How to test entanglement for meson-antimeson systems? An experimental realisation.

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Theoretical justification

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

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

- The $\mathrm{B}^0\bar{B}^0$ system exhibits flavor oscillations, which occur synchronised during the entanglement.

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

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

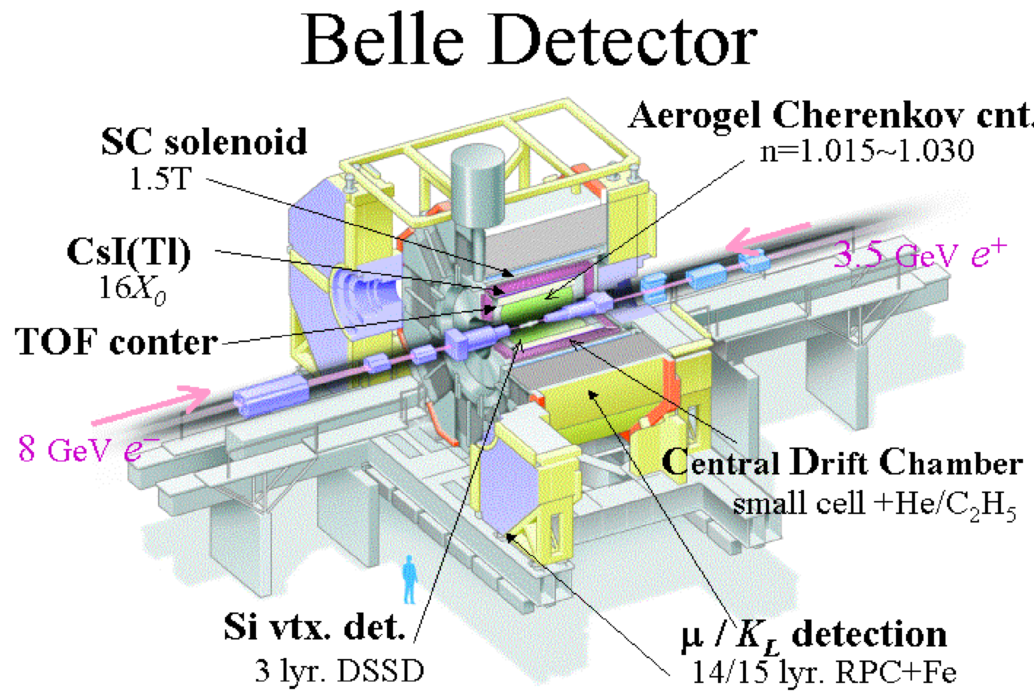
A general decoherence model

- Deviations from the well understood mixing behavior can indicate the early collapse of the entangled state.
- Very general ansatz according to Bertlmann-Hiesmayr, that uses an open quantum formalism to describe those deviations leads to an extension of flavor correlation asymmetry.

