LHCb γ Extraction with $B_s \to D_s K$ and $B_d \to D^{(*)}\pi$

Physics Motivation and Observables

Experimental Essentials

Reconstruction of $B_d \to D^{(*)}\pi$ and $B_s \to D_s K$

'Conventional' γ extraction with $B_s \to D_s K$ and the problem of discrete ambiguities

Extracting γ with $B_s \to D_s K$ and $B_d \to D\pi$ under U-spin symmetry

Conclusions

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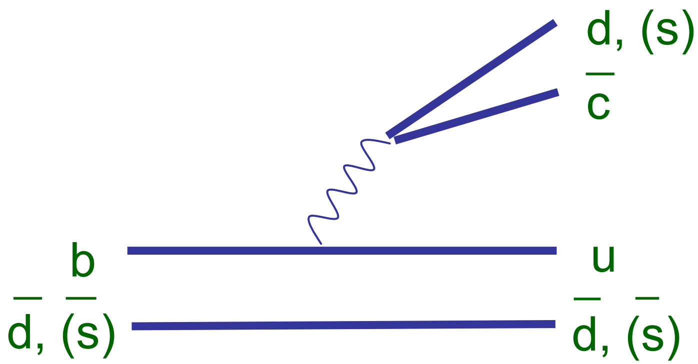
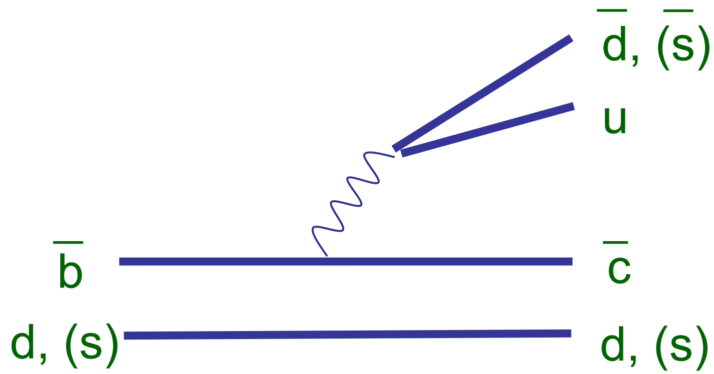
Interest of $B_s \to D_s K$, $B_d \to D^{(*)}\pi$ Decays

Consider the below two tree diagrams, & the $B_{d(s)} \leftrightarrow \overline{B}_{d(s)}$ mixing graphs





Interference means that a time dependent analysis of the four rates:

$$B_{d(s)},\ B_{d(s)} \to D_{d(s)}^{(*)+}\ K^-\ (\pi^-)\ ,\ \ D_{d(s)}^{(*)-}\ K^+(\pi^+)$$

allows a theoretically clean extraction of $(\Phi_{d\,(s)} + \gamma)$. Here $\Phi_{d(s)}$ is the weak mixing phase associated with the mixing, = 2β (-2χ) in SM, which can be fixed with high precision from elsewhere $\to$ determine γ !

What are our observables?

Take $B_s \to D_s K$ as an example. From 4 flavour tagged rates, we construct 2 asymmetries which involve 6 observables: C_s, S_s, $\overline{C}_s$, $\overline{S}_s$, $A_{\Delta\Gamma}$ and $\overline{A}_{\Delta\Gamma}$

$$\mathcal{A}_{\rm CP}(D_s^+ K^-) \equiv \frac{B_s^0 \to D_s^+ K^- \; - \; \overline{B_s^0} \to D_s^+ K^-}{B_s^0 \to D_s^+ K^- \; + \; \overline{B_s^0} \to D_s^+ K^-}$$

$$= \frac{C_s \cos \Delta m_s t \; + \; S_s \sin \Delta m_s t}{\cosh(\Delta\Gamma_s t/2) \; - \; A_{\Delta\Gamma} \sinh(\Delta\Gamma_s t/2)}$$

$$\mathcal{A}_{\rm CP}(D_s^- K^+) \equiv \frac{B_s^0 \to D_s^- K^+ \; - \; \overline{B_s^0} \to D_s^- K^+}{B_s^0 \to D_s^- K^+ \; + \; \overline{B_s^0} \to D_s^- K^+}$$

$$= \frac{\overline{C}_s \cos \Delta m_s t \; + \; \overline{S}_s \sin \Delta m_s t}{\cosh(\Delta\Gamma_s t/2) \; - \; \overline{A}_{\Delta\Gamma} \sinh(\Delta\Gamma_s t/2)}$$

Practically, we measure $A_{\Delta\Gamma}$ and $\overline{A}_{\Delta\Gamma}$ from time evolution of untagged rates

For B_d case we only have 4 observables: C_d, S_d, $\overline{C}_d$, $\overline{S}_d$ ($\Delta\Gamma_d$ very small !)

What do the Observables Tell Us ?

Observables functions of following parameters: r_s, δ_s,Φ_s, r_d, δ_d,Φ_d and γ

For $B_d \to D\pi$ and $B_s \to D_s K$ we have:

$$C = -\left(\frac{1-r^2}{1+r^2}\right), \qquad S = \frac{2r\ \sin(\phi+\gamma+\delta)}{1+r^2}$$

$$\overline{C} = +\left(\frac{1-r^2}{1+r^2}\right), \qquad \overline{S} = \frac{2r\ \sin(\phi+\gamma-\delta)}{1+r^2}$$

(For $D^*\pi$ channel the S and $\overline{S}$ terms pick up a minus sign.)
And for $B_s \to D_s K$ we have:

$$A_{\Delta\Gamma} = -\frac{2r_s\ \cos(\phi_s+\gamma+\delta_s)}{1+r_s^2} \qquad \overline{A_{\Delta\Gamma}} = -\frac{2r_s\ \cos(\phi_s+\gamma-\delta_s)}{1+r_s^2}$$

So from these observables (and taking $\Phi_{s,d}$ from elsewhere) we can get γ !

A remark about the 'r' factors

The r factors expresses the ratio of the interfering tree amplitudes:

Unknown hadronic factors of order 1

$$r_s = f_s^{\rm CKM} a_s \qquad r_d = f_d^{\rm CKM} a_d$$

~0.4 ~0.02

We need to know these factors to get out the phase information of interest:

eg. $$S = \frac{2r \sin(\phi + \gamma + \delta)}{1 + r^2}$$

In principle they can be fixed from the cosine amplitudes:

