Measurement of EPR-type flavour entanglement in $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ decays

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The EPR argument (1935)

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

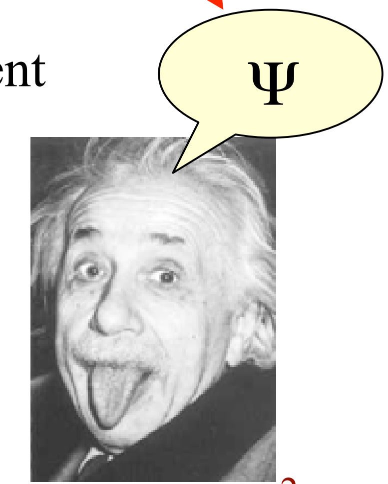
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

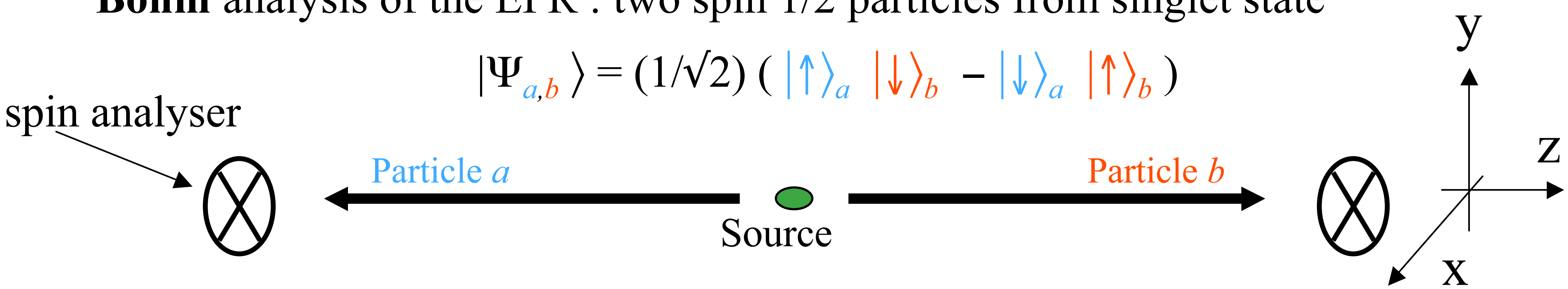
- A "complete theory" contain an element for each element of reality
- EPR consider an entangled two particle system and the measurement of two non-commuting observables (position and momentum)
- Entanglement to transport the information from one sub-system to the other
- EPR identify a contradiction with the QM rule for non-commuting observables.



Bohm (1951), entangled states

Bohm analysis of the EPR : two spin 1/2 particles from singlet state

$$|\Psi_{a,b}\rangle = (1/\sqrt{2})\,(\,|\uparrow\rangle_a\,|\downarrow\rangle_b - |\downarrow\rangle_a\,|\uparrow\rangle_b\,)$$



* The two spin are entangled: a measurement $S_x = +1/2$ of the spin projection //x for particle **a** implies that we can predict the outcome of a measurement for **b**: $S_x = -1/2$.

* This will happen even if the decision to orient the polarizer for particle **a** is done at the very last moment => no causal connection.

How to cure this ?

- with the introduction of a new instantaneous communication channel between the two sub-systems ...
- or with the introduction of some new hidden information for particle **b**, so that the particle knows how to behave.

=> QM is incomplete.

J. S. Bell, the experiments...

* This problem was revitalized in 1964, when Bell suggested a way to distinguish QM from local models featuring hidden variables (J. S. Bell, Physics **1**, 195 (1964)).

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* Several experiments have been done with photon pairs, atoms,...

* Tests have been carried out on correlated $K^0 \overline{K}^0$

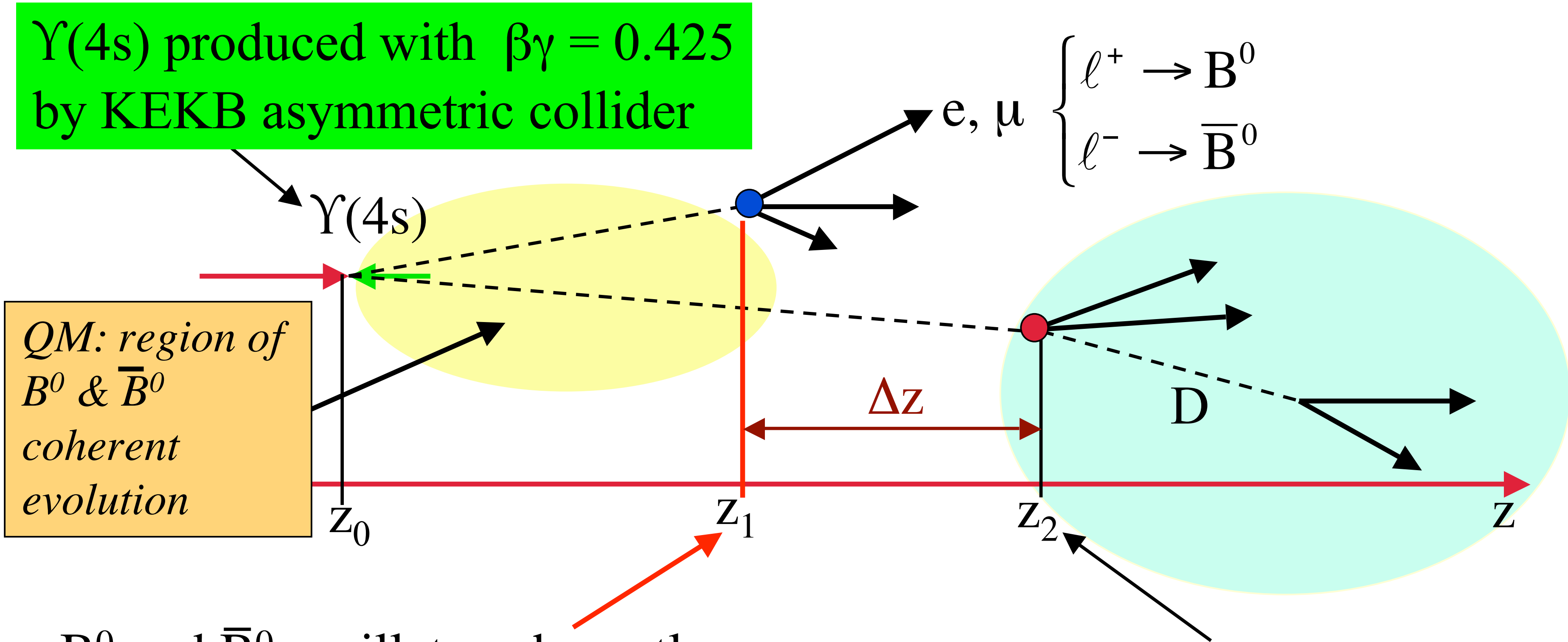
  Apostolakis *et al.*, CPLEAR collab., Phys. Lett. B **422**, 339 (1998)

  Ambrosino *et al.*, KLOE collab., Phys. Lett. B **642**, 315 (2006).

In BELLE we have the opportunity to study the flavour entanglement in B^0 pairs from $\Upsilon(4s) \rightarrow B^0 \overline{B}^0$

$$|\Psi_{\Upsilon(4s)}\rangle = (1/\sqrt{2}) \left(|B^0\rangle_a |\overline{B}^0\rangle_b - |\overline{B}^0\rangle_a |B^0\rangle_b \right)$$

Study of correlated $B^0\ \overline{B}^0$



B^0 and $\overline{B}^0$ oscillate coherently.
When the first decays, the other is known to be of the opposite flavour, at the same proper time

Than the other B^0 oscillates freely before decaying after a time given by

$$\Delta t \approx \Delta z / c\,\beta\,\gamma$$

N.B. : production vertex position z_0 not very well known : only Δz is available !

Predictions from QM for entangled pairs

Time (Δt)-dependent decay rate into two Opposite Flavour (OF) states

$$R_{OF} \propto 1 + \cos(\Delta m_d \Delta t)$$

Δm_d is the mass difference of the two mass eigenstates

idem, into two Same Flavour (SF) states

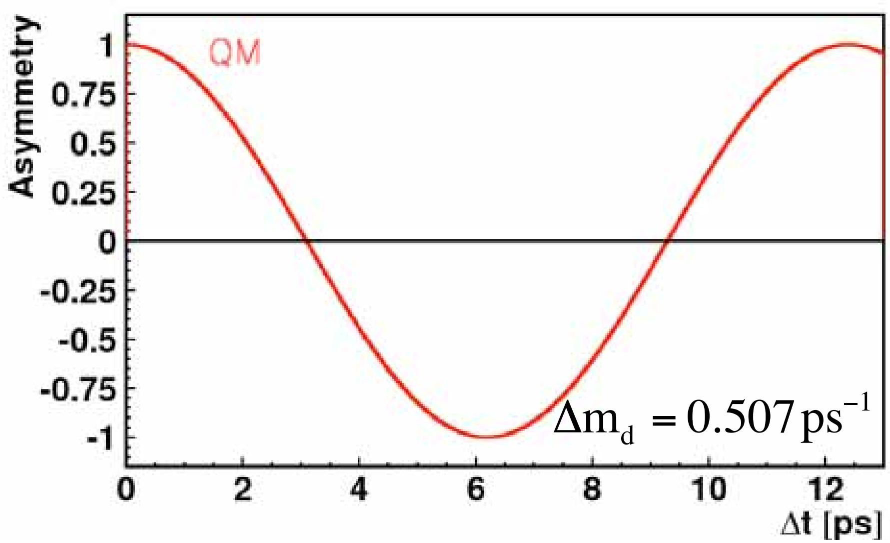
$$R_{SF} \propto 1 - \cos(\Delta m_d \Delta t)$$

=> we obtain the

time-dependent asymmetry

$$A_{QM}(\Delta t) = \frac{R_{OF} - R_{SF}}{R_{OF} + R_{SF}}(\Delta t) =$$

$$= \cos(\Delta m_d \Delta t)$$



(ignoring CP violation effects $O(10^{-4})$, and taking $\Delta\Gamma_d = 0$)

Local Realism by Pompili & Selleri (PS)

Local Realism, each B has "elements of reality" (hidden variables)

λ_1 : CP = +1 or -1
λ_2 : Flavour = +1 or -1

=> 4 basic states B^0_H, $\bar{B}^0_H$, B^0_L, $\bar{B}^0_L$
indexed by i = 1, 2, 3, 4

* Mass states are stable in time, simultaneous anti-correlated flavor jumps.

The model works with probabilities $p_{ij}(t|0)$ = prob for a B to be in the state j at proper time t=t, conditional of having been in state i at t=0.

* p_{ij} set to be consistent with single B^0 evolution ~ $\exp\{(\Gamma/2 + im)t\}$.
* PS build a model with a minimal amount of assumptions

⇒They only determine upper and lower limits for combined probabilities ...

