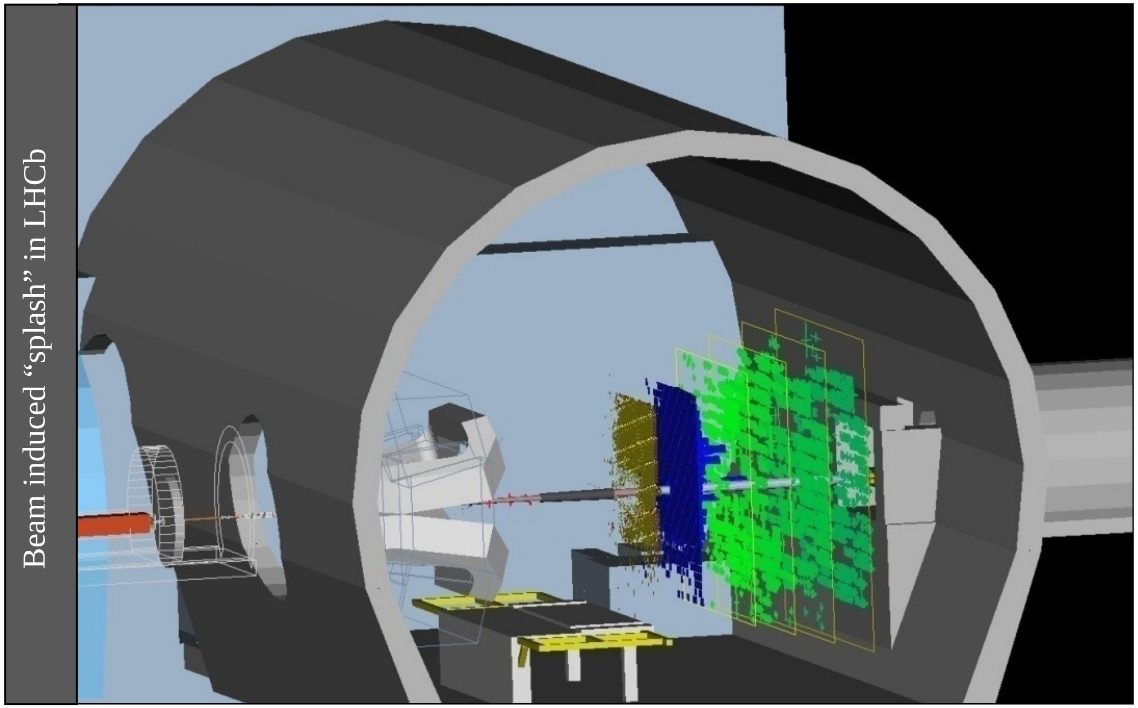
Imperial College London



An experimental perspective on Heavy Flavour physics

Ulrik Egede

14 December 2009

A selective approach

To give a comprehensive overview of experimental results in Heavy Flavour Physics is simply impossible

- The number of publications from mainly BaBar and Belle, but also CDF, D0, CLEO and BES are truly staggering.

I will focus on a few of the key measurements and also ignore large parts.

Exclusion of some class of results might mean lack of knowledge from my side rather than lack of importance.

Heavy flavour oscillations

The discovery of B^0-$\overline{B}^0$ oscillations by ARGUS in 1987

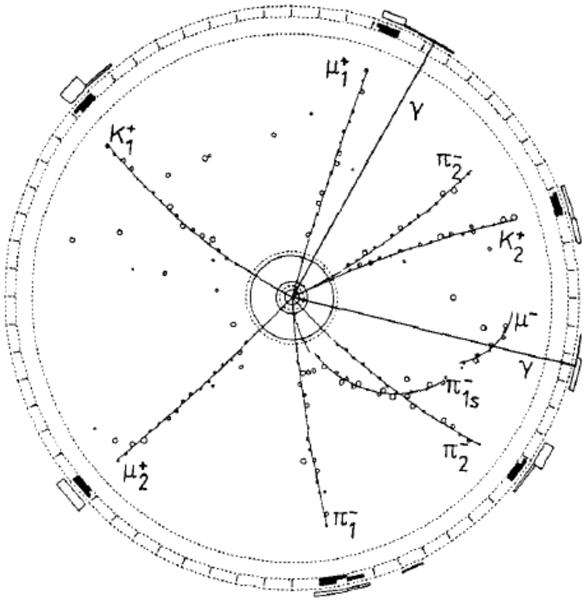
- Found that oscillation probability larger than expected

$$x = \frac{\Delta m}{\Gamma} > 0.44$$

- A clear indication of a very heavy top quark
  - Interestingly the letter does not make a big issue of this but does in a table have

$$m_t > 50\,\mathrm{GeV}/c^2$$

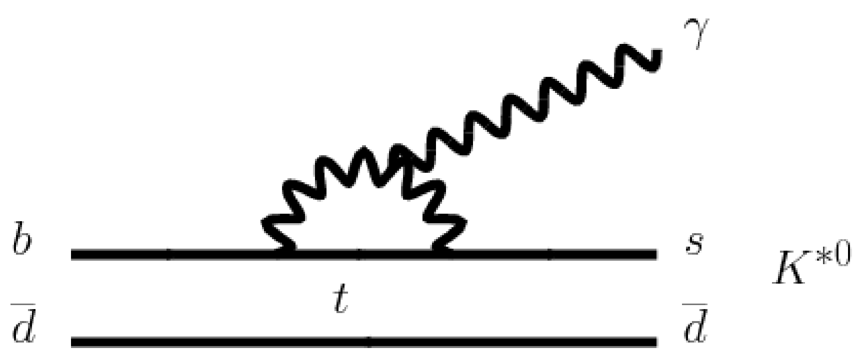
PLB192,245

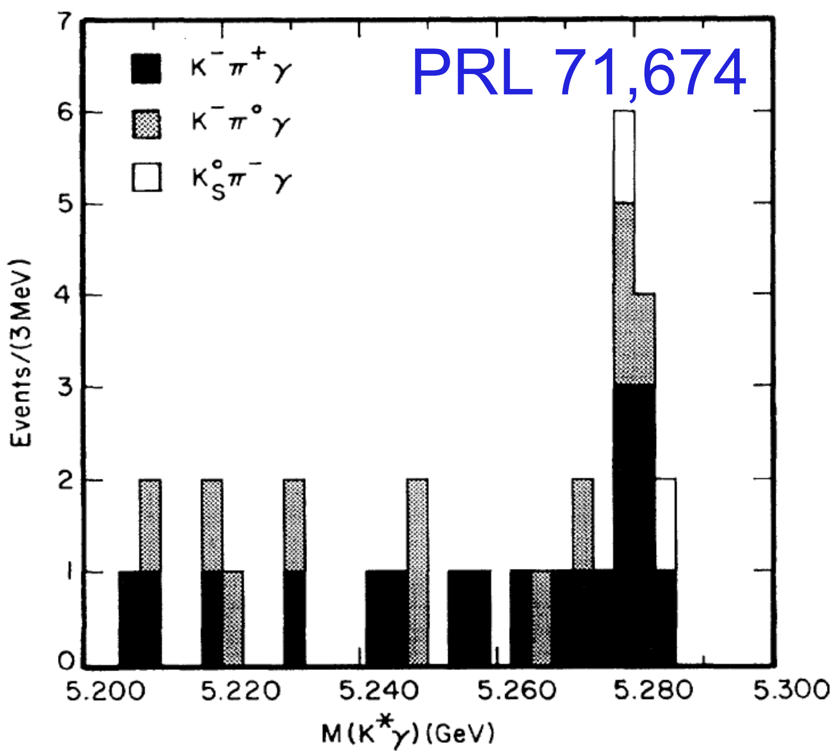


Penguin decays

Discovery of B→K*γ by CLEO in 1993 was a clear evidence for the existence of penguin decays

- The BR fitted well with the expectations from the SM at the time.
- SM is the dominant contributor to FCNC decays

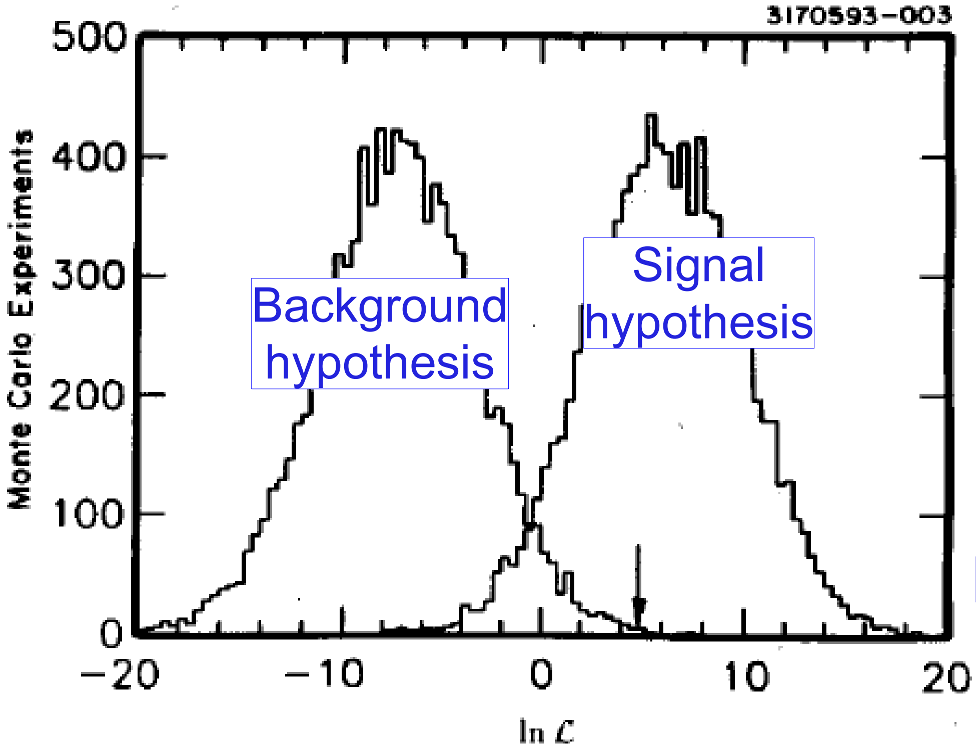




Penguin decays

Significance

- Evaluated from likelihood distributions of signal and background samples
- 0.11% probability to be a background fluctuation.



PRL 71,674

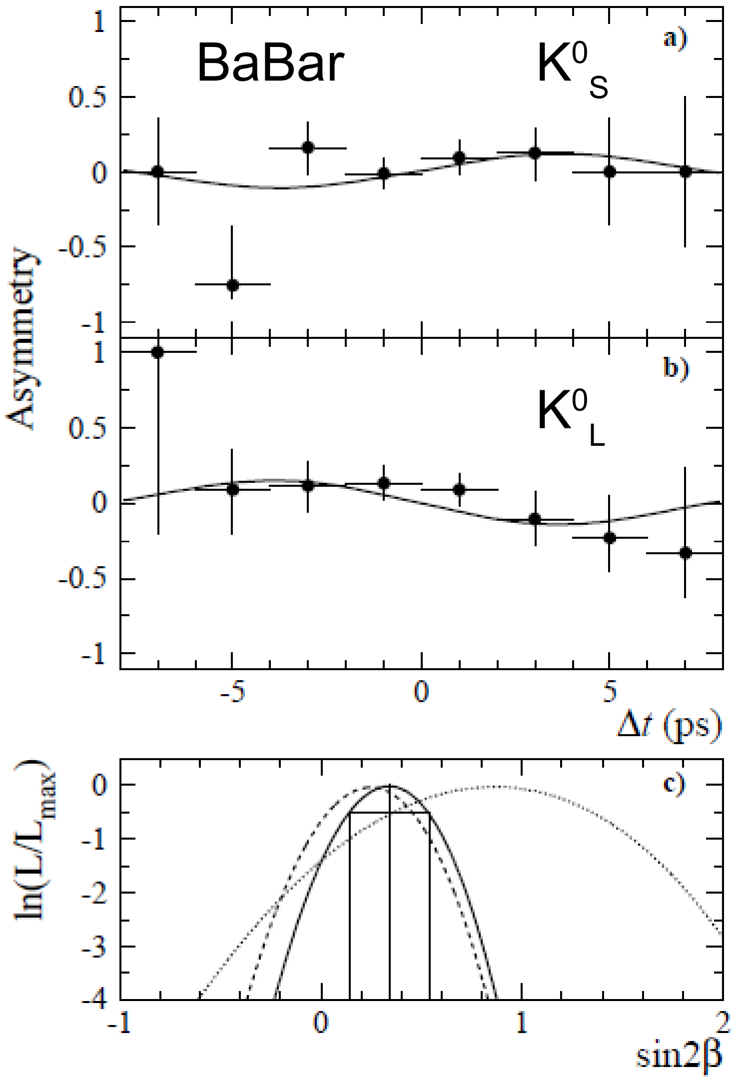
CP violation in B system

The discovery of CP violation in B^0 decays through $B^0 \rightarrow J/\Psi\ K^0_{S/L}$

Exp.	Paper	Sin 2β
BaBar	PRL 86, 2515 (2001)	0.34±0.20±0.05
BELLE	PRL86, 2509 (2001)	0.58±0.33±0.10

In 2001 this showed that the SM was also the dominant part of CP violation in mesons.