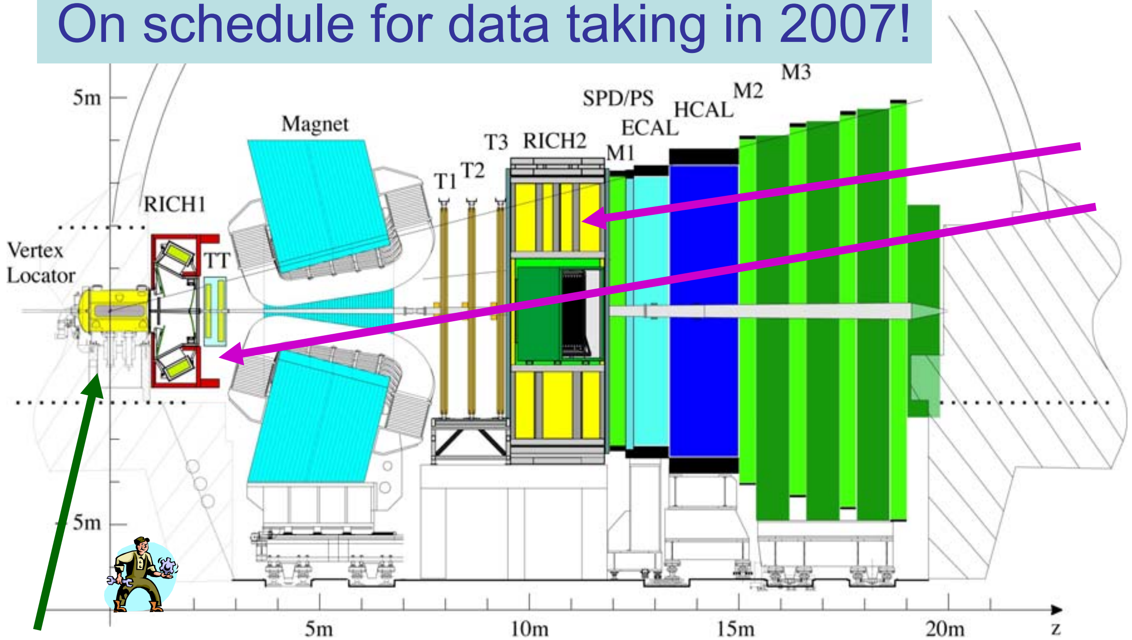
$$C = -\left(\frac{1-r^2}{1+r^2}\right), \qquad \overline{C} = +\left(\frac{1-r^2}{1+r^2}\right)$$

Works well in B_s case, but for the B_d $C, (\overline{C}) \approx (-)1$ & we have no sensitivity!

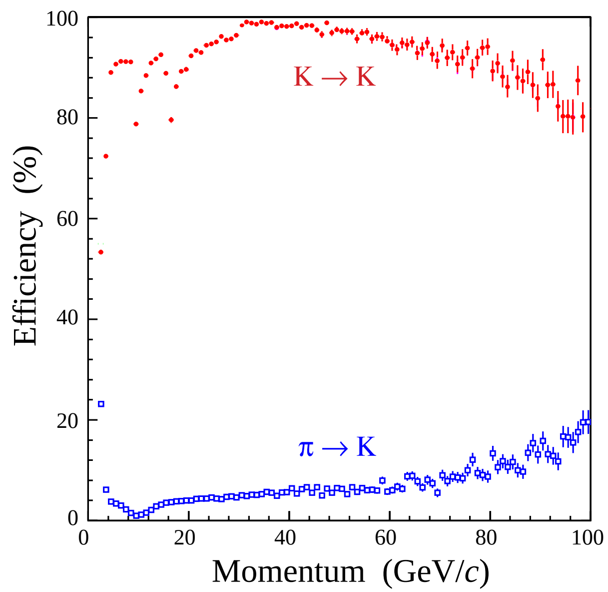
→need to make assumptions about r_d to extract γ from B_d data alone

LHCb: experimental essentials

On schedule for data taking in 2007!



2) RICH system provides
PID over 100 GeV span:



1) Vertex Locator (VELO) with Si sensors 8mm from beamline.

Primary vertex resolution:

~ 8 μm (x,y) and ~ 44 μm (z)

Impact parameter resolution:

~ 40 μm

3) Trigger optimised for B physics:

- High pt tracks (esp. hadrons)
- Lifetime trigger with VELO info

30% efficiency for D_sK and $D^{(*)}\pi$

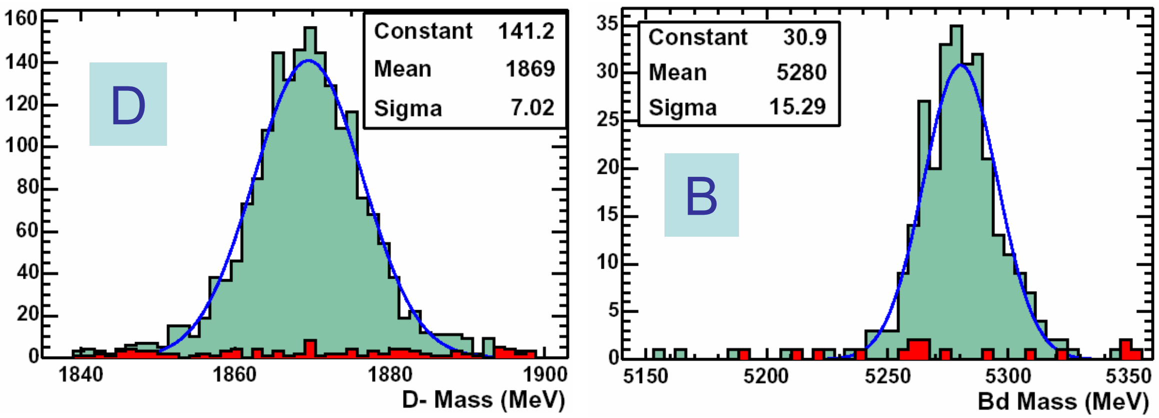
Performance in $B_d \to D^*\pi$, $D\pi$

Performance in $B_d \to D^*(D^0\pi)\pi$, $D^0 \to K\pi$ reported in 'Reoptimisation TDR'

206k events / year, Bck/Sig < 0.3 (1 yr = 2 fb^{-1})

Can be improved by adding other exclusive, and semi-inclusive, D_0 decays

Recently, a preliminary study performed of $B_d \to D^-\pi^+$, $D^- \to K^-\pi^+\pi^+$



210k events/year

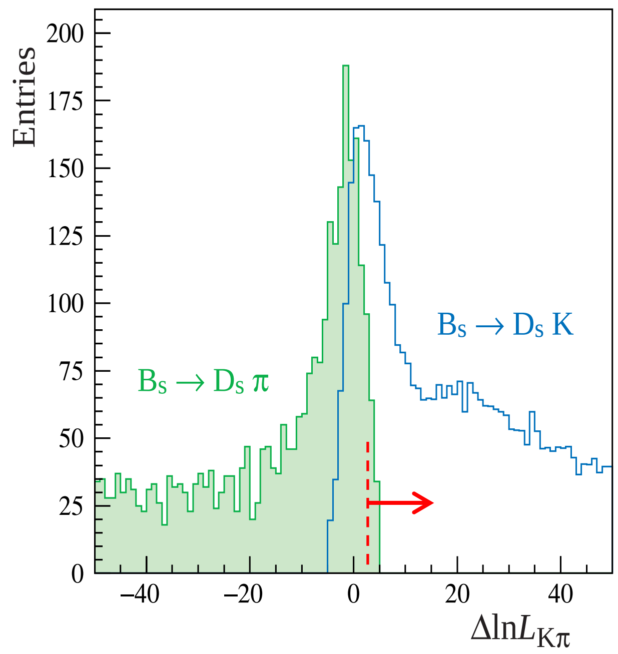
Bck/sig ~ 0.3

If r_d is constrained using external information, γ can then be extracted !

