Stability of nonlocal quantum correlations in neutral B-meson systems

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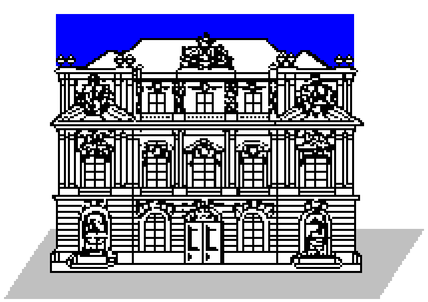
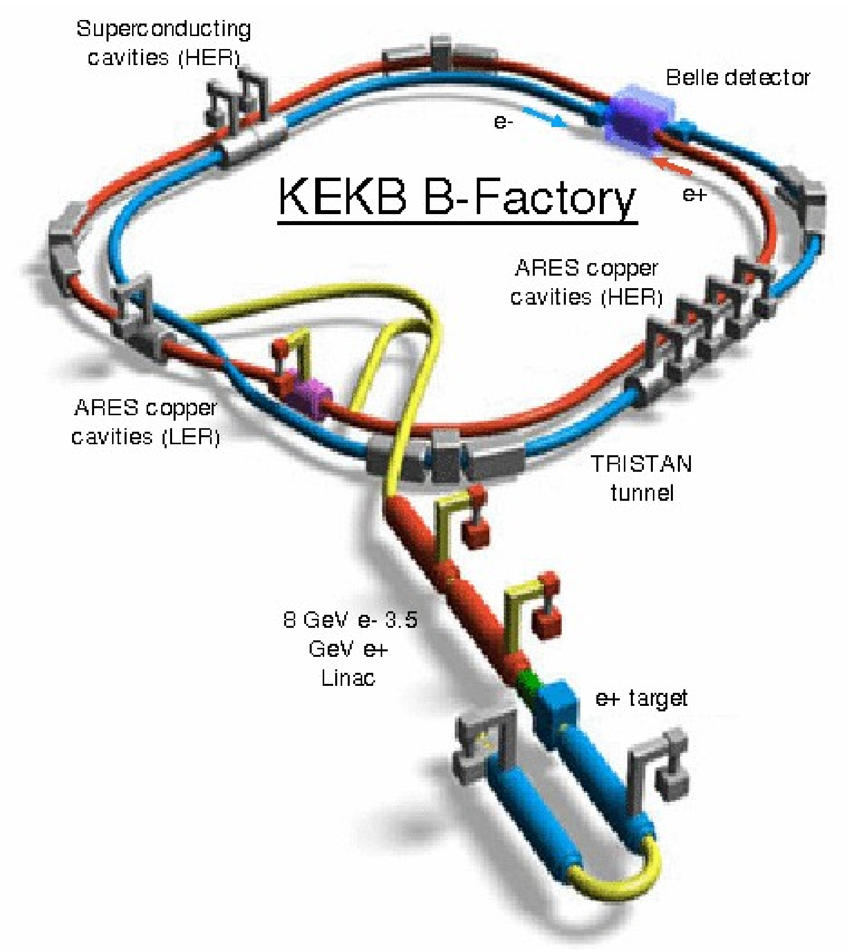
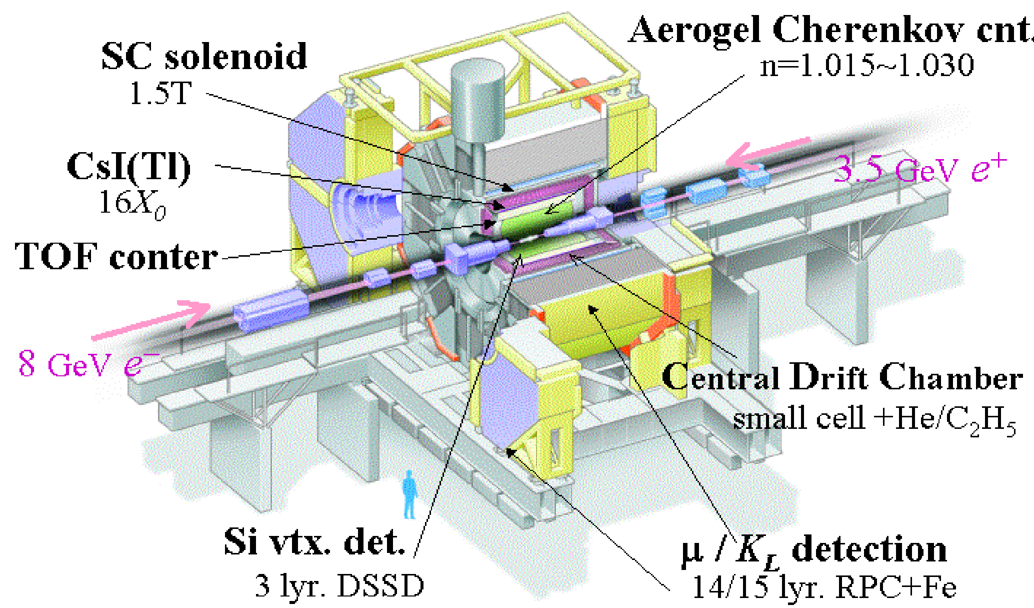


