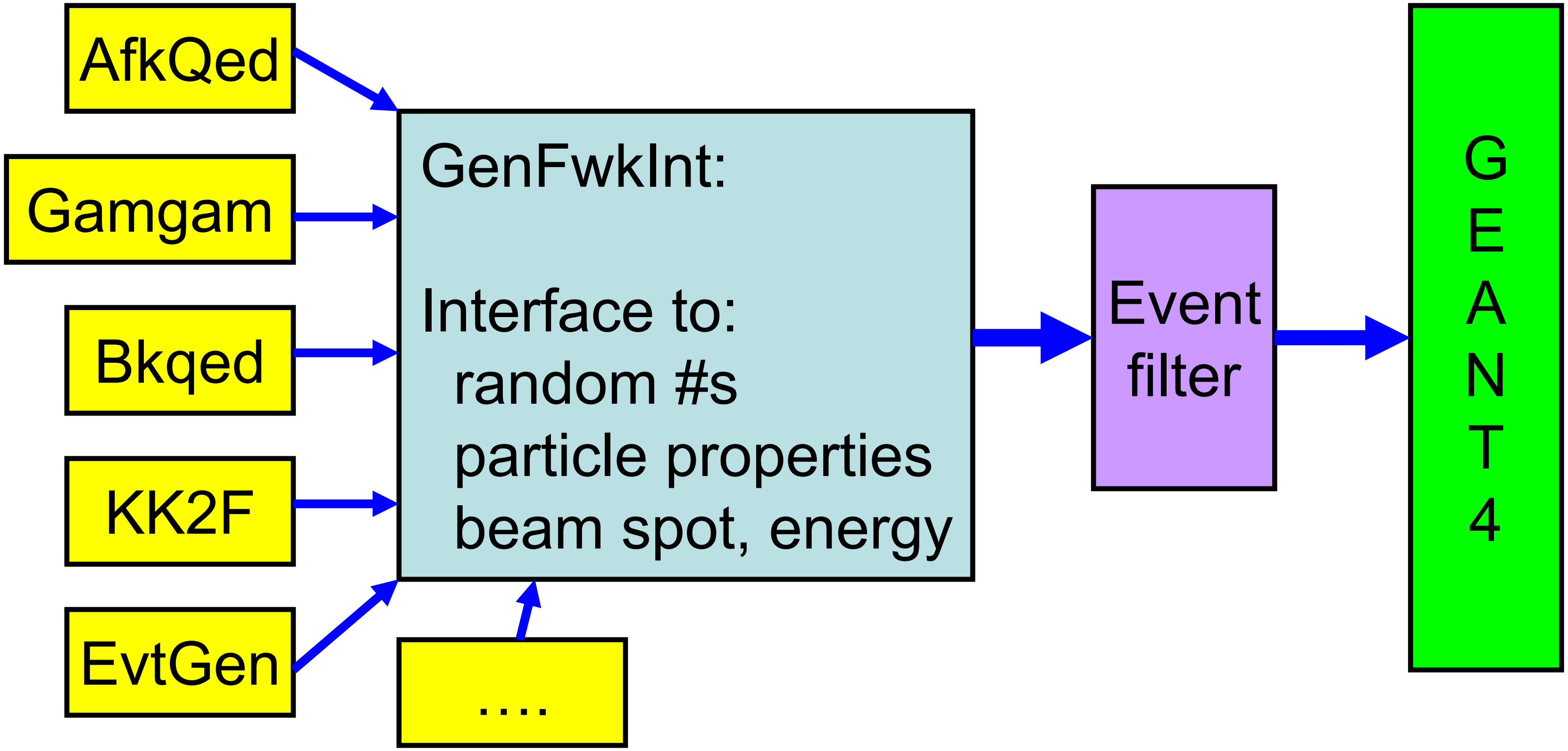
BABAR Physics Generators.

David Lange
Lawrence Livermore Laboratory

- BaBarians need Monte Carlo to solve many different types of problems
  - CP violation
  - Rare decay mode searches
  - Angular analyses
  - Charm production and decay
  - Tau decay
  - 2 photon physics
  - Etc…