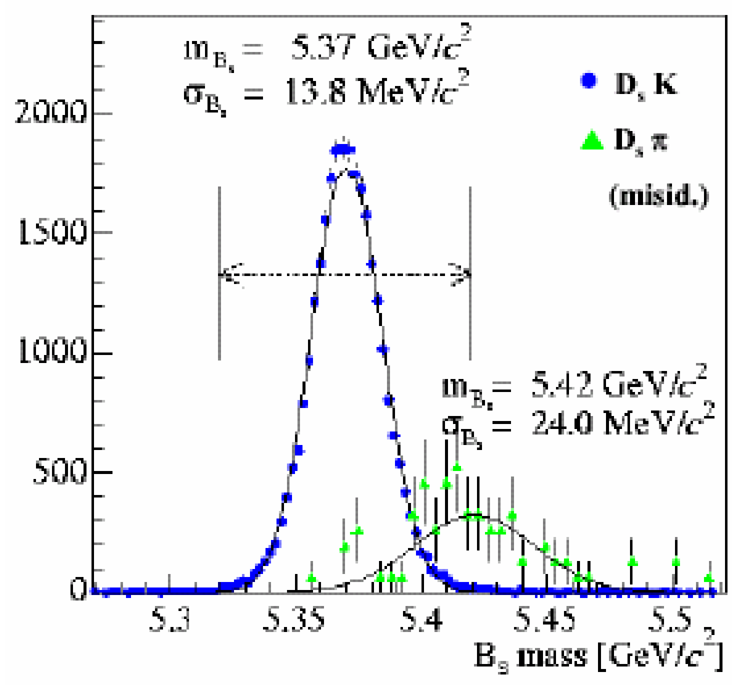
Selection of $B_s \to D_s K$

Main background to $B_s \to D_s K$ comes from $B_s \to D_s \pi$, which is ~12x more common

Suppress with cut on log likelihood particle hypothesis in RICH



Final $D_s\pi$ contamination ~ 10%



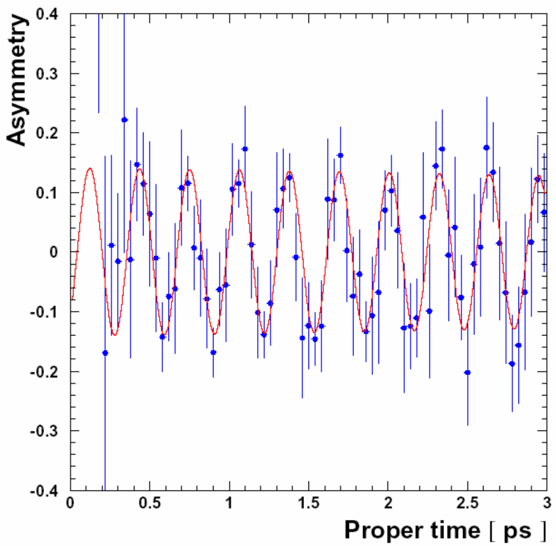
Annual yield of 5.4k events

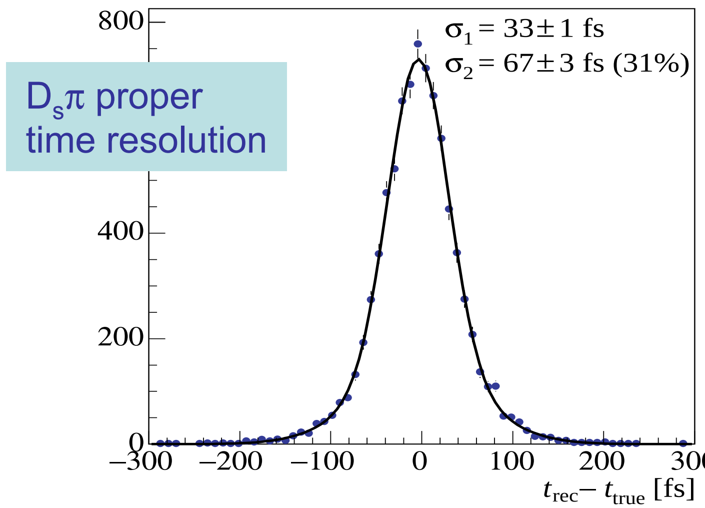
Bck (generic) / Sig < 0.5

Resolving the B_s Oscillations

Measuring the asymmetries requires resolving the oscillations…

…which requires excellent proper time resolution.





In this example (Δm_s=20 ps^{-1}) mean resolution ≈ 15% oscillation period. Finite proper time resolution suppresses CP amplitudes by 30%.

New development: increase output rate of LHCb up to 2 kHz to collect high statistics calibration channels (eg. lifetime unbiased J/ψ sample) to study proper time resolution in detail, and keep systematics low !

Conventional γ Extraction from $B_s \rightarrow D_s K$

LHCb has performed ‘conventional’ study of sensitivity to γ.

Fit the four decay rates as a function of proper time:

$$B_s, \overline{B}_s \rightarrow D_s^+ K^-, D_s^- K^+$$

This allows ($\Phi_s + \gamma$) to be extracted, and hence γ , as Φ_s can be fixed from measurements in other channels, such as $B_s \rightarrow J/\Psi\Phi$

Resulting precision on γ is 14 degrees, in one year’s running.
(Assumes Δm_s=20 ps^{-1} and $\Delta\Gamma$ = -0.15 ps^{-1})

Theoretically clean, so error will steadily decrease with operation.

However, possibility of nuisance from (multiple) ambiguous solutions !

The ambiguity problem – and a (partial) way out

Tagged observables depend on

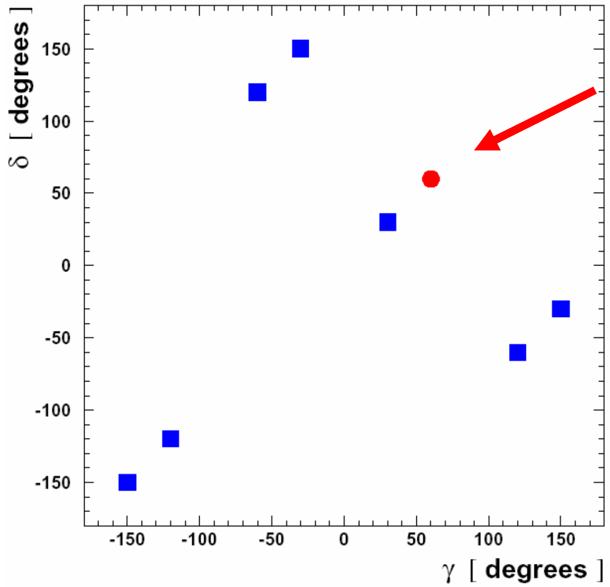
$$\sin(\Phi_s + \gamma \pm \delta)$$

8-fold discrete ambiguity !

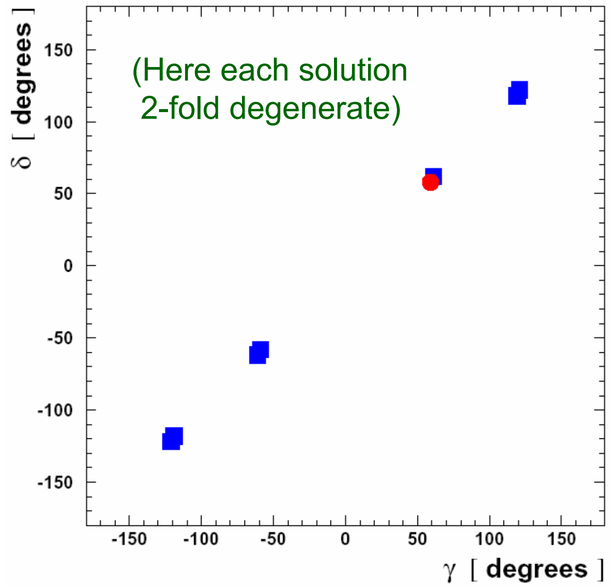
Untagged observables depend on

$$\cos(\Phi_s + \gamma \pm \delta)$$

Also 8-fold ambiguity – but not the same fake solutions as tagged case



True value:
γ=60, δ=60



With perfect knowledge of $S, \bar{S}$ & $A_{\Delta\Gamma}, \overline{A_{\Delta\Gamma}}$ end up with only 2 possibilities !