The BELLE experiment



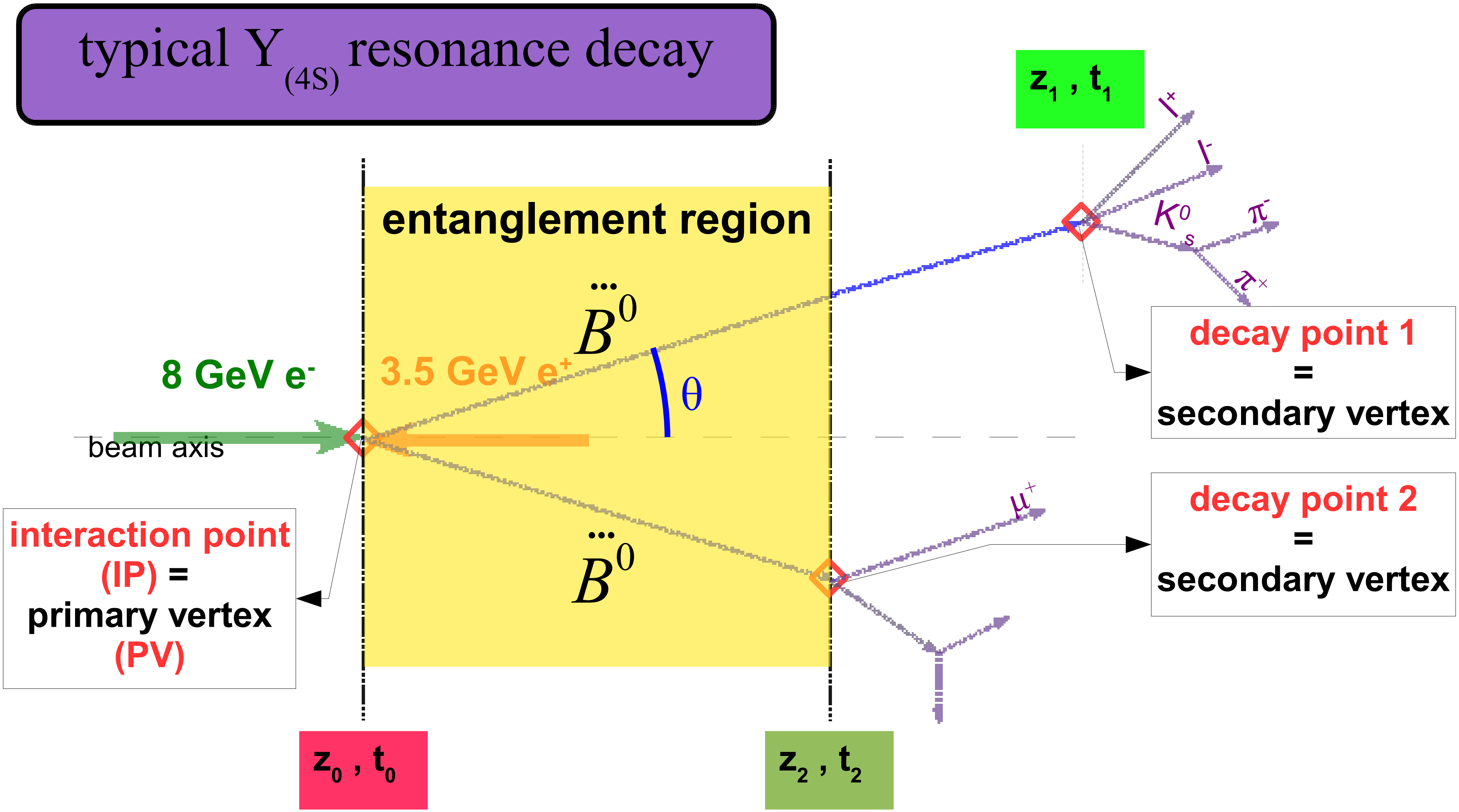
Location: Tsukuba, Japan

Belle Detector



- operational since 1999
- accumulated luminosity of 800 fb^{-1} (apprx. 800 million BB events)
- main design intentions: CP violation, verification of CKM theory
- HEPHY contributes since 2001

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



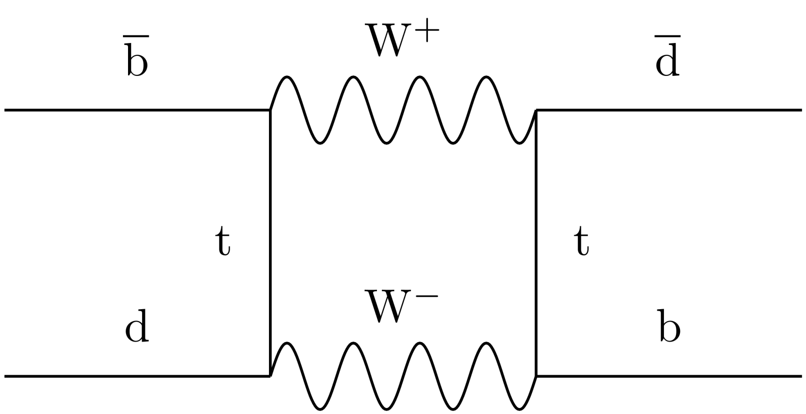
- $\beta\gamma c\tau_{B^\circ} = 196\ \mu m$ (LAB)
- $\Delta m = 0.489\ 10^{12}\ \hbar s^{-1} = 0.754\ \tau_{B^\circ}^{-1}$

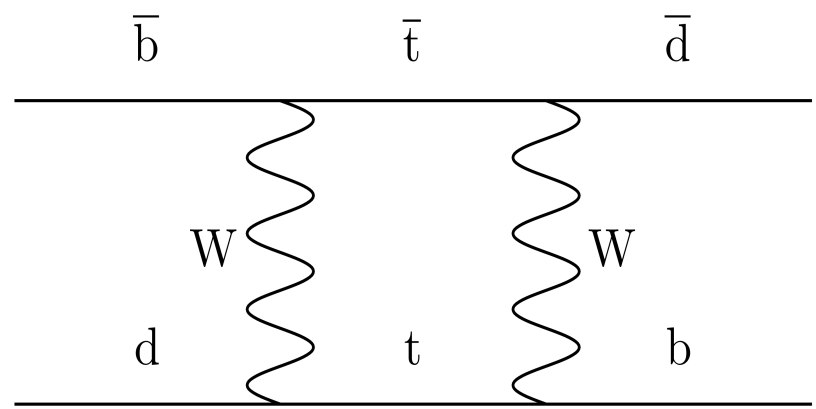
Entangled B mesons

- Analog to spin correlations in entangled photon systems, a flavor correlation entanglement in massive meson-pairs being produced by the same interaction is possible.

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\{|B^0\bar{B}^0\rangle - |\bar{B}^0B^0\rangle\}$$

- The $\mathrm{B}^0\bar{B}^0$ system exhibits flavor oscillations, which occur synchronised for both mesons. Oscillations are due to the non-beauty conserving weak interaction processes.





The mass basis

- The mass eigenstates for this system are defined by

$$|B_L\rangle = p\,|B^0\rangle + q\left|\bar{B}^0\right\rangle$$
$$|B_H\rangle = p\,|B^0\rangle - q\left|\bar{B}^0\right\rangle$$

- With the simple time evolutions

$$|B_L(t)\rangle = e^{-i\lambda_L t}\,|B_L(0)\rangle$$
$$|B_H(t)\rangle = e^{-i\lambda_H t}\,|B_H(0)\rangle$$

where $\lambda_{H,L} = M_{H,L} - \frac{i}{2}\Gamma_{H,L}$

- Allows to calculate transition probabilities of the form

$$P(B^0 \longrightarrow B^0(t)) = \frac{1}{4}\left[e^{-\Gamma_L t} + e^{-\Gamma_H t} + 2\cos(\Delta m t)e^{-\Gamma t}\right]$$
$$P(B^0 \longrightarrow \bar{B}^0(t)) = \frac{|p|^2}{4|q|^2}\left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2\cos(\Delta m t)e^{-\Gamma t}\right]$$

