SHERPA

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Outline

The SHERPA project

- Started in 1997 as a diploma thesis (R.Kuhn).
- Soon: Aiming at developing a completely independent new event generation framework in C++.
- Fully automated matrix element generation as core.
- Unique feature: Multi-jet ME+PS merging.
- First proof-of-concept version released in 2003, still with routines "borrowed" from PYTHIA: SHERPA 1.0.α.

  T.Gleisberg et al., JHEP **0402** 056 (2004)
- Currently: At version 1.1.3, by now independent.

  T.Gleisberg et al., JHEP **0902** 007 (2009)
- Near future: Version 1.2, with many new attractions.

Simulation's paradigm

Basic strategy

- Signal/background:

  Exact matrix elements: AMEGIC++
- QCD-Bremsstrahlung:

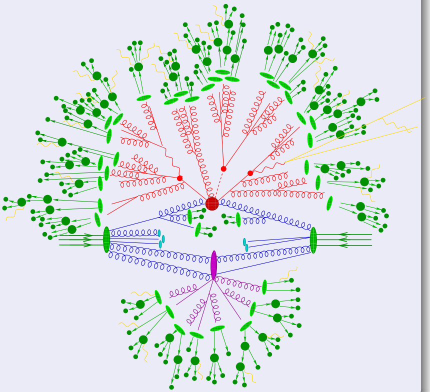
  Parton showers: APACIC++
- Multiple interactions:

  Beyond factorisation: AMISIC++
- Hadronisation:

  Non-perturbative QCD: AHADIC++
- Hadron decays:

  Encoding the PDG: HADRONS++ & PHOTONS++

Sketch of an event



Automated cross section calculation AMEGIC++

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

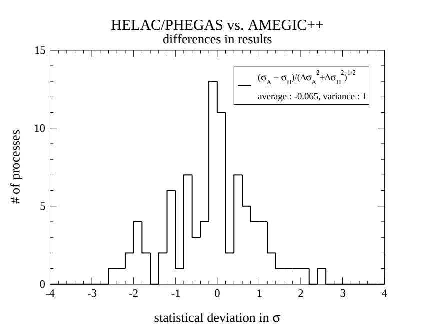
- Uses helicity/recursion methods;
- Helicity method supplemented with "factoring out" (taming the factorial growth)
- Phase space integration through multi-channeling (i.e. one phasespace mapping/Feynman diagram)
- Implemented & tested models: SM, SM+AGC, THDM, MSSM, ADD.
- Tested in $>$ 1000 SM & $>$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

  T.Gleisberg & F.K., Eur.Phys.J.**C53** (2008) 501.
- Ongoing development: 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



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):

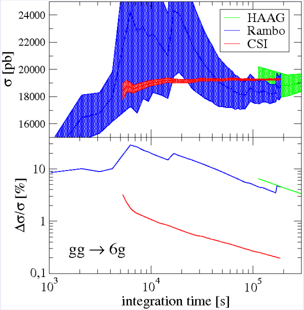
$gg \longrightarrow ng$	Cross section [pb]				
n $\sqrt{s}$ [GeV]	8 1500	9 2000	10 2500	11 3500	12 5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
Alpgen	0.719(19)				

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

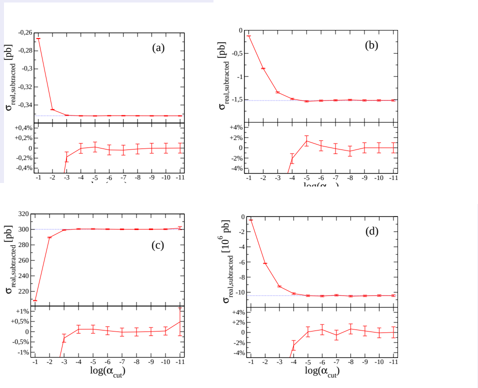
- Colour-dressed Berends-Giele amplitudes in the SM
- Fully recursive phase space generation
- Example results (phase space performance):



