EvtGen in LHC

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EvtGen origin

- EvtGen was written by BABAr authors Anders Ryd and David Lange
- Why is EvtGen different?
  - **EvtGen handels decays of particles with spin degrees**
  - **Provides spin algebra operations for cascade decays with any number of generations**
  - **Amplitude approach allows to generate decays with interference effects needed correctly to describe:**
    - **CP violation – interference in weak sector**
    - **Interference effects in strong sector**
    - **Resonant vrt non resonant decays**

  - **EvtGen is tuned to Babar, Belle experimental data – source of new phyics information – more rich than just PDF data.**

EvtGen and hadron collider experiments

- In 2000 an agreement was achieved between Babar authors of EvtGen and CDF, D0 and LHC representatives about using Babar EvtGen code in other experiments.
- Because of huge changes needed for using EvtGen in LHC environment – it was finally decided that the LHC-specific changes will not be implemented within BABAr version
- However LHC build so called LHC version of EvtGen
- Core of EvtGen program is always taken from Babar updates.
- This allow LHC to benefit from new Babar(Belle) tunings to experimental data.

LHC B-physics modelling and LHC version of EvtGen

- Babar version of EvtGen itelf has a production part – this describe a production of B-mesons in e+e- collisions with production of Upsilon decaying to two coherent states of B-mesons.
- LHC B-physic modeling starts from p-p collision with bb production – generators used are Pythia, Herwig and can be in priciple other generators.
- EvtGen is used to handel decays of B-hadrons – after B-hadrons are created in hadronization models
- Technically the hand-over is done via HepMC – which is commonly used Generator Model tool for storing events.
    - Interfaces code takes B-hadrons from HepMC convert them into EvtGen particle model object and after decay the de ay products are returned back to HepMC.

LHC B-physics modelling and LHC version of EvtGen, cont

- Hand-over between Pythia, Herwig and EvtGen has following problems:
  - **Pythia and Hewrwig are spin blind – at least current versions. So any particle is produced without spin considerations – no production polarizations.**
    - **Particles passed to EvtGen are assigned by spin and by polarization – by hand. Which means without any model describing the production polarization process.**
    - **Even if a decay of this particle is treated fairly in EvtGen – it is an isolated object within the rest of event which is spinless.**
    - **Even if HepMC has in priciple tools to store poarization information – it has no meaning if the production models are spinless.**
  - **Where to decay excited B-hadrons?**
    - **In EvtGen – because they have spins.**
    - **In Pythia/Herwig – because they are connected with B-hadronization model - were tuned together vrt b-jet multiplicities data…**

LHC B-physics modelling and LHC version of EvtGen, cont

- Despite of previous comments – EvtGen provides us with correct angular distributions of secondary particles – in the B-hadron frame. It also hadles CP violation correctly. So there is no doubt of necessity to use it.
- LHC specific features that required intervention in EvtGen code
  - **Bs and Lambda_b and many excited states are not in Babar**
  - **B-mesons in LHC decay incoherently – unlike in Babar**
  - **EvtGen returns part of B-hadorn decays back to JetSet. LHC version is returninf them back to Pythia.**

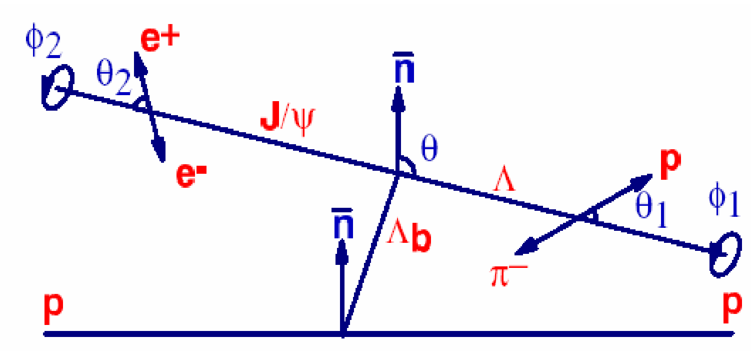
Examples of applications of EvtGen typical for LHC environment

Lambda_b polarization and decay

Use of EvtGen to generate polarized Lambda $_b$ in the cascade decay :