PRL 86, 2515 (2001)



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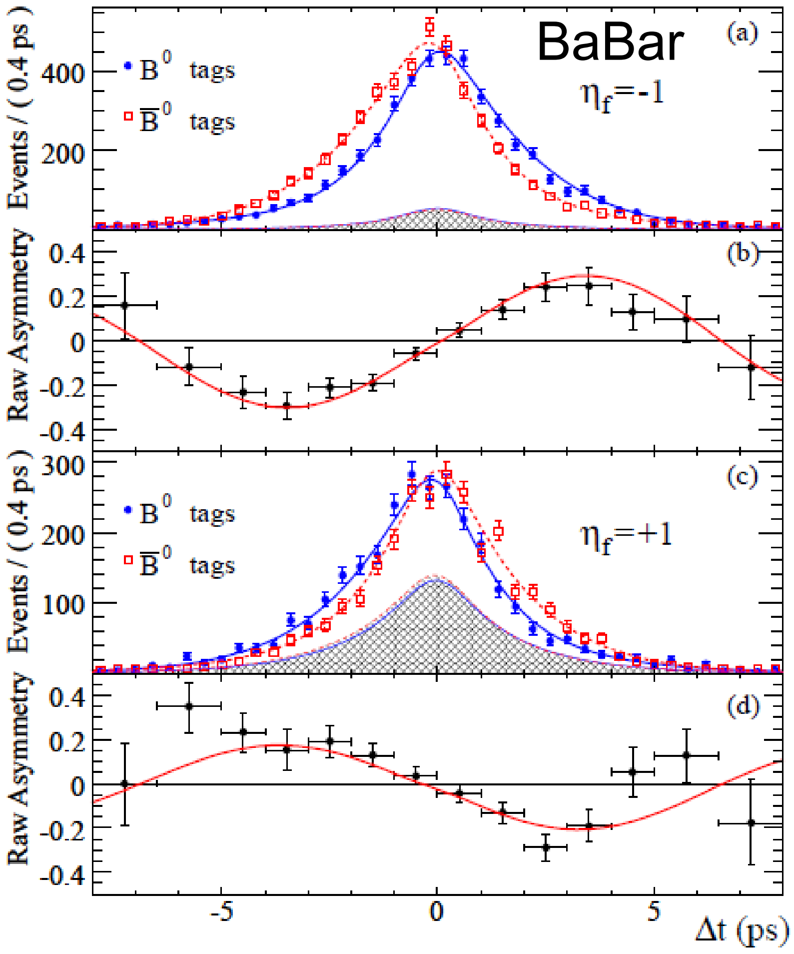
BaBar	PRD 79, 072009 (2009)	0.67±0.03±0.01
BELLE	PRL 98, 031802 (2007)	0.64±0.03±0.02

PRD 79 072009 (2009)

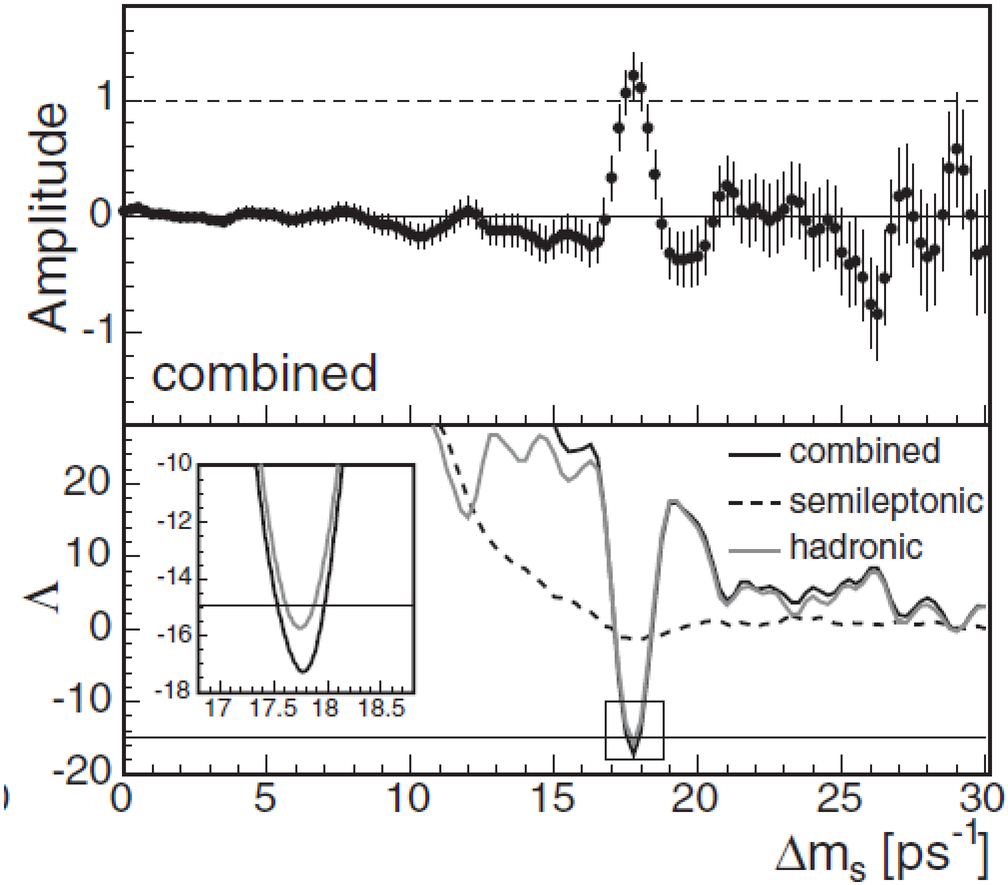


Now one of the precision measurements

Oscillations in B^0_s system

2006 saw the observation of B^0_s oscillations from CDF

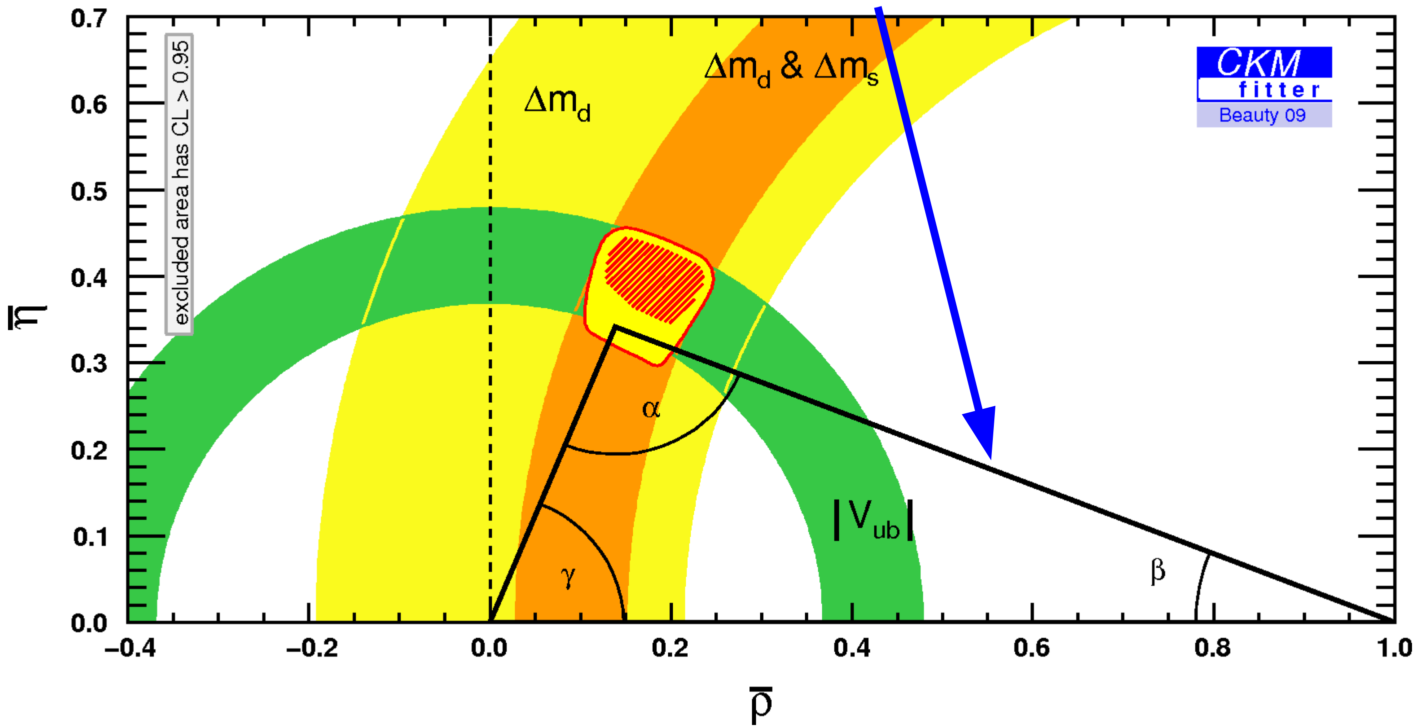
$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$ PRL 97, 242003



Oscillations in B^0_s system

If assuming SM

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi \sqrt{\frac{\Delta m_d}{\Delta m_s}\frac{m_{B^0}}{m_{B^0_s}}}$$



Dominated by theory uncertainty on ξ so no further benefits from experimental precision

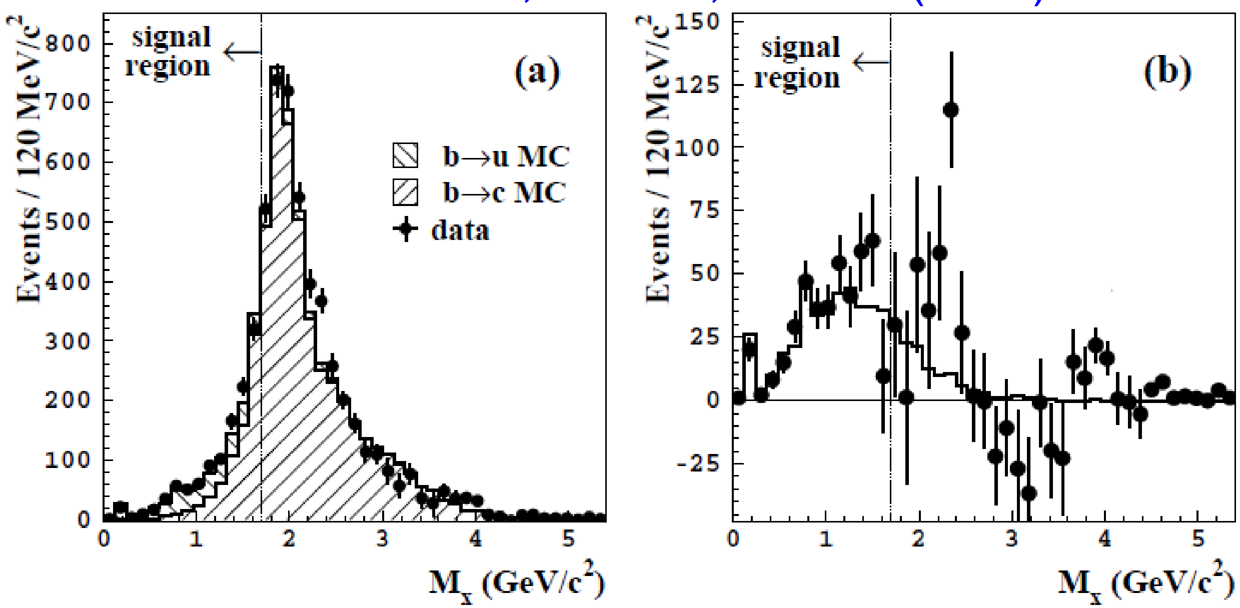
V_{ub} (inclusive)

Not in itself a measurement that is sensitive to NP

Instead provides a strong constraint on Unitarity triangle.

Due to background from $b \to c l \nu$ it is impossible to reconstruct $b \to u l \nu$ in a fully inclusive way.

