iPHE

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BELLE

Measurement of Δm_d with Belle

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Outline

- Introduction (Belle & Δm_d)
- Dilepton measurement
- Semi-leptonic measurement
- $D^*\pi$ partial reconstruction
- Hadronic modes measurement
- Belle and world averages

The Belle Experiment

KEKB:

CMS energy @ $\Upsilon(4S)$

$\beta\gamma = 0.425$

SVD:

$\sigma_z \approx 55\mu m$

for 1 GeV/c at 90°

CDC:

$\sigma_p/p \approx 0.35\%$

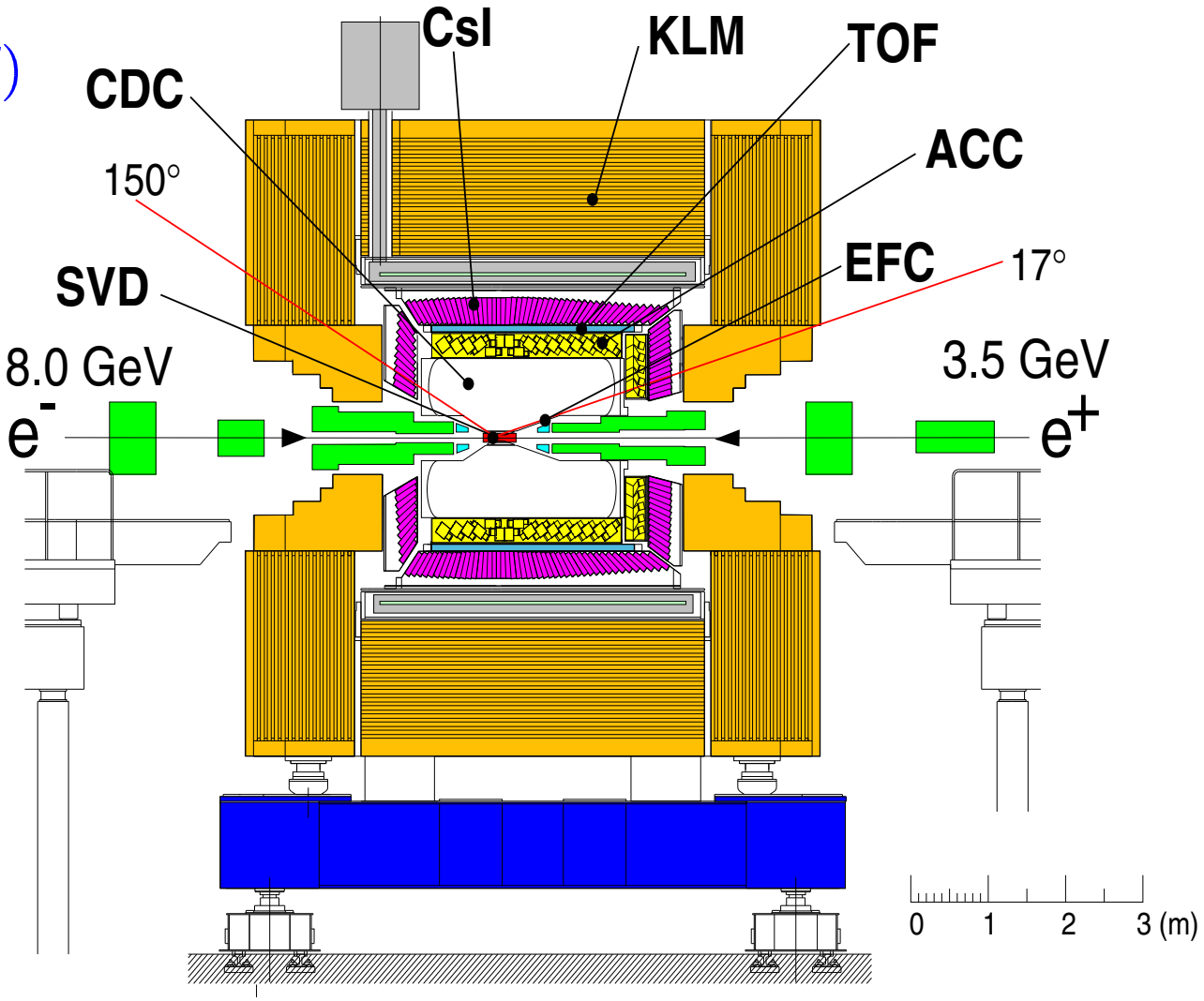
at 1 GeV/c

KLM:

$\epsilon_\mu > 90\%, \sim 2\%$ fakes

Magnet: 1.5 T

Superconducting solenoid



B Mixing basics

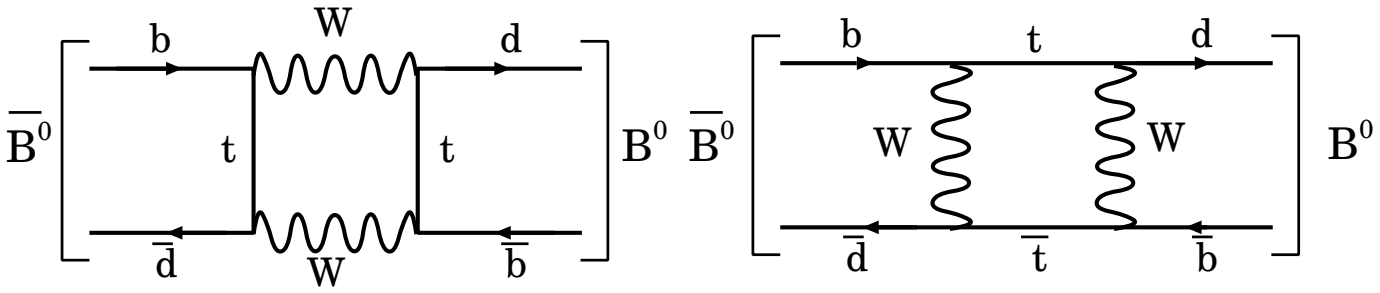
Eigenstates of H^{eff}: $|B_\pm\rangle = p\left|B^0\right\rangle \pm q\left|\overline{B}^0\right\rangle$ (with CPT invariance)

Time evolution of pure $\left|B^0\right\rangle$ state:

$$\left|B^0(t)\right\rangle = g_+(t)\left|B^0\right\rangle + \frac{q}{p}g_-(t)\left|\overline{B}^0\right\rangle$$

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma_d}{2}t\right) \pm \cos(\Delta m_d\, t)\right]$$

In the SM: mixing through second order "box diagrams":

