Seminar at LPNHE Paris

CP violation with heavy mesons

Malcolm John

10 May 2012

UNIVERSITY OF OXFORD

THE ROYAL SOCIETY

Three subjects

Observation of direct *CP* violation in B^+ decays

1fb^{-1} arXiv:1203.3662

Searches for time-dependent *CP*-violation in the mixing and decay of B_s mesons

1fb^{-1} LHCb-CONF-2012-002

Evidence for direct *CP* violation in D^0 decays

0.6fb^{-1} arXiv:1112.0938

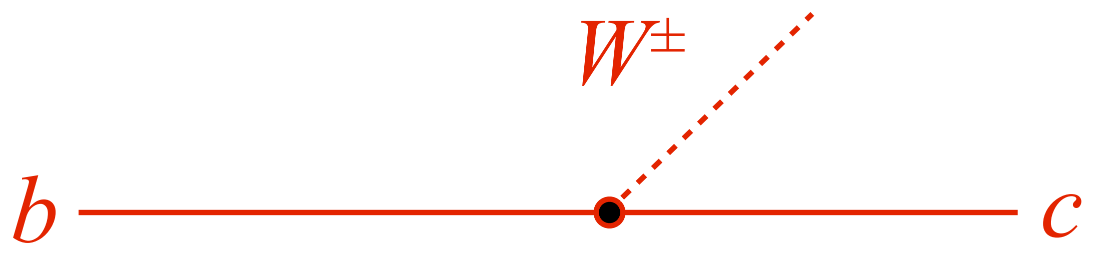
Why chase *CP* violation in B^+ decays?

CP violation known only to occur in the weak interaction of quarks

$$\begin{bmatrix} d & s & b \end{bmatrix}$$

$$\begin{bmatrix} u \\ c \\ t \end{bmatrix}$$

by emission or absorption of a
$W^{\pm}$ boson, quarks change flavour



CKM model: 3 quark generations ⇒ 3 mixing angles, 1 phase

$$V_{CKM} = \begin{matrix} \\ u \\ c \\ t \end{matrix} \begin{matrix} d & s & b \\ \left(\begin{matrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 \\ -\lambda+\frac{1}{2}A^2\lambda^5(1-2(\rho+i\eta)) \\ A\lambda^3(1-(1-\frac{1}{2}\lambda^2)(\rho-i\eta)) \end{matrix} \right. & \begin{matrix} \lambda \\ 1-\frac{1}{2}\lambda^2-\frac{1}{8}(1+4A^2)\lambda^4 \\ -A\lambda^2+\frac{1}{2}A\lambda^4(1-2(\rho-i\eta)) \end{matrix} & \left. \begin{matrix} A\lambda^3(\rho-i\eta) \\ A\lambda^2 \\ 1-\frac{1}{2}A^2\lambda^4 \end{matrix} \right) \end{matrix} + \mathcal{O}(\lambda^7)$$

Wolfenstein expansion in powers of the Cabibbo angle, λ, up to λ^6

This single phase give rise to *all* CP violation phenomena

$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array}\!\!\begin{array}{c} d \qquad\qquad\qquad\qquad s \qquad\qquad\qquad\qquad b \\ \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5(1-2(\rho+i\eta)) & 1-\frac{1}{2}\lambda^2-\frac{1}{8}(1+4A^2)\lambda^4 & A\lambda^2 \\ A\lambda^3(1-(1-\frac{1}{2}\lambda^2)(\rho-i\eta)) & -A\lambda^2+\frac{1}{2}A\lambda^4(1-2(\rho-i\eta)) & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix} \end{array} + \mathcal{O}(\lambda^7)$$

Wolfenstein expansion in powers of the Cabibbo angle, λ, up to λ^6

$$0 = 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} + \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}$$

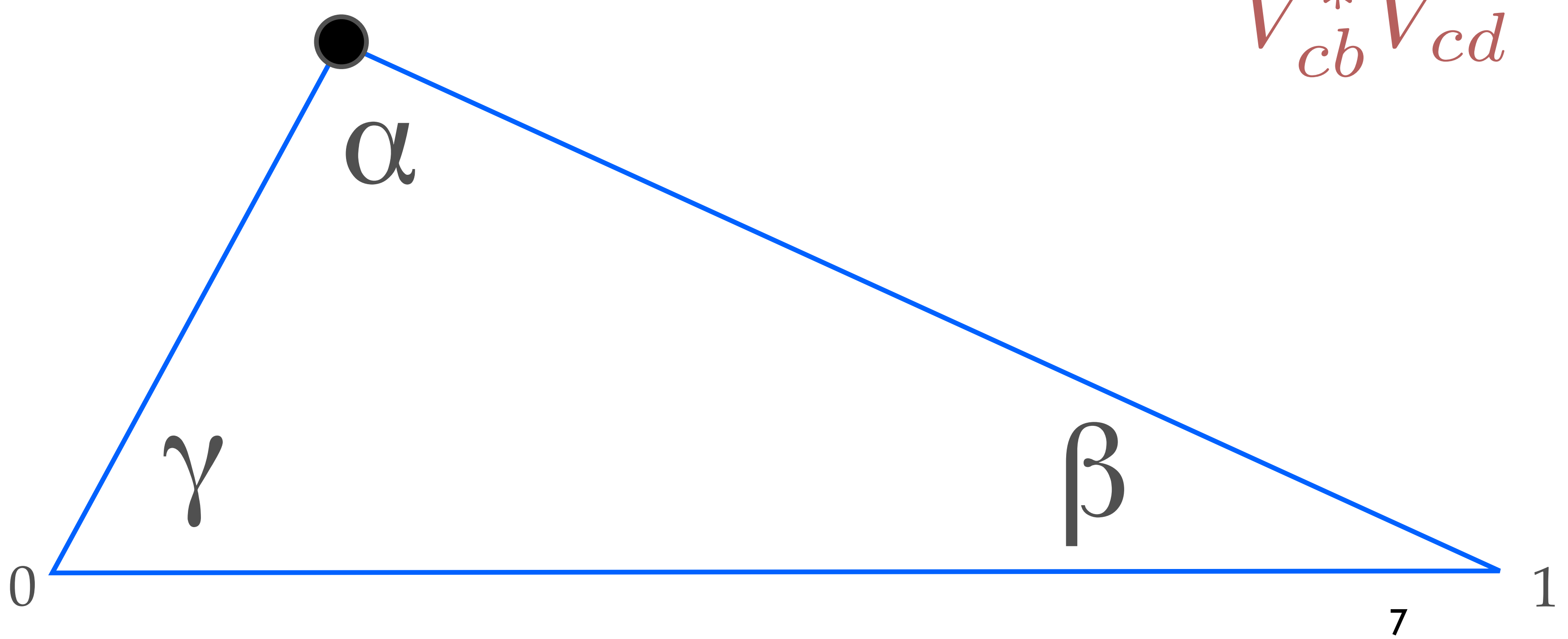
Testing the unitarity of this matrix is a huge part of flavour physics

$$V_{CKM} = \begin{matrix} u \\ c \\ t \end{matrix} \overset{\begin{matrix} d & s & b \end{matrix}}{\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5(1-2(\rho+i\eta)) & 1-\frac{1}{2}\lambda^2-\frac{1}{8}(1+4A^2)\lambda^4 & A\lambda^2 \\ A\lambda^3(1-(1-\frac{1}{2}\lambda^2)(\rho-i\eta)) & -A\lambda^2+\frac{1}{2}A\lambda^4(1-2(\rho-i\eta)) & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}} + \mathcal{O}(\lambda^7)$$

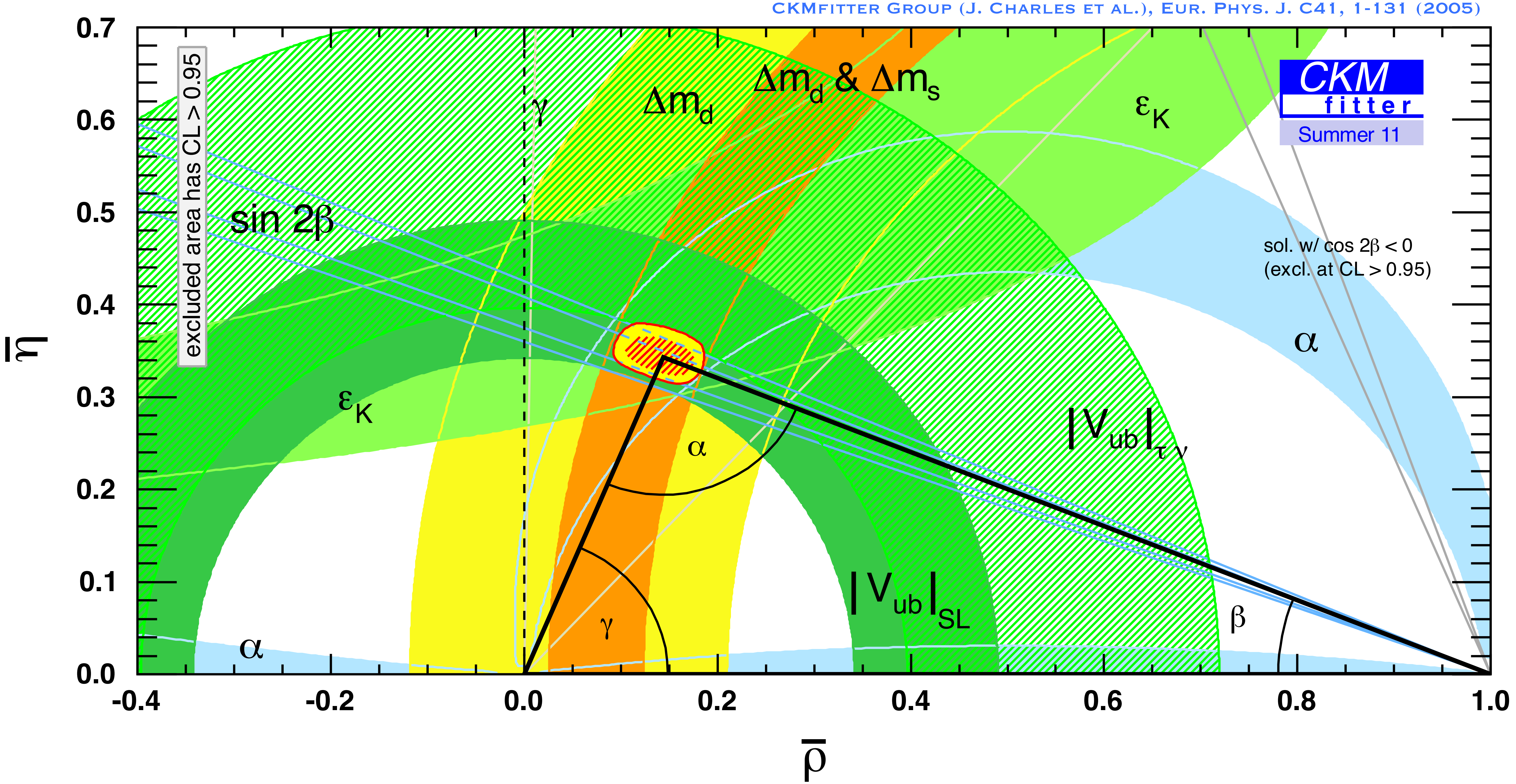
Wolfenstein expansion in powers of the Cabibbo angle, λ, up to λ^6

$$0 = 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} + \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}$$

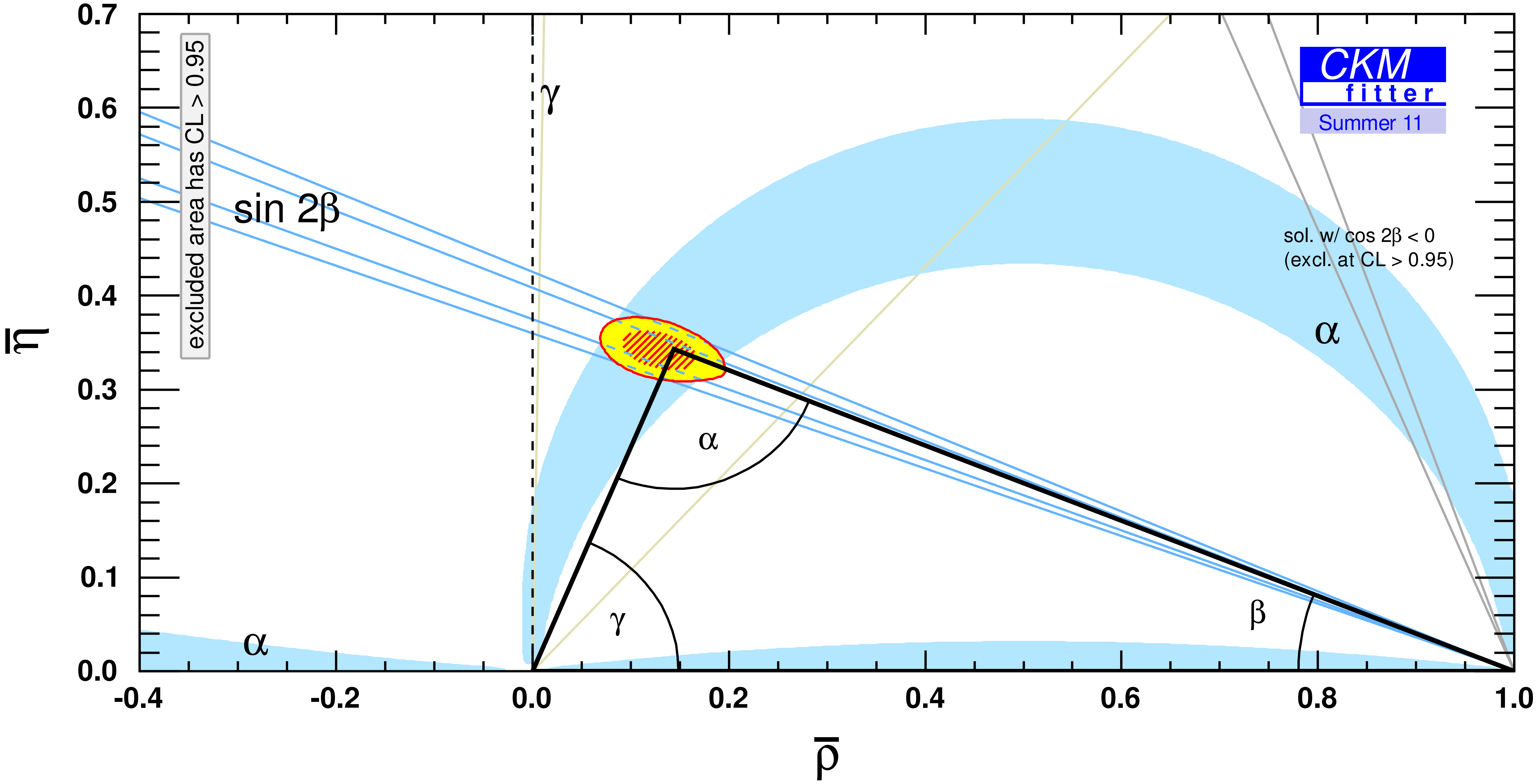
γ



We know the Standard Model describes Nature well.



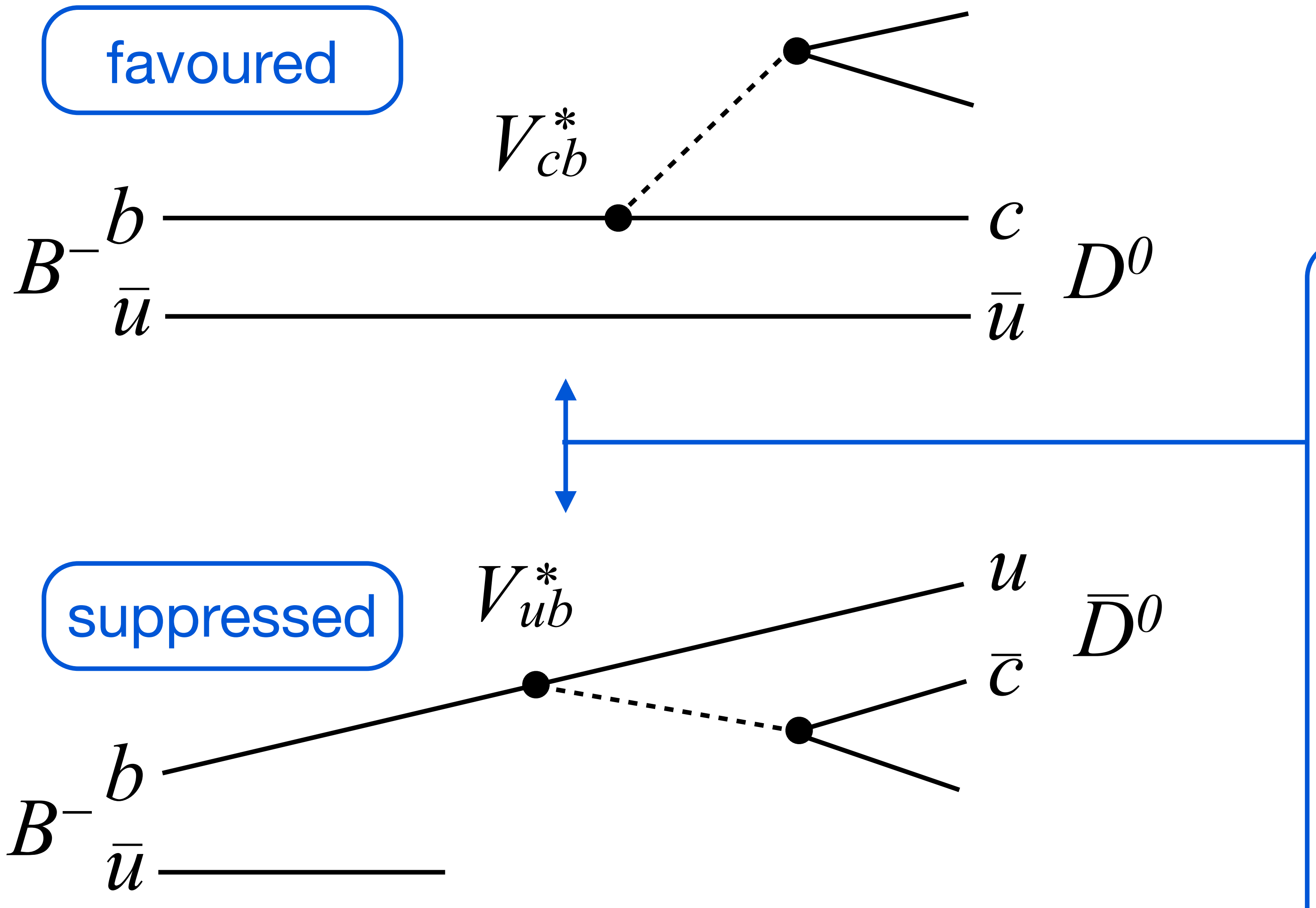
But γ is poorly determined by direct methods; “direct” == “tree process”



Simple ways to measure γ with trees

How could we measure γ ?

- Need a $b \to c$ and $b \to u$ transition



weak phase difference:

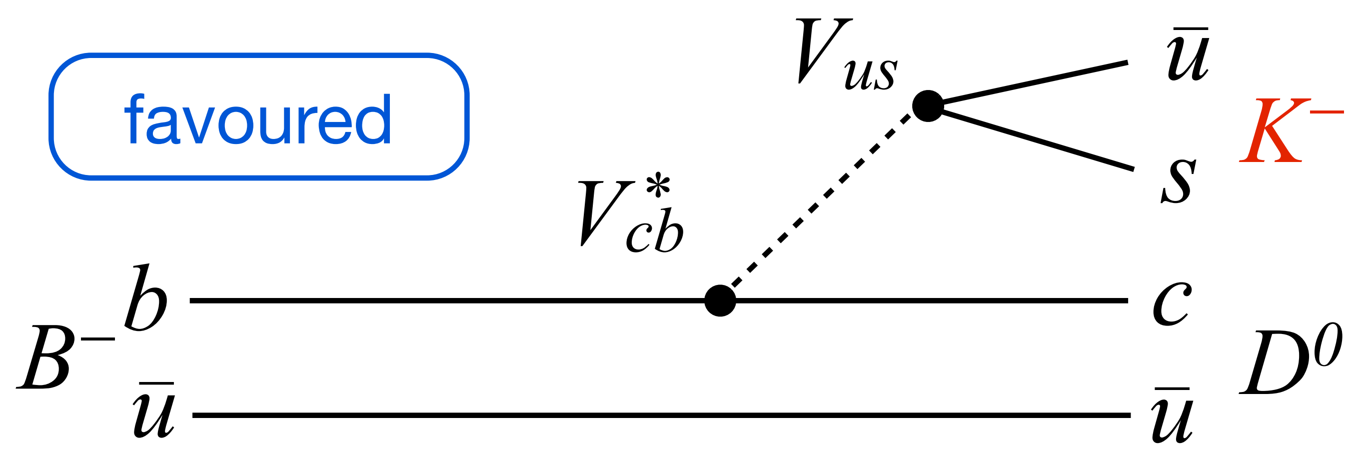
$$= \arg\left(-\frac{V_{ub}^*}{V_{cb}^*}\right)$$

$$= \gamma$$

How could we measure γ ?

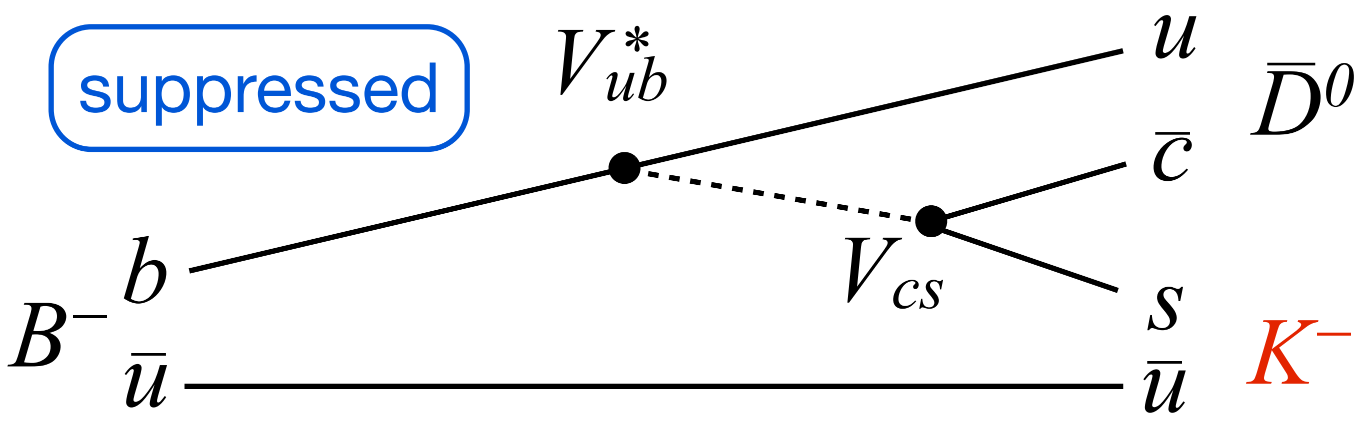
- Need a $b \to c$ and $b \to u$ transition of similar probability

favoured



$r_B \approx 0.1$

suppressed



relative amplitude:

$$\left|\frac{V_{cs} V_{ub}^*}{V_{us} V_{cb}^*}\right| f_{col}$$

$$= r_B$$

relative strong phase:

$$= \delta_B$$

weak phase difference:

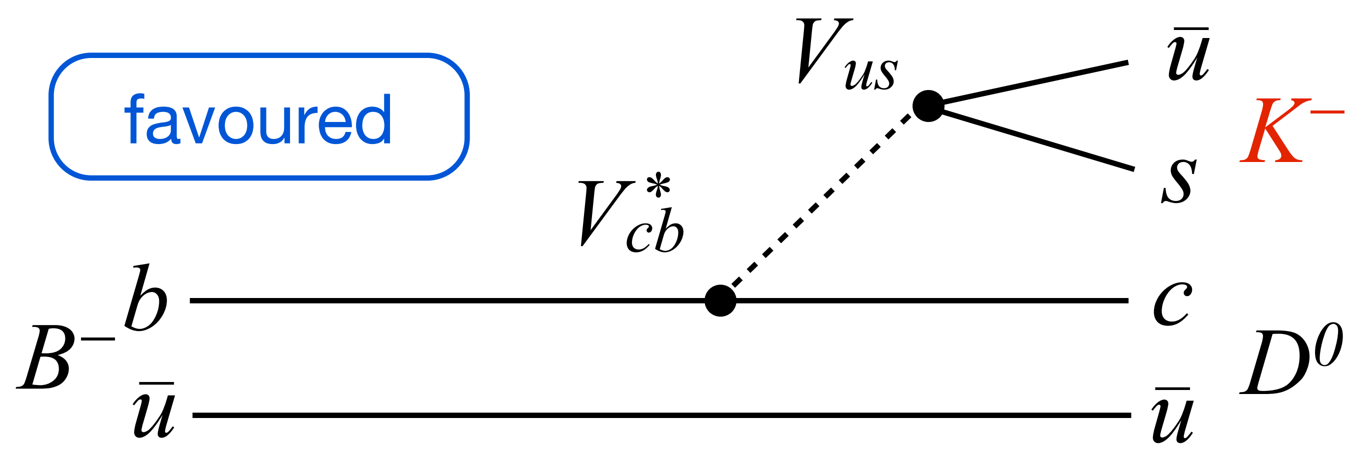
$$\arg\left(\frac{V_{cs} V_{ub}^*}{V_{us} V_{cb}^*}\right)$$

$$= \arg\left(-\frac{V_{ub}^*}{V_{cb}^*}\right)$$

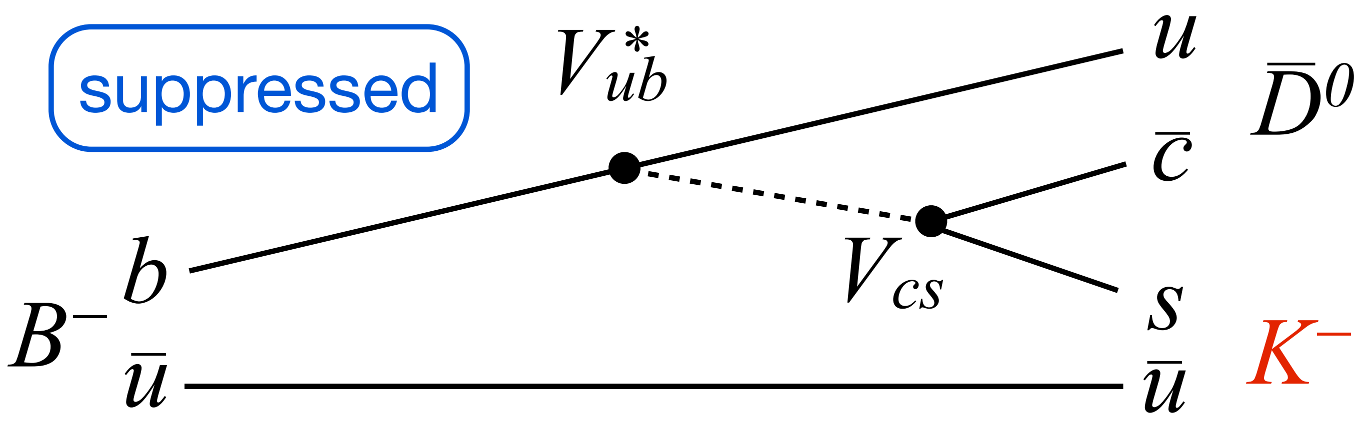
$$= \gamma$$

How could we measure γ ?

- Need a $b \to c$ and $b \to u$ transition of similar probability and a <u>common final state</u>



$r_B \approx 0.1$



$$D^0/\bar{D}^0 \to K^+K^-$$
$$D^0/\bar{D}^0 \to \pi^+\pi^-$$

relative amplitude:

$$\left|\frac{V_{cs}V_{ub}^*}{V_{us}V_{cb}^*}\right| f_{col} = r_B$$

weak phase difference:

$$\arg\left(\frac{V_{cs}\,V_{ub}^*}{V_{us}\,V_{cb}^*}\right) = \arg\left(-\frac{V_{ub}^*}{V_{cb}^*}\right) = \gamma$$

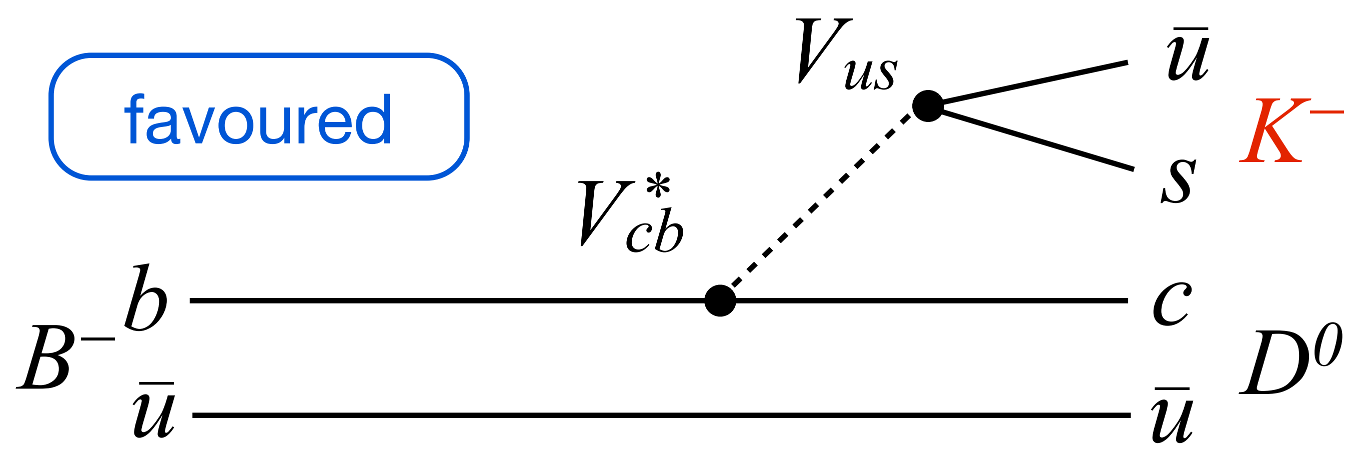
relative strong phase:

$$= \delta_B$$

How could we measure γ ?

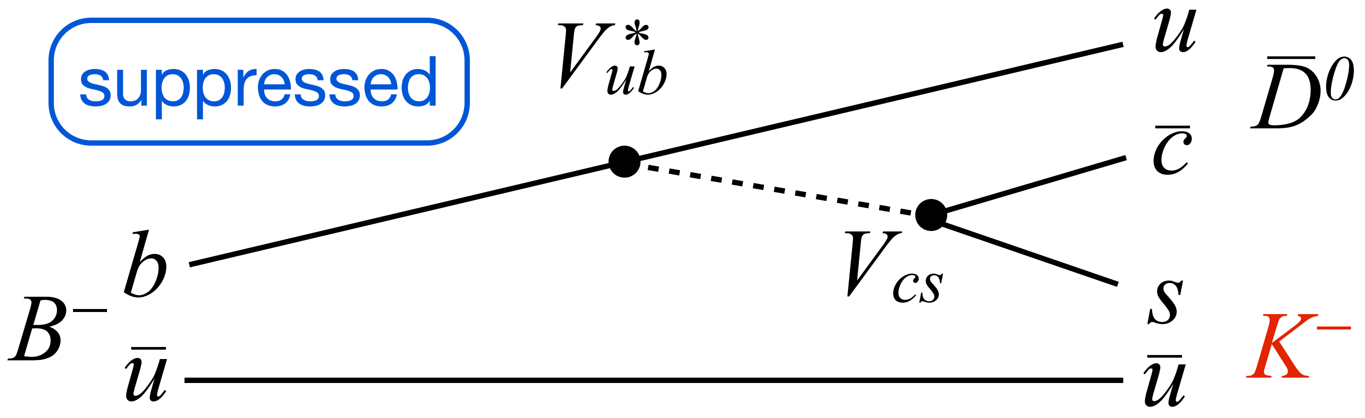
- Need a $b \to c$ and $b \to u$ transition of similar probability and a common final state

favoured



$r_B \approx 0.1$

suppressed



$$D^0/\bar{D}^0 \;\to K^+K^- \;\; \to \pi^+\pi^-$$

CP eigenstates

Nota bene:

$D \to K^+K^-, \pi^+\pi^-$ are *CP*+ eigenstates

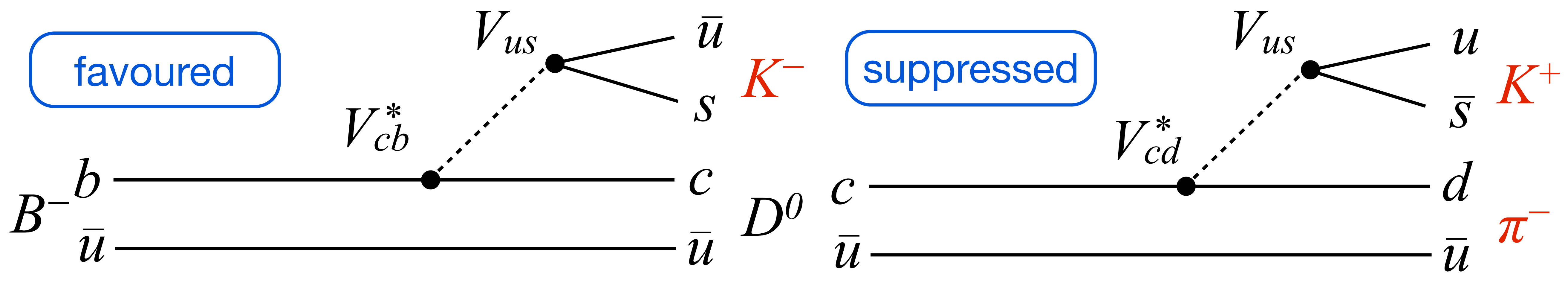
$D \to K^0\pi^0, K^0\omega...$ are *CP*– eigenstates

However:

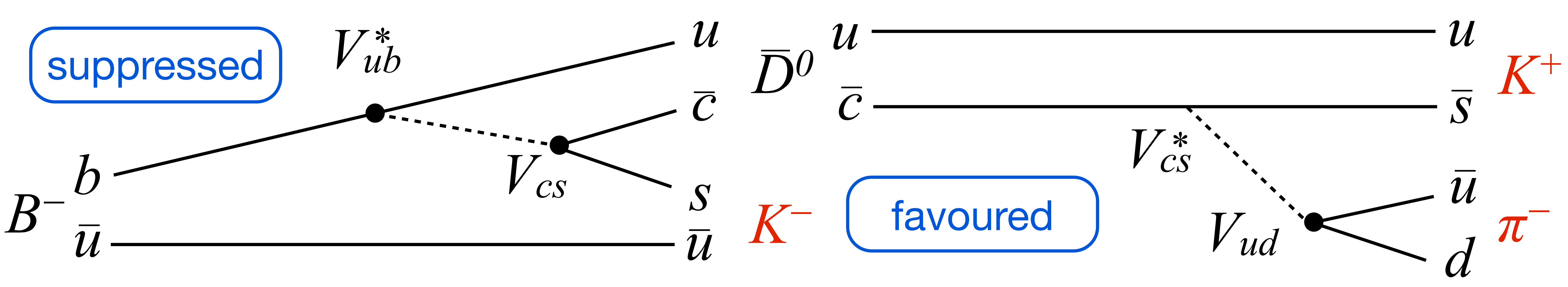
modes with $K^0 + \pi^0$ are difficult to trigger and reconstruct at LHCb so are not considered [yet].

But the larger the interference, the greater the sensitivity to γ

- Need a $b \rightarrow c$ and $b \rightarrow u$ transition of similar probability and a common final state



$r_B \approx 0.1$ $r_D \approx 0.06$ $r_D / r_B \approx 0.6 \sim 1$



$B^- \to DK^-$ $D, \to K^+K^-, \pi^+\pi^-$

favoured ⊕ suppressed ⊗ *CP* eigenstates

“*CP*” or “GLW” modes

M. Gronau and D. London, *How to determine all the angles of the unitarity triangle from $B^0_d \to DK^0_S$ and $B^0_s \to D\phi$*, Phys. Lett. **B253** (1991) 483; M. Gronau and D. Wyler, *On determining a weak phase from CP asymmetries in charged B decays*, Phys. Lett. **B265** (1991)

$B^- \to DK^-$ $D \to \pi^-K^+$

favoured ⊕ suppressed ⊗ suppressed ⊕ favoured

“ADS” mode

D. Atwood, I. Dunietz, and A. Soni, *Enhanced CP violation with $B \to KD^0(\overline{D}^0)$ modes and extraction of the CKM angle γ*, Phys.Rev.Lett. **78** (1997) 3257, arXiv:hep-ph/9612433;

$B^- \to DK^-$ $D \to K^-\pi^+$

favoured ⊕ suppressed ⊗ favoured ⊕ suppressed

“Favoured” mode

- Logic is equally applicable to $B^- \to D\pi^-$ though r_B, and hence the interference is smaller

$$r_{B(\pi)} \sim 0.01 \text{ compared to } r_{B(K)} \sim 0.1$$

- The “physics” observables are ratios of branching fractions and CP asymmetries
- All mode has dependence on γ though this is essentially negligible in the favoured mode

The "physics" observables

CP modes

$$\frac{<\Gamma(B^{\pm}\to[\pi\pi]_D K^{\pm}),\ \Gamma(B^{\pm}\to[KK]_D K^{\pm})>}{\Gamma(B^{\pm}\to[K\pi]_D K^{\pm})}$$

favoured mode

average of *KK* and *ππ modes*

$$\frac{\Gamma(B^{-}\to D_{CP}K^{-}) - \Gamma(B^{+}\to D_{CP}K^{+})}{\Gamma(B^{-}\to D_{CP}K^{-}) + \Gamma(B^{+}\to D_{CP}K^{+})}$$

$$R_{CP+} = 1 + {r_B}^2 + 2r_B \cos\delta_B \cos\gamma$$

$$A_{CP+} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + {r_B}^2 + 2r_B \cos\delta_B \cos\gamma}$$

ADS mode

$$\frac{\Gamma(B^{\pm}\to[\pi K]_D K^{\pm})}{\Gamma(B^{\pm}\to[K\pi]_D K^{\pm})}$$

favoured mode

effective BF~10^{-7}

$$\frac{\Gamma(B^{-}\to D_{ADS}K^{-}) - \Gamma(B^{+}\to D_{ADS}K^{+})}{\Gamma(B^{-}\to D_{ADS}K^{-}) + \Gamma(B^{+}\to D_{ADS}K^{+})}$$

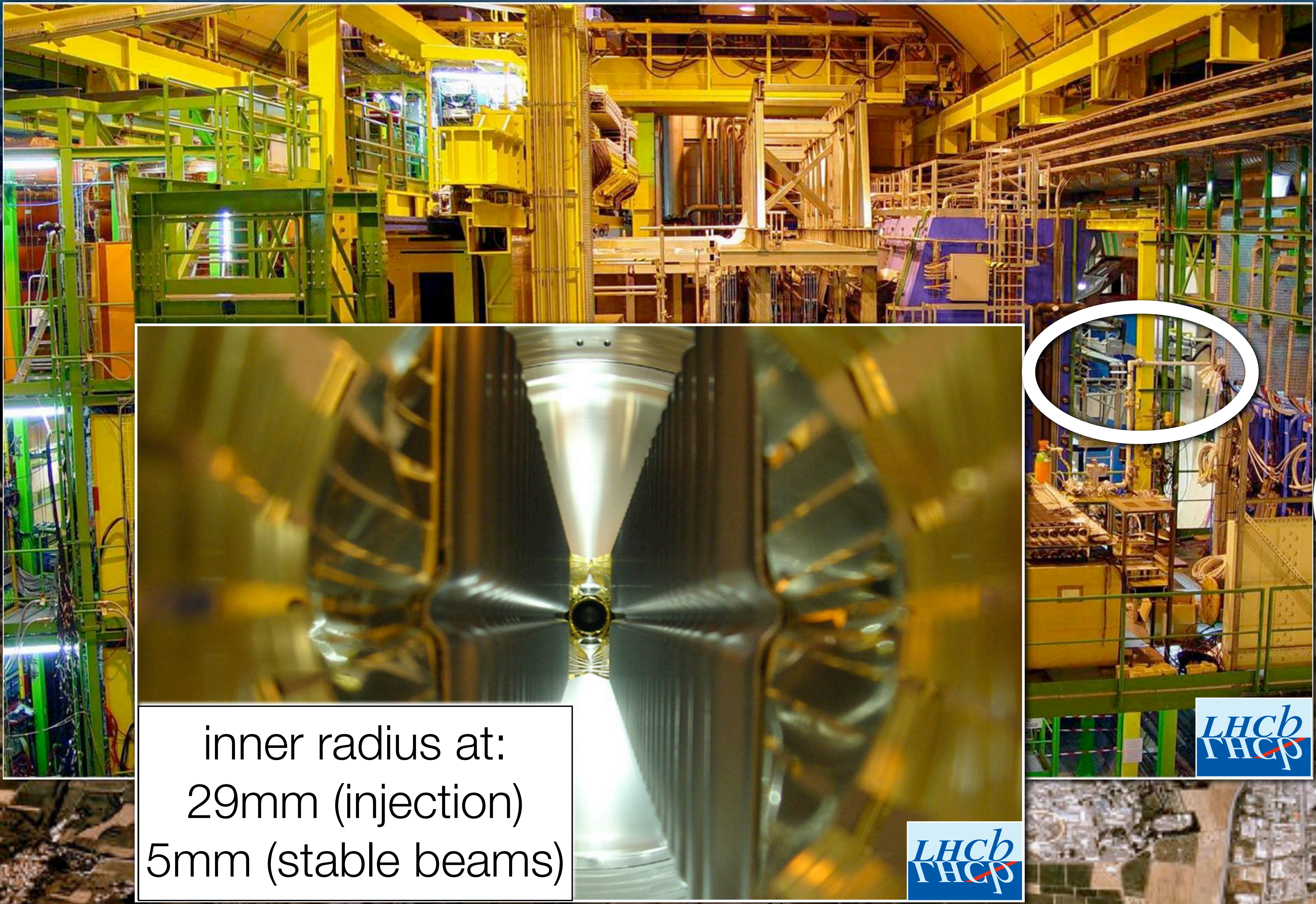
$$R^{ADS} = \frac{{r_B}^2 + {r_D}^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}{1 + (r_B r_D)^2 + 2r_B r_D \cos(\delta_B - \delta_D)\cos\gamma}$$

$$A^{ADS} = \frac{2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{{r_B}^2 + {r_D}^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}$$

So, where might we find billions of $B^{\pm}$?

