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IFJ-PAN

Herwig++ Team Members

Main Development:

Stefan Gieseke, David Grellscheid, Alberto Ribon, Peter Richardson, Mike Seymour, PS, Bryan Webber

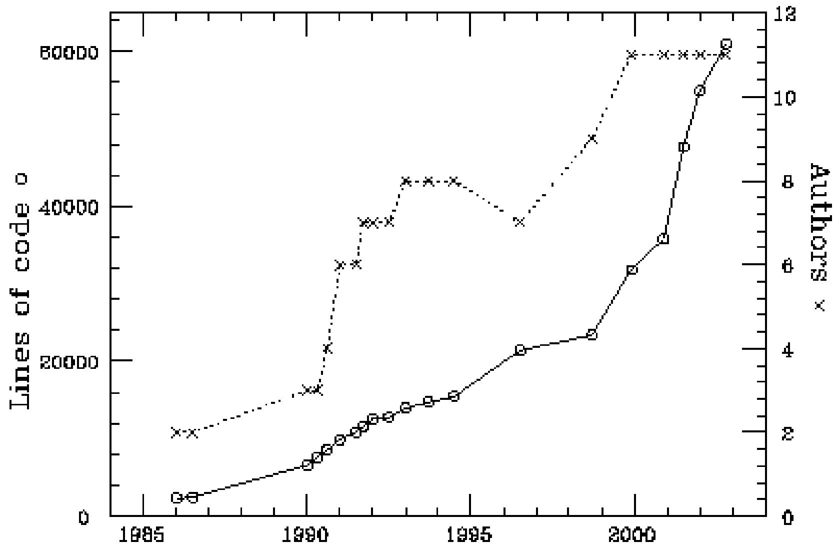
Sub-Project Development:

CKKW: Simon Plätzer, MC@NLO: Seyi Latunde-Dada, Top-Decays: Keith Hamilton

- Why Herwig++
- New Parton Shower Variables
- New Hadron Decay Matrix Elements
  - Spin Correlations
- Current Status
  - $e^+e^- \rightarrow$ q qbar + X
  - P P $\rightarrow l^+l^- + X, l^\pm \nu + X$
  - CKKW algorithm
  - MC@NLO method

Complete rewrite in C++

- Aim for full multi-purpose generator for LHC and future colliders
- Preserve main features of HERWIG
  - Angular ordered shower
  - Cluster Hadronization
- New features and improvements
  - Improved evolution for heavy quarks
  - Consistent radiation for unstable particles



Growth of HERWIG

Quasi-Collinear Limit (heavy quarks)

Sudakov-basis *p,n* with $p^2 = M^2$, $n^2 = 0$

$$p_q = z\,p + \beta_q n - q_T$$

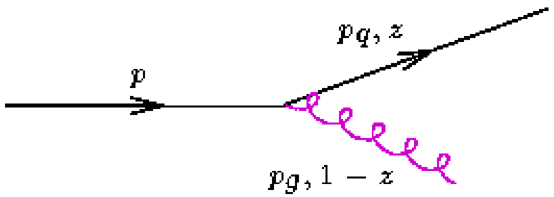
$$p_g = (1-z)\,p + \beta_g n + q_T$$

Quasi-Collinear limit for radiation off heavy quark,

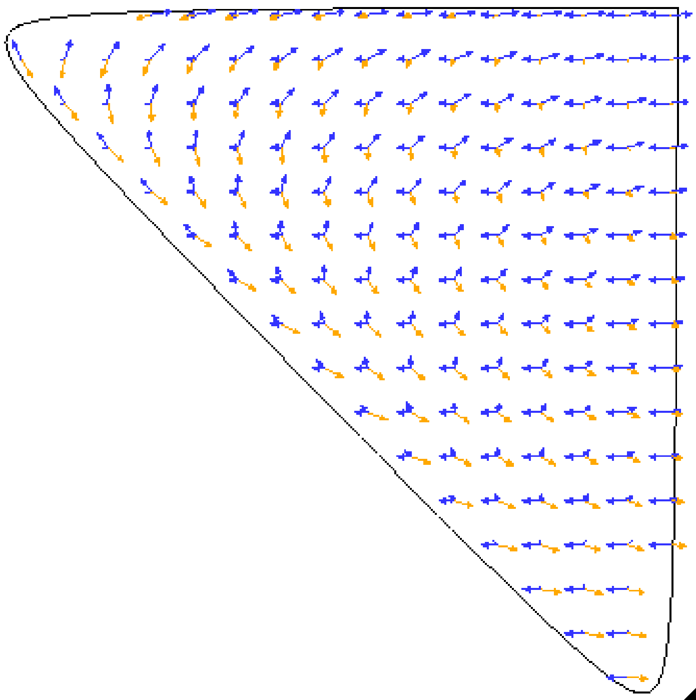
$$P_{gq}(z,\boldsymbol{q}^2,m^2) = C_F\left[\frac{1+z^2}{1-z} - \frac{2z(1-z)m^2}{\boldsymbol{q}^2+(1-z)^2 m^2}\right]$$

$$= \frac{C_F}{1-z}\left[1+z^2 - \frac{2m^2}{z\tilde{q}^2}\right]$$

Single emission:



