IMPLEMENTATION OF MONTE CARLO ALGORITHMS FOR MULTIDIMENSIONAL RANDOM NUMBER GENERATION in SIMUB – Physics Generator of B Meson Decays

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- **Motivation of the work**
- **Monte Carlo methods for random number generation**
- **General structure of SIMUB and data flow**
- **Current status of SIMUB**
- **Current status of B-decay mass production for CMS**
- **SIMUB performance demonstration:**
  - **production of $b\bar{b}$ pairs and B mesons**
  - **B decays**
    - **semileptonic decays $B \to D\mu\nu$ and $B \to D^*\mu\nu$**
    - **CMS golden decay $B \to J/\psi(\to \mu^+\mu^-)\,\phi(K^+K^-)$**
  - **Comparison between SIMUB and PYTHIA**
- **Plans**

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MOTIVATION OF THE WORK

Existing and widely used MC generators are not suitable for detail physics studies of dynamics of B-decay modes which are of great interest for CMS

Generators:

QQ: http://www.lns.cornell.edu/public/CLEO/soft/QQ/;

EvtGen: http://www.slac.stanford.edu/~ lange/EvtGen/;

Physics Models:

QQ and EvtGen: sequential two-body decays within helicity formalism;

SIMUB: transversity formalism with full time-angle correlations

QQ and EvtGen: algorithm based on sequential two-body decays does not take in account

- the explicit form of time evolution of $B^0 - \overline{B^0}$ system
- the angle correlations in case of decays

$$B^0(t),\, \overline{B^0}(t) \to a(\to a_1 a_2)\, b(\to b_1 b_2)$$

with a and b being vector mesons

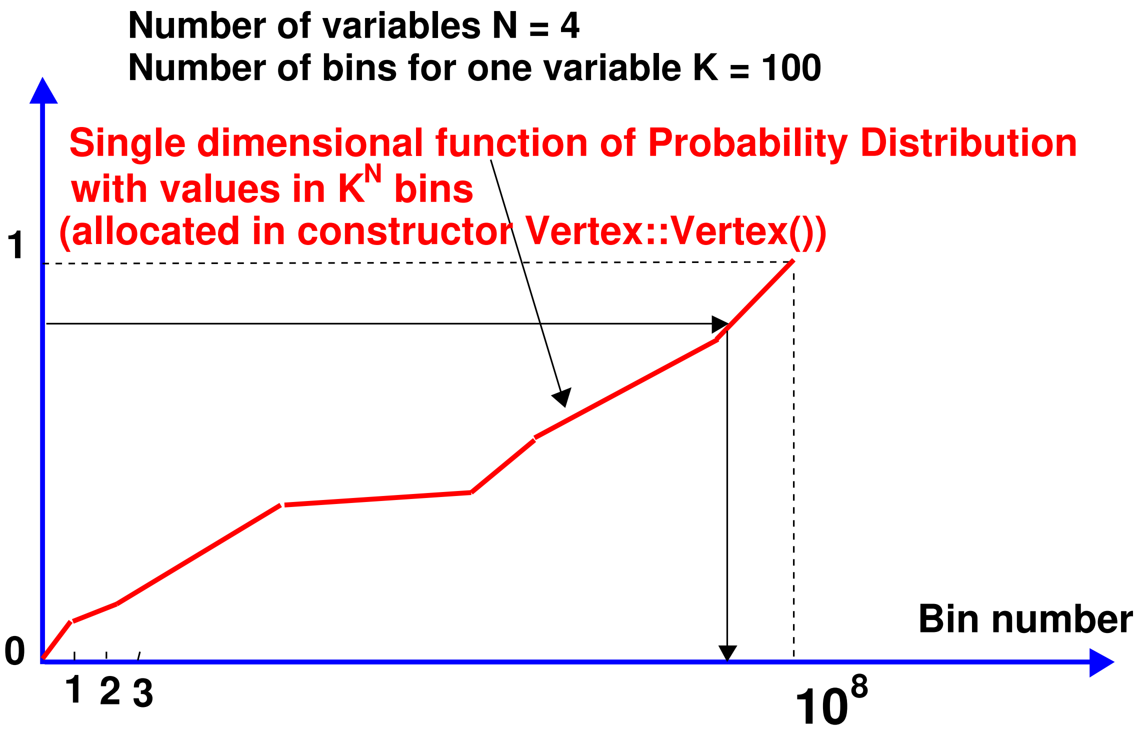
SIMUB: time-dependent angular correlations

MONTE CARLO METHODS of Random Number Generation in SIMUB

Simultaneous simulations of $N+1$-dimensional distribution (N angles and B lifetime) at the step of decay vertex simulation in SIMUB

MC METHOD 1

The method is based on the filling of the large single-dimensional array representing numerically the distribution function $f_0(\cos\Theta_{a_1}, \cos\Theta_{b_1}, \chi, t)$.
The memory space for this array is allocated by constructor of class `Vertex` during all time of existence of this class sample.



MC Method 1: Memory Consuming method

MC METHOD 2

Functions of probabylity density distribution

$$f_0(\mathbf{cos}\Theta_{a_1}, \mathbf{cos}\Theta_{b_1}, \chi, t)$$

— time-dependent angular distribution

$$\Downarrow$$

$$\begin{aligned}
f_1^{(1)}(\mathbf{cos}\Theta_{b_1}, \chi, t) &= \int_{-1}^{1} d\mathbf{cos}\Theta_{a_1} f_0(\mathbf{cos}\Theta_{a_1}, \mathbf{cos}\Theta_{b_1}, \chi, t) \\
f_1^{(2)}(\mathbf{cos}\Theta_{a_1}, \chi, t) &= \int_{-1}^{1} d\mathbf{cos}\Theta_{b_1} f_0(\mathbf{cos}\Theta_{a_1}, \mathbf{cos}\Theta_{b_1}, \chi, t) \\
f_2(\chi, t) &= \int_{-1}^{1} d\mathbf{cos}\Theta_{b_1} f_1^{(1)}(\mathbf{cos}\Theta_{b_1}, \chi, t) \\
f_3(t) &= \int_{0}^{2\pi} d\chi f_2(\chi, t)
\end{aligned}$$

