An Introduction to Using EvtGen

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March 2, 2004

Alea iacta est, "The die is cast", Julius Ceasar Jan. 10, 49BC as he crossed Rubicon.

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Outline:

- What problems EvtGen can and can not solve
- Selection algorithm
- Physics processes that are implemented
- How to write your own physics modules
- Using EvtGen in CLEO-c

This talk borrows much from a tutorial D. Lange and I gave for an LHC generator workshop in the summer of '03

Motivation

- Why should you care about EvtGen in CLEO-c?
  - We have been generating the 'million MC' samples using Evtgen.
  - Further simulation of hadronic decays in CLEO-c will be done with EvtGen.
  - Continuum simulated via EvtGen using the “Lund Area Law”.
  - Radiative return events are simulated via EvtGen.
  - EvtGen is integrated in the suez framework.

Sequential decays

- Many decays have interesting sequential decay chains:

$$B \to D^* \ell \nu \qquad \qquad B \to D^* \ell \nu$$
$$\hookrightarrow D\pi \qquad \qquad \hookrightarrow D\gamma$$

$$B \to D^* \; D^* \qquad \qquad B \to D^* \; D^*$$
$$\hookrightarrow D\pi \hookrightarrow D\pi \qquad \qquad \hookrightarrow D\pi \hookrightarrow D\gamma$$

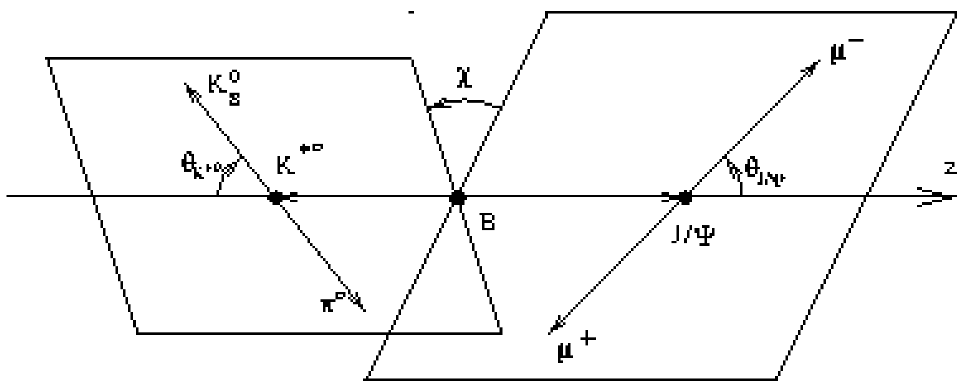
- Want to correctly simulate these decay chains while only implementing the nodes in the decay tree.

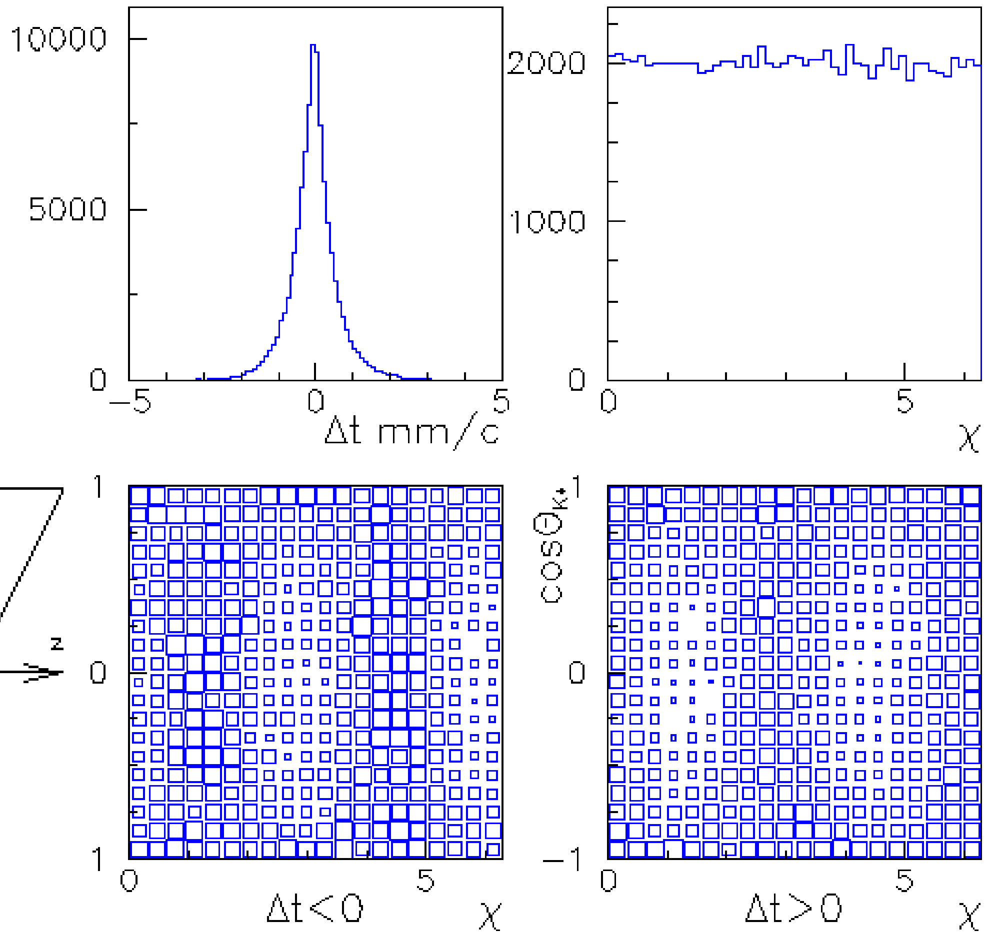
ıc nodes in the decay tree:

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

CP violating decays

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





Decay amplitudes are used instead of probabilities

- EvtGen works with amplitudes to correctly handle sequential decays:

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

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

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

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

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

Selection algorithm (I)

- Generate the *B->D*lν* decay

$$P = \sum_{\lambda_{D^*}\lambda_\tau} |A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau}|^2$$

num probability and acccpt

- Compare with maximum probability and accept or reject generated *B->D*lν* decay.
  - Maximum probability specified in code.
    - Can instead be generated on the fly, however this leads to the output of event *N* depending on the random number sequence used to determine the max probability.
- Regenerate *B->D*lν* decay until combination is accepted.