$q\bar{q}g$–Phase space $(x, \bar{x})$



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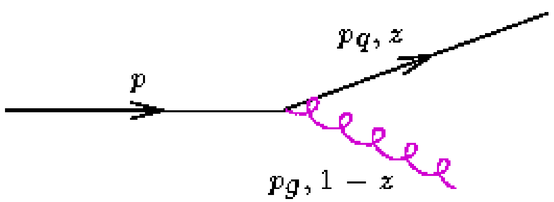
$$= \frac{C_F}{1-z}\left[1+z^2 - \frac{2m^2}{z\tilde{q}^2}\right]$$

New evolution variable for q->qg, similar for other splittings

$$\tilde{q}^2 = \frac{q^2}{z^2(1-z)^2} + \frac{m^2}{z^2}$$

Single emission:



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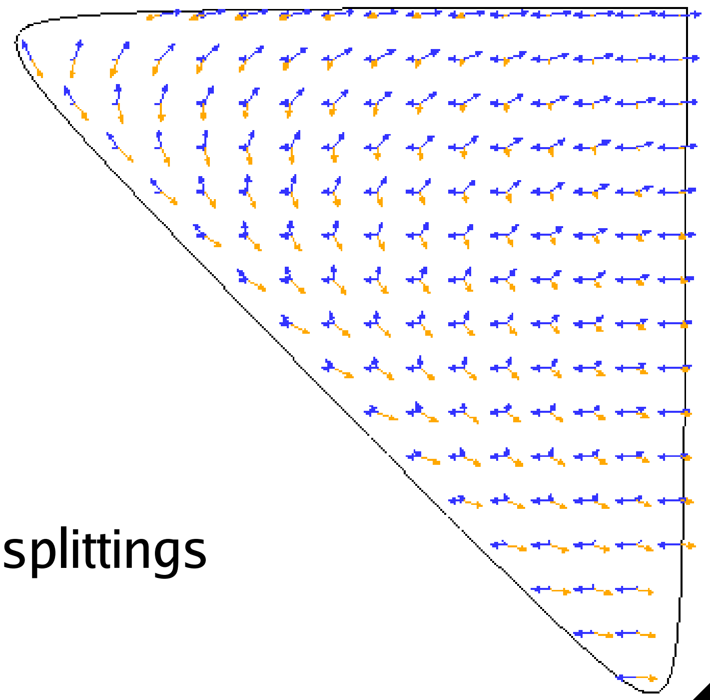
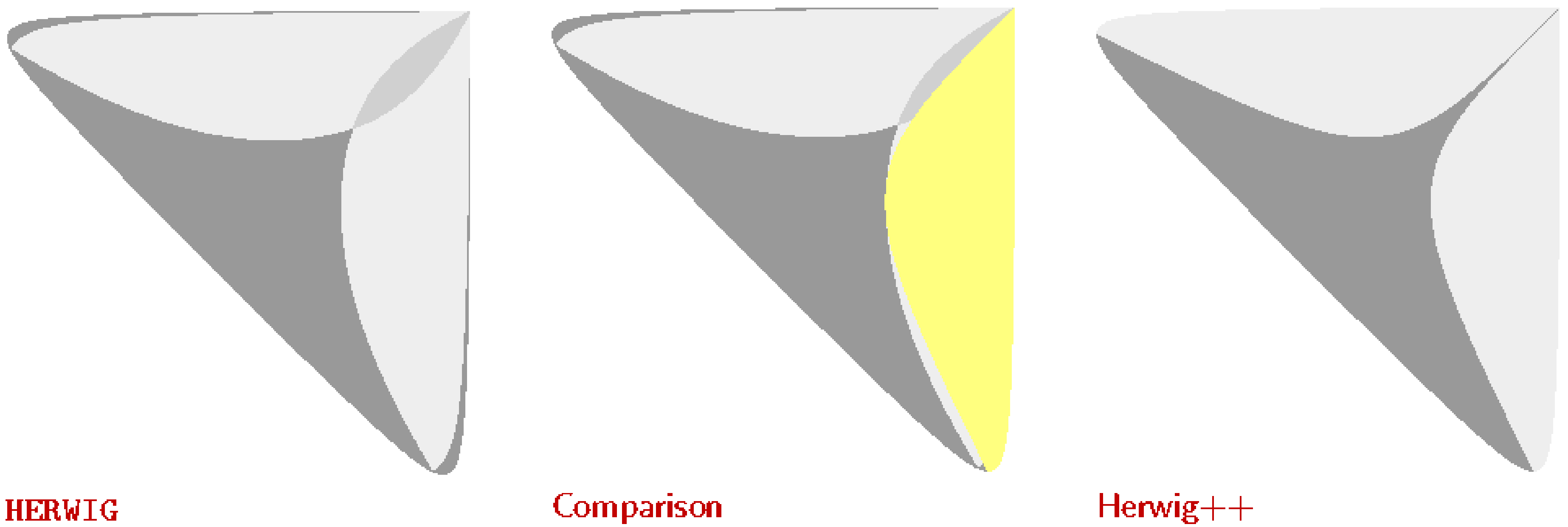


