Charm Physics in LHCb

Walter M. Bonivento

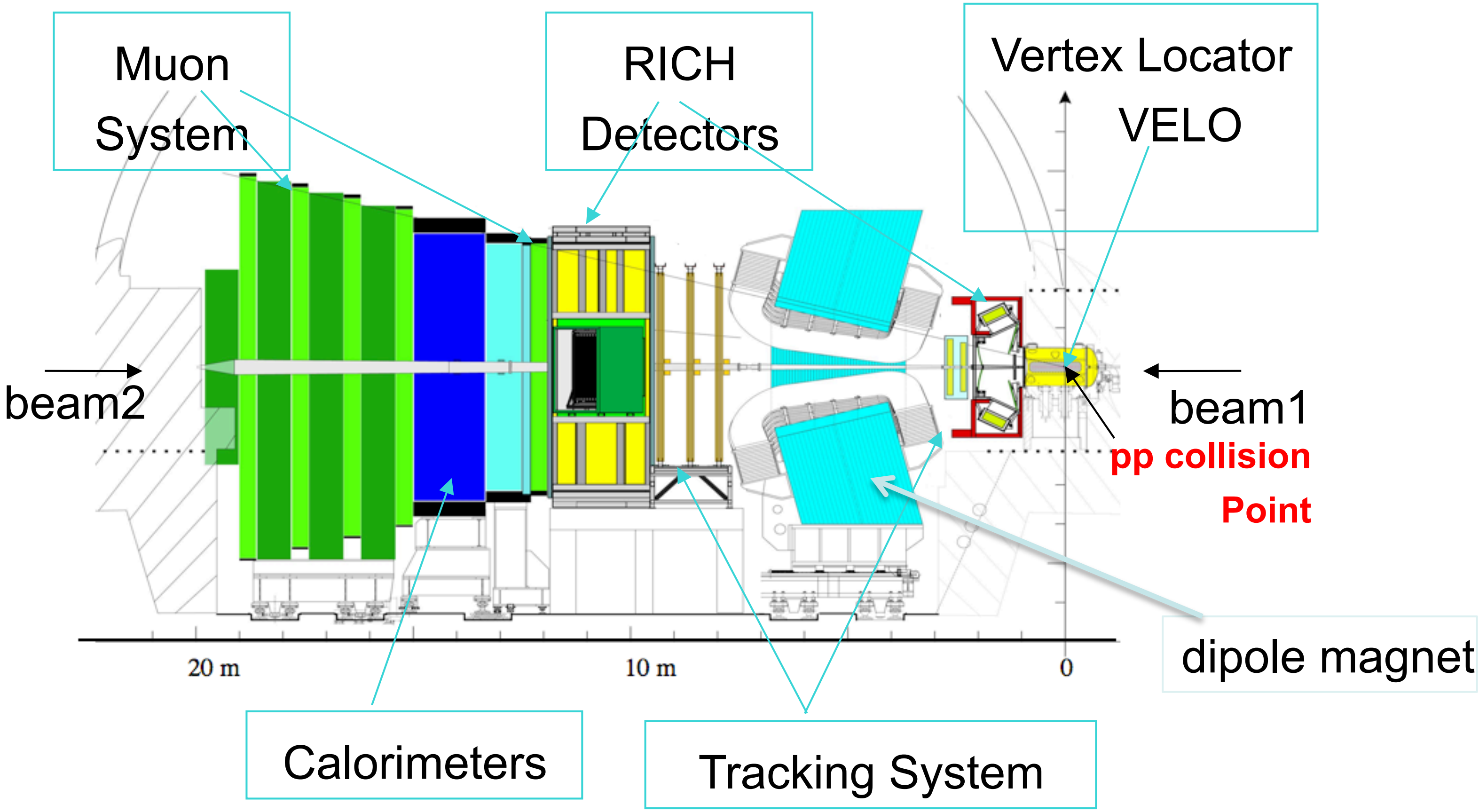
INFN Cagliari

on behalf of the LHCb collaboration

1. The LHCb experiment
2. Charm in LHCb
3. Spectroscopy
4. Mixing and indirect CPV
5. Direct CPV → **evidence at 3.5σ in $\Delta A_{CP}(KK/\pi\pi)$**
6. Rare decays