First steps towards NLO

Automated Catani-Seymour subtraction

T.Gleisberg & F.K., Eur.Phys.J.**C53** (2008) 501



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

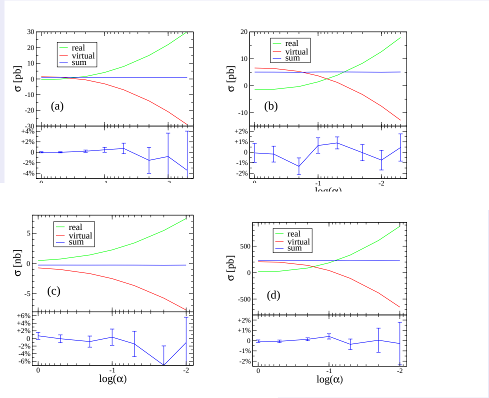
(b) $e^+e^- \longrightarrow$ 3jets

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

(d) $pp \longrightarrow$ 2jets

Automated Catani-Seymour subtraction

T.Gleisberg & F.K., Eur.Phys.J.**C53** (2008) 501



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

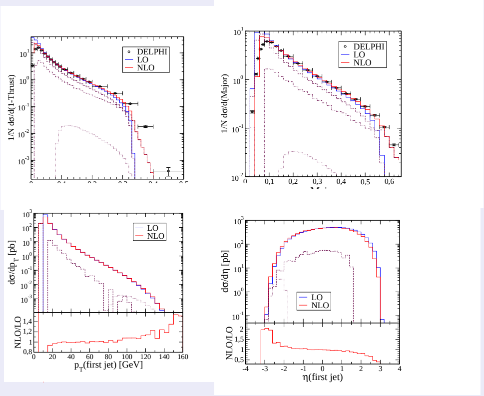
(b) $e^+e^- \longrightarrow$ 3jets

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

(d) $pp \longrightarrow W$

Automated Catani-Seymour subtraction

T.Gleisberg & F.K., Eur.Phys.J.**C53** (2008) 501



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.

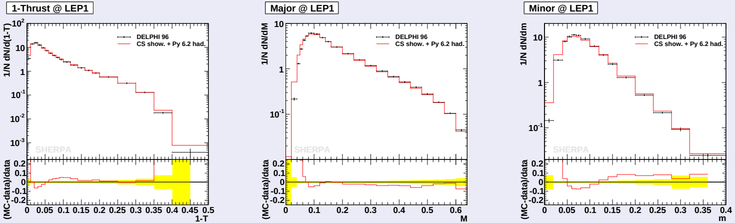
- Catani-Seymour dipole subtraction terms as universal framework for QCD NLO calculations.
- Factorisation formulae for real emission process:

  Full phase space coverage & good approx. to ME.
- Added benefit: All particles always on-shell

Matching/merging with ME improved.

Results in e^+e^- collisions at LEP1

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



Results in e^+e^- collisions at LEP1

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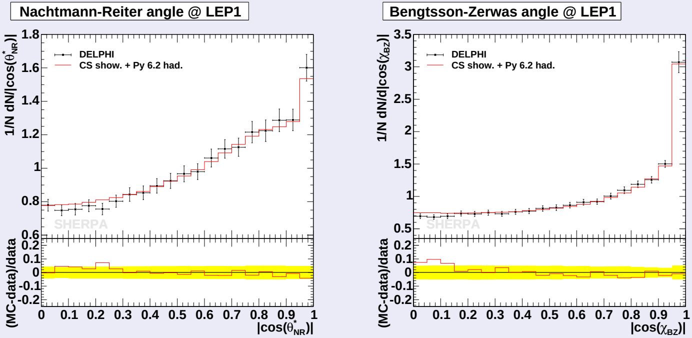
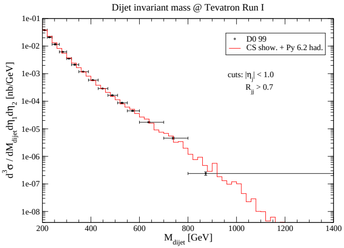
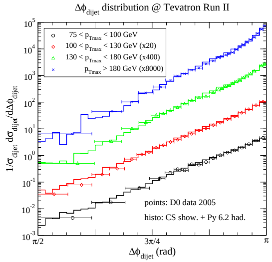


CS-Shower: Results in $p\bar{p}$ collisions

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





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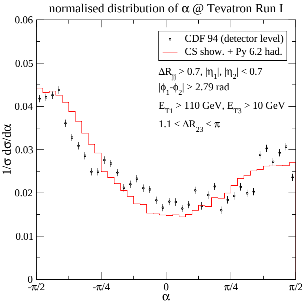
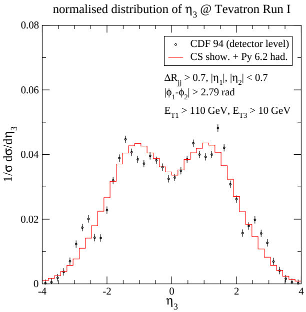




