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

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# The EPR argument (1935)

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## 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)

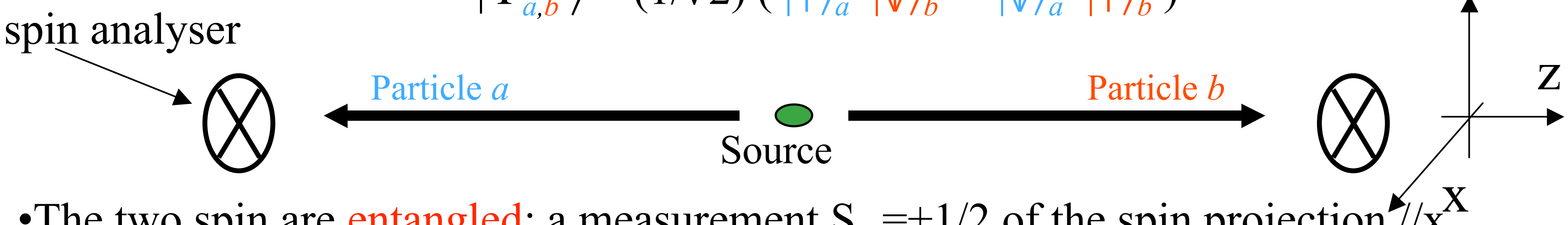
In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by 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.

- Definition of "element of reality". A "complete theory" must contain a representation for each element of reality;
- EPR consider an "entangled system" of two particles and the measurement of two non-commuting observables (position and momentum);
- Entanglement is used 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 : 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 the problem ?
- 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.

# Bell (1964), QM vs local models,...

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)).

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).

# Study of $\Upsilon(4s) \to B^0 \overline{B}^0$

The $\Upsilon(4s) \to B^0 \overline{B}^0$ is another case of entangled system: the pair flavour wave function is

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

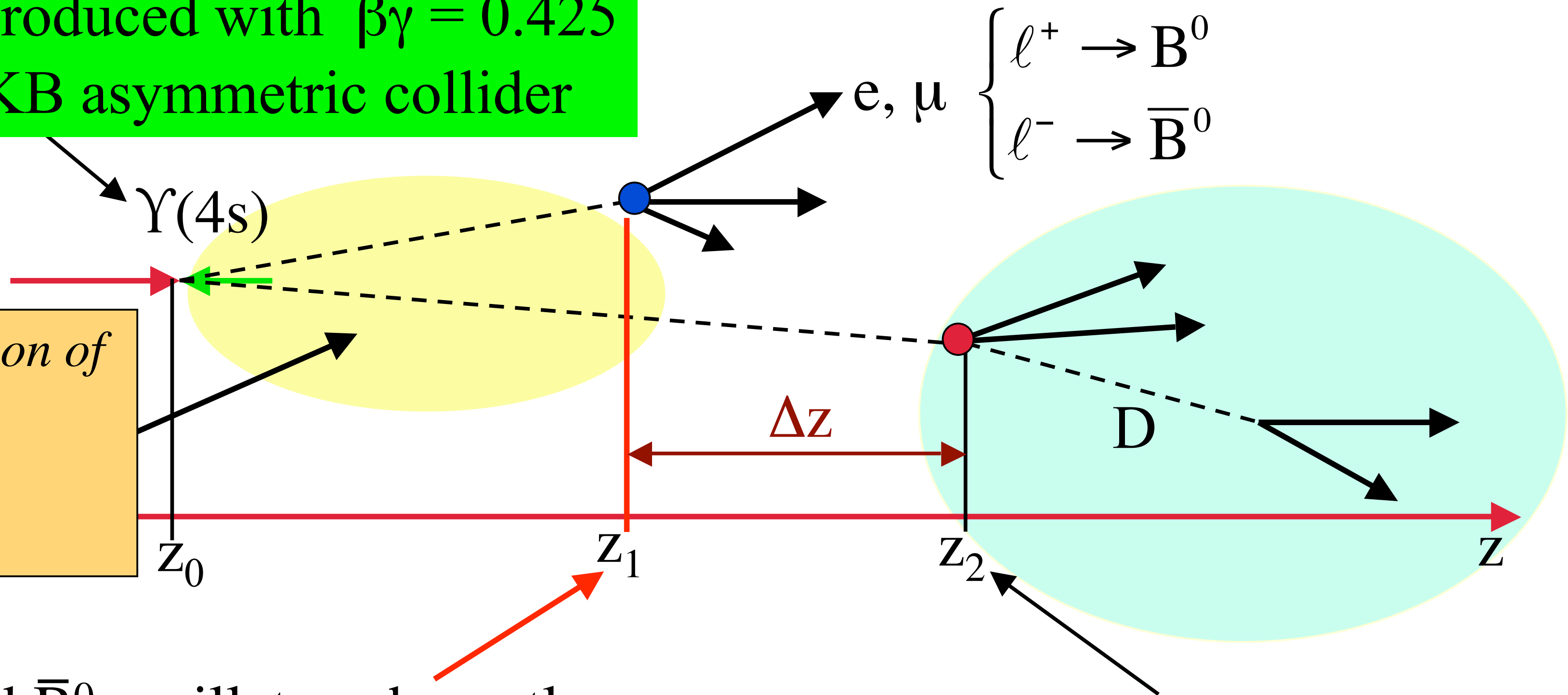
decays occurring at the same proper time are fully correlated: the flavor-specific decay of one meson fixes the (previously undetermined) flavour of the other meson.

$\Rightarrow$ we use the KEKB / BELLE data to explore for the first time this sector

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

$\Upsilon(4s)$ produced with $\beta\gamma = 0.425$ by KEKB asymmetric collider

*QM: region of $B^0$ & $\overline{B}^0$ coherent evolution*




$B^0$ 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 $\Delta z$ is available !

# Predictions from QM for entangled pairs

Time ($\Delta t$)-dependent decay rate into two Opposite Flavour (OF) states

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

$\Delta m_d$ is the mass difference of the two mass eigenstates

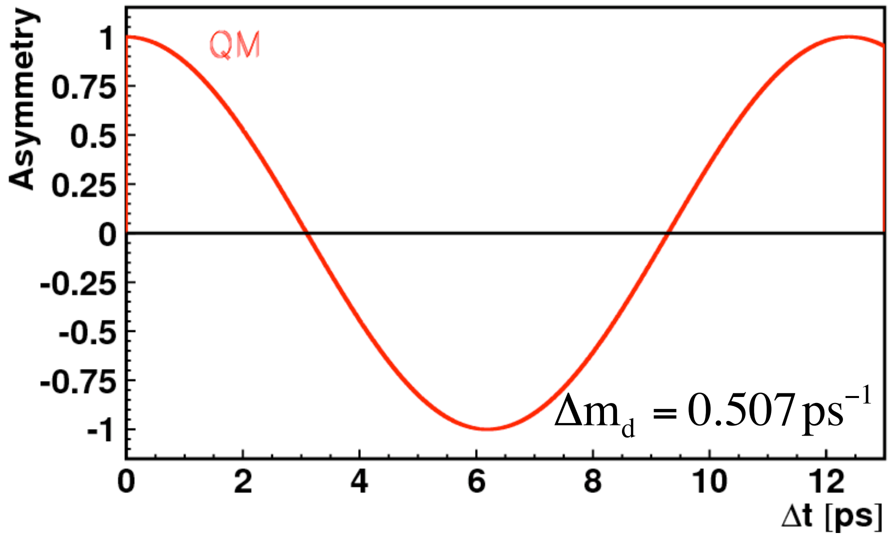
idem, into two Same Flavour (SF) states

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

=> 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" (hiddden variables)

$\left.\begin{array}{l}\lambda_1 : \text{CP} = +1 \text{ or } -1 \\ \lambda_2 : \text{Flavour} = +1 \text{ or } -1\end{array}\right\}$ => 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)

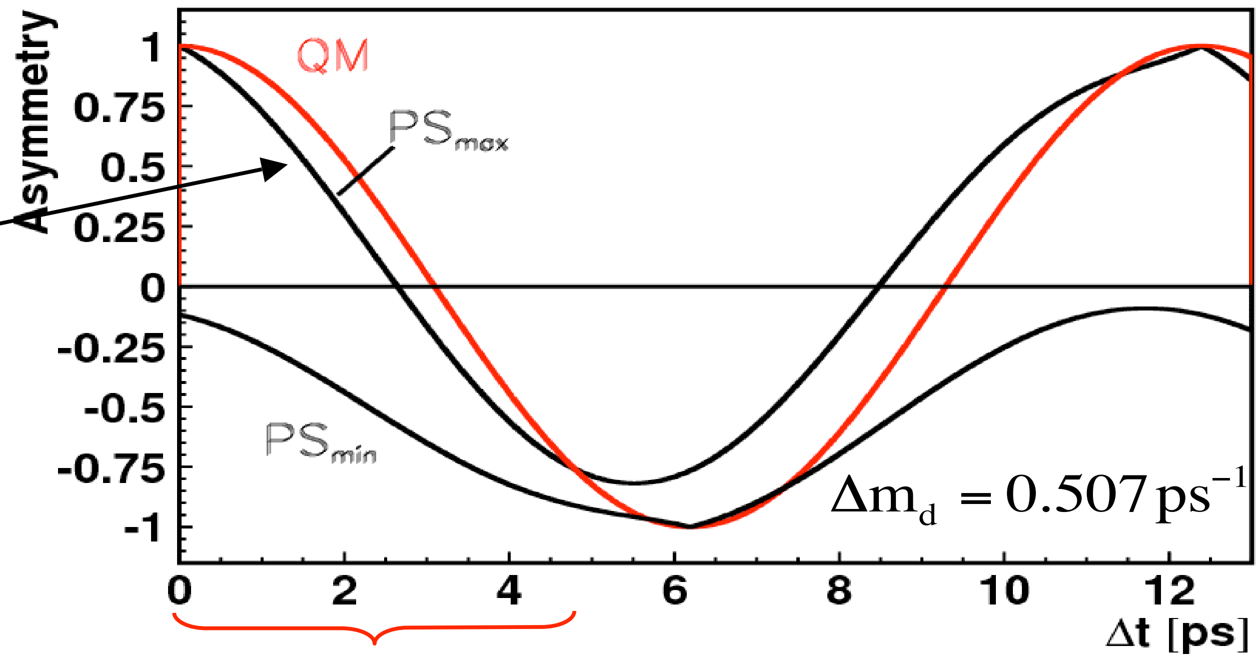
=> analytical expressions for A corresponding to the limits. The Amax is

