Study on decoherence in flavor entangled B^0 meson pairs at BELLE

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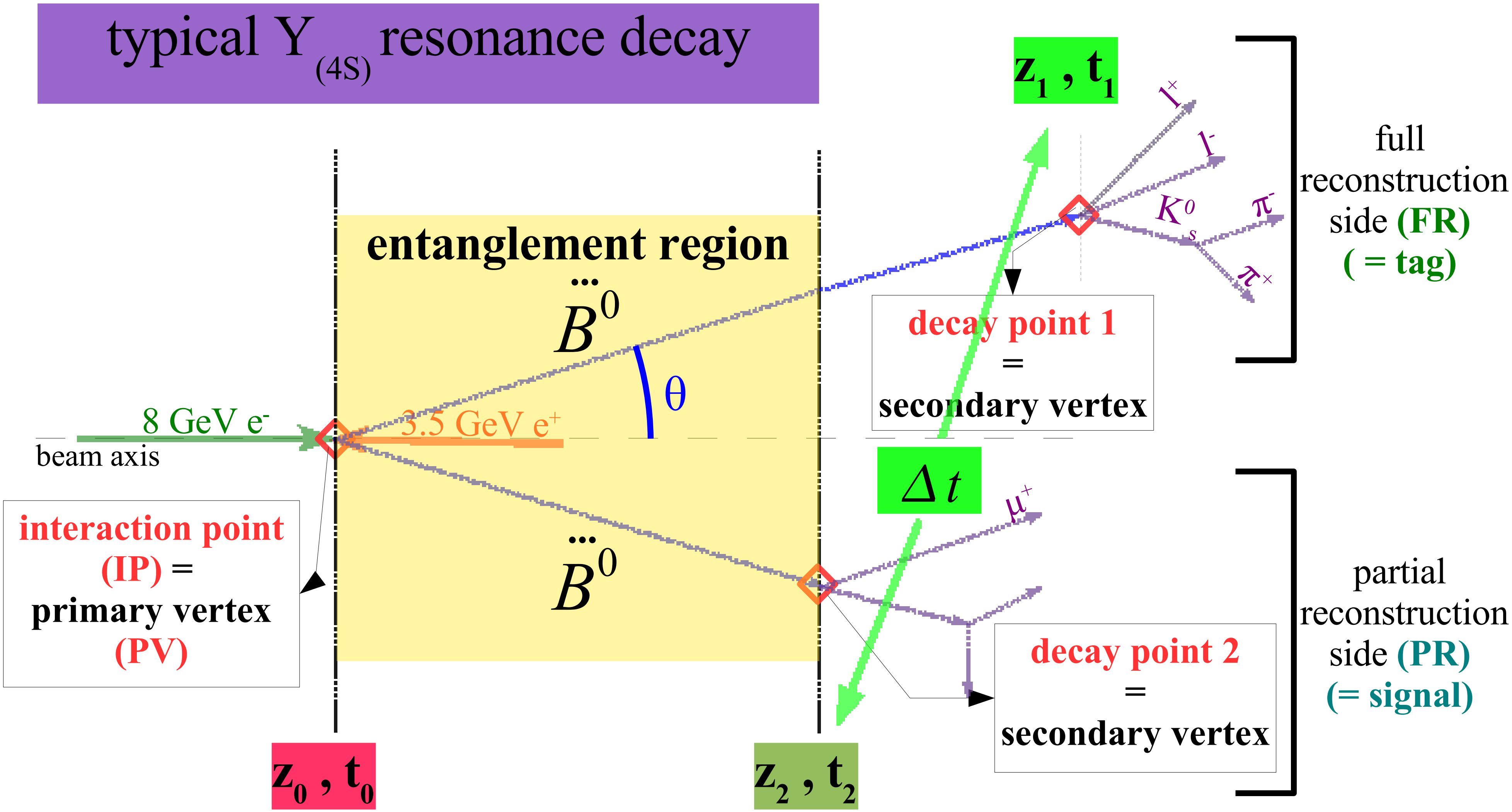
The $B^0 \bar{B}^0$ decay, terminology



- $\beta\gamma c\tau_{B0} = 196\ \mu m$ (LAB)
- $\Delta m = 0.489\ 10^{12}\ \hbar s^{-1} = 0.754\ \tau_{B0}^{-1}$

QM and flavour asymmetry

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

$$A^{QM}(\Delta t) = P_{SF}(t_1,t_2) - P_{OF}(t_1,t_2) = \cos(\Delta m \Delta t)$$

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

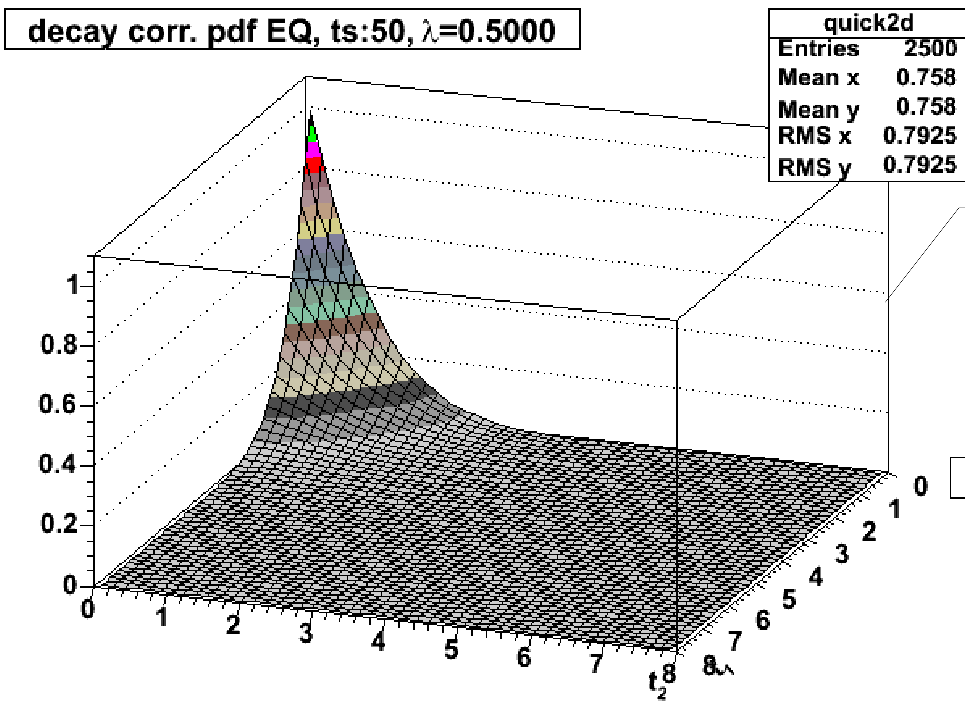
(model to describe coherence dissipation)

$$P_{SF}(t_1,t_2,\lambda) = \frac{1}{2}(1-\cos(\Delta m \Delta t)\exp(-\lambda \min(t_1,t_2)))$$
$$P_{OF}(t_1,t_2,\lambda) = \frac{1}{2}(1+\cos(\Delta m \Delta t)\exp(-\lambda \min(t_1,t_2)))$$

