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Charm physics

Marco Gersabeck
The University of Manchester

UK HEP Forum - Quarks and Leptons
Abingdon - 15 November 2013

The very beginning

Prog. Theor. Phys. Vol. 46 (1971), No. 5

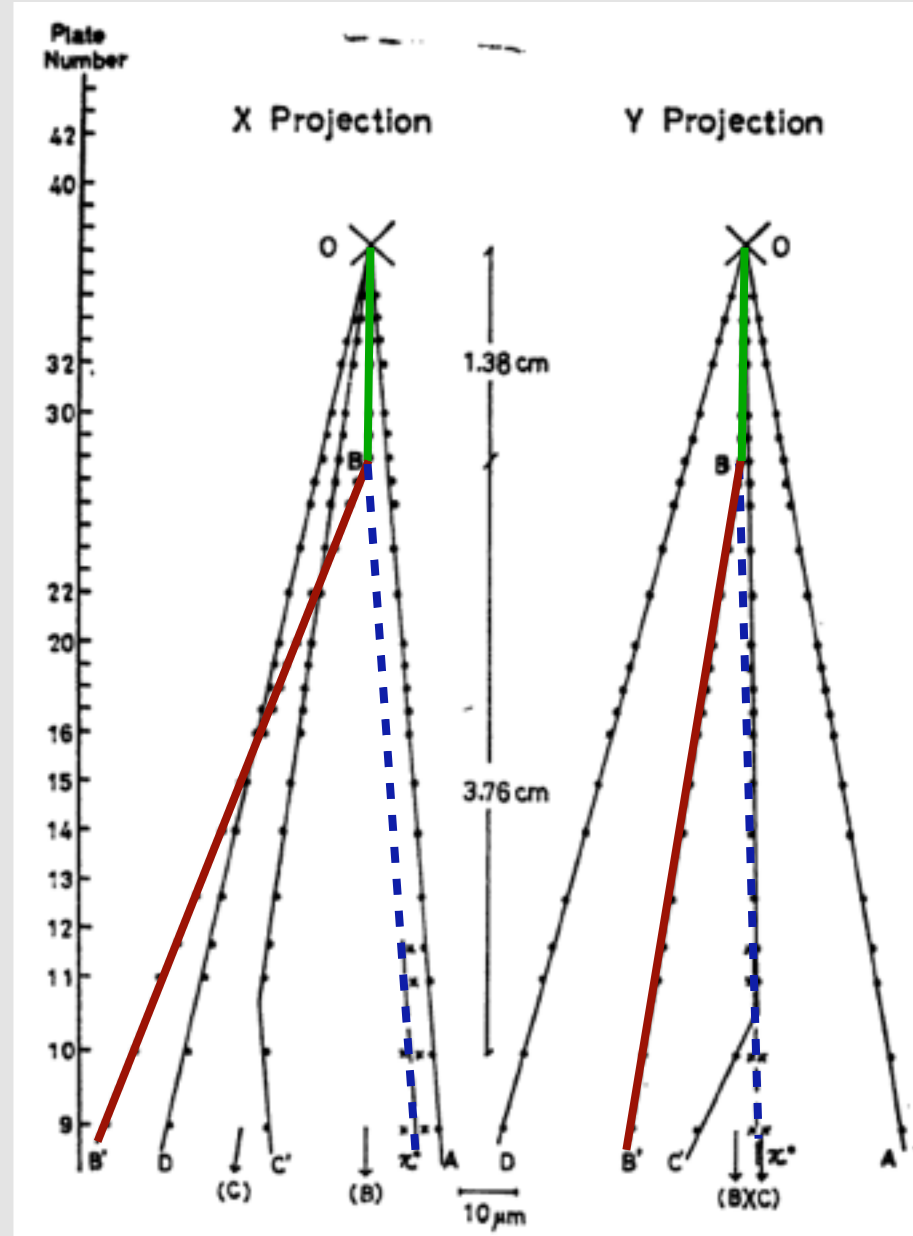
A Possible Decay in Flight of a New Type Particle

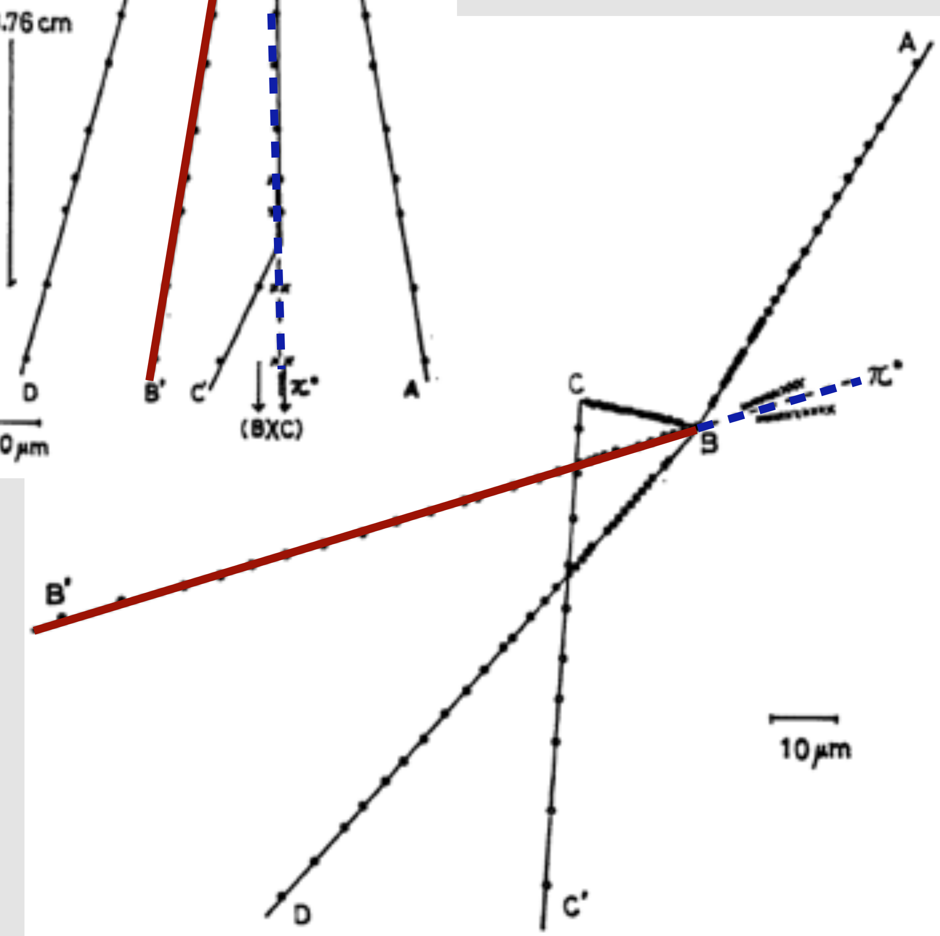
Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study
University of Tokyo
**Yokohama National University*

August 9, 1971

- Cosmic showers
- Observed in emulsion chambers
- 500 hours aboard a cargo plane





Assumed decay mode	M_x GeV	T_x sec
$X \to \pi^0 + \pi^\pm$	1.78	2.2×10^{-14}
$X \to \pi^0 + p$	2.95	3.6×10^{-14}

Introduction

Summary of Charm Phys… 25 minutes:

$\mathcal{O}$(40) exp. presentations
with $\langle N_{res} \rangle \sim 5$
$\mathcal{O}$(30 s) / present.
$\mathcal{O}$(5 s) / result

useless to try to give an overview of presentations

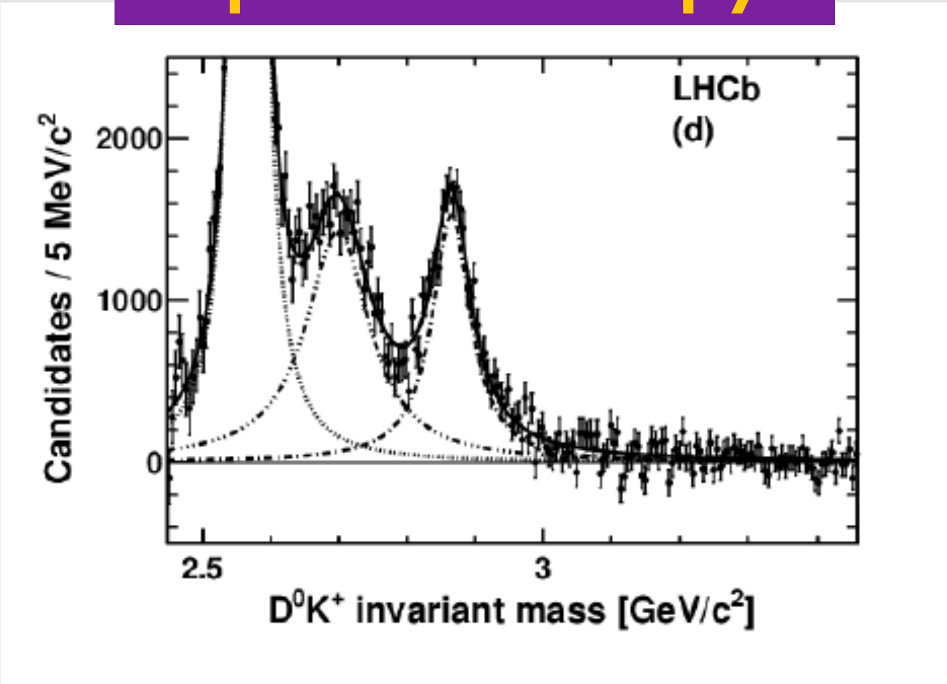
⇒ completely personal(ized) view and summary

Please refer to Bostjan's CHARM conference summary and references therein

What I will not cover

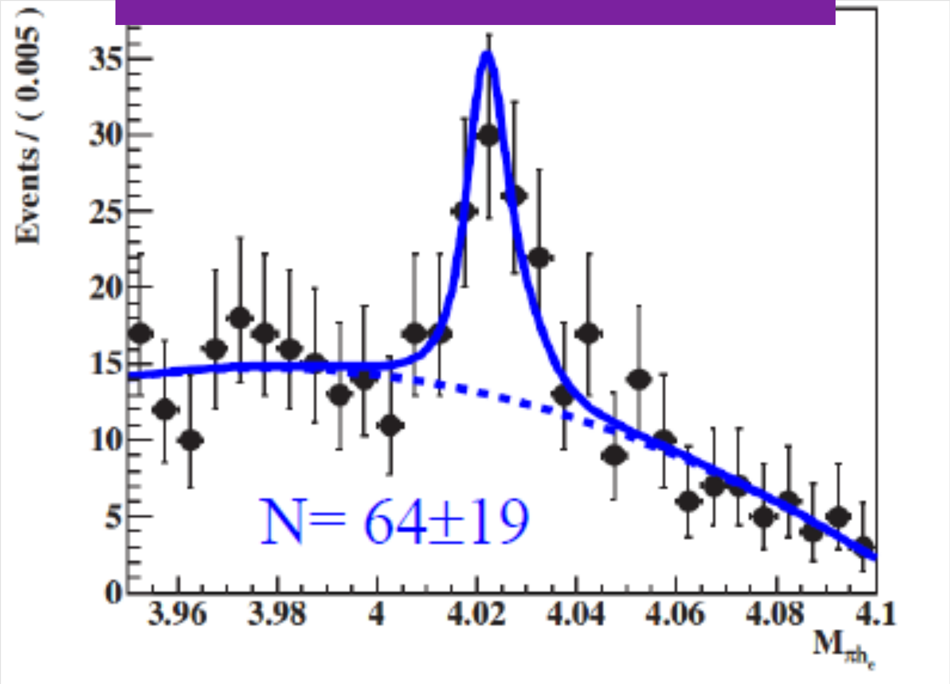
Spectroscopy

JHEP 1210, 151 (2012)



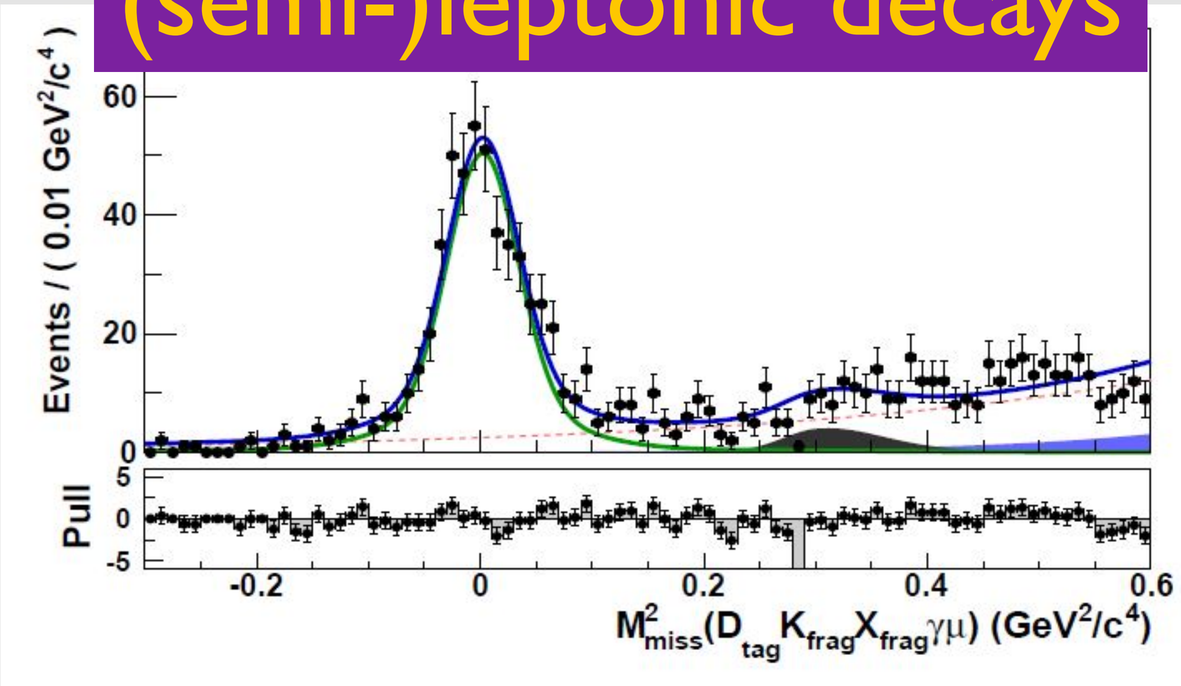
Exotic charm

BESIII, preliminary



(semi-)leptonic decays

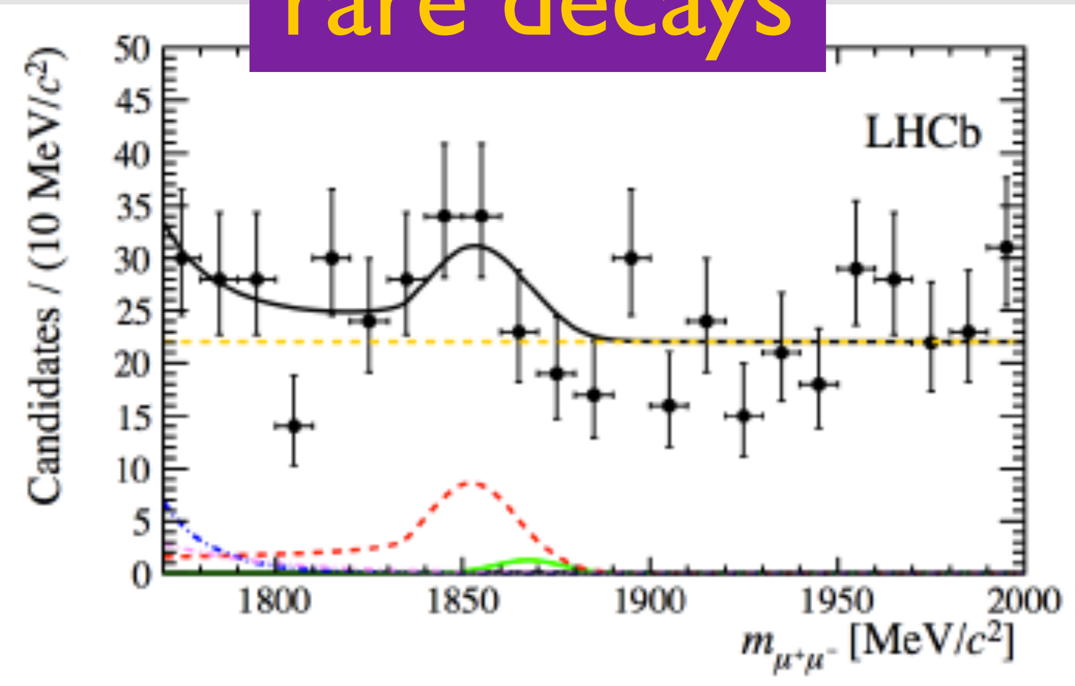
arXiv:1307.6240



see Christine Davies' talk

rare decays

PLB 725 (2013) 1



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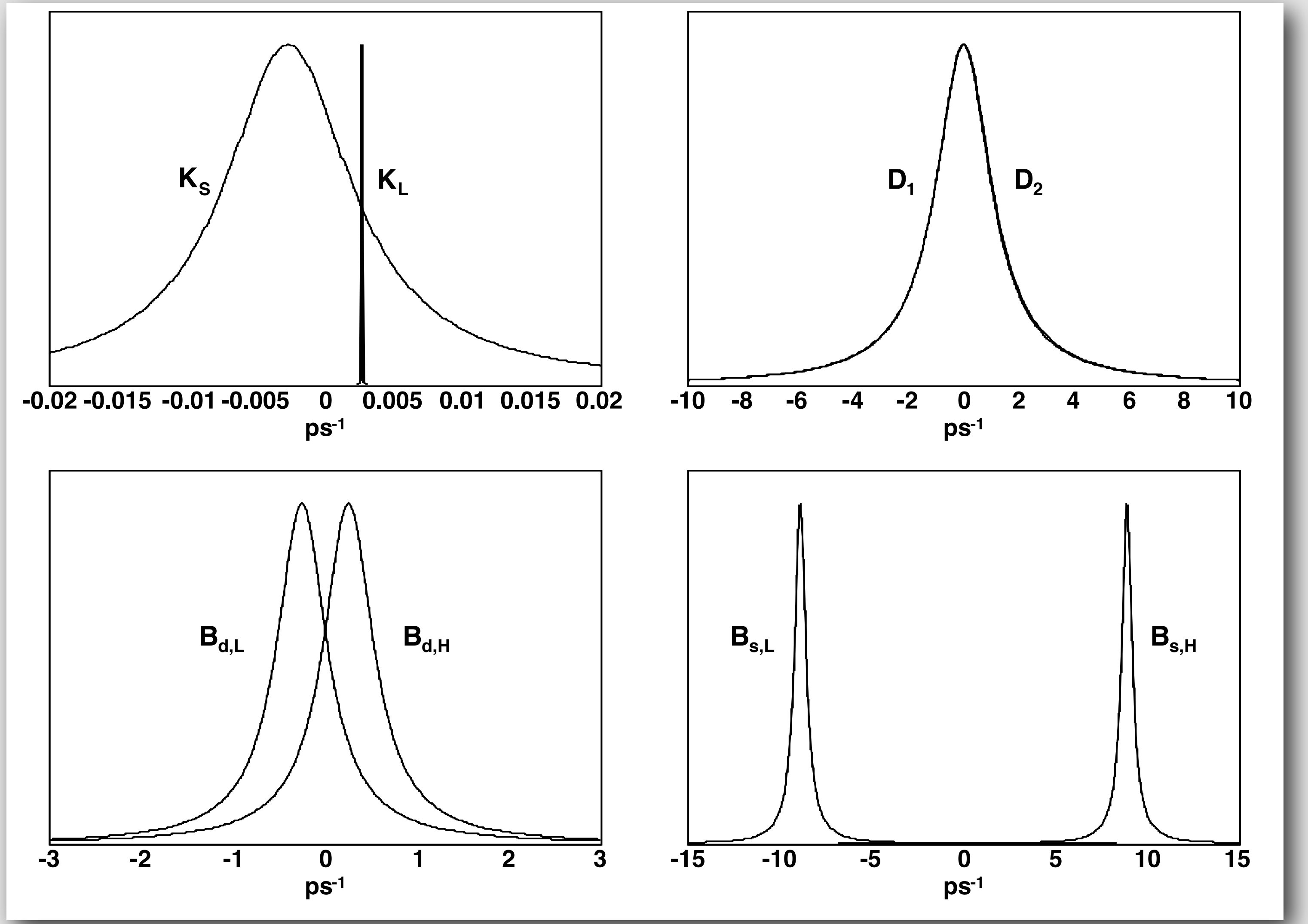
Mixing and CP violation