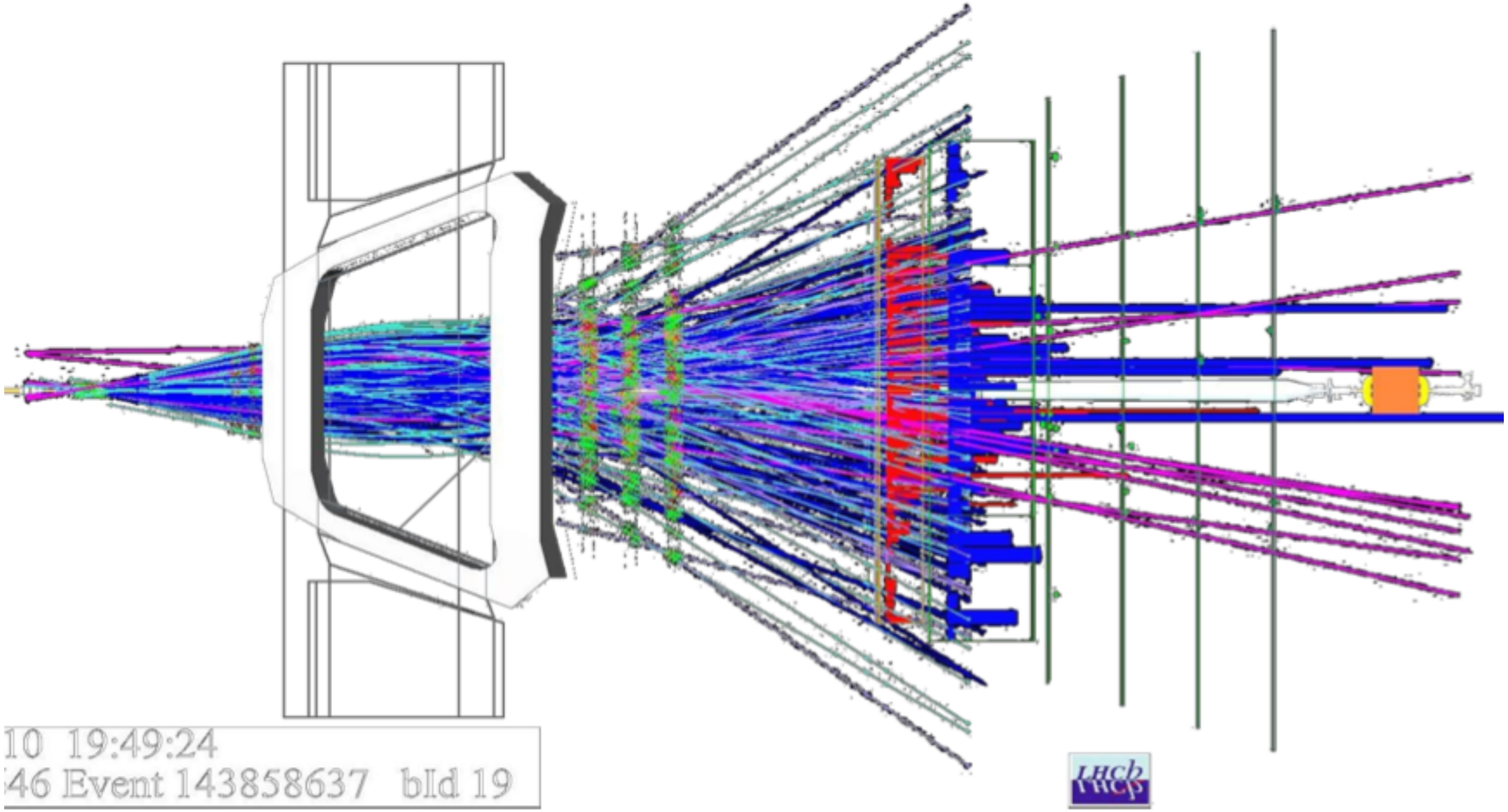
Collaboration

The LHCb detector



CERN LHC: pp machine with √s=7TeV (due to the 2008 accident)
Pseudo-rapidity coverage → 1.9-4.9
Originally designed for b physics, but now is pursuing a wide charm physics program

A typical event!



Challenges and goodies of charm physics in LHCb

- at 7 TeV:
  - σ(ccbar) ≈ 6mb
  - σ(bbar) ≈ 0.3mb
  - σ(pp inelastic)≈60mb
- → **huge σ(ccbar) cross section**
    - background from secondary charm from b already low from the start of the selection
    - and very favorable ratio to inelastic σ (only a factor of 10!)

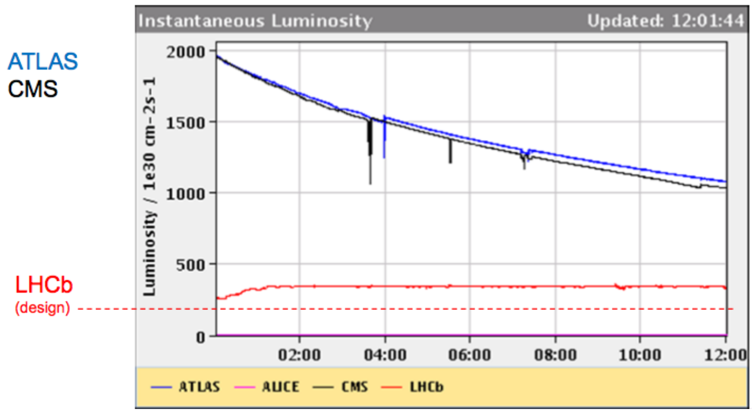
  → high purity selections with few and soft IP, displaced vertex and p_T cuts

  → very large yields (the highest on the market)
- however due to lower D meson daughter p_T and IP wrt B mesons, trigger thresholds have to be kept low

  → tough requirements for trigger, tracking, online and offline reconstruction, both for bandwidth and timing, and last but not least storage!
- we mostly concentrate on channels with charged tracks in the final state

The LHCb running conditions