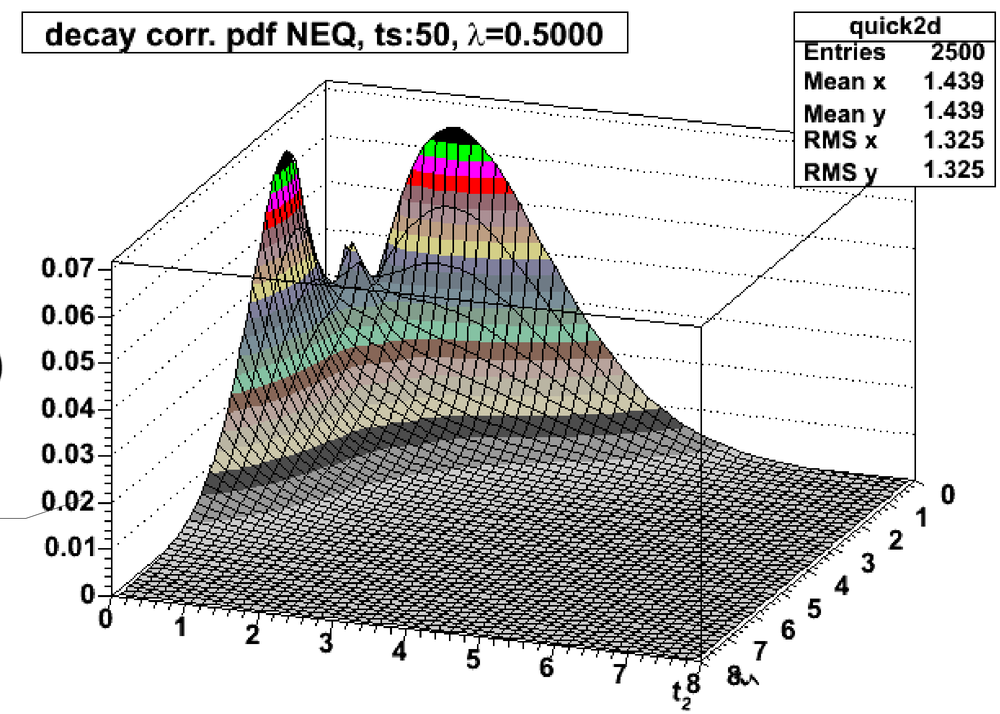
$$p_{SF}(t_1,t_2,\lambda) = P_{SF}(t_1,t_2,\lambda)\exp(-t_1)\exp(-t_2)$$
$$p_{OF}(t_1,t_2,\lambda) = P_{OF}(t_1,t_2,\lambda)\exp(-t_1)\exp(-t_2)$$

- 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 according to Bertlmann-Hiesmayr
- probabilities of Same/Other flavor pair
- lifetime corrected pseudo pdfs

Probability distribution behaviour



Opposite flavor distribution

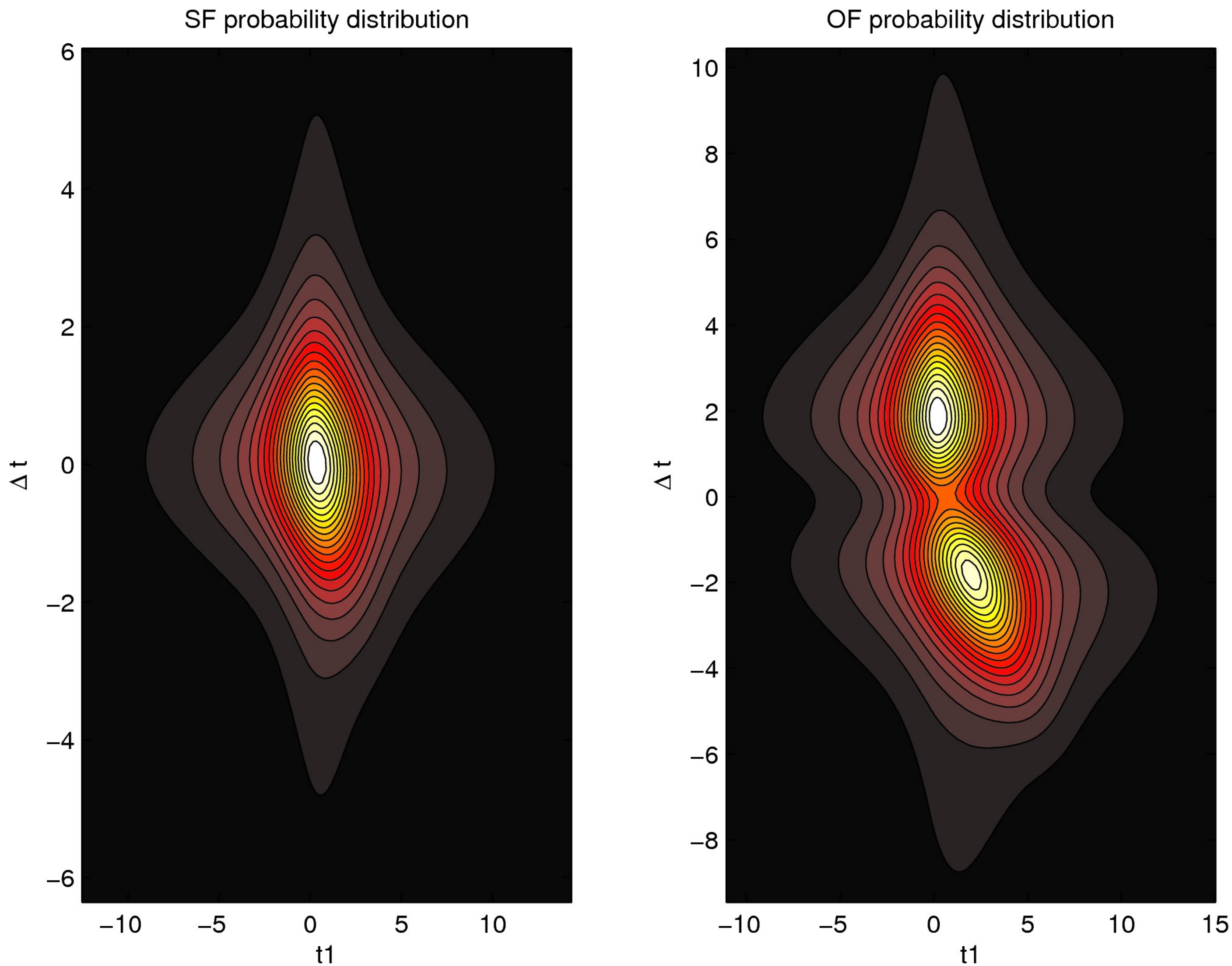


$$p_{SF}(t_1, t_2, \lambda) = P_{SF}(t_1, t_2, \lambda) \exp(-t_1) \exp(-t_2)$$

$$p_{OF}(t_1, t_2, \lambda) = P_{OF}(t_1, t_2, \lambda) \exp(-t_1) \exp(-t_2)$$

Same flavor distribution

chosen problem parametrisation



- pdf with error for Same (SF) and Opposite flavor (OF) in parametrisation $(t1,\Delta t)$
  - giving better resolution
  - minimal covariance in between

Log likelihood fit

- using numeric convolution on normalized pdfs for treating the time measurement errors
  - convolution kernel in the case of the given problem: double gaussian + back2back negative exponential on each time axis t1, Δt

$$f_{SF}^{marg.}(t_1|\lambda)) = p_{SF}(t_1|\lambda) \otimes (G(t_1|\mu_C, \sigma_C) + G(t_1|\mu_T, \sigma_T) + E^{b2b}(t_1|\mu_T, \tau_T))$$