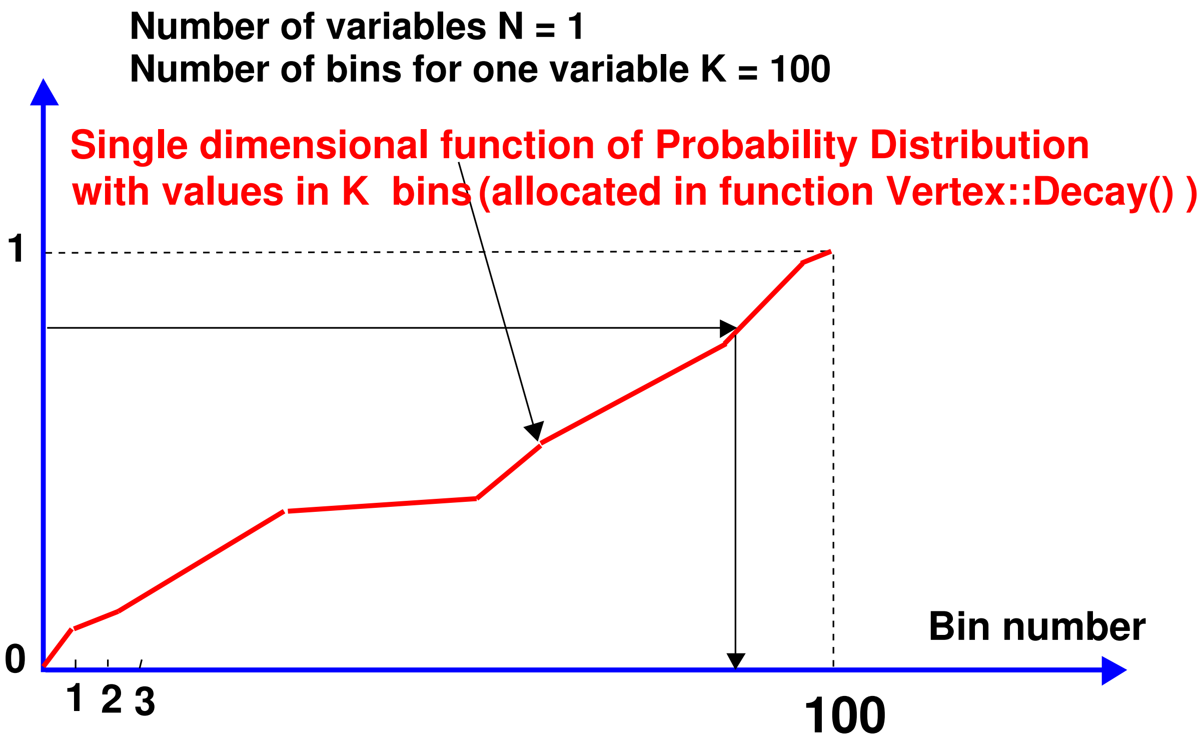
Algorithm of sequential random numbers generation by using single-dimensional generator:

- t is simulated according to f_3
- χ is simulated according to f_2 with fixed t
- $\mathbf{cos}\Theta_{b_1}$ is simulated according to f_1 with fixed t, χ
- $\mathbf{cos}\Theta_{a_1}$ is simulated according to f_0 with fixed t, χ, $\mathbf{cos}\Theta_{b_1}$

MC METHOD 2 (continue)

In MC Method 2 the constructor of class `Vertex` does not fill any arrays and, therefore, it does not allocate any memory. To perform decay, the program allocates four times the single dimensional arrays with their total size equal to 4xK, where K is generator resolution.

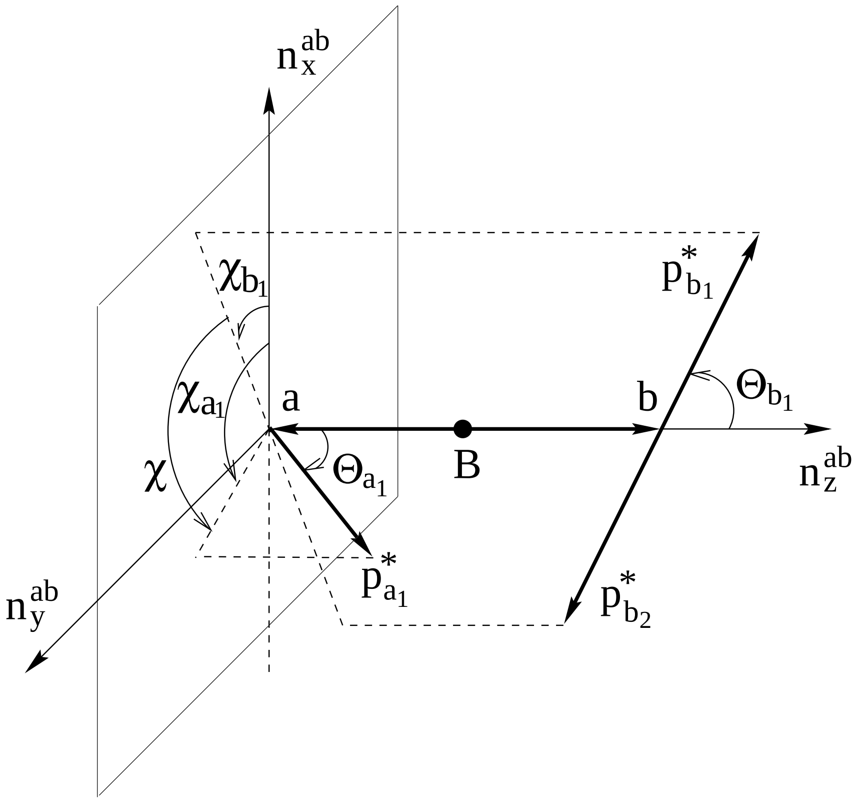
The time consuming per decay is larger than in MC Method 1 but in MC Method 2 about 10000 decays per minute **can be generated with resolution K = 100.**



MC method 2 : Time Consuming Method

MC Method 2 does not restrict the generator resolution

ALGORITHM OF MC SIMULATION OF DECAY $B^0(t) \to a(\to a_1 a_2) b(\to b_1 b_2)$



- random generation of $\mathbf{cos}\Theta_{a_1}$, $\mathbf{cos}\Theta_{b_1}$, χ, t according to time-depemdent angular distribution
  $f_0(\mathbf{cos}\Theta_{a_1}, \mathbf{cos}\Theta_{b_1}, \chi, t) = \sum_{i=1}^{6} \mathcal{O}_i(t) g_i(\Theta_{a_1}, \Theta_{b_1}, \chi)$,
  where $\mathcal{O}_k$ are observables, g_i are angular correlation function;

- Helicity Frame :
  - $\mathbf{n}_z^{ab}$ is an axis along a momentum of b in the rest frame of B ;
  - $\mathbf{n}_x^{ab}$ is an arbitrary axis in the plane normal to the z axis ;
  - $\mathbf{n}_y^{ab} = \mathbf{n}_z^{ab} \times \mathbf{n}_x^{ab}$;