Versatile set of generators address these needs

Generators framework



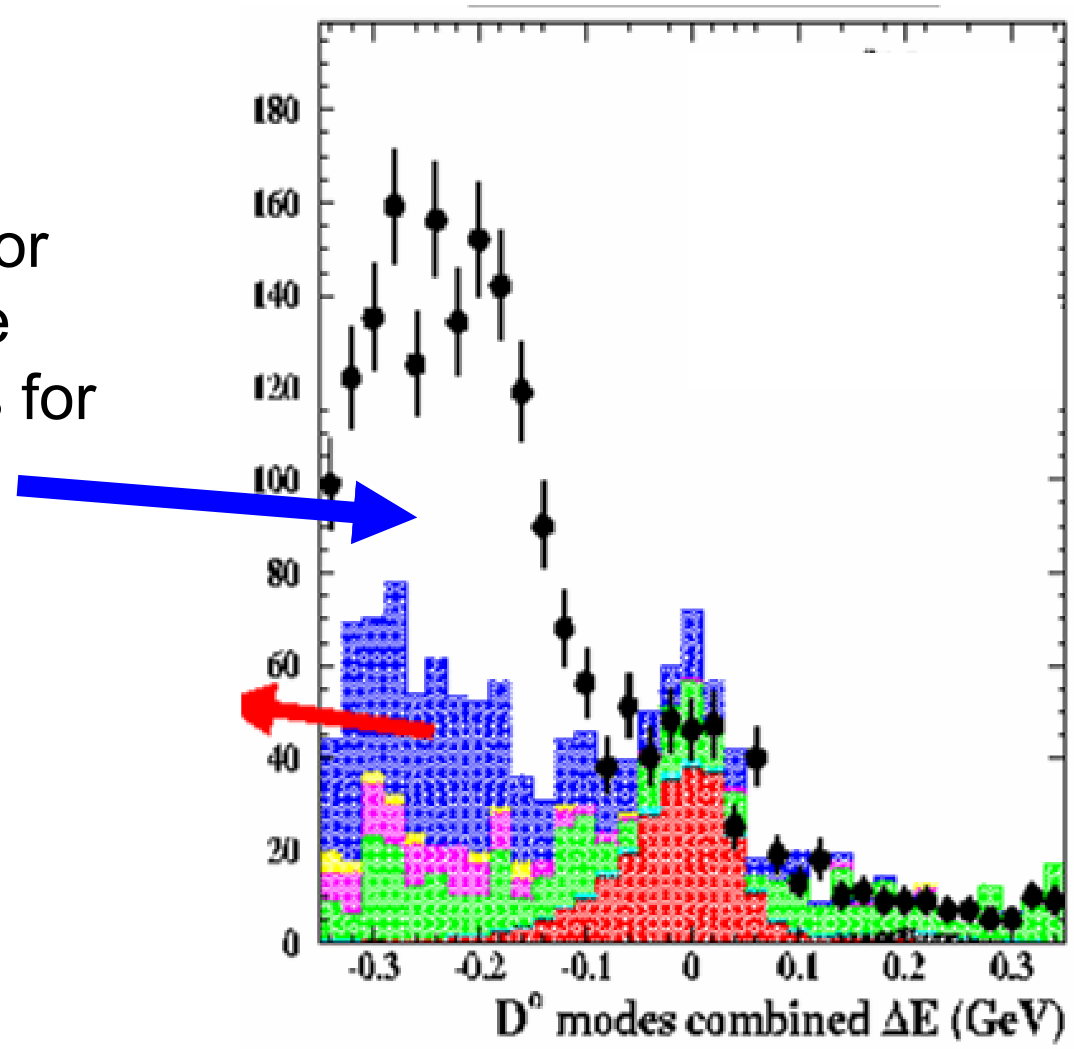
- Development of (or incorporation of) new generators in generators framework largely user driven.

B physics generator: EvtGen

- Developed to provide generator level simulation with precision and flexibility needed for BABARs current and future sample of B mesons
  - Approximately 250M B decays collected by BABAR so far.
- In particular, we worried about:
  - Angular correlations in sequential decays
  - CP violating decays
  - Resonant substructure
  - Specialize matrix elements for rare decays
- Modular structure: Easy extension of the generator as new decays are considered.
- Straightforward interface.

Given large data sample, detailed effects must be modeled in generic B Monte Carlo

Mixed up two decay amplitudes in $B \to D^*\rho$ for generic MC led to large data vs MC differences for some analyses.



Sequential decays

- Many B meson decays have interesting sequential decay chains:

$$B \to D^* \ell\nu \quad \llcorner\!\!\to D\pi$$

$$B \to D^* \ell\nu \quad \llcorner\!\!\to D\gamma$$

$$B \to D^* \quad D^* \quad \llcorner\!\!\to D\pi \quad \llcorner\!\!\to D\pi$$

$$B \to D^* \quad D^* \quad \llcorner\!\!\to D\pi \quad \llcorner\!\!\to D\gamma$$

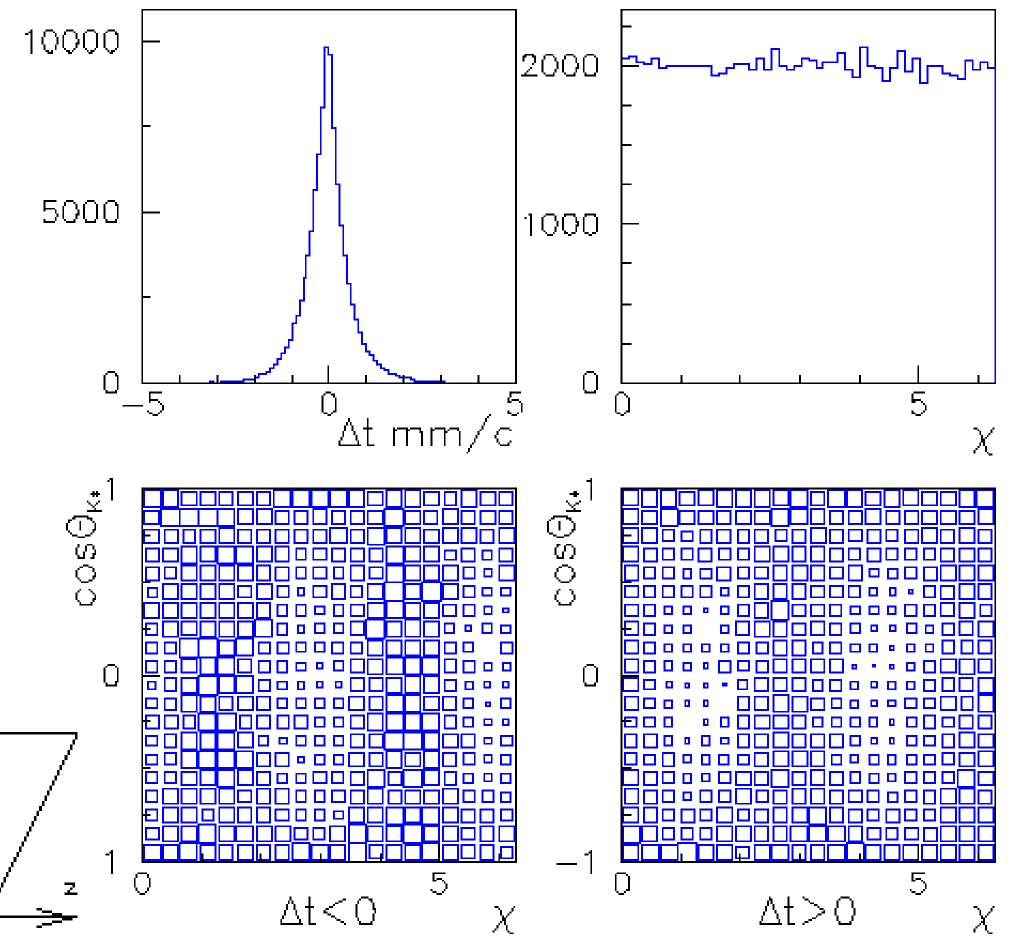
- Want to correctly simulate these decay chains while only implementing the nodes in the decay tree.