$\Lambda_b \to J/\psi\ \Lambda_0$

$J/\psi \to \mu\mu$, $\Lambda_0 \to \pi p$



Probability function

$$w(\Omega,\Omega_1,\Omega_2) = \frac{1}{(4\pi)^3}\sum_{i=0}^{i=19} f_{1i} f_{2i}(P_b,\alpha_\Lambda) F_i(\theta,\theta_1,\theta_2,\phi_1,\phi_2)$$

i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
1	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	P_b	$\cos\theta$
2	$a_+a_+^* - a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\cos\theta_1$
3	$a_+a_+^* + a_-a_-^* - b_+b_+^* - b_-b_-^*$	$P_b\alpha_\Lambda$	$\cos\theta\cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	1	$d^2_{00}(\theta_2)$
5	$-a_+a_+^* + a_-a_-^* + \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	P_b	$d^2_{00}(\theta_2)\cos\theta$
6	$-a_+a_+^* + a_-a_-^* - \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	α_Λ	$d^2_{00}(\theta_2)\cos\theta_1$
7	$-a_+a_+^* - a_-a_-^* - \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	$P_b\alpha_\Lambda$	$d^2_{00}(\theta_2)\cos\theta\cos\theta_1$
8	$-3Re(a_+a_-^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos\phi_1$
9	$3Im(a_+a_-^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin\phi_1$
10	$-\frac{3}{2}Re(b_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2 cos(\phi_1+2\phi_2)$
11	$\frac{3}{2}Im(b_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2 sin(\phi_1+2\phi_2)$
12	$-\frac{3}{\sqrt{2}}Re(b_-a_+^* + a_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\cos\phi_2$
13	$\frac{3}{\sqrt{2}}Im(b_-a_+^* + a_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\sin\phi_2$
14	$-\frac{3}{\sqrt{2}}Re(b_-a_-^* + a_+b_+^*)$	$P_b\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1+\phi_2)$
15	$\frac{3}{\sqrt{2}}Im(b_-a_-^* + a_+b_+^*)$	$P_b\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1+\phi_2)$
16	$\frac{3}{\sqrt{2}}Re(a_-b_+^* - b_-a_+^*)$	P_b	$\sin\theta\sin\theta_2\cos\theta_2\cos\phi_2$
17	$-\frac{3}{\sqrt{2}}Im(a_-b_+^* - b_-a_+^*)$	P_b	$\sin\theta\sin\theta_2\cos\theta_2\sin\phi_2$
18	$\frac{3}{\sqrt{2}}Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1+\phi_2)$
19	$\frac{3}{\sqrt{2}}Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1+\phi_2)$