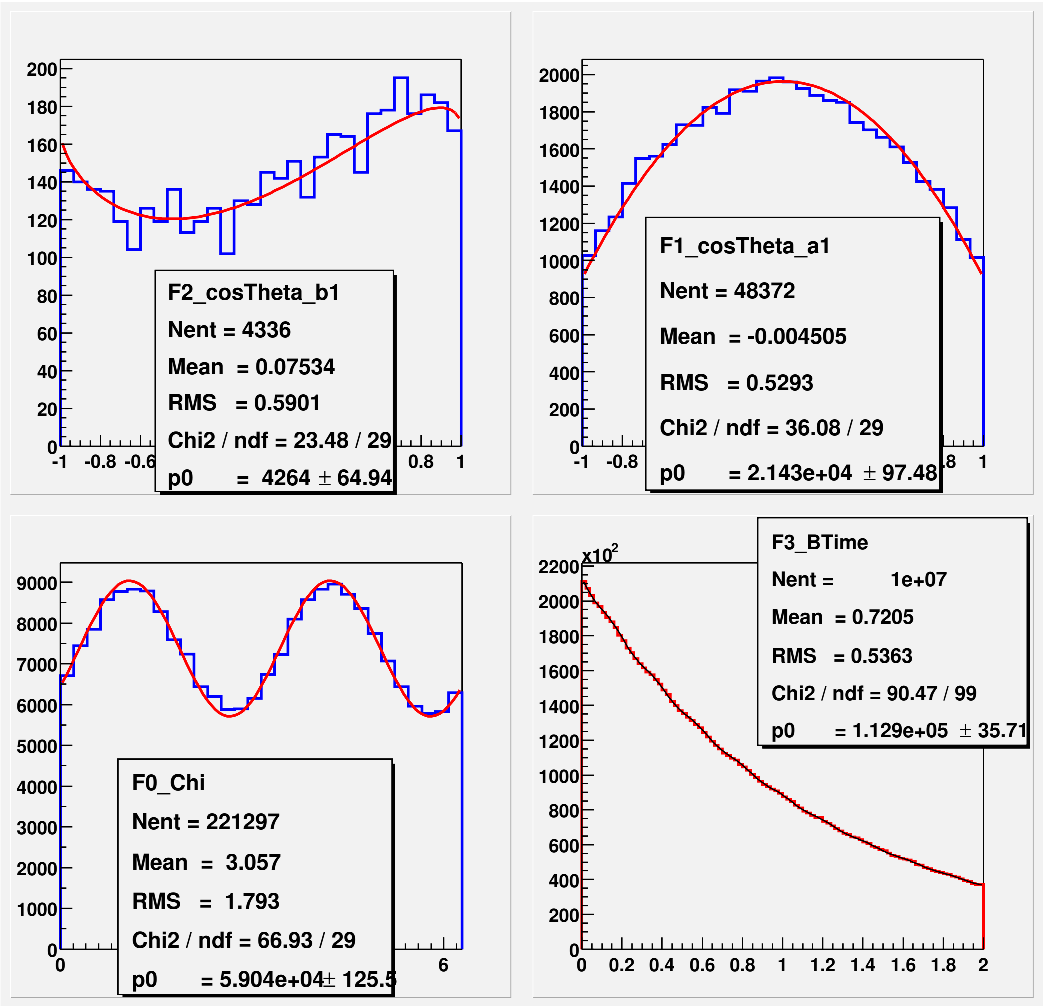
- for $b \to b_1 b_2$ in c.m.s of b we use generated value of polar angle Θ_{b_1} while asimutal angle χ_{b_1} is simulated uniformly;

- for $a \to a_1 a_2$ in c.m.s of a we use generated value of polar angle Θ_{a_1} while asimutal angle is calculated as $\chi_{a_1} = \chi_{b_1} + \chi$

Test of Random Number Generations

"Golden mode" $B_s^0(t) \to J/\Psi(\to \mu^+\mu^-)\phi(K^+K^-)$,
time-angle variable in "helicity frame"

10.000.000 events



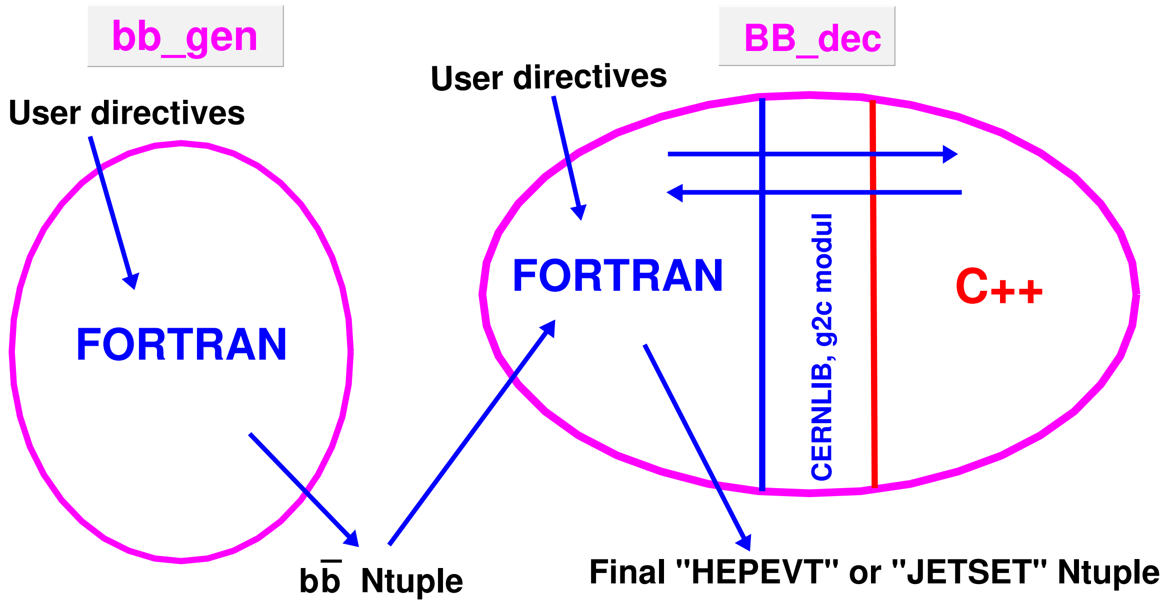
- Last figure: B lifetime distribution; histogram is fitted by $P \times f_3(t)$, where P is the fit parameter;

- Third figure: χ distribution for fixed $t = \langle t \rangle$ (slice over t); histogram is fitted by $P \times f_2(\chi, \langle t \rangle)$;

- Second figure: $\cos\Theta_{a_1}$ distribution for fixed $t = \langle t \rangle$ and $\chi = \langle \chi \rangle$ (slices over t and χ); histogram is fitted by function $P \times f_1^{(2)}(\cos\Theta_{a_1}, \langle \chi \rangle, \langle t \rangle)$;

- First figure: $\cos\Theta_{b_1}$ distribution for fixed $t = \langle t \rangle$ and $\chi = \langle \chi \rangle$ and $\cos\Theta_{a_1} = \langle \cos\Theta_{a_1} \rangle$ (slices over t, χ and $\cos\Theta_{a_1}$); histogram is fitted by $P \times f_0(\langle \cos\Theta_{a_1} \rangle, \cos\Theta_{b_1}, \langle \chi \rangle, \langle t \rangle)$.

Structure of SIMUB and Data Flow

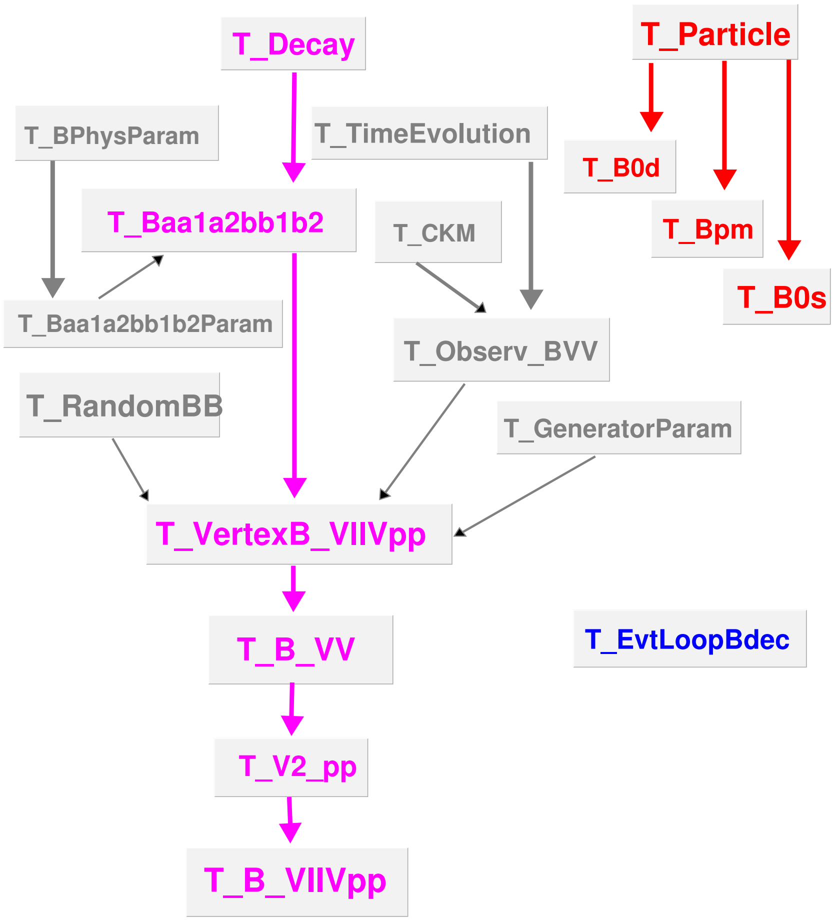


C++ part performs only the decays of B mesons

FORTRAN part is based on the package by M.Konecki and A.Starodumov: http://cmsdoc.cern.ch/~bphys/