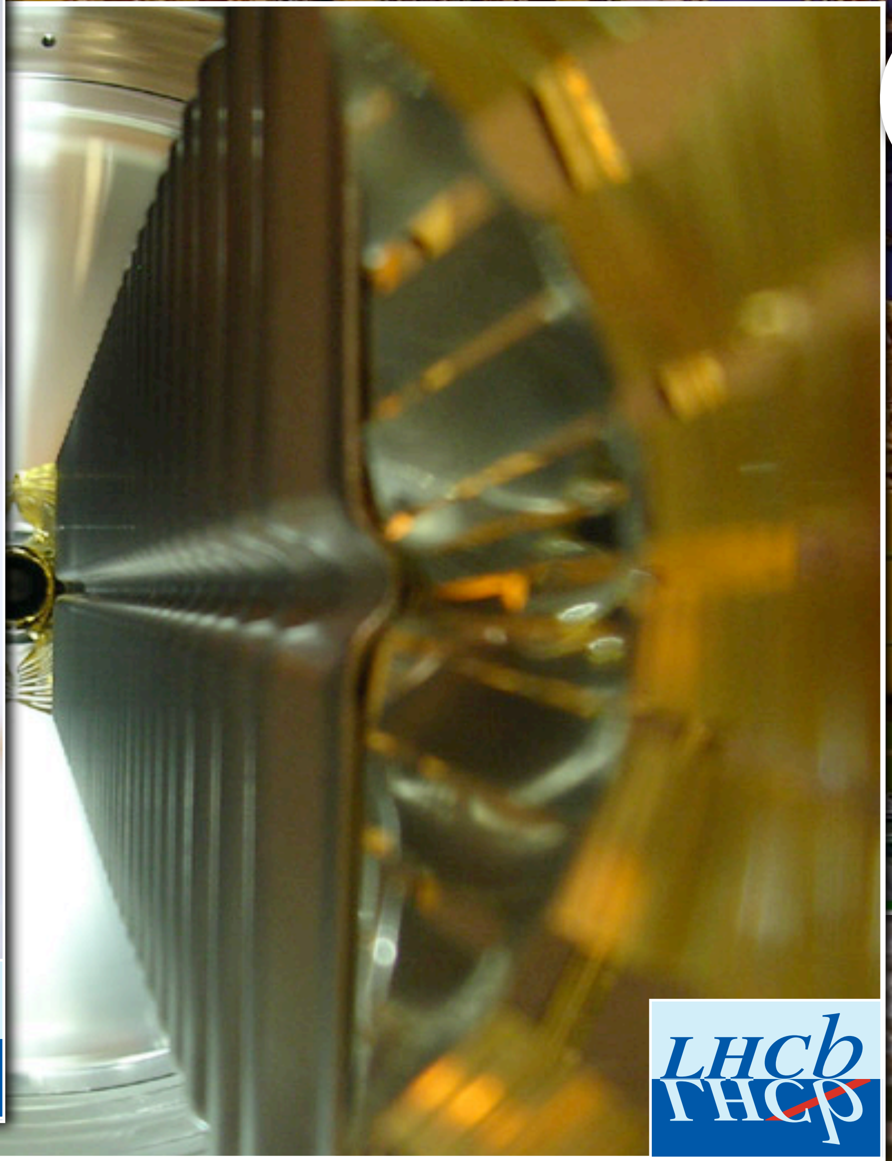
You will recognise this...

And at point 8, LHCb



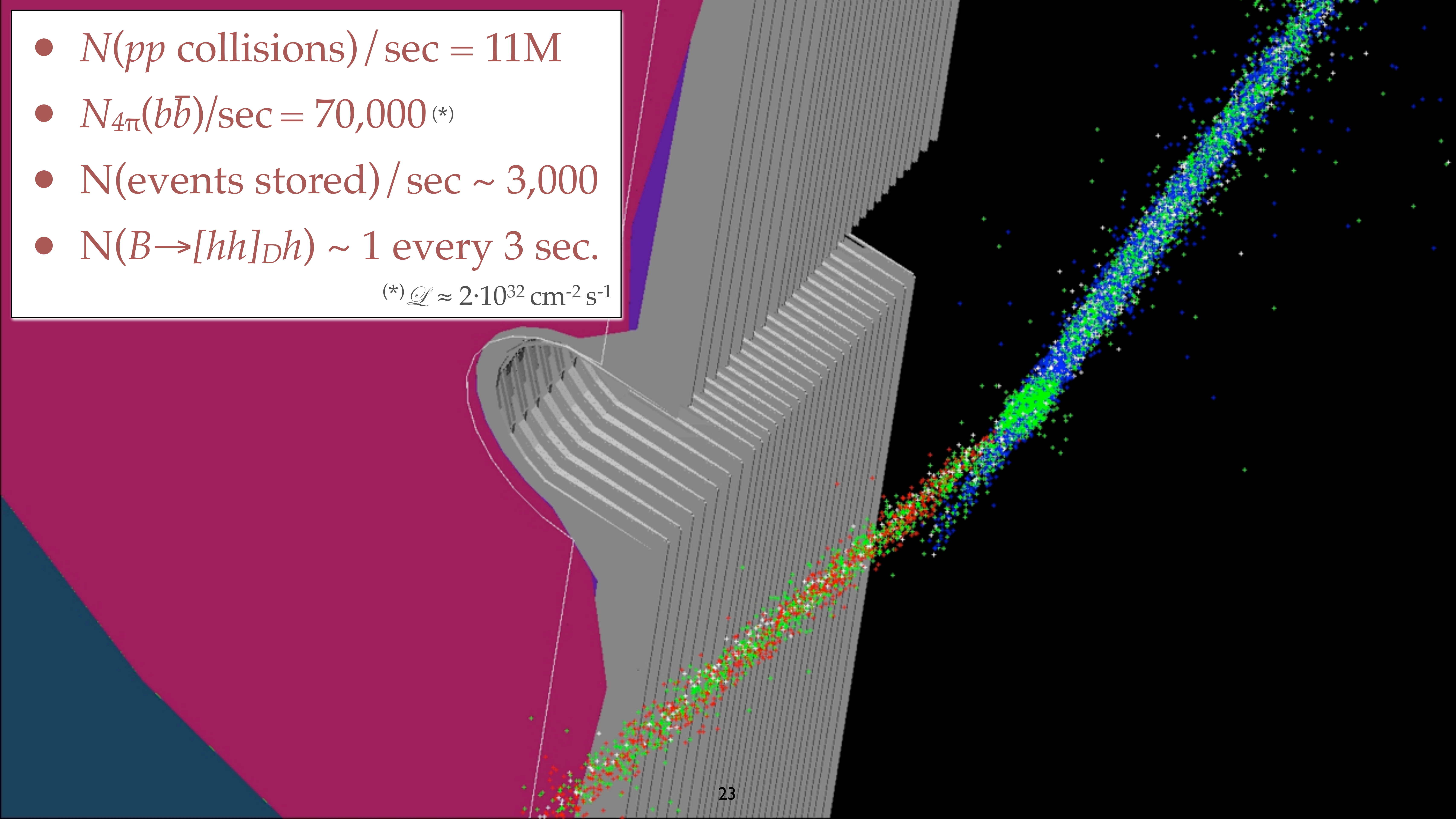
inner radius at:
29mm (injection)
5mm (stable beams)

Silicon strip vertex detector.
>40μm pitch at 8.2mm radius



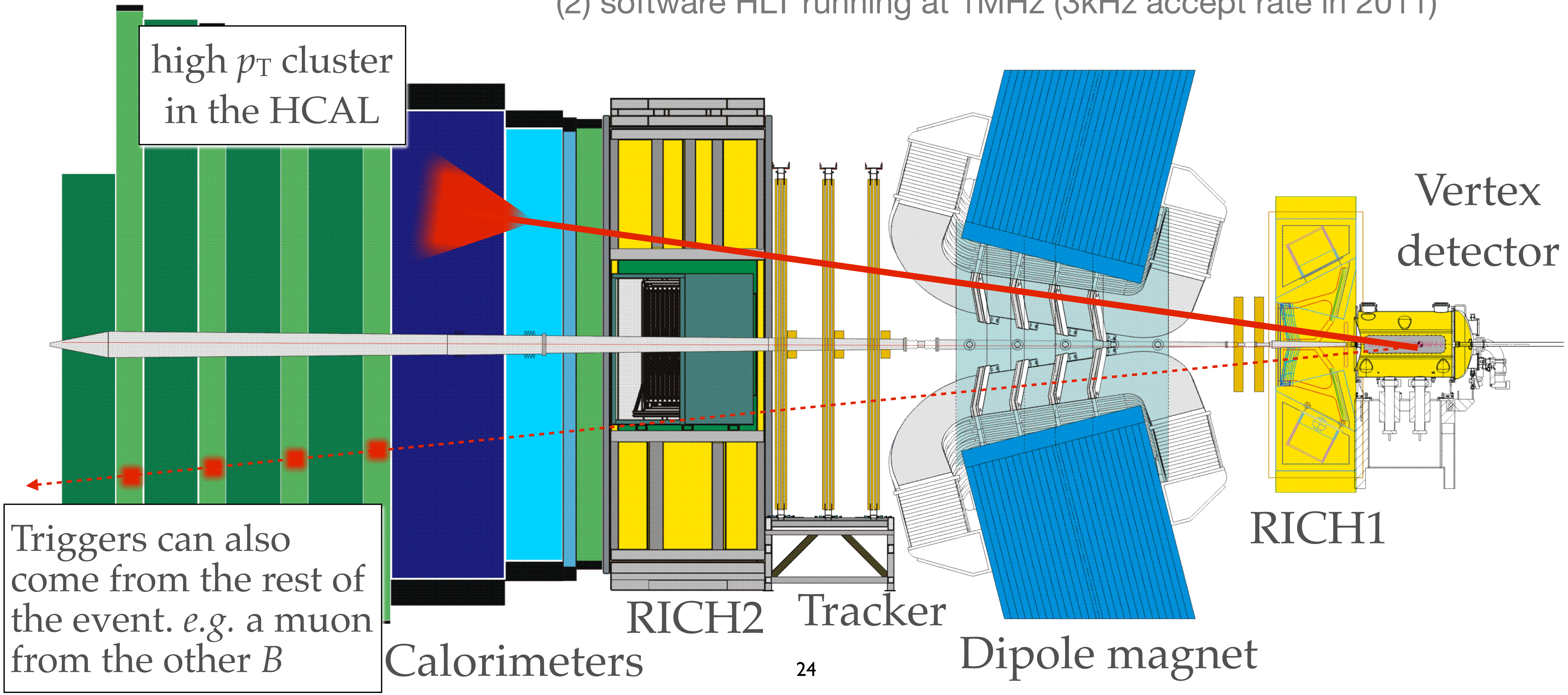
- $N(pp$ collisions$)\,/\,$sec = 11M
- $N_{4\pi}(b\bar{b})$/sec = 70,000 (*)
- N(events stored) / sec ~ 3,000
- $N(B \to [hh]_D h)$ ~ 1 every 3 sec.

(*) $\mathscr{L} \approx 2{\cdot}10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



Triggering of the exclusive hadronic final state: $B^{\pm} \to [h^{+}h^{-}]_{D}\, h^{\pm}$

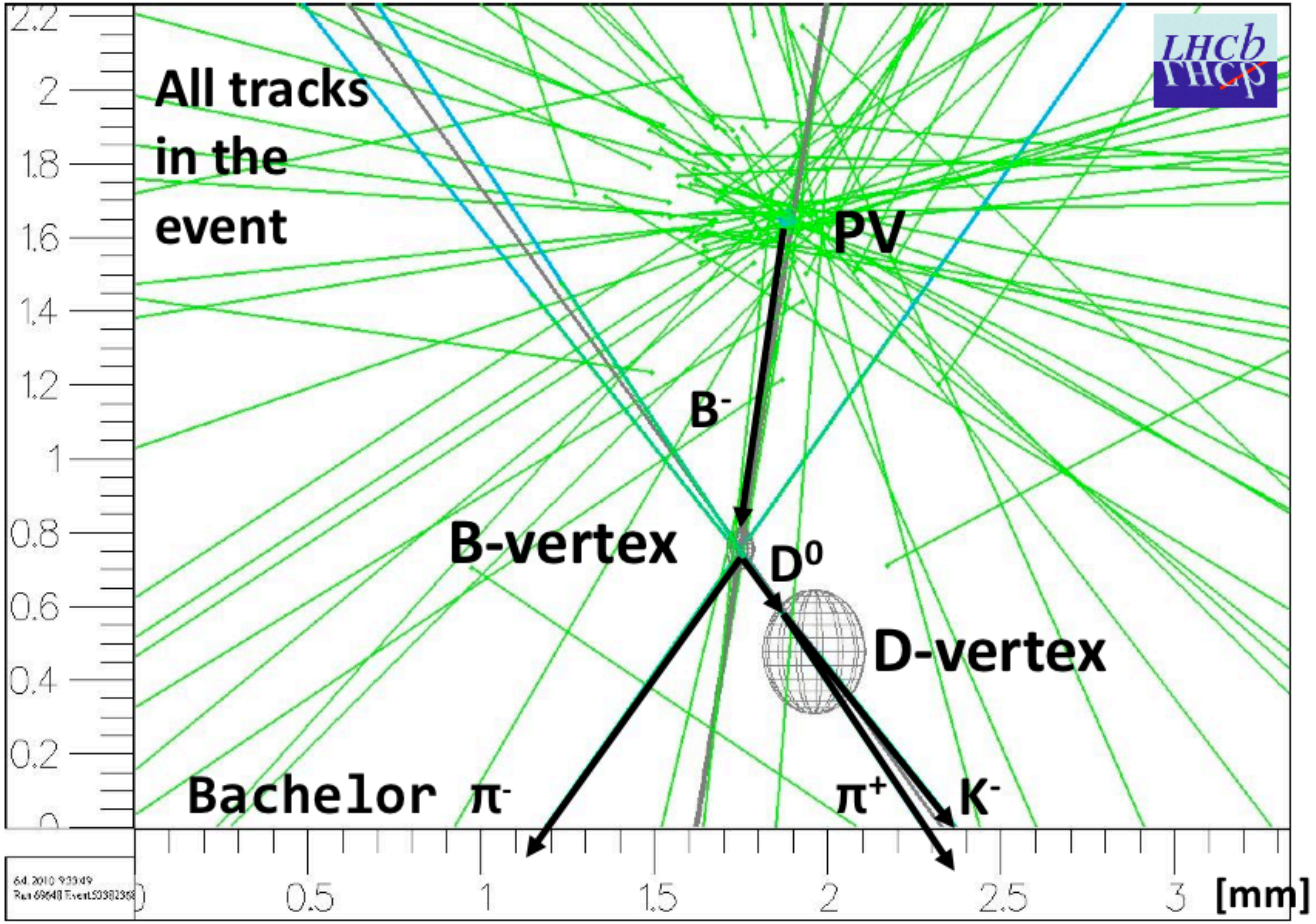
- LHCb has a two-stage trigger. (1) hardware "L0" trigger running at 40MHz (decisions at 11MHz)
  (2) software HLT running at 1MHz (3kHz accept rate in 2011)



The high level trigger for $B^{\pm} \rightarrow [h^{+}h^{-}]_{D}\, h^{\pm}$

- Find a high quality, high p_{T}, high impact parameter track (this is often the ‘bachelor’ π or K from the B decay)

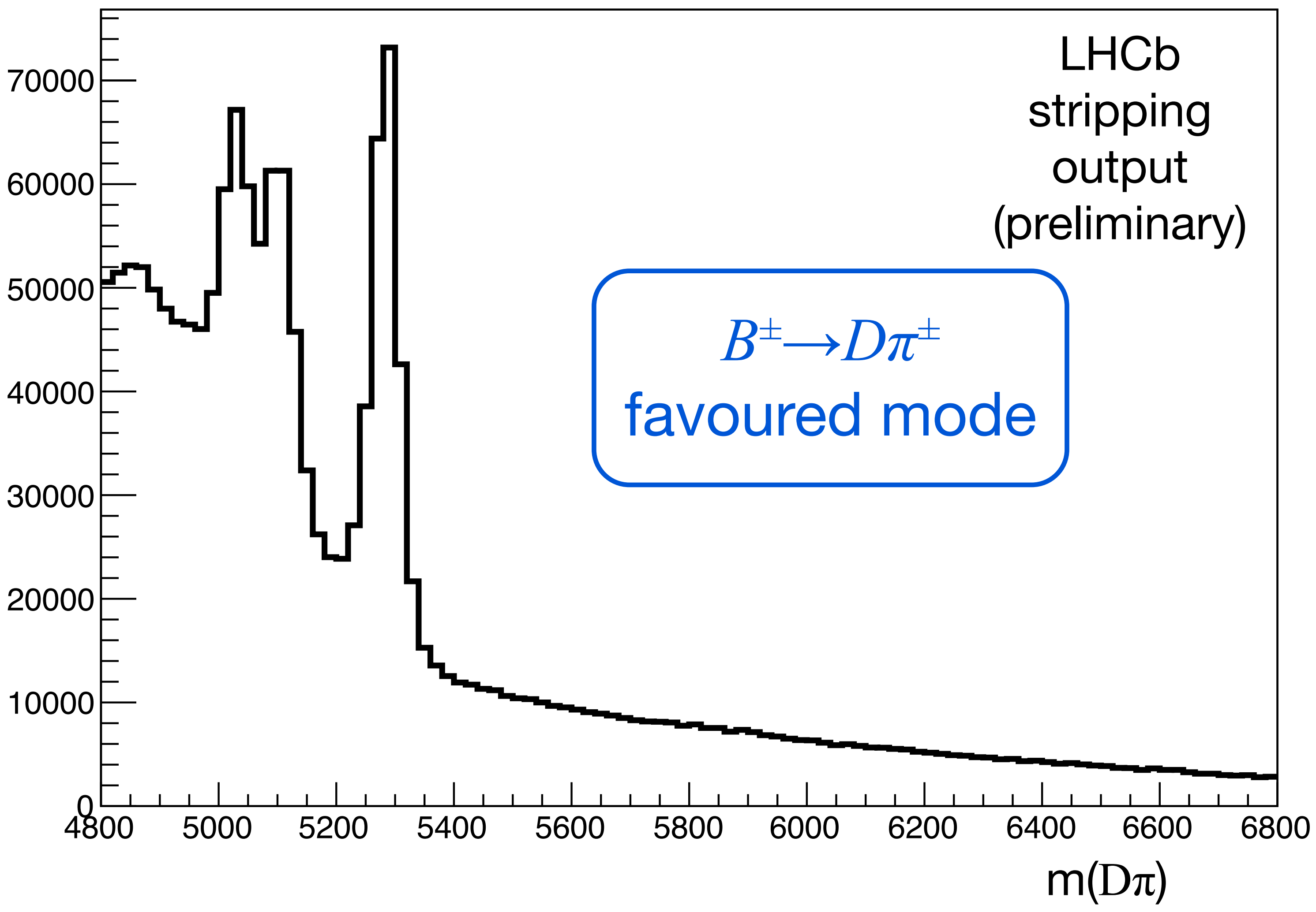
- If this successful, then require it to be part of a good quality displaced vertex, consistent with the B mass.
  - In 2011, a decision tree algorithm has been successfully used.

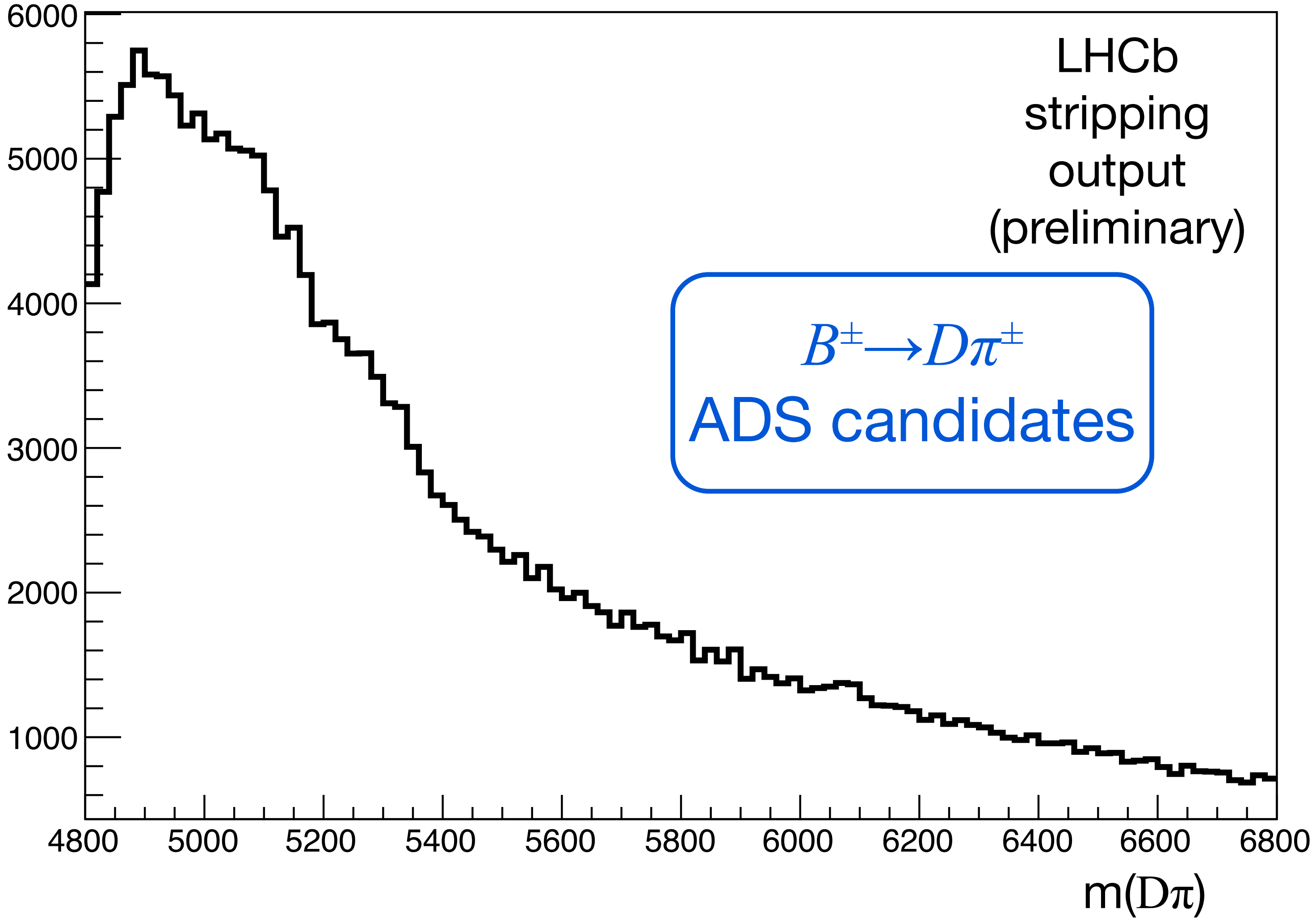


Signal selection and extraction

Analysis of $B^{\pm} \rightarrow [h^{+}h^{-}]_D h^{\pm}$

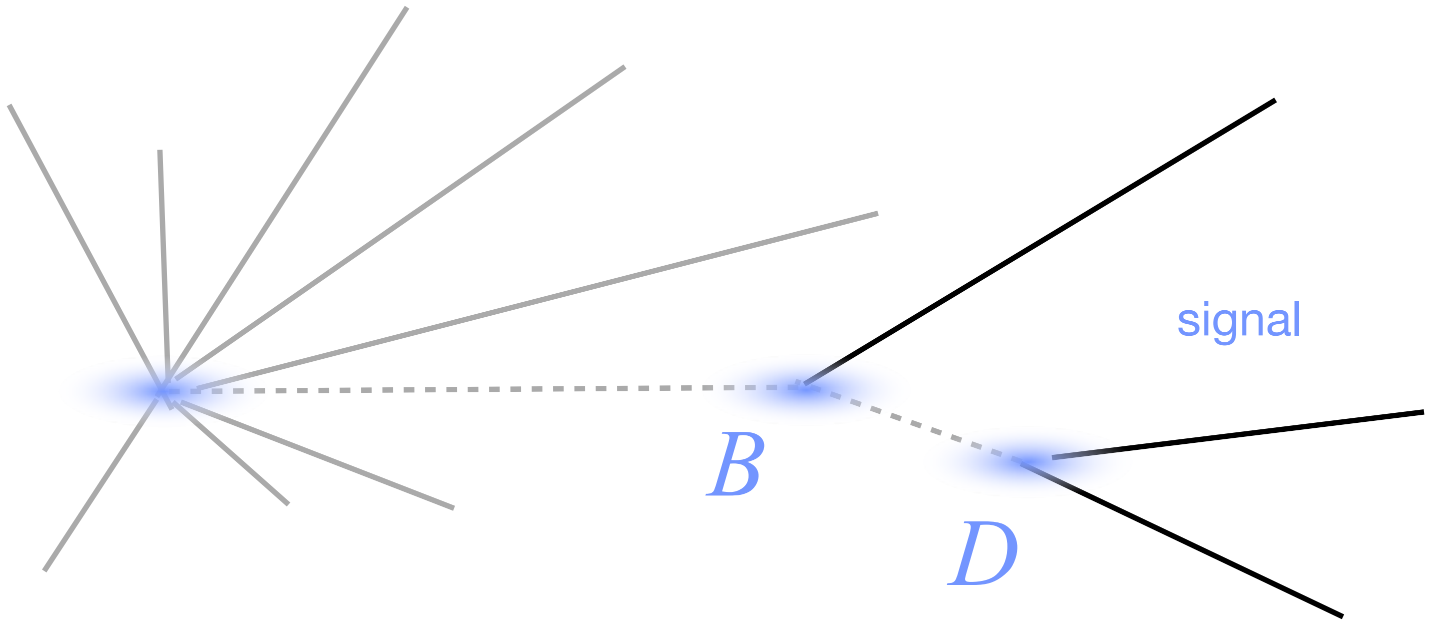
- The full 2011 dataset is used in this analysis, approximately **1 fb^{-1}**
- *B* candidates are refitted, constraining vertices to points and the *D*-candidate mass to m(D^0)$_{PDG}$
- The data are “stripped” down to a manageable size with a loose selection.
  - At this point *B* peaks are clearly visible in the most abundant modes

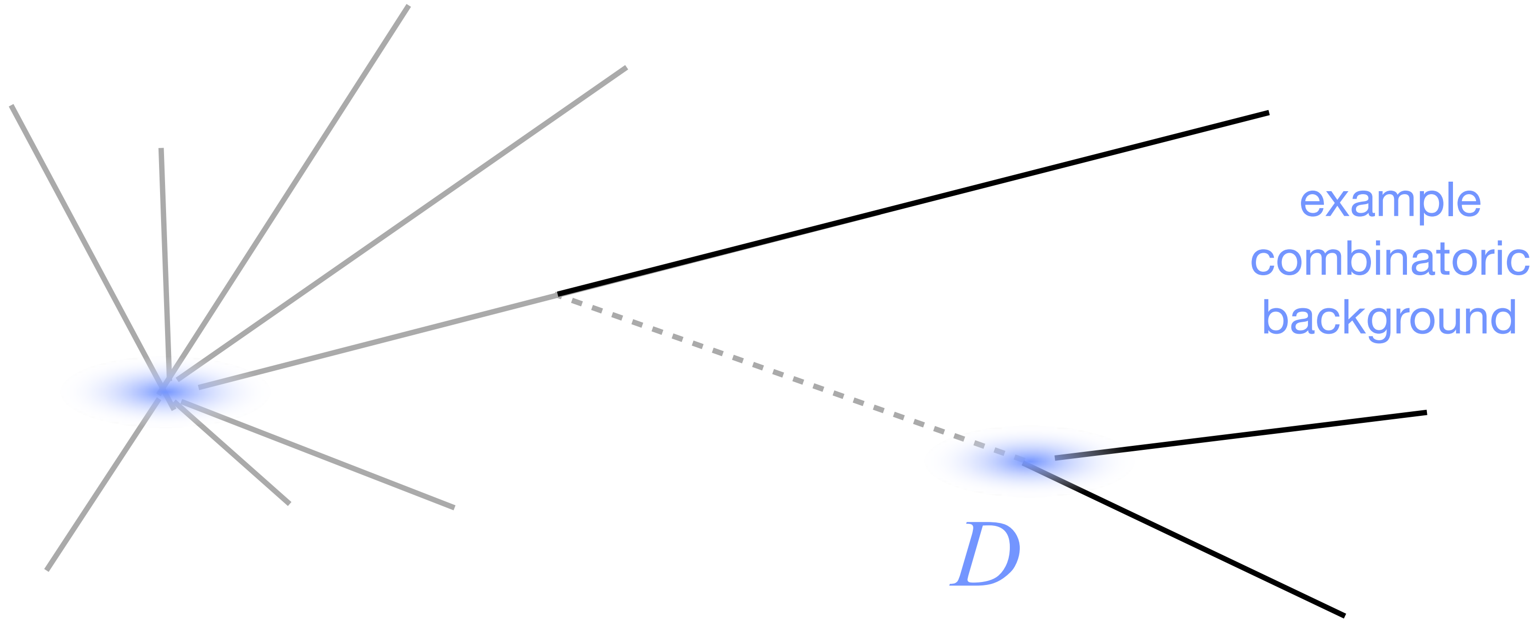




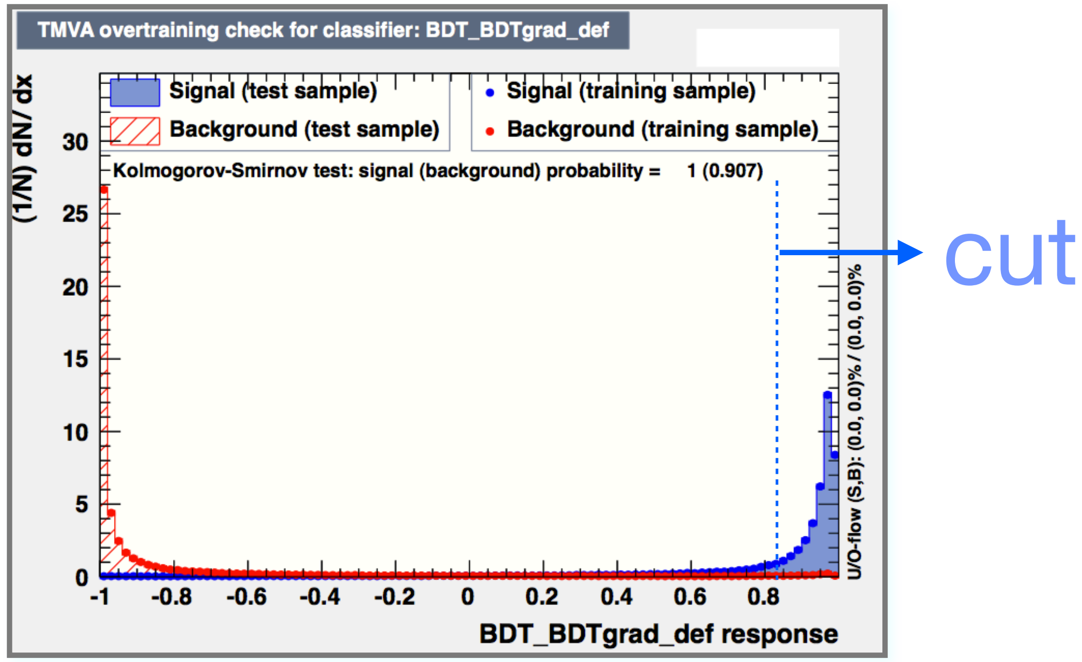
Minimising combinatoric background

- Use the TMVA Boosted Decision Tree with 20 variables.
- Train on a simulated $B^{\pm}\rightarrow[K\pi]_{D}K^{\pm}$ sample vs. the data sidebands from the **2010 dataset** (35 pb^{-1})

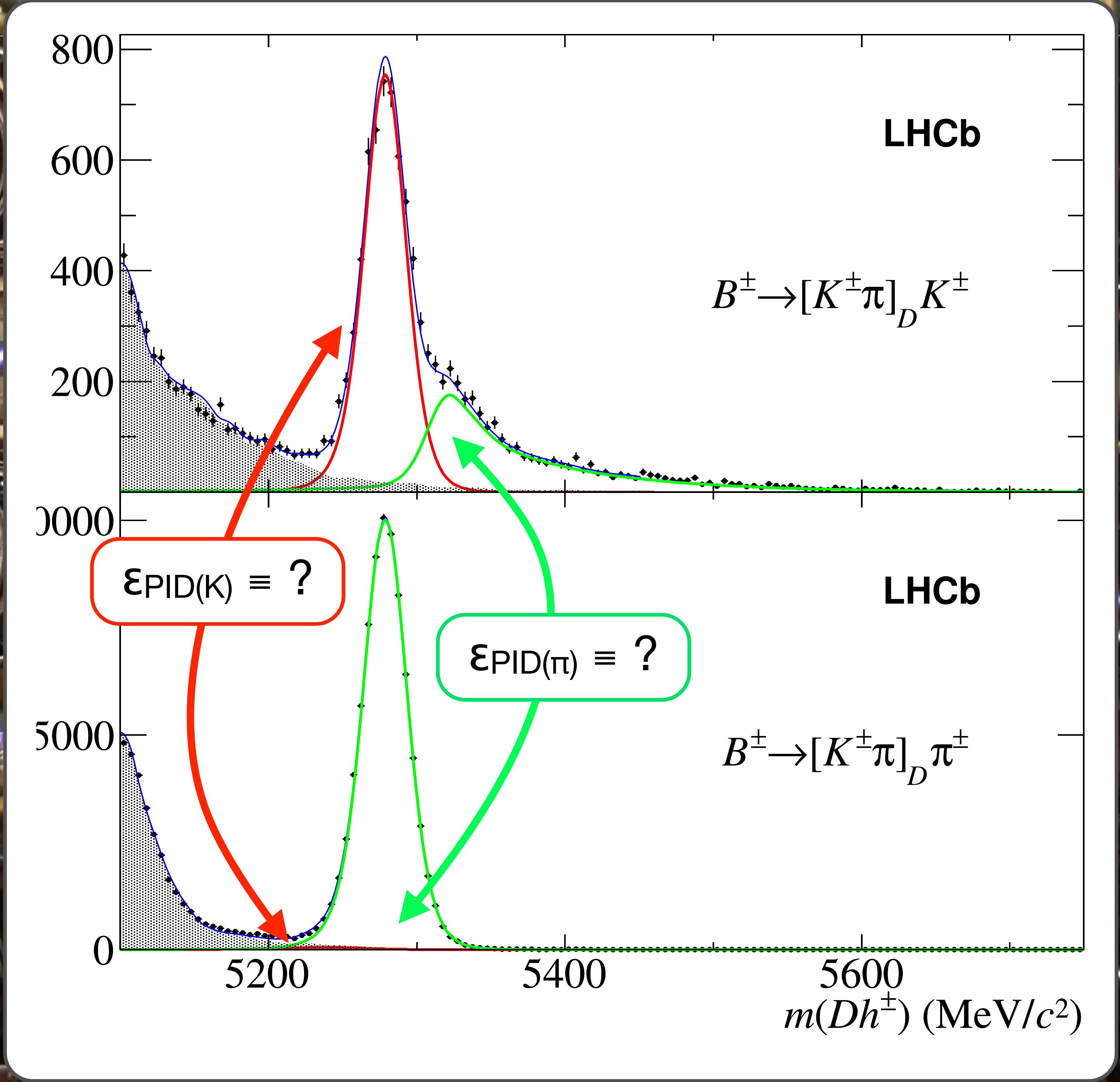




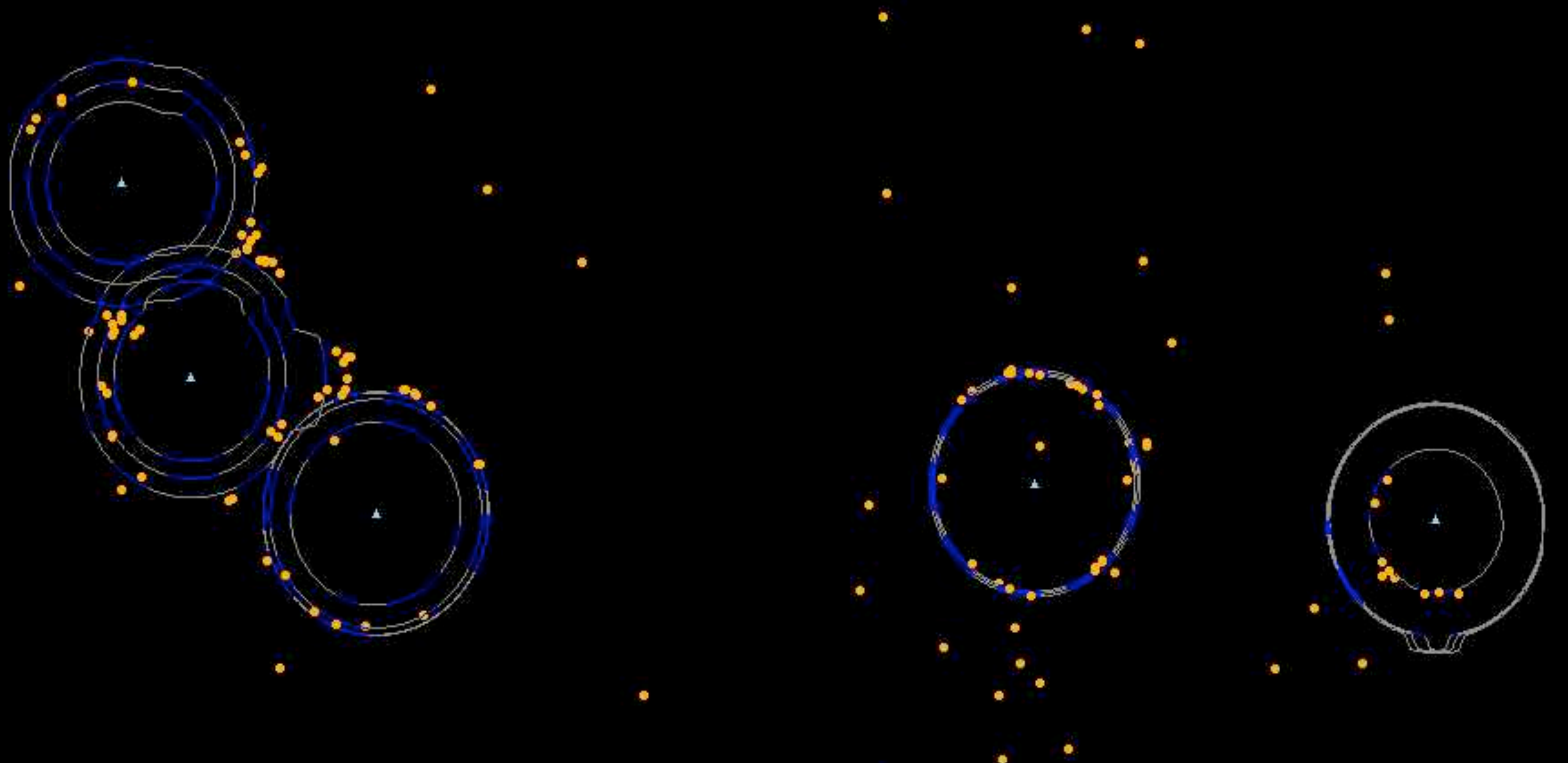
- Useful quantities to distinguish the signal:
  - Transverse momenta
  - Impact parameters
  - Flight distances
  - Quality of vertices
  - Distances of closest approach
  - Comparison of momentum and spatial vectors
  - And some pT information from the rest of the event