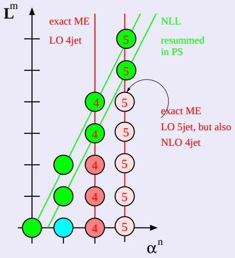
From partons to hadrons

- Experimental definition of jets based on hadrons.
- But: Hadronisation 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.

n-jet rates @ NLL

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

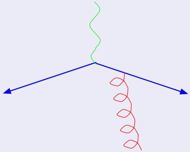
At NLL-Accuracy

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

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

Sudakov weights

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



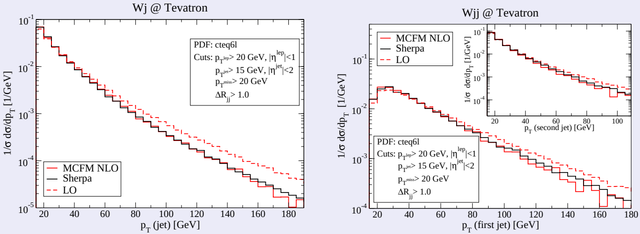
$$\mathcal{W}_{\rm Sud} = \frac{\alpha_s(q)}{\alpha_s(Q_{\rm jet})} \cdot \Delta_q(E_{\rm c.m.}, Q_{\rm jet}) \frac{\Delta_q(E_{\rm c.m.}, Q_{\rm jet})}{\Delta_q(q, Q_{\rm jet})} \Delta_q(q, Q_{\rm jet})\Delta_g(q, Q_{\rm jet})$$

Algorithm as scale-setting prescription

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

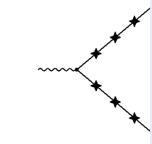
Comparison with MCFM; J.Campbell and R.K.Ellis, Phys. Rev. D **65** (2002) 113007

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.

Vetoing the shower



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

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

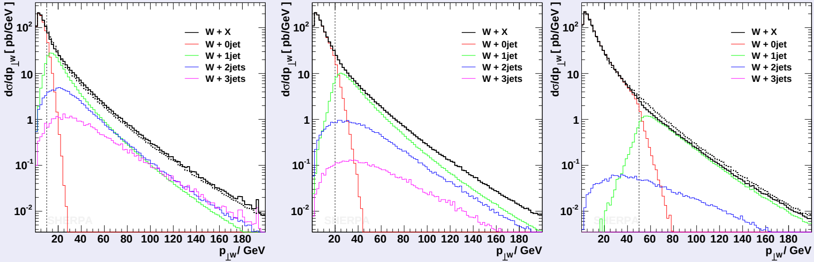
$\Longrightarrow$ Cancels dependence on $Q_{\rm jet}$.

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

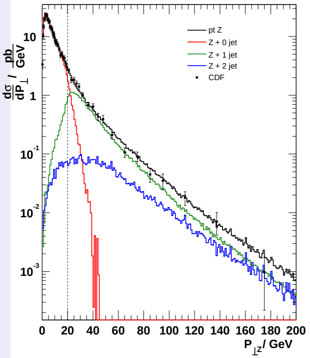
$Q_{\rm jet} = 10\,{\rm GeV}$ $Q_{\rm jet} = 30\,{\rm GeV}$ $Q_{\rm jet} = 50\,{\rm GeV}$

