Neutral B_d Mixing: Δm_d

Past Measurements & SuperB Projections

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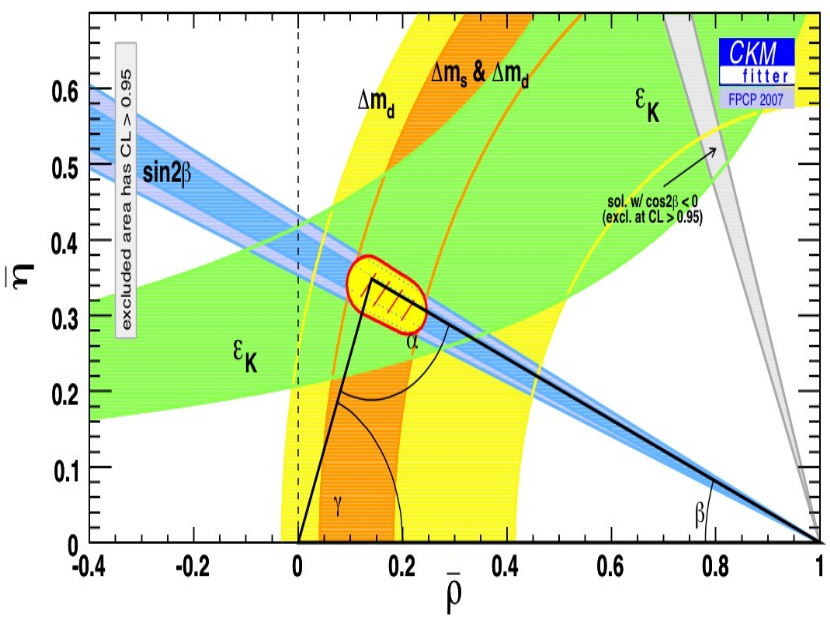
Outline

- Motivation: Precision Measurement of Vtd in CKM.
- History of Measurements of Δm_d .
- B-Factory - Inclusive Measurement: Dileptons
- B-Factory - Loose reconstruction: $D^*\ell\nu$ & $D^*\pi$
- B-Factory - Fully reconstructed B decays
- Tevatron result, and LHCb projection
- Outlook for SuperB measurements with 10, 75 iab.
- Conclusions

Motivation 1

- Δm_d and Δm_s are among the best experimental handles we have for Vtd and Vts of the CKM Matrix.

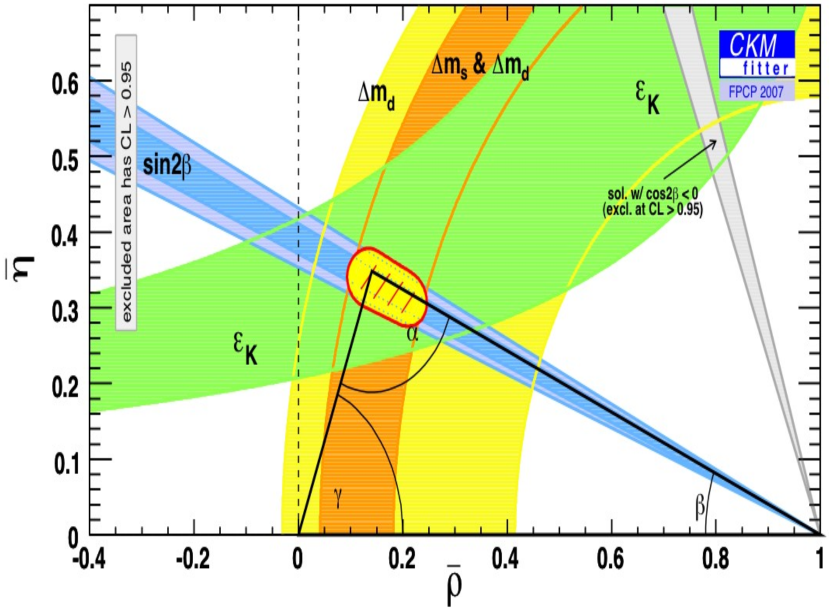
$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2 =$$
$$= \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{cb}|^2 \lambda^2 \left((1-\bar{\rho})^2 + \bar{\eta}^2\right)$$



- B->dγ and B->sγ also measure Vtd and Vts, but have different hadronic factors, and larger experimental errors.
- Vtd and Vts determine the length of the upper side, and combined with sin(2β) probe the (ρ,η) corner of the UT.