BELLE, PRL 95, 241801 (2005)



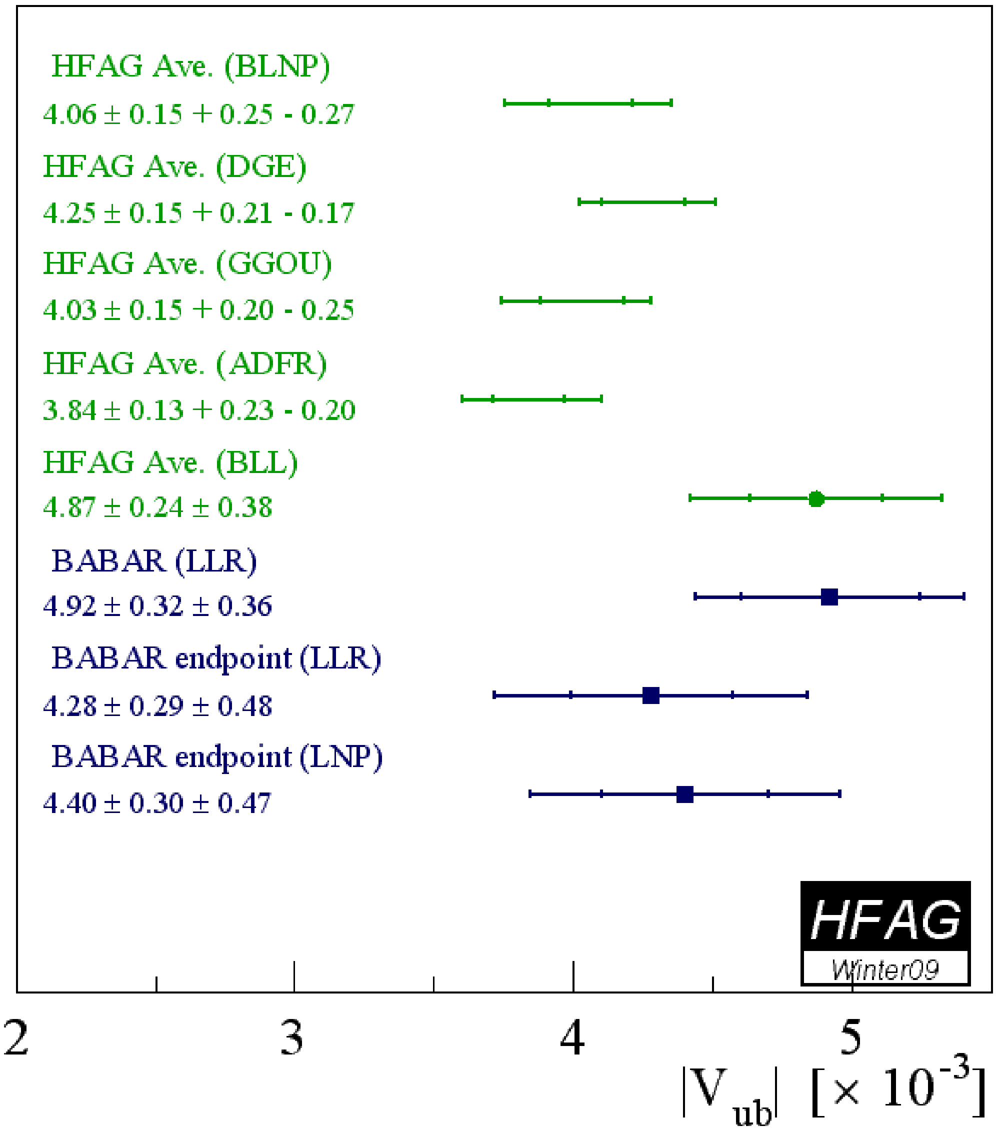
V_{ub} (inclusive)

Different analyses selects different regions of phase space.

Different theoretical models used for combination.

Arithmetic average of these gives

$|V_{ub}|=(411+27-28) \times 10-5$

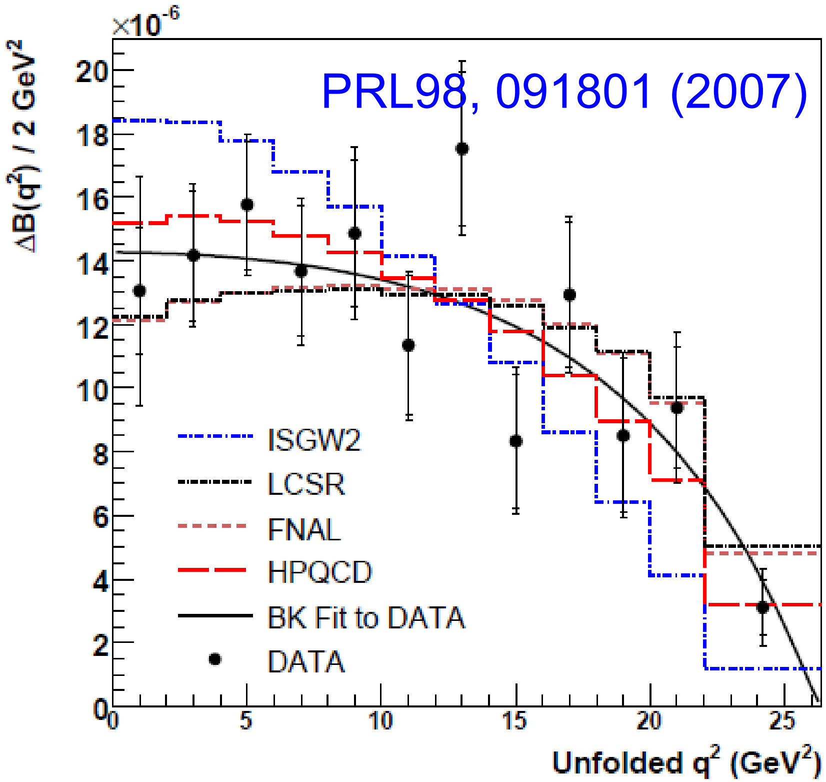


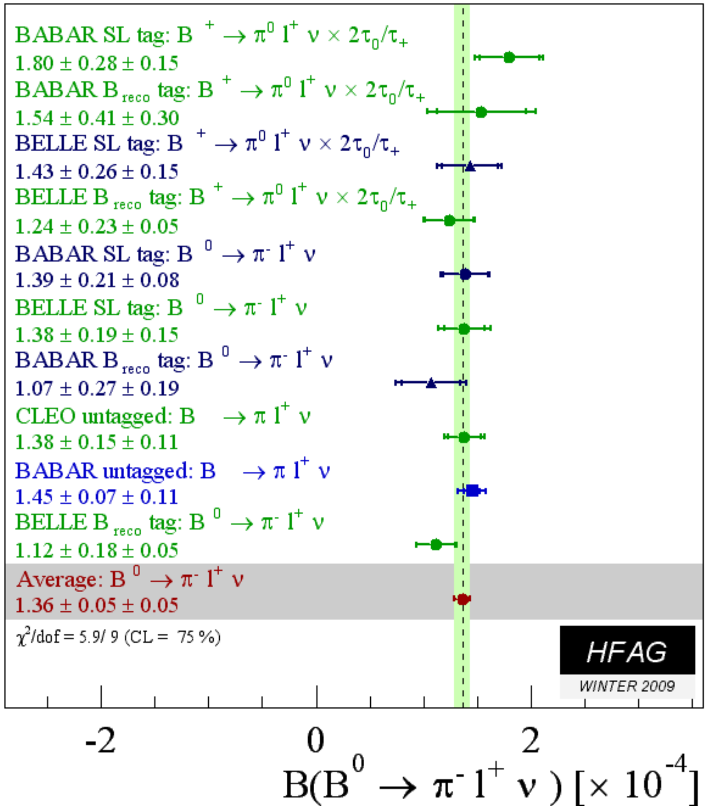
V_{ub} (exclusive)

Measurement can be done with exclusive $B \to \pi l \nu$ decay as well.

A fit to the momentum transfer squared (q^2) is performed

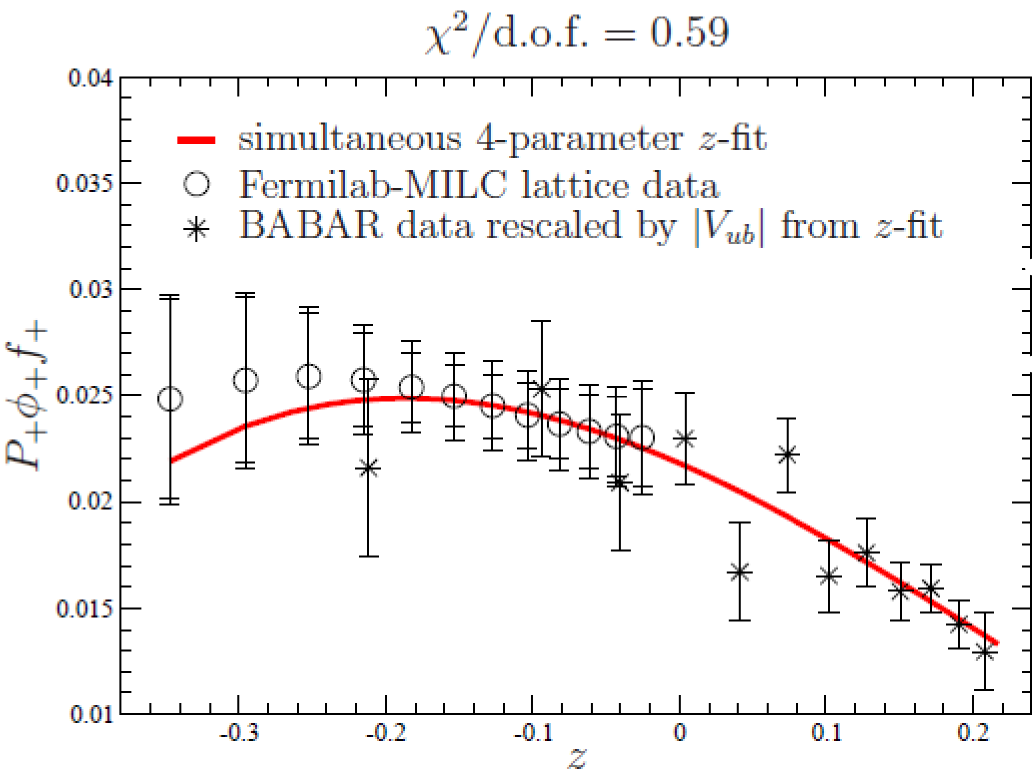
BR($B \to \pi l \nu$) extracted





V_{ub} (exclusive)

To get from exclusive BR to V_{ub}, requires the use of either LQCD (high q^2) or light cone sum rules (low q^2) to get form factor.



One result to quote is

$V_{ub} = (3.38 \pm 0.36)10^{-3}$

ArXiv 0907.5386

Errors are of similar size to the errors from the inclusive measurements.

Oscillations in D^0 system

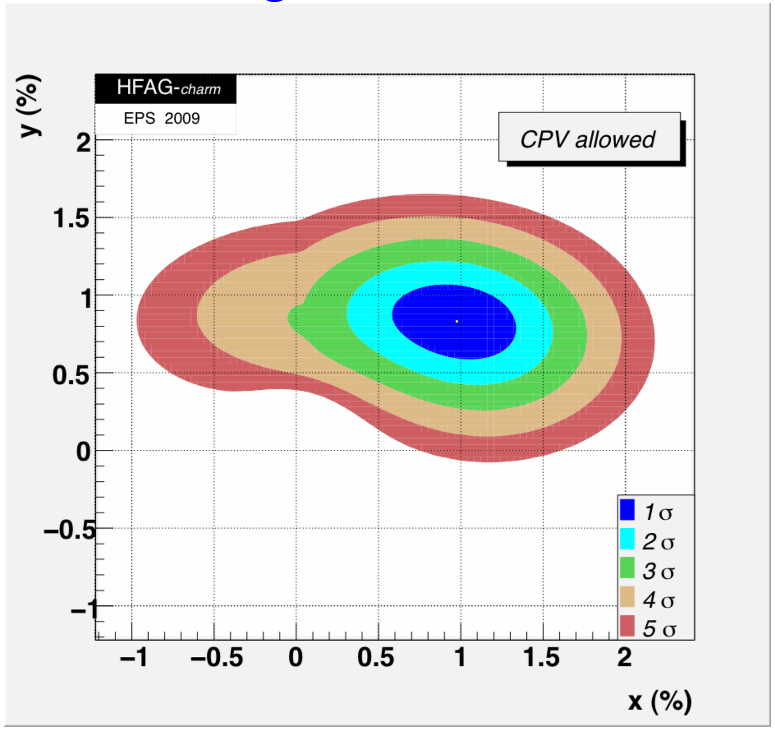
Oscillations in the D^0 system finally discovered in 2006 after many years of searching

- Both x and y are at the % level
- At the high end of SM predictions but in no way excluded.
- Frustrating!