- see ATLAS Note *ATL-PHYS-94-036*

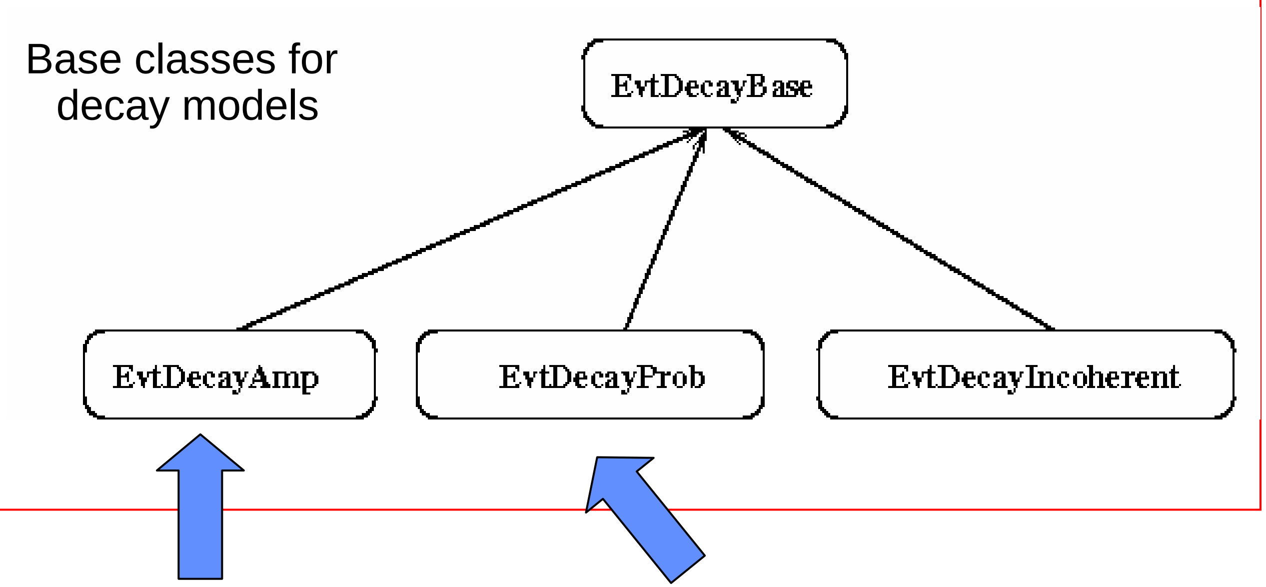
Angular distribution

$\Lambda_b \to J/\psi(\mu\mu)\Lambda(\pi p)$ depends on 5 angles + 6 parameters of the 4 complex helicity amplitudes + polarization P_b. Helicity amplitudes and P_b have to be simultaneously determined.

Two different methods have been implemented in EvtGen :

- **EvtDecayAmp** allows to specify the complete decay amplitudes
- **EvtDecayProb** allows to calculate a probability for the decay that is used in an accept/reject method

EvtGen stucture



Set the Λ_b polarization ``by hand'' and decay with helicity amplitudes (HELAMP CLASS)
See next slide

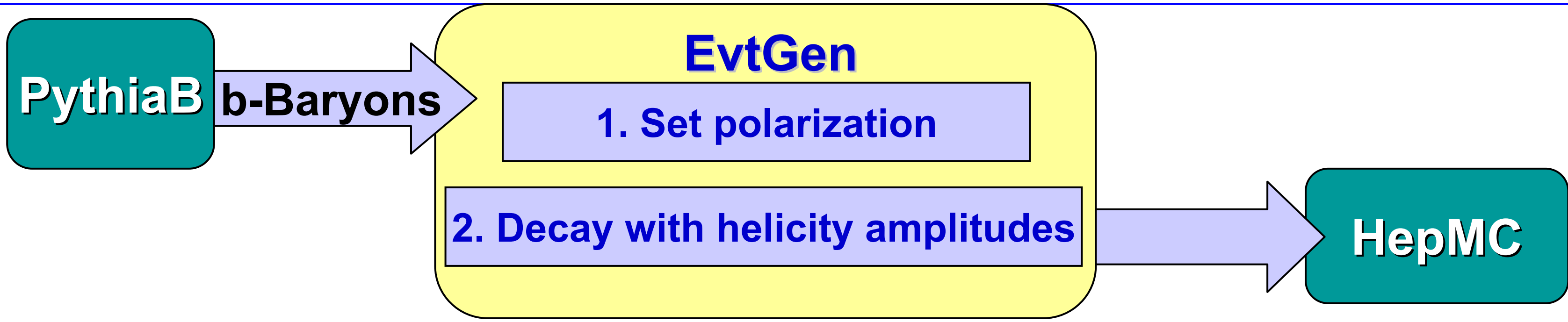
To validate HELAMP
use of the probability service of EvtGen
→ Implementation of the probability function

Method Used

Get unpolarized baryons from Pythia

EvtGen uses spinor algebra and helicity amplitudes

- it's possible to set the polarization of the particle before the particle is decayed
- .. and obtain the correct angular distributions



1.

B hadrons can be only polarized perpendicular to the production plane

- **Calculate the polarization vector** $$\vec{P} = \frac{\hat{z}\times\vec{p}}{|\hat{z}\times\vec{p}|}$$
- **Calculate the spin density matrix** $$\rho \approx 1 + \vec{\sigma}\cdot\vec{P}$$

Associate the density matrix to the particle

particle->SetForwardSpinDensity(ρ)

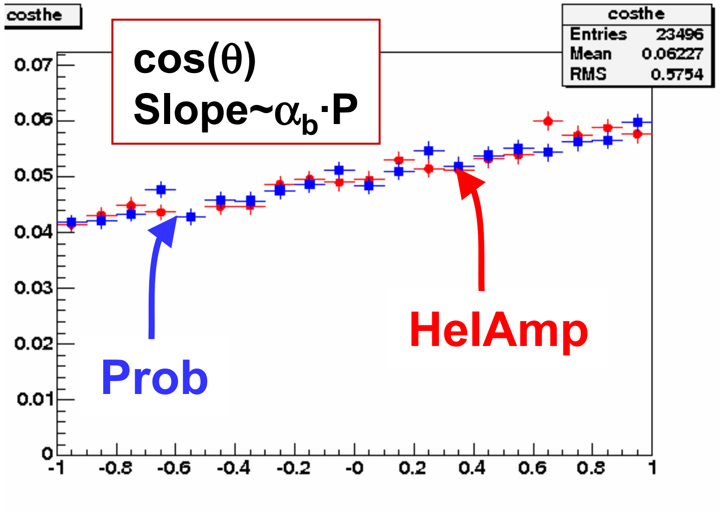
2.