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

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

$\neq$ QM

Only $\Delta t$ is known: need to integrate over $t_{min}$




$A_{QM} > A_{PS}$ in the $\Delta t$ region below ~5 ps

# Spontaneous immediate Disentanglement (SD)

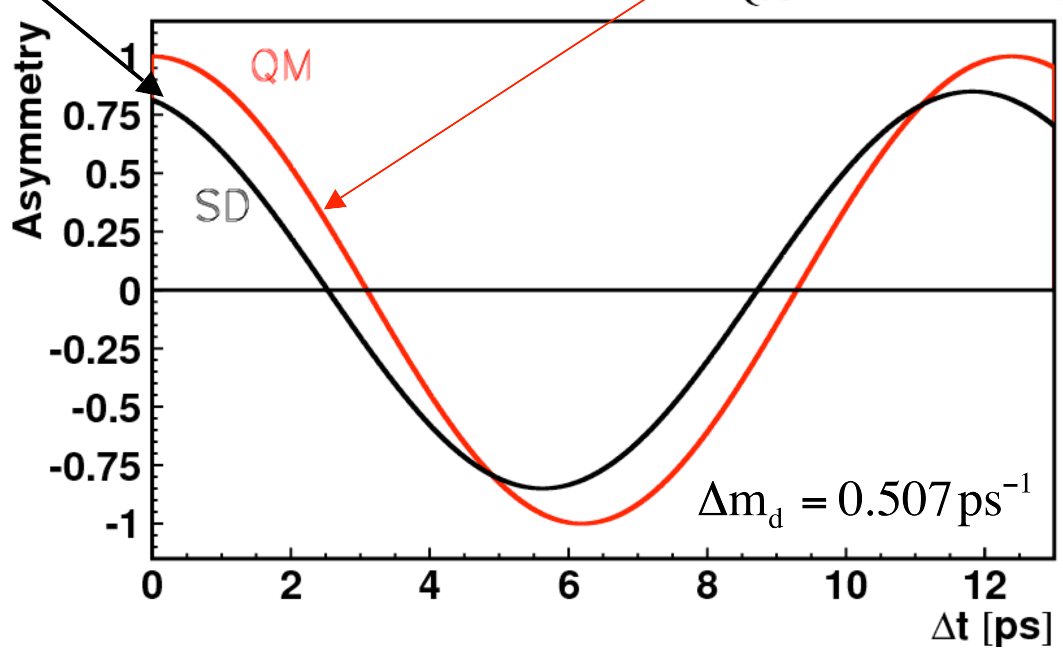
Just after the decay into opposite flavor states, we considers an independent evolution for the $B^0$ pair

$\neq$ QM

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

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 $\Delta t$) 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

# 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 $\sigma dE/dx = 6.9\%$**

**TOF $\sigma TOF = 95ps$**

**Aerogel Cerenkov ACC**

**Efficiency = ~90%,**

**Fake rate = ~6% → 3.5GeV/c**

**γ, e± : ECL (CsI crystals)**

**$\sigma E/E \sim 1.8\%$ @ E=1GeV**

**e± : efficiency > 90%**

**~0.3% fake for p > 1GeV/c**

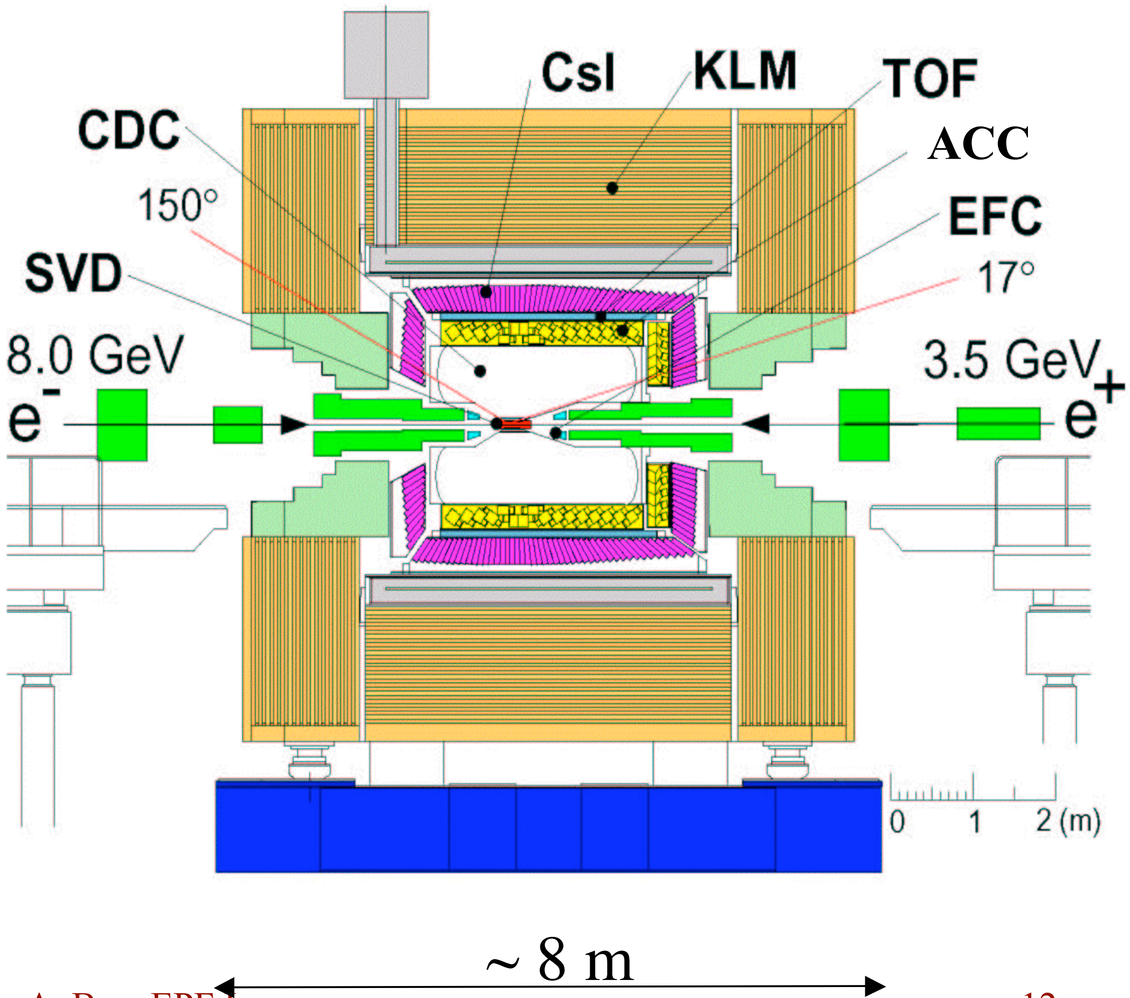
**$K_L$ and μ± : KLM (RPC)**

**μ± : efficiency > 90%**

**<2% fake at p > 1GeV/c**

this study considers

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



# Event selection and tagging

* First B measured via

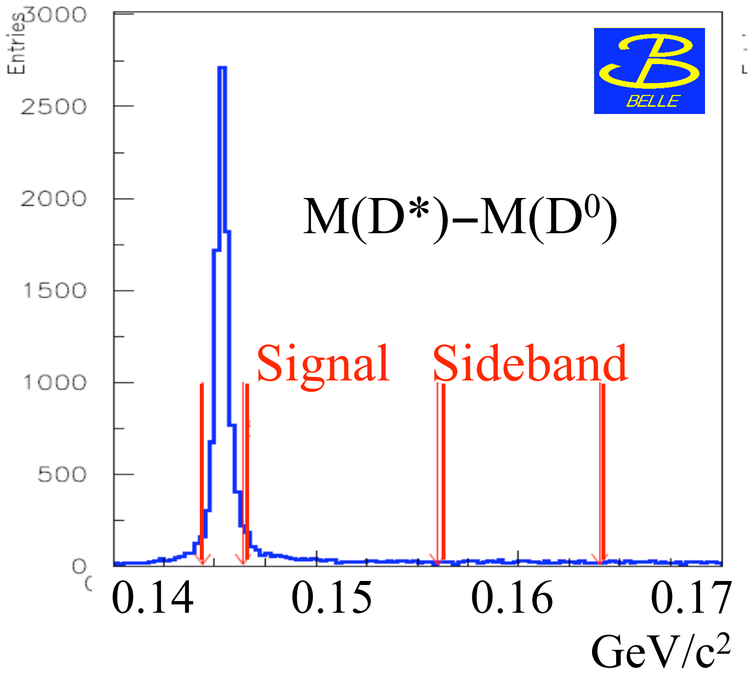
$$B^0 \to D^{*-}\ell^+\nu$$

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

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

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

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

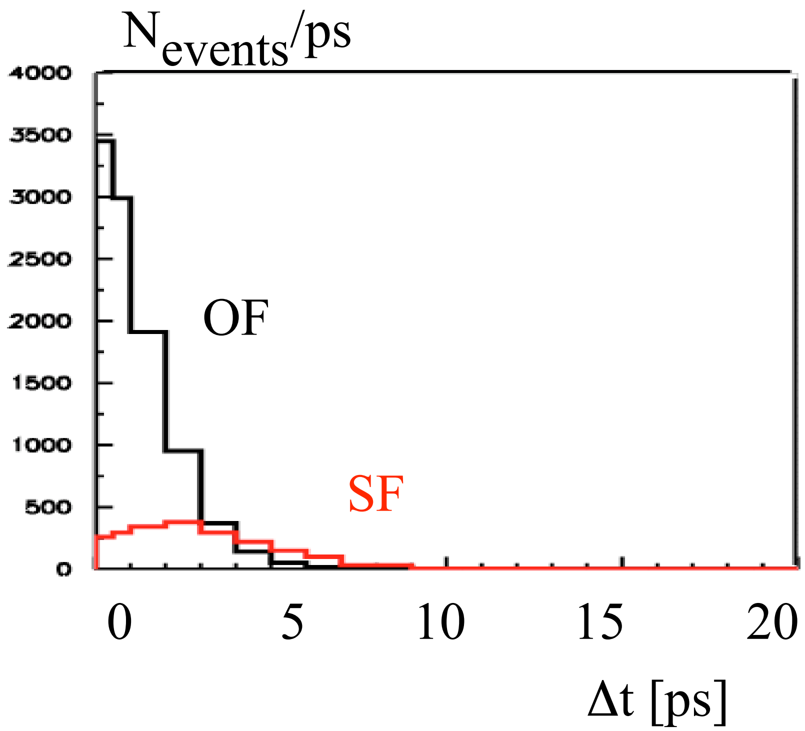



* All the remaining tracks are used to guess the flavour of second B, from the standard Belle flavour tagging procedure. We select the best purity subset, from semileptonic decays

$$B \to X\ell\nu$$

# Event selection and tagging

After selection, we obtain 6718 OF and 1847 SF events.
The $\Delta z$ is obtained from track fit of the two vertices and converted into a $\Delta t$ value.
We obtain the OF and SF distributions, with 11 variable-size bins (to account to the fast falling statistics)




| $\Delta t$ bin | window [ps] |
|---|---|
| 1 | 0 - 0.5 |
| 2 | 0.5 - 1 |
| 3 | 1 - 2 |
| 4 | 2 - 3 |
| 5 | 3 - 4 |
| 6 | 4 - 5 |
| 7 | 5 - 6 |
| 8 | 6 - 7 |
| 9 | 7 - 9 |
| 10 | 9 - 13 |
| 11 | 13 - 20 |