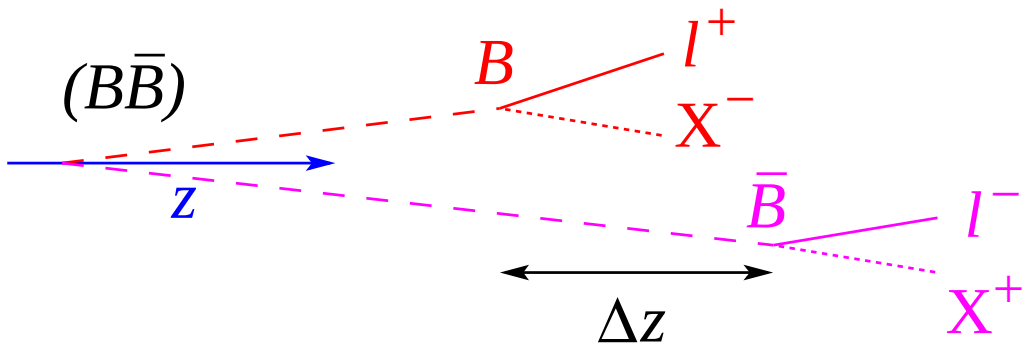


$$\Rightarrow \quad \Delta m_d \propto |V_{tb}^* V_{td}|^2$$

B Mixing At Belle

- Mixing through second order "box diagrams"
- $\Upsilon(4S) \to B^0\overline{B}^0$ pair $\Rightarrow$ evolves into:
  - Same Flavour state: $P^{\rm SF} = \frac{1}{4\tau_{B^0}} e^{\frac{-|\Delta t|}{\tau_{B^0}}} [1 - \cos(\Delta m_d \Delta t)]$
  - Opposite Flavour state: $P^{\rm OF} = \frac{1}{4\tau_{B^0}} e^{\frac{-|\Delta t|}{\tau_{B^0}}} [1 + \cos(\Delta m_d \Delta t)]$

  $\Delta m_d = m(B_H) - m(B_L)$: mass difference between mass eigenstates
- Proper time difference of decays: z separation $\Rightarrow \Delta t \approx \frac{\Delta z}{\beta\gamma c}$



- B flavour: from flavour specific decay modes.

Dilepton Analysis – Selection

Selection Criteria and Classification ($B^0 \to X^- l^+ \nu_l$ on each side)

Tags: two fast leptons ($1.1 < p^* < 2.3$ GeV/c)

Proper time: z separation ("IP constrained fit" for each lepton)

"Signal": primary leptons from $B^\pm$ (OF) or B^0 (OF and SF)

Background:
– secondary lepton(s)
– fake lepton(s)

Selection Result on 29.4 + 3.0 fb^{-1} (31.9M B$\overline{\text{B}}$)

Leptons type	on-resonance		off-resonance	
	SF	OF	SF	OF
ee	9877	52141	107	1513
$\mu\mu$	15503	65435	1464	4452
$e\mu$	24458	113305	976	4404
Total	**49838**	**230881**	**2548**	**10368**

Dilepton Analysis – Fitting procedure

Signal PDFs: Analytical function $*$ resolution function (from J/ψ)

$$B^{\pm}: \quad N_{\Upsilon(4S)} \cdot f_{+} \cdot b_{+}^{2} \cdot \eta^{+} \cdot \frac{e^{-|\Delta t|/\tau_{\mathrm{B}^{+}}}}{2\tau_{\mathrm{B}^{+}}} * R(\Delta t)$$

$$B^{0}: \quad N_{\Upsilon(4S)} \cdot f_{0} \cdot b_{0}^{2} \cdot \eta^{\mathrm{unm(mix)}} \cdot \frac{e^{-|\Delta t|/\tau_{\mathrm{B}^{0}}}}{4\tau_{\mathrm{B}^{0}}}(1 \pm \cos(\Delta m_{d}\,\Delta t)) * R(\Delta t)$$

Background PDFs: from Monte Carlo (with corrections)

Experimental parameters:

Signal: η^{+} (OF), η^{unm} (OF), η^{mix} (SF) $\longrightarrow$ *fixed ratios*

Background:
- correct tag: $\epsilon^{+}_{\mathrm{OF}}$, $\epsilon^{\mathrm{mix}}_{\mathrm{SF}}$, $\epsilon^{\mathrm{unm}}_{\mathrm{OF}}$ $\longrightarrow$ *fixed ratios*
- wrong tag: $\epsilon^{+}_{\mathrm{SF}}$, $\epsilon^{\mathrm{unm}}_{\mathrm{SF}}$, $\epsilon^{\mathrm{mix}}_{\mathrm{OF}}$ $\longrightarrow$ *fixed ratios*
- continuum contribution $\longrightarrow$ *fixed*

$\Longrightarrow$ Binned maximum likelihood with Δm_{d}, f_{+}/f_{0}, $\eta^{+}/\epsilon^{+}_{\mathrm{OF}}$, $\eta^{+}/\epsilon^{+}_{\mathrm{SF}}$

Dilepton Analysis – Fit result

Preliminary! BELLE-CONF 0205

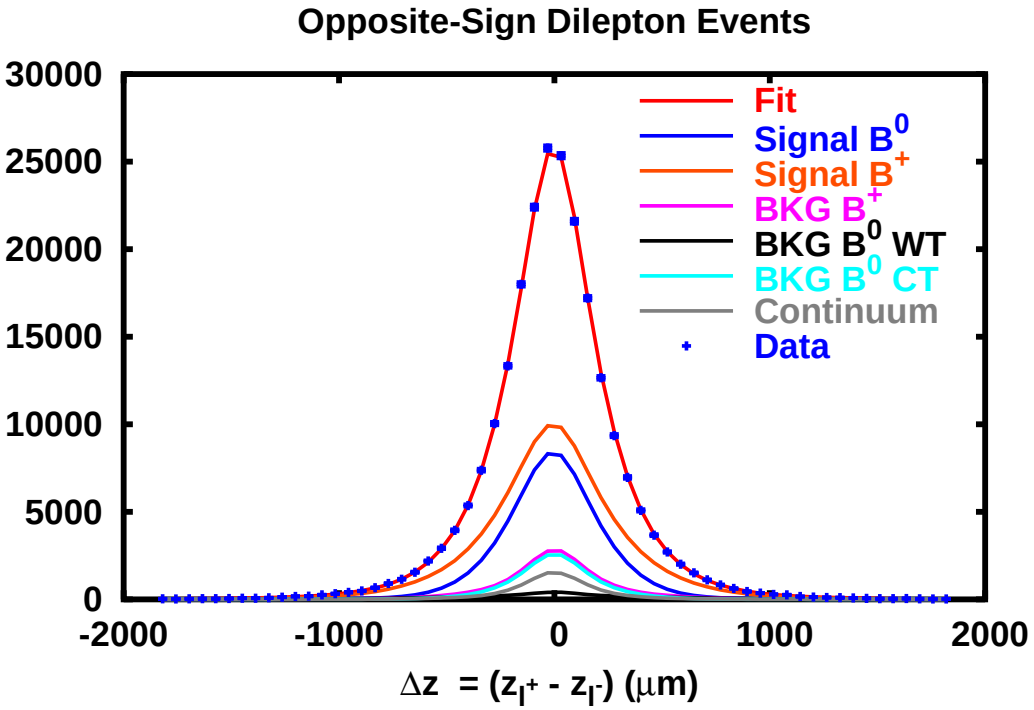
$$\Delta m_d = 0.503 \pm 0.008 \pm 0.009 \text{ ps}^{-1}$$