$q\bar{q}g$ Phase Space old vs new variables



✘ Larger dead region

✓ Smooth Coverage of soft region

✓ No overlapping regions of phase space

New Evolution Variables

- Kinematics allow better treatment of heavy particles, avoiding overlapping regions in phase-space, particularly for soft emissions
- Argument of running coupling chosen as

$$\alpha_S(z^2(1-z)^2\tilde{q}^2)$$

- Angular ordering given as

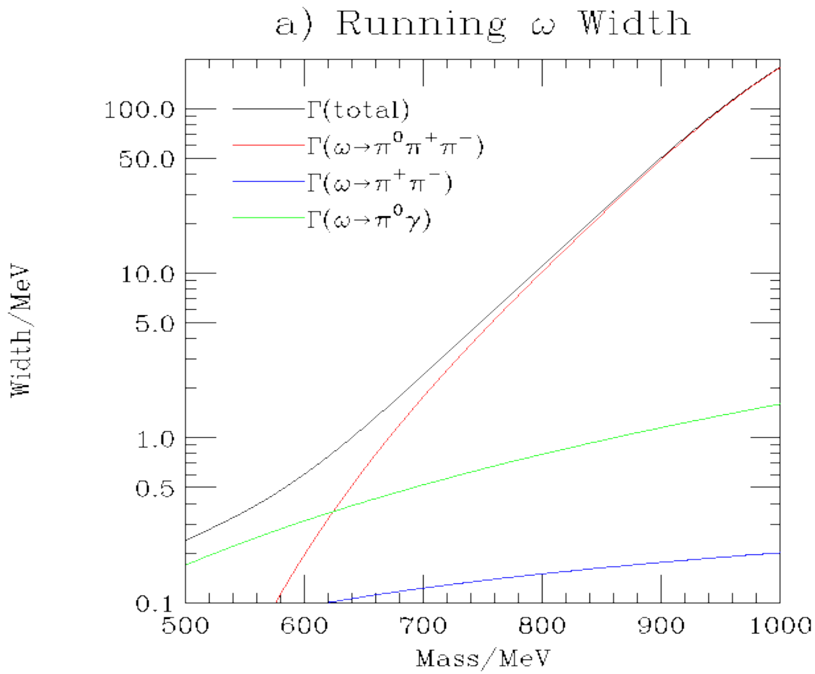
$$\tilde{q}_{i+1} < z_i \tilde{q}_i, \qquad \tilde{k}_{i+1} < (1-z_i)\tilde{q}_{i.}$$