Mixing

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Mass eigenstates

Flavour eigenstates



$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

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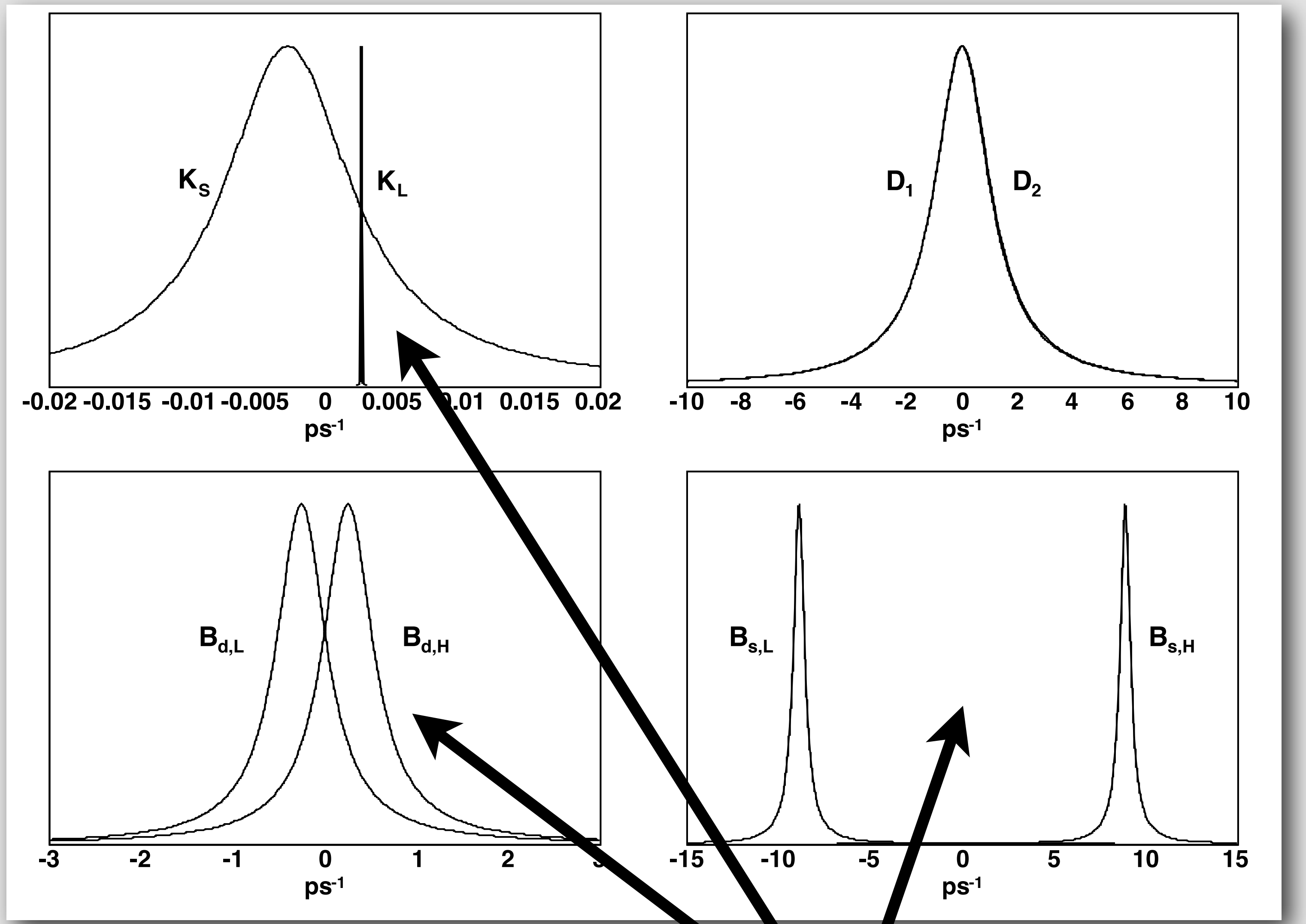
Mass eigenstates Flavour eigenstates



Mass difference

→ Oscillation

$$\Delta m \equiv m_2 - m_1$$

$$x \equiv \Delta m / \Gamma$$

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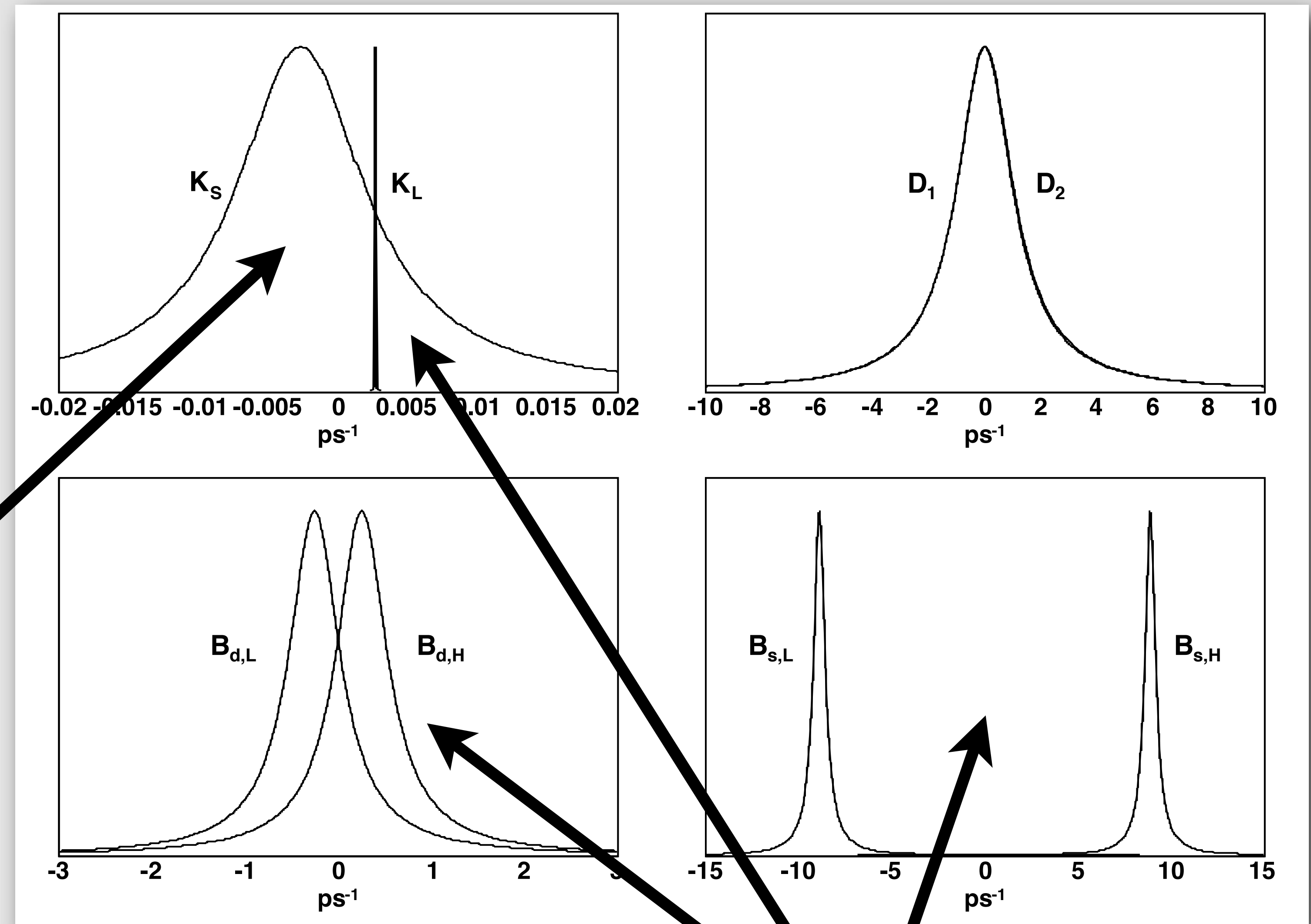

Width difference

→ Lifetime difference

$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$

$y \equiv \Delta\Gamma/(2\Gamma)$

$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

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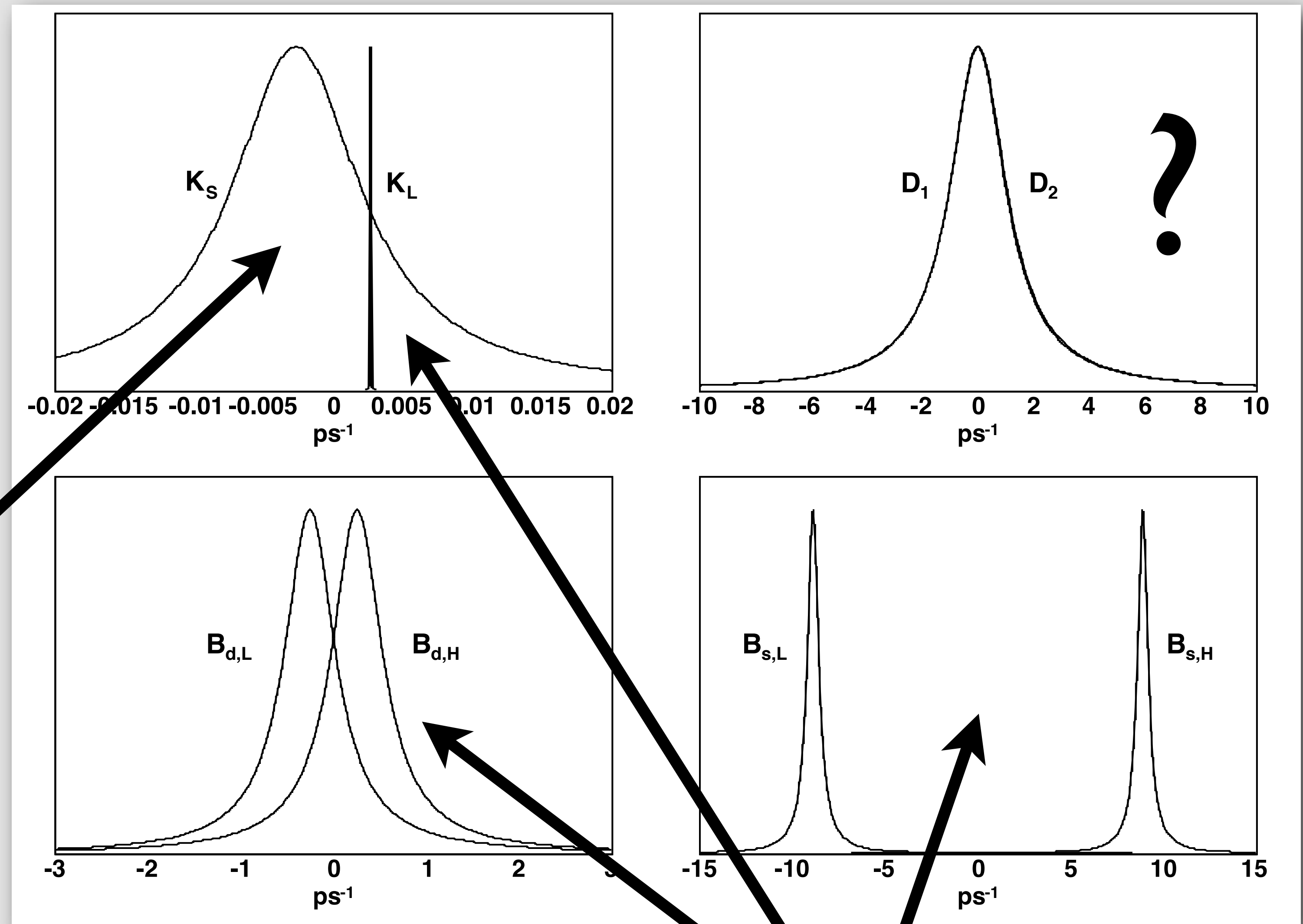

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CP violation in mixing

- CP conservation implies that mass eigenstates are CP eigenstates

$$\mathcal{CP}|M_{1,2}\rangle = \pm|M_{1,2}\rangle \qquad |M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

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- CP violation in mixing if $q \neq \pm p$
- Two possibilities $|q/p| \neq 1$ $\Im(q/p) \neq 0$

CP violation in mixing

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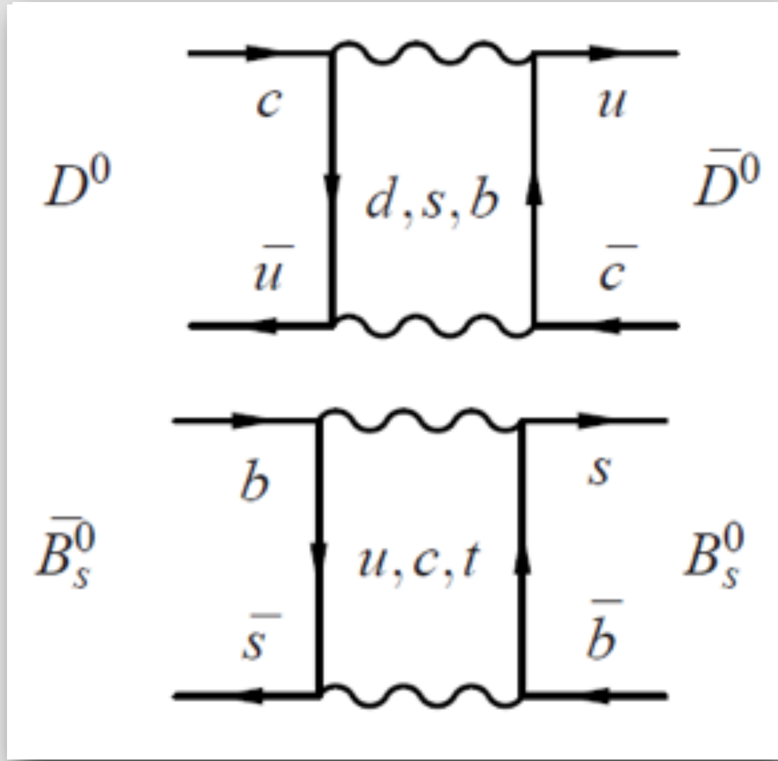
- CP violation in mixing if $q \neq \pm p$
- Two possibilities $|q/p| \neq 1$ $\Im(q/p) \neq 0$

- Mass eigenstates and CP eigenstates no longer the same $\mathcal{CP}|M_{1,2}\rangle \neq \pm|M_{1,2}\rangle$
- Decays to CP eigenstates now possible from both mass eigenstates

D^0 mixing theory



- Mixing box contains down-type quarks
- No dominance of top mass as in B sector
- CKM-suppression balances GIM cancellation
- Charm mass neither small nor large
- Huge cancellations
  - ➡ Long-distance effects become important
- Over 1000 lifetimes for 1 full oscillation
- Difficult to measure
  - ➡ CP violation even more tricky to discover

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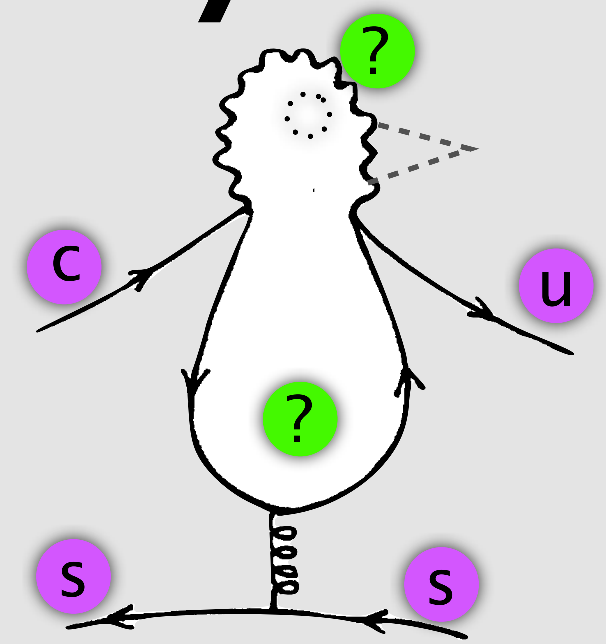
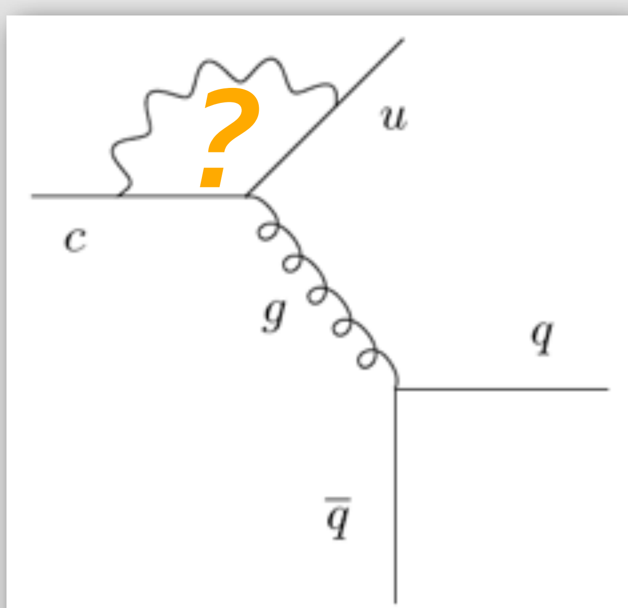
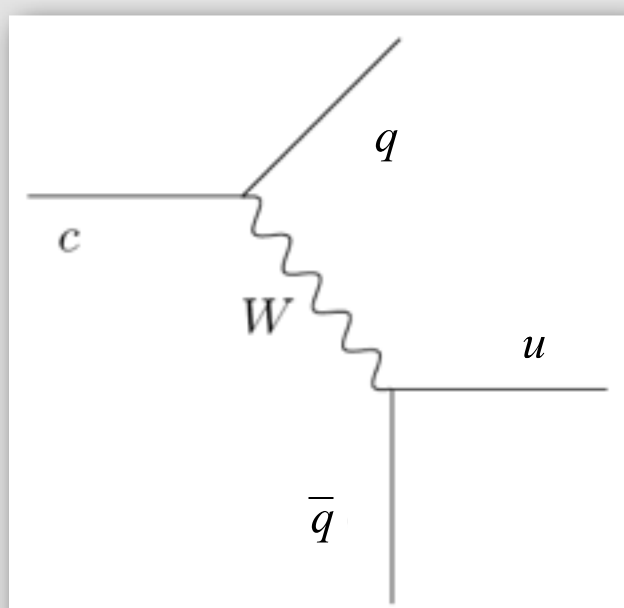
CP violation in decay