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

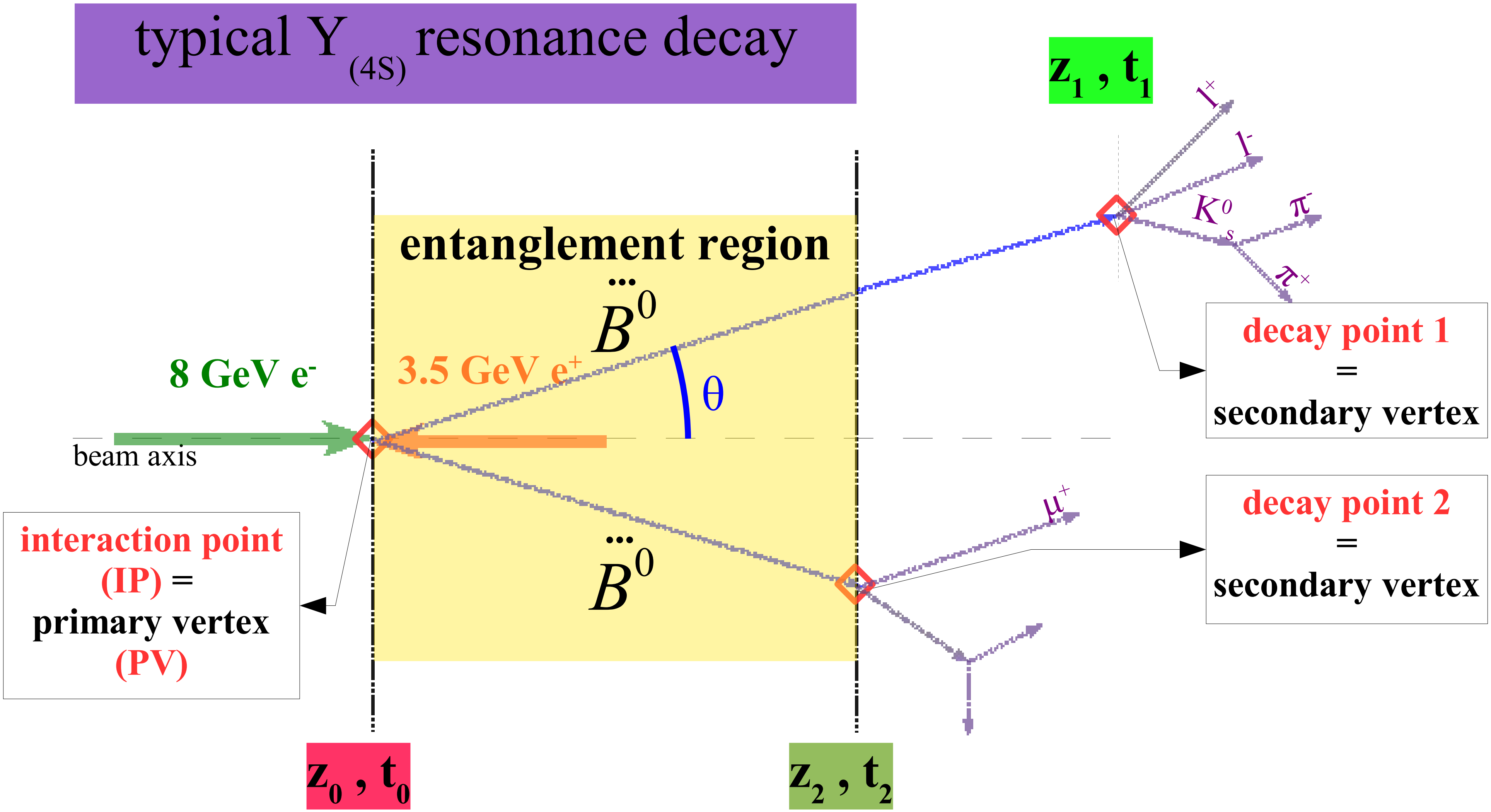
- This "dissipative coherence model", allows for arbitrary sources of decoherence (e.g. influence of quantum gravity, dynamical state reductions...) and covers a class of possible scenarios.
- Model parameter λ to measure (equivalent to inverse lifetime of entangled state)
- General QM predicts $\lambda = 0$

The BELLE experiment



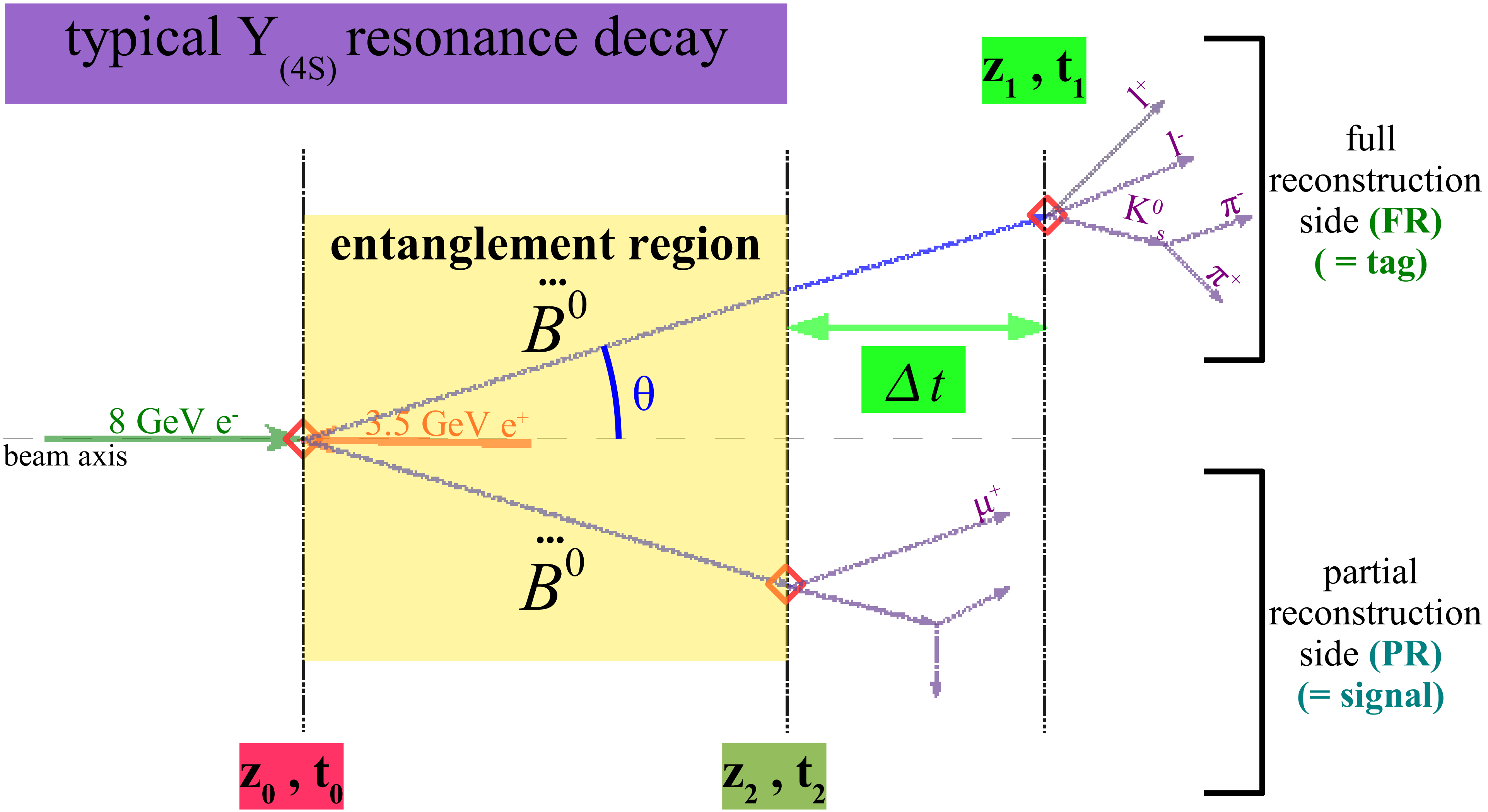
- operational since 1999
- accumulated luminosity of 700 fb-1 (apprx. 700 million BB events)
- main design intentions: CP violation, verification of CKM theory