The observation concludes the discovery of oscillations in mesons.

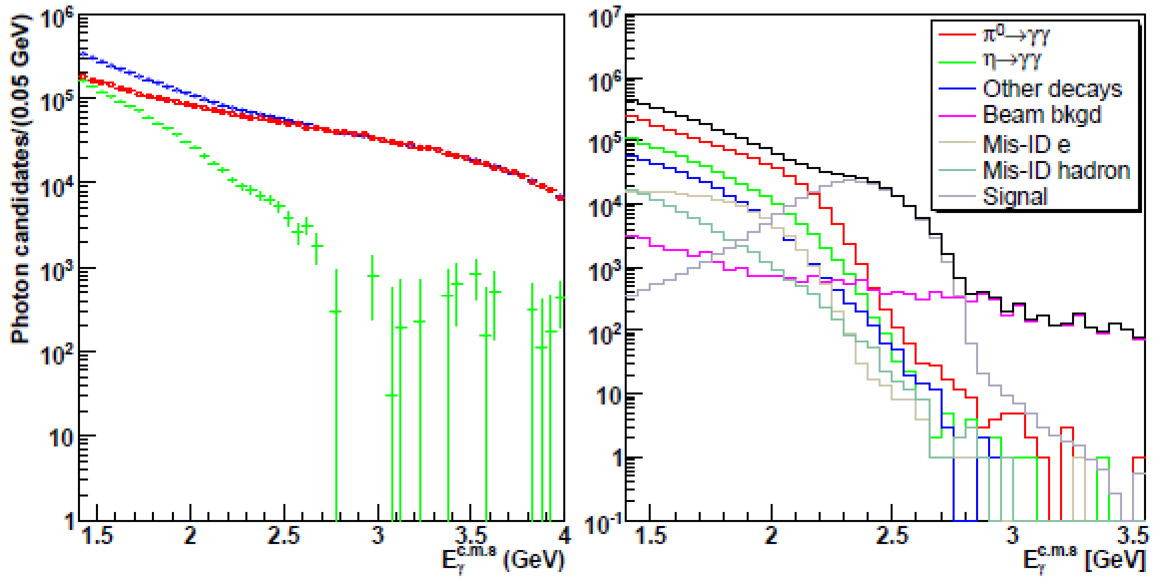
- No $T^0\overline{T}^0$ oscillations as no hadronisation.

No mixing excluded at 10 σ



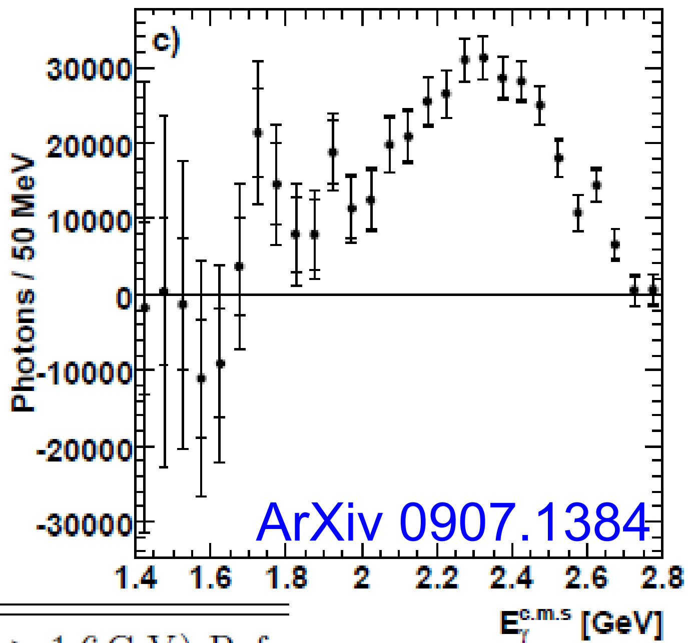
Inclusive b→sγ

- NNLO calculations from theory reduce the theoretical error to ~10% in SM
  - Similar type error in many SUSY scenarios as well
- Experimental measurement a challenge due to backgrounds
  - Has to introduce photon energy cut-off



Inclusive $b \to s\gamma$

- Latest BELLE measurement has $E_\gamma > 1.7$ GeV
  - Experimental extrapolation to 1.6 GeV
  - Theory calculation from 1.6 GeV to zero



ArXiv 0907.1384

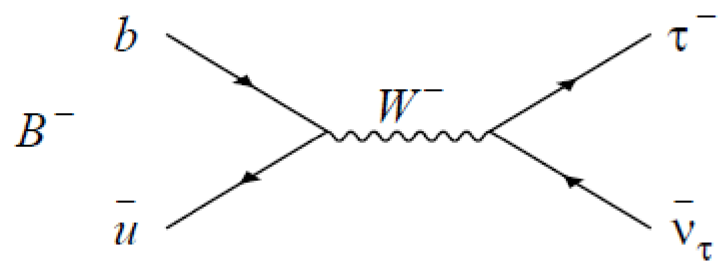
Method	Data set	$E_\gamma^{\min}$	$\mathcal{B}(E_\gamma > E_\gamma^{\min})$	$\mathcal{B}(E_\gamma > 1.6\,\mathrm{GeV})$	Ref.
CLEO fully inclusive	9	2.0	$305 \pm 41 \pm 26$	329 ± 53	[555]
BABAR fully inclusive	82	1.9	$367 \pm 29 \pm 34 \pm 29$	392 ± 56	[551]
BABAR semi-inclusive	82	1.9	$327 \pm 18\,^{+55}_{-40}\,^{+4}_{-9}$	349 ± 57	[552]
BABAR *B*-recoil	210	1.9	$366 \pm 85 \pm 60$	391 ± 111	[669]
Belle semi-inclusive	6	2.24	—	369 ± 94	[670]
Belle fully inclusive	605	1.7	$332 \pm 16 \pm 37 \pm 1$	337 ± 43	[662]
Average	–	–	–	$352 \pm 23 \pm 9$	
Theory prediction	–	–	–	315 ± 23	[645]

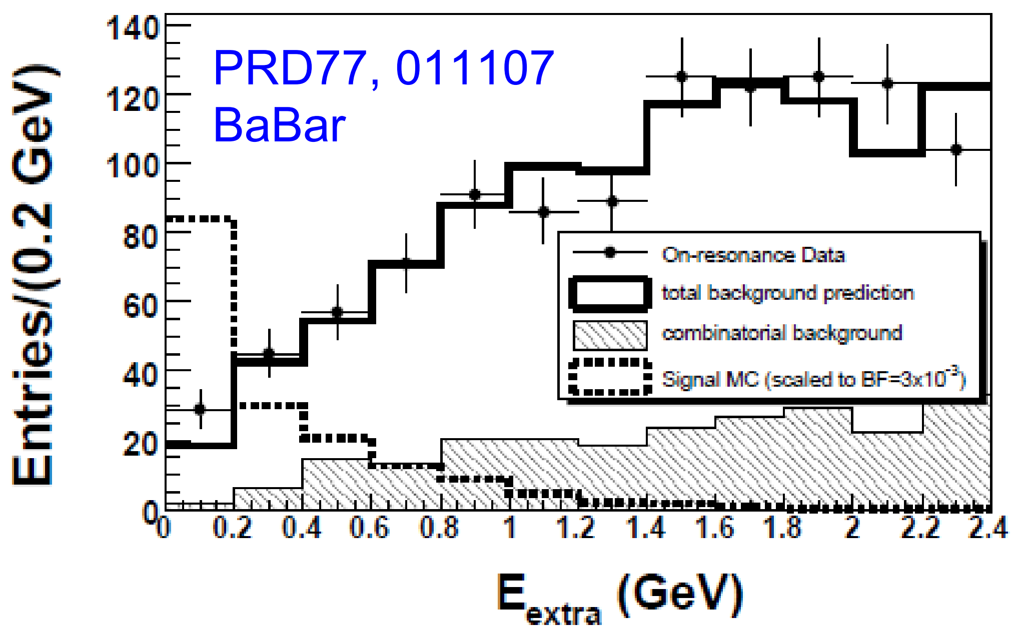
ArXiv 0907.5386

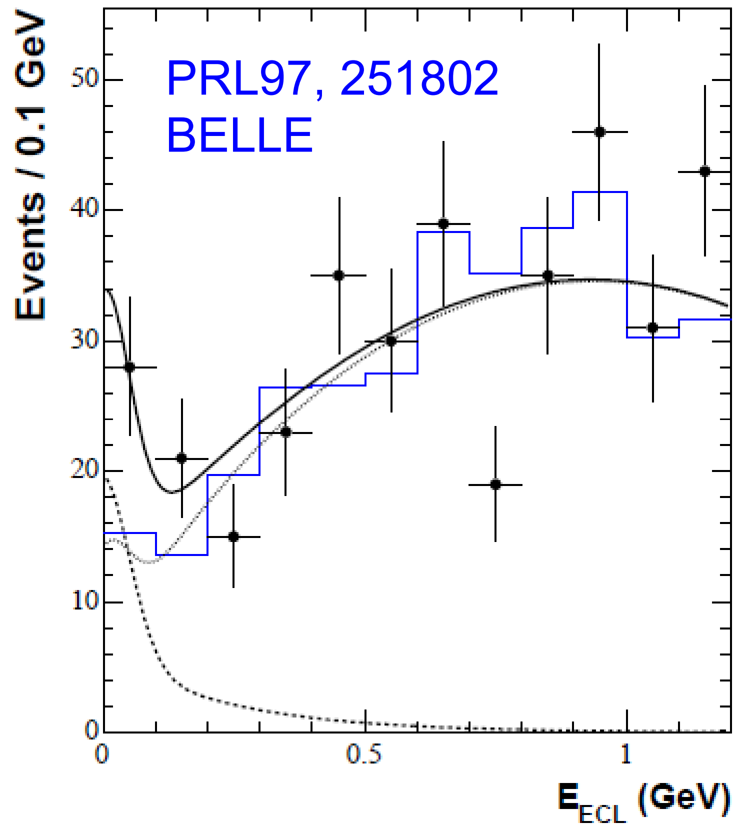
$B^+ \to \tau\nu$

Due to the multiple neutrinos in the final state this is a challenging measurement

Analysis is using recoil tagging (see later)