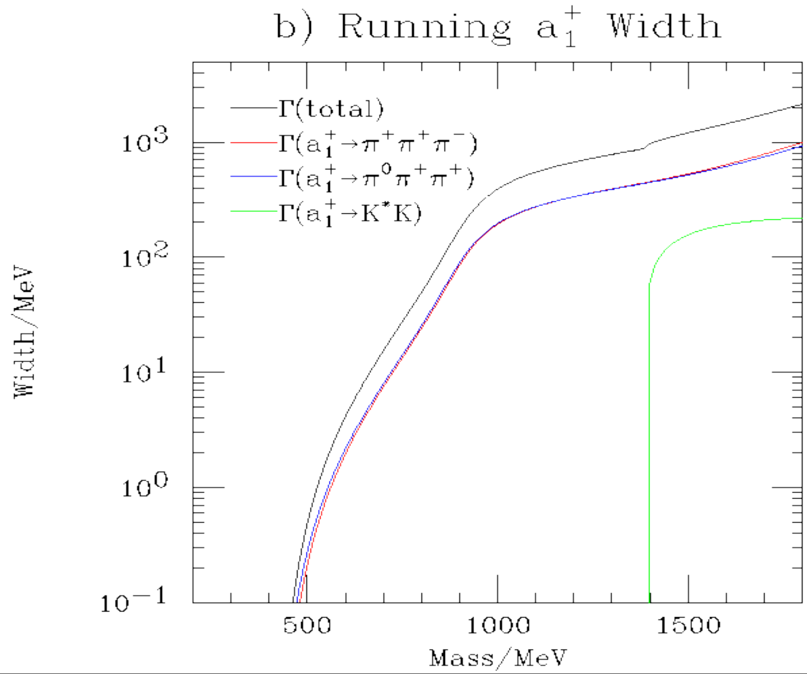
- Technically a reinterpretation of known evolution variables; Sudakov's remain the same, branching probability given by

$$dP(a \rightarrow bc) = \frac{d\tilde{q}^2}{\tilde{q}^2}\frac{C_i \alpha_S}{2\pi} P_{bc}(z, \tilde{q})\, dz$$

- FORTRAN Herwig hadrons produced on-shell only
- Fundamental particles smeared by Breit-Wigner
- Hadrons include factor

$$\frac{1}{\pi}\int_{m^2_{min}}^{m^2_{max}} dm^2 \frac{m\,\Gamma(m)}{(m^2-M^2)^2+m^2\,\Gamma(m)^2}$$



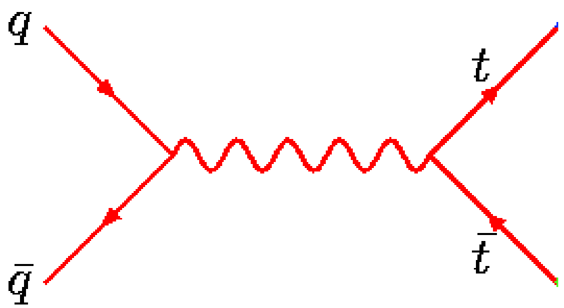


Spin Correlations

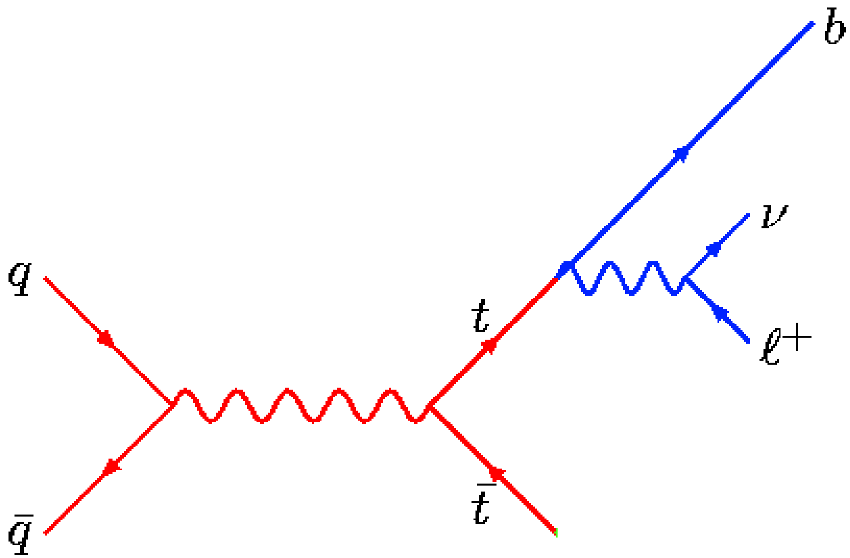
- Structure of decays in Herwig++ based on spin correlations
- Present method with an example, $qq \to tt$ followed by partonic decay of top quarks
- First generate momentum of top quarks using polarized cross-section

$$|\mathcal{M}|^2 = \rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}_{\kappa_1\kappa_2;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\kappa'_1\kappa'_2;\lambda'_1\ldots\lambda'_n}$$

Spin Correlations



$$|\mathcal{M}|^2 = \rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}^{q\bar{q}\to t\bar{t}}_{\kappa_1\kappa_2;\lambda_t\lambda_{\bar{t}}}\mathcal{M}^{*q\bar{q}\to t\bar{t}}_{\kappa'_1\kappa'_2;\lambda'_t\lambda'_{\bar{t}}}$$