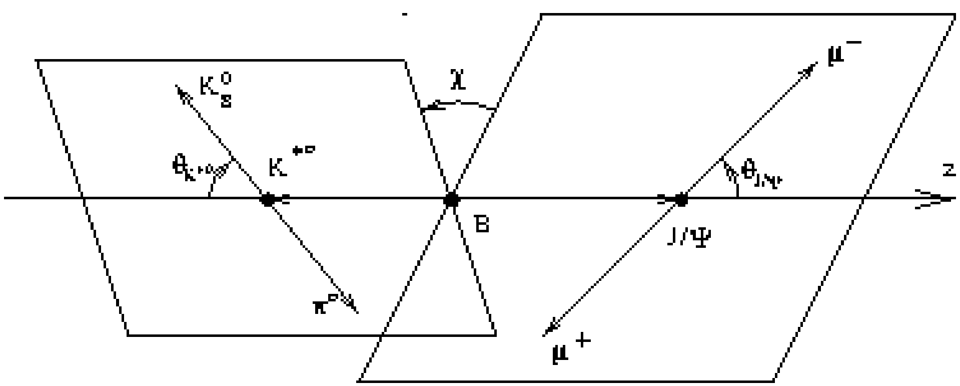
$$B \to D^* \ell\nu \qquad B \to D^* D^*$$

$$D^* \to D\pi \qquad D^* \to D\gamma$$

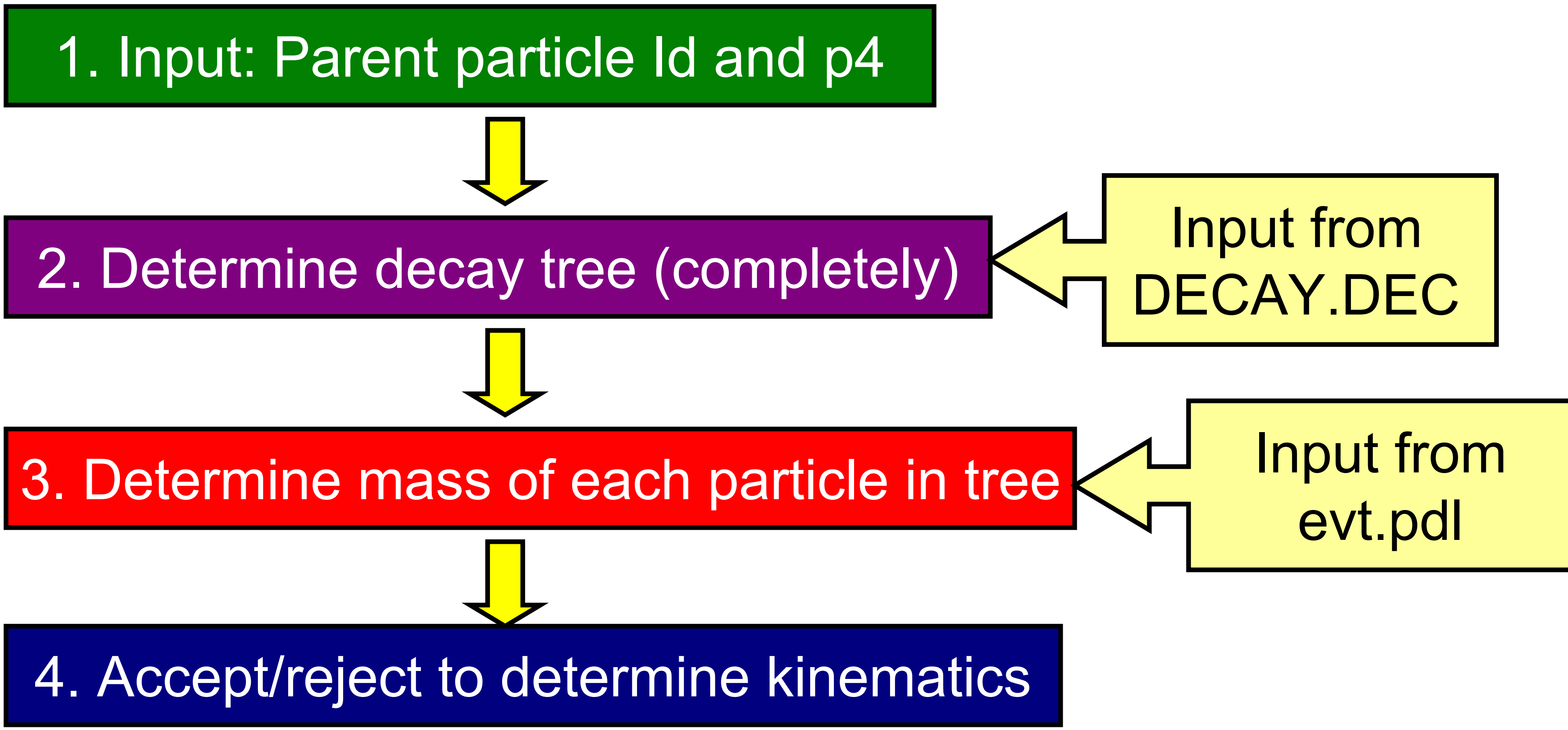
CP violating decays

- $B \rightarrow J/\psi K^{*0}$ $(K^{*0} \rightarrow K_s \pi^0)$
  - Angular correlations and time dependence





EvtGen decay algorithm



- Configuration specified by input files at run time.
  - Users override generic DECAY.DEC to generate MC as needed.

