Searches for Quantum Decoherence at Belle and Belle II

(Super)KEKB and Belle (II)
Entanglement of B-Mesons in Υ(4s) decays
B^0 Oscillations and CP Violation
Can Bell's Inequality be checked?

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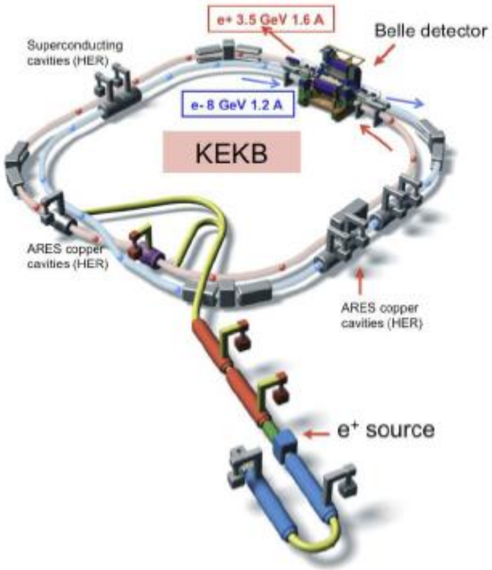
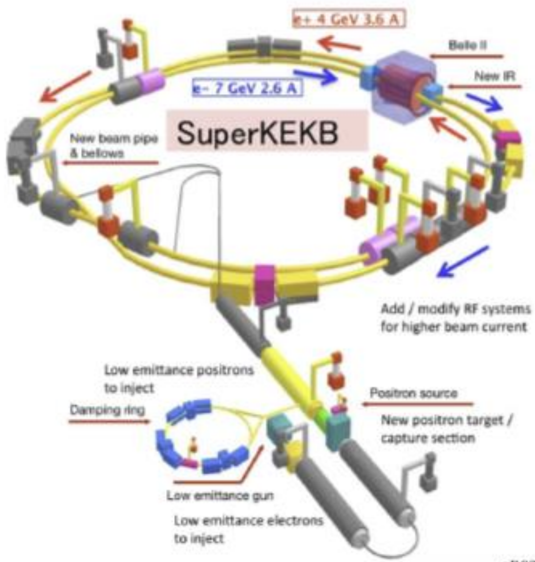
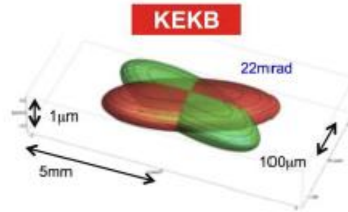
On behalf of Belle and Belle II

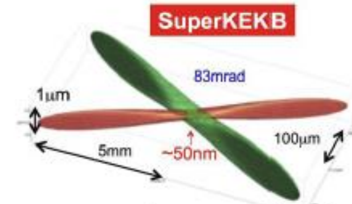
Effects of decoherence on time dependent measurements
Indirect indicators
Measurement at Belle
Plans at Belle II
Conclusions

Accelerator: KEKB and superKEKB









$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

$$\mathcal{L}_{\rm II}^{\rm peak} \approx 30 \times \mathcal{L}_{\rm I}^{\rm peak}$$

$$\int^{\rm goal} \mathcal{L}_{\rm II}\, dt = 50\ {\rm ab}^{-1} \approx 50 \int \mathcal{L}_{\rm I}\, dt$$

- moderately increased beam currents
- Squeeze beams @IP by ~1/20

3

KEKB:
1999-2010

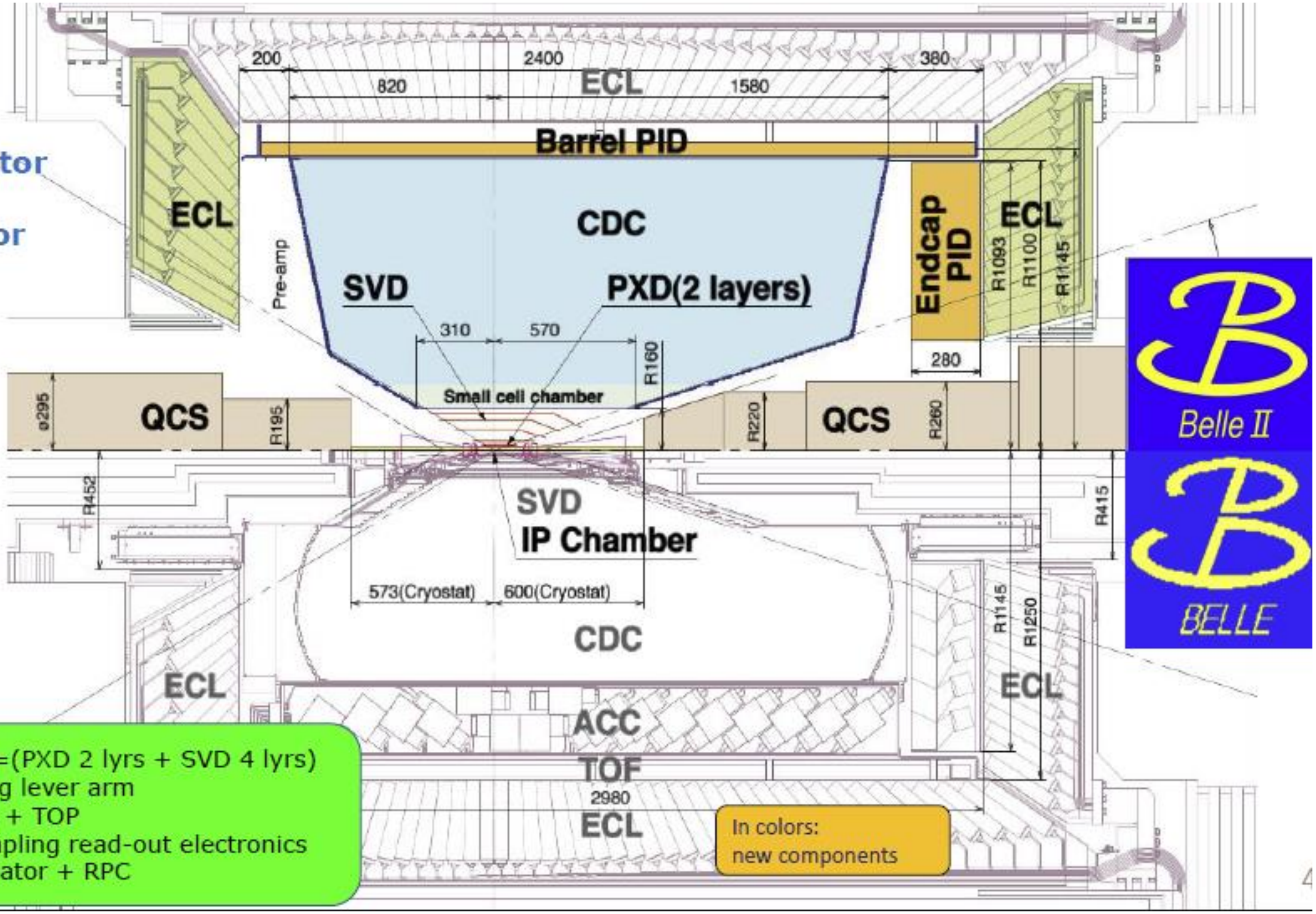
$\beta\gamma = 0.42$
(8 GeV, 3.5 GeV)

	KEKB/Belle	SuperKEKB/Belle II	
		achieved	target
$\mathcal{L}_{peak}$ [$cm^{-2}s^{-1}$]	2.1×10^{34}	**4.7×10^{34} world record**	$\sim6\times10^{35}$
$\mathcal{L}_{int}$ [fb^{-1}]	1,004 ($711_{\Upsilon(4S)}$)	**424 ($362_{\Upsilon(4S)}$)**	50,000
$N(B\bar{B})_{\Upsilon(4S)}$	772×10^6	**387×10^6**	$\sim5\times10^{10}$

superKEKB:
2019 - …..

