (baryon/strangeness suppression).
- Primordial cluster mass spectrum universal.



Spin correlations in $H \to \tau^+\tau^-$

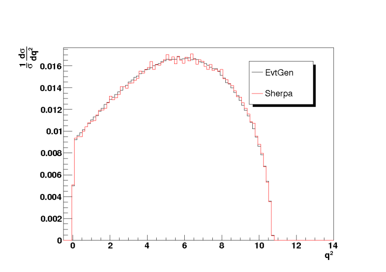
Angle of planes of decay products $(pi\nu)$ in c.m.s

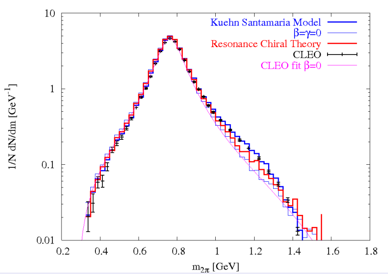


Decay matrix elements: Form factors

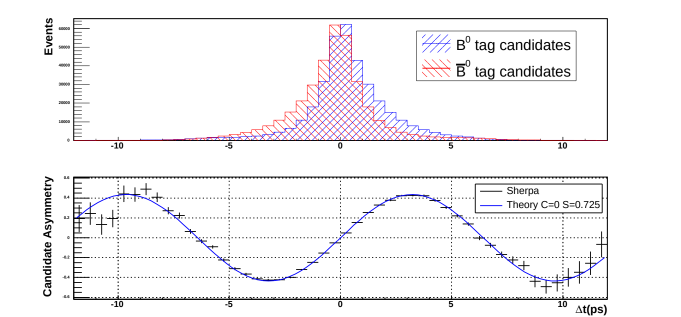
$B \longrightarrow D^* \ell \nu$

$\tau \longrightarrow \pi \pi \nu$





$B\bar{B}$-mixing and decay into $J/\Psi K_S$



Summary & outlook

Outlook

- Immediate future: finish SHERPA (time horizon: this year)
  - Validate SHERPA for Higgs production processes
  - How about SUSY at LHC ?
  - Finish implementation of hadronization & hadron decays
  - New model for underlying event (BFKL-based)
- Near future: extend SHERPA (time horizon: next year)
  - Implement more models (RPV, UED, Gravitinos)
  - New parton shower(s) (better suited for MC@NLO)
  - Play: Phenomenology with a nice & versatile tool
  - Start going NLO (QCD) in merging
- Far future: go to precision level (time horizon: five years)
  - Play more
  - Further validation vs. (LHC) data; further learning
  - Go QCD NLO in **BOTH** matrix elements and merging

Summary & outlook

Outlook

- Science fiction: Prepare for LC physics
  - QED ISR in the spirit of YFS for e^+e^- collisions
  - Include electroweak NLO corrections
  - Electroweak showering/Sudakov effects (resummation)
  - Photon-photon physics (underlying event in e^+e^-)
  - Include Weizsaecker-Williams, Beamstrahlung
  - Go to NNLO QCD (if possible), may need new shower.