Studies of decoherence models with entangled neutral B meson pairs at BELLE

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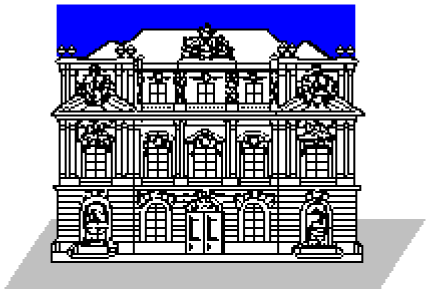
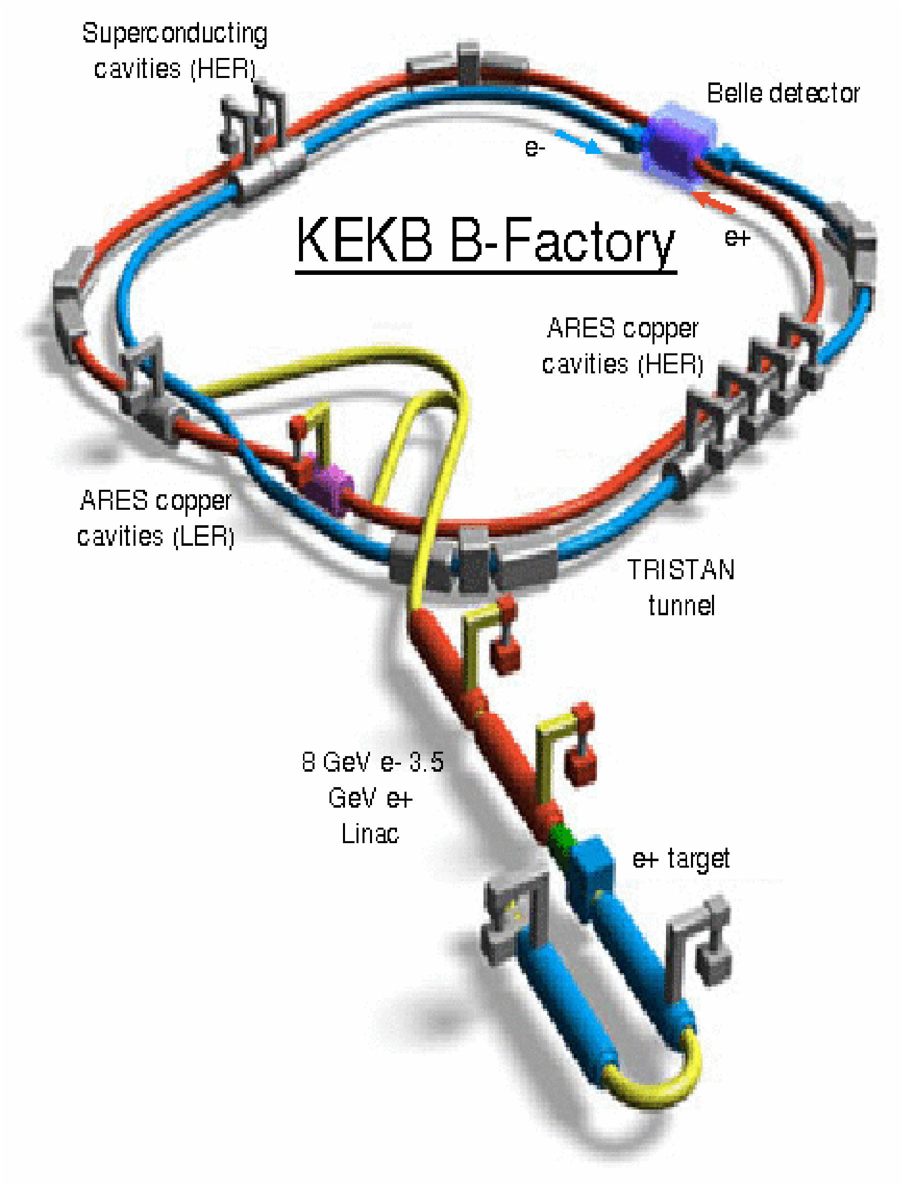
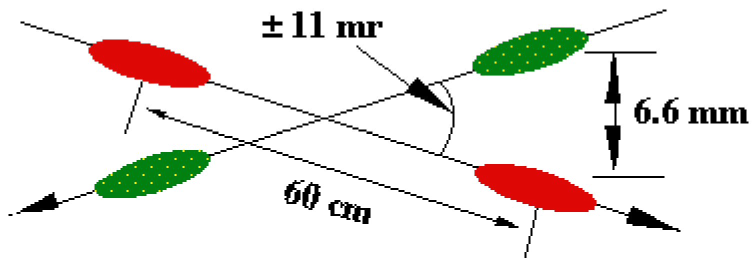


"CoMo@BELLE"