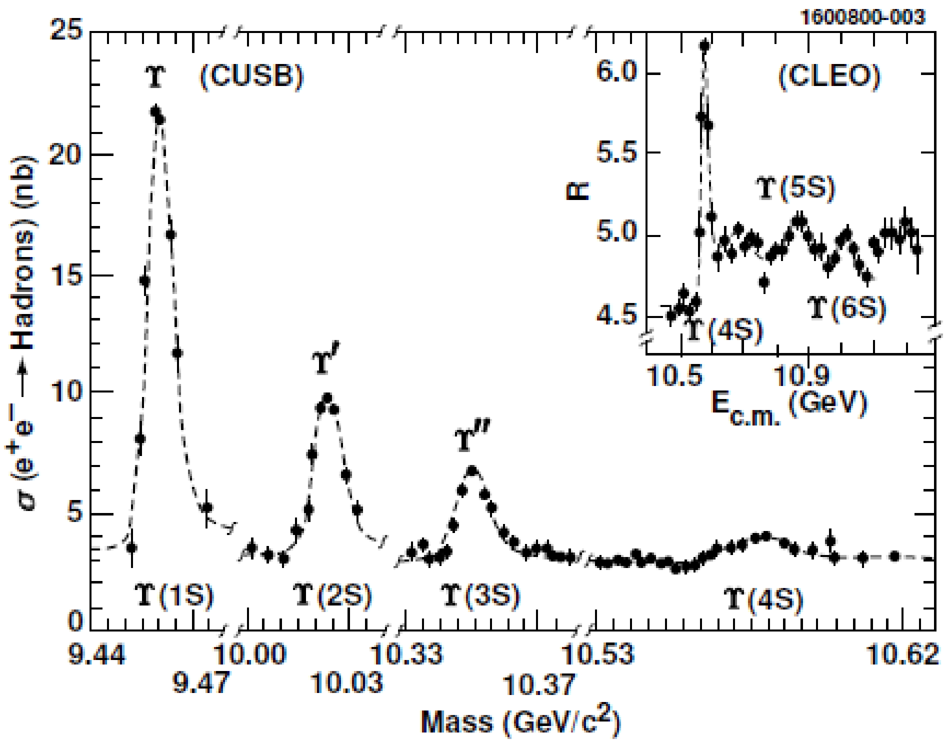
$\beta\gamma = 0.28$
(7 GeV, 4 GeV)

Belle (II)



SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → ARICH + TOP
ECL: waveform sampling read-out electronics
KLM: RPC → Scintillator + RPC

Υ(4s)



e+ e- → Υ(4s) → B^0 $\bar{B}^0$

m(Υ(4s)) = 10.579 (Γ=0.0205) GeV
2 x m(B^0) = 10.558 GeV
ΔE = 21 MeV
m(B*) - m(B) = 45.2 MeV

Entanglement in Υ(4s) decays

$B^0/\overline{B}^0$ from a Υ(4s) decay are supposed to be in an entangled state

$$\Psi = \frac{1}{\sqrt{2}}\left[\,|B^0(p)\rangle|\overline{B}^0(-p)\rangle - |\overline{B}^0(p)\rangle|B^0(-p)\rangle\,\right]$$

If one B decays, the common wave function collapses and the $B^0/\overline{B}^0$ are in a defined state.

$\gamma\beta c\tau/r(B^0) \sim 5\text{x}10^{10}$ => well separated spatially

Measurements of Δm_d and CP violation are based on entanglement (B-tag).

1) Can we demonstrate the entanglement (e.g. checking Bell's inequality) ?

2) How certain are we that the entanglement is always 100% ?

$\Upsilon(4s) \rightarrow B^0\,\overline{B}^0\,\gamma$
Decoherence due to interaction with (BSM) background fields

Such effects could lead to systematic errors of our CP violation measurements

B^0 $\overline{B}^0$ mixing

Due to weak interaction a B^0 can transform into its antiparticle
Formally this is described by a new (weak) base of B^0_L and B^0_H

$$|B_{\mathrm{L,H}}\rangle = p|B_q^0\rangle \pm q|\overline{B}_q^0\rangle$$

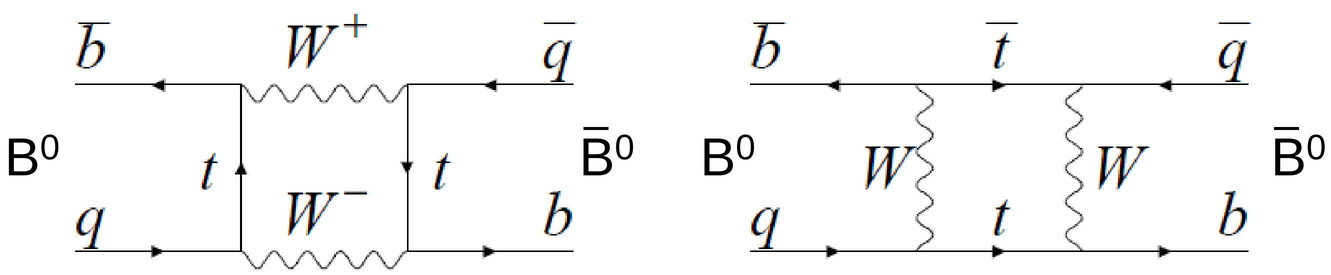
$|p/q| = 1$ (CP conserved)

These two states interfere and resulting in time dependent oscillations

$$P(B^0 \to \overline{B}^0) = \tfrac{1}{2}\,\Gamma\, \exp(-\Gamma t)\,(1-\cos(\Delta m\, t))$$

$$P(B^0 \to B^0) = \tfrac{1}{2}\,\Gamma\, \exp(-\Gamma t)\,(1+\cos(\Delta m\, t))$$

Δm: mass difference of B^0_H and B^0_L



+ diagrams with u,c exchange

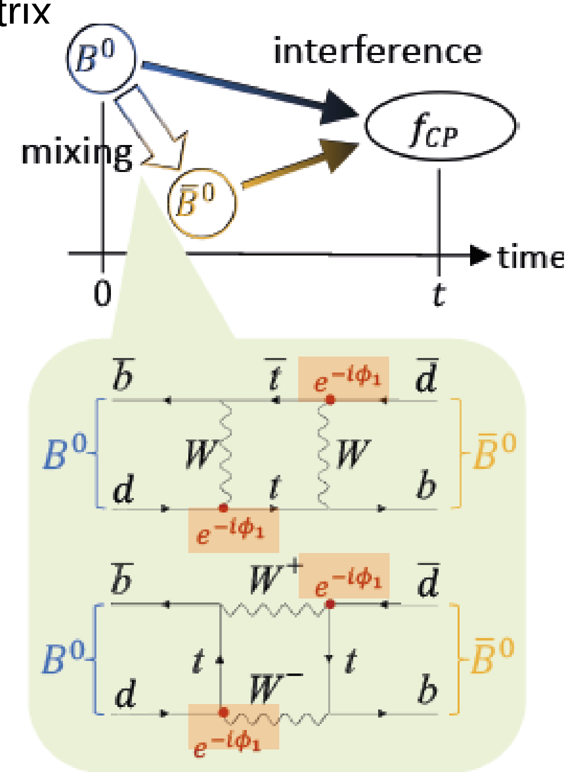
CP violation

Weak interaction is also a source for CP violation

CP violation is a consequence of the complex phase of the CKM matrix

It happens if two (or more) amplitudes interfere

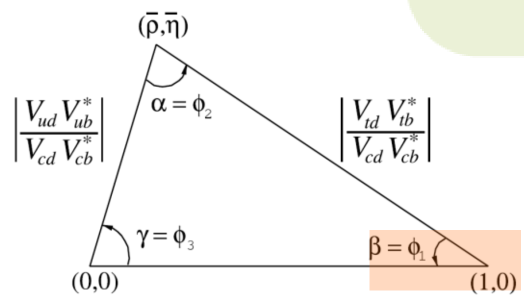
$A_f(B^0 \to f) = A_1 \exp(i\phi_w) + A_2 \exp(i\phi_s)$
$A_b(\bar{B}^0 \to \bar{f}) = A_1 \exp(-i\phi_w) + A_2 \exp(i\phi_s)$ $\Rightarrow |A_f|^2 \neq |A_b|^2$



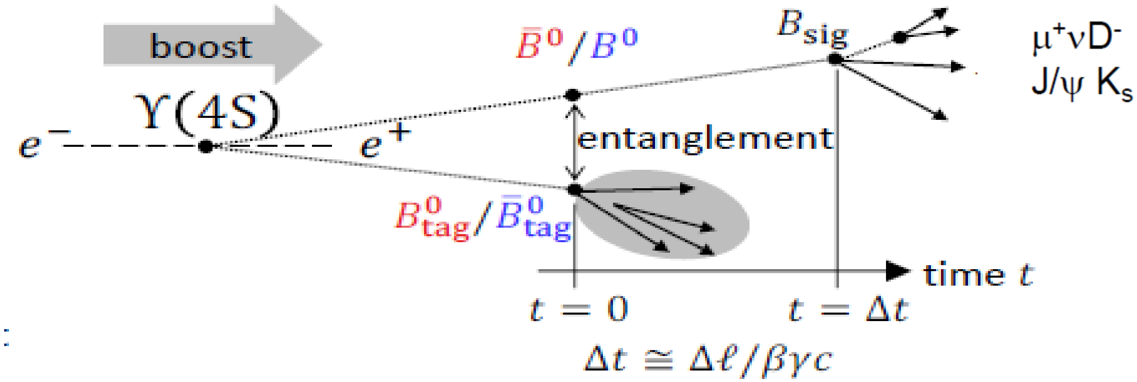
In decays this happens either by interference of different decay amplitudes (tree and higher order)
or (more important) by interference of mixing and decay