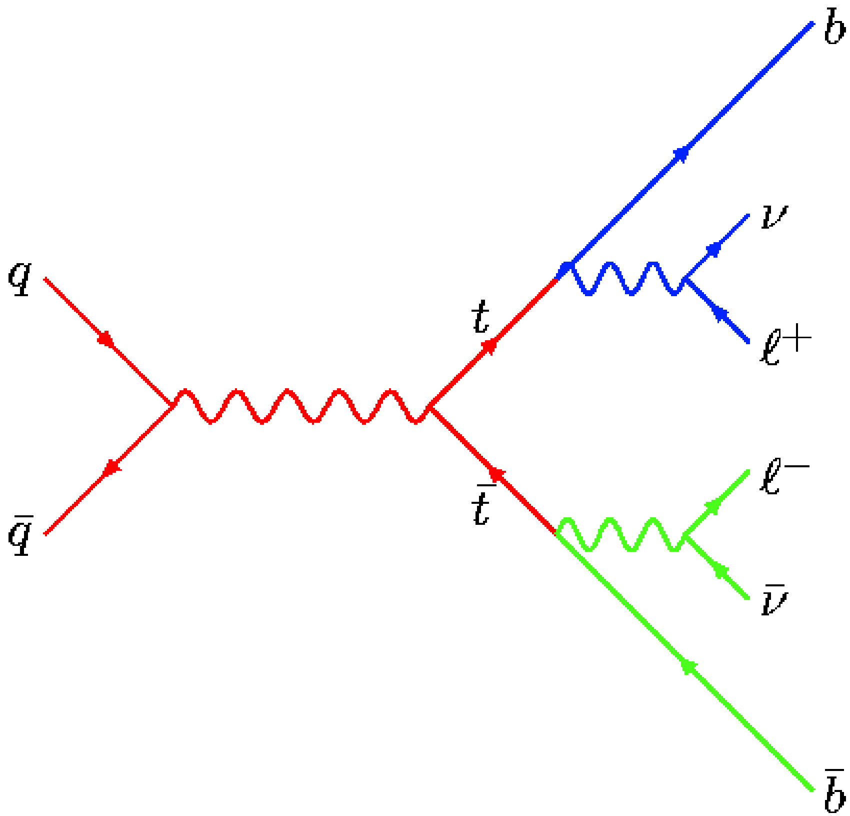
- Outgoing quark selected at random, spin density computed

$$\rho_{\lambda_j \lambda'_j} = \frac{1}{N_\rho} \rho^1_{\kappa_1 \kappa'_1} \rho^2_{\kappa_2 \kappa'_2} \prod_{i \neq j} D^i_{\lambda_i \lambda'_i} \mathcal{M}_{\kappa_1 \kappa_2; \lambda_1 \ldots \lambda_j \ldots \lambda_n} \mathcal{M}^*_{\kappa'_1 \kappa'_2; \lambda'_1 \ldots \lambda'_j \ldots \lambda'_n}$$

- Momenta of decay particles produced using

$$\rho_{\lambda_0 \lambda'_0} \mathcal{M}_{\lambda_0; \lambda_1 \ldots \lambda_n} \mathcal{M}^*_{\lambda'_0; \lambda'_1 \ldots \lambda'_n}$$

$$|\mathcal{M}|^2 = \rho^1_{\kappa_1 \kappa'_1} \rho^2_{\kappa_2 \kappa'_2} \mathcal{M}^{q\bar{q} \to t\bar{t}}_{\kappa_1 \kappa_2; \lambda_t \lambda_{\bar{t}}} \mathcal{M}^{*q\bar{q} \to t\bar{t}}_{\kappa'_1 \kappa'_2; \lambda'_t \lambda'_{\bar{t}}} \mathcal{M}^{t \to bl\nu}_{\lambda_t} \mathcal{M}^{*t \to bl\nu}_{\lambda'_t}$$



$$|\mathcal{M}|^2 = \rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\mathcal{M}^{q\bar{q}\to t\bar{t}}_{\kappa_1\kappa_2;\lambda_t\lambda_{\bar{t}}}\mathcal{M}^{*q\bar{q}\to t\bar{t}}_{\kappa'_1\kappa'_2;\lambda'_t\lambda'_{\bar{t}}}$$
$$\mathcal{M}^{t\to bl\nu}_{\lambda_t}\mathcal{M}^{*t\to bl\nu}_{\lambda'_t}$$
$$\mathcal{M}^{\bar{t}\to\bar{b}l\nu}_{\lambda_{\bar{t}}}\mathcal{M}^{*\bar{t}\to\bar{b}l\nu}_{\lambda'_{\bar{t}}}$$