Decay amplitudes are used instead of probabilities

- EvtGen works with amplitudes to correctly handle sequential decays:

$$B \to D^* \quad \tau\nu$$
$$\hookrightarrow D\pi \quad \hookrightarrow \pi\nu$$

$$d\Gamma = |A|^2 d\phi \qquad A = \sum_{\lambda_{D^*}\lambda_\tau} A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau} A^{D^*\to D\pi}_{\lambda_{D^*}} A^{\tau\to\pi\nu}_{\lambda_\tau}$$

$$A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau} \equiv \langle \lambda_{D^*}\lambda_\tau | H | B \rangle$$

$$\sum_{\lambda_{D^*}} |\lambda_{D^*}\rangle\langle\lambda_{D^*}| = I$$

- Nodes in the decay tree are implemented as “models”. The framework of EvtGen handles the bookkeeping needed to correctly generate the full decay tree.

Advantages to using decay amplitudes

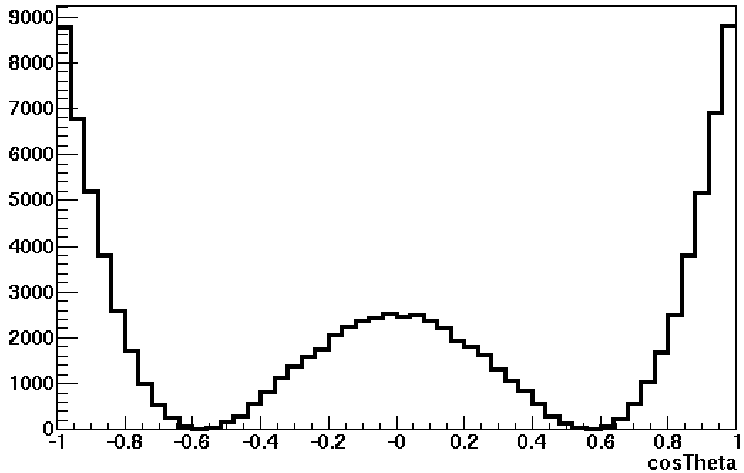
- Implementation of decay models is simplified by using amplitudes instead of probabilities.
- Keeping track of the spin density matrices allows us to generate each node of the decay chain independently.
  - More efficient
  - Avoids the need to determine uncountable # of maximum probabilities
- Generalizes to arbitrarily long decay chains
- Calculation of probabilities and spin density matrices are done by the framework. Models specify only the decay amplitudes.
- However: No interference between particles on different branches of decay tree.

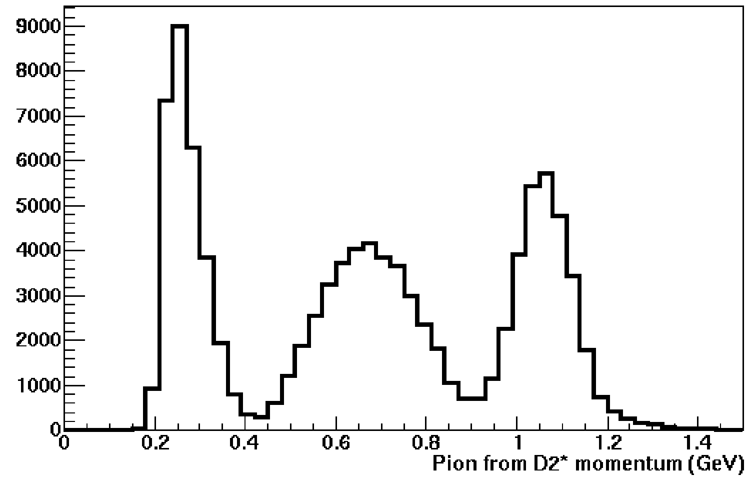
Available decay models

- General purpose models that decay according to specified helicity or partial wave amplitudes
  - Handle decays to two body final states with arbitrary spins. Amplitudes specified at run time.
- Specific CP violating models
- Semileptonic form-factor models
- Dalitz decays
  - Specific: D, η, π^0, ω
  - General Pseudoscalar → 3 Pseudoscalar
- $B \rightarrow Kll$, $b \rightarrow s\gamma$
- Use PHOTOS package for final state radiation.
  - On by default for all decays.

HELAMP/PARTWAVE models

- $B \rightarrow D_2^{**}\pi \quad D_2^{**} \rightarrow D\pi$
  - Known and nontrivial kinematical distributions.
  - For decays with multiple allowed partial waves, weights are specified as model argument





Available decay modes (III)

- SSD_CP model simulates CP violation for final states with a scalar + either a scalar, vector, or tensor.
  - $B \rightarrow \pi\pi$, $B \rightarrow J/\psi Ks$, $B \rightarrow D^*\pi$, etc.
  - Specify in decay table:
    - Δm
    - $\Delta\Gamma/\Gamma$
    - q/p
    - $A(B \rightarrow f)$, $A(Bbar \rightarrow f)$,$A(B \rightarrow fbar)$,$A(Bbar \rightarrow fbar)$
    - z
  - Flexible but relatively new model, so we are still gaining experience with all the possible use cases.