- FORTRAN program generates $b\bar{b}$ pairs by using PYTHIA and "SIMUB/bb_gen" creates the $b\bar{b}$-event Ntuples;
- FORTRAN part inside of "SIMUB/BB_dec":
  - reads the user directives;
  - opens the Ntuples with $b\bar{b}$ pairs and reads the $b\bar{b}$ events;
  - performs the fragmentation by using PYTHIA;
  - stops the process on the stage before B decays and passes the information about B momentum and vertex **to C++ part**;
  - receives B decay data **from C++ part** ;
  - adds the decay data to PYTHIA common blocks;
  - transforms data to the HEPEVT format by using PYTHIA facilities;
  - writes the event to final NTUPLE (for CMSIM)

Inheritance of C++ Classes in SIMUB



- T_Decay – defines the **types of decays**:
  - three types of decays are included now in SIMUB:
    - $B(t), \bar{B}(t) \to V_1(\to ll)V_2(\to pp)$ (see Figure);
    - $B \to P(\to pp)\mu\nu$;
    - $B \to V(\to pp)\mu\nu$;
  - Standart Model physical parameters: CKM matrix, weak mixing phase, decay weak phases;
  - generator parameters: resolutions, random number seed;
- T_Particle – defines the particles with definite decay channels:
  - physics parameters of concrete particle;
  - set of concrete decay channels for the particles;
- T_EvtLoopBdec – loop over the events and interface between FORTRAN and C++ parts of `BB_dec` program

CURRENT STATUS OF SIMUB

1. **The starting version** of the package SIMUB_V_0 is created and tested on Linux (RedHat 6.1, 6.2) platform.

2. The package **SIMUB_V_0** and **documentation** for user one can find on the SIMUB Package Home Page: **http://cmsdoc.cern.ch/~ shulga/SIMUB/SIMUB.html**.

3. SIMUB provides **framework** for user to perform:
   - B decays with **full physics** description (dynamical modes);
   - B-decays with **kinematics** simulations only (kinematical PYTHIA-based modes).

4. The exclusive channels $B \to \pi\pi$, $B \to K\pi$ are implemented in PYTHIA mode;

5. The semileptonic exclusive channels $B \to D\mu\nu$, $B \to D^{\star}\mu\nu$ and decays $B_s^0(t), \bar{B}0_s(t) \to J/\Psi\,\phi$, $B, \bar{B} \to J/\Psi\,K^*$ are implemented both in dynamical and PYTHIA modes;

6. SIMUB provides MC simulation **tools** for exclusive **B-trigger** studies;

7. SIMUB package provides unique tools for **physics studies** of dynamical mechanisms of the **semileptonic** and CMS **"golden"** B-decay channels.

CURRENT STATUS OF MASS PRODUCTION FOR CMS B PHYSICS

1. The mass production of events with $b\bar{b}$ pairs is in progress:
   - more than 13 000 000 events is already generated at Dubna (PYTHIA 6.158, MSEL=1, with fragmentation stopped at quark level);
   - 115 files with 9 000 000 events from Dubna $b\bar{b}$ production are on Castor: /castor/cern.ch/user/b/bphys/gen;
2. Starting samples with "golden" B decay mode and with simeleptonic modes are ready for **CMSIM-ORCA** simulation.

SIMUB performance demonstration

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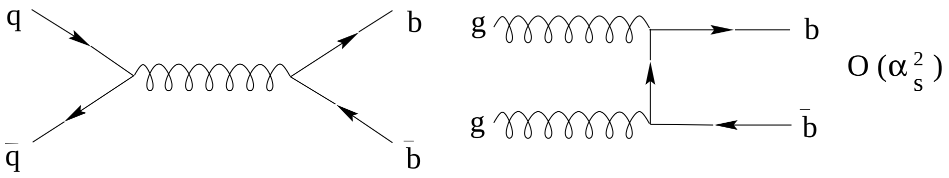
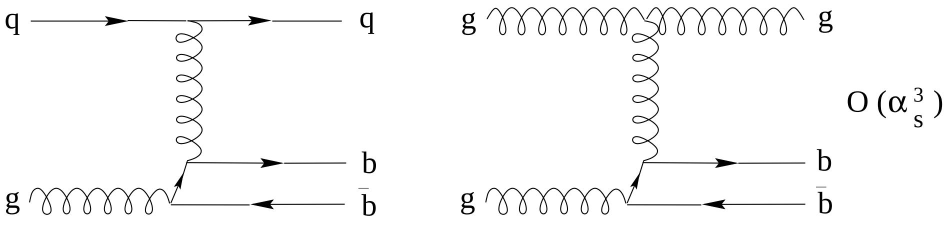
CORRELATED $b\bar{b}$ PRODUCTION

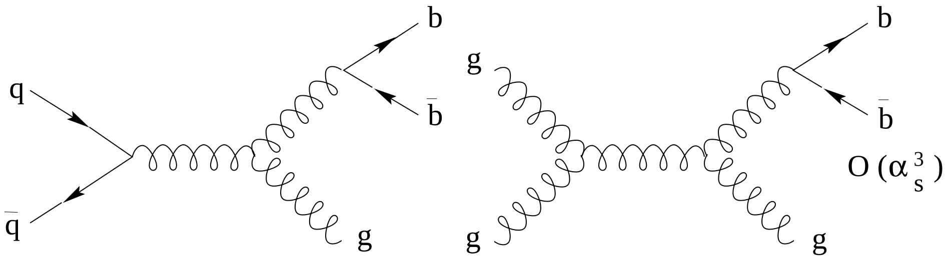
Parton fusion :



Flavour excitation:



Gluon splitting:



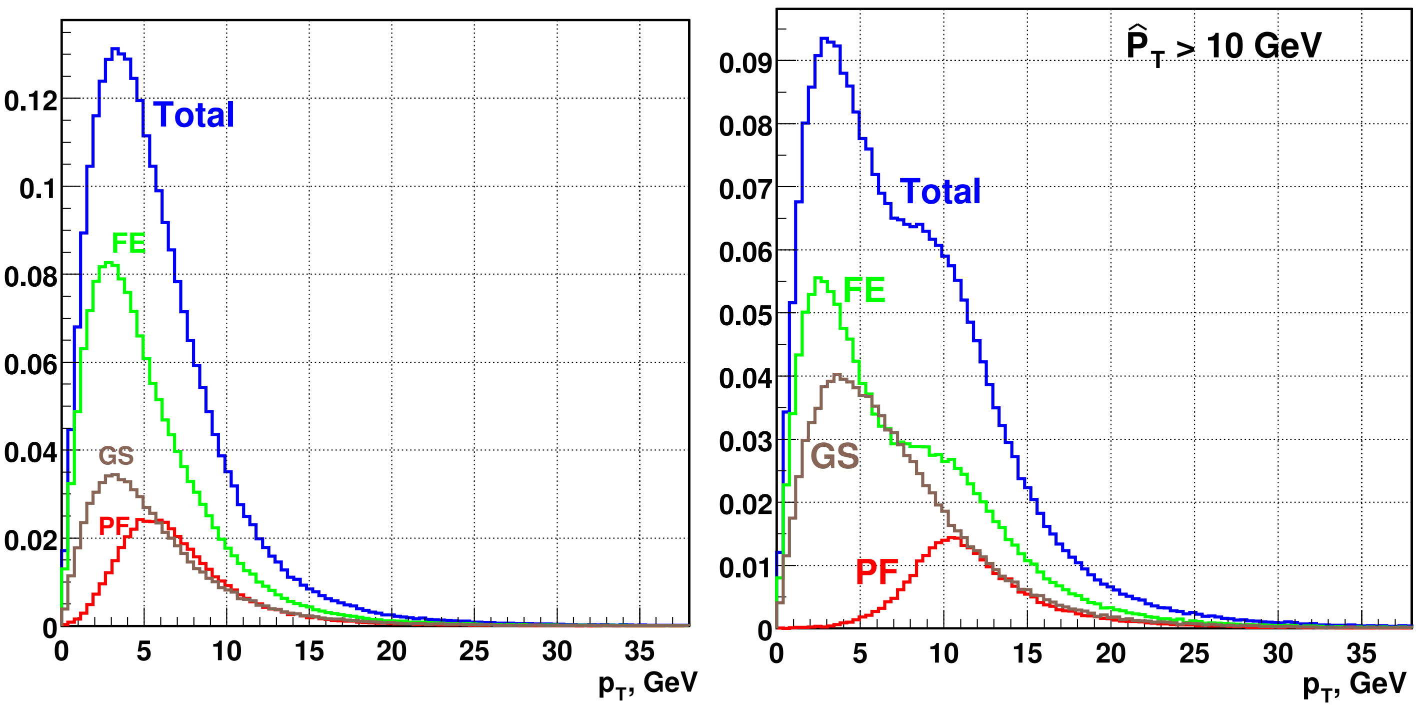
- At LHC energies the next-to-leading order graphs of flavour excitation and gluon splitting become to be dominating relative to the lowest-order graphs of the parton fusion;

- Minimum bias events MSEL $= 1$: all QCD $2 \to 2$ subprocesses, but the rate of $b\bar{b}$ events is turn to be less than 1% of all generated pp interactions: This is a main reason to separate the $b\bar{b}$ generation from fragmentation, B generation and decays;

- All three mechanisms (parton fusion, flavour excitation, gluon splitting) contribute to $b\bar{b}$ production;

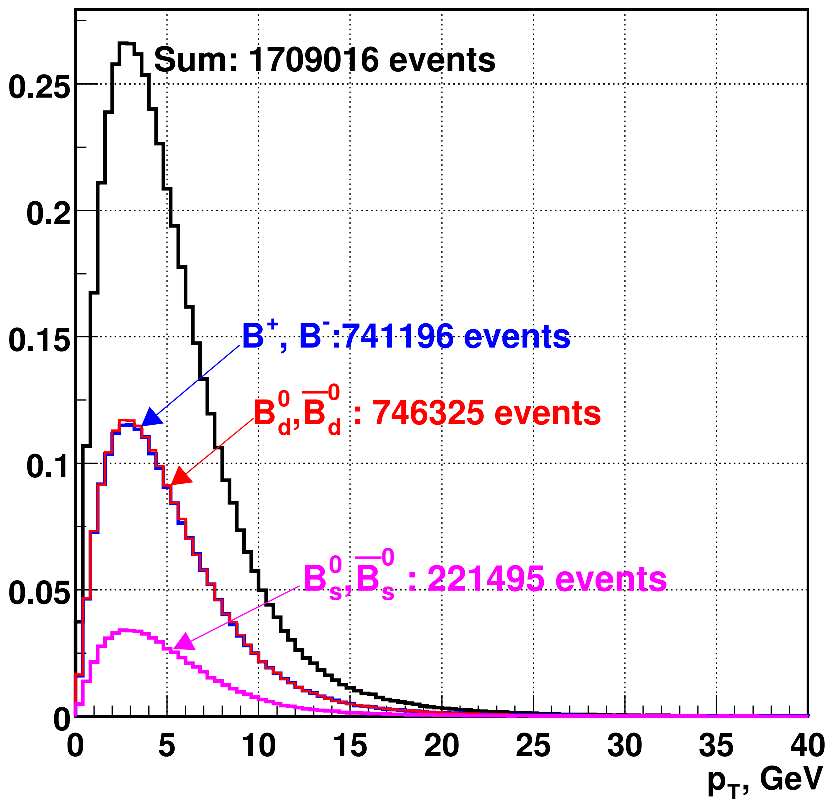
- Transverse momentum, $\hat{P}_T$, of the partons produced in a hard interaction in $2 \to 2$ processes:
  `CKIN(3) = 0` – no $\hat{P}_T$ cutoff (by default in PYTHIA)
  `CKIN(3) = 10` – cutoff $\hat{P}_T \geq 10$ GeV.

- Contribution of different mechanisms to the b-quark distribution on the transverse momentum p_T:



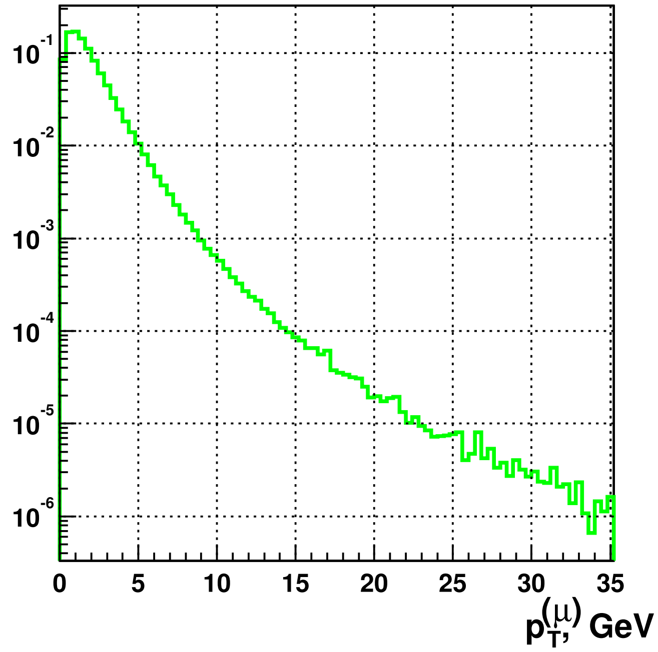
- p_T-distribution for B mesons:

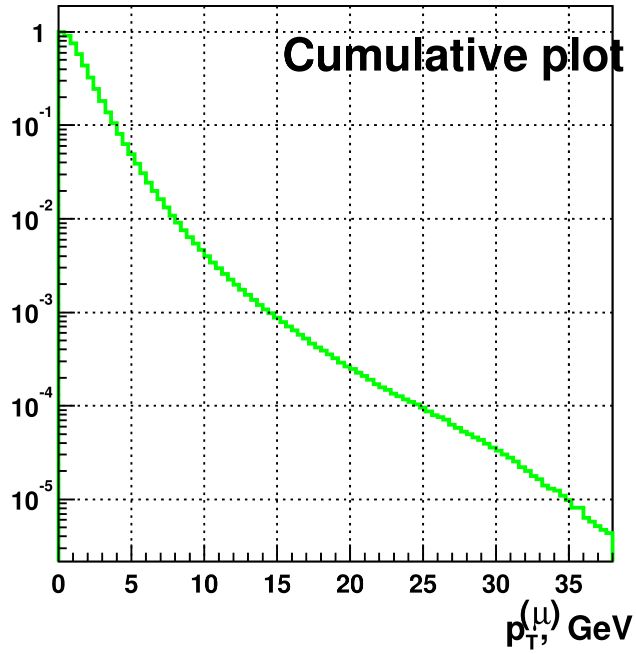
926344 B events (integral = 1)



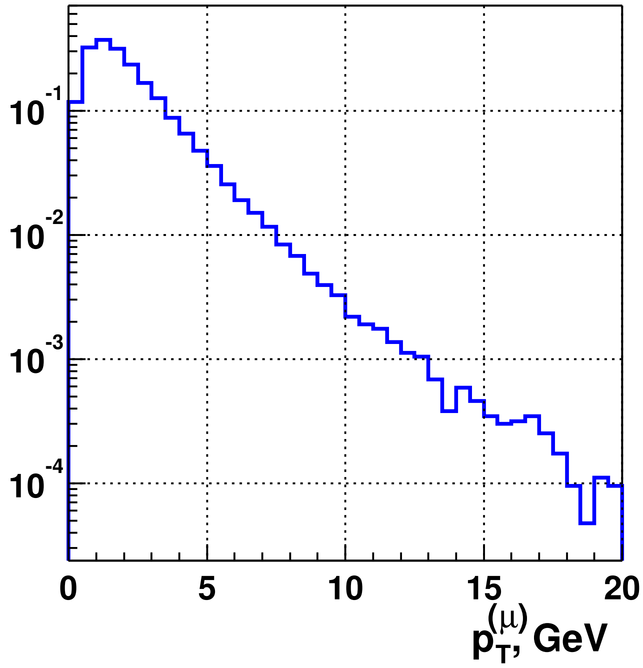
MUON PLOTS FOR B DECAYS:
Semileptonic Decays $B \to D\mu\nu$, $B \to D^*\mu\nu$ and "Golden" Decay $B \to J/\psi(\to \mu^+\mu^-)\,\phi(K^+K^-)$

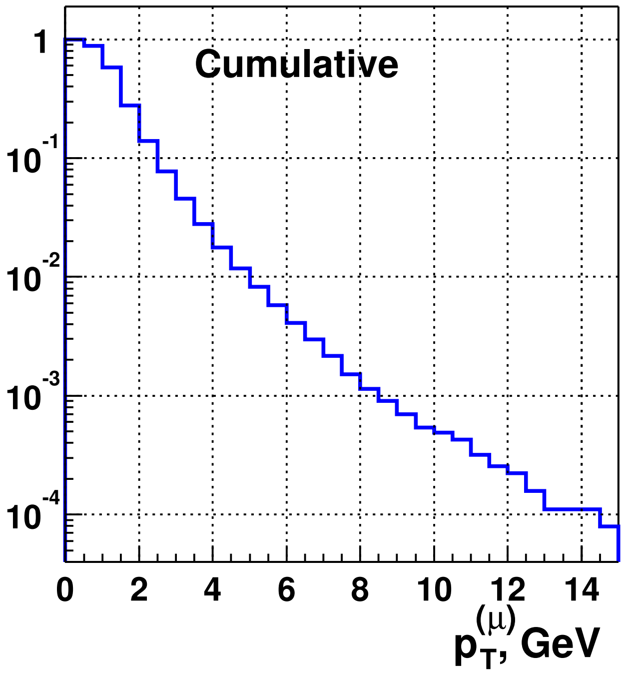
Muon transverse momentum $p_T^{(\mu)}$ and muon cumulative plot for semileptonic decays





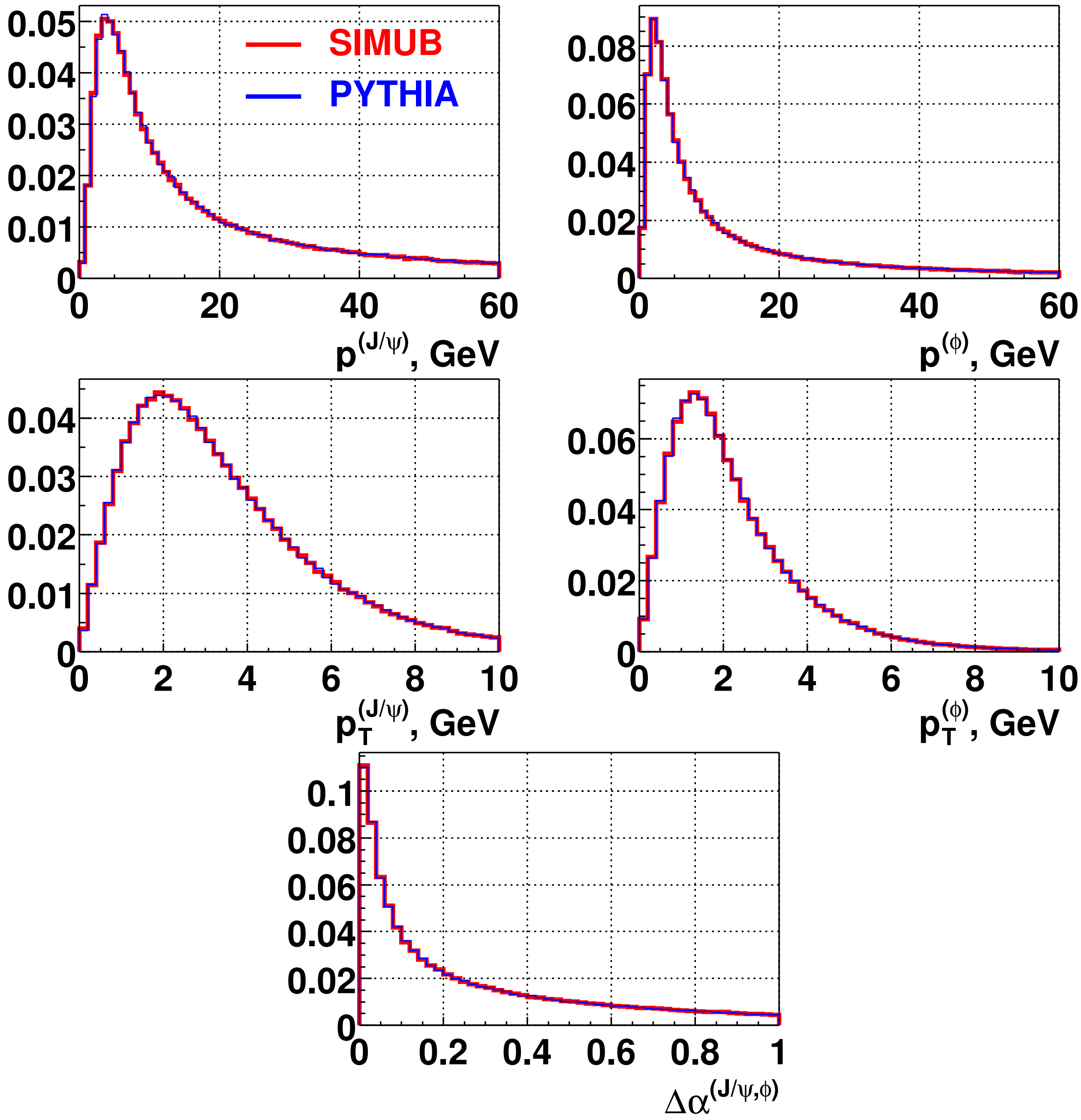
Muon transverse momentum $p_T^{(\mu)}$ and cumulative plot for minimal $p_T^{(\mu)}$ of two muons for "golden" decay