# Background and wrong flavour tags

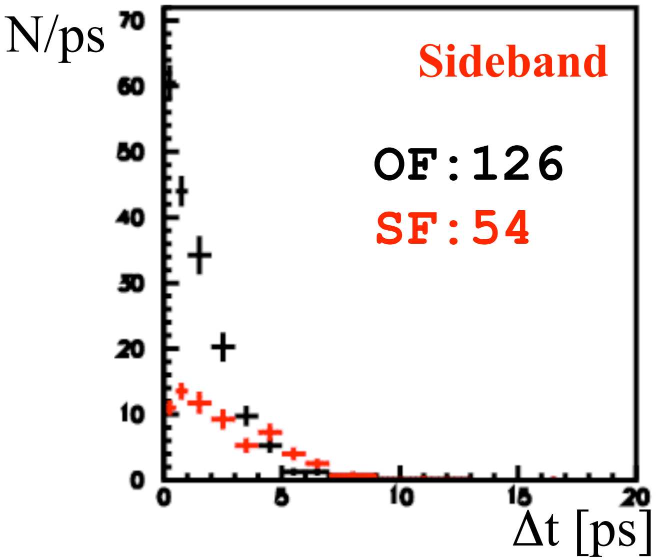
We correct bin by bin the OF and SF distributions for the following sources of background:

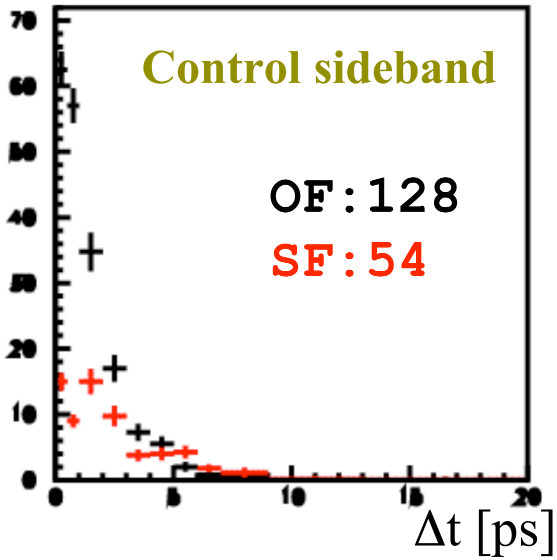
- Fake D*
- Uncorrelated D*-leptons, mainly D* from one $B^0$ and the lepton from the other
- $B^{\pm} \rightarrow D^{**}\, l\, \nu$

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

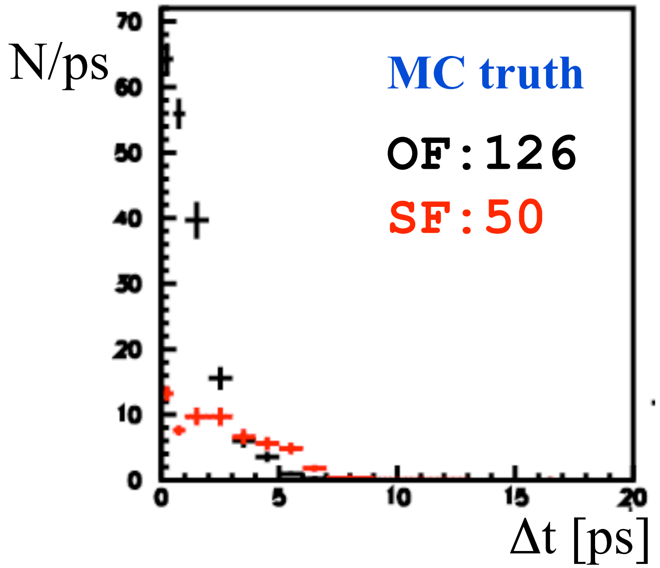
| | OF events | SF events |
|---|---|---|
| Selected | 6718 | 1847 |
| Fake $D^*$ | -126 | -54 |
| Uncor. $D^*l$ | -78 | -237 |
| $B^{\pm}$ | -254 | -1 |
| Wrg Flv | -22 +86 | -86 +22 |
| N events | 6324 | 1619 |

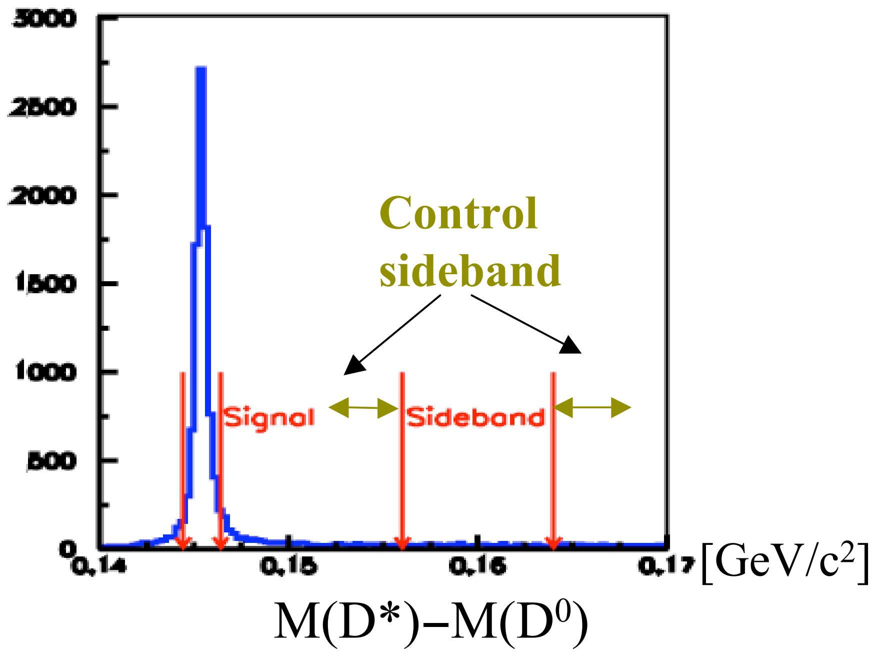
# An example: background from fake D*



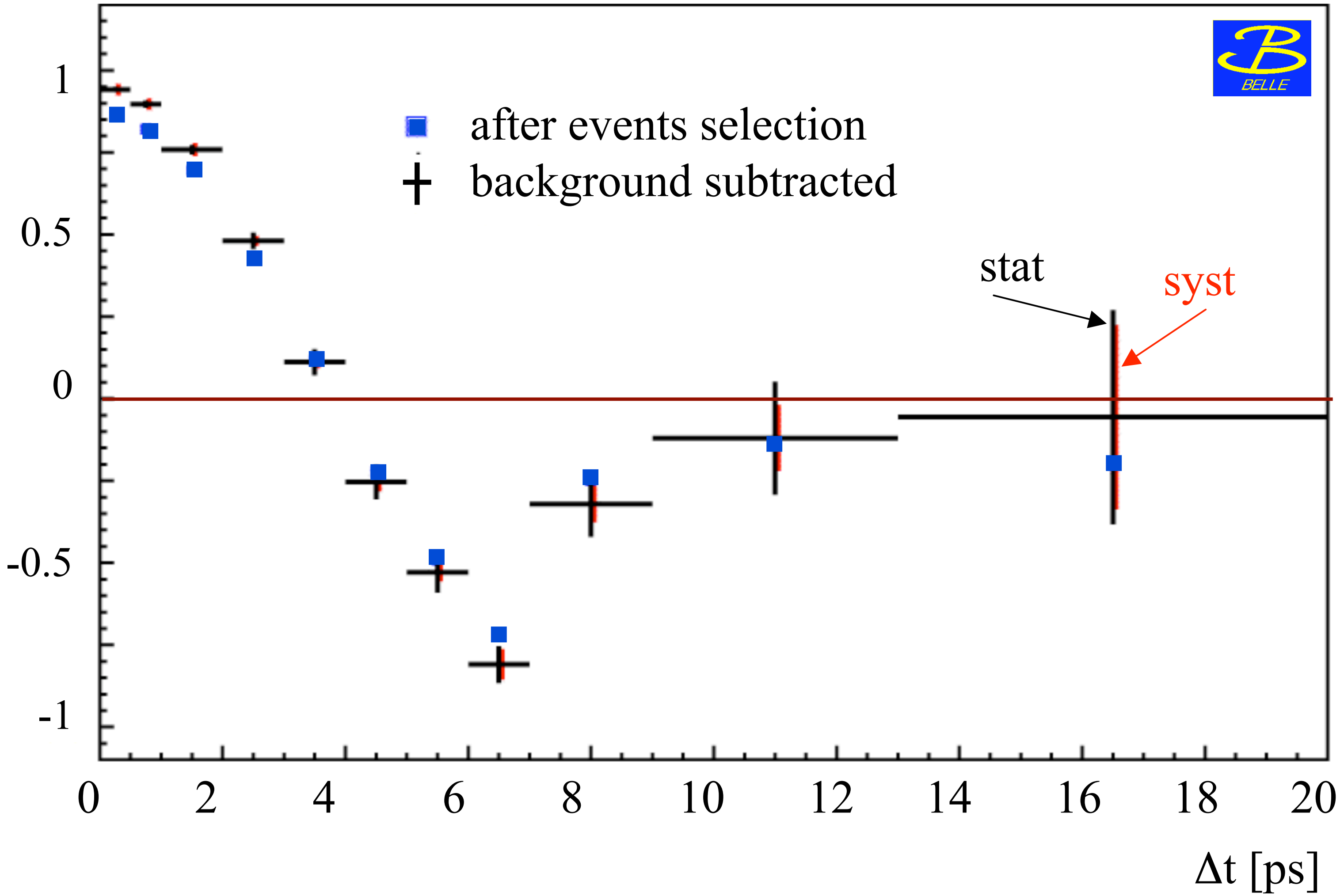




from M(D*)-M(D0) sideband.
Cross-check and systematics from control sideband.
Check with MC truth.