The two particle system

- General prerequisite for many measurements is that entanglement is undisturbed until one of the mesons decays; the asymmetry between same flavor (SF) and opposite flavor (OF) pair events is defined as:

$$A^{QM}(\Delta t) = \frac{N_{OF}(t_1,t_2) - N_{SF}(t_1,t_2)}{N_{OF}(t_1,t_2) + N_{SF}(t_1,t_2)} = \frac{\cos(\Delta m \Delta t)}{\cosh(\frac{1}{2}\Delta\Gamma\Delta t)}$$

- Deviations from the well understood mixing behavior can indicate the early collapse of the entangled state.
- Introducing concept of decoherence to describe gradual loss of entanglement in the initially entangled two-particle system.
- Employing the density matrix formalism to achieve this.
- From asymmetry we derive 2D probability density functions

A general decoherence model

- With a modified form of the von Neumann equation

$$\frac{\partial}{\partial t}\rho = -iH\rho + i\rho H^\dagger - D[\rho]$$

  using the notion of dynamical maps

- Allows very general ansatz according to Bertlmann-Hiesmayr, that uses an open quantum formalism to describe those deviations. This leads to an extension of flavor correlation asymmetry.

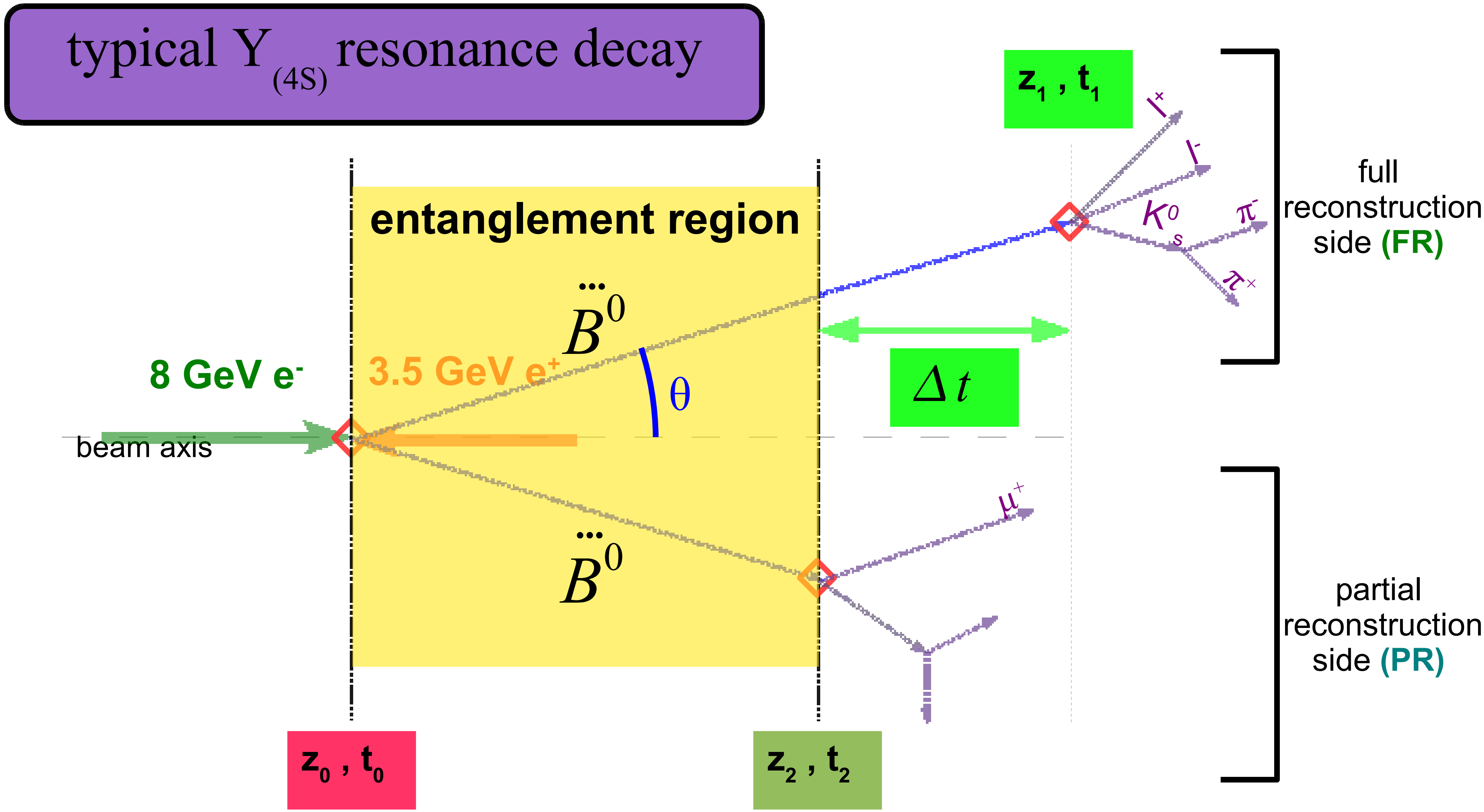
$$A^{BH}(t_1, t_2, \lambda) = \cos(\Delta m \Delta t) \exp(-\lambda \min(t_1, t_2))$$

- This "dissipative coherence model", allows for arbitrary sources of decoherence (e.g. influence of quantum gravity) and covers a class of possible scenarios.

- Model parameter λ to measure (equivalent to inverse lifetime of entangled state)