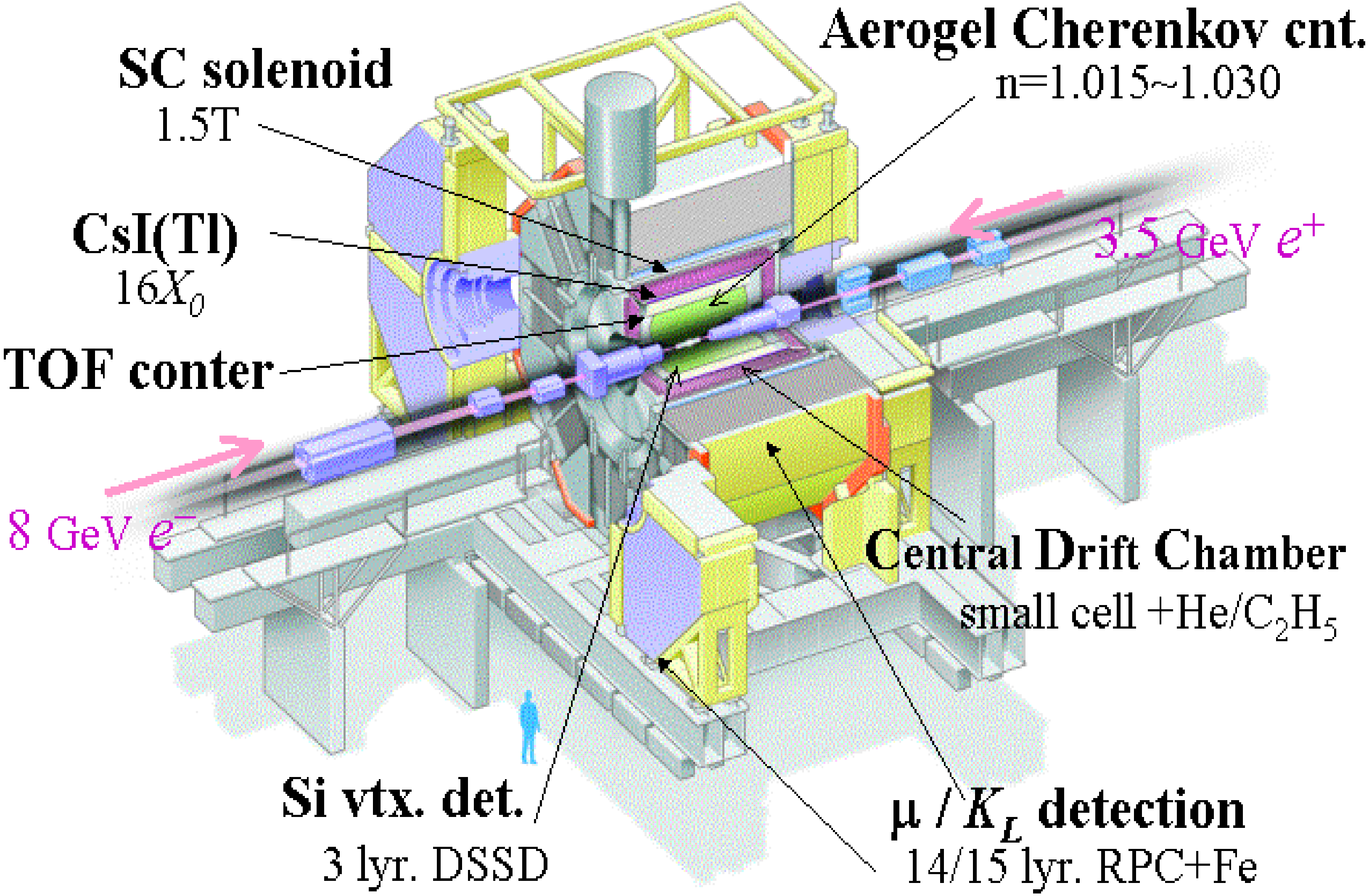
The BELLE experiment



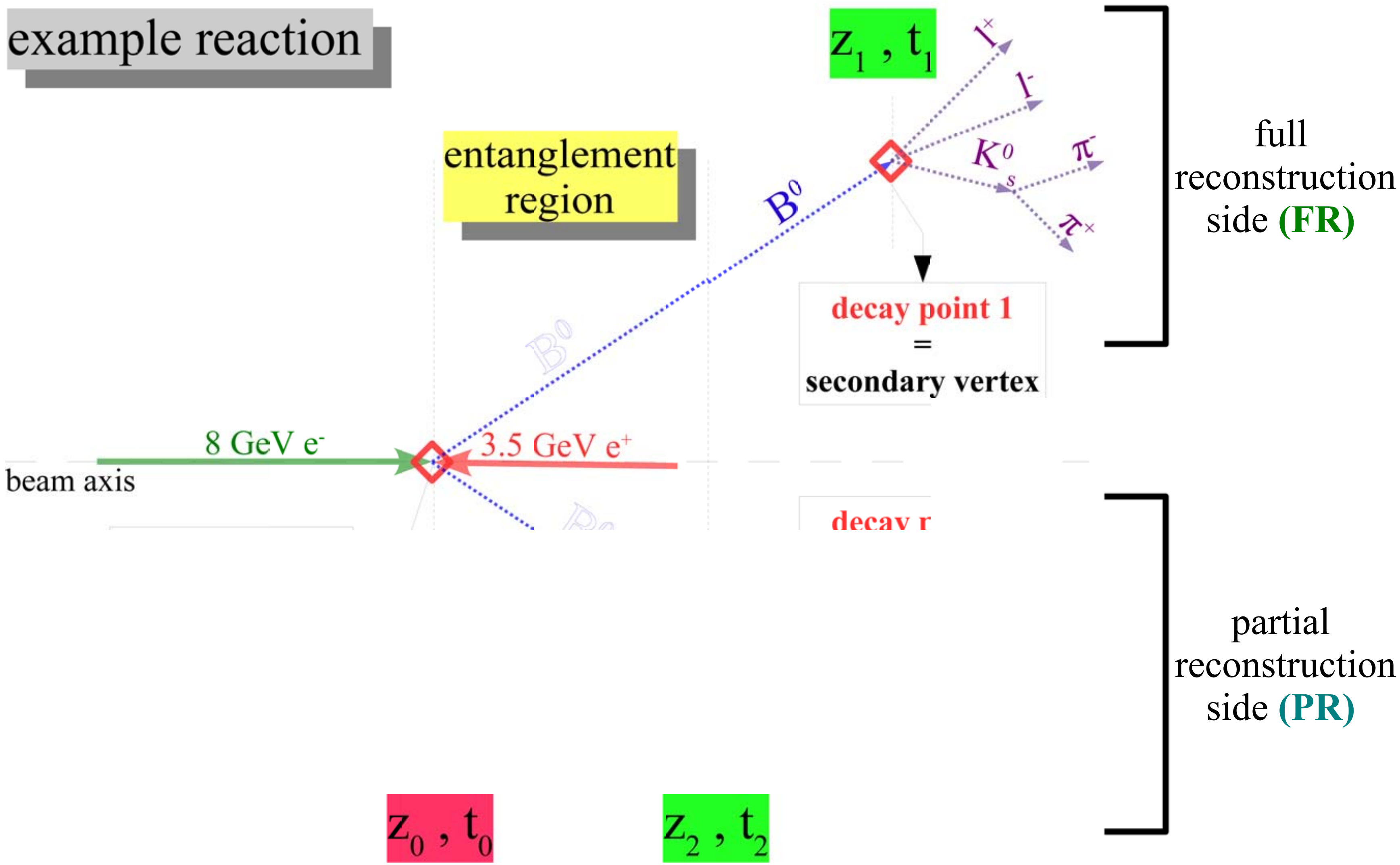
- Location: Tsukuba, about 60 km NE of Tokyo
- asymmetric $e^+ e^-$ collider at Y(4s) resonance; so called "B-factory"
- 5,000 bunches in a ring of 3km; bunch spacing of 0.6m



Belle Detector

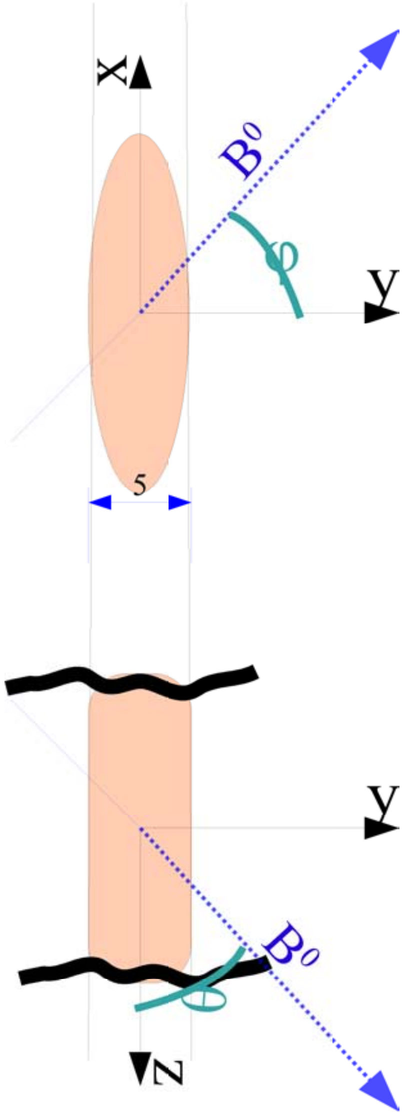


The $B^0\overline{B}^0$ decay



- $\beta\gamma c\tau_{B0} = 462\ \mu m$ (LAB)
- $\Delta m = 0.489\ 10^{12}\ \hbar s^{-1} = 0.754\ \tau_{B0}^{-1}$

The beam interaction profile (BIP)



<u>z-resolutions:</u>

- σ_z(FR): 50 μm
- σ_z(PR): 120 μm
- possible improvement with better vertex reconstruction
- intersecting the FR side B vector with the BIP to get z_0
- limits to the possible polar angles of B-meson plane
- BIP extensions:

σ_x	80	μm
σ_y	5	μm
σ_z	3000	μm

expected time resolutions

- various effects will deteriorate the resolution
  - dominating effect z-coordinate resolution: $\sigma_z^{lab} \rightarrow \sigma_t^{CMS}$
  - measurement errors on momentum vector direction
  - angular dependence of σ_{z0}
- time resolutions for z_1, z_2 in CMS

	σ_z^{lab} [μm]	σ_t^{lab} [ps]	σ_t^{CMS} [ps]	σ_t^{CMS} [τ_B]
full	50	0,43	0,39	0,2
partial	120	1,02	0,94	0,5

QM and flavour asymmetry

$$E^{QM}(\Delta t) = \frac{N(=|t_1,t_2) - N(\neq|t_1,t_2)}{N(=|t_1,t_2) + N(\neq|t_1,t_2)} = \frac{\cos(\Delta m \Delta t)}{\cosh(\frac{1}{2}\Delta\Gamma\Delta t)}$$

$$A^{QM}(\Delta t) = P(=|t_1,t_2) - P(\neq|t_1,t_2) = \cos(\Delta m \Delta t)$$

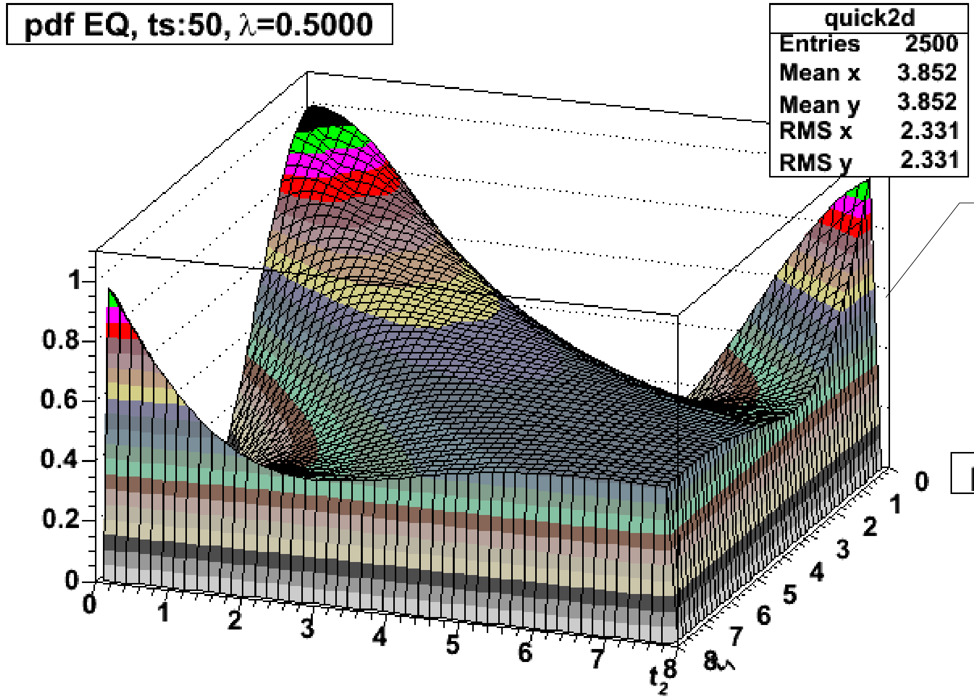
$$A^{QM}(\Delta t, \lambda) = \cos(\Delta m \Delta t)\exp(-\lambda \min(t_1,t_2))$$

$$P(=|t_1,t_2,\lambda) = \tfrac{1}{2}(1 + \cos(\Delta m \Delta t)\exp(-\lambda \min(t_1,t_2)))$$
$$P(\neq|t_1,t_2,\lambda) = \tfrac{1}{2}(1 - \cos(\Delta m \Delta t)\exp(-\lambda \min(t_1,t_2)))$$

$$p(=|t_1,t_2,\lambda) = P(=|t_1,t_2,\lambda)\exp(-t_1)\exp(-t_2)$$
$$p(\neq|t_1,t_2,\lambda) = P(\neq|t_1,t_2,\lambda)\exp(-t_1)\exp(-t_2)$$