- CP violation in decays requires interference of several amplitudes
- Example:
  - ➡ singly Cabibbo-suppressed (SCS) decays
    $c \to d\bar{d}u$ ($D^0 \to \pi^-\pi^+$) or $c \to s\bar{s}u$ ($D^0 \to K^-K^+$)
- Only SCS decays have gluonic penguin contributions (need $q\bar{q}$)
- Penguins can carry strong and weak phase w.r.t. trees





$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

V_{cd}: very small imaginary part

CP violation in decay

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- Divide amplitudes into leading and sub-leading parts:
  $A(D\rightarrow f) = C(1+re^{i(\delta+\phi)})$
  $A(\overline{D}\rightarrow f) = C(1+re^{i(\delta-\phi)})$
- r is the ratio of sub-leading over leading amplitude
- CP violation requires difference in strong (δ) and weak phase (ϕ):
  $a_{CP} \equiv [\Gamma(D\rightarrow f)-\Gamma(\overline{D}\rightarrow f)] / [\Gamma(D\rightarrow f)+\Gamma(\overline{D}\rightarrow f)]$
  $= 2\, r \sin(\delta) \sin(\phi)$
  with $\Gamma(D\rightarrow f) = {}_0\!\int^\infty \Gamma(D(t)\rightarrow f)\, dt \propto |A|^2$

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Latest results

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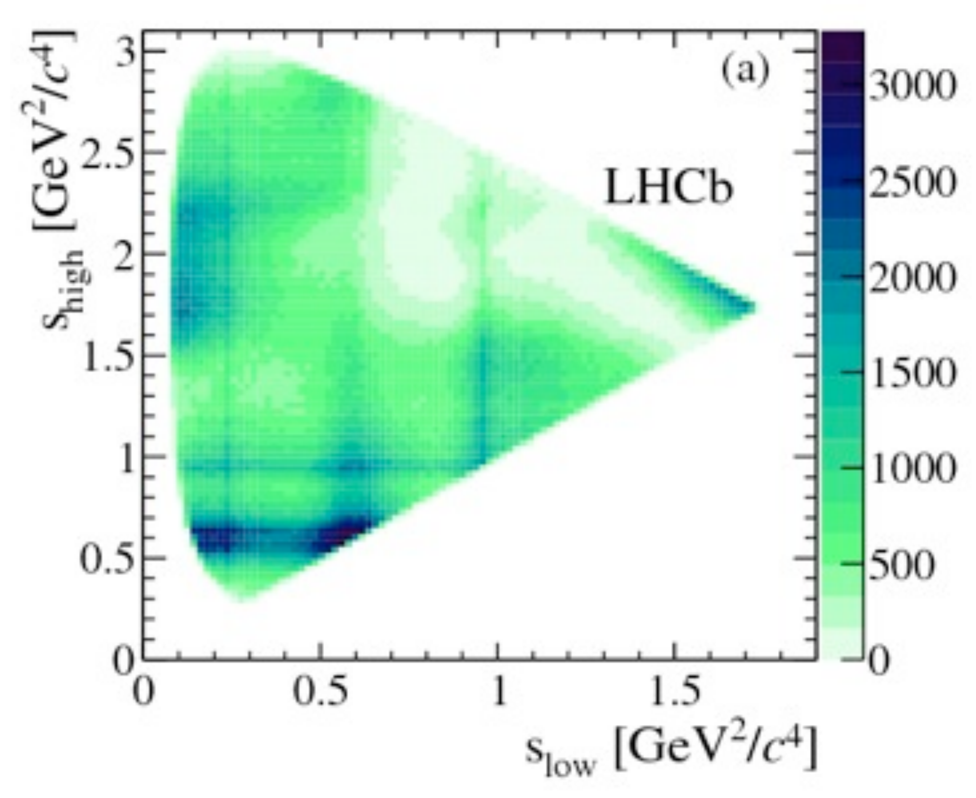
LHCb-PAPER-2013-057



$D^+ \to 3\pi$

- Model-independent searches for CP violation
  - ➡ Over 3M D^+ & D^- decays in 1 fb^{-1}
  - ➡ Search for asymmetry significances in bins of phase space
  - ➡ Search for local asymmetries through un-binned comparison with nearest neighbours

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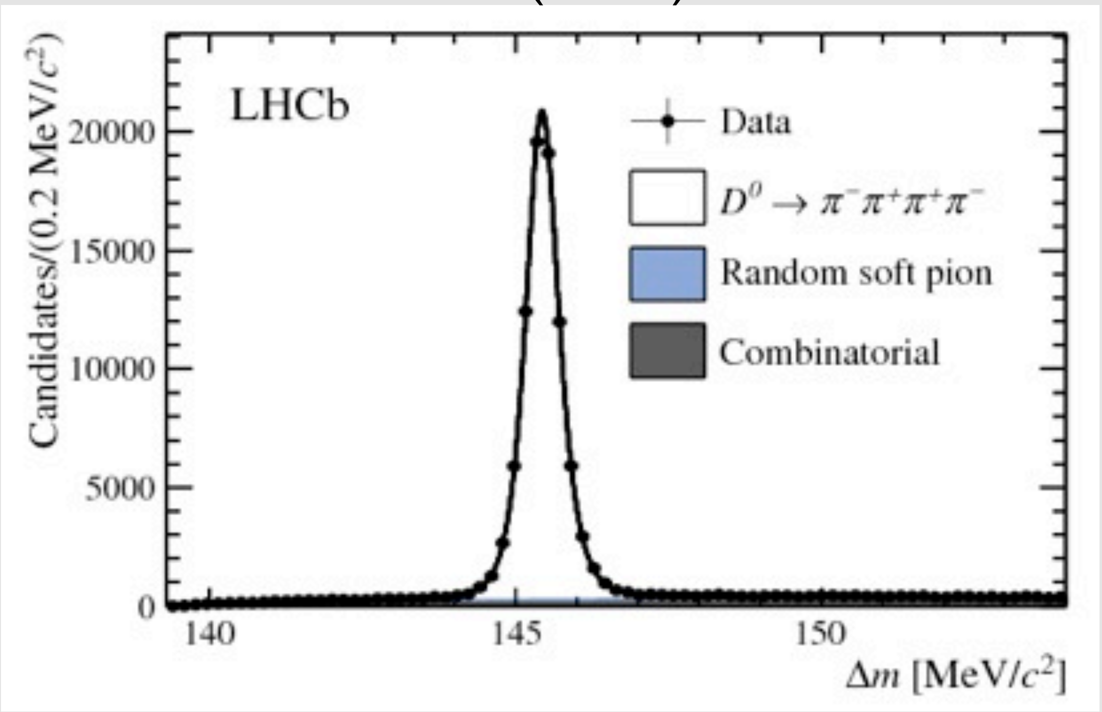
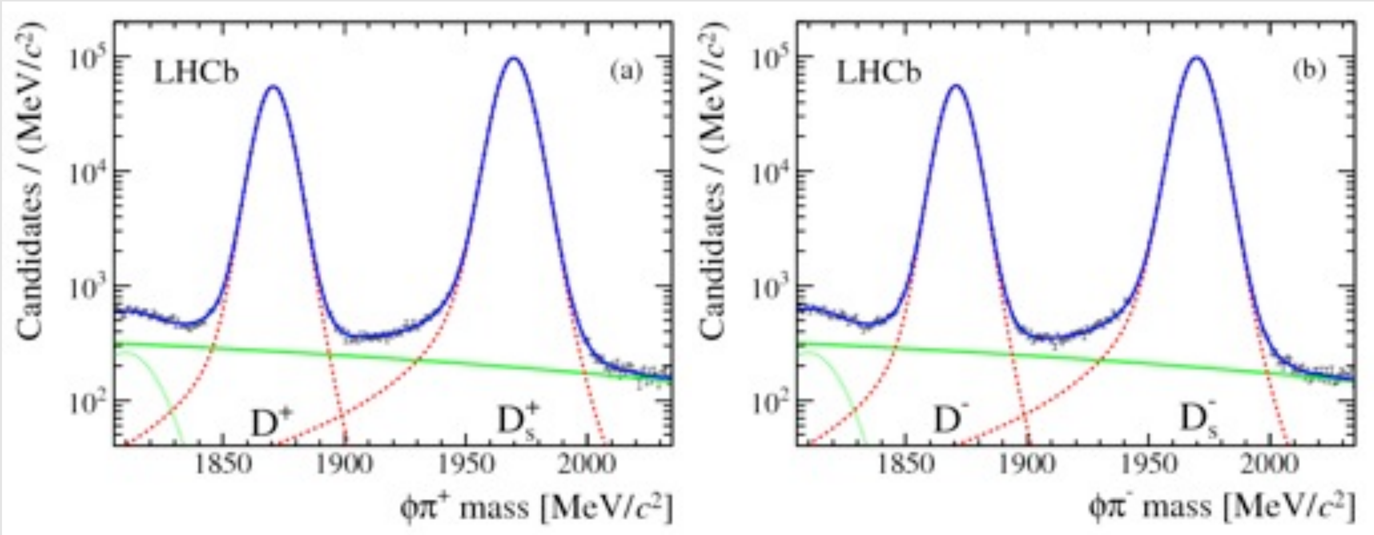
PLB 726 (2013) 623

$D^0 \rightarrow 4h$



- 4-body phase space has 5 dimensions!
- Analyse 1 fb^{-1} of $D^0 \rightarrow 4\pi/KK\pi\pi$ decays
  - ➡ Use search for asymmetry significances in 128/32 bins of 5D phase space
  - ➡ Local CP asymmetry never exceeds 5%

2-body CP violation



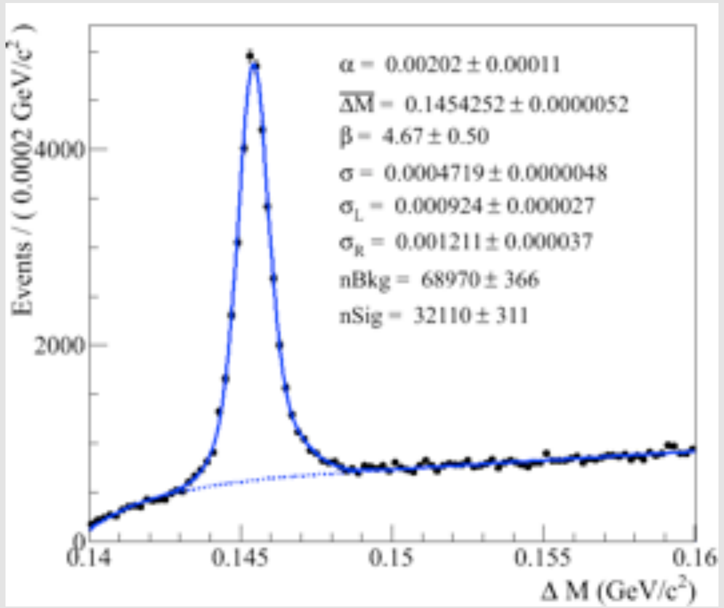
JHEP 06 (2013) 112

- LHCb: high precision charged particles (based on $1\,fb^{-1}$)

➡ $A_{CP}(D^+ \to \phi\pi) = (-0.04 \pm 0.14 \pm 0.14)\%$

- Belle: neutral final states (expected precision for $966\ fb^{-1}$)

➡ $\sigma(A_{CP}(D^0 \to \pi^0\pi^0)) = 0.6\%$



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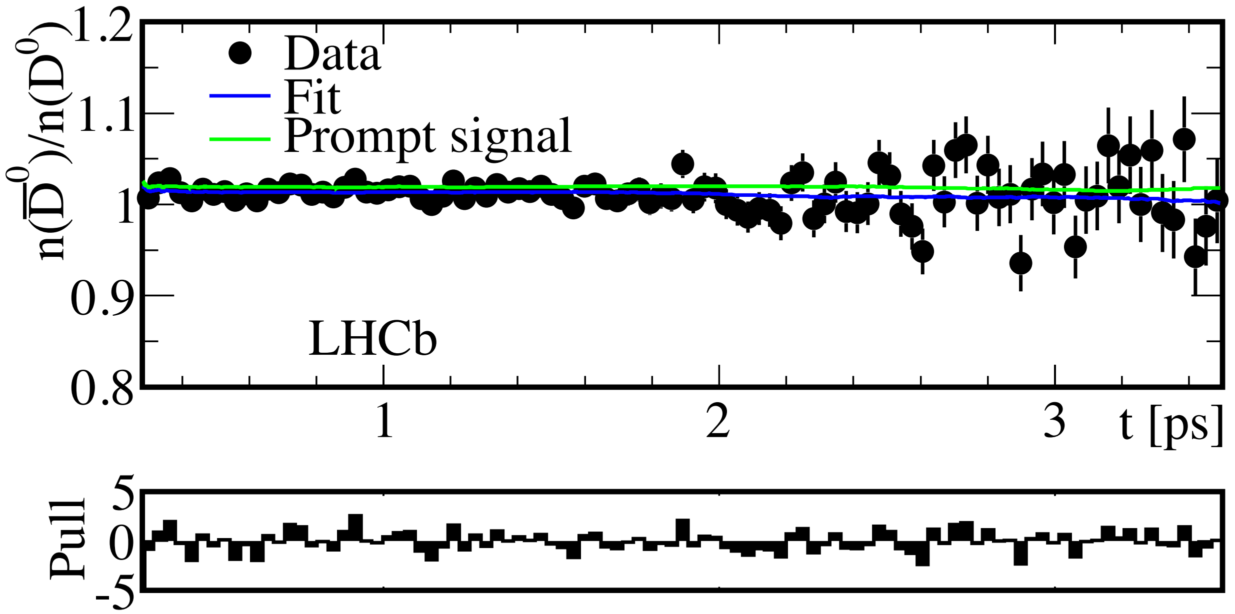
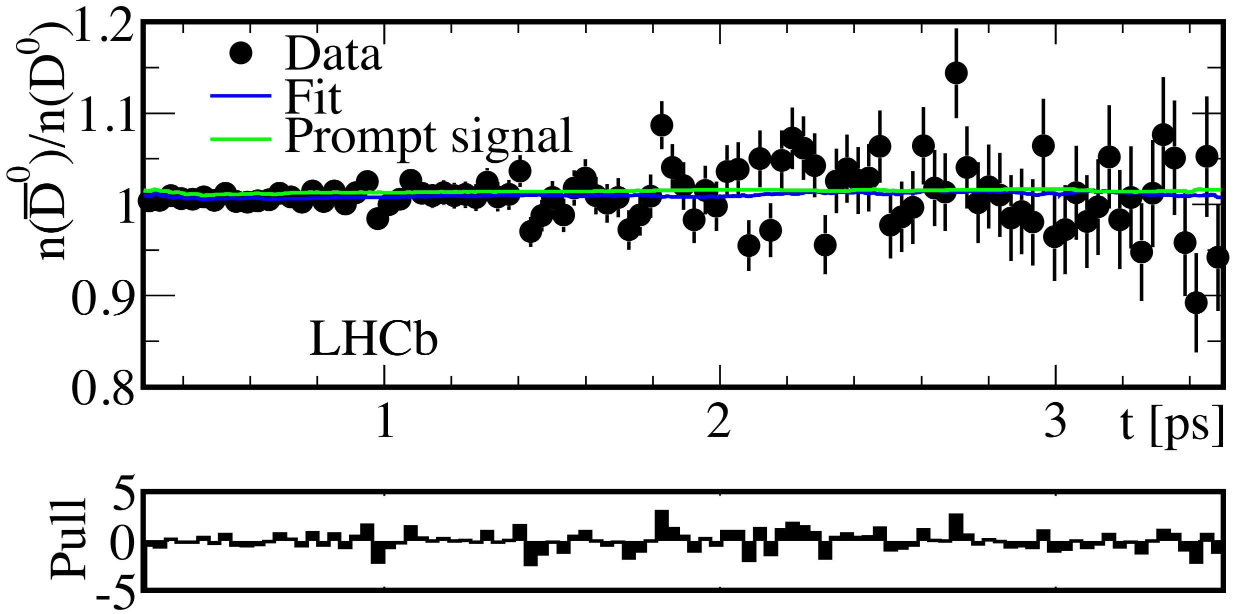
CP violation in decay

- Range of new measurements with increasing precision in several decay modes
- Route forward:
  - ➡ Need measurements in several modes to identify potential sources of CP violation
  - ➡ Model-independent measurements are discovery strategies
  - ➡ Need model-dependent measurements for quantitative interpretation