F. Selleri, Phys. Rev. A **56** (1997) 3493
A. Pompili, and F. Selleri, Eur. Phys. J. C **14** (2000) 469

Local Realism by Pompili & Selleri (2)

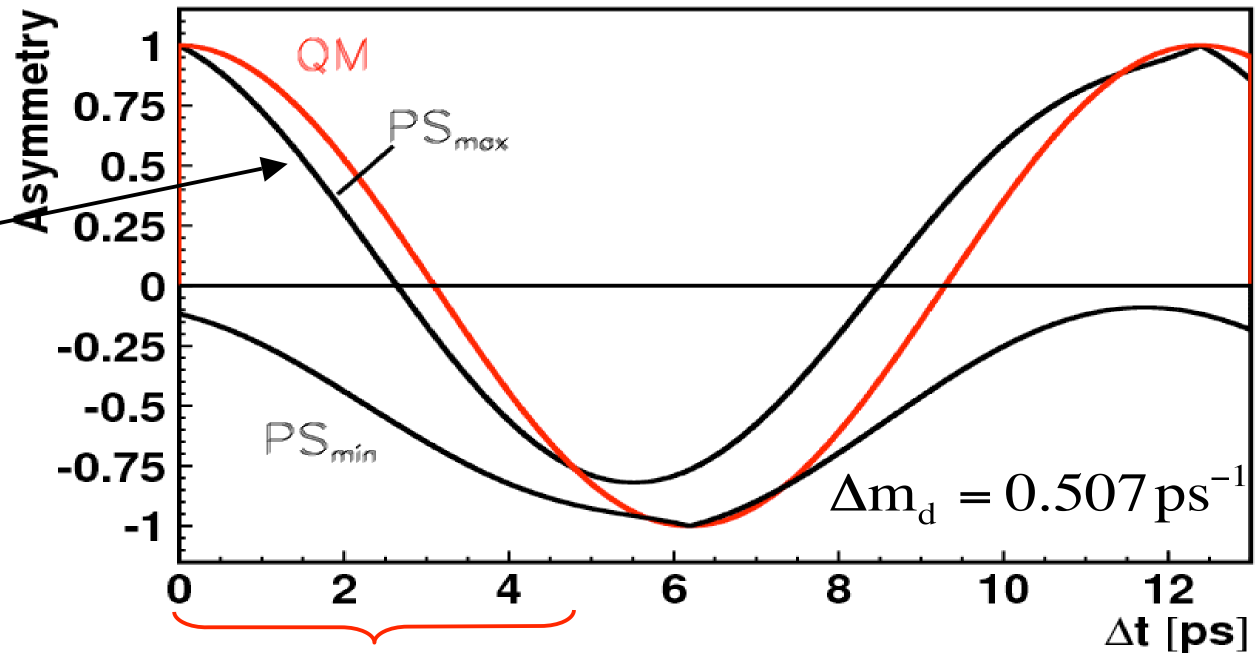
=> analytical expressions for A corresponding to the limits. The Amax is

$$A_{PS_{max}}(t_1,t_2) = 1 - \left|\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{min}) + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{min})\right|$$

$$t_{min} = \min(t_1,t_2)$$

≠ QM

Only Δt is known: need to integrate over t_{min}



$A_{QM} > A_{PS}$ in the Δt region below ~5 ps

Spontaneous immediate Disentanglement (SD)

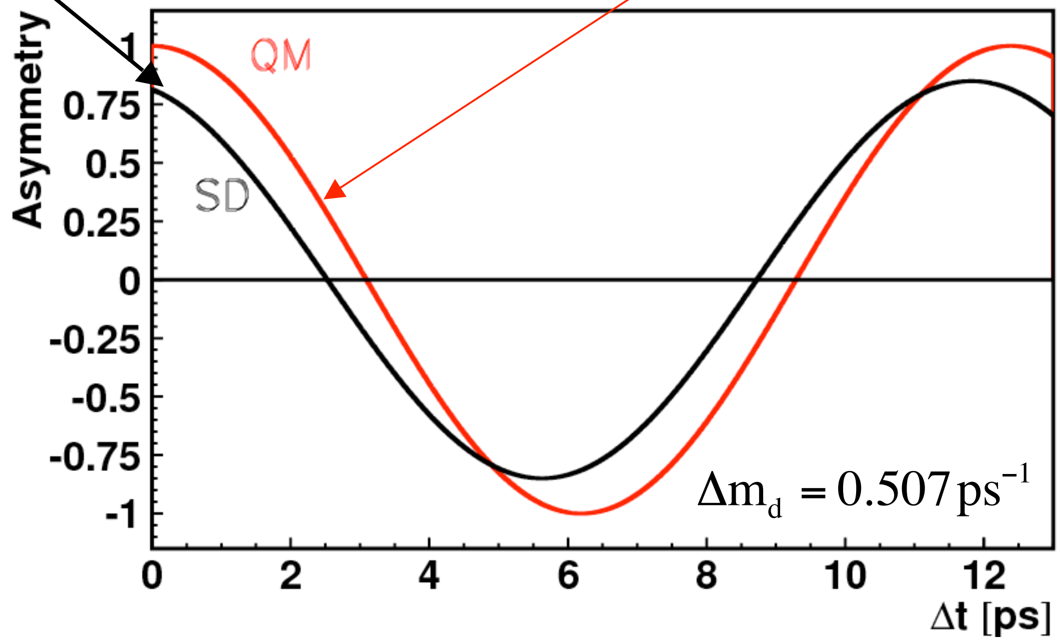
Just after the decay into opposite flavor states, we considers an independent evolution for the B^0 pair

≠ QM

$$A_{SD}(t_1, t_2) = \cos(\Delta m_d t_1)\cos(\Delta m_d t_2) = \frac{1}{2}[\cos(\Delta m_d (t_1 + t_2)) + \cos(\Delta m_d \Delta t)]$$

integrating out $t_1 + t_2$ gives:

$A_{QM}(\Delta t) = \cos(\Delta m_d \Delta t)$



Analysis goals and methods

We want to provide FULLY CORRECTED time-dependent asymmetry.

For this, we will

-- subtract all backgrounds

-- correct for events with wrong flavour associations

-- correct for the detector effects (resolution in Δt) by a deconvolution procedure

=> the result can then be directly compared to the models:

We will use our data to test

- the Pompili and Selleri model,
- the Spontaneous Disentanglement model,
- and we will check for some partial contamination by SD-like events, i.e. we search for decoherence effects from New Physics

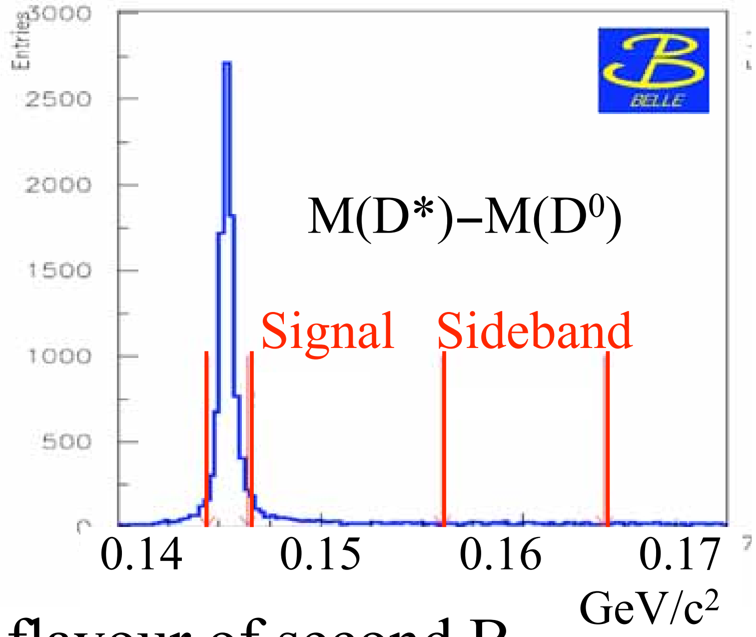
Event selection and tagging

* First B measured via

$$B^0 \to D^{*-}\ell^+\nu$$

$$D^{*-} \to \overline{D}^0\pi^-_{slow}$$

$$\overline{D}^0 \to K^+\pi^-,\quad K^+\pi^-\pi^0,\quad K^+\pi^-\pi^+\pi^-$$

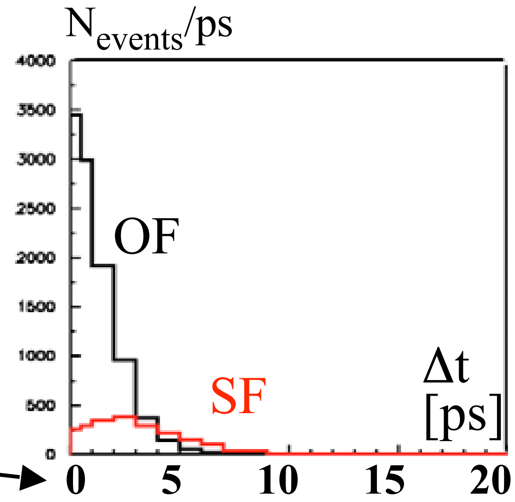


* Remaining tracks are used to guess the flavour of second B, from the standard Belle flavour tagging procedure.

From a total of 152 10^6 B^0B^0 pairs:

– 6718 OF and 1847 SF events after selection.

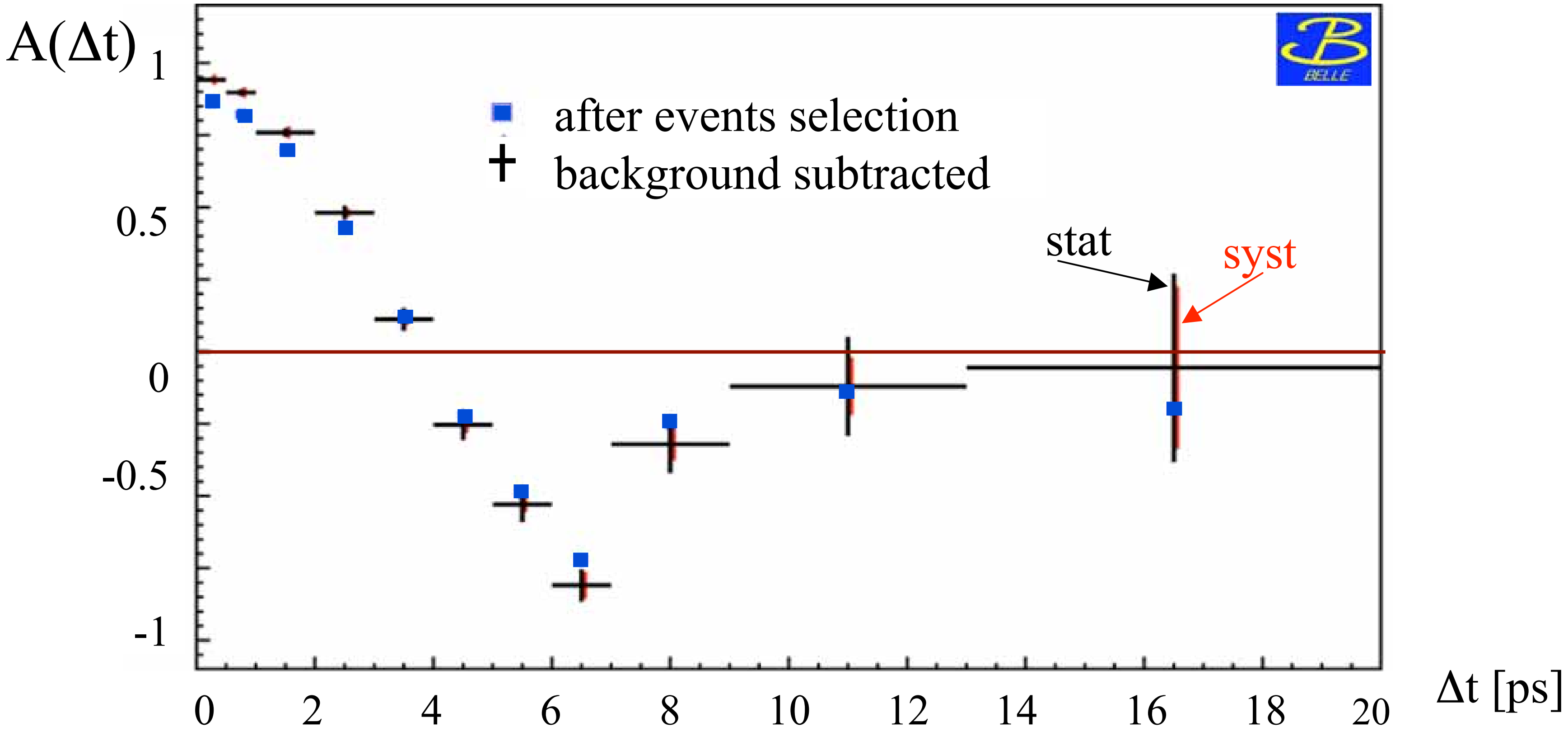
– Δz is obtained from track fit of the two vertices and converted into a Δt value



Time-dependent asymmetry

We correct bin by bin the OF and SF distributions for

- ♦ Fake D* background
- ♦ Uncorrelated D*-leptons, mainly D* and leptons from different B^0
- ♦ $B^{\pm} \to D^{**}\, l\, \nu$ background
- ♦ ~1.5% fraction of wrong flavour associations



Data deconvolution

Deconvolution is performed using response matrices for OF and SF distributions. The two 11x11 matrices are build from GEANT MC events. We use a procedure based on **singular value decomposition**, from H. Höcker and V. Kartvelishvili, NIM A **372** 469 (1996).

