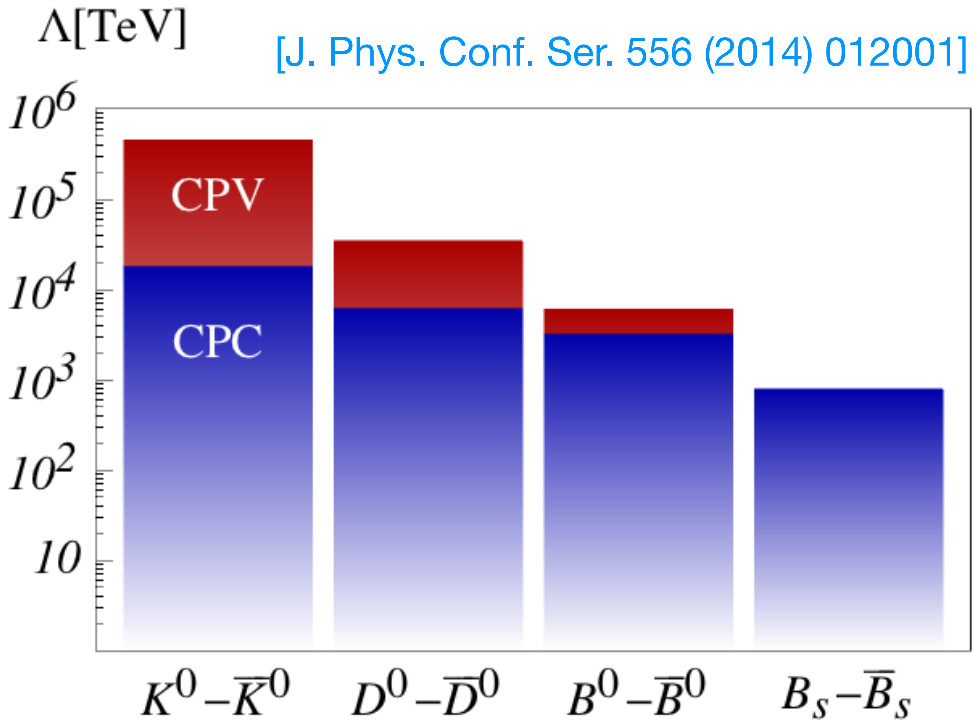
LHCP2015
August 31-September 5 2015
St Petersburg, Russia

# LHCb results on charm mixing, decay and CP violation

Angelo Di Canto (CERN) on behalf of LHCb

# Why is charm charming?

- Unique and powerful probe of flavour effects beyond the standard model
- Charm quark is the only up-type quark for which we can study mixing and CPV
    - Complements searches done in K and B systems, interplays with high-$p_T$ (top physics) and low-energy (EDMs) probes
    - Gives the best bounds on generic new physics models after kaon mixing
- LHCb has the opportunity to exploit fully the charm sector as a probe for new physics



[J. Phys. Conf. Ser. 556 (2014) 012001]

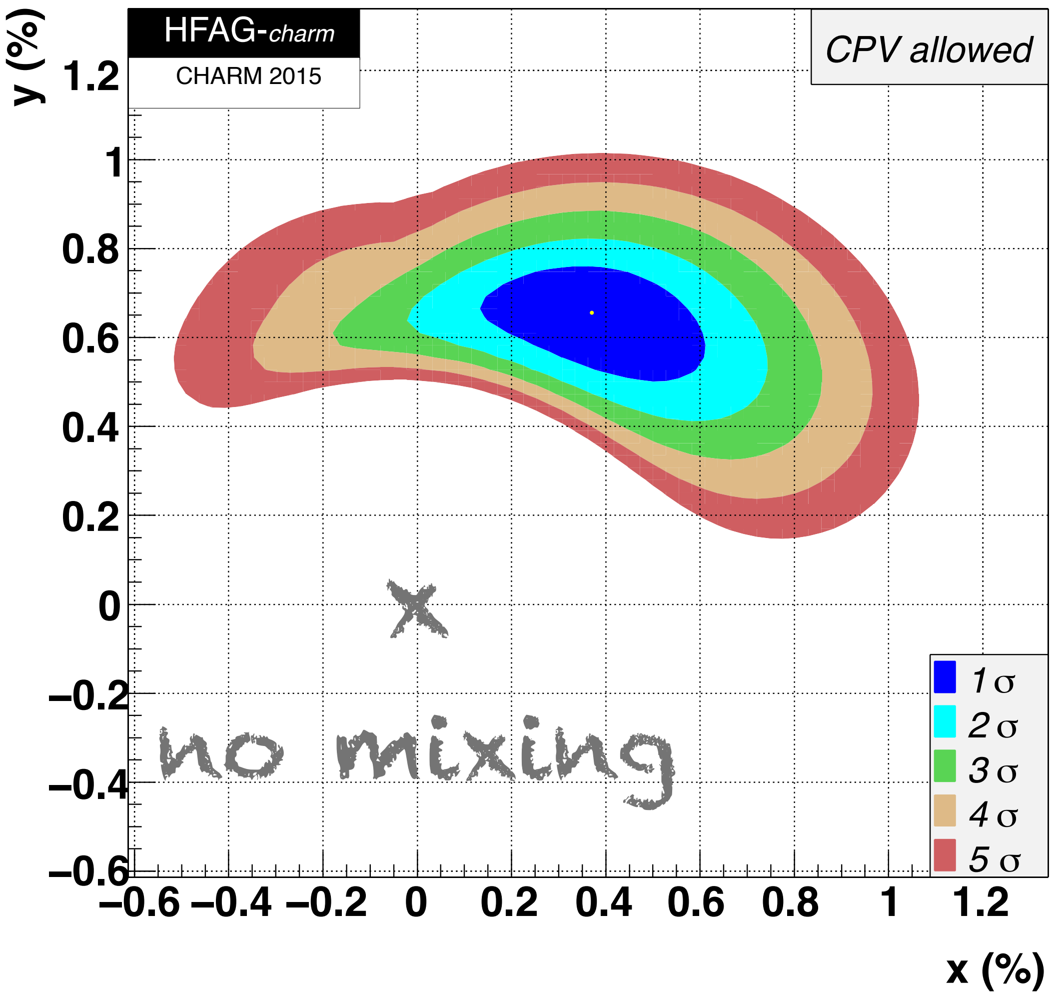
# Charm mixing and CP violation

- Mixing is well established, but CP violation is not
- Available mixing measurements are mostly based on decays to two-body final states
  - These are primarily sensitive to y (x≤0 excluded only at 2.1σ)
- It is crucial to improve sensitivity on x as the most sensitive CP-violation observables are proportional to x sin$\phi$
  - Need more measurements of multibody decays