Indirect CP violation

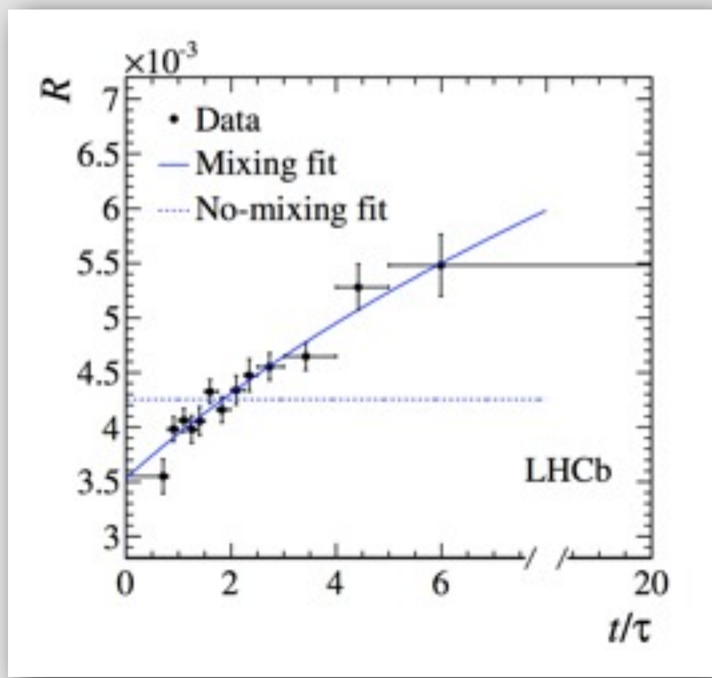
- Measure asymmetries of effective lifetimes of decays to CP eigenstates:
  - ➡ $A_\Gamma \approx A_M\, y \cos\Phi + x \sin\Phi \equiv A_{CP}^{ind}$
- Measurements use $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays (1 fb^{-1})
  - ➡ $A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$
  - ➡ $A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$

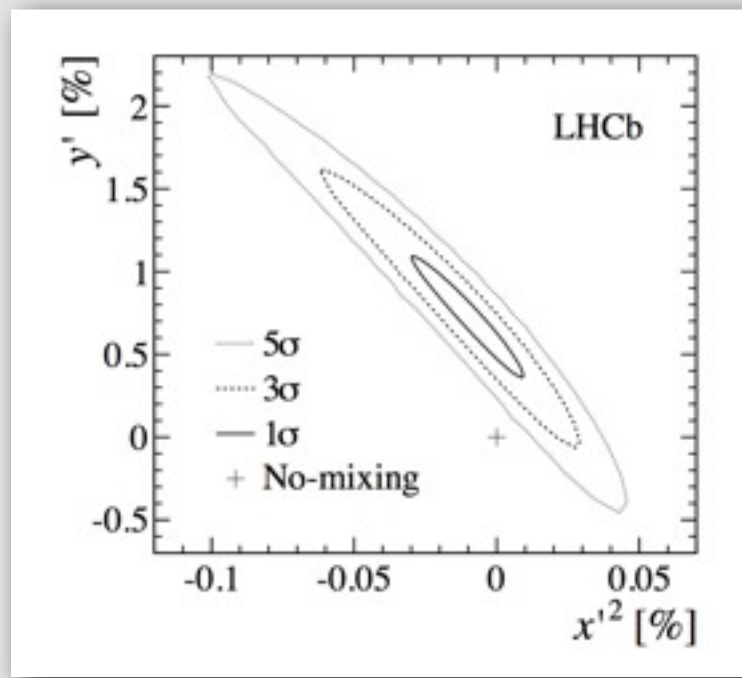


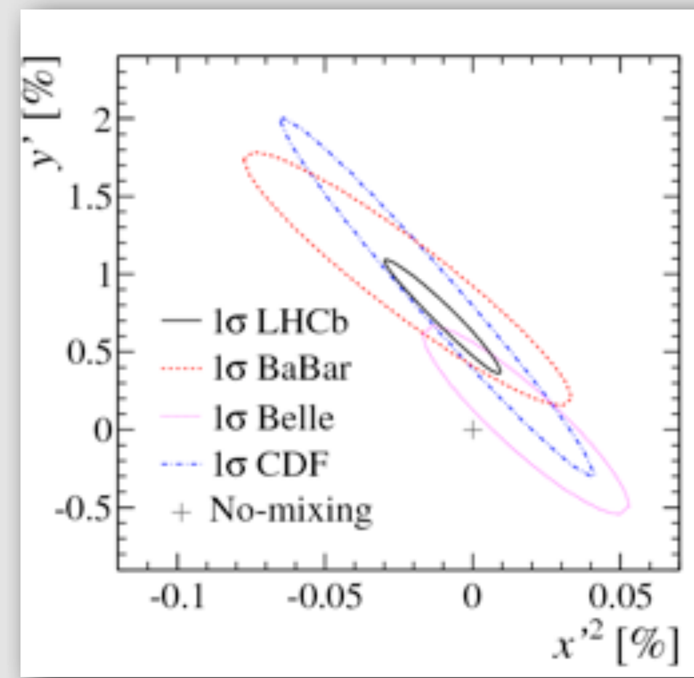


LHCb-PAPER-2013-054

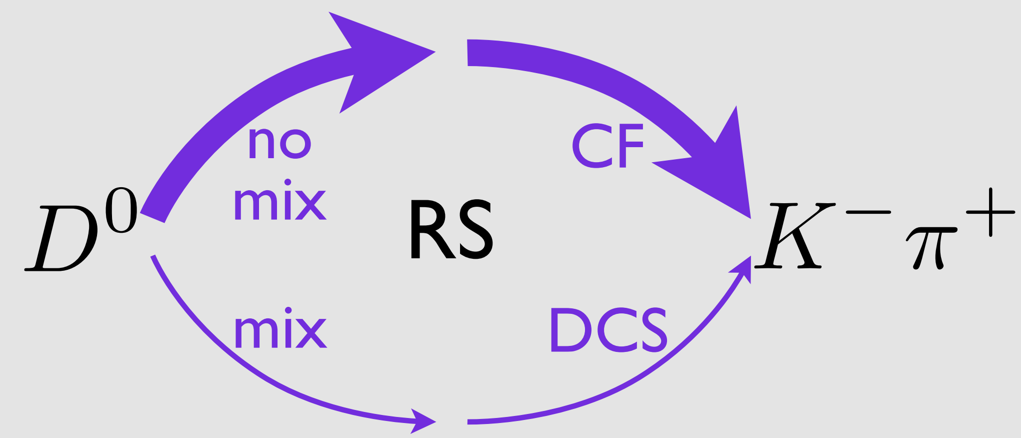
Mixing discovery

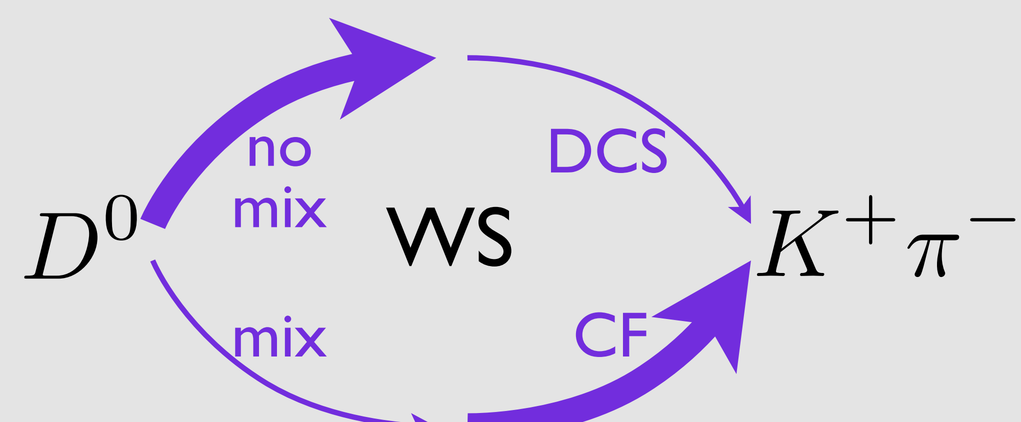






$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} (\frac{t}{\tau})^2$$

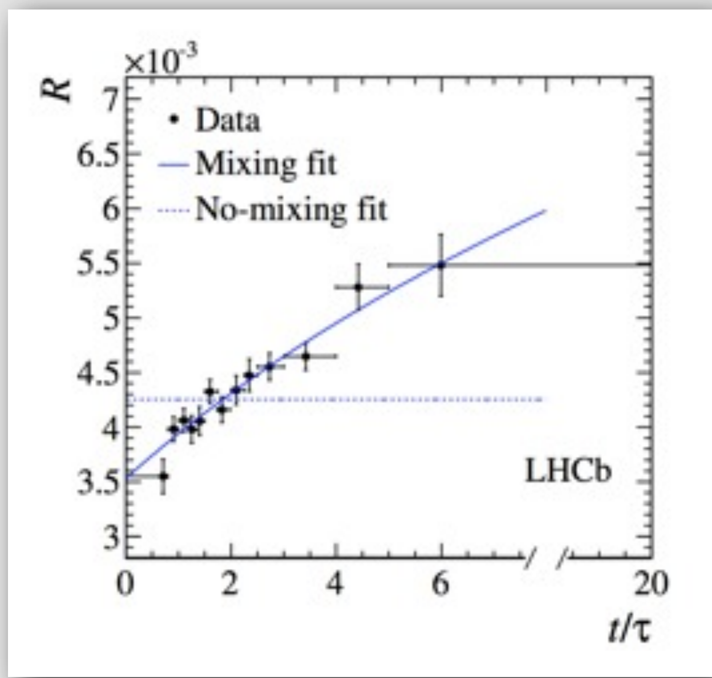


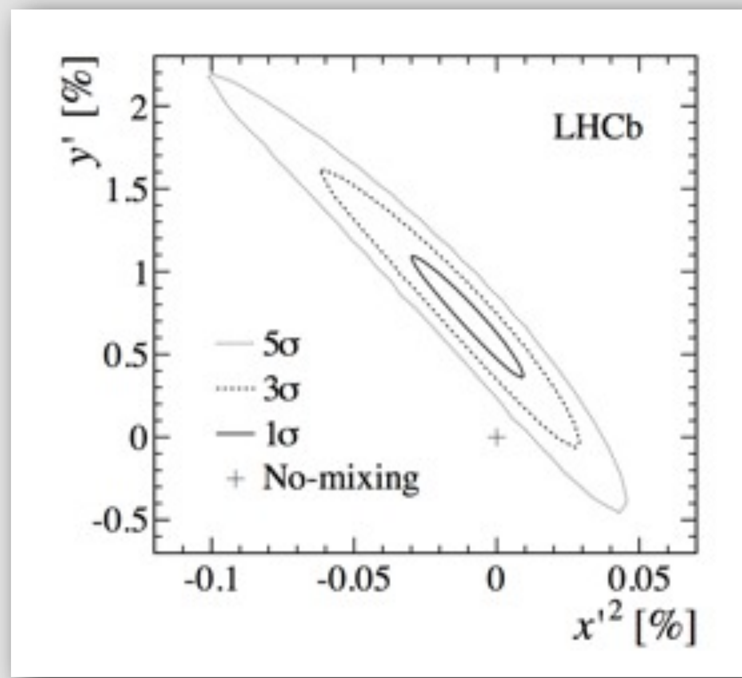


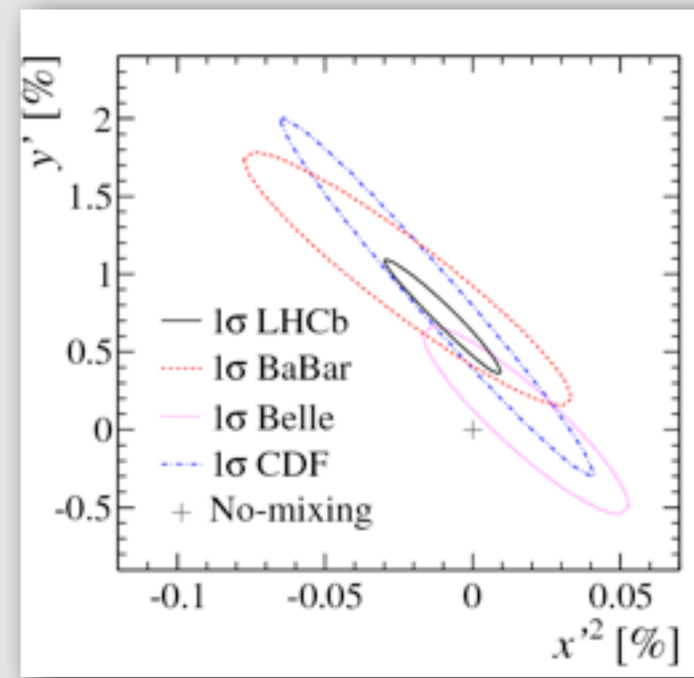
- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference

Phys. Rev. Lett. 110, 101802 (2013)

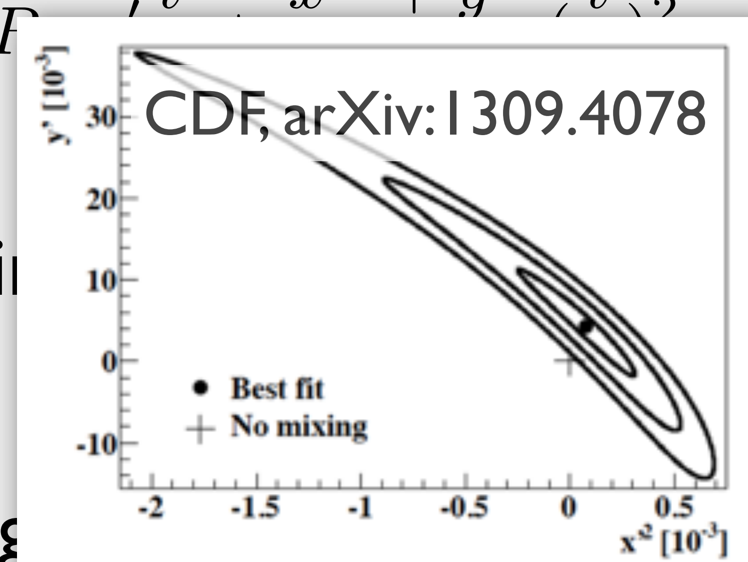
Mixing discovery



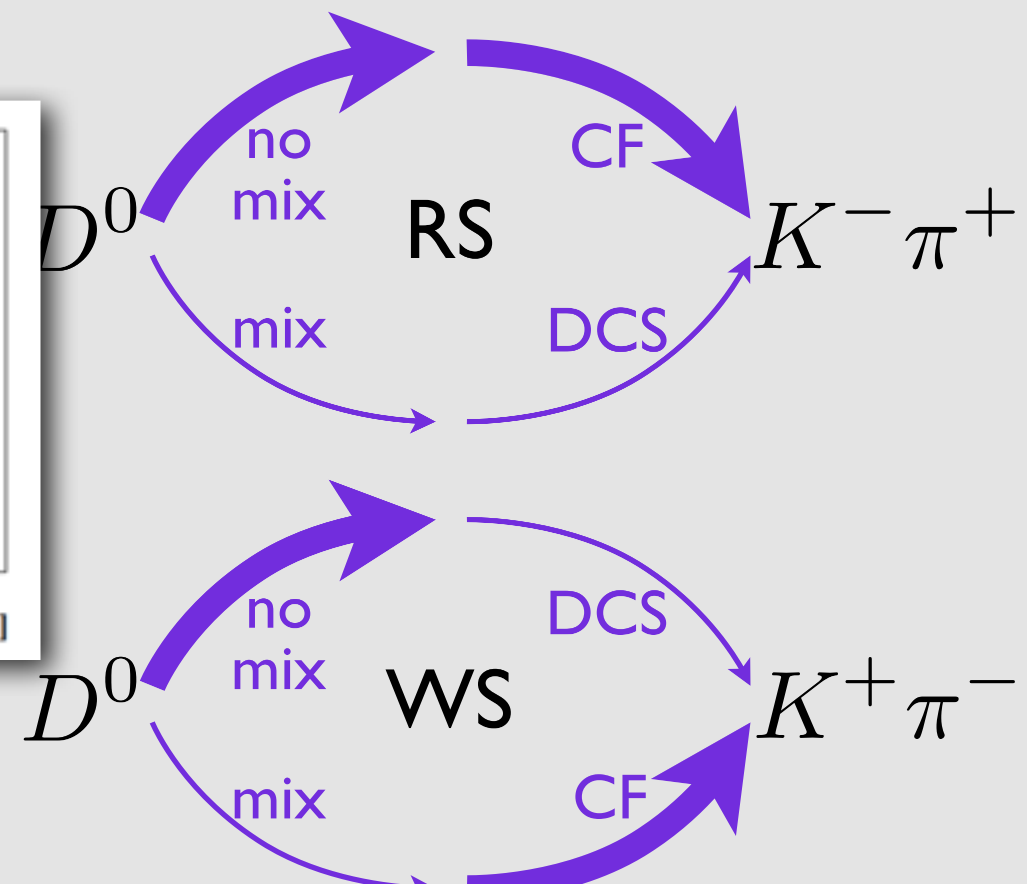




$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R \quad \frac{t}{} \quad \frac{x'^2 + y'^2}{} \quad t$$



- First single-experi… >5σ significance
- Rotation of mixing… strong phase difference



Phys. Rev. Lett. 110, 101802 (2013)

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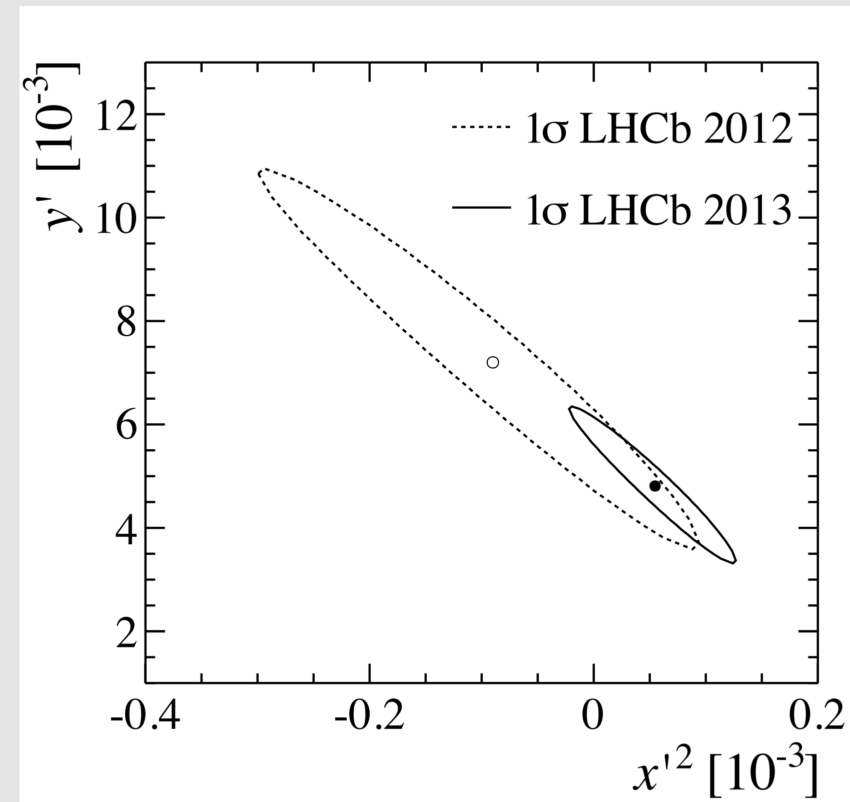
Mixing and CP violation