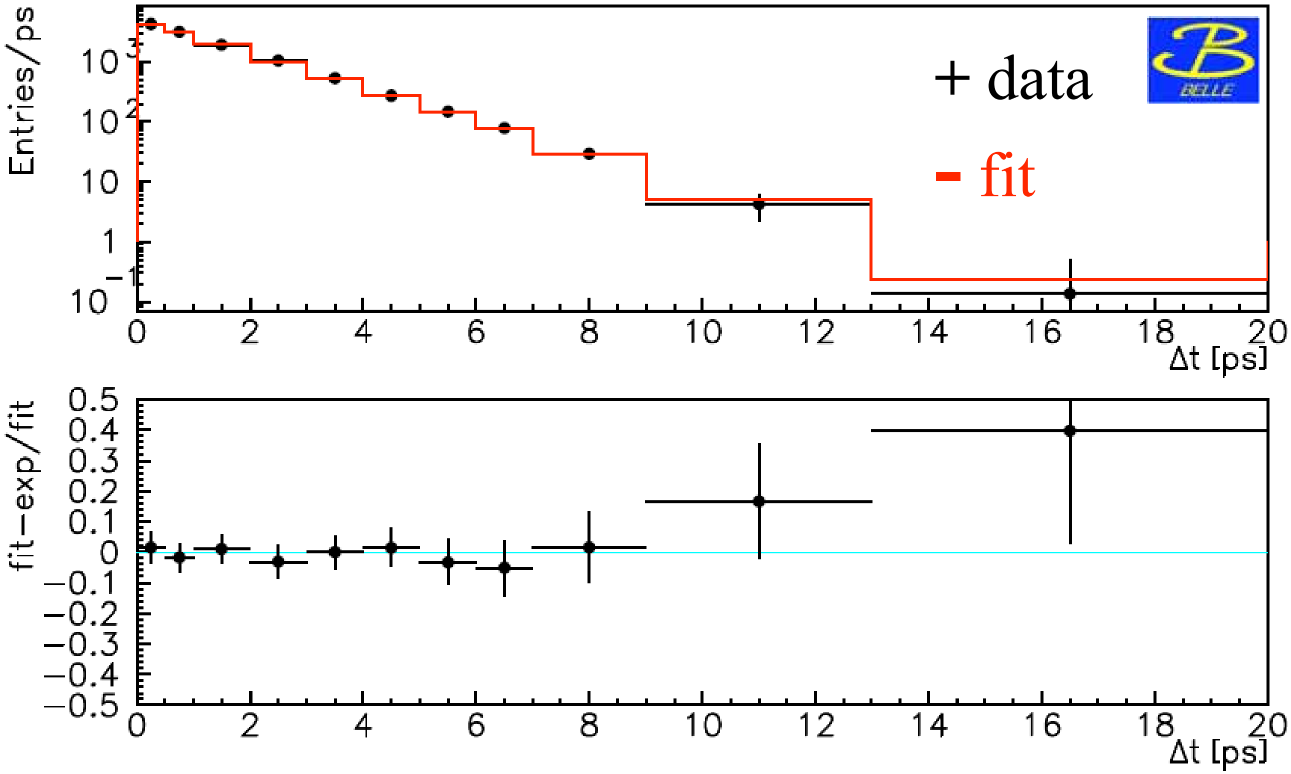
Toy MC of the 3 models (QM, PS and SD) have been used to study the method and to estimate the associated systematic error.

The result is given here:

	Window	Asymmetry		Systematic errors				
Δt bin	window [ps]	A and total error	stat. error	total	event sel.	bkgd sub.	wrong tags	deconvol.
1	0.0 – 0.5	1.013 ± 0.028	0.020	0.019	0.005	0.006	0.010	0.014
2	0.5 – 1.0	0.916 ± 0.022	0.015	0.016	0.006	0.007	0.010	0.009
3	1.0 – 2.0	0.699 ± 0.038	0.029	0.024	0.013	0.005	0.009	0.017
4	2.0 – 3.0	0.339 ± 0.056	0.047	0.031	0.008	0.005	0.007	0.029
5	3.0 – 4.0	-0.136 ± 0.075	0.060	0.045	0.009	0.009	0.007	0.042
6	4.0 – 5.0	-0.634 ± 0.084	0.062	0.057	0.021	0.014	0.013	0.049
7	5.0 – 6.0	-0.961 ± 0.077	0.060	0.048	0.020	0.017	0.012	0.038
8	6.0 – 7.0	-0.974 ± 0.080	0.060	0.053	0.034	0.025	0.020	0.025
9	7.0 – 9.0	-0.675 ± 0.109	0.092	0.058	0.041	0.027	0.022	0.022
10	9.0 – 13.0	0.089 ± 0.193	0.161	0.107	0.067	0.063	0.038	0.039
11	13.0 – 20.0	0.243 ± 0.435	0.240	0.363	0.145	0.226	0.080	0.231

Before to compare with the models, a cross check with the B^0 lifetime...

Add OF+SF distributions and fit for τ_{B^0}

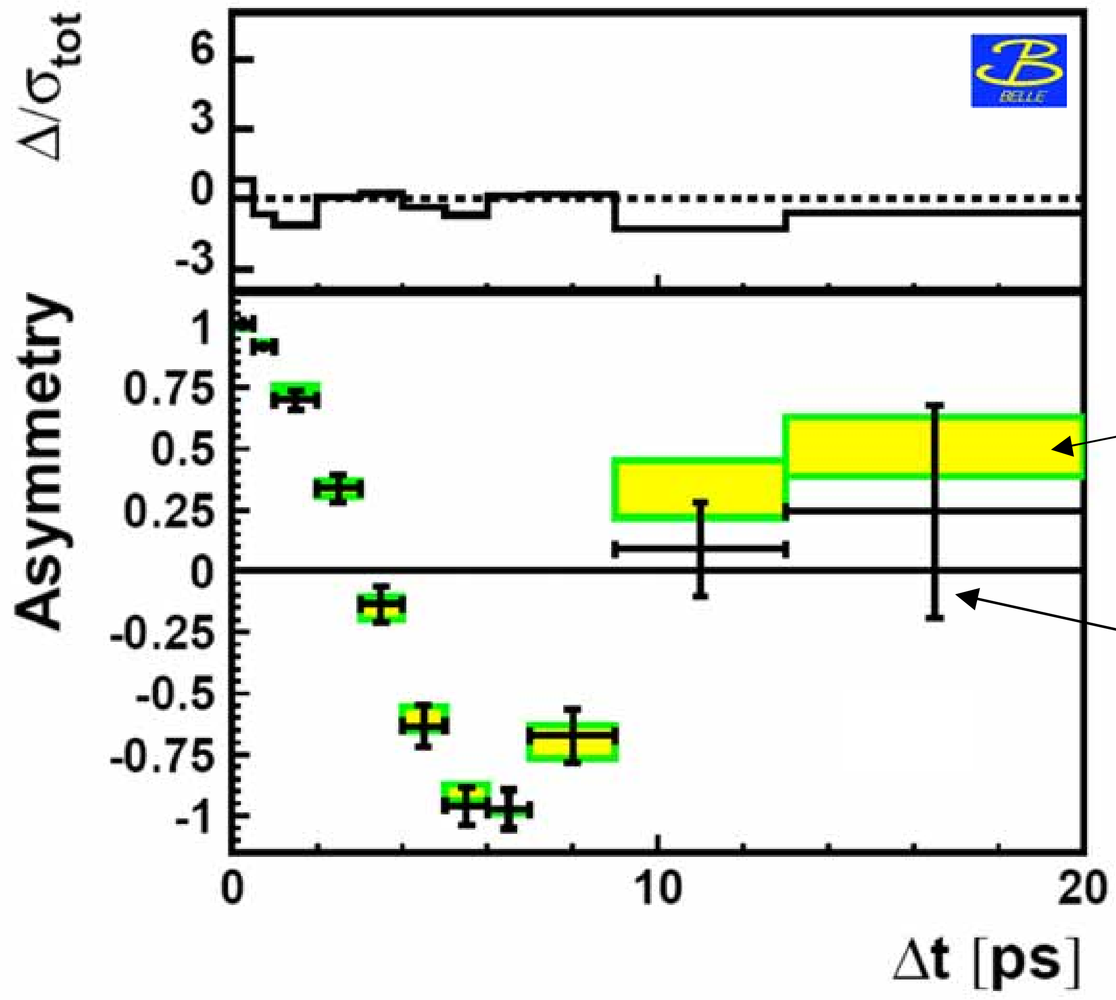


τ_{B^0} = 1.532±0.017(stat) ps => consistent with PDG value

χ^2 = 3/11 bins

Comparison with QM

Least-square fits including a term taking the world-average Δm_d into account. To avoid bias we discard BaBar and BELLE measurements, giving $\langle \Delta m_d \rangle = (0.496 \pm 0.013)\ ps^{-1}$



fitted value:

$\Delta m_d = (0.501 \pm 0.009)\ ps^{-1}$

$\chi^2 = 5.2$ (11 dof)