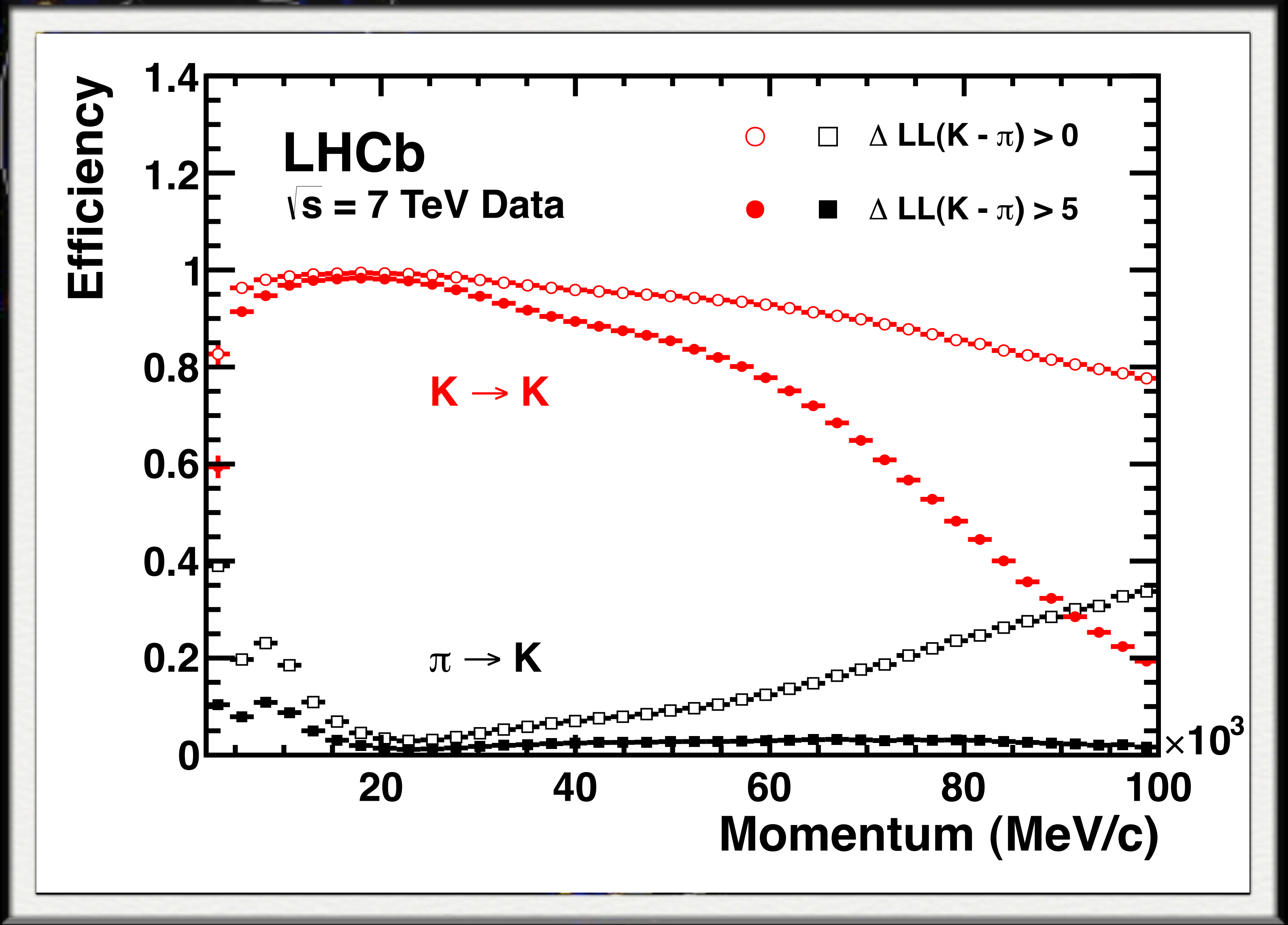
Dedicated particle identification

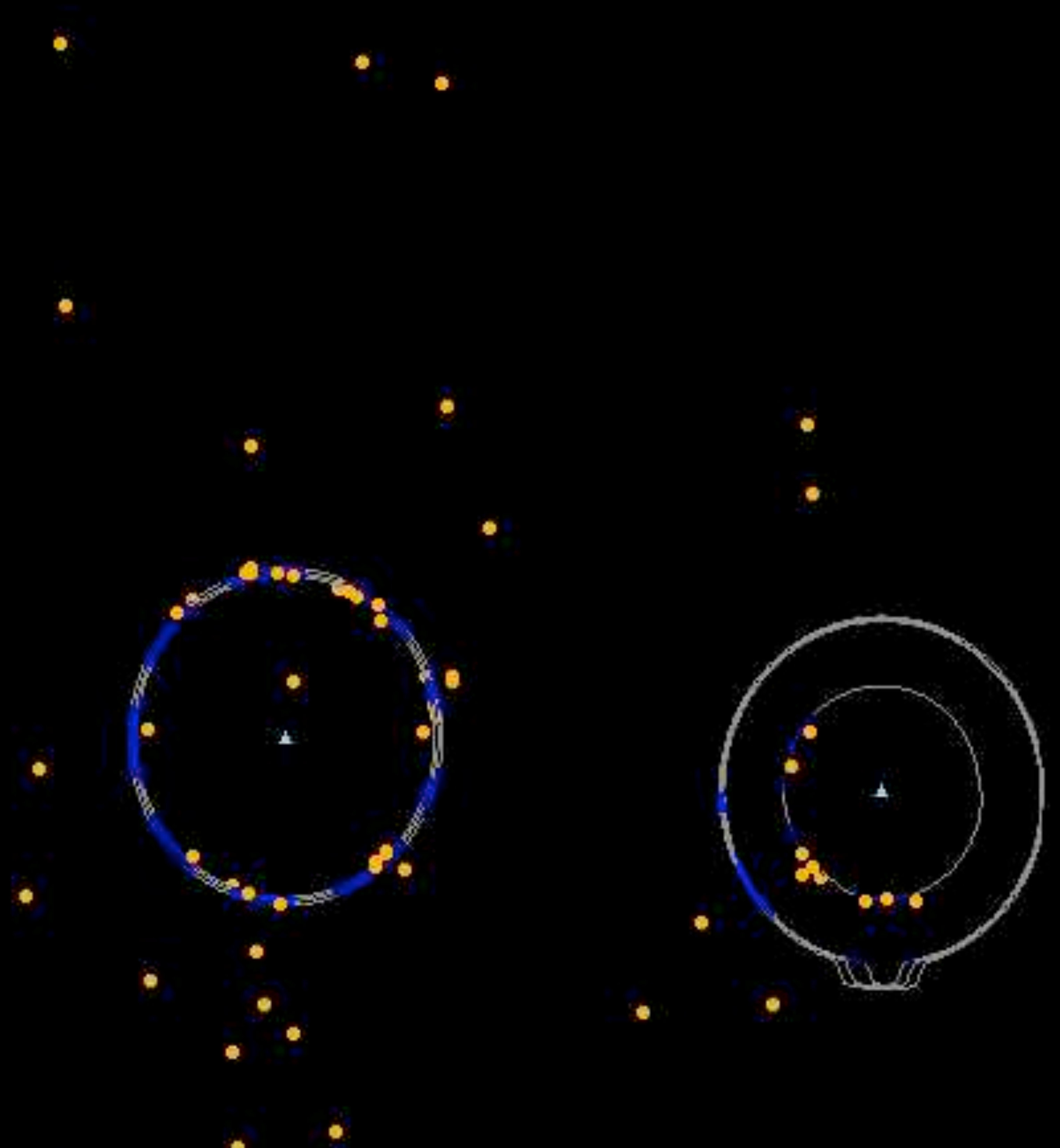


Dedicated particle identification

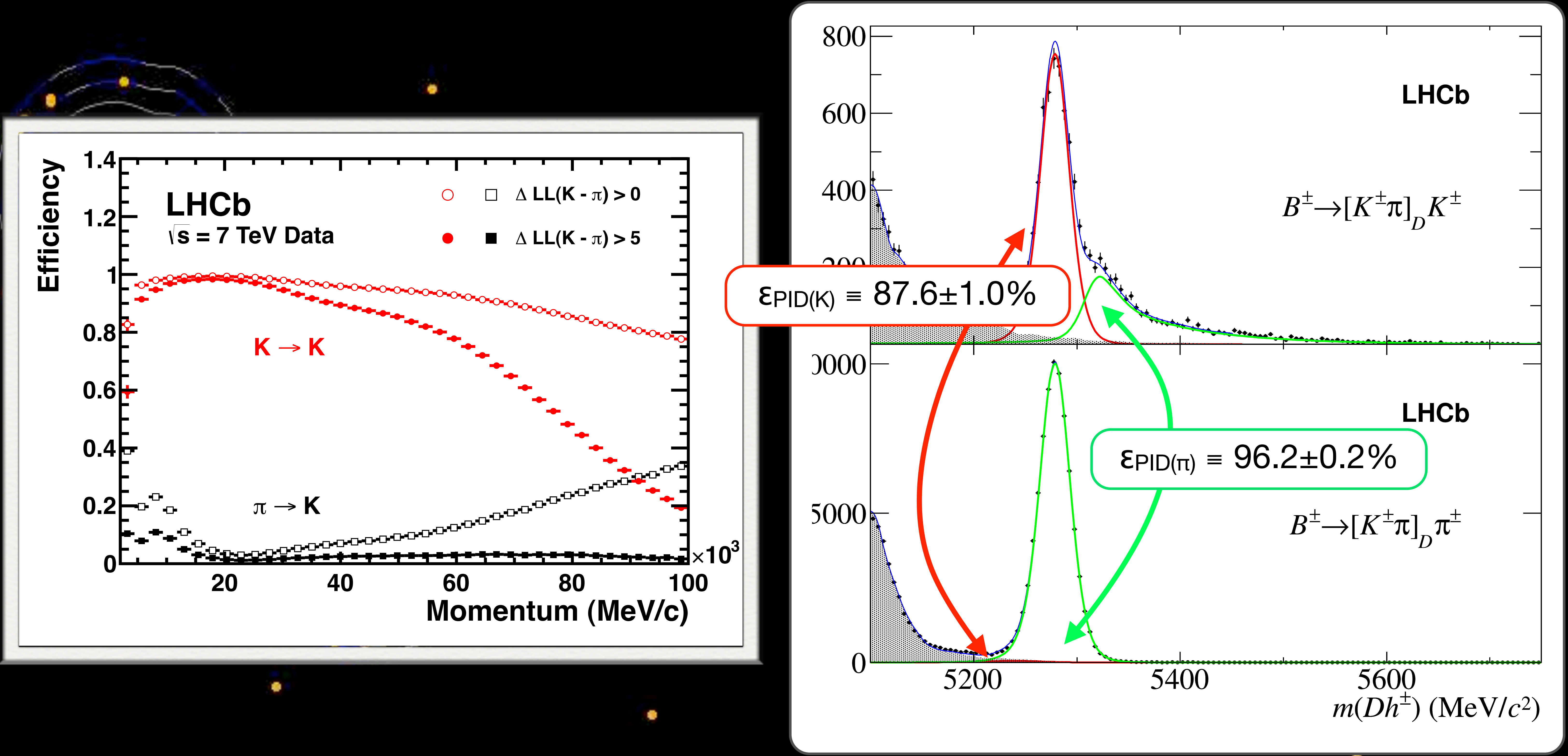


Achieves pion-kaon separation from ~5 to 100 GeV/*c*

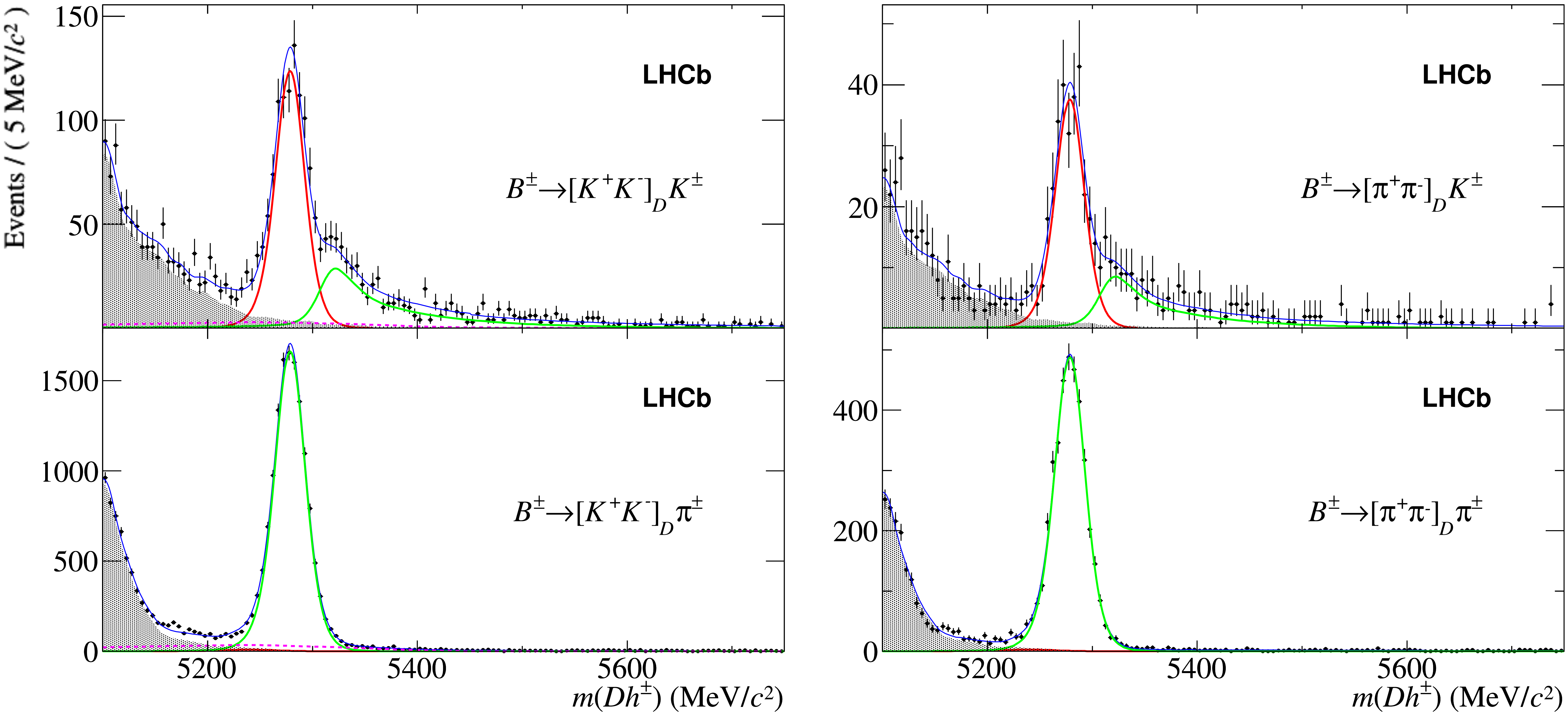




• The result is applicable to all modes considered



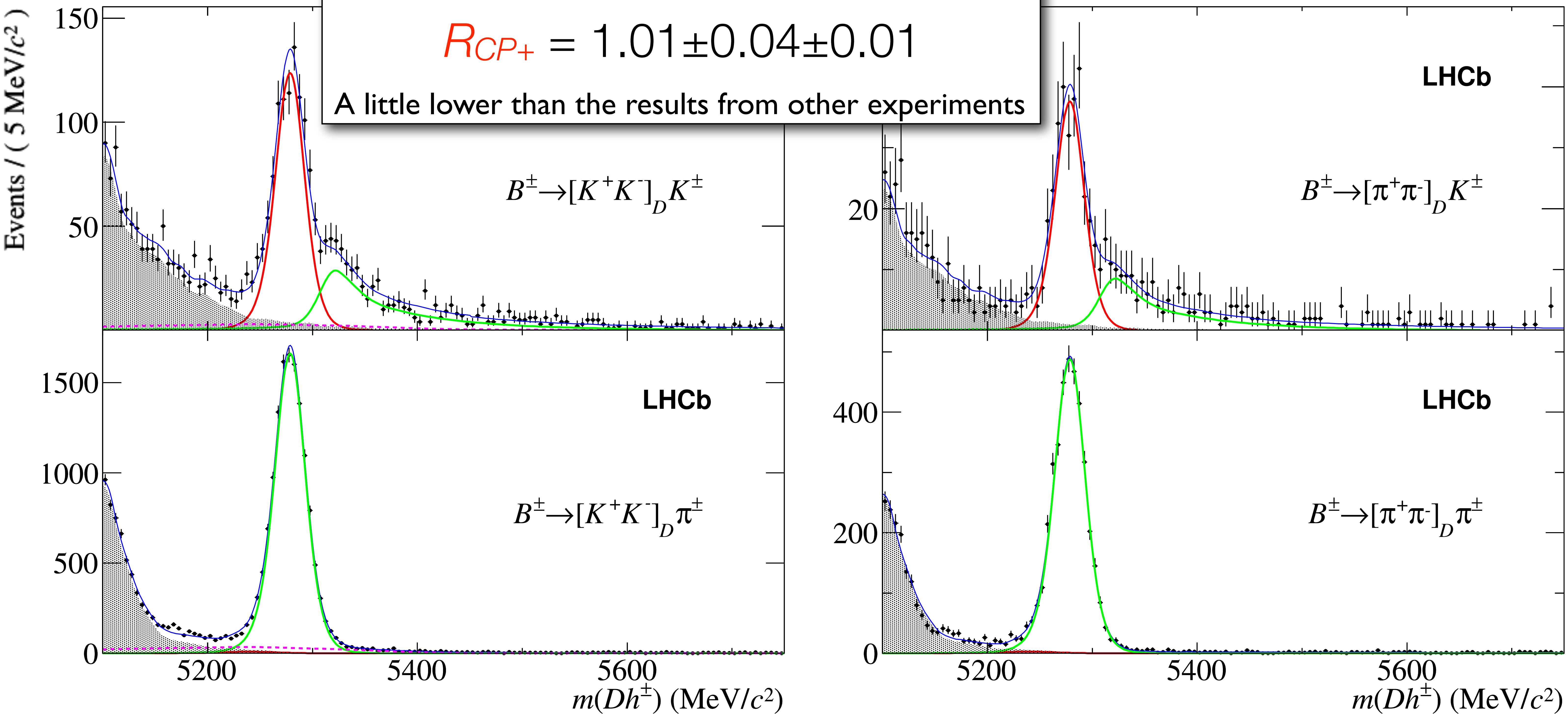
The *CP* eigenstate modes



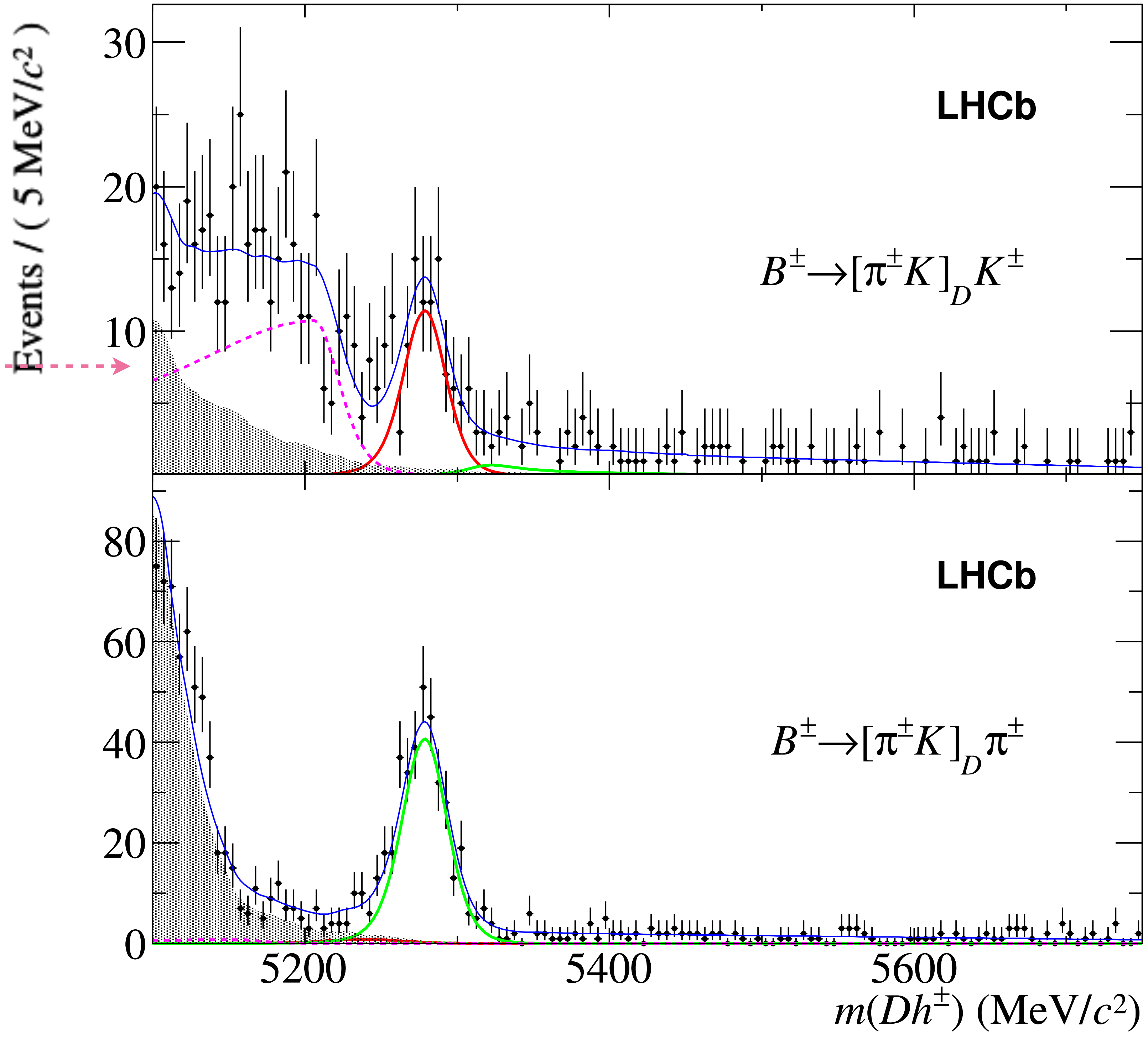
The *CP* eigenstate modes

R_{CP+} = 1.01±0.04±0.01

A little lower than the results from other experiments

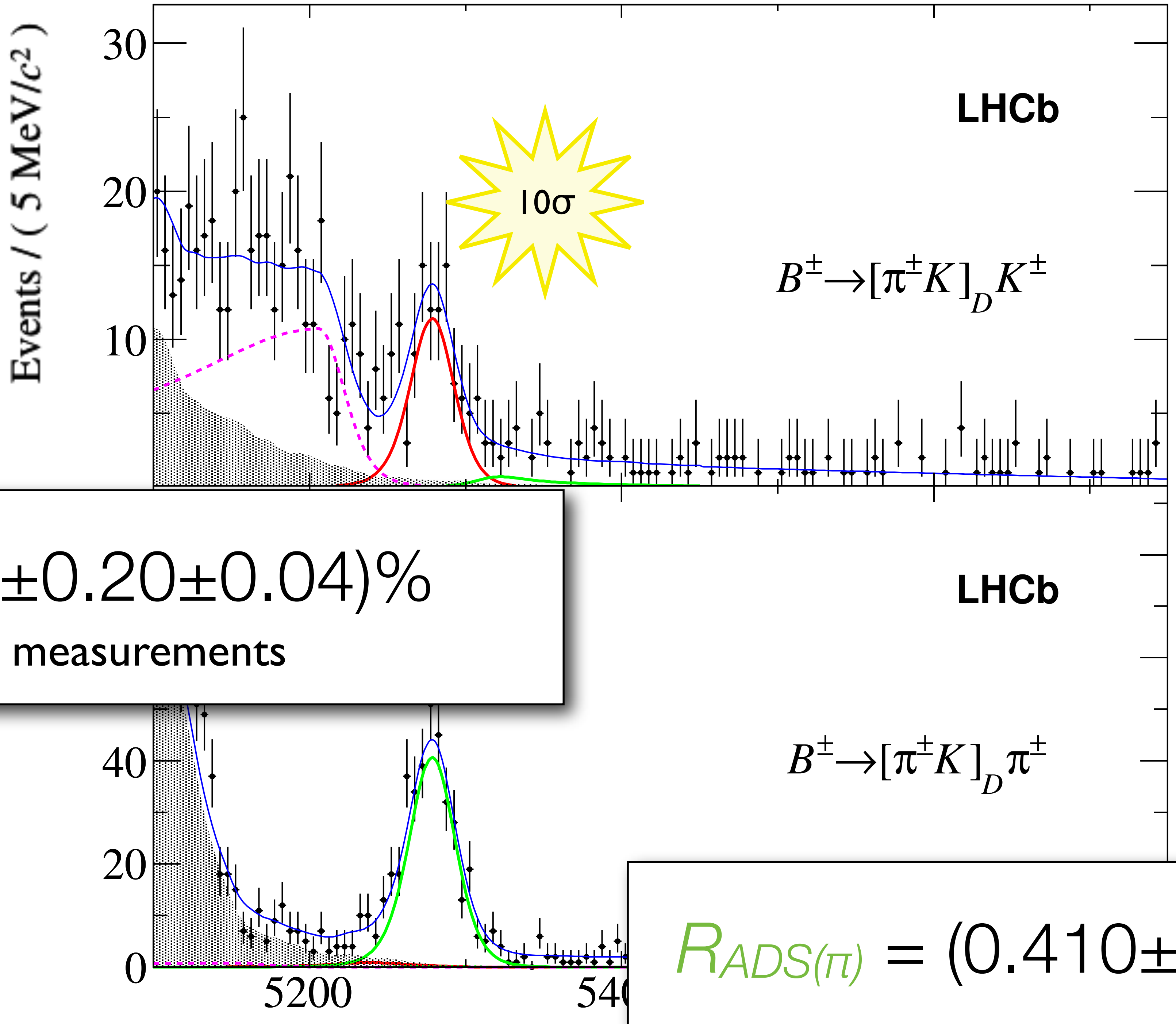


First observation of the $DK^{\pm}$, ADS mode



$B_s\to D^0K^*$
$\to K^-\pi^+K^+\pi^-$
$(4.7\pm1.4)\times10^{-4}$

First observation of the *DK*±, ADS mode



$\mathscr{B}(B^{\pm}\to[\pi^{\pm}K^{+}]_D K^{\pm})$
$\approx (2.2 \pm 0.3)\times 10^{-7}$

R_{ADS} = (1.52±0.20±0.04)%

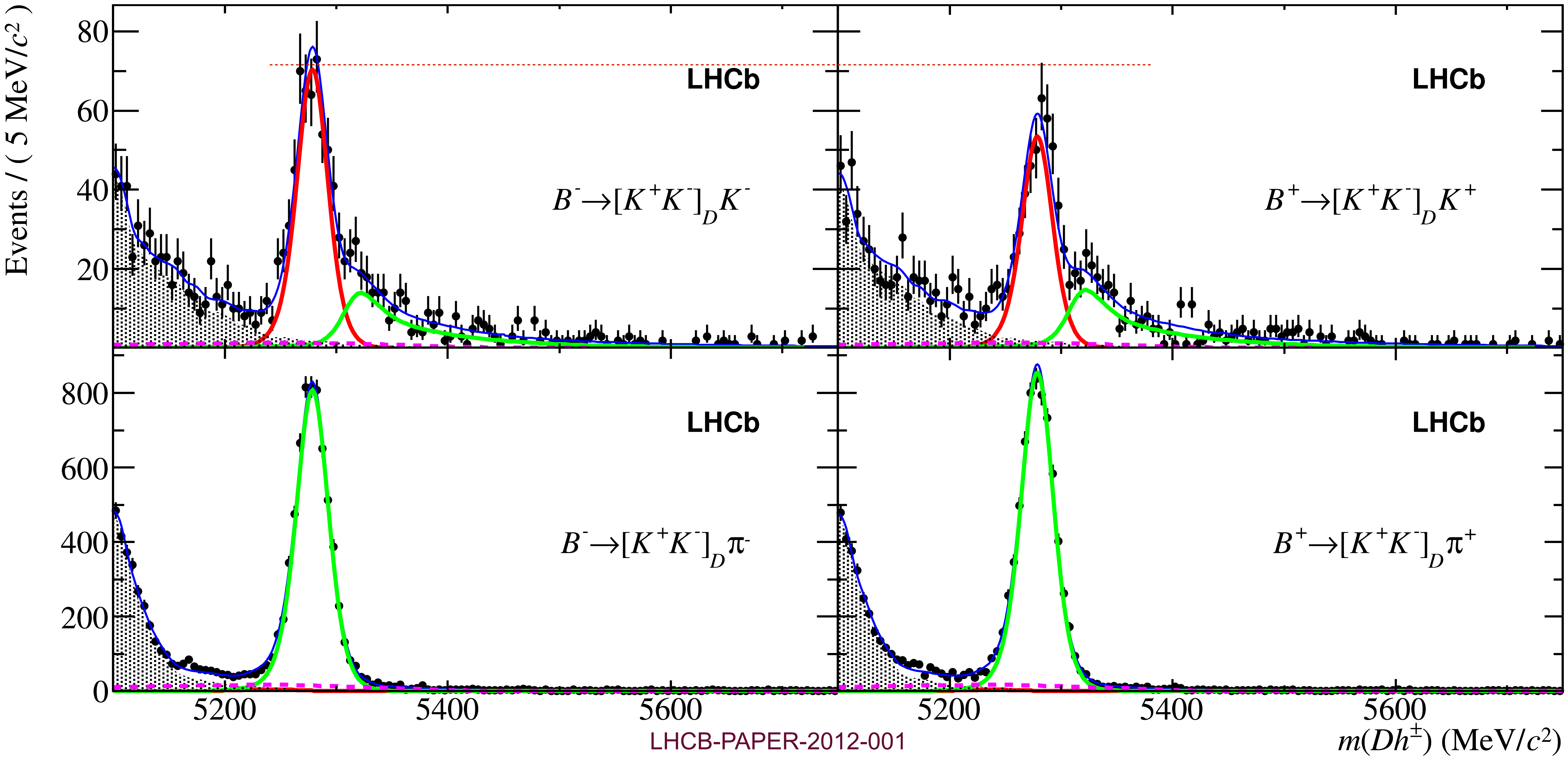
Compatible with previous measurements

$R_{ADS(\pi)}$ = (0.410±0.025±0.005)%

~2σ higher than previous measurements

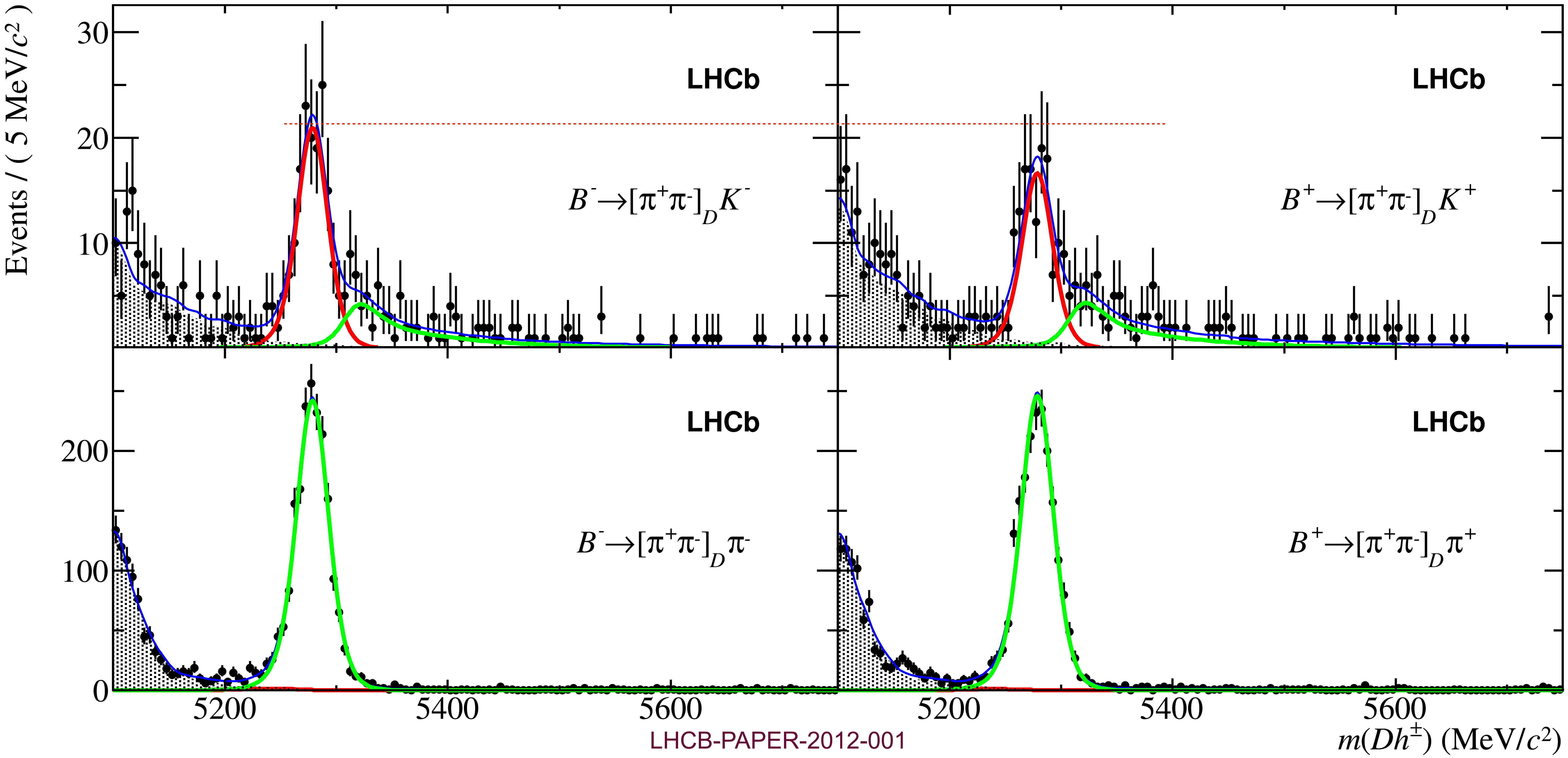
What about *CP* violation?

KK mode, split by the charge of the *B*



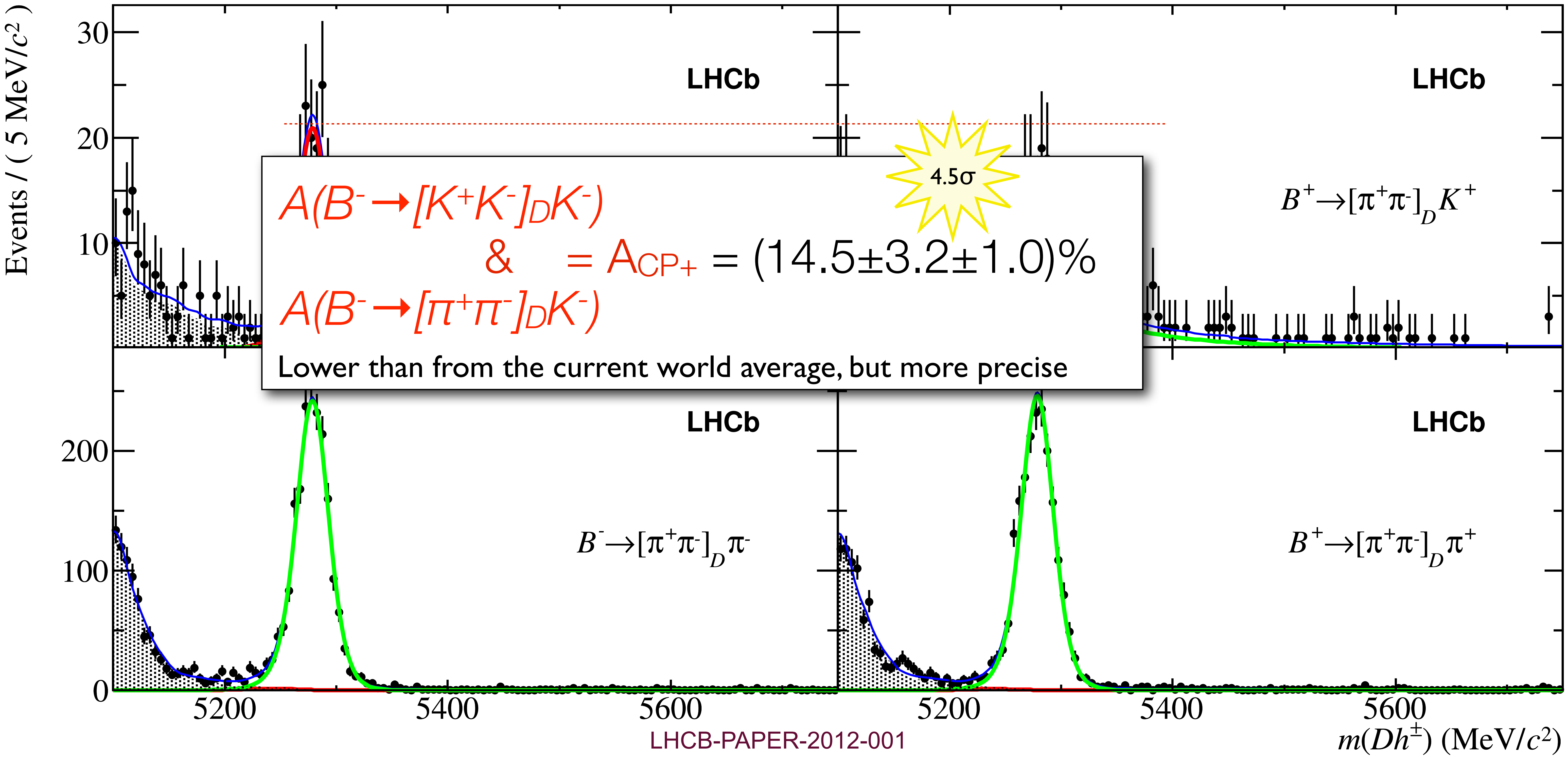
LHCB-PAPER-2012-001

$\pi\pi$ mode, split by the charge of the *B*



LHCB-PAPER-2012-001

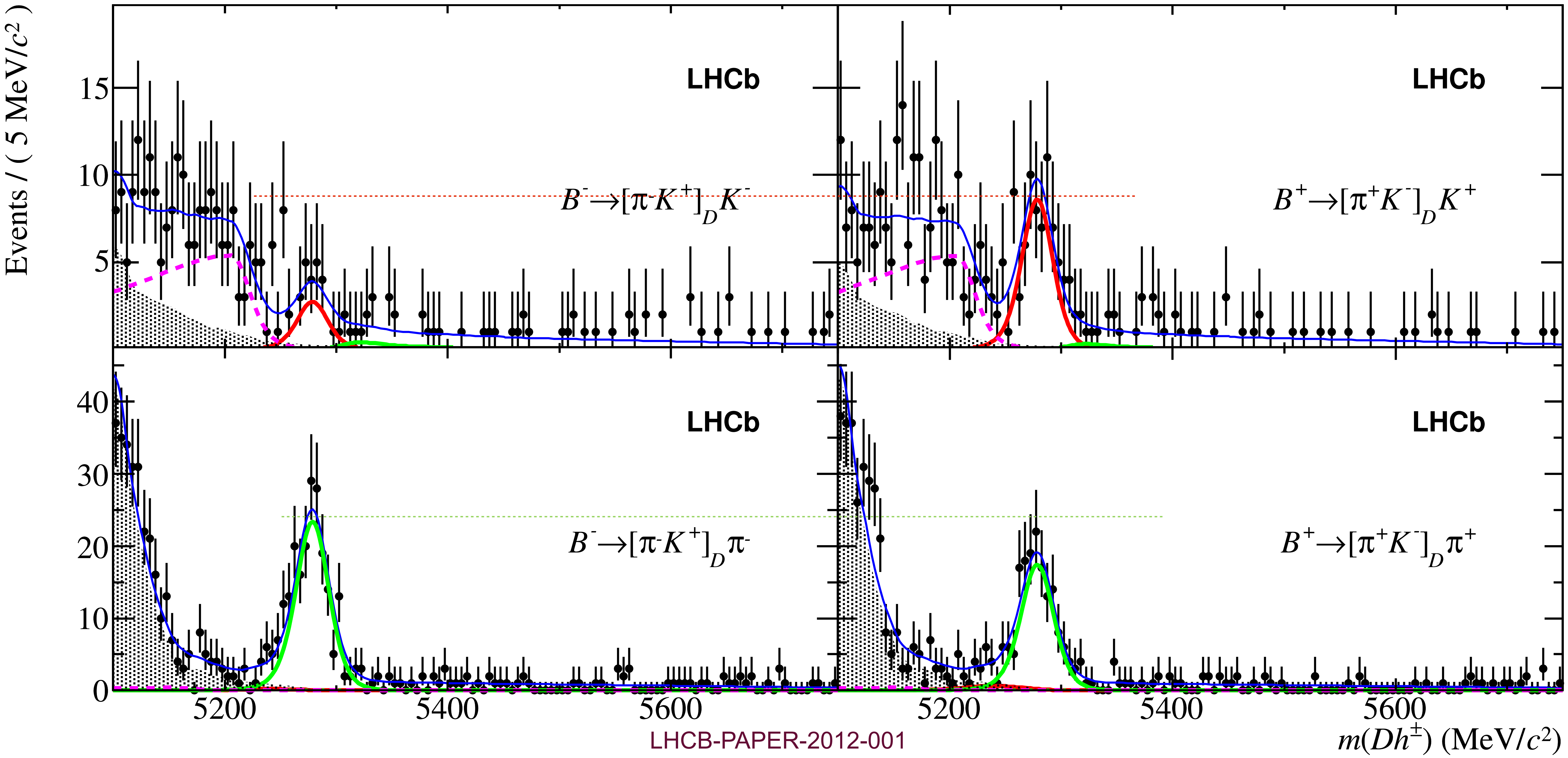
$\pi\pi$ mode, split by the charge of the B



$A(B^- \to [K^+K^-]_D K^-)$ & $A(B^- \to [\pi^+\pi^-]_D K^-)$ $= A_{CP+} = (14.5 \pm 3.2 \pm 1.0)\%$

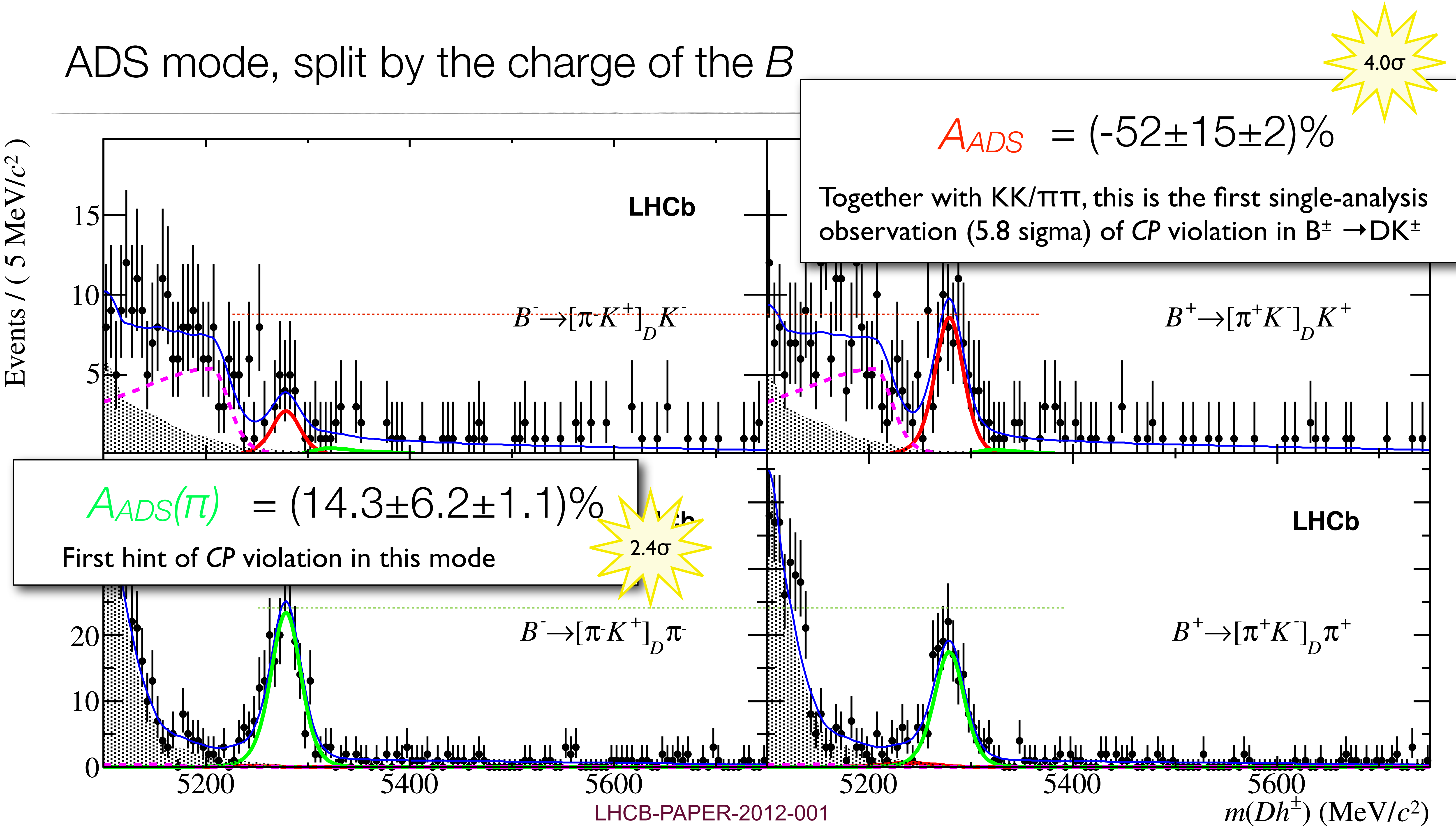
Lower than from the current world average, but more precise

ADS mode, split by the charge of the *B*



LHCB-PAPER-2012-001

ADS mode, split by the charge of the *B*



A_{ADS} = (-52±15±2)%

Together with KK/ππ, this is the first single-analysis observation (5.8 sigma) of *CP* violation in B± →DK±

$A_{ADS}(\pi)$ = (14.3±6.2±1.1)%

First hint of *CP* violation in this mode

LHCB-PAPER-2012-001

Interpretation and [near] future

But how does this tie-in with γ?