Decay table format

```
Decay D*+
    0.683 D0 pi+      VSS;
    0.306 D+ pi0      VSS;
    0.011 D+ gamma    PARTWAVE 0. 0. 1. 0. 0. 0.;
Enddecay
```

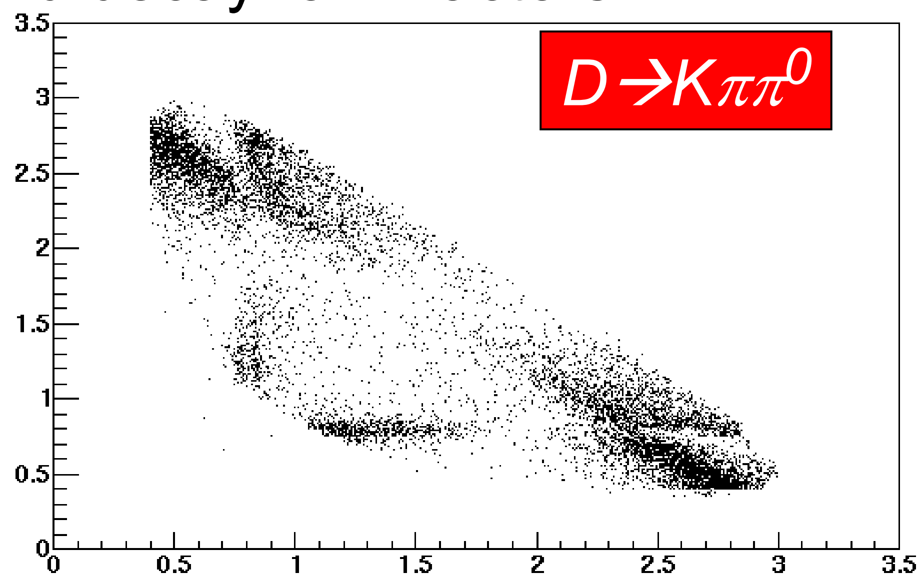
- For each entry in the "Decay" stanza, specify
  - branching fraction (renormalized to 1.0),
  - List of daughters
  - Decay model
  - Decay model arguments (if any).
    - Arguments interpreted as either floats or strings
- About 4000 decays specified in DECAY.DEC

Jetset 7.4 used for inclusive decay generation

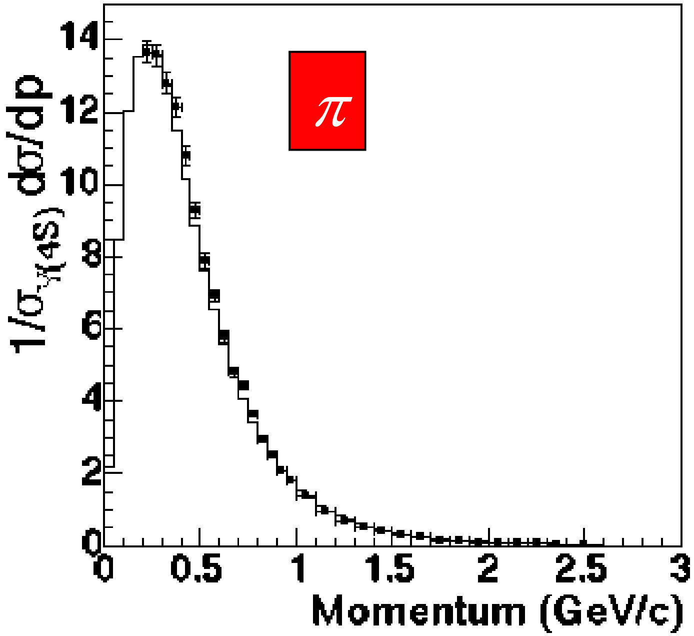
- We rely on Jetset to handle *ee*→*qq* fragmentation and B decays not specified in the decay table.
  - B decays:
    - Approximately 40% of the *B* decay width is not explicitly listed in decay table.
    - Pythia decays are accepted if generated mode is not specified in the decay table.
    - We have performed some tuning to improve the data vs. MC agreement
      - BF to charmless non-resonant states too big.
      - D* production in both *B* and *ee*→*cc* decays