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$x = (m_1 - m_2)/\Gamma$$

$$y = (\Gamma_1 - \Gamma_2)/2\Gamma$$

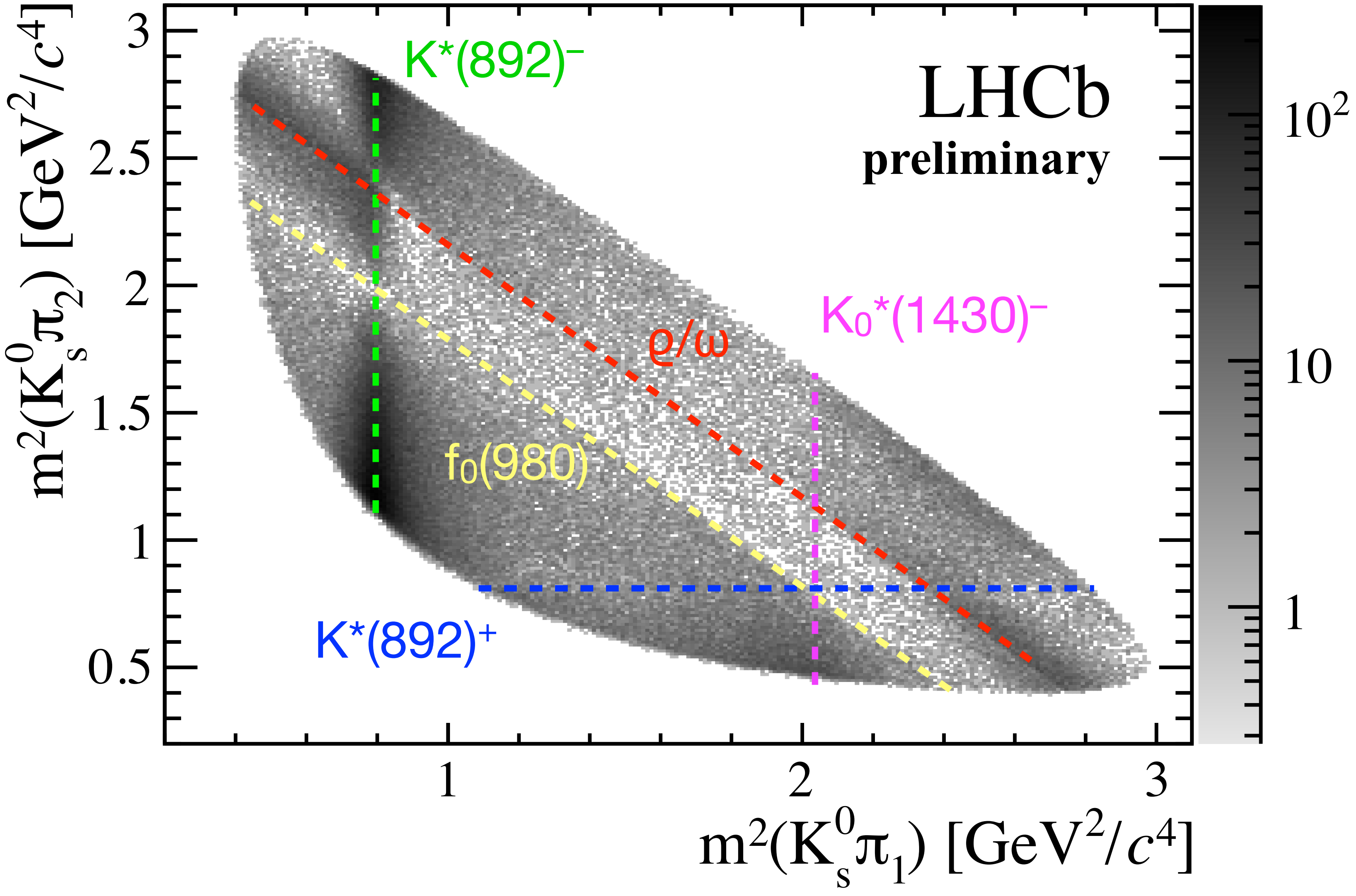


New for LHCP

# First LHCb measurement of charm mixing with multibody decays

# Mixing with $D^0 \rightarrow K_S \pi^+ \pi^-$

$$\mathcal{P}_{D^0} \propto e^{-\Gamma t}\{|\mathcal{A}_{D^0}|^2 - \mathrm{Re}[\mathcal{A}^*_{D^0}\mathcal{A}_{\overline{D}^0}(y+ix)]\Gamma t\}$$



- Multiple interfering amplitudes enhance the sensitivity to mixing
- Requires a challenging time-dependent Dalitz-plot analysis

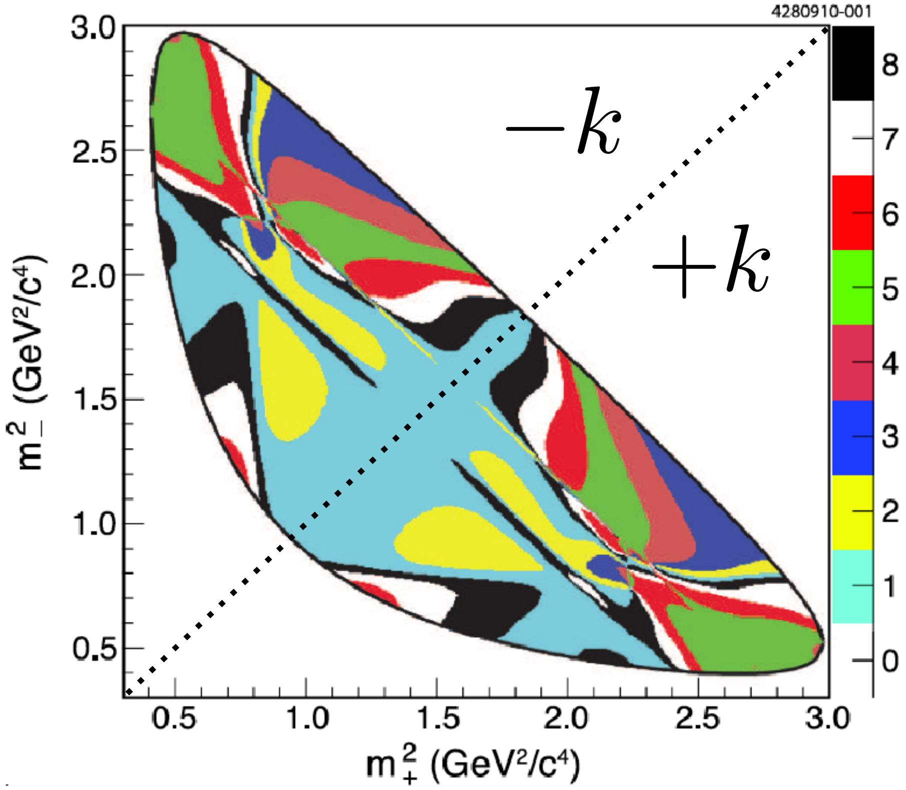
# $D^0 \rightarrow K_S \pi^+ \pi^-$ with a model-independent approach

- Avoid amplitude analysis by integrating over Dalitz-plot bins with constant strong-phase variation [PRD 82 (2010) 034033]

$$\mathcal{P}^k_{D^0} \propto e^{-\Gamma t}\left[T_k - \sqrt{T_k T_{-k}}(y c_k - x s_k)\Gamma t\right]$$

$$T_k = \int_k |\mathcal{A}_{D^0}|^2 \, d\mathcal{D}$$

$$c_k - i s_k = \frac{1}{\sqrt{T_k T_{-k}}} \int_k \mathcal{A}^*_{D^0} \mathcal{A}_{\overline{D}^0} \, d\mathcal{D}$$



- Constrain hadronic parameters ($T_k$,$c_k$,$s_k$) to values measured by the CLEO experiment [PRD 82 (2010) 112006]

- Mostly insensitive to variation of efficiency over the Dalitz plot

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(in preparation)

# Analysis overview

- Flavour tagging provided by $D^{*+} \to D^0\pi^+$
- Simultaneous fit to all Dalitz bins
  - *$\Delta m$-$m(D^0)$* fit separates charm signal from background
  - *$t$-$\log(\chi^2_{IP})$* fit determines the time evolution separating primary D* from a small fraction of B→D*X decays.
- Decay-time acceptance determined from data
- Validated by measuring the $D^0$ lifetime consistent with the world-average value