2010 was a “learning phase” year with fast varying running conditions and luminosity at the end of it we collected 37pb^{-1} and we were running at a pile-up of up to 2.5 in average (with the design being 0.4) but we coped well with it!



2011

In 2011 we’ve been running with more steady conditions with

-pile-up of ≈1.5

-with up to L=4•10^{-32} cm^{-1}s^{-1} (2x the design value but at 0.5xσ) with luminosity leveling

Overall we collected up to more than 1fb^{-1} (while GPE collected about 5pb^{-1})

The trigger and charm physics

hardware

LHC rate ~ 10 MHz

cc fraction ~ 10%

L0 E_T trigger ~ 1 MHz

cc fraction ~ 50%

After the hardware trigger have ~ 500 kHz of cc events

No possibility of an inclusive charm trigger!

Use exclusive triggers tuned for the needs of specific analyses to deliver high signal efficiency and purity

software

High P_T,IP track ~ 50 kHz (50% eff.)

Exclusive D->hh/3h/4h ~ 1 kHz (50-90% eff.)

out for 3kHz total

Already at trigger level selections very similar to offline (S/B about 1)!!!
Then we write down to disk at 200Hz rate (stripping)
at $L=3.5 \bullet 10^{-32}$ $cm^{-1}s^{-1}$ we collect:

$5 * 10^3$ tagged $D^{*\pm} \rightarrow (D0 \rightarrow K^{\pm}K^{\mp})\ \pi^{\pm}$

$3 * 10^5$ untagged $D^0 \rightarrow K^-\pi^+$ per pb^{-1} (now we have $>1fb^{-1}$) !!