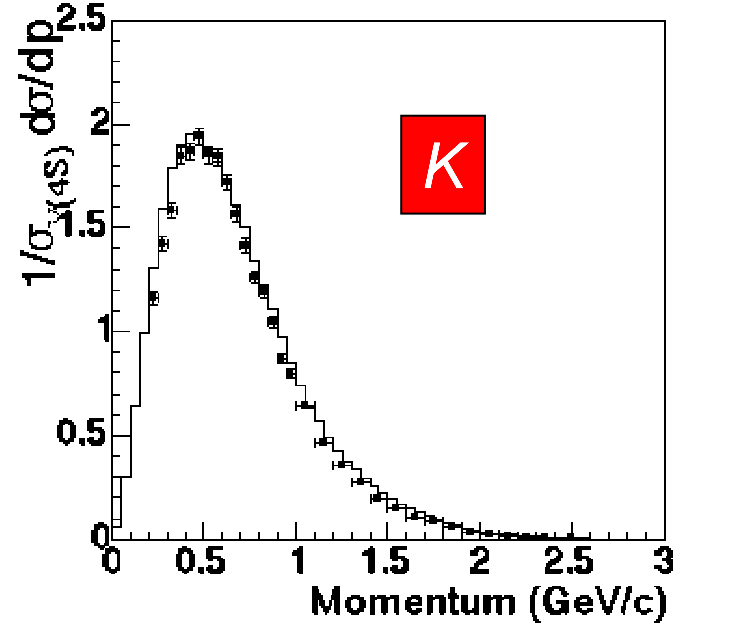
Lineshapes and Dalitz plots

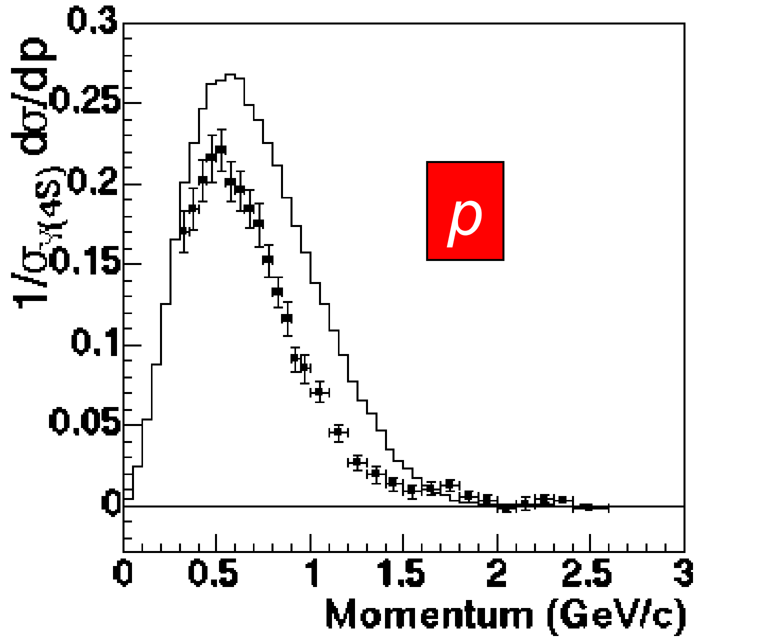
- Try to use relativistic Breit-Wigners for all particles with finite width.
  - Only for decays to two daughters
    - Otherwise non-rel. BW.
  - Particles produced by Jetset have non-rel BW
- Include where possible
  - phase space factors, birth and decay form factors.
- Minimize use of mass cutoffs
  - Still needed in many cases to prevent crashes due to pathological configurations.
- Moving towards integrated lineshape and Dalitz plot code.