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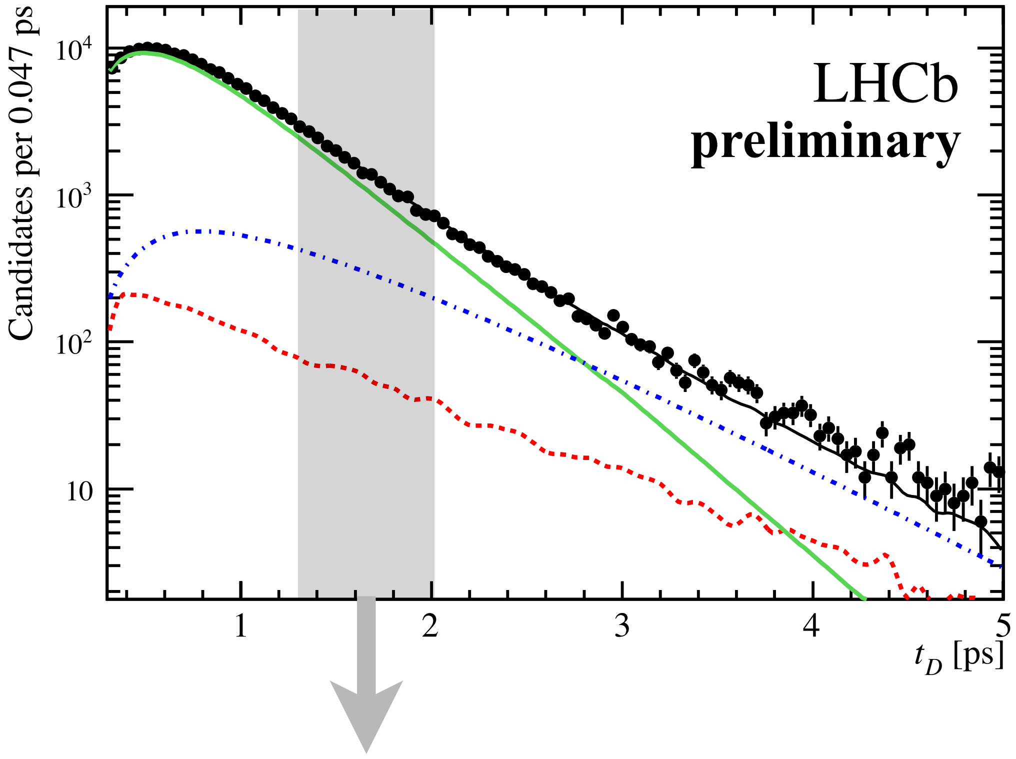
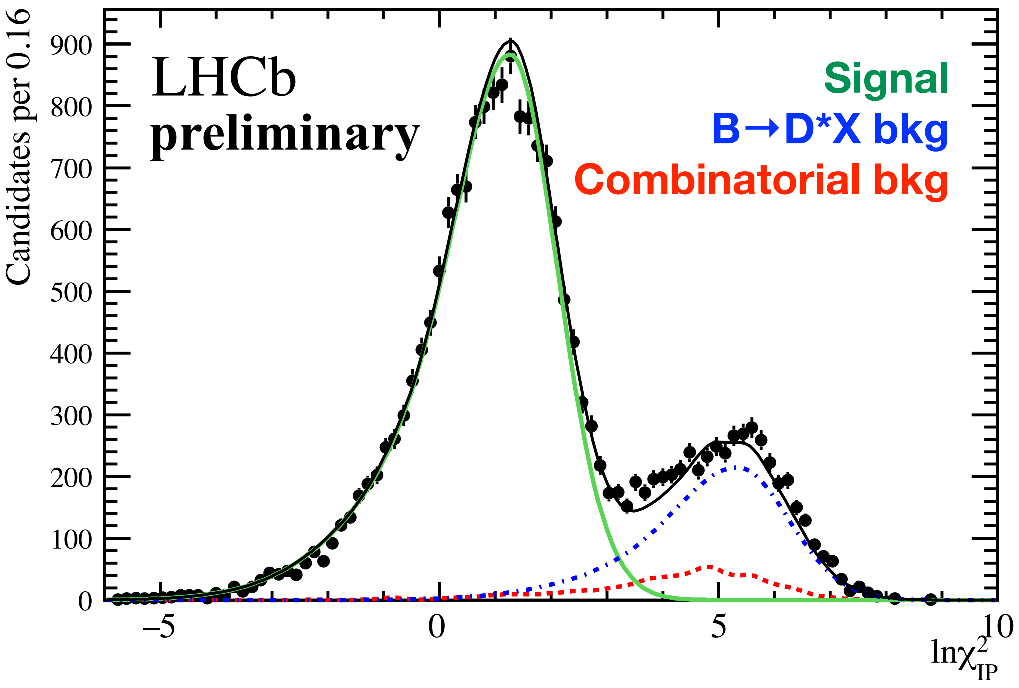
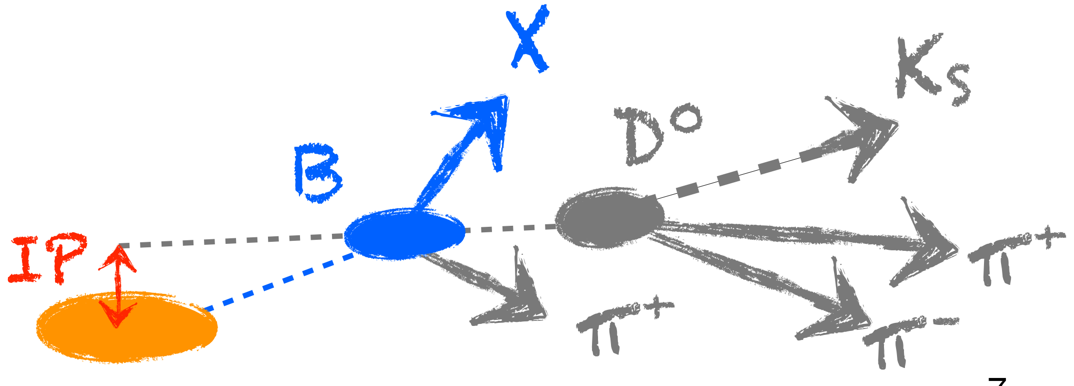






# Results (preliminary)

- First model-independent measurement of x and y

$$x = (0.86 \pm 0.53 \pm 0.17) \times 10^{-2}$$

$$y = (0.03 \pm 0.46 \pm 0.13) \times 10^{-2}$$

- Compatible (but not yet competitive) with other experiments

Belle [PRD 89 (2014) 091103]

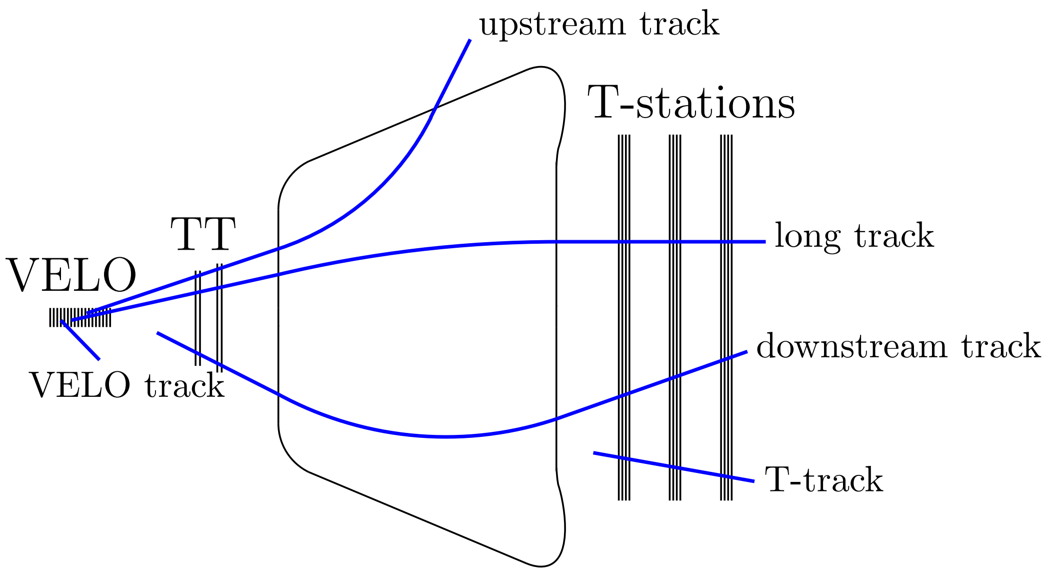
$$x = (0.56 \pm 0.19^{+0.07}_{-0.13}) \times 10^{-2}$$