- All of the physics observables may be written in terms of the “fundamental” parameters: r_B, γ, δ_B
- A full multi-mode treatment, leading to an LHCb measurement of r_B, γ, δ_B is in preparation.
- However, in the short-term, we can get an idea by using the standard equations (below);
  - take the strong phase δ_D is well known. (neglecting a ±12° uncertainty)

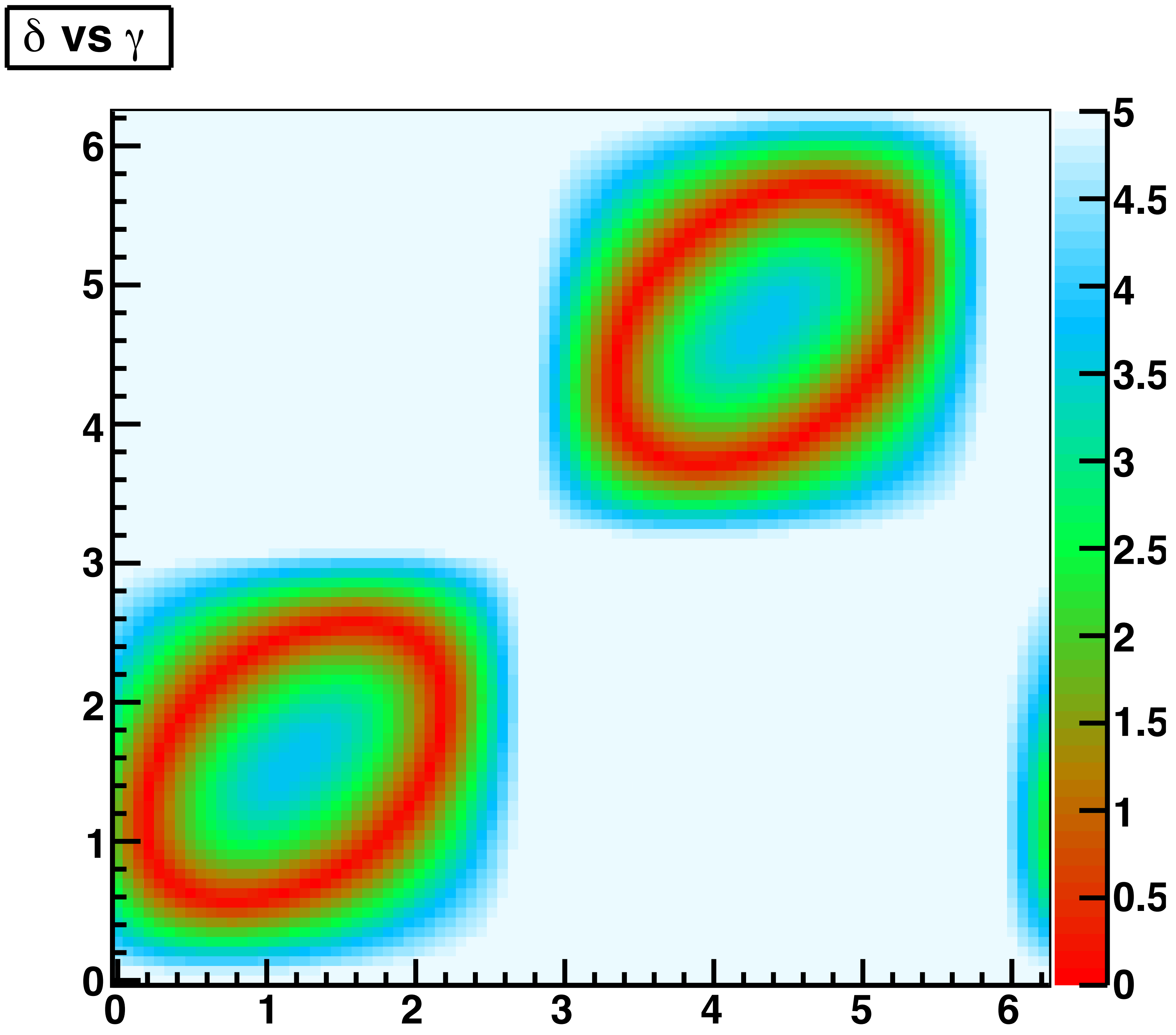
$$R_{CP+} = 1 + {r_B}^2 + 2r_B \cos\delta_B \cos\gamma$$

$$A_{CP+} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + {r_B}^2 + 2r_B \cos\delta_B \cos\gamma}$$

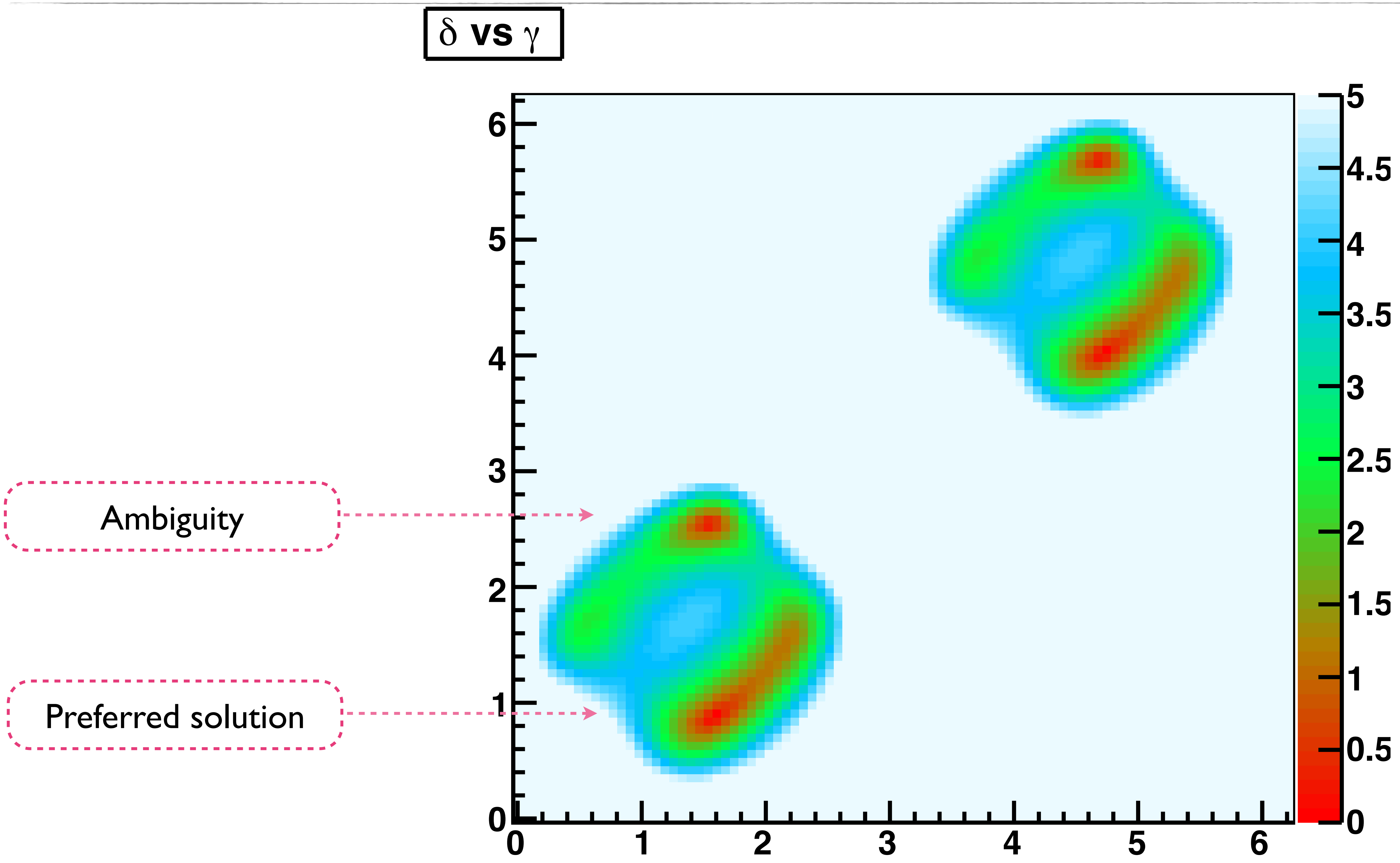
$$R^{ADS} = \frac{{r_B}^2 + {r_D}^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos\gamma}{1 + (r_B r_D)^2 + 2r_B r_D \cos(\delta_B - \delta_D) \cos\gamma}$$

$$A^{ADS} = \frac{2r_B r_D \sin(\delta_B + \delta_D) \sin\gamma}{{r_B}^2 + {r_D}^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos\gamma}$$

Using: $R_{ADS(K)}$ and $A_{ADS(K)}$



Using: $R_{ADS(K)}$ and $A_{ADS(K)}$ and R_{CP+} and A_{CP+}



This is just the first step for LHCb!

Many direct CPV analyses coming to maturity:

$B^- \to D\, K^-$

$D \to K^+\pi^-$
$D \to K^-K^+$
$D \to \pi^-\pi^+$

presented today.

$D \to K_S{}^0\pi^+\pi^-$
$D \to K_S{}^0K^+K^-$
$D \to K^+\pi^-\pi^+\pi^-$
$D \to K^+\pi^-\pi^0$

$\bar{B}^0 \to D\, K^{*0}$

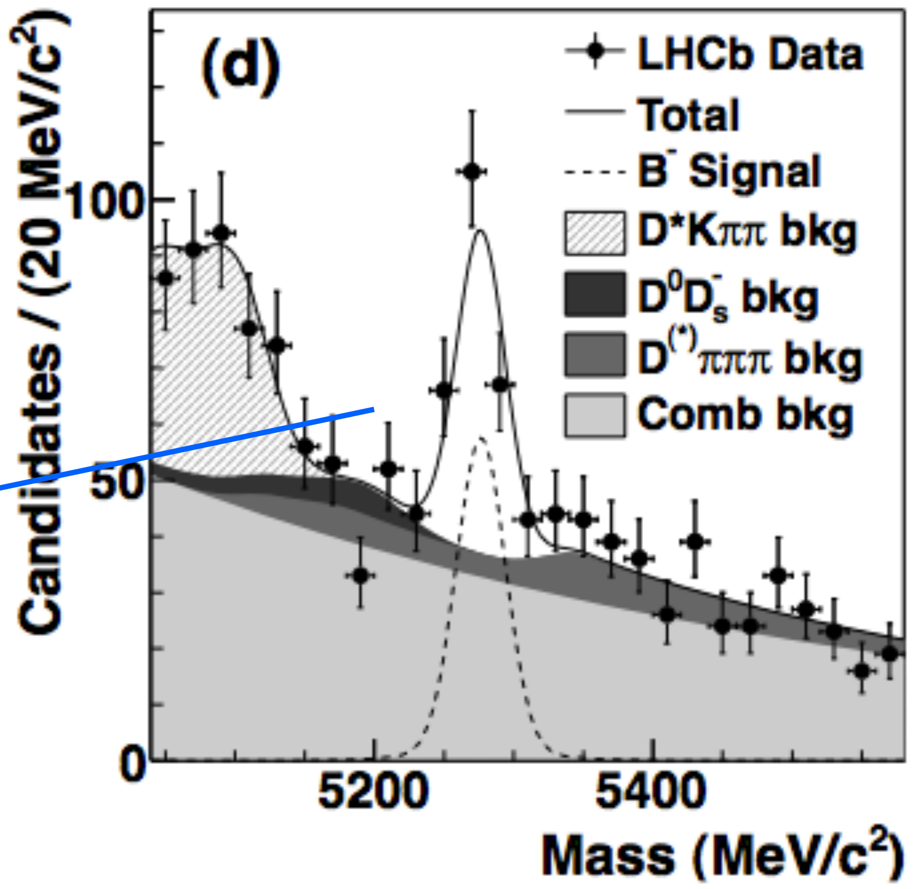
$D \to K^+\pi^-$
$D \to K^-K^+$
$D \to \pi^-\pi^+$

$B^- \to D\, K^-\pi^+\pi^-$

$D \to K^+\pi^-$
$D \to K^-K^+$
$D \to \pi^-\pi^+$

Favoured mode first observed in 2010

arXiv:1201.4402

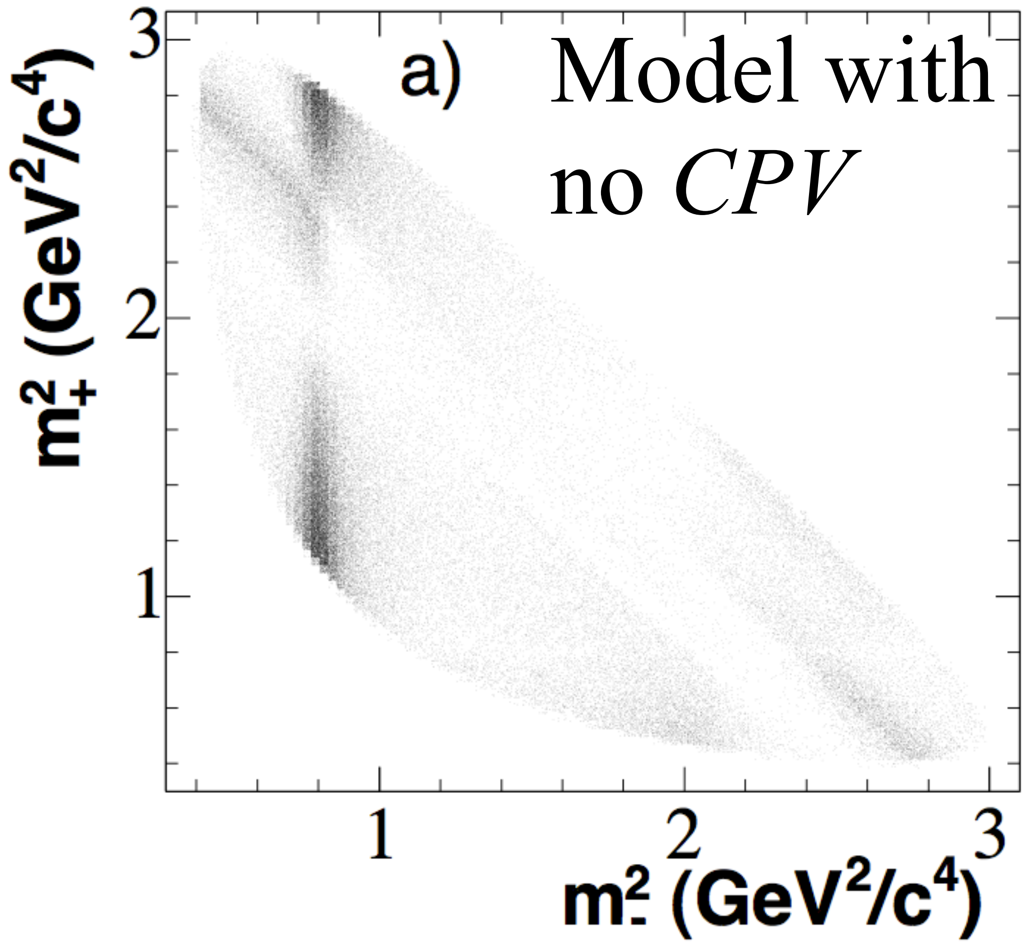


Summer 2012: important contribution from the “GGSZ” method

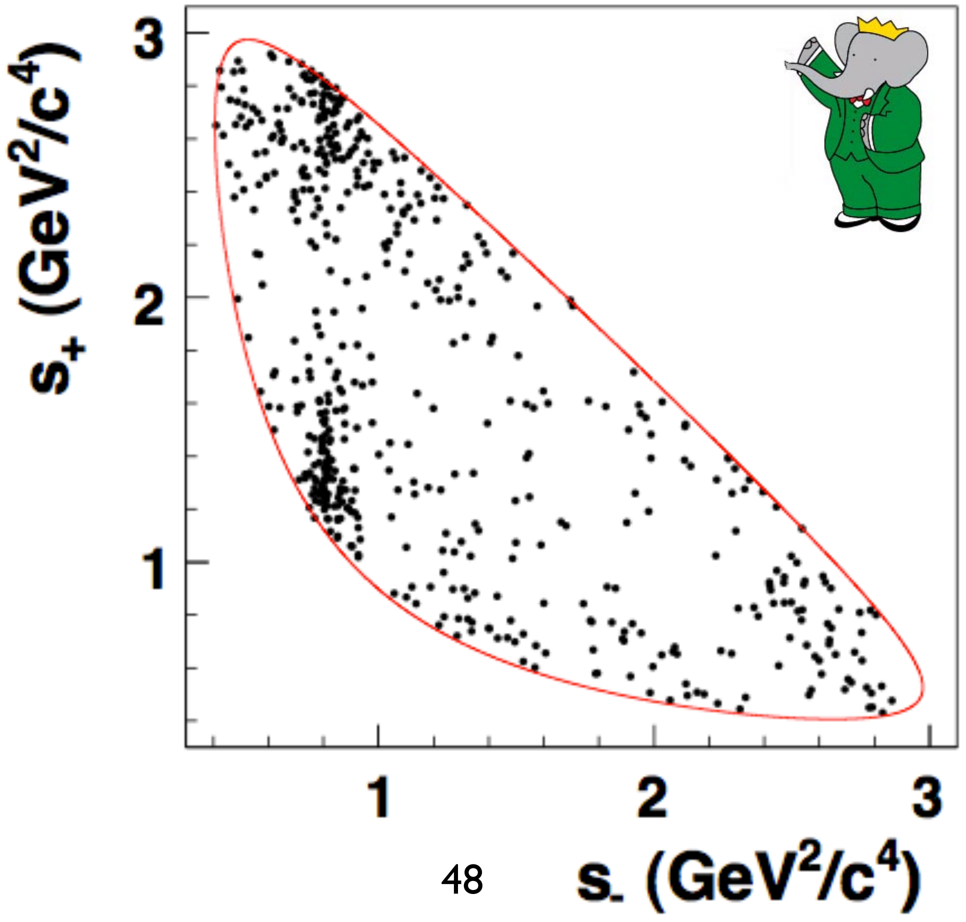
- Exactly the same idea: interference between b→u and b→c transitions but this time, use a three-body common final state

$$B^- \to D\,K^-$$
$$D \to K_S^0\pi^+\pi^-$$

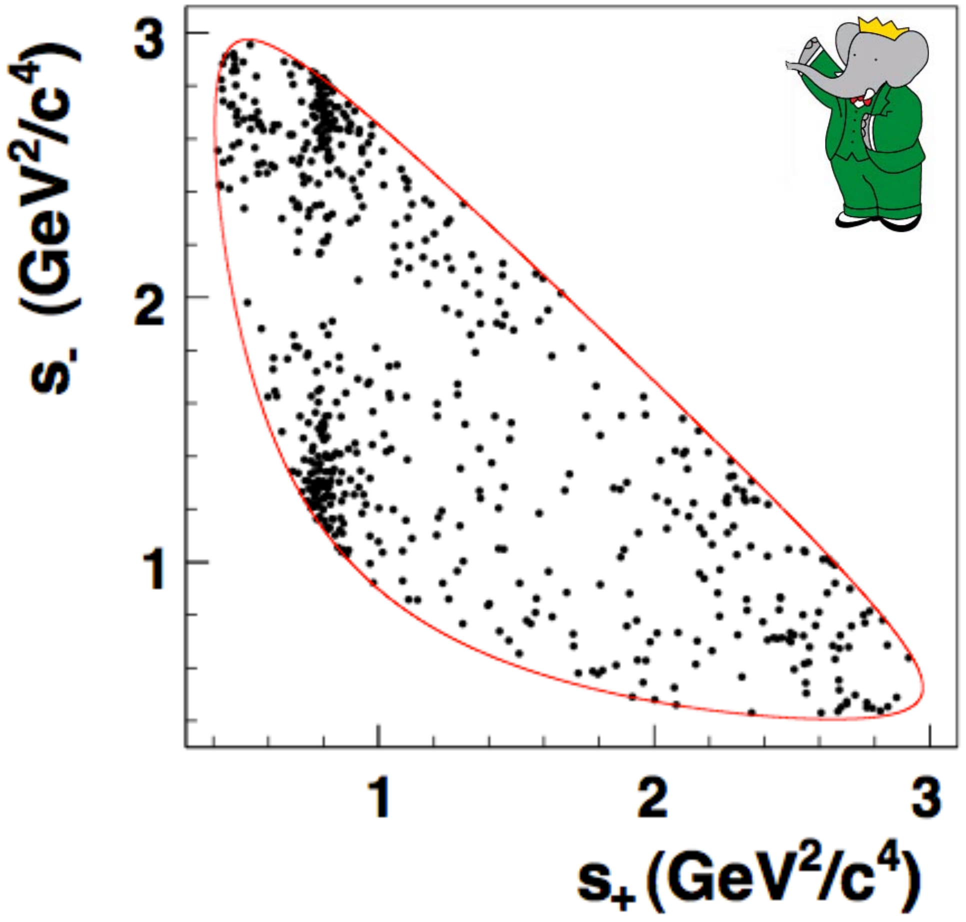
- This method is particularly useful for combatting the trigonometric ambiguities present in the determination of γ from the ADS & *CP* methods



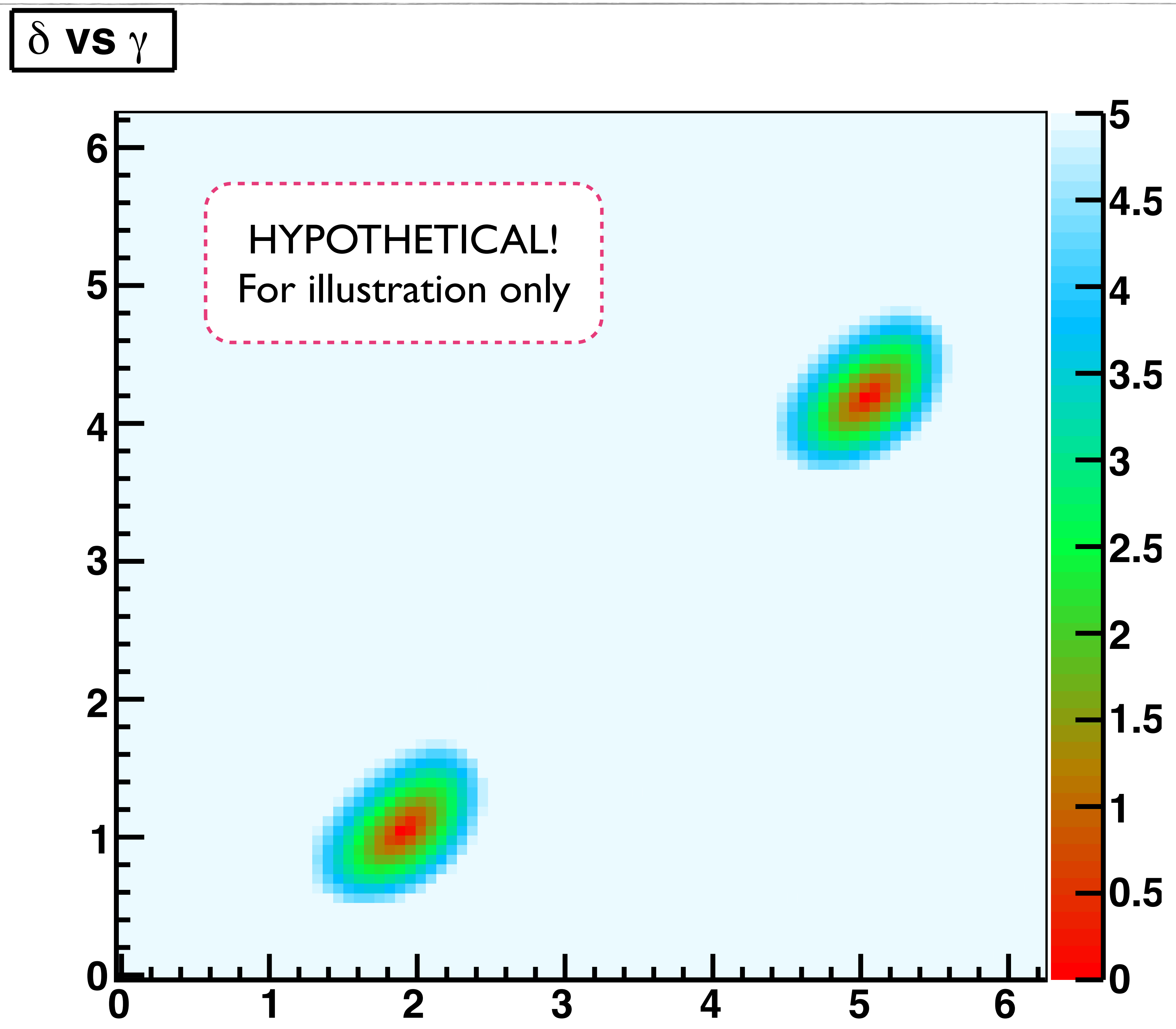
$B^- \to D\,K^-$



$B^+ \to D\,K^+$



Using: $R_{ADS(K)}$ and $A_{ADS(K)}$ and R_{CP+} and A_{CP+} and the GGSZ modes



And unique to LHCb: γ from B_s tree decays

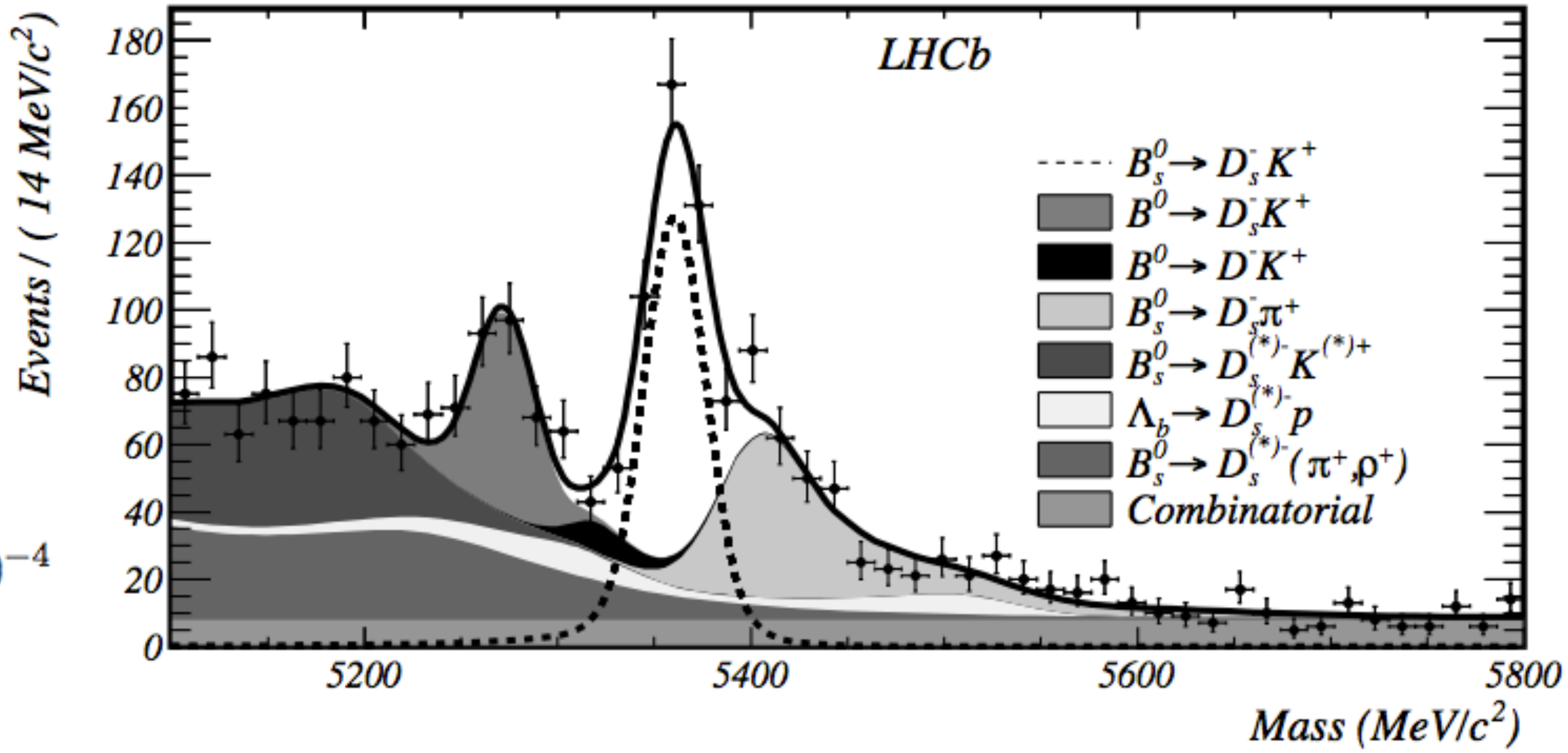
Precise measurement of

$$B_s^0 \rightarrow D_s^- K^+$$

branching now made. Time-dependent measurement of γ on-going.

$$\mathcal{B}(B_s^0 \rightarrow D_s^- K^+) = (1.90 \pm 0.12 \pm 0.13)^{+0.12}_{-0.14} \times 10^{-4}$$

LHCB-PAPER-2011-022



LHCb is on-track to make a combined measurement of γ using $B^{\pm}$,B^0,B_s tree decays, to an accuracy of 5~8° with the 2011+2012 dataset.

Neutral meson formalism

The time evolution of a two-state mixing system is well known

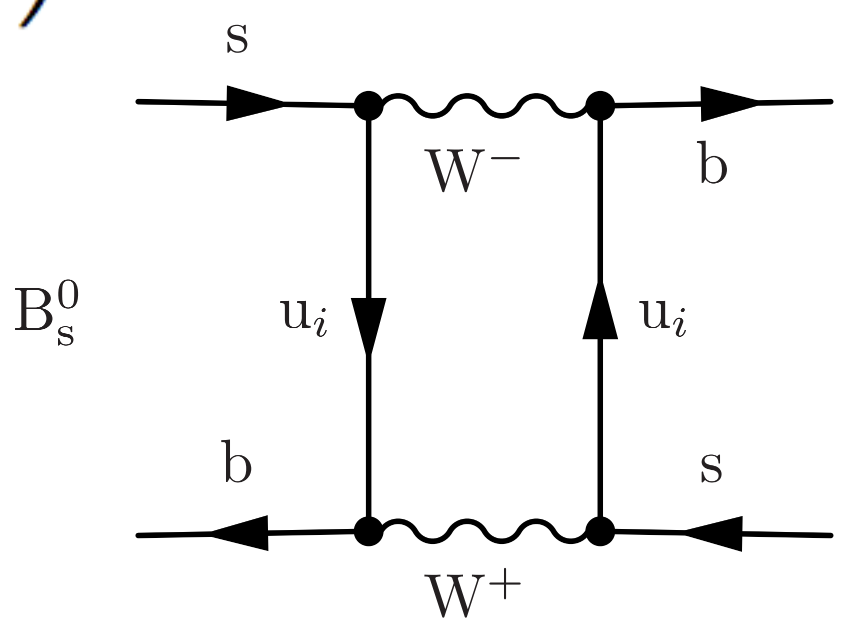
$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(\hat{M}^q - \frac{i}{2}\hat{\Gamma}^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

Trivial case. Applies to $B^{\pm}$ decays

$$\begin{pmatrix} M_{11} & 0 \\ 0 & M_{22} \end{pmatrix} \qquad \begin{pmatrix} \Gamma_{11} & 0 \\ 0 & \Gamma_{22} \end{pmatrix}$$

Mixing can occur with B^0 and B_s

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \qquad \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$



And CP violation in mixing occurs if $\phi_q = \arg(-M_{12}^q/\Gamma_{12}^q)$ is non-zero.

Diagonalising the matrix obtains the two [observable] mass eigenstates. Referred to the Heavy and Light states.

$$B_{q,H} := p\,B_q + q\,\bar{B}_q$$

$$B_{q,L} := p\,B_q - q\,\bar{B}_q$$

$$|p|^2 + |q|^2 = 1$$

Properties

If there is no *CP* violation, *p*=*q*=√2,
***B**$_H$* **is pure *CP*+** and ***B**$_L$* **is pure *CP*−**

$$B_{q,H} := p\, B_q + q\, \bar{B}_q$$
$$B_{q,L} := p\, B_q - q\, \bar{B}_q$$

$$|p|^2 + |q|^2 = 1$$

In addition to the *CP* violating phase, two other observables can be measured:

The mass difference

$$\Delta M_q := M_H^q - M_L^q = 2|M_{12}^q| \left(1 - \frac{1}{8}\frac{|\Gamma_{12}^q|^2}{|M_{12}^q|^2}\sin^2\phi_q + \ldots\right)$$

B^0 : Δm_d = 0.507±0.004 ps^{-1} (SM: 0.54±0.09 ps^{-1})

B_s : Δm_s = 17.69±0.08 ps^{-1} (SM: 17.3±2.6 ps^{-1})

The lifetime difference

$$\Delta\Gamma_q := \Gamma_L^q - \Gamma_H^q = 2|\Gamma_{12}^q| \cos\phi_q \left(1 + \frac{1}{8}\frac{|\Gamma_{12}^q|^2}{|M_{12}^q|^2}\sin^2\phi_q + \ldots\right)$$

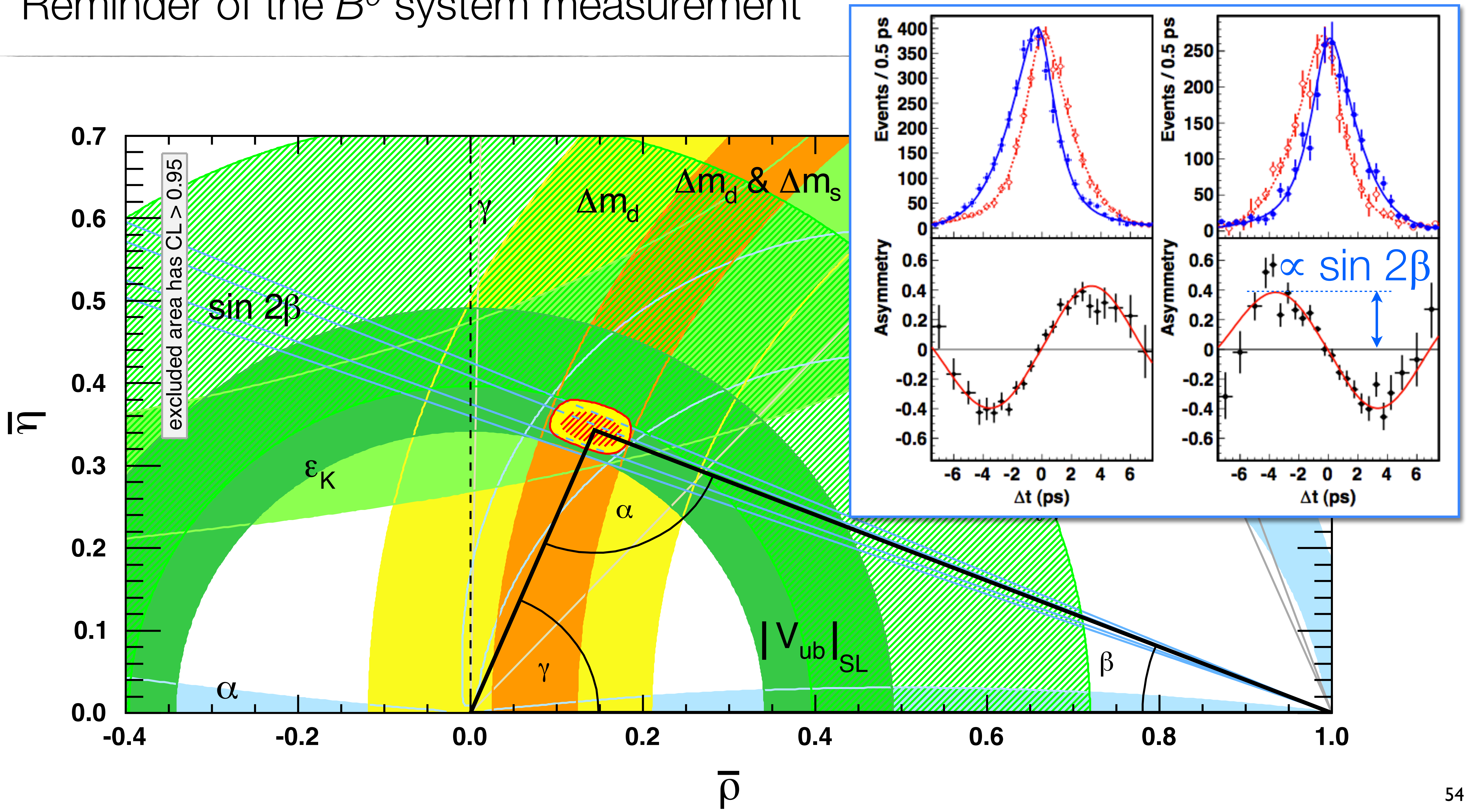
B^0 : $\Delta\Gamma_d$ = small (SM: ~0)

B_s : $\Delta\Gamma_s$ = 0.100±0.013 ps^{-1} (SM: 0.087±0.021 ps^{-1})