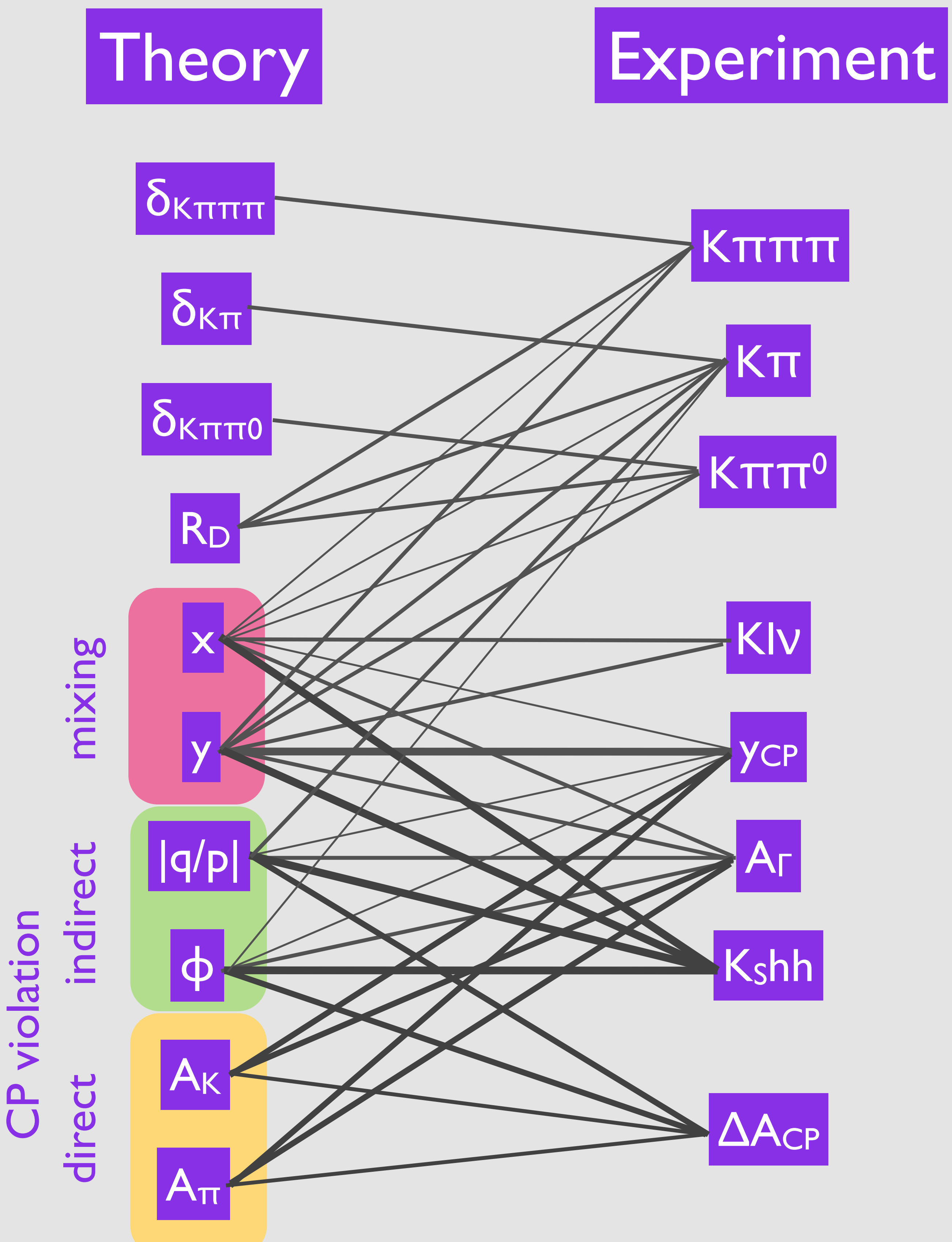
- Update with 3 fb^{-1}
- Split by flavour to search for CP violation
  - ➡ $x'^{\pm}=|q/p|^{\pm1}(x' \cos\Phi \pm y' \sin\Phi)$
  - ➡ $y'^{\pm}=|q/p|^{\pm1}(y' \cos\Phi \mp x' \sin\Phi)$
- No indication for CP violation



LHCb-PAPER-2013-053
accepted by PRL

R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$

Interplay



- Additional measurement possibilities available for mixing and indirect CPV
- Interplay with direct CPV
- $K_S hh$ proven very powerful by B-factories
- All these measurements are ongoing or in preparation at LHCb

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Access to theory parameters

- $A_\Gamma \approx A_M\, y \cos\Phi + x \sin\Phi$,
  $A_M \equiv (|q/p| - |p/q|) / (|q/p| + |p/q|)$
  - ➡ Need input on mixing parameters to gain sensitivity on $|q/p|$ and Φ
- $y_{CP} \approx y \cos\Phi + A_M\, x \sin\Phi$
  - ➡ Gives access to y for small Φ
- WS $K\pi$ $(x', y') = (x, y)$ rotated by δ
  - ➡ Good access to $|q/p|$

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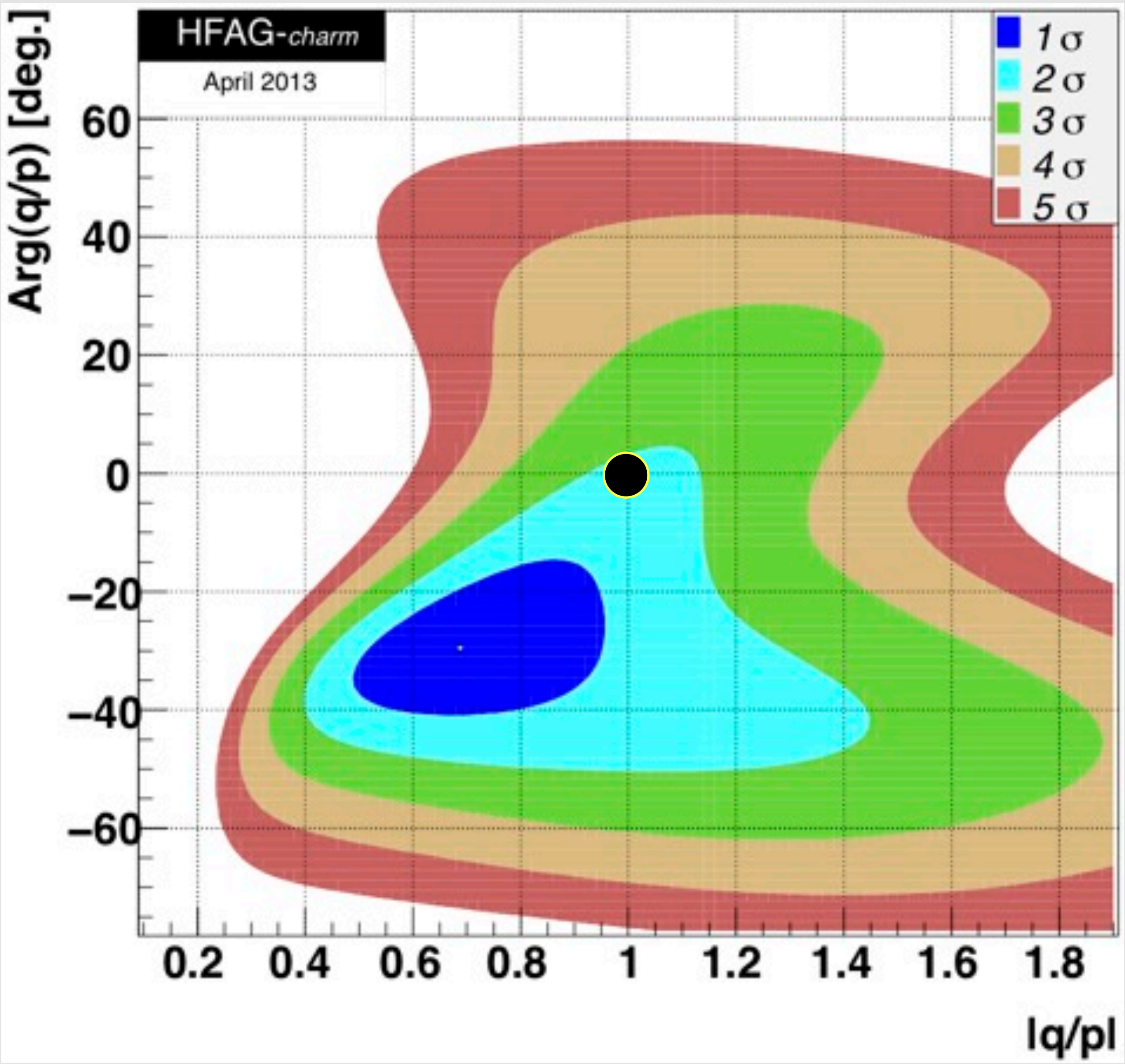
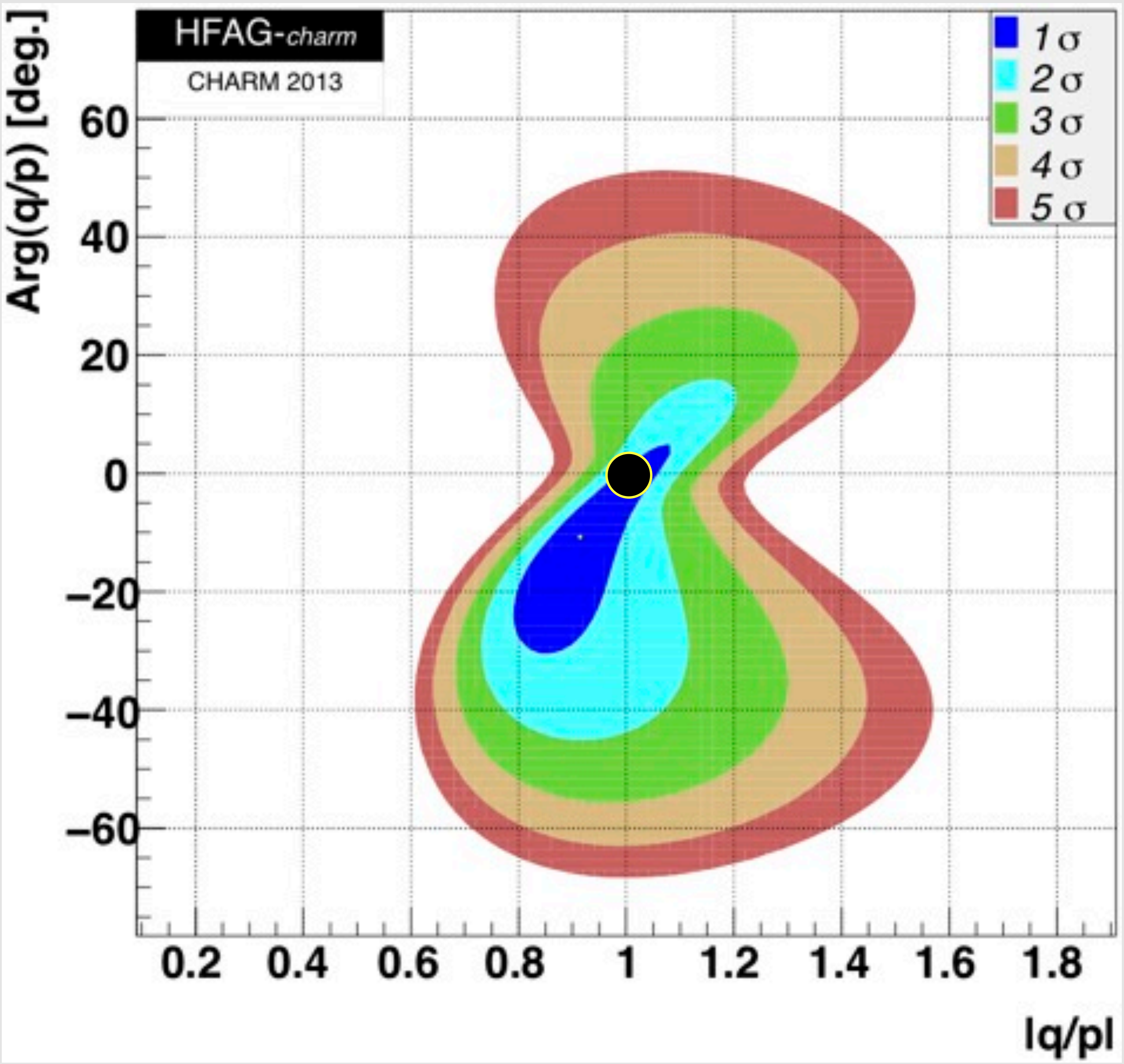
CHARM (r)evolution



BEFORE

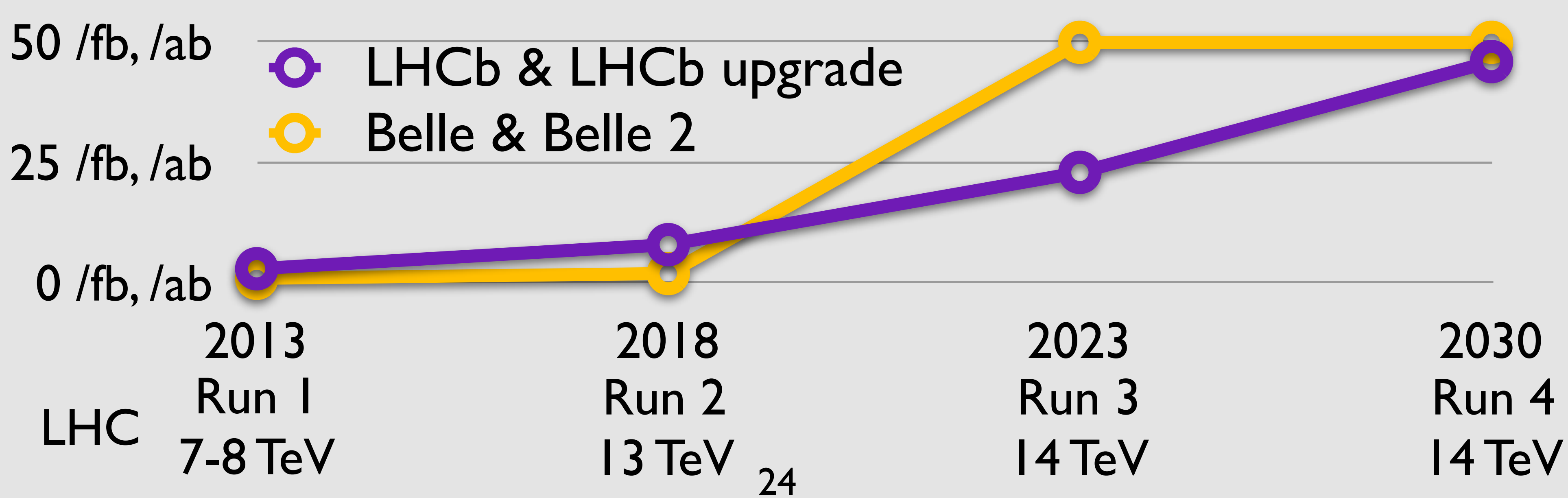


AFTER

Towards a charming future

The agenda

- Charm physics has proven to be successful at both e^+e^- and hadron colliders
- Expect most measurements to be statistics limited and most question to remain open
- Next generation experiments: precision charm physics
  - ➡ Belle 2 construction underway
  - ➡ LHCb upgrade in R&D stage



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Future interplay

- Study expected LHCb-only sensitivities to indirect CP violation parameters
- Involves several measurements
  - ➡ $K_S\pi\pi$
  - ➡ $A_\Gamma(KK)$, $A_\Gamma(\pi\pi)$
  - ➡ WS mixing and CPV in $D^0 \to K\pi$
- Use promptly produced $D^* \to D^0\pi$ decays only
  - ➡ Large sample of $B \to D^0\mu X$ decays with complementary decay-time coverage not included
- Use statistical uncertainties only
  - ➡ Extrapolated using production cross-section increase ($\propto\sqrt{s}$) and assumed changes in trigger efficiency (worse for Run 2, better thereafter)
- Central values based on published results (LHCb-PAPER-2013-053, LHCb-PAPER-2013-054) and extrapolation from Belle $D^0 \to K_S\pi\pi$ (PRL 99 (2007) 131803)