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



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

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

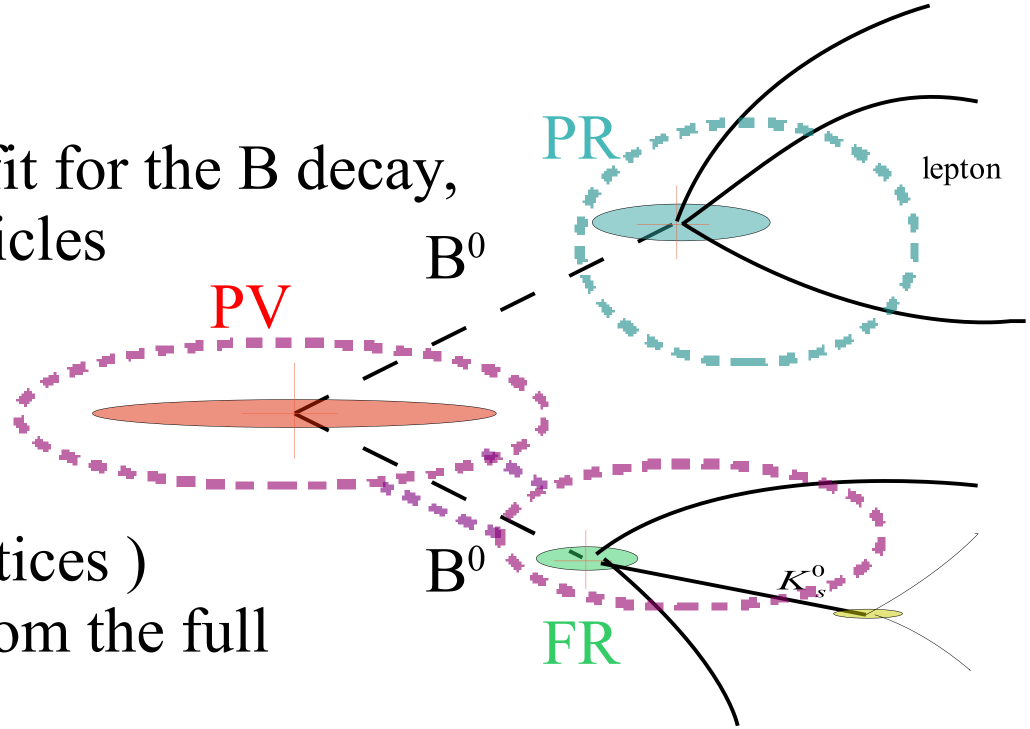


$\Delta t = \Delta z / \beta\gamma c \qquad \beta\gamma = 0{,}425$

vertex reconstruction method

•**Partial Reconstruction** side:

- collect charged particles
- make **PR** Vertex constrained fit for the B decay, with all charged daughter particles