# Time-dependent asymmetry before and after background subtraction



# 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).

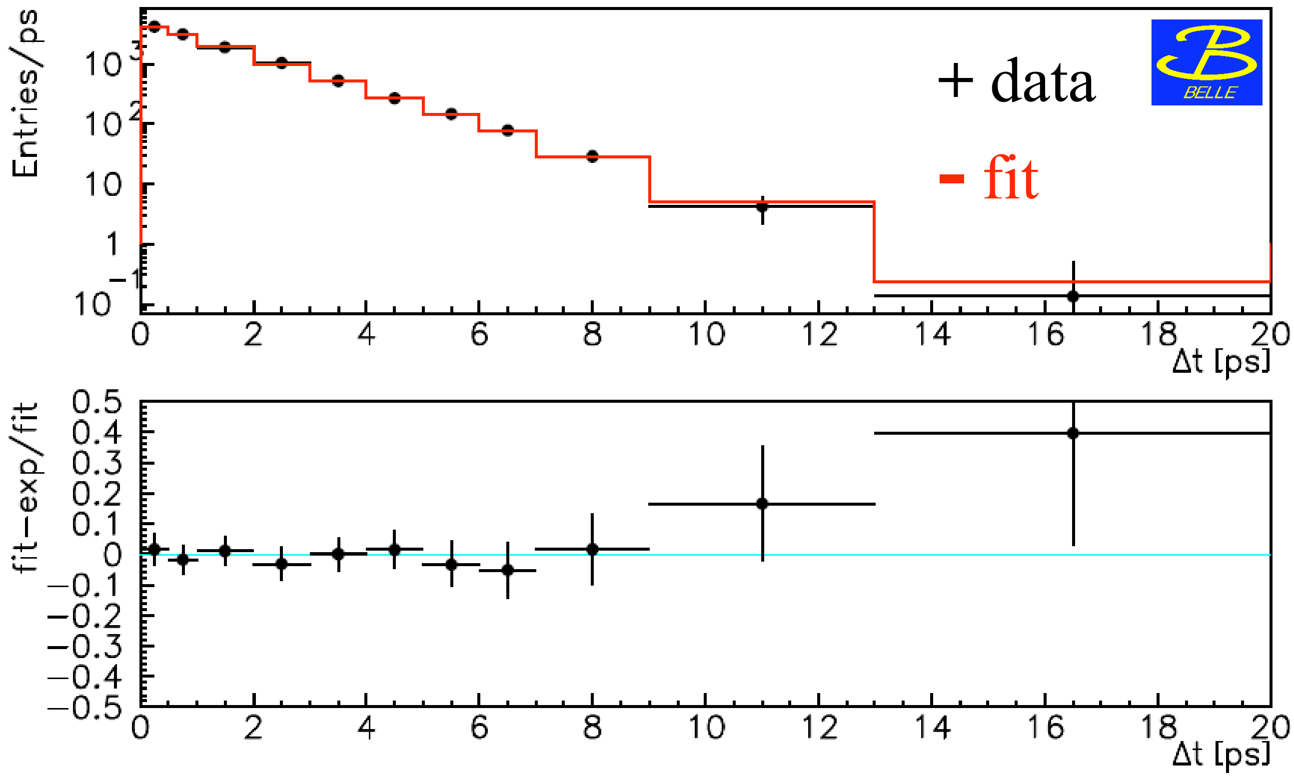
Toy MC of the 3 models (QM, PS and SD) have been used to study the method and to estimate the associated systematic error.

The result is given here:

| | Window | Asymmetry | | Systematic errors | | | | |
|---|---|---|---|---|---|---|---|---|
| $\Delta t$ bin | window [ps] | $A$ and total error | stat. error | total | event sel. | bkgd sub. | wrong tags | deconvol. |
| 1 | 0.0 – 0.5 | $1.013 \pm 0.028$ | 0.020 | 0.019 | 0.005 | 0.006 | 0.010 | 0.014 |
| 2 | 0.5 – 1.0 | $0.916 \pm 0.022$ | 0.015 | 0.016 | 0.006 | 0.007 | 0.010 | 0.009 |
| 3 | 1.0 – 2.0 | $0.699 \pm 0.038$ | 0.029 | 0.024 | 0.013 | 0.005 | 0.009 | 0.017 |
| 4 | 2.0 – 3.0 | $0.339 \pm 0.056$ | 0.047 | 0.031 | 0.008 | 0.005 | 0.007 | 0.029 |
| 5 | 3.0 – 4.0 | $-0.136 \pm 0.075$ | 0.060 | 0.045 | 0.009 | 0.009 | 0.007 | 0.042 |
| 6 | 4.0 – 5.0 | $-0.634 \pm 0.084$ | 0.062 | 0.057 | 0.021 | 0.014 | 0.013 | 0.049 |
| 7 | 5.0 – 6.0 | $-0.961 \pm 0.077$ | 0.060 | 0.048 | 0.020 | 0.017 | 0.012 | 0.038 |
| 8 | 6.0 – 7.0 | $-0.974 \pm 0.080$ | 0.060 | 0.053 | 0.034 | 0.025 | 0.020 | 0.025 |
| 9 | 7.0 – 9.0 | $-0.675 \pm 0.109$ | 0.092 | 0.058 | 0.041 | 0.027 | 0.022 | 0.022 |
| 10 | 9.0 – 13.0 | $0.089 \pm 0.193$ | 0.161 | 0.107 | 0.067 | 0.063 | 0.038 | 0.039 |
| 11 | 13.0 – 20.0 | $0.243 \pm 0.435$ | 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 $\tau_{B^0}$

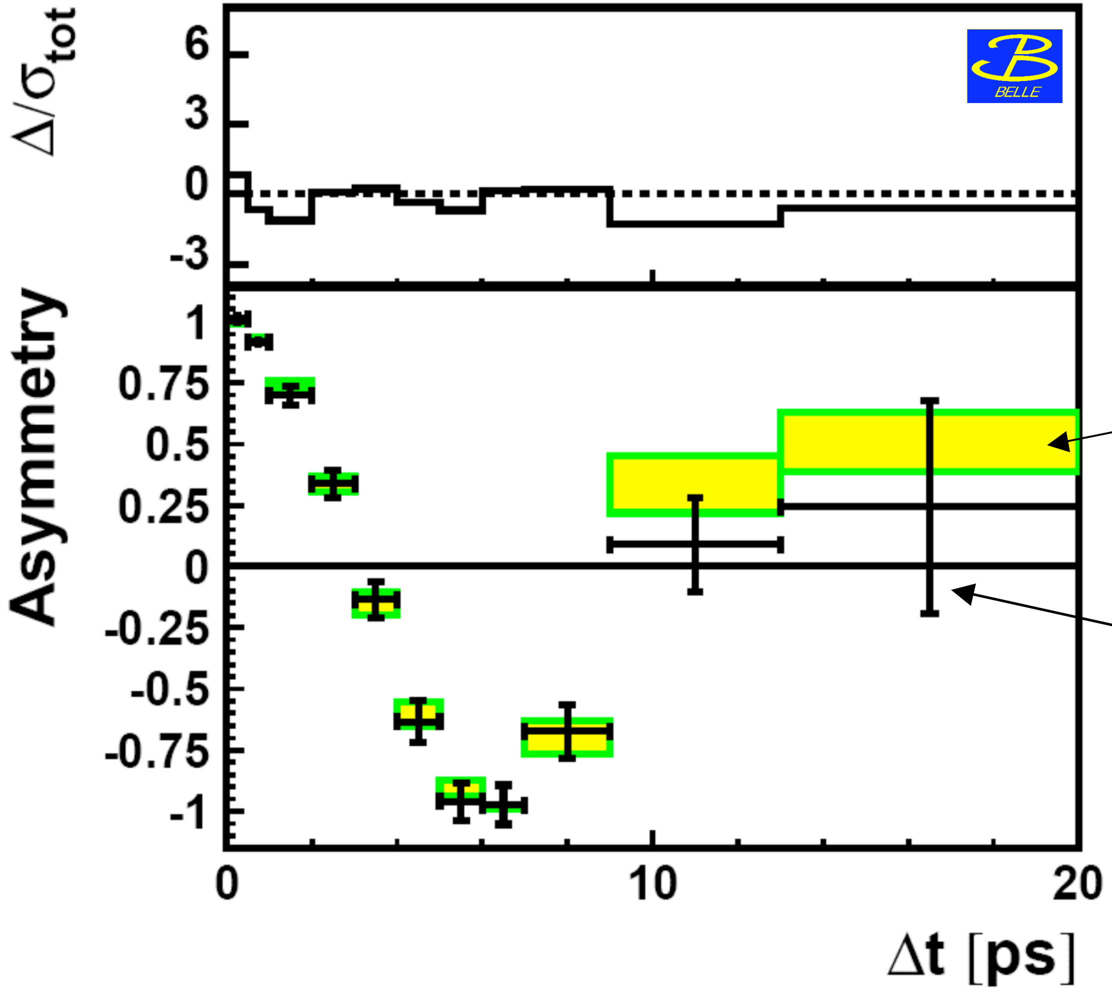



$\tau_{B^0}$ = 1.532±0.017(stat) ps => consistent with PDG value

$\chi^2$ = 3/11 bins

# Comparison with QM

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




fitted value:

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

$\mathbf{\chi^2 = 5.2\ (11\ dof)}$

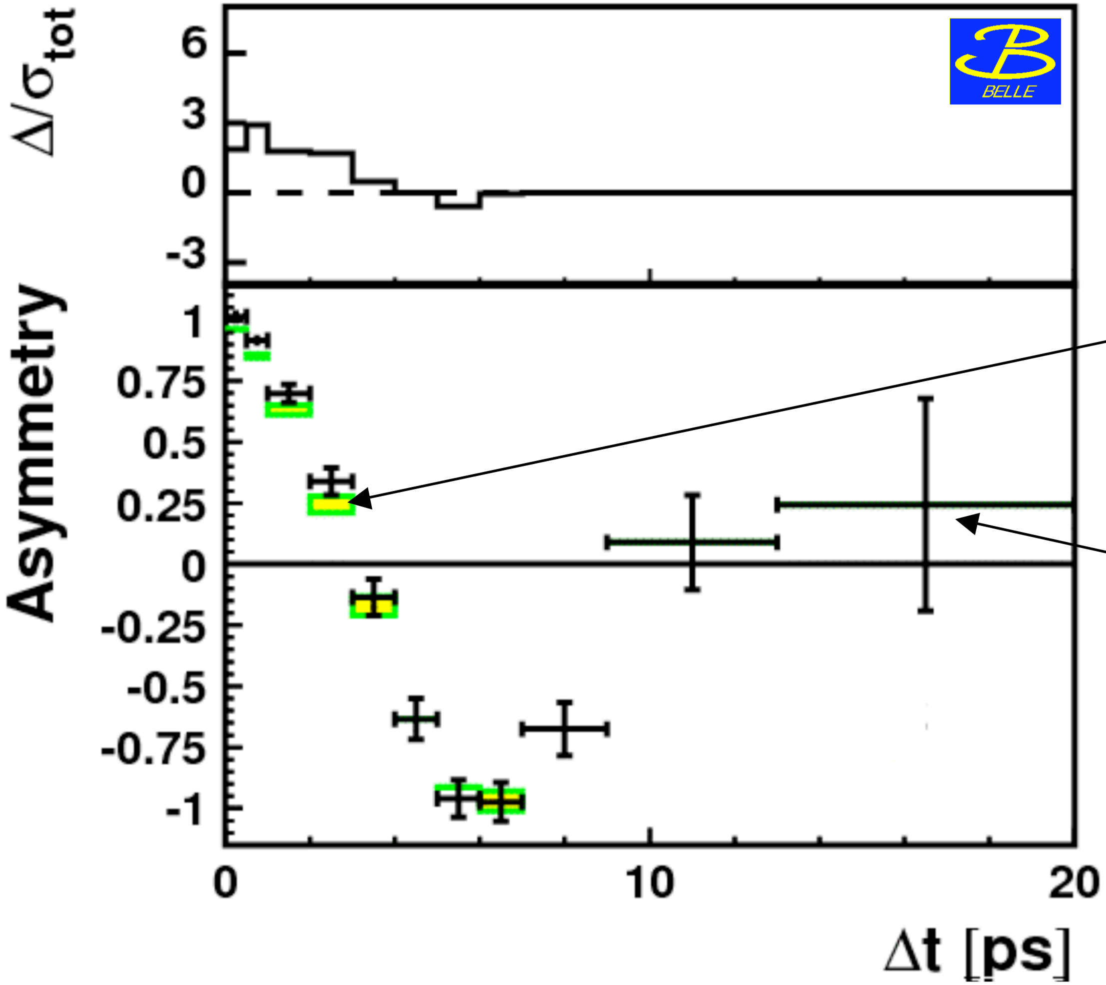
QM (error from $\Delta m_d$)

Data

=> Data fits QM

# Comparison with PS model

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




fitted value:

$\Delta m_d$=(0.447±0.010)ps$^{-1}$

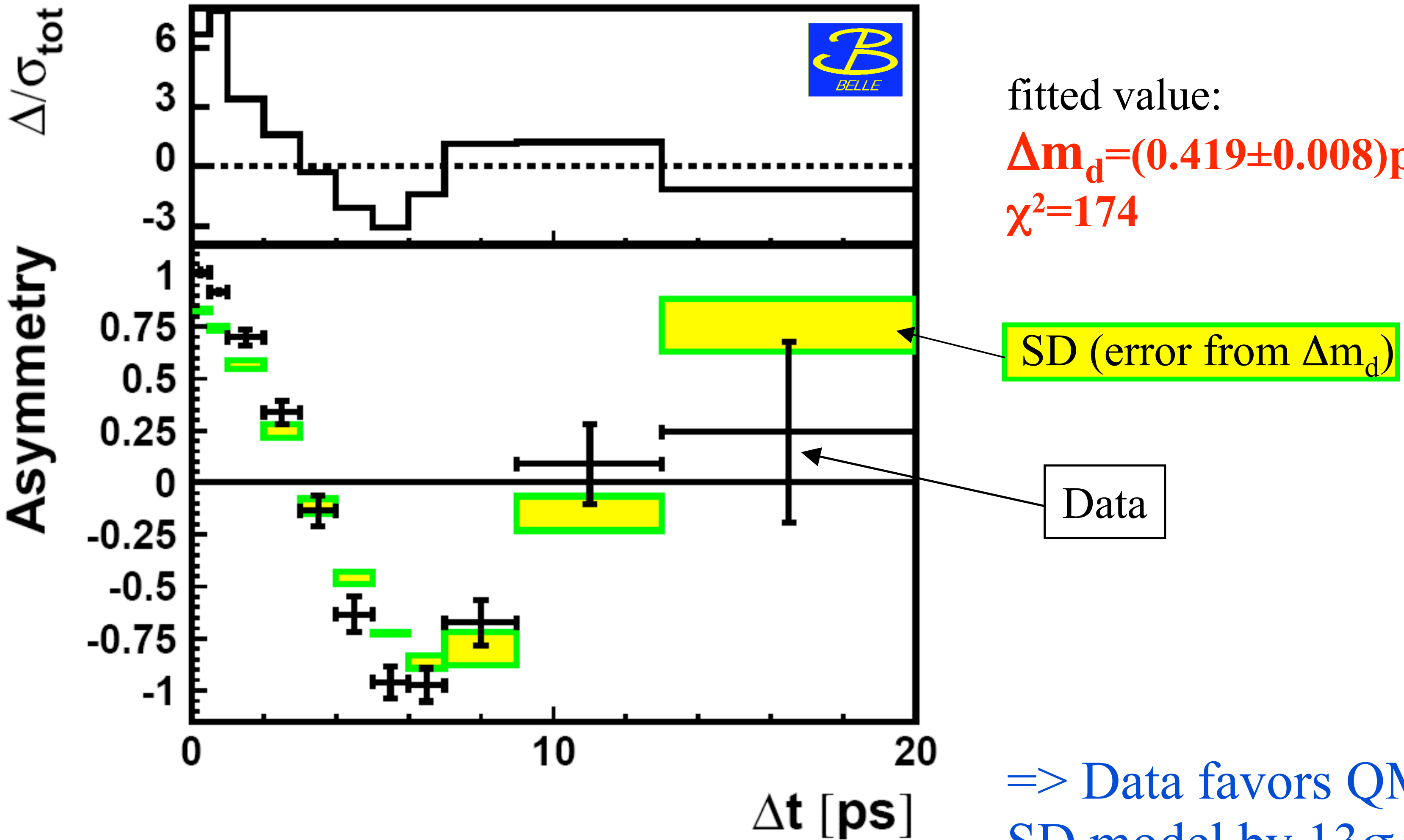
$\chi^2$=31.3

PS (error from $\Delta m_d$)

Data

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

# Comparison with SD model




fitted value:

$\Delta m_d = (0.419 \pm 0.008)\,ps^{-1}$

$\chi^2 = 174$

=> 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 $\lambda_{K0} = 0.4 \pm 0.7$
- KLOE $\lambda_{K0} = ( 0.10 \pm 0.22 \pm 0.04 )\ 10^{-5}$

# CONCLUSION

We have performed the first experimental test 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 $5.1\sigma$.
* A model with immediate disentanglement into flavour eigenstates is excluded by $13\sigma$.
* A decoherent fraction into flavour eigenstates was found to be $0.029 \pm 0.057$, consistent with no decoherence.

BACK UP
SLIDES

# Decoherence

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

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

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

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P. Heberard's $\zeta$ parameter for decoherence in $B_H$, $B_L$ :

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

At present, this result is not considered robust enough.

Previous mesurements in $K^0$ system:

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

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

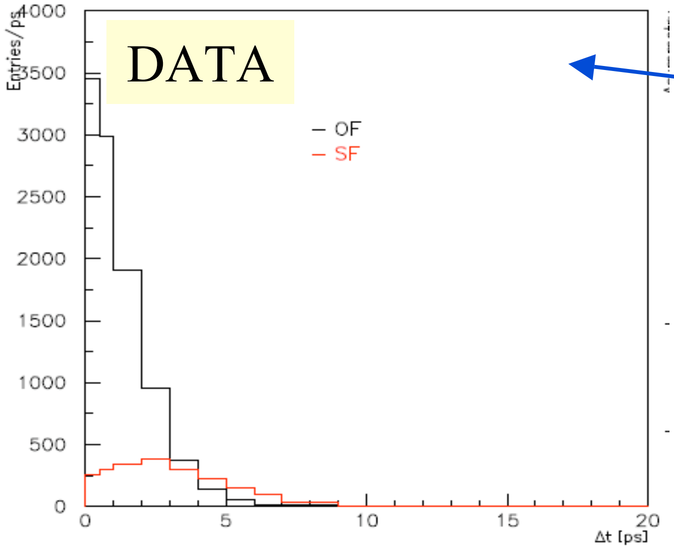
# Event selection

Semileptonic B side:

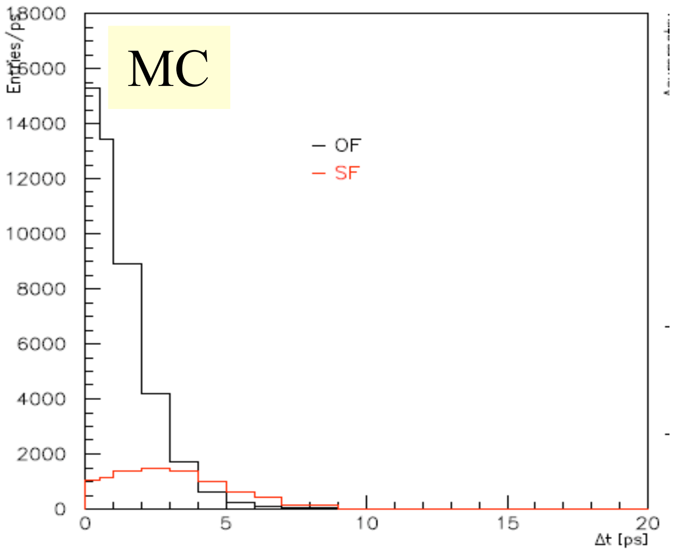
| Variable | Cuts |
|---|---|
| $P^{CMS}_{lepton}$ | $1.4GeV/c < P^{CMS}_{lepton} < 2.4GeV/c$ |
| Slow $\pi$ vertex constr. to B | $\chi^2/dof < 100$ |
| $K/\pi$ likelihood for $\pi$ | $K3\pi$ mode: $Prob_{K/\pi} < 0.5$<br>$K\pi, K\pi\pi^0$ mode: $Prob_{K/\pi} < 0.3$ |
| $P_{\pi^0}$ | $P_{\pi^0} > 0.2GeV/c$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