Preliminary $\Upsilon(4S) \rightarrow \pi/K/p$ spectra from BABAR

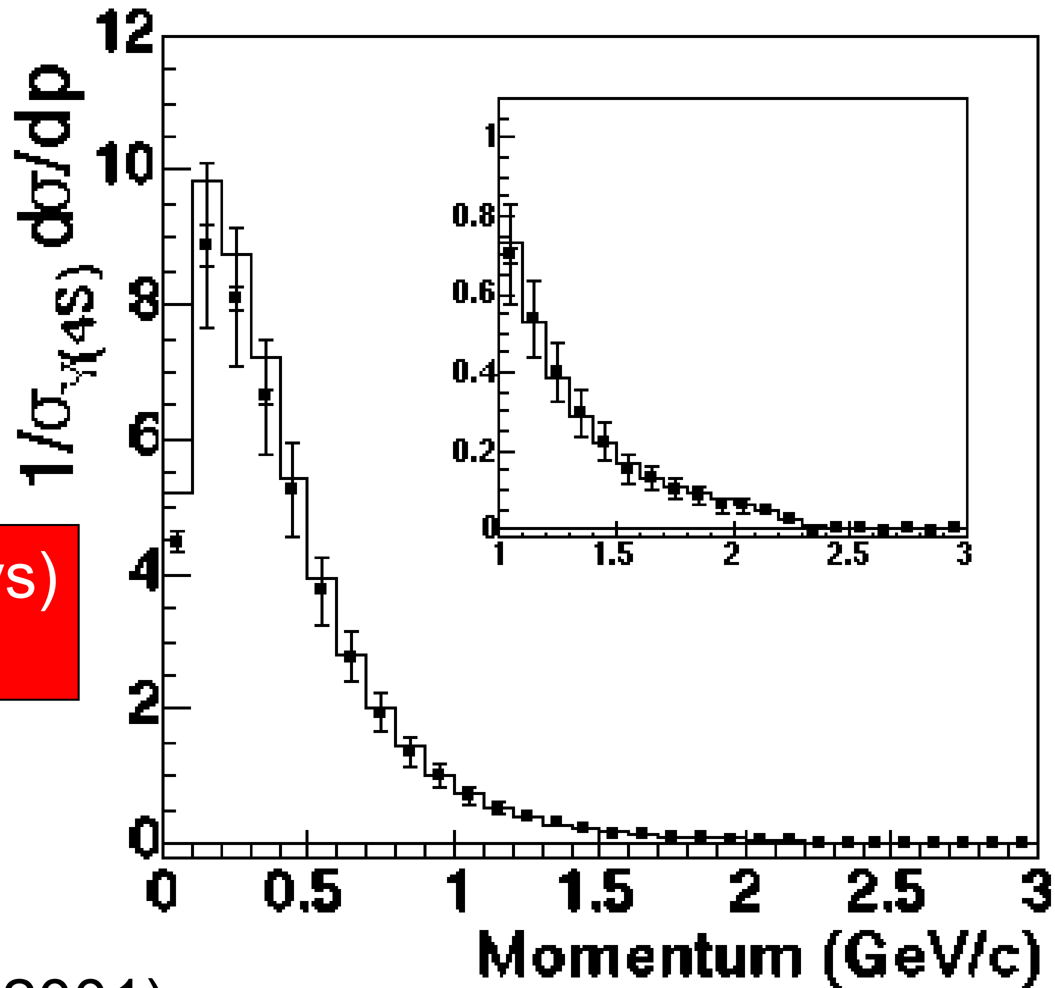






	BABAR	EvtGen
π	7.73+-0.32	7.98
K	1.54+-0.04	1.61
p	0.155+-0.004	0.224

π^0 multiplicity and momentum spectrum



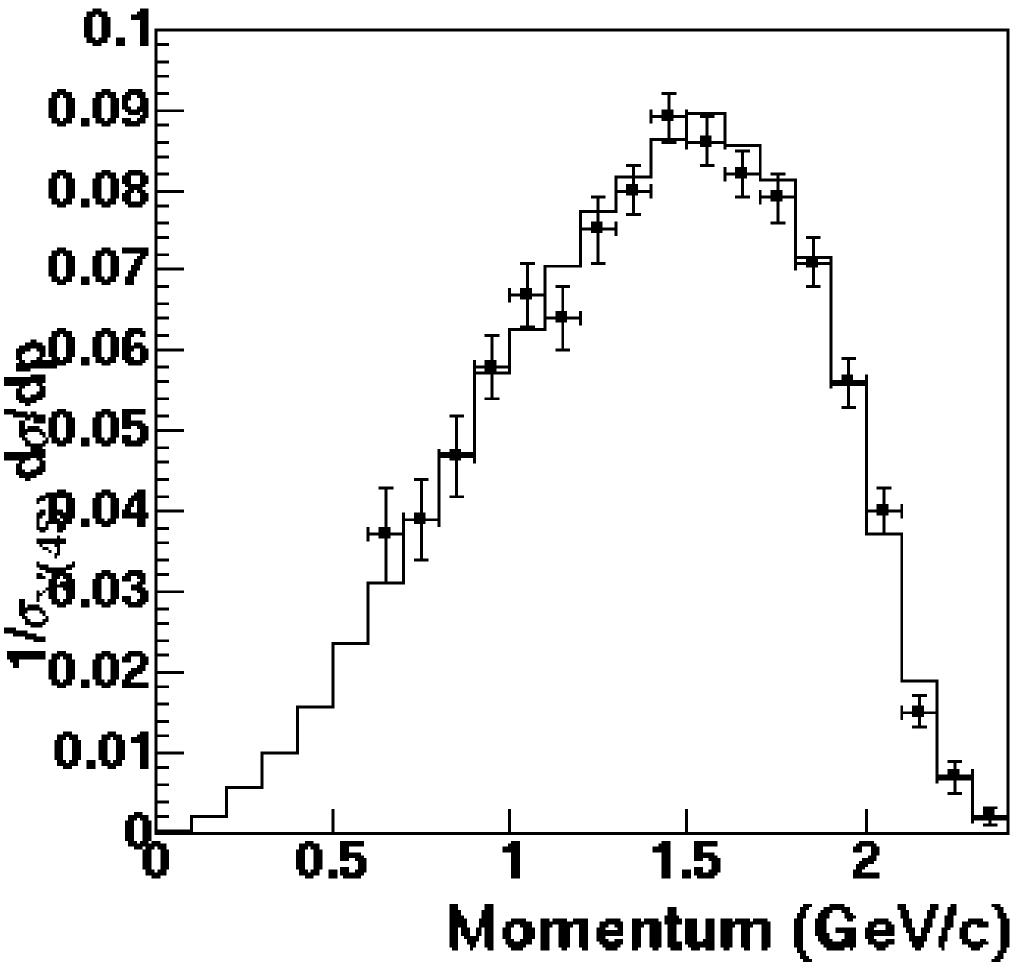
Points = Belle (stat+sys)
Histogram = EvtGen

- PRD 64, 072001, (2001)

$B \rightarrow Xl\nu$ lepton energy spectrum

- Lepton energy spectrum tuned using CLEO data.
  - PRL 76 1570 (1996)

Mode	BF (%)
$D^*l\nu$	5.6
$Dl\nu$	2.1
$D_1^{**}(2420)l\nu$	0.56
$D_0^{**}l\nu$	0.2
$D_1^{**'}(2460)l\nu$	0.37
$D_2^{**}(2460)l\nu$	0.37
$D^*\pi l\nu$	0.3
$D\pi l\nu$	0.9



Inclusive resonance production in B decays

	PDG03	EvtGen
$B \to Xe\nu$	10.7 +/- 0.28	10.6
$B \to D^{+-}X$	24.5 +/- 2.1	32.4
$B \to D^{0}X$	64.0 +/- 2.9	68.2
$B \to D^{*+-}X$	22.5 +/- 1.5	26.2
$B \to D^{*0}X$	26.0 +/- 2.7	25.7
$B \to D^{(*)}D^{(*)}K$	7.1+2.7-1.7	7.7
$B \to J/\psi X$	1.090 +/- 0.035	1.04
$B \to K^{*+-}X$	18 +/- 6	17.5
$B \to \eta X$	17.6 +/- 1.6	22.8
$B \to \Lambda_c X$	6.4 +/- 1.1	3.7
$B \to \Lambda X$	4.0 +/- 0.5	4.6
$B \to \phi X$	3.5 +/- 0.7	4.7

PDG B→D(*) production BFs not consistent with isospin (and B(B→X)=1) at several sigma level

Monte Carlo production cycles

- BABAR generates Monte Carlo to match reconstruction code releases.
- Production generators “frozen” for each cycle
  - DECAY.DEC in particular.
  - Bug fixes ok
  - Rarely, we include updates for new results. More often, improved in next production cycle.
- Given release cycle timescales, we must support multiple release cycles until analysis are completed on data from old releases.

Infrastructure for “Signal” Monte Carlo is independent of release cycles.

- Special (“user”) decay files to specify desired changes to DECAY.DEC.
- Generator level filters.

