CP Violation and Rare Decays in the Charm System at LHCb

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On behalf of the LHCb collaboration

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Introduction

The Charm system provides good tools to seek NP…

- **SM: CPV is very small, Rare Decays are very rare**
  - *Charm decays are essentially a two-family story: no CPV at first order*
  - *FCNC's that provide higher order effects are very suppressed by GIM*

- **This offers a list of 'surprises' that could sign the presence of NP**
  - *CPV at O(1%) in the mixing or in certain decays*
  - *Rare decays with a branching ratio $O(10^{-9}-10^{-8})$*
  - *Bonus: charm involve up-type quark FCNC, thus NP couplings hardly tested with B, K*

- **LHCb aims at a thorough exploration. In this talk:**
  - *Charm mixing: x' & y' with WS $D^0 \rightarrow K^+\pi^-$ decays*
  - *CP violation: $D \rightarrow K^+K^-$, $\pi^+\pi^-$, $K^+K^-\pi^+$, $\pi^+\pi^-\pi^+\pi^-$*
  - *Rare decays: $D \rightarrow \mu^+\mu^-$, $D \rightarrow \pi^+\mu^+\mu^-$*

2010/2011 data

~ 1 fb^{-1}

[1] Phys. Lett. B694: 209-216, 2010

[2] LHCb-CONF-2010-013, LHCB-PAPER-2012-041, arXiv:1302.2864

- **Huge b and c production in high E p-p collisions**

  - @ $\sqrt{s}$=7 TeV: $\sigma(pp \rightarrow b\bar{b}+X)=(284 \pm 20 \pm 49)\ \mu b$ [1]

  $\sigma(pp \rightarrow c\bar{c}+X)=(6100 \pm 930)\ \mu b$ [2]

  ➔ ~10^{12} $c\bar{c}$ pairs per fb^{-1} in LHCb's acceptance. 3 fb^{-1} collected so far !

- **LHCb is optimized for *Flavor Physics* in a *hadronic* environment.**

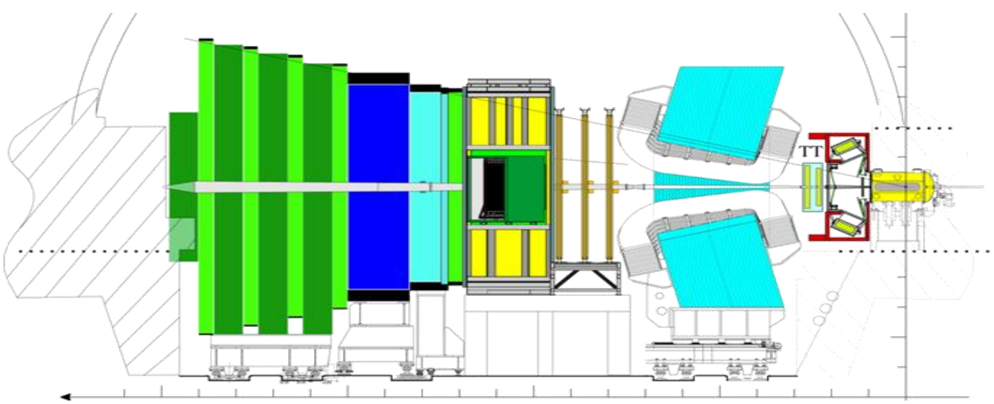
  - Forward detector, performant vertexing, p and M reconstruction, particle-ID

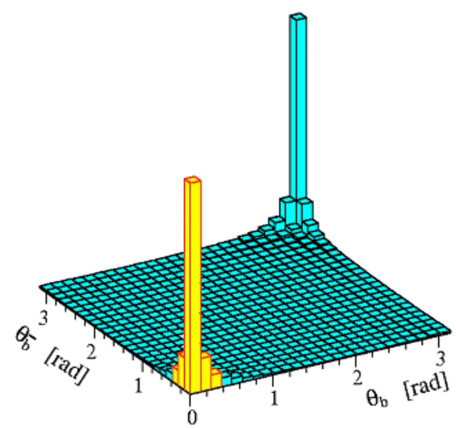
  - Very selective, polyvalent and configurable trigger:

  - 1 hardware trigger (L0) followed by 2 software triggers (HLT1-2)

  L0: ~ 15 MHz → 1MHz

  HLT: ~1MHz to ~ 3 kHz (4.5 kHz) with ~1 kHz (2 kHz) for charm in 2011 (2012)





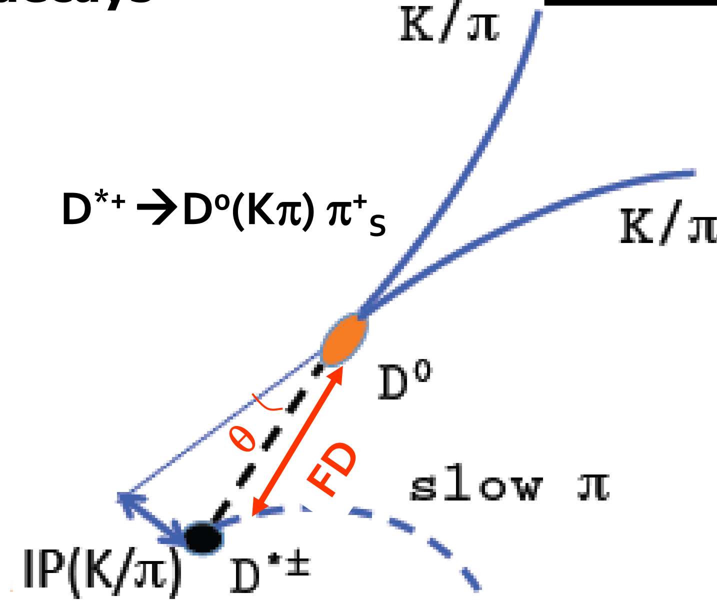
Charm Measurements @ LHCb: typical ingredients

P, PT, IP, PID , cosθ, FD

S/B

- **All selections use typical features of D decays**

  - *D→hh(h): Cut based selection*
    (low multiplicity, high BF's, low peaking BKG)
  - *D→hhhh: Multivariate analysis*
    (high multiplicity so large BKG)
  - *Rare decays: Multivariate analysis + PID*
    (large combinatorial and peaking BKG,
    Ex: $B(D^0 \to \pi^+\pi^-) > 10^6\, B(D \to \mu\mu)$)

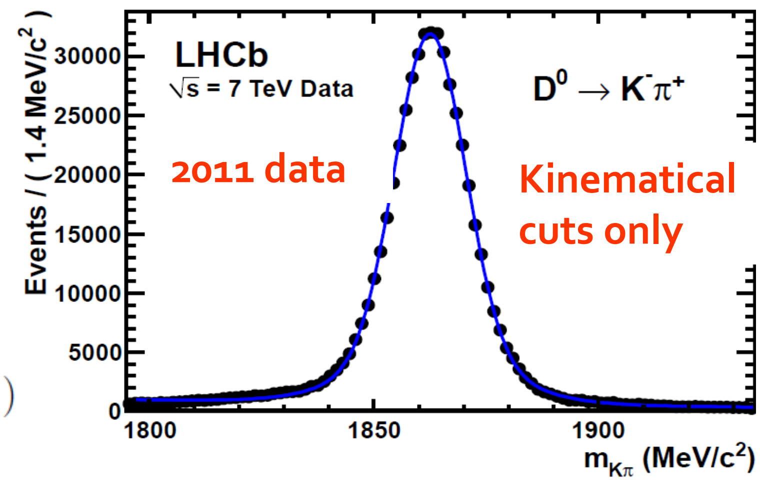


Reliable Meas't

- **Control modes and normalization**

  - *Huge data samples of $D^0 \to K^-\pi^+$, $B \to J\psi(\mu\mu)X$,… to determine tracking and PID efficiencies from data*
  - *Modes similar to the signal with a larger and known BF to further minimize systematics.*

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N_{D^{*+}\to D^0(\to\mu^+\mu^-)\pi^+}}{N_{D^{*+}\to D^0(\to\pi^+\pi^-)\pi^+}} \frac{\varepsilon_{\pi\pi}}{\varepsilon_{\mu\mu}} \cdot \mathcal{B}(D^0 \to \pi^+\pi^-)$$

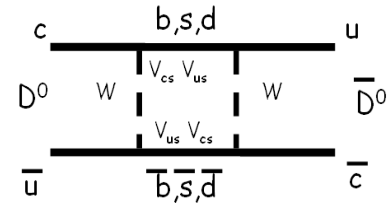


Charm Mixing

Charm mixing

- **Effective Hamiltonian that allows to focus on time evolution in $\{|D^0\rangle, |\bar{D}^0\rangle\}$ basis, but also accounts for its decay (non hermitian)**

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

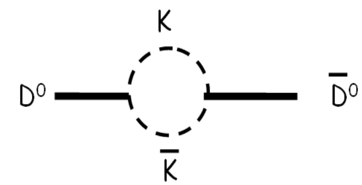


Physical states

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

Flavor states

$$|D^0(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\bar{D}^0\rangle$$
$$|\bar{D}^0(t)\rangle = g_+(t)|\bar{D}^0\rangle + \frac{p}{q}g_-(t)|D^0\rangle$$



- **Physical states eigenvalues rule ($M_{1,2} \pm i\Gamma_{1,2}$) the mixing time evolution. $|g_\pm(t)|^2$ can be written in terms of *x* and *y***

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2 \qquad\qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

- **Hard to predict. Expected small in SM (GIM suppr.): x,y ~ 0.1 to 1%**

  - B-factories and FNAL: strong evidence that mixing exists.

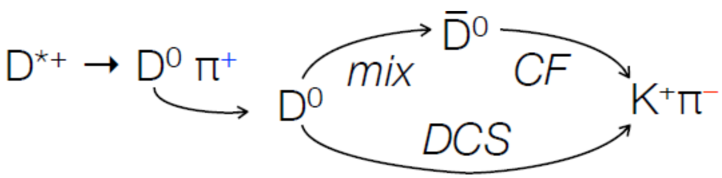
  - CPV in this mixing still to be discovered: good probe for NP.

LHCb with $1fb^{-1}$: observe mixing at $>5\sigma$ with one single measurement

LHCb with $3fb^{-1}$: search for CPV in mixing

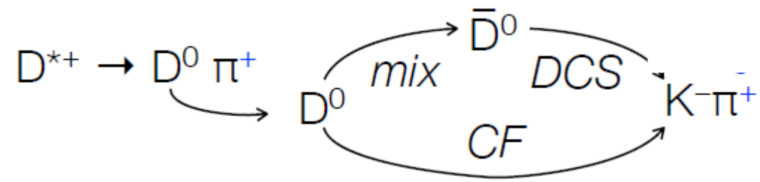
Time dependent $D^0 \rightarrow K\pi$ WS/RS ratio

Wrong Sign events (WS)



vs.

Right Sign events (RS)



$$\rightarrow \quad R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\, y' t + \frac{x'^2 + y'^2}{4} t^2$$

$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

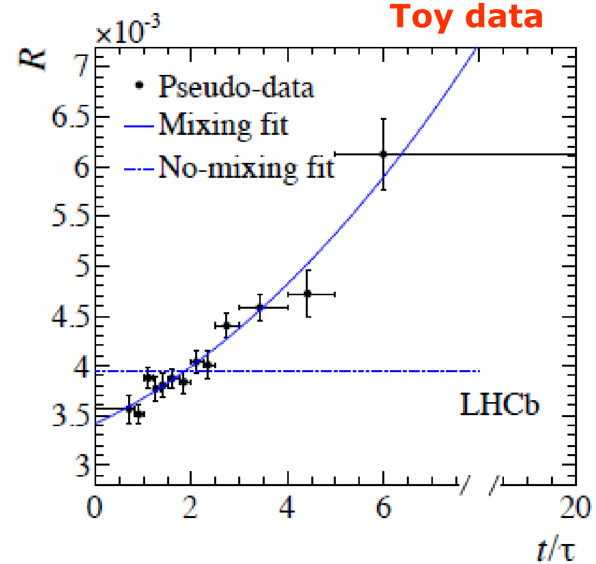
Assuming x,y small and no CPV

- **Count decays in 13 bins of decay time to get**

  $R_i = N(D^0 \rightarrow K^+\pi^- + \overline{D}^0 \rightarrow K^-\pi^+)_i \,/\, N(D^0 \rightarrow K^-\pi^+ + \overline{D}^0 \rightarrow K^+\pi^-)_i$

- **χ^2 fit of R(t) this to these data points**

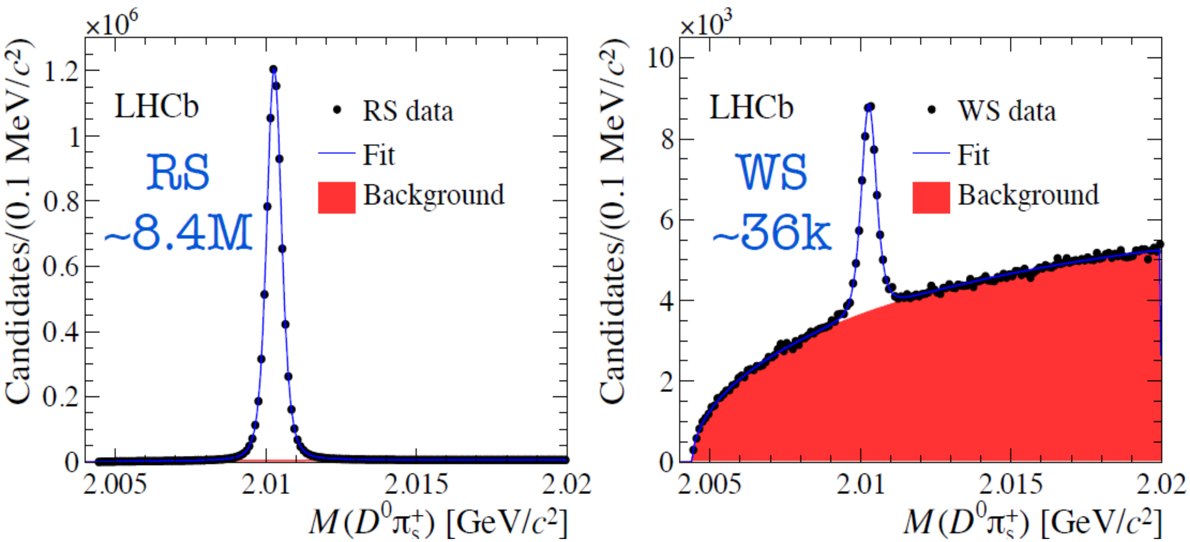
Toy data



Time dependent $D^0 \to K\pi$ WS/RS ratio

- **Exploit $D^* \to D^0\pi_s$ to tells D^0 from $\overline{D}^0$, maximize S/B, extract $N(D \to K\pi)$'s**

Time integrated yields



Clean signature

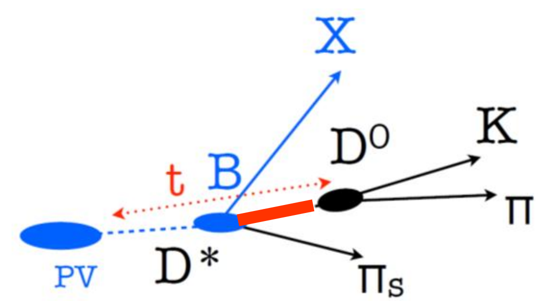
- *$\sigma M(D^0\pi_s) \sim \sigma p(\pi_s)$*
- *$\sigma M(D^0\pi_s) < 1$ MeV thanks to a kinematical fit forcing to come from the Primary Vertex.*

Large yields

- *4110 (949000) WS(RS) in bin 5*
- *910 (165200) WS(RS) in bin 13*

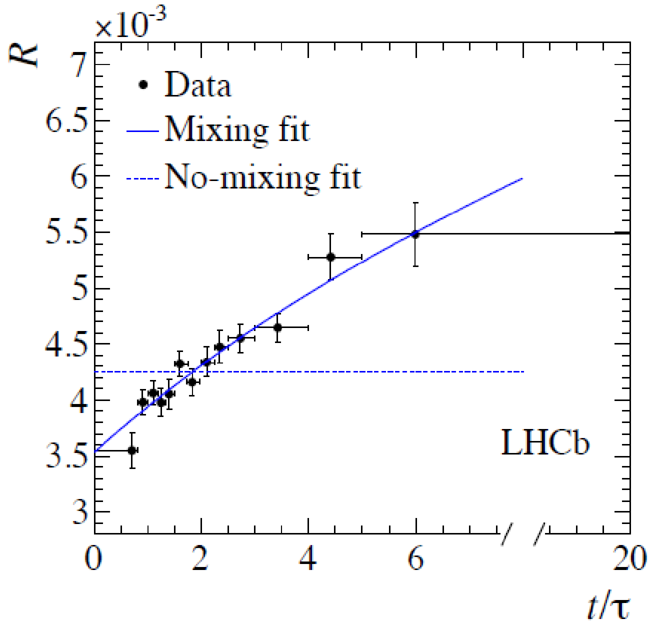
Systematic uncertainties mostly cancel in the ratio.
Remaining biases on R_i are included in the fit.