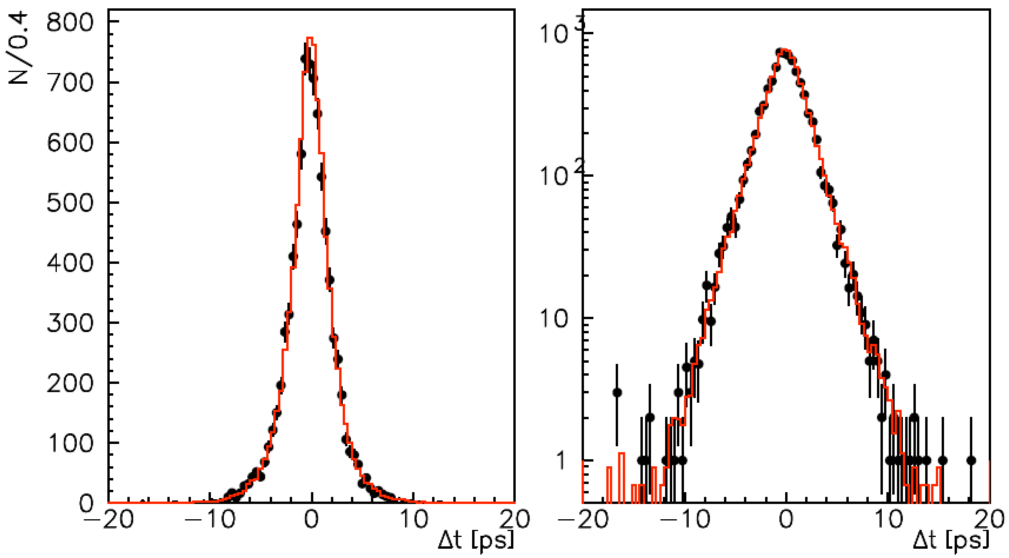
# After event selection: MC vs Data




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




Data and MC (OF+SF)(Δt) distributions

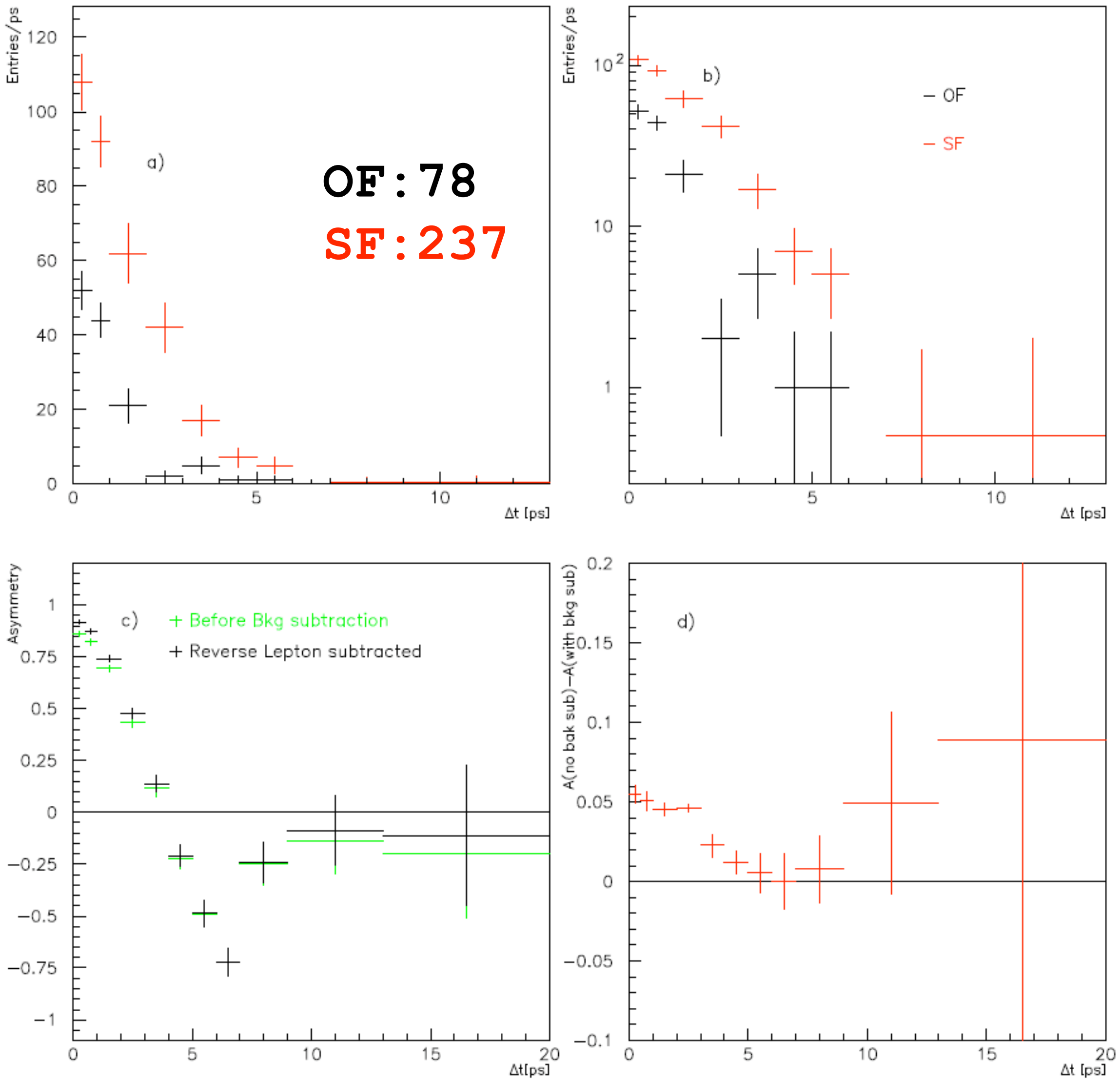


# Background: Wrong D*l combination

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

- Estimated by reversed lepton momentum

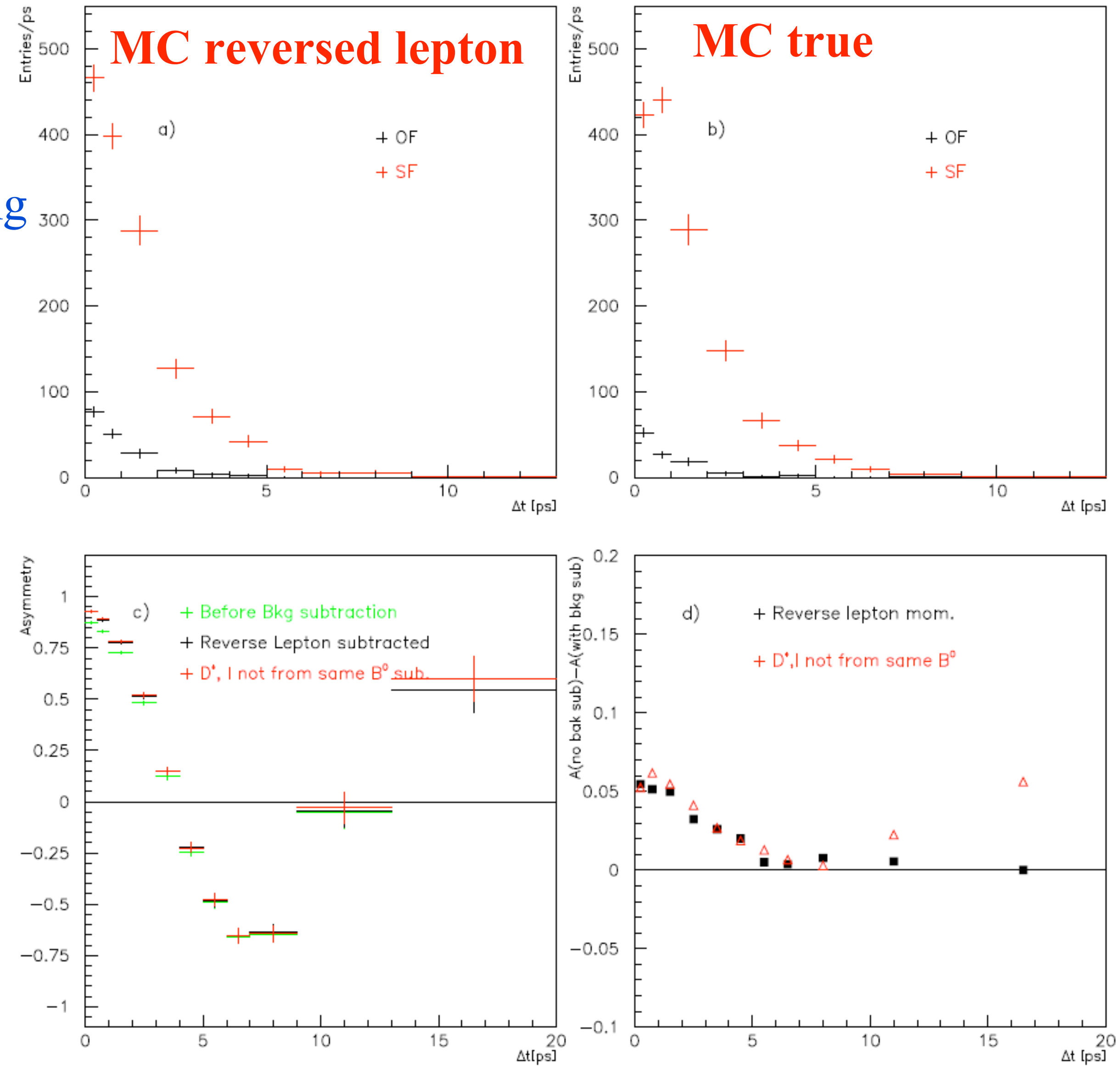
- Systematics: moving the OF(SF) to +1(−1) σ and calculate the asymmetry variation.