Precise measurements of CP violation are the primary goals of the Belle and Belle II experiments

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Phenomenology



Υ(4s) created at t=0 and decays in $B^0/\bar{B}^0$

Tag: one B^0 decays at t_1 in a way that we know whether it is B^0 or $\bar{B}^0$ (e.g. $\mu^+\nu D^-$)
(in practice: use a BDT or NN to determine the decay state)

The other B^0 (always in the opposite state because of entanglement) starts oscillating

Sig: the other B^0 decays at t_2 in the signal mode we are interested in

oscillation (Δm) measurement: $\mu^+\nu D^-$
CP violation (sin(2β)): $J/\psi\ K_s$

From the spatial separation and the known boost we determine $\Delta t = t_2 - t_1$

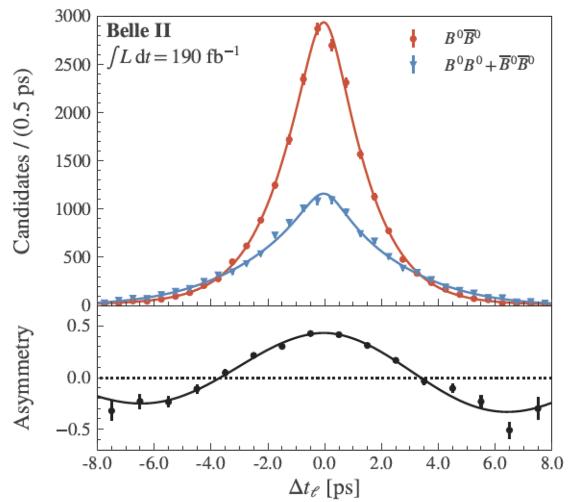
Phenomenology

Oscillations:

$$P(B^0 \rightarrow \overline{B}^0) = ½\, \Gamma \exp(-\Gamma\Delta t)\, (1-\cos(\Delta m\, \Delta t))$$

$$A_{osc} = \frac{N(B^0 \rightarrow B^0) - N(B^0 \rightarrow \overline{B^0})}{N(B^0 \rightarrow B^0) + N(B^0 \rightarrow \overline{B^0})} = \cos(\Delta m \Delta t)$$

In reality: take into account mistag, resolution, background



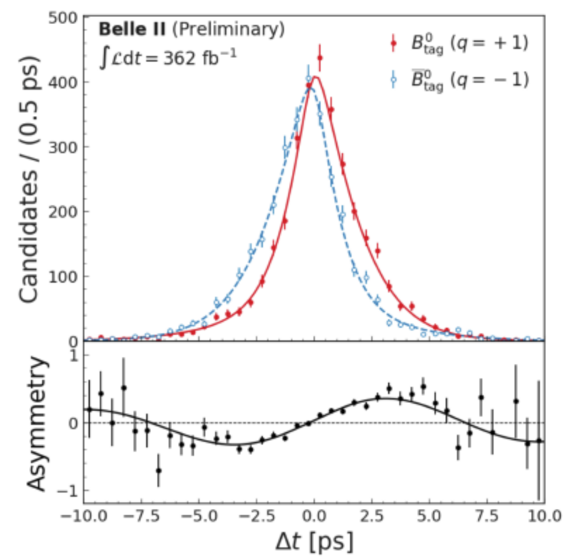
Mixing indu̲ced (or time dependent) CP violation (TDCPV):

'Golden mode' $\overline{B}^0(q=+1)$; $B^0(q=-1) \rightarrow J/\psi\, K_s$

$$P(\Delta t,q) = ¼\, \Gamma \exp(-\Gamma\Delta t)\, \{1 + q\, [S \sin(\Delta m\Delta t) - C \cos(\Delta m\Delta t)]\}$$

For $J/\psi\, K_s$ $S = \sin(2\beta)$ $C \sim 0$

$$a_{CP} = \frac{N(\overline{B^0} \rightarrow f_{CP}) - N(B^0 \rightarrow f_{CP})}{N(\overline{B^0} \rightarrow f_{CP}) + N(B^0 \rightarrow f_{CP})} = S \sin(\Delta m \Delta t)$$

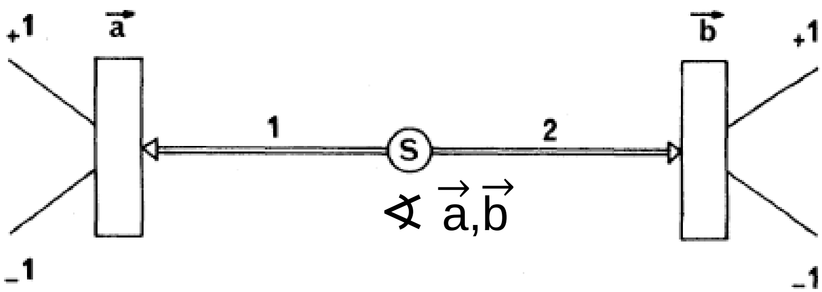


Can we check Bell's inequality?

Classical Aspect type correlation experiment
A. Aspect et al, Phys. Rev. Lett 49, 1804 (1982)

correlation coeffs in data *vs* QM
optimum relative angles 22.5° and 67.5°

spin-singlet state of photons or particles: $\frac{1}{\sqrt{2}}\left[|\Uparrow\rangle_1\,|\Downarrow\rangle_2 - |\Downarrow\rangle_1\,|\Uparrow\rangle_2\right]$



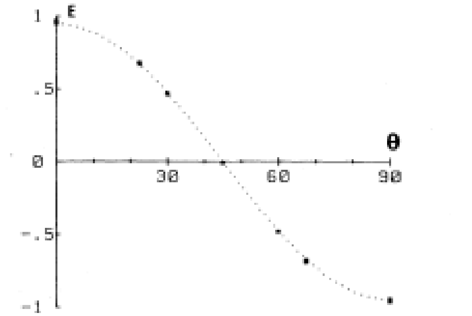


FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ±2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ±1.

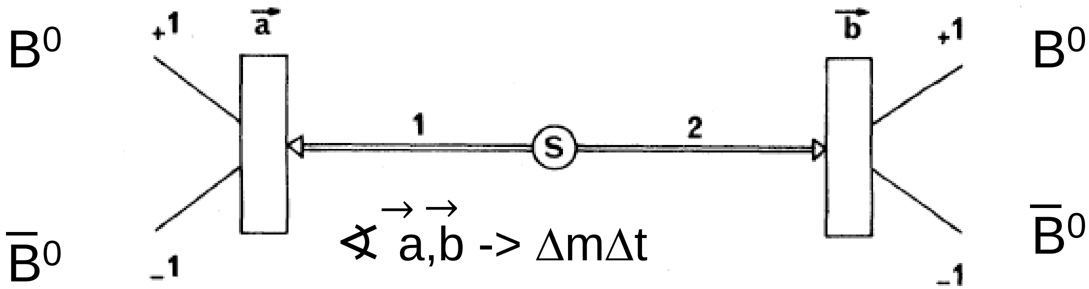
- Bell's Theorem (via Clauser, Horne, Shimony, and Holt):
  - correlation coeff: $E(\vec{a},\vec{b}) = \frac{R_{++}(\vec{a},\vec{b})+R_{--}(\vec{a},\vec{b})-R_{+-}(\vec{a},\vec{b})-R_{-+}(\vec{a},\vec{b})}{R_{++}(\vec{a},\vec{b})+R_{--}(\vec{a},\vec{b})-R_{+-}(\vec{a},\vec{b})+R_{-+}(\vec{a},\vec{b})}$
  - $S = E(\vec{a},\vec{b}) - E(\vec{a},\vec{b}') + E(\vec{a}',\vec{b}) + E(\vec{a}',\vec{b}')$
  - $|S| \leq 2$ for any local realistic model; $S_{QM} = \pm 2\sqrt{2}$ for optimal settings