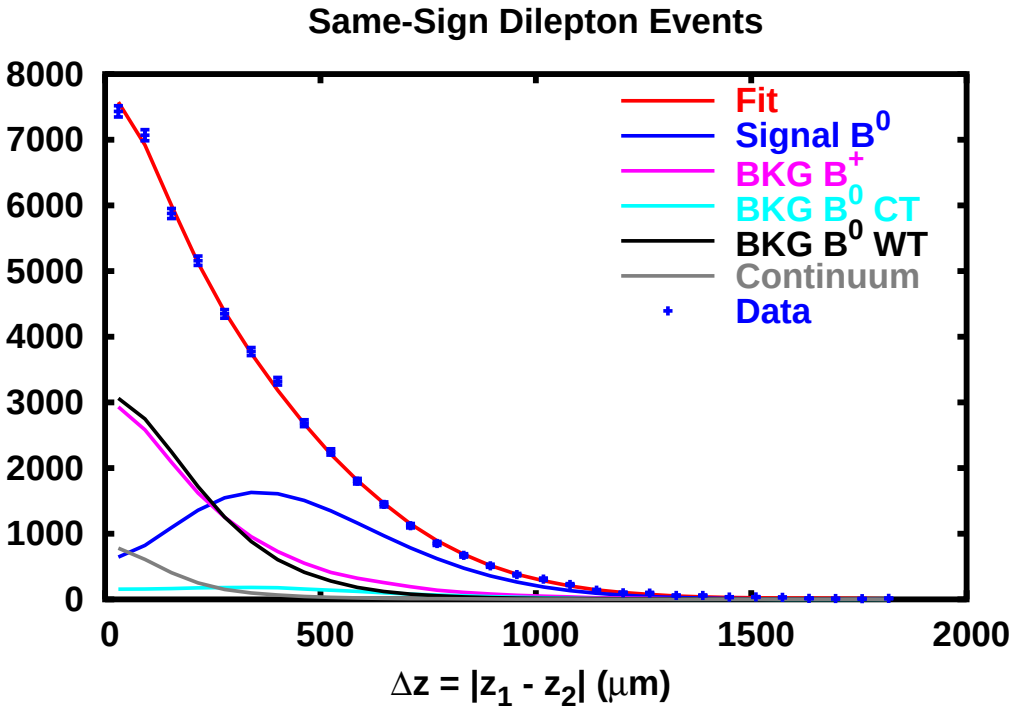
$$f_+/f_0 = 1.01 \pm 0.03 \pm 0.08$$

$$\chi^2/ndf = 139/86$$

Main systematics

Source	Δm_d	f_+/f_0
τ_{B^0}/τ_{B^+}	± 0.005	± 0.07
Δz resolution	± 0.005	± 0.02
MC stat	± 0.004	± 0.01
MC Δz resol.	± 0.003	± 0.02





Dilepton Analysis – CPT Fit

Neutral B signal PDFs:

replace "$\cos(\Delta m_d\,\Delta t)$" by:

$$|\cos\theta|^2 + (1 - |\cos\theta|^2)\cos(\Delta m_d\,\Delta t) - 2Im(\cos\theta)\sin(\Delta m_d\,\Delta t)$$

θ complex, CPT violated if $\theta \neq \frac{\pi}{2}$

Fit result:

$$\begin{aligned} \Delta m_d &= 0.503 \pm 0.08\ \text{ps}^{-1}\ \text{(stat. only)} \\ f_+/f_0 &= 1.02 \pm 0.03\ \text{(stat. only)} \end{aligned}$$

$$\begin{aligned} Re(\cos\theta) &= 0.00 \pm 0.12 \pm 0.01 \\ Im(\cos\theta) &= 0.03 \pm 0.01 \pm 0.02 \end{aligned}$$

Belle limits on CPT-violation: Preliminary!

$$|Re(\cos\theta)| < 0.197 \implies \left|\frac{m_{B^0} - m_{\overline{B}^0}}{m_{B^0}}\right| < 1.20 \cdot 10^{-14} \quad \text{(90\% CL)}$$

$$|Im(\cos\theta)| < 0.059 \implies \left|\frac{\Gamma_{B^0} - \Gamma_{\overline{B}^0}}{\Gamma_{B^0}}\right| < 0.09 \quad \text{(90\% CL)}$$

Semi-leptonic Analysis

Signal: full reconstruction

hep-ex/0207045
BELLE-CONF 0203

$$B \to D^{*-} l^+ \nu_l$$
$$D^{*-} \to \overline{D}^0 \pi^-$$
$$\overline{D}^0 \to K^+\pi^-,\ K^+\pi^-\pi^0 \text{ or } K^+\pi^-\pi^+\pi^-$$

$$\cos\theta_{B,D^*l} = \frac{(E^*_B - E*_{D^*l})^2 - |\vec{p}^*_B|^2 - |\vec{p}^*_{D^*l}|^2}{2|\vec{p}^*_B||\vec{p}^*_{D^*l}|}$$

+ *flavour tag* on opposite side (multi-dimensional likelihood)

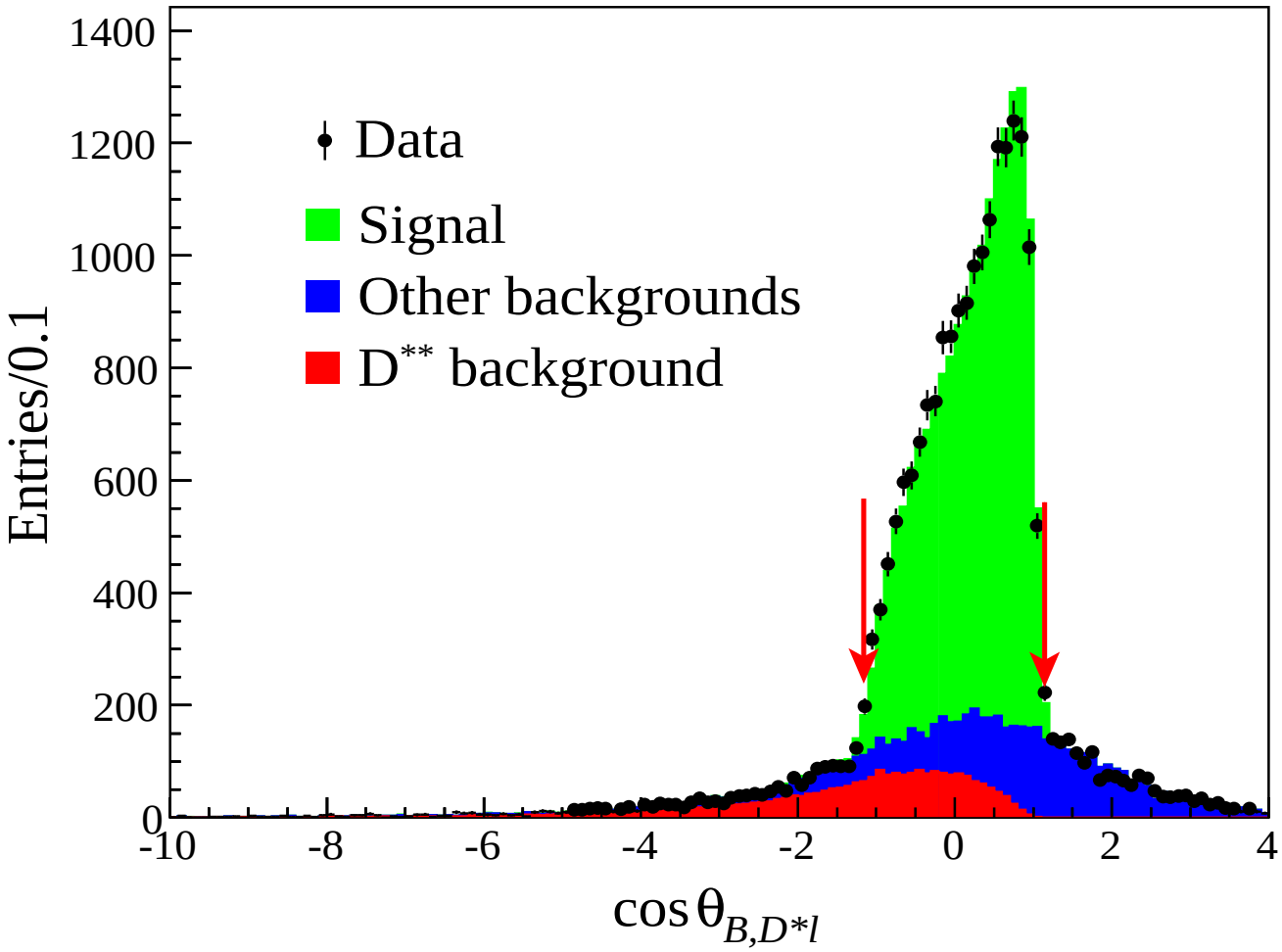
Backgrounds:

Fraction	*Type*	*Estimation*
7.8%	fake D^*	D^0 side-bands & wrong-sign comb.
2.6%	random D^*l	from $\cos\theta_{B,D^*_l}$: uncorrelated
7.4%	$B \to D^{**}l\nu$	fit $\cos\theta_{B,D^*_l}$
1.8%	continuum	from off-resonance data

Semi-leptonic – Background fractions

Candidates: 16397 events
of 31.3M $B\overline{B}$

Purity: 80.4%



$|\cos\theta_{B,D^*l}| < 1.1$

Semi-leptonic – Fitting

Signal PDF:

$$P^{\mathrm{OF(SF)}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 \pm (1 - 2\omega_l)\cos(\Delta m_d\, \Delta t)\right]$$

$l = 1, \ldots, 6$: classes of flavour-tagging "dilution factors"

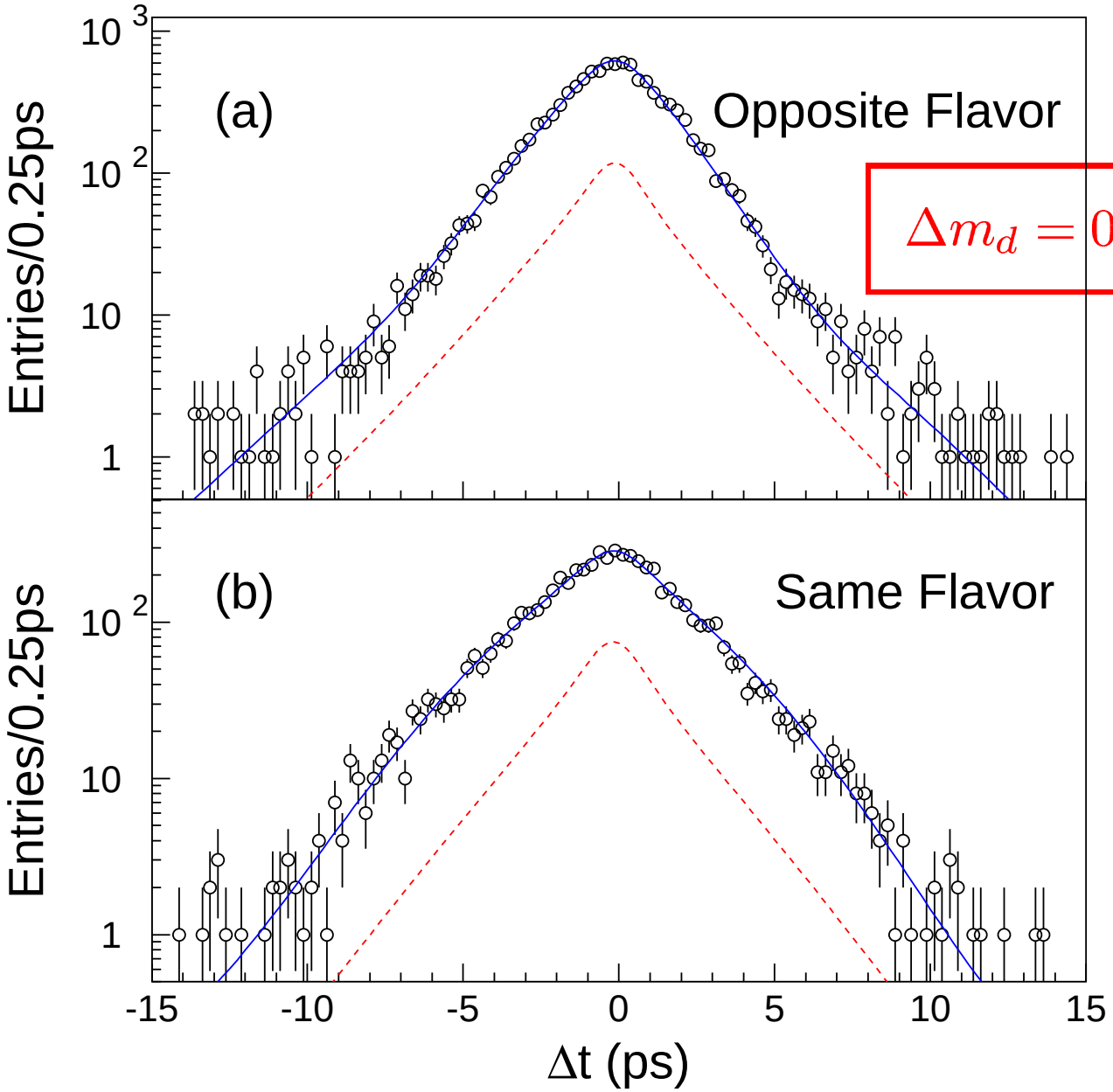
Resolution function: double gaussian from *untagged* Δt distribution.