Selection algorithm (II)

- Average over τ spin and calculate the *D** spin density matrix:

$$\rho^{D^*}_{\lambda_{D^*}\lambda'_{D^*}} = \sum_{\lambda_\tau} A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau}\left(A^{B\to D^*\tau\nu}_{\lambda'_{D^*}\lambda_\tau}\right)^*$$

: $D^* \to D\pi$ decay

- Generate the $D^*\text{->}D\pi$ decay

$D^* \to D\pi$ decay

$$P = \sum_{\lambda_{D^*}\lambda'_{D^*}} \rho^{D^*}_{\lambda_{D^*}\lambda'_{D^*}} A^{D^*\to D\pi}_{\lambda_{D^*}}\left(A^{D^*\to D\pi}_{\lambda'_{D^*}}\right)^*$$

- Compare with maximum probability and accept or reject generated $D^*\text{->}D\pi$ decay
- Regenerate $D^*\text{->}D\pi$ decay until accepted. The $B\text{->}D^* l\nu$ decay is not regenerated.

Selection algorithm (III)

- Calculate the spin density matrix for the τ

$$\rho^{\tau}_{\lambda_\tau \lambda'_\tau} = \sum_{\lambda_{D^*} \lambda'_{D^*}} \hat{\rho}^{D^*}_{\lambda_{D^*} \lambda'_{D^*}} A^{B\to D^*\tau\nu}_{\lambda_{D^*} \lambda_\tau} (A^{B\to D^*\tau\nu}_{\lambda'_{D^*} \lambda'_\tau})^*$$

- Where:

$$\hat{\rho}^{D^*}_{\lambda_{D^*} \lambda'_{D^*}} \equiv A^{D^*\to D\pi}_{\lambda_{D^*}} (A^{D^*\to D\pi}_{\lambda'_{D^*}})^*$$

c the $\tau \to \pi\nu$ decay

- Generate the $\tau \to \pi\nu$ decay

$$P = \sum_{\lambda_\tau \lambda'_\tau} \rho^{\tau}_{\lambda_\tau \lambda'_\tau} A^{\tau\to\pi\nu}_{\lambda_\tau} (A^{\tau\to\pi\nu}_{\lambda'_\tau})^*$$

- Compare with maximum probability and accept or reject generated $\tau \to \pi\nu$ decay.
- Regenerate $\tau \to \pi\nu$ decay until accepted. The *B->D*l*ν and *D*->D*π decays are not regenerated.

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.

States in EvtGen

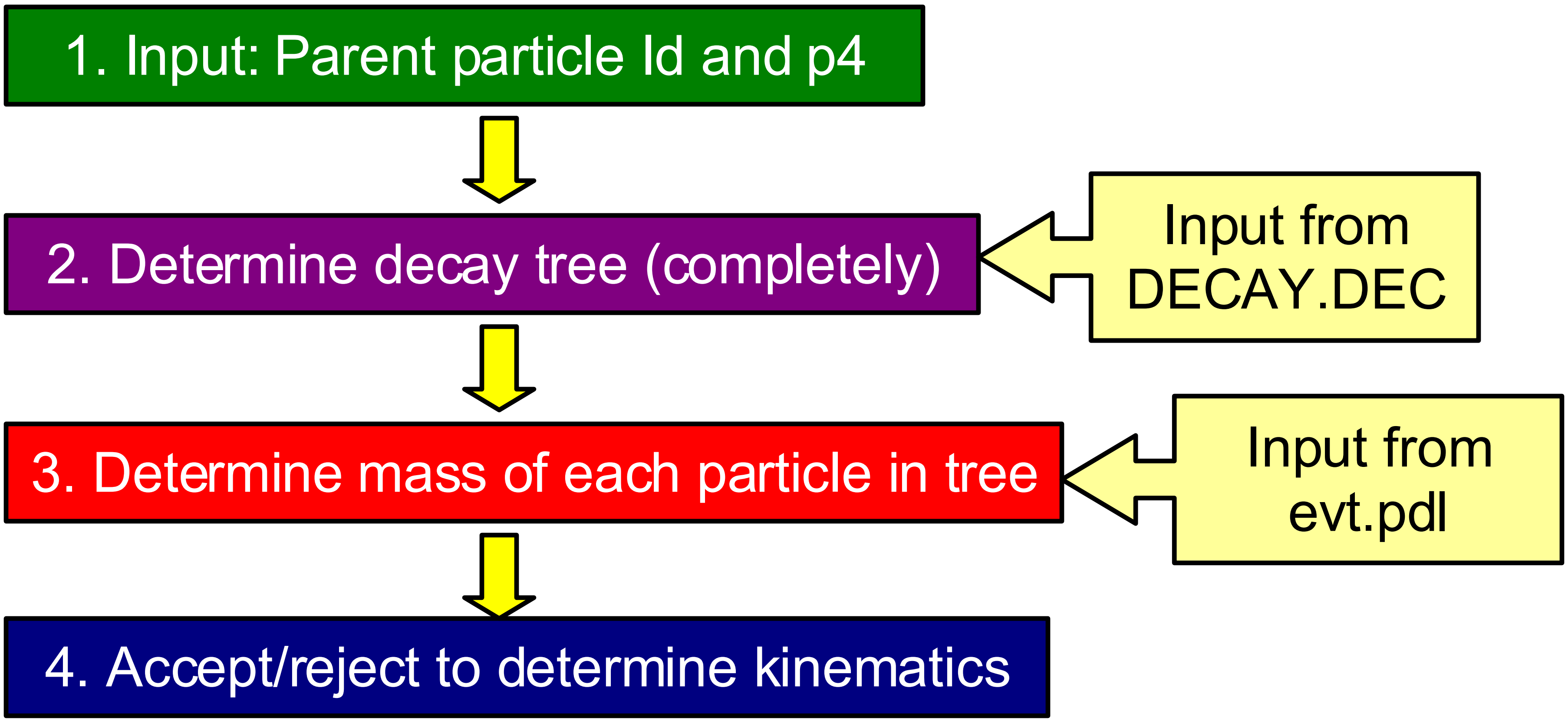
- EvtGen works with amplitudes. The amplitudes are specified as amplitudes between the initial and final state in a set of basis vector provided by EvtGen.
- EvtGen uses the following representation for the lower spin states:

Class name	Rep.	J	States	Example
EvtScalarParticle	1	0	1	π, B^0
EvtDiracParticle	u_α	1/2	2	e, τ
EvtNeutrinoParticle	u_α	1/2	1	ν_e
EvtVectorParticle	ϵ^μ	1	3	ρ, J/Ψ
EvtPhotonParticle	ϵ^μ	1	2	γ
EvtTensorParticle	$T^{\mu\nu}$	2	5	D_2^*, f_2

lifferent types of particles that supported by EvtGen. The sp
resentation has not yet been implemented.