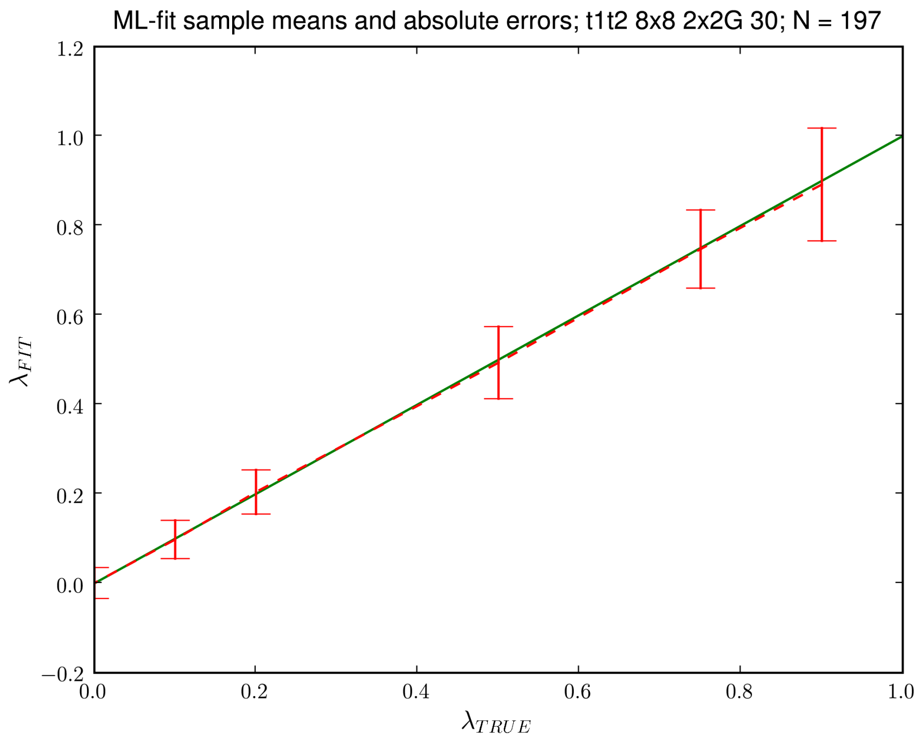
  - same for other time parameter and flavor
- with a total 2 dimensional pdf (same for OF)

$$f_{SF}(t_1, \Delta t|\lambda)) = f_{SF}^{marg.}(t_1|\lambda)) \times f_{SF}^{marg.}(\Delta t|\lambda))$$

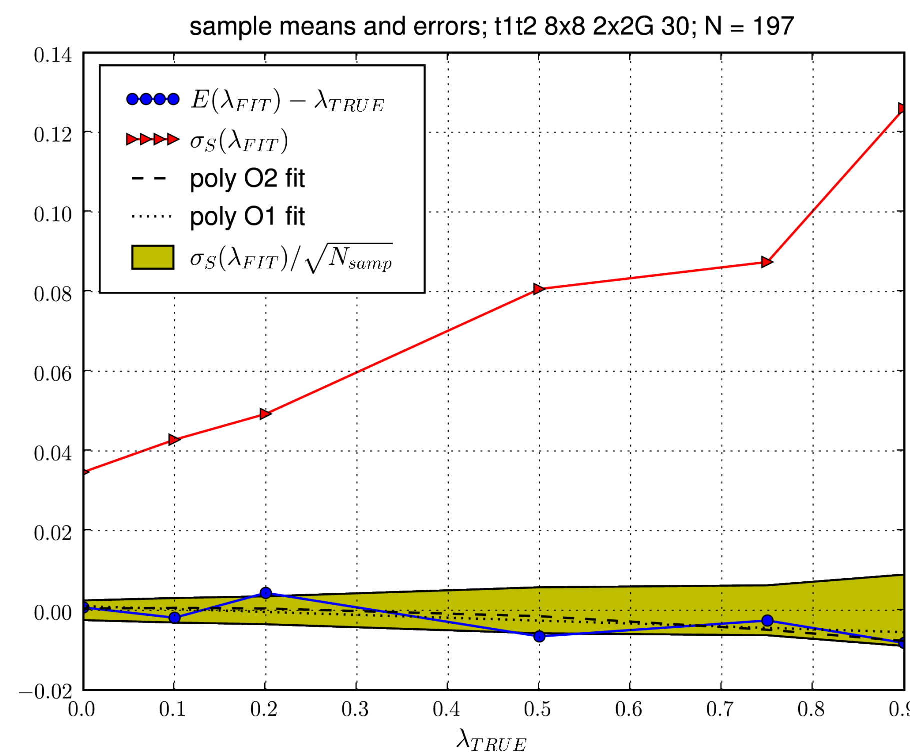
- for all measured/generated decay time tuples calculate (according to their flavor)

$$\mathcal{L}_{SF}(\lambda) = \sum_{i=1}^{n} \log f_{SF}(t_1^i, t_2^i|\lambda)$$
$$\mathcal{L}(\lambda) = \mathcal{L}_{SF}(\lambda) + \mathcal{L}_{OF}(\lambda)$$

desired behavior of ML-fit



- getting fit working was one of the core problems in this study.
- example given for (t1,t2) RF is sum of 2 gaussians

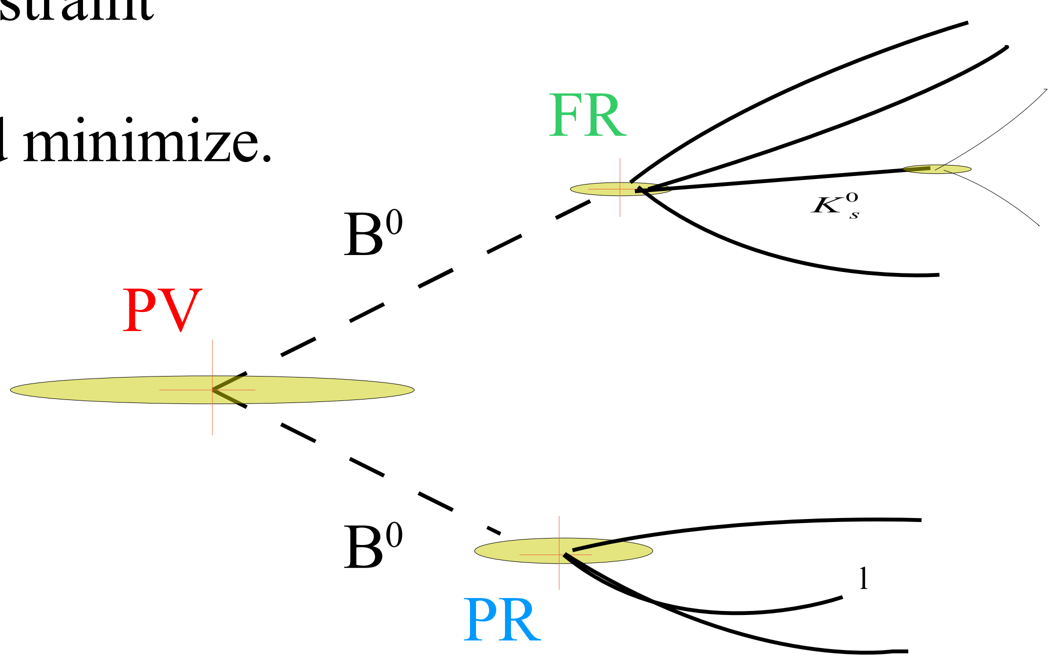


- various difficulties
  - low resolution of time coordinates
  - formulation of resolution functions

vertex fitting procedure PR

Partial Reconstruction side:

- take selected charged
- make list of ExKFitterParticles (daughters) from tracks
- define **PR** Vertex constraint for the B decay, linking all the daughters to the constraint
- link the B^0 vertex to the constraint
- instanciate ExKFitter
- hand over the constraint and minimize.



vertex fitting procedure FR

Full Reconstruction side:

(doing an inclusive fit of **FR** and primary vertex (**PV**))