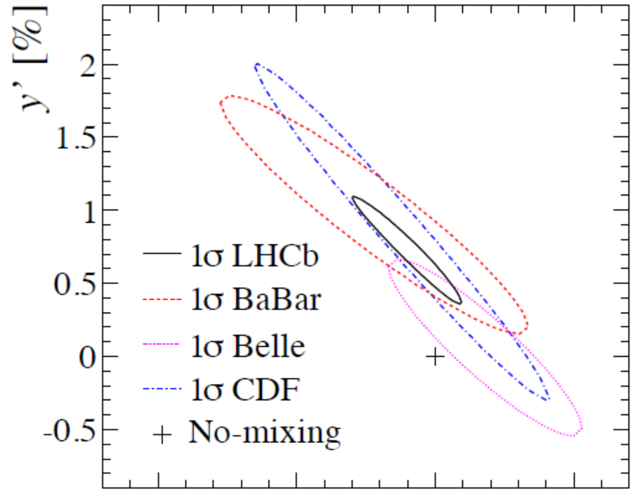
- *D^0 from B decays (**t** wrong since B is long lived)*
- *Double mis-ID: $D^0 \to K^-\pi^+$ (RS) seen as $D^0 \to K^+\pi^-$ (WS)*

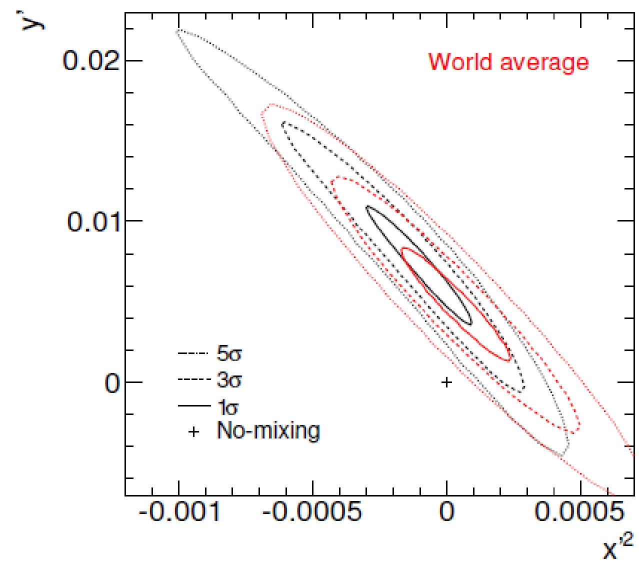


Submitted to PRL, arXiv:1211.1230v1

1 fb^{-1}, 2011 data







$$x'^2 = (-0.09 \pm 0.13)\times 10^{-3}$$

$$y' = (7.2 \pm 2.4)\times 10^{-3}$$

Systematic uncertainties:

10% of $\sigma y'$; 11% of $\sigma x'^2$

Mixing established at 9.1σ ! 1st individual measurement > 5σ

CPV in 2-body Charm Decays

$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

- **CPV we're after: ~1% at most.**

  → Difficulty: Production and detection asymmetries can reach 1%.

Measure:

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

- First order Taylor Expansion:

$$A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

Wanted Physics CP asymmetry

Detection asymmetry of D

Detection asymmetry of the slow pion

Production asymmetry

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

When $f=\pi^+\pi^-$ or K^+K^-: no detection asymmetry between D and D

→ $A_D(f)=0$

Similar for $f=\pi^+\pi^-$ and K^+K^- (D^* and π_s production/detection ~independent of D^0 f-state)

$$\Delta A_{RAW} = A_{RAW}(K^+K^-) - A_{RAW}(\pi^+\pi^-) = \Delta A_{CP}$$

$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

0.6 fb^{-1}

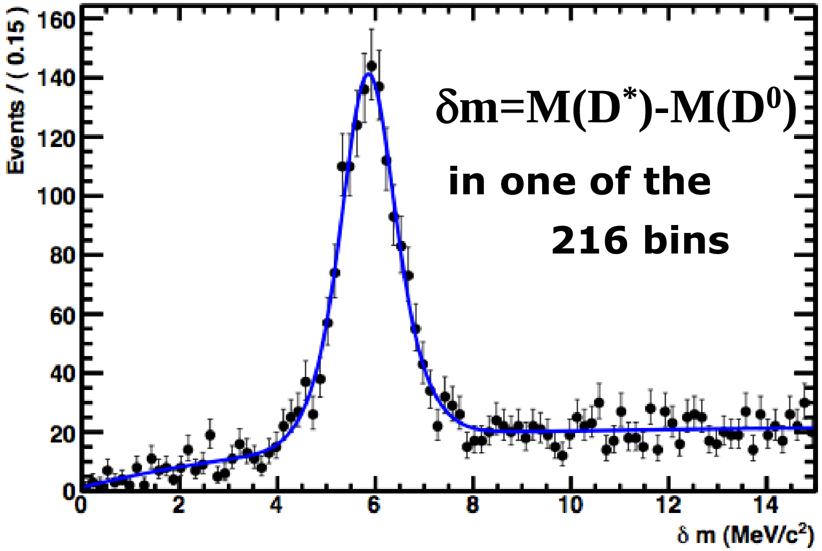
Phys.Rev.Lett. 108 (2012) 111602

- **Fit to δm distributions in 216 bins**

  54 bins in $P_{T,D*} \times \eta_{D*} \times P_{slow\,\pi} \times$ left/right

  $\times$ 2 Mag Up / Mag Down

  $\times$ 2 Before/After an LHC technical stop



➔ **A_{RAW} and ΔA_{RAW} in each bin, then weighted average**

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

(χ^2 / NDF = 211/215)

3.5 σ from no CPV.

World average (HFAG)

$$\Delta A_{CP}^{dir} = (-0.678 \pm 0.147)\%$$

CP Violation across the Dalitz Space

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

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

Model independent search for CPV (Miranda Approach)

- Look for **local** asymmetries across Dalitz Plots.

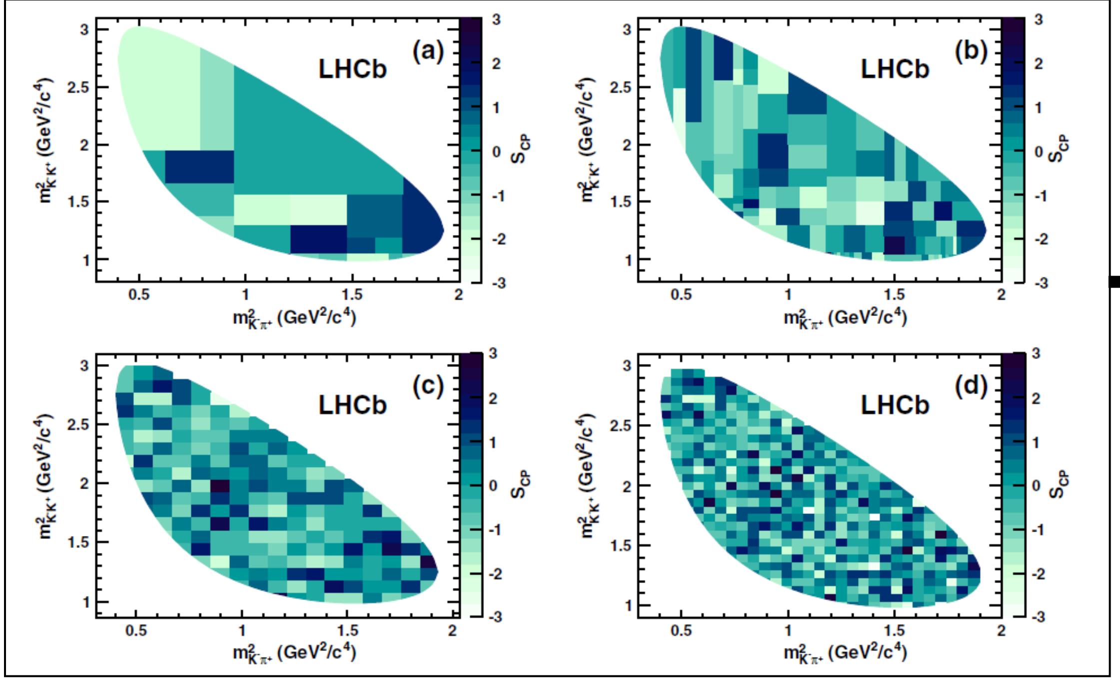
$$\chi^2 = \sum_{i=1}^{Nbins} \left(S_{CP}^{i}\right)^2 \qquad S_{CP}^{i} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}, \qquad \alpha = \frac{N_{tot}(D^+)}{N_{tot}(D^-)},$$

- Sensitivity to a given CPV scenario depends on the binning: try several !

- Check detection asymmetries: compute χ^2 for non CPV control modes.

- **First application of this method: $D^+ \to K^-K^+\pi^+$ with 2010 data (35 pb^{-1})**

S_{CP} across the DP for $D^+ \to K^+K^-\pi^+$



Control modes: $D_S \to K^-K^+\pi^+$, $D^+ \to K^-\pi^+\pi^+$

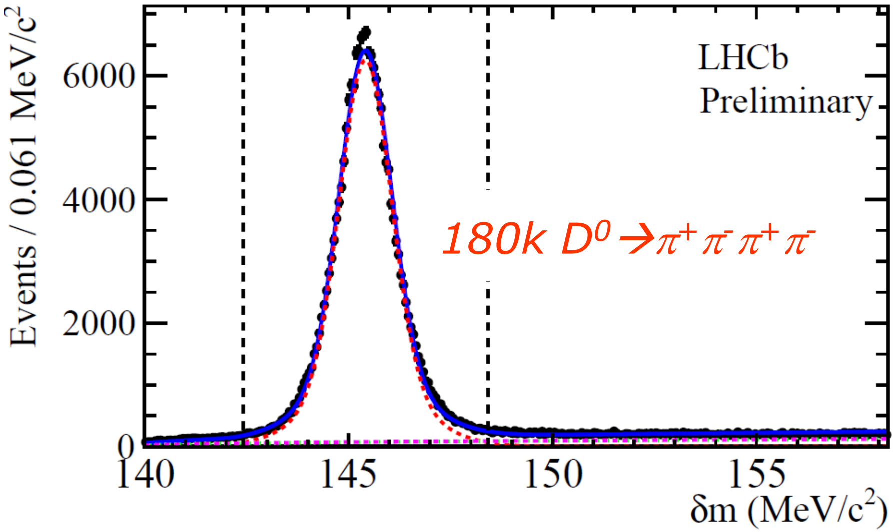
Binning	p-value (%)
Adaptive I	12.7
Adaptive II	10.6
Uniform I	82.1
Uniform II	60.5

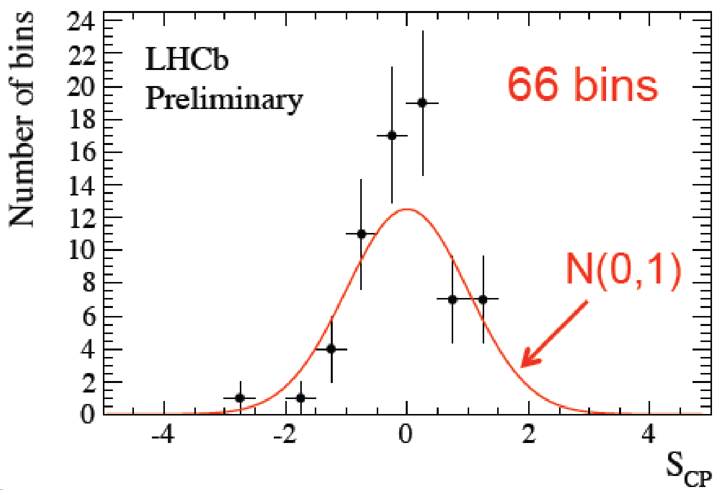
No evidence for CPV !

PHYSICAL REVIEW D 84, 112008 (2011)

Model independent search for CPV: $D^0 \to \pi^+\pi^-\pi^+\pi^-$

- **High multiplicity causes large background: selection uses a NN.**
- **Control mode: 1.3M $D^0 \to K^-\pi^+\pi^-\pi^+$**
- **4-body: S^i_{CP} measured in bins of a 5D Dalitz Plot.**
- **Tries 3 different binnings.**





1 fb-1 , LHCb-CONF-2012-019

Bins	p-values (%)
15	97.1
29	95.6
66	99.8

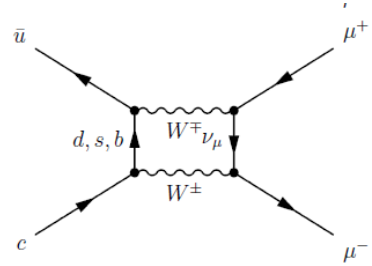
➔ No evidence for CPV

Rare decays

Motivations

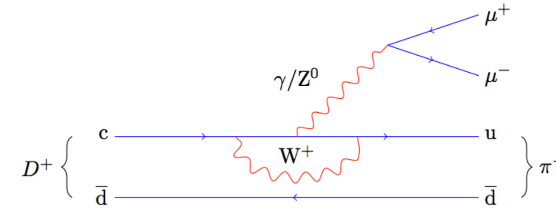
- **SD contributions are good tools to probe NP (very strong GIM suppression)**

$D^0 \to \mu^+\mu^-$



$B_{SM} \sim 10^{-18}$ [1]

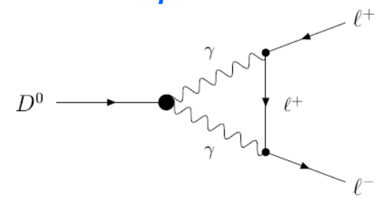
$D \to h(h')\mu^+\mu^-$



$\sim 10^{-11}$-10^{-9} [3]

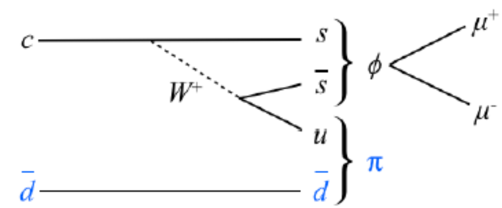
- **Branching ratios dominated by LD effects, via intermediate states**

2-photon



$B_{SM} < 6.\ 10^{-11}$ [1,2]

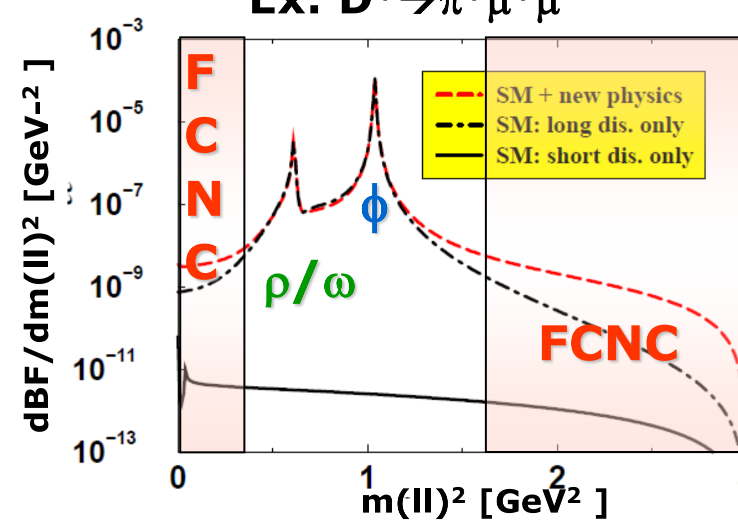
Resonances



$B_{SM} \sim 10^{-8}$ to 10^{-5} [4]

- **NP might change the picture, making the SD contribution measurable**
  - *Via the total BF: $D^0 \to \mu\mu$ [5]*
  - *Via partial BF's or asymmetries (CP, FB, …) to avoid LD contributions: $D \to h(h')\mu^+\mu^-$ [6]*

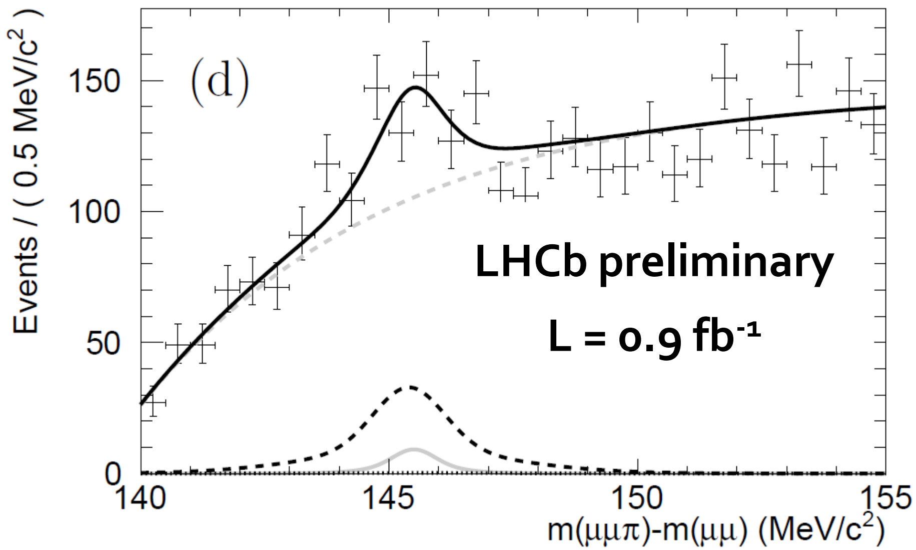
Ex: $D^+ \to \pi^+\mu^+\mu^-$



D→μμ

Measurement relative to the $D^0 \to \pi\pi$ channel

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N_{D^{*+}\to D^0(\to\mu^+\mu^-)\pi^+}}{N_{D^{*+}\to D^0(\to\pi^+\pi^-)\pi^+}} \frac{\varepsilon_{\pi\pi}}{\varepsilon_{\mu\mu}} \cdot \mathcal{B}(D^0 \to \pi^+\pi^-)$$