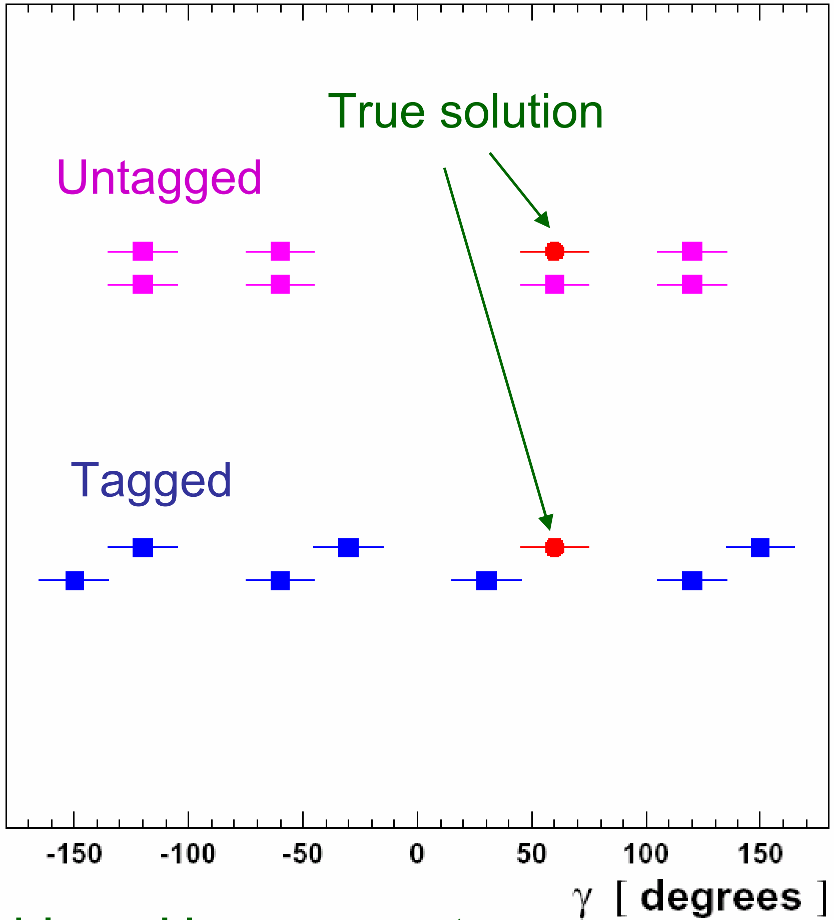
(Not an option for the B_d case as untagged observables are unobservable…)

Resolving ambiguities through comparison of tagged and untagged observables

Comparison of solutions with tagged and untagged observables in principle allows number of possible solutions to be reduced to two

However, precision on measurements may well mean that this is not so straightforward!

Particularly the case if $\Delta\Gamma$ is small !



Other methods needed to tackle problem. Here present U-spin analysis inspired by R.Fleischer, Nucl Phys B 671 (2003) 459-482.

Overview of the U-Spin Analysis

Consider decays related by U-spin ($s \leftrightarrow d$) symmetry: $B_s \rightarrow D_s K$ and $B_d \rightarrow D\pi$

Measure the sine amplitudes in the asymmetries for both: S_s, $\overline{S}_s$, S_d, $\overline{S}_d$

These depend on:

γ, Φ_s , Φ_d

$r_s = f_s^{CKM}\, a_s$, $r_d = f_d^{CKM}\, a_d$

δ_s , δ_d

Hadronic terms for which U-spin symmetry will be important !

Illustrate possibilities with 3 stage analysis:

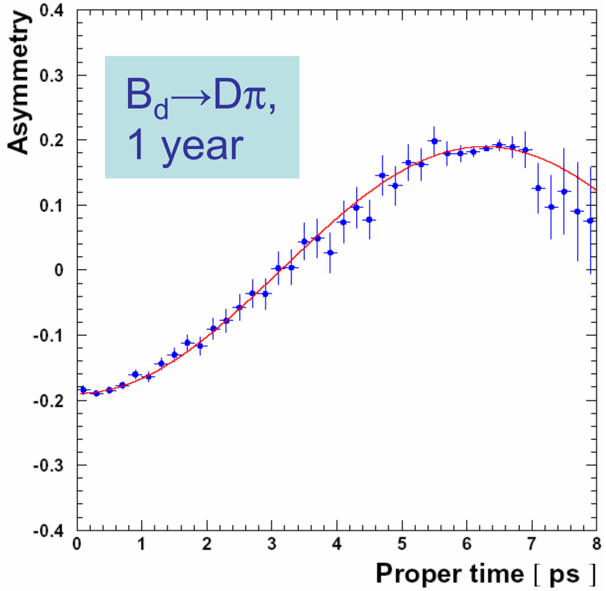
- 'Strong U-spin' :
  Using 4 observables form 2 expressions, each of which can be used to extract γ under assumption that $a_s \approx a_d$ and $\delta_s \approx \delta_d$
- 'U-spin phase':
  Eliminate a_s, a_d from above 2 expressions to give single equation which will give γ under assumption that $\delta_s \approx \delta_d$
- 'U-spin 2 amplitude':
  As above, but now eliminate phases and ask that $a_s \approx a_d$

Inputs to U-Spin Sensitivity Studies

Need to know likely precisions on sine amplitude observables

LHCb

Take estimated yields & performance on $B_s \to D_s K$ and $B_d \to D\pi$ and perform 'toy MC' studies to estimate precision on S, S



1 year errors on $S_d, \bar{S}_d = 0.014$

$S_s, \bar{S}_s = 0.14$

Assume these will scale as $1/\sqrt{N}$ years (systematics small & set from calibration data)

B-factories

B factories already probing $B_d \to D\pi$ and will have impressive precision by 2008. Take Belle result in PRL 93 031802 (2004) and extrapolate up to 2000-2500 fb^{-1} to guesstimate total B-factory dataset in 2008

$\to$ (final) B-factory error on $S_d, \bar{S}_d = 0.015$

Strong U-Spin Assumption

Combine D_sK and $D\pi$ sine term amplitudes to give two *exact* expressions:

$$\left(\frac{a_s \cos\delta_s}{a_d \cos\delta_d}\right) = -\frac{1}{R}\left(\frac{\sin(\phi_d+\gamma)}{\sin(\phi_s+\gamma)}\right)\left(\frac{S_s+\overline{S_s}}{S_d+\overline{S_d}}\right) \quad (1)$$

$$\left(\frac{a_s \sin\delta_s}{a_d \sin\delta_d}\right) = -\frac{1}{R}\left(\frac{\cos(\phi_d+\gamma)}{\cos(\phi_s+\gamma)}\right)\left(\frac{S_s-\overline{S_s}}{S_d-\overline{S_d}}\right) \quad (2)$$

Here:

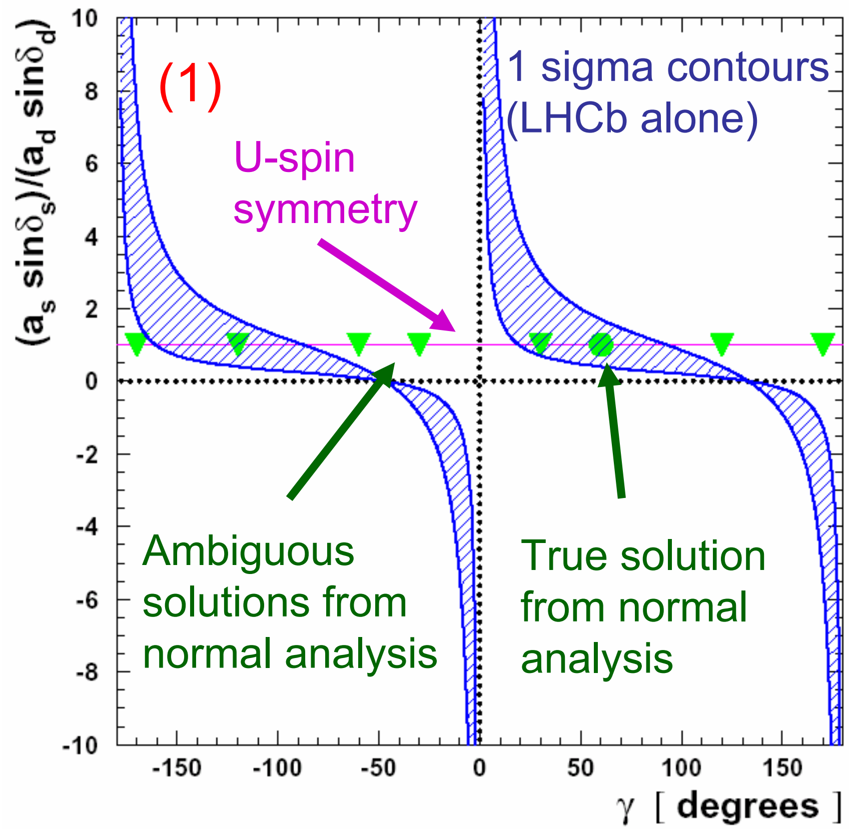
$$R = \left(\frac{1-\lambda^2}{\lambda^2}\right)\left(\frac{1+r_d^2}{1+r_s^2}\right)$$

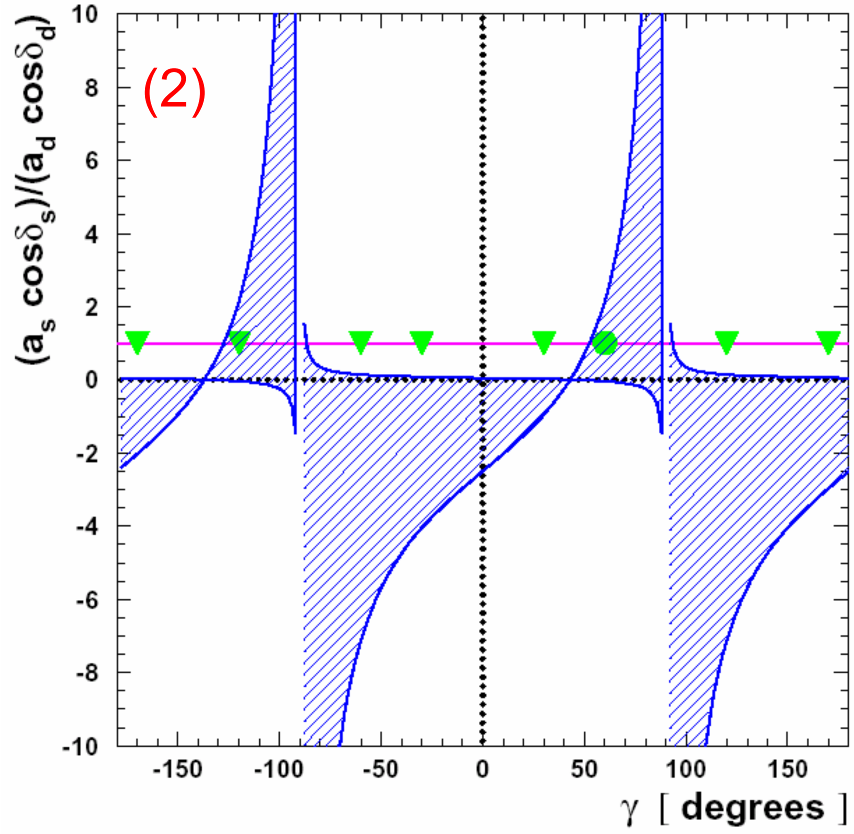
which is a factor we can fix to 5–10 % (1 yr) from data. No need to know r_d !

Under perfect U-spin symmetry the LHS of both expressions is unity. ($a_s = a_d$ *and* $\delta_s = \delta_d$). Hence this gives us a combined B_s / B_d way to find γ.