Unbinned likelihood fit:

$$L_i^{\mathrm{OF(SF)}} = (1 - f_{\mathrm{bg}}^l)\left[(1 - f_{D^{**}}^l) F_{\mathrm{sig}}^{\mathrm{OF(SF)}}(\Delta t_i) + f_{D^{**}}^l F_{D^{**}}^{\mathrm{OF(SF)}}(\Delta t_i)\right]$$
$$+ f_{\mathrm{bg}}^l \sum_k f_k^l f_{lk}^{\mathrm{OF(SF)}} F_k^{\mathrm{OF(SF)}}(\Delta t_i) \qquad (f_{lk}^{\mathrm{OF}} + f_{lk}^{\mathrm{SF}} = 1)$$

$\Longrightarrow$ simultaneous fit to signal region and D^{**} dominated region of Δm_d, ω_l and bkg. normalisations

Semi-leptonic – Fit Result



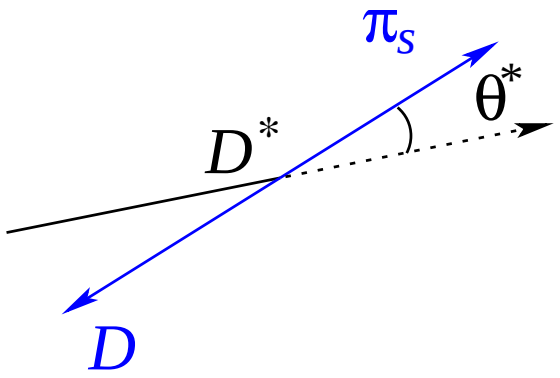
$$\Delta m_d = 0.494 \pm 0.012 \pm 0.015 \text{ ps}^{-1}$$

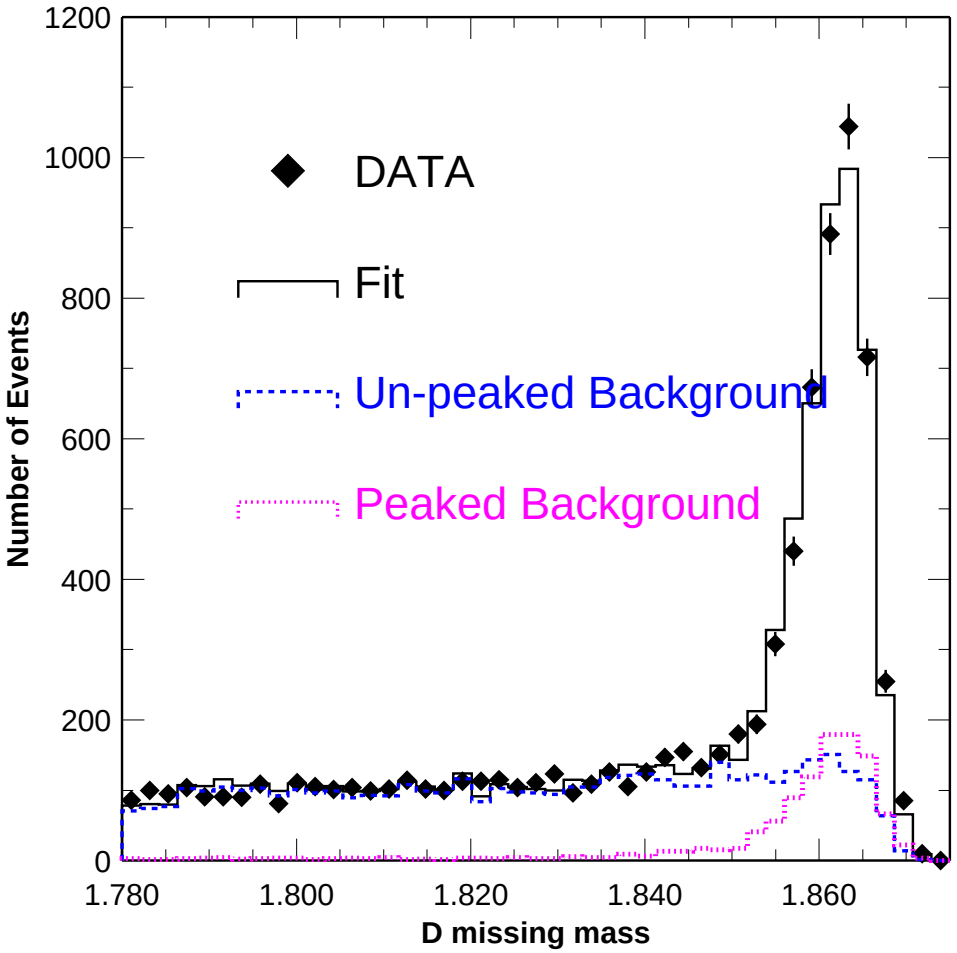
Partial reconstruction

$B^0 \to D^{*-}\pi_f^+, D^{*-} \to D^0\pi_s^-$

$\Rightarrow$ use D^0 missing mass and "helicity" angle $\theta^*_{\pi_s}$

$+ B^0 \to X^+ l^- \nu$ on opposite side (fast lepton)