We are just starting to analyze the 1fb^{-1} sample (which allows us to have the largest c-meson and baryons sample of history) and we already got one surprise!!!!

Charm meson spectroscopy

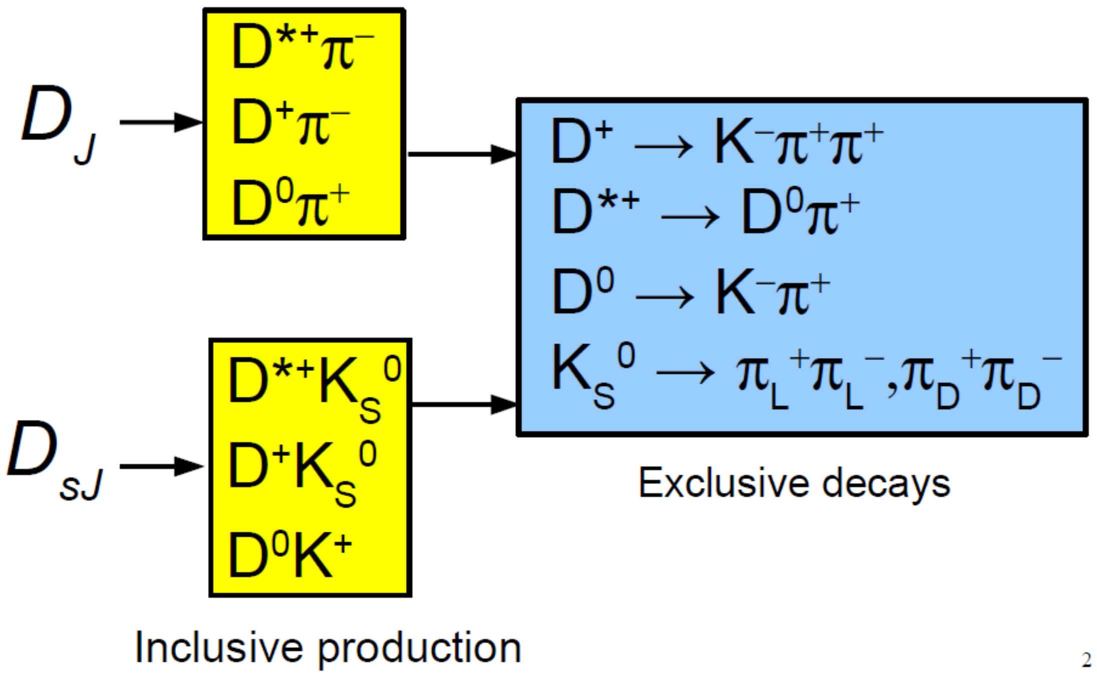
Predictions of the D and D_s mass eigenstates were performed in 1985 using QCD potential models.

The masses of $D_{(s)1}$ and $D^{*}_{(s)2}$ states were successfully predicted before their discoveries.

In 2003 observation of two unexpected new states: $D^{*}_{s0}(2317)$ and $D_{s1}(2460)$.