- Also J=3/2 EvtRaritaSchwinger 4 states
- Higher spin states are represented by a generic helicity state basis

EvtGen decay algorithm



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

The decay table (DECAY.DEC)

- We continue to increase the ability to control EvtGen via $C3_DATA/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

Defining particle decays

```
Decay D*+
    0.683 D0  pi+    VSS;
    0.306 D+  pi0    VSS;
    0.011 D+  gamma  VSP_PWAVE;
Enddecay
```

Particle to decay

Branching fraction

Decay model

Daughters

";" to end each mode definition

End of decay stanza

Defines three decay modes of the D*+

Branching fractions will be rescaled to sum to 1.0

Particle "aliases"

```
Alias MyD*+ D*+

Decay B0
    1.0 MyD*+ pi-        SVS;
Enddecay

Decay MyD*+
    1.0 D0      pi+      VSS;
Enddecay
```

- In this case, all B0s will decay to $D^{*+}\pi^{-}$, with D^{*+}->$D^{0}\pi^{+}$. However, other D^{*+} in the event will decay as defined in DECAY.DEC.

Model arguments

HQET parameters

Some models takes arguments:

```
Decay B0
1.00 D*-    e+   nu_e          PHOTOS HQET 0.92 1.18 0.72;
Enddecay
```

These arguments can be accessed in the model using the methods:

getNArg() returns the number of arguments
getArg(i) returns the ith argument

evt.pdl format

Particle properties are defined in $C3_DATA/evt.pdl:

```
Add p Lepton mu-   13   0.1056584 0      0    -3 1 658654. 13
Add p Lepton mu+ -13  0.1056584 0      0     3 1 658654. 0
Add p Meson pi+   211  0.139570  0      0     3 0  7804.5 101
Add p Meson pi-   -211  0.138570  0      0    -3 0  7804.5 0
Add p Meson rho+ 213 0.7685       0.151 0.4  3 2        0   121
Add p Meson rho- -213 0.7685       0.151 0.4 -3 2        0   0
…..
```

- 4^{th} column=particle name, 5^{th}=stdhep number, 6^{th}=mass (GeV/c2), 7^{th}=Width (GeV/c2), 8^{th}=Mass cutoff, 9^{th}=3*charge, 10th 2*spin, 11^{th}=ct (mm), 12^{th} Lund-KC number (for Pythia interface)

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
- $B \to Kll$, $b \to s\gamma$
- Use PHOTOS package for final state radiation.
  - On by default for all decays.

Semileptonic decays

- HQET - Heavy Quark Effective Theory inspired form factor param.
- ISGW, ISGW2 - Quark model based prediction, Isgur, Scora et al.
- MELIKHOV - Quark model based prediction
- SLPOLE - Generic spcification of form factors based on a lattice inspired parametrization.
- VUB - For generic b->ulnu decays, uses JetSet for fragmentation.
- GOITY_ROBERTS - Decays to non resonant D(*)pi lnu.

BABAR uses, HQET, ISGW2, VUB, and GOITY_ROBERTS in its simulation.
ISGW2 should support D, D_s and B_s decays as well as B decays.

Generic amplitudes

- HELAMP, PARTWAVE - generic two-body decays specified by the helicity or partial wave amplitudes.
- SLN - Decay of scalar to lepton and neutrino.
- PHSP - N-body phase space.
- SVS, STS - Scalar decay to vector (or tensor) and scalar.
- VSS, TSS - decay of vector or tensor particle to a pair of scalars.
- VLL, SLL - Decay of vector or scalar to two leptons.
- VSP_PWAVE, vector to scalar and photon, e.g., D*->Dγ

Special matrix elements

- BTOXSGAMMA - b->X_s γ with JetSet fragmentation.
- BTOXSLL - b->$X_s$ll with JetSet fragmentation.
- D_DALITZ - 3-body *D*-decays with substructure.
- ETA_DALITZ - η–>3π with measured dalitz amplitude.
- KSTARNUNU - B->K*nunubar
- LNUGAMMA - B->lnu γ
- OMEGA_DALITZ - Dalitz structure in the ω->3π decay
- PHI_DALITZ - Dalitz structure in the ϕ->3π decay
- PTO3P - scalar to 3 scalars decay where you can specify intermediate resonances
- TAUHADNU - hadronic 1, 2, and 3 pion final states.
- TAULNUNU - leptonic tau decays.
- VSS_BMIX - Upsilon(4S) to BBbar, including mixing.
- VVPIPI - decay of vector to vector and two pions, *e.g.* psi'->psi pi pi.
- VECTORISR - ISR production of vector mesons: e+e- -> Vγ

Writing new Physics Models

- This part of the tutorial deals with writing new models
  - A model is a C++ class that implements the calculation of amplitudes for a given process.
  - This class has to be registered with the frame work in order to be used.
  - The model has a name which is used to indentify the model in the decay table.
- There are currently about 80 decay models implemented in EvtGen.

Example decay: V->SS

To illustrate how a decay model is written we will use the example of the decay of a vector particle to two scalars. The amplitude for this decay is given simply by:

$$A = \varepsilon^{\mu} v_{\mu}$$

Where ε is the polarization vector of the initial vector meson and v is the four-velocity of one of the final state particles.

We will illustrate how we write the class, EvtVSS, to implement the calculation of this amplitude for a model named 'VSS'.

EvtVSS.hh (simplified)

```
#ifndef EVTVSS_HH
#define EVTVSS_HH

#include "EvtGenBase/EvtDecayAmp.hh"

class EvtParticle;

class EvtVSS:public  EvtDecayAmp  {

public:
  EvtVSS() {}
  virtual ~EvtVSS();

  void getName(std::string& name);
  EvtDecayBase* clone();

  void decay(EvtParticle *p);
  void init();
  void initProbMax();

};
#endif
```

EvtVSS.cc

```
#include <stdlib.h>
#include "EvtGenBase/EvtParticle.hh"
#include "EvtGenBase/EvtGenKine.hh"
#include "EvtGenBase/EvtPDL.hh"
#include "EvtGenBase/EvtVector4C.hh"
#include "EvtGenBase/EvtVector4R.hh"
#include "EvtGenBase/EvtReport.hh"
#include "EvtGenModels/EvtVSS.hh"
#include <string>

EvtVSS::~EvtVSS() {}

void EvtVSS::getName(std::string& model_name){
 model_name="VSS";
}

EvtDecayBase* EvtVSS::clone(){
 return new EvtVSS;
}

void EvtVSS::initProbMax() {
  setProbMax(1.0);
}
```

```
void EvtVSS::init(){
 // check that there are 0 arguments
 checkNArg(0);

 // check that there are 2 daughters
 checkNDaug(2);

 // check the parent and daughter spins
 checkSpinParent(EvtSpinType::VECTOR);
 checkSpinDaughter(0,EvtSpinType::SCALAR);
 checkSpinDaughter(1,EvtSpinType::SCALAR);
}


void EvtVSS::decay( EvtParticle *p){

 p->initializePhaseSpace(getNDaug(),getDaugs());

 EvtVector4R pdaug = p->getDaug(0)->getP4();

 double norm=1.0/pdaug.d3mag();
 vertex(0,norm*pdaug*(p->eps(0)));
 vertex(1,norm*pdaug*(p->eps(1)));
 vertex(2,norm*pdaug*(p->eps(2)));

 return;
}
```