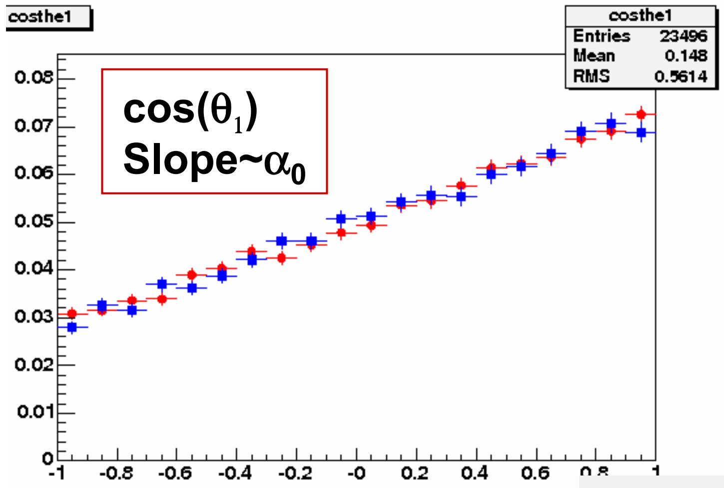
Adopt EvtGen class "HELAMP" to introduce a theoretical model for Λ_b decay

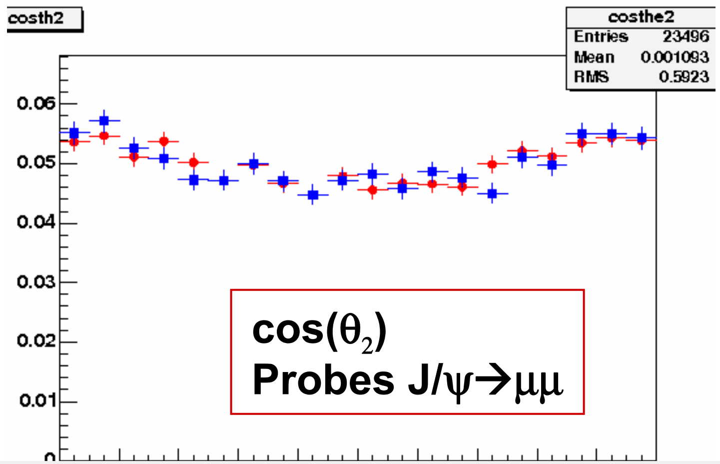
A PQCD Model*

- 5 angular distributions are generated using both the probability function and HelAmp

- a_+ = -0.0176 - 0.4290i
- a_- = 0.0867 + 0.2454i
- b_+ = -0.0810 - 0.2837i
- b_- = 0.0296 + 0.8124i
- α_b=-.457, P=-40%
- Blue squares are events generated according to probability function (in EvtGen)
- Red circles are events generated with helicity amplitudes in EvtGen