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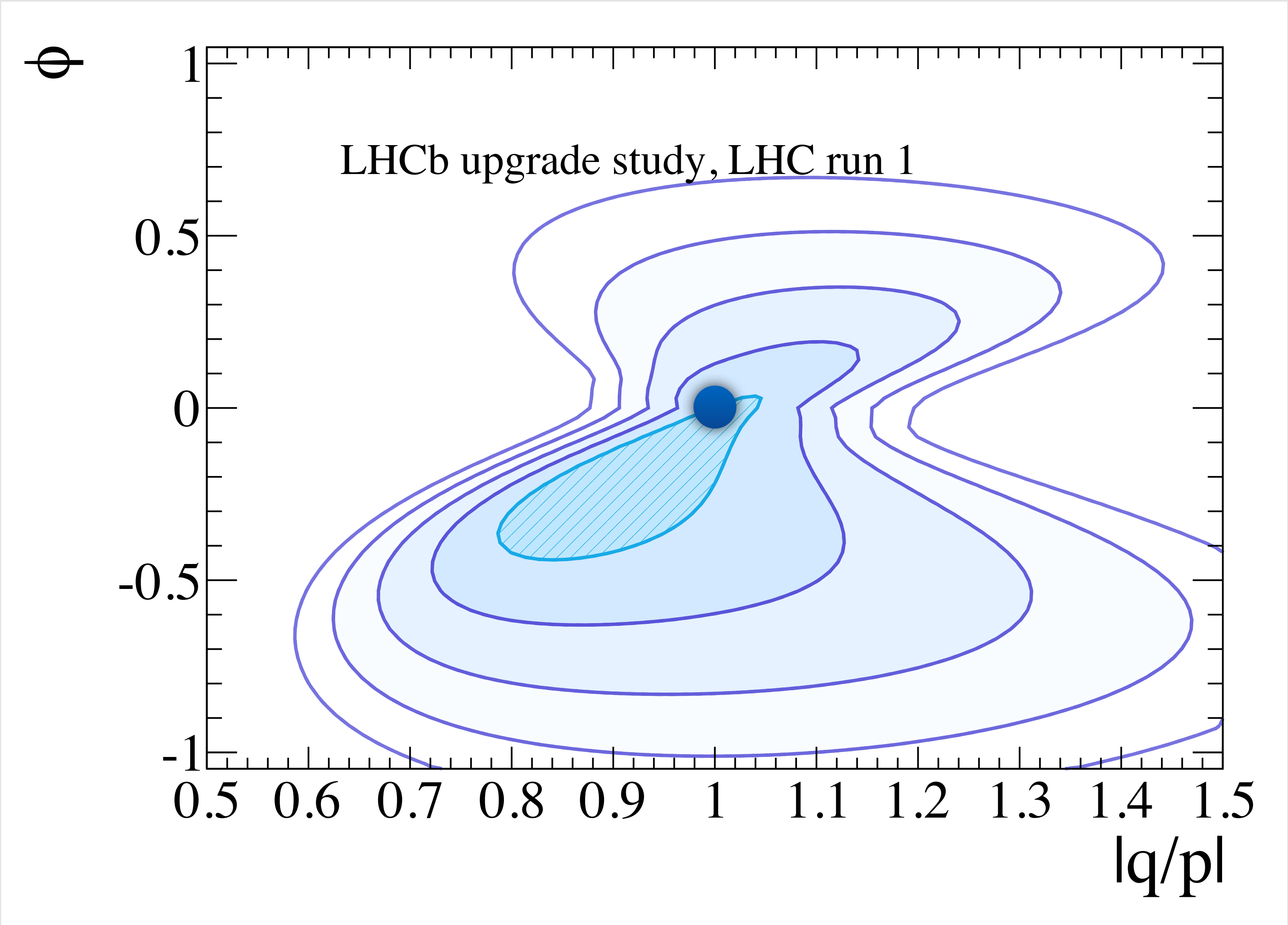
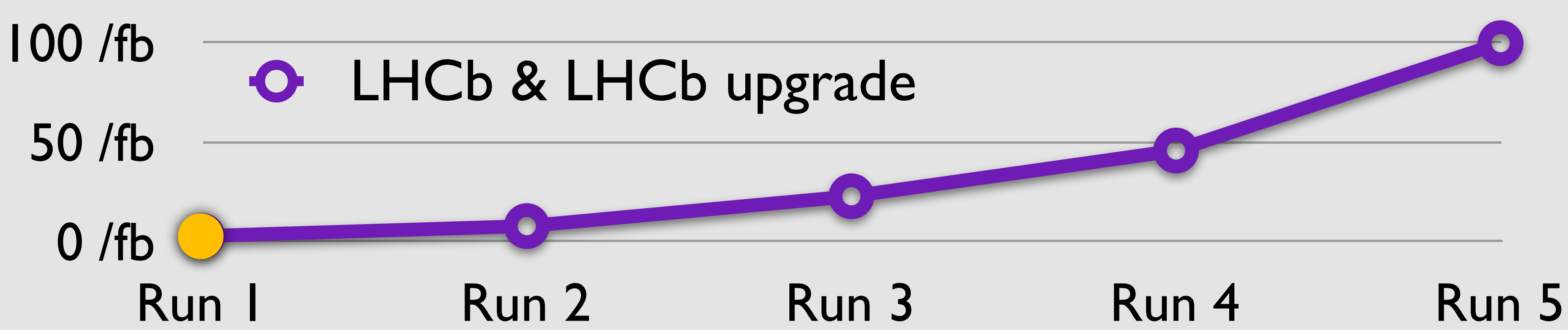
Future interplay





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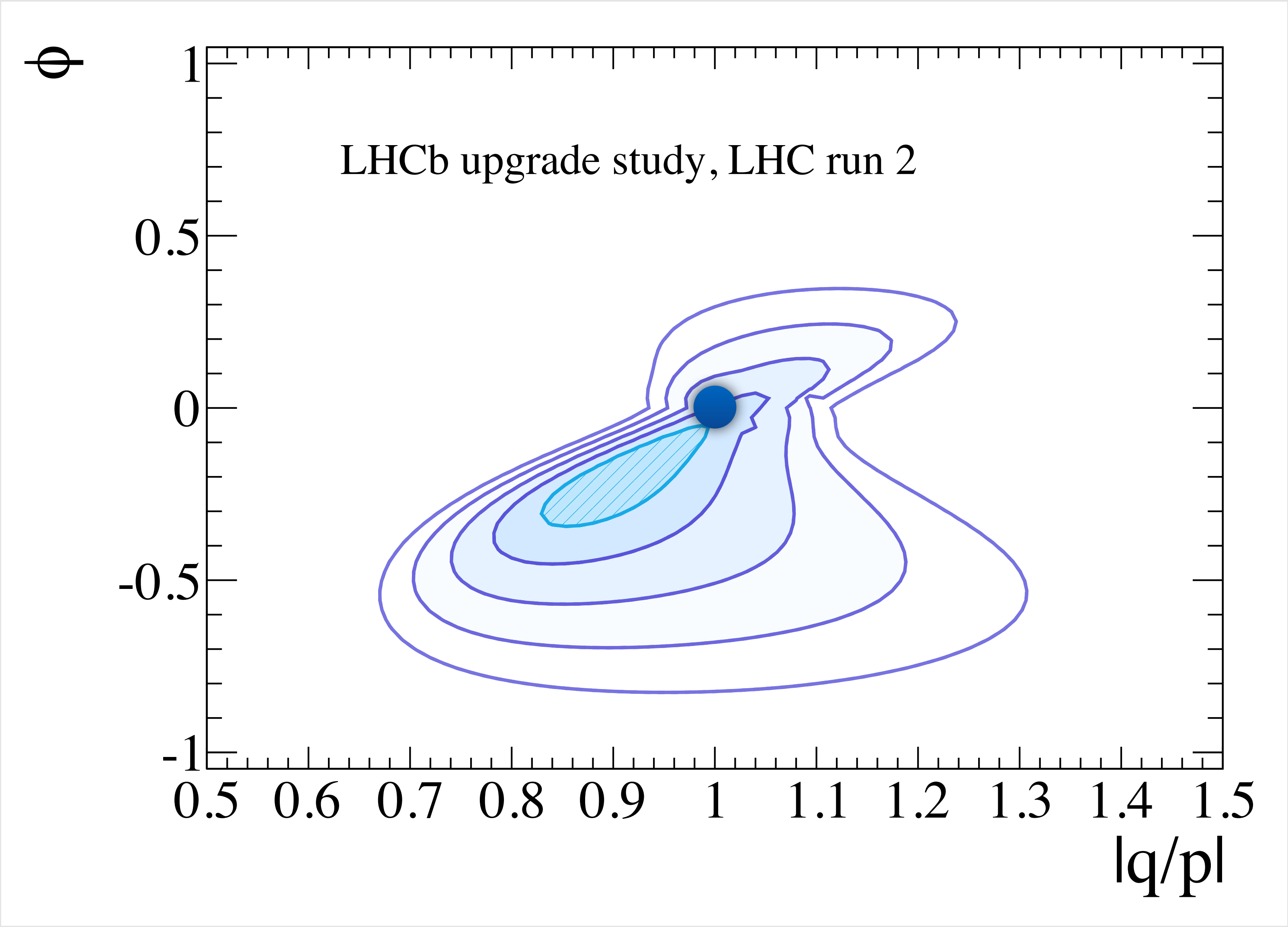
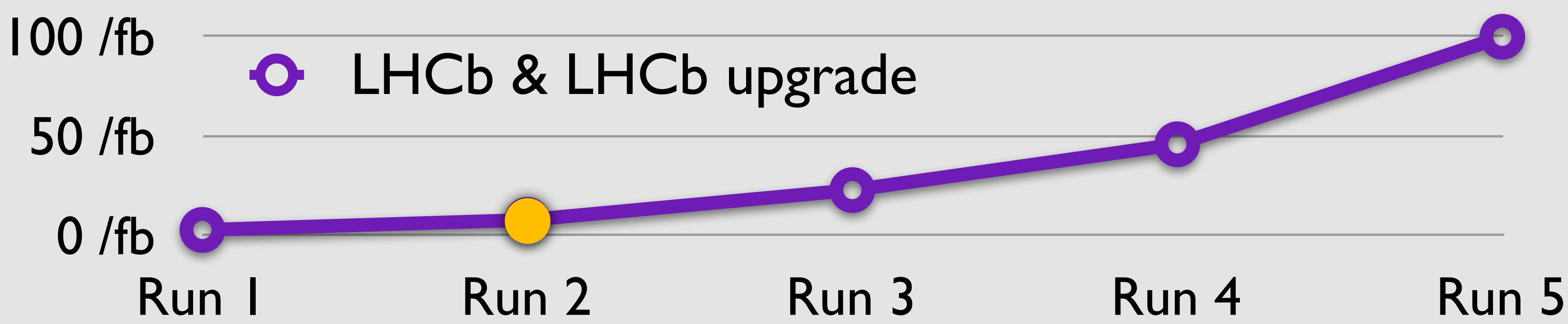
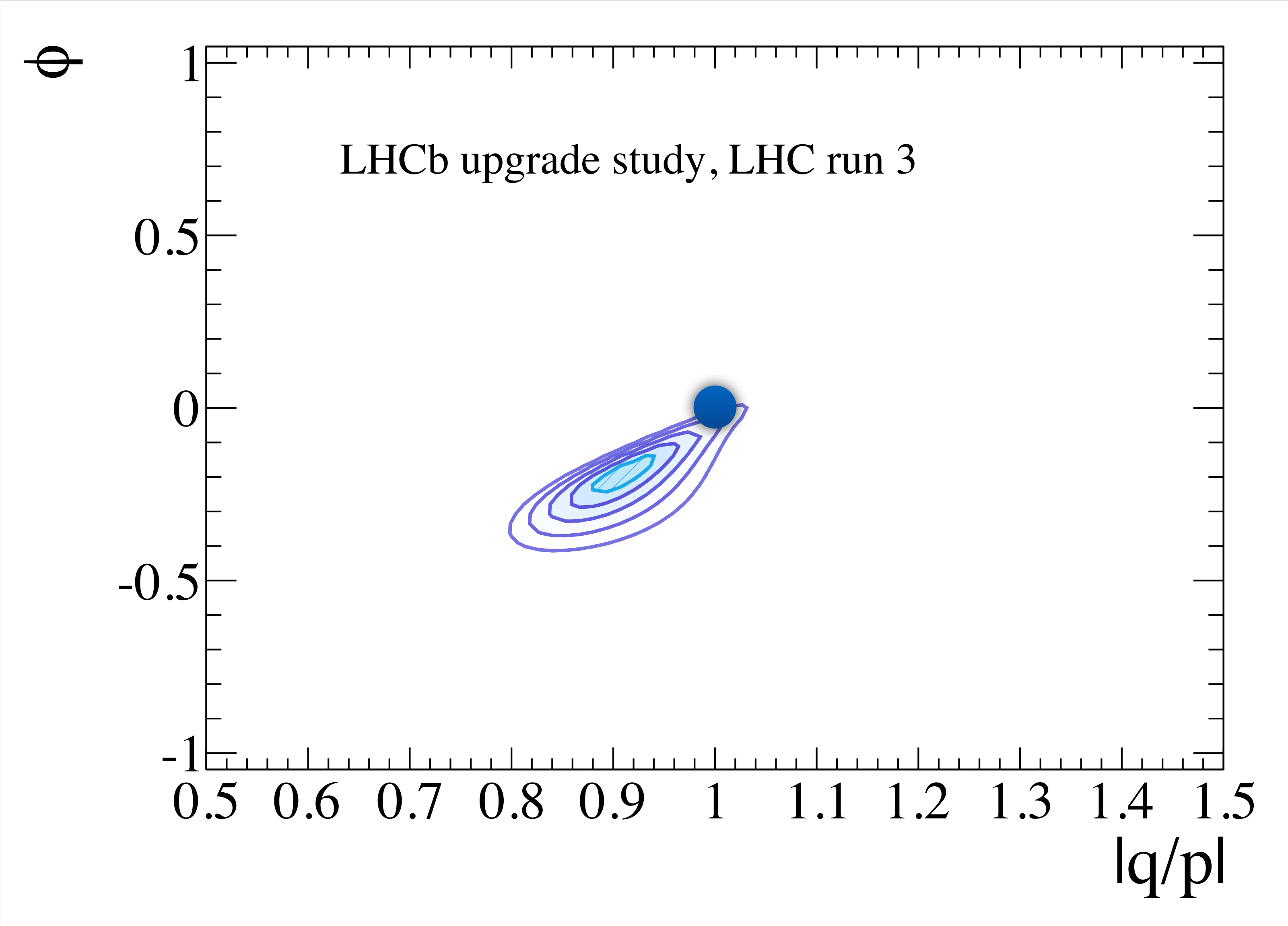
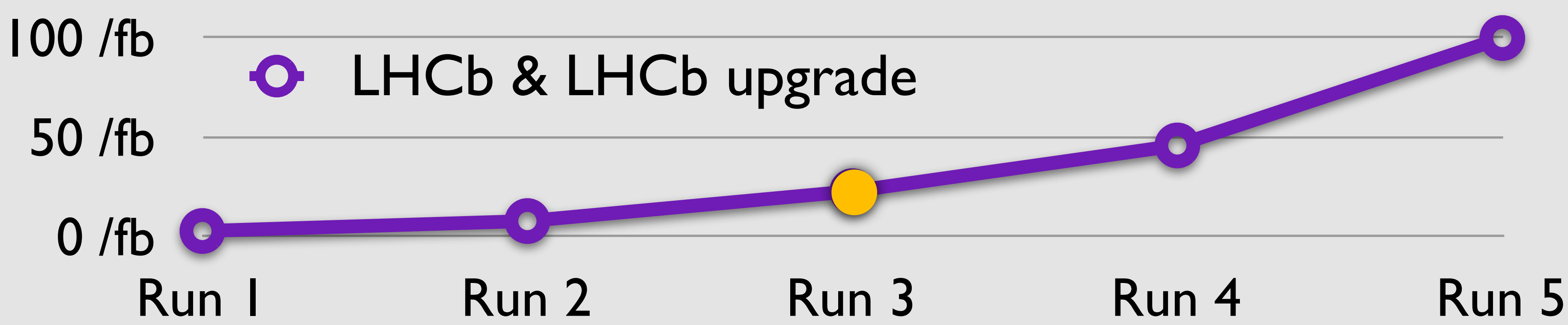