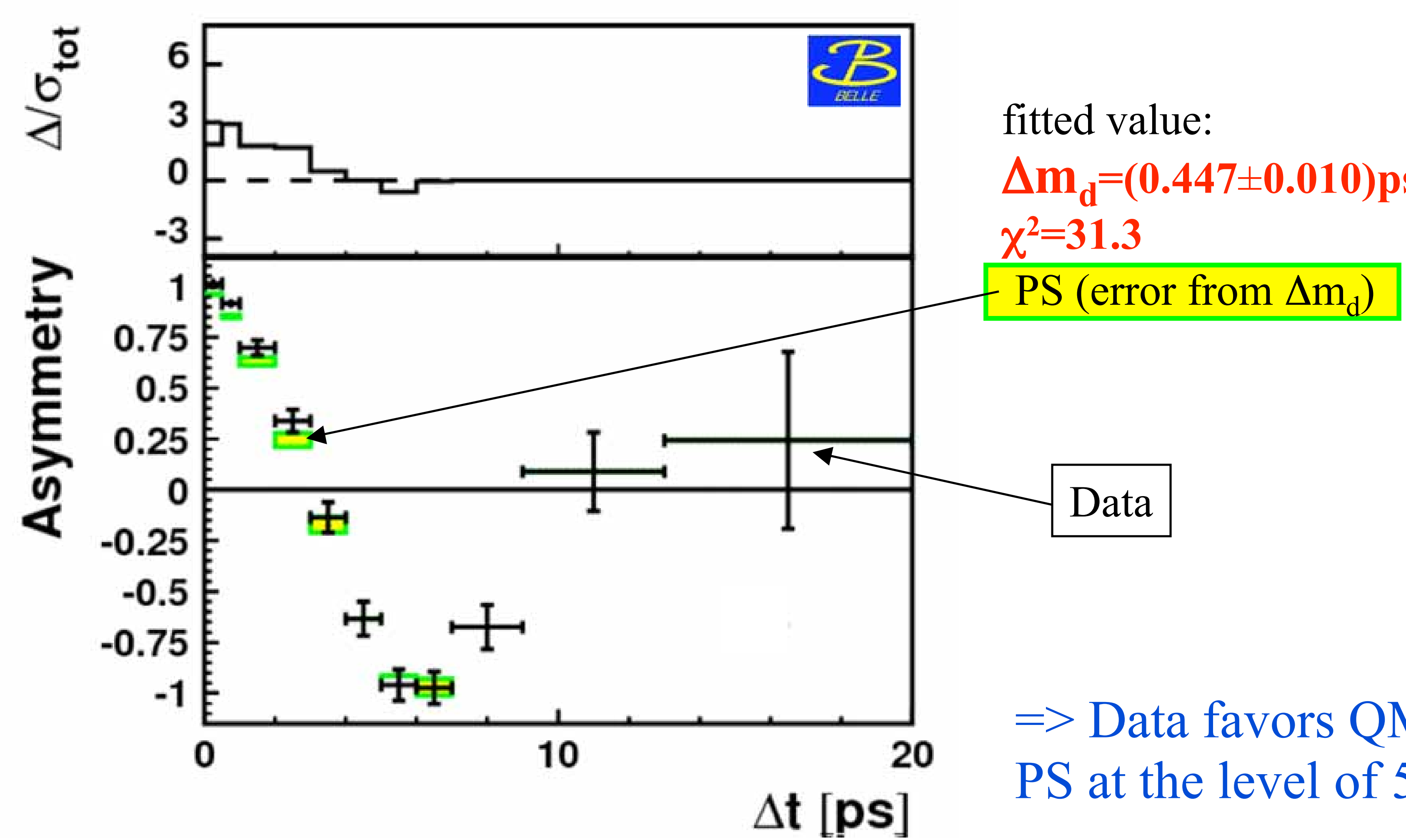
QM (error from Δm_d)

Data

=> Data fits QM

Comparison with PS model

Fit data to PS model, using the closest boundary. We conservatively assign a null deviation when data falls between boundaries



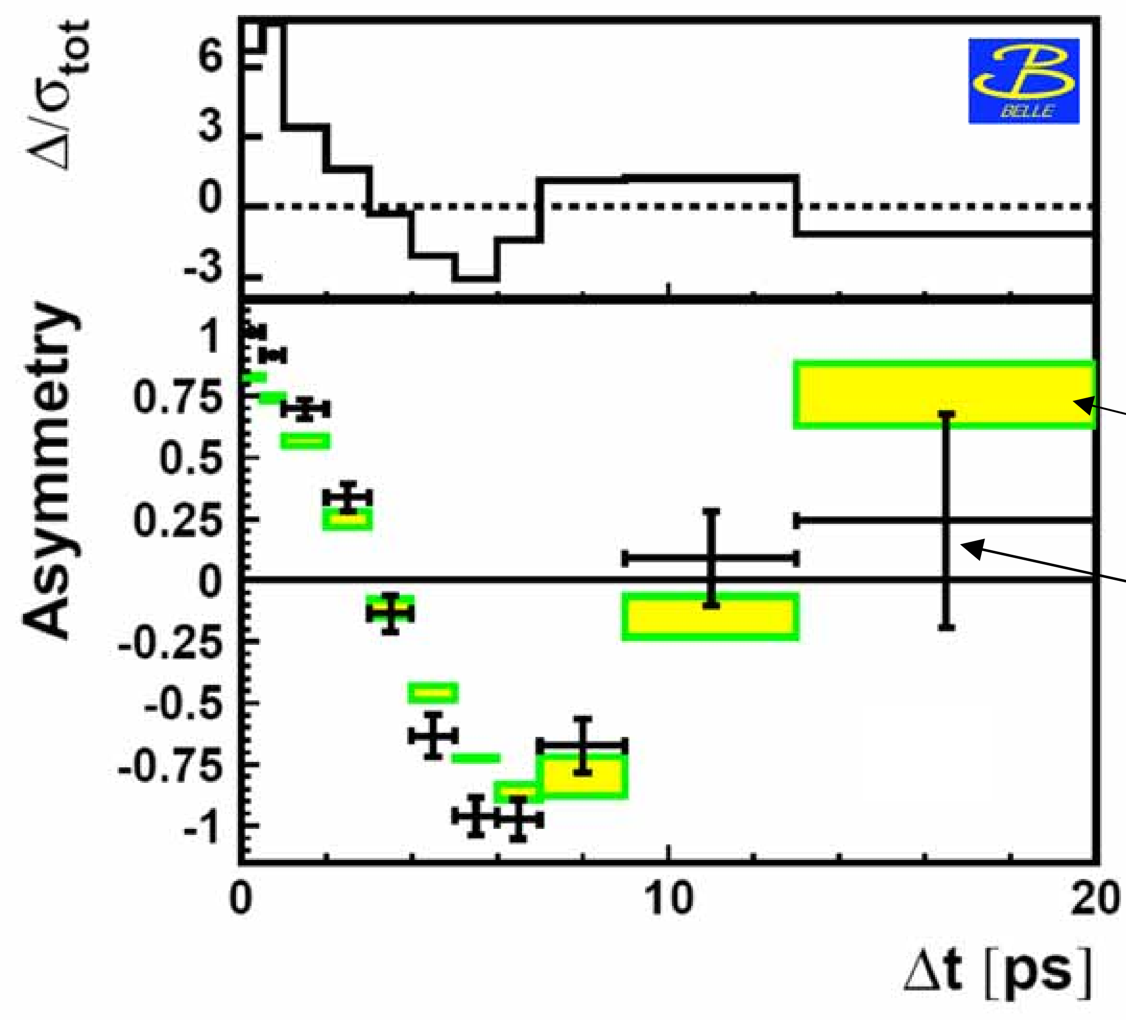
fitted value:

Δm_d=(0.447±0.010)ps^{-1}

χ^2=31.3

=> Data favors QM over PS at the level of 5.1σ

Comparison with SD model



fitted value:

Δm_d=(0.419±0.008)ps^{-1}

χ^2=174

SD (error from Δm_d)

Data

=> Data favors QM over SD model by 13σ.

Search for New Physics: Decoherence

Decoherent fraction into B^0, $\bar{B}^0$ by fitting $(1-\lambda_{B_d})A_{QM} + \lambda_{B_d} A_{SD}$

We obtain $\boldsymbol{\lambda_{B_d} = 0.029 \pm 0.057}$

=> consistent with no decoherence

Previous measurements in K^0 system:

•From CPLEAR measurement: Phys. Lett. B **422**, 339 (1998)

Bertlmann *et al.* Phys. Rev. D **60** 114032 (1999)

has deduced $\boldsymbol{\lambda_{K^0} = 0.4 \pm 0.7}$

•KLOE $\boldsymbol{\lambda_{K^0} = (\,0.10 \pm 0.22 \pm 0.04\,)\,10^{-5}}$

CONCLUSION

We have performed an experimental study of the EPR-type flavour entanglement in $\Upsilon(4s) \rightarrow B^0\bar{B}^0$ decays.

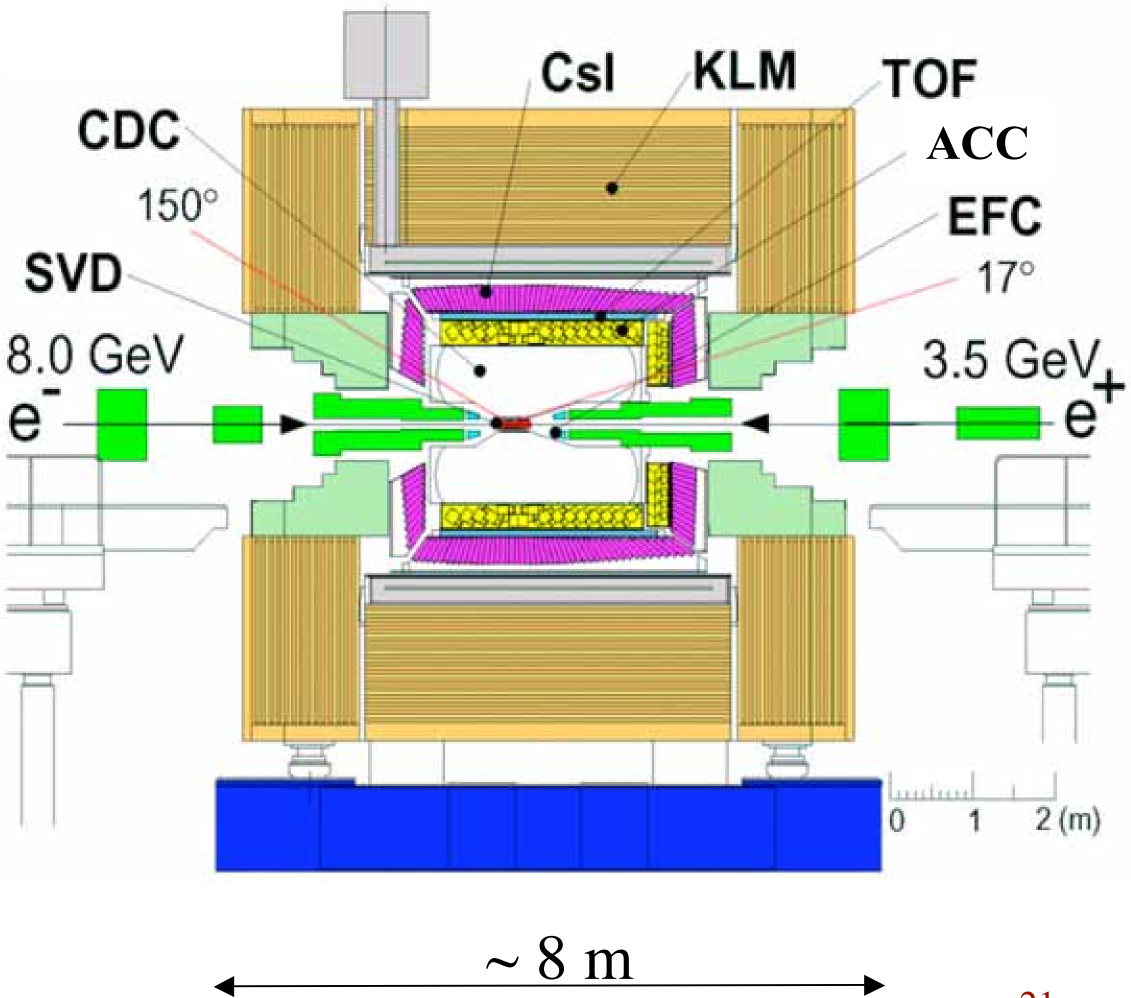
We have measured the time-dependent asymmetry due to flavour oscillation. The asymmetry has been corrected for the experimental effects and can be used directly to compare with the different theoretical models.