$S = 2.697 \pm 0.015$; *cf.* $S_{QM} = 2.70 \pm 0.05$

Replace ↑ by B^0 and ↓ by $\overline{B}^0$

Bell's inequality with $B^0\overline{B}^0$

$$\frac{1}{\sqrt{2}}\left[\,|B^0(p)\rangle|\overline{B}^0(-p)\rangle - |\overline{B}^0(p)\rangle|B^0(-p)\rangle\,\right]$$



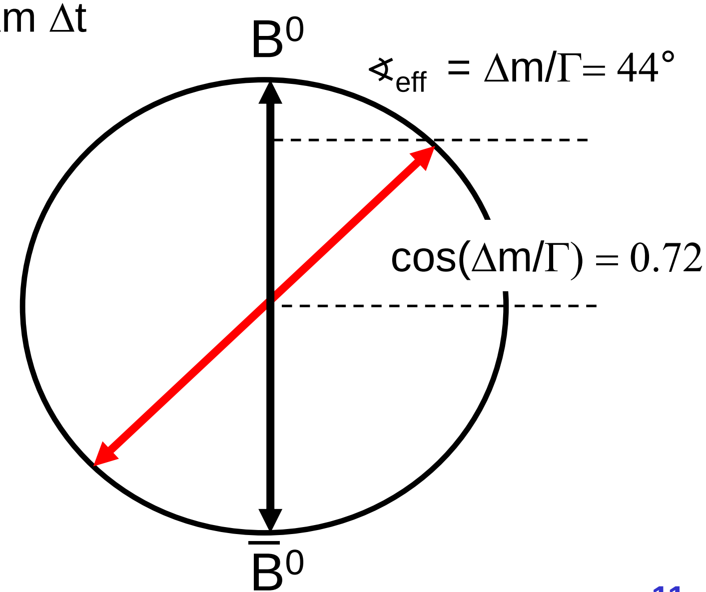
Replace the angle between the polarizers by $\sphericalangle_{eff} = \Delta m\,\Delta t$

S = 2.8 (for $\sphericalangle_{eff}$ = 45°, 90° and 135°)

(A. Go & Chung Li, quant-ph/0310192v1 (2003):
S = 2.725 ± 0.167 ± 0.092 (Belle data))

Non QM test: Assume complete decoherence
(both B oscillate independently from t=0)

S = 2.3 S(decoherent) > 2 for $\Delta m/\Gamma < 2$



What's wrong? => high correlation due to short lifetime

No way for Bell at Belle (II)

Bertlmann, Bramon, Garbarino, Hiesmayr, Phys. Lett. A 332, 355-360 (2004)

crucial parameter $x_d = \Delta m_d/\Gamma_d$:
rate of oscillation relative to decay

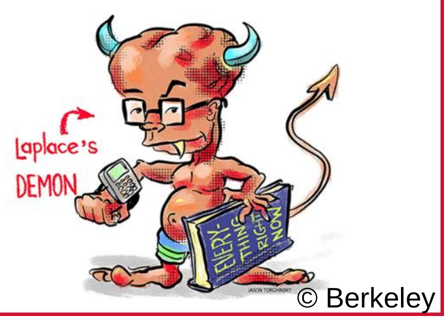
Bell test impossible if $x < 2.0$:

system	x
$B^0/\overline{B}^0$	0.77
$K^0/\overline{K}^0$	0.95
$D^0/\overline{D}^0$	< 0.03
$B^0_s/\overline{B}^0_s$	~ 26

Furthermore:

We rely on the random decays of both Bs.

No (reasonable) way to **actively** determine ∢ a,b -> ΔmΔt.



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A kind of Laplace demon could tune hidden parameters (t_1,t_2, decay type) so that QM and Bell's inequality is emulated, despite it's not QM and local.
No practical way to close this loophole.

What's left to be done

We can still calculate effects of special decoherent or non local models
Fit (modified) time dependence to data

- Spontaneous decoherence (SD):

  entanglement is lost at t=0 for a certain fraction of events
  decoherence fraction ζ

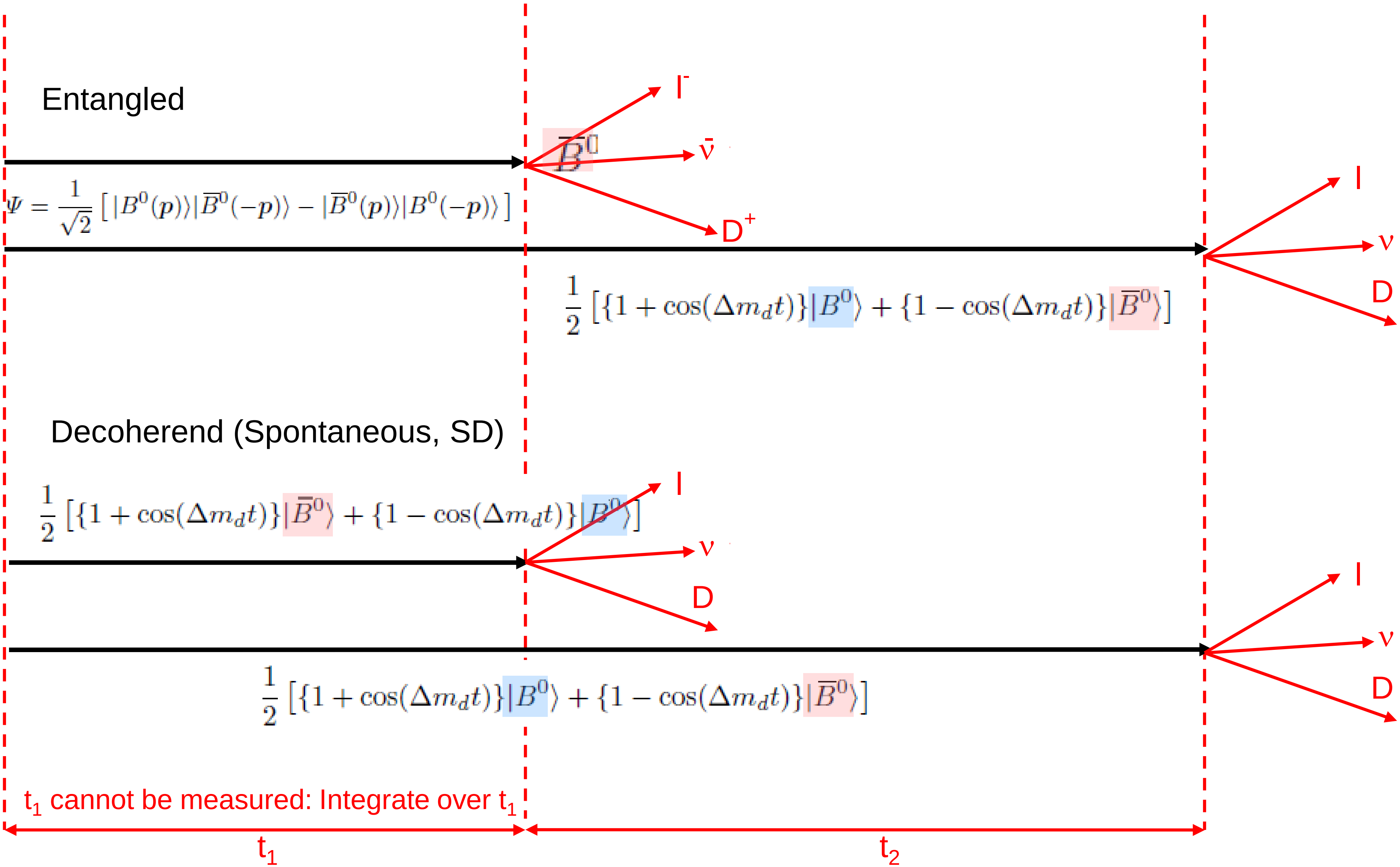
- Pompili Selleri model (PS) (Eur. Phys. J. C14, 469 (2000)):

  local realism, which reproduces oscillation phenomenology

- Lindblad type decoherence (Comm. Math. Phys. 48(2) 119)

  Loss of coherence due to interaction with environment.
  coherence is gradually lost within a decoherence time τ_{dec}
  a) $\tau_{dec} << \tau_B$: equivalent to SD
  b) $\tau_{dec} >> \tau_B$: can be ignored

Time dependence if decoherent



Spontaneous Decoherence

$B^0/\overline{B}^0$ Oscillations: Probability to measure a same sign (SS) event:

a) Full coherence:

$$P(B^0B^0,\overline{B^0B^0}) = \frac{1}{2}\Gamma\exp(-\Gamma t_2)(1-\cos\Delta m t_2)$$

b) Full decoherence (Spontaneous decoherence, SD)