Registering the model

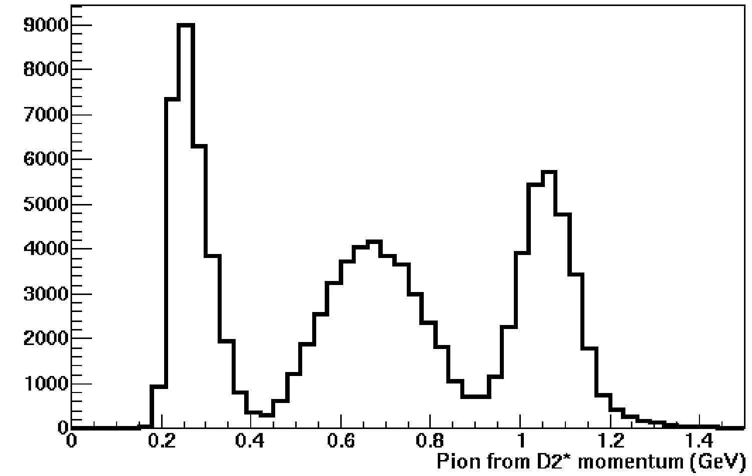
The last step to do before you can use a model is to register it with the EvtGen framework. This is done in the EvtModelReg.cc:

```
modelist.Register(new EvtVSS);
```

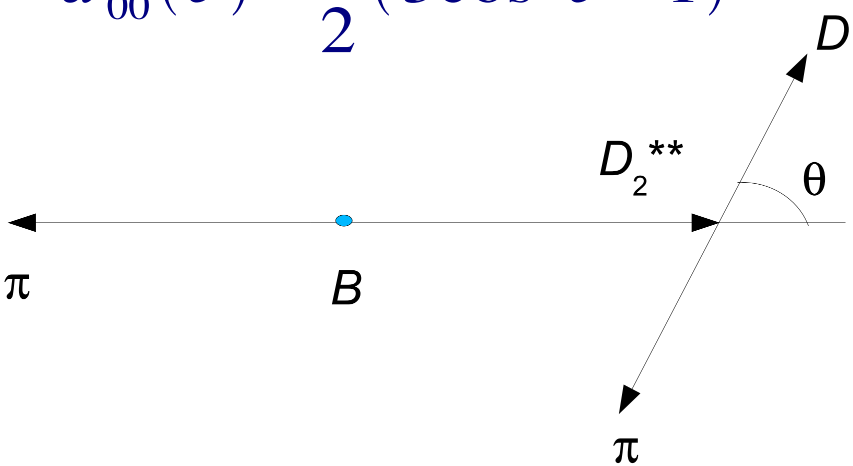
For each instance of a decay in the decay table that uses the VSS model
a new instance of the EvtVSS class is created using the clone method.

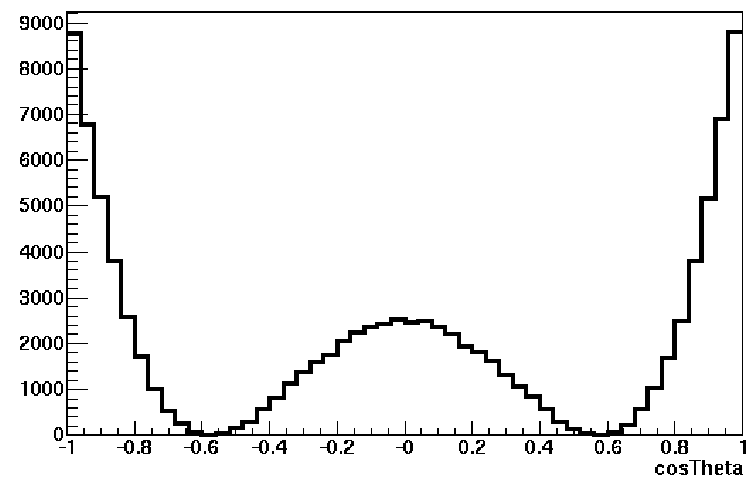
HELAMP and PARTWAVE models

- *B->D$_2$**π*   *D$_2$**->Dπ*
  - Known and nontrivial kinematical distributions.
  - For decays with multiple allowed partial waves, amplitudes are specified as model argument



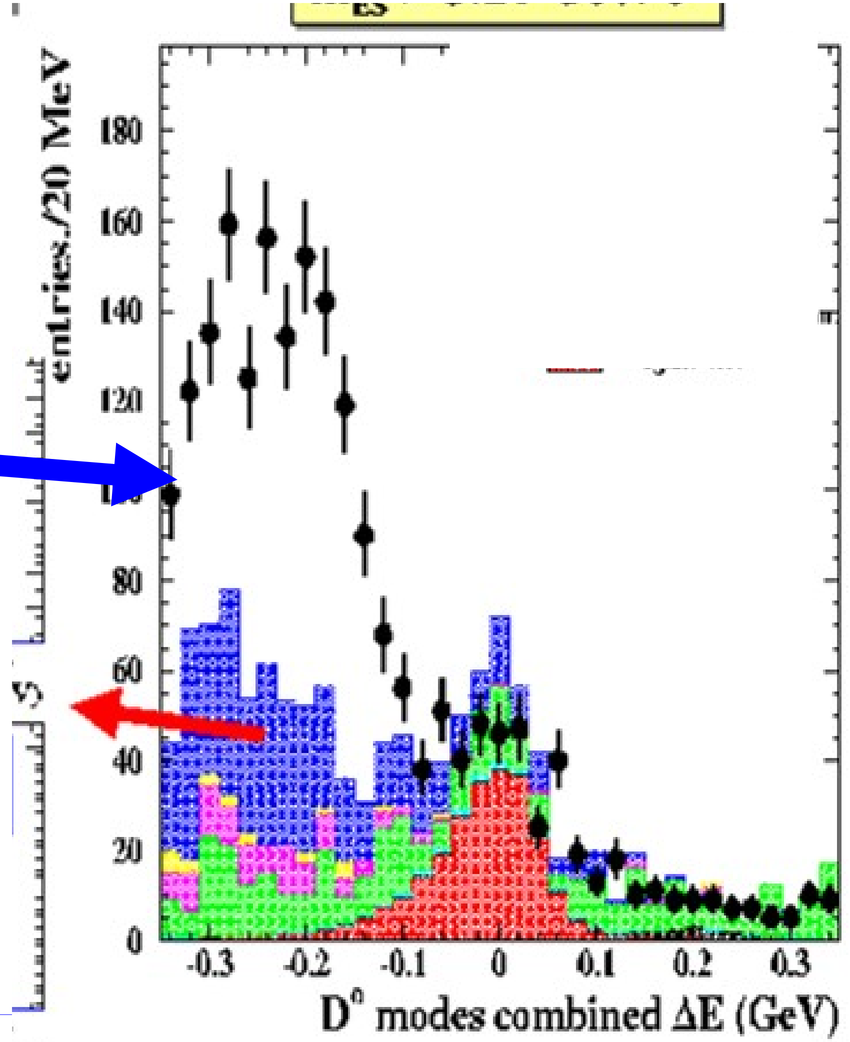
$$A = d^2_{00}(\theta) = \frac{1}{2}(3\cos^2\theta - 1)$$