Signal

Comb. background:

Peaking backgrounds: $D^0 \to \pi^+\pi^-$

- *Reduced using Muon ID.*

- *Yield floated in this fit within limits determined from MC + $D \to K\pi$ control sample to determine $\pi \Leftrightarrow \mu$ misID rate*

→ $$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3\ (1.1) \cdot 10^{-8} \quad \text{at } 95\ (90)\%\text{CL}$$

CERN-LHCb-CONF-2012-005

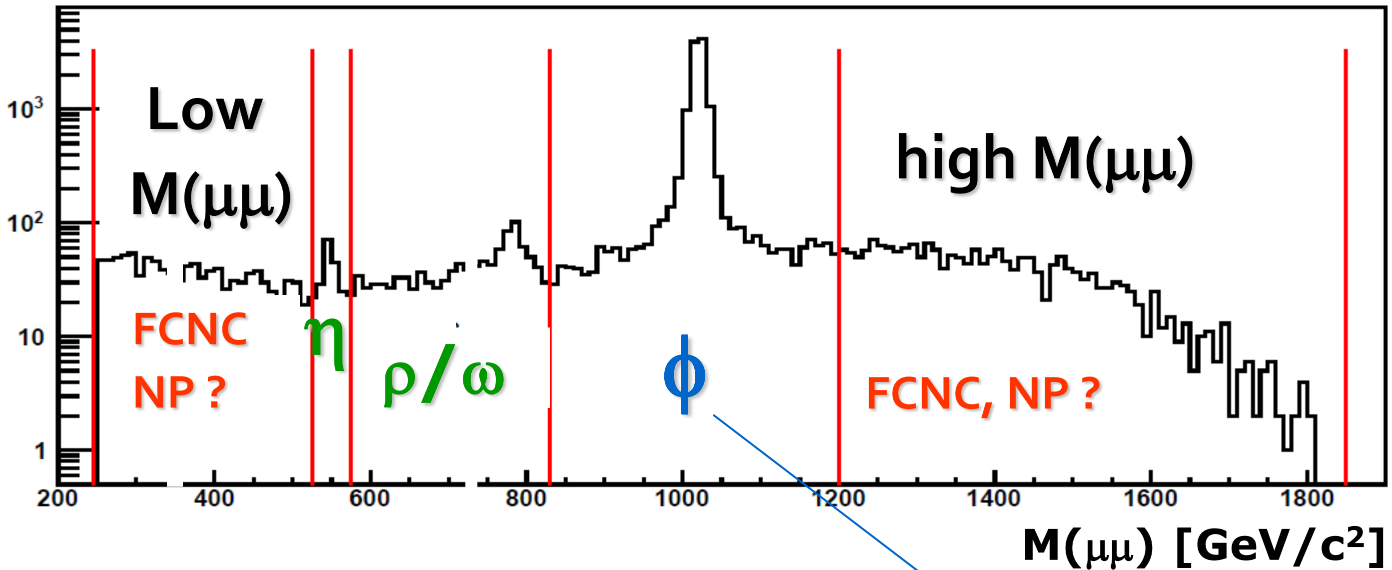
→ **~10 times better than Belle's limit.**

(Phys. Rev. D81 (2010) 091102, arXiv:1003.2345)

→ **Still orders of magnitude above SM, paper with improved analysis in preparation**

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

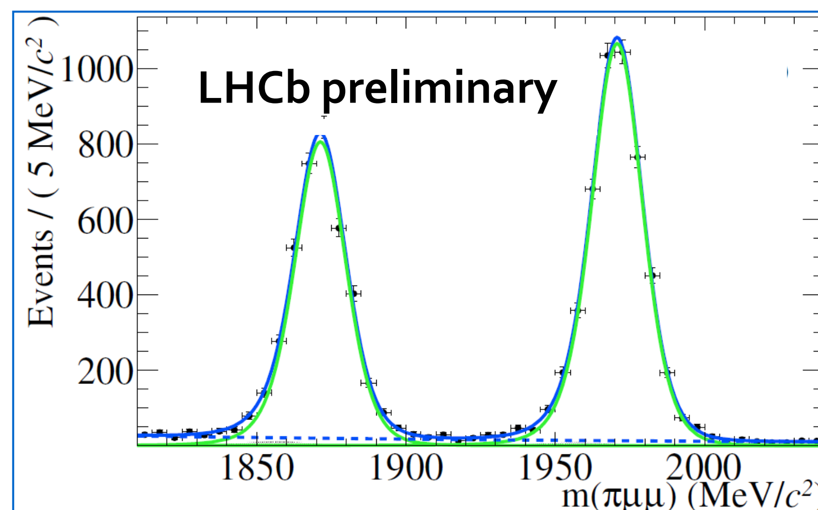
5 regions of the dimuon spectrum studied simultaneously



NEW !

- $D^+_{(s)} \to \pi^+ \phi(\mu^+\mu^-)$ **used as** ***Standard Candles***

  - *Normalization mode: minimize σ(syst) since the final state is the same as the signal.*
  - *Signal proxy to optimize the selection (BDT + muon ID) and help the fit (provides signal shape)*
  - *The error on their BF is the dominant systematic uncertainty in this analysis*



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

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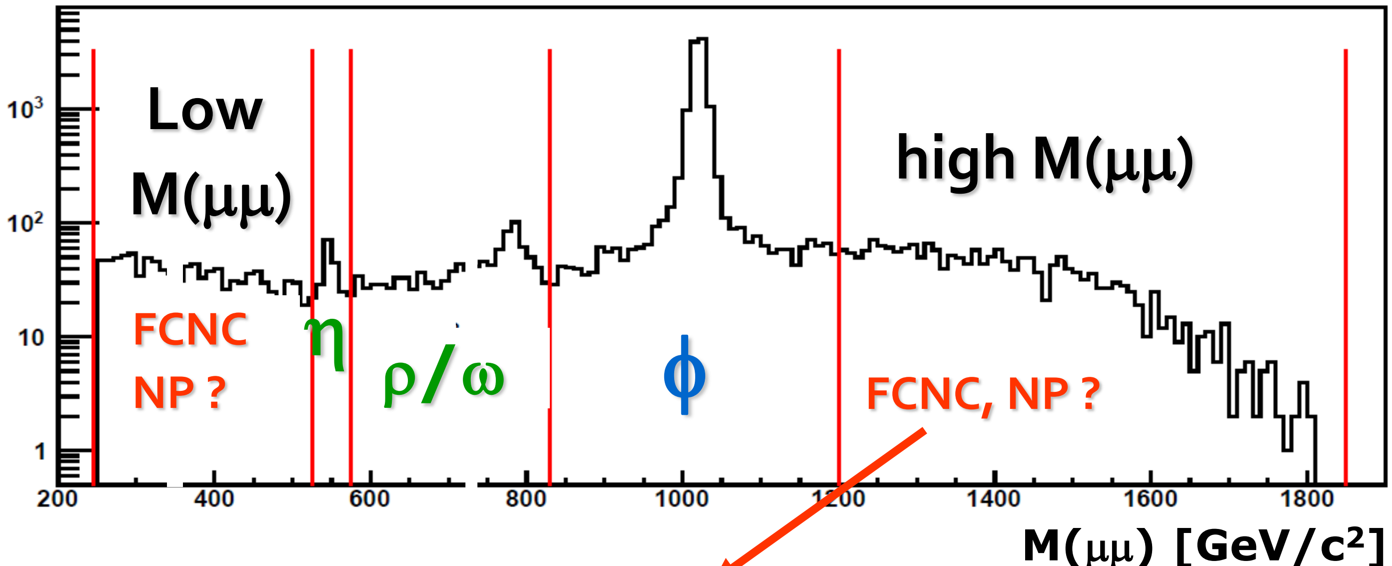
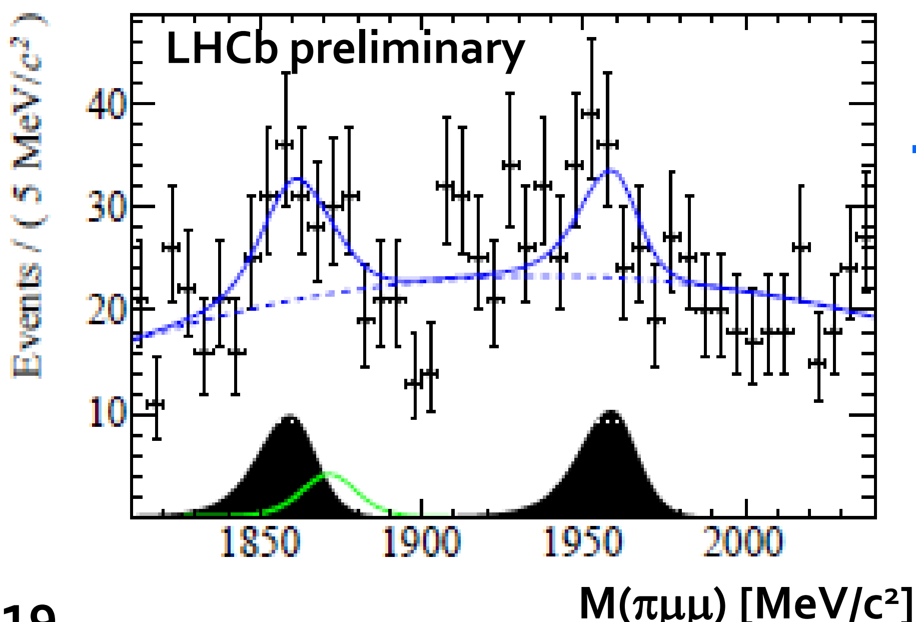


NEW !



- Signal
- Comb. background:
- Peaking backgrounds: $D^+_s \to \pi^+\pi^+\pi^-$

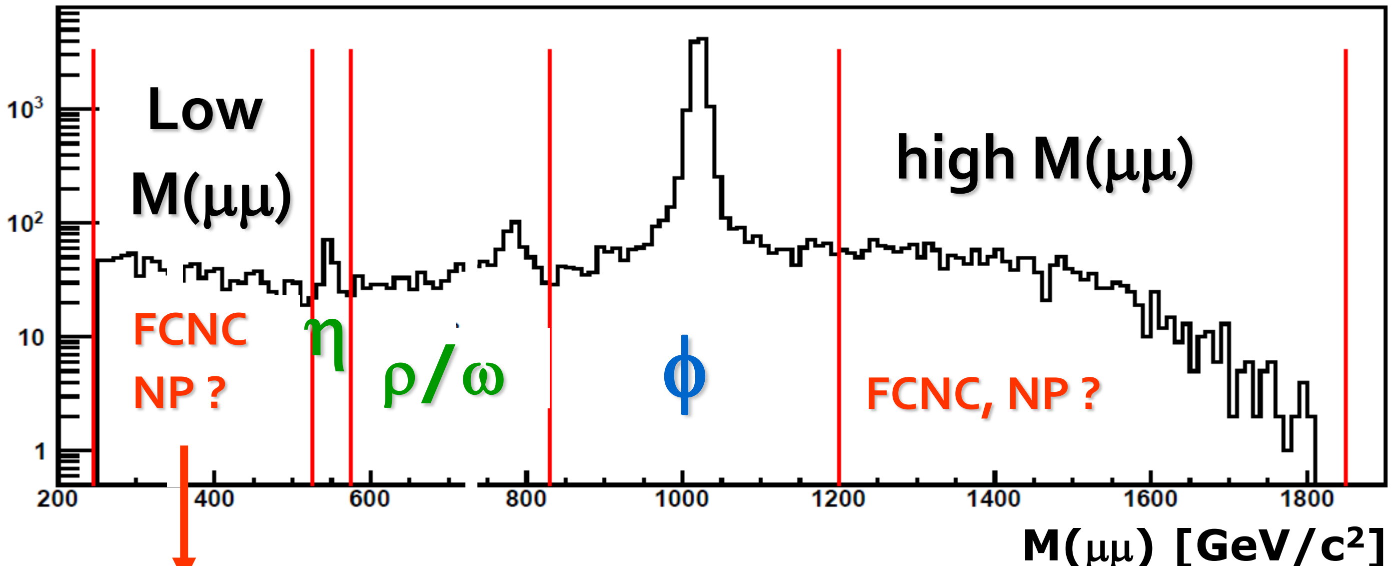
- Shapes determined by loosening muon ID

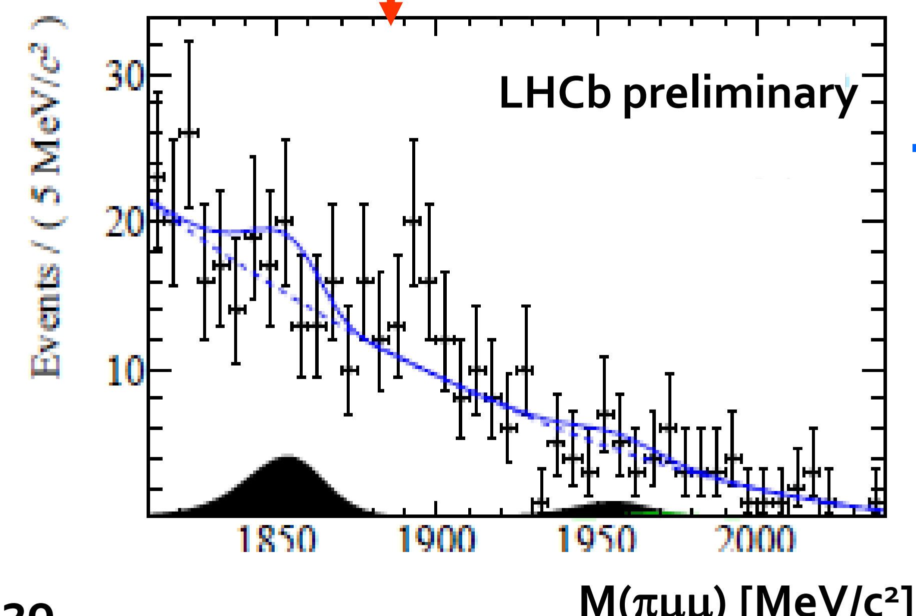
- Then the fit is able to determine the yields

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

5 regions of the dimuon spectrum studied simultaneously

NEW !





Signal

Comb. background:

Peaking backgrounds: $D^+_s \to \pi^+\pi^+\pi^-$

- *Shapes determined by loosening muon ID*
- *Then the fit is able to determine the yields*

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

1 fb^{-1}

LHCb-PAPER-2012-051
Preliminary results

NEW !

Upper limits $\times 10^{-8}$ @ 90% (95%) C.L.		
Region	$B(D^+ \to \pi^+\mu^+\mu^-)$	$B(D_S \to \pi^+\mu^+\mu^-)$
Low $M(\mu\mu)$	2.0 (2.5)	6.9 (7.7)
High $M(\mu\mu)$	2.6 (2.9)	16.0 (18.6)
Total (1)	7.3 (8.3)	41.0 (47.7)

(1) Total non resonant BF, extrapolated from the high $M(\mu\mu)$ region (phase space model).

Conclusion: - Limits of the order of a few 10^{-8} (10^{-7}) for D^+ (D_S) decays.

- 50 to 100 times better than before (D0, Babar).

(V. Abazov et al., Phys.Rev. Lett. 100 (2008) 101801, arXiv:0708.2094 ;
J. Lees et al., Phys.Rev. D84 (2011) 072006, arXiv:1107.4465)

- Still above largest theory predictions ($\sim 10^{-8}$).

Lepton Number Violation: $D^+_{(s)} \rightarrow \pi^- \mu^+ \mu^+$

LHCb-PAPER-2012-051
Preliminary results

- **Same approach as for $D^+_{(s)} \rightarrow \pi^+ \mu^+ \mu^-$ with 4 regions in $M(\mu\pi)$:**

(if mediated by a Majorana neutrino, larger significance in region where its mass peaks)

1 fb^{-1}

Upper limits $\times 10^{-8}$ @ 90% (95%) C.L.

Region [MeV/c²]	$B(D^+ \rightarrow \pi^- \mu^+ \mu^+)$	$B(D_s \rightarrow \pi^- \mu^+ \mu^+)$
250<M(μμ) <1140	1.4 (1.7)	6.2 (7.6)
1140<M(μμ)<1340	1.1 (1.3)	4.4 (5.3)
1340<M(μμ)<1540	1.3 (1.5)	6.0 (7.3)
1540<M(μμ)	1.3 (1.5)	7.5 (8.7)
Total	2.2 (2.5)	12.0 (14.1)

NEW !