Update in a moment

Reminder of the B^0 system measurement

Latest sin 2β measurement from Belle. arXiv:1201.4643v1



The CKM triangle relevant to the B_s system has a rather different shape

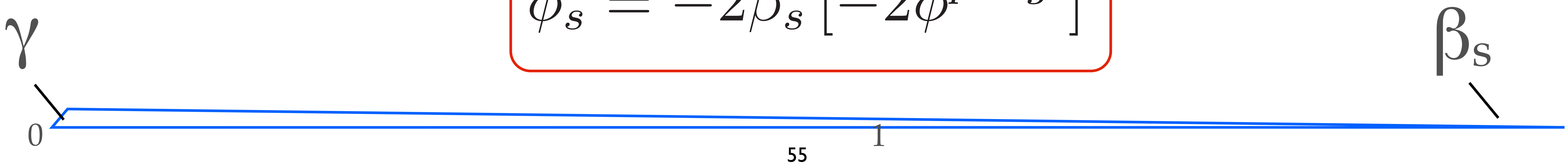
$$
\begin{array}{c} \\ V_{CKM} \end{array} = \begin{array}{c} \\ u \\ c \\ t \end{array}
\begin{array}{c} d \\ \left(\begin{array}{c} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 \\ -\lambda+\frac{1}{2}A^2\lambda^5(1-2(\rho+i\eta)) \\ A\lambda^3(1-(1-\frac{1}{2}\lambda^2)(\rho-i\eta)) \end{array} \right. \end{array}
\begin{array}{c} s \\ \lambda \\ 1-\frac{1}{2}\lambda^2-\frac{1}{8}(1+4A^2)\lambda^4 \\ -A\lambda^2+\frac{1}{2}A\lambda^4(1-2(\rho-i\eta)) \end{array}
\begin{array}{c} b \\ \left. \begin{array}{c} A\lambda^3(\rho-i\eta) \\ A\lambda^2 \\ 1-\frac{1}{2}A^2\lambda^4 \end{array} \right) \end{array} + \mathcal{O}(\lambda^7)
$$

Wolfenstein expansion in powers of the Cabibbo angle, λ, up to λ^6

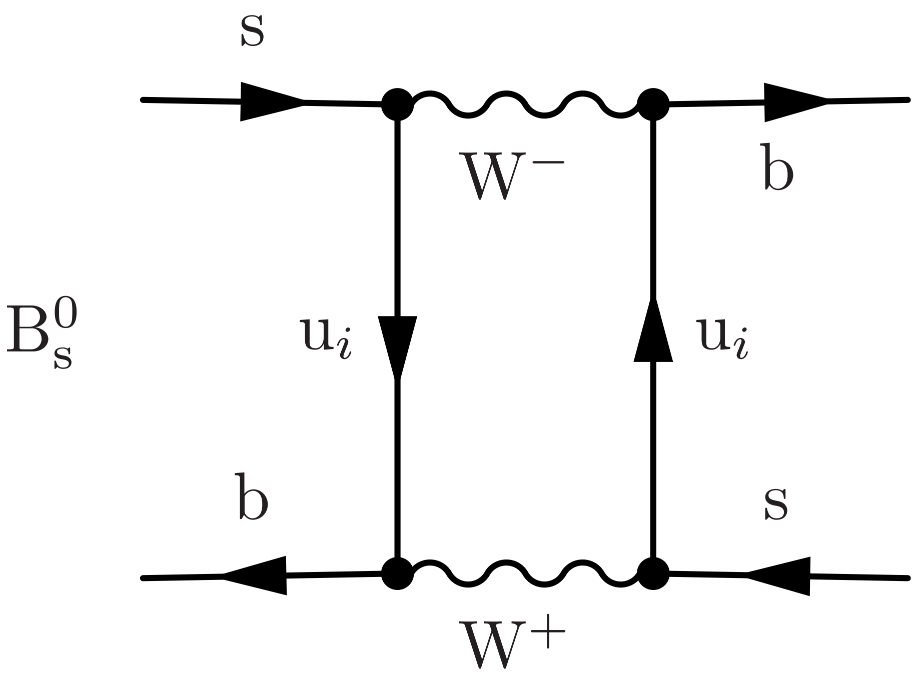
$$0 = 1 + \frac{V_{tb}^* V_{ts}}{V_{cb}^* V_{cs}} + \frac{V_{ub}^* V_{us}}{V_{cb}^* V_{cs}}$$

SM

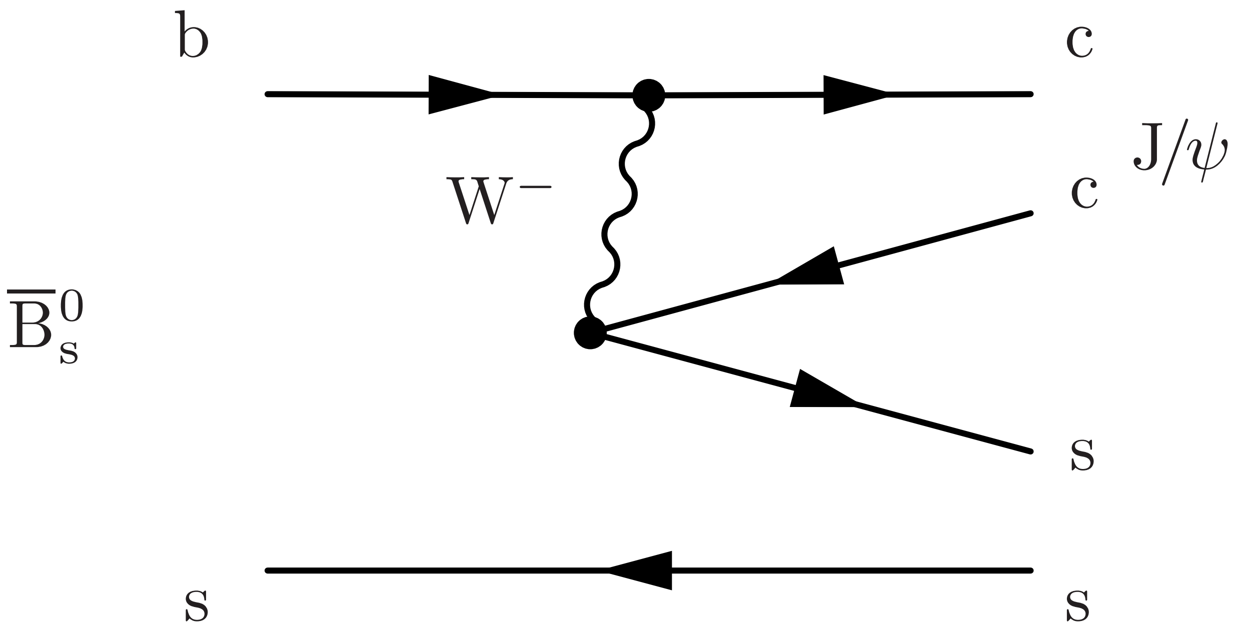
$$\phi_s = -2\beta_s \left[-2\phi^{peng.}\right]$$



Possible penguin pollution

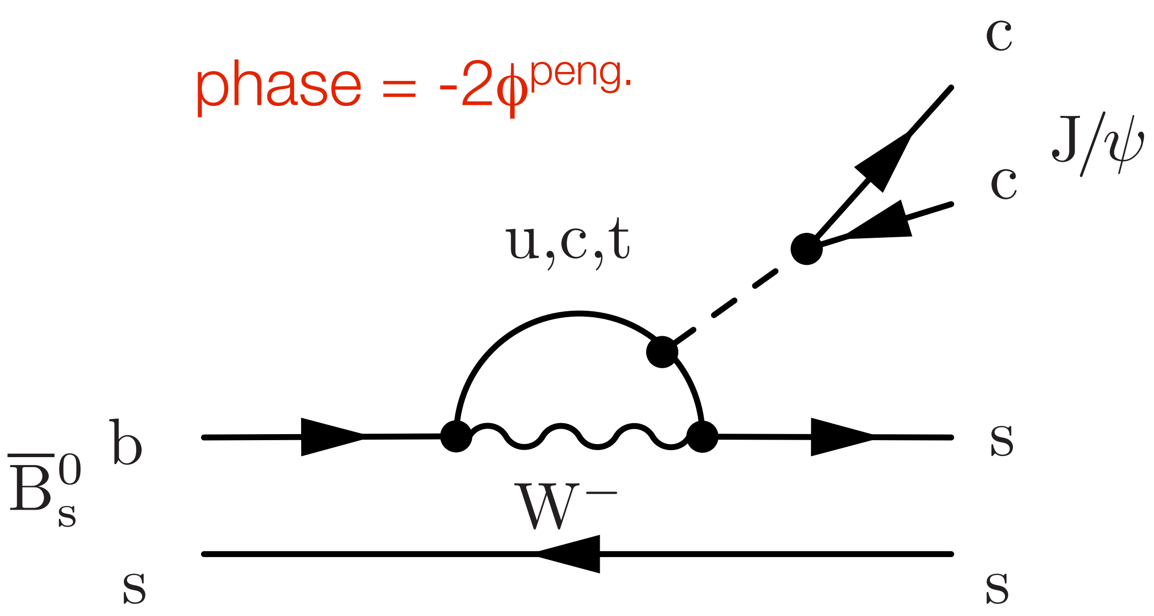


phase = $-2\beta_s$



phase = 0·

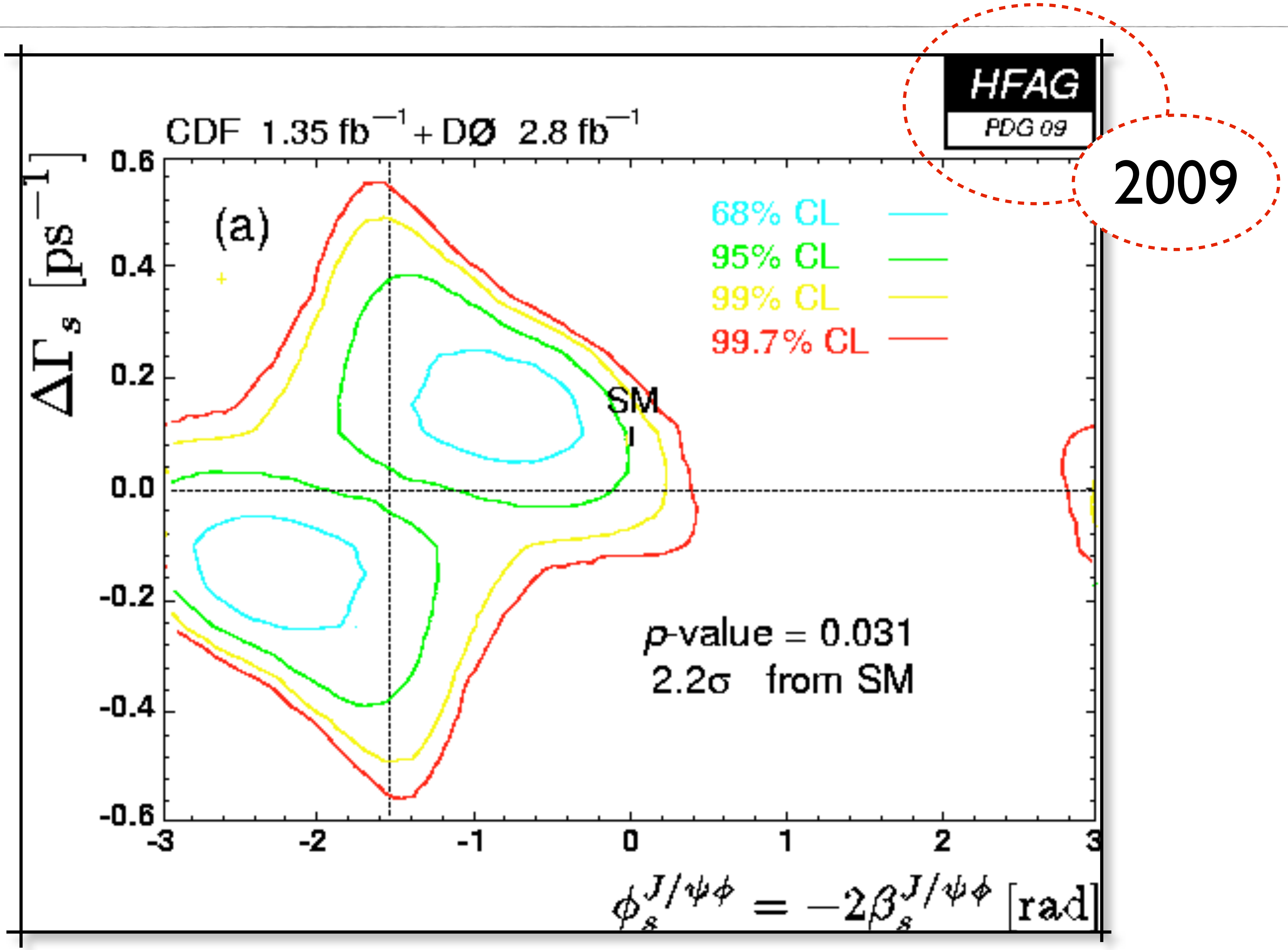
phase = $-2\phi^{peng.}$



penguin phase and amplitude is unknown though expected small

ϕ_s from $B_s \to J/\psi\ \phi$

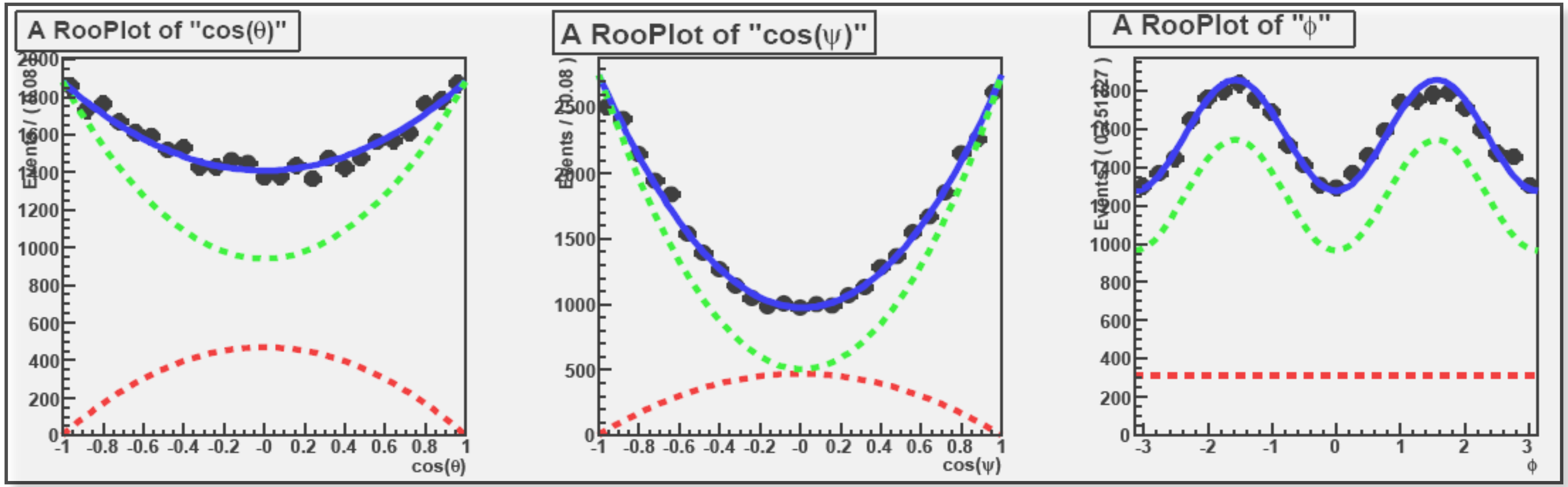
Three years ago...



Angular analysis is needed to separate the CP+ and CP- components

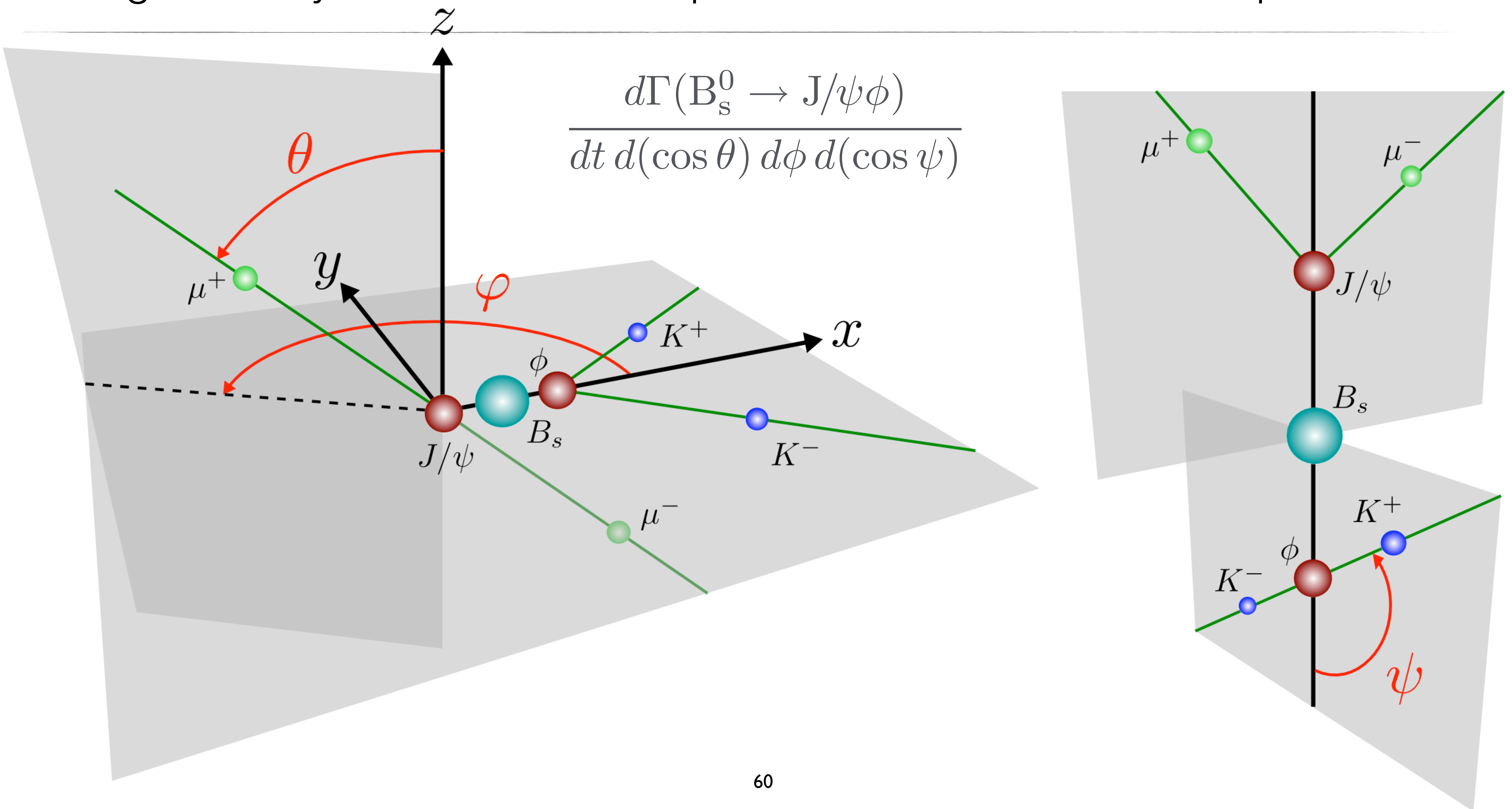
- In the B_s rest frame, ϕ and J/ψ have relative orbital momentum ℓ =0,1,2
- Since $CP|f> = (-1)^{\ell}\ |f>$, the final state is mixture of CP even (ℓ =0,2) and CP odd (ℓ =1)
- Three angles θ, φ, ψ describe directions of final decay products $J/\psi \to \mu\mu$ and $\phi \to K^+K$ from which the CP+ and CP- components may be extracted

SIMULATION



Angular analysis is needed to separate the CP+ and CP- components

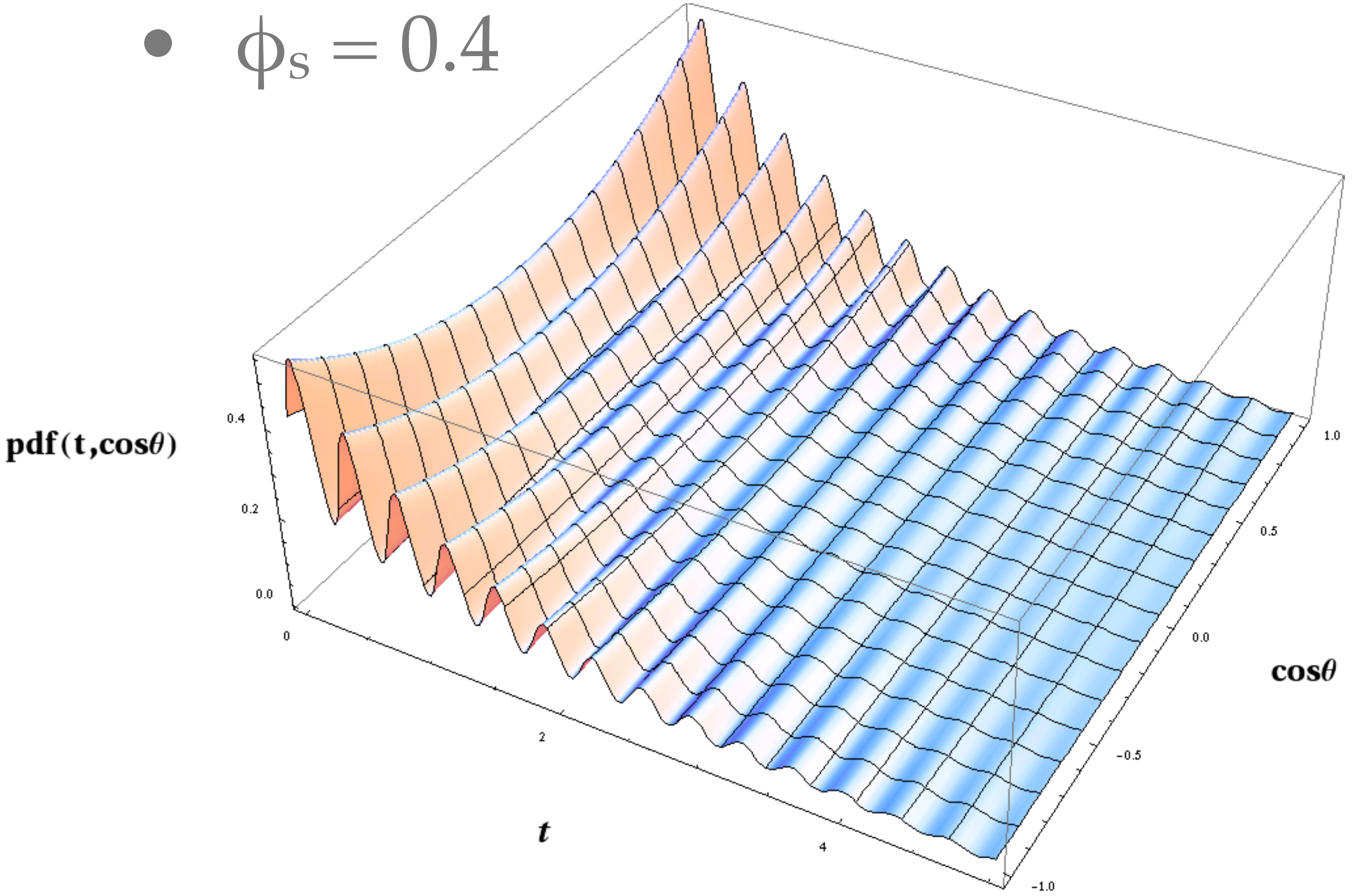
$$\frac{d\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d(\cos\theta)\, d\phi\, d(\cos\psi)}$$



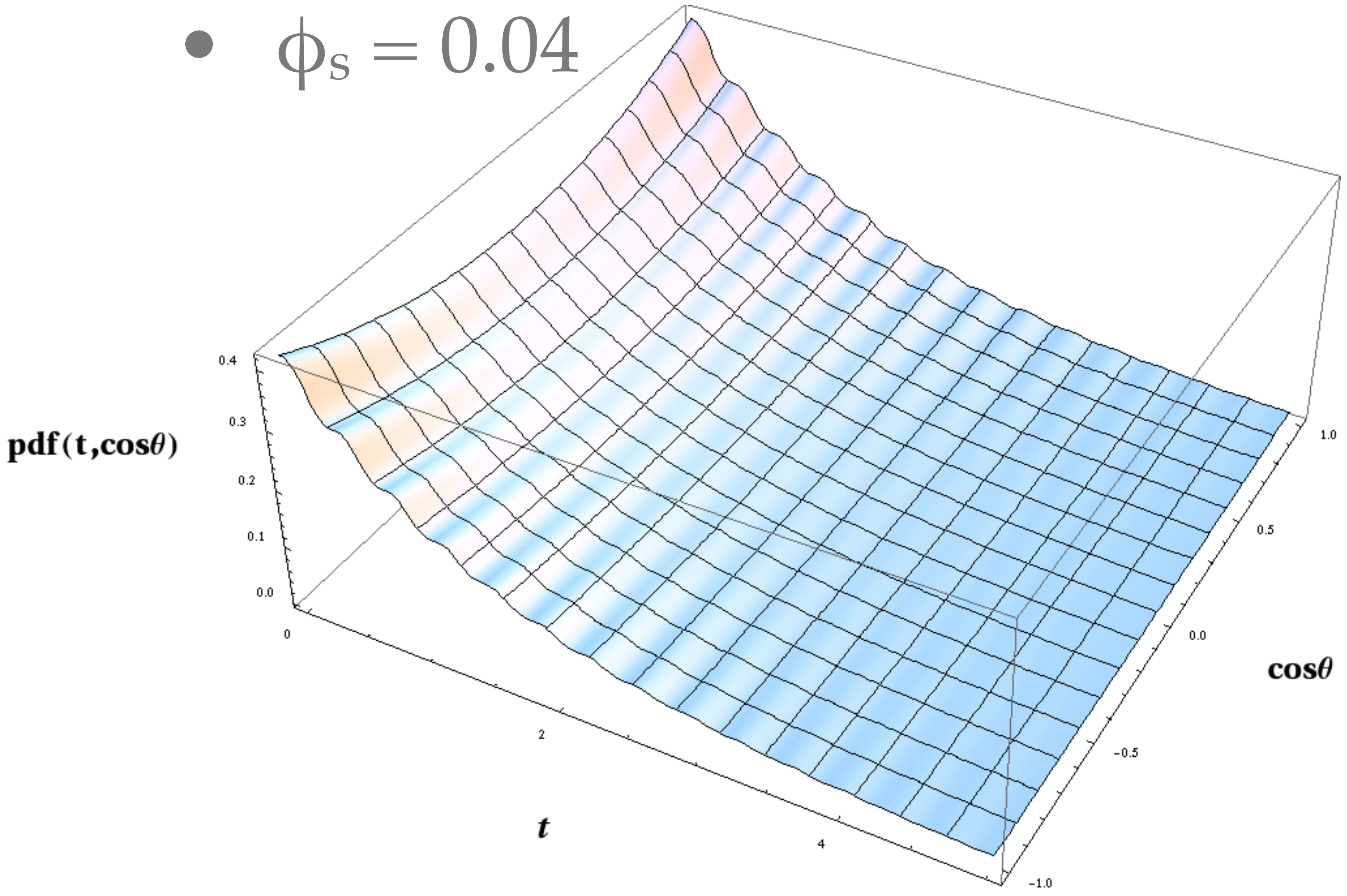
Visualise the expected PDF after integrating over 2 of the 3 angles

- Amplitude of “wiggles” ∝ sin ϕ_s

  - $\phi_s = 0.4$

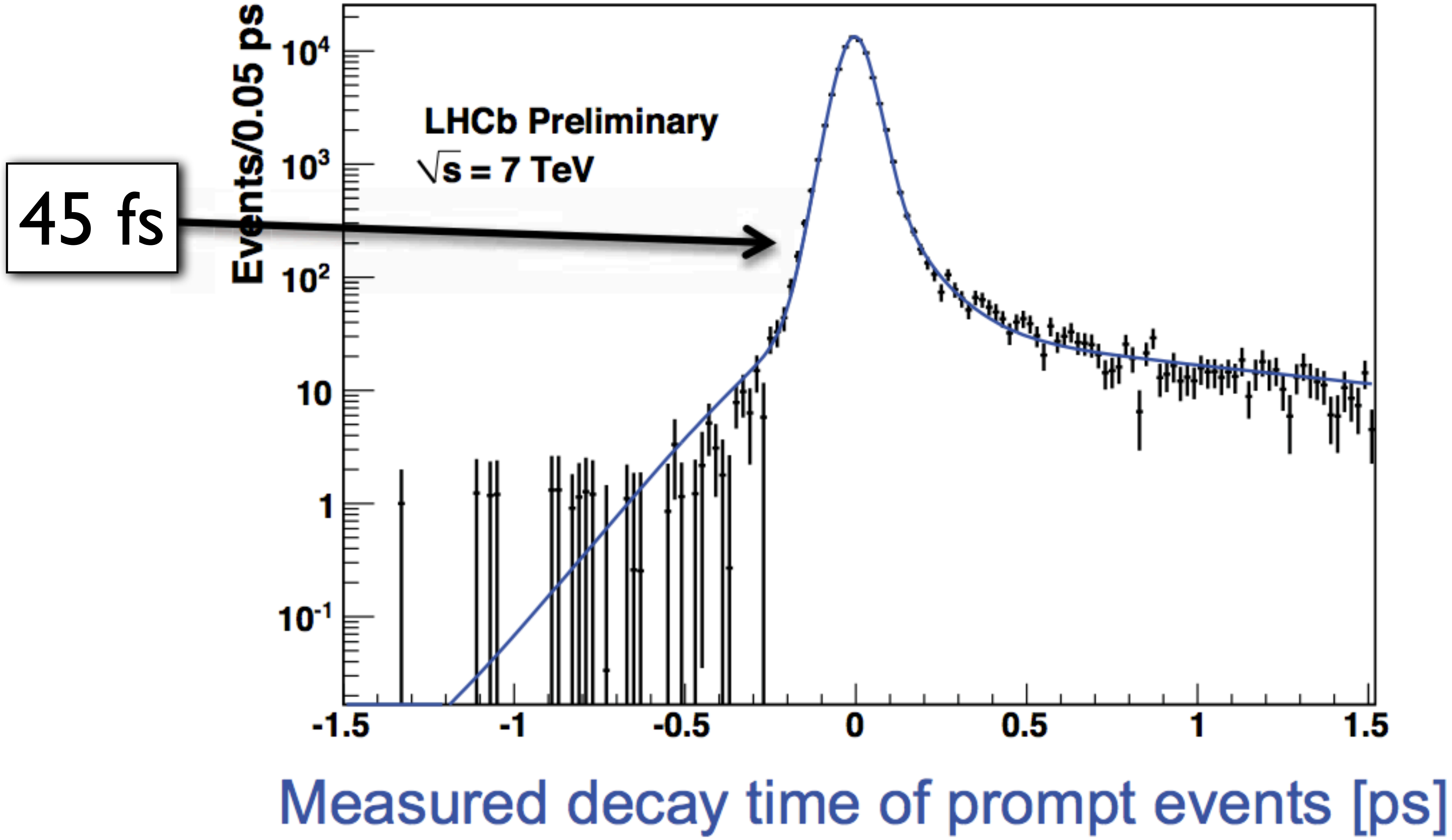


  - $\phi_s = 0.04$

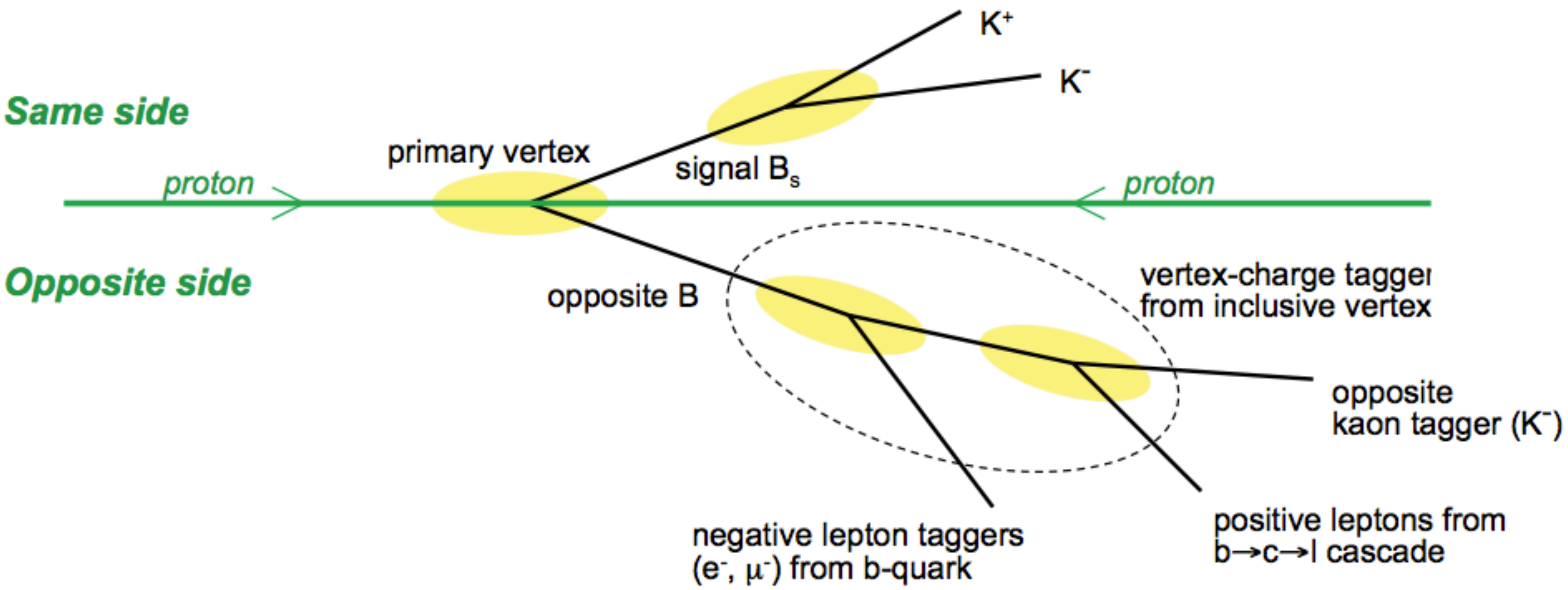


Again, the vertex detector plays a vital role

- Need to have a good proper time resolution with respect to the meson oscillation period, ~350 fs



And importantly, need to tag the flavour at production



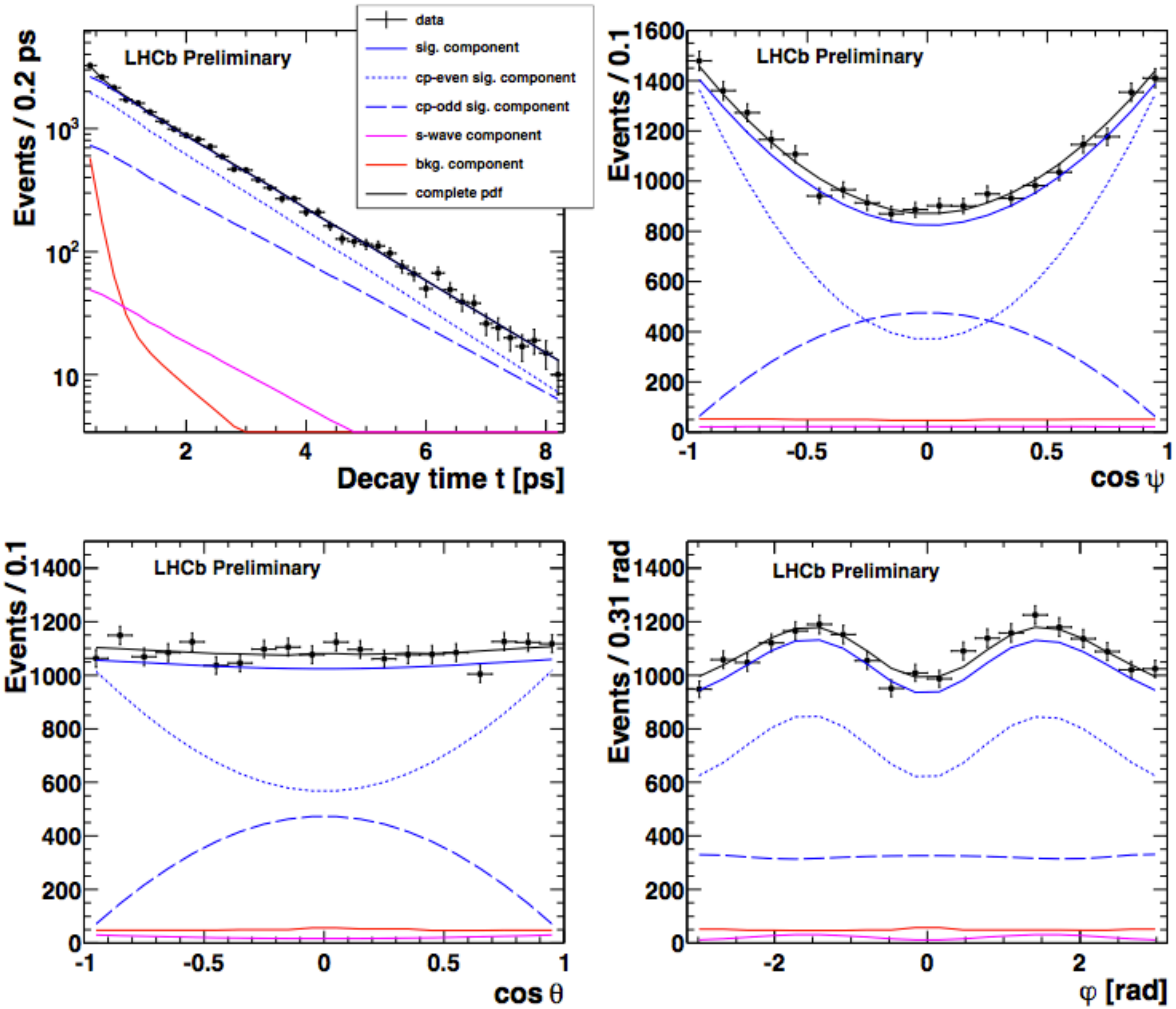
tagging efficiency ε_{tag} ~ 33%

effective mistag ω_{tag} ~ 36.8%

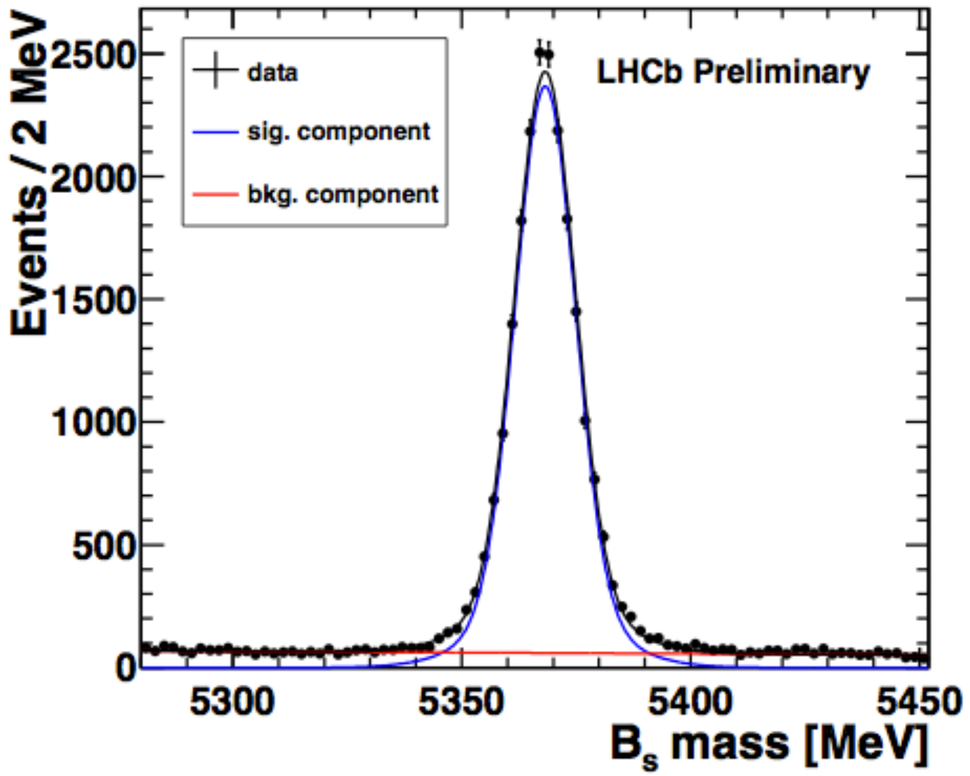
effective tagging power $\varepsilon_{tag}(1 - 2\omega_{tag})^2$ ~ 2.3%