- Outgoing quark selected at random, spin density computed

$$\rho_{\lambda_j\lambda'_j} = \frac{1}{N_\rho}\rho^1_{\kappa_1\kappa'_1}\rho^2_{\kappa_2\kappa'_2}\prod_{i\neq j}D^i_{\lambda_i\lambda'_i}\mathcal{M}_{\kappa_1\kappa_2;\lambda_1\ldots\lambda_j\ldots\lambda_n}\mathcal{M}^*_{\kappa'_1\kappa'_2;\lambda'_1\ldots\lambda'_j\ldots\lambda'_n}$$

- Momenta of decay particles produced using

$$\rho_{\lambda_0\lambda'_0}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\lambda'_0;\lambda'_1\ldots\lambda'_n}$$

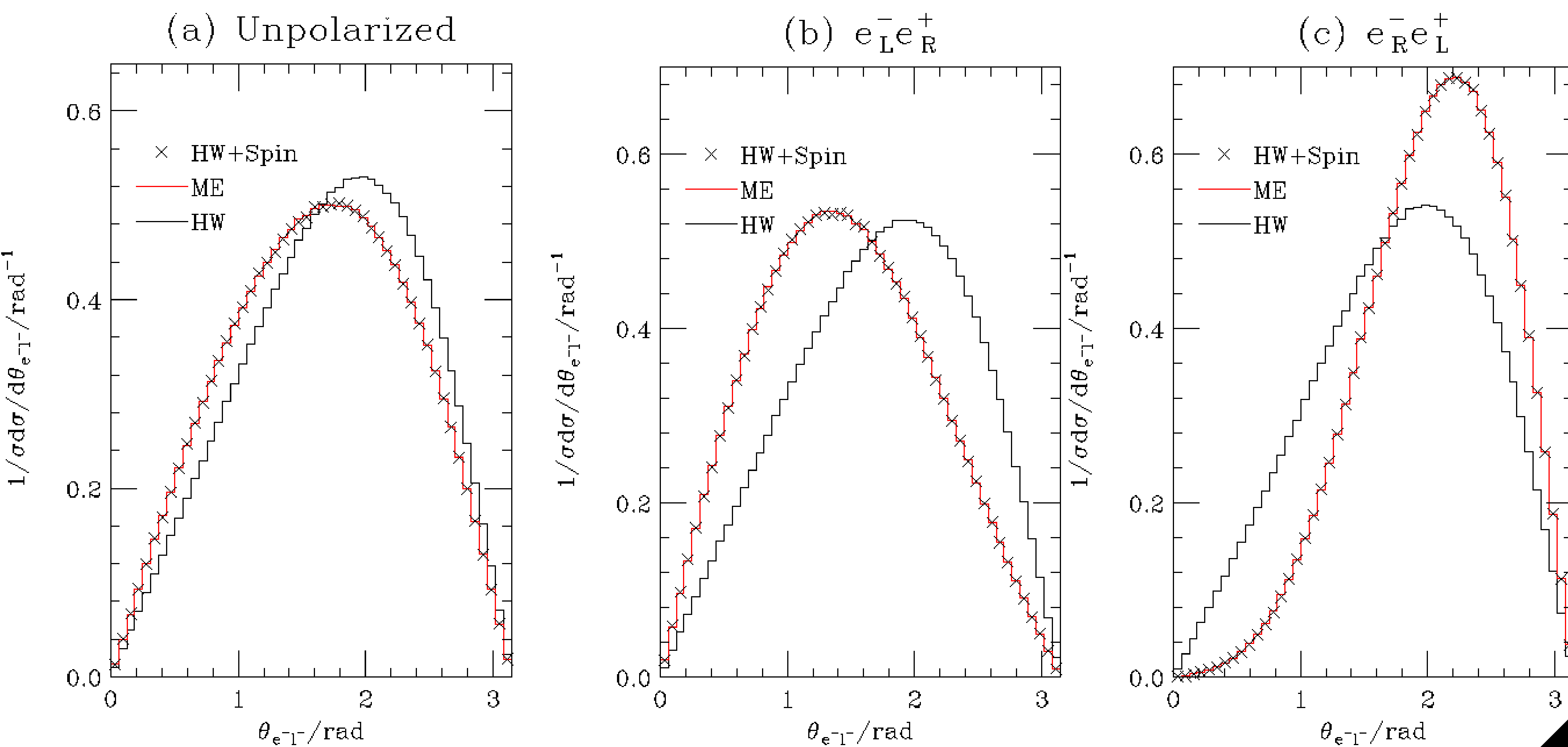
- After one chain finished, decay matrix computed

$$D_{\lambda_0\lambda'_0} = \frac{1}{N_D}\mathcal{M}_{\lambda_0;\lambda_1\ldots\lambda_n}\mathcal{M}^*_{\lambda'_0;\lambda'_1\ldots\lambda'_n}\prod_{i=1,n}D^i_{\lambda_i\lambda'_i}$$