Conclusion: **- No sign of LNV**

- Limits of the order of a few 10^{-8} (10^{-7}) for D^+ (D_s) decays.

- 100 times better than before (Babar).

(J. Lees et al., Phys.Rev. D84 (2011) 072006, arXiv:1107.4465)

Summary

- **LHCb has a copious Charm Physics program**
- **A good start with 2010/2011 data:**
  - *First evidence for Charm mixing in a single measurement*
  - *Intriguing $\Delta A_{CP}(KK/\pi\pi)$*
  - *3 body and 4 body Dalitz Analyses.*
  - *Limits on rare decays ($D \to (\pi)\mu\mu$) improved by two orders of magnitude*

And many on-going analyses

- *New rare decays:* $D^{+}_{(S)} \to K^{+}\mu^{+}\mu^{-}$, $D^{0} \to K^{-}K^{+}\mu^{+}\mu^{-}$, $D^{0} \to K\pi\mu^{+}\mu^{-}$
- *WS/RS mixing including search for CPV*
- $A_{CP}(D^{+} \to \phi\pi^{+} - D^{0} \to K_{S}\pi^{+})$
- *T-odd asymmetry with* $D^{0} \to K^{-}K^{+}\pi^{-}\pi^{+}$
- *Mixing with* $D^{0} \to K_{S}hh$
- Λ_{c} *decays*
- …

Back-up I

References on Rare decays

[1] G. Burdman et al, Phys. Rev. D66 (2002) 014009, hep-ph/0112235

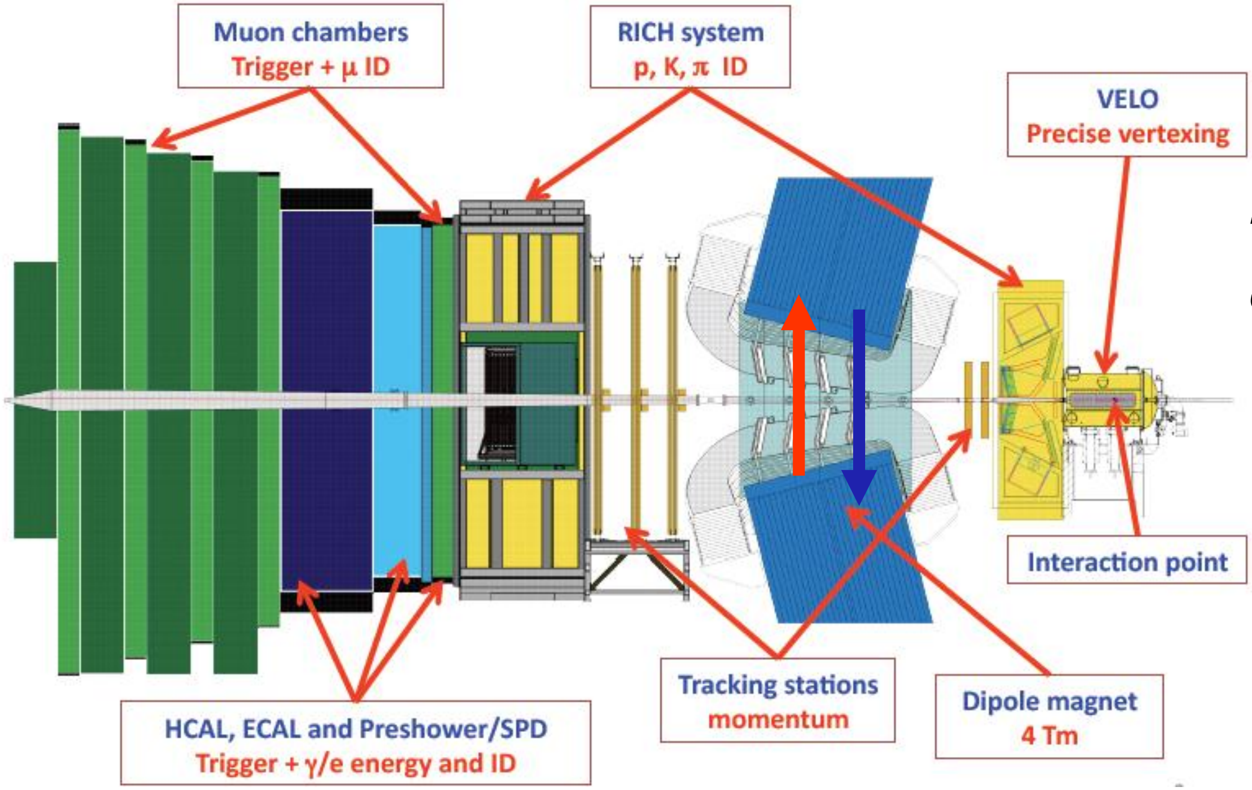
[2] BABAR Collaboration Collaboration, arXiv:1110.6480

[3] S. Fajfer et al, Phys. Rev. D64 (2001) 114009, hep-ph/0106333 ;
Phys. Rev. D76 (2007),074010, arXiv0706.1133;
M. Artuso et al., Eur. Phys. J. C57 (2008) 309, arXiv:0801.1833 ;
L. Cappiello et al., arXiv:1209.4235v1

[4] Particle Data Group.

[5] E. Golowich et al, Phys. Rev. D79 (2009) 11030, arXiv:0903.2830

[6] S. Fajfer et al, arXiv:1208.0759v2;
L. Cappiello et al., arXiv:1209.4235v1



*B-field polarity can be reversed: **Up** or **Down***

Typical Performance

- *Charged tracks momentum: $\sigma p/p$=0.35-0.55%, σm=10-20 MeV/c^2*
- *ECAL: $\sigma E/E = 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)*
- *muon-ID $\varepsilon(\mu \to \mu)$ ~95%, mis-ID rate($\pi \to \mu$)~1%*
- *K-π separation $\varepsilon(K \to K)$ ~95%, mis-ID rate($\pi \to K$)~10%*
- *Proper time: σ_t~ 30-50 fs, σ_z~ 60μm (Prim. Vtx) σ_z~ 150 μm (Secondary Vtx)*

Charm Measurements @ LHCb: typical ingredients

Get data

- **Trigger: too much data for generic selection**

- *Each (group of) mode(s): a dedicated 'line' in HLT2*

- *Line = a selection, can be close to the offline sel.*

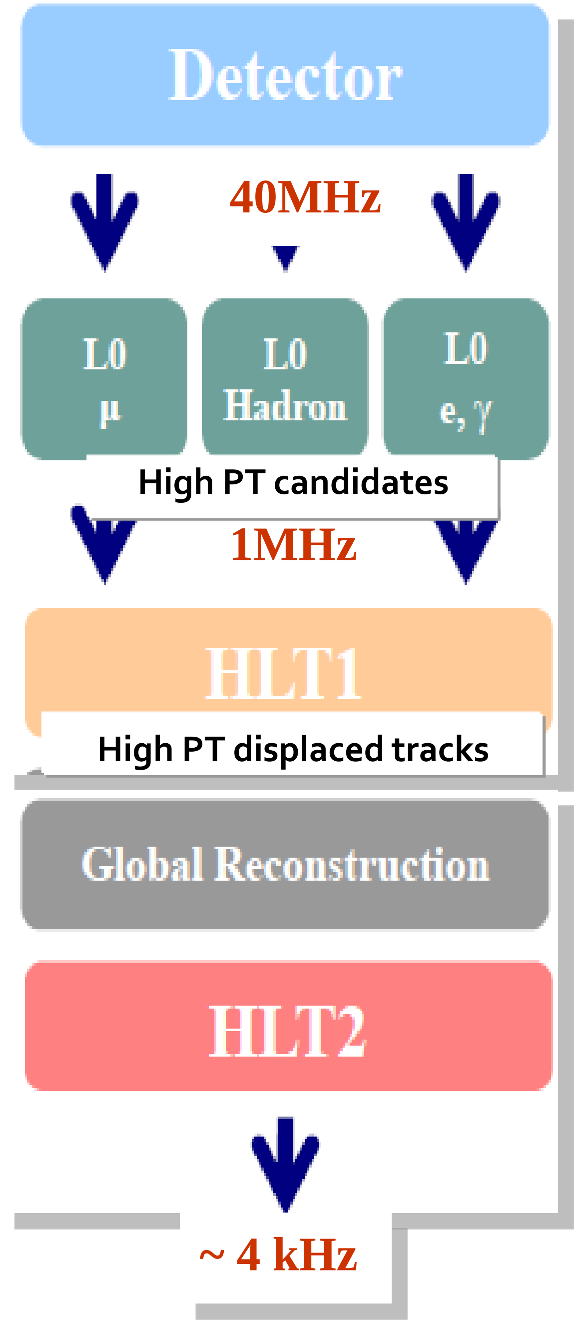
- *Needed both for the signal and control modes*

- *Thanks to very flexible/configurable trigger design: lines added/removed/updated every few months*

- **Stripping (~ offline HLT)**

  - Lines run a few times per year to provide analysis with only the data they need

  - Make CPU demand match resource



Charm mixing

- **Effective Hamiltonian that allow to focus on time evolution in {|D^0>,|D^0>} basis, but also accounts for its decay (non hermitian)**

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Physical states

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

Flavor states

$$|D^0(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\overline{D}^0\rangle$$

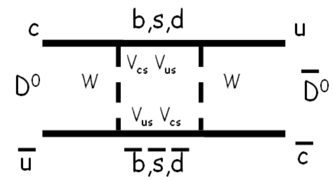
$$|\overline{D}^0(t)\rangle = g_+(t)|\overline{D}^0\rangle + \frac{p}{q}g_-(t)|D^0\rangle$$

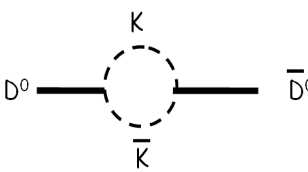
- **Physical states eigenvalues rule ($M_{1,2} \pm i\Gamma_{1,2}$) the mixing time evolution. $|g_\pm(t)|^2$ can be written in terms of *x* and *y***

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2 \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

- **Hard to predict x & y. Two theoretical approaches evaluate 0.1 to 1%**

  - *OPE based on 4-fermions local operators: box diagrams either GIM (s,d in the loop) or CKM suppressed (b)*
  - *Sum of hadronic intermediate states GIM suppression broken only by SU(3)F breaking.*

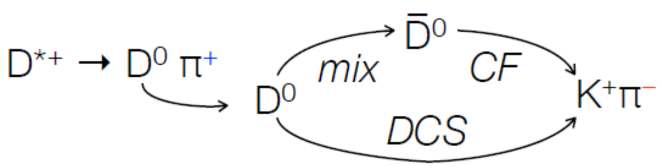




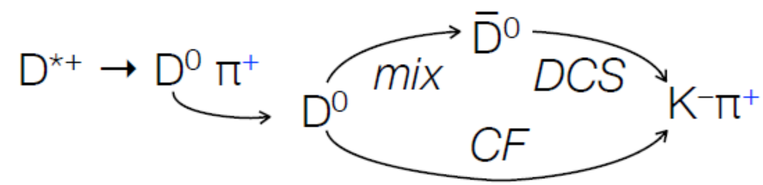
Mixing Measurements at LHCb

- **1st way: observe a decay at too high a rate, unless the D flavor flipped**

Wrong Sign events (WS) | *Right Sign events (RS)*



vs.



➔ $$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\, y' t + \frac{x'^2 + y'^2}{4} t^2$$

$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

Assuming x,y small and no CPV

- **2nd way: measure different lifetimes in $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$**

  - *CP-even eigenstates couple to $|D_1\rangle = |D^0\rangle + |\bar{D}^0\rangle$ (assume no CPV)*

    → *Measured lifetime distribution ~ exp($-i\Gamma_1 t$)*

  - *Flavor eigenstates couple to a mixture of $|D_1\rangle$ and $|D_2\rangle$*

    → *Measured lifetime distribution ~ exp($-i\Gamma_1 t$)+ exp($-i\Gamma_2 t$)*

➔ $$y_{CP} \equiv \frac{\hat{\Gamma}(D^0 \rightarrow K^+K^-)}{\hat{\Gamma}(D^0 \rightarrow K^-\pi^+)} - 1$$

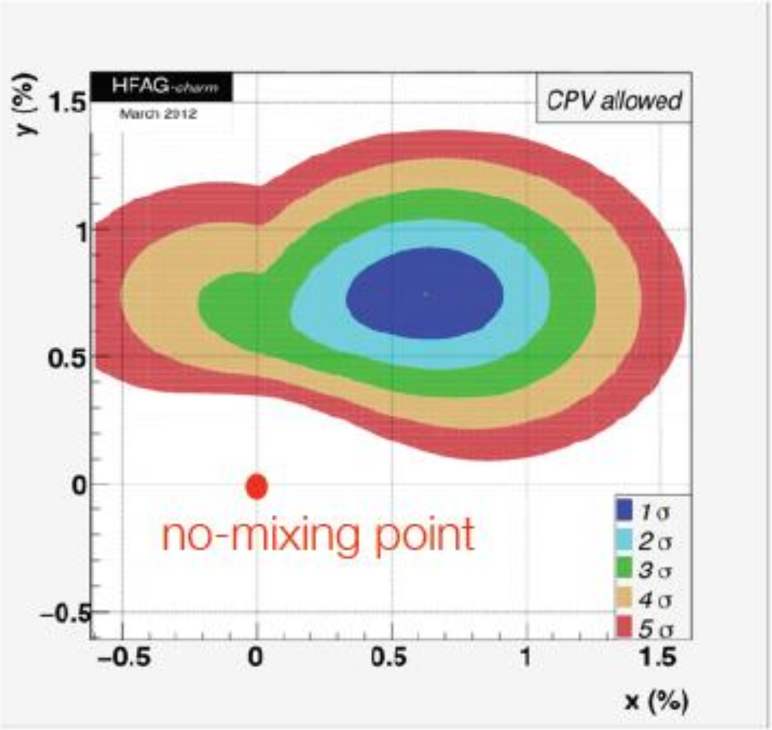
- **These suppressions make charm mixing far slower than for in K, B, B_S**
- **Less good at interfering with the decay to enhance a potential CPV signal. *However* still a good tool to seek NP**

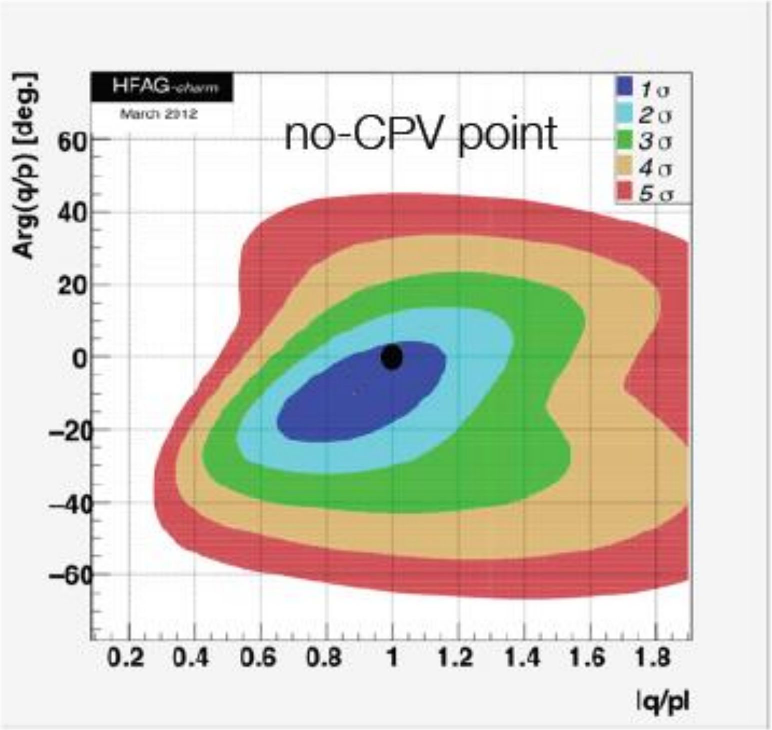
  - CPV in the mixing should have a low SM background

  - |x|>>|y| would also be a sign (x generated by virtual intermediate states: more sensitive to heavy NP particles)

Charm mixing: State of the Art in 2012

- **HFAG [3]**





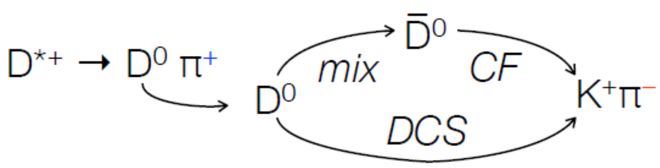
$$x = (0.63 \pm 0.19)\ \%$$

$$y = (0.73 \pm 0.11)\ \%$$

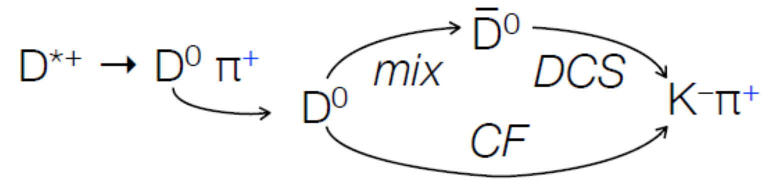
Mixing Measurements at LHCb

- **1st way: observe a decay at too high a rate, unless the D flavor flipped**

Wrong Sign events (WS) | *Right Sign events (RS)*



vs.