* The asymmetry is consistent with QM predictions
* The local realistic model of Pompili and Selleri is disfavoured at the level of 5.1σ.
* A model with immediate disentanglement into flavour eigenstates is excluded by 13σ.
•A decoherent fraction into flavour eigenstates is found to be 0.029 ± 0.057, consistent with no decoherence.

BACK UP
SLIDES

The Belle Detector

Silicon Vertex Detector SVD
resolution on $\Delta z \sim 100\ \mu m$
Central Drift Chamber CDC
$(\sigma Pt/Pt)^2 = (0.0019\ Pt)^2 + (0.0030)^2$
K/π separation :
dE/dx in CDC σdE/dx =6.9%
TOF σTOF = 95ps
Aerogel Cerenkov ACC
Efficiency = ~90%,
Fake rate = ~6% →3.5GeV/c
γ, e± : ECL (CsI crystals)
σE/E ~ 1.8% @ E=1GeV
e± : efficiency > 90%
~0.3% fake for p > 1GeV/c
K_L and μ± : KLM (RPC)
μ± : efficiency > 90%
<2% fake at p > 1GeV/c



this study considers
152 10^6 $B^0\overline{B}^0$ pairs

Decoherence

Decoherence in B^0, $\overline{B}^0$

$A = (1-\lambda)A_{QM}+\lambda A_{SD}$ => $\lambda_{B_d} = 0.029 \pm 0.057$

Previous mesurements in K^0 system:

•From CPLEAR measurement, PLB 422, 339 (1998) , Bertlmann *et al.* PRD **60** 114032 (1999) has deduced $\lambda_{K0} = 0.4 \pm 0.7$

•KLOE $\lambda_{K0} = (0.10 \pm 0.22 \pm 0.04)\ 10^{-5}$

P. Heberard's ζ parameter for decoherence in B_H, B_L :

$A = (1-\zeta)A_{QM}$ => $\zeta_{B_d} = 0.004 \pm 0.017$ (preliminary)

Previous mesurements in K^0 system:

•CPLEAR $\zeta_{K^0} = 0.13^{+0.16}_{-0.15}$

•KLOE $\zeta_{K^0} = 0.018 \pm 0.040 \pm 0.007$

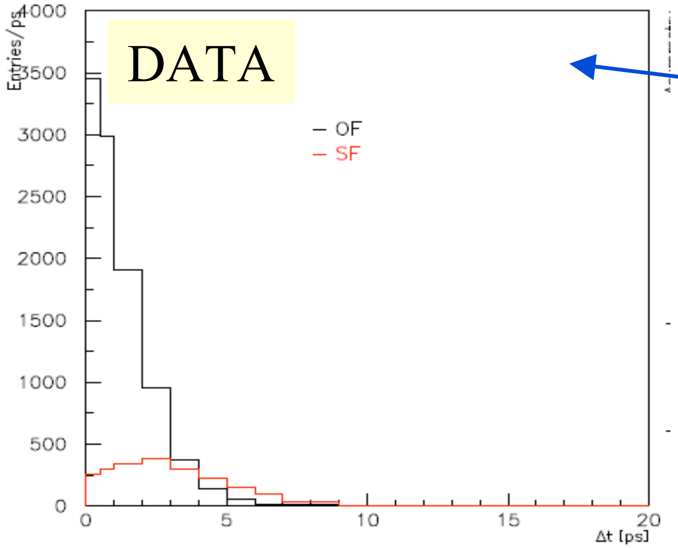
Event selection

Semileptonic B side:

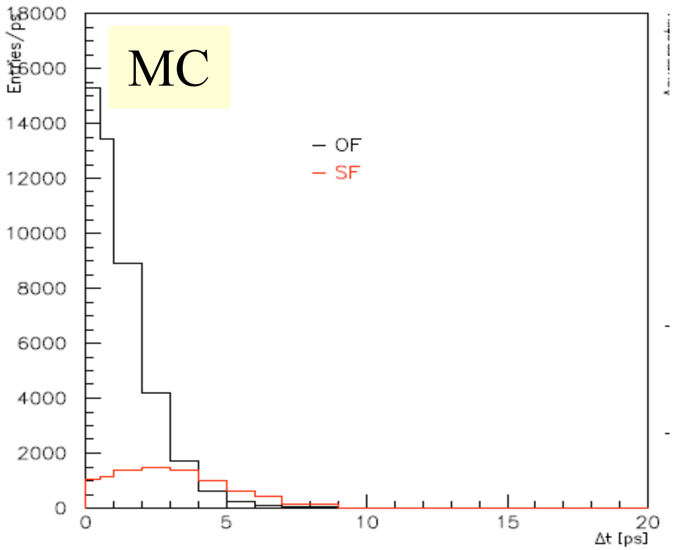
Variable	Cuts
P_{lepton}^{CMS}	$1.4GeV/c < P_{lepton}^{CMS} < 2.4GeV/c$
Slow π vertex constr. to B	$\chi^2/dof < 100$
K/π likelihood for π	$K3\pi$ mode: $Prob_{K/\pi} < 0.5$ $K\pi, K\pi\pi^0$ mode: $Prob_{K/\pi} < 0.3$
P_{π^0}	$P_{\pi^0} > 0.2GeV/c$
P_γ	$P_\gamma > 0.08\ GeV/c$
$P_{K,\pi}$ ($K3\pi$ mode)	$P_{K,\pi} > 0.2GeV/c$
Impact parameters	$\|dr_{IP}\| < 0.2$cm
$\cos(\theta_{B,D^*l})$	$\|\cos(\theta_{B,D^*l})\| < 1.1$
D^0 mass	$-37MeV/c^2 < M_{K\pi\pi^0} - M_{D^0} < 23MeV/c^2$ $-13MeV/c^2 < M_{K\pi,K3\pi} - M_{D^0} < 13MeV/c^2$
$M_{D^*} - M_{D^0}$	$144.4MeV/c^2 < M_{D^*} - M_{D^0} < 146.4MeV/c^2$
$P_{D^*}^{CMS}$	$P_{D^*}^{CMS} < 2.6GeV/c$
B^0 vertex	$\chi^2/dof < 75$
B_{tag} vertex	$\chi^2/dof < 75$

All other tracks are used to identify the flavor of the accompanying B.

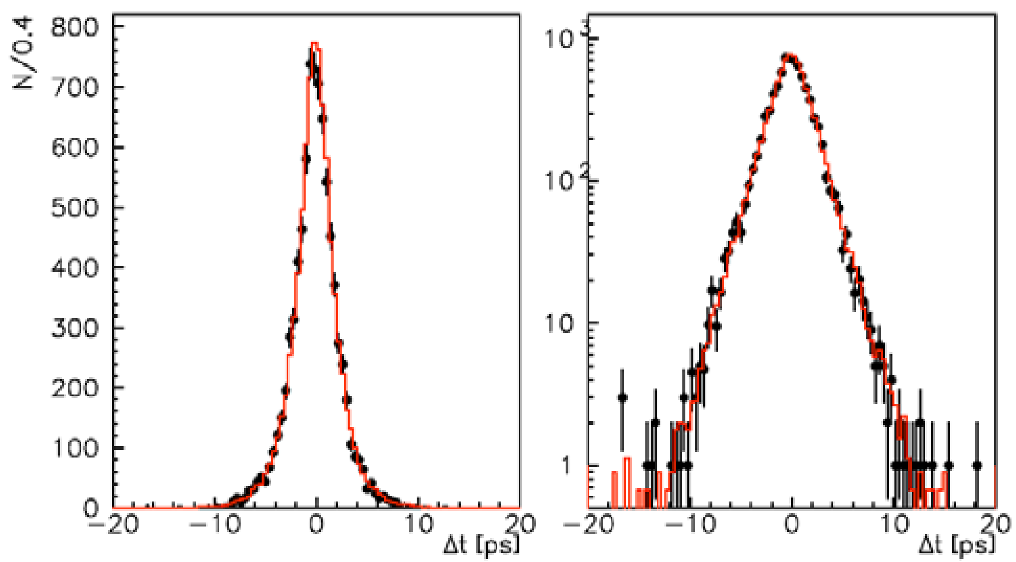
After event selection: MC vs Data



Total of 6718 (OF) and 1847 (SF) events selected



Data and MC (OF+SF)(Δt) distributions



Background and wrong flavour tags

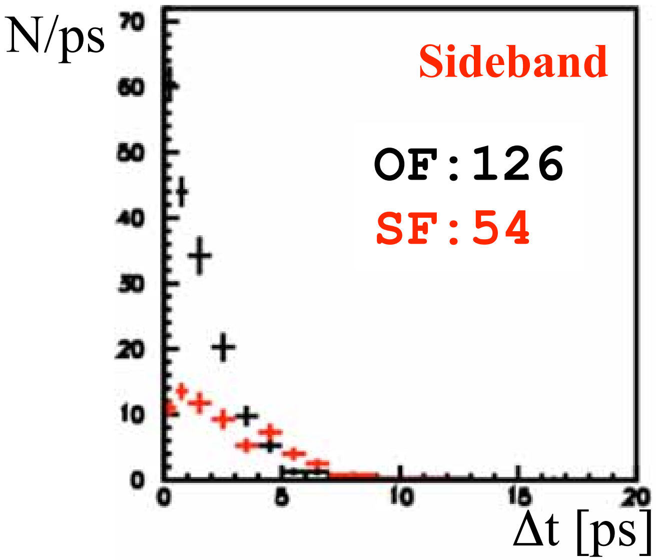
We correct bin by bin the OF and SF distributions for the following sources of background:

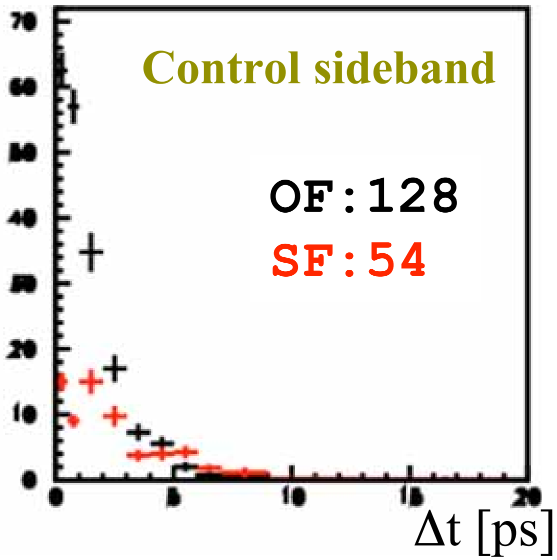
- Fake D*
- Uncorrelated D*-leptons, mainly D* from one B^0 and the lepton from the other
- $B^{\pm} \rightarrow D^{**}\, l\, \nu$