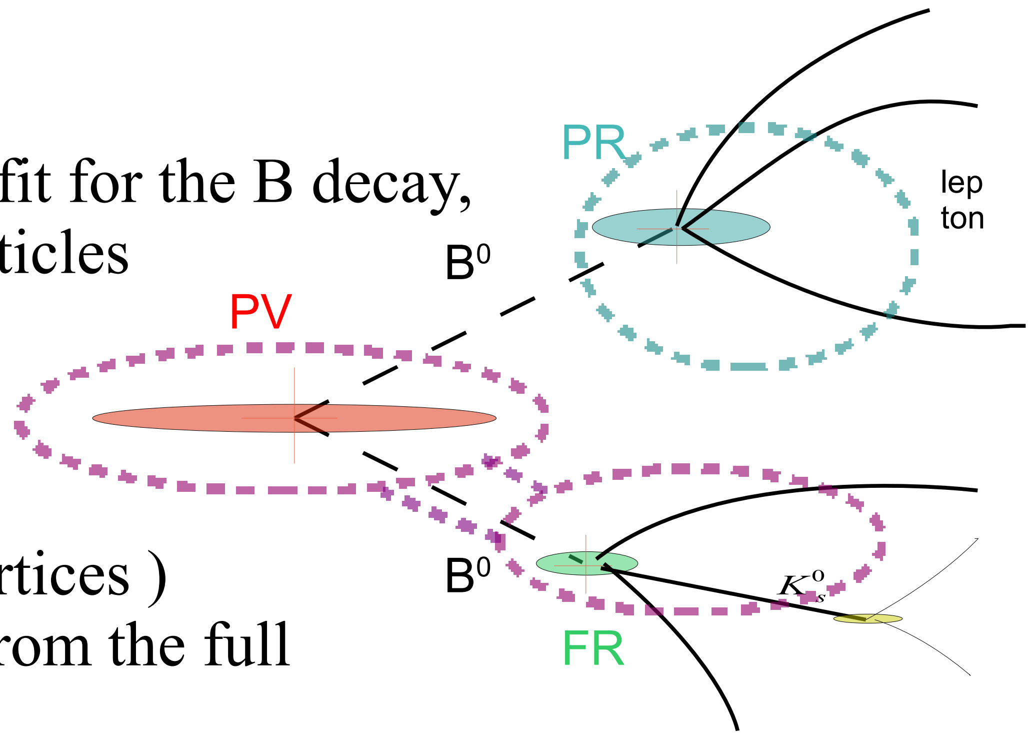
- General QM predicts $\lambda = 0$

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



$\Delta t = \Delta z / \beta\gamma c \qquad \beta\gamma = 0{,}425$

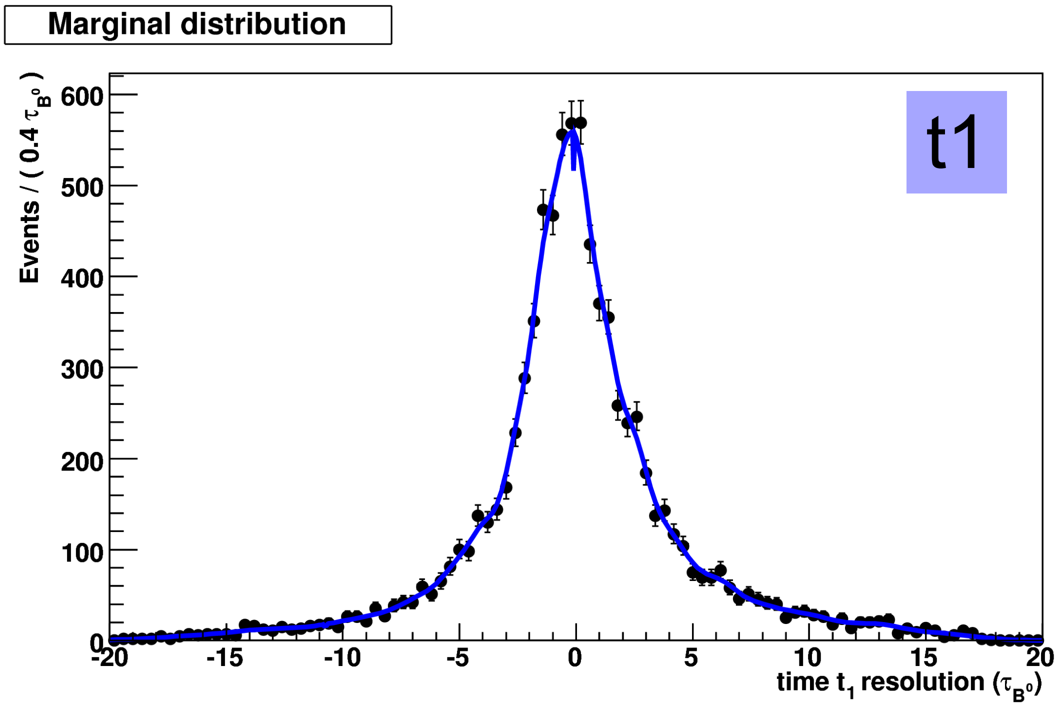
Reconstruction method

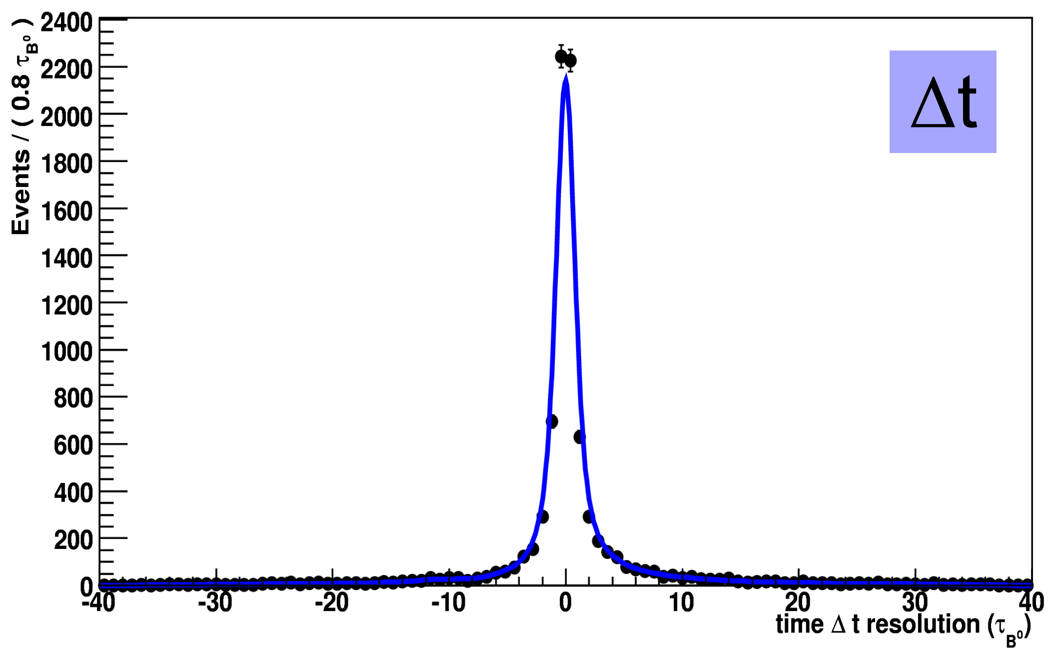


•**Partial Reconstruction** side:
- collect charged particles
- make **PR** Vertex constrained fit for the B decay, with all charged daughter particles

•**Full Reconstruction** side:
•(inclusive fit of **FR** and **PV** vertices)
- take charged and K^0_s tracks from the full reconstruction information
- initialize fitter **PV** with BIP
- define **FR** Vertex constraint for the B decay, with all daughter particles
- add the mother B^0 to the constraint
- define **PV** vertex constraint and connect to the mother B^0.