➔ $$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\, y' t + \frac{x'^2 + y'^2}{4} t^2$$

$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

9

Assuming x,y small and no CPV

- **2nd way: measure different lifetimes in $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$**

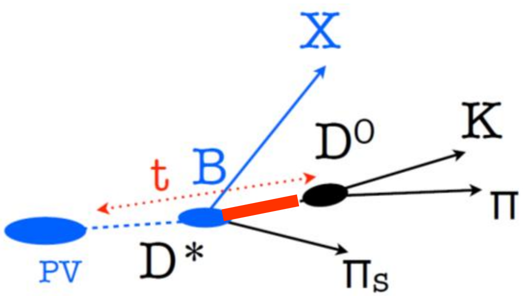
  - *CP-even eigenstates couple to $|D_1\rangle = |D^0\rangle + |D^0\rangle$ (assume no CPV)*
    - *→ Measured lifetime distribution ~ $\exp(-i\Gamma_1 t)$*
  - *Flavor eigenstates couple to a mixture of $|D_1\rangle$ and $|D_2\rangle$*
    - *→ Measured lifetime distribution ~ $\exp(-i\Gamma_1 t) + \exp(-i\Gamma_2 t)$*

➔ $$y_{CP} \equiv \frac{\hat{\Gamma}(D^0 \rightarrow K^+K^-)}{\hat{\Gamma}(D^0 \rightarrow K^-\pi^+)} - 1$$

Systematic uncertainties

Anything that distorts R_i's !

- **Reconstruction effects mostly cancel in the ratio**
- **3% of D^0's are likely to come from B decays: same R(t) but t is wrong !**

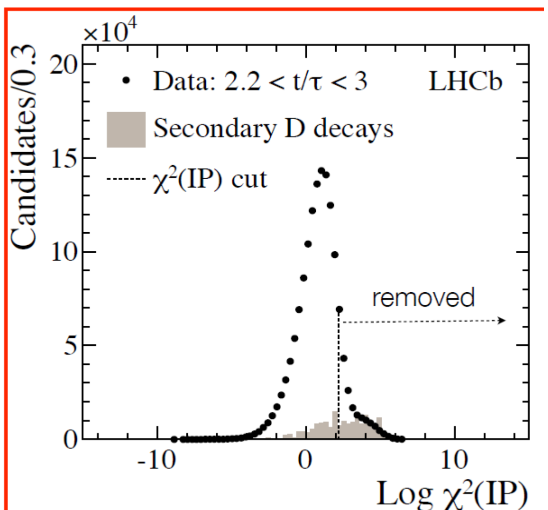


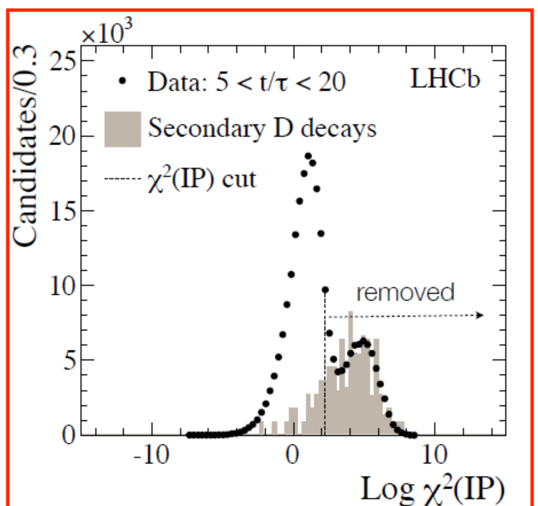
Fit $R^m(t)$ instead of R(t) and see the difference

$$R^m(t) = \frac{N^{WS}(t) + N_B^{WS}(t)}{N^{RS}(t) + N_B^{RS}(t)} = R(t)\left\{1 - f_B^{RS}(t)\left[1 - \frac{R_B(t)}{R(t)}\right]\right\}$$

Fraction of secondary in each bin
Fit the D log(IPχ^2)

Fit assuming $R_B(t) = R_D = R(0)\ \forall t$
(R(t): monotoneous increasing function)

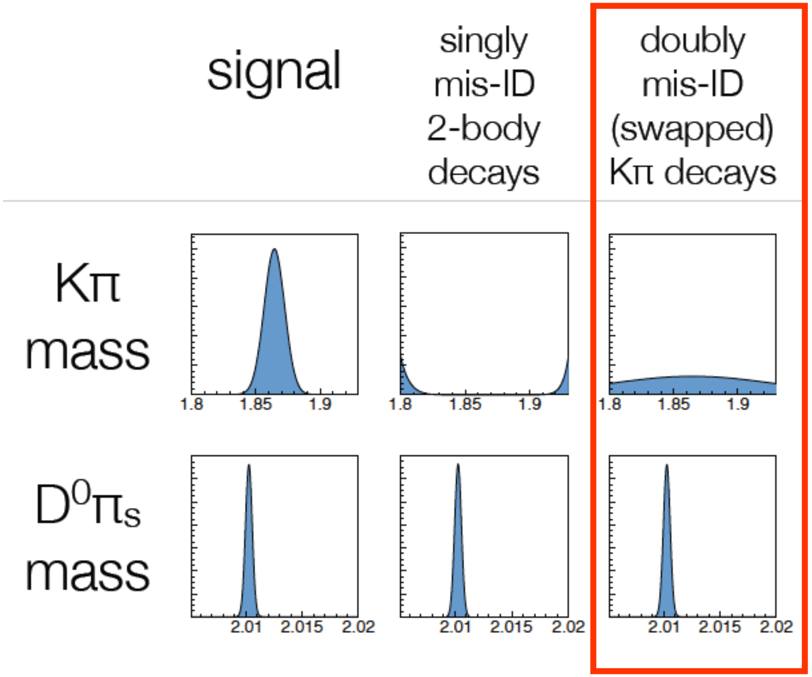




Systematic uncertainties

Anything that distorts R_i's !

- **Reconstruction effects mostly cancel in the ratio**
- **Peaking backgrounds surviving tight M_{D0} and PID cuts**

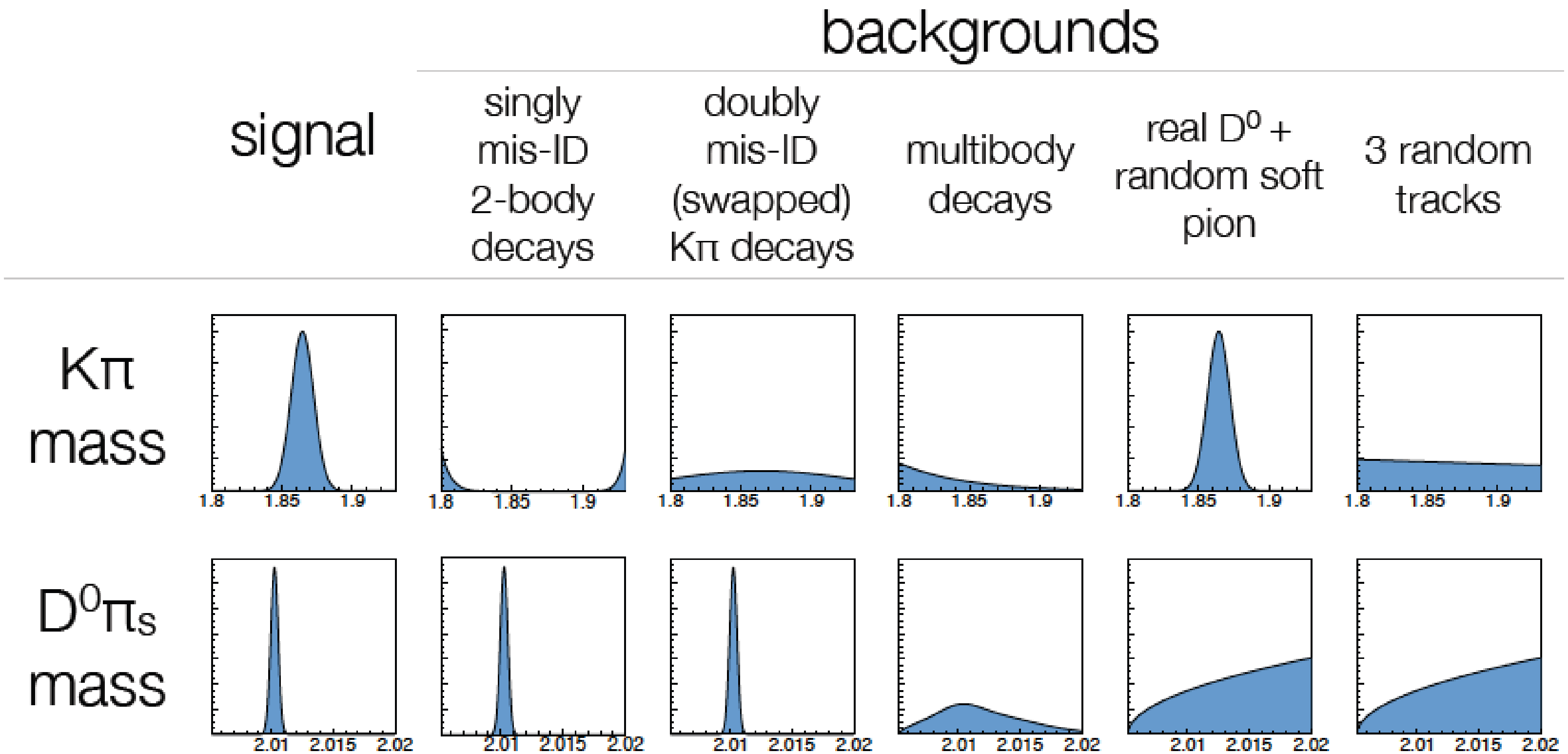


M_{D0} sideband: misidentified RS decays are (0.4±0.2) % of the WS sample

Fit with:

$$R^m(t) = R(t) + N^{RS}(\text{double mis-IS}) / N^{RS}$$

$D^* \rightarrow D^0(\rightarrow K\pi)\pi$ signal vs backgrounds



Cut tight on PID and D^0 mass to reduce physics bkg and fit $D^0\pi_s$ mass, then consider only signal and random pions in the fit

	ΔR_D	$\Delta y'$	$\Delta x'^2$
Asymmetries in detection or production	$<0.001\sigma$	$<0.001\sigma$	$<0.001\sigma$
VELO lenght scale	0	0.003σ	0.001σ
Multiple candidates	0.02σ	0.06σ	0.07σ

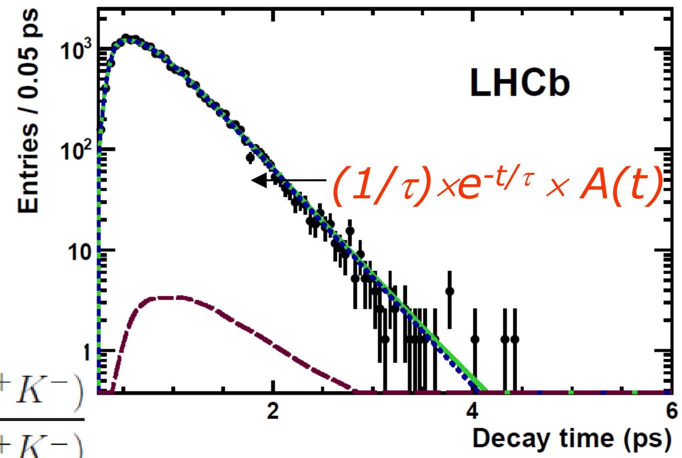
Cross-checks

- We perform the measurement in statistically independent sub-samples of the data and find consistent results
  - different data-taking periods,
  - magnet polarities,
  - number of reconstructed primary vertices
- Also use alternative decay-time binning schemes or alternative fit methods to separate signal and background, and find no significant variations in the estimated mixing parameters

y_{CP} and A_Γ with two-body D decays

Measurement technique

- **Measure the proper decay time distribution of $D^0 \to K^-\pi^+$, K^+K^- and fit an exponential model to extract effective lifetimes → $\hat{\Gamma}$**

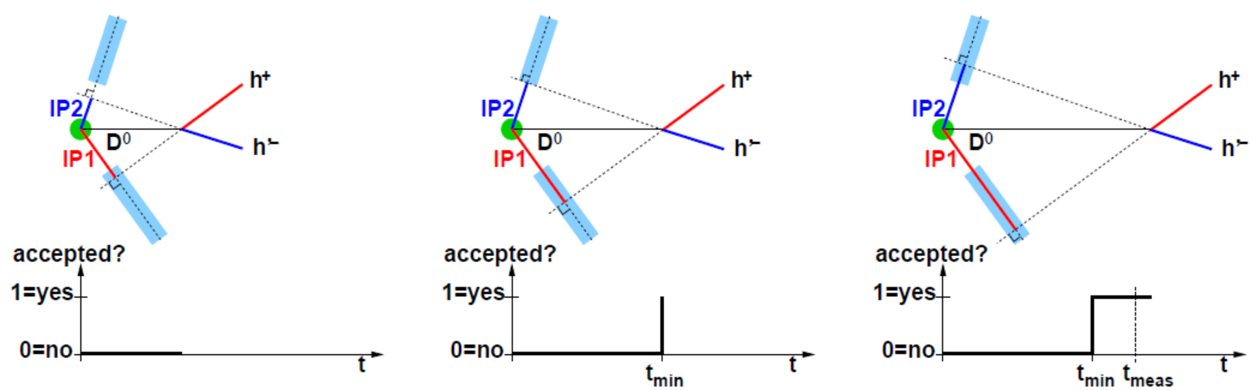


$$y_{CP} \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^-\pi^+)} - 1 \quad A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-) - \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^+K^-) + \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}$$

- **Key point I : treating the experimental distortion of this distribution**

→ Swimming: data driven determination of the time acceptance A(t)

- Event by event method: given its kinematics, an event is accepted by the lifetime biasing cuts (ex: IPχ2, Flying Distance,..) based on *t* only.
- Replay the selection, with recomputed cut variables, for several values of *t.*



Measurement technique

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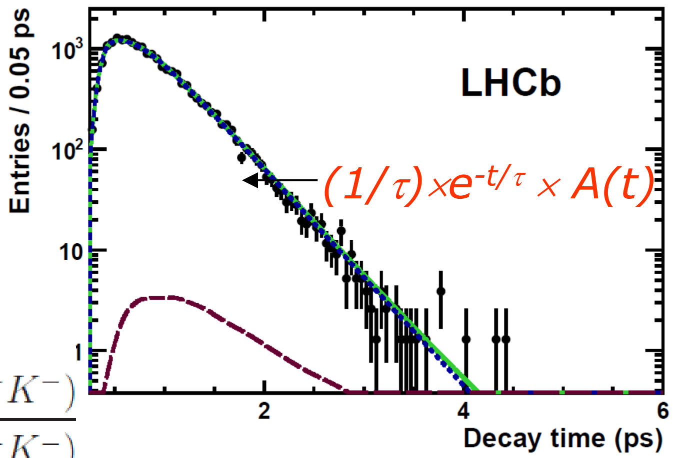

$$y_{CP} \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^-\pi^+)} - 1 \quad A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-) - \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^+K^-) + \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}$$

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- Event by event method: given its kinematics, an event is accepted by the lifetime biasing cuts (ex: IPχ2, Flying Distance,..) based on *t* only.

- Replay the selection, with recomputed cut variables, for several values of *t.*

- Tracks hits are hard to move → move the primary vertex instead.

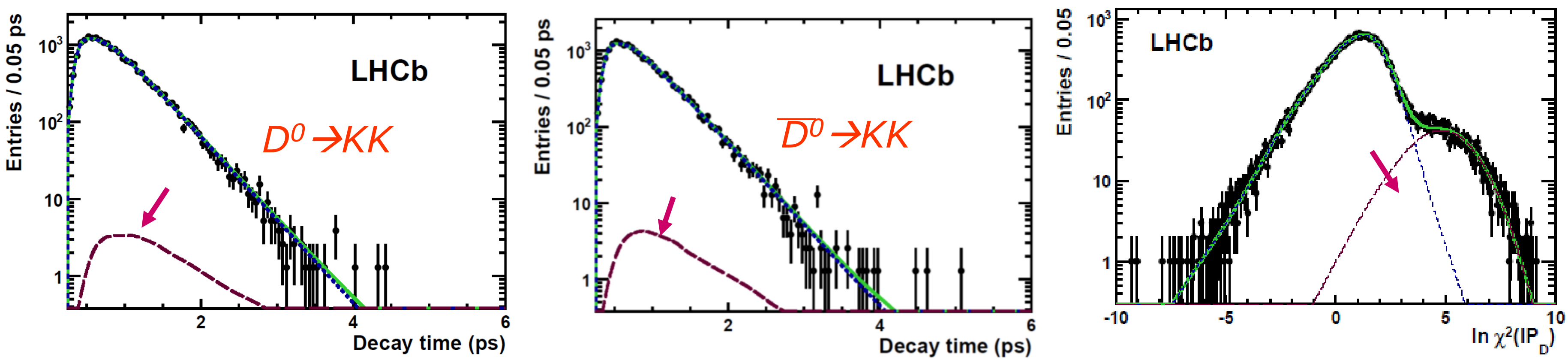
- HLT uses biasing cuts ! But one key feature of LHCb's trigger:

HLT can be re-run exactly offline !