Subsequent plots assume γ=60 deg, δ=60 deg, Φ_s=0 deg, Φ_d=47 deg

Full U-Spin Symmetry: 1 year

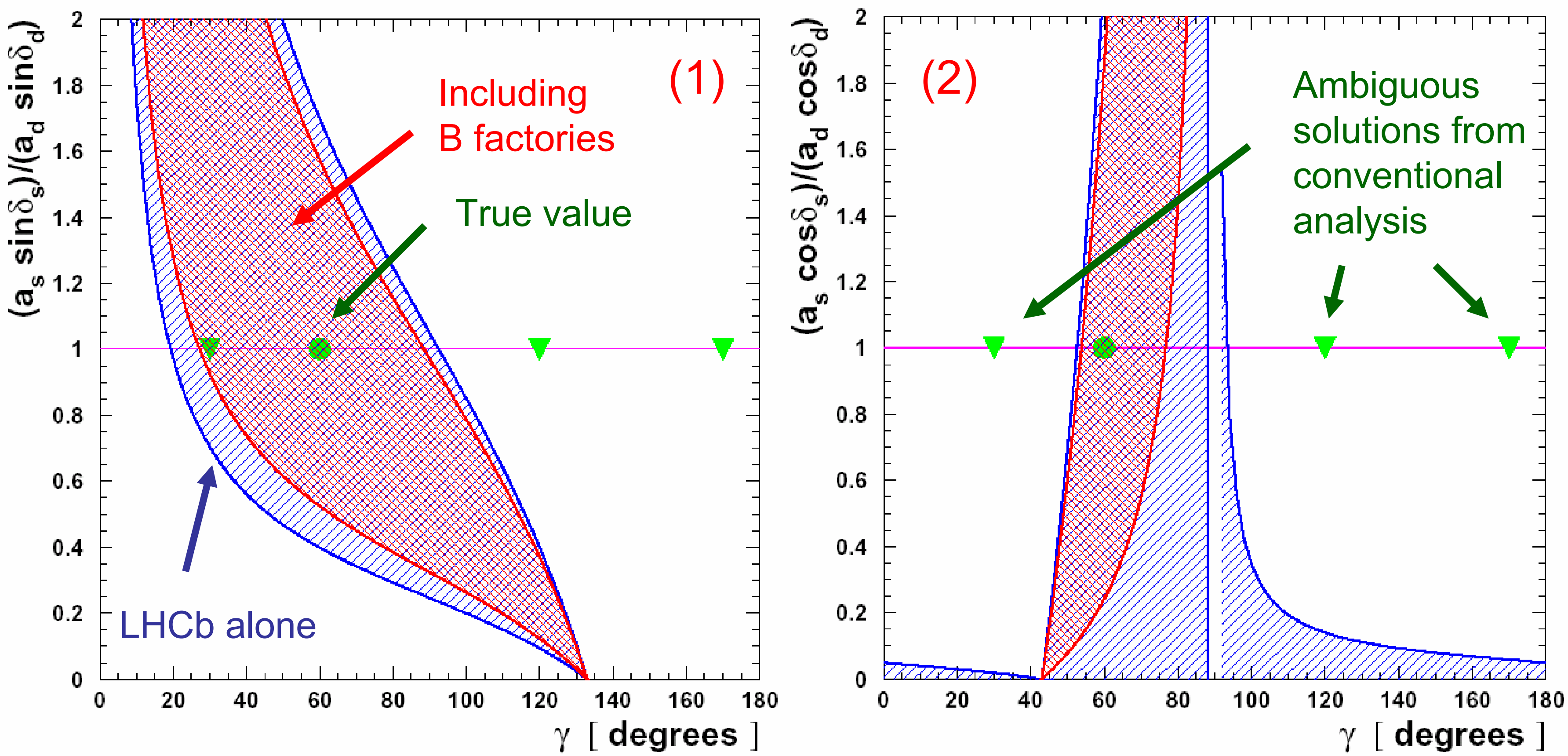




Only 2-fold ambiguity! Negative γ solution implies very large δ. Disfavoured by factorisation.

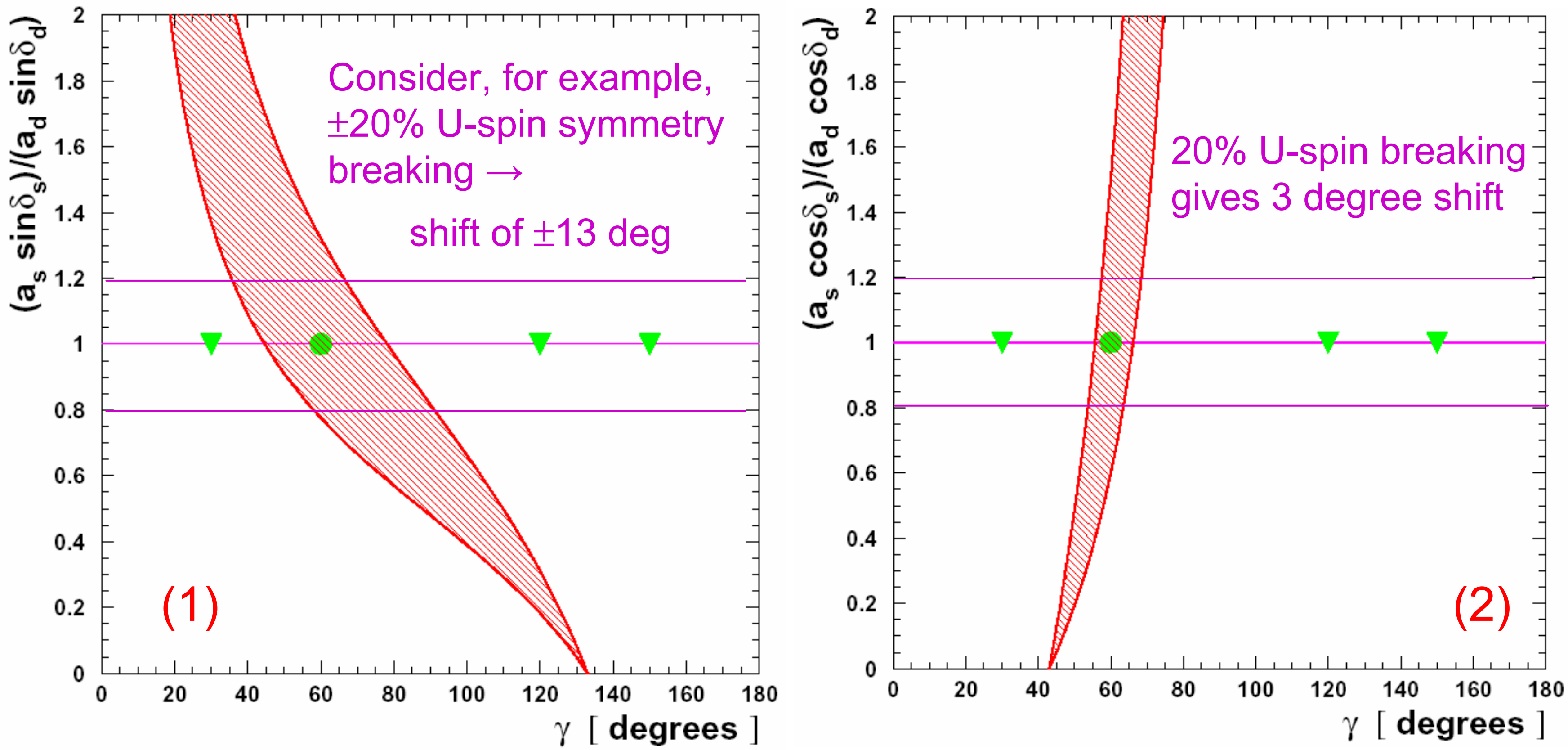
Wide bands because sign of S_d-$\overline{S}_d$ not properly resolved.

Full U-Spin Symmetry: 1 year – interesting quadrant with B factory input



Ambiguous solutions disfavoured - B factory data a big help.
Expression (2) gives errors of +16, -7 degrees.

Full U-Spin Symmetry: 5 years



Both expressions now giving very interesting precision on γ .
Right hand plot has precision of 5 degrees, and small systematic.
Ambiguous solutions now excluded.