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

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

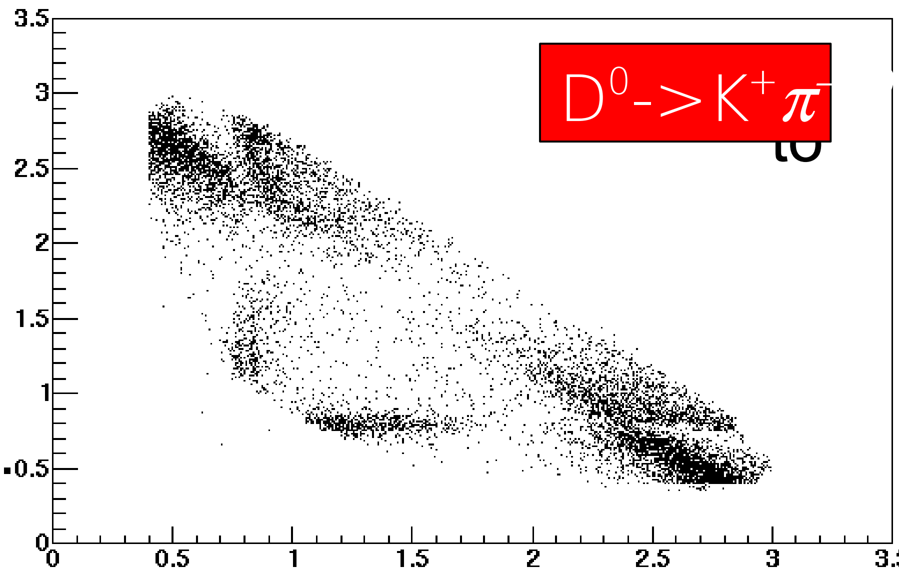


Jetset 7.4 used for inclusive decay generation

- 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

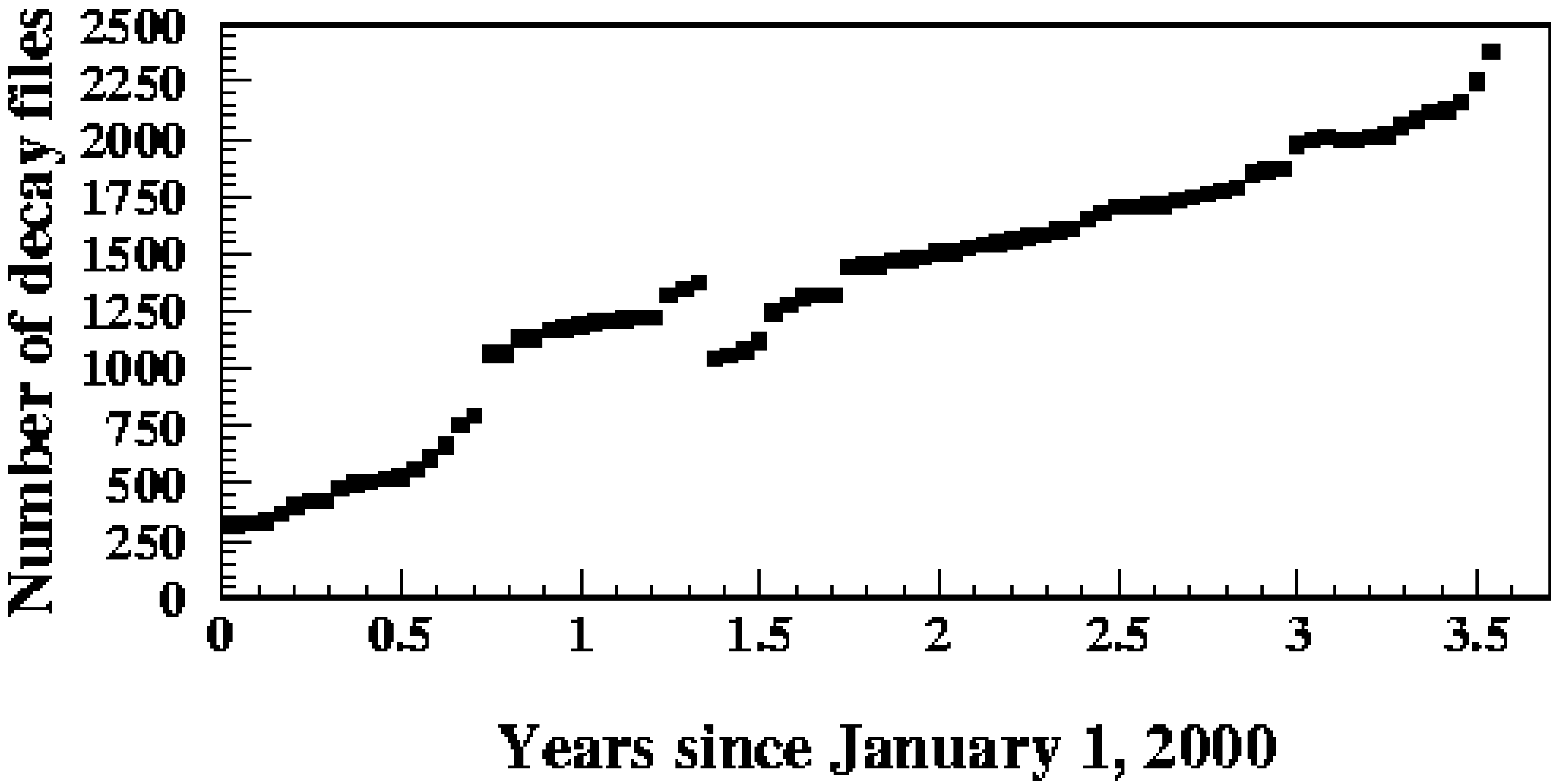
- Try to use relativistic Breit-Wigners for all particles with finite width.
  - Only for decays to two daughters
    - Otherwise non-rel BW.
  - Particles produced by Jetset have non-rel BW
- Include where possible
  - phase space factors, birth and decay form factors.
- Minimize use of mass cutoffs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



Monte Carlo production in BABAR

- 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..
- Last production cycle has now produced 2.1B events.