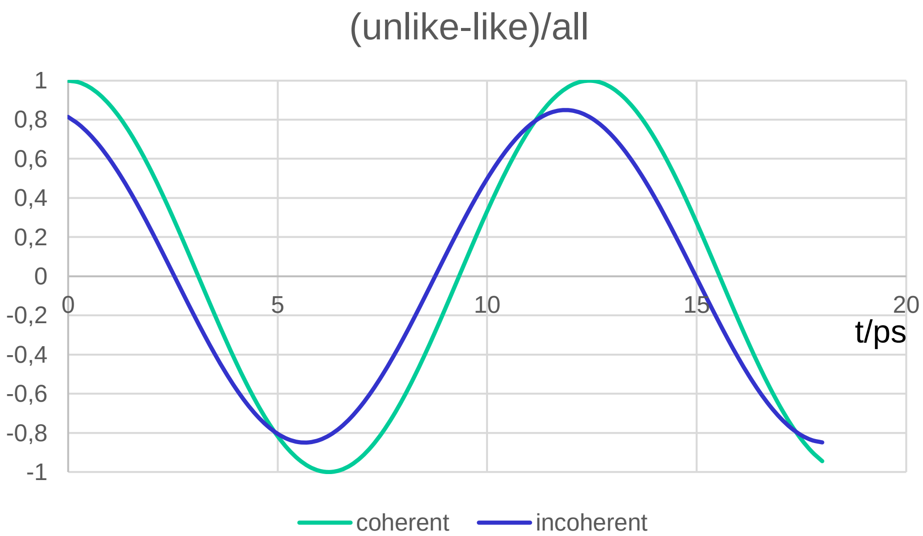
$$P(B^0B^0,\overline{B^0B^0}) = \frac{1}{2}\Gamma\exp(-\Gamma t_2)(1-\frac{1}{2}\frac{\Delta m + 2\Gamma^2}{\Gamma^2+\Delta m^2}\cos\Delta m t_2 + \frac{1}{2}\frac{\Gamma\Delta m}{\Gamma^2+\Delta m^2}\sin\Delta m t_2)$$

Damping by $\frac{1}{2}\frac{\Delta m + 2\Gamma^2}{\Gamma^2+\Delta m^2}$ ~ 0.81

Additional SIN-term: $\frac{1}{2}\frac{\Gamma\Delta m}{\Gamma^2+\Delta m^2}$ ~ 0.24

(using PDG averages: $\Delta m = 0.505 \pm 0.002\ \text{ps}^{-1}$, $\Gamma = 0.658 \pm 0.002\ \text{ps}^{-1}$)

Time Dependence (SD)



The damping is probably difficult to measure, as it could be interpreted as mistag.

The SIN term (or phase shift) should be measurable.

Similar damping and phase shifts in measurements of time dependent CP violation

The damping could lead to a wrong measurement of sin(2β).
This might be compensated if the mistag is calibrated using oscillation measurements.

The phase shift leads to a cross talk between S and C.

Indirect Indicator: χ

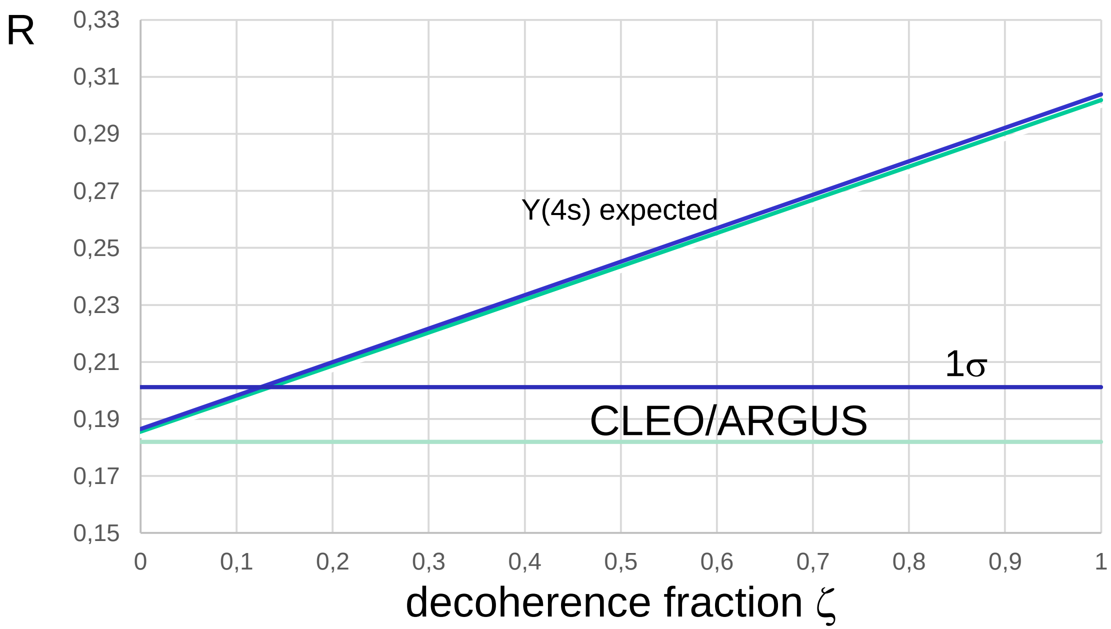
Time integrated oscillations: measure $\chi = \frac{1}{2}\,\Delta m^2/(\Delta m^2 + \Gamma^2)$ using dilepton events

Use Δm from LHCb as reference (no entanglement at LHCb!)

Coherence: $R = (N^{++} + N^{--})/(N^{++} + N^{--} + N^{+-}) = \chi$

SD: $R = (N^{++} + N^{--})/(N^{++} + N^{--} + N^{+-}) = 2(\chi - \chi^2)$

Use χ calculated from LHCb's Δm measurement (always decoherent)

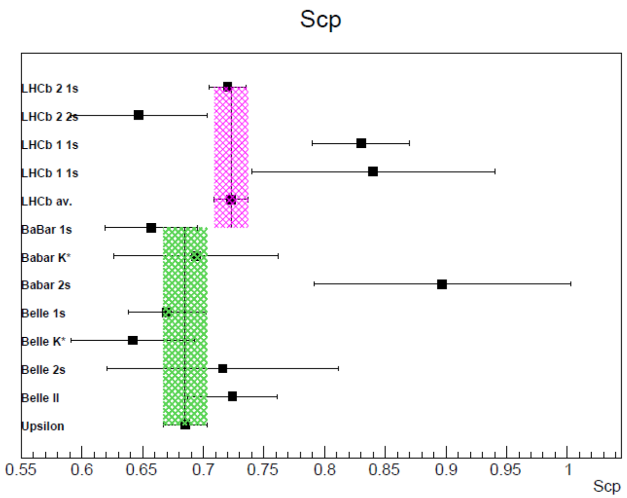


Old CLEO/ARGUS measurement of $R = 0.182 \pm 0.015$ (PDG) compatible with ~10% decoherence

Should be able to do much better at Belle II

Indirect Indicators: TDCPV

Compare S_{CP} and C_{CP} measurements at LHCb (always decoherent) and at Υ(4s)

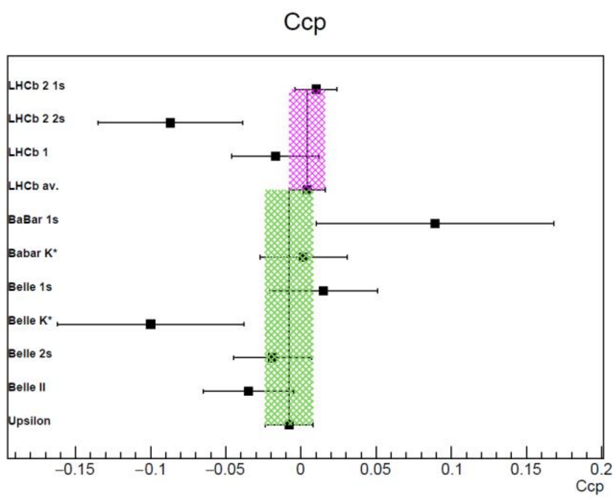


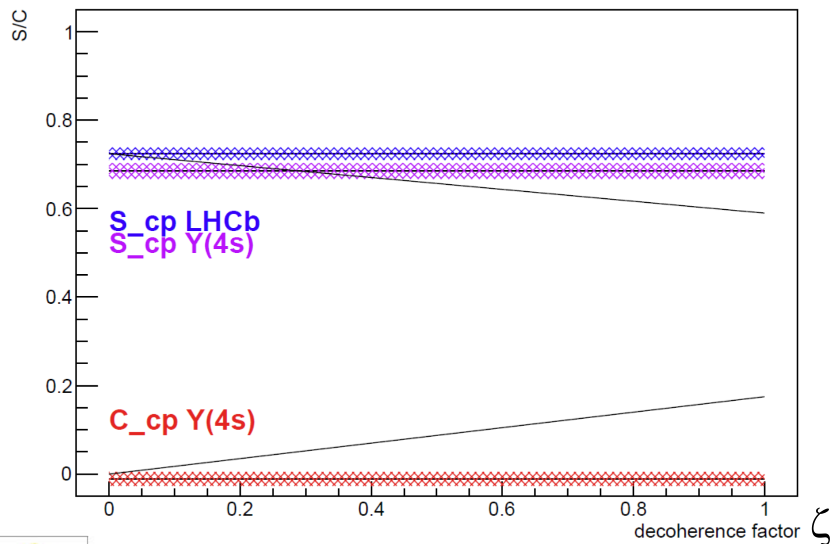
$$(1+q[S\sin\Delta mt - C\cos\Delta mt])$$