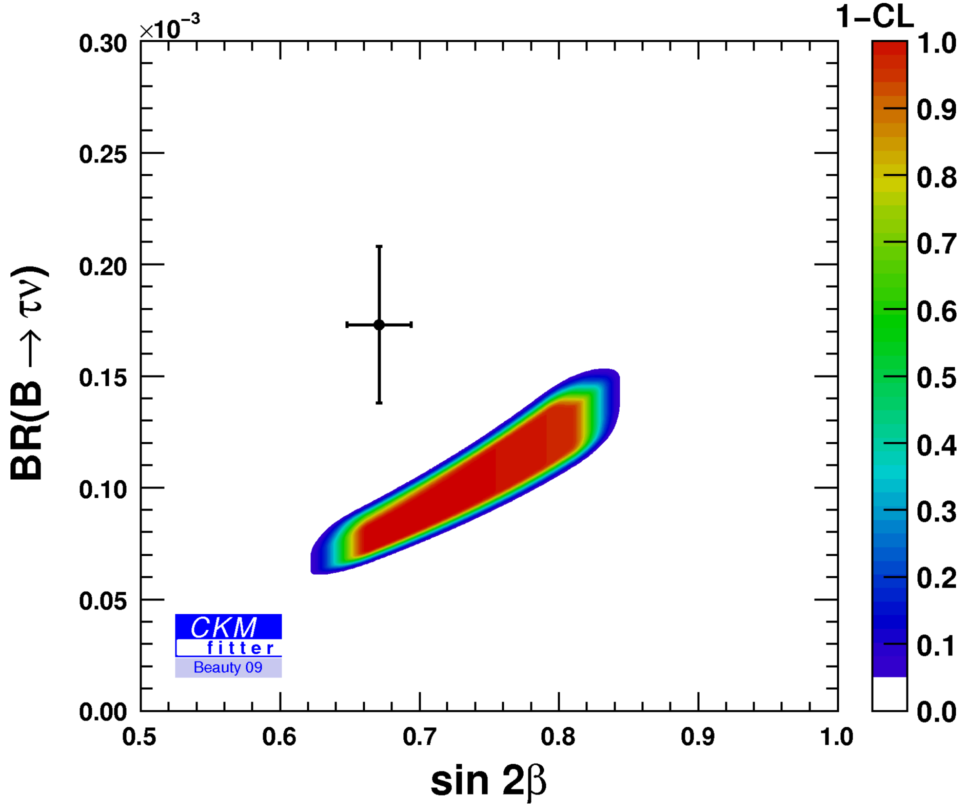




$B^+ \to \tau\nu$

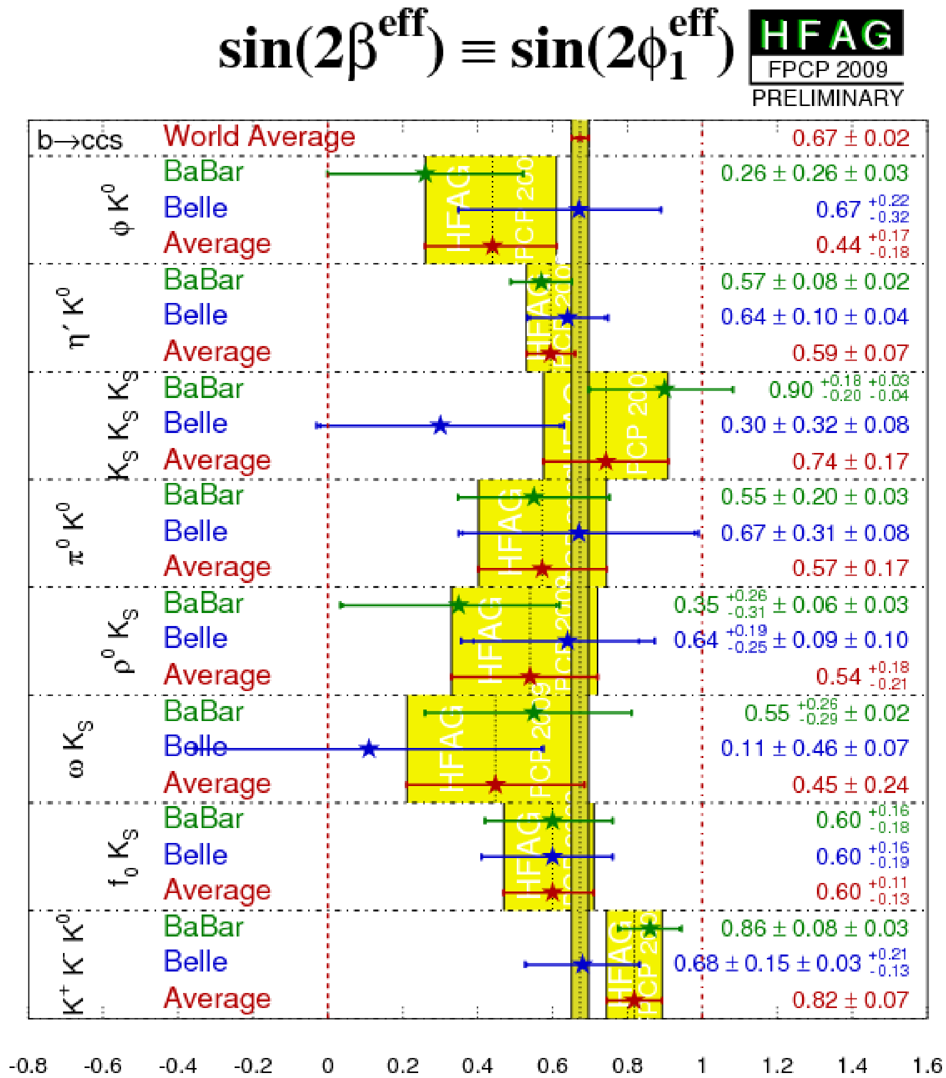
This decay has a very precise prediction in the SM

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$



Sin 2β from penguins

- A multitude of measurements of sin 2β in gluonic penguins
- At a time a large discrepancy was developing compared to sin 2β from charmonium decays
- Theoretically difficult for high precision
  - Move towards few high quality channels.



Isospin ratio in $B \rightarrow K^{(*)}l^+l^-$

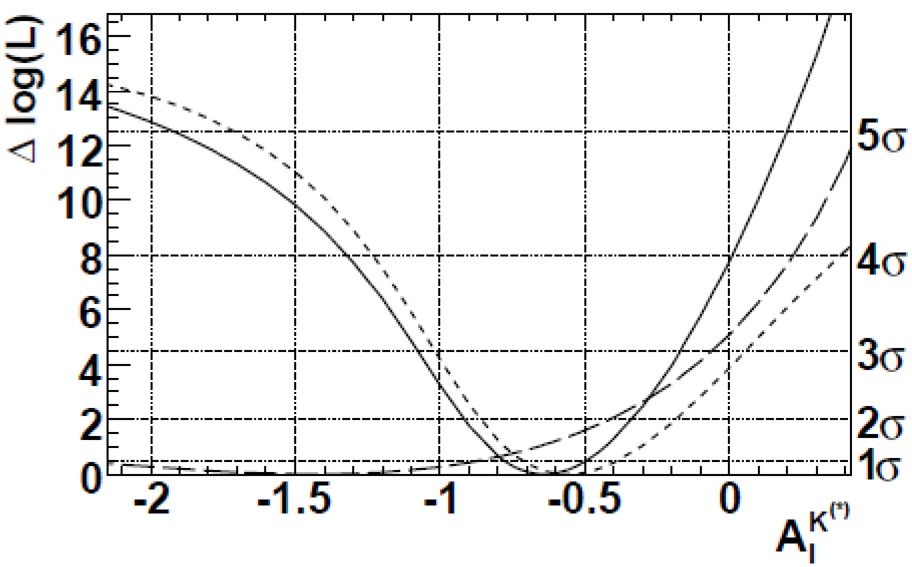
Looking at the isospin asymmetry

$$A_I^{K^{(*)}} \equiv \frac{\mathcal{B}(B^0 \rightarrow K^{(*)0}\ell^+\ell^-) - r\mathcal{B}(B^\pm \rightarrow K^{(*)\pm}\ell^+\ell^-)}{\mathcal{B}(B^0 \rightarrow K^{(*)0}\ell^+\ell^-) + r\mathcal{B}(B^\pm \rightarrow K^{(*)\pm}\ell^+\ell^-)}$$

For q^2 (di-lepton mass) < 7 GeV^2
BaBar PRL 102:091803,2009
sees $A_I = -0.56 +0.17 -0.15 \pm 0.03$

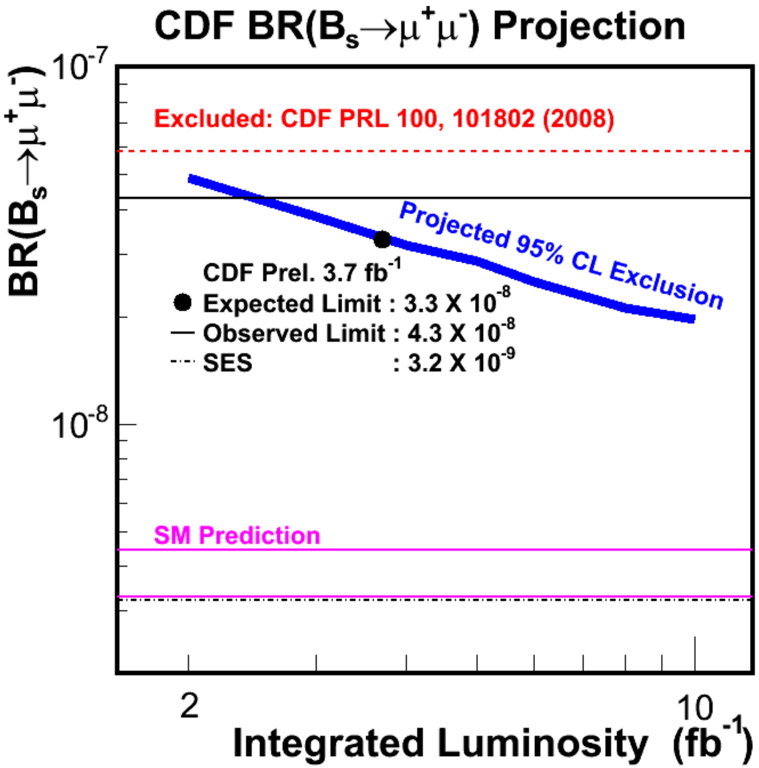
For K*γ (i.e. q2=0)
PRL.103:211802,2009 they
see $0.017 < A_I < 0.116$

PRL 102:091803,2009



$B_s \to \mu^+\mu^-$

- Decay a very sensitive probe for Higgs sector of any New Physics model
- SM BR predicted to 10% precision at $3.6 \pm 0.3\ 10^{-9}$
- Currently best result is from CDF 3.7 fb^{-1}
  - BR < 4.3 10^{-8} 95%CL
- LHC will quickly catch up.
- We will very soon know if this is exciting.
- On the other hand, if limit goes below ~5 10^{-9} it will be hard to identify New Physics.



$B_s \to J/\Psi\ \varphi$

The equivalent time dependent CPV measurement to $B_d \to J/\Psi\ K^0_s$ but more exciting and much harder

Exciting

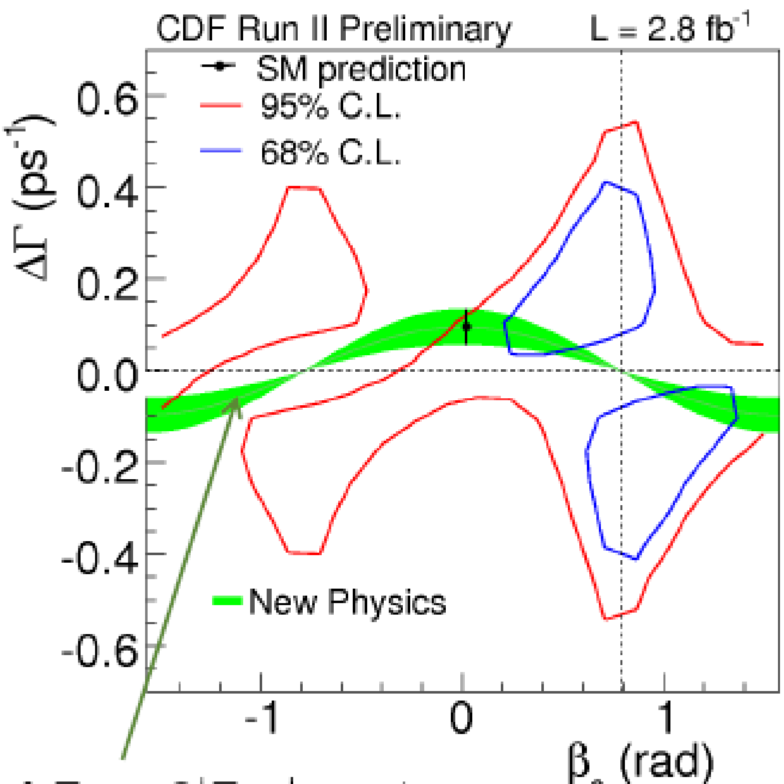
- The non-vanishing $\Delta\Gamma$ in B_s oscillations gives another observable
- As SM value of CPV any significant value is New Physics

Harder

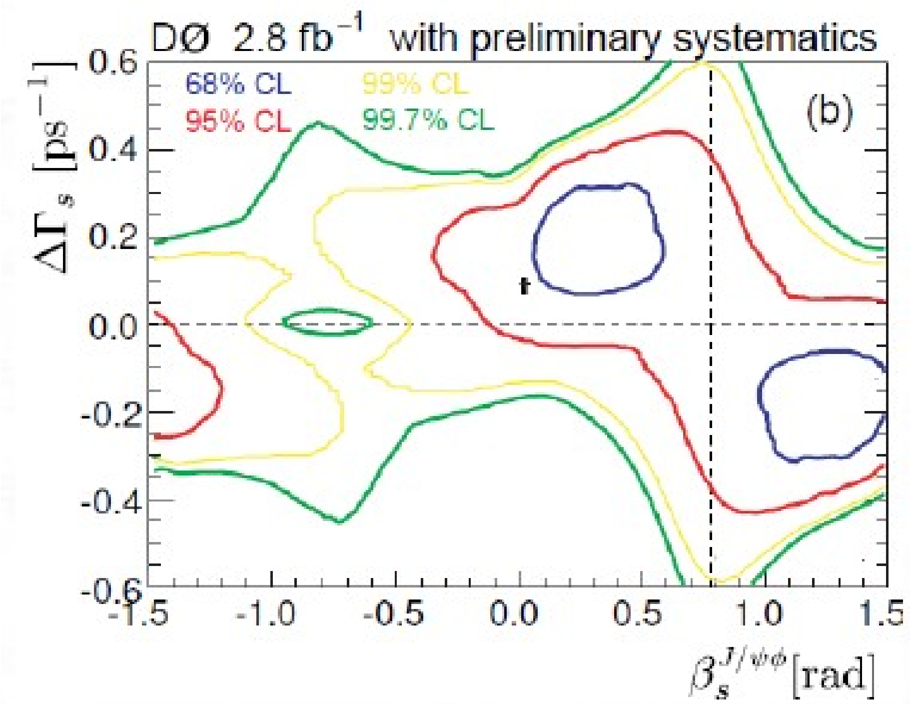
- B_s oscillations are fast and can only be done at hadron machines.
- Angular analysis as final state is vector-vector with CP even and CP odd components.
- Need to fit for $\Delta\Gamma$ as well.