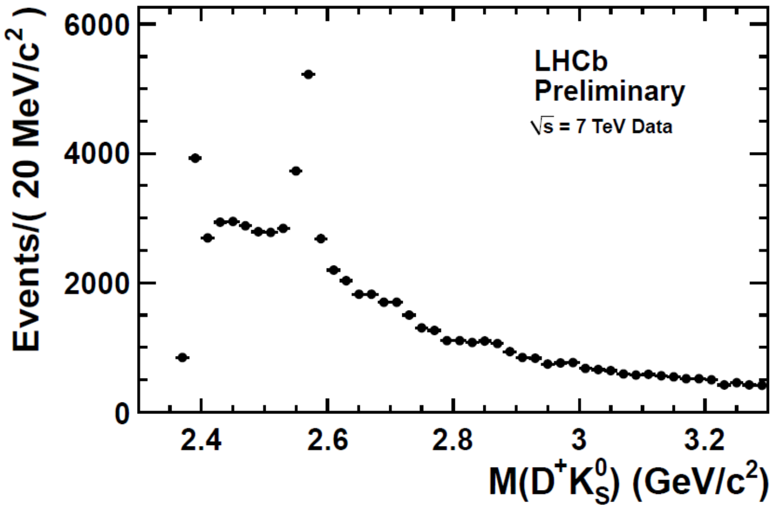
Recently BaBar and Belle observed new D_J and D_{sJ} states: D(2550), $D^{*}(2600)$, D (2750), $D^{*}(2760)$, $D_{s1}^{*}(2710)$, $D_{sJ}^{*}(2860)$, $D_{sJ}(3040)$. Many of them need to be confirmed.

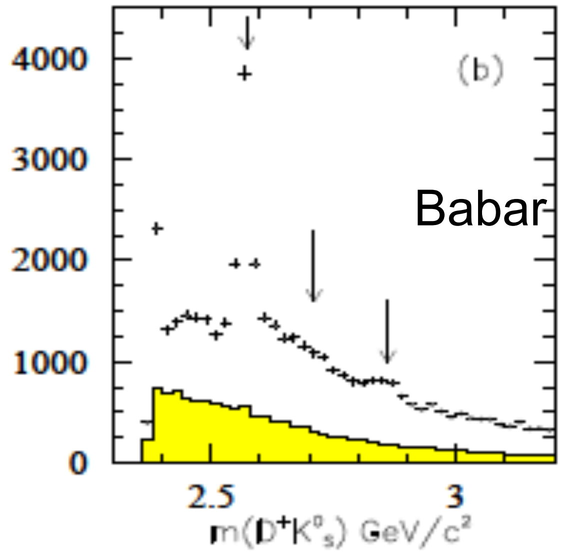
Decay modes



We are now starting to investigate charmed baryons spectroscopy as well

Example: $D^+K_s^0$





Preliminary: 2011 data
$320 pb^{-1}$

Thank to the excellent performances of LHC and LHCb detector, D_J and D_{sJ} spectroscopy feasible with the same sensitivity of the B-factories

Phys.Rev.D 80, 092003(2009)

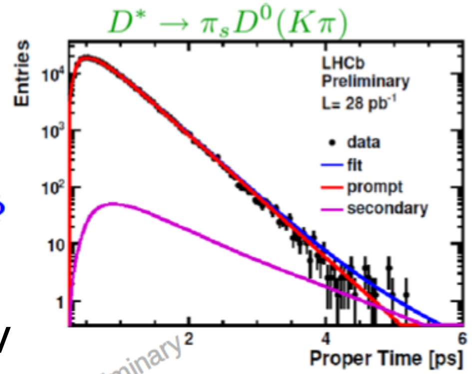
Resonance	Mass (MeV/c²)	Width (MeV)
$D_{s1}^*(2700)$	$2710 \pm 2\ ^{+12}_{-7}$	$149 \pm 7\ ^{+39}_{-52}$
$D_{sJ}^*(2860)$	$2862 \pm 2\ ^{+5}_{-2}$	$48 \pm 3 \pm 6$

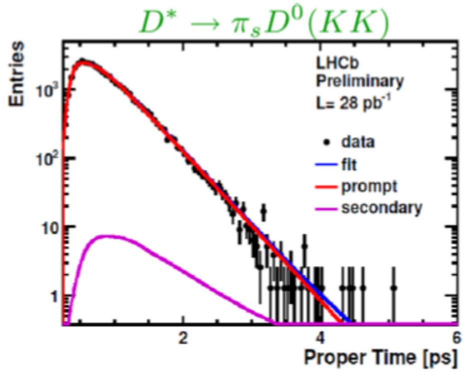
Mixing

Preliminary measurements with 2010 data L=28pb^{-1}

$$y_{CP} = \frac{\Gamma(D^0 \to KK)}{\Gamma(D^0 \to K\pi)} - 1 = y\cos\Phi - \frac{1}{2} y R_M \sin\Phi$$