# 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

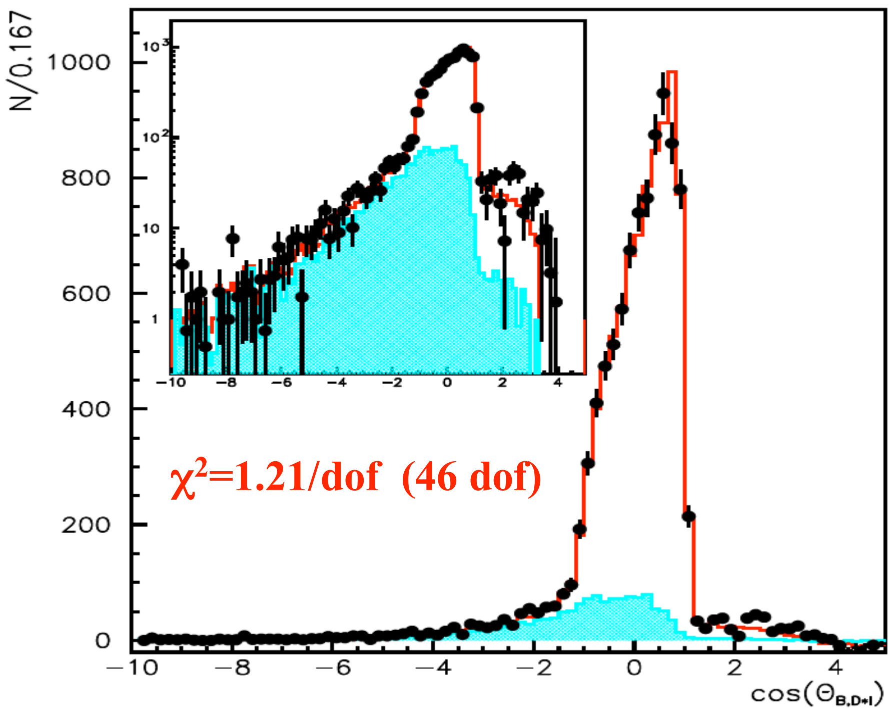
angle$(\vec{p}^{\,*}_B, \vec{p}^{\,*}_{D^*\ell})$

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

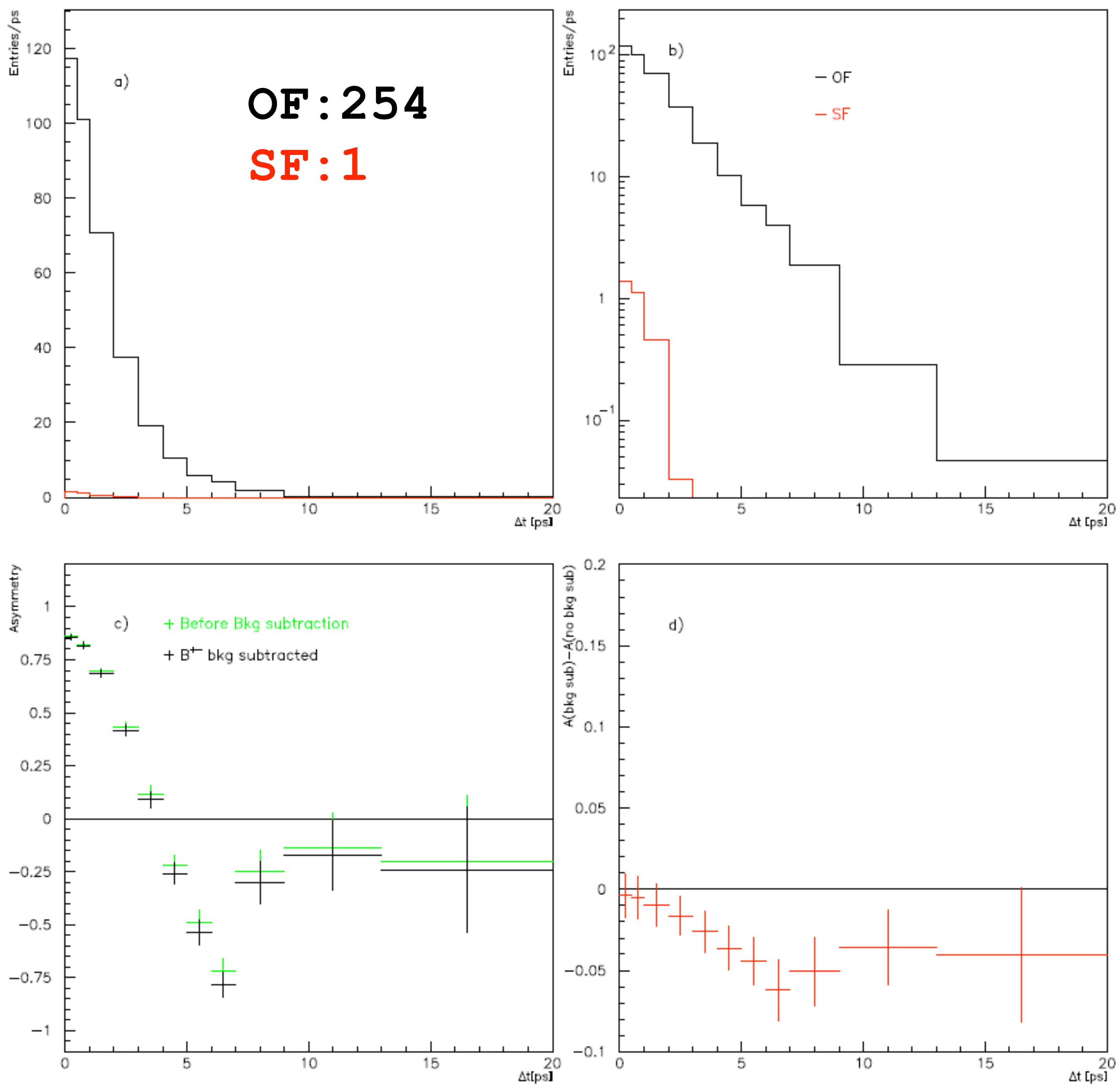
fit $\cos(\theta_{B,D^*\ell})$ distribution using MC shapes for $D^*\ell\nu$ and $D^{**}\ell\nu$

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

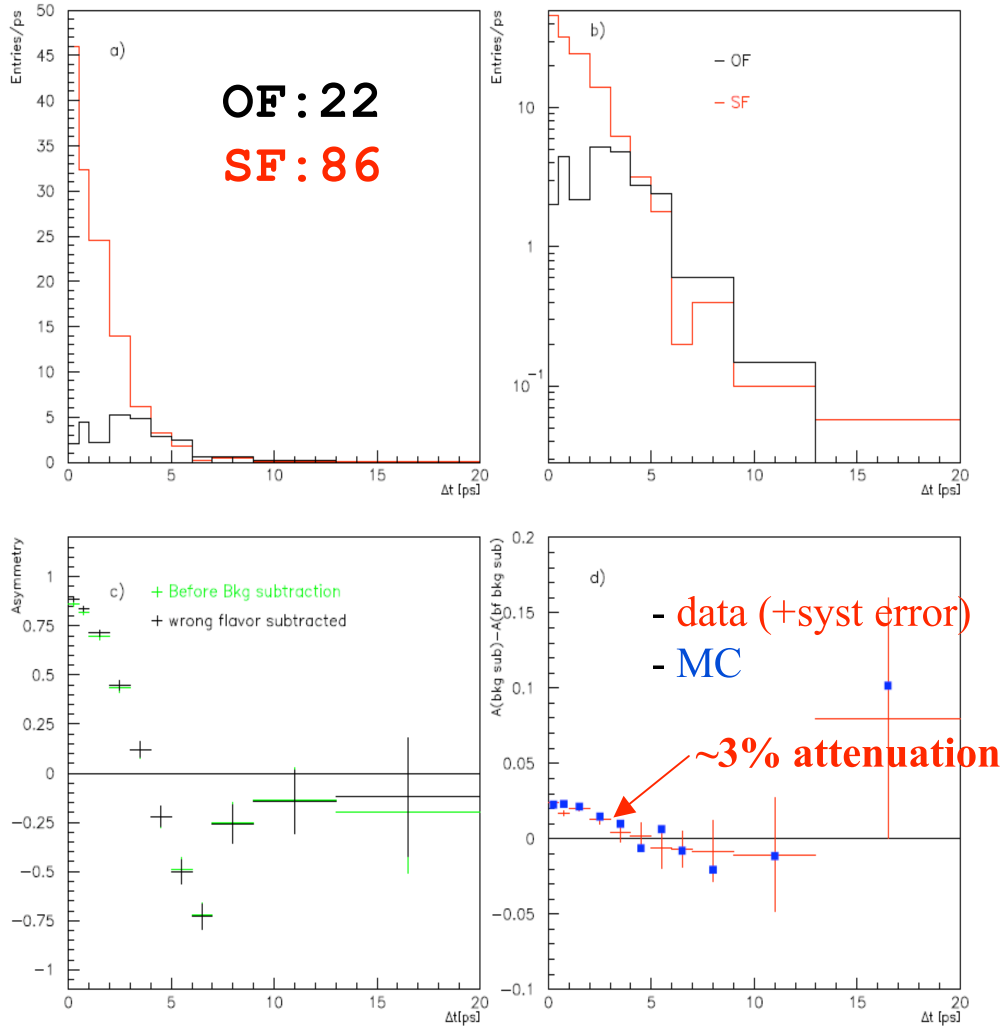


# Wrong Flavor

- Use MC to estimate the wrong flavor
- High purity events: $\omega$=0.015$\pm$0.006
- Expect attenuation on the asymmetry:

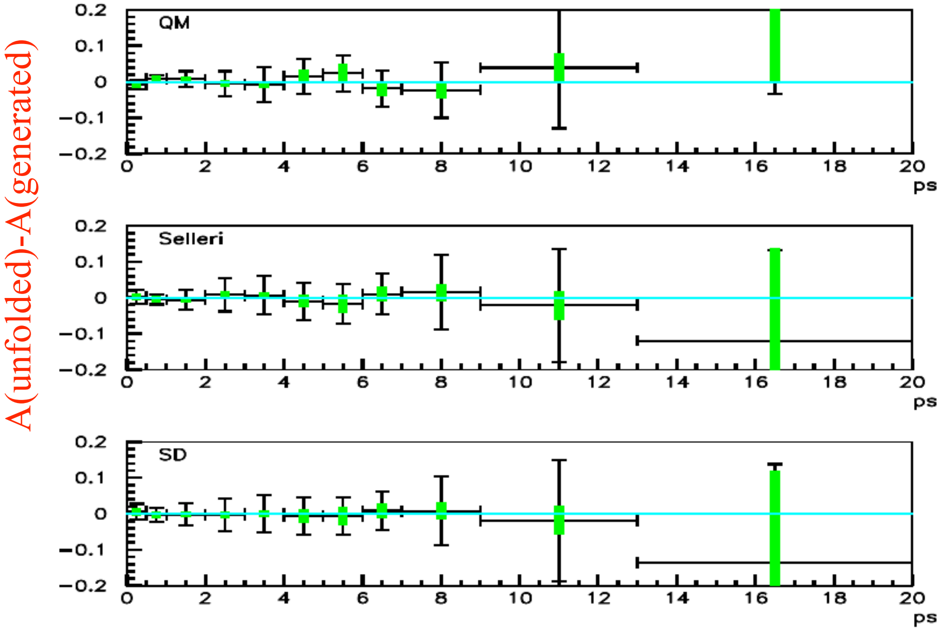
$$A(\Delta t) = (1-2\omega)\cos(\Delta m \Delta t)$$
$$= 0.970 \cos(\Delta m \Delta t)$$

=> ~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.