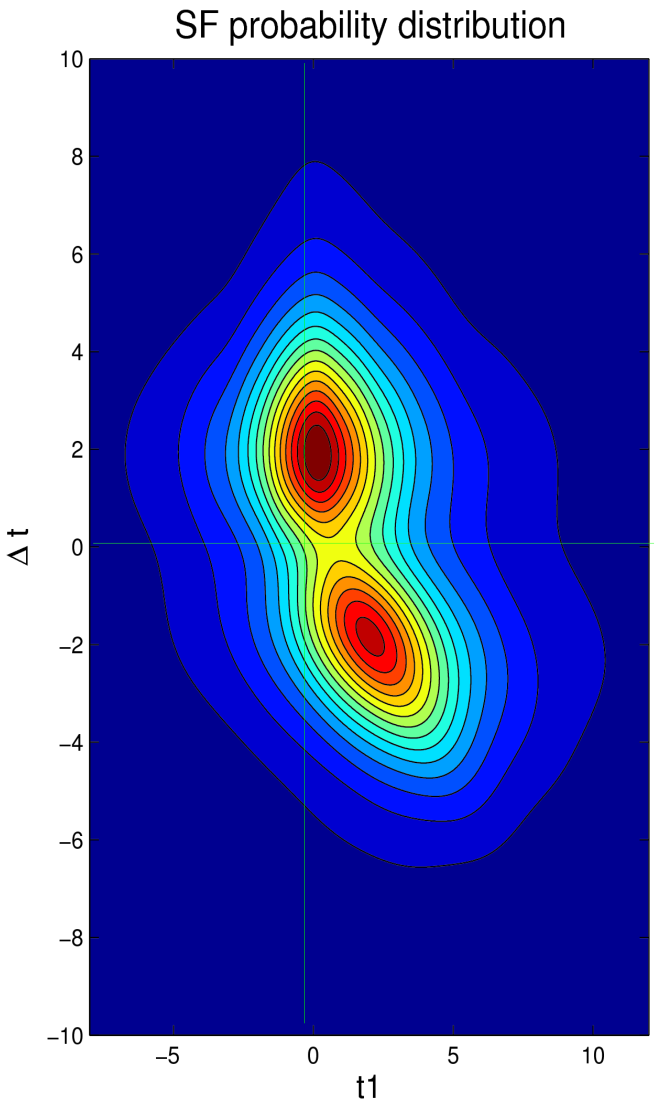
2D resolution function (RF)

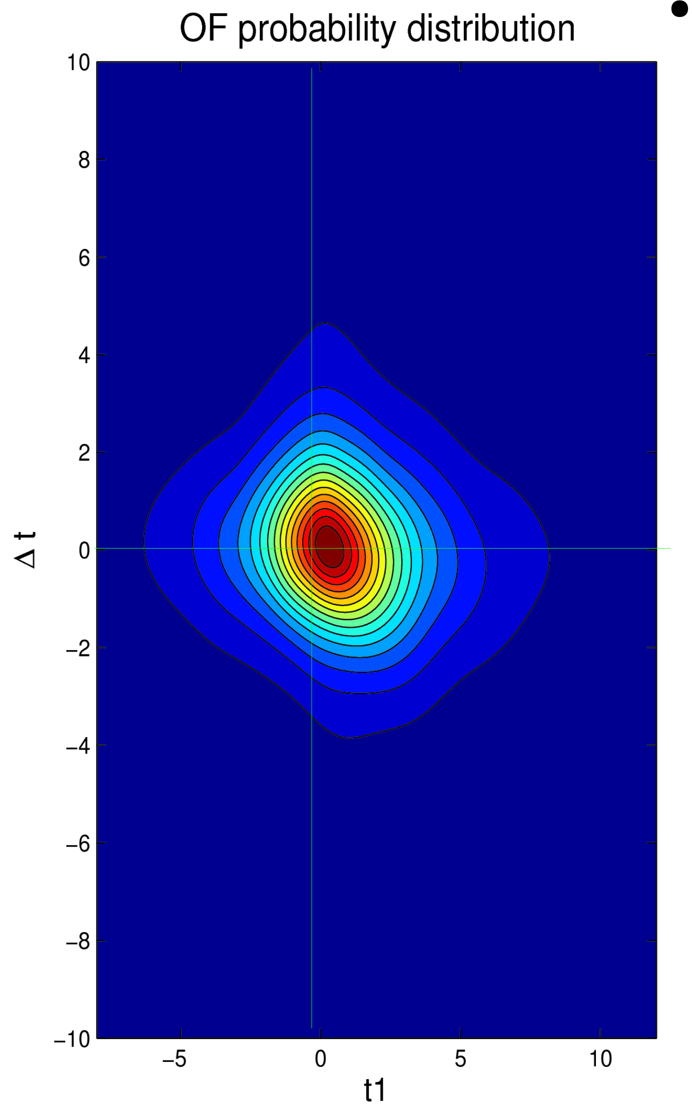




- marginal distributions of RF fit over deviation from monte carlo truth
- projections shown for **t1,Δt** parameter
- RF determined by unbinned 2D method, using “keys-pdf” kernel estimator
- high resolution model of this function is crucial for numerical treatment
- RF used in numerical FFT convolution algorithm to get the expected distribution of signal data events