Motivation 2

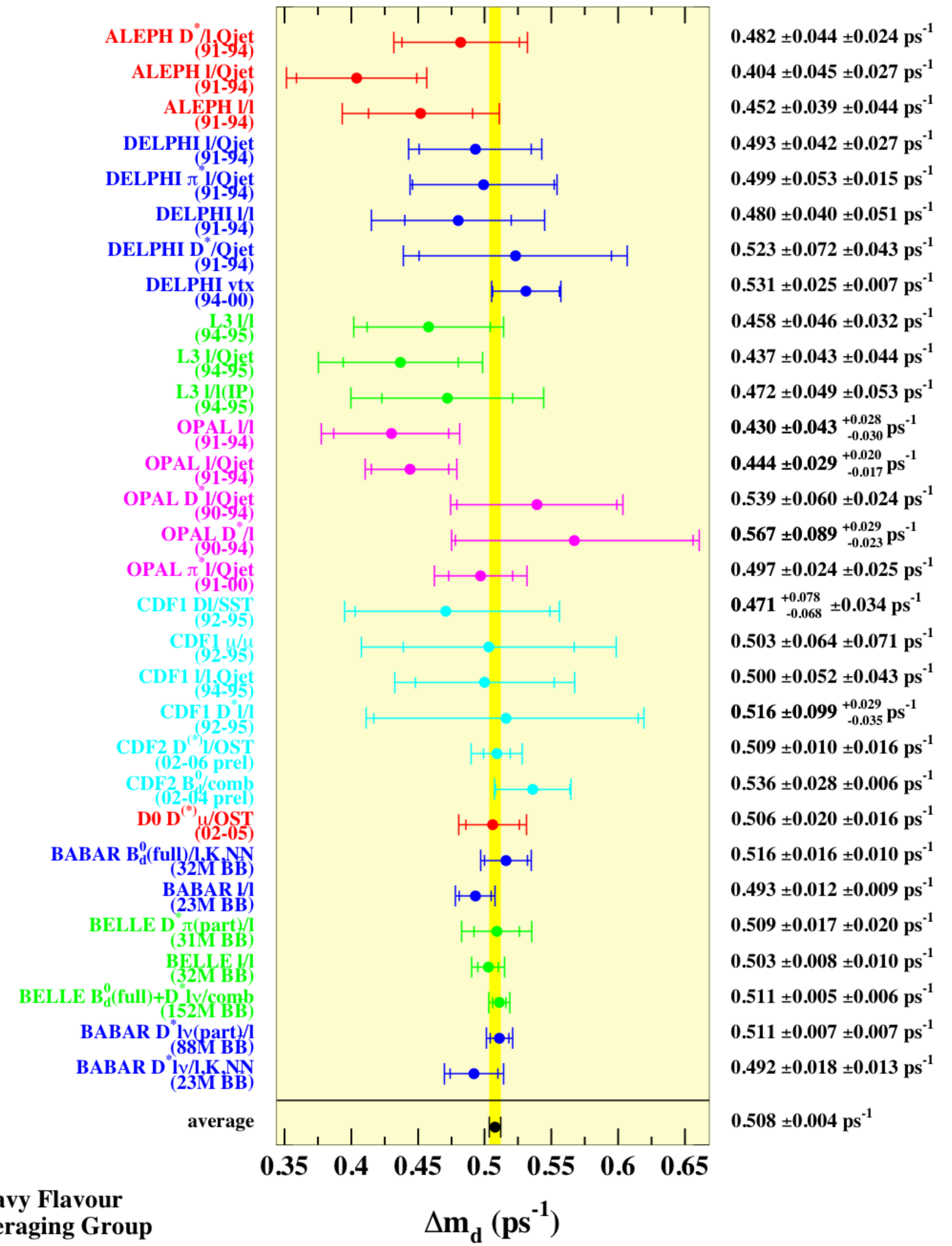
- The uncertainty (width of the circle) is currently limited by the lattice calculations of the hadronic factors $f_B^2 B_B$.
- For the ratio, $\Delta m_d/\Delta m_s$ the uncertainty in the lattice hadronic quantities is less than for either individual frequency (1/3rd).
- LHCb will measure Δm_s precisely, ideally Δm_d should be too.