We also correct for a ~1.5% fraction of wrong flavour associations

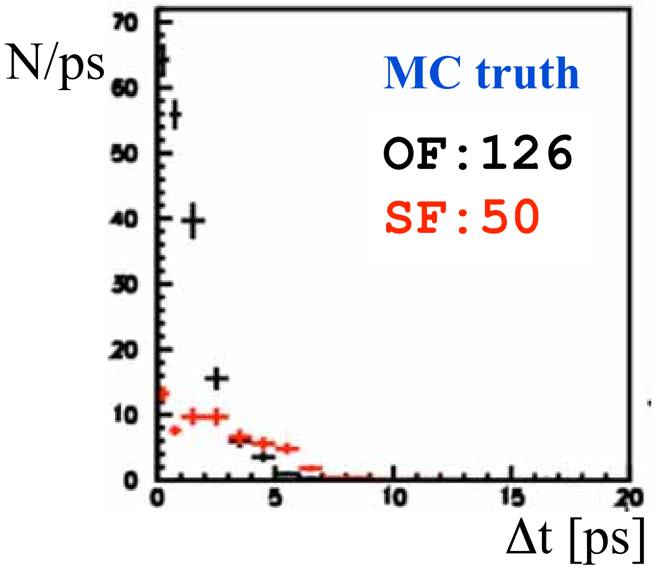
	OF events	SF events
Selected	6718	1847
Fake D^*	-126	-54
Uncor. D^*l	-78	-237
$B^{\pm}$	-254	-1
Wrg Flv	-22 +86	-86 +22
N events	6324	1619

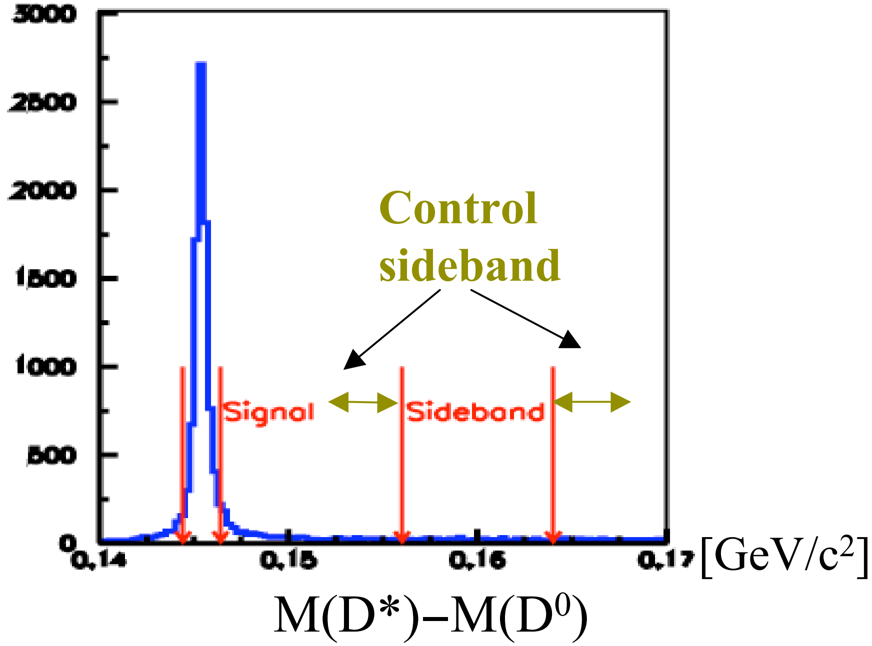
An example: background from fake D*





from M(D*)-M(D0) sideband.
Cross-check and systematics from control sideband.
Check with MC truth.



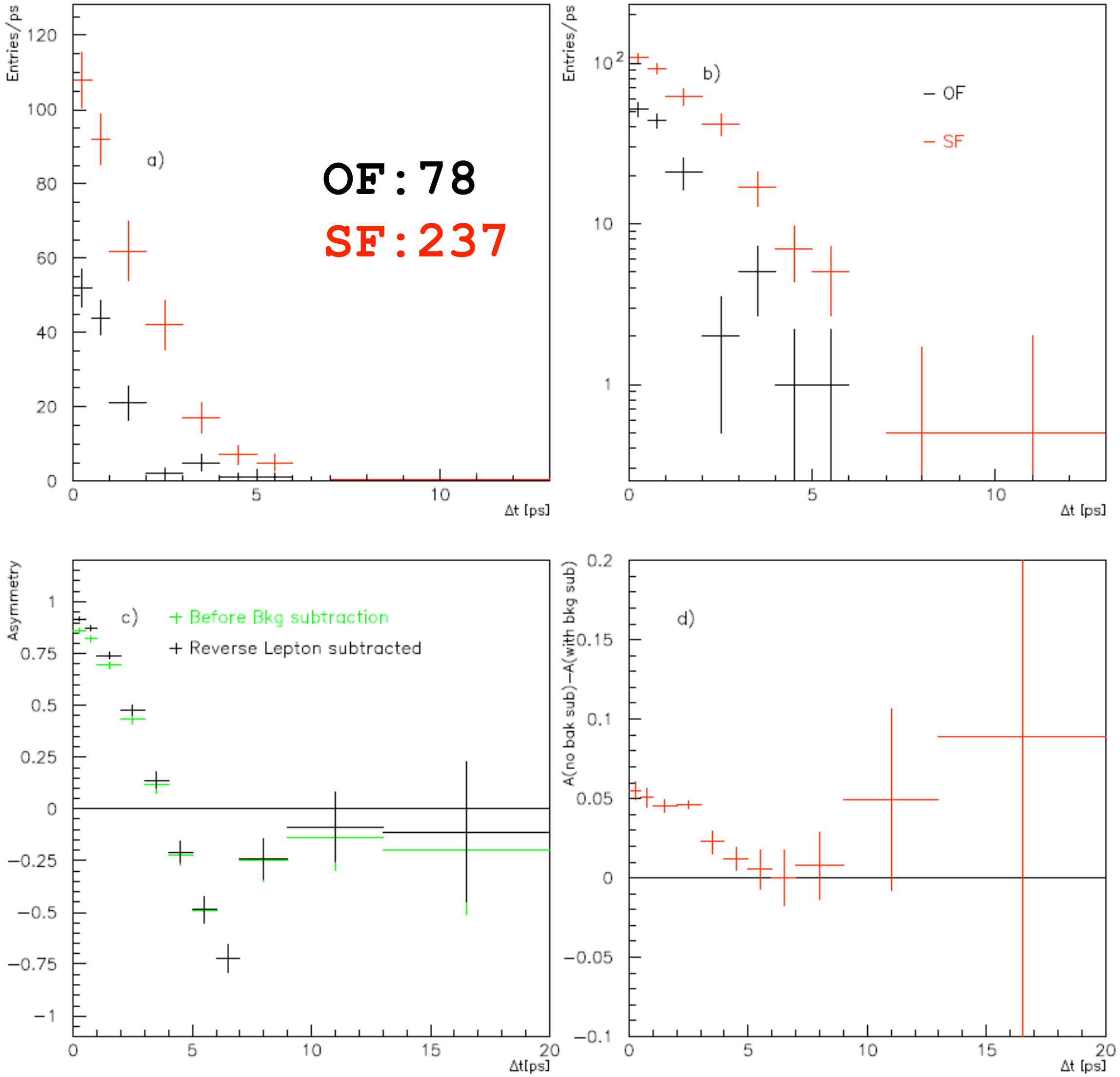


Background: Wrong D*l combination

• Mainly due to lepton & D* coming from different B^0.

•Estimated by reversed lepton momentum

•Systematics: moving the OF(SF) to +1(−1) σ and calculate the asymmetry variation.

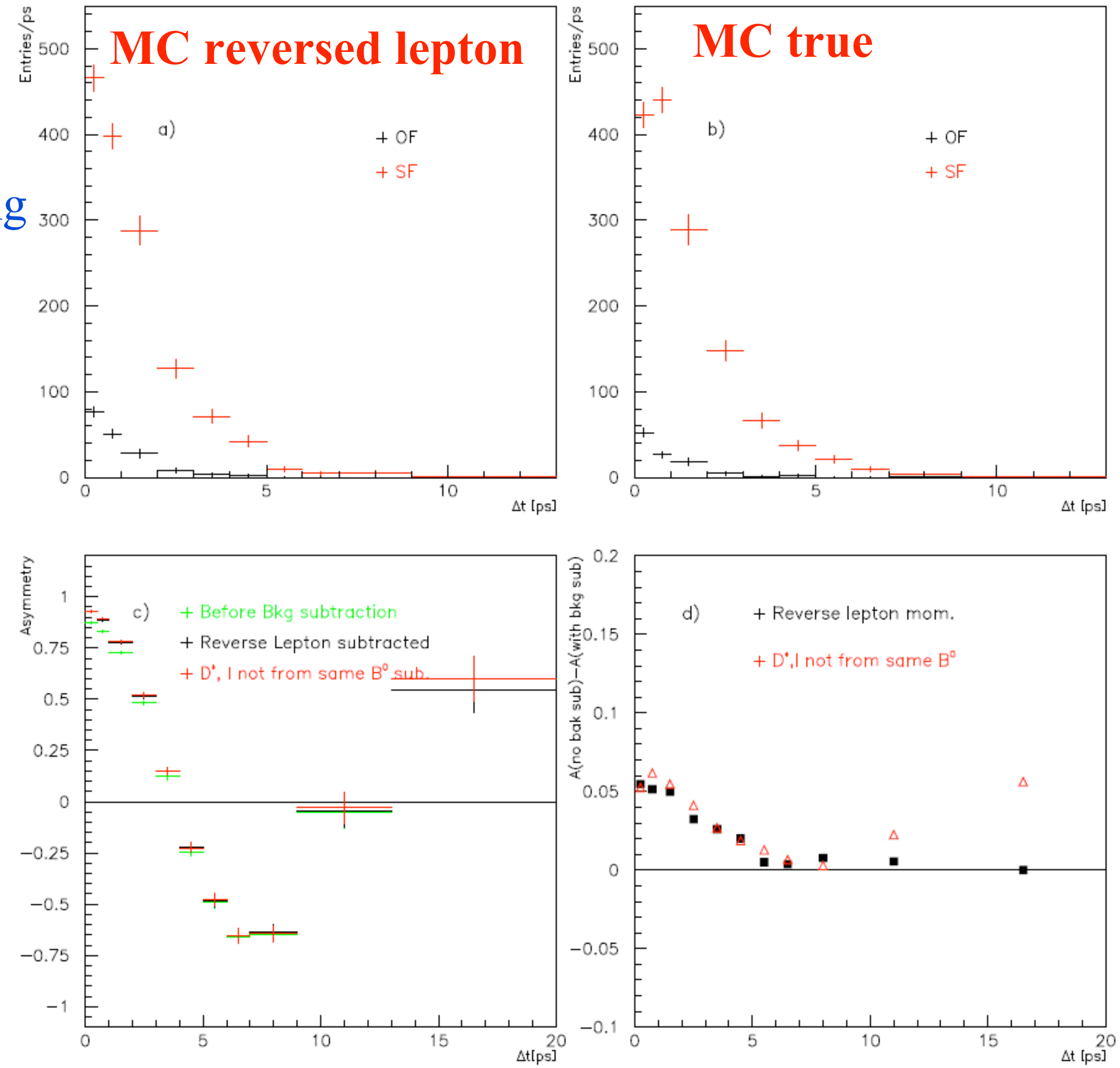


Wrong D*l: consistency checks

- Check: compare MC reversed lepton distributions with D*l not from same B (using MC truth info)

=> we get consistent results.

- The effect on the asymmetry is similar for MC and data.