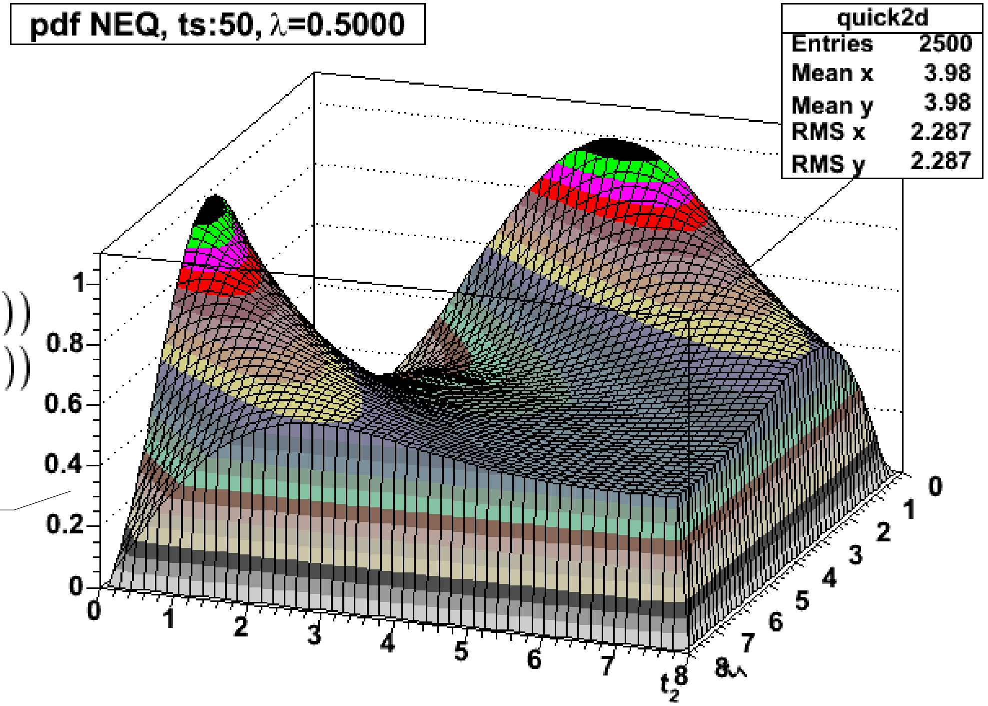
- QM ratio of events to be expected for meson pairs
- normalize to the number of events, defining asymmetry
- inclusion of one possible coherence model term
- probabilities of non-/ equal flavour pair
- lifetime corrected pseudo pdfs

Probability distribution behaviour



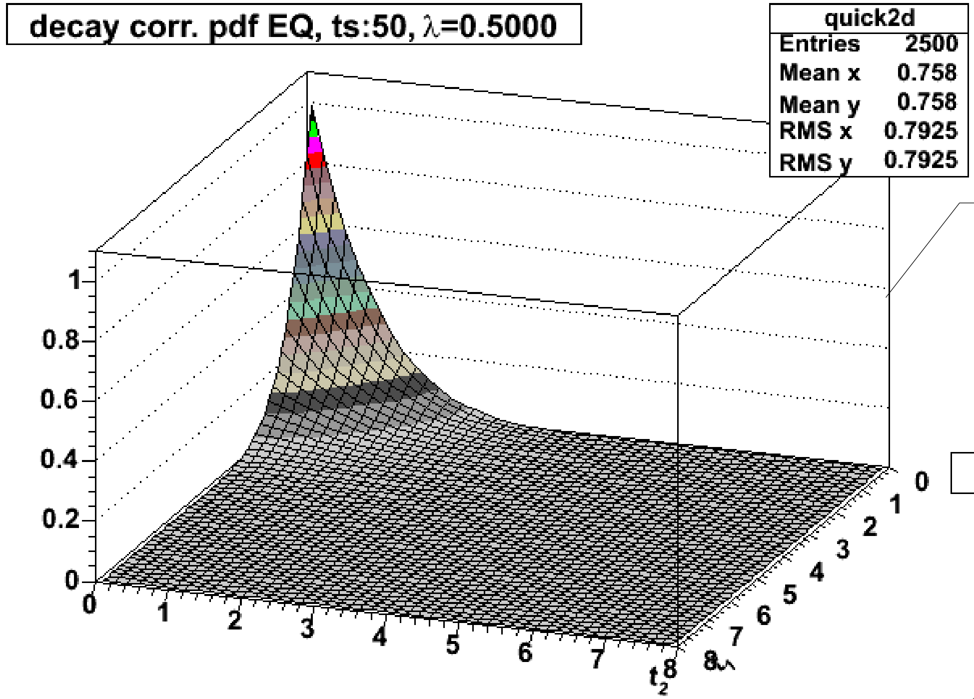
equal flavour distribution

$$P(= |t_1, t_2, \lambda) = \frac{1}{2}(1 + \cos(\Delta m \Delta t)\exp(-\lambda \min(t_1, t_2)))$$
$$P(\neq |t_1, t_2, \lambda) = \frac{1}{2}(1 - \cos(\Delta m \Delta t)\exp(-\lambda \min(t_1, t_2)))$$



non-equal flavour distribution

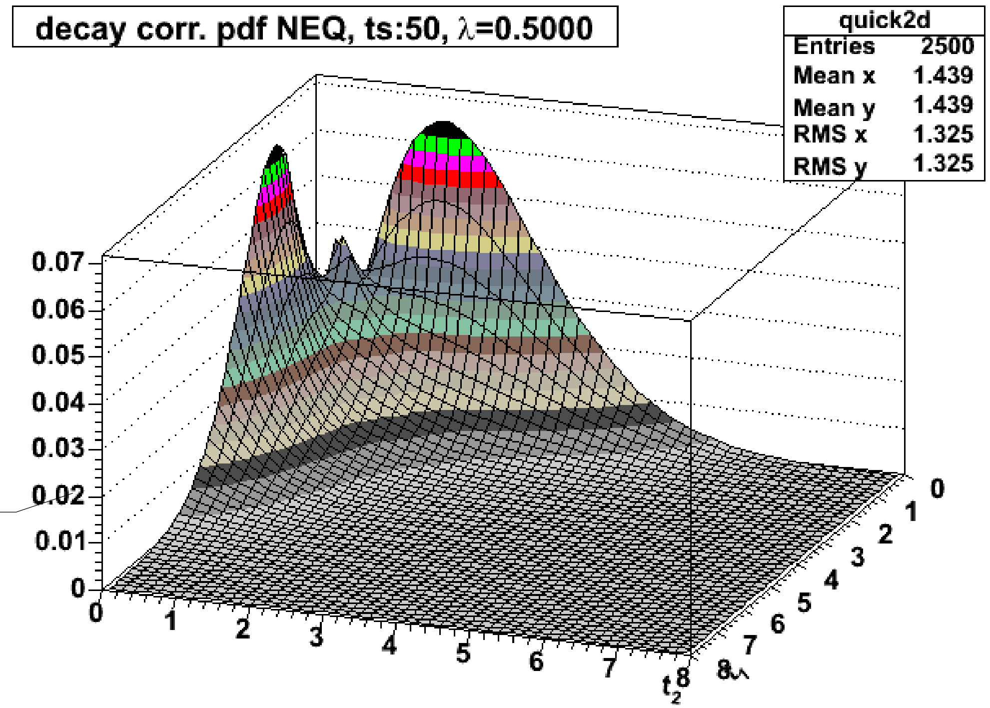
Probability distribution behaviour, time corr.



equal flavour distribution

$$p(= |t_1, t_2, \lambda) = P(= |t_1, t_2, \lambda) \exp(-t_1) \exp(-t_2)$$
$$p(\neq |t_1, t_2, \lambda) = P(\neq |t_1, t_2, \lambda) \exp(-t_1) \exp(-t_2)$$

non-equal flavour distribution



Simulation

$$\{T_1, T_2\}^n \qquad pdf(T_a) = \frac{1}{\tau_a} \exp\left(-\frac{t_a}{\tau_a}\right)$$

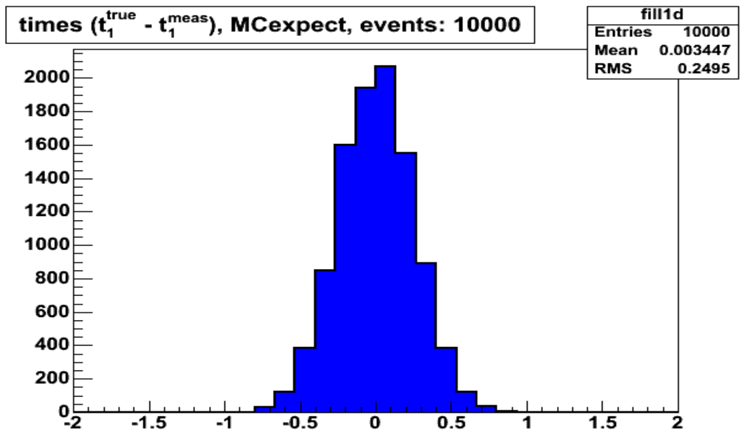
$$\{E_1, E_2\}^n \qquad pdf(E_a) = \frac{1}{\sqrt{2\pi}\sigma_a} \exp\left(-\frac{E_a^2}{2\sigma_a^2}\right)$$