$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{td}|^2}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s} |V_{ts}|^2} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\lambda^2/2}\right)^2 \frac{((1-\bar{\rho})^2+\bar{\eta}^2)}{\left(1+\frac{\lambda^2}{1-\lambda^2/2}\bar{\rho}\right)^2+\lambda^4\bar{\eta}^2}$$

History

- Long history of B mixing studies, from 1994-today.
- Early measurements were mostly time-integrated.
- New precision era began with time-dependent measurements at B-Factories.
- PDG 2008: $\Delta m_d = 0.507 \pm 0.003$ (stat) $\pm$ 0.003 (syst)
- An improved measurement needs $\leq$ 1% errors!



Heavy Flavour Averaging Group

Predictions Are Risky

- Numbers taken from Snowmass 2001 report.
- Measuring Vtd using Δm_d (errors are stat/syst).

Date	2001	2006	2011
Errors on Δm_d	1%/1%	0.2%/0.5%	0.05%/0.2%
Errors on $f_{Bd}\sqrt{B_{Bd}}$	20.00%	15.00%	5.00%

- 2008 PDG average: Expt: 1%/1%   Theory: ~10%
- Today these numbers are far too optimistic for the experiments but reasonable for the theory side.
- So please take the following predictions of experimental errors with a grain of salt.

Time–Dependence

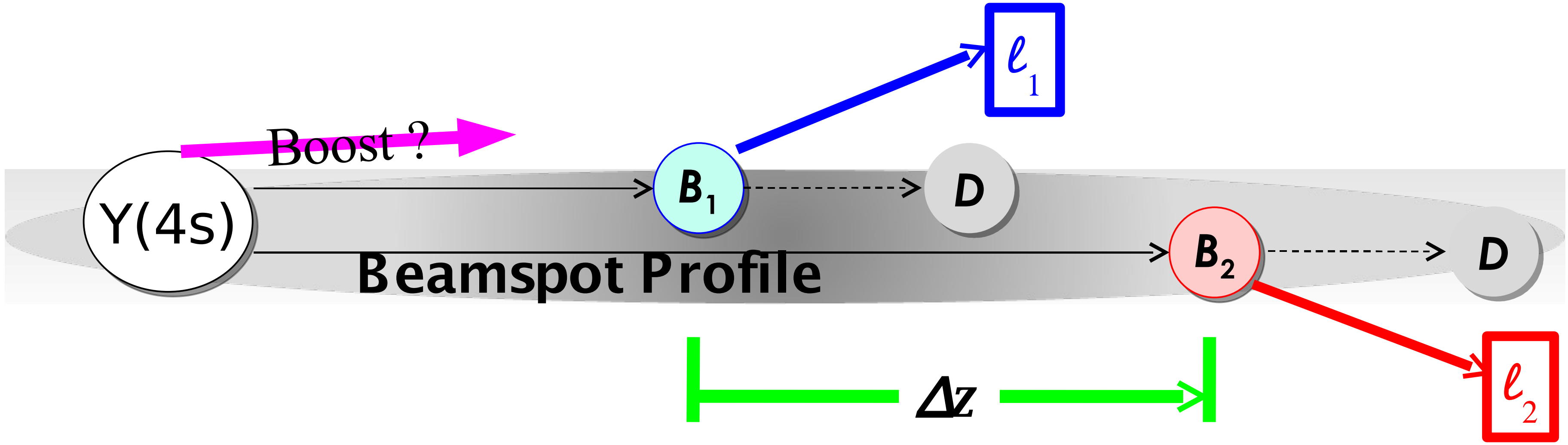
- A general expression for the time-dependence:

$$\frac{1}{2}e^{-\Gamma|\Delta t|}\Big[\frac{|\eta_+|^2+|\eta_-|^2}{2}\cosh\left(\frac{\Delta\Gamma_d}{2}\Delta t\right)-\mathcal{R}e(\eta_+\eta_-^*)\sinh\left(\frac{\Delta\Gamma_d}{2}\Delta t\right)$$
$$+\frac{|\eta_+|^2-|\eta_-|^2}{2}\cos\left(\Delta m_d\Delta t\right)-\mathcal{I}m(\eta_+\eta_-^*)\sin\left(\Delta m_d\Delta t\right)\Big].$$

- We neglect ΔΓ, CPV, CPT V, only measure frequency:

$$\mathcal{P}^+(\Delta t)=\frac{e^{-|\Delta t|/\tau_{B^0}}}{8\tau_{B^0}}[1+\cos(\Delta m_d\Delta t)] \qquad B^0\bar{B}^0$$
$$\mathcal{P}^-(\Delta t)=\frac{e^{-|\Delta t|/\tau_{B^0}}}{8\tau_{B^0}}[1-\cos(\Delta m_d\Delta t)] \qquad B^0B^0 \text{ or } \bar{B}^0\bar{B}^0$$

Inclusive: Dileptons 1



- Both BaBar and Belle published papers with this technique.
- Very inclusive, no B reconstruction, only use two leptons.
- Averages over boost and beamspot direction effects.
- Large B^+, and charm decay backgrounds included in fit.
- Highest statistics method available.