* $\Lambda_b \to \Lambda J/\psi$ decay in perturbative QCD

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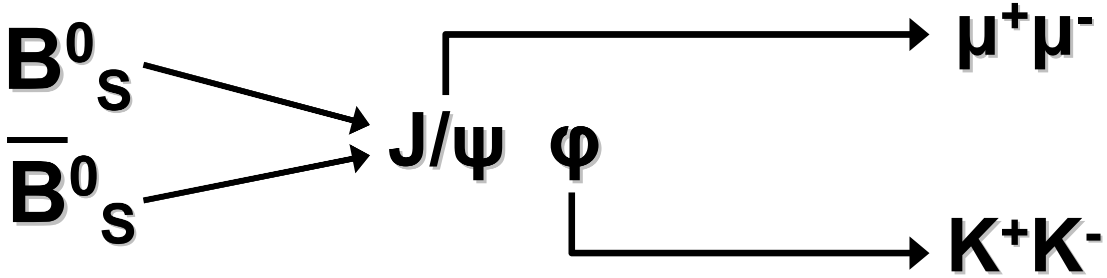
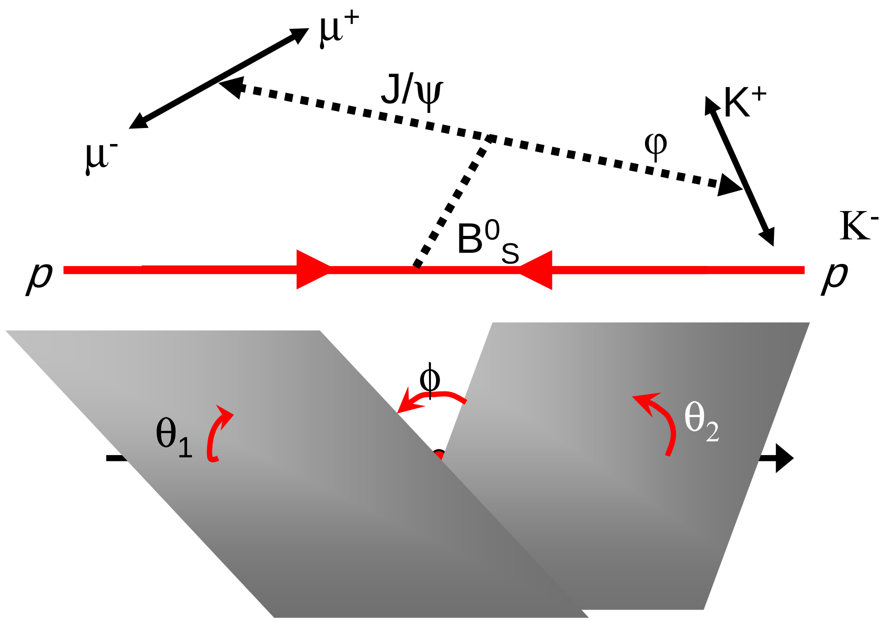
Institute of Physics, Academia Sinica, Taipei, Taiwan 115, Republic of China

The Decay



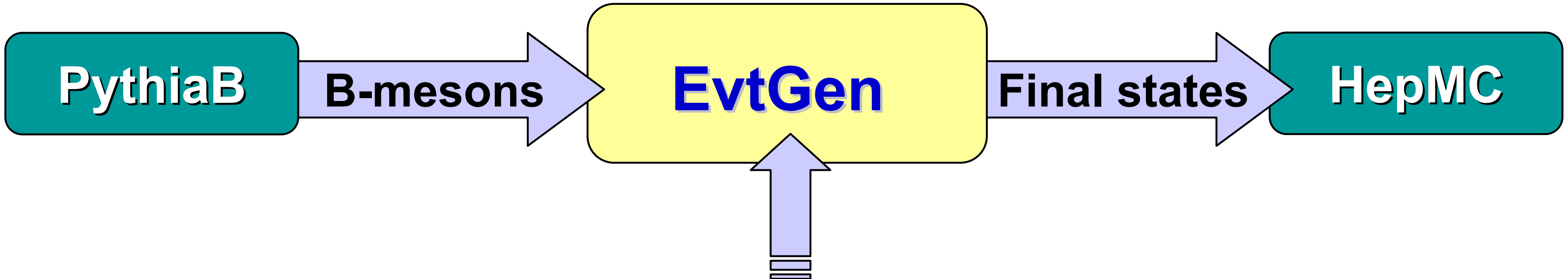
- Angular distribution depends on three helicity amplitudes and three angles: implemented in EvtGen class SVV_HELAMP
- The angular distribution is modified by the CP-violating terms