- Narrow width matrix element

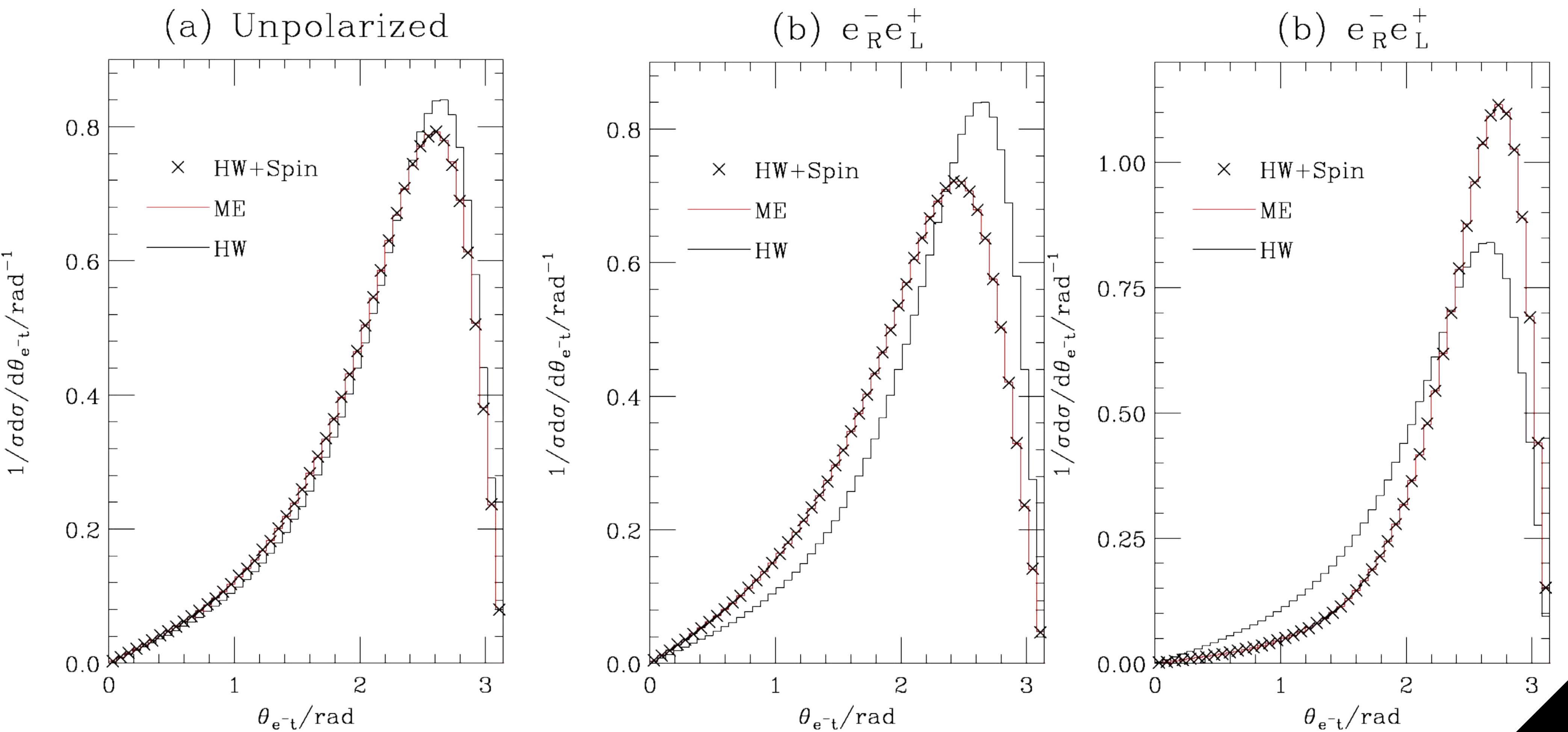
Top pair production in e^+e^- collisions

- Look at semi-leptonic decays of both top quarks
  - Angle between lepton produced from antitop decay and the beam