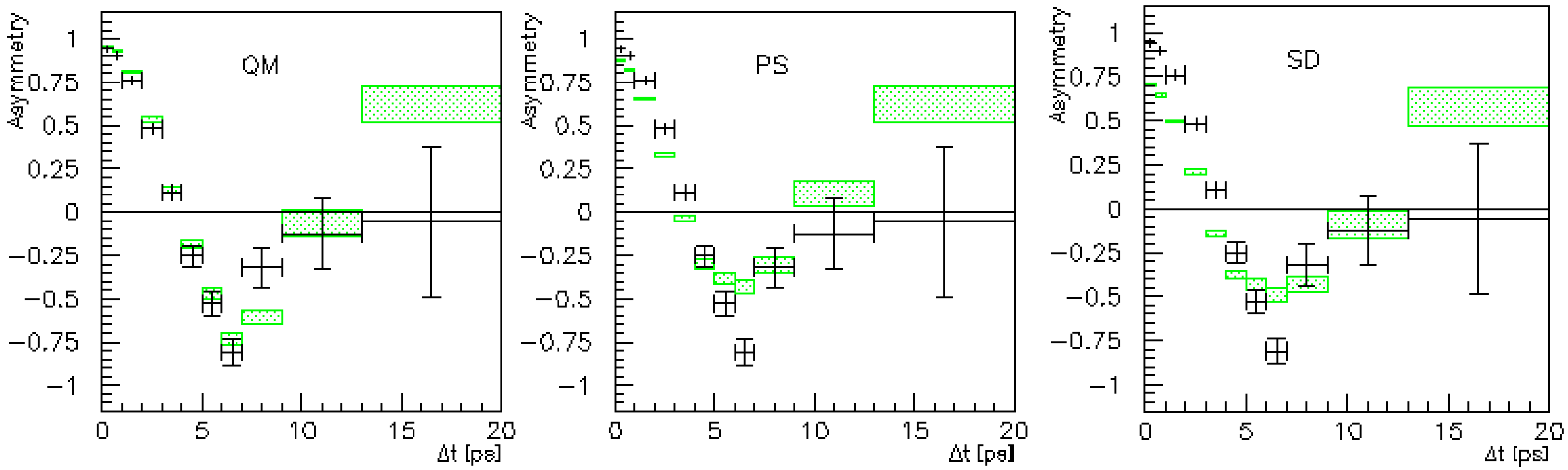



| $\Delta t$ bin | analysis | deconvolution | syst. |
|---|---|---|---|
| 1 | 0.0130 | 0.0141 | 0.0192 |
| 2 | 0.0132 | 0.0089 | 0.0159 |
| 3 | 0.0165 | 0.0171 | 0.0238 |
| 4 | 0.0115 | 0.0293 | 0.0314 |
| 5 | 0.0147 | 0.0423 | 0.0448 |
| 6 | 0.0283 | 0.0493 | 0.0568 |
| 7 | 0.0289 | 0.0379 | 0.0476 |
| 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.

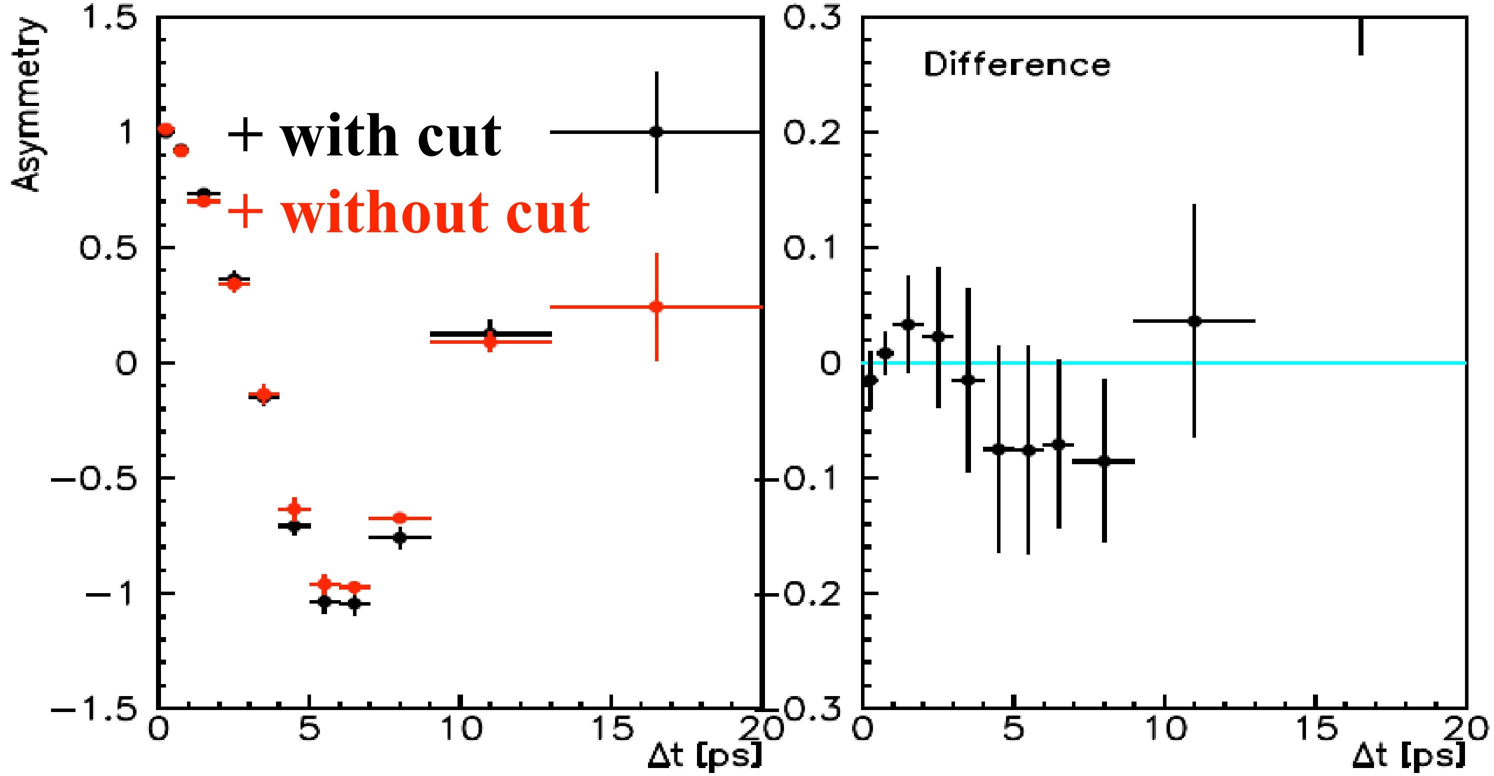
Since our MC is generated with QM correlation, we re-weight each event to produce the prediction of PS and SD models.




Δm is fixed.  The result favors QM

# Cross check: extra $\Delta z$ resolution cut

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

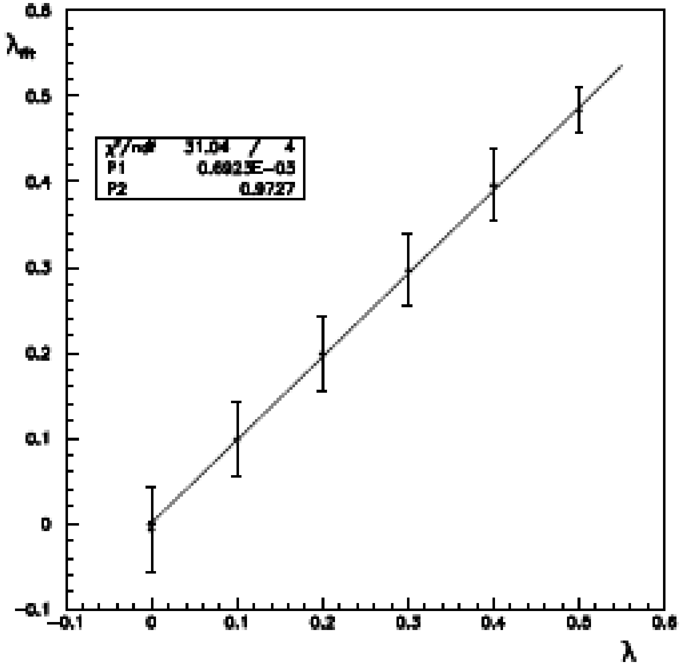



=> results are consistent

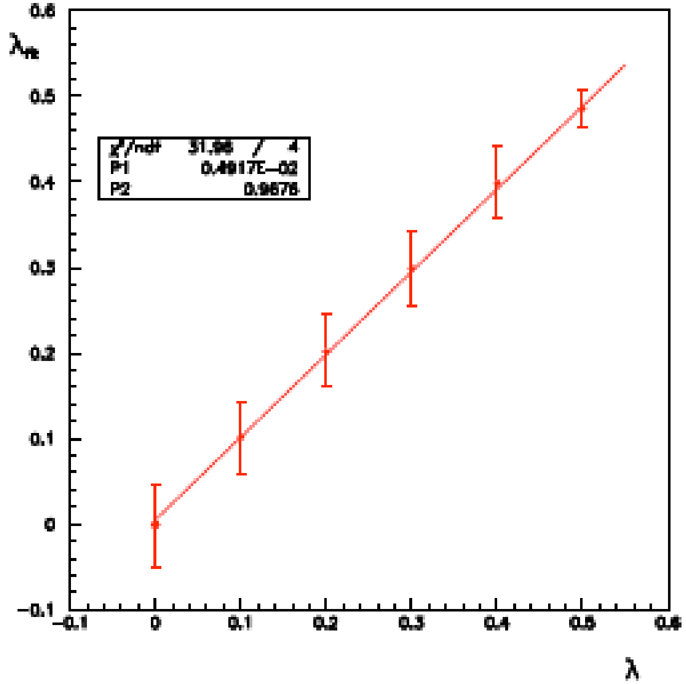
# Sensitivity to λ

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