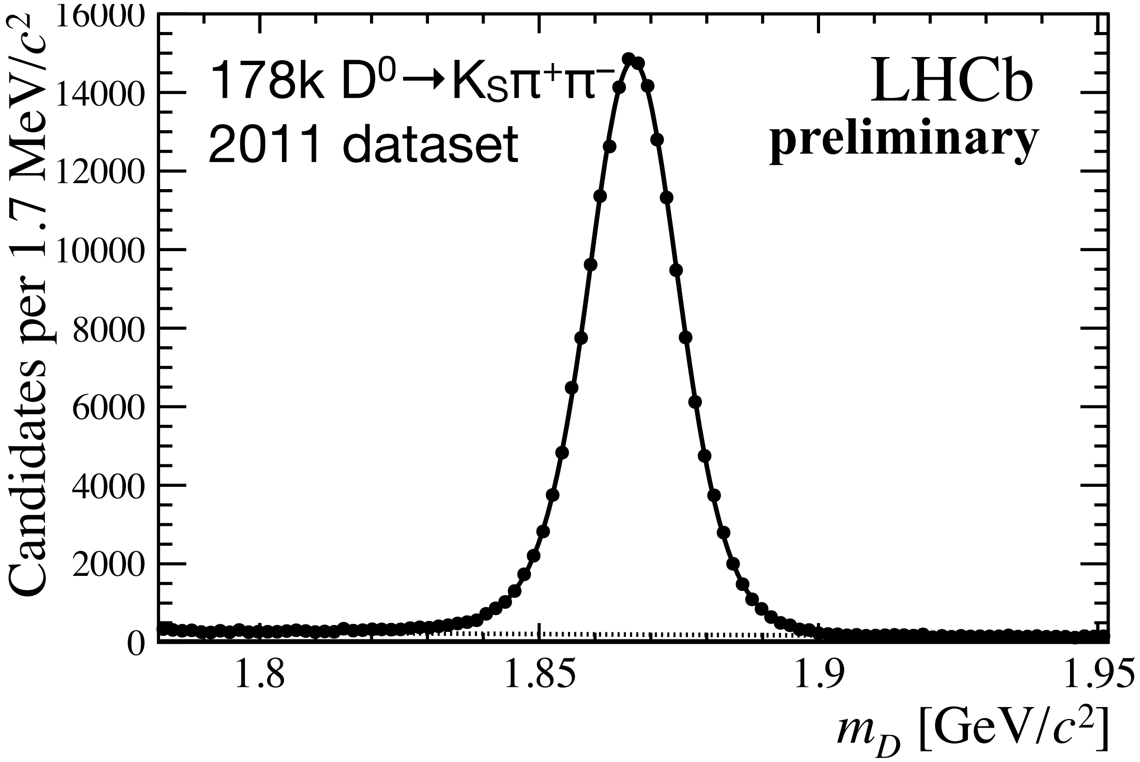
$$y = (0.30 \pm 0.15^{+0.05}_{-0.08}) \times 10^{-2}$$

BaBar [PRL 105 (2010) 081803]

$$x = (0.16 \pm 0.23 \pm 0.14) \times 10^{-2}$$

$$y = (0.57 \pm 0.20 \pm 0.15) \times 10^{-2}$$





- Statistical precision limited by lack of trigger in 2011 for $K_S$ decaying downstream of the VELO
  - Approximately 10x more signal yield expected in 2012 data

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(in preparation)

# First LHCb amplitude analysis of charm decays

# Amplitude analysis of $D^0 \to K_S K^\pm \pi^\mp$

- Benchmark for future LHCb multibody analysis
    - $D^0 \to K_S \pi^+ \pi^-$
    - $D^+ \to \pi^+ \pi^- \pi^+$
    - etc…
- Useful for future measurements of charm mixing and determinations of γ in $B^- \to D^0 K^-$ decays
- Full Run 1 dataset with $K_S$ decaying both in the VELO or downstream of the VELO

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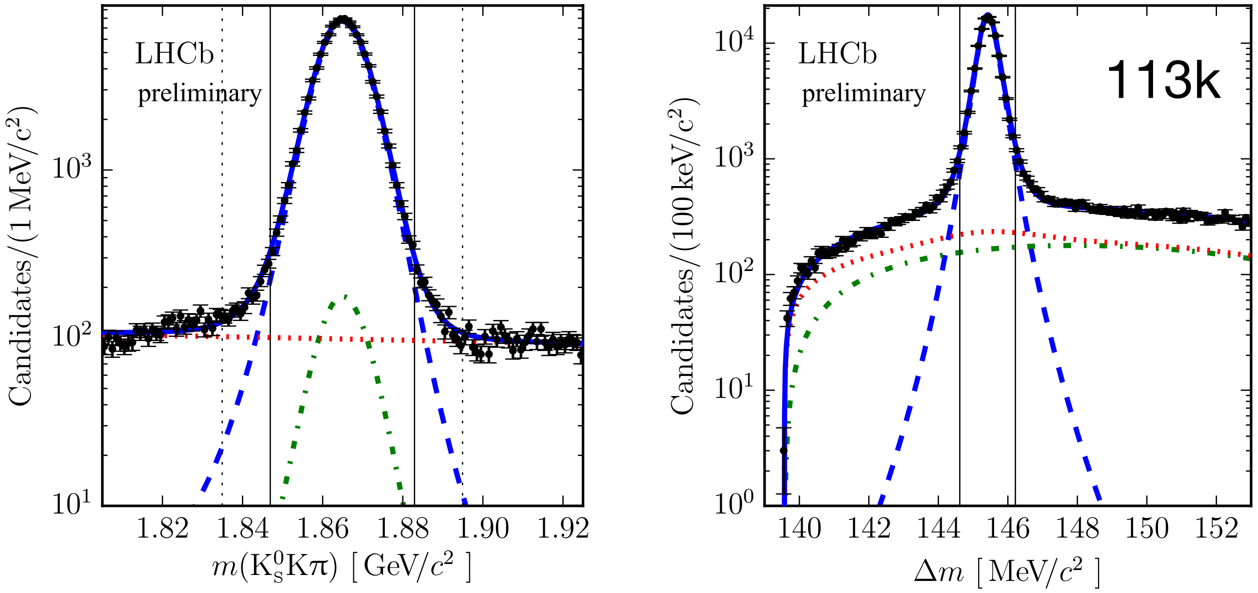
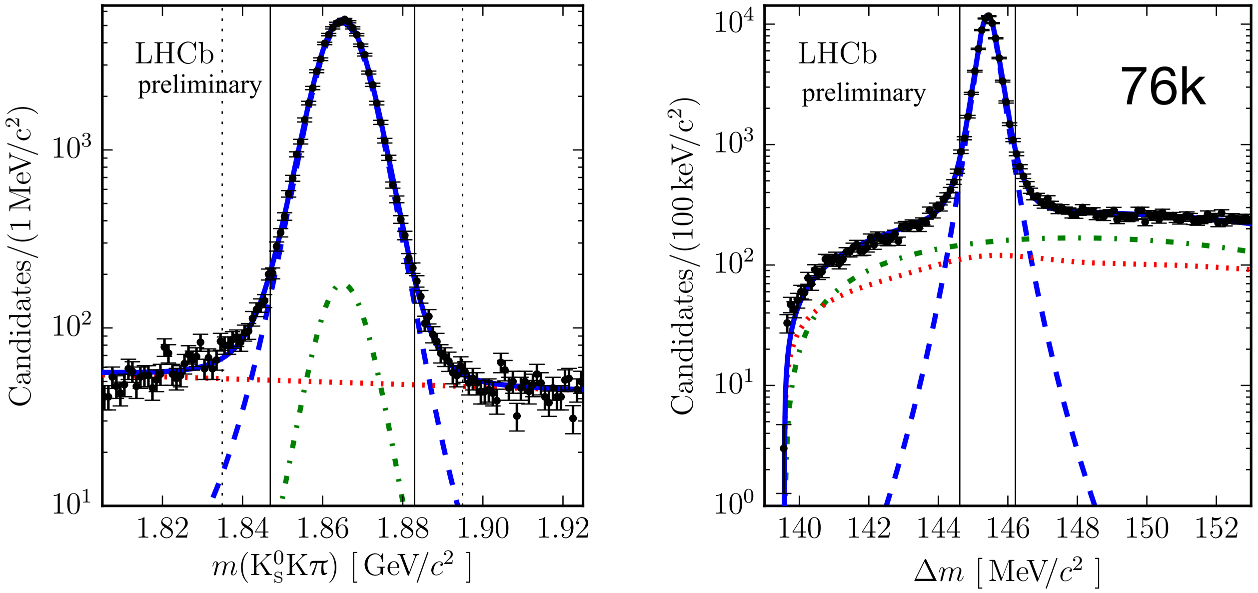
(in preparation)

$D^{*+} \to D^0(\to K_S K^- \pi^+)\pi^+$ (favoured)