$B_s \rightarrow J/\Psi\ \varphi$

Measurements from the Tevatron have a central value with large CPV.

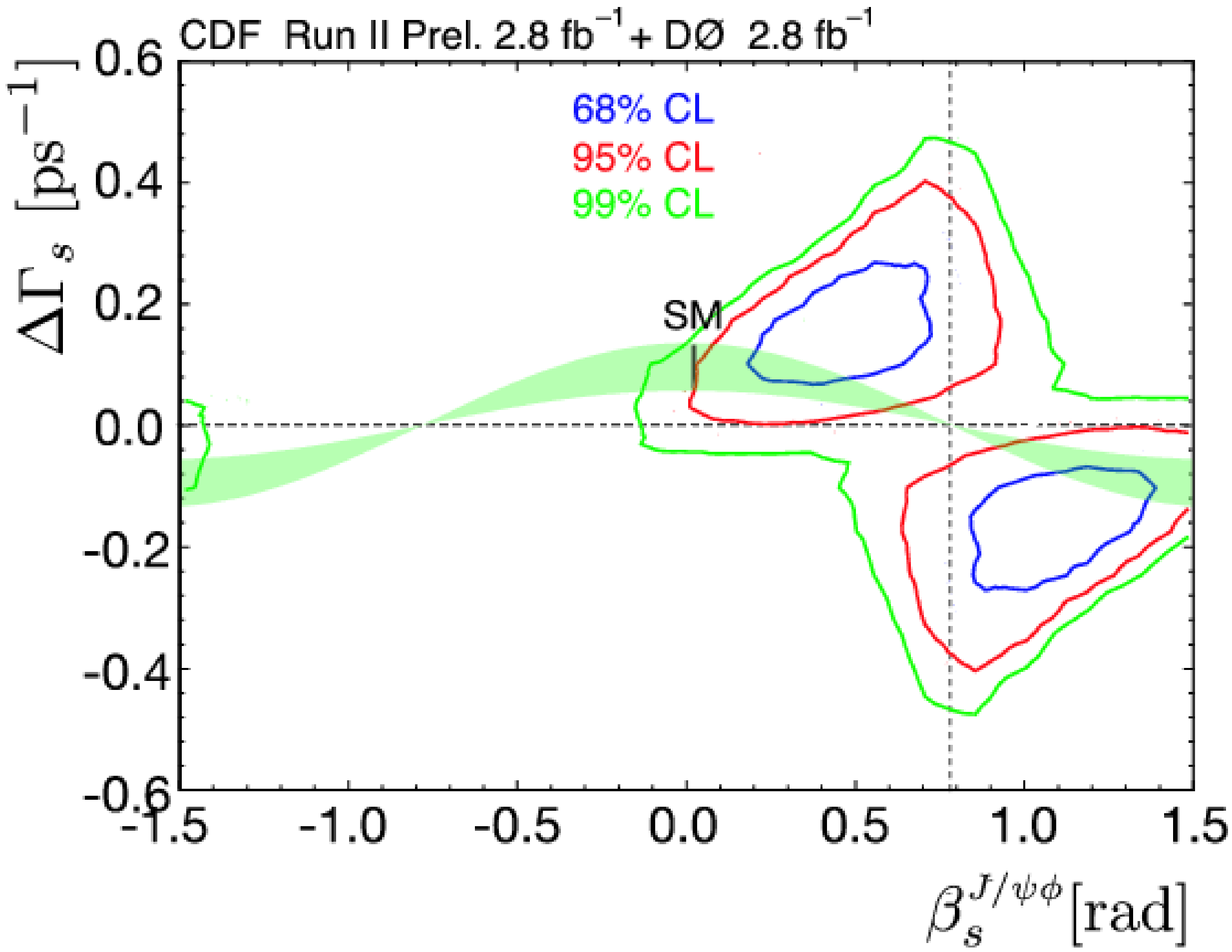


$\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$



$B_s \to J/\Psi\ \phi$

For CPV we have combined result β_s is within [0.10, 1.42] at 95% CL. 2.3 σ from SM value.



Branching ratio for $B_d \rightarrow K^*\gamma$

Huge increase in statistics for decay

Year	Pub	Events	BR ($\times 10^{-6}$)
1993	PRL 71,674	8	45.5 ± 7.0 ± 3.4
2004	PR D69, 112001	474	40.1 ± 2.1 ± 1.7
2009	PRL 103, 211802	2700	44.7 ± 10 ± 1.6
2010?		34k / fb^{-1}	

Theoretical prediction of BR cannot match experimental precision

- Look at inclusive decays
- Look at at other observables like polarization of photons

Properties of $B_d \to K^*\gamma$

The decay is sensitive to two Wilson coefficients

- $C_7^{(eff)}$ and $C_7'^{(eff)}$

In SM these are well calculated

- $C_7^{(eff)}$ known with 10% relative accuracy
- $C_7'^{(eff)}/C_7^{(eff)} \sim 0.04$ (more or less m_s/m_b)

Exclusive BR measures $|C_7^{(eff)}|^2+|C_7'^{(eff)}|^2$

- Measurement destroyed by form factor that adds large uncertainty

Instead look at γ_L/γ_R which directly measures $C_7'^{(eff)}/C_7^{(eff)}$

- But how to measure the polarisation of a final state photon!?

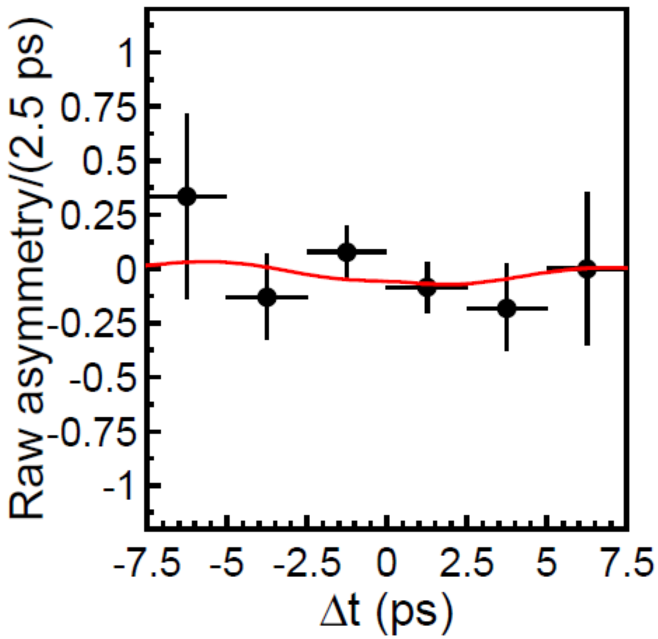
Measure photon polarization in $B_d \rightarrow K^* \gamma$

With only $C_7^{(eff)}$ we have $\overline{B}_d \rightarrow \overline{K}^{*0} \gamma_L$ and $B_d \rightarrow K^{*0} \gamma_R$.

- As final states are different there is no interference from B oscillations.

Or in other words time dependent CP violation is reduced from level in $B_d \rightarrow J/\Psi K^0_s$ by factor 2 $C_7^{'(eff)}/C_7^{(eff)}$

- Need shared final state $K^{*0}/\overline{K}^{*0} \rightarrow K^0_s \pi^0$ for this measurement to work.
- Belle measures S=−0.3±0.4±0.1 from PRD74:111104,2006
- We really need this as a 5% measurement.



Introduce $B_s \to \varphi\gamma$

- The decay $B_s \to \varphi\gamma$ looks in principle hopeless
  - Should measure time dependent CPV in $B_s \to J/\Psi\varphi$ reduced by factor $2\, C_7^{\prime(\mathrm{eff})}/C_7^{(\mathrm{eff})}$
  - CPV in $B_s \to J/\Psi\varphi$ in SM is around 0.04
- (Expected) width difference $\Delta\Gamma$ between B_s eigenstates comes to the rescue.

$$\Gamma(\mathrm{B}_q(\bar{\mathrm{B}}_q) \to f^{CP}\gamma) \propto e^{-\Gamma_q t}\left(\cosh\frac{\Delta\Gamma_q t}{2} - \boxed{\mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_q t}{2}} \pm \right.$$
$$\left. \pm \mathcal{C}\cos\Delta m_q t \mp \mathcal{S}\sin\Delta m_q t\right)$$

- $A^{\Delta} \sim 2\, C_7^{\prime(\mathrm{eff})}/C_7^{(\mathrm{eff})}$

F.Muheim, Y.Xie & R.Zwicky, Phys.Lett.B664:174-179,2008

  - No flavour tagging required
  - Only charged particles in final state it

Introduce $B_s \to \varphi\gamma$

LHCb expects 11k events in a nominal year (2 fb^{-1}) of running.

- This gives statistical resolution in $C_7^{'(eff)}/C_7^{(eff)}$ of around 0.1
- Factor 2 better than result from full B-factory measurement

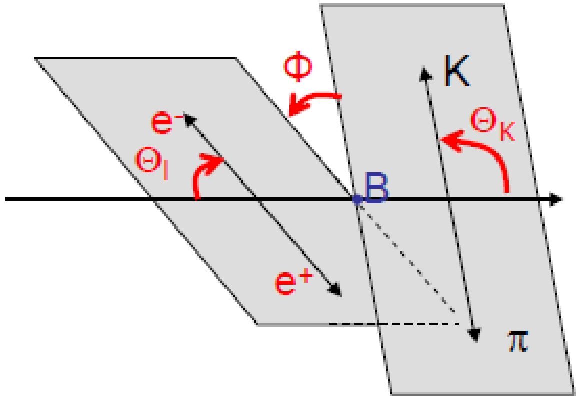
Very challenging systematics of method.

- In reality measure an effective lifetime that is different from the true B_s lifetime.
- Sensitive to bias in lifetime and to acceptance (efficiency as function of proper time)

Look at $B_d \to K^{*0} e^+ e^-$

Another way to find the photon polarisation is to let the photon "decay"

- Look at $B_d \to K^{*0} e^+ e^-$ for very low e^+e^- invariant masses



Distribution in φ angle measures $C_7^{'(eff)}/C_7^{(eff)}$

Small statistics

- Background rejection a big issue

Easy systematics

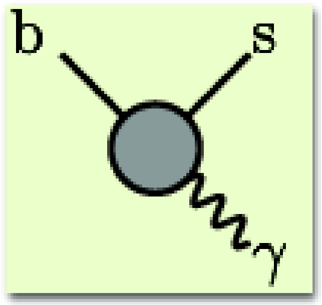
As good as $B_s \to \varphi\gamma$?

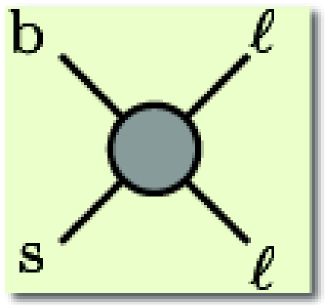
Progress to $B_d \to K^{*0}\mu^+\mu^-$

Much better statistics for $B_d \to K^{*0}\mu^+\mu^-$ compared to $B_d \to K^{*0}e^+e^-$ as muons are easier to trigger and reconstruct.