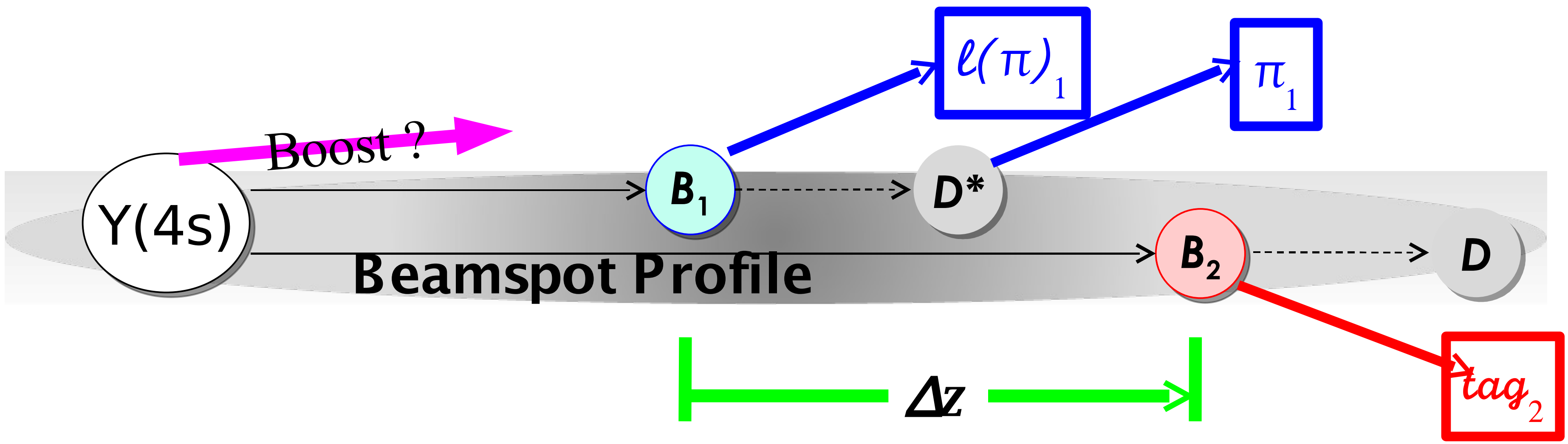
Inclusive: Dileptons 2

- BaBar (2002): PRL 88 221803, 23M B pairs, 20.7 ifb.
- Δm_d = 0.493 $\pm$ 0.012 (stat) $\pm$ 0.009 (syst)
- Largest systematics: B lifetimes (PDG 2002) 0.0064, Δt-dependence of signal resolution function 0.0043

- Belle (2003): PRD 67 052004, ~30M B pairs, 29.4 ifb.
- Δm_d = 0.503 $\pm$ 0.008 (stat) $\pm$ 0.010 (syst)
- Dominant systematics: B^+ lifetime 0.0053, Δt resolution function 0.0047

- B lifetimes are known much better now, but Δt resolution functions are still quite tricky (boost + beamspot effects)

Loose Reconstruction 1



- Both BaBar and Belle published papers using this technique.
- Inclusive: partial B reconstruction with lepton/pion plus soft pion for one side, tag the other side (leptons).
- Less sensitive to boost and beamspot direction effects.
- Still large B^+, and charm decay backgrounds included in fit.