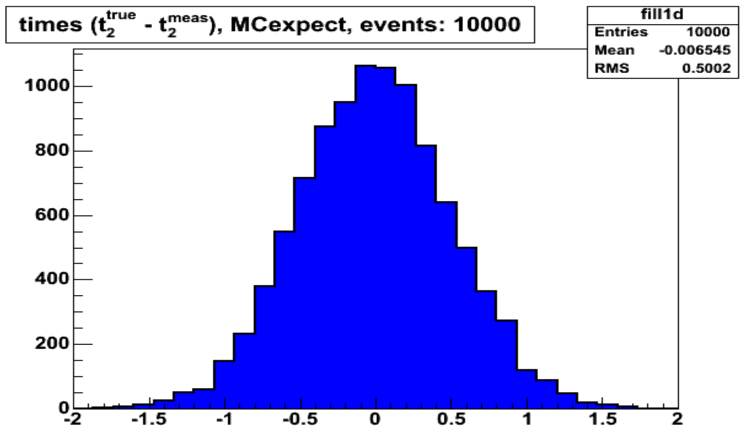
$$\{m_1, m_2\}^n = \{T_1 + E_1, T_2 + E_2\}^n$$

$$P(F_1^i = \text{non} - \text{anti}) = \frac{1}{2}$$

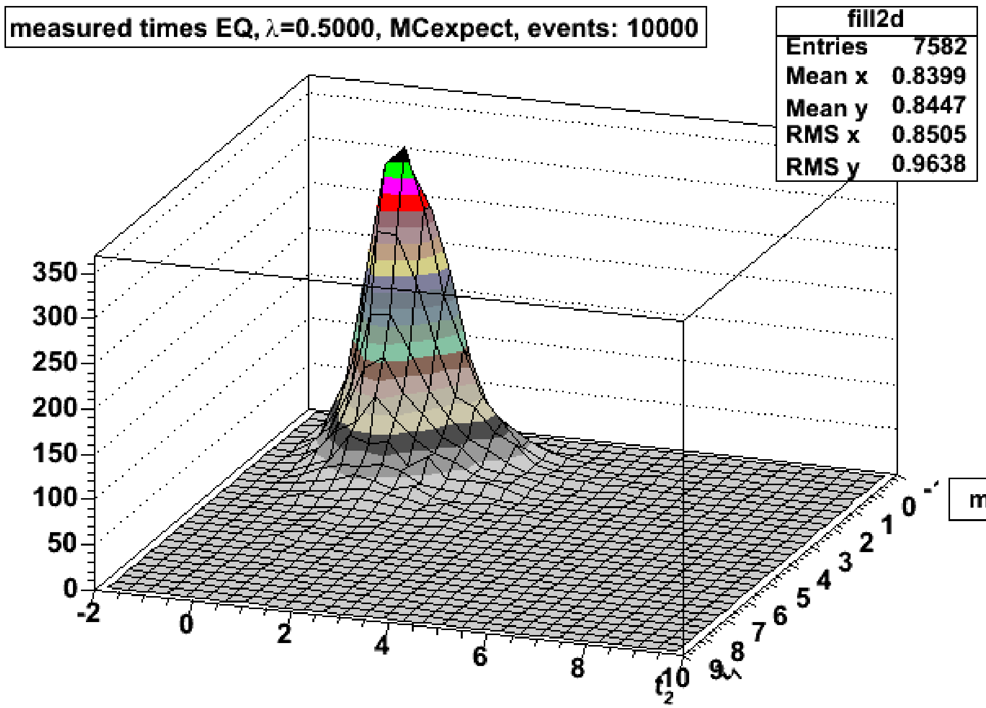
$$P(F_2^i = F_1^i | t_1^i, t_2^i) = P(= | t_1^i, t_2^i)$$

- generating exponential decay-times ("MC-truth")
- generating gaussian measurement errors
- simulated measurement
- flavour simulation
  - one picked at random
  - second picked according to P(=)



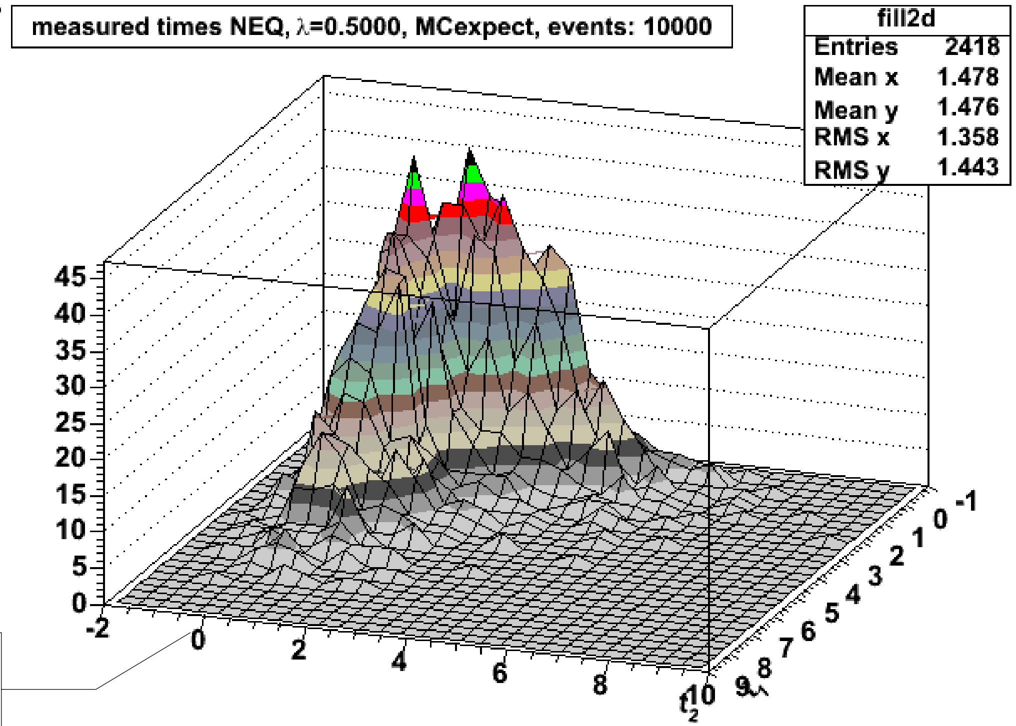


Resulting distributions



equal flavour distribution

- degrading resolution visible in more spread and more characteristic non-equal distribution



- deviations from the previous flavour distributions due to the missing error treatment in generated pdfs ...

non-equal flavour distribution

Log likelihood fit

- using convolution on the normalized pdfs for treating the time measurement errors
  - most simple case: use single gaussian convolution kernel on each time axis
- pdfs corrected for the decay-times of the mesons:

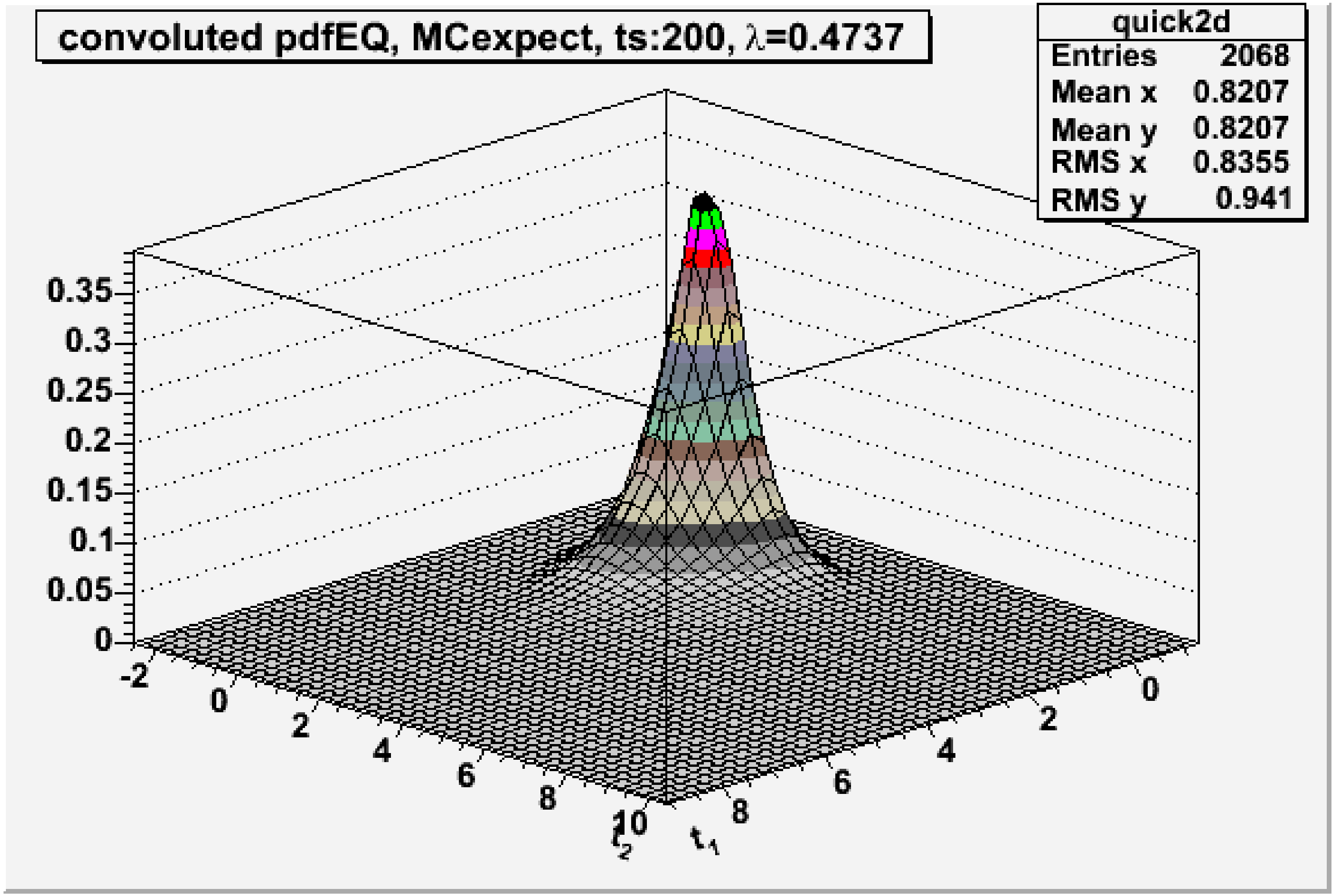
$$f(t_1, t_2| =, \sigma_1, \sigma_2, \lambda)) = \int\int \frac{p(= |t_1, t_2, \lambda)}{\int\int p(= |t_1, t_2, \lambda)} k(t_1, t_2, t_1', t_2') dt_1' dt_2'$$