- Muon mass means we can't replicate the previous measurement.
- However, we get access to so much more

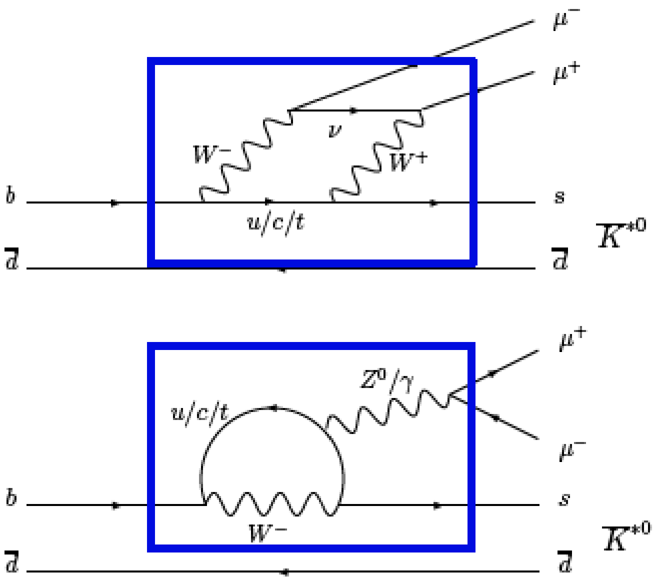
Interference between these





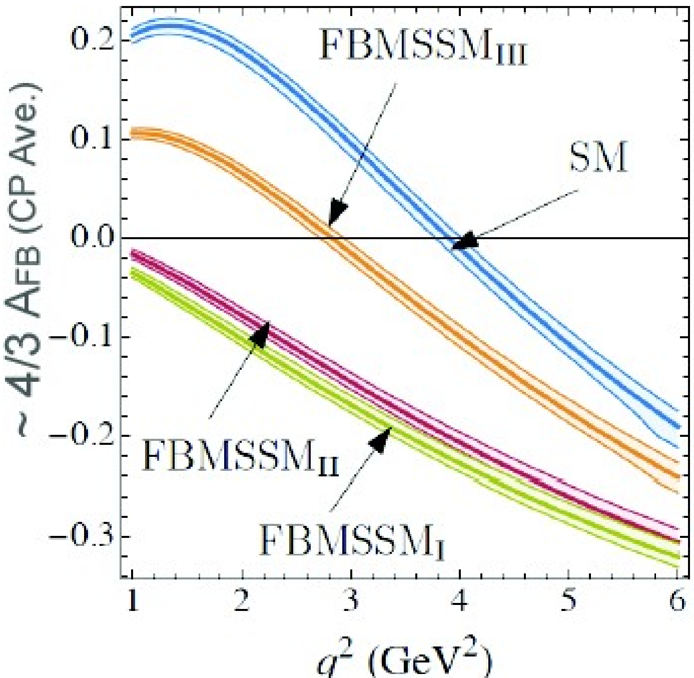
$O_{7\gamma}$ $O_{9,10}$

... and their primed counterparts



What to measure in $B_d \to K^{*0}\mu^+\mu^-$

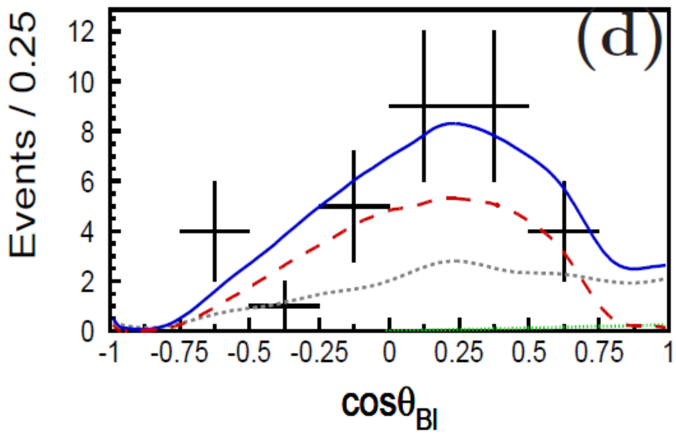
- As an exclusive decay we need to find a way to cancel form factors
  - In full expression we have 9 form factors
  - Can in low q^2 region use SCET to reduce this to just 2
- Most well known is A_{FB}, the forward-backward asymmetry
  - FF cancellation only at zero crossing point
- Sensitive to changes in C_7 and C_9



Altmannshofer et al, JHEP 0901:019,2009

Current measurements of A_{FB}

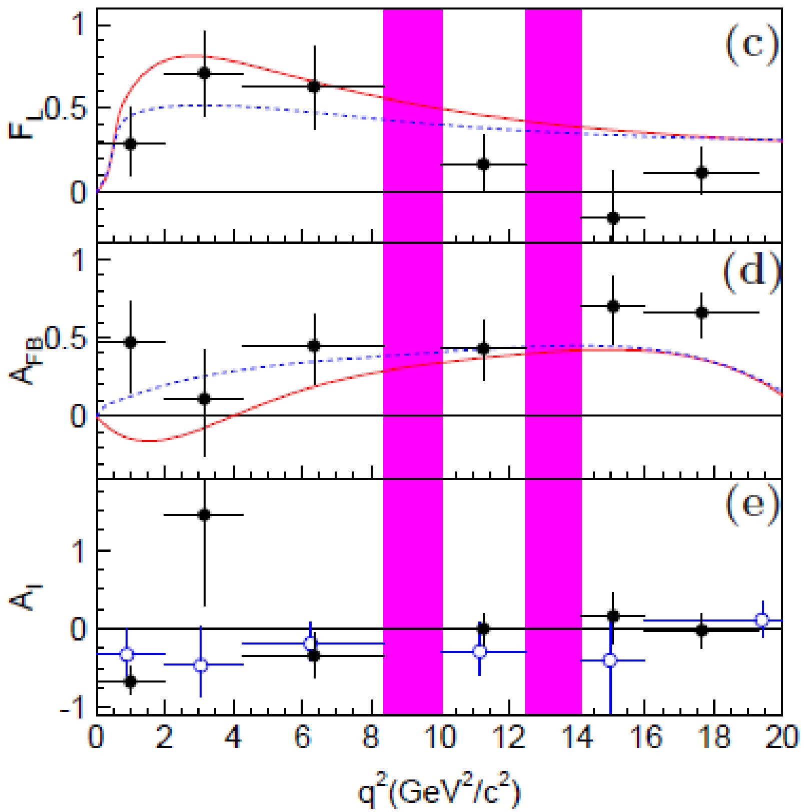
- Three results have arrived in the past 2 years
  - Belle PRL 103:171801 (2009).
  - BaBar PRD 79:031102 (2009)
  - CDF preliminary (HCP 2009)
- Example below of θ_l in $q^2 < 2\ \mathrm{GeV}^2$ from Belle
  - Clearly statistics are still very limited for this type of measurement.



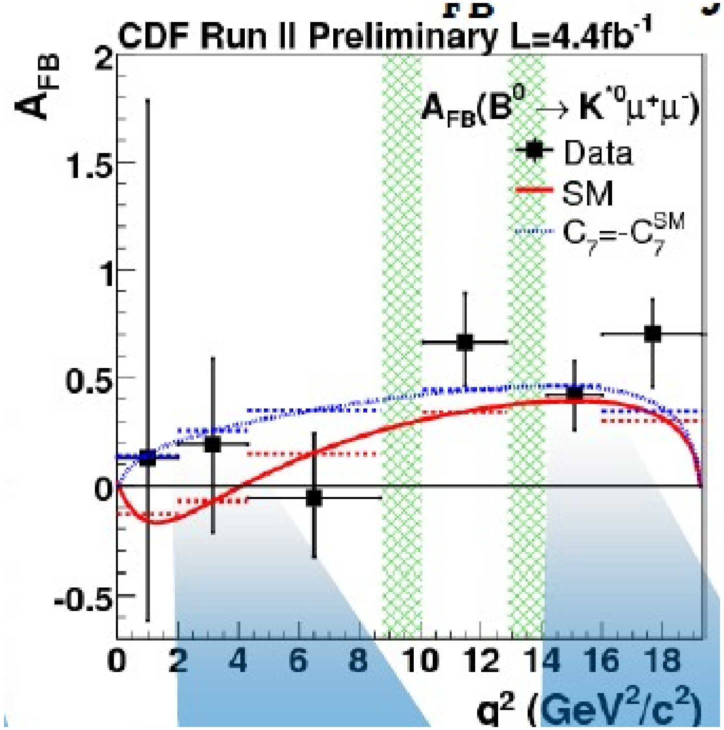
Current measurements of A_{FB}

Results are interesting in that all 3 experiments see sign of A_{FB} in low q^2 region which is opposite to SM.

Belle

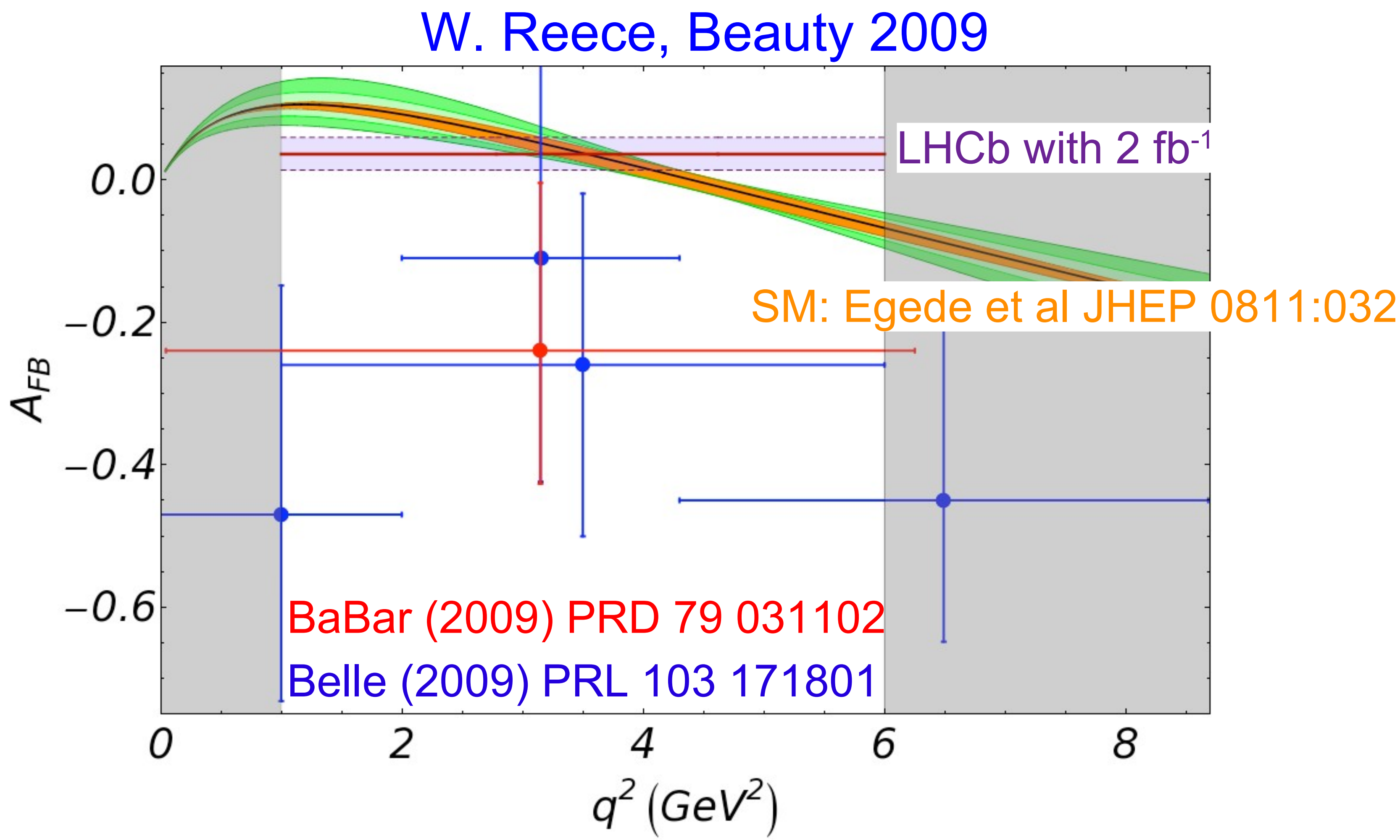


CDF



Current measurements of A_{FB}

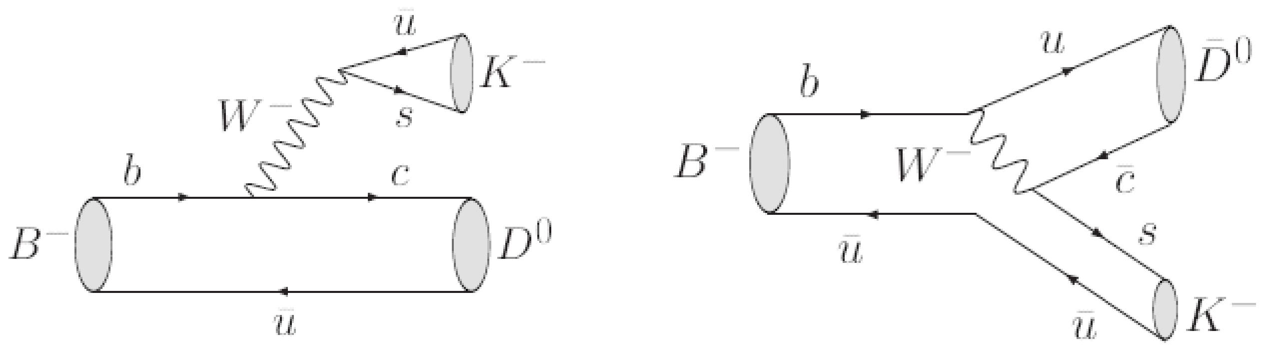
Just 0.1 fb^{-1} should give equivalent result for LHCb



CP angle γ

A multitude of methods available for measuring CP angle γ.