Background: $B^{\pm} \to D^{**}\, \ell\, \nu$

$B^0 \to D^{**-}\, \ell^+ \nu$ has flavor mixing, signal

$B^+ \to \overline{D}^{**0}\, \ell^+ \nu$ background

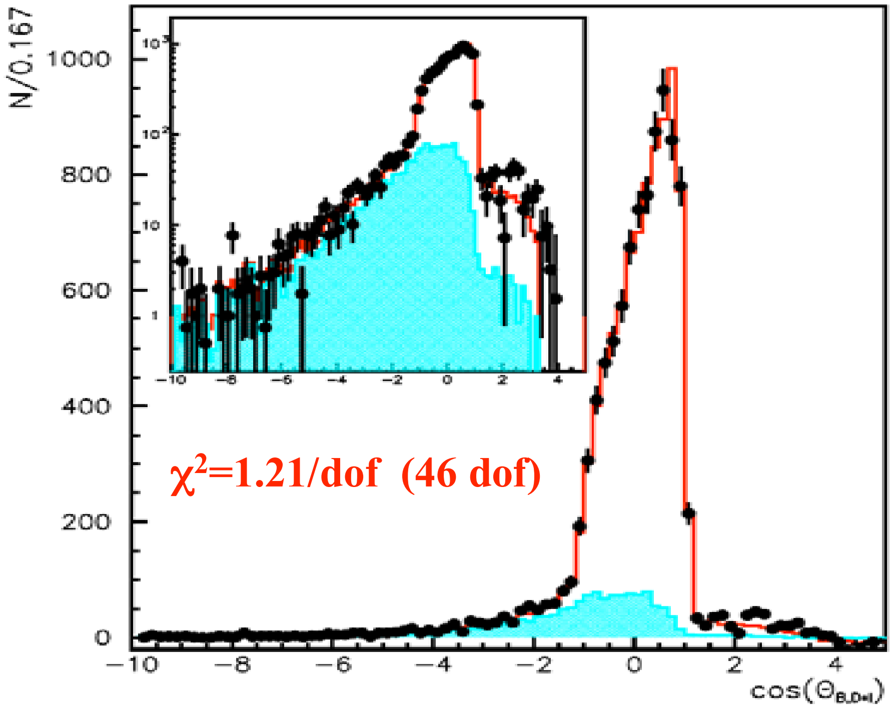
angle$(\vec{p}^{\,*}_B, \vec{p}^{\,*}_{D^*\ell})$

$$(E_B^* - E_{D^*l}^*)^2 - |p_B^*|^2 - |p_{D^*l}^*|^2 + 2|p_B^*||p_{D^*l}^*|\cos(\theta_{B,D^*l}) = M_\nu^2 \approx 0$$

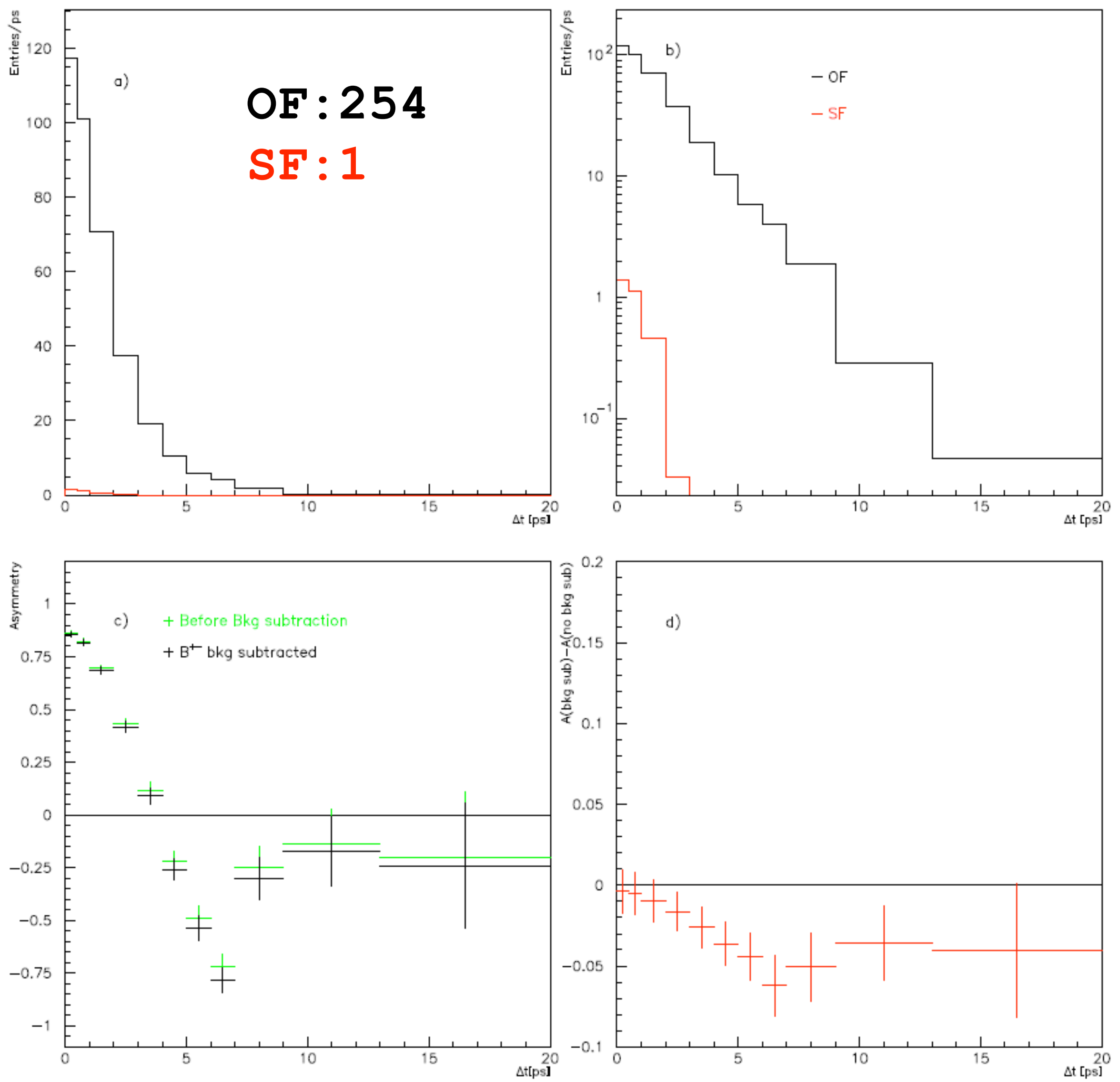
fit $\cos(\theta_{B,D^*\ell})$ distribution using MC shapes for $D^*\ell\nu$ and $D^{**}\ell\nu$

Systematics:

- 7% error on the fit
- 20% error on the ratio of the fractions of $B^0 \to D^{**}\ell\nu$ and $B^{\pm} \to D^{**}\ell\nu$



Background: $B^{\pm} \rightarrow D^{**}l\nu$

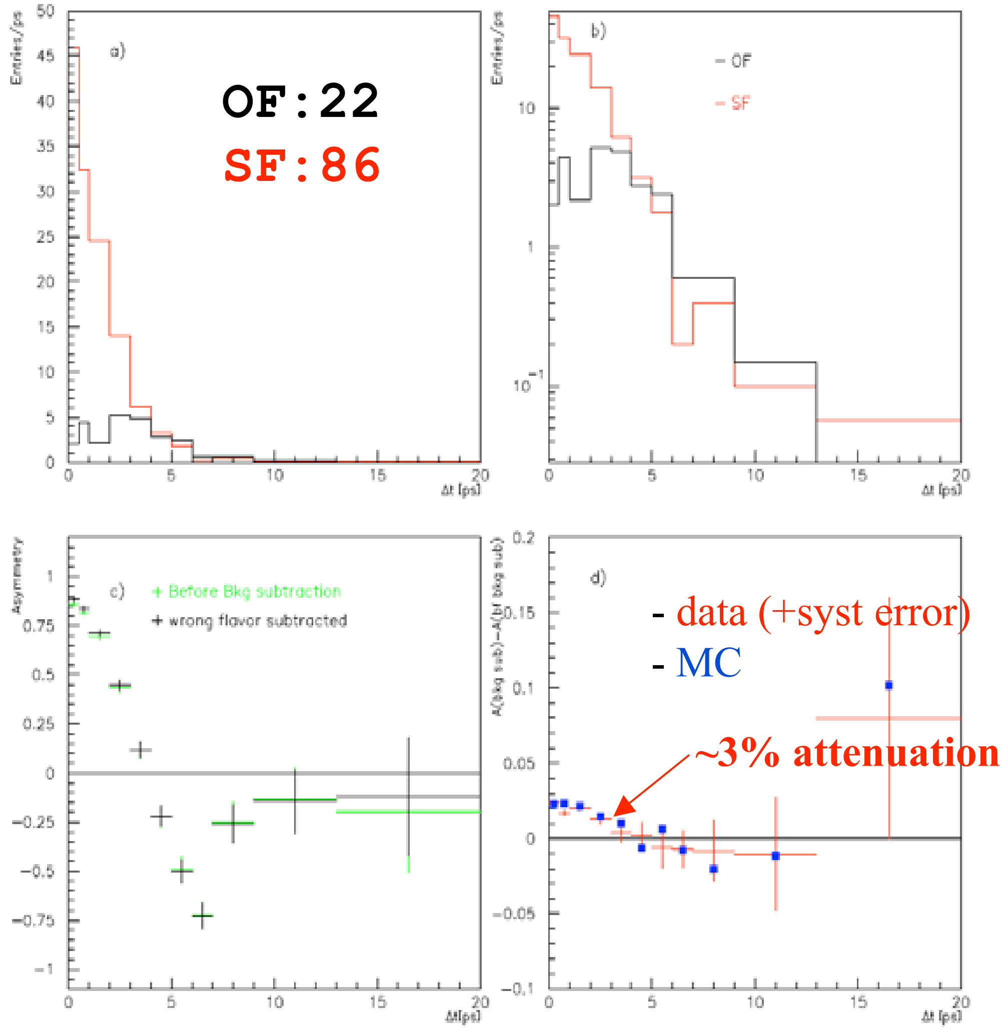


Wrong Flavor

- Use MC to estimate the wrong flavor
- High purity events: $\omega=0.015\pm0.006$
- Expect attenuation on the asymmetry:

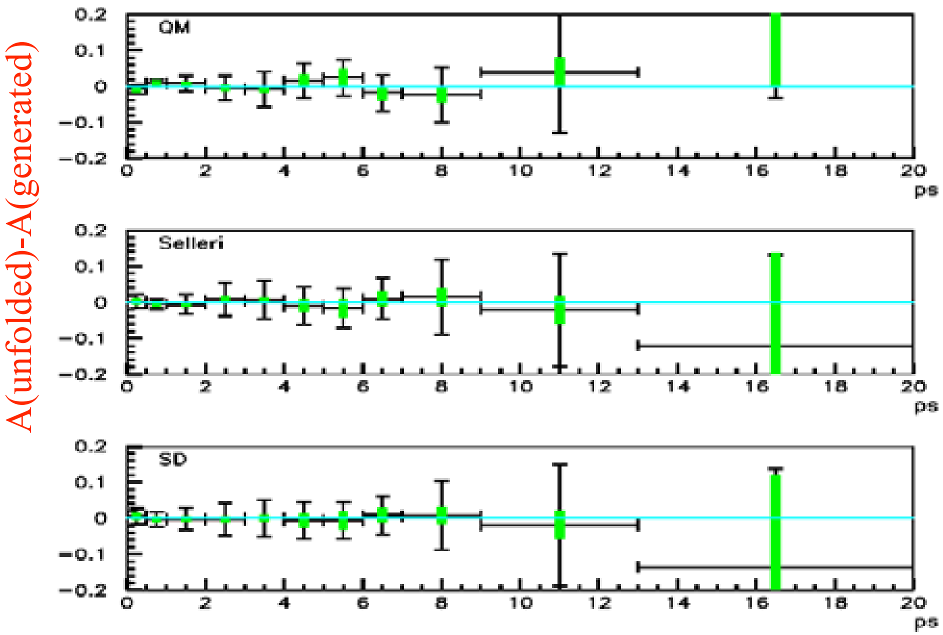
$$A(\Delta t) = (1-2\omega)\cos(\Delta m\Delta t)$$
$$= 0.970\cos(\Delta m\Delta t)$$

=> ~3% attenuation



Toy MC study of deconvolution

- Toy MC with parametrized resolution in Δz
- Simulate 400 "runs", each consists of
  - ~35000 "MC" events based on QM
  - ~7000 "Data" events based on QM, LR or SD
- Produce 2 unfolding matrices for SF and OF events from "MC"
- Deconvolution performed on "Data" separately for SF and OF.
- Correct for residual systematic effects.