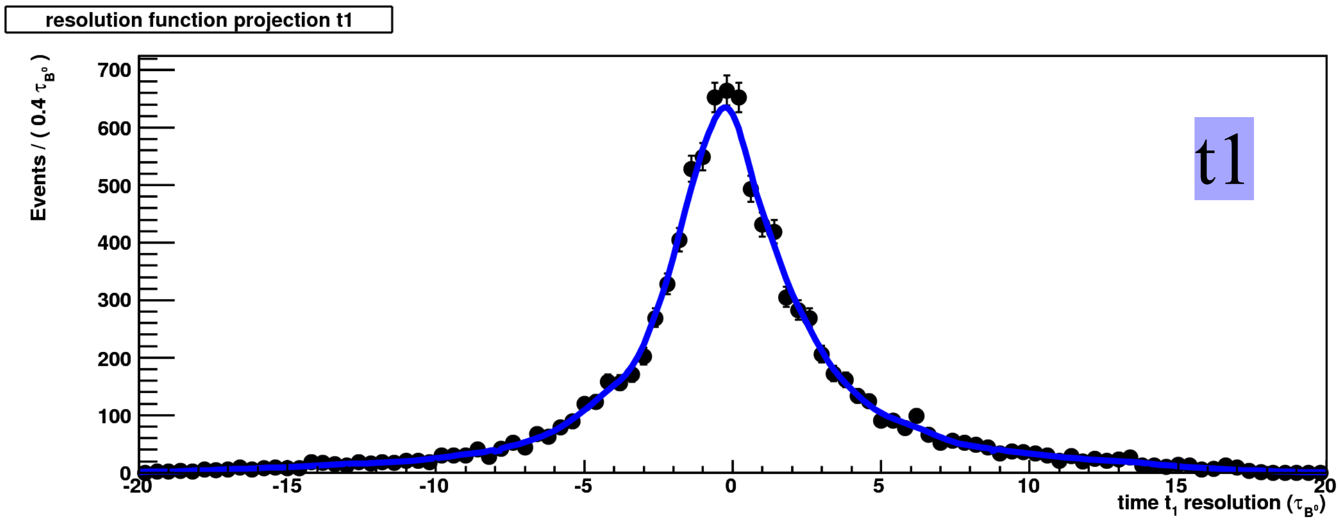


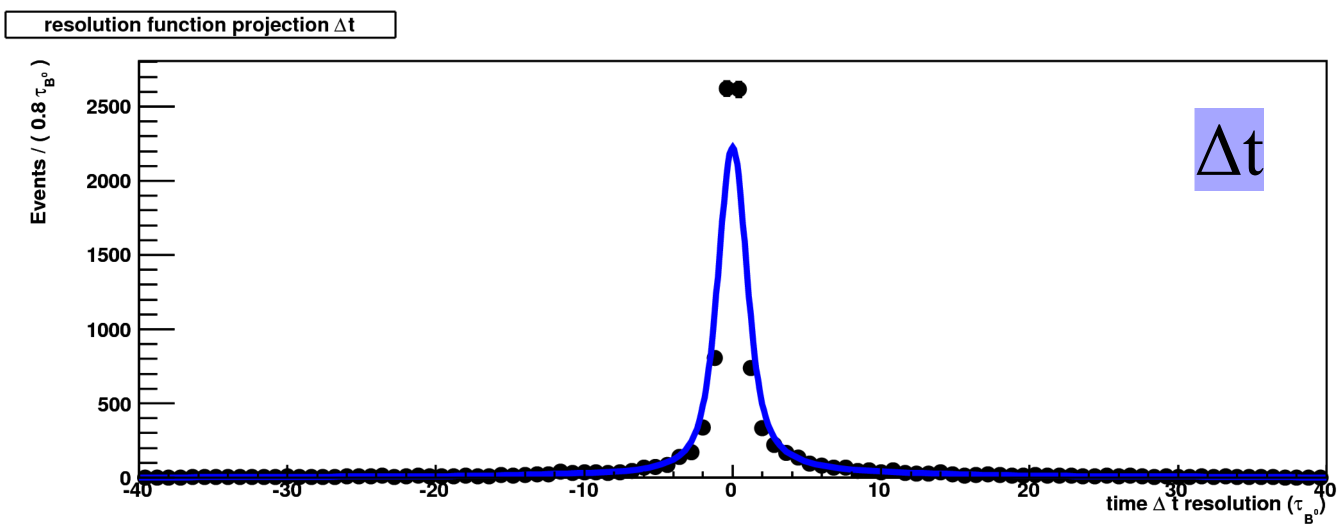
•**Full Reconstruction** side:

•(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.