NB: tagging is much less precise, i.e. more diluted at LHCb than the B factories

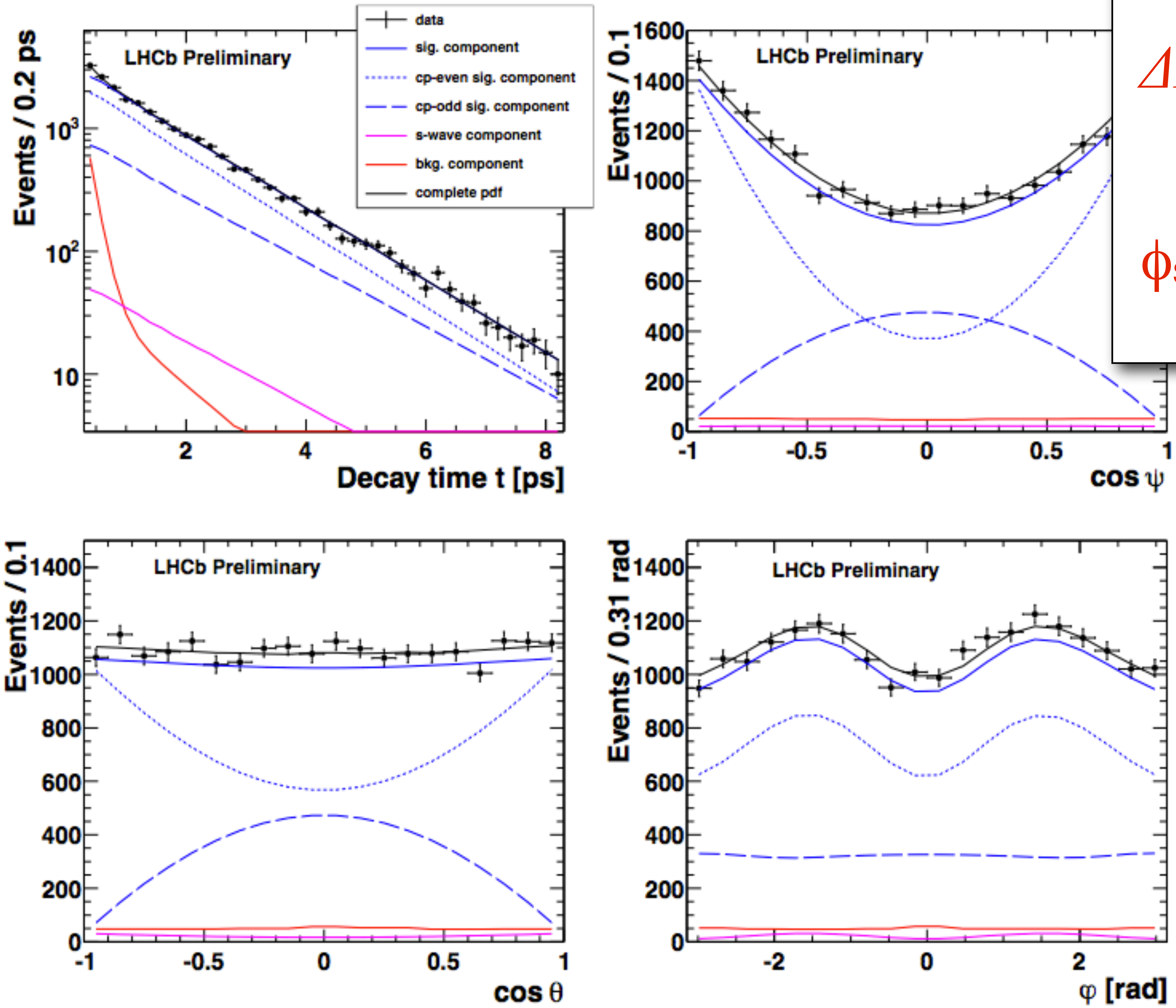
Fit to data in four variables



- As the full CP information is extracted, the lifetimes of the Heavy and Light mass eigenstates are fit for separately, i.e. $\Delta\Gamma_s$



Fit to data in four variables

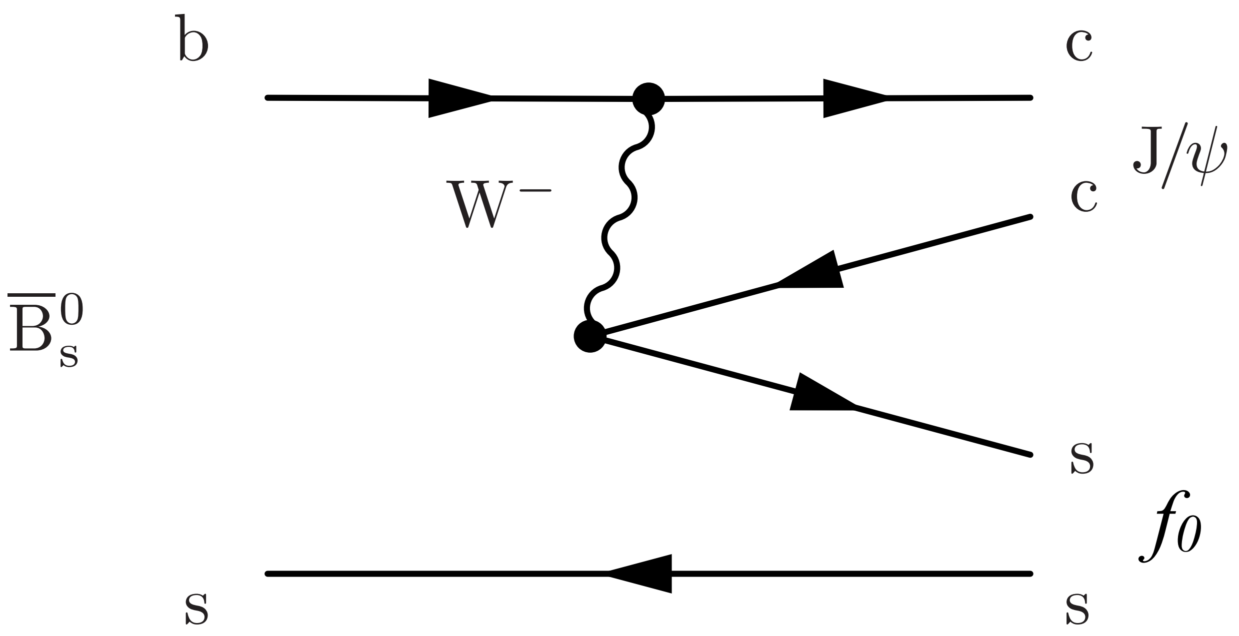


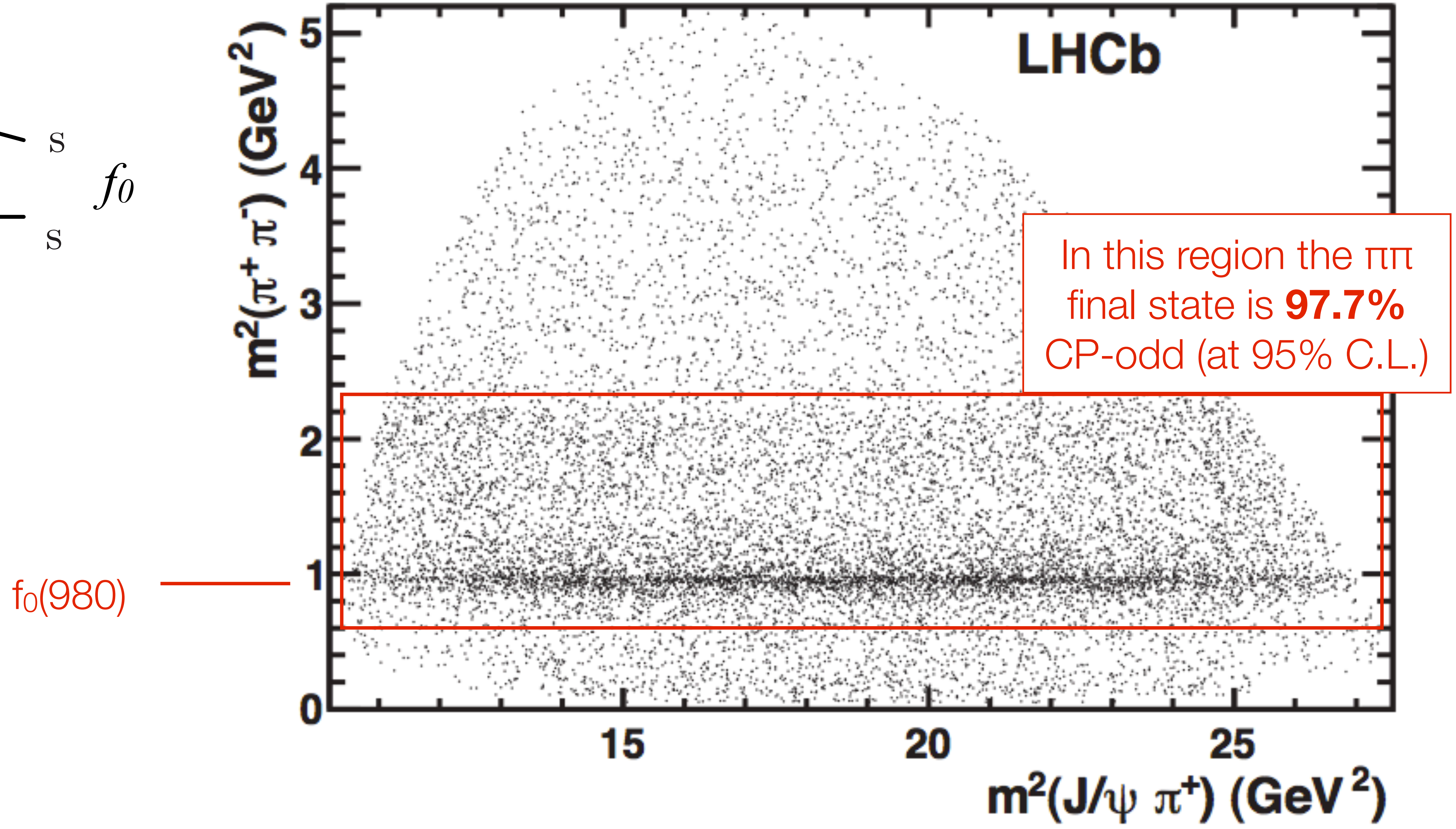
$\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006\ \text{ps}^{-1}$

$\phi_s = -0.001 \pm 0.101 \pm 0.027\ \text{rad.}$

ϕ_s from $B_s \to J/\psi\ \pi^+\pi^-$

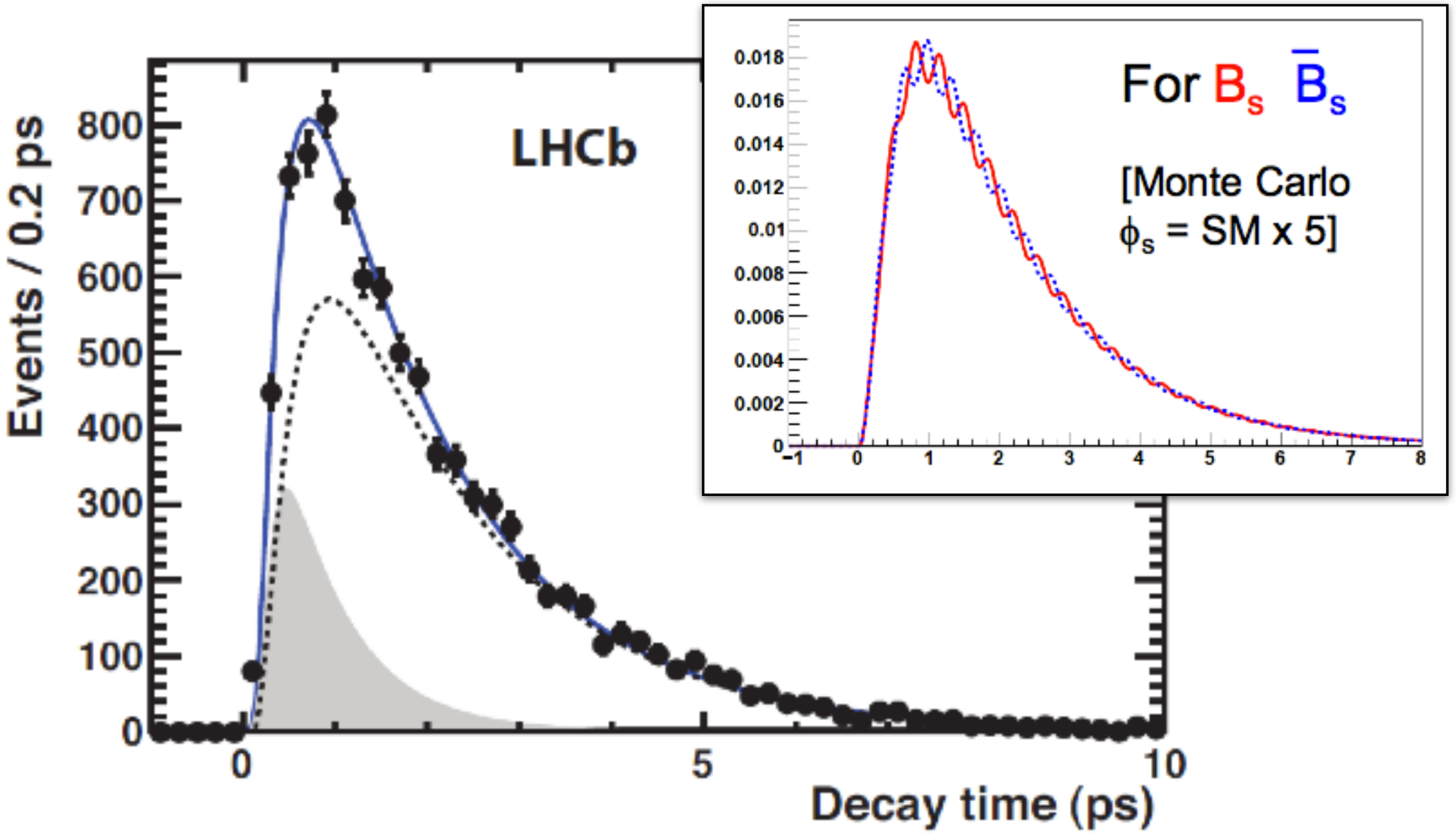
If just one CP eigenstate is present, the analysis is simpler

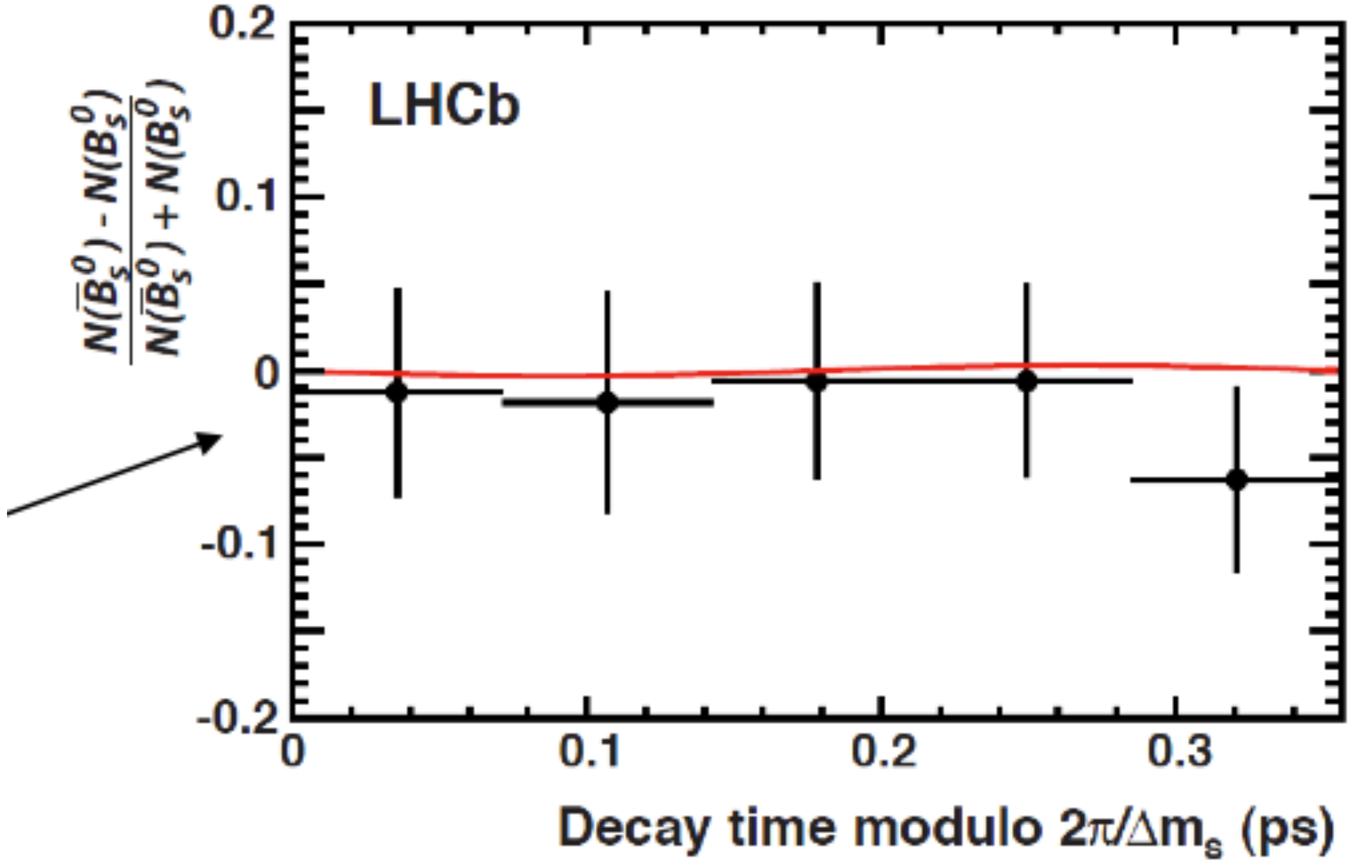




If just one CP eigenstate is present, the analysis is simpler

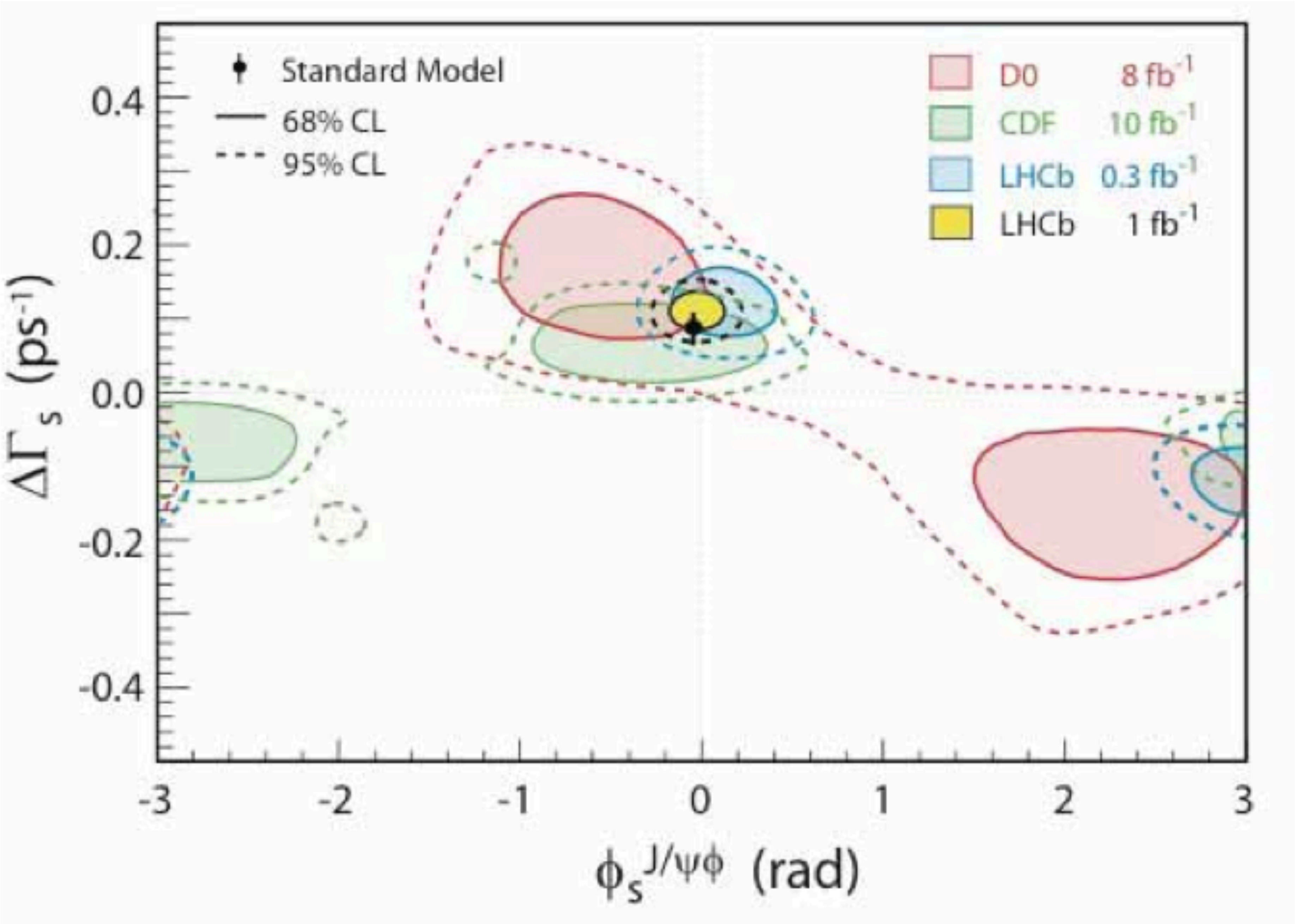
$$\Gamma\left(\overset{(-)}{B}{}^0_s \to f_-\right) = \frac{\mathcal{N}}{2} e^{-\Gamma_s t}\left\{ e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) \pm \sin\phi_s \sin(\Delta m_s t)\right\}$$





$B_s \to J/\psi\, \pi^+\pi^-$ result: $\phi_s = -0.02 \pm 0.17 \pm 0.02$ rad

Pictorial world summary and final LHCb result

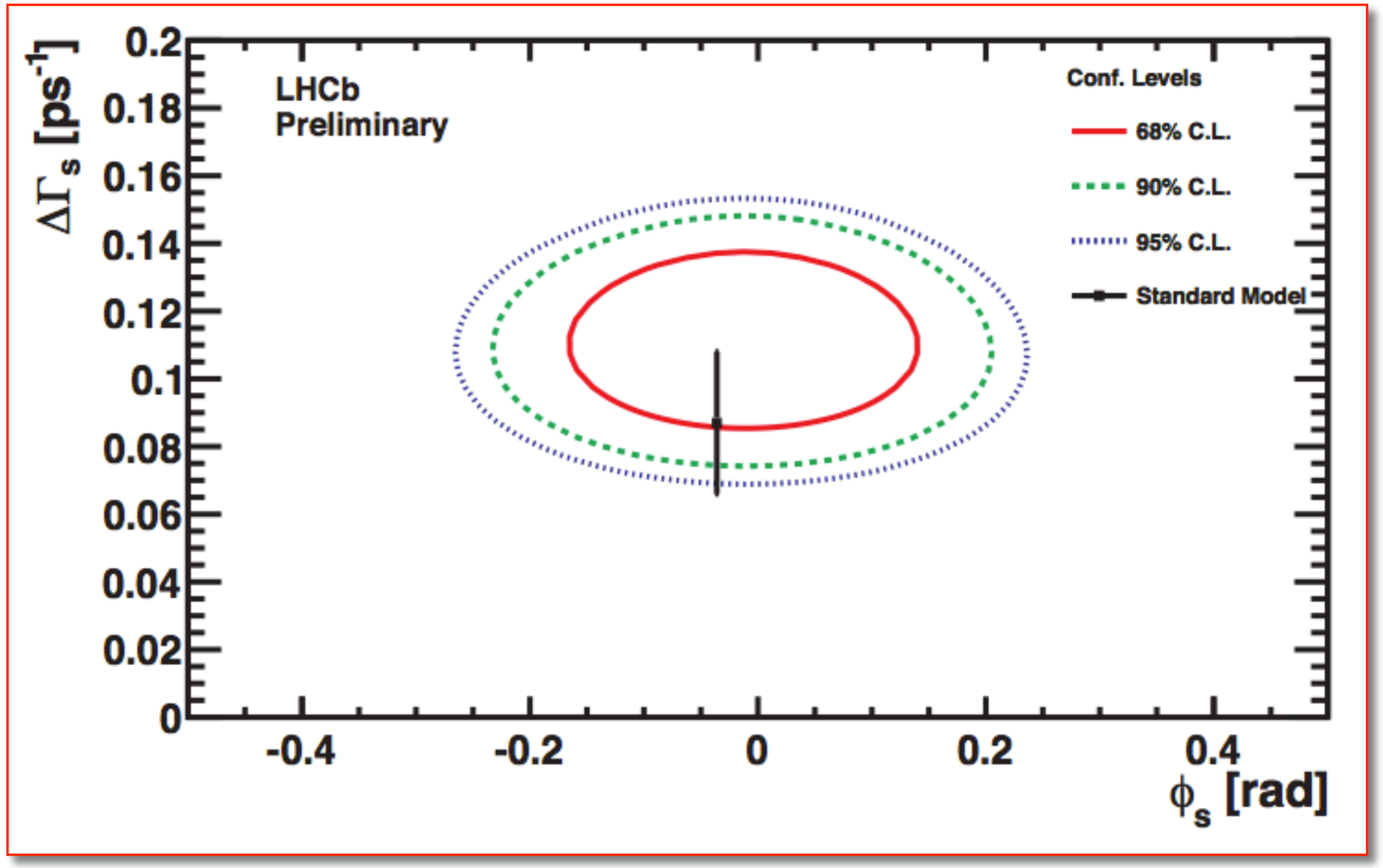


$\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006\ \mathrm{ps}^{-1}$

$J/\psi\varphi$ only
(SM: $0.087 \pm 0.021\ \mathrm{ps}^{-1}$)

$\phi_s = -0.002 \pm 0.083 \pm 0.027$ rad.

$J/\psi\ \pi+\pi-$ and $J/\psi\varphi$
(SM: -0.036 ± 0.002 rad.)



ΔA_{CP}

CP violation in charm is suppressed in the SM

$$V_{CKM} = \begin{matrix} & d & s & b \\ u & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ c & -\lambda+\frac{1}{2}A^2\lambda^5(1-2(\rho+i\eta)) & 1-\frac{1}{2}\lambda^2-\frac{1}{8}(1+4A^2)\lambda^4 & A\lambda^2 \\ t & A\lambda^3(1-(1-\frac{1}{2}\lambda^2)(\rho-i\eta)) & -A\lambda^2+\frac{1}{2}A\lambda^4(1-2(\rho-i\eta)) & 1-\frac{1}{2}A^2\lambda^4 \end{matrix} + \mathcal{O}(\lambda^7)$$

Wolfenstein expansion in powers of the Cabibbo angle, λ, up to λ^6

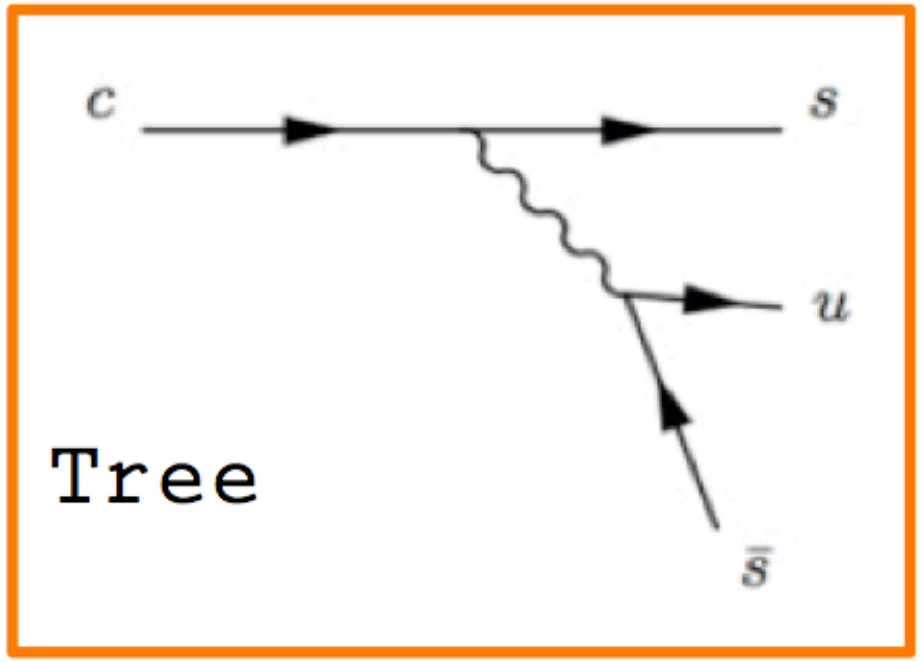
$$0 = V_{us}^* V_{cs} + V_{ub}^* V_{cb} + V_{ud}^* V_{cd}$$

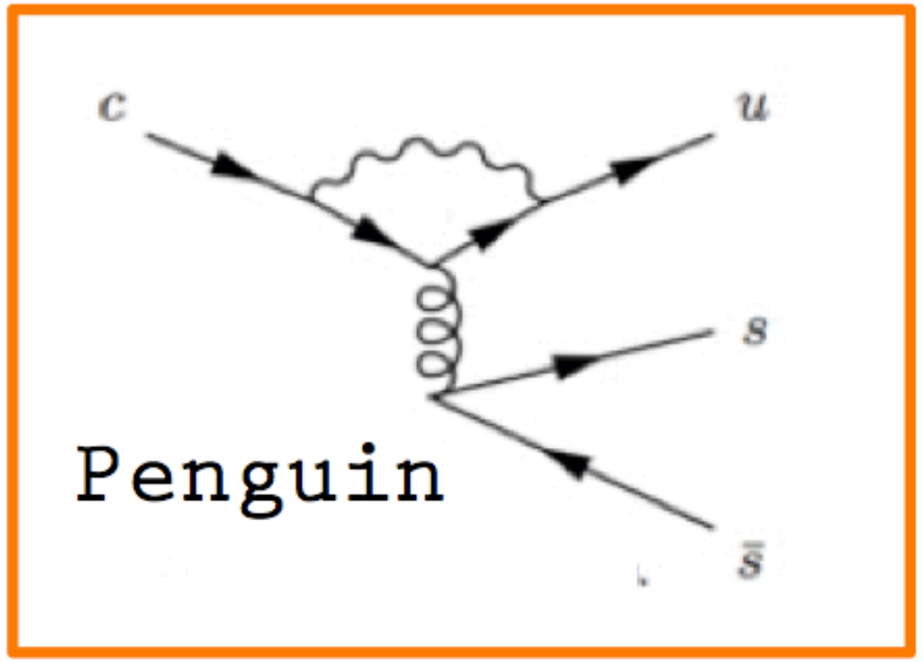
$\propto\lambda$ $\propto\lambda^5$ $\propto\lambda$

if the b contribution can be neglected then only two generations contribute, i.e. approximates to a real Cabibbo matrix, and no CP violating phases

Where to look for CP violation in charm

- A good bet is singly Cabibbo suppressed decays
- Interference between tree and penguin may generate *CP* asymmetries





- And look for it at LHCb where huge D-meson samples are appearing

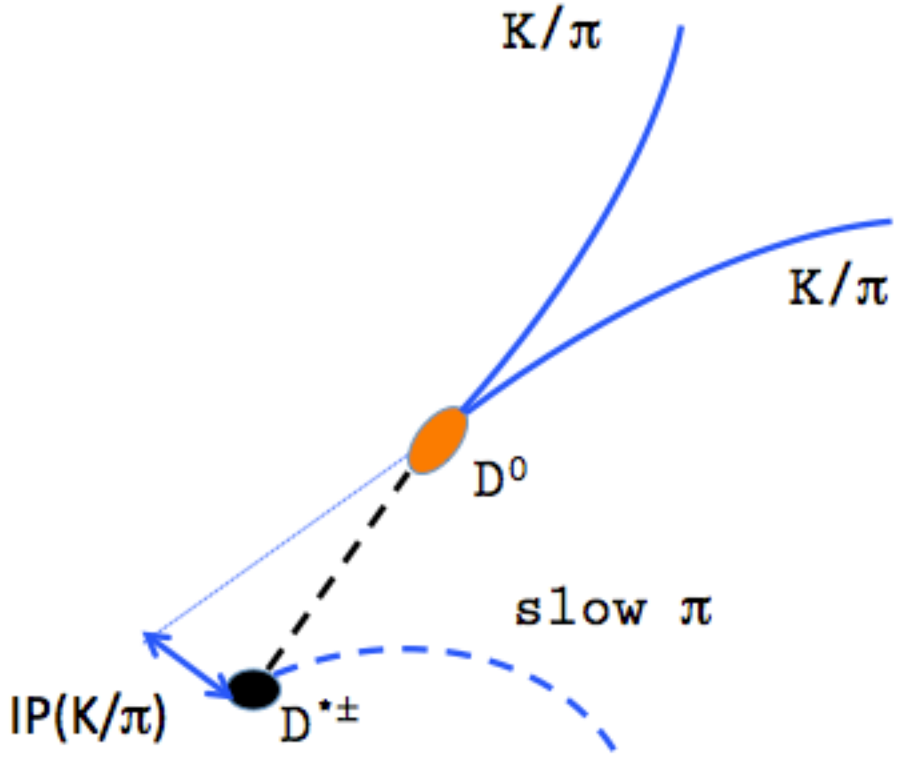
$$\sigma_{b\bar{b}}(pp \rightarrow bbX) = (284 \pm 20 \pm 49)\,\mu b$$
$$\sigma_{c\bar{c}}(pp \rightarrow ccX) = (6.10 \pm 0.93)\,mb$$

Time-integrated CP asymmetry

- We would like to measure (for *f=CP* eigenstate, *KK* or *ππ*):

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

- What we can measure is:



$$A_{raw}(f) = \frac{N(D^{*+} \to D^0(f)\pi_s^+) - N(D^{*-} \to \overline{D}^0(\overline{f})\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) + N(D^{*-} \to \overline{D}^0(\overline{f})\pi_s^-)}$$

The "slow" pion from the D tags the flavour of the $D^0/\overline{D}^0$*

Detector effects are present in the raw asymmetry

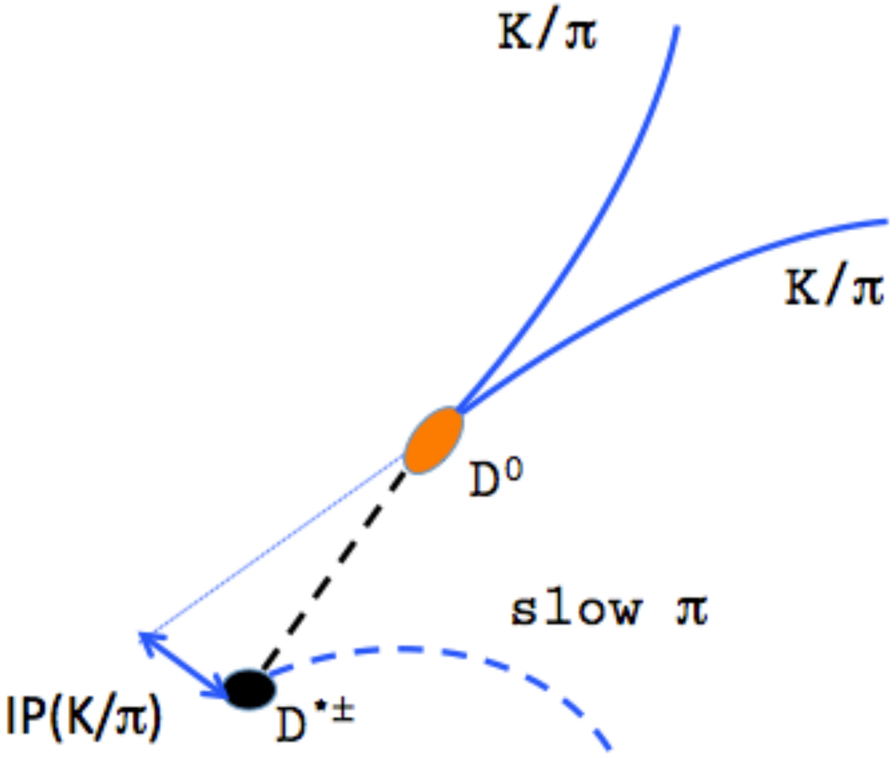
$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

Physics CP asymmetry

Detection asymmetry of D^0

Detection asymmetry of "slow" pions

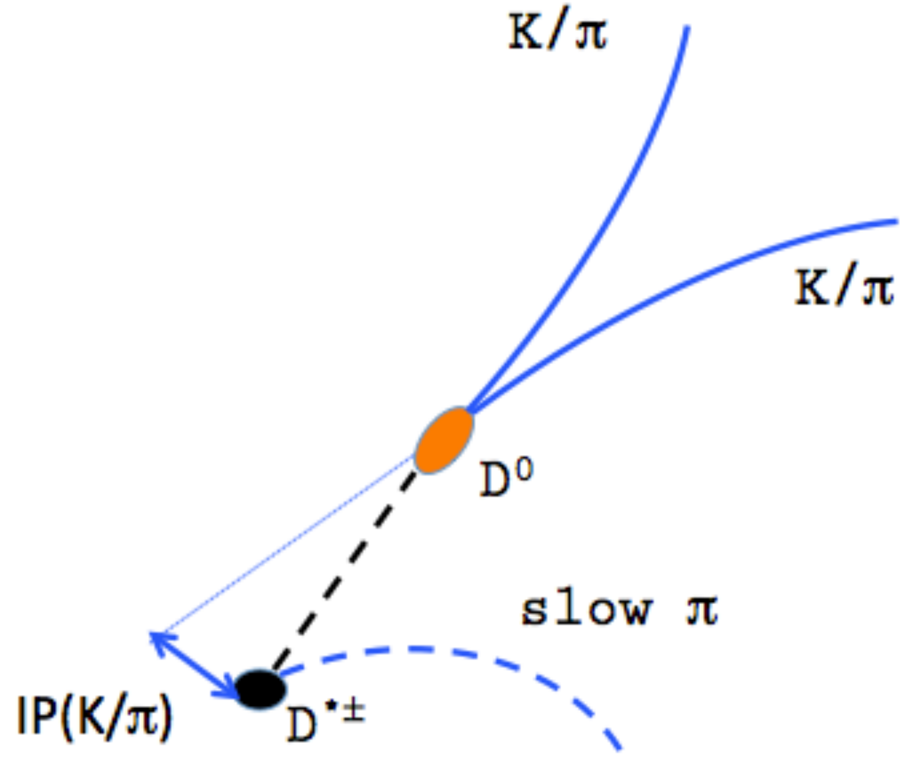
Production asymmetry

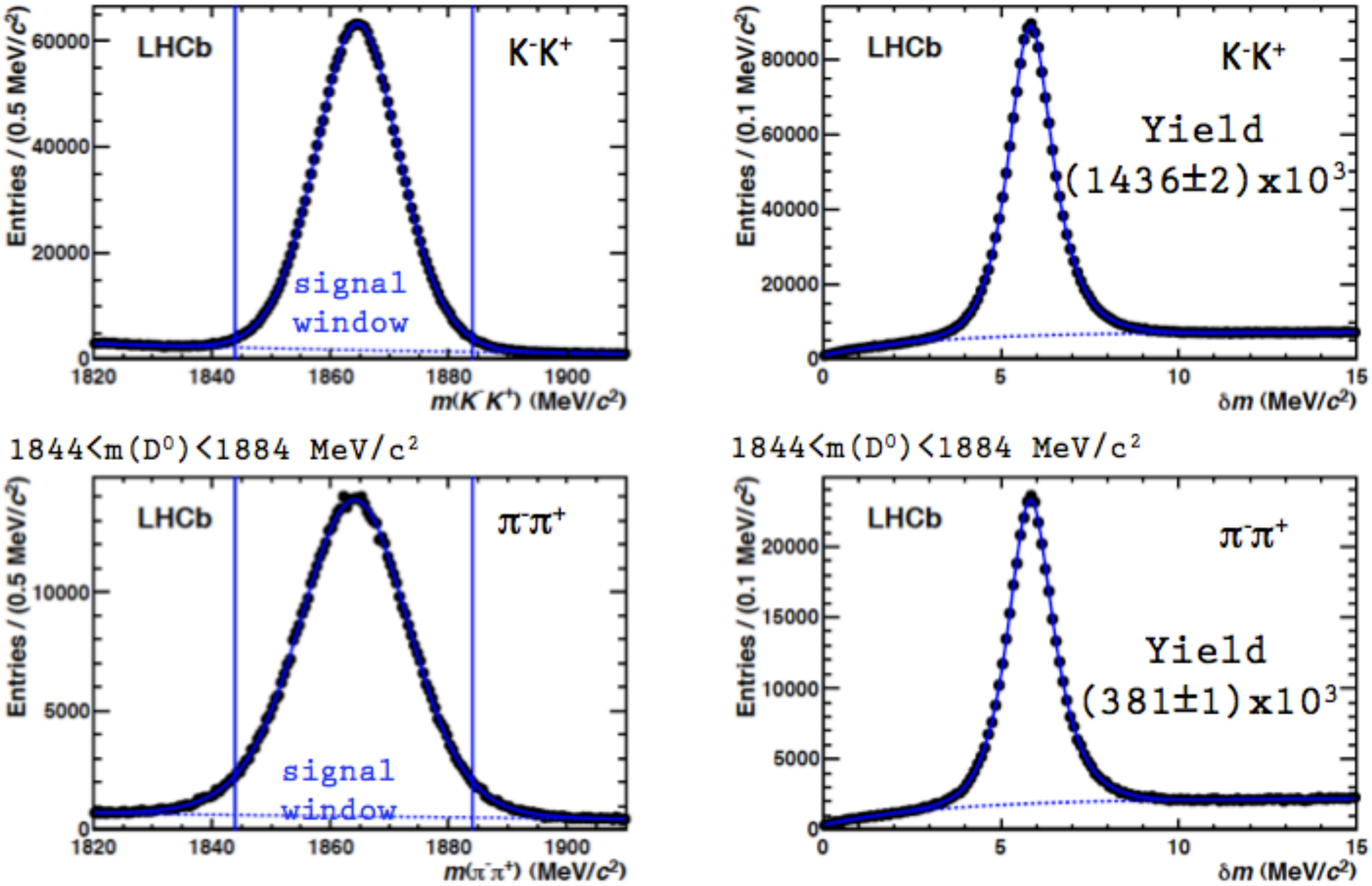


- But everything cancels, in principle, in the double difference

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

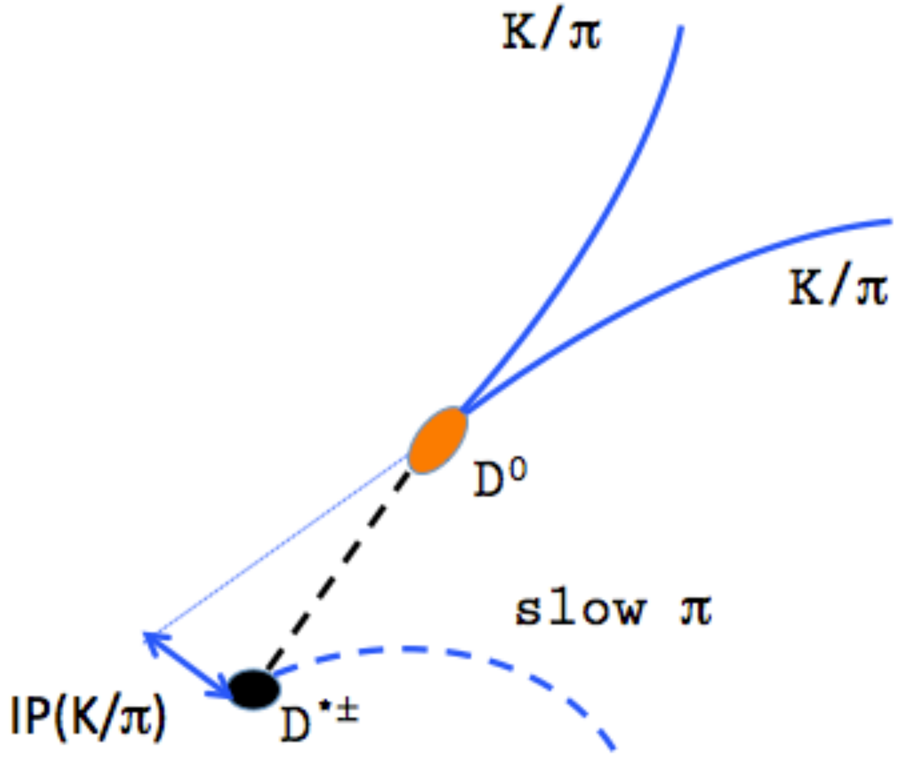
Mass fits to the total, selected dataset





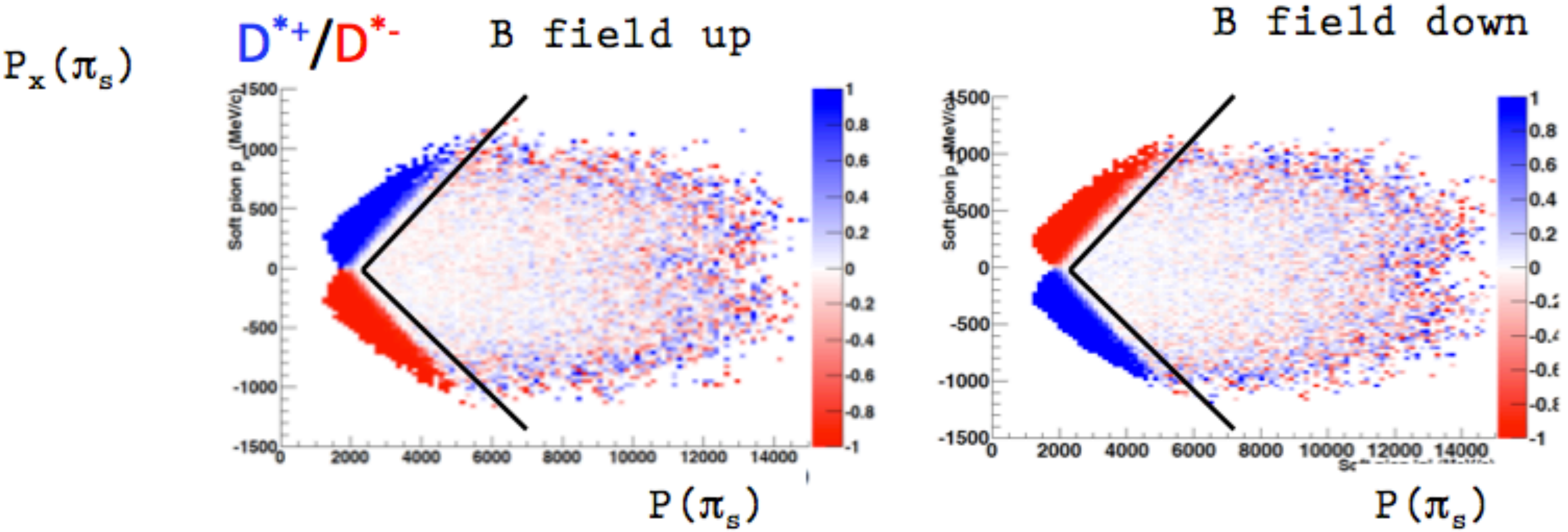
Robustness against systematic effects

- The cancellation of the instrumentation asymmetries is unfortunately not exact. Second-order dependences on the KK/ππ efficiency ratio could reintroduce small asymmetries



- Solution: separate the dataset into several kinematic bins (p_T and pseudorapidity of the D*, and momentum of the slow pion)
- Similarly, analyse the dipole-up/down data separately, and the left and right hemisphere of LHCb separately.
- In total 216 statistically independent measurements of ΔA_{CP}

Also minimise headaches by applying judicious fiducial cuts

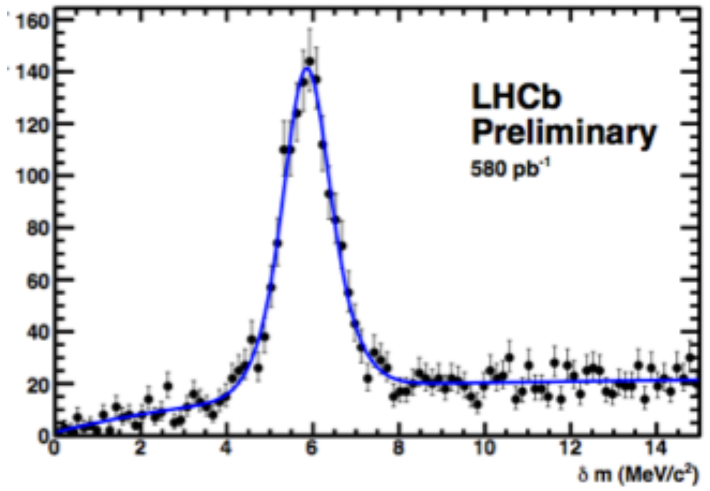


Exclude regions of phase space where only one charge of the slow pion are seen.
i.e. Don't rely on the UP and DOWN magnet samples to exactly cancel!