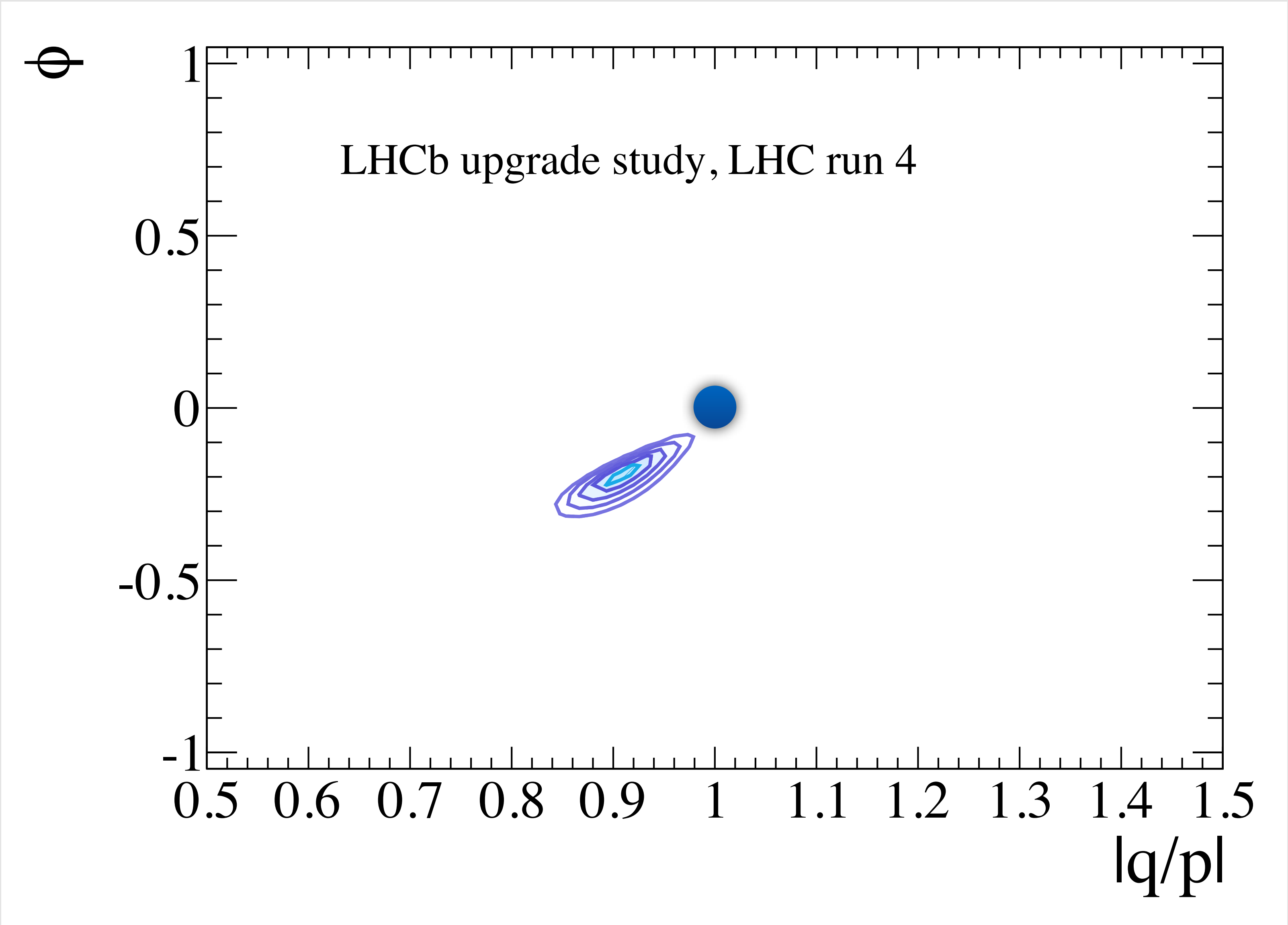


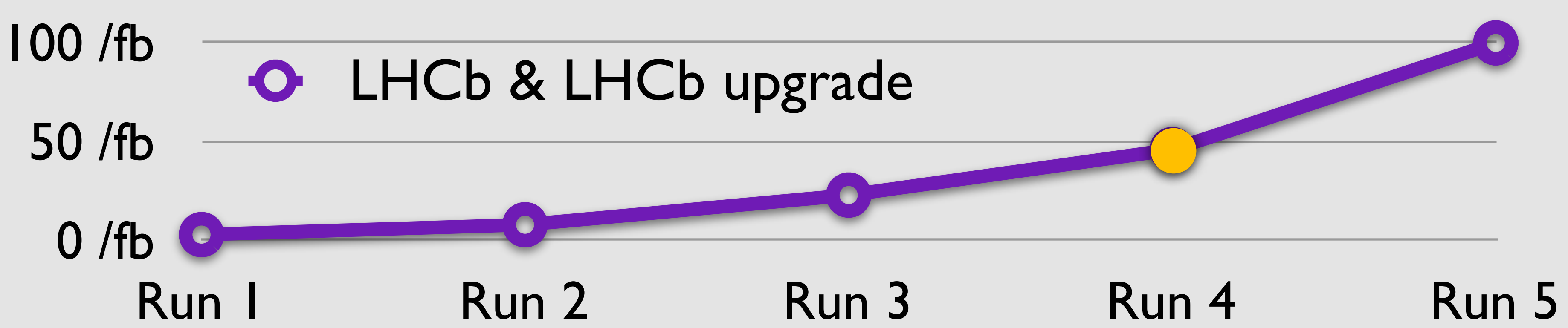
Future interplay



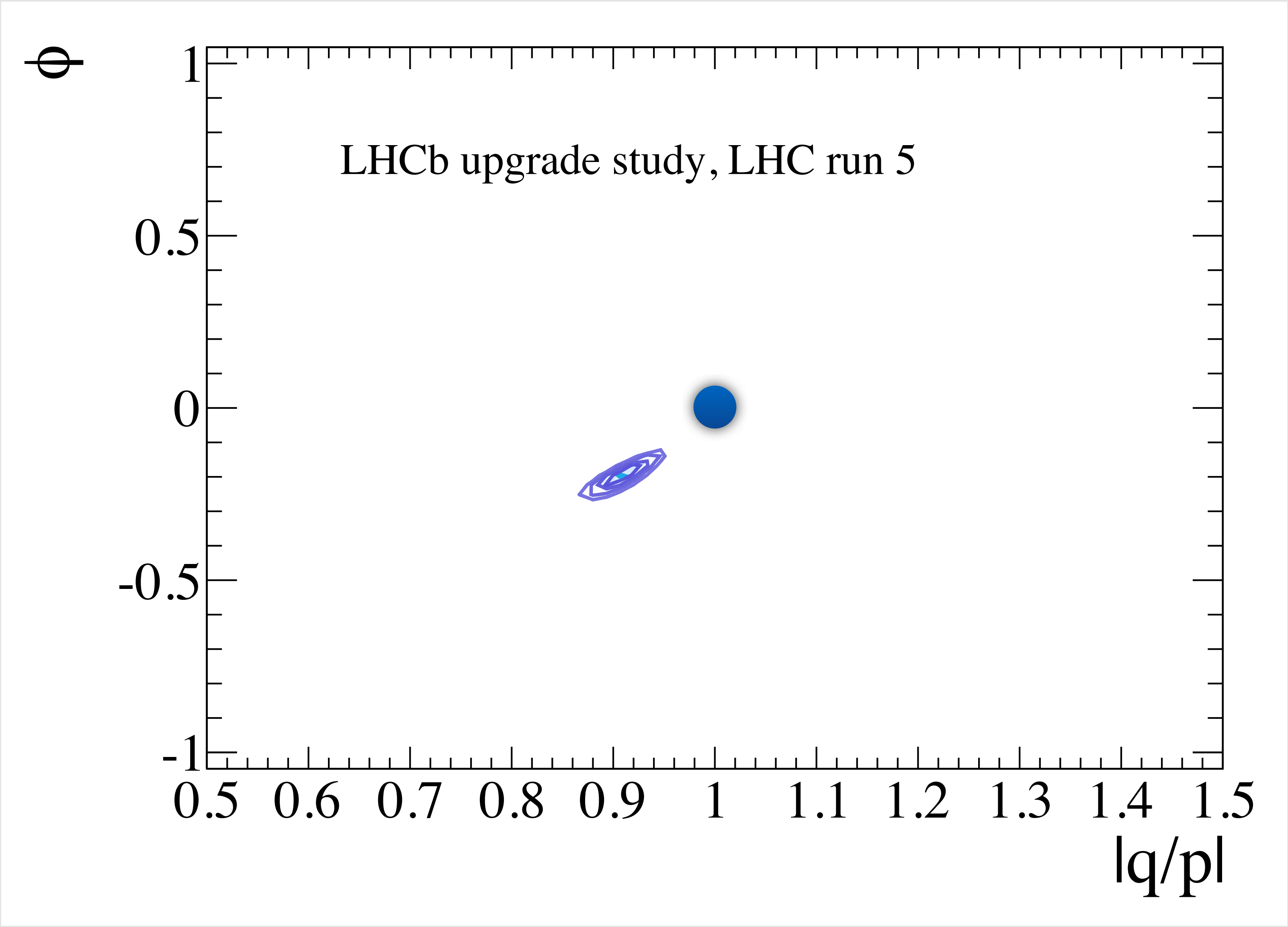


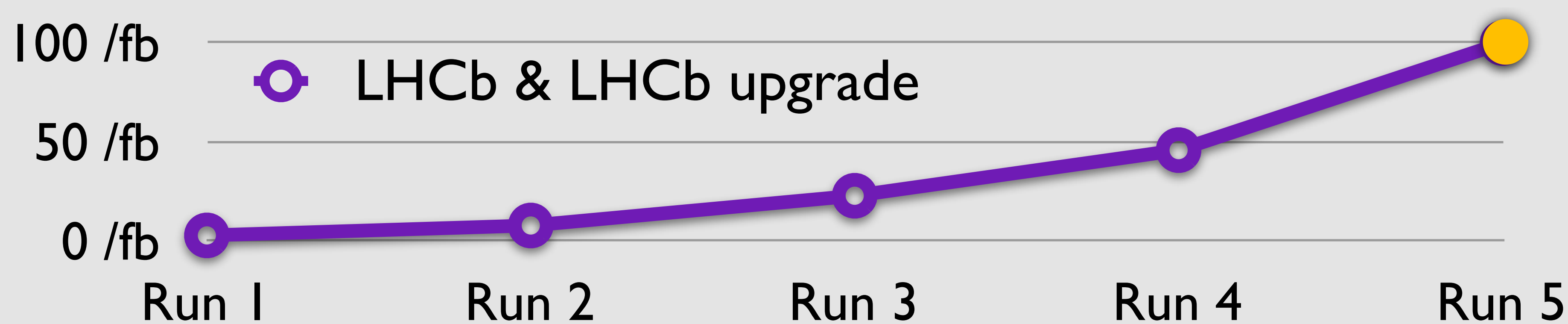
Future interplay

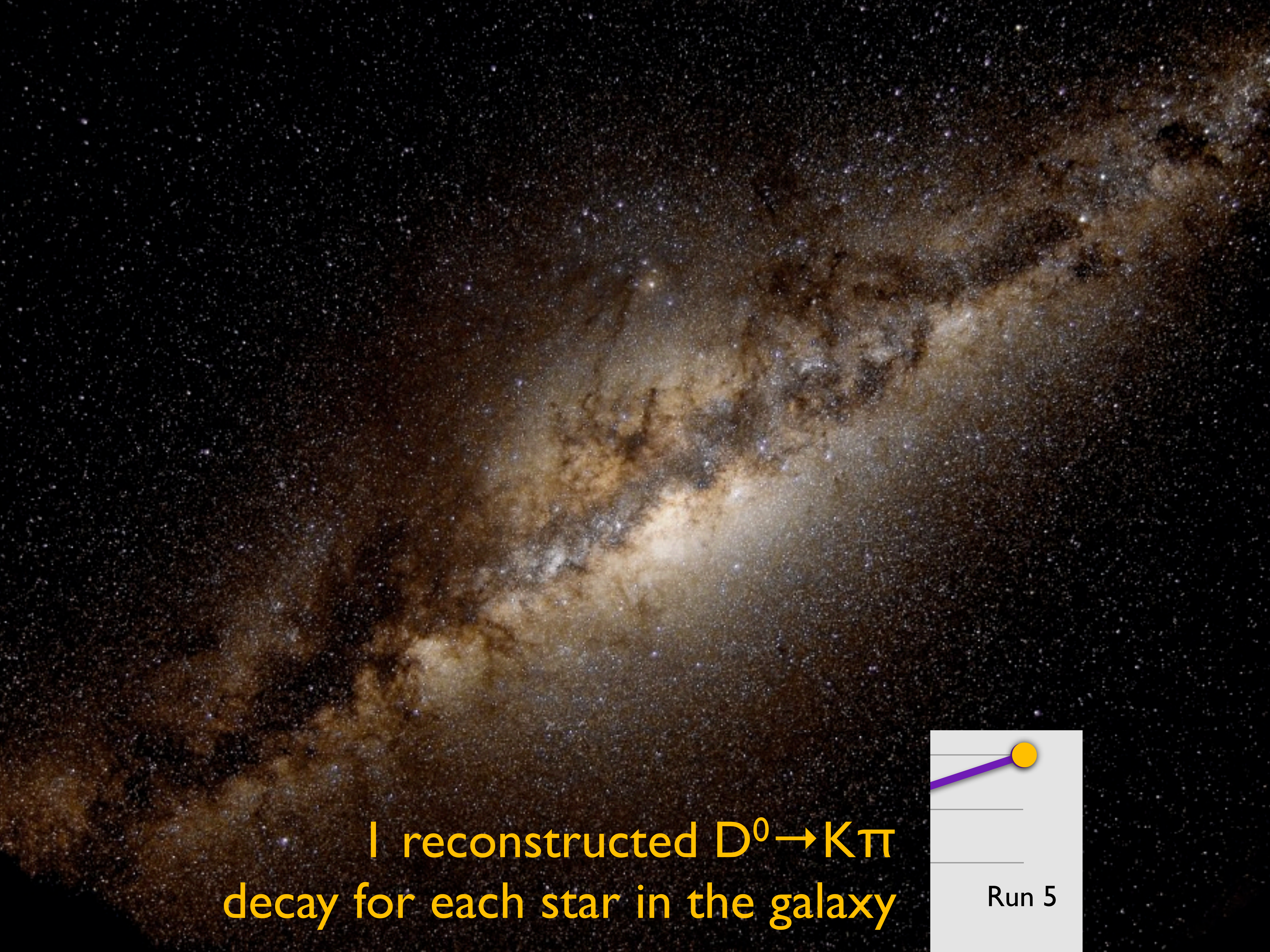




Future interplay

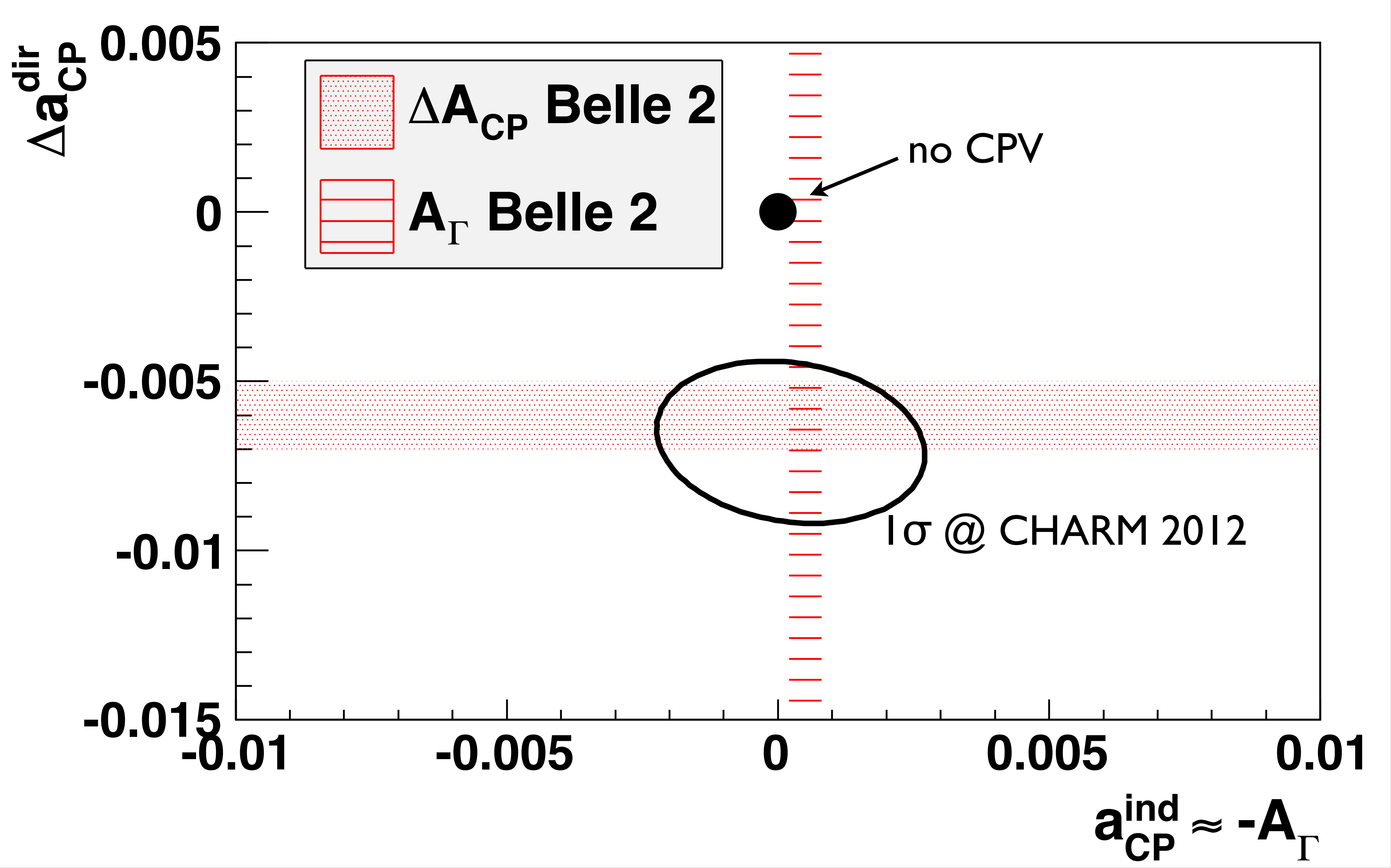




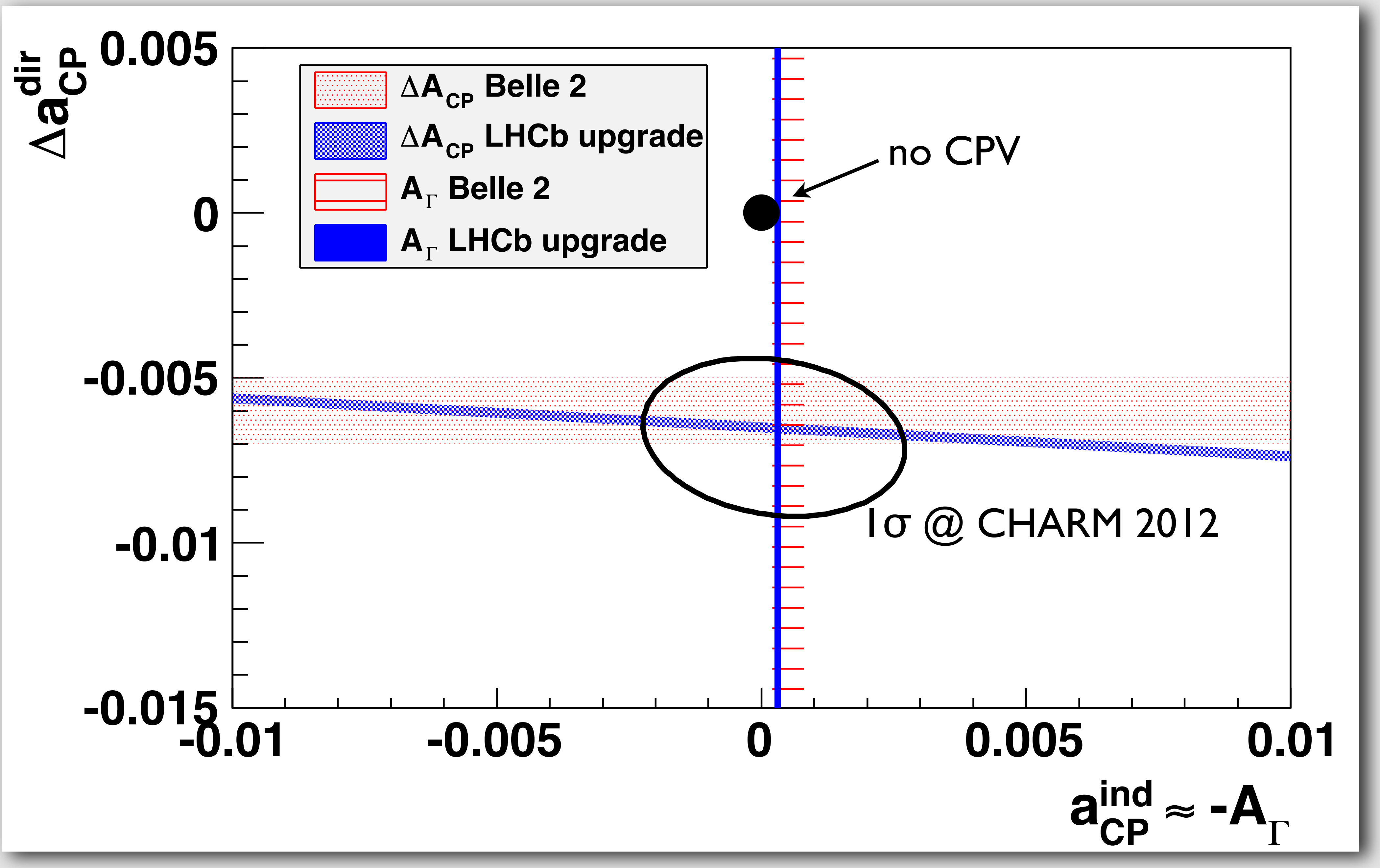


1 reconstructed $D^0 \to K\pi$ decay for each star in the galaxy

Future interplay - II



Future interplay - II



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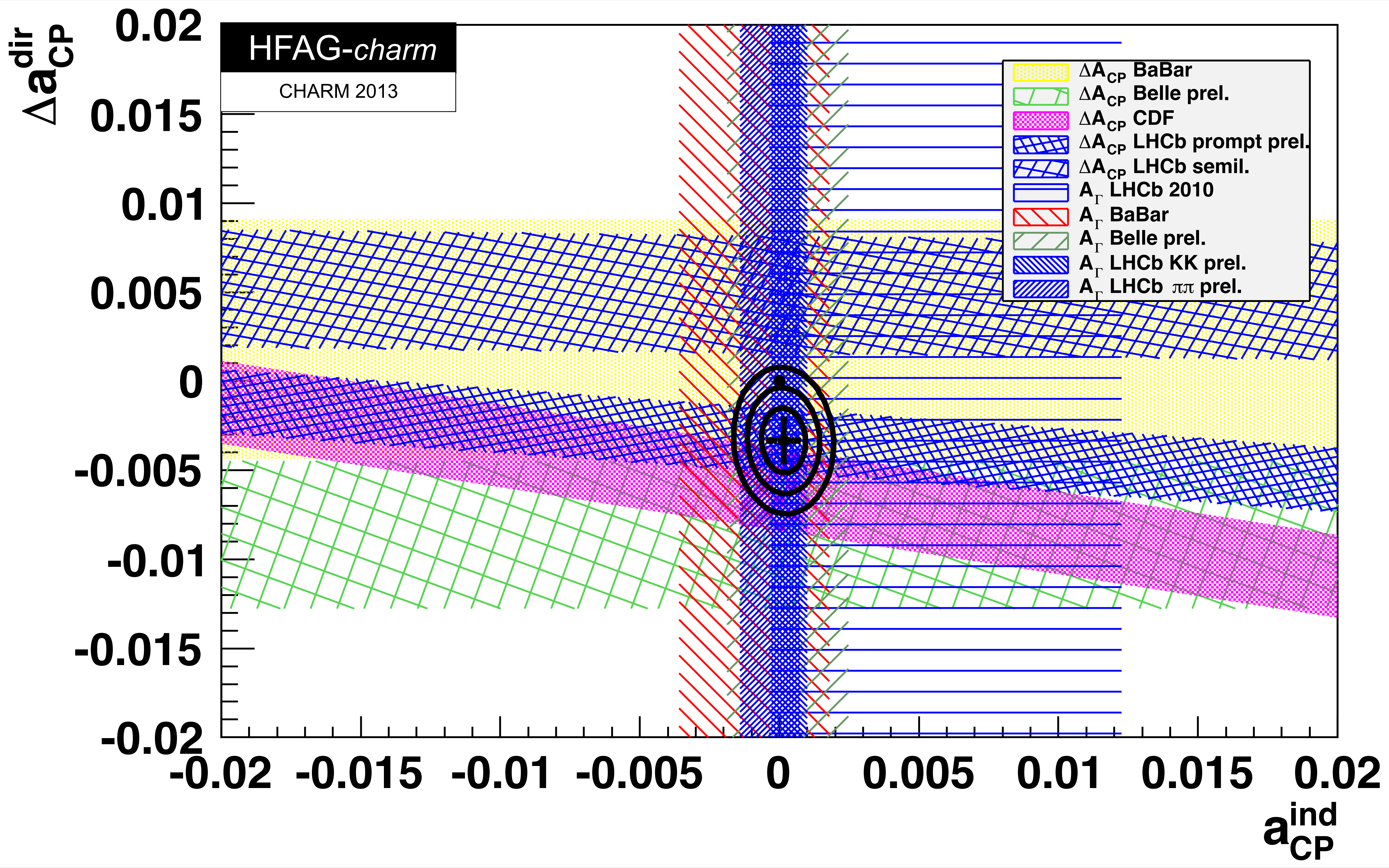
Conclusions