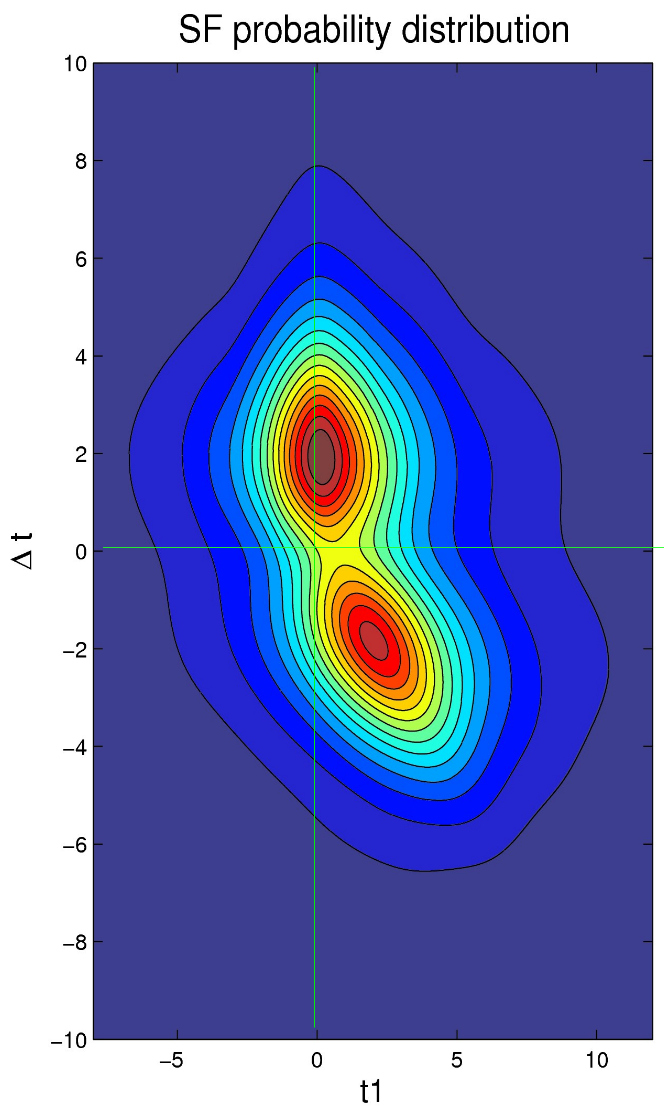
2D resolution function (RF)

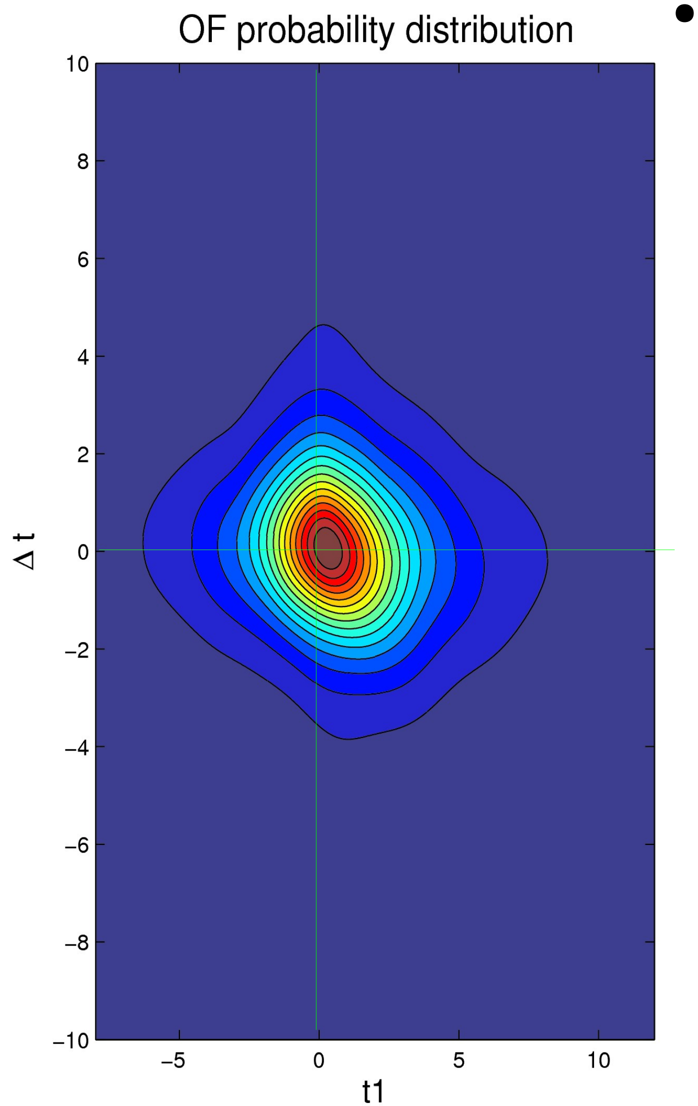




- marginal distributions of RF fit over deviation from monte carlo truth
- projections shown for **t1,Δt** parameter
- RF determined by unbinned 2D method, using “keys-pdf” kernel estimator
- high resolution model of this function is crucial for numerical treatment
- RF used in numerical FFT convolution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