$$\left(1+q\left[\frac{\Delta m\Gamma}{2(\Gamma^2+\Delta m^2)}C+\frac{\Delta m^2+2\Gamma^2}{2(\Gamma^2+\Delta m^2)}S\right]\sin\Delta mt_2+q\left[\frac{\Delta m\Gamma}{2(\Gamma^2+\Delta m^2)}S-\frac{\Delta m^2+2\Gamma^2}{2(\Gamma^2+\Delta m^2)}C\right]\cos\Delta mt_2\right)$$

Same damping (0.81) and x-talk factors (0.24) as on slide 3

Compatible with up to 5-20% decoherence, preferred: 10% (1.7σ)





My averages, no correlations!

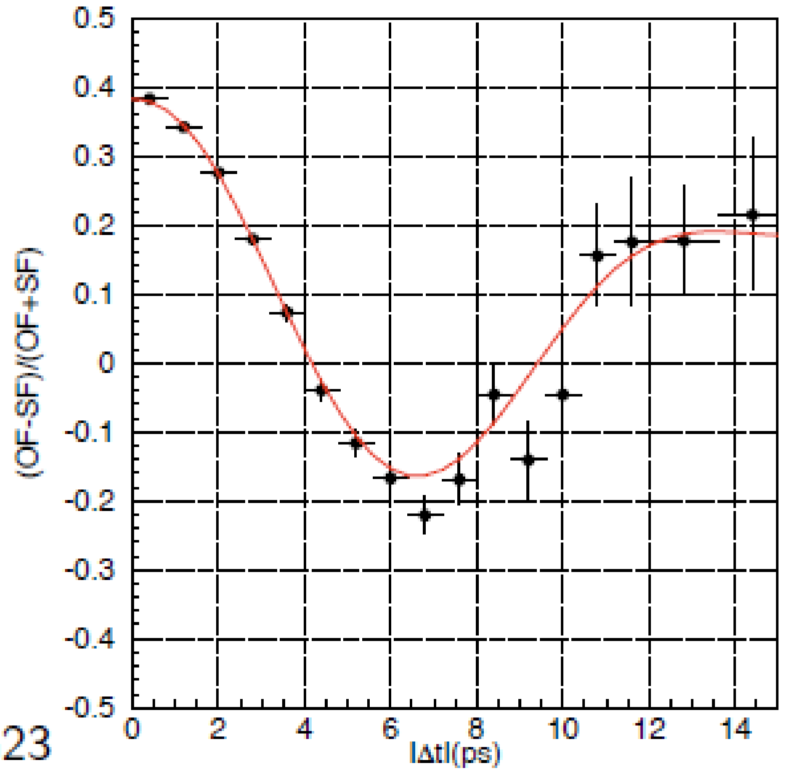
mistag calibration could cancel damping partially!

Belle Analysis

A.Go & Belle, Phys. Rev. Lett 99 (2007) 131802

Belle's most current $\sin 2\phi_1$, $|\lambda|$, τ_B, Δm_d measurement at the time:

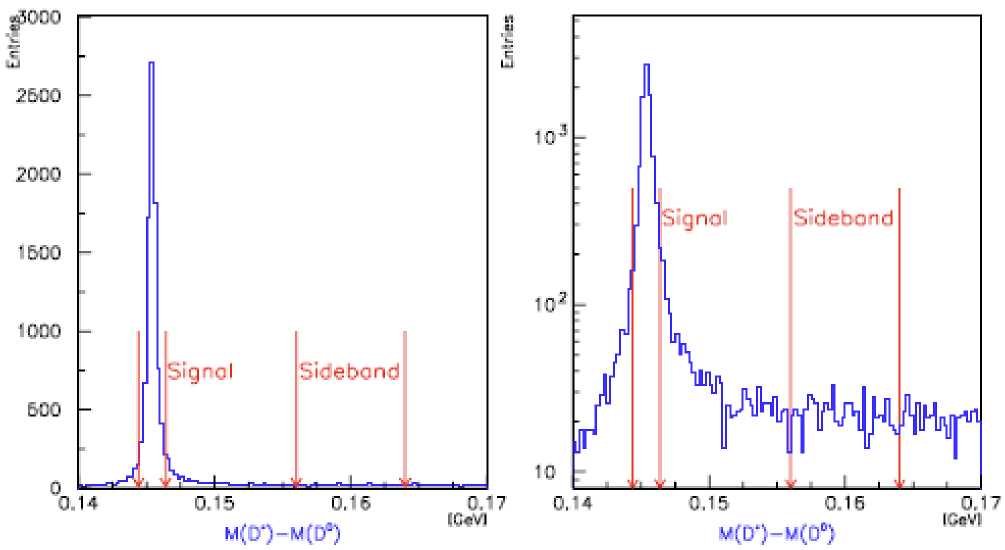
- 152×10^6 $B\overline{B}$ pairs
  - $5\times$ the discovery dataset
  - $\frac{1}{5}\times$ the eventual dataset
- 5417 CP- and 177368 flavour-eigenstate B-decay candidates
- sample purities vary 63–98% depending on the decay mode
- multivariate flavour-tagging of the other B decay; $\epsilon_{eff} = 28.7\%$
- $\Delta m_d = (0.511 \pm 0.005 \pm 0.006)\,\mathrm{ps}^{-1}$
  cf. $(0.5065 \pm 0.0019)\,\mathrm{ps}^{-1}$ PDG23



We then adapted this in various ways ...

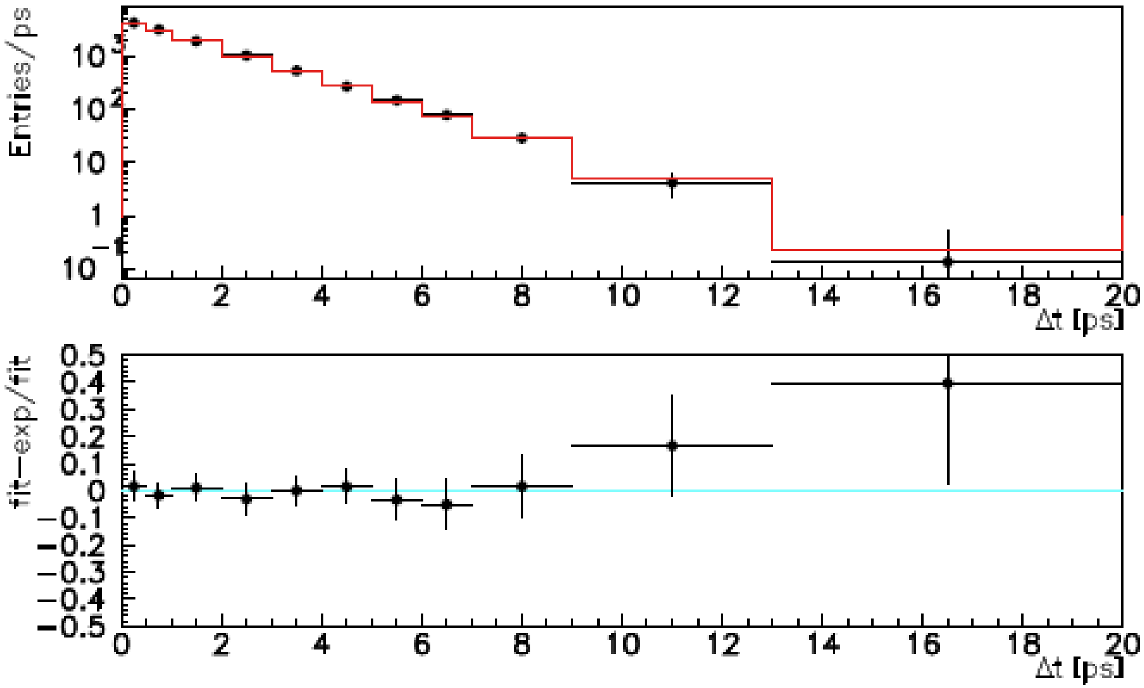
Event Selection

- restrict 177368 → 84823 flavour eigenstates, choosing only $B^0 \to D^{*-}\ell^+\nu$ where the lepton explicitly determines the B-flavour
- restrict 84823 → 8565 by choosing only the best flavour tags of the other B: highest of 7 purity categories; leptons only
- signal relies on $D^{*-} \to \overline{D}^0\pi^-$ tag: energy release $Q \ll m_\pi \ll m_D$
- estimate background under peak using sideband region:



Check: fit B^0 lifetime

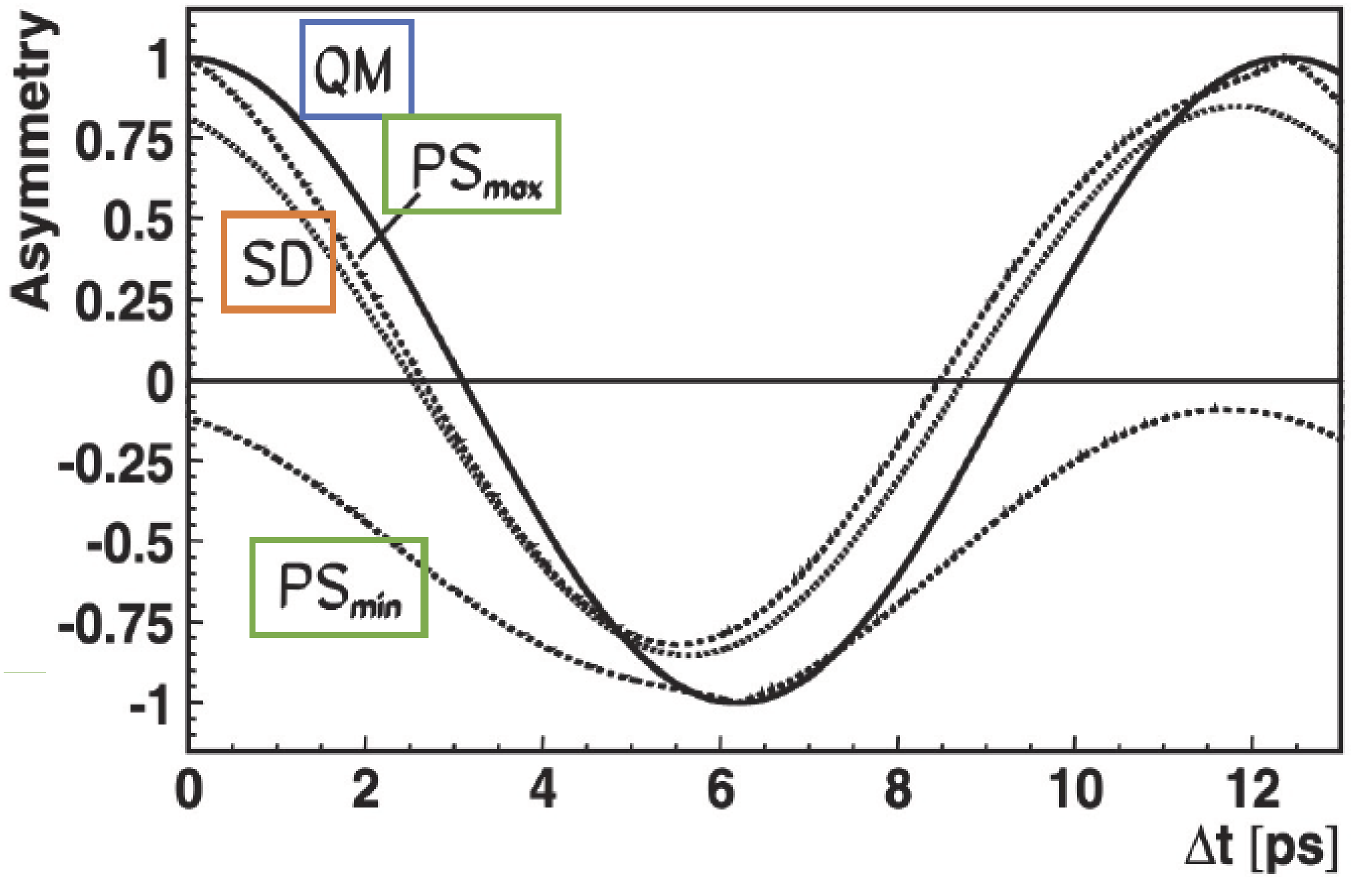
- Background subtraction, deconvolution of Δt resolution, mistag…..
- Fit for the B^0 lifetime:



finds lifetime $\tau_B^0 =$ $(1.532 \pm 0.017)\,\mathrm{ps}$, with $\chi^2/n_{dof} = 3/11$

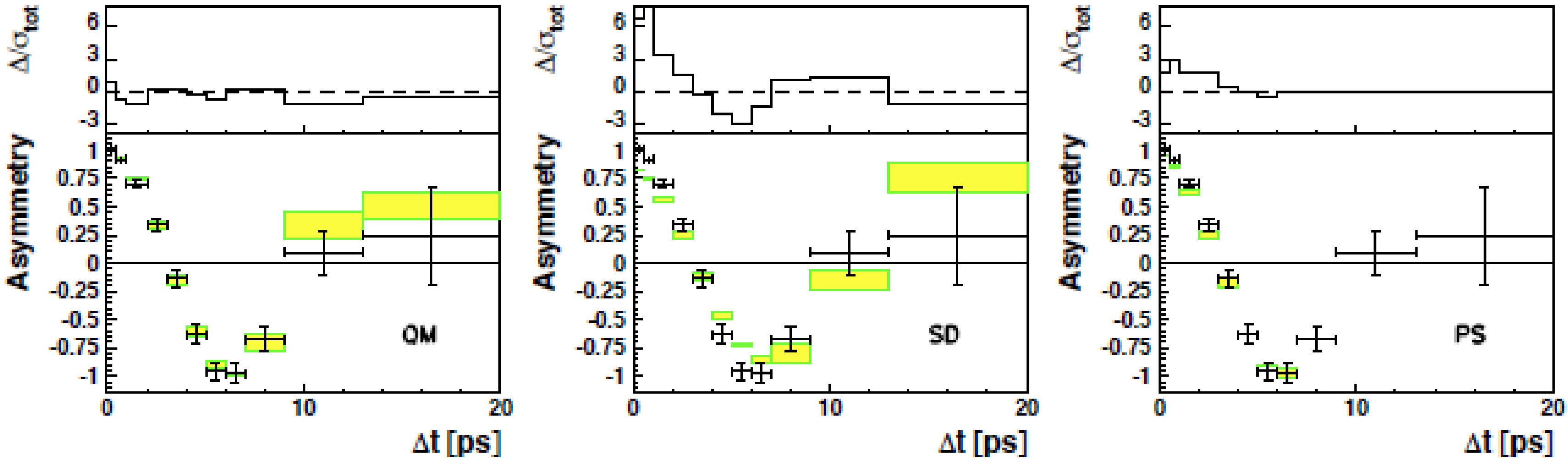
cf. world average $(1.530 \pm 0.009)\,\mathrm{ps}$ from PDG2006

Fit functions



QM: standard quantum mechanical entanglement
SD: spontaneous decoherence
PM: A. Pompili & F. Selleri, Eur. Phys. J. C14, 469 (2000)

Results



QM fits well

$\chi^2/n_{dof} = 5/11$

SD disfavoured: 13σ

$\chi^2/n_{dof} = 174/11$

PS disfavoured: 5.1σ

$\chi^2/n_{dof} = 31/11$

- "SD fraction": $(1 - \zeta_{B^0\overline{B}^0})A_{QM} + \zeta_{B^0\overline{B}^0}A_{SD}$, $\zeta_{B^0\overline{B}^0} = 0.029 \pm 0.057$
- Pompili-Selleri class: QM-like states, stable mass, flavor correlations; QM predictions for *single B-mesons* preserved

What do we learn?

SD excluded by 13σ, but more relevant is the fraction of decoherent events

$f = (1-\zeta)\, A_{QM} + \zeta\, A_{SD}$ $\zeta = 0.029 \pm 0.057$

A fraction of ~10% is still possible!