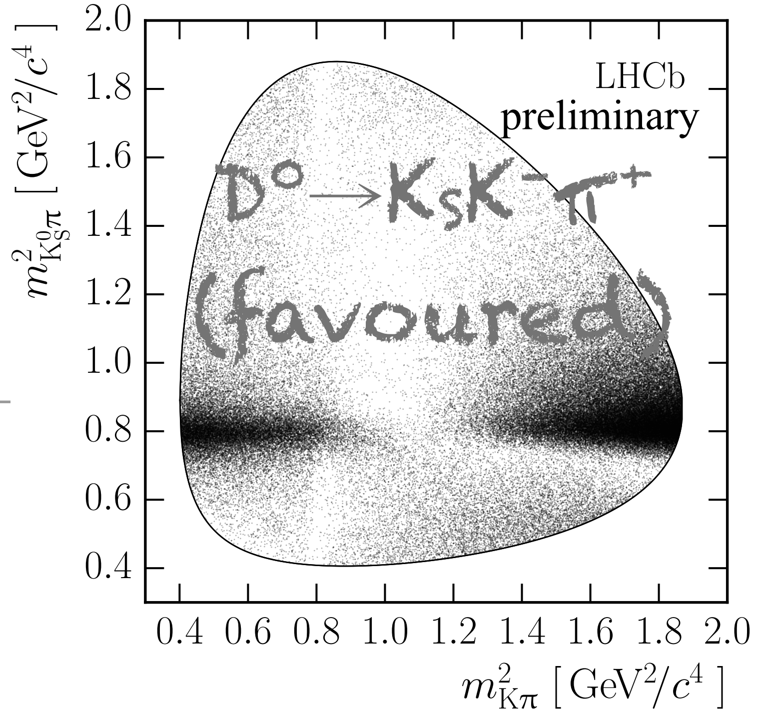
$D^{*+} \to D^0(\to K_S K^+ \pi^-)\pi^+$ (suppressed)

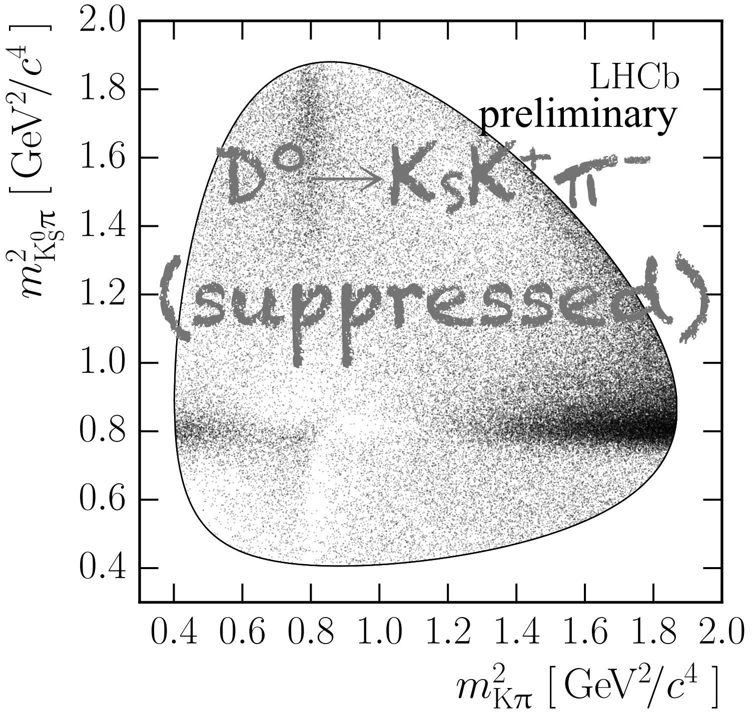
# Details on amplitude model

- Isobar model

$$A(m_1^2,m_2^2) = \Sigma_k \, \underset{\text{amplitude}}{a_k} \, \underset{\text{phase}}{e^{i\phi_k}} \, \underset{\text{lineshape}}{f_k(m_1^2,m_2^2)}$$

- Considered up to 15 resonances:
  - K*(892,1410,1680)$^{\pm,0}$ and K*$_{0,2}$(1430)$^{\pm,0}$ → K$_{(S)}$π
  - a$_0$(980,1450)$^{\pm}$, a2(1320)$^{\pm}$ and ρ(1450,1700)$^{\pm}$ → K$_S$K
- Relativistic Breit-Wigner shapes for all but
  - ρ(1450,1700)$^{\pm}$ → Gounaris-Sakurai function for P-wave ππ scattering
  - a$_0$(980)$^{\pm}$ → Flatté form for near-threshold state
- Two different parameterisations for K$_{(S)}$π S-wave: LASS or generalised LASS (GLASS)





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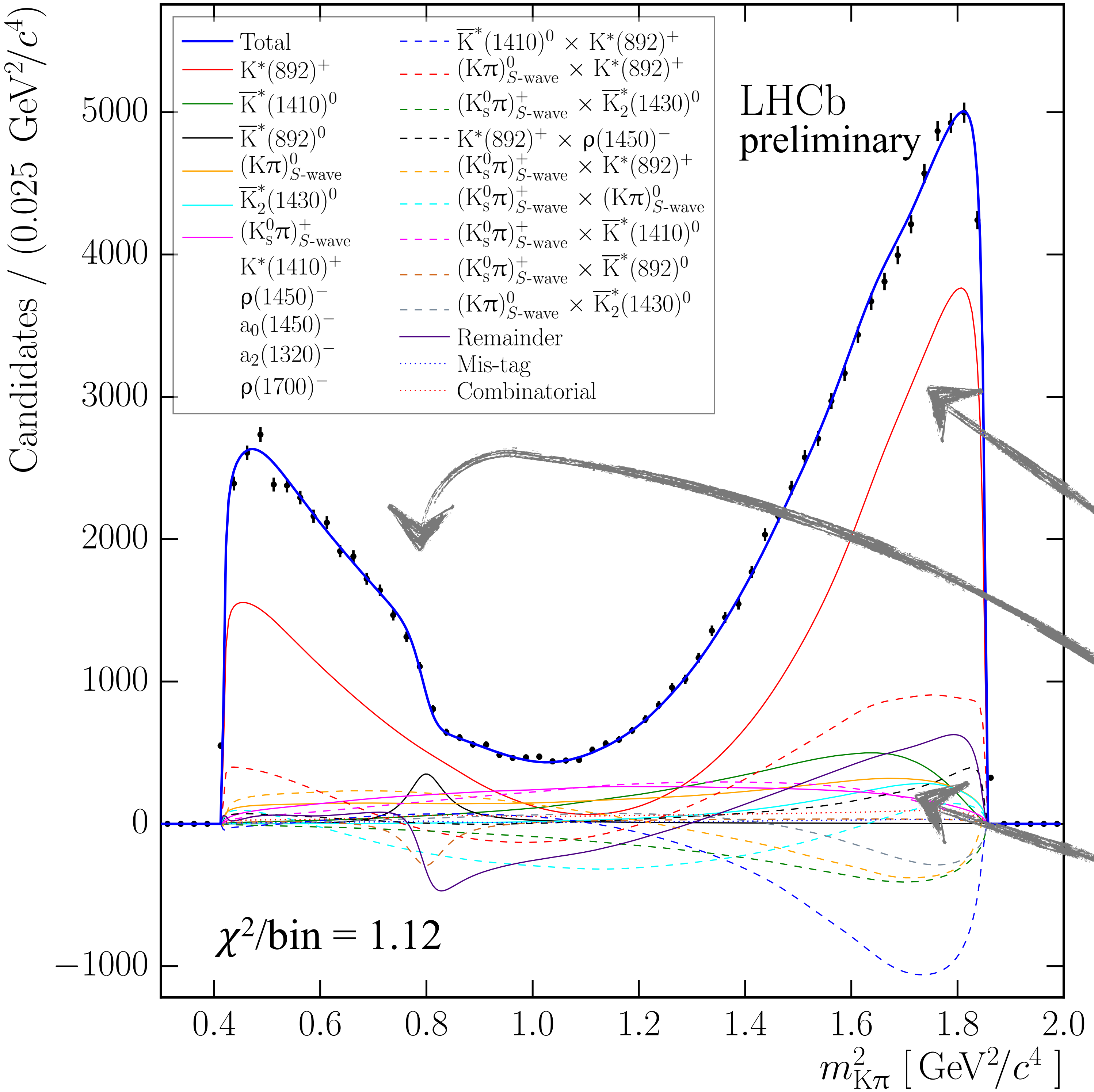
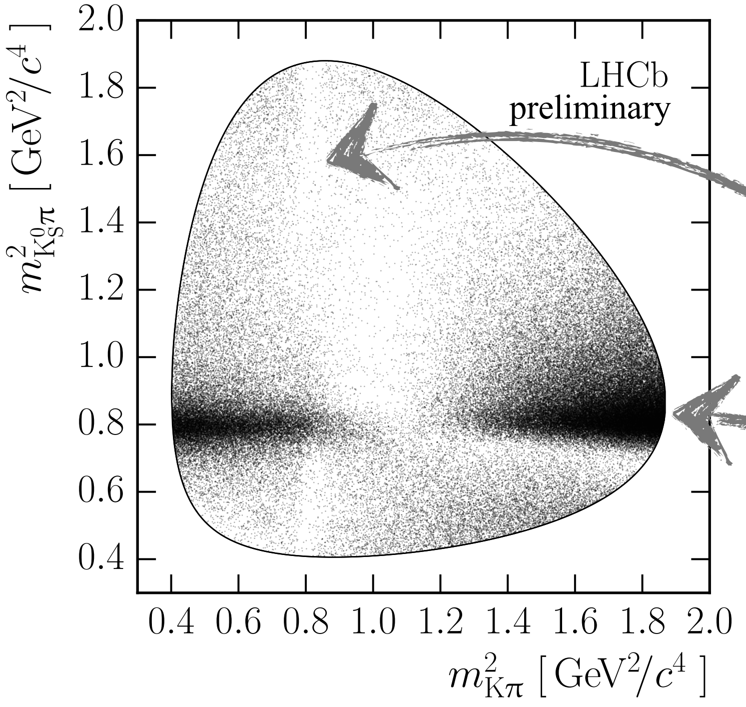
(in preparation)