Top pair production in e^+e^- collisions

- Look at semi-leptonic decays of both top quarks
  - Angle between lepton and top



- Spin correlations
  - FORTRAN: only fundamental particles
  - C++: general structure for all particles
- Many general vertex structures implemented
- Also model specific vertices
  - Standard Model
    - ffg, ffH, ffγ, ffW, ffZ, gggg, ggg, WWH, WWW,WWWW
  - Randall-Sundrum
    - ffG_R, $ffVG_R$, SSG_R, VVG_R, $VVVG_R$
- Vertex and Spin structures allow for easy matrix element implementation of decays

- Tau Decays (most models from TAUOLA)

$$\mathcal{M} = 2^{-1/2} G_F \bar{u}(p_{\nu_\tau}) \gamma^\mu (1-\gamma_5) u(p_\tau) J_\mu$$

- Vector Meson Decays

$$\mathcal{M} = \epsilon^\mu J_\mu$$

- Tensor Meson Decays

$$\mathcal{M} = \epsilon^{\mu\nu} T_{\mu\nu}$$

- Scalar Decays (P $\rightarrow$ V ff, P $\rightarrow$ VV)
- Semi-leptonic Decays (P $\rightarrow$ Plν, P $\rightarrow$ Vlν, P $\rightarrow$ Tlν)
- Baryon Decays (B $\rightarrow$ B'lν, B $\rightarrow$ B' P, B $\rightarrow$ B'γ)

Current Status $e^+e^- \to q\ qbar + X$

- Version available:
  http://hepforge.cedar.ac.uk/herwig/
  - Full shower evolution with new variables
  - Improved cluster hadronization implemented
  - Spin correlation of decays implemented
  - New hadron decays implemented
  - Soft and hard matrix element corrections implemented
- e^+e^- results (compared with LEP) published hep-ph/0311208 (without spin correlations and improved hadron decays)
- Improvements underway
  - CKKW implementation
  - MC@NLO

Current Status pp collisions

- Initial State Radiation implemented
  - Backward evolution algorithm
    - MRST PDFs used; data available for 1996,1998,1999,2001,2002,2003
  - Using new variables
- Only pp to leptons implemented so far
- UA5 underlying event model almost complete
- Jimmy and Ivan underlying events under development
- Beta version released hep-ph/0602069
- Currently undergoing debugging and comparison to FORTRAN Herwig and data.

CKKW Algorithm

- Algorithm used to match tree-level n-jet matrix elements with parton shower
  - Uses a jet measure to divide phase space into hard and soft regions
- Overview of method
  - Parton Shower is evolved normally, i.e. probability of evolving from scale t_1 to t_2 with no emission (IR cutoff t_0) is

$$\mathcal{P}_{no}(t_1, t_2) = \frac{\Delta(t_1, t_0)}{\Delta(t_2, t_0)}$$

  - Scale t_2 found and p_T of emission computed
    - If p_T of emission is too hard, emission is vetoed
      - Shower continues evolution from t_2

CKKW in Herwig++

- Original Method used k_T-jet measure to define jets

$$y_{ij} = \frac{2\,min(E_i^2, E_j^2)}{Q^2}(1-\cos\theta_{ij}) > y_{cut}$$

- Particular form of Sudakov form factor Implicitly leads to evolution variable $(p_T/z(1-z))^2$
- Can be modified to use any infrared safe jet measure
- Herwig++
  - Also uses Durham jet measure; uses new parton shower variables and modified Sudakov's
  - Currently being tested for e^+e^- events.

MC@NLO

- Matches full NLO Matrix element with parton shower
- Poles of Virtual and Real components canceled separately
  - Local Counterterm
- To avoid double counting of emissions, local counterterm is defined by the kernel of the parton shower
  - Evolution variables differ for different showers
  - Each new parton shower must have counterterms redefined

- MC@NLO approach separates *n* emission hard matrix element from *n+1* emission matrix element
  - Two distinct class of events
  - Weight of some events can be negative
- Purely collinear (initial-state) events are mapped by a longitudinal boost to *n* emission events
- Implemented in FORTRAN HERWIG for several hard matrix elements
- Work underway for new variables of Herwig++
  - Implementing $e^+e^- \to$ q qbar + gluon

Summary

- Herwig++ has been released for e^+e^- collisions
- Beta version released for pp collisions
  - New Variables
  - Improved Hadronization
  - New Decay Matrix Elements
  - Spin Correlations
- Currently work being done on
  - CKKW implementation
  - MC@NLO implementation
- Validation of physics for pp collisions underway
  - Herwig++ 2.0 release in the near future