This could lead to a shift of our S_{cp} measurements by ΔS_{cp} ~ 0.012 (@ Υ(4s))

The total systematic errors of the Belle II J/ψ K_s analysis is 0.014 !

largest single systematic error?

Belle II 362 fb^{-1}, preliminary

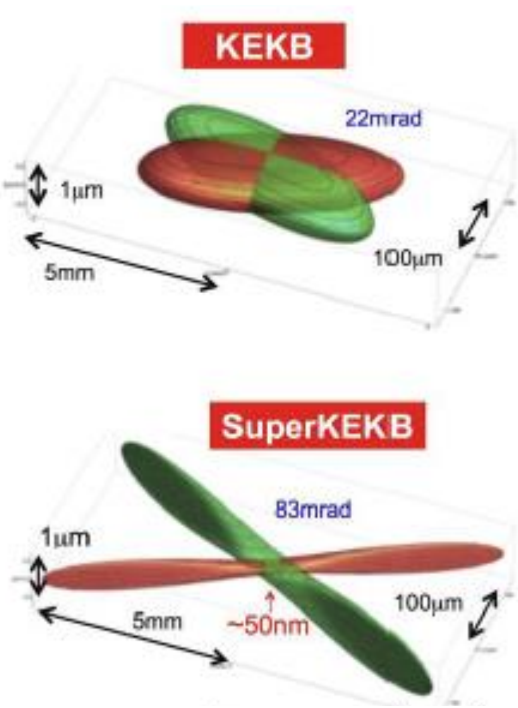
Source	$\sigma(\varepsilon_{tag})$ [%]	$\sigma(S_{CP})$	$\sigma(C_{CP})$
$B^0 \to D^{(*)-}\pi^+$sample size	0.43	0.004	0.007
$B^0 \to J/\psi K^0_S$ sample size		0.035	0.026
Fit model			
Analysis bias	0.02	0.002	0.005
Fixed resolution parameters	0.07	0.004	0.004
τ & Δm_d	0.06	0.001	0.000
$\sigma_{\Delta t}$ binning	0.04	0.000	0.000
Δt measurement			
Alignment	0.06	0.005	0.003
Beam spot	0.16	0.002	0.002
CMS Energy	0.03	0.000	0.001
Backgrounds			
$B^0 \to D^{(*)-}\pi^+$sWeight bias	0.24	0.001	0.001
$B^0 \to D^{(*)-}\pi^+ \Delta E$ background	0.11	0.001	0.001
Signal ΔE shape	0.08	0.002	0.000
Tag-side interference	—	0.010	0.007
Total systematic	0.34	0.014	0.012

Plans @ Belle II

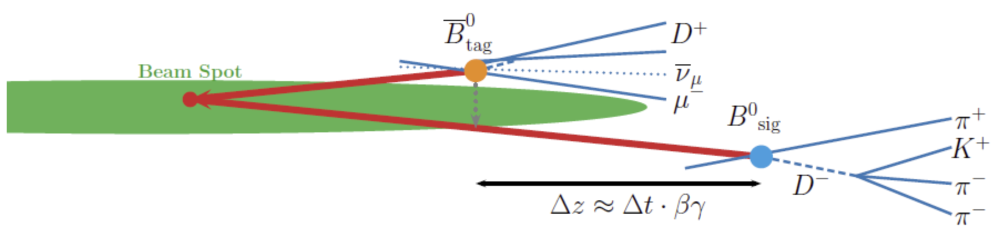
Repeat Belle analysis with higher statistics, more channels, better resolution

$$B^0 \rightarrow D^{-}\pi^{+}, D^{*-}\pi^{+}, D^{*-}\rho^{+}$$

Make use of better vertex resolution and smaller interaction region:



	KEKB	superKEKB
σ_x	150 µm	10 µm
σ_y	940 nm	50 nm
σ_z, eff	7 mm	0.25 mm



$\gamma\beta\tau c$ = 0.125 mm

Not perfect yet, but some chance to limit t_1

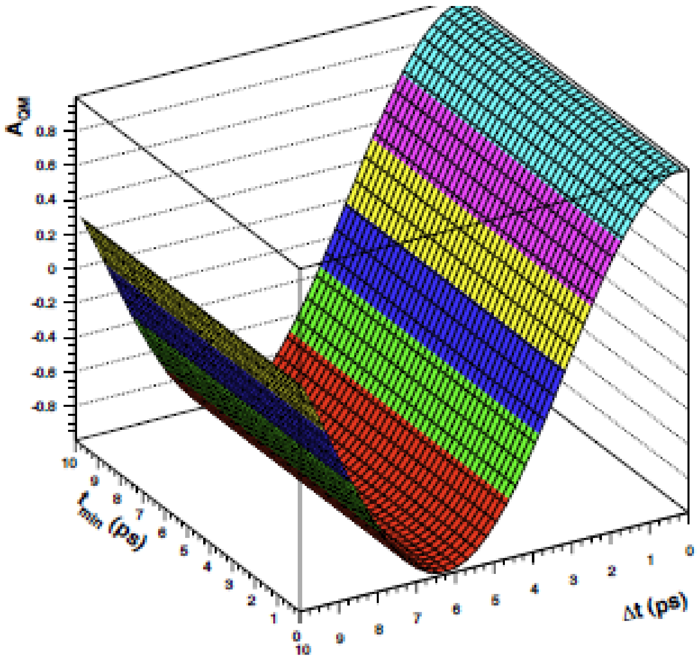
Transverse separation ~50 µm

Vertex resolution σ_{res} ~20 µm

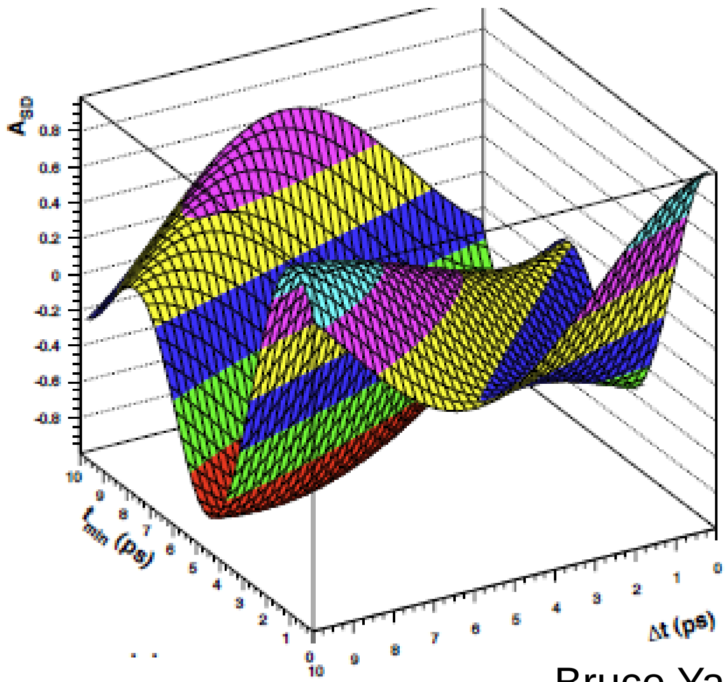
Discrimination Power

Access to t_1 adds a new dimensions and should result higher sensitivity

Asymmetry for QM



Asymmetry for SD



Bruce Yabsley

Entanglement: depends only on Δt

Decoherence: depends on t_1 and Δt

Setting a lower limit on t_1 could also make a check of Bell's inequality possible (randomize)

Conclusions

- ‘Aspect’ style experiments to check Bell’s inequality are not possible with $\Upsilon(4s) \rightarrow B^0 \bar{B}^0$
  - no active measurement (random decay of the B^0): conspiracy loophole!
  - short B^0 lifetime induces correlations which violate Bell’s inequality even for a local realistic scenario.
- QM and alternative models can be tested fitting the time dependence of B^0 oscillations. Belle analysis: alternative scenarios excluded by 13σ (SD) and 5.1σ (PS).
- A fraction of ~10% of decoherent events is still compatible with the data.
- Possible systematic error of our time dependent CP violation measurements (so far not taken into account!).
- Belle II has the potential to improve on this.
- **Questions to theory: what mechanisms (SM or BSM) could lead to a loss of coherence?**

With contributions from Sven Vahsen & team (Hawaii),
Bruce Yabsley (Sidney)
Fumiaki Otani, Takeo Higuchi (IPMU)

Backup: LHCb

Any entanglement destroyed by fragmentation and hadronization

B^0/B(any) system created with many other hadrons: mixed state

Primary Vertex detectable: each B^0 timed independently