# Results w/ GLASS (preliminary)

$D^0 \to K_S K^- \pi^+$ (favoured)





K*(892)⁺ dominant

K*(892)° interferes destructively

$(K\pi)^{0,+}$ S-wave large

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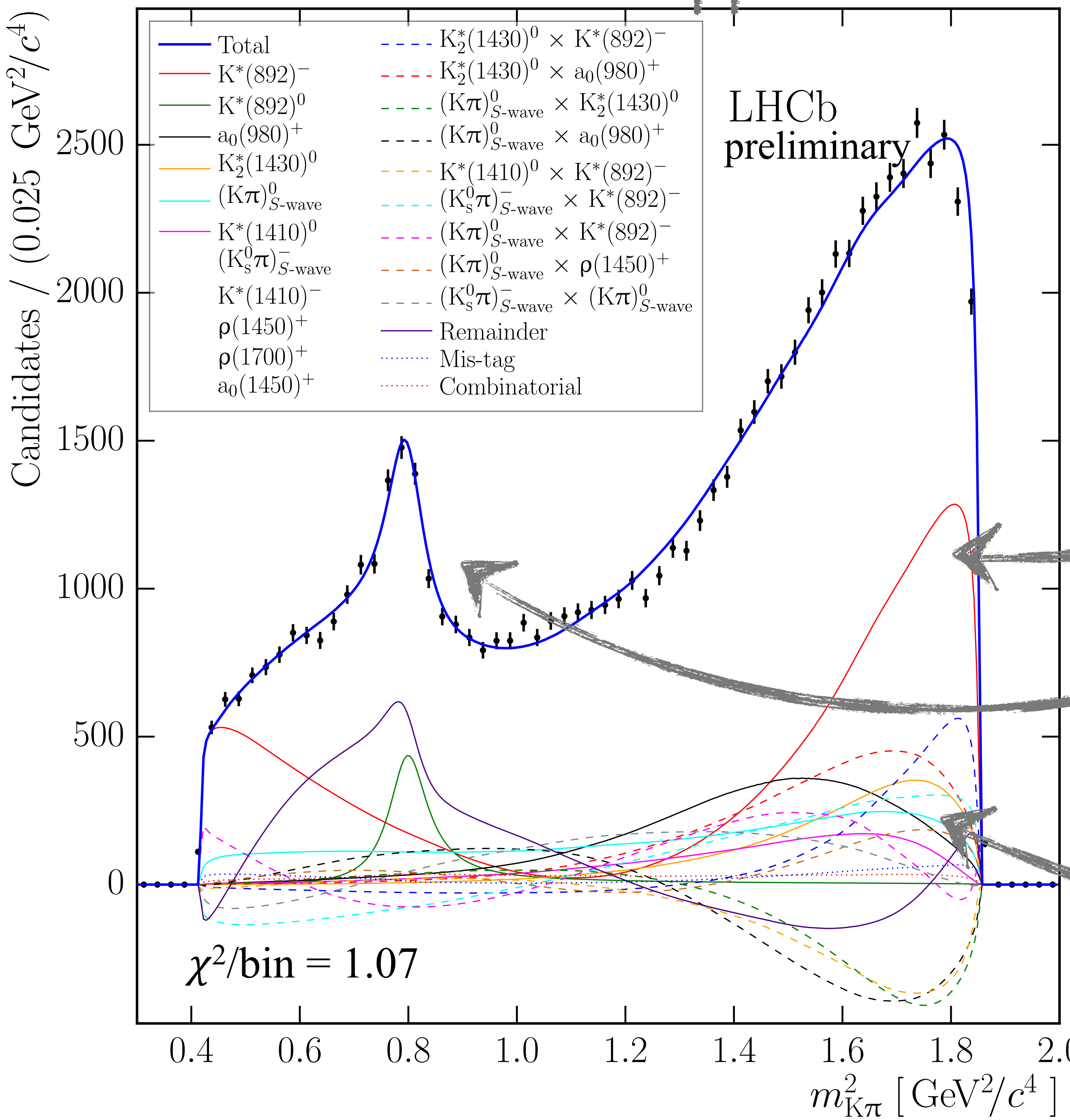
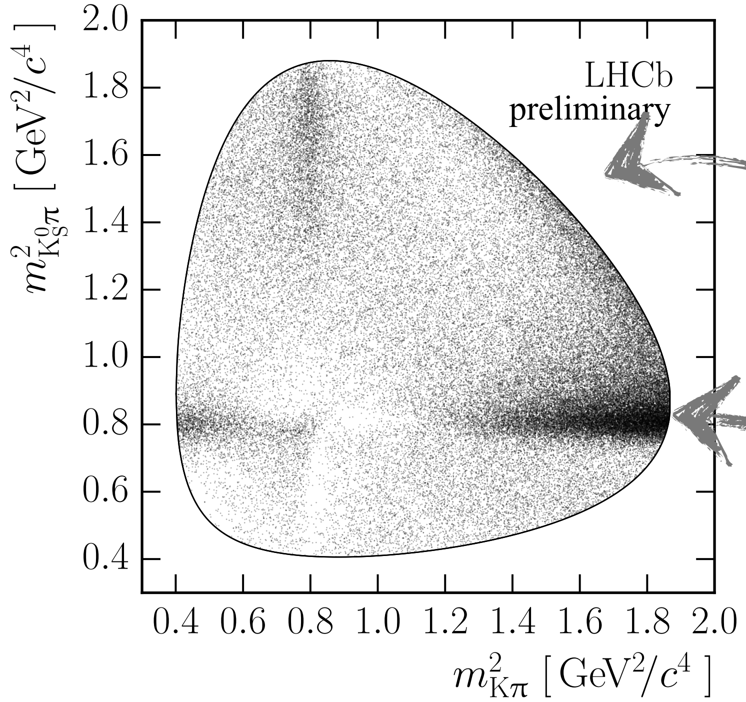
(in preparation)

# Results w/ GLASS (preliminary)

$D^0 \to K_S K^+ \pi^-$ (suppressed)





$K^*(892)^-$ dominant

$K^*(892)^0$ interferes constructively

$(K\pi)^0$ S-wave and $a_0(980)^+$ large

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(in preparation)