■ **Key point II : D^0 from B decays**

- *background to prompt D^0 with a different decay time distribution*
- *treated by the fit, using the D(IPχ2) distribution*

➔ *Model used in the fit = dominant systematic uncertainty*



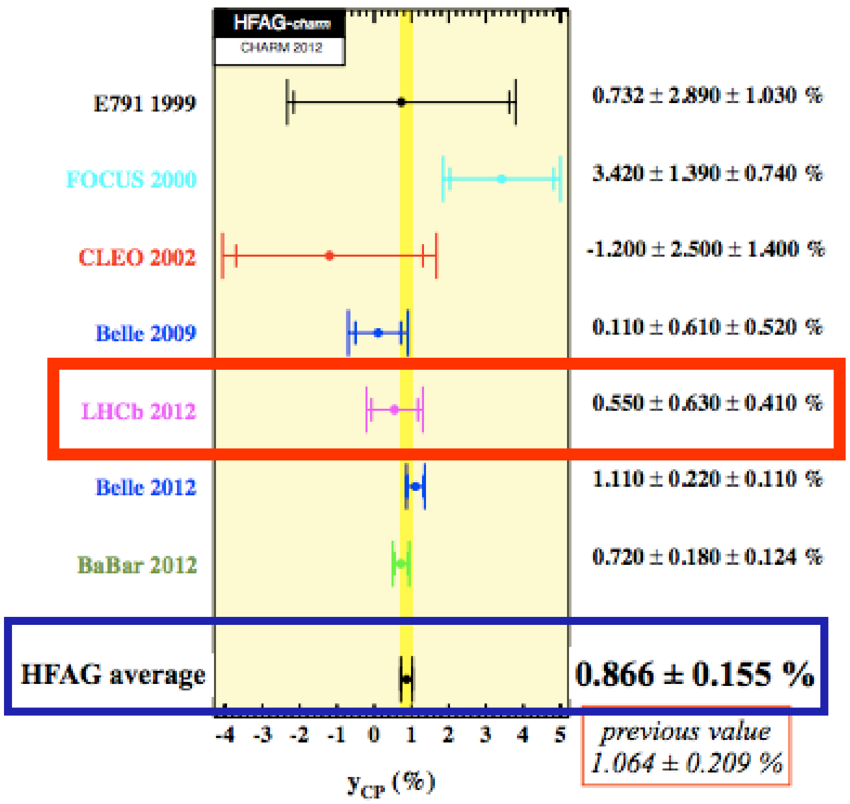
Results

29 pb^{-1}, 2010 data.

$$y_{CP} = (5.5 \pm 6.3_{\text{stat}} \pm 4.1_{\text{syst}}) \times 10^{-3}.$$

$$A_{\Gamma} = (-5.9 \pm 5.9_{\text{stat}} \pm 2.1_{\text{syst}}) \times 10^{-3}$$

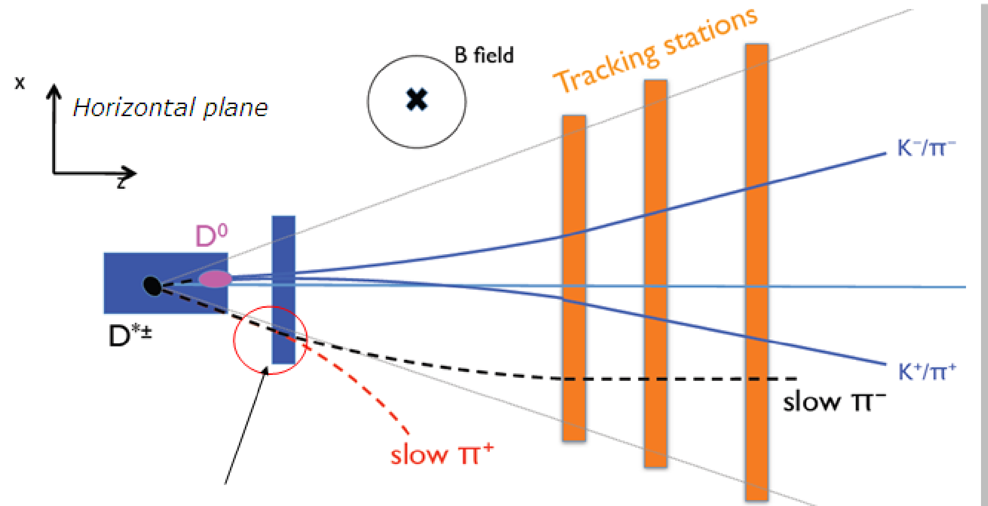
J.Phys.G39 (2012) 045005, arXiv:1112.4698v1



Will be much improved with LHCb's full sample: 3 fb^{-1}

$\Delta A_{RAW} = A_{RAW}(K^+K^-) - A_{RAW}(\pi^+\pi^-) = \Delta A_{CP}$

- **This is a very robust observable !**
- **Yet not perfect. Ex:**



  - *$\vec{B}$ causes $A_D(\pi_s)$*

    π^+/π^- bent in opposite directions

    → each sees a different detector

    if left-right asymmetries.

➔ Kinematic regions where A_{RAW} can reach 100% !

  - *Large asymmetries (>>1%) cause the Taylor Expansion to break down.*

    Large A_D close to detector's edges

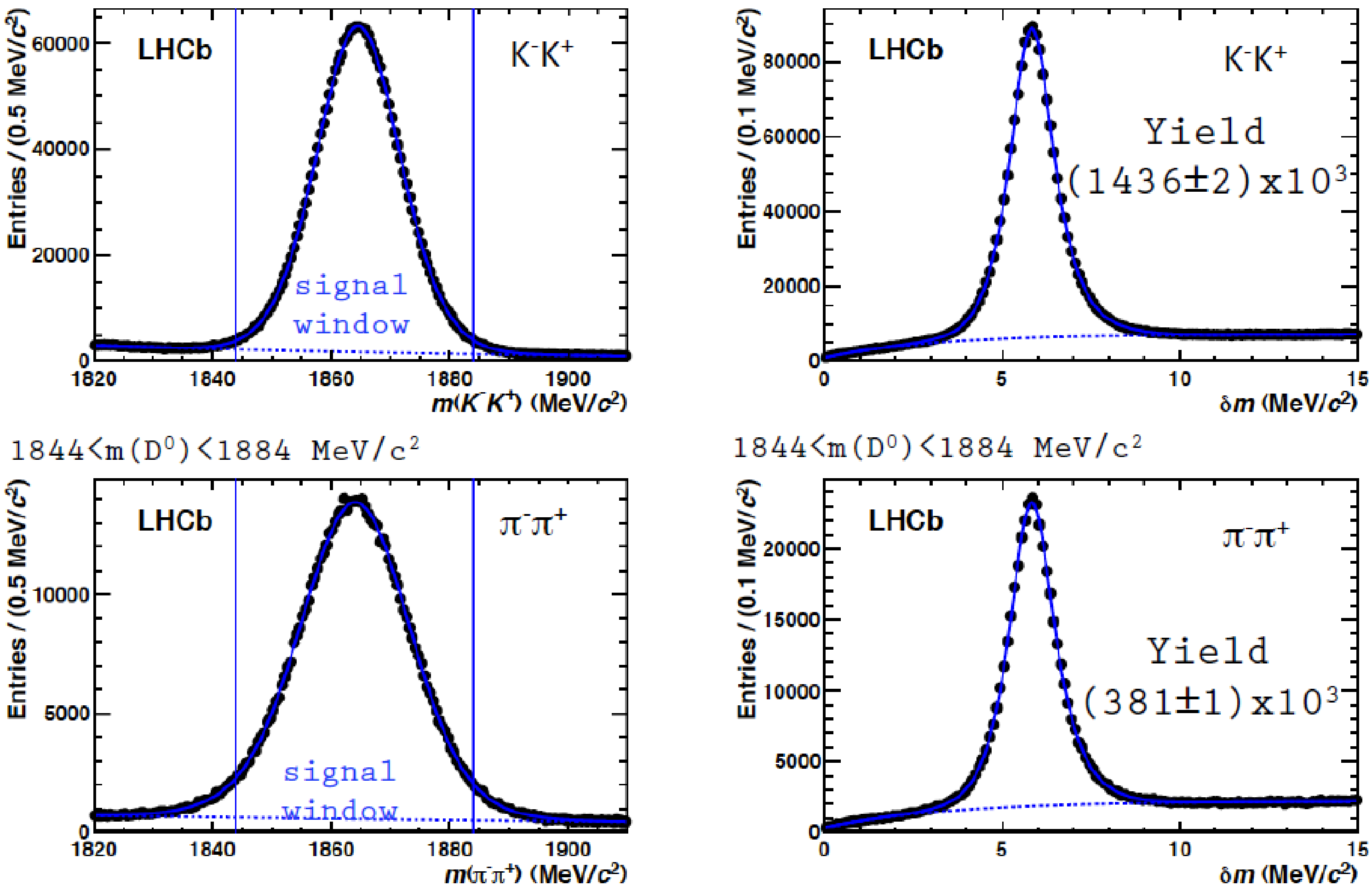
  - *$A_P(D^*)$ depends on $\vec{p}$. So do the particle reco and selection, thus $A_D(\pi_s)$!*

    KK and $\pi\pi$ selections favor different regions (PID efficiency also depends on $\vec{p}$)

- **Main protections**
  - *Measurements in separate bins of P_T and η of D*'s, P of π_S*
  - *Combine opposite B polarities (up & down) to cancel left/right det. asymmetry*
  - *Fiducial cuts to remove regions of large asymmetry*
  - *Many checks/systematics (back-up slides: compare ΔA_{CP} with or w/o binning, consistency between the various bins, between up and down polarities, etc…)*

$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

$\delta m = m(h^+h^-\pi^+) - m(h^+h) - m(\pi^+)$



Systematics

Effect	Uncertainty
ΔA_{CP} with vs. without Fiducial cuts	**0.01%**
Background peaks (+their asymmetry) from $m(D^0)$ sideband injected into TOYs to check the effect on the fit.	**0.04%**
ΔA_{CP} with fit vs. sideband subtraction cuts	**0.08%**
ΔA_{CP} with multiple candidates vs. only one allowed per event	**0.06%**
ΔA_{CP} with kinematical bins vs. one single bin	**0.02%**
TOTAL	**0.11%**

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

3.5 σ from no CPV.

Cross Checks

- Electron and muon vetoes on the soft pion and D^0 daughters
- Different kinematic binnings
- Stability of result vs data-taking runs
- Stability vs kinematic variables
- Toy MC studies of fit procedure, statistical errors
- Tightening of PID cuts on D^0 daughters
- Tightening of kinematic cuts
- Variation with event track multiplicity
- Use of other signal, background line-shapes in the fit
- Use of alternative offline processing (skimming/stripping)
- Internal consistency between subsamples (splitting left/right, field up/ field down)

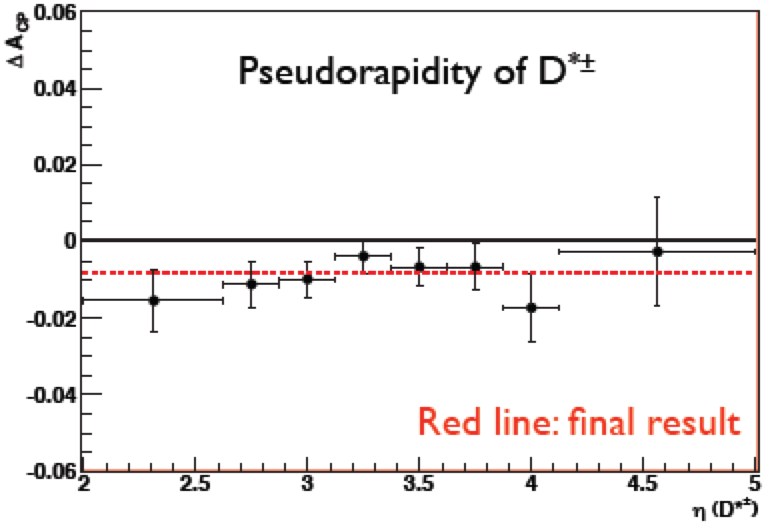
Cross Checks

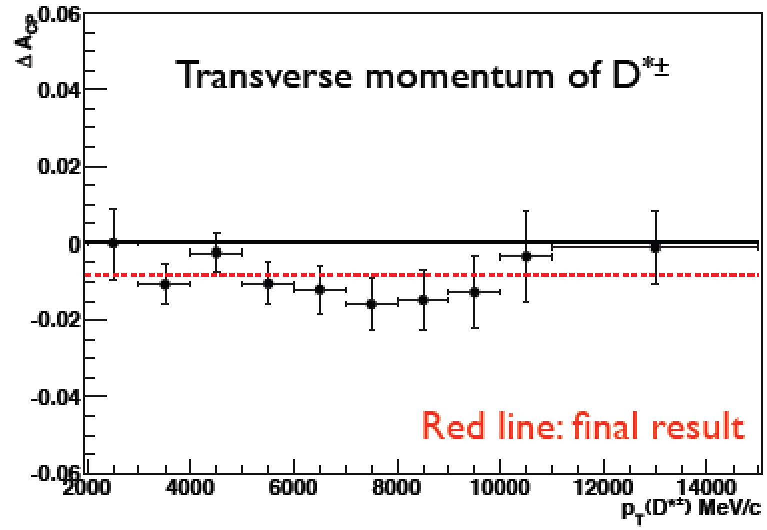
- **Flavor physics means precision physics, ie many cross checks**
  - *- Different kinematic binnings*
  - *- Remove fiducial cuts*
  - *- Tightening of PID cuts on D daughters (correlated with P, and bkg level)*
  - *- Impact of neglecting some backgrounds.*
  - *- Alternative signal & bkg shapes in the fit, compare with mere sideband sub.*
  - *- Alternative online/offline processing (trigger, selection, signal region, etc…)*
  - *- Stability of result vs data-taking time*
  - *- Control mode resembling the signal (ex: $D_s \rightarrow \phi\pi$; DP outside the phi region)*
  - *- Internal consistency among subsamples (left vs. right, field up vs. down)*
  - *- Electron and muon vetoes on the soft pion and D^0 daughters*
  - *- Variation with event track multiplicity*

  - *- Toy MC studies of fit procedure, statistical errors*
  - *- Stability vs kinematic variables*

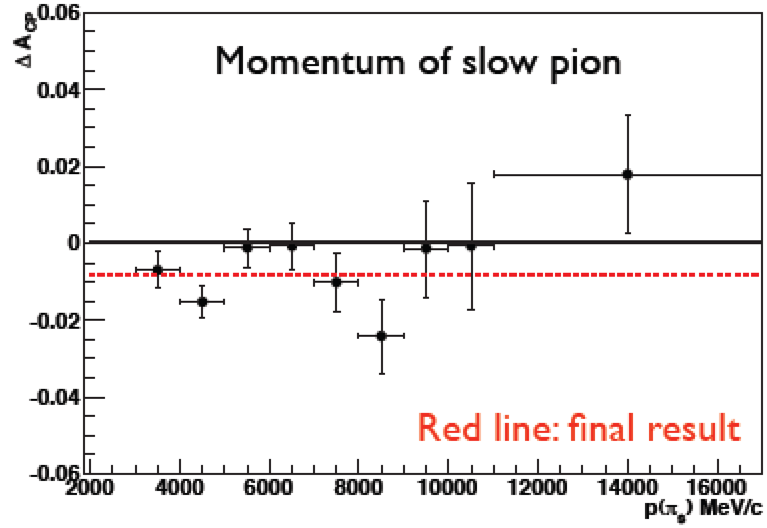
Please check if other tests have been done by one of the ANA