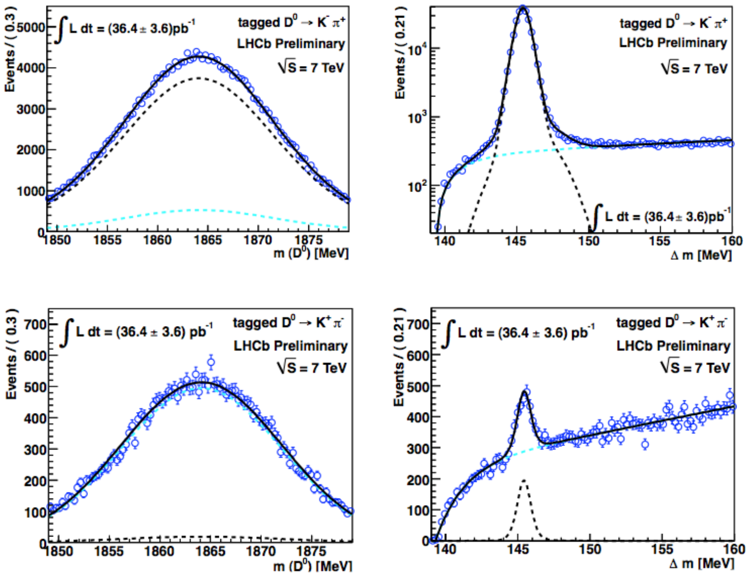
A paper is about to come on arXiv





preliminary result

$y_{CP} = (0.55 \pm 0.63\,(stat)\ \pm 0.41\,(syst))\%$



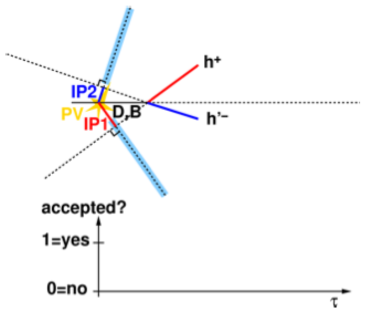
	WS/RS of $D \to K\pi$ decays (%)
$R_{measured}$	$0.442 \pm 0.033\ (stat.)\ \pm 0.042\ (sys.)$
$R_{acc\,cor}$	$0.409 \pm 0.031\ (stat.)\ \pm 0.039(sys.)\ ^{+0.028}_{-0.020}\ (sys.\ mixing)$
$R(PDG)$	0.380 ± 0.018

mixing with wrong sign $D^0 \to K\pi$:
→ measures x' and y'
with 2010 data only time-integrated measurement

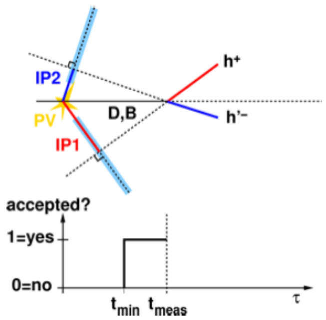
At present no 5σ measurement of mixing ≠0; for sure we expect to do it with LHCb: scaling of $\sigma_{stat}(y_{CP})$=0.03-0.04% with 5fb^{-1}