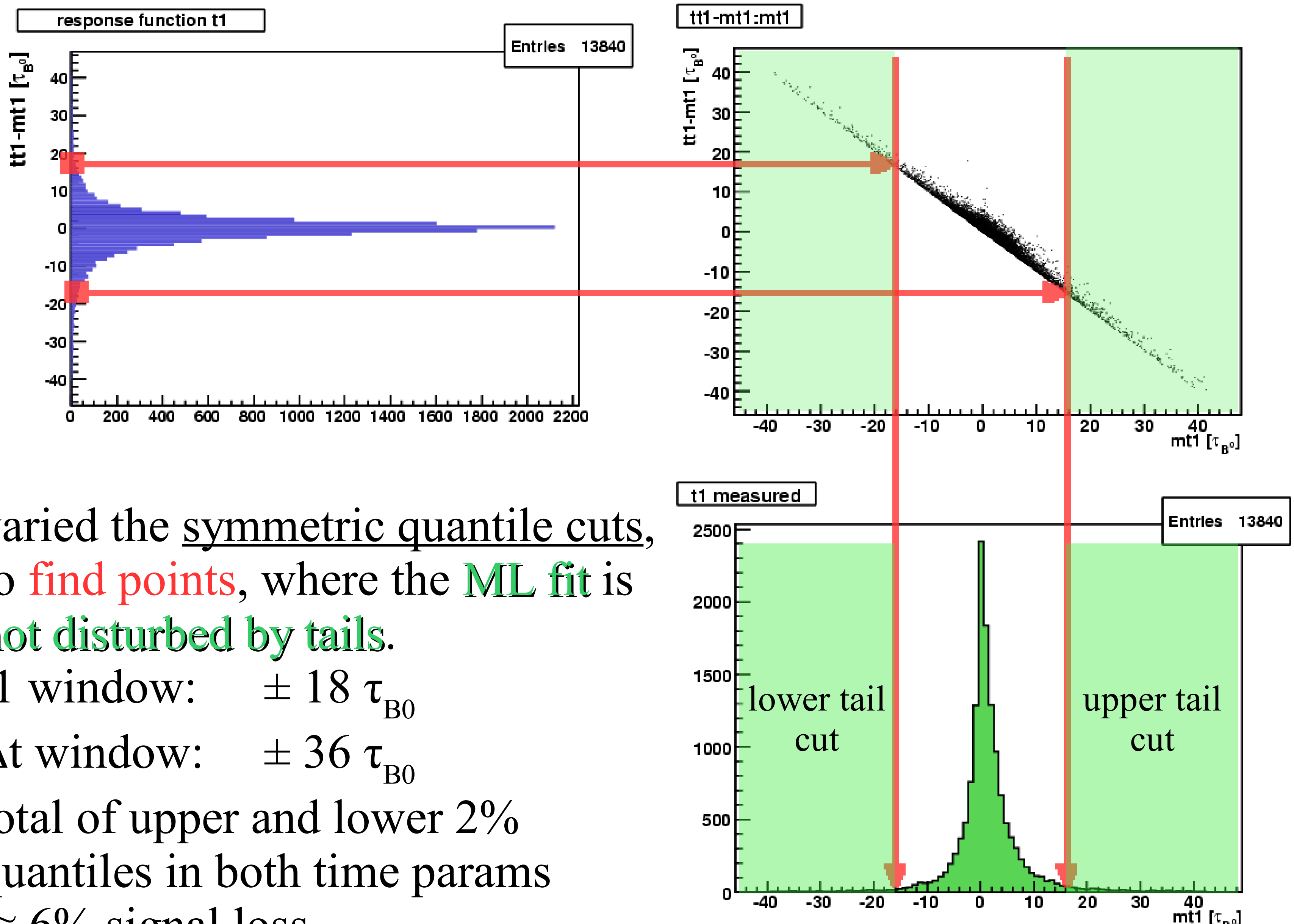
convoluted signal pdf





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

cleanup data cuts

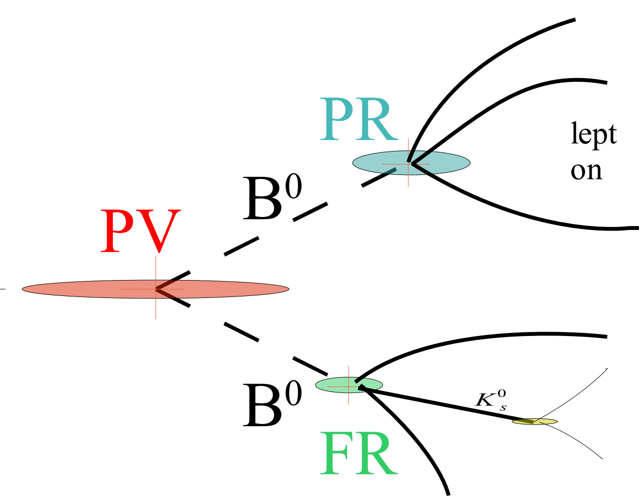


- varied the symmetric quantile cuts, to find points, where the ML fit is not disturbed by tails.
- t1 window: $\pm 18\ \tau_{B0}$
- Δt window: $\pm 36\ \tau_{B0}$
- total of upper and lower 2% quantiles in both time params $\approx$ 6% signal loss