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



- Large rate of special MC requests.

Using EvtGen in suez

In releases newer than Dec10_03, using EvtGen is easy:

```
cleog gen EvtGenProd $env(NUMEVT) out $fileout run 200556
    -user_decay $env(UDECAY)  -post {
    proc sel RunEventNumberProc
}
```

Where -user_decay <file> specifies a user file to overwrite the default decay file as given in $C3_DATA/DECAY.DEC

Currently EvtGenProd creates an initial virtual photon (vpho) that is decayed using jetset to a quark anti-quark pair:

```
Decay vpho
1.000             JSCONT 0;
Enddecay
```

Writing a user decay file

```
#
Alias myD0 D0
Alias myanti-D0 anti-D0
#
Decay vpho
0.500    myD0  anti-D0          VSS;
0.500    D0    myanti-D0        VSS;
Enddecay
#
Decay myD0
1.000    eta  pi0            PHSP;
Enddecay
#
Decay myanti-D0
1.000    eta  pi0            PHSP;
Enddecay
#
End
```

LundAreaLaw

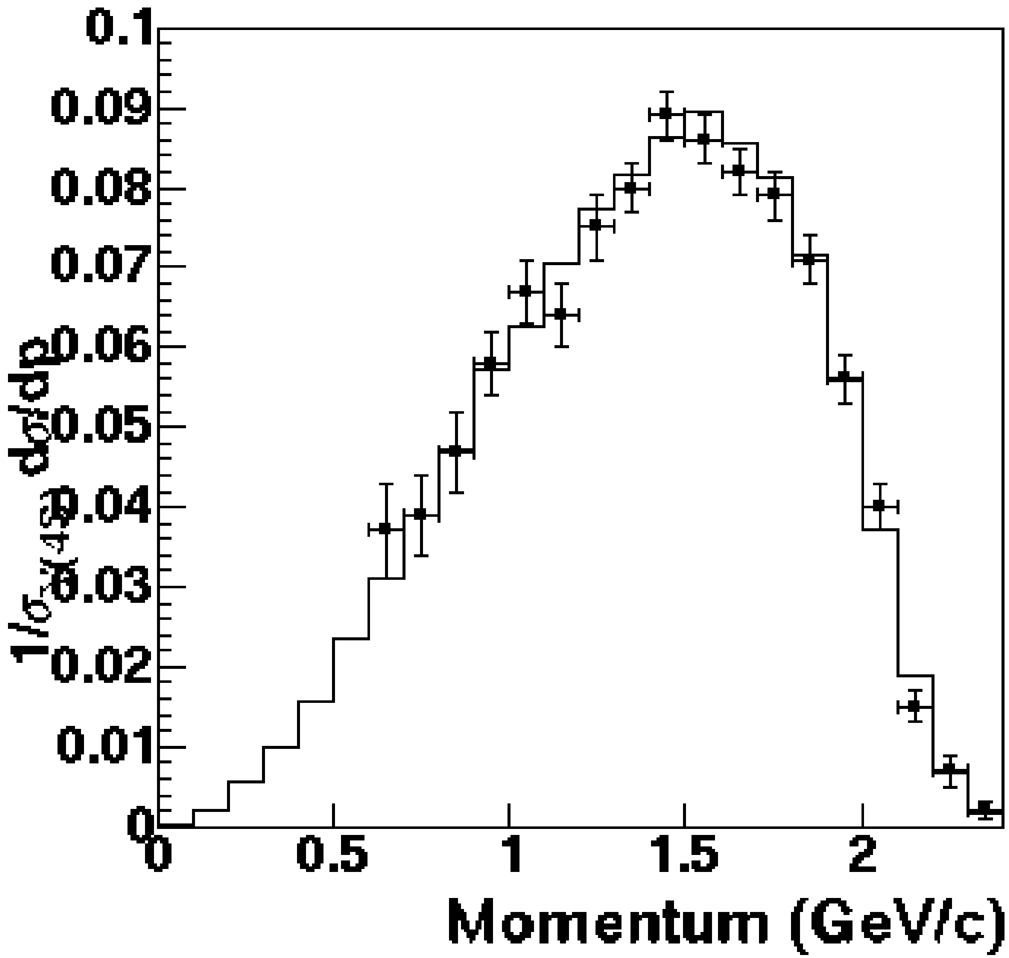
- Jim N. and I added the LundAreaLaw to EvtGen
  - The lund area law is a modified version of JetSet that should produce a more accurate fragmentation at low energy, in particular it should simulate baryon production better.
- To use the lund area law for the fragmentation in e^+e^-:

```
Decay vpho
1.000              LUNDAREALAW  0;
Enddecay
End
```