- Charm physics has received precision input from hadron colliders
- Large advances in searches for CP violation
  - ➡ Reached sub-10^{-3} precision
  - ➡ Also large numbers of charm baryons available
- Need combination of measurements to
  - ➡ Extract mixing and indirect CPV parameters
  - ➡ Identify source of possible direct CPV
- Experimental upgrade programmes, particularly LHCb upgrade, vital for charm physics

Backup


HFAG-charm
CHARM 2013
Δa_{CP}^{dir}
a_{CP}^{ind}
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
ΔA_{CP} BaBar
ΔA_{CP} Belle prel.
ΔA_{CP} CDF
ΔA_{CP} LHCb prompt prel.
ΔA_{CP} LHCb semil.
A_{Γ} LHCb 2010
A_{Γ} BaBar
A_{Γ} Belle prel.
A_{Γ} LHCb KK prel.
A_{Γ} LHCb $\pi\pi$ prel.

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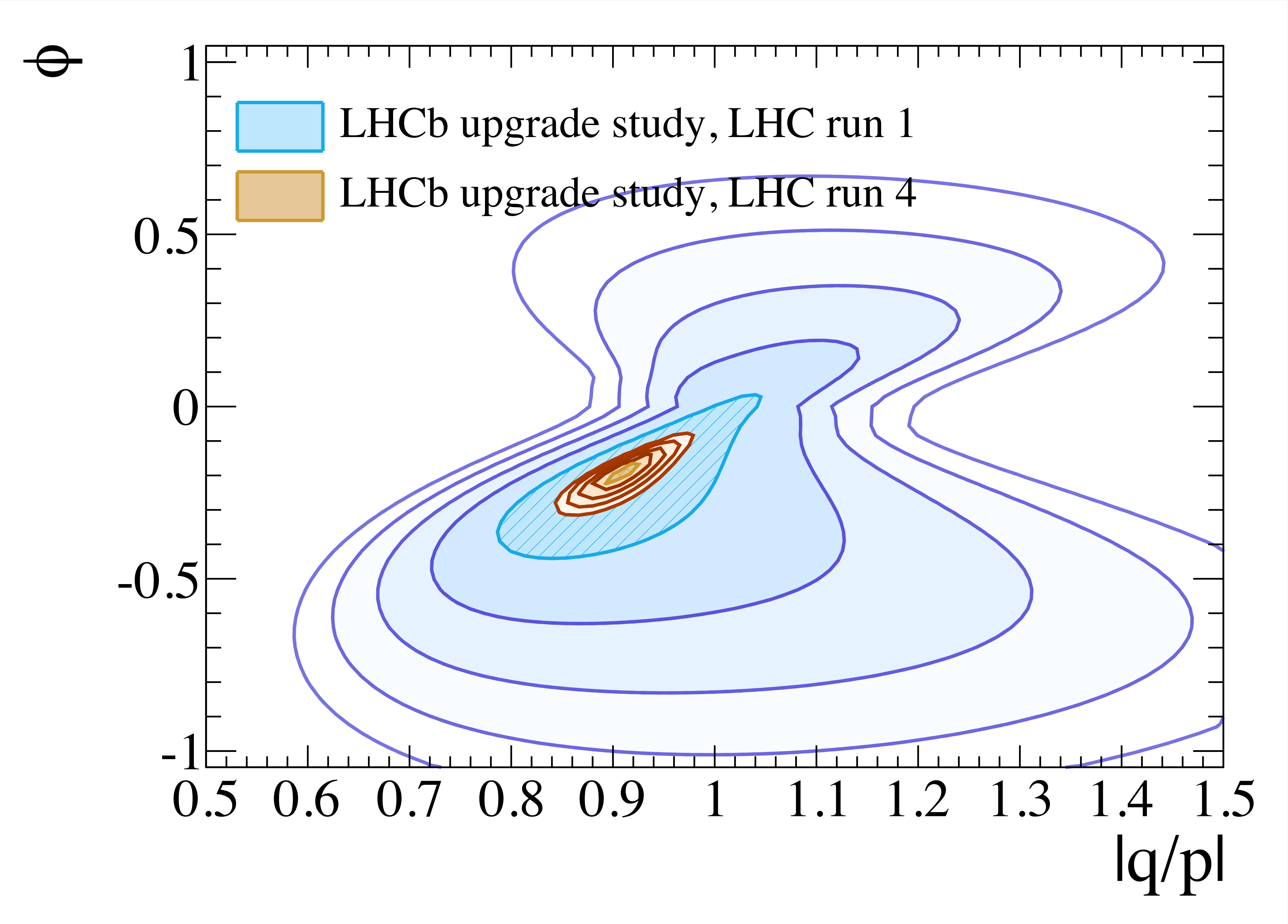
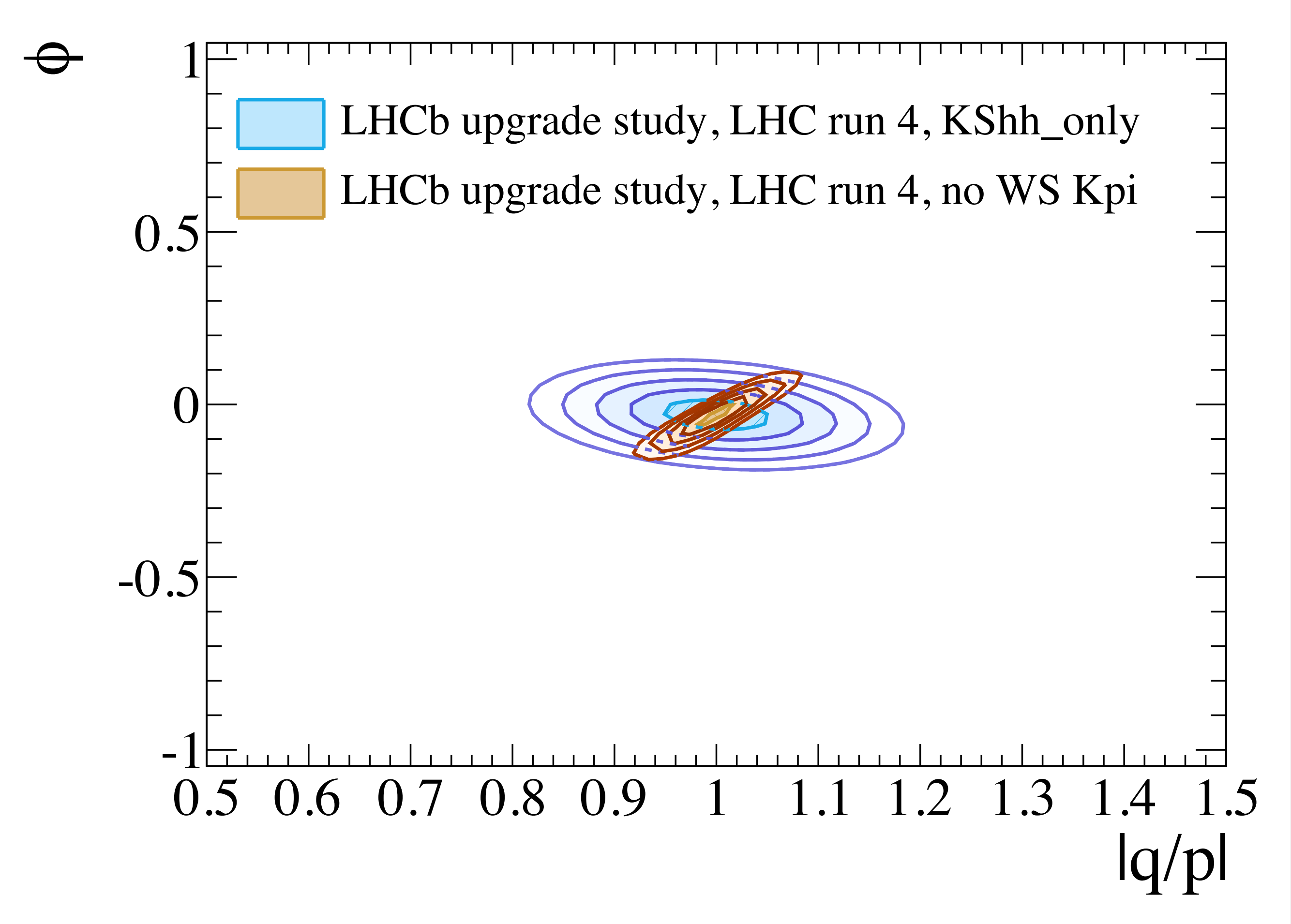
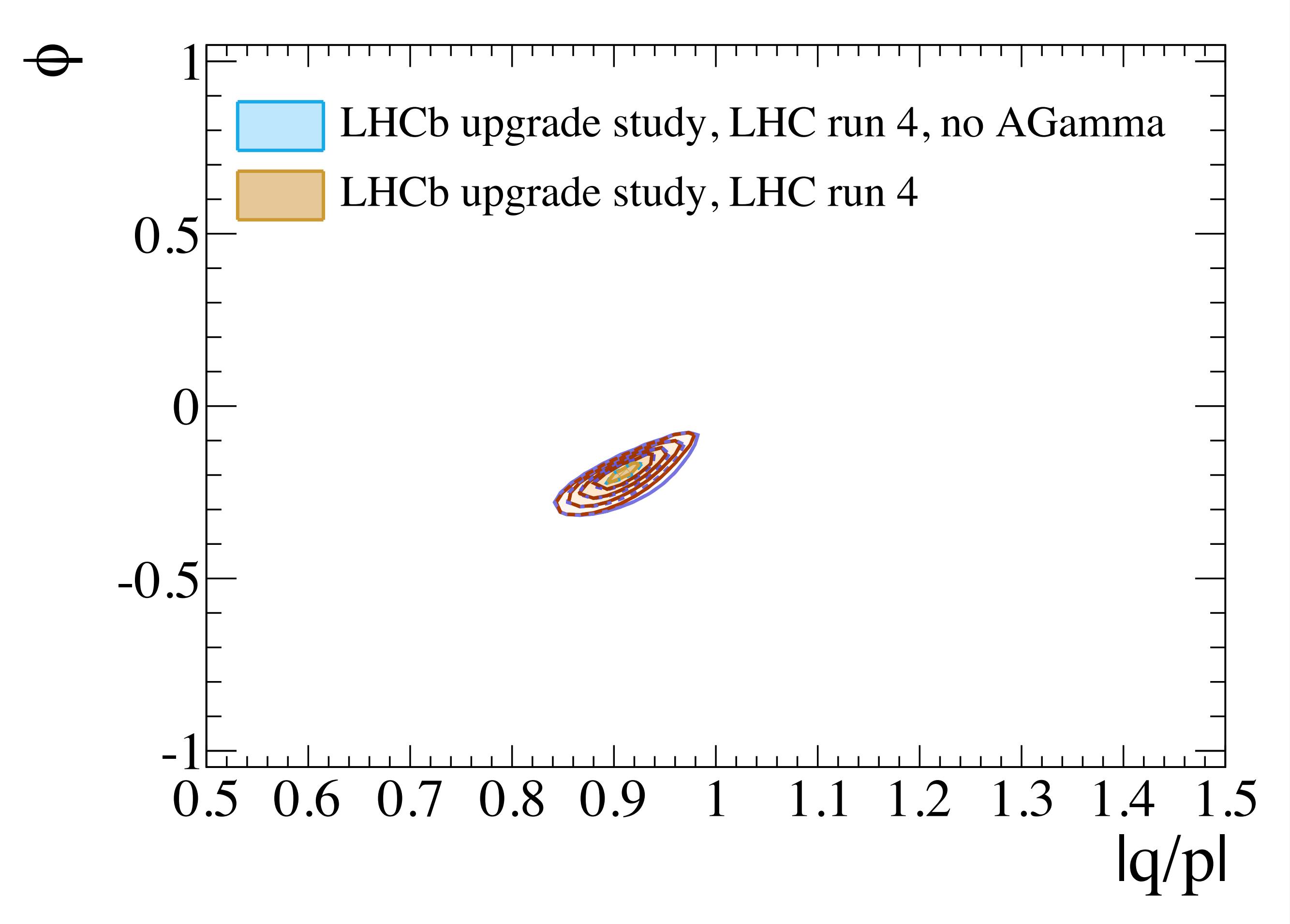
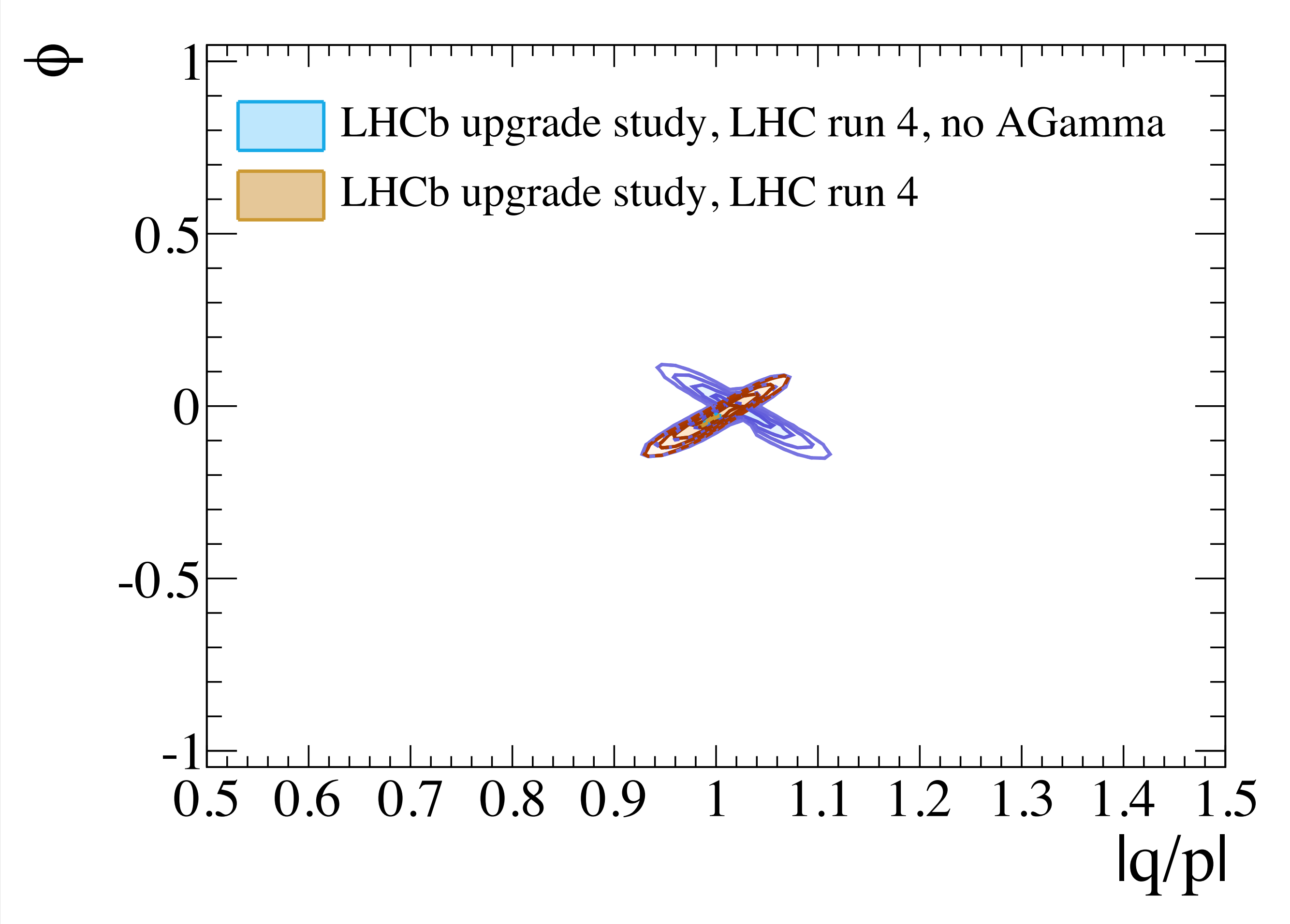



φ
LHCb upgrade study, LHC run 4, KShh_only
LHCb upgrade study, LHC run 4, no WS Kpi
1
0.5
0
-0.5
-1
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
|q/p|


φ
LHCb upgrade study, LHC run 4, no AGamma
LHCb upgrade study, LHC run 4
1
0.5
0
-0.5
-1
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
|q/p|


φ
LHCb upgrade study, LHC run 4, no AGamma
LHCb upgrade study, LHC run 4
1
0.5
0
-0.5
-1
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
|q/p|