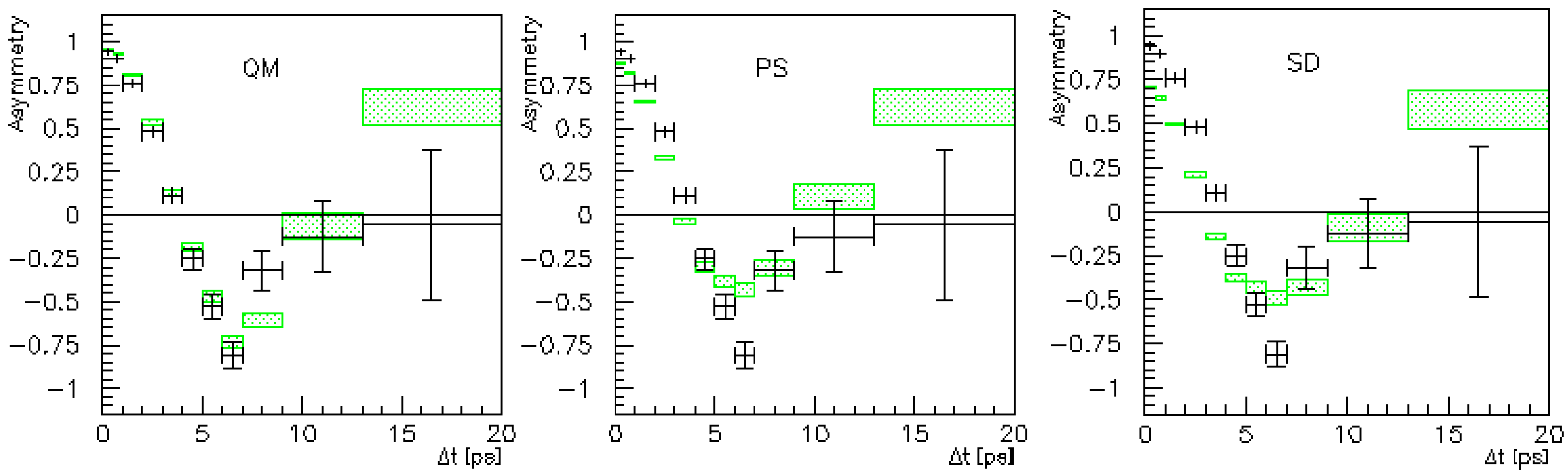


Δt bin	analysis	deconvolution	syst.
1	0.0130	0.0141	0.0192
2	0.0132	0.0089	0.0159
3	0.0165	0.0171	0.0238
4	0.0115	0.0293	0.0314
5	0.0147	0.0423	0.0448
6	0.0283	0.0493	0.0568
7	0.0289	0.0379	0.0476
8	0.0465	0.0251	0.0528
9	0.0539	0.0221	0.0583
10	0.0995	0.0389	0.1069
11	0.2802	0.2311	0.3632

Cross check: Forward Test

At this stage, one can compare data with MC prediction for QM, LR and SD results.

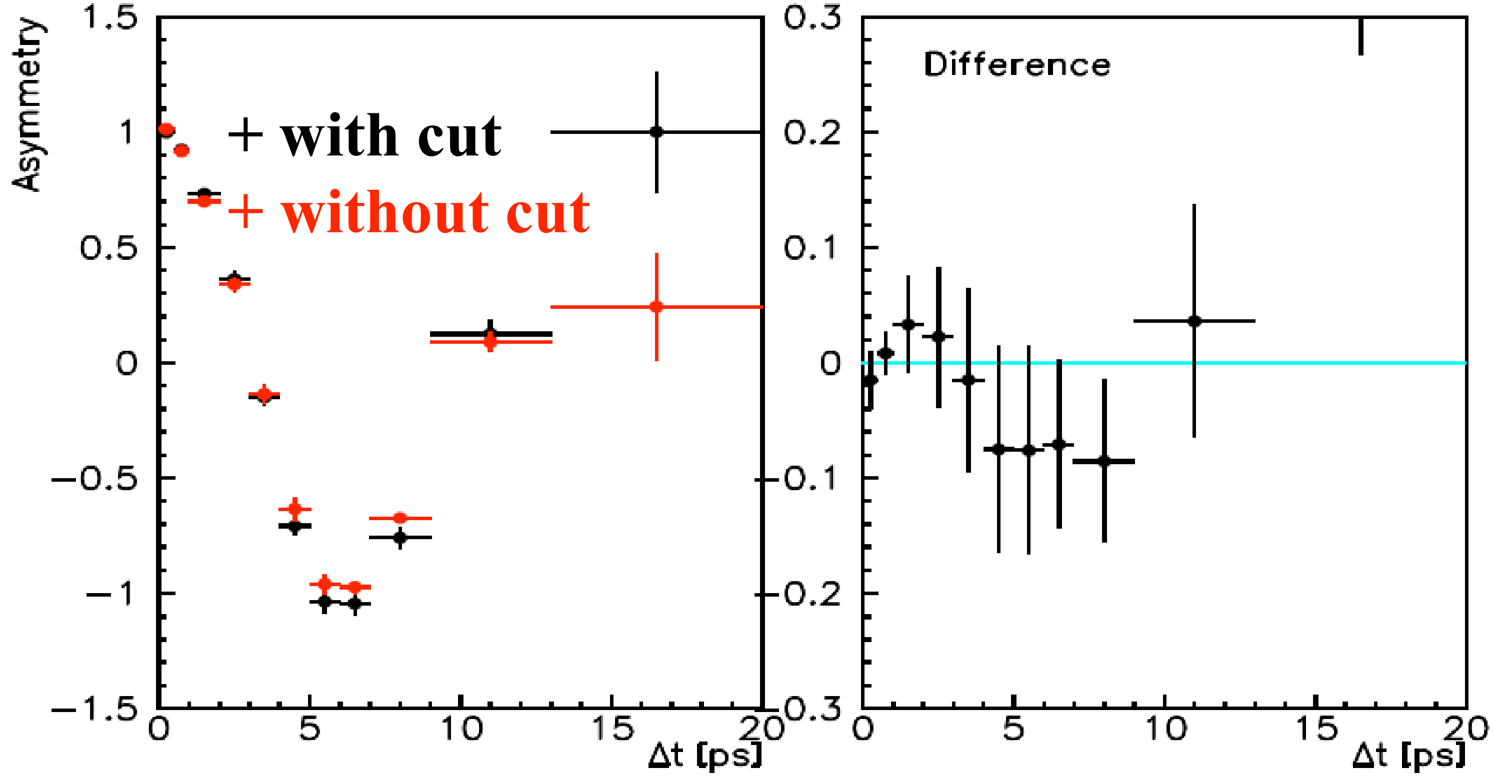
Since our MC is generated with QM correlation, we re-weight each event to produce the prediction of PS and SD models.



Δm is fixed. The result favors QM

Cross check: extra Δz resolution cut

Select events with better Δz resolution by adding a cut $\sigma(V_z) < 100\ \mu m$ cut on both B decay vertices. This discards ~18% of the events.

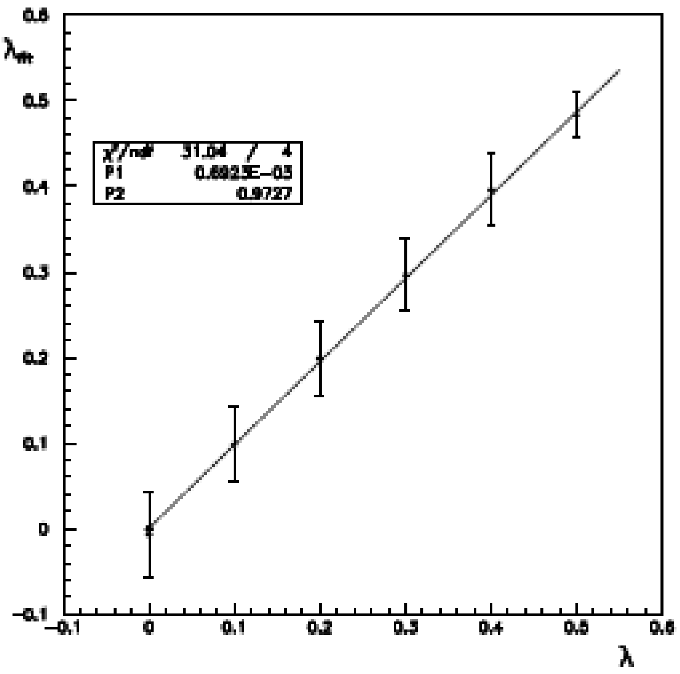


=> results are consistent

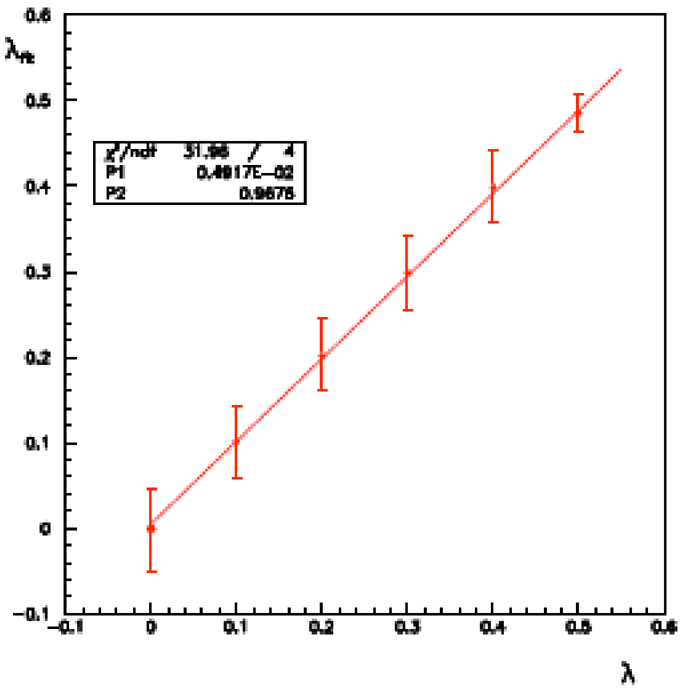
Sensitivity to λ

Toy MC study of sensitivity to decoherence. Fit of $(1-\lambda)A_{QM} + \lambda A_{SD}$

λ from fit vs λ generated



using corrected data



using raw data

Sensitivity to Δm

Fitted Δm vs generated