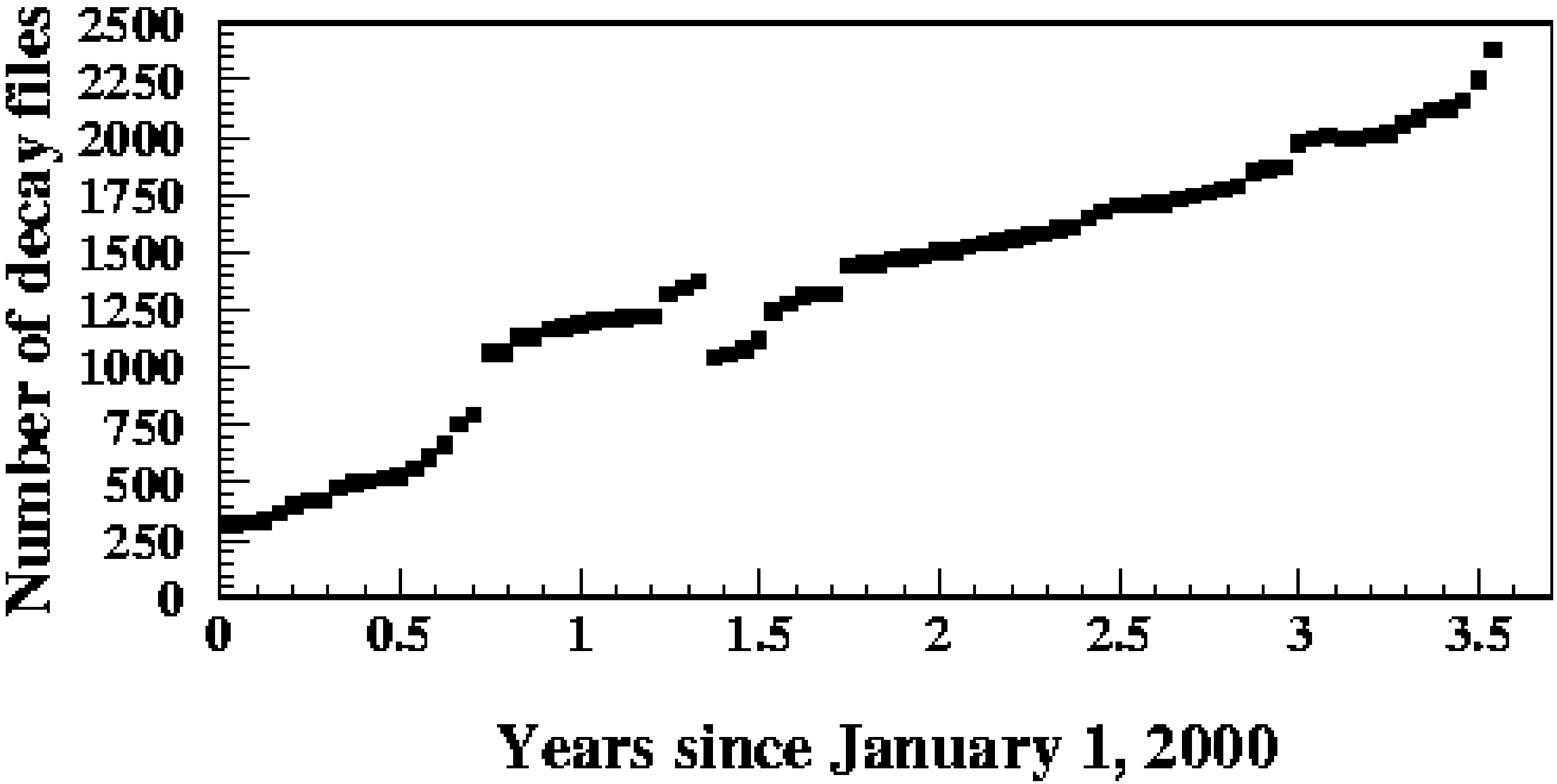
- Production updates these files as requested.
  - Sometimes a special production release is required. This leads to much slower turn around.

The decay table (DECAY.DEC)

- We continue to increase the ability to control EvtGen via DECAY.DEC
  - Decays and branching fractions
  - Particle masses, widths, lineshapes
  - Try to avoid hardwiring numbers that control decay models, instead specifying them as arguments.
  - Control of usage of PHOTOS packages

Additional control avoids the need to change software to produce MC for systematic studies

Users test and commit generator control files to CVS for centralized MC generation



- Large rate of special MC requests.

Generator level filter

- Given processing rate of generator level MC vs. that of BABAR's full Geant4 simulation, filtering events at the generator level is very beneficial to some analyses.
  - Filter on particle properties
    - Particle type
    - Momentum, theta, etc.
  - Filter on combinations of generated particles
    - Eg: Ask for two pions with $m(\pi\pi)$>5.0 GeV
    - Users can do mock up simple "analysis" algorithms

  - Especially low efficiency filters initially led to problems with repeated random number sequences.

Conclusions and plans for EvtGen

- EvtGen available via web page:
  - http://www.slac.stanford.edu/~lange/EvtGen
  - Most recent tar file ~July 1, 2003.
  - Depends on
    - Cernlib (2002):PHOTOS and Pythia
  - Our example test program also depends on
    - CLHEP: Random numbers
    - Root: Histograms in test program
  - Development driven by B_d physics, but essentially all development translates to B_s decays.
    - Mixing and CP
    - Lacking fully developed decay table.
    - Essentially all needed models are already defined.

Conclusions and plans

- BABAR generator development is user driven
  - Generators group benefits greatly from user requests, ideas, bug reports.
  - Its tough to stay ahead, have frequent last minute requests for new features.
- Decay tables show generally good agreement wrt PDG averages
  - We do not take them too literally (though many users correct MC to exactly match).
  - We believe that there will be significant work in coming years to retune decay tables as B factory results on inclusive particle production are completed.