Final measurement fit

- Cut on D^0 mass and fit the D^*-D^0 mass difference only in 216 bins

One example bin:



$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$

Largest systematics from:
Alternative fit procedure (0.08%)
Multiple candidate choice (0.06%)
Hypothetical peaking bkgd (0.04%)

Consistency: $\chi^2/NDF = 211/215$, prob = 56%

Many, many cross-checks performed, some examples

- Tighter PID cuts using the RICH information

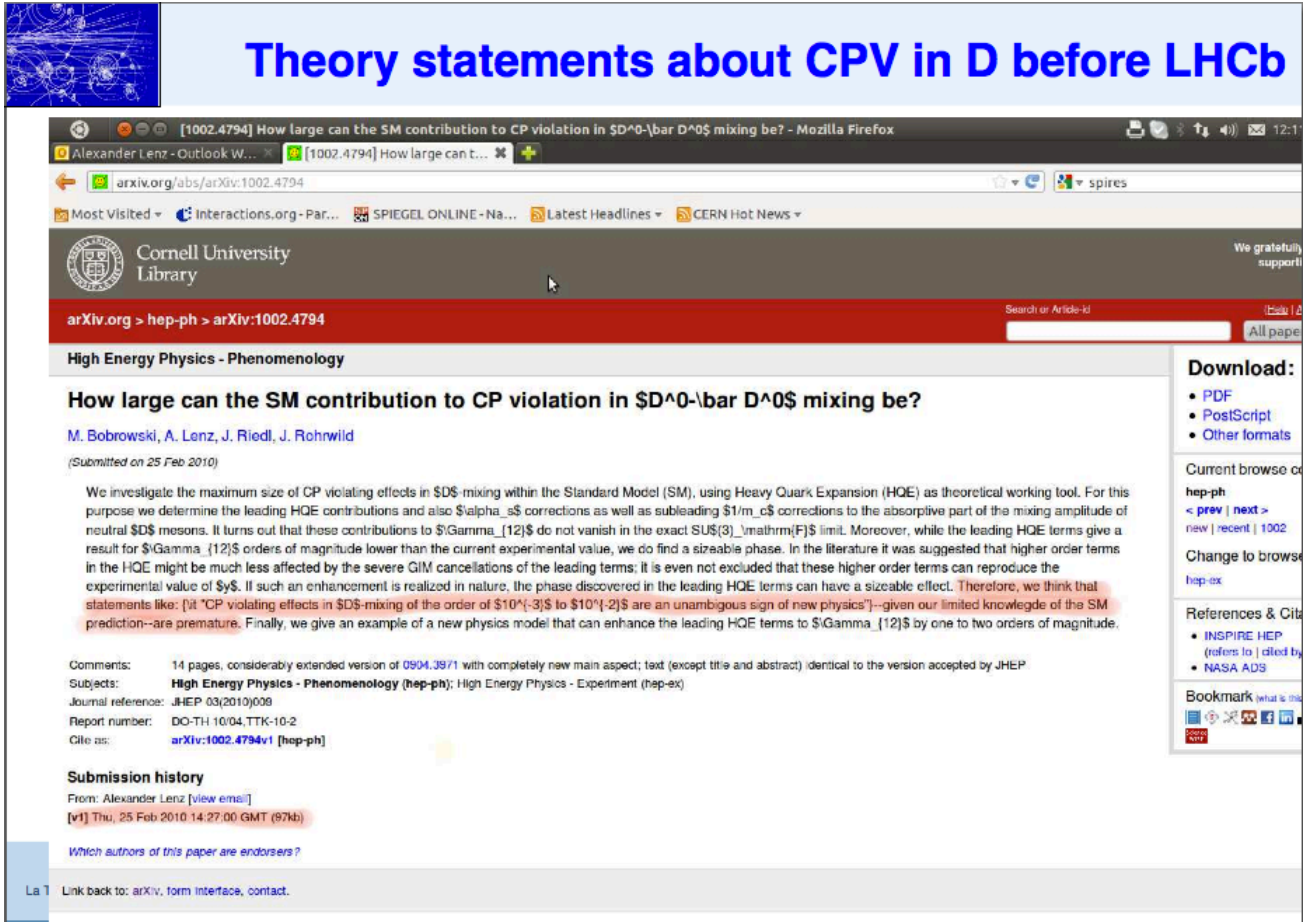
ΔA_{CP} = (-0.88 ± 0.26)% *tight....* ΔA_{CP} = (-1.03 ± 0.31)% *tighter....*

- Examine different times, polarity and hemisphere of the detector

Subsample	ΔA_{CP}	χ^2/ndf
Pre-TS, field up, left	$(-1.22 \pm 0.59)\%$	13/26(98%)
Pre-TS, field up, right	$(-1.43 \pm 0.59)\%$	27/26(39%)
Pre-TS, field down, left	$(-0.59 \pm 0.52)\%$	19/26(84%)
Pre-TS, field down, right	$(-0.51 \pm 0.52)\%$	29/26(30%)
Post-TS, field up, left	$(-0.79 \pm 0.90)\%$	26/26(44%)
Post-TS, field up, right	$(+0.42 \pm 0.93)\%$	21/26(77%)
Post-TS, field down, left	$(-0.24 \pm 0.56)\%$	34/26(15%)
Post-TS, field down, right	$(-1.59 \pm 0.57)\%$	35/26(12%)
All data	$(-0.82 \pm 0.21)\%$	211/215(56%)

Consistency:
χ^2/NDF = 6.7/7
prob = 45%

Initial euphoria has given way; the SM is probably not under threat



Theory statements about CPV in D before LHCb

[1002.4794] How large can the SM contribution to CP violation in $D^0-\bar D^0$ mixing be? - Mozilla Firefox

arxiv.org/abs/arXiv:1002.4794

Cornell University Library

arXiv.org > hep-ph > arXiv:1002.4794

High Energy Physics - Phenomenology

How large can the SM contribution to CP violation in $D^0-\bar D^0$ mixing be?

M. Bobrowski, A. Lenz, J. Riedl, J. Rohrwild

(Submitted on 25 Feb 2010)

We investigate the maximum size of CP violating effects in D-mixing within the Standard Model (SM), using Heavy Quark Expansion (HQE) as theoretical working tool. For this purpose we determine the leading HQE contributions and also α_s corrections as well as subleading $1/m_c$ corrections to the absorptive part of the mixing amplitude of neutral D mesons. It turns out that these contributions to Γ_{12} do not vanish in the exact $SU(3)_\mathrm{F}$ limit. Moreover, while the leading HQE terms give a result for Γ_{12} orders of magnitude lower than the current experimental value, we do find a sizeable phase. In the literature it was suggested that higher order terms in the HQE might be much less affected by the severe GIM cancellations of the leading terms; it is even not excluded that these higher order terms can reproduce the experimental value of y. If such an enhancement is realized in nature, the phase discovered in the leading HQE terms can have a sizeable effect. Therefore, we think that statements like: {\it "CP violating effects in D-mixing of the order of 10^{-3} to 10^{-2} are an unambigous sign of new physics"}--given our limited knowlegde of the SM prediction--are premature. Finally, we give an example of a new physics model that can enhance the leading HQE terms to Γ_{12} by one to two orders of magnitude.

Comments: 14 pages, considerably extended version of 0904.3971 with completely new main aspect; text (except title and abstract) identical to the version accepted by JHEP
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex)
Journal reference: JHEP 03(2010)009
Report number: DO-TH 10/04,TTK-10-2
Cite as: arXiv:1002.4794v1 [hep-ph]

Submission history

From: Alexander Lenz [view email]
[v1] Thu, 25 Feb 2010 14:27:00 GMT (97kb)

Which authors of this paper are endorsers?

Link back to: arXiv, form interface, contact.

Download:
- PDF
- PostScript
- Other formats

Alexander Lenz, Moriond 2012

Nevertheless, LHCb will continue to explore CPV in charm

- Considerable efforts to make the LHCb trigger more favourable to charm in 2012 will mean a quadrupling of the dataset, not x2.5.
- Instead of using the slow pion, an analysis using the muon from semi-leptonic B decays is underway. i.e. ΔA_{CP} from $B \to D^0 \mu^{\pm} \nu$
- Other singly Cabibbo suppressed decays under study, notably the Dalitz analysis of flavour-tagged $D^0 \to K_S \pi\pi$

Conclusion

Observation of direct *CP* violation in B^+ decays

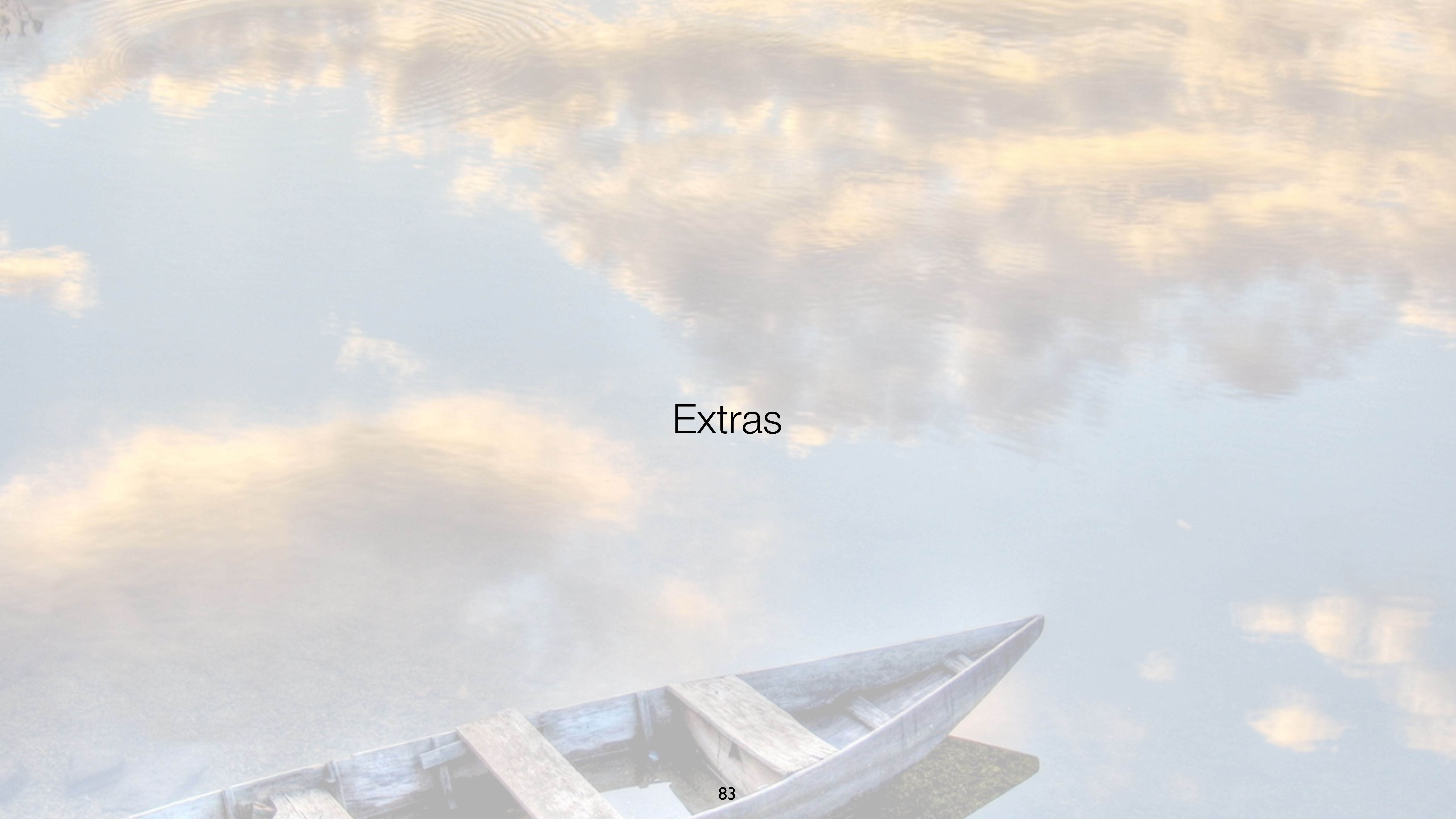
Important step toward a measurement of γ with ~10% precision in the next 12-15 months

Searches for time-dependent *CP*-violation in the mixing and decay of B_s mesons

Hints of unexpectedly large CP violation in the Bs system have been wiped away. Efforts continue, but quantifying the penguin contribution in both B^0 and B_s systems needs the LHCb upgrade

Evidence for direct *CP* violation in D^0 decays

Llook to confirm this result in the next 18 months

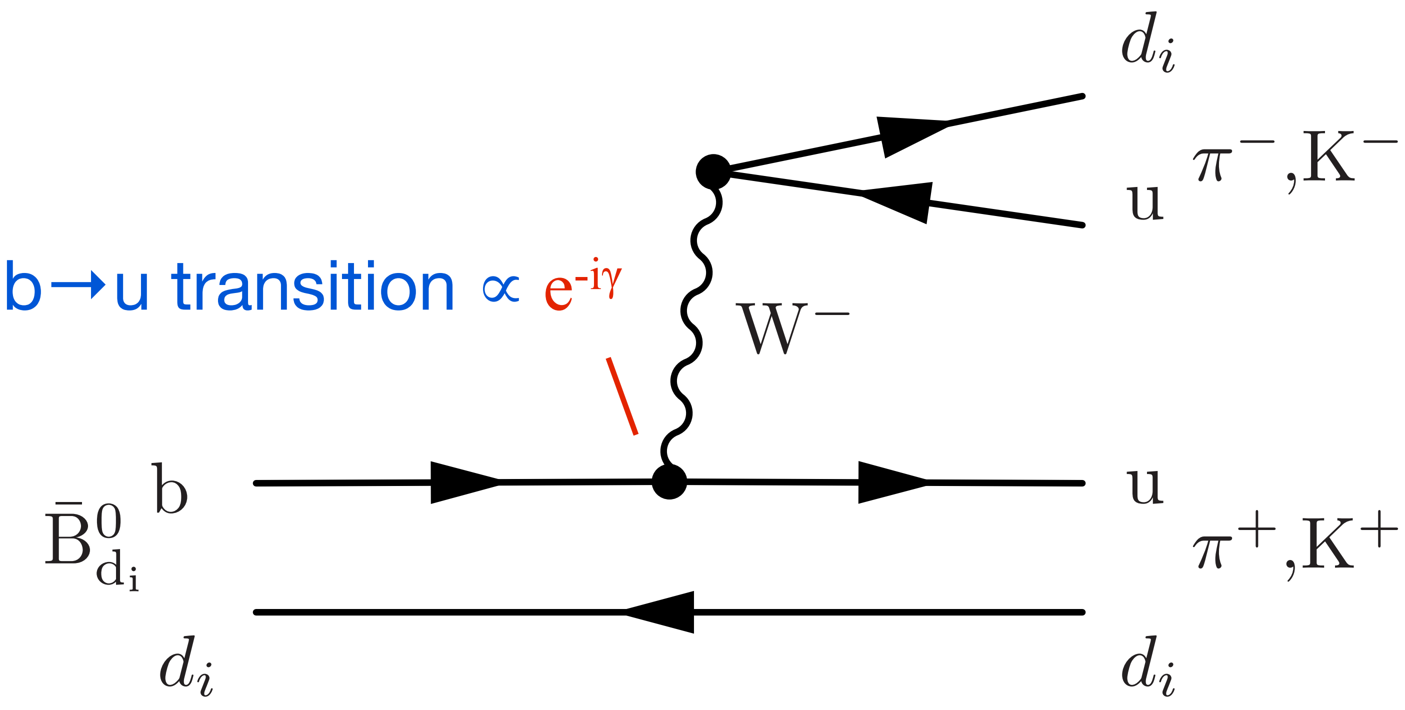


Extras

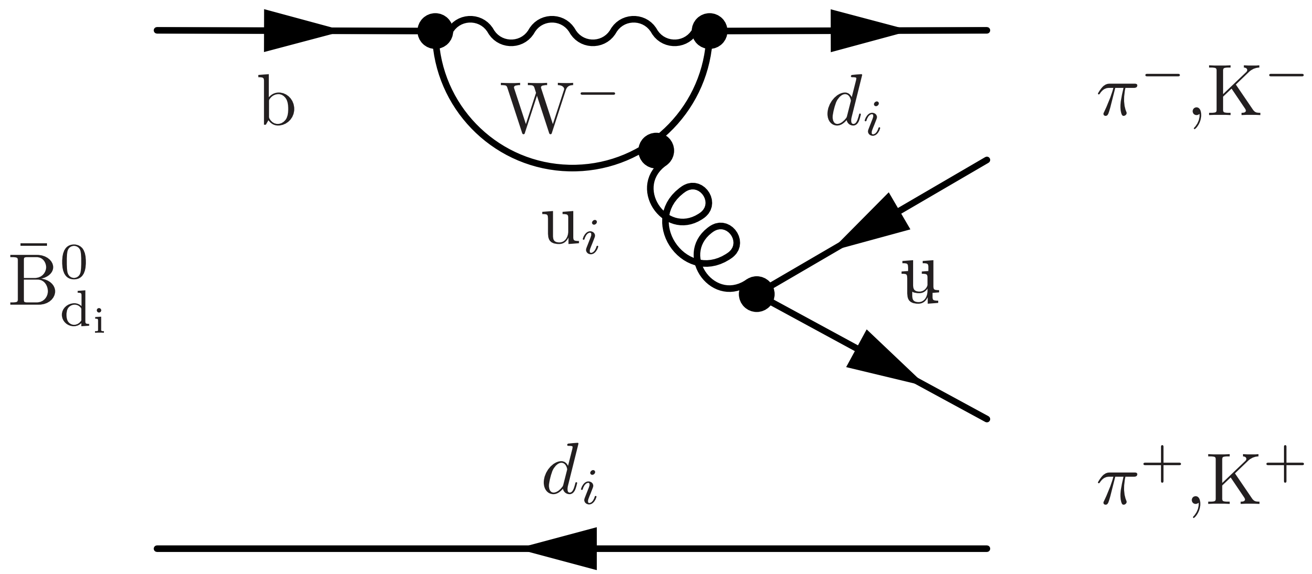
Uses of γ from trees: comparison with loop-mediated processes

- Charmless decays of B_d and B_s mesons can exhibit CP violation from tree-penguin interference

b→u transition ∝ $e^{-i\gamma}$



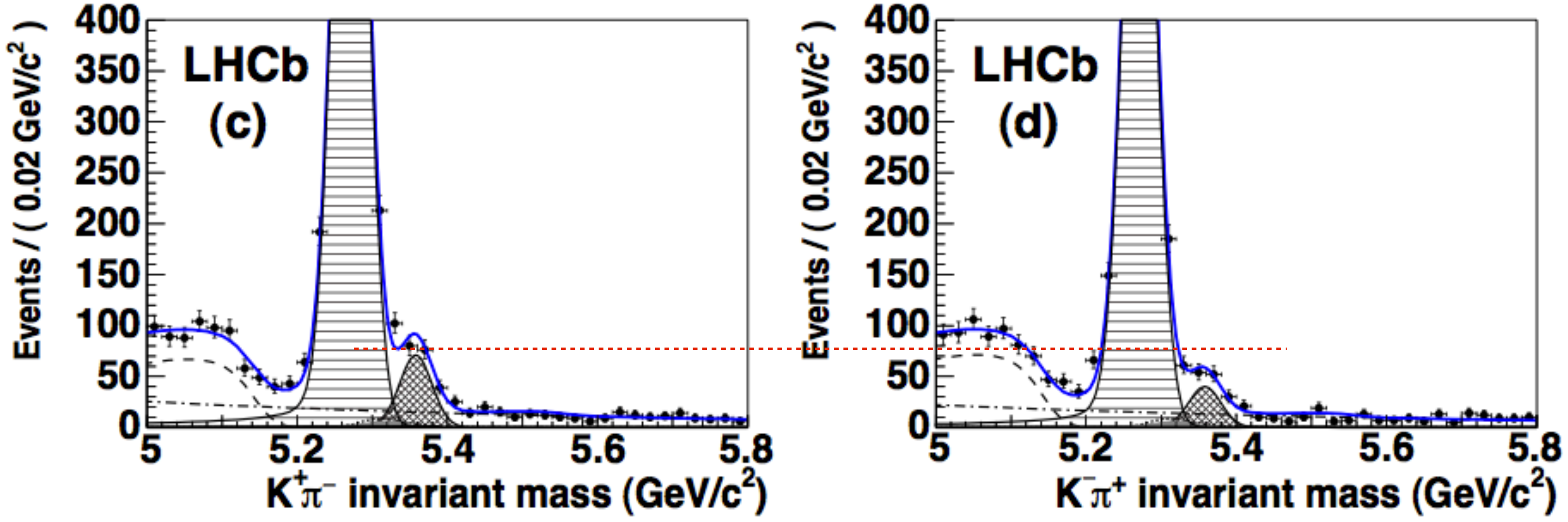
Penguin diagram could contribute a new phase



- Aside:

First evidence of direct *CP* violation in charmless two-body decays of B_s^0 mesons

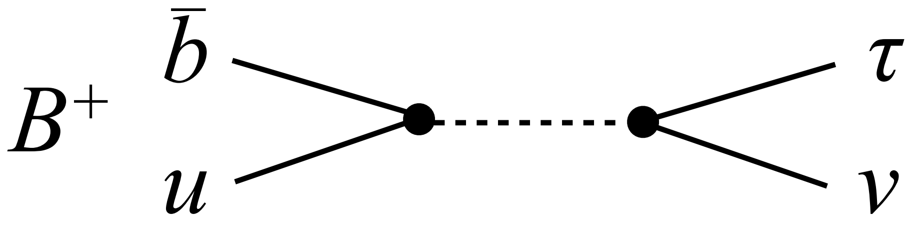
LHCb. arXiv:1202.6251

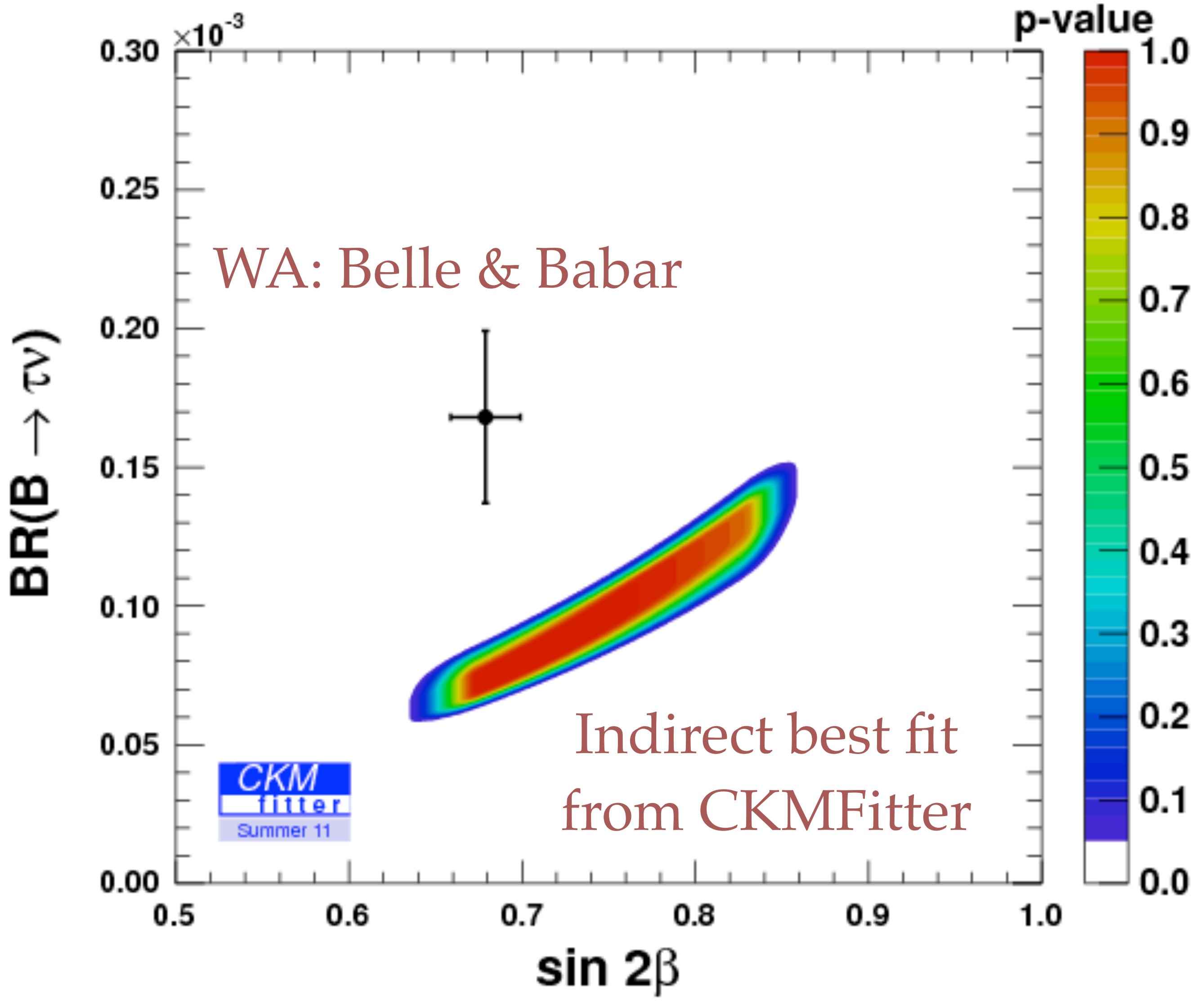


Uses of γ from trees: CKM triangle metrology

- $\sin 2\beta$ is the most precisely determined component of the unitarity triangle
  - the penguin contribution is usually neglected, but, this could be naive

- An example of tension in the unitarity triangle is with $|V_{ub}|$ from $B^+ \to \tau^+ \nu$ and $\sin 2\beta$
  - This is a simple tree decay (exchange diagram)
  - Small theoretical uncertainties.



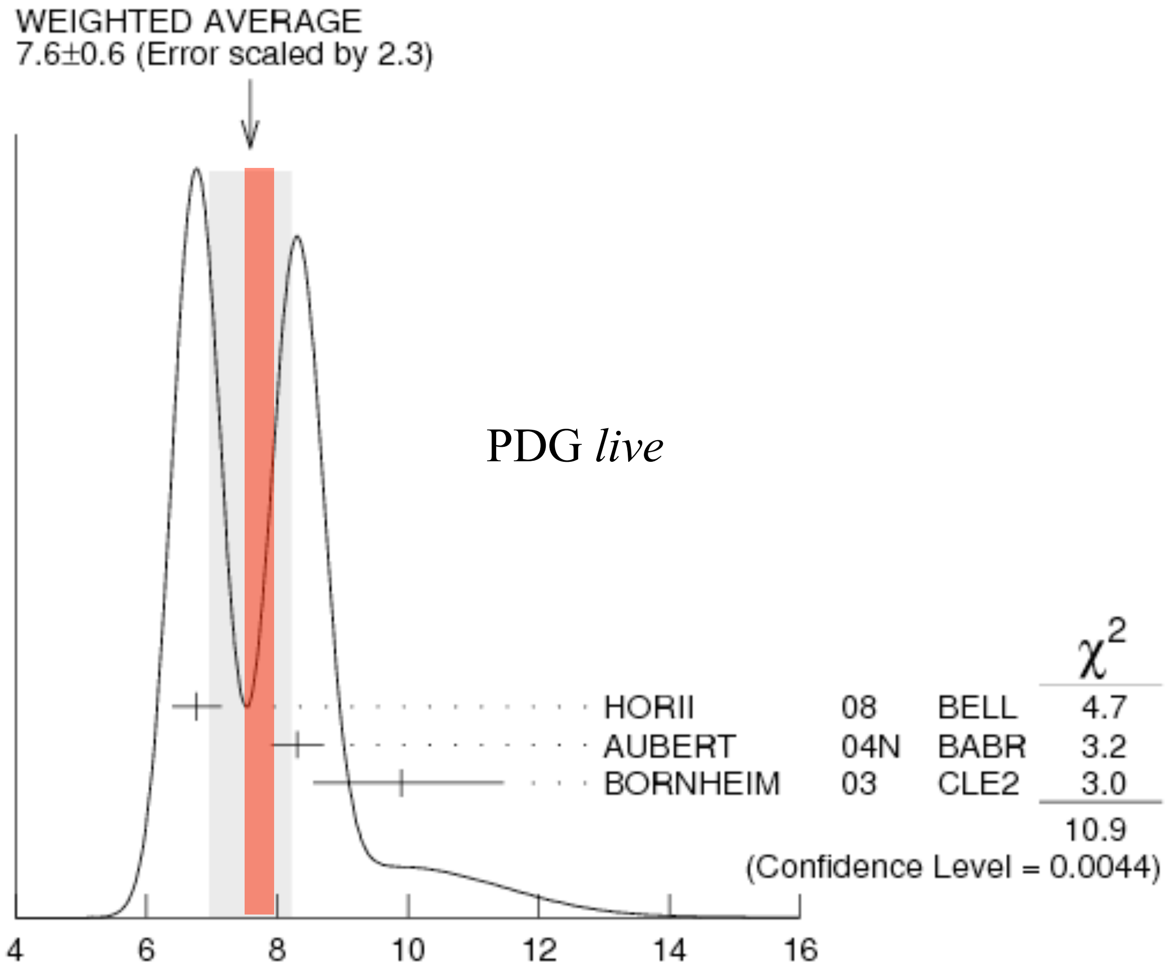


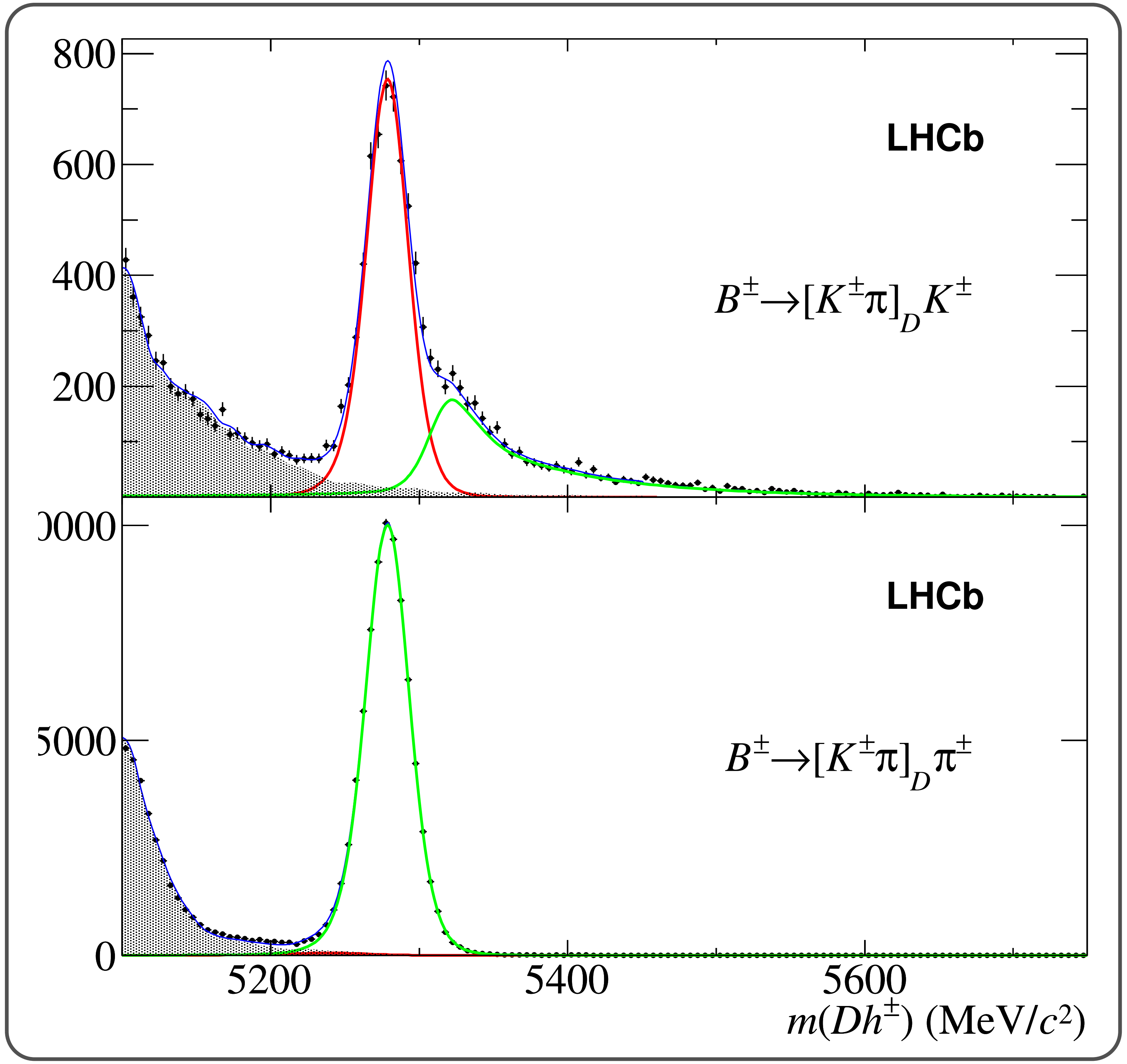
- As we seek to test the unitarity of the CKM model, it becomes increasingly important to distinguish tree measurements from those with sensitivity to loops.