i	$f_i^{+(-)}$			F_i
1	$\lvert A_0\rvert^2$	1	$e^{-\Gamma_L t} \mp e^{-\frac{1}{2}(\Gamma_L+\Gamma_H)t} \sin(\Delta m_s t)\xi$	$\cos^2\theta_1 \sin^2\theta_2$
2	$\lvert A_\parallel\rvert^2$	$\frac{1}{4}$	$e^{-\Gamma_L t} \mp e^{-\frac{1}{2}(\Gamma_L+\Gamma_H)t} \sin(\Delta m_s t)\xi$	$\sin^2\theta_1(1+\cos^2\theta_2)$
3	$\lvert A_\perp\rvert^2$	$\frac{1}{4}$	$e^{-\Gamma_H t} \pm e^{-\frac{1}{2}(\Gamma_L+\Gamma_H)t} \sin(\Delta m_s t)\xi$	$\sin^2\theta_1(1+\cos^2\theta_2)$
4	$\lvert A_\parallel\rvert^2$	$\frac{-1}{4}$	$e^{-\Gamma_L t} \mp e^{-\frac{1}{2}(\Gamma_L+\Gamma_H)t} \sin(\Delta m_s t)\xi$	$\sin^2\theta_1 \sin^2\theta_2 \cos 2\phi$
5	$\lvert A_\perp\rvert^2$	$\frac{1}{2}$	$e^{-\Gamma_H t} \pm e^{-\frac{1}{2}(\Gamma_L+\Gamma_H)t} \sin(\Delta m_s t)\xi$	$\sin^2\theta_1 \sin^2\theta_2 \cos 2\phi$
6	$\lvert A_\perp\rvert\lvert A_\parallel\rvert$	$\frac{1}{2}$	$\frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t})\cos(\delta_1)\xi$ $\pm e^{-\frac{1}{2}(\Gamma_L+\Gamma_H)t} \sin(\delta_1 - \Delta m_s t)$	$\sin^2\theta_1 \sin^2\theta_2 \sin 2\phi$
7	$\lvert A_0\rvert\lvert A_\parallel\rvert$	$\frac{-\sqrt{2}}{4}$	$\cos(\delta_2 - \delta_1)(e^{-\Gamma_L t}$ $\mp e^{-\frac{1}{2}(\Gamma_L+\Gamma_H)t} \sin(\Delta m_s t)\xi)$	$\sin 2\theta_1 \sin 2\theta_2 \cos\phi$
8	$\lvert A_0\rvert\lvert A_\perp\rvert$	$\frac{\sqrt{2}}{4}$	$\frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t})\cos(\delta_2)\xi$ $\pm e^{-\frac{1}{2}(\Gamma_L+\Gamma_H)t} \sin(\delta_2 - \Delta m_s t)$	$\sin 2\theta_1 \sin 2\theta_2 \sin\phi$

Implementation in EvtGen

The complex decay amplitude is constructed from the ΔB=2 amplitude (B_s-$\bar{B}_s$) and the ΔB=1 amplitude ($B_s \rightarrow J/\psi\varphi$)