Candidates: 4889 events
of 31.3M $B\overline{B}$

Signal yield (from fit): 3433±81 events

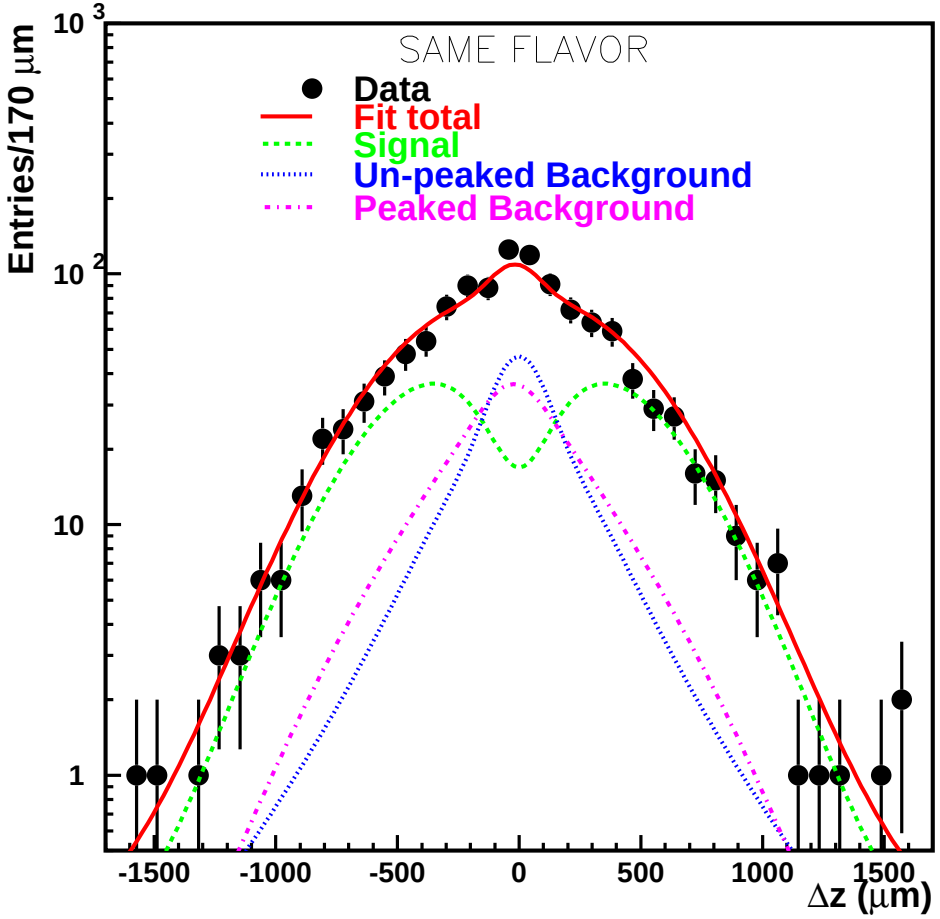
Purity: 70%

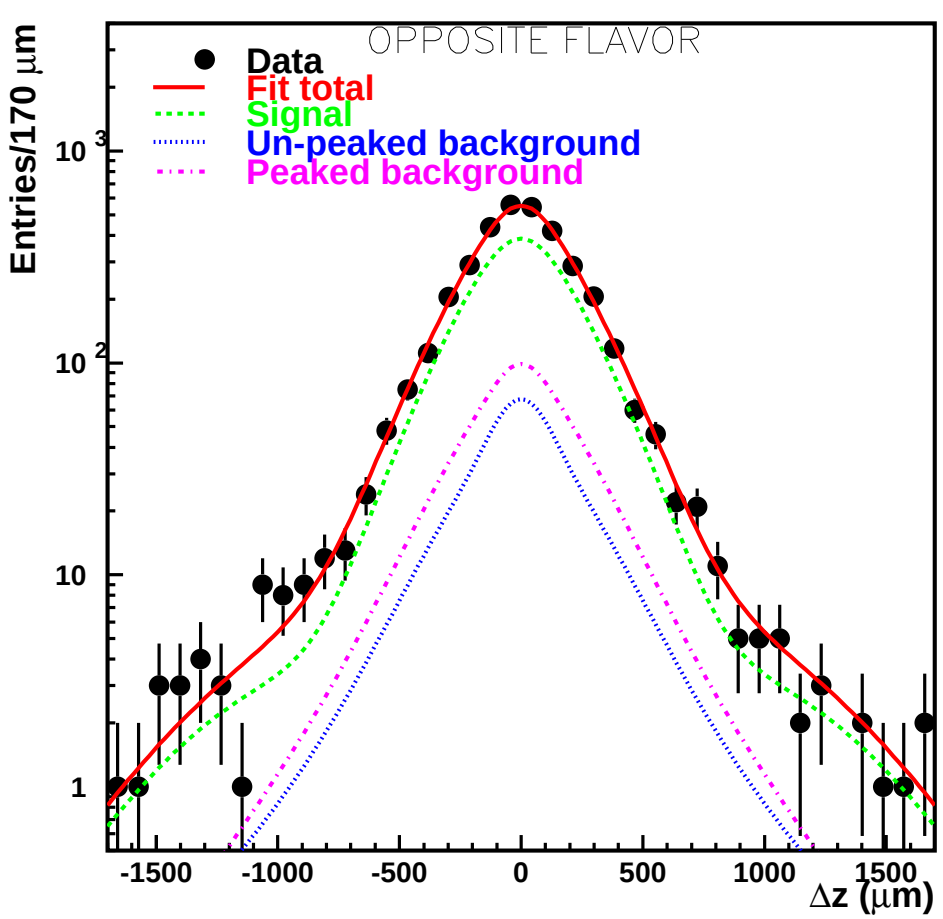
Peaked bkg.:
$B^0 \to D^{*-} l^+ \nu_l, D^{**-}\pi^+$

Partial reconstruction - Result

BELLE-CONF 0204

$$\Delta m_d = 0.505 \pm 0.017 \pm 0.020 \text{ ps}^{-1}$$





Will also be used to extract $\arg\left(-\frac{V_{ub}^* V_{cd}}{V_{cb} V_{ud}^*} \frac{V_{td}^* V_{tb}}{V_{td} V_{tb}^*}\right) = 2\phi_1 + \phi_3$

Hadronic Modes

Full reconstruction of:

hep-ex/0207022 (to appear in PLB)
BELLE-CONF 0206

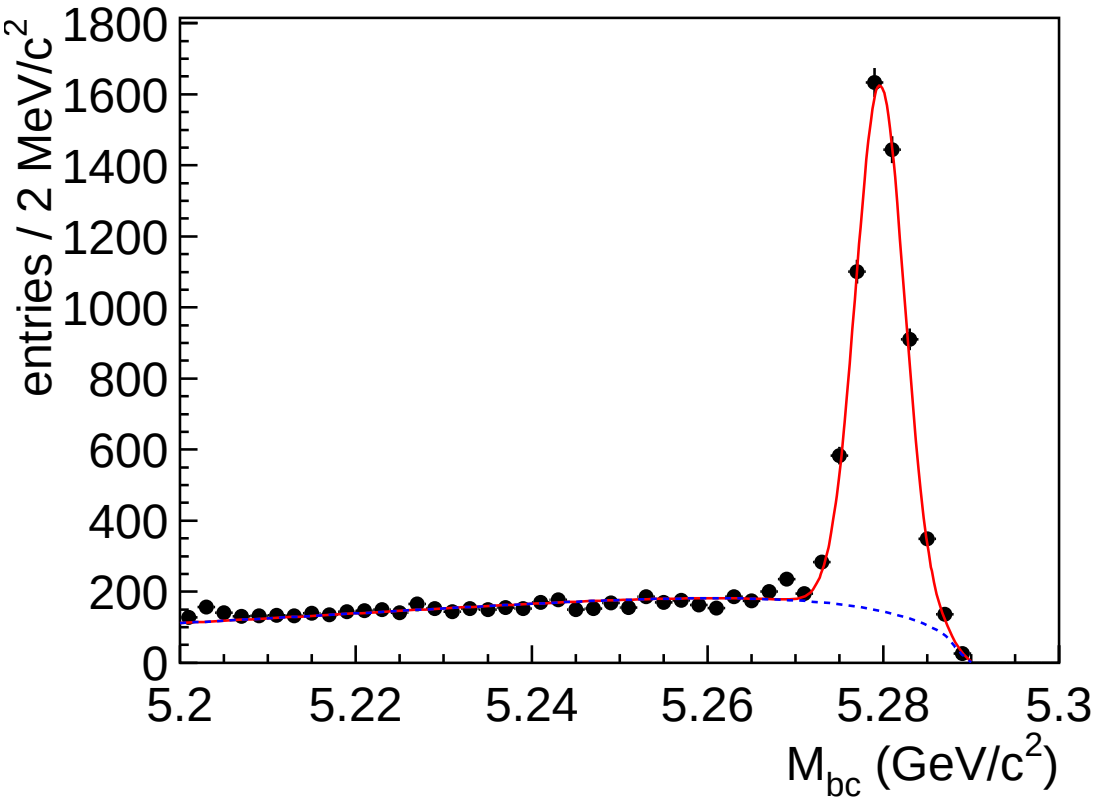
$$\overline{B}^0 \to D^+(K^-\pi^+\pi^+)\pi^-$$
$$D^{*+}\pi^-, \rho^-(\pi^-\pi^0)$$
$$D^{*+} \to D^0\pi^+$$
$$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$$