First result: the ratio of $B^- \to D^0 h^-$ branching fractions

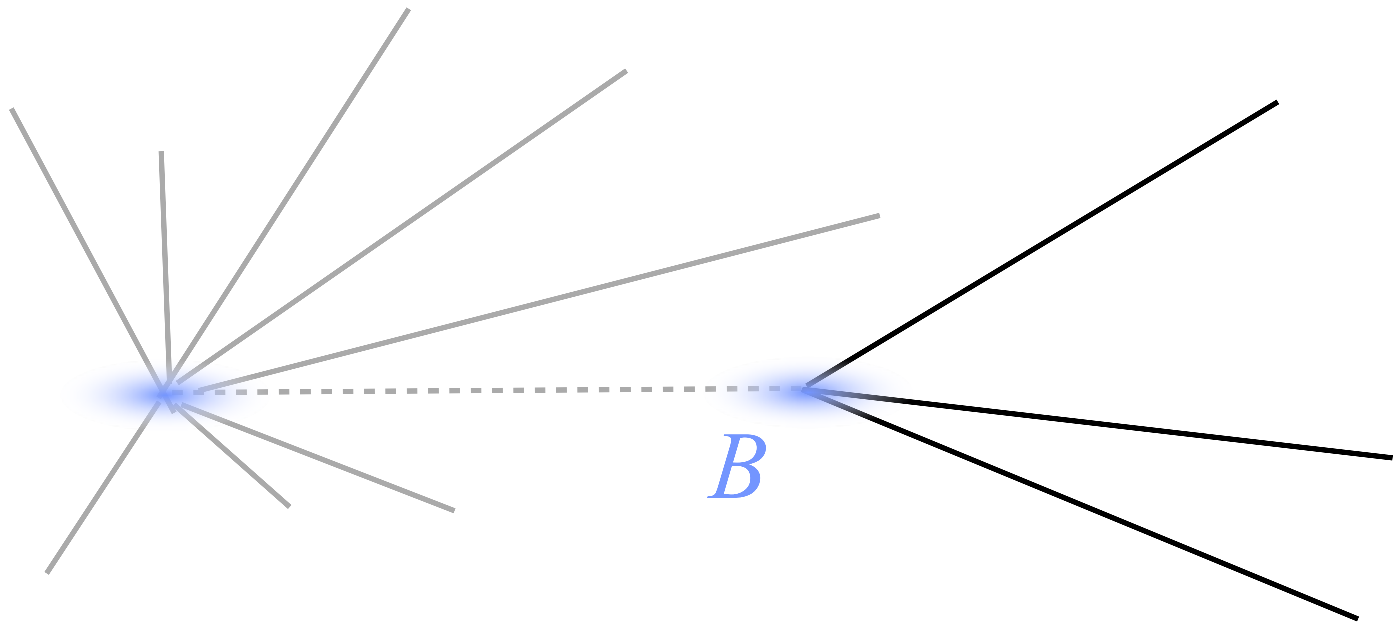
$$\frac{\Gamma(B^- \to D^0 K^-)}{\Gamma(B^- \to D^0 \pi^-)} = (7.74 \pm 0.12 \pm 0.19)\%$$

A factor 2 more precise than current world average



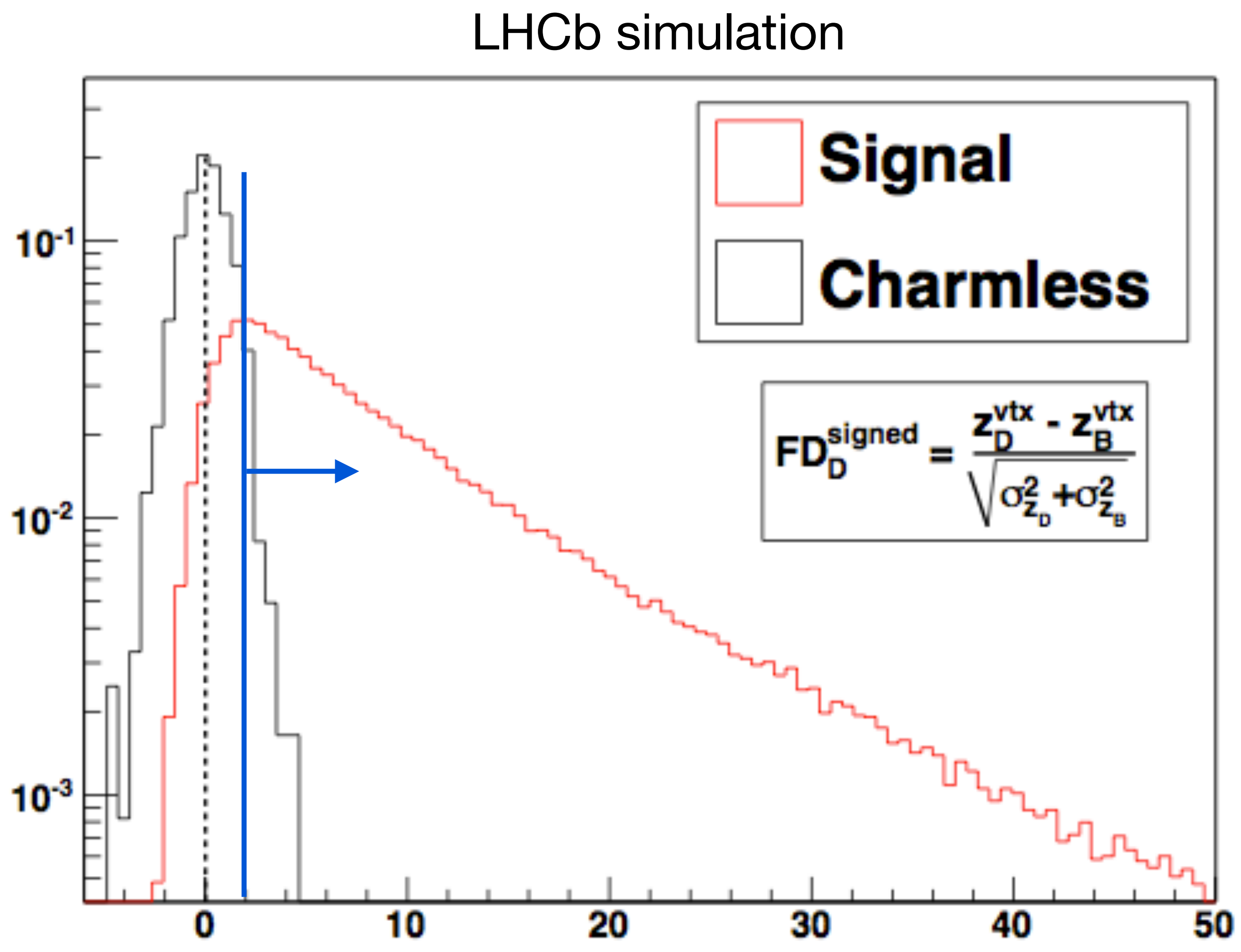


Non-true-*D* peaking backgrounds in the *CP* and ADS modes



e.g. $B^{\pm}\to[\pi\pi]K^{\pm}$ suffers from:

$B^{\pm}\to K\pi\pi^{\pm}$	Charmless
$B^{\pm}\to[K\pi]\pi^{\pm}$	Cross feed
$B^{\pm}\to[\pi\pi\pi^{0}]\pi^{\pm}$	Part. reco. cross feed



- Thanks to the large boost at LHCb non-true-*D* backgrounds can be easily removed.
- The above cut is ~85% efficient and removes 97% of zero-lifetime backgrounds

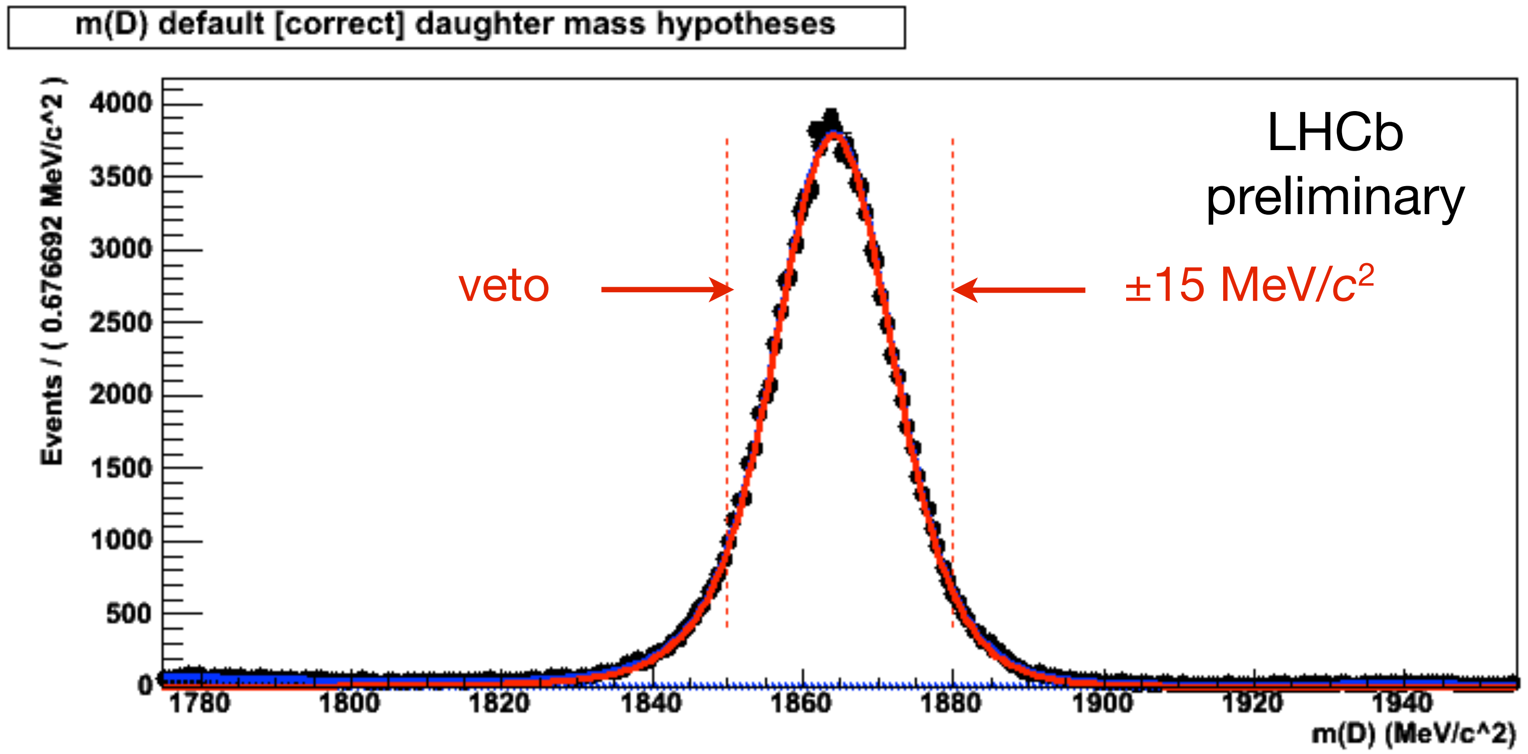
Favoured mode→ADS mode cross feed

$B^{\pm}\to[K\pi]h^{\pm}$

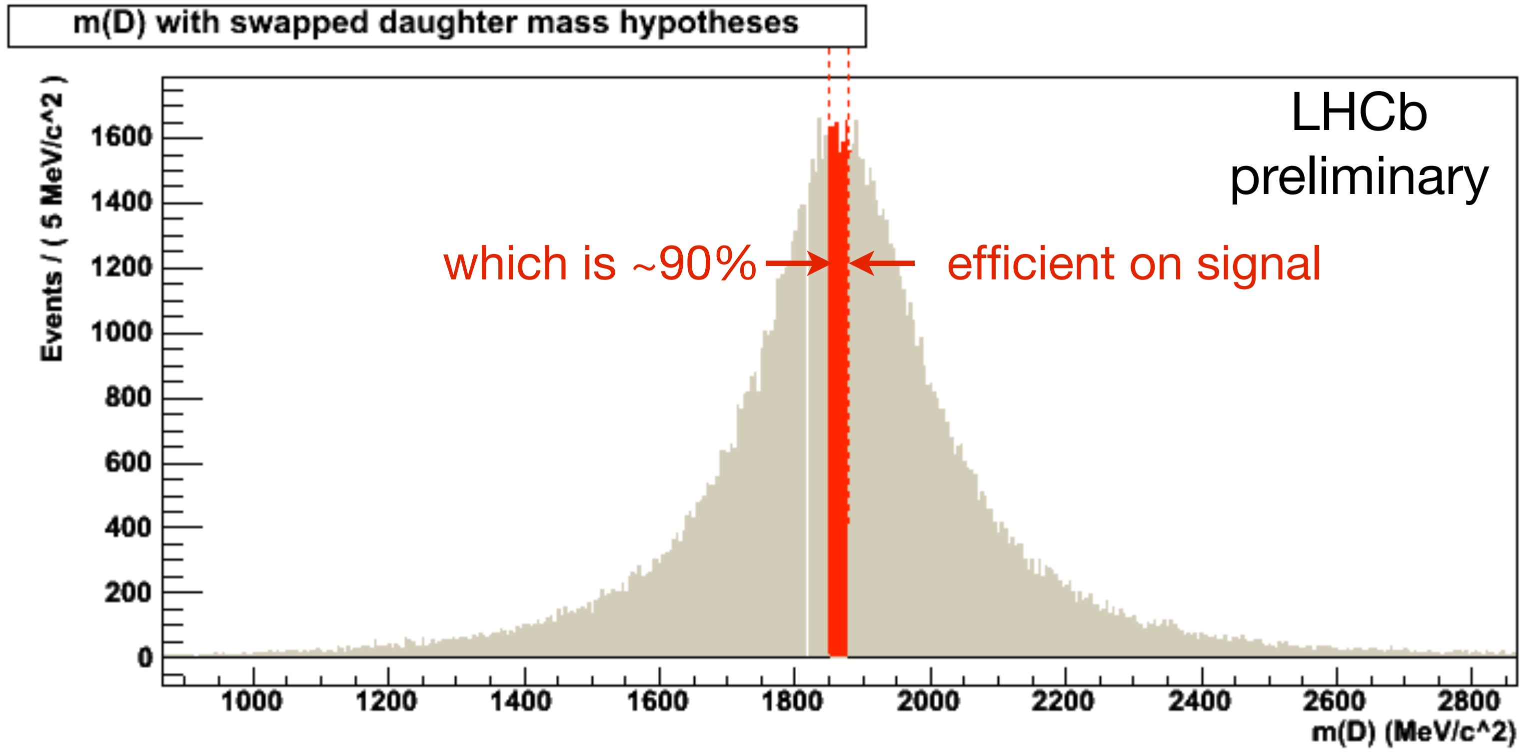
double ↓ ↓ misID

$B^{\pm}\to[\pi K]h^{\pm}$

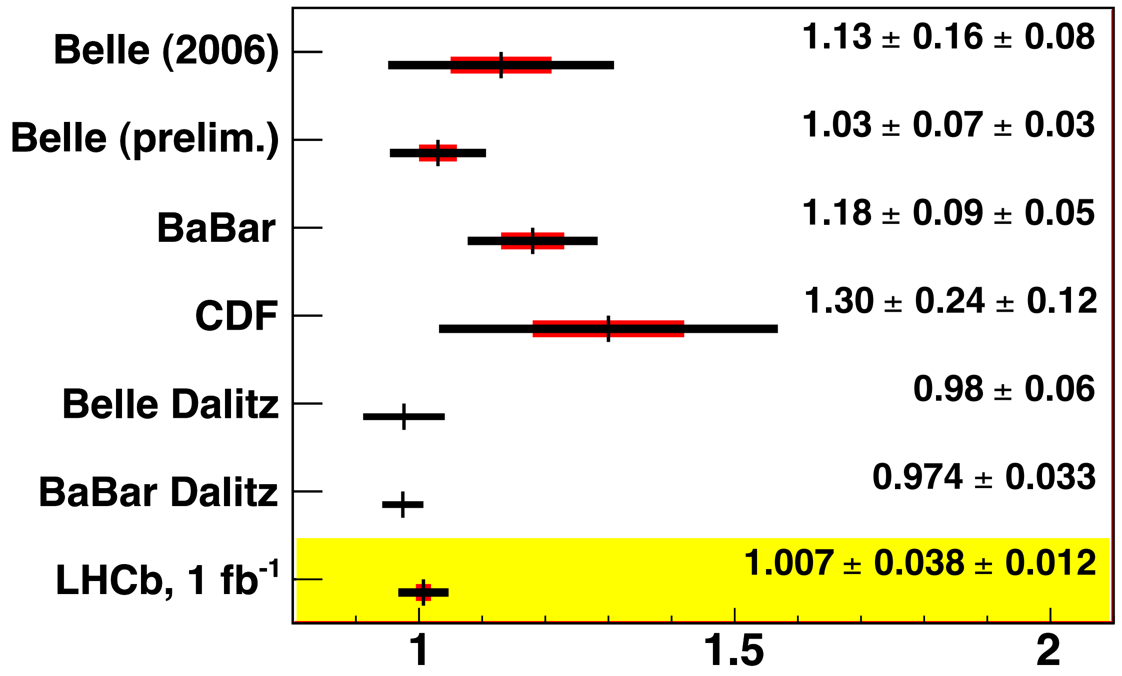
check for by swapping mass hypothesis back



- Combat with PID cuts on the *D* daughter tracks.
- But this is not sufficient. A veto is needed.

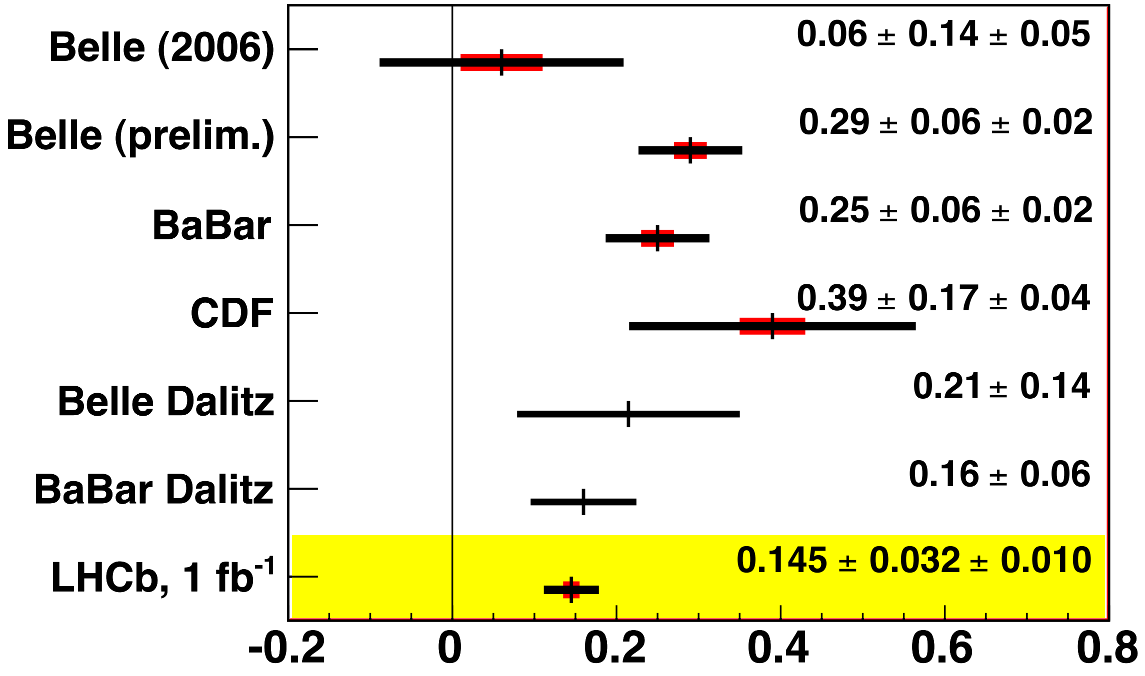


- After PID cuts and the veto, the expected cross feed rate is 6×10^{-5}.
- This is just 2% of $R_{ADS(\pi)}$.

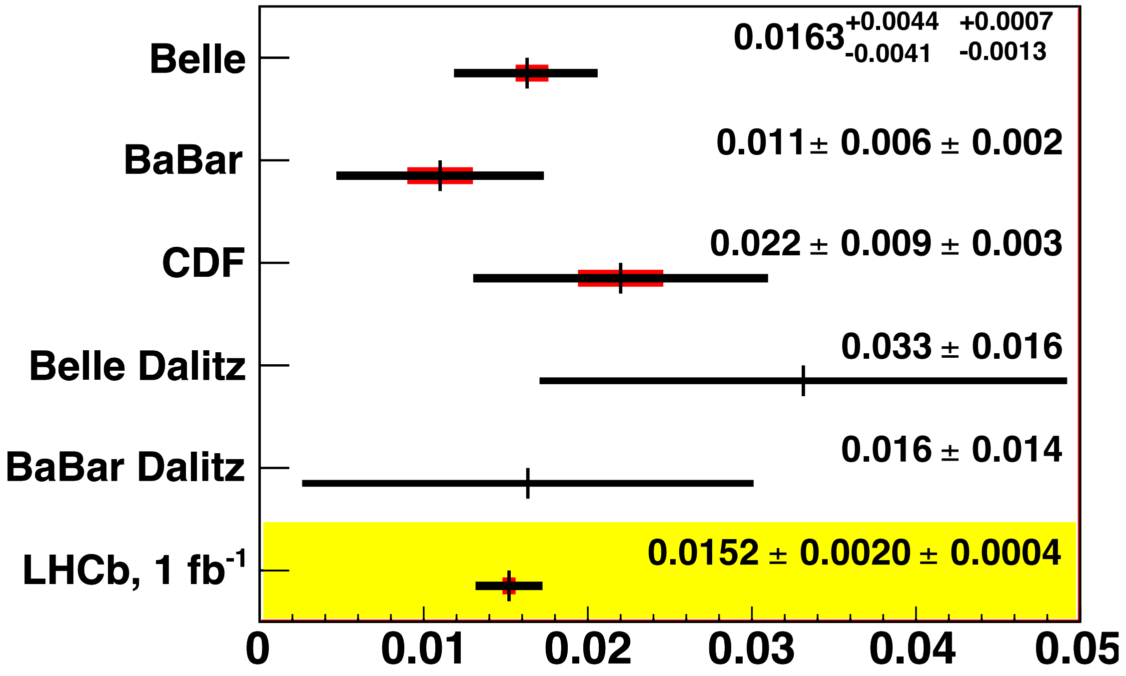


$$R_{CP+} = 1 + r_B{}^2 + 2r_B \cos\delta_B \cos\gamma$$

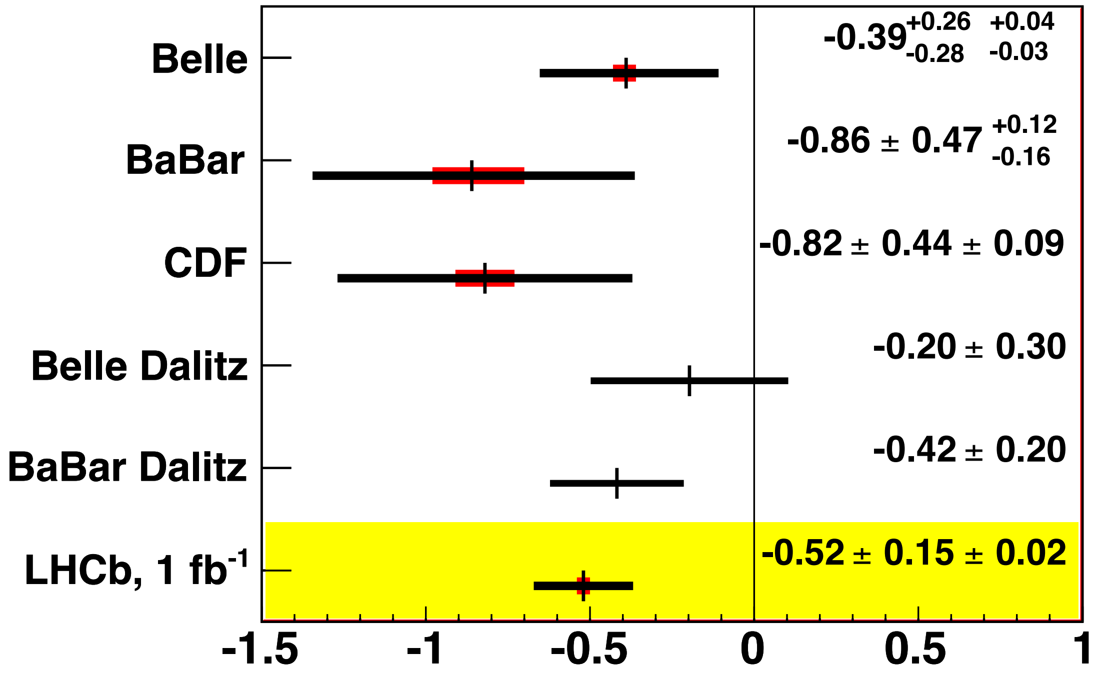
GGSZ methods measure the underlying parameters, r_B,γ,δ. From these, we can calculate the four observables for comparison.



$$A_{CP+} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + r_B{}^2 + 2r_B \cos\delta_B \cos\gamma}$$

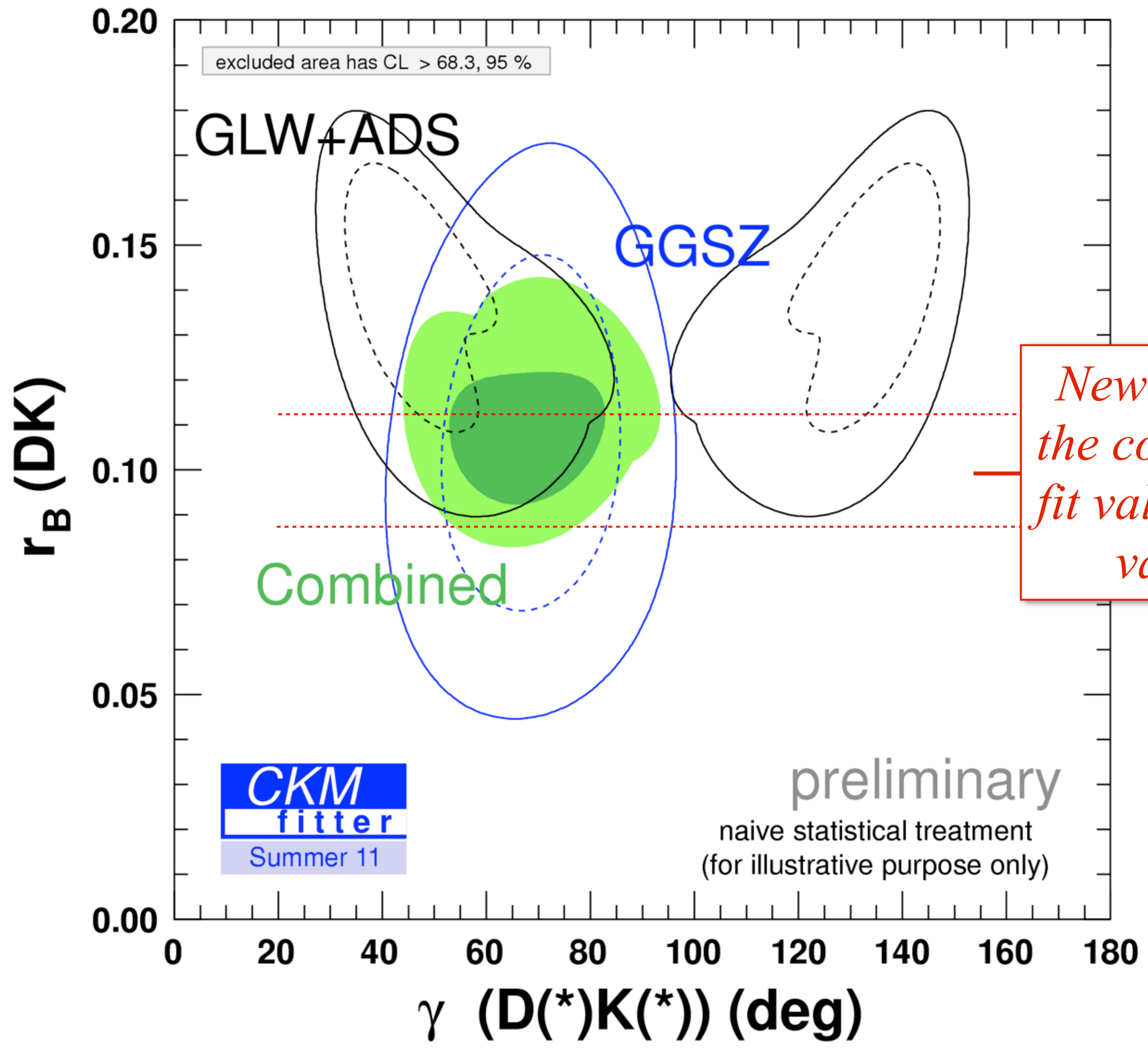


$$R^{ADS} = \frac{r_B{}^2 + r_D{}^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}{1 + (r_B r_D)^2 + 2r_B r_D \cos(\delta_B - \delta_D)\cos\gamma}$$

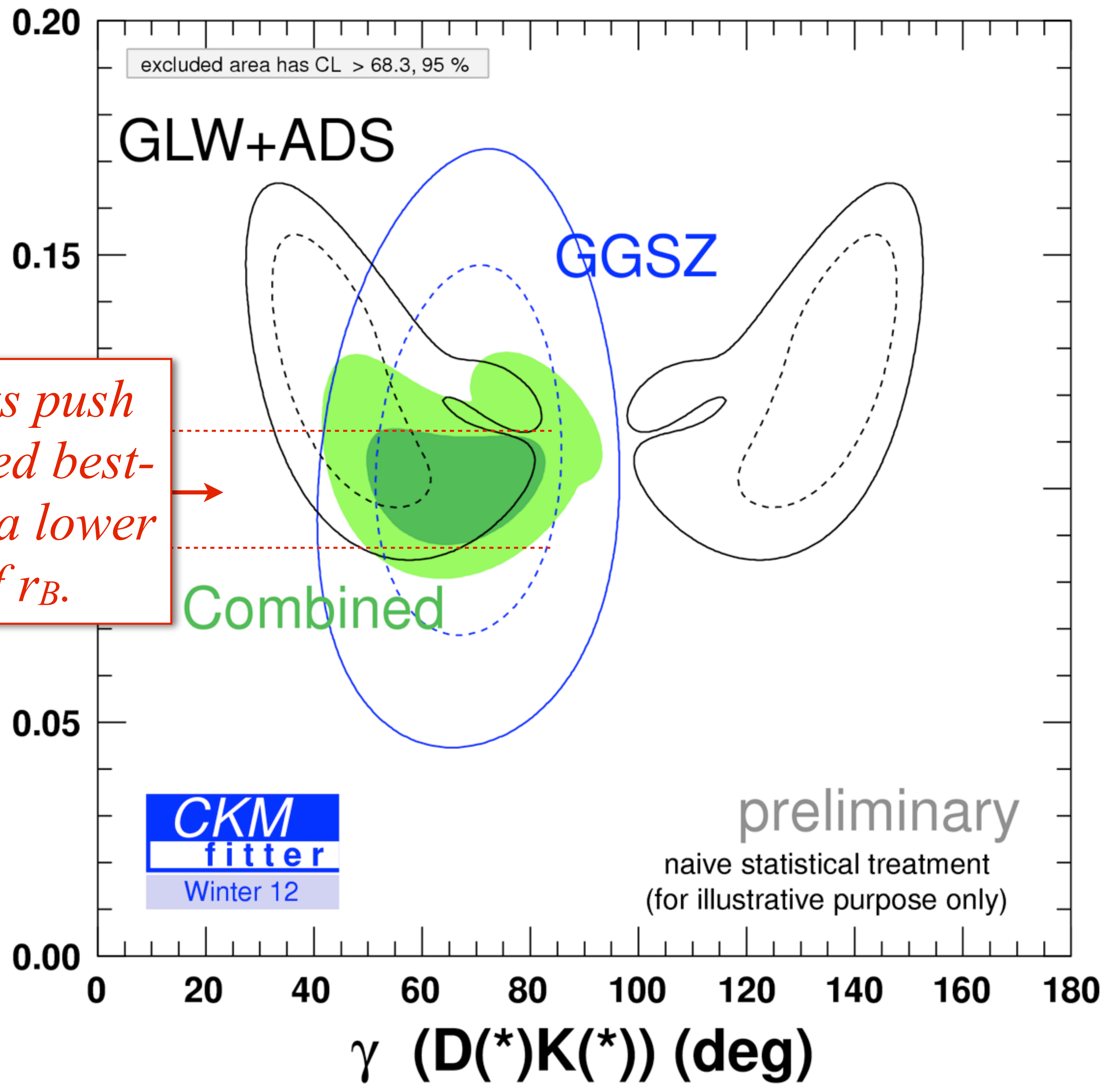


$$A^{ADS} = \frac{2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{r_B{}^2 + r_D{}^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}$$

Many thanks to the CKMFitter collaboration for absorbing these results



New results push the combined best-fit value to a lower value of r_B.



Dealing with production/detection asymmetries

$B^\pm \to [K\pi]_D h^\pm$	$A_{CP}((K\pi)_D\pi) = A_{raw}((K\pi)_D\pi) - A_{Prod} - A_K$ $A_{CP}((K\pi)_D K) = A_{raw}((K\pi)_D K) - A_{Prod} - 2\times A_K$
$B^\pm \to [\pi K]_D h^\pm$	$A_{CP}((\pi K)_D\pi) = A_{raw}((\pi K)_D\pi) - A_{Prod} + A_K$ $A_{CP}((\pi K)_D K) = A_{raw}((\pi K)_D K) - A_{Prod}$
$B^\pm \to [KK]_D h^\pm$	$A_{CP}((KK)_D\pi) = A_{raw}((KK)_D\pi) - A_{Prod}$ $A_{CP}((KK)_D K) = A_{raw}((KK)_D K) - A_{Prod} - A_K$
$B^\pm \to [\pi\pi]_D h^\pm$	$A_{CP}((\pi\pi)_D\pi) = A_{raw}((\pi\pi)_D\pi) - A_{Prod}$ $A_{CP}((\pi\pi)_D K) = A_{raw}((\pi\pi)_D K) - A_{Prod} - A_K$

$A^{J/\psi K^\pm}_{Raw} = -0.012\pm0.004$

$+A_{PDG}$, -0.001 ± 0.007

→

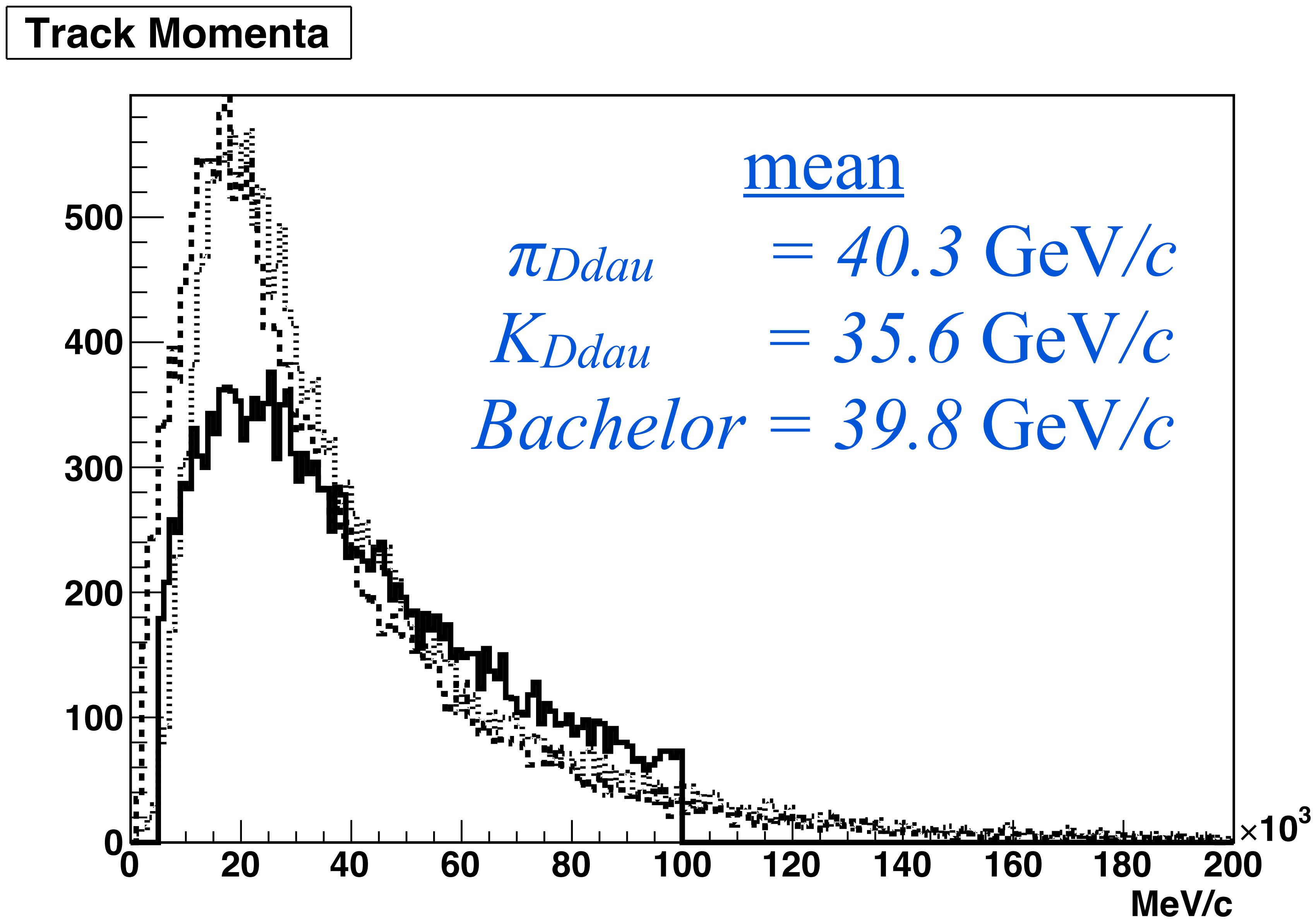
FIXED (%)

$A_{Prod} = -0.8\pm0.7$

$A_K = -0.5\pm0.7$

$A_\pi = 0.0\pm0.7$

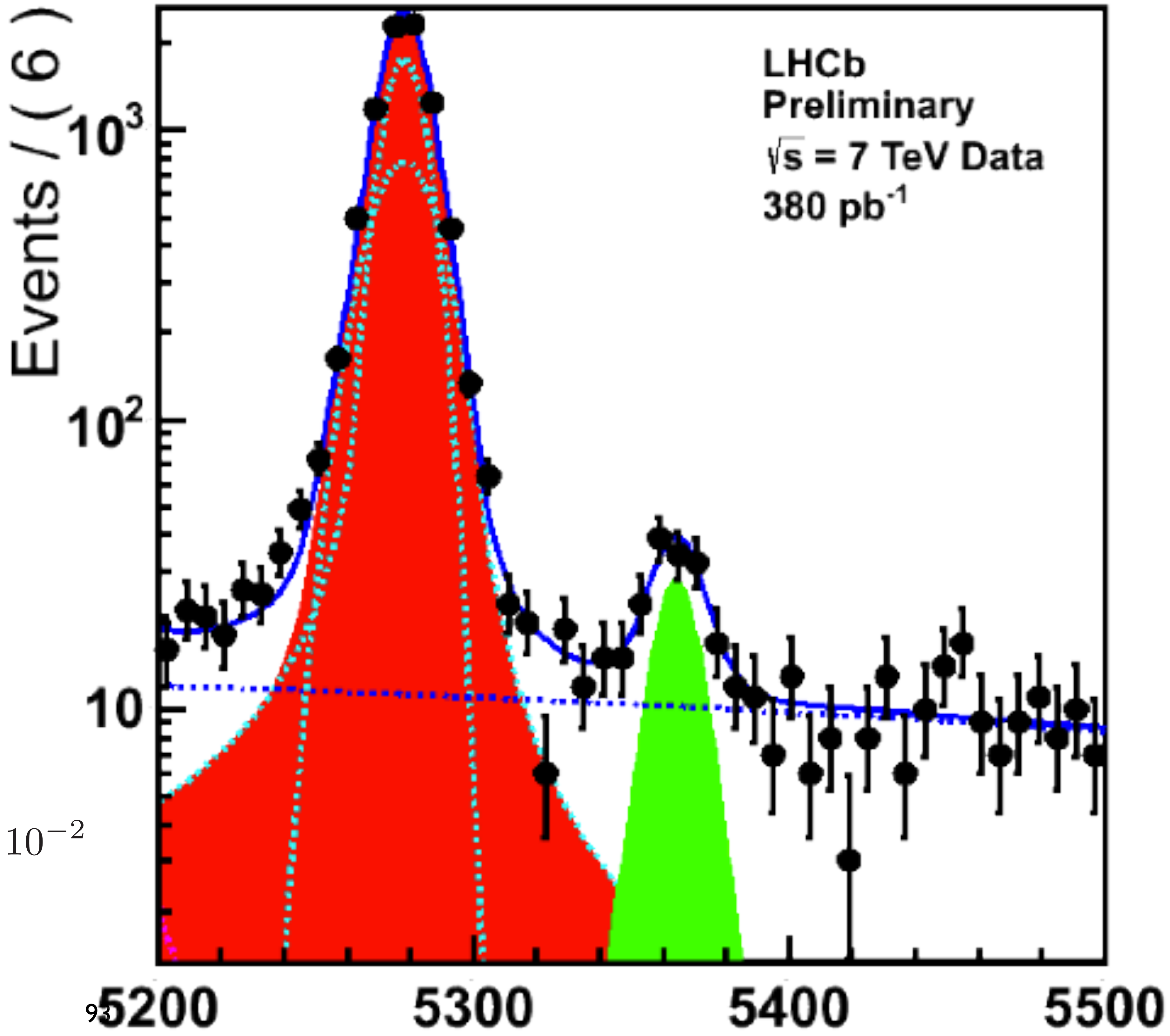
Track momentum of final sample



Penguins in sin(2β): $B_s \to J/\psi K_S$

LHCb-CONF-2011-048

- The unitarity triangle shows some tension between $|V_{ub}|$ and sin(2β).
- How much of "sin(2β)" is sin(2β)? How large are the hadronic penguin contributions?
- Could be eventually deduced by comparing $B_d \to J/\psi K_S^0$ and its U-spin partner: $B_s \to J/\psi K_S^0$
- First step: confirmation in LHCb dataset.



$$\frac{\mathcal{B}(B_s \to J/\psi \mathrm{K_S^0})}{\mathcal{B}(B_d \to J\psi \mathrm{K_S^0})} = (3.78 \pm 0.58 \pm 0.20 \pm 0.30) \times 10^{-2}$$

DACP elsewhere...

Experimental status
(individual A_{CP})

Year	Experiment	CP Asymmetry in the decay mode D0 to π+π-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2010	CDF	M.J. Morello (CDF Collab.), Preprint (CHARM 2010).	+0.0022 ± 0.0024 ± 0.0011
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 2008).	+0.0043 ± 0.0052 ± 0.0012
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
.	.	COMBOS average	+0.0020 ± 0.0022

Year	Experiment	CP Asymmetry in the decay mode D0 to K+K-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2011	CDF	A. Di Canto (CDF Collab.), Preprint (BEAUTY 2011).	-0.0024 ± 0.0022 ± 0.0010
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).	-0.0043 ± 0.0030 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	+0.0000 ± 0.0034 ± 0.0013
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.000 ± 0.022 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	-0.001 ± 0.022 ± 0.015
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.010 ± 0.049 ± 0.012
1995	CLEO	J.E. Bartelt et al. (CLEO Collab.), Phys. Rev. D 52, 4860 (1995).	+0.080 ± 0.061
1994	E687	P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).	+0.024 ± 0.084
.	.	COMBOS average	-0.0023 ± 0.0017