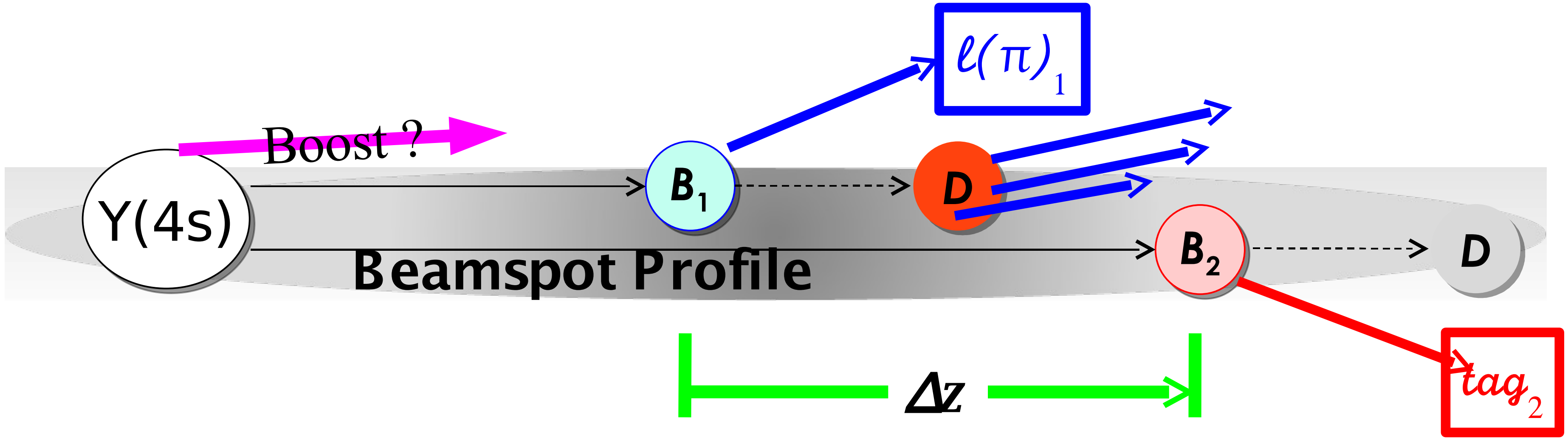
Loose Reconstruction 2

- Belle D* pi (2003): PRD 67 092004, 31.3M B pairs, 29.1 ifb.
- Δm_d = 0.509 $\pm$ 0.017 (stat) $\pm$ 0.02 (syst)
- Dominant Systematics: bkg fraction 0.014, Δt resolution function 0.012, background shape 0.005, B^0 lifetime 0.005.

- BaBar $D^* l \nu$ (2006): PRD 73 012004, 88M B pairs, 81 ifb.
- Δm_d = 0.511 $\pm$ 0.007 (stat) $\pm$ 0.007 (syst)
- Dominant Systematics: Analysis bias 0.0035, Δt and $\sigma(\Delta t)$ cuts 0.0033, detector alignment 0.0038

- Again we see that the limiting systematics are related to the lifetimes, the Δt resolution function, and Δz -> Δt.

Fully Reconstructed B 1



- Both BaBar and Belle published papers using this technique.
- Fully reconstruct a B meson (B_{reco}), in flavor/CP eigenstate. Tag and vertex the other side (leptons, kaons, NN).
- Not especially sensitive to boost, beamspot effects.
- Very small B^+ and charm decay background influence.

Fully Reconstructed B 2

- BaBar (2002): PRL 88 221802, 32M B pairs, ~ 30 ifb.
- Δm_d = 0.516 $\pm$ 0.016 (stat) $\pm$ 0.01 (syst)
- Dominant systematics: B^0 lifetime 0.006, Δt resolution function & SVT alignment 0.005, z scale & boost 0.002

- Belle (2005): PRD 71 072003, 152M B pairs, 140 ifb.
- Δm_d = 0.511 $\pm$ 0.005 (stat) $\pm$ 0.006 (syst)
- Systematics: Vtx reconstruction 0.003, D** bkg shape 0.004, Possible fit bias 0.002, Bkg Δt shape 0.002

- Again we see early errors from B0 lifetimes, and possible fit bias related to the Δt resolution function.

Tevatron Run II

- D0 (2006) : B->DXμν, PRD 74 112002, 1 ifb.
- Δm_d = 0.506 $\pm$ 0.02 (stat) $\pm$ 0.016 (syst)
- Systematics: Br(B->D*πμνX) 0.0078, 1σ variation of 2004 PDG value, K-factor=PT(μD^0)/PT(B) +0.0098 – 0.0094.

- CDF (2006) FPCP Unpublished: PRD 71 072003, 152M B pairs, 140 ifb.
- Δm_d = 0.506 $\pm$ 0.01 (stat) $\pm$ 0.016 (syst)
- Emphasis is on methods for Bs mixing.
- They have double the D0 statistical precision, with the same luminosity, and the same systematics?