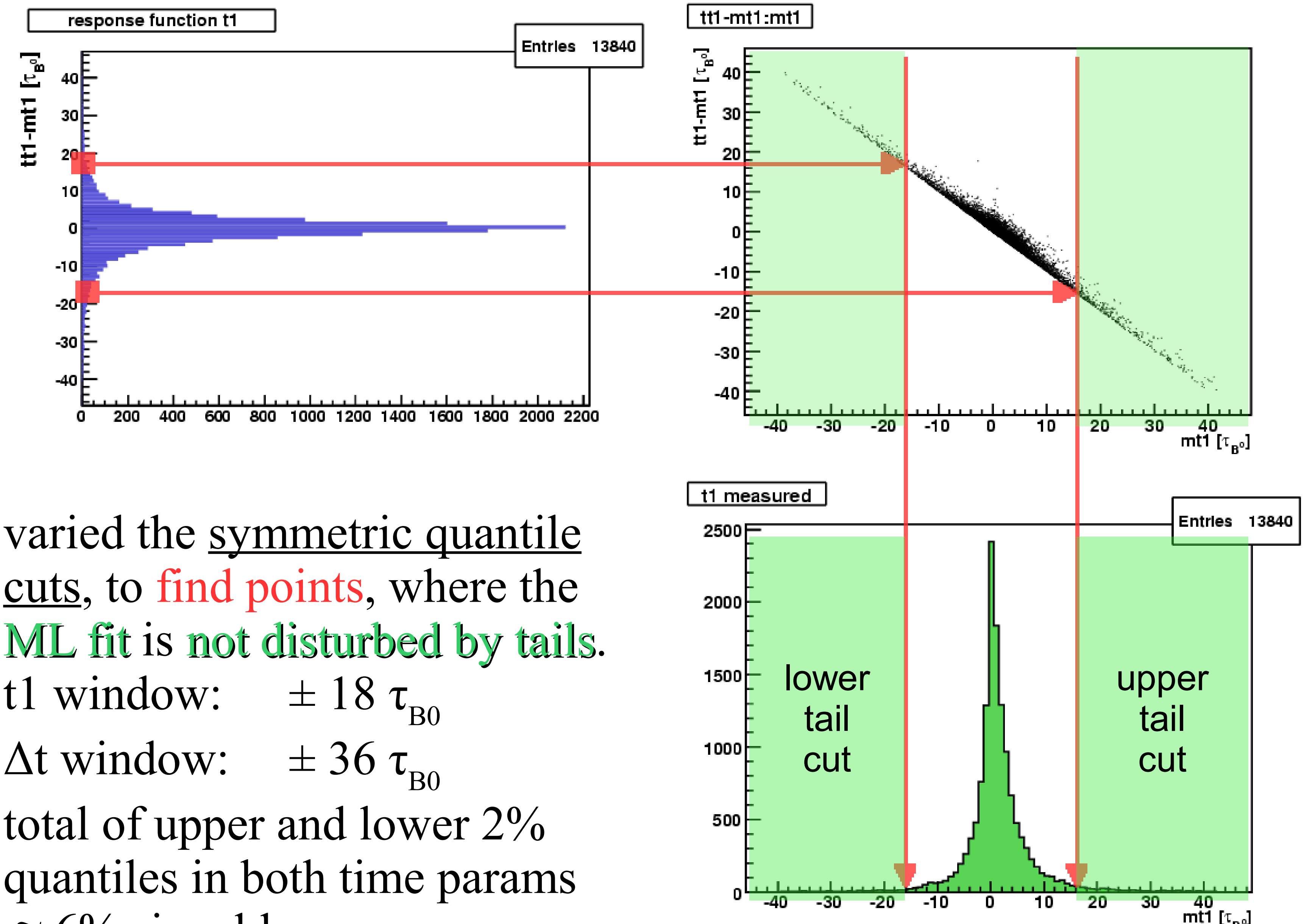
convoluted signal pdf





- expected signal pdfs for Same (SF) and Opposite flavor (OF) events in parametrisation ($t1, \Delta t$) for model parameter $\lambda = 0$
  - different from 0 only in narrow range around (0,0)
  - even more so for increasing (damping) model parameter

Cleanup data cuts

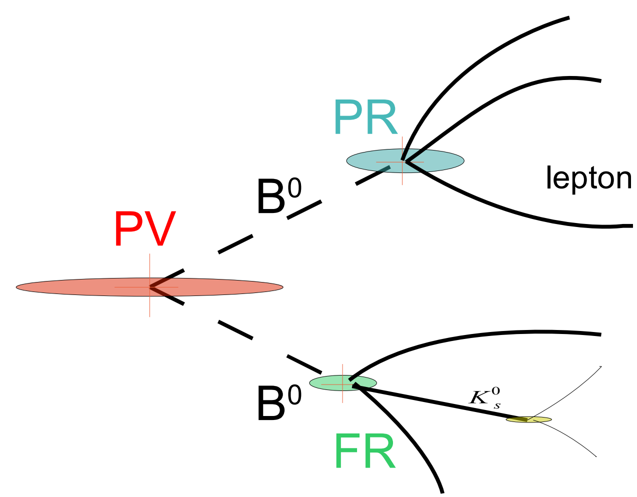


- varied the symmetric quantile cuts, to find points, where the ML fit is not disturbed by tails.
- t1 window: $\pm 18\ \tau_{B0}$
- Δt window: $\pm 36\ \tau_{B0}$
- total of upper and lower 2% quantiles in both time params $\approx$ 6% signal loss