# Plenty of auxiliary measurements (preliminary)

All world's best results

| | |
|---|---|
| Model-dependent search for CP violation | Consistent with CP symmetry with ~50% *p*-value |
| Ratio of suppressed to favoured BF<br>Coherence factor | $\frac{\mathcal{B}(D^0 \to K^0_S K^- \pi^+)}{\mathcal{B}(D^0 \to K^0_S K^+ \pi^-)} = 0.655 \pm 0.004 \pm 0.006$<br>$\frac{\mathcal{B}(D^0 \to K^{*+} K^-)}{\mathcal{B}(D^0 \to K^{*-} K^+)} = 0.370 \pm 0.003 \pm 0.012$ |
| Coherence factor and strong-phase difference | $R_{K^0_S K\pi} = 0.573 \pm 0.007 \pm 0.019$<br>$R_{K^* K} = 0.831 \pm 0.004 \pm 0.010$<br>$\delta_{K^0_S K\pi} - \delta_{K * K} = (0.2 \pm 0.6 \pm 1.1)^\circ$ |
| CP-even fraction | $F_+ = 0.777 \pm 0.003 \pm 0.009$ |
| SU(3) | Favours small η-η' mixing angle |

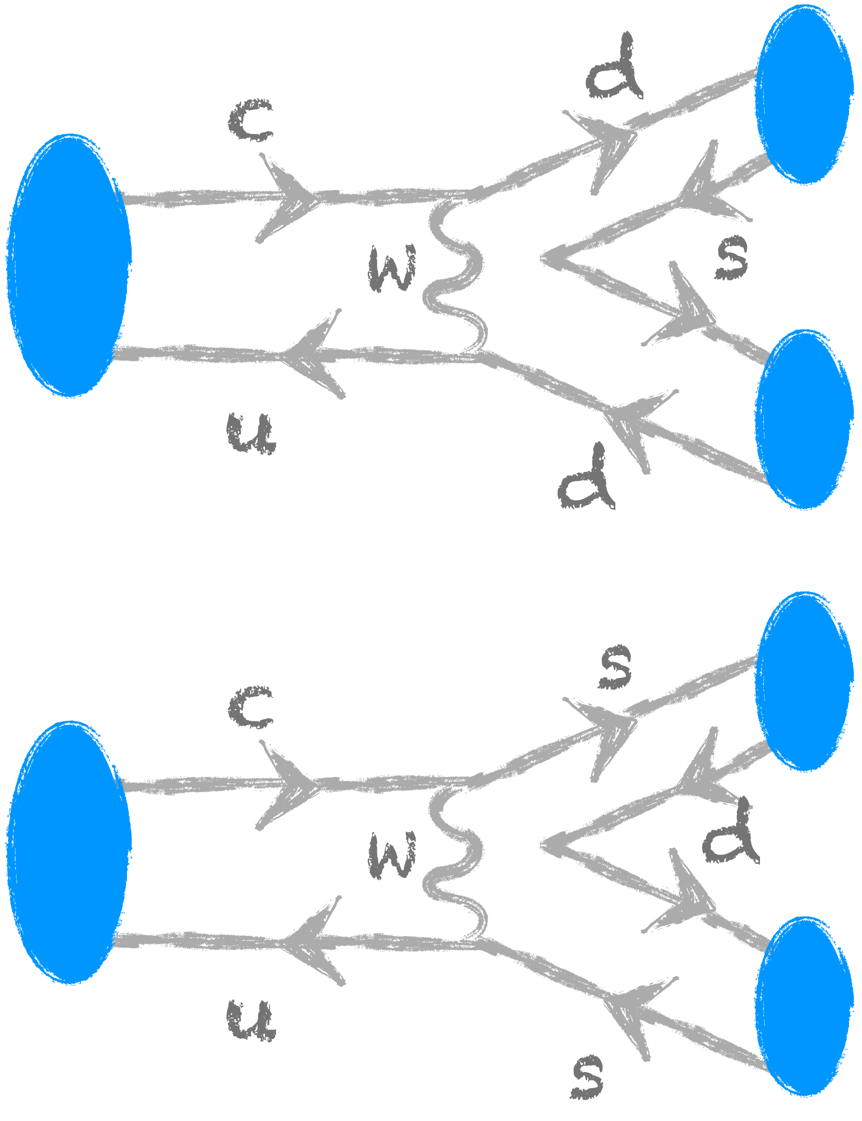
LHCb-PAPER-2015-026
(in preparation)

# More CP violation searches

# CP violation in $D^0 \to K_S K_S$

- Decay amplitude dominated by long-distance contributions
  - Short-distance amplitudes largely cancel, but interference can enhance the CP asymmetry to O(1%)
- Experimentally challenging: vertexing of two (very) long-lived particles
- Only previous measurement from CLEO has poor precision [PRD 63 (2001) 071101]

$$A_{CP} = (23 \pm 19) \times 10^{-2}$$



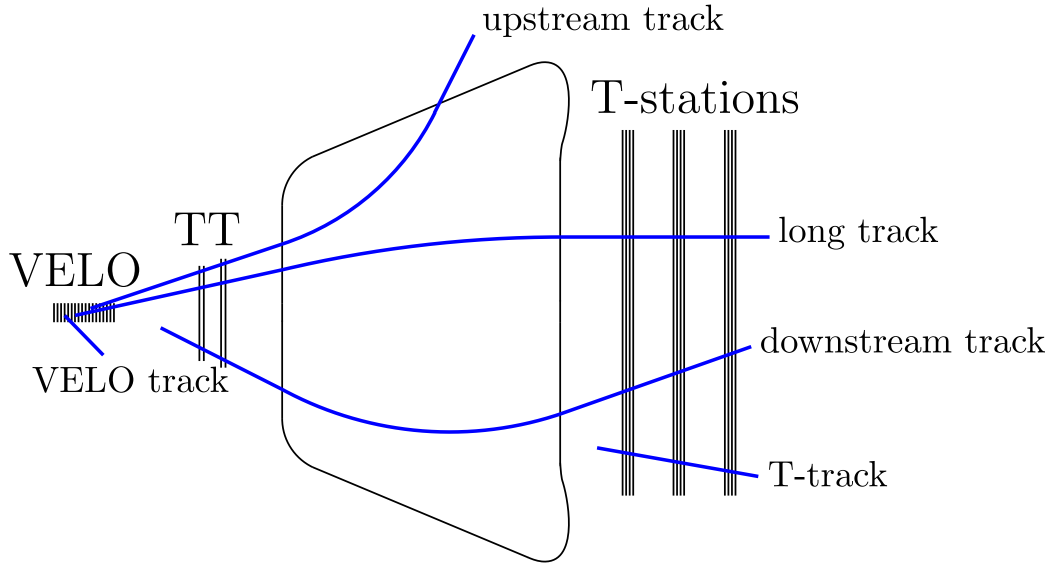
$$V_{cd}V^*_{ud} \approx -V_{cs}V^*_{us}$$