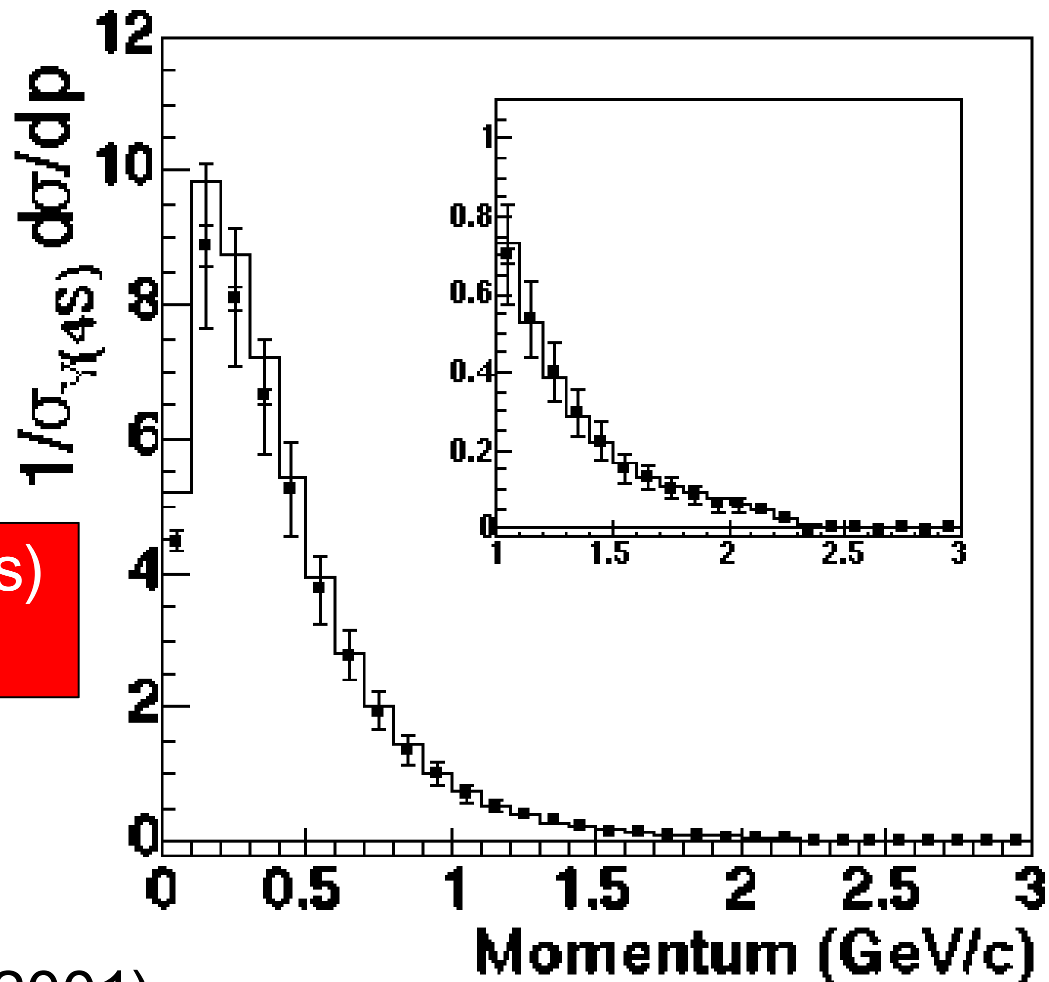
*B->Xlν l*epton energy spectrum

- 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



π^0 momentum spectrum



Points = Belle (stat+sys)
Histogram = EvtGen

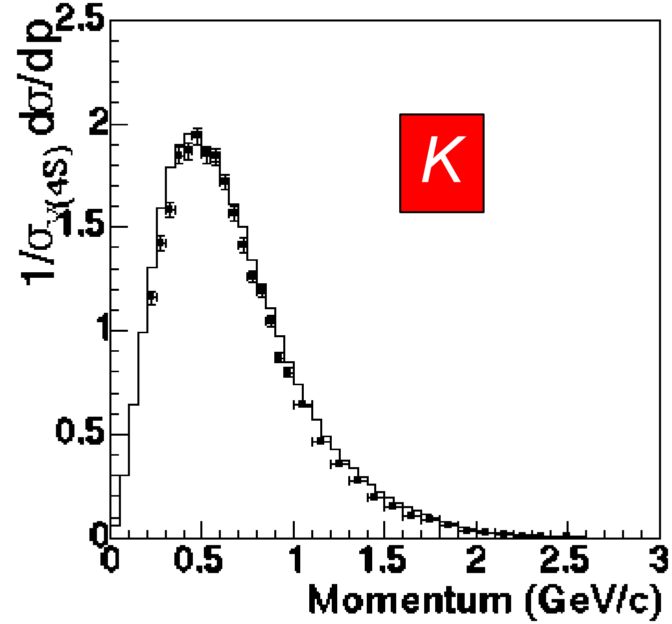
- PRD 64, 072001, (2001)

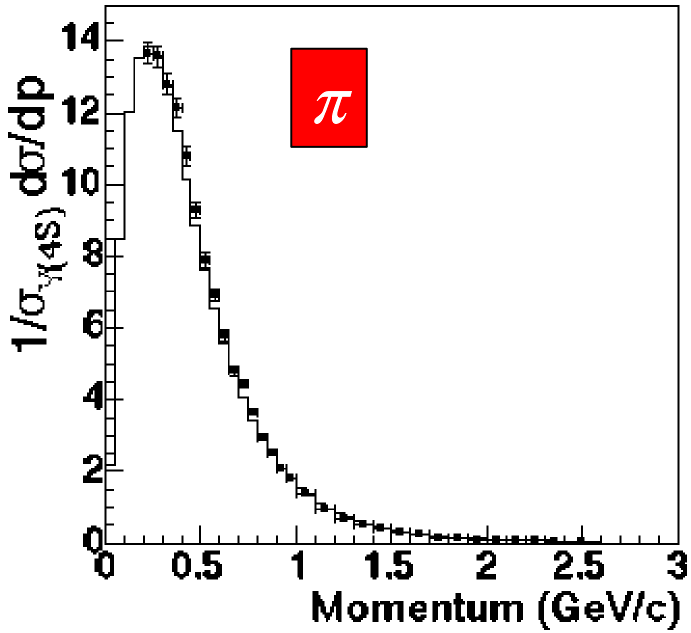
Inclusive resonance production in B decays

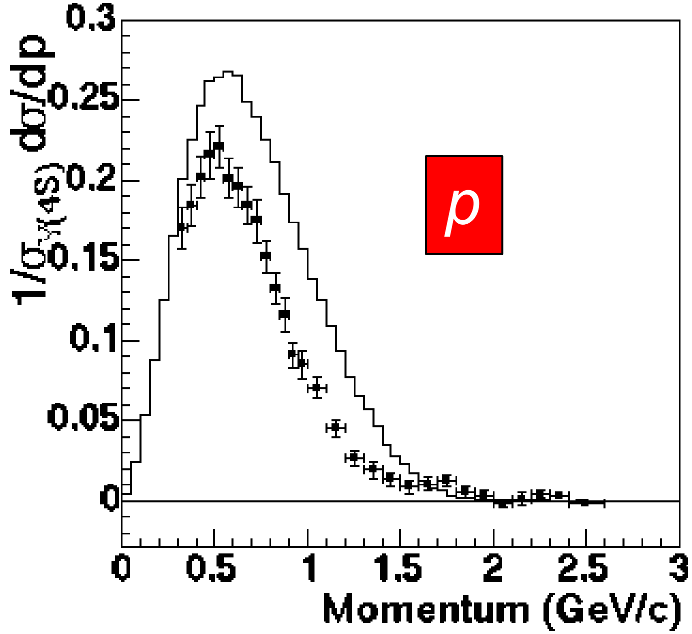
	PDG03	EvtGen
$B\text{->}Xe\nu$	10.7 +/- 0.28	10.6
$B\text{->}D^{+-}X$	24.5 +/- 2.1	32.4
$B\text{->}D^{0}X$	64.0 +/- 2.9	68.2
$B\text{->}D^{*+-}X$	22.5 +/- 1.5	26.2
$B\text{->}D^{*0}X$	26.0 +/- 2.7	25.7
$B\text{->}D^{(*)}D^{(*)}K$	7.1+2.7-1.7	7.7
$B\text{->}J/\psi X$	1.090 +/- 0.035	1.04
$B\text{->}K^{*+-}X$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