$$k(t_1, t_2, t_1', t_2' | \sigma_1, \sigma_2) = \frac{1}{2\pi\sigma_1\sigma_2} \exp\left(-\frac{(t_1 - t_1')^2}{2\sigma_1^2}\right) \exp\left(-\frac{(t_2 - t_2')^2}{2\sigma_2^2}\right)$$

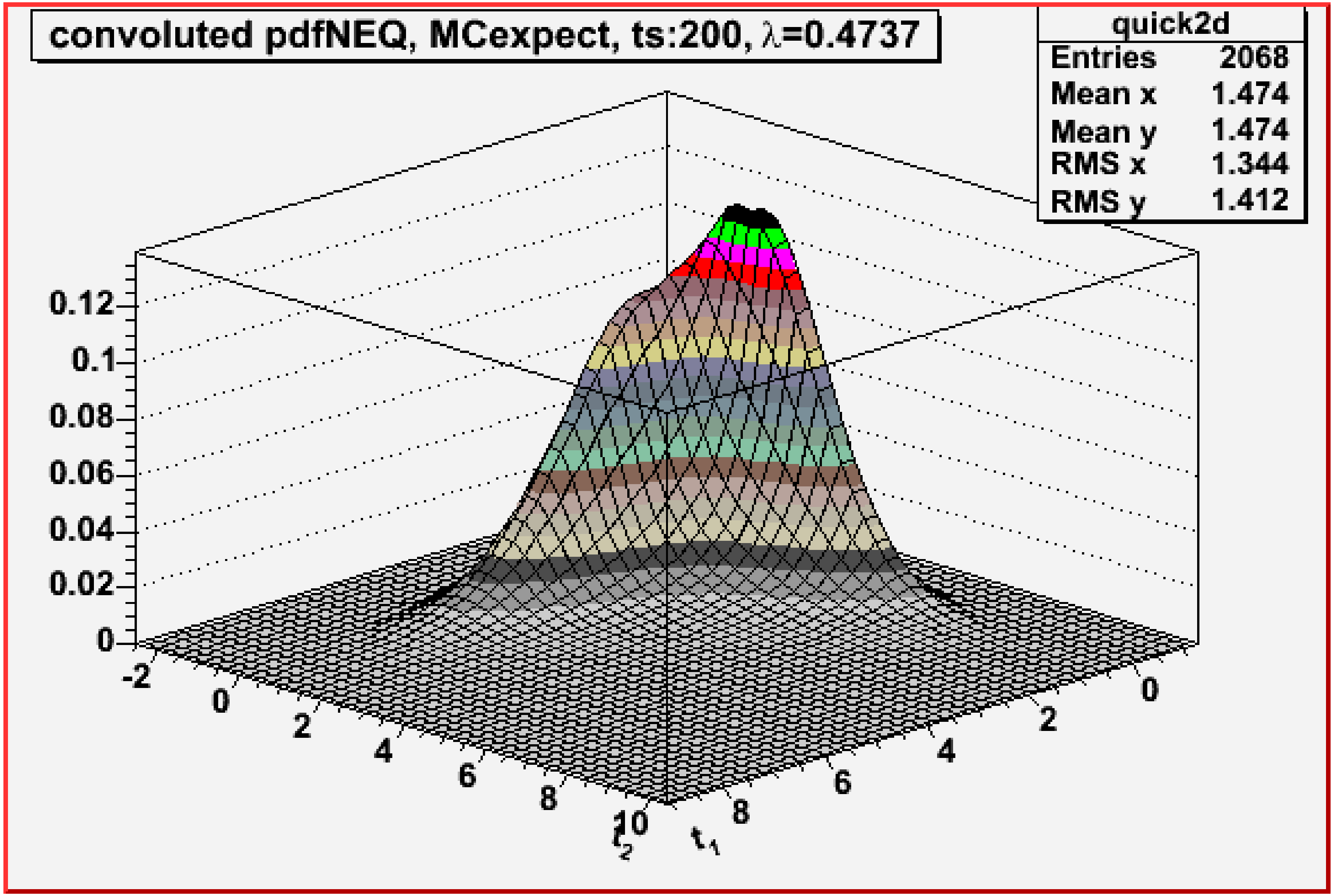
- for all measured/generated decay time tuples calculate (according to their flavour)

$$\mathcal{L}(\lambda| =) = \sum_{i=1}^{n} \log f(t_1^i, t_2^i | =, \sigma_1, \sigma_2, \lambda)$$
$$\mathcal{L}(\lambda) = \mathcal{L}(\lambda| =) + \mathcal{L}(\lambda| \neq)$$