- take selected charged and vee2 (K^0_S) tracks from Brecon, with daughters of K^0_S clipped
- make list of ExKFitterParticles (daughters) from both kinds of tracks
- initialize ExKFitterVertex **PV** with BIP
- define **FR** Vertex constraint for the B decay, linking all the daughters to the constraint
- link the B^0 vertex to the constraint
- link all daughters to the mother B^0 (Bmo)
- link the Bmo to the **FR** Vertex constrain
- define **PV** Vertex constraint and link the primary vertex and Bmo to it.
- instanciate ExKFitter
- hand over the constraints and minimize.

reconstruction: standard data cuts summary

- <u>curl removal</u> (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
- <u>impact params</u> selection (Kakuno criteria)
  $p_T < 0.25 < p_T < 0.5 < p_T$ **each case**
  with according maximum pivot offsets ($d\rho$, dz)
- gammas: <u>cluster energy</u> selection (Kakuno criteria) $E_{min}(\theta)$

generic MC input description

- generic MC (fullrec V1) FR side mixed events:

  $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$ (+ charge conjugates)
- 492663 events (exp 7-19 + 21-25)
- remaining $B^0\bar{B}^0$ events with 1 lepton on PR-side: → 58449 (11.86 %)
- after quality cuts: reduced to signal events → 13929 events
  - on FR side: only events with truly FR- originating tracks allowed
  - on PR side: only events with truly PR-originating lepton(s) allowed

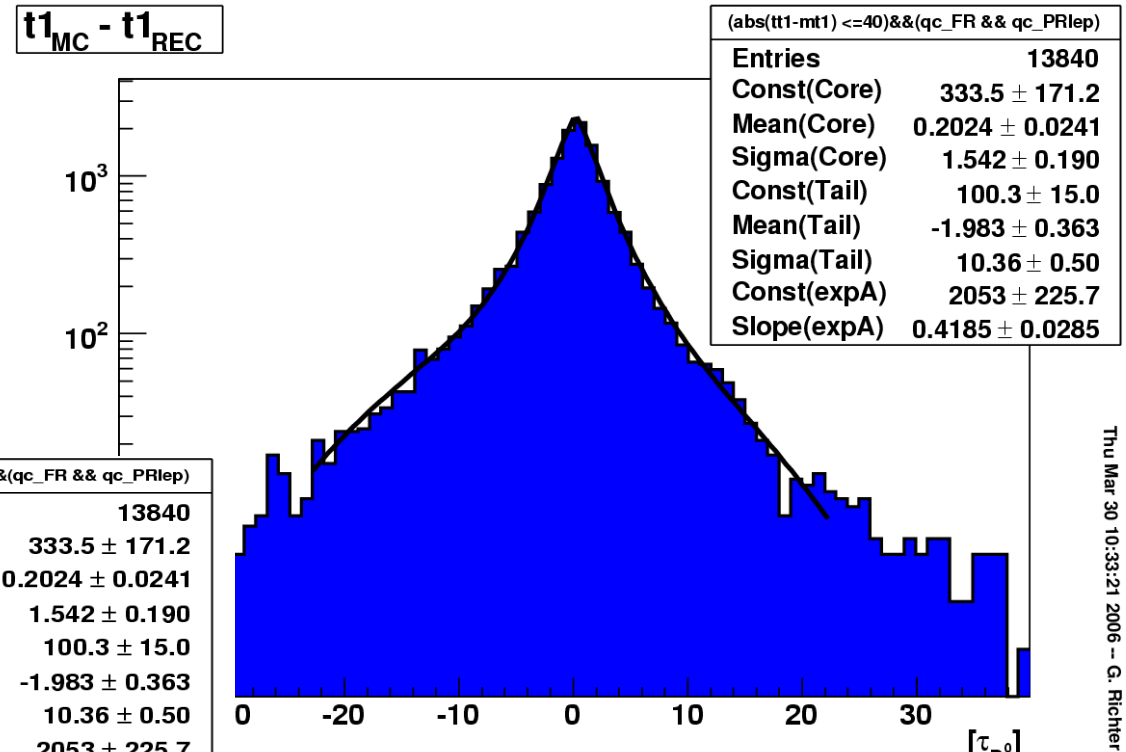
signal MC input

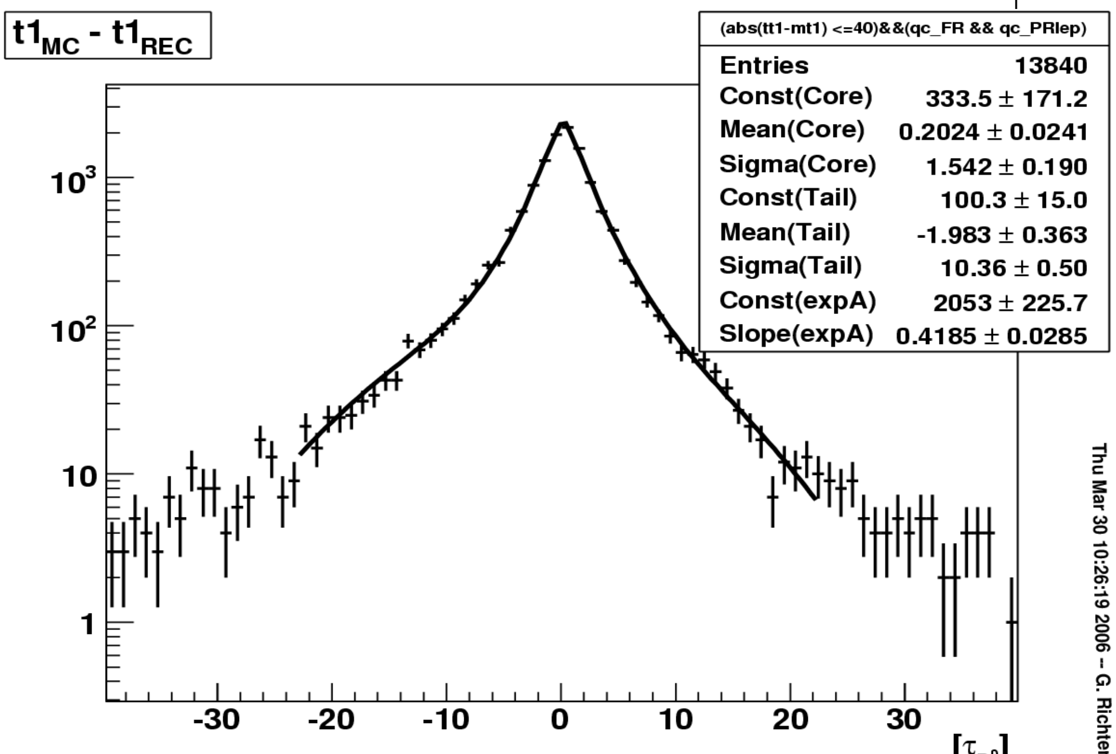
- EvtGen modification according to presented decoherence model
- modified decay model VSS_BMIX to produce the 500k signal MC events for each
  - **λ = 0.25**
  - **λ = 0.5**
- with decay topologies:
  - Full Recconstruction side: B mixed
  - Partial Reconstruction side: $B \rightarrow D X l \nu$