From Tevatron to LHCb

- Not an expert, just a simple luminosity scaling.
- Tevatron results were based on 1 ifb, LHCb will have 10 ifb in a few years.
- Statistical error for the same technique will go from:

  D0: 0.02 down to 0.006.

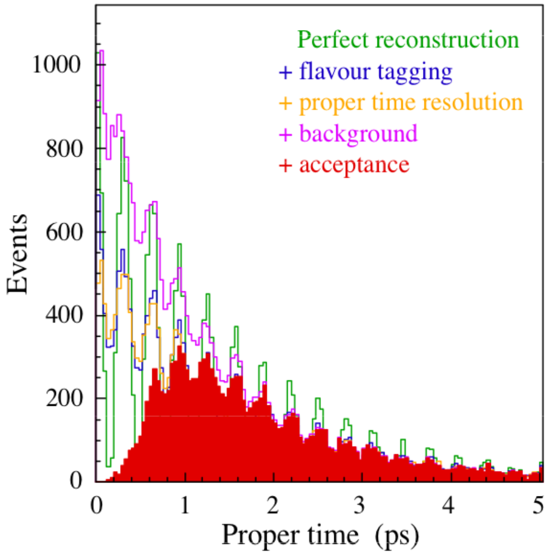
  CDF: 0.01 down to 0.003.
- Result would be badly systematically limited, unless they do substantial work to improve the analysis method.
- A B-Factory measurement can achieve this same ***statistical*** precision with today's datasets, but would also be systematics limited.

LHCb Projections for Bs

- Taken from CKM2008 workshop – P. Robbe.
- Is Bd Mixing only of interest as a Bs calibration? How much effort will be put into the systematics?

B_s lifetime, mixing, $\Delta\Gamma$ sensitivities

- Estimated from toy Monte-Carlo using resolutions, efficiencies, tagging from full Monte-Carlo simulation, with ω=0.37
- Mistag will be evaluated from data using control chanels ($B^0 \to J/\psi\ K^{*0}$, $B^+ \to J/\psi\ K^+$)
- Sensitivities (stat only):
  - $\sigma(\tau_s)$=0.013 ps
  - $\sigma(\Delta m_s)$=0.008 ps^{-1}
  - $\sigma(\Delta\Gamma_s)$=0.03 ps^{-1} (Input=0.068 ps^{-1})



Lifetime and mixing will be dominated by systematic errors

SuperB Statistical Errors

- Scale the statistical errors by integrated luminosity.
- Two scenarios, 10 iab, and 75 iab complete data set.
- Dileptons:

  10 iab: 0.0005, or 0.1%.

  75 iab: 0.0002 or 0.04%.
- Partial Reconstruction:

  10 iab: 0.0006-0.0009, or 0.2%.

  75 iab: 0.0002-0.0003, or 0.05%.
- Fully Reconstructed B with Tagging:

  10 iab: 0.0006-0.0009, or 0.2%.

  75 iab: 0.0002-0.0003, or 0.05%.

SuperB Systematics 1

- All techniques will be systematics dominated at SuperB. (They are now for B-Factories).
- 1) $B^{0/+}$ lifetimes: errors better now (~1/3rd).
- PDG 2000: $\sigma(\tau_{B0}) = 0.032$, 2008: $\sigma(\tau_{B0}) = 0.009$.
- PDG 2000: $\sigma(\tau_{B+}) = 0.028$, 2008: $\sigma(\tau_{B+}) = 0.011$.
- Even better if the lifetimes float in the same fit.
- 2) Need to reduce the errors from Δz -> Δt and Δt resolution function (separate physics / detector).
- This depends on the average boost, and the beamspot size, independent of tracking resolution.
- SuperB beamspot size along z will be important.

SuperB Systematics 2

- Full B reconstruction seems the most straightforward way to reduce the dt dependence of smearing.
- What would the statistics be to reconstruct both B?
- From 2002 BaBar Breco: 6.3k signal evts /32M B pairs = 0.02% efficiency.
- On 75 ab? $75*1.0^{9} * (2.0^{-4})^{2}$ = 3k events. Not enough!
- What about if we fully reconstruct one side, and use partial reconstruction on the other side?
- From BaBar 2006 partial reco: 50k evts / 88M B pairs = 0.06% efficiency. Only a factor of 3 higher.
- But maybe the efficiency would be higher for the partial reco side with the reco side already used?