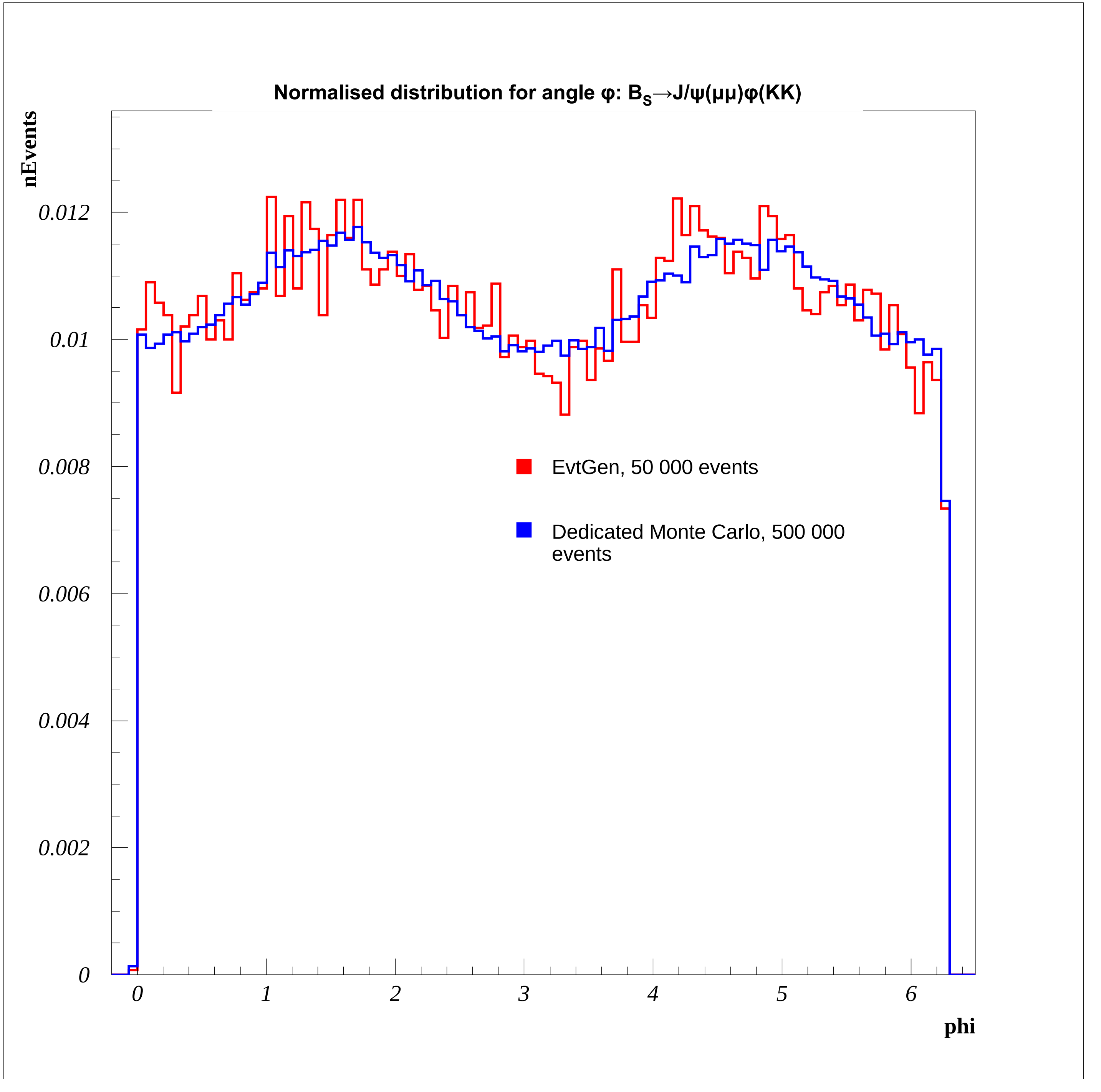
$$A_{B_s \rightarrow f} = g_+(t)\langle f|H_{eff}|B_s^0\rangle + \alpha g_-(t)\langle f|H_{eff}|\bar{B}_s^0\rangle$$

$$|B^0_{s,phys}(t)\rangle = g_+(t)|B_s^0(0)\rangle + \alpha g_-(t)|\bar{B}_s^0(0)\rangle$$

$$\alpha = e^{-i\phi_s^{WEAK}}$$

$$g_+(t) = e^{-i\left[\left(m_L+m_H\right)/2\right]t} e^{-\left(\Gamma/2\right)t} \cos\left[\frac{1}{2}\left(\Delta mt - \frac{i}{2}\Delta\Gamma\, t\right)\right]$$

$$g_-(t) = e^{-i\left[\left(m_L+m_H\right)/2\right]t} e^{-\left(\Gamma/2\right)t}\, i \sin\left[\frac{1}{2}\left(\Delta mt - \frac{i}{2}\Delta\Gamma\, t\right)\right]$$



Normalised distribution for angle φ: $B_s \to J/\psi(\mu\mu)\varphi(KK)$
nEvents
0.012
0.01
0.008
0.006
0.004
0.002
0
0
1
2
3
4
5
6
phi
EvtGen, 50 000 events
Dedicated Monte Carlo, 500 000 events

- We have introduced interference between mixing and decay amplitudes
- Spin configuration have been validated against independent direct Monte Carlo generations
  - Scalar → vector + vector ($B_s \to J/\psi\varphi$)
- These new contributions will be added to the LHC EvtGen release

Summary

- EvtGen in LHC is actively used by LHCb ATLAS and CMS production of events,
- Collaboration of LHC experiments via LCG is vital
- EVtGEn is very modular – so authors can easily implemetn their models in language of EvtGen.
- Not many theory authors use EvtGEn as tool for manipulating with spinors – they prefere to claculate PDF from amplitudes within their models – by themselves
- Untill the producitonmodels (Pthia, Herwig) are spinless we cannot claim a fair teatment of the whole problem,
- Neverthless we can claim that anglular distributions and CP violation terams are generated fairly – using EvtGen.