resolution function model in t1

RF fit shown for **t1** parameter

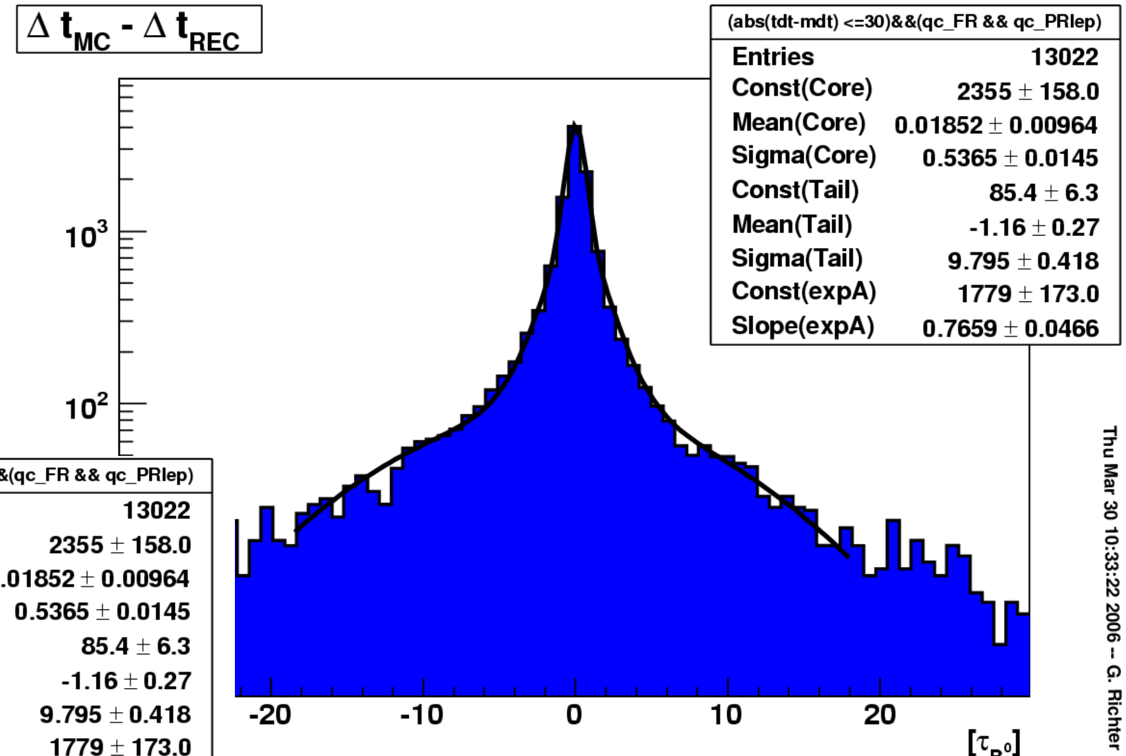
good accordance of fit function up to +/- 4 mm

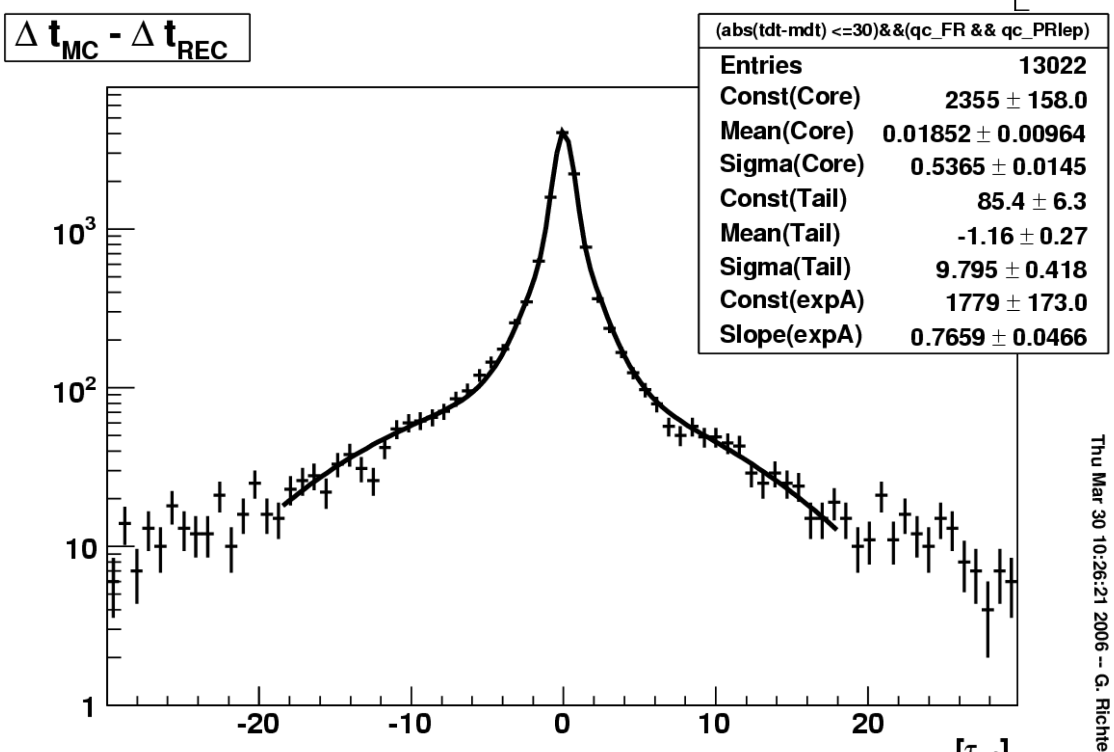




resolution function model in Δt

RF fit shown for $\Delta \mathbf{t}$ parameter
good accordance of fit function up to +/- 4 mm





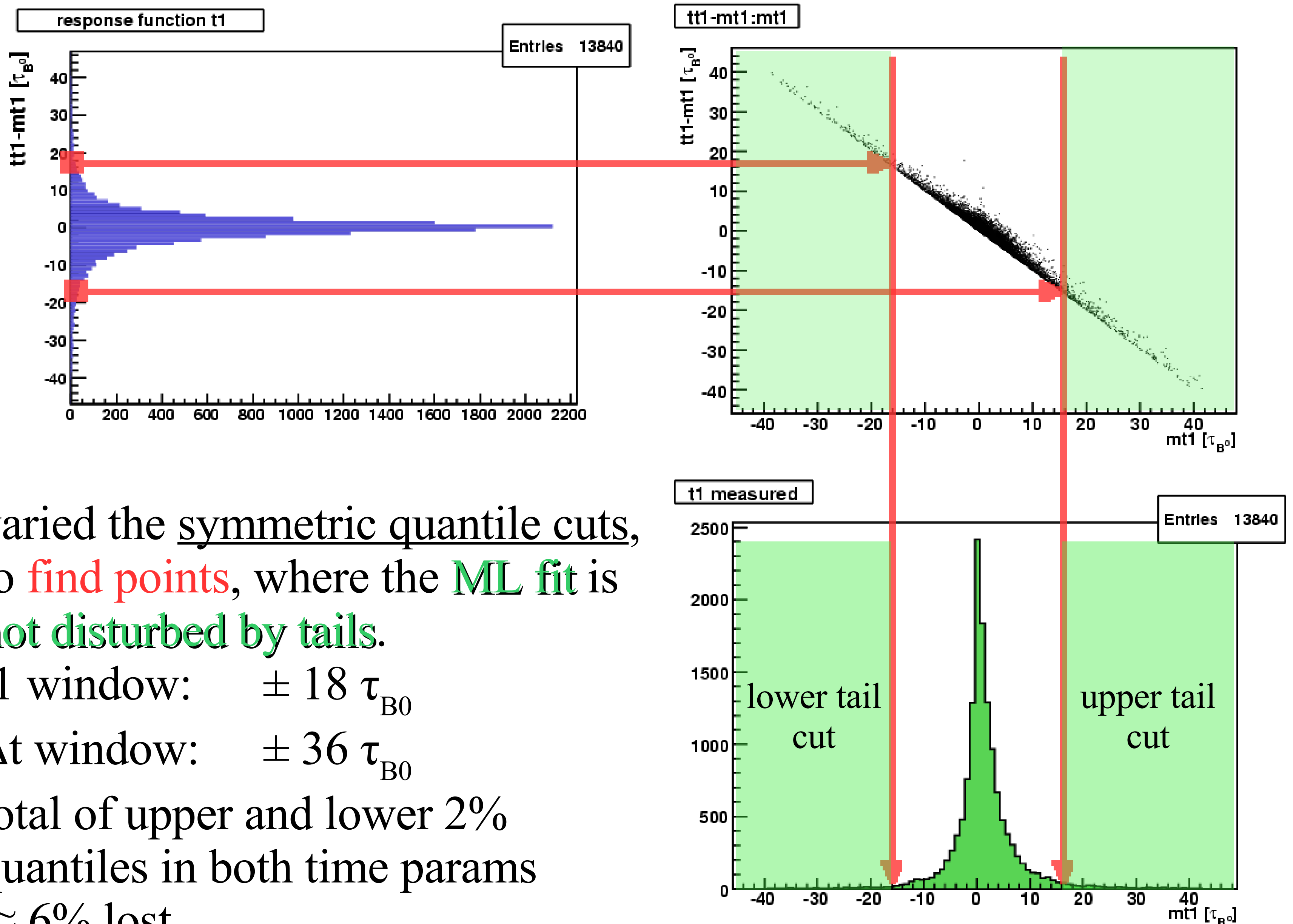
2D correlations of RF in (t1,Δt)