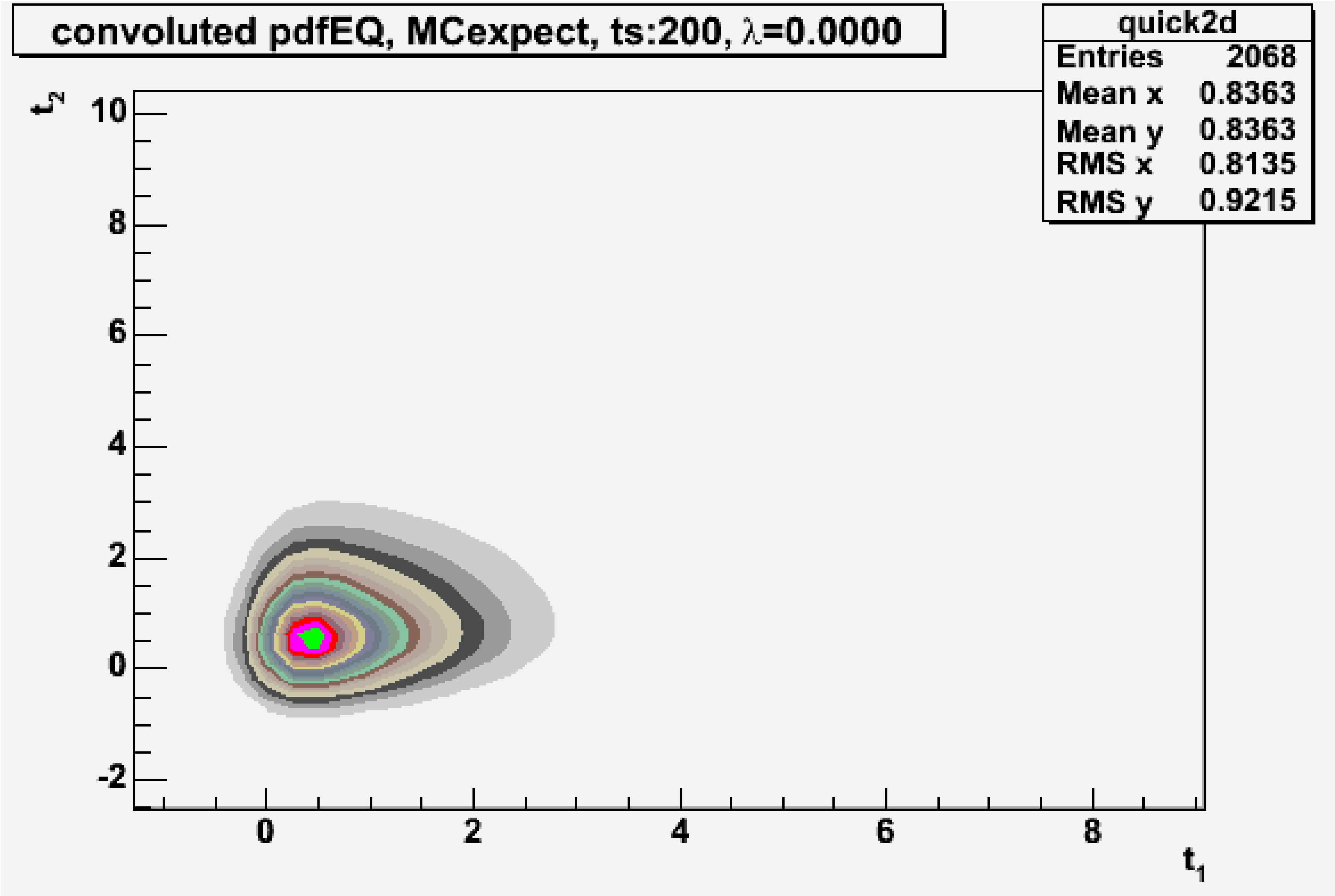
convoluted pdf equal flavour



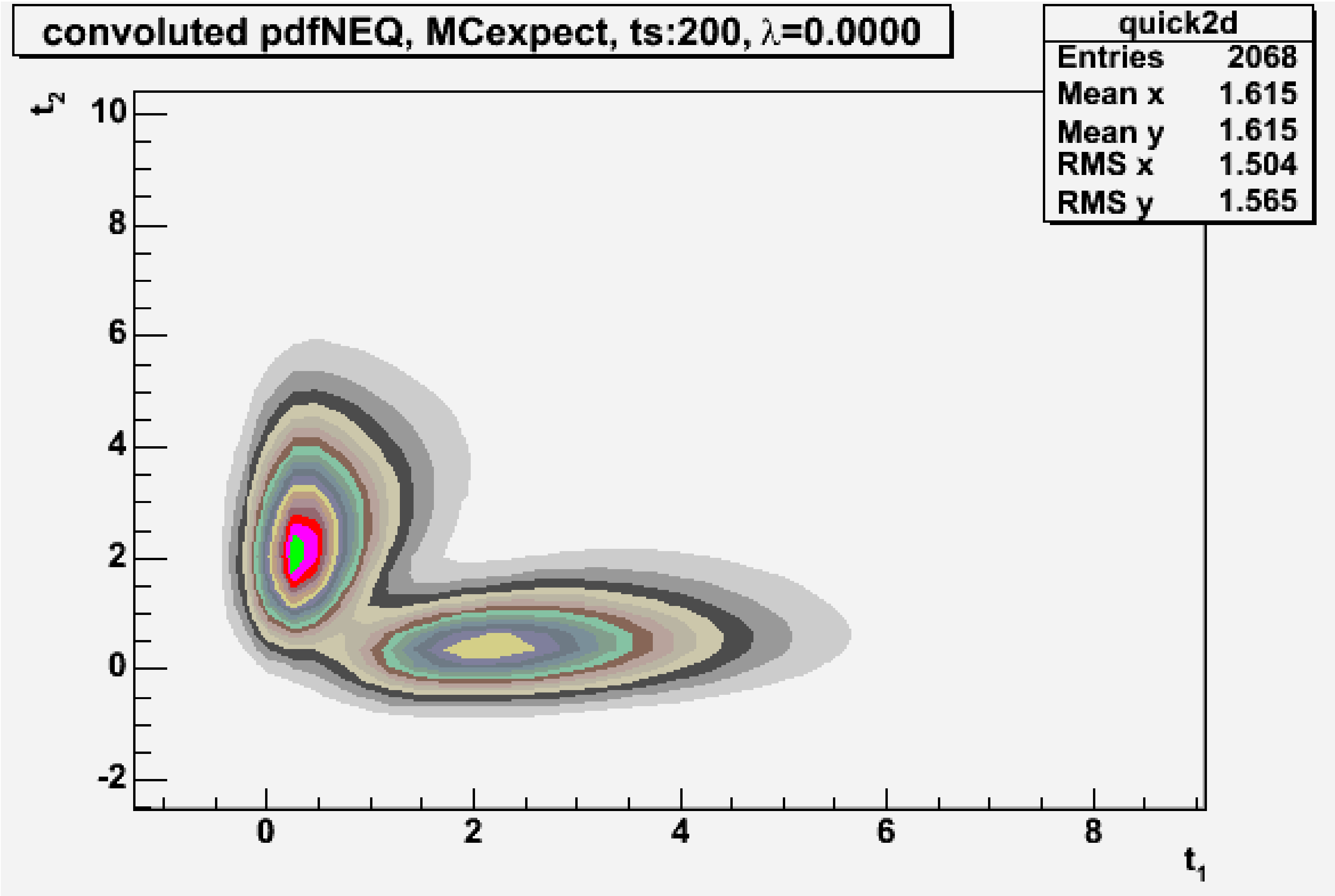
convoluted pdf non-equal flavour



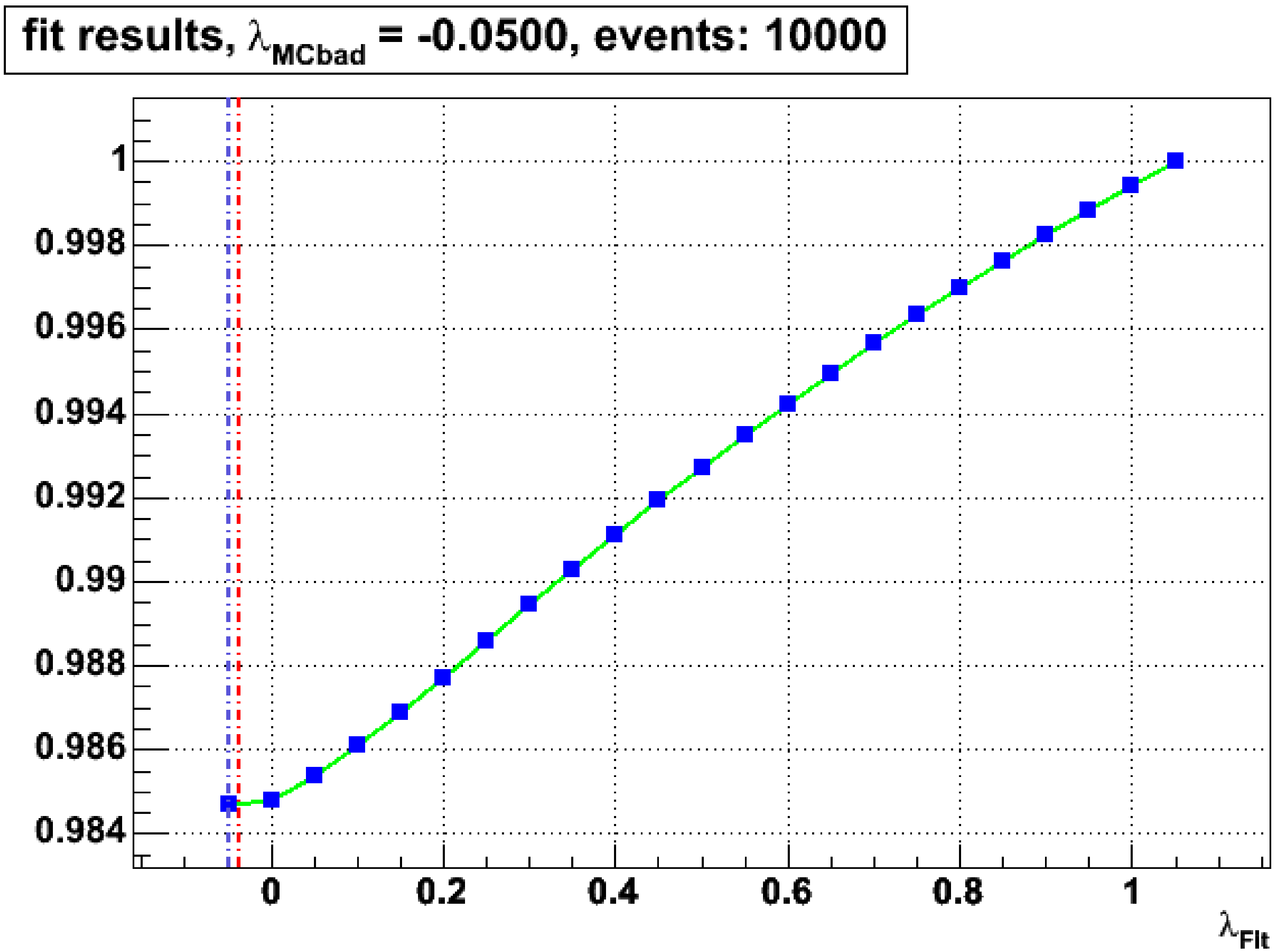
Behaviour of the pdf, EQ flavour



Behaviour of the pdf, NEQ flavour



Behaviour of the fit minimum



"moving closer to BELLE data" the BELLE GEANT MC-data

- MC data produced in amount of 3 times the measurement data
- sufficient statistics for background estimation
- used MC is as close as possible to real experiment data
- reconstruction was run filtering for one fully reconstructable B meson

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"B  decay modes code"