While strategies for measuring γ in the past dominated by time dependent analysis of $B_s \to D_s^+ K^-$, it is now B_d decays that dominate



Measurements of γ provides “SM clean” measurement from tree level diagrams.

CP angle γ

GLW: Measure direct CPV in decays $B^+ \rightarrow D_{CP} K^+$, $D_{CP} \rightarrow K^+K^-, \pi^+\pi^-$, ...

ADS: Look instead at the $D^0 \rightarrow K^+\pi^-$ decay interfering with the doubly Cabibbo suppressed $\overline{D}^0 \rightarrow K^+\pi^-$.

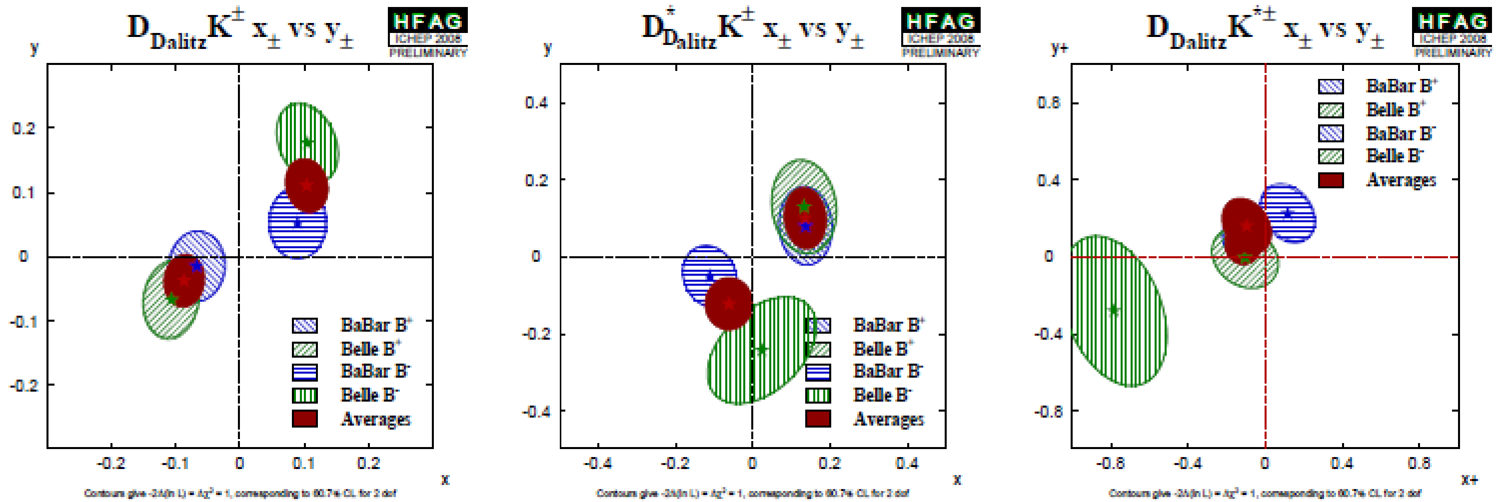
Dalitz: Use the final state $D0 \rightarrow K^0_s \pi^+\pi^-$ and extract everything from Dalitz plot analysis.

Dalitz analysis of $B^0 \rightarrow D^0 K^+ \pi^-$ final state also possible.

All methods make simultaneous determination of γ wiht nuisance parameters such as the strong phase difference δ, and the relative strength of amplitudes r_B.

CP angle γ

Dalitz method currently the most sensitive



Results derived in terms of Cartesian coordinates (x,y) to get error treatment correct as $r_B \rightarrow 0$.

The uncertainty on γ is currently in tens of degrees. LHCb will be able to bring this down to a few degrees.

Theoretical errors are minimal for most methods.

Current experimental status

If the goal of heavy flavour physics is to observe physics not described by the Standard Model we have not yet achieved it

As we have seen there are multiple effects in the 2 to 3 σ region but nothing beyond that.

There are now 3 challenges for the long term future

- Get more statistics for the future
- Beat down experimental systematics
- Reduce or work around theoretical errors

LHCb upgrade and Super-B factories take different routes to achieve this.

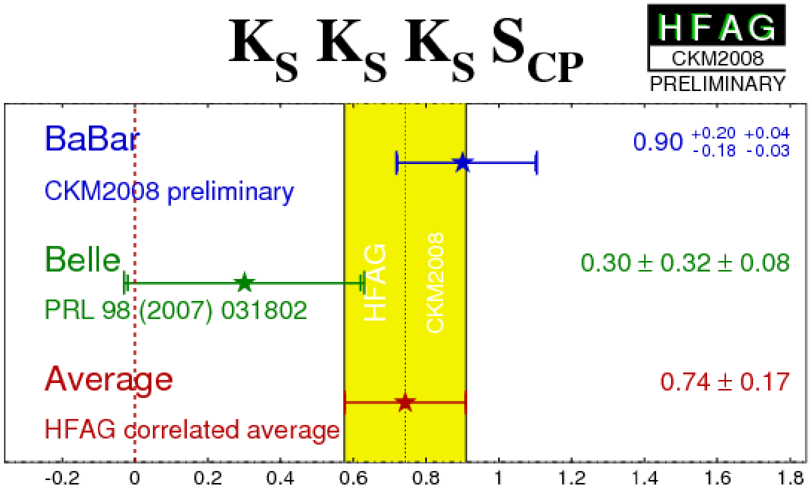
Sin 2β measurements

Measurement from $b \rightarrow c\bar{c}s$

- HFAG average is sin 2β = 0.691±0.031.
- No need for much better precision.

$B^0 \rightarrow K^0_s\, K^0_s\, K^0_s$

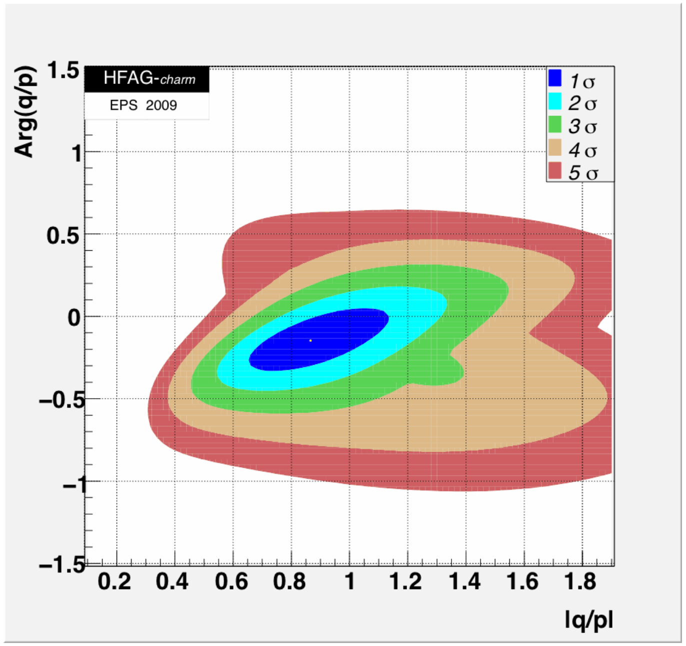
- Theory predicts $\Delta s_f = |\sin 2\beta - \sin 2\beta_{eff}| < 0.05$
- To reach theory error at an SFF would take about 75 ab^{-1}.
- A difference would be strong sign of NP in either box or penguin.



CP violation in D mesons

Further accuracy on parameters for D^0 oscillations is of limited interest.

- SM predictions have large uncertainty.
- However, a discovery of CP violation would be clean NP signature, and we need to know the oscillations parameters for this.



Current experimental results have very low precision

Statistics will be there for LHCb, but systematics obviously a big challenge

Recoil tagging

The method of (fully) reconstructing one of the B-mesons at the Υ(4S) resonance gives the possibility to obtain a very clean signal sample from the other B.

At a Super-B factory this method has potential for channels which are currently systematic limited

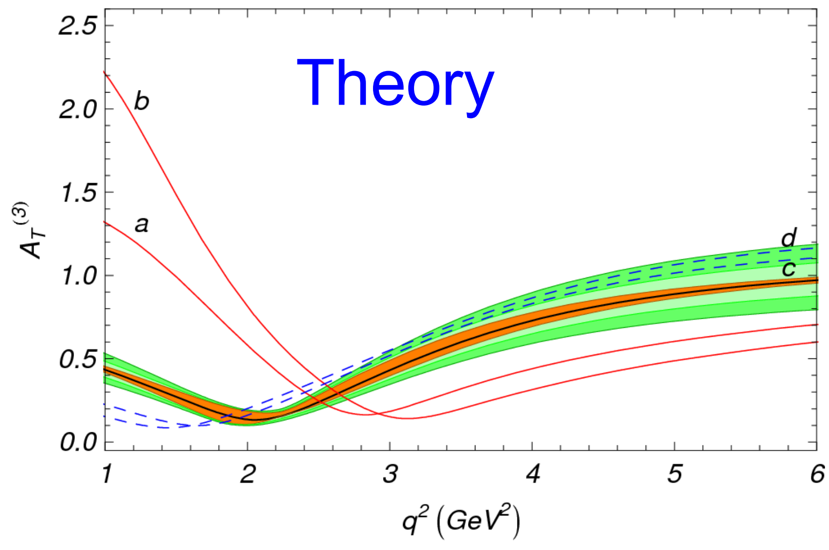
- $B+ \rightarrow \tau\nu$
- $B \rightarrow X_s\gamma$ inclusive BR
- Measurements of V_{ub}

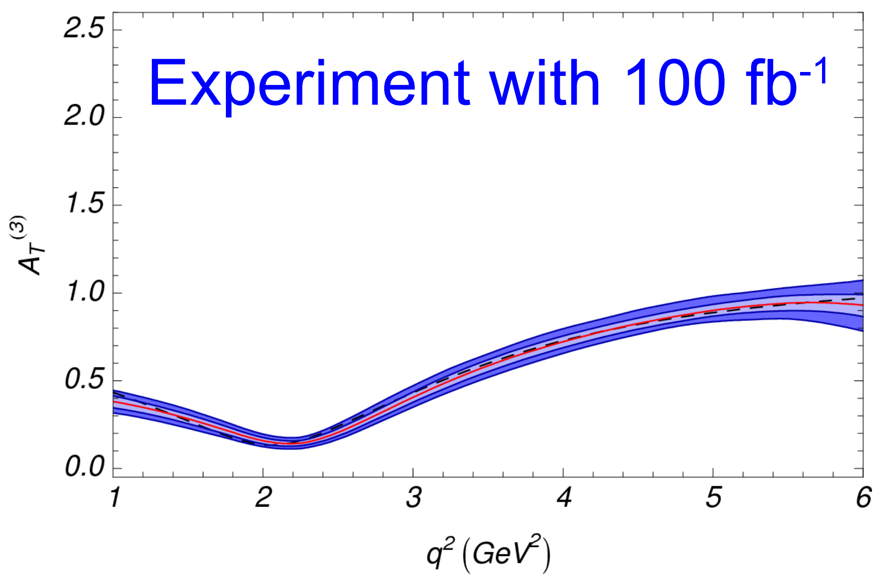
To really gain from this method data samples of the order of 75 ab^{-1} are required.

Further observables in $B_d \rightarrow K^{*0}\mu^+\mu^-$

A full angular analysis of the $B_d \rightarrow K^{*0}\mu^+\mu^-$ decay carries a multitude of observables.

To take full advantage of these will take very large datasets which will only be available at an LHCb-upgrade.





Conclusion

- An amazing amount of results have been accumulated in the past decade for heavy flavour physics
- Some hints for New Physics
  - Phase in Bs oscillations
  - $B^+ \to \tau^+ \nu$ branching ratio
  - Isospin asymmetry in $Bd \to K^{(*)} l^+ l^-$
- ... but no clear signals
- Future discoveries and precision measurements around the corner
  - $B_s \to \mu^+ \mu^-$
  - CP angle γ
  - A_{FB} in $B_d \to K^{*0} \mu^+ \mu^-$