Cross Checks

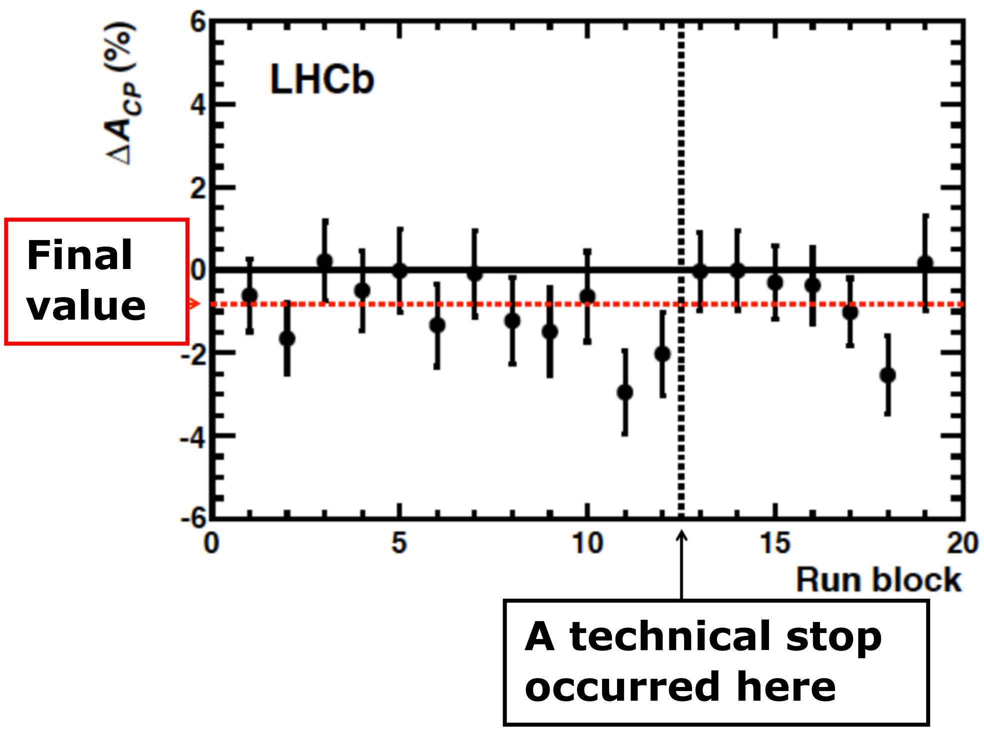




- **No evidence of dependence on relevant kinematic variables**



■ **Stability with time**



■ **Stability wrt PID**

No significant variation of ΔA_{CP} when tightening the cut on the hadron PID information provided by the RICH

PID tight+

$\Delta A_{CP} = (-0.88 \pm 0.26_{stat})\%$

PID tight++

$\Delta A_{CP} = (-1.03 \pm 0.31_{stat})\%$

■ **Internal consistency: a closer look**

Split the 216 bins into 8 smaller sets and check χ^2 for each, and between them:

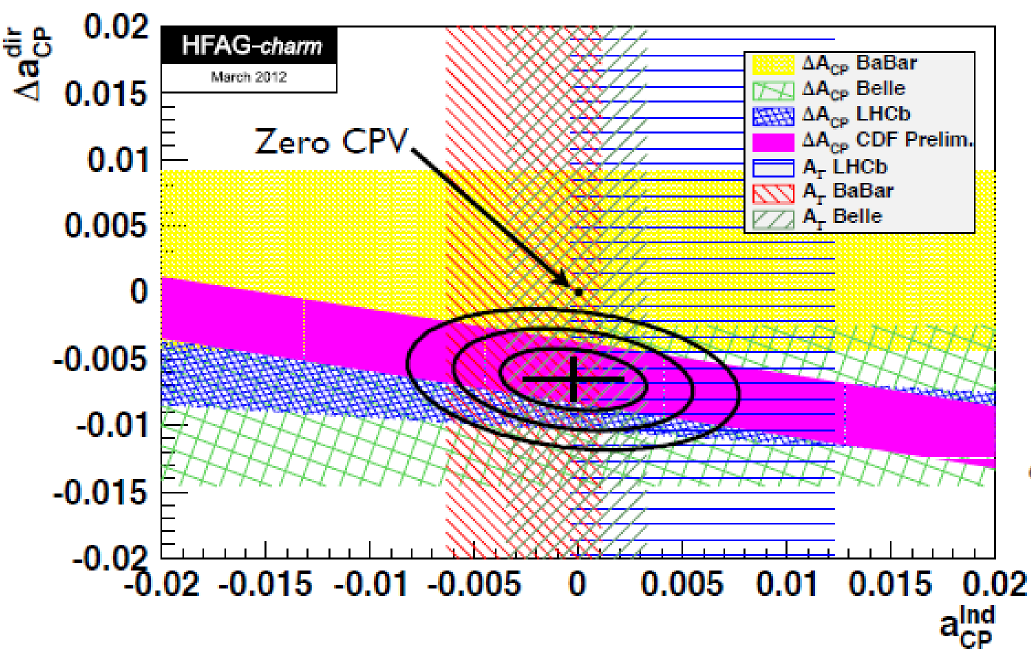
χ^2 / NDF = 6.7/7

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%)

World Wide

Year	Experiment	Results	$\Delta\langle t\rangle/\tau$	$\overline{\langle t\rangle}/\tau$
2007	Belle	$A_\Gamma = (0.01 \pm 0.30\ \text{(stat.)} \pm 0.15\ \text{(syst.)})\%$	-	-
2008	BaBar	$A_\Gamma = (0.26 \pm 0.36\ \text{(stat.)} \pm 0.08\ \text{(syst.)})\%$	-	-
2011	LHCb	$A_\Gamma = (-0.59 \pm 0.59\ \text{(stat.)} \pm 0.21\ \text{(syst.)})\%$	-	-
2008	BaBar	$A_{CP}(KK) = (0.00 \pm 0.34\ \text{(stat.)} \pm 0.13\ \text{(syst.)})\%$ $A_{CP}(\pi\pi) = (-0.24 \pm 0.52\ \text{(stat.)} \pm 0.22\ \text{(syst.)})\%$	0.00	1.00
2008	Belle	$\Delta A_{CP} = (-0.86 \pm 0.60\ \text{(stat.)} \pm 0.07\ \text{(syst.)})\%$	0.00	1.00
2011	LHCb	$\Delta A_{CP} = (-0.82 \pm 0.21\ \text{(stat.)} \pm 0.11\ \text{(syst.)})\%$	0.10	2.08
2012	CDF Prelim.	$\Delta A_{CP} = (-0.62 \pm 0.21\ \text{(stat.)} \pm 0.10\ \text{(syst.)})\%$	0.25	2.58

CDF public note 10784



$$a_{CP}^{\text{ind}} = (-0.025 \pm 0.231)\%$$

$$\Delta a_{CP}^{\text{dir}} = (-0.656 \pm 0.154)\%$$

Agreement with no CPV: 2×10^{-5}

World Average

- Can be combined with other measurements of ΔA_{CP} and with measurements of A_Γ by disentangling direct & indirect CPV.

$$A_{CP}(f) \approx a_{CP}^{\rm dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{\rm ind}$$

- *Depends on <t> in the D^0 sample (~time given the mixing to interfere).*

- *$D^0 \to \pi\ \pi$ and $D^0 \to \pi\ \pi$ can have different time acceptance*

$$\Delta A_{CP} = \left[a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+)\right] + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\rm ind}$$

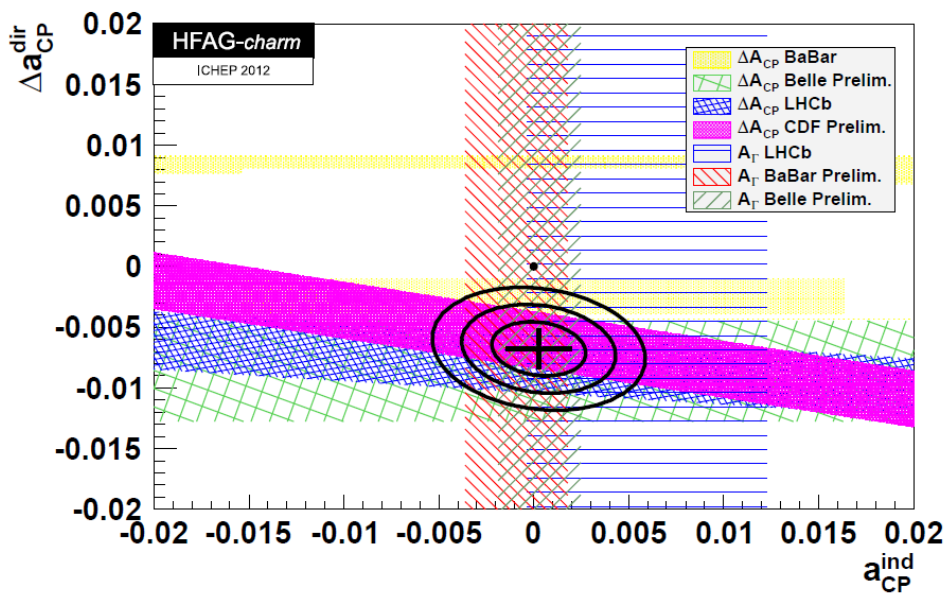
→ *Also measured Δ<t>: Contribution of indirect CPV < 10%*

- **HFAG average**

$a_{CP}^{\rm ind}$ = (0.027 ± 0.163)%

$\Delta a_{CP}^{\rm dir}$ = (−0.678 ± 0.147)%

Agreement with no CPV: 6×10^{-5}



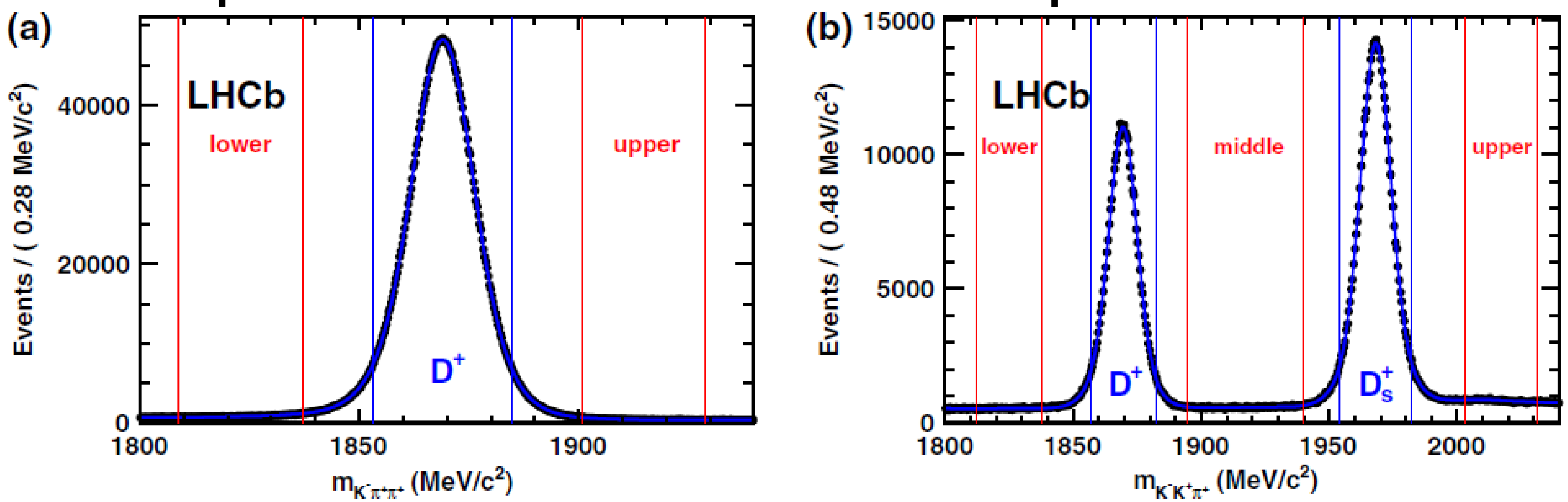
(see http://www.slac.stanford.edu/xorg/hfag/charm/ICHEP12/DCPV/direct_indirect_cpv.html)

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

PHYSICAL REVIEW D 84, 112008 (2011), 35 pb^{-1}

- **High signal statistics.**
- **Control of the artificial asymmetries thanks to large control samples:** *$D^+ \to K^-\pi^+\pi^+$, $D_S \to K^-K^+\pi^+$*

35 pb-1 35 pb-1

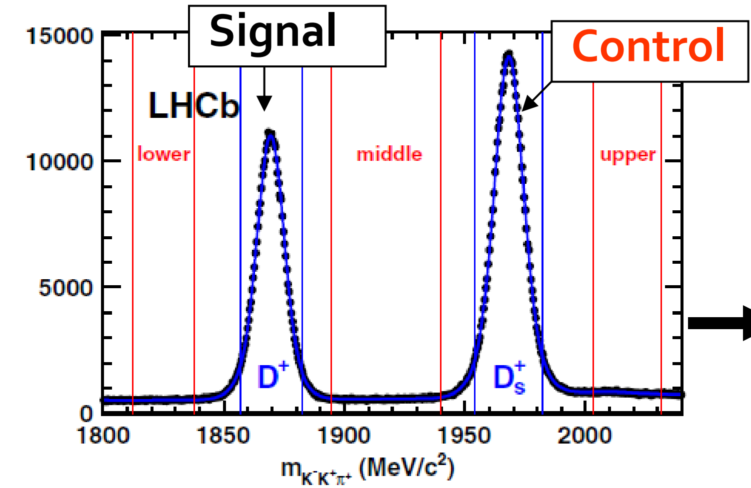


$$D^+ \to K^-K^+\pi^+ \quad (3.284 \pm 0.006) \times 10^5$$
$$D_s^+ \to K^-K^+\pi^+ \quad (4.615 \pm 0.012) \times 10^5$$
$$D^+ \to K^-\pi^+\pi^+ \quad (3.3777 \pm 0.0037) \times 10^6$$

Larger than in all previous studies (Babar, Belle, CLEO-c)

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

PHYSICAL REVIEW D 84, 112008 (2011)



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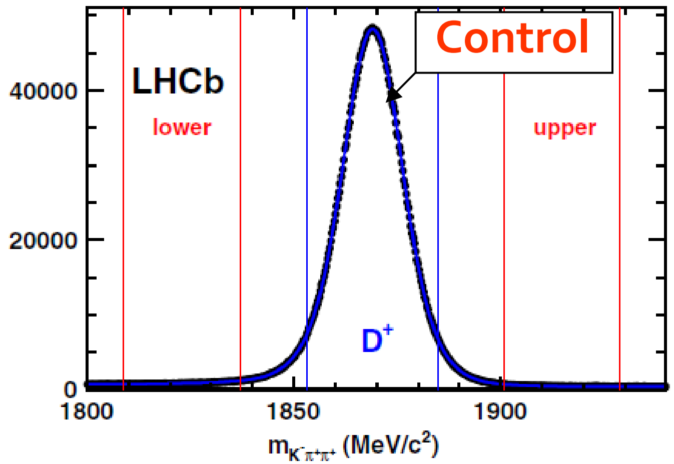
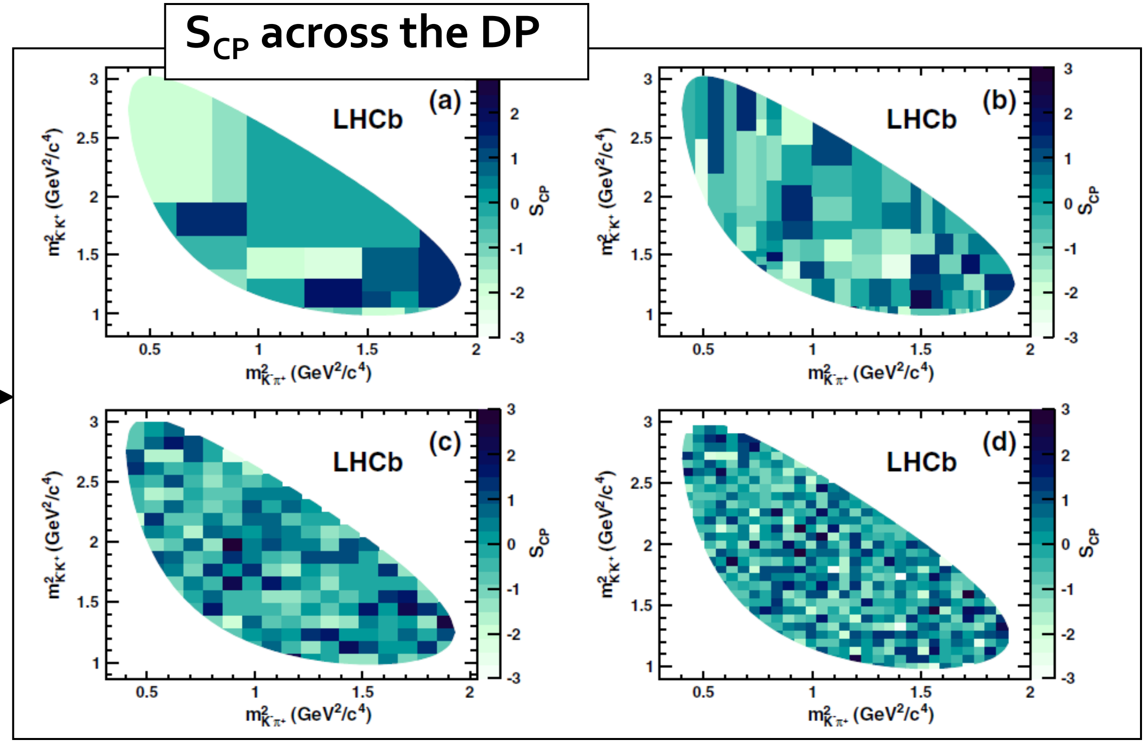


$$D^+ \to K^- \pi^+ \pi^+ \quad (3.3777 \pm 0.0037) \times 10^6$$



p-value for $\chi^2 = \Sigma(S^i_{CP})^2$

Binning	p-value (%)
Adaptive I	12.7
Adaptive II	10.6
Uniform I	82.1
Uniform II	60.5

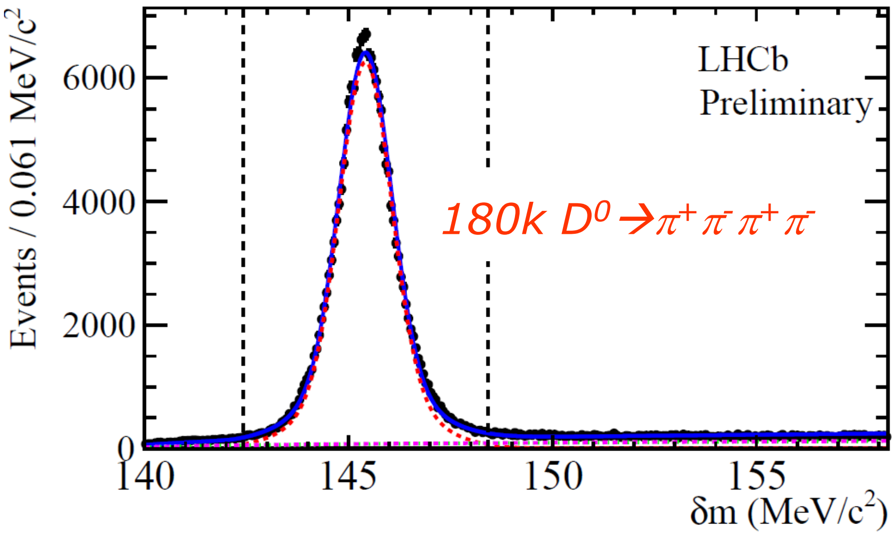
No evidence for CPV !