2 : B0B --> D+ pi-
1 : B0B --> D*+ pi-
6 : B0B --> D+ rho-
5 : B0B --> D*+ rho-
10 : B0B --> D+ a1-
9 : B0B --> D*+ a1-
```

- $450*10^6$ B^0 or $\bar{B}^0$
- reconstructed B-s: 150000
- efficiency: 0.03 %

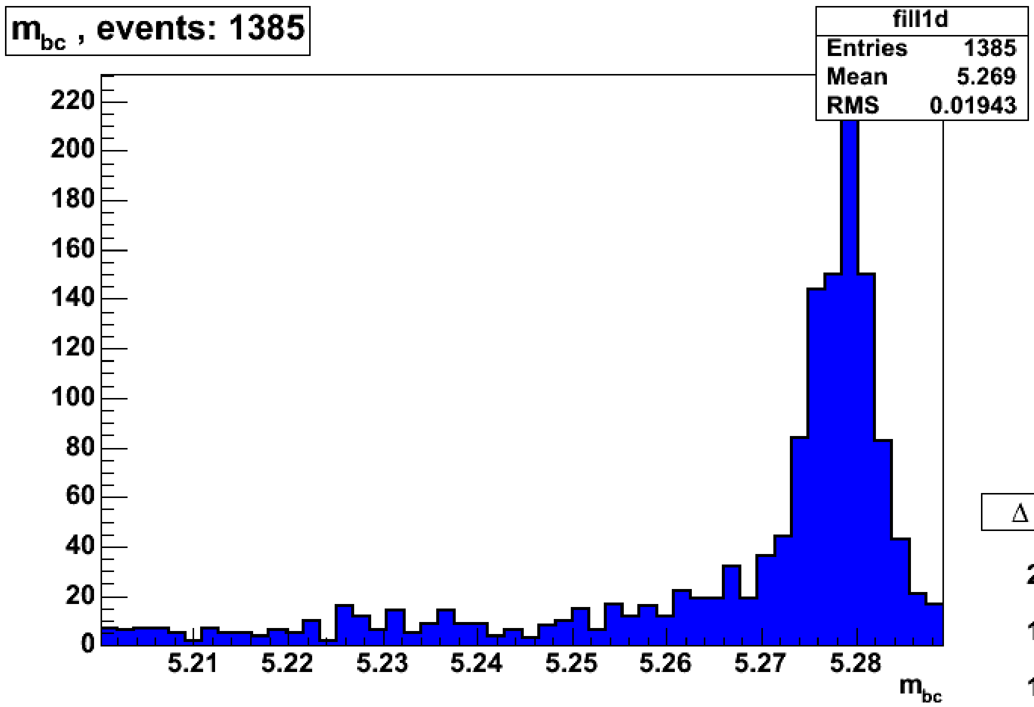
reconstruction sequence

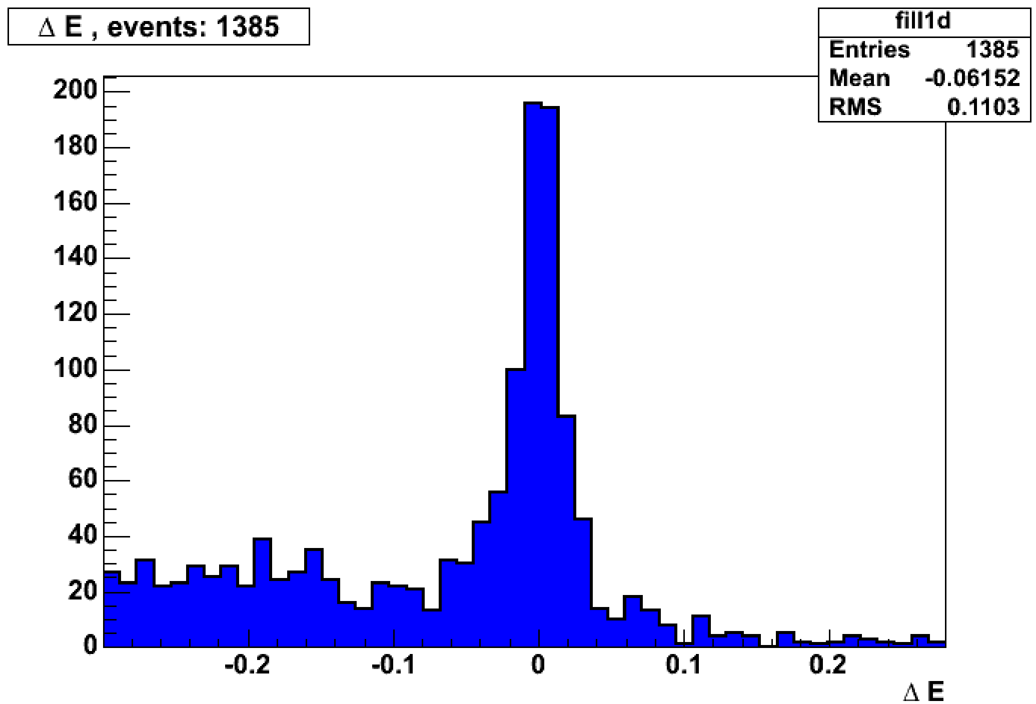
- Example decay tree
- cross check with "MC-truth" to estimate & classify different sources of background contamination in data
  - bottom up
  - top down

$$B^0 \rightarrow D^{*-}\ \pi^+$$
$$D^{*-} \rightarrow \overline{D^0}\ \pi^-$$
$$\overline{D^0} \rightarrow K^+\ \pi^-$$

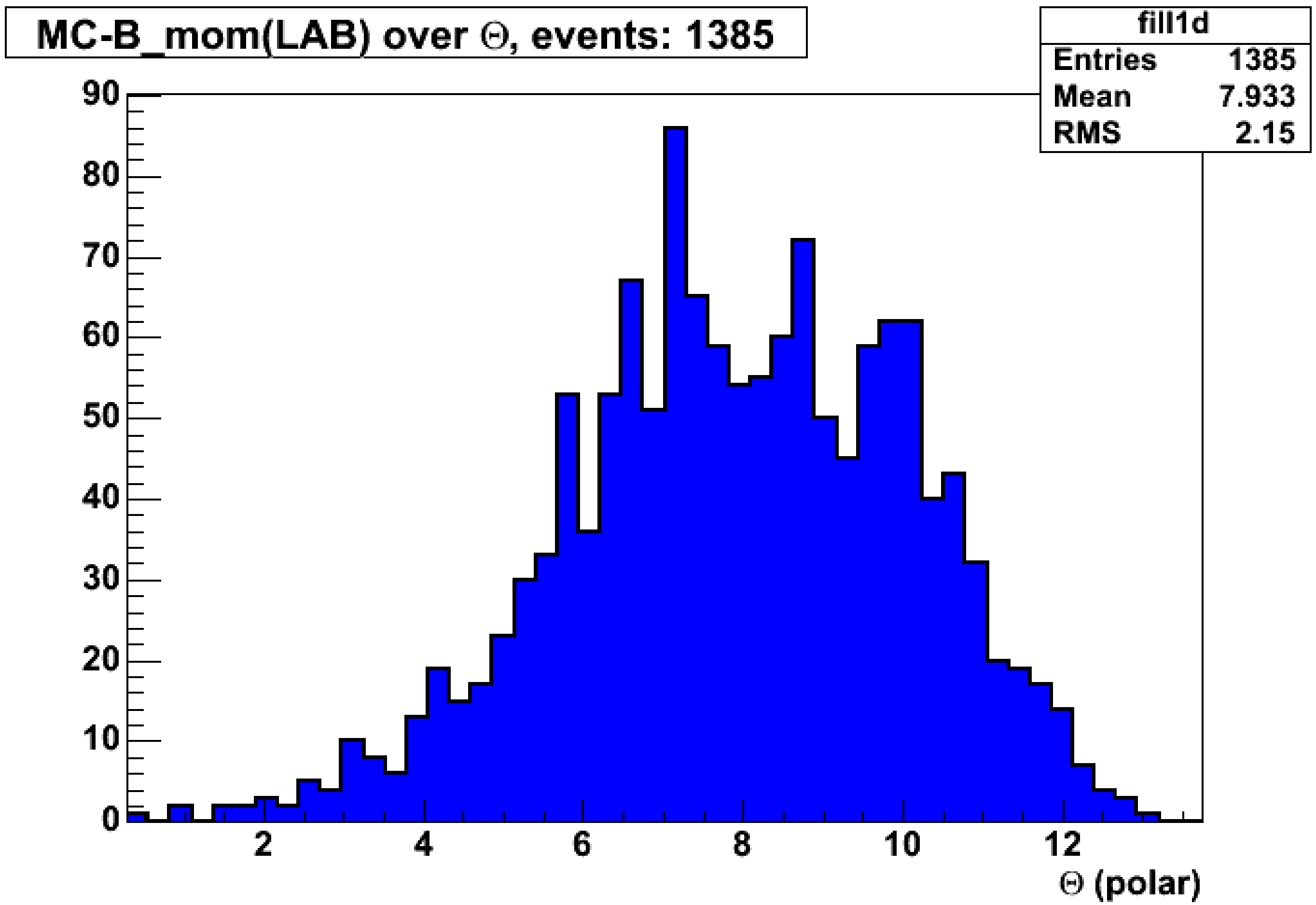
$$\overline{B^0} \rightarrow D^{*+}\ \pi^-$$
$$D^{*+} \rightarrow D^0\ \pi^+$$
$$D^0 \rightarrow K^-\ \pi^+$$

checking the reconstructed B



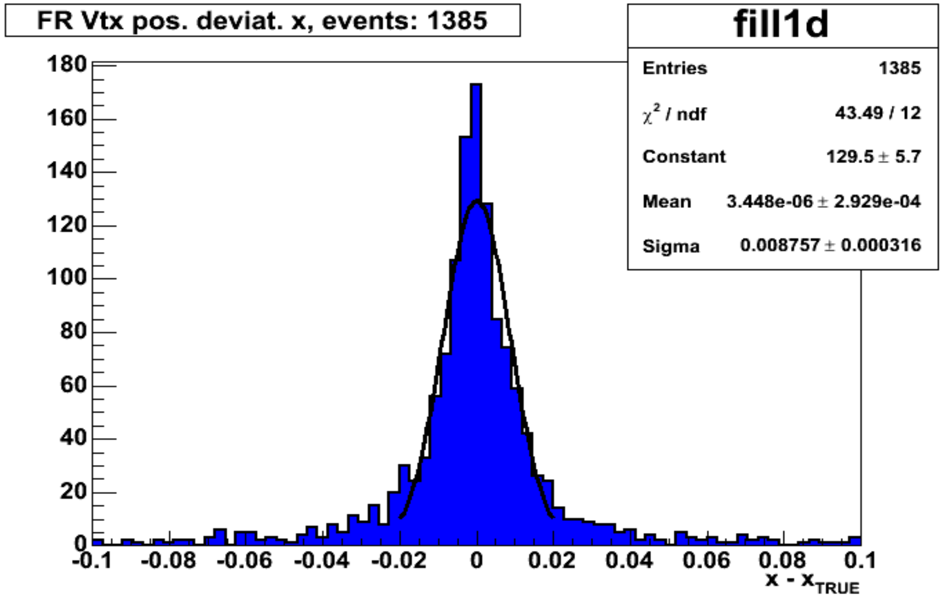


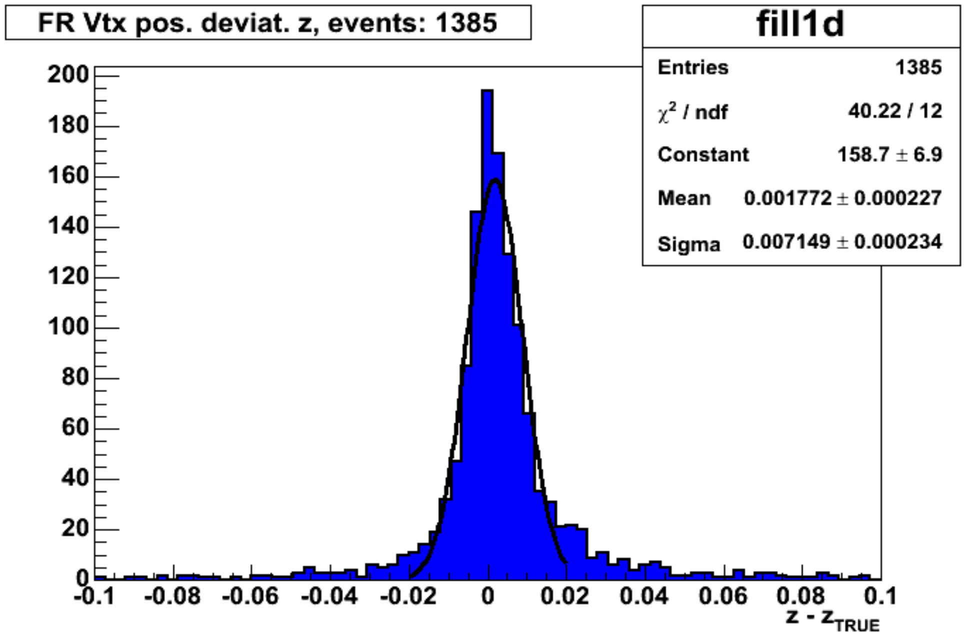
Angular B momentum dependence

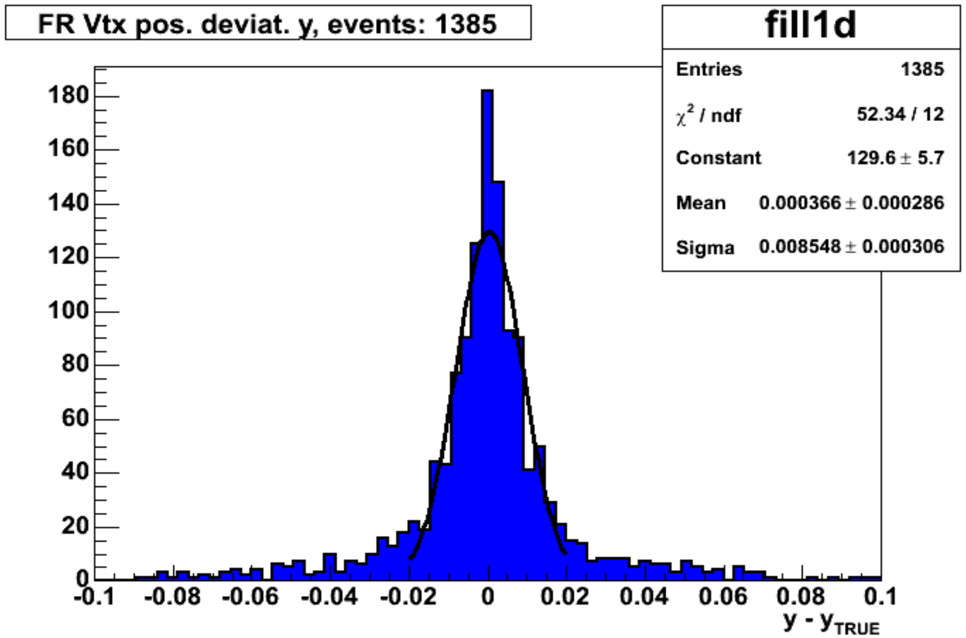