PDG B->D(*) production Bfs not consistent with isospin (and B(B->X)=1) at several sigma level

Preliminary Υ(4S)->π/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

Conclusion

- EvtGen has been interfaced to the CLEO-c framework (suez).
- EvtGen provides generic tools to solve a number of problems in simulation of particle decays
  - Still some updates/improvements are needed for the CLEO-c era.
- Used by BABAR/Belle/CDF/LHC exp. for *B*-decays
  - Headache to maintain fixes from different places...
- Modular framework
  - Makes it easy to add new physics models.
- Much tuning has been done at the $\Upsilon(4S)$, hope that we will similarly improve the simulation at the 'lower' energies.

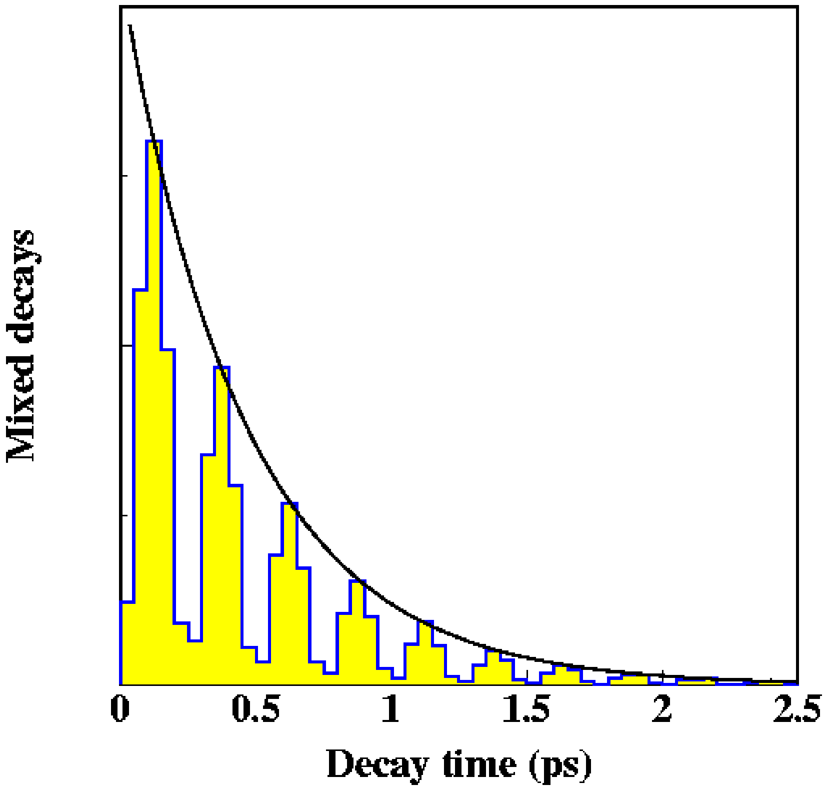
Available decay modes (III)

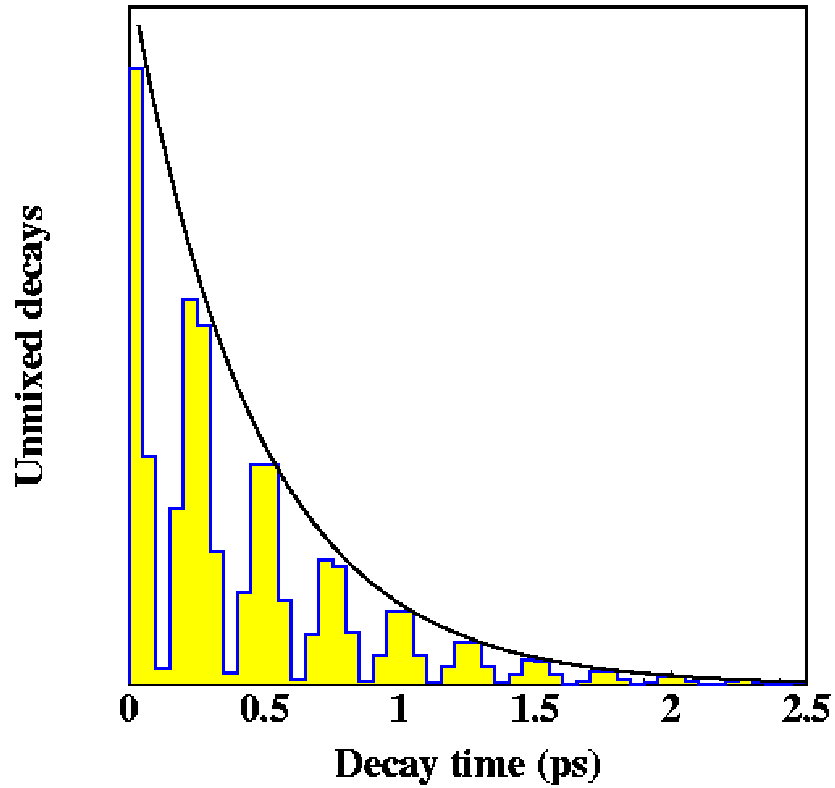
- SSD_CP model simulates CP violation for final states with a pseudoscalar + either a scalar,vector, or tensor.
  - B->$\pi\pi$, B->J/ψKs, B->D*π, etc.
  - Specify in decay table:
    - Δm
    - $\Delta\Gamma/\Gamma$
    - *q/p*
    - *A(B->f), A(Bbar->f,A(B->fbar),A(Bbar->fbar)*
    - *z*
  - Flexible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

B_s physics in EvtGen

Items different wrt $\Upsilon(4S) \rightarrow BB$ decays:

- Large # of common final states
- Incoherent mixing





Conclude about common final states

Basic EvtGen interface (EvtGen.cc)

```
EvtGen myGenerator(
                <DECAY.DEC location>,
                <evt.pdl location>
                <randomNumberEngine>.
                <FSR generator>);

myGenerator.readUDecay(<user decay file>);
EvtParticle *myParentParticle;
….. (Set up parent particle properties)….

myGenerator.generateEvent(myParentParticle,t_init);
```

Optional: PHOTOS is default.