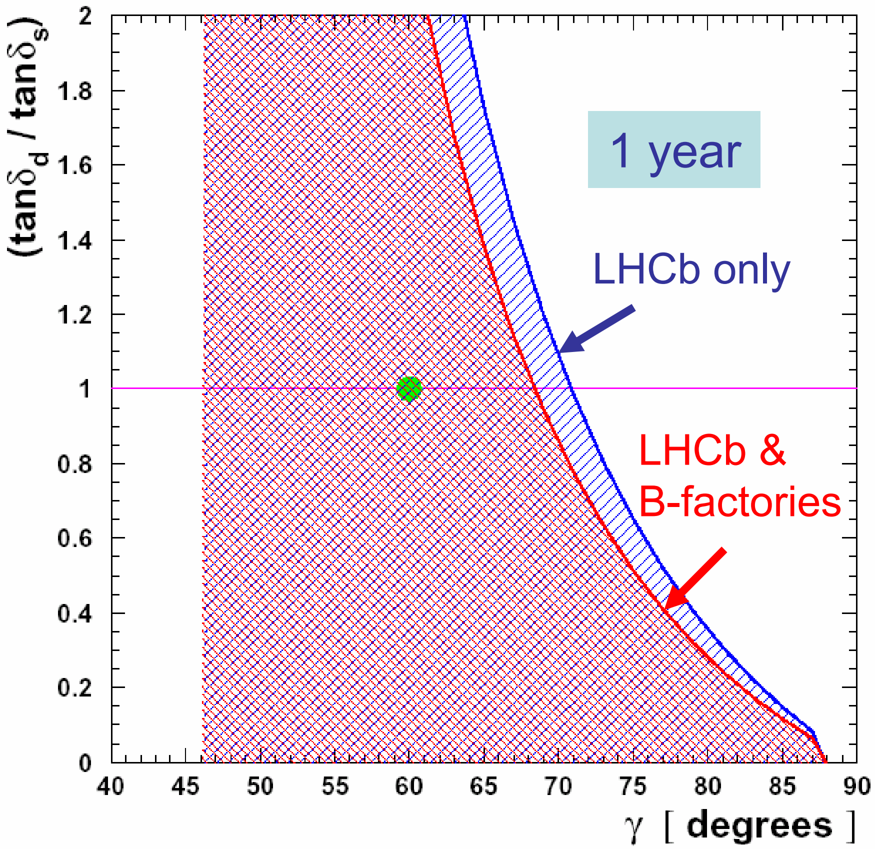
U-Spin Phase Symmetry Assumption

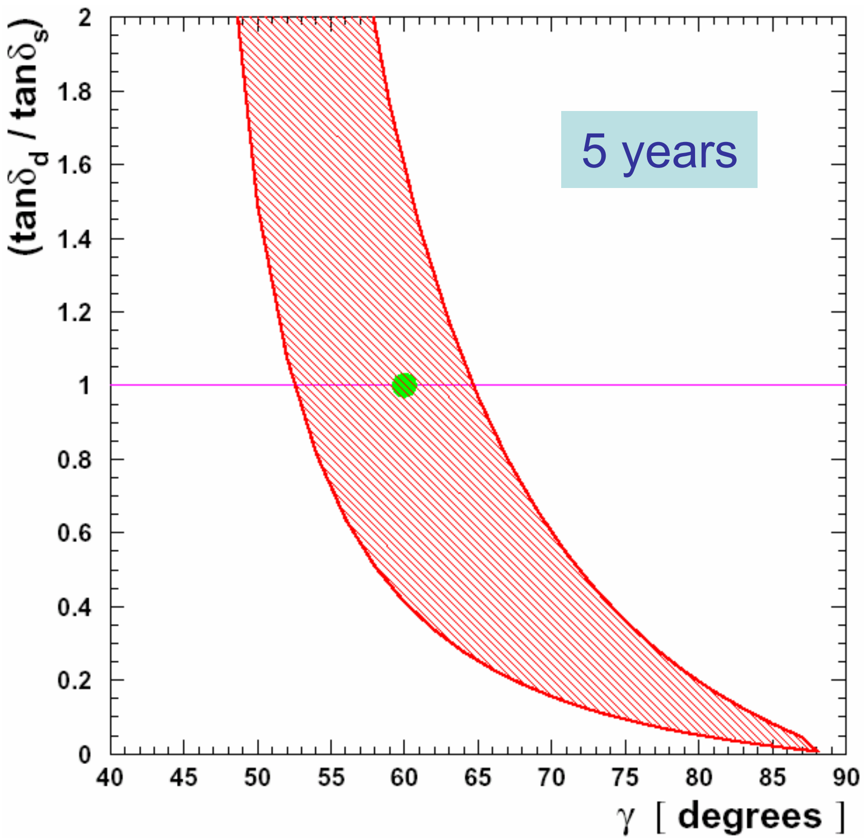
Now make no assumption about a_d and a_s. Eliminate them from previous expressions (now NO r_d or r_s knowledge needed) to give:

$$\frac{\tan\delta_d}{\tan\delta_s} = \left(\frac{S_s + \overline{S_s}}{S_s - \overline{S_s}}\right)\left(\frac{S_d - \overline{S_d}}{S_d + \overline{S_d}}\right)\frac{\tan(\phi_d + \gamma)}{\tan(\phi_s + \gamma)}$$

We use this, and then require that $\delta_d = \delta_s$ to extract γ

U-Spin Phase Symmetry Assumption





Useful upper error of 9 degrees

Precision of +5, -8 degrees, & good systematic robustness
(2 degree error for ±20% breaking)

U-Spin Amplitude Symmetry Assumption

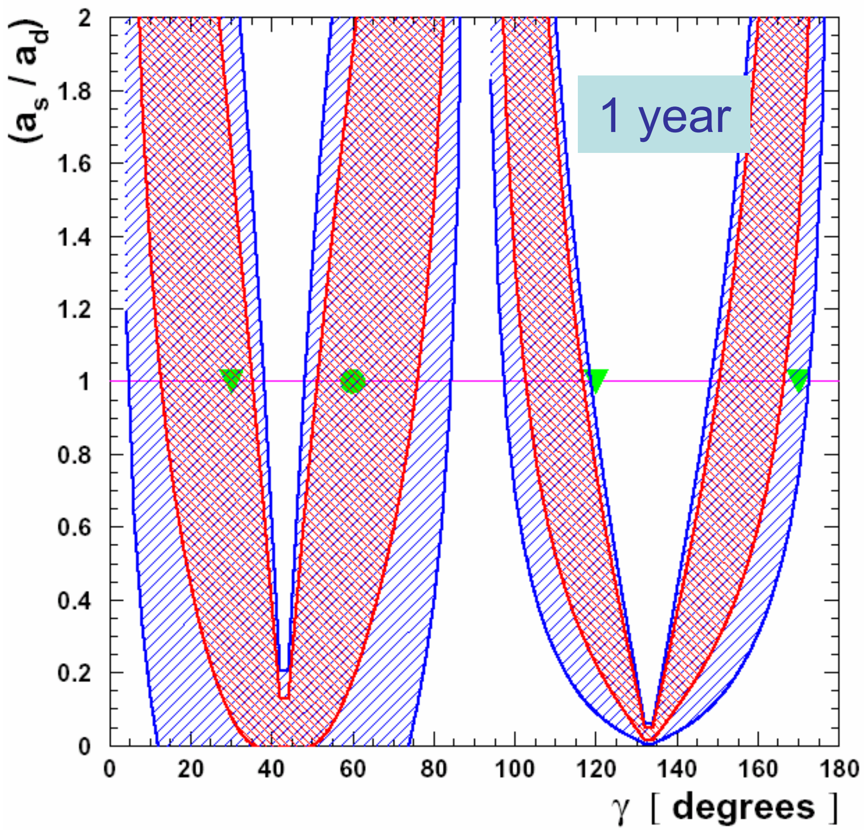
Rather than eliminate a_s, a_d from our starting two expressions, may instead eliminate $\delta_{d,s}$. Now find γ under assumption that $a_s/a_d \approx 1$.