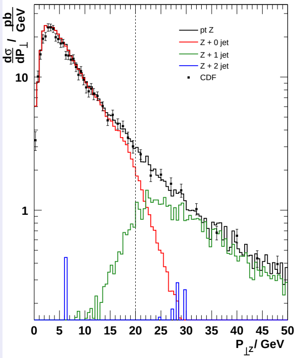


Comparison with data from Tevatron

$p_\perp$ of Z-bosons

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

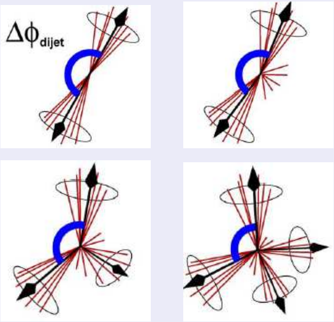




Azimuthal decorrelations of jets at the Tevatron

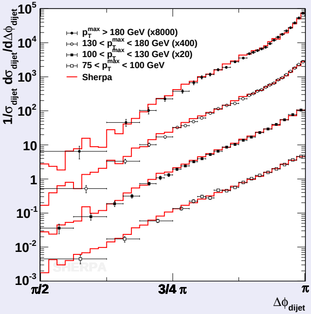
Idea

- Check QCD radiation pattern



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

D0, Phys.Rev.Lett.**94** (2005) 221801



Improving the algorithm

Using the shower

- Two problems in the description so far:
  - Typically jet variable and ordering variable in parton shower not identical $\longrightarrow$ mismatches in kinematics/ordering.
  - Sudakov form factors in parton shower and 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 and veto event if a jet was generated.

COMIX+Catani-Seymour shower

Results in e^+e^- collisions at LEP1

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

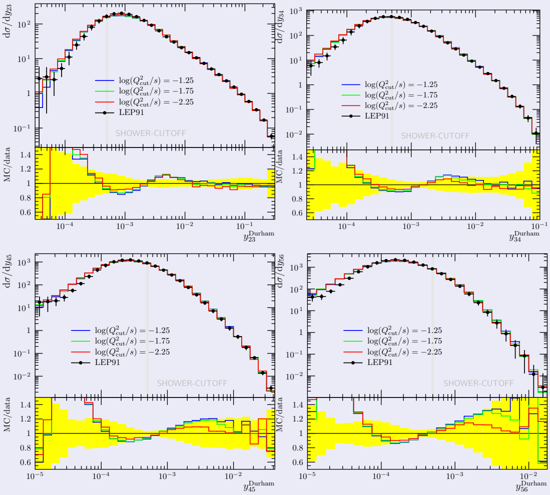
- Stabilisation of total cross sections (vs. $Q_{\rm cut}$ and $N_{\rm max}$)

(Normalise MC to total cross section)

$\log_{10} Q^2_{\rm cut}/s$	$N_{\rm max}$				
	0	1	2	3	4
-1.25	40.17(1)	39.65(3)	39.66(3)	39.66(3)	39.67(3)
-1.75		39.38(5)	39.29(6)	39.13(5)	39.13(5)
-2.25		39.27(8)	38.35(9)	37.89(11)	37.60(10)

Results in e^+e^- collisions at LEP1

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

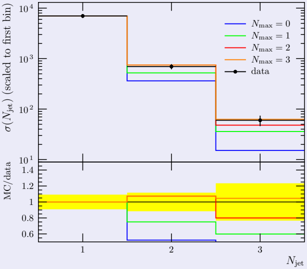


Results for $Z+$ jets at Tevatron

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

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

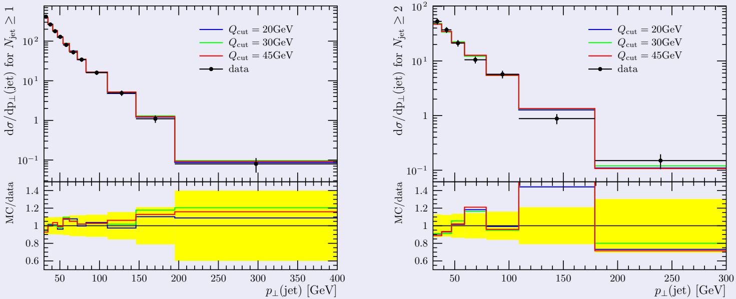
$Q_{\rm cut}$	$N_{\rm max}$						
	0	1	2	3	4	5	6
20 GeV	192.6(1)	191.0(3)	190.5(4)	189.0(5)	189.4(7)	188.2(8)	189.9(10)
30 GeV		192.3(2)	192.7(2)	192.6(3)	192.9(3)	192.7(3)	193.2(3)
45 GeV		193.6(1)	194.4(1)	194.3(1)	194.4(1)	194.6(2)	194.4(1)



Results for $Z+$ jets at Tevatron

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

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



Soft physics simulation in Sherpa

- Implemented a new version of cluster fragmentation

  (still needs a tuning - and debugging);

- a new module for the simulation of hadron and τ decays with special emphasis on τ, B and D decays, including mixing, CP-violation etc.