SuperB Systematics 3

- The Big Question:

  Can SuperB achieve 0.1 % or better systematics?

- The main interest in B_d mixing physics seems to be in $\Delta\Gamma$, CPV, and possible CPT tests.
- These are only true tests of the SM at 10^{-3} precision.
- Of course there are important charge asymmetry systematics to worry about, that don't affect Δm.
- To fully exploit the ability of precision flavor measurements to test the CKM picture, there should be efforts to measure **all** of the B mixing parameters, Δm, τ, $\Delta\Gamma$, q/p, etc, as precisely as possible.

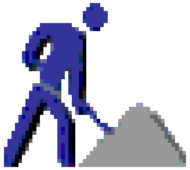
SuperB Outlook

- All three B-Factory analysis methods are capable of roughly equal statistical precision.
- Some systematics are shared in common (especially B lifetimes and resolution function issues). Inclusive or partial reconstruction techniques have issues with charm backgrounds.
- B lifetimes can be either measured well, or floated.
- Reconstructing at least one B seems to reduce the Δt resolution problems a lot (less smearing from the B flight and beamspot location).
- Will there be BaBar / Belle publications on 2008 data?
- Perhaps there are new methods/ideas out there to try.

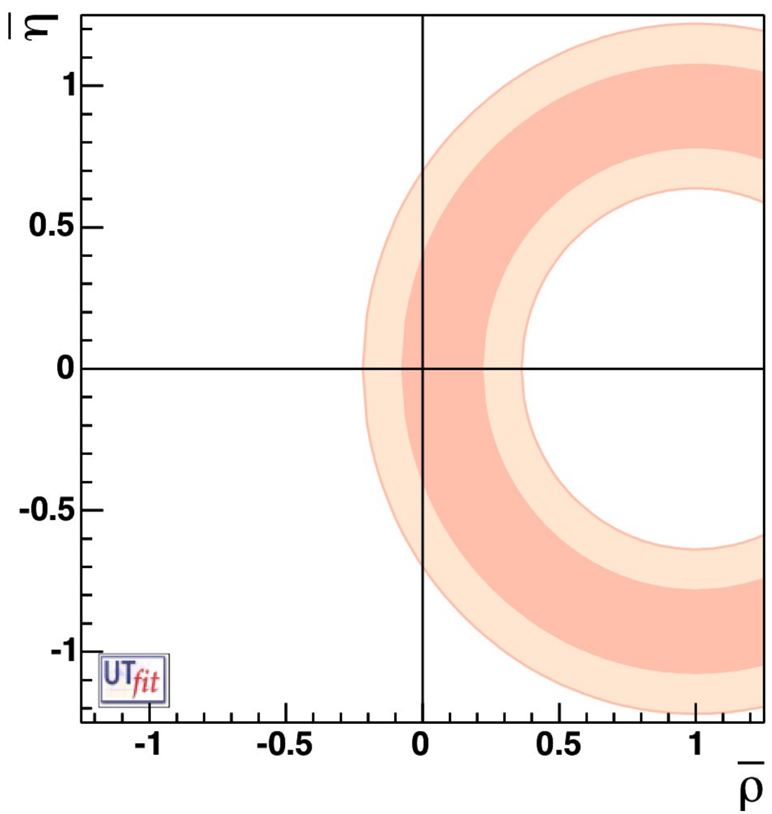
Summary

- Three main techniques have been used for measuring Δm_d at the B-Factories: dileptons, partial reconstruction and full reconstruction.
- All techniques are now, and will be in future, severely systematics limited without a lot of effort being put in.
- But the statistics are there for staggering precision!
- My crude estimate suggests LHCb will not compete.
- Δm_d measurement has the potential to be a very powerful, precise CKM test, **especially in conjunction with measurements of $\Delta\Gamma$ and possible CP/CPT violation.**