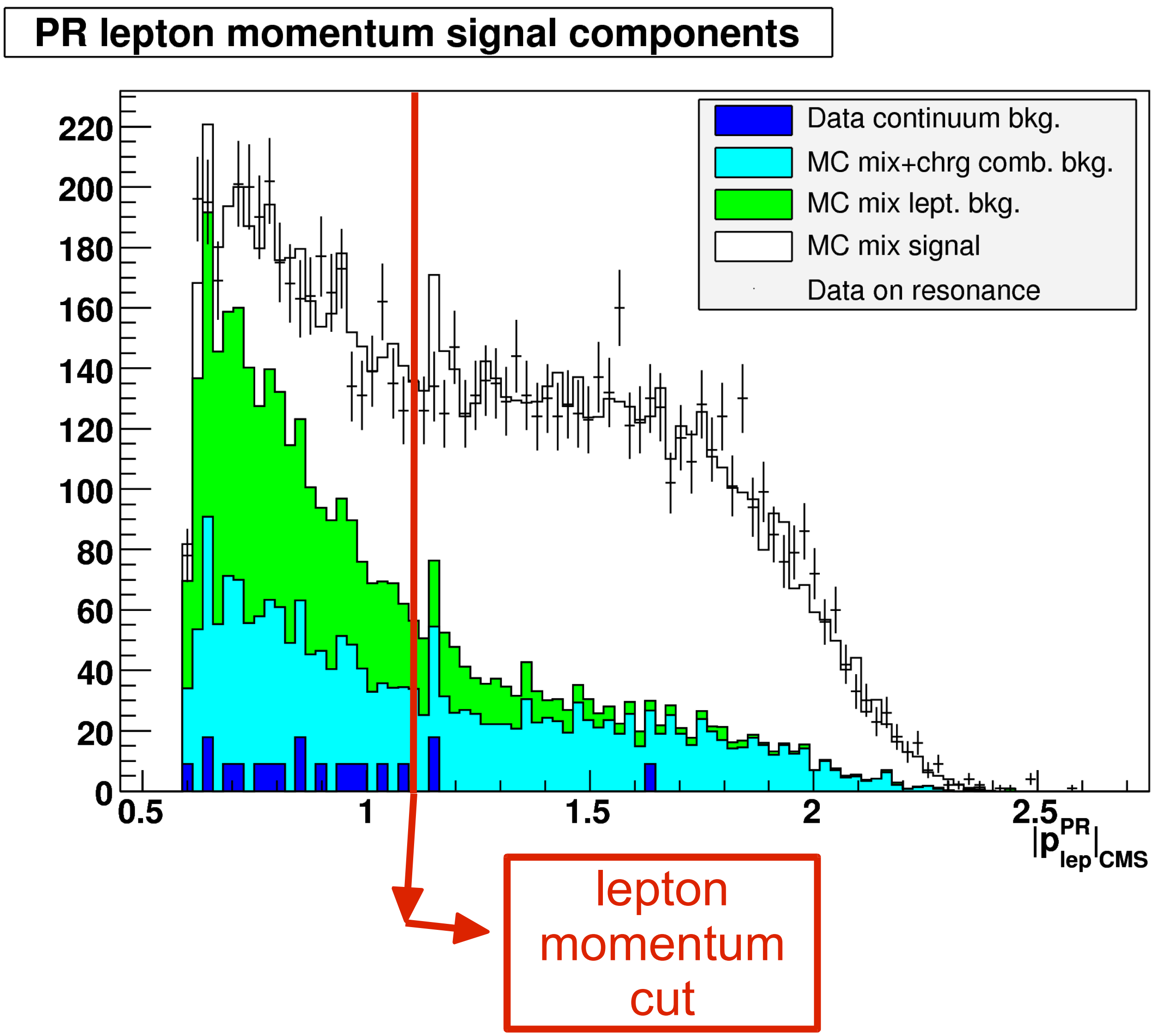
background components in MC

What can go wrong in the reconstruction?

Full Reconstruction side \ Partial Reconstruction side	mistake	all OK
mistake	combinatorial background events	combinatorial background events
all OK	fake or secondary leptons	good signal events



determining background fractions



- background events have distribution very similar to signal in plane (t1,Δt)
- therefore need discriminating variable to estimate components
- variable is momentum of PR-side lepton
- fit of histogram components against data events.

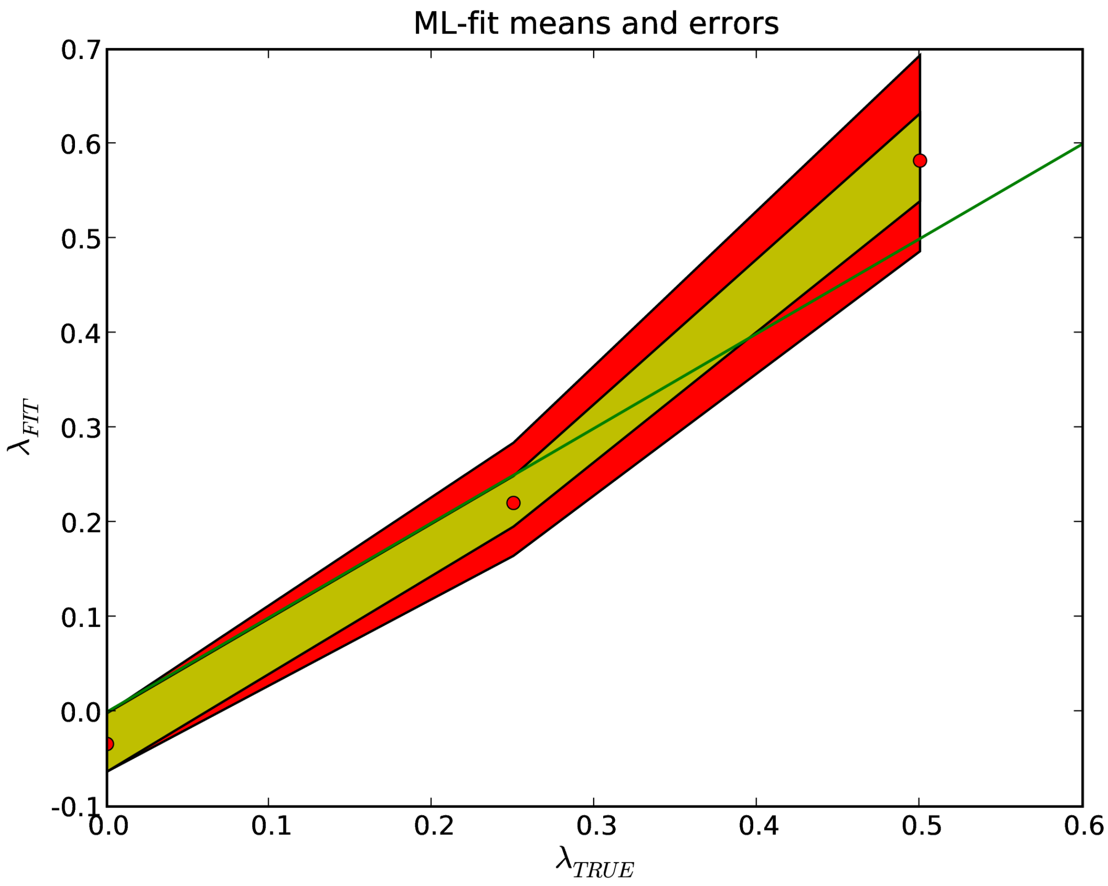
to summarize...

1. reconstruct the event vertices, from z-coordinates of vertices calculate the decay-times
2. clean up the event-data for good signal events
3. determine resolution function from MC truth
4. determine reconstruction failures and define background components
5. find good model for background shapes
6. iterate over maximum likelihood parameter fit:
   - Likelihood function with background components:

$$\mathcal{L}(\lambda) = \sum_i \log\left(w_S p_S(t_1^i, \Delta t^i|\lambda) + \sum_k w_B^k p_B^k(t_1^i, \Delta t^i)\right)$$