+ *flavour tagging*
on the opposite side

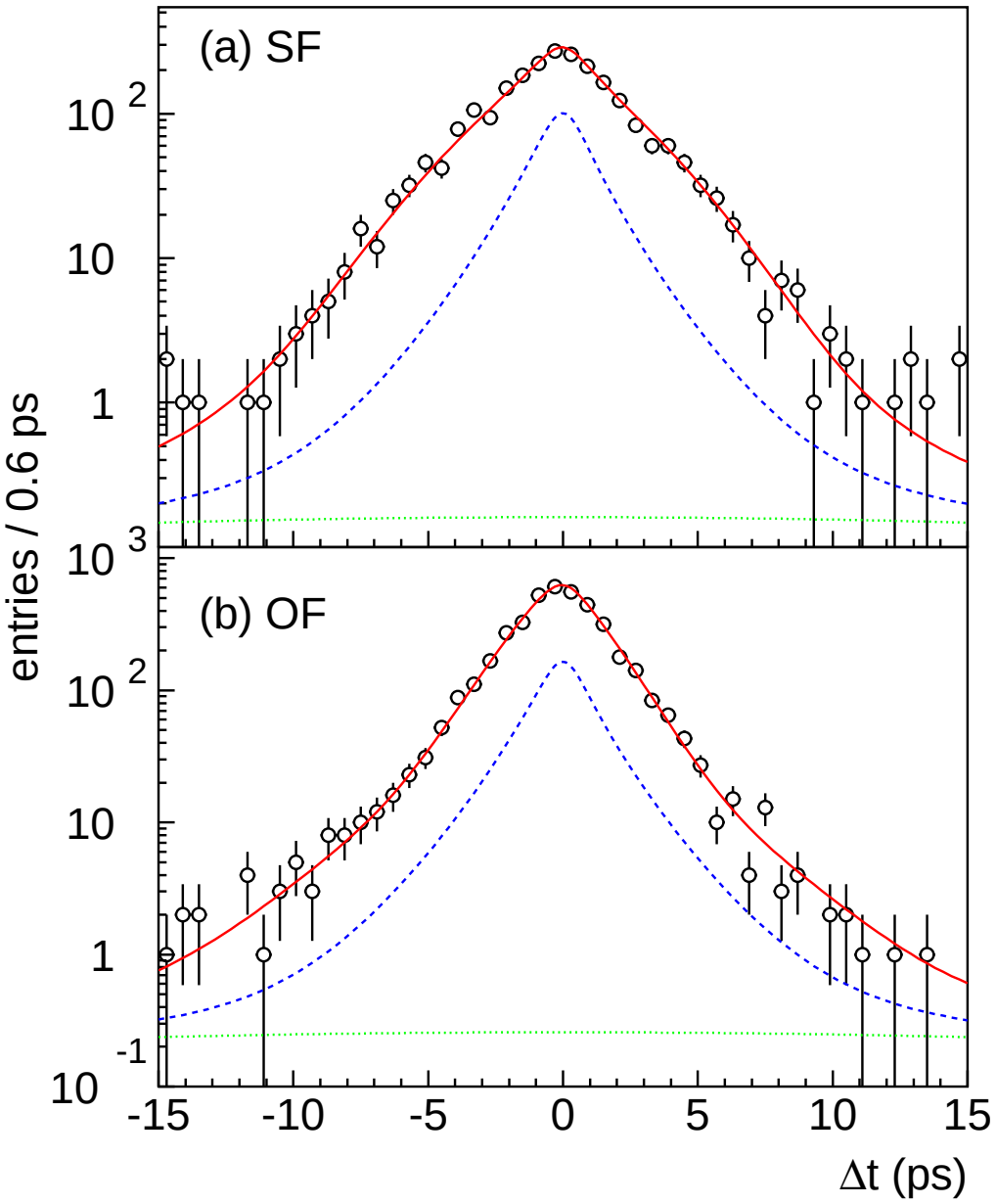
$$\Delta E = E_B^* - E_{\rm beam}^*$$
$$M_{\rm bc} = \sqrt{{E_{\rm beam}^*}^2 - {p_B^*}^2}$$

Candidates: 6660 events
of 31.3M $B\overline{B}$

Purity: 79%

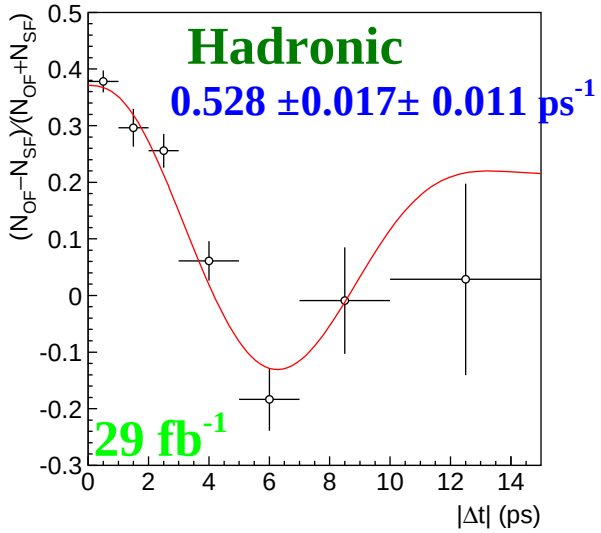


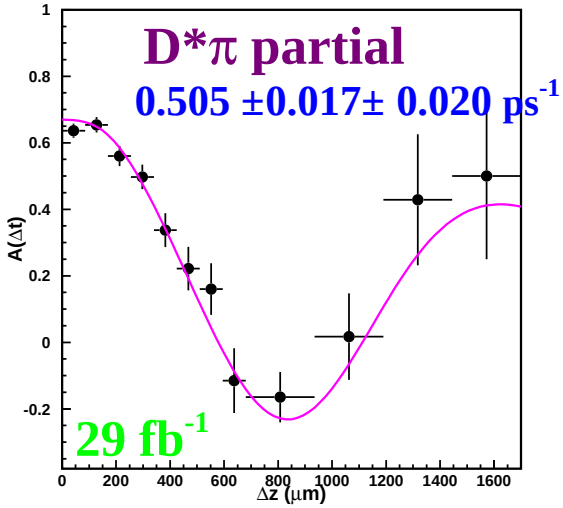
Hadronic Modes - Result

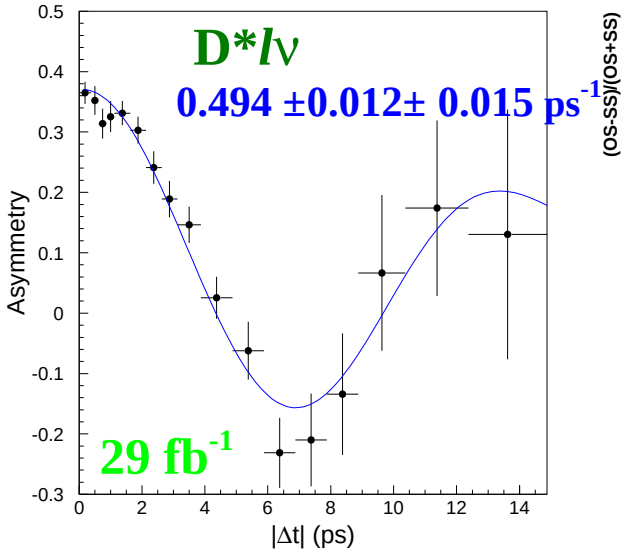


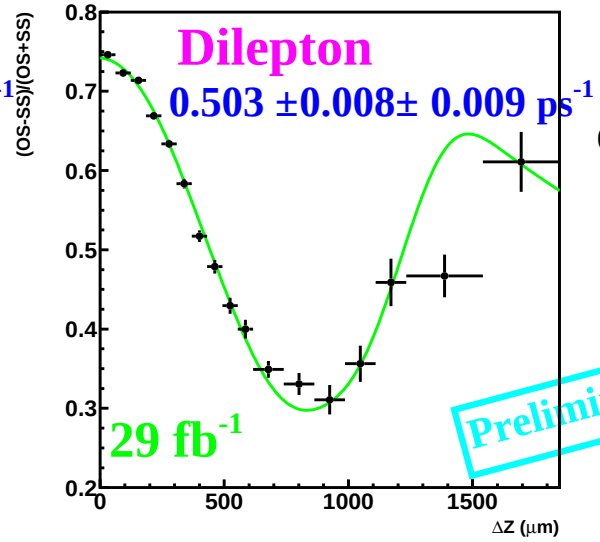
$$\Delta m_d = 0.528 \pm 0.017 \pm 0.011 \text{ ps}^{-1}$$