Extra Slides

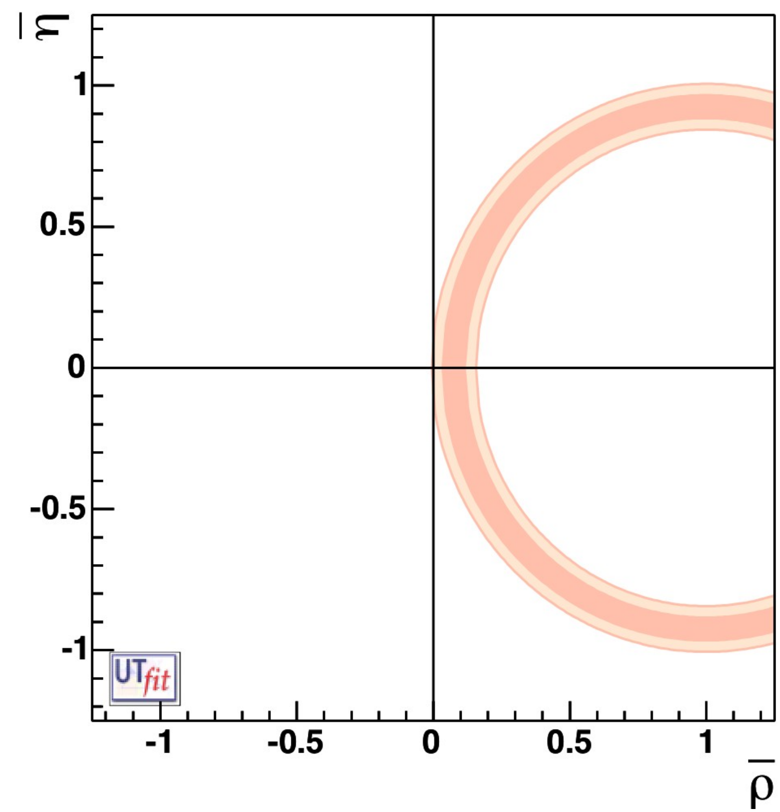


UT Constraints



Δm_d UTFit 2008

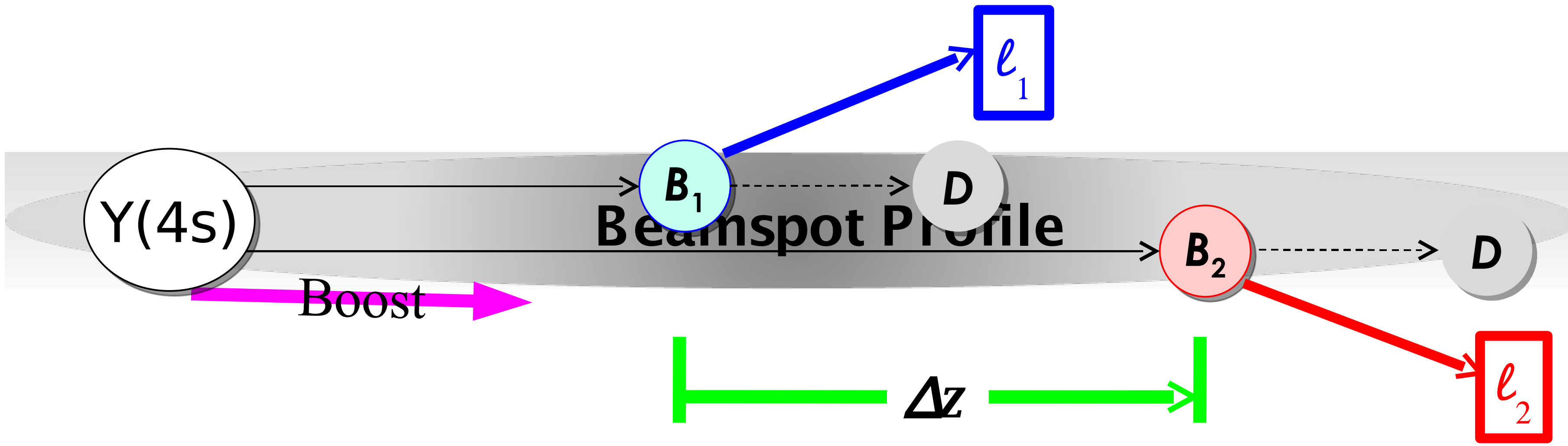
Limited by Lattice errors.



Δm_s UTFit 2008 better.

Limited by Lattice errors.

Δt Dependent Resolution



• Whenever the B mesons are not fully reconstructed, there are issues in using the lepton z coordinates to obtain the proper time.
• Even if the detector resolution is perfect, the lepton z decay point may not extrapolate to the B decay point.
• The B's have large boost along the beam (z) direction, so the longer the decay time, the more distance they travel.
• This correlates the B flight distance with the decay time, means that Δt and $\sigma(\Delta t)$ are correlated.