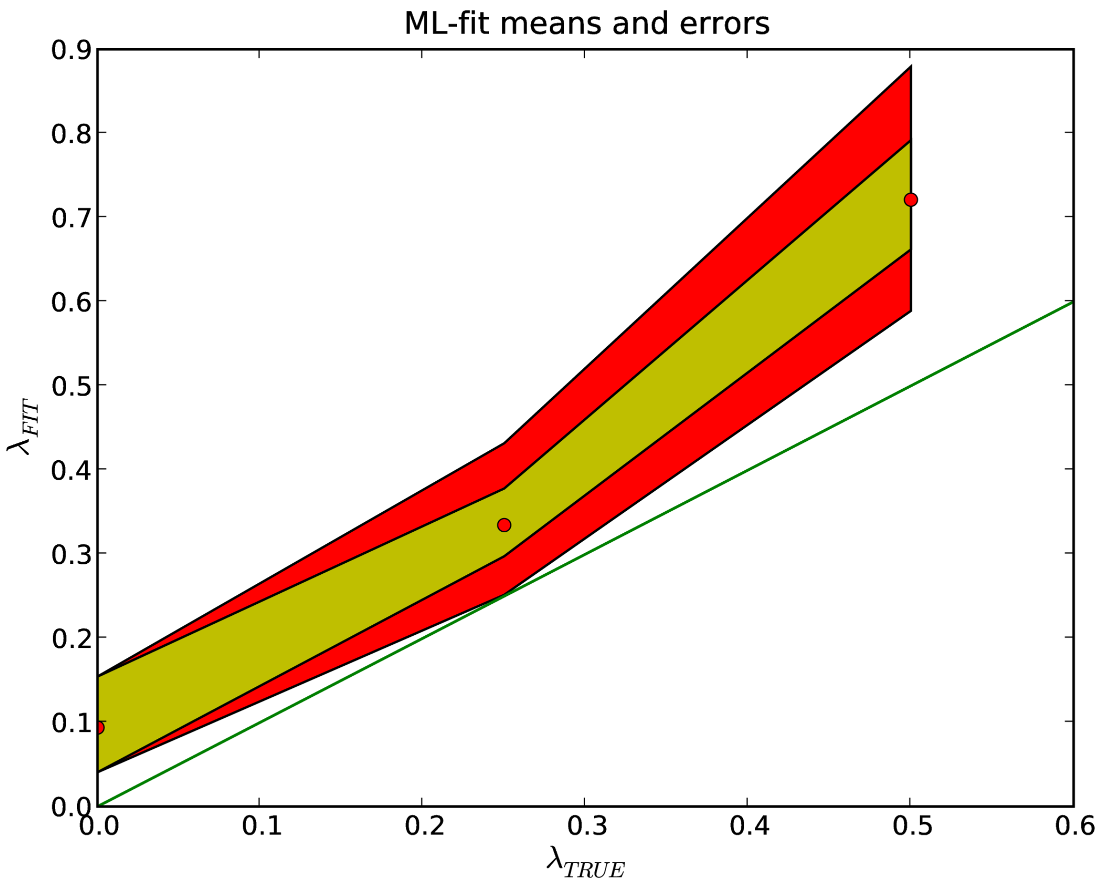
7. result is model parameter of maximum likelihood.

Results on signal events, full detector MC



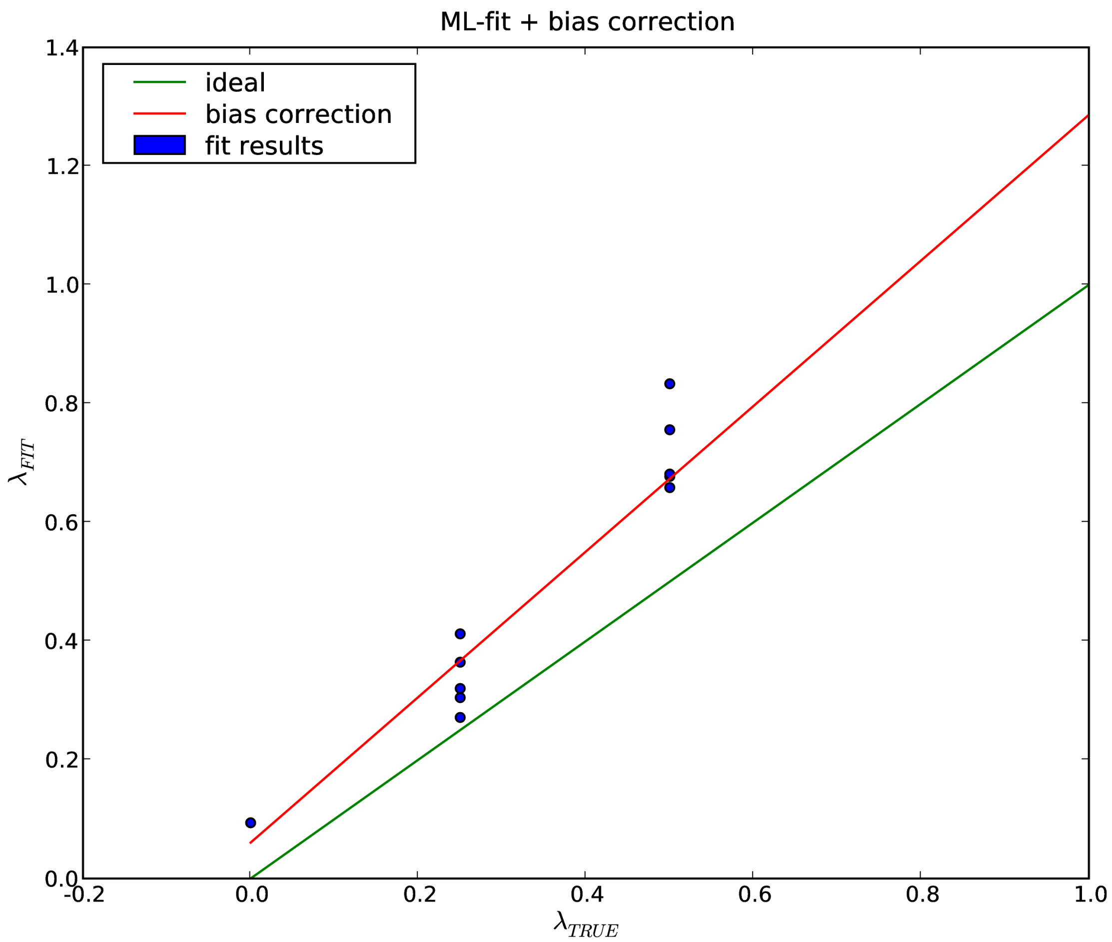
- Fit results show good agreement with the true parameter values within errors of single measurement
- Slight deviations possible when going towards large parameter values (similarity of decoherence term and lifetime limitations ?)

Results with included background, full detector MC



- Fit results show definite biasing effect
- Source most probably numerical deficiencies of algorithm
- Have to correct for the biasing effects
- Assuming linear deviations

Bias correction



- Bias correction line introduces rather big systematic effect around parameter value of 0
- Biggest contribution in systematic error estimations
- Have to estimate systematic contribution conservatively

Systematic error contributions and final result

- Background fraction fit
  $\sigma_{SYS} = 0.0174$
- Resolution function
  $\sigma_{SYS} = 0.0175$
- Bias correction
  $\sigma_{SYS} = 0.1$
- Overall systematic error
  $\sigma_{SYS} = 0.103$

- Bias corrected final fit result

  $\lambda = -0.044\ ^{+0.057}_{-0.048} \pm 0.103$
- Shows statistical compatibility with the QM assumed value of $\lambda = 0$
- Meaning:
  No decoherence occurring in the entangled state until one meson decays