  (up to now around 200 decay modes with form factors);

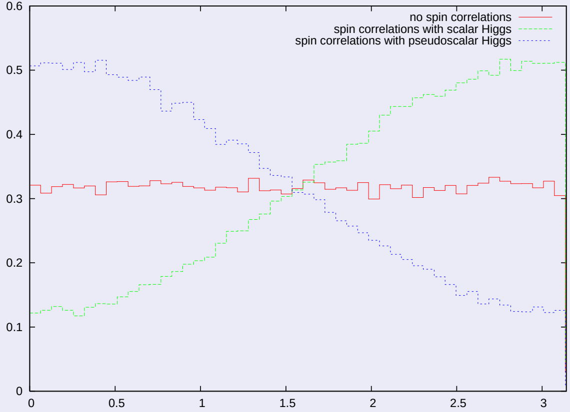
- a new module for the simulation of photon radiation in hadron decays based on the YFS approach

  (big advantage: can be systematically improved in α - done e.g. for some τ-decays, $V \to \ell\bar{\ell}$ and similar);

- all in current release, Sherpa 1.1.

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

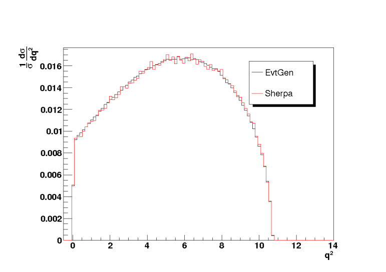
Angle of planes of decay products $(\pi\nu)$ in c.m.s

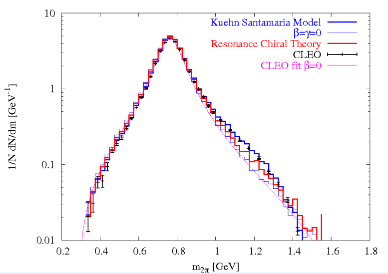


Example (2): Form factors in decays

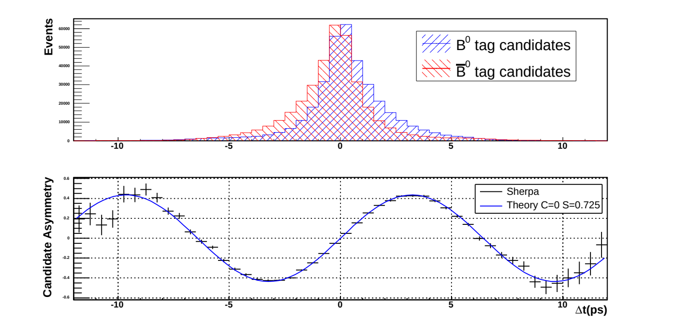
$B \to D^* \ell \nu$

$\tau \to \pi \pi \nu$

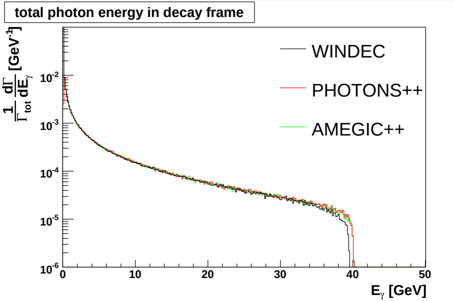




Example (3): $B\bar{B}$-mixing and decay into $J/\Psi K_S$



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



Forthcoming attractions

New features in version 1.2 (experimental)

- Including new ME generator COMIX:
  - Will allow for significantly higher multiplicities: $pp \to V + (\leq 6)j$, $Q\bar{Q} + (\leq 6)j$, $(\leq 6)j$ quite painless,

    (even more feasible - but painful due to integration)
  - No more libraries written out, compiled and linked.
- Including new Catani-Seymour shower

  (+ merging, of course);
- Automated decay chains for **all** heavy particles

  (up to now only user-defined decay chains feasible);
- Automated Catani-Seymour subtraction (massive dipoles work in progress).

Summary

- Many interesting signals at LHC “spoiled” by QCD.
- Simulation tools mandatory for success of LHC
- Merging of ME& PS extremely powerful & complementary to MC@NLO.
- Sherpa a versatile tool - new features becoming available: more BSM models, higher ME multis, new showers, new UE, hadronisation and hadron decays.
- Time to validate essential tools is now!
- By end of 2009: CKKW@NLO for e^+e^- collisions hadron collisions could be a bit more tricky.