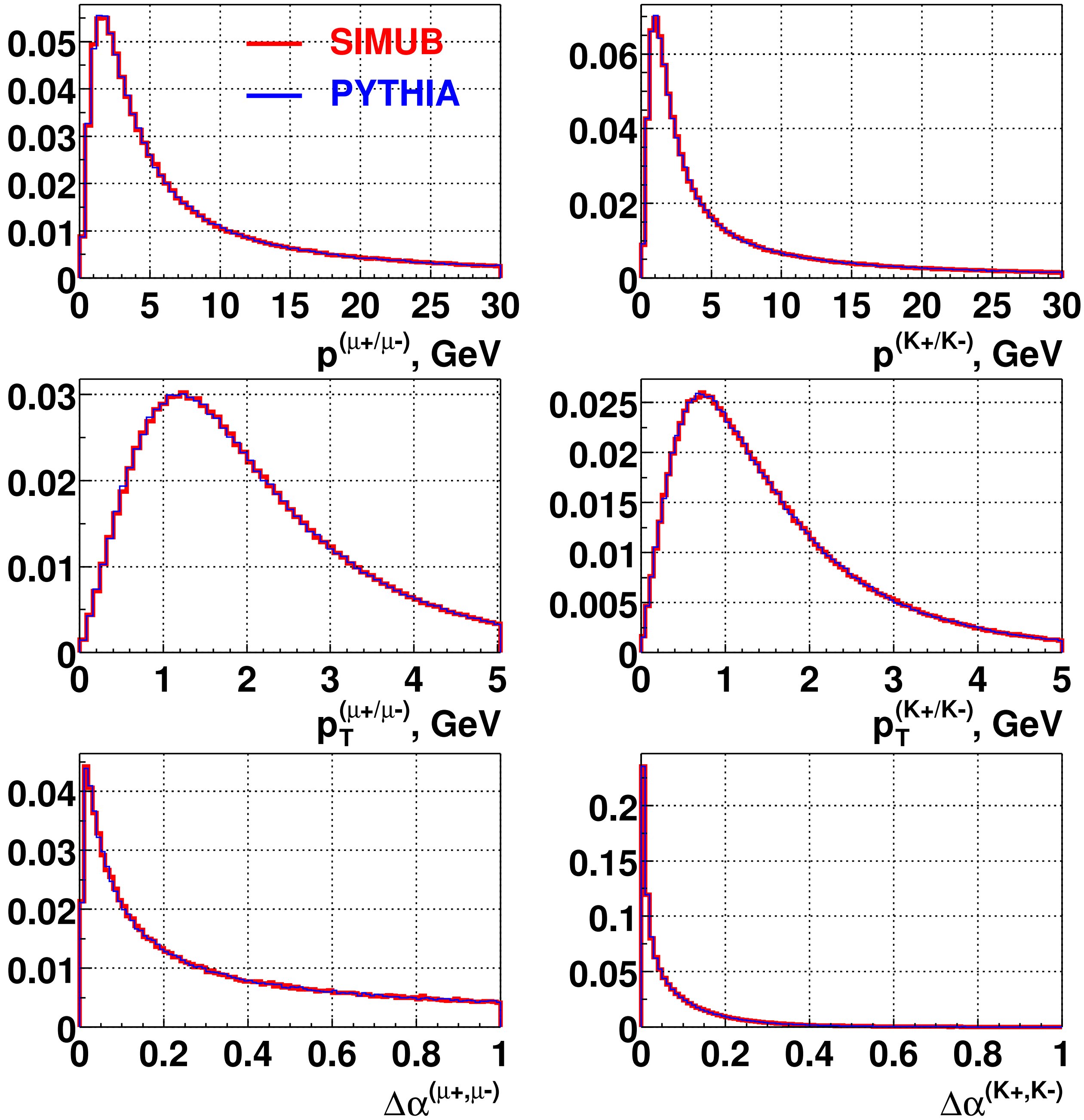


$B \to J/\psi(\to \mu^+\mu^-)\,\phi(K^+K^-)$: COMPARISON BETWEEN SIMUB AND PYTHIA

- **Laboratory system**:
  momentum (p, p_T) and angular-difference ($\Delta\alpha$) distributions for J/ψ (left) and ϕ (right)



- **Laboratory system**:
momentum (p, p_T) and angular-difference ($\Delta\alpha$) distributions for $\mu^+\mu^-$ (left) and K^+K^- (right)



Large boost from helicity to Lab. systems

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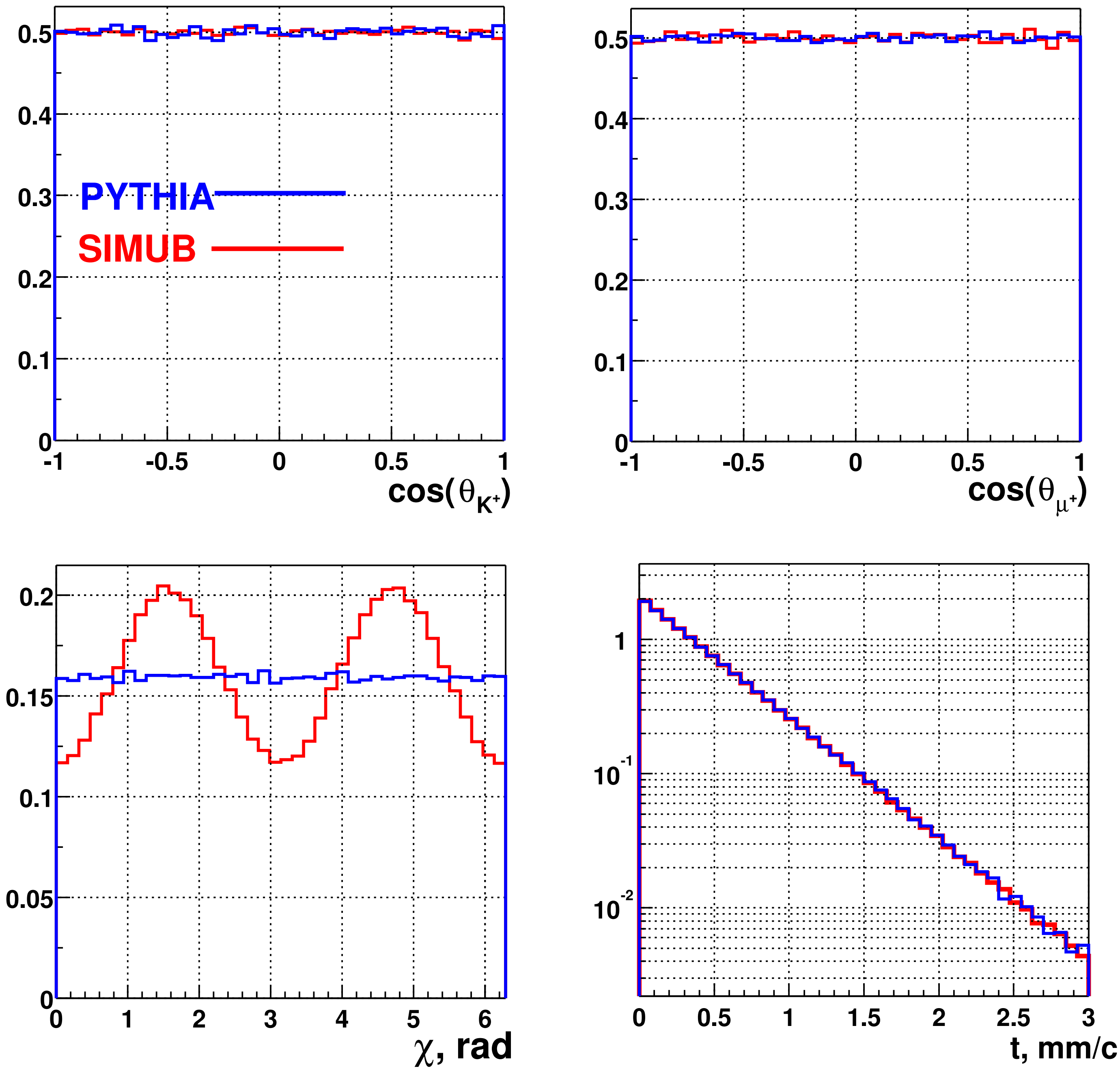
In Lab. system, the distributions generated by SIMUB practically coincide with those generated by PYTHIA