- tested the the 2 marginal distribution functions for separability

$$f_{SF}(t_1, \Delta t|\lambda)) = f_{SF}^{marg.}(t_1|\lambda)) \times f_{SF}^{marg.}(\Delta t|\lambda))$$

  - allowing to abandon time consuming 2D convolution
    - speed improvement making the whole thing feasible
- 2D normalized plot shows almost no deviations between
  - fit product of 2 marginal distributions
  - the fitted 2D histogram

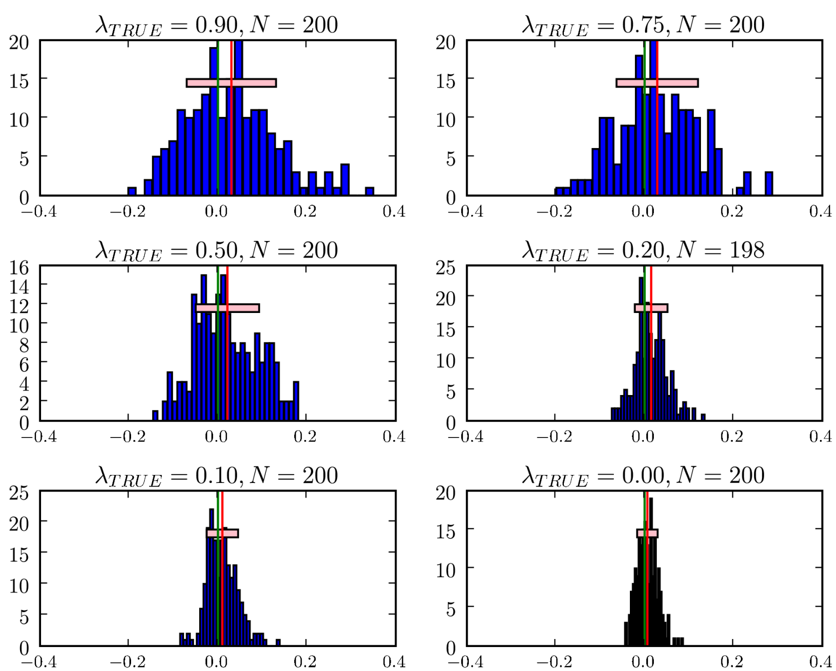
applied data-window cuts for MLfit

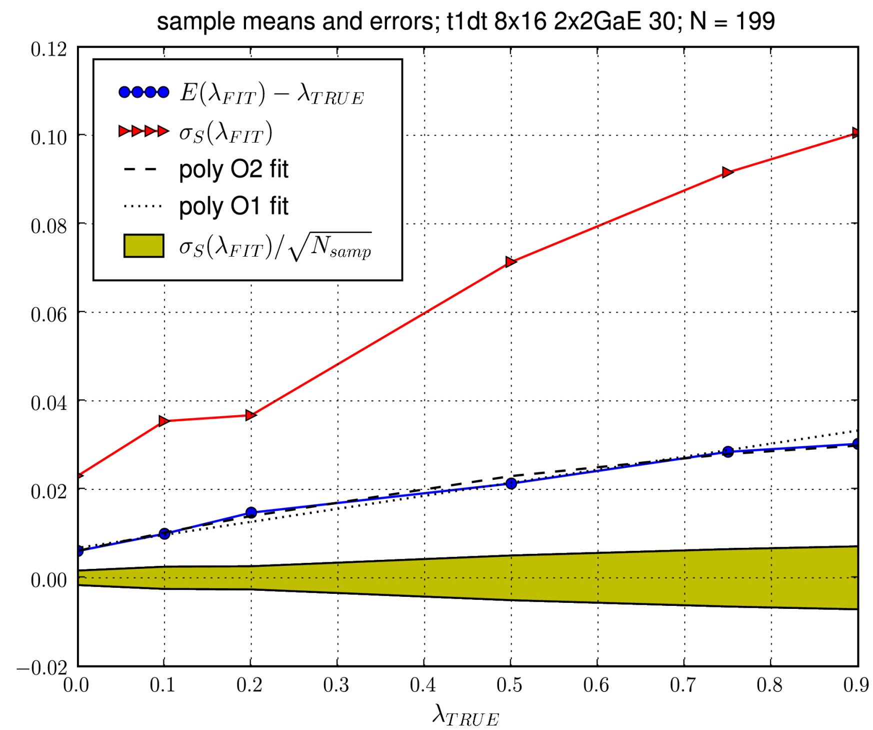


- varied the symmetric quantile cuts, to find points, where the ML fit is not disturbed by tails.
- t1 window: $\pm 18\ \tau_{B0}$
- Δt window: $\pm 36\ \tau_{B0}$
- total of upper and lower 2% quantiles in both time params $\approx$ 6% lost

test with full RF on toy MC

- multiple re-fitting (N=200)
- shows good results within expected single fit errors