*-Same plots for **control modes**: no artificial asymmetry!*

$D^0 \to \pi^+\pi^-\pi^+\pi^-$

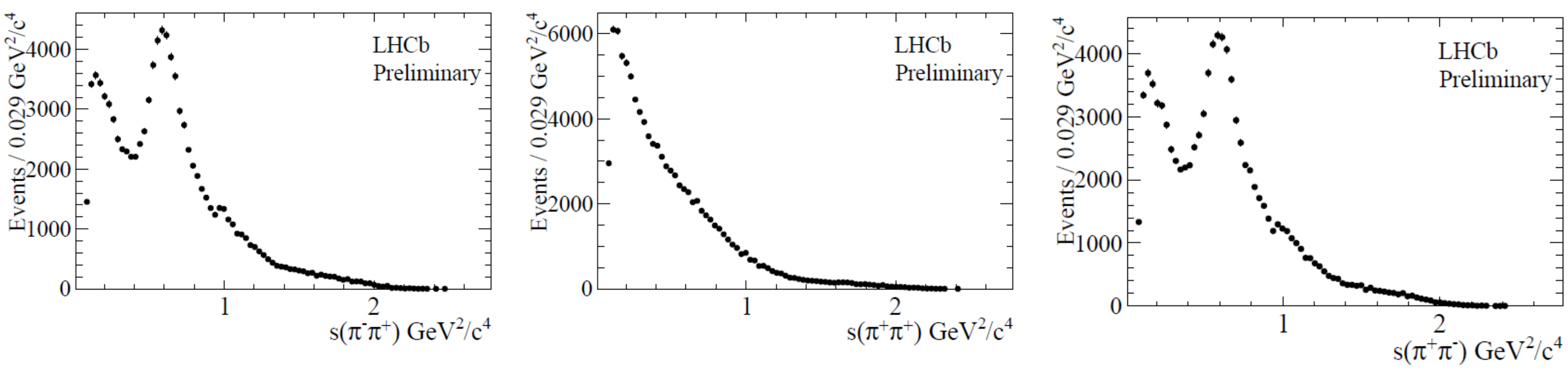
P, 1 fb^{-1}

- Use D^* tag the D^0 flavor
- High purity and statistics despite the large background inherent to 4-body decays. Used a NN[1].
- High statistics CP conserving control mode: 1.3M $D^0 \to K^-\pi^+\pi^-\pi^+$



- 4-body: 5D phase space necessary to fully describe the decay.

  → S^i_{CP}'s measured in bins of a 5D Dalitz Plot.



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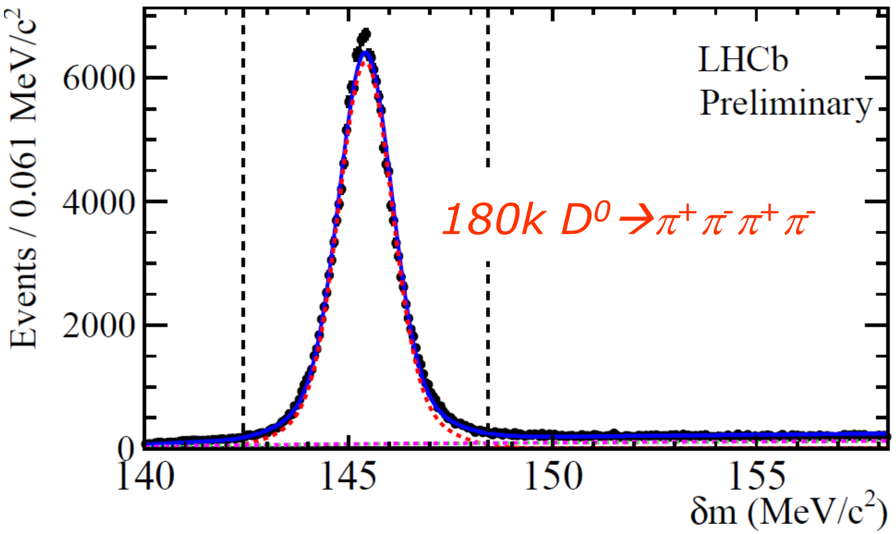

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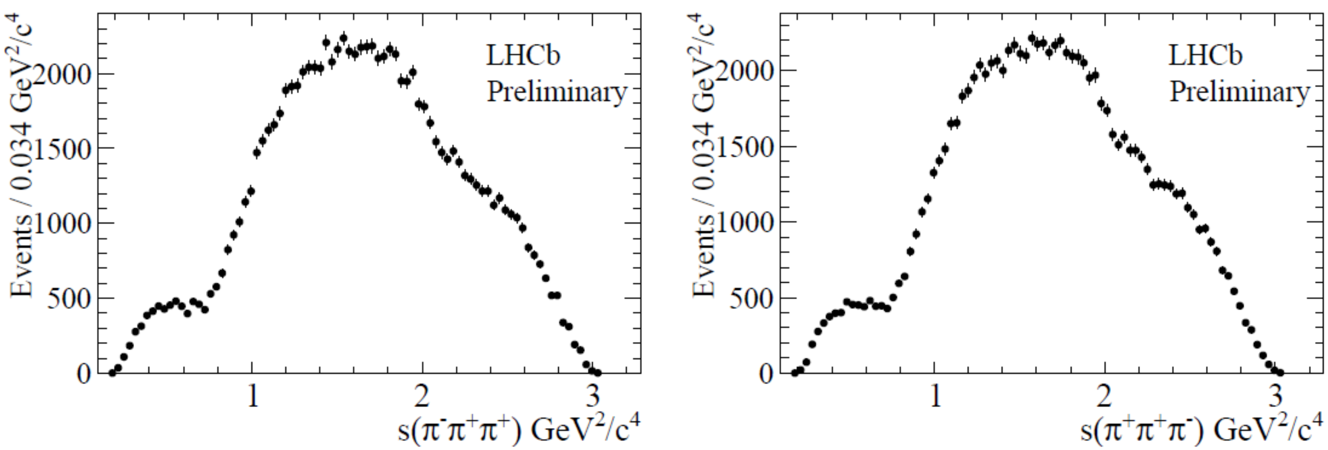
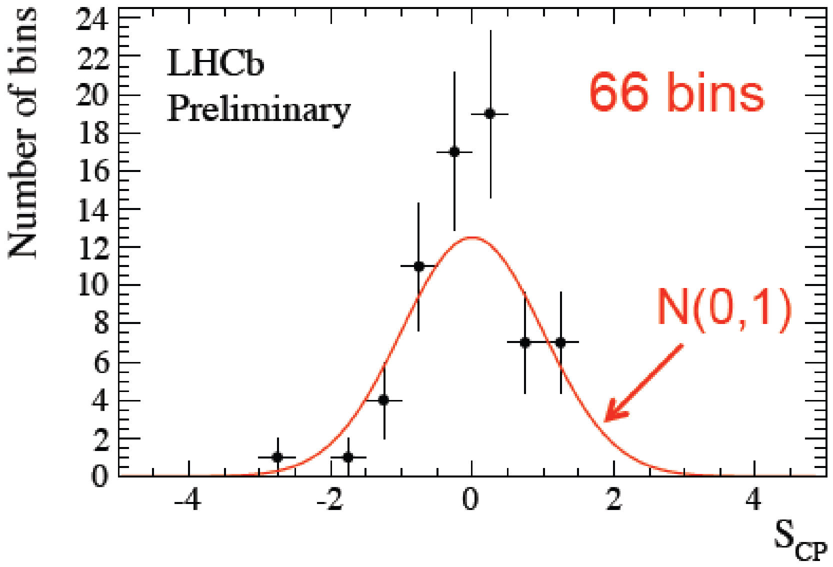


$D^0 \to \pi^+\pi^-\pi^+\pi^-$

P, 1 fb-1



Bins	p-values (%)
15	97.1
29	95.6
66	99.8

LHCb-CONF-2012-019

p-values assuming no CPV close to 1.

➔ *No evidence of CPV*

$D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$

P, 1 fb-1

- **Checks for non CPV asymmetries: measure $\chi 2$**
  - *Several binnings*
  - *Separately for magnet up and down*
  - *For $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$*
  - *For D^0 (mag up/left) vs. $\overline{D^0}$ (mag down/right)*

    Equivalent to D^0 vs. D^0 with a single magnet polarity
  - *For the background from the sideband*
  - *For Many different time periods*

$D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$

	p-values %		
Bins	Magnet down	Magnet up	Combined polarities
7	6.67	58.8	5.18
23	16.5	71.1	32.2
49	45.3	37.3	20.0
91	30.3	35.4	20.0
150	15.3	61.4	30.3

$D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$, 10 time-ordered samples

	p-values (%)	
data subset	Magnet down	Magnet up
1	9.15	11.0
2	15.3	81.1
3	91.4	75.9
4	76.7	86.1
5	1.59	18.3
6	35.6	50.8
7	5.77	99.8
8	40.6	26.0
9	76.8	71.1
10	17.8	66.9

D→μμ

CERN-LHCb-CONF-2012-005

Single event sensitivity

Quantity	Value
$N^{sig}_{D^0\to\pi^+\pi^-}$	1710 ± 47
$\varepsilon_{trig}(\pi\pi)$	$(13.96 \pm 1.24)\%$
$\varepsilon_{trig}(\mu\mu)$	$(82.54 \pm 3.13)\%$
$\frac{\varepsilon_{sel}(\pi\pi)}{\varepsilon_{sel}(\mu\mu)}$	0.95 ± 0.06
Prescale on $D^0 \to \pi^+\pi^-$	0.0015
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	$(1.397 \pm 0.026) \cdot 10^{-3}$
α	$(1.96 \pm 0.23) \cdot 10^{-10}$

Yields

Channel	Fitted value
$D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+$	204 ± 33
$D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+$	$(0.49 \pm 0.42) \cdot 10^{-8}$
$D^{*+} \to D^0(\to K^-\pi^+)\pi^+$	380.3 ± 34.1
Comb. background	7439.6 ± 95.9

→ $$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3\ (1.1) \cdot 10^{-8} \quad \text{at } 95\ (90)\%\text{CL}$$

LHCb Preliminary

One order of magnitude below Belle [XX]

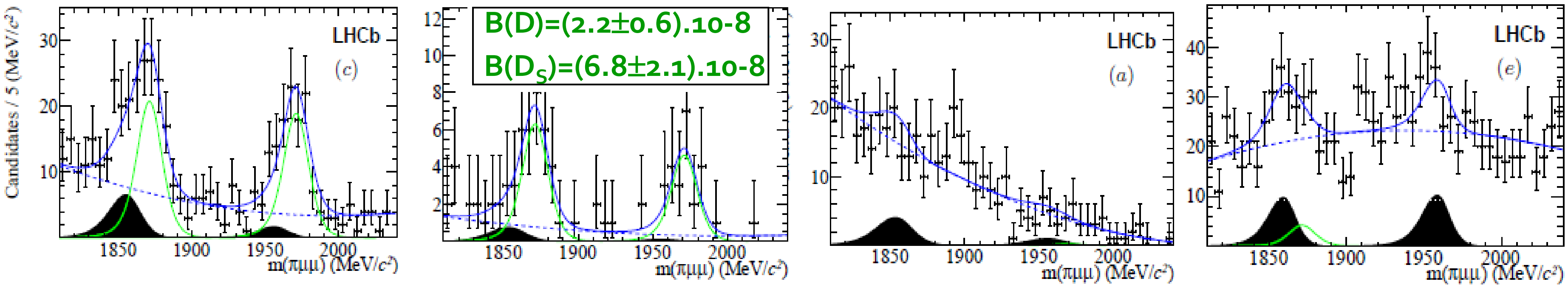
Stay tuned: An improved analysis presented in a few weeks !

$D^+ \to \pi^+\mu^+\mu^-$ and $D_s \to \pi^+\mu^+\mu^-$

1 fb^{-1}

LHCb-PAPER-2012-051
To be submitted to PLB

ρ/ω region | **η region** | **Low M(μμ)** | **High M(μμ)**



Upper limits ×10^{-8} @ 90% (95%) C.L.

Region	$B(D^+ \to \pi^+\mu^+\mu^-)$	$B(D_s \to \pi^+\mu^+\mu^-)$
Low M(μμ)	2.0 (2.5)	6.9 (7.7)
High M(μμ)	2.6 (2.9)	16.0 (18.6)
Total (1)	7.3 (8.3)	41.0 (47.7)

NEW !

(1) Total non resonant BF, extrapolated from the high M(μμ) region (phase space model).

→ 2 orders of mag. better than previous limits (D0 [XX], Babar [XX])

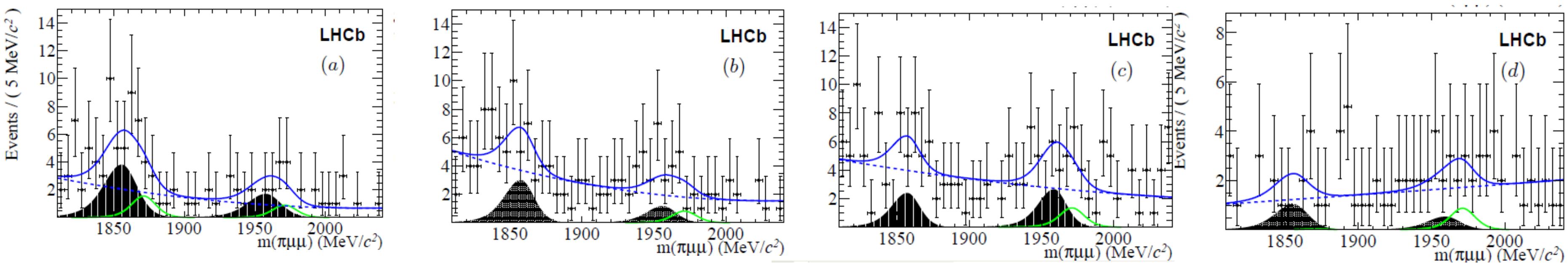
→ Still above largest theory predictions (~10^{-8})

Lepton Number Violation: $D^+ \to \pi^- \mu^+ \mu^+$ and $D_s \to \pi^- \mu^+ \mu^+$

LHCb-PAPER-2012-051
To be submitted to PLB

- **Same approach as for $D^+_{(s)} \to \pi^+ \mu^+ \mu^-$ with 4 regions in $M(\mu\pi)$:**

(if mediated by a Majorana neutrino, larger significance in region where its mass peaks)



1 fb⁻¹

Upper limits ×10^{-8} @ 90% (95%) C.L.

Region [MeV/c²]	$B(D^+ \to \pi^- \mu^+ \mu^+)$	$B(D_s \to \pi^- \mu^+ \mu^+)$
$250 < M(\mu\mu) < 1140$	1.4 (1.7)	6.2 (7.6)
$1140 < M(\mu\mu) < 1340$	1.1 (1.3)	4.4 (5.3)
$1340 < M(\mu\mu) < 1540$	1.3 (1.5)	6.0 (7.3)
$1540 < M(\mu\mu)$	1.3 (1.5)	7.5 (8.7)
Total	2.2 (2.5)	12.0 (14.1)

NEW !

→ **No LNV signal**

→ **2 orders of mag. better than previous limits (Babar [XX])**

Implications of LHCb measurements and future prospects

The LHCb collaboration[†]

and

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