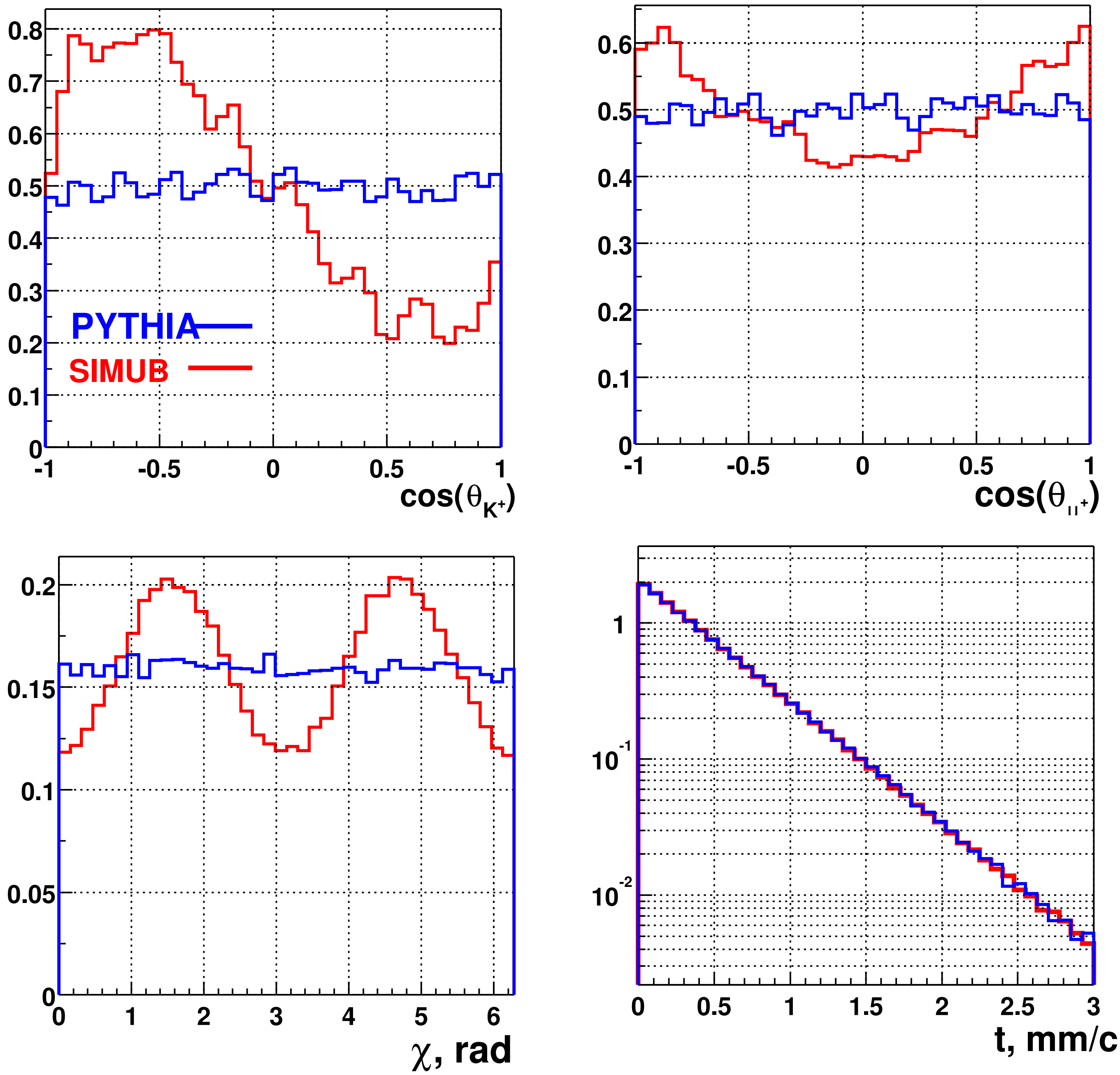
- **Helicity frame**:

  Time and angular distributions ($\cos\Theta_{K^+}$, $\cos\Theta_{\mu^+}$, χ) without cutting of slices over time and angles



$$\boxed{1\ \mathbf{mm}/c \approx 3.33 \times 10^{-12}\ \mathbf{sec}}$$

- **Helicity frame**:
  Time and angular distributions ($\cos\Theta_{K+}$, $\cos\Theta_{\mu}^{+}$, χ) with cutting of slices over time and angles:



$$
\begin{array}{rl}
\chi: & 0.01\ \mathrm{mm}/c < t < 0.19\ \mathrm{mm/c} \\
\cos\Theta_{\mu+}: & 0.01\ \mathrm{mm}/c < t < 0.19\ \mathrm{mm/c}\,, \quad 0.3\ \mathrm{rad} < \chi < 0.6\ \mathrm{rad} \\
\cos\Theta_{K+}: & 0.01\ \mathrm{mm}/c < t < 0.19\ \mathrm{mm/c}\,, \quad 0.3\ \mathrm{rad} < \chi < 0.6\ \mathrm{rad} \\
 & 0.7 < \cos\Theta_{\mu+} < 1
\end{array}
$$

PLANS

- The full mass production for several B decay modes within a chain SIMUB+CMSIM+ORCA
- Physics study of "golden decay" at generator level
- Physics study of "golden decay" with full detector simulations
- Further development of the package SIMUB:
  - classification of decay modes;
  - definition of user keys for all modes;
  - algorithms for new decay channels and physics mechanisms