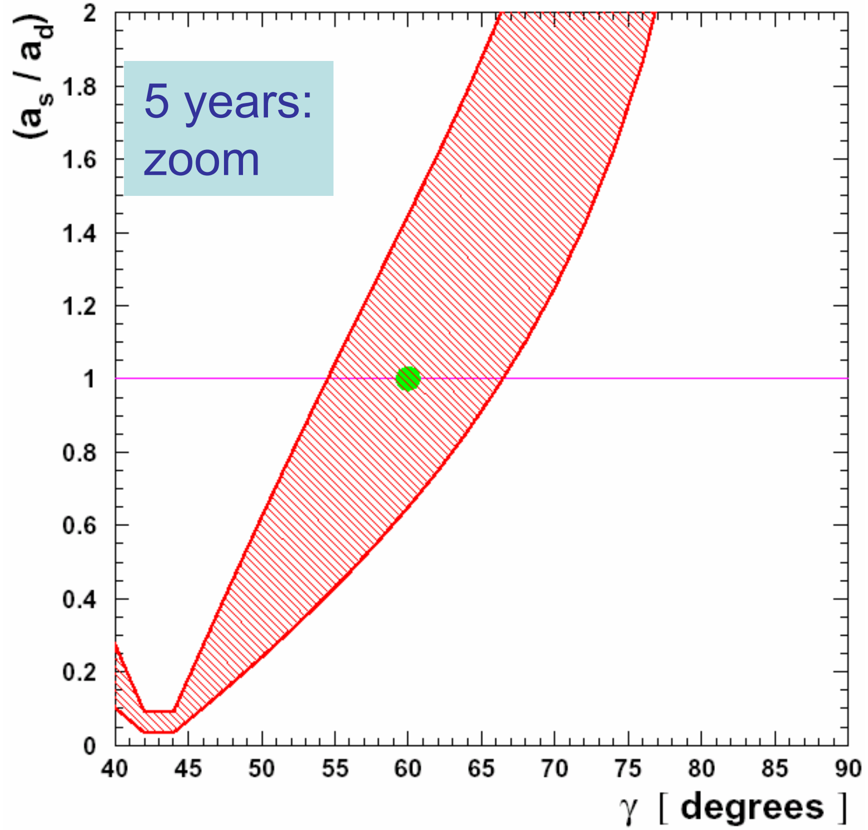
$$\frac{a_s}{a_d} = \pm \frac{1}{R} \frac{\sin 2(\phi_d + \gamma)}{\sin 2(\phi_s + \gamma)} \sqrt{\frac{(S_s^+)^2 \cos^2(\phi_s + \gamma) + (S_s^-)^2 \sin^2(\phi_s + \gamma)}{(S_d^+)^2 \cos^2(\phi_d + \gamma) + (S_d^-)^2 \sin^2(\phi_d + \gamma)}}$$

where $$S_{s,d}^{\pm} = (S_{s,d} \pm \overline{S_{s,d}}) \,/\, 2$$

Comparison with previous allows U-spin breaking effects to be decoupled

U-Spin Amplitude Symmetry Assumption



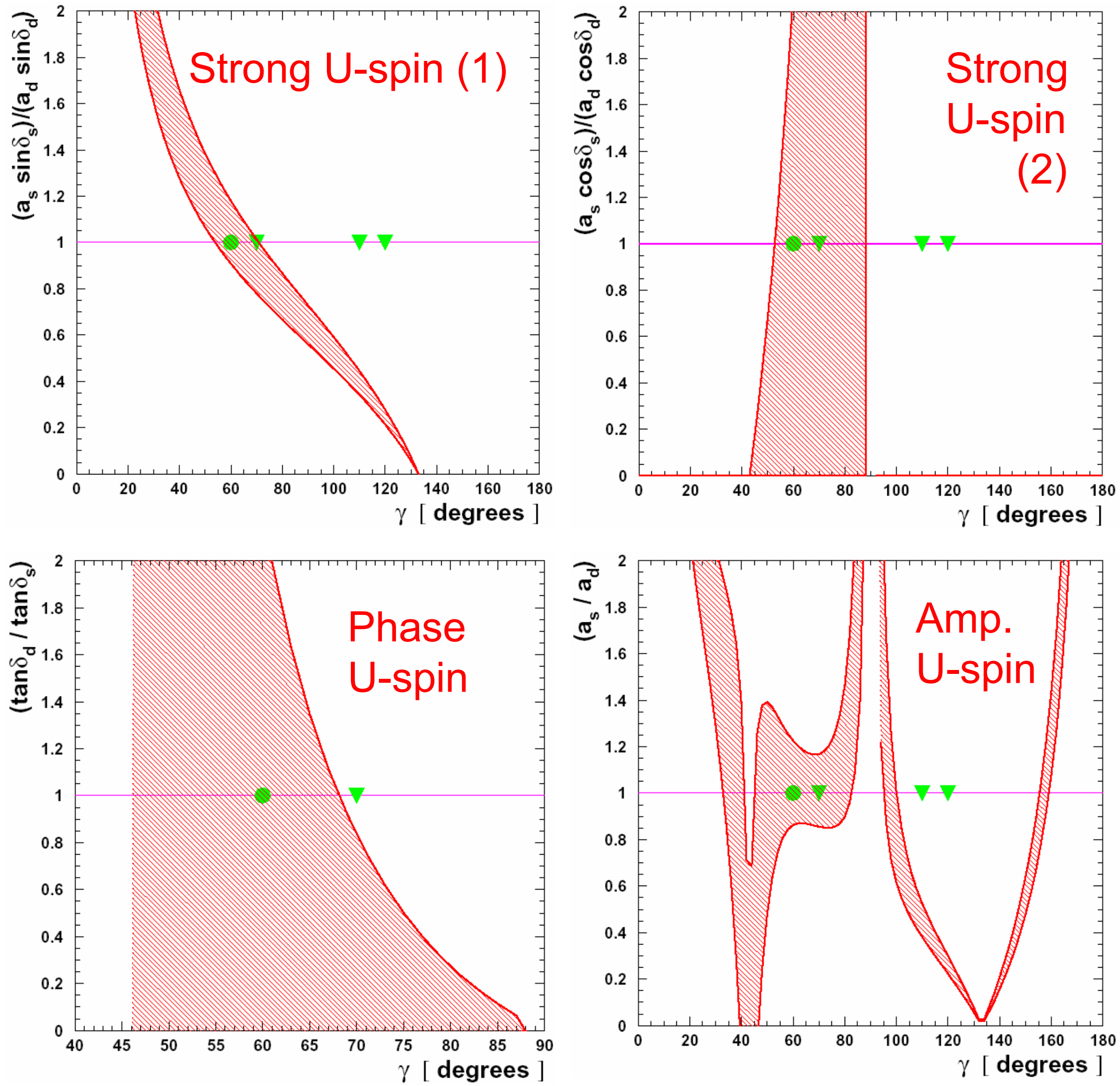


New solutions – but we know these are bogus! Again including B-factory data is helpful.

Statistical precision is ~6 degrees, and the U-spin breaking (± 20%) error is about 3 degrees.

A Less Favourable Scenario

Precision & usefulness of results using U-spin method depend on position in parameter space.



These plots show the results for 5 years running, assuming γ=60 deg, δ=20 deg.

Conclusions

LHCb expects high yields in $B_s \rightarrow D_s K$ (5k p.a.) and $D(*)\pi$ (~200k p.a.)

Usefulness of B_d channels in isolation dependent in knowledge of r_d

γ can be extracted from B_s decays with precision of 14 degrees / year.
However ambiguous solutions may pose problems! Ways forward:

- Untagged observables resolve ambiguities, but effectiveness depends on value of $\Delta\Gamma_s$
- U-spin combination with B_d observables a promising strategy
  - → No need to know troublesome r_d factor
  - → Different combination strategies possible, which allow U-spin symmetry assumptions to be varied and assessed
  - → Precision of method dependent on position in parameter space
  - → B-factory input very valuable in early years of LHC operation

We shall exploit all methods in order to learn all we can from these channels!