The FR vertex

- the reconstructed FR-vertex positional resolution checked against MC-truth





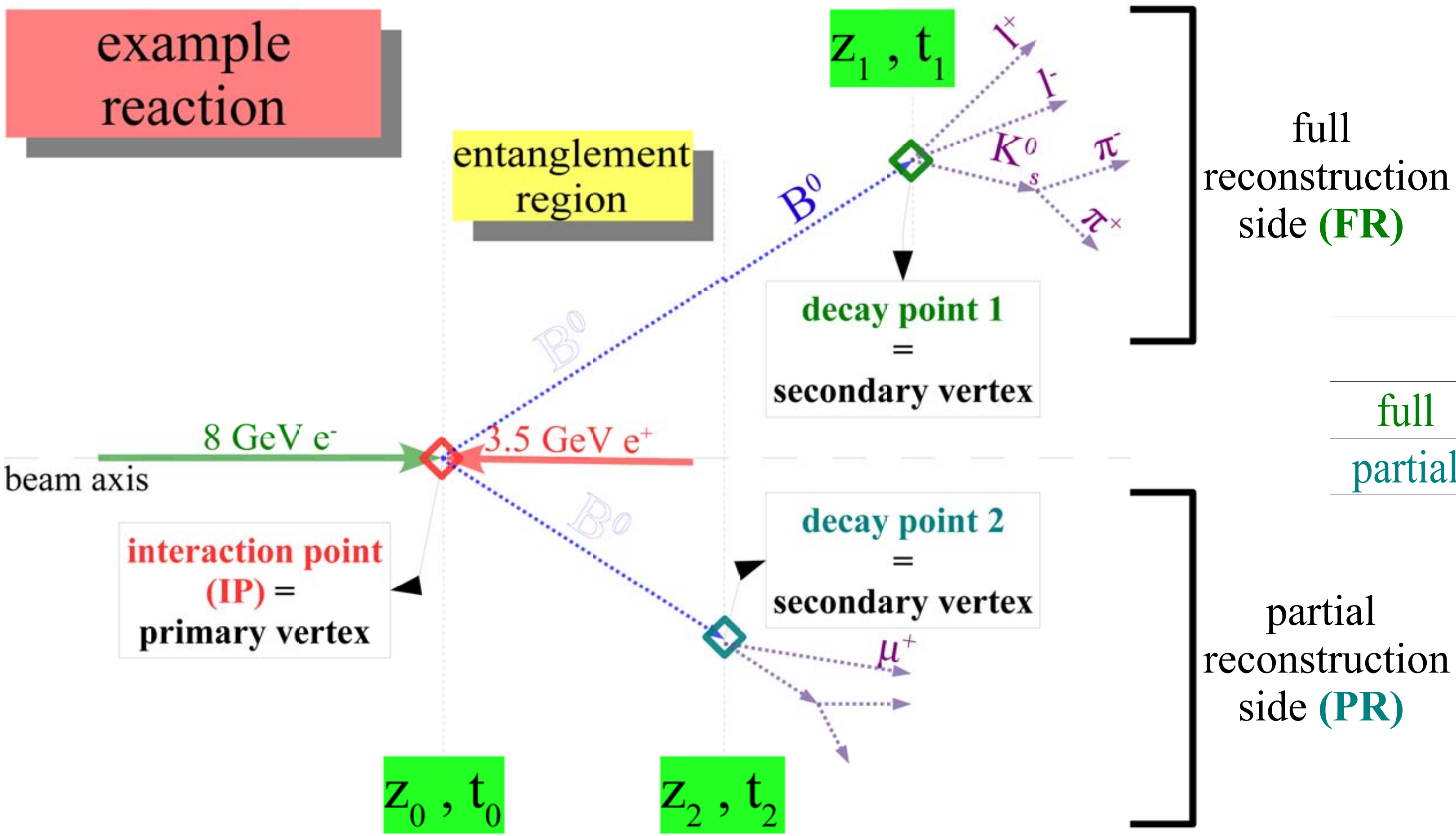


Summary & outlook

- a toy MC has been created to show the feasibility of fitting the model parameter λ
- primary particle and z_1 reconstruction efforts successful
- TODO:
  - verification of momentum resolution of reconstructed B-mesons
  - z_0, z_2 reconstruction
  - consistency check with MC-data ($\lambda = 0$)
  - modification of MC for generation of ($\lambda \neq 0$), and fitting those data
  - move on to experiment data

Thanks for the attention

QM coherence model investigations



expected resolutions

	σ_z^{lab} [μm]	σ_t^{CMS} [τ_B]
full	50	0,2
partial	120	0,5

- $c\tau_{B0} = 462$ μm (LAB)
- $\Delta m = 0.489 \; 10^{12} \; \hbar s^{-1} = 0.754 \; \tau_{B0}$

QM predicted asymmetry + CoMo

$$A^{QM}(\Delta t, \lambda) = \cos(\Delta m \Delta t) \exp(-\lambda \min(t_1, t_2))$$