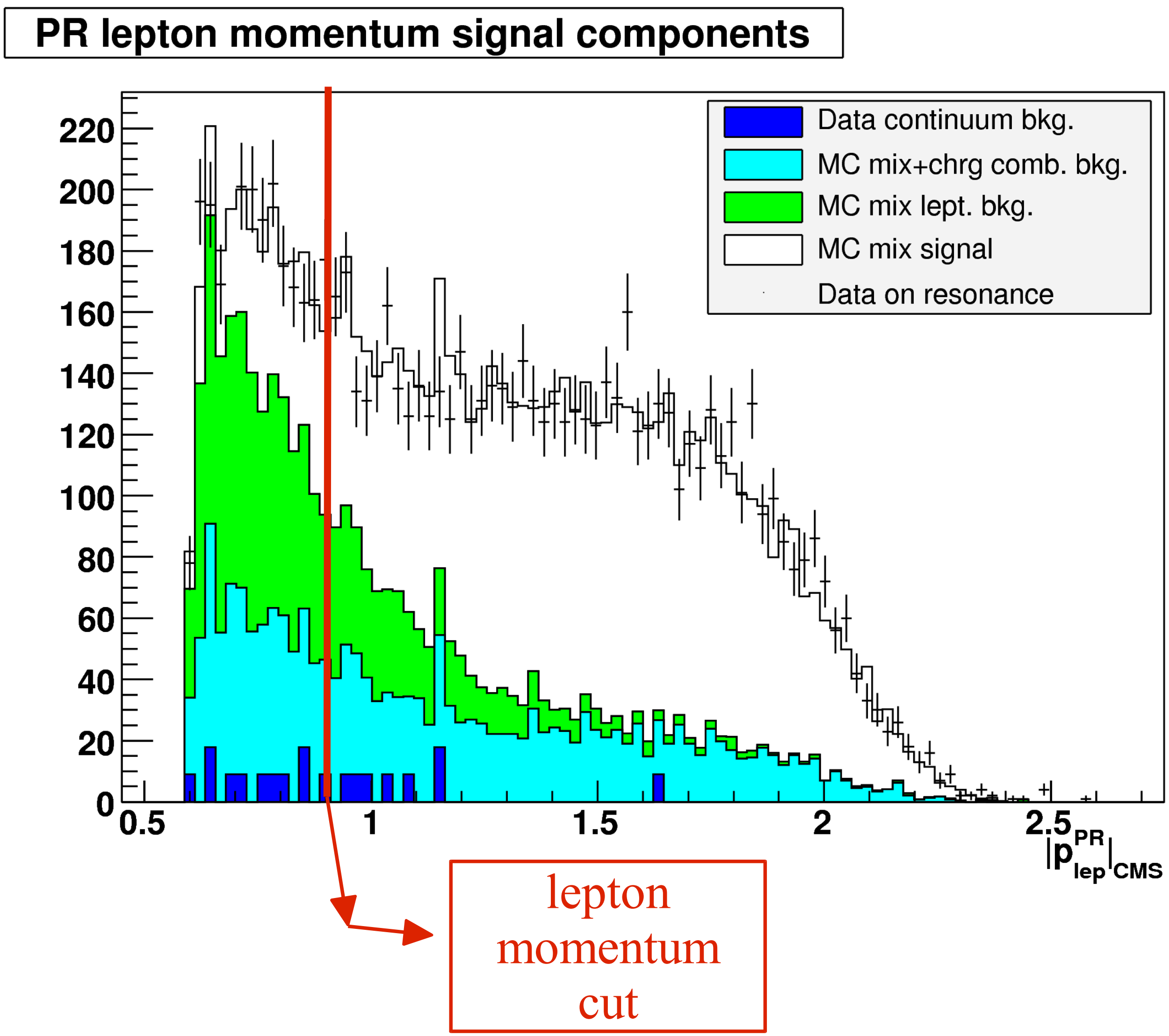
background components in MC

What can go wrong in the reconstruction?

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



determining background fractions



- background events have distribution very similar to signal in plane (t1,Δt)
- therefor 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 signal background components
5. find good model for background shapes
6. iterate over maximum likelihood parameter fit:
   - Likelihood function with 2 background components:

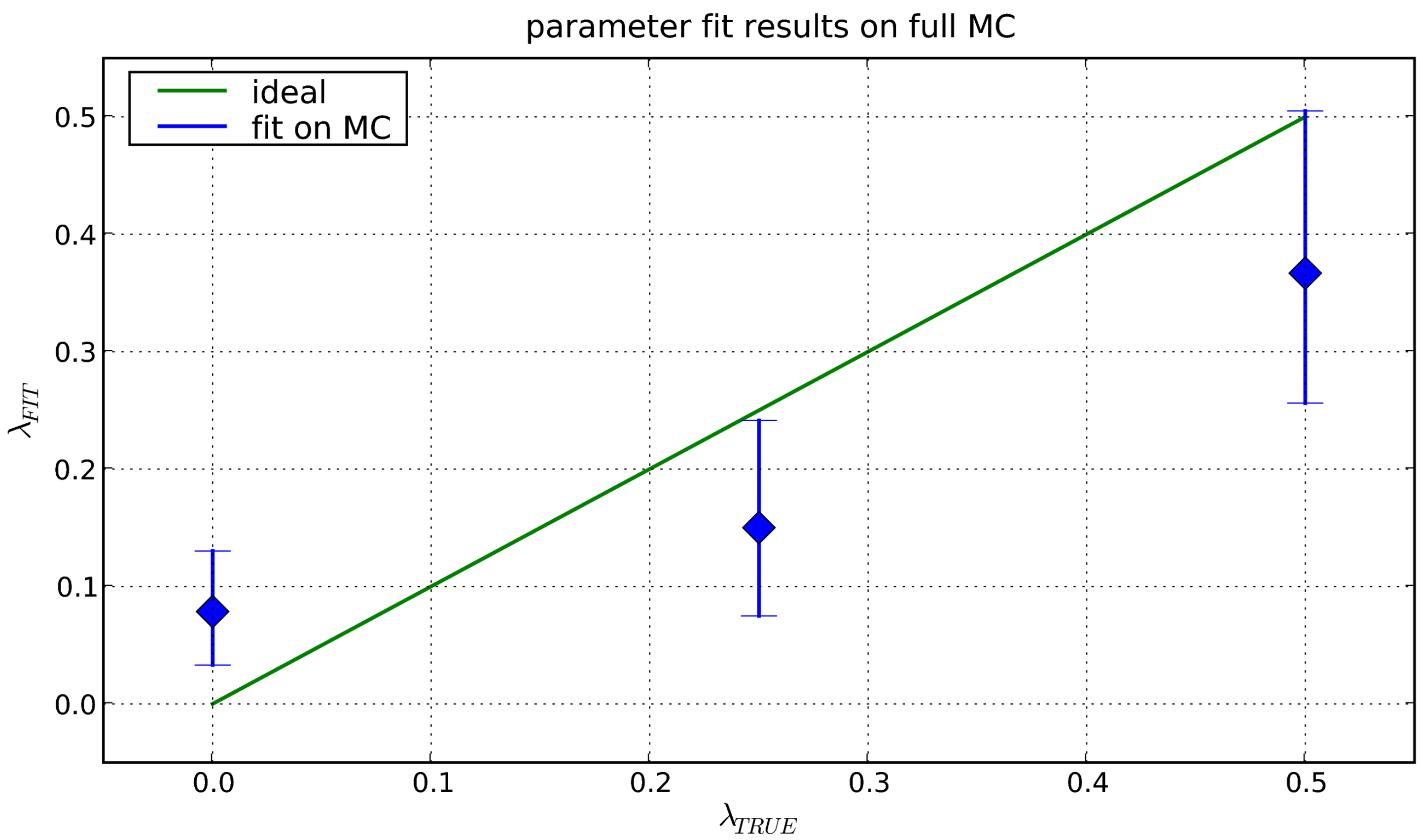
$$\mathcal{L}(\lambda) = \sum_i \log \left(w_S p_S(t_1^i, \Delta t^i | \lambda) + \sum_k w_B^k p_B^k(t_1^i, \Delta t^i) \right)$$

7. result is model parameter of maximum likelihood.

Results on full detector MC

λ MC	λ fit	λ low	λ hi
0	0,0849	0,0385	0,1376
0,25	0,1501	0,0749	0,2413
0,5	0,3668	0,2561	0,5050

- tests on datasets produced by the full simulated reconstruction chain



preliminary result

- no systematics included yet
- purely statistical error

$$\lambda = -0.1503\,_{-0.0389}^{+0.0457}$$

- corresponds to a confidence level limit:

$$\lambda < 0.0147 \qquad (CL = 90\%)$$

- in comparison to a study by Apollo Go:

$$\lambda = 0.029 \pm 0.057$$
$$\lambda < 0.0866 \qquad (CL = 90\%)$$

Thanks for the attention

reconstruction: standard data cuts summary

- curl removal (pairwise track comparison), allow:
  $p_T > 0.275$ GeV/c **or**
  pairwise $\Delta p > 0.1$ GeV/c **or**
  θ plane distance $>15^o$ **then**
  take the track with smaller pivot offset
- impact params selection (Kakuno criteria)
  $p_T < 0.25 < p_T < 0.5 < p_T$ **each case**
  with according maximum pivot offsets ($d\rho$, dz)
- gammas: cluster energy selection (Kakuno criteria) $E_{min}(\theta)$

regarding the comparison of figures

- study of A. Go/A. Bay gives "estimate fraction" parameter

$$(1-\xi)A^{QM} + \xi A^{SD}$$

  - which essentially is convex mixture of B^0-pairs adhering to QM and some that behave like in the SD model.
    (while the asymmetries are like differences of probabilities)

- model A^{BH} describes decoherence on level of amplitudes

- for comparison, do an expansion

$$\begin{aligned} A^{BH} &= A^{QM} \exp\left(-\lambda \min\left(t_1, t_2\right)\right) \\ &\approx A^{QM} \exp\left(-\lambda t\right) \\ &\approx (1-\lambda t)A^{QM} + O((\lambda t)^2)A^{QM} \end{aligned}$$

  - question about equivalence of higher orders remains

- result will be comparable estimate of fraction at $t = 0$