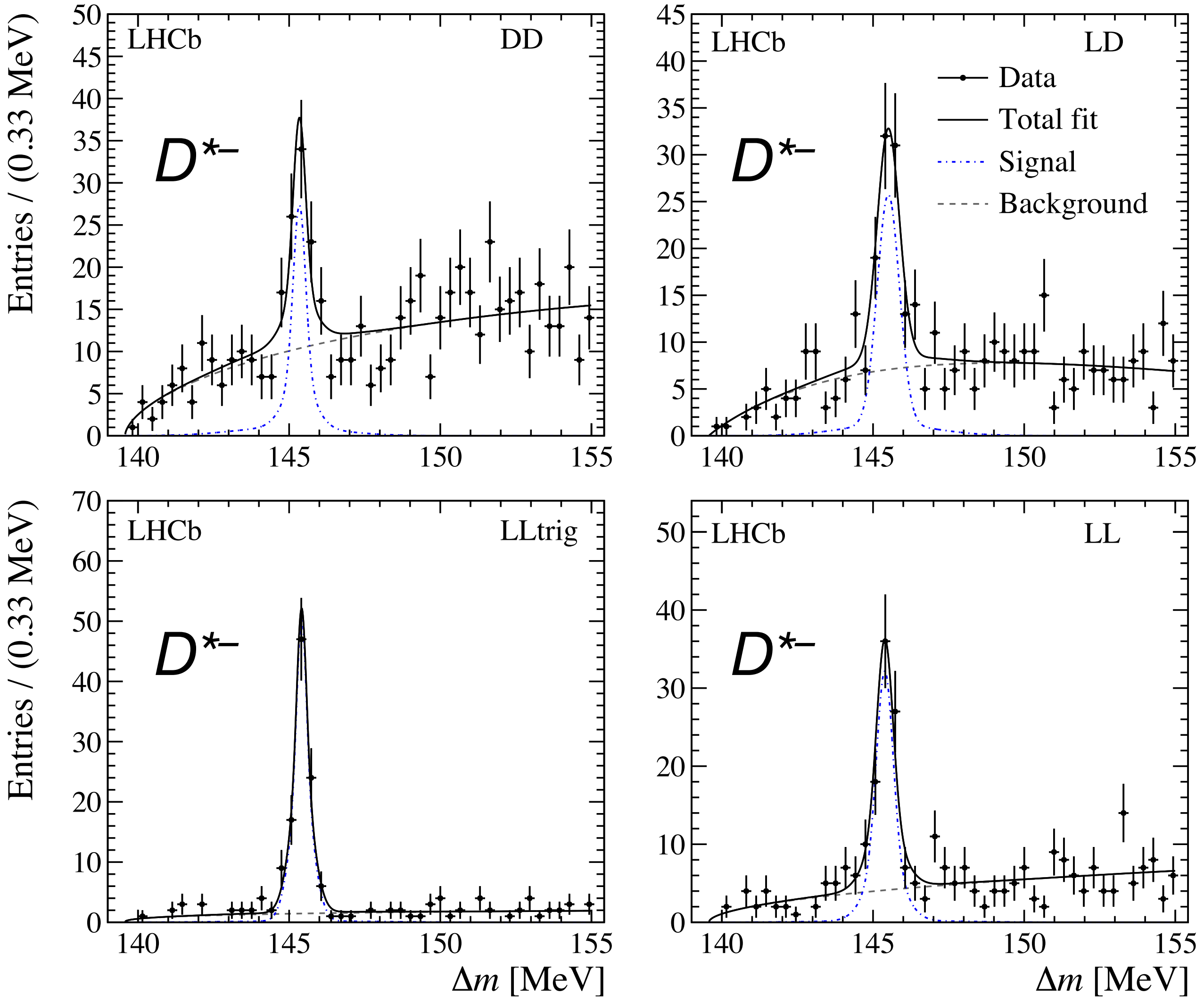
# CP violation in $D^0 \rightarrow K_S K_S$

- Flavour tagging provided by $D^{*+} \rightarrow D^0 \pi^+$
- Candidates separated according to where the two $K_S$ decay
- Total of ~600 candidates in full Run 1 dataset

$$A_{CP} = (-2.9 \pm 5.2 \pm 2.2) \times 10^{-2}$$

- Significant improvement over previous measurement, though with no indication of CP violation
- Run 2 sensitivity will greatly improve thanks to more dedicated trigger lines





LHCb-PAPER-2015-030
[arXiv:1508.06087]

# Charming results from LHCb…

arXiv:1508.06087
JHEP 04 (2015) 043
PLB 740 (2015) 158
JHEP 10 (2014) 005
JHEP 10 (2014) 025
JHEP 07 (2014) 041
PRL 112 (2014) 041801
PLB 728 (2014) 234
PLB 728 (2014) 585
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JHEP 12 (2013) 90
JHEP 09 (2013) 145

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**Search for the doubly charmed baryon $\Xi_{cc}^+$**

The LHCb collaboration

*E-mail:* matthew.charles@cern.ch

Abstract: A search for the doubly charmed baryon $\Xi_{cc}^+$ in the decay mode $\Xi_{cc}^+$ is performed with a data sample, corresponding to an integrated luminosity of 0 $pp$ collisions recorded at a centre-of-mass energy of 7 TeV. No significant signal is the mass range 3300–3800 MeV/$c^2$. Upper limits at the 95% confidence level on the the cross-section times branching fraction to that of the $\Lambda_c^+$, $R$, are a fu and lifetime. The largest upper limits range from $R < 1.5$ for $\times 10^{-4}$ for a lifetime of 400 fs.

and resonance production, Hadr

**Prompt charm production in $pp$ collisions at $\sqrt{s} = 7$ TeV**

Physics Letters B 724 (20

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Physics Letters B

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**Search for $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_{(s)} \to \pi^-\mu^+\mu^+$ decays** ☆

LHCb Collaboration

ARTICLE INFO

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ABSTRACT

A search for non-resonant $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_{(s)} \to \pi^-\mu^+\mu^+$ decays is performed using proton–proton collision data, corresponding to an integrated luminosity of 1.0 fb$^{-1}$, at $\sqrt{s} = 7$ TeV recorded by the LHCb experiment in 2011. No signals are observed and the 90% (95%) confidence level (CL) limits on the branching fractions are found to be

$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3\ (8.3) \times 10^{-8}$,
$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1\ (4.8) \times 10^{-7}$,
$\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2\ (2.5) \times 10^{-8}$,
$\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2\ (1.4) \times 10^{-7}$.

These limits are the most stringent to date.

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**Search for the rare decay $D^0 \to \mu^+\mu^-$** ☆

LHCb Collaboration

ARTICLE INFO

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ABSTRACT

A search for the rare decay $D^0 \to \mu^+\mu^-$ is performed using a data sample, corresponding to an integrated luminosity of 0.9 fb$^{-1}$, of $pp$ collisions collected at a centre-of-mass energy of 7 TeV by the LHCb experiment. The observed number of events is consistent with the background expectations and corresponds to an upper limit of $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2\ (7.6) \times 10^{-9}$ at 90% (95%) confidence level. This result represents an improvement of more than a factor twenty with respect to previous measurements.

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**dy of $D_{sJ}$ decays to $D^+K^0_S$ and $D^0K^+$ final states $pp$ collisions**

he LHCb collaboration

Abstract: A study of $D^+K^0_S$ and $D^0K^+$ final states is performed in a sample of 1.0 fb$^{-1}$ of $pp$ collision data collected at a centre-of-mass energy of $\sqrt{s} = 7$ TeV with the LHCb detector. We confirm the existence of the nd $D^*_{sJ}(2860)^+$ excited states and measure their masses a

.5(syst) MeV/$c^2$,
1(syst) MeV/$c^2$,
(syst) MeV/$c^2$,
(syst) MeV/$c^2$.

Selected for a Viewpoint in *Physics*

PRL **110,** 101802 (2013) PHYSICAL REVIEW LETTERS week ending 8 MARCH 2013

**Observation of $D^0 - \bar{D}^0$ Oscillations**

R. Aaij *et al.**
(LHCb Collaboration)
(Received 6 November 2012; published 5 March 2013)

We report a measurement of the time-dependent ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ decay rates in $D^{*+}$-tagged events using 1.0 fb$^{-1}$ of integrated luminosity recorded by the LHCb experiment. We measure the mixing parameters $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$, $y' = (7.2 \pm 2.4) \times 10^{-3}$, and the ratio of doubly-Cabibbo-suppressed to Cabibbo-favored decay rates $R_D = (3.52 \pm 0.15) \times 10^{-3}$, where the uncertainties include statistical and systematic sources. The result excludes the no-mixing hypothesis with a probability corresponding to 9.1 standard deviations and represents the first observation of $D^0 - \bar{D}^0$ oscillations from a single measurement.

DOI: 10.1103/PhysRevLett.110.101802 PACS numbers: 12.15.Ff, 13.25.Ft, 14.40.Lb

PLB 724 (2013) 203
PLB 725 (2013) 16
JHEP 06 (2013) 112
JHEP 06 (2013) 65
PLB 723 (2013) 33
NPB 871 (2013) 1
PRL 110 (2013) 101802
PLB 718 (2013) 902
JHEP 10 (2012) 151
PLB 713 (2012) 186
JHEP 04 (2012) 129
PRL 108 (2012) 111602
PRD 84 (2011) 112008

More Run 1 results to come… and Run 2 just started
(with 2x more charm produced at 13 TeV)