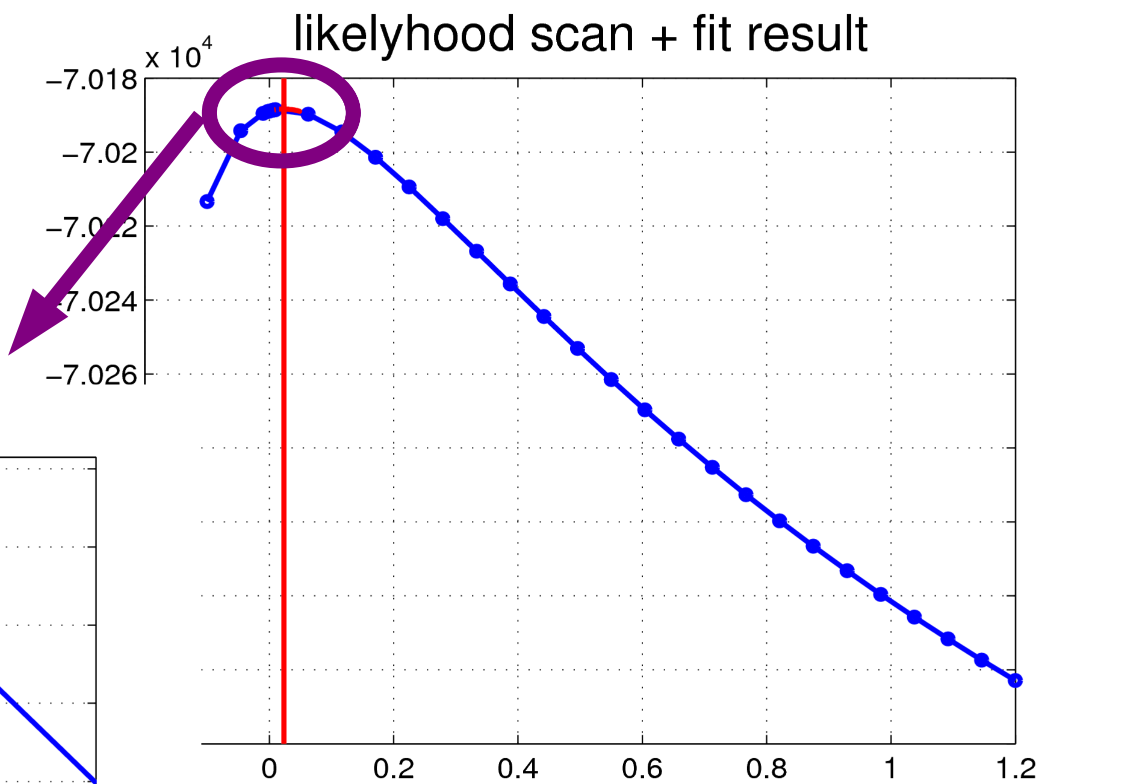


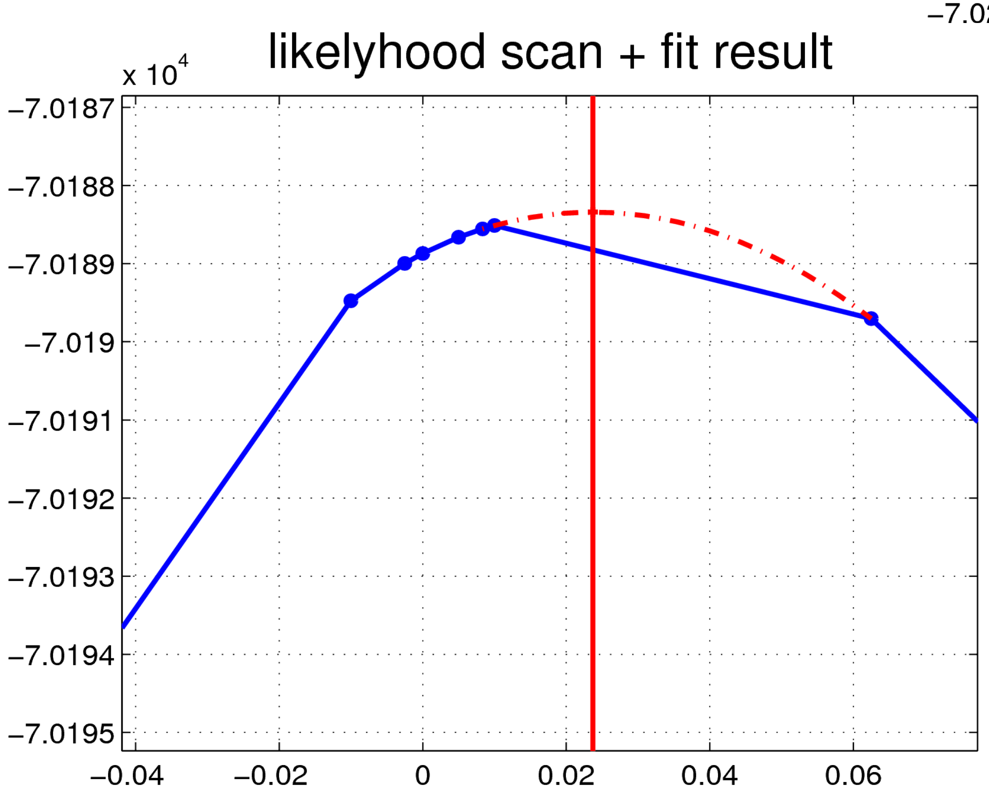


- bias below the scan-step size of $\Delta\lambda_{TRUE} \approx 0.04$

application of method to generic MC

- input data: $\lambda_{TRUE} = 0$
- $\lambda_{FIT} = 0.02372496$
- $\sigma_{FIT} = 0.02348621$