Belle Summary









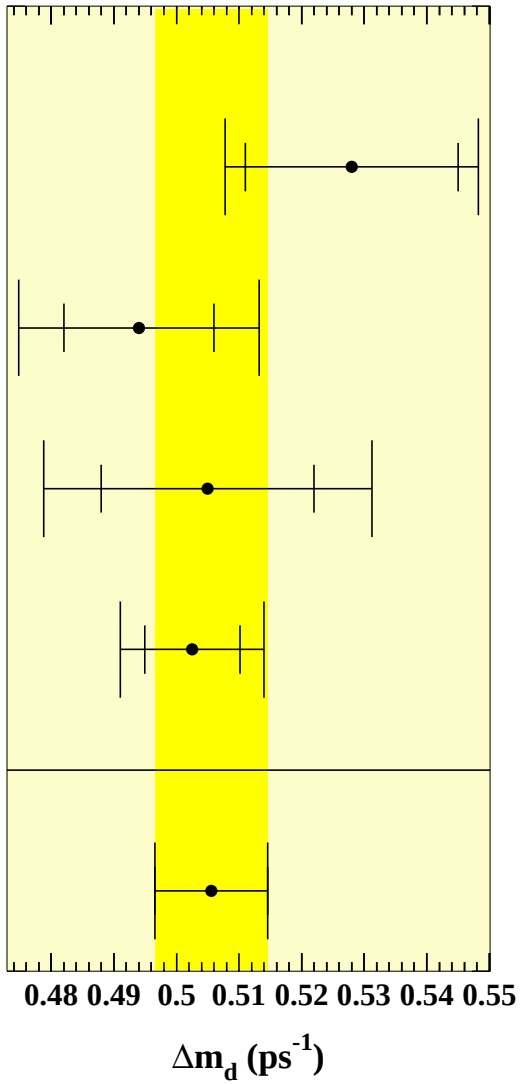
B^0_d(full)/comb
$0.528 \pm 0.017 \pm 0.011$ ps^{-1}
(31M $B\bar{B}$)

D^*lν/comb
$0.494 \pm 0.012 \pm 0.015$ ps^{-1}
(31M $B\bar{B}$)

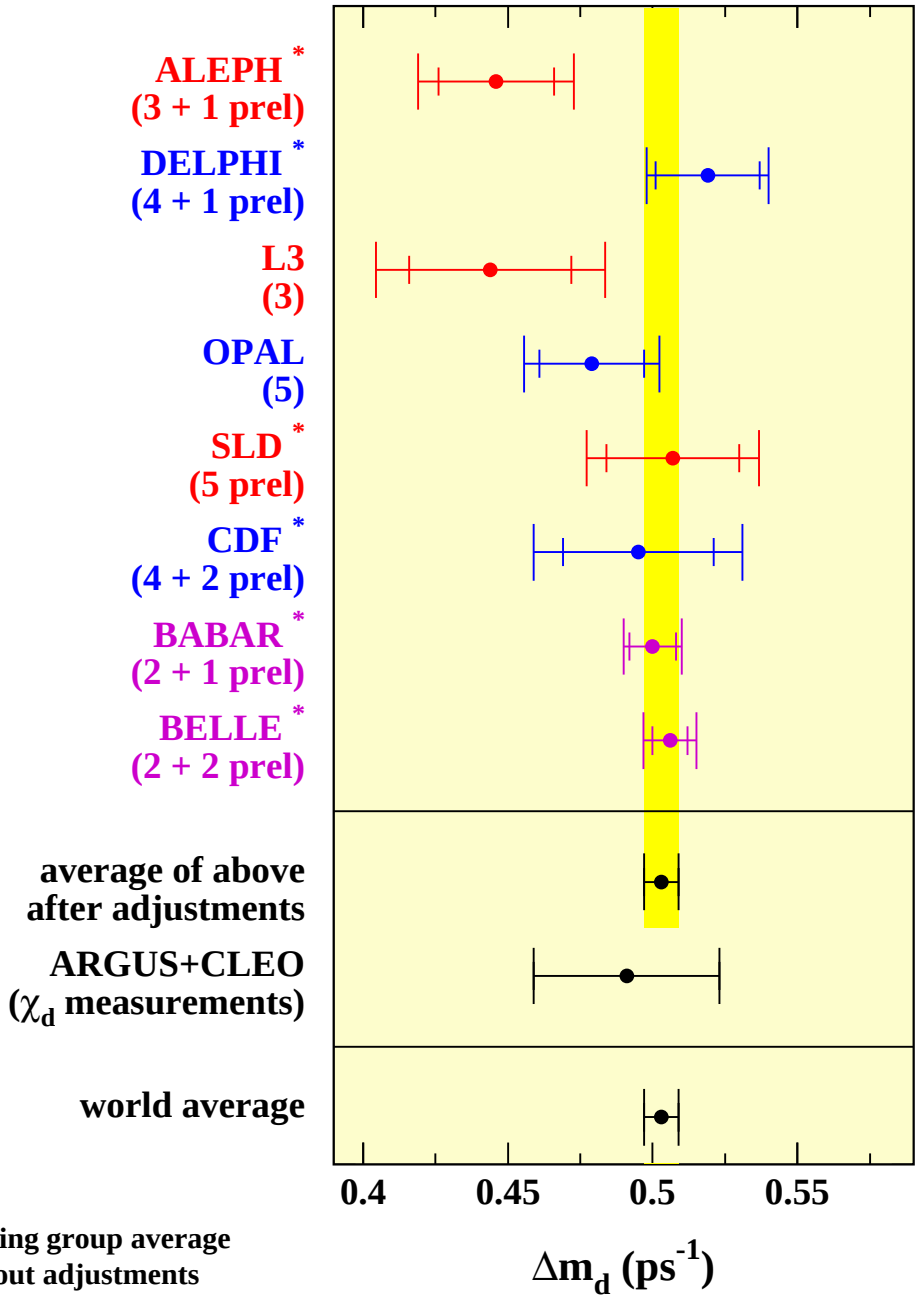
$D^*\pi$(part)/l
$0.505 \pm 0.017 \pm 0.020$ ps^{-1}
(31M $B\bar{B}$ prel)

l/l
$0.503 \pm 0.008 \pm 0.009$ ps^{-1}
(32M $B\bar{B}$ prel)

BELLE average
0.506 ± 0.009 ps^{-1}



World Average



LEP+SLD+CDF:
0.498 ± 0.013 ps^{-1}

BaBar+Belle:
0.503 ± 0.007 ps^{-1}

World: 0.503 ± 0.006 ps^{-1}

* working group average without adjustments