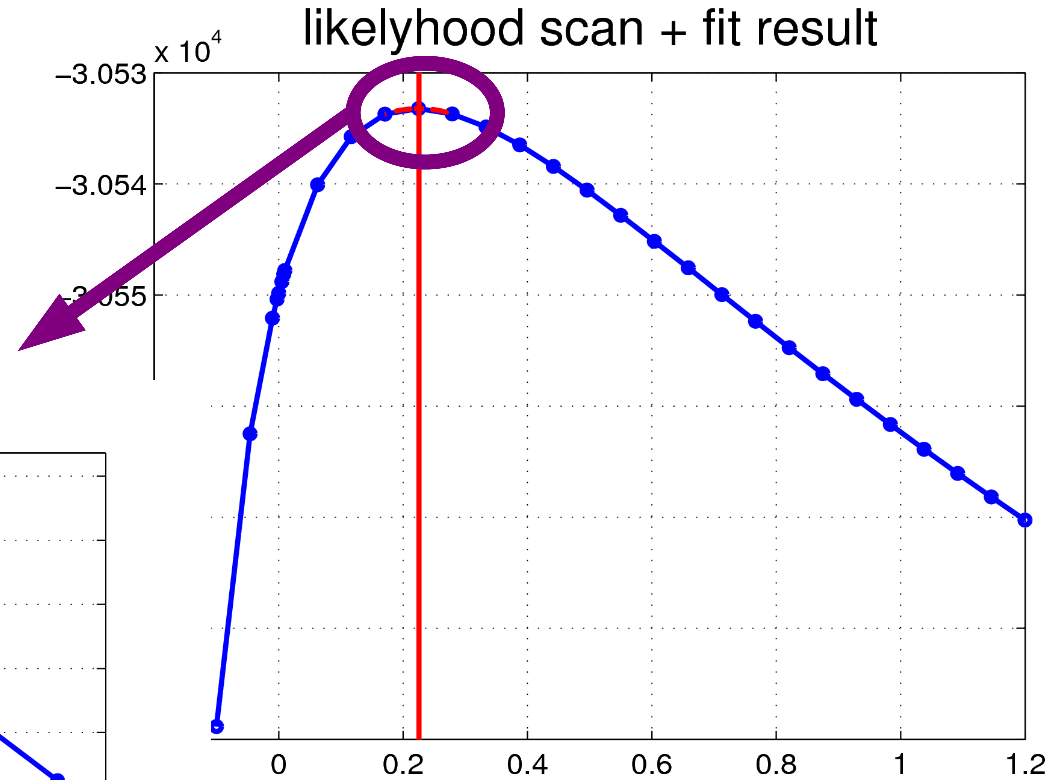


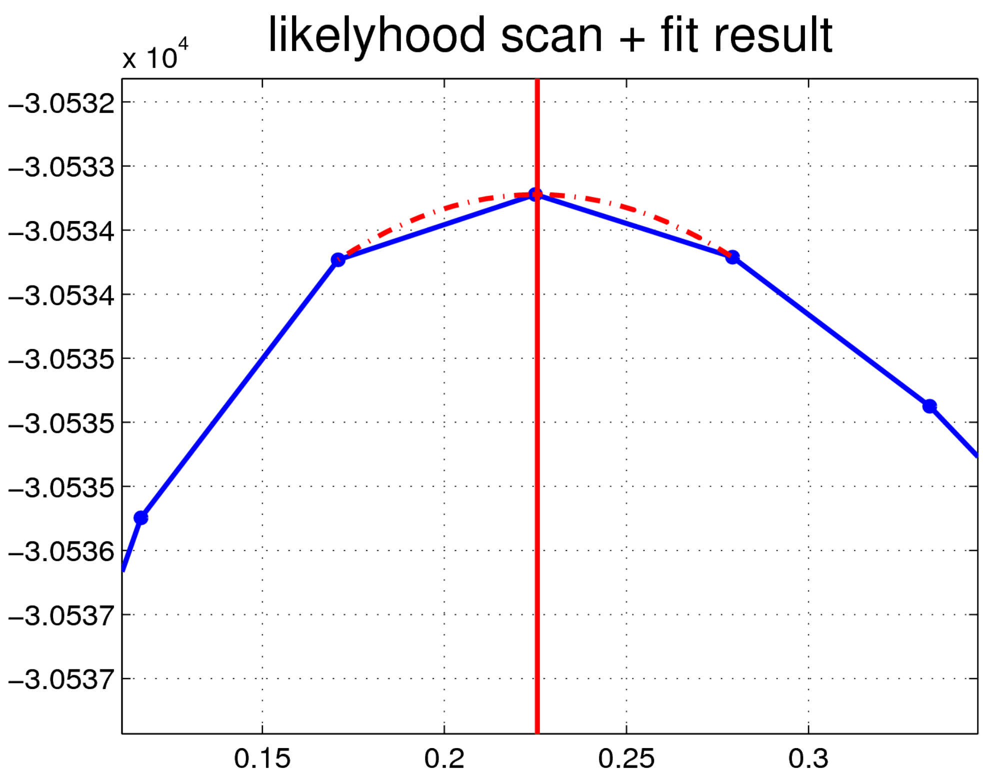
full reconstruction chain

- EvtGen $\lambda = 0.0$
- Gsim
- fullrec V1
- recB_t012

application of method to signal MC

- input data: $\lambda_{TRUE} = 0.25$
- $\lambda_{FIT} = 0.22556399$
- $\sigma_{FIT} = 0.05418214$



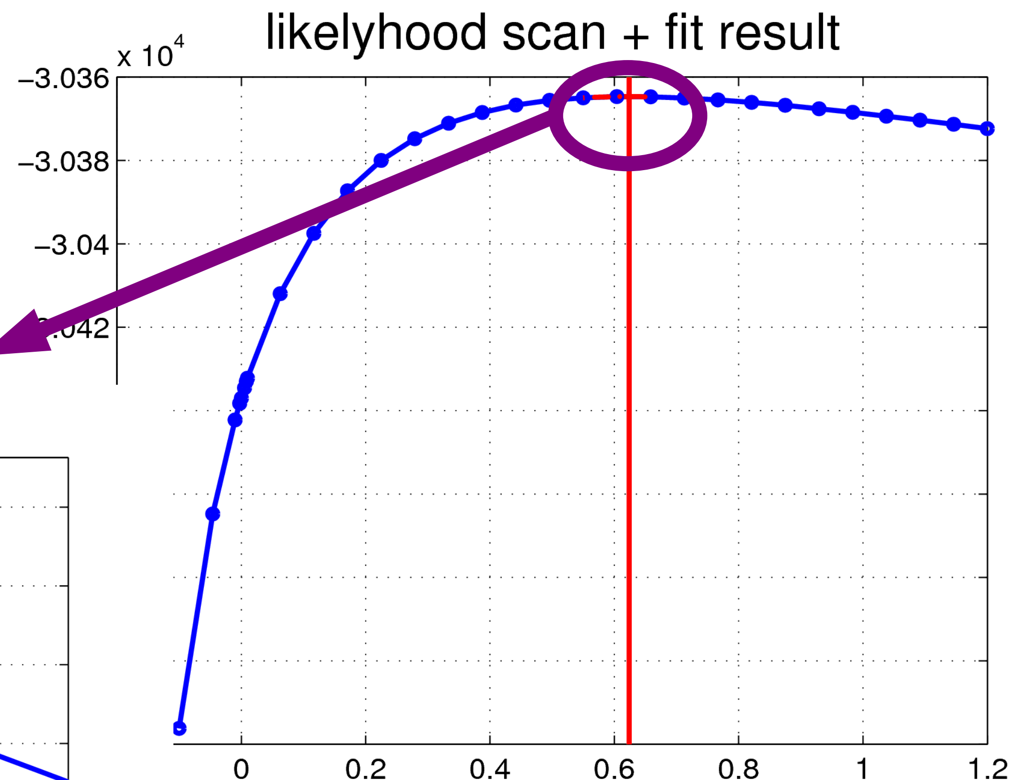


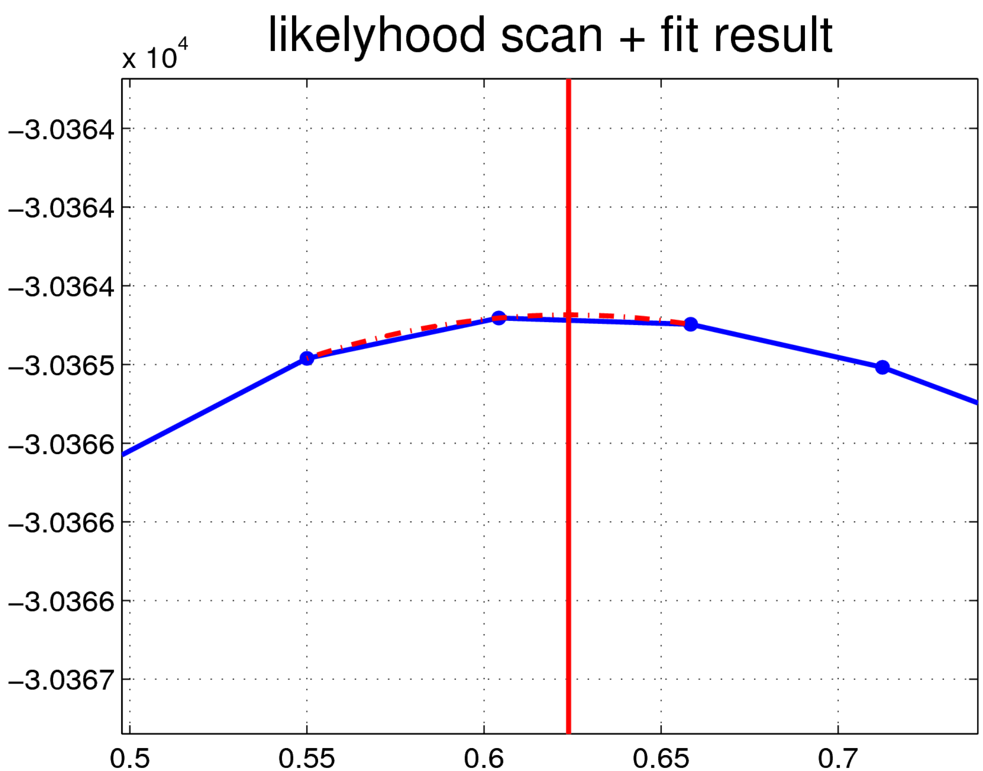
full reconstruction chain

- EvtGen $\lambda = 0.25$
- Gsim
- fullrec V1
- recB_t012

application of method to signal MC

- input data: $\lambda_{TRUE} = 0.5$
- $\lambda_{FIT} = 0.62387652$
- $\sigma_{FIT} = 0.09947637$





full reconstruction chain

- EvtGen $\lambda = 0.5$
- Gsim
- fullrec V1
- recB_t012

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 $t = 0$

latest steps

tackling the background estimation

starting to define other background influences using beam constrained mass sideband normalisations

- have reconstructed mdst to work with:

source	type	λ
MC	generic	0.0
MC	signal	0.25
MC	signal	0.5
MC	charged	0.0
DATA	continuum	???
DATA	on resonance	???

Thanks for the attention