Two main experimental issues

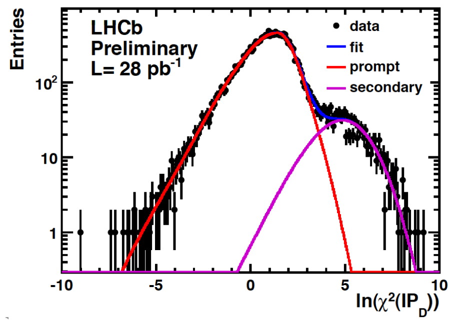
- **Need to determine lifetime acceptance in real data**
  - Key ingredient to the method is an event by event based lifetime acceptance which takes trigger and selection into account: this is possible in LHCb since the lifetime bias is in the software trigger
  - results are used in the normalization of the PDF in the fitting procedure

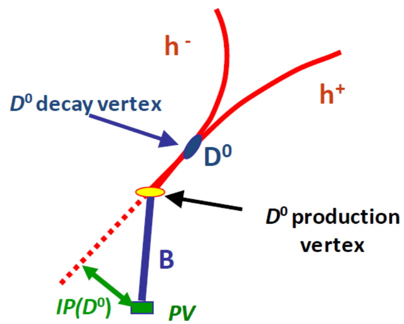


swiming method



•prompt-secondary D separation





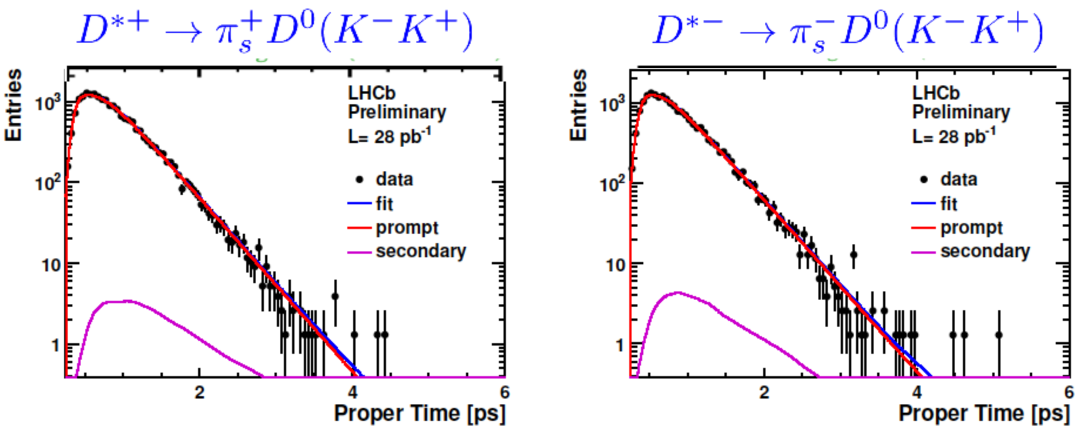
CP Violation

- **3 types of CP violation:**
  - In mixing: rate of $D^0 \rightarrow D^0$bar and D^0bar$\rightarrow D^0$ differ — indirect
  - In decay: amplitudes for a process and its conjugate differ — direct
  - In interference: between mixing and decay diagrams
- **In the SM, indirect CP violation in charm is expected to be very small and universal between CP eigenstates**
  - Exactly how small is a matter of debate... but <few 10^{-4} looks as a reasonable recent estimate
- Direct CP violation can be larger in SM, very dependent on final state (therefore we must search wherever we can)
  - in singly-Cabibbo-suppressed modes O (few 10^{-3}) possible (in particular as a post-diction now)
- Both can be enhanced by NP, in principle up to O(%)
- **In LHCb we have now the statistics to make O(0.1-0.2%) measurements!**

Measurement of indirect CPV

Preliminary A_Γ measurement available using 28 pb^{-1} of 2010 data, using $D^* \to D^0\pi$, $D^0 \to K^+K^-$ decays.

$$A_\Gamma = \frac{\Gamma(D^0 \to KK) - \Gamma(\overline{D^0} \to KK)}{\Gamma(D^0 \to KK) + \Gamma(\overline{D^0} \to KK)} = \frac{1}{2} R_M y \cos\Phi - x \sin\Phi$$



Preliminary result:

A_Γ = (- 5.9 ± 5.9 ± 2.1) x 10^{-3}

WA_{HFAG} A_Γ = (0.12±0.25)%

Belle: A_Γ = (0.1 ± 3.0±1.5)×10^{-3}
Phys.Rev.Lett. 98 (2007) 211803

BaBar: A_Γ = (2.6 ± 3.6±0.8)×10^{-3}
Phys.Rev. D78 (2008) 011105

LHCb-CONF-2011-046

220k $D^0 \to K\pi$ events used to determine D^0 lifetime τ=(410.3±0.9) fs, PDG:(410.1±1.5) fs

A paper is about to come on arXiv
Expected precision with 5fb^{-1} → $2*10^{-4}$

Experimental issues with time integrated CPV in LHCb

- **Experimentally, we have to cope with fake asymmetries**:
  - production asymmetries (pp collider)
  - detection asymmetries (different K+/K- interaction lengths, soft pion efficiency asymmetry)
  - backgrounds
- **Moreover the dipole magnet makes the detector left-right asymmetric for + charge and – charge particles**
  - a localized detector inefficiency translates into a fake CPV asymmetry

1) **we developed robust observables**:

- Miranda technique for SCS decay $D^+ \rightarrow K^+K^-\pi^-$
- difference of two CPV asymmetries in SCS decays into CP eigenstates $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$
- develop fiducial cuts to exclude kinematic zones leading to potentially high systematics effects

2) **swap the magnetic field from time to time**

- signal purity is a must → excellent detector performance

D->KKπ: the method

- **Model-independent search for CPV in Dalitz plot distribution**
- **Compare binned, normalized Dalitz plots for D^+ and D^-**
  - Production asymmetry cancels completely after normalization.
  - Efficiency asymmetries that are flat across Dalitz plot also cancel.
- Method based on asymmetry significance (*)

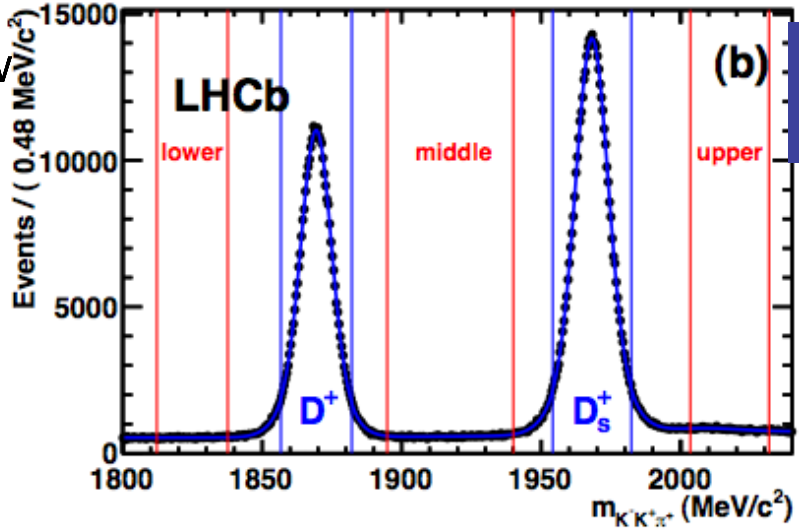
$$\mathcal{S}^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}, \qquad \alpha = \frac{N_{\mathrm{tot}}(D^+)}{N_{\mathrm{tot}}(D^-)}$$

  - In absence of asymmetry, values distributed as Gaussian (μ=0, σ=1)
  - Figure of merit for statistical test: sum of squares of S^i_{CP} is a χ2

(*) Phys. Rev. D80 (2009) 096006
See also BaBar: Phys.Rev. D78:051102 (2008); our 2010 dataset contains 10x more events, and is of comparable size of Belle analysis of D→φπ:(arXiv: 0807.4545)
(2011 is another x30 !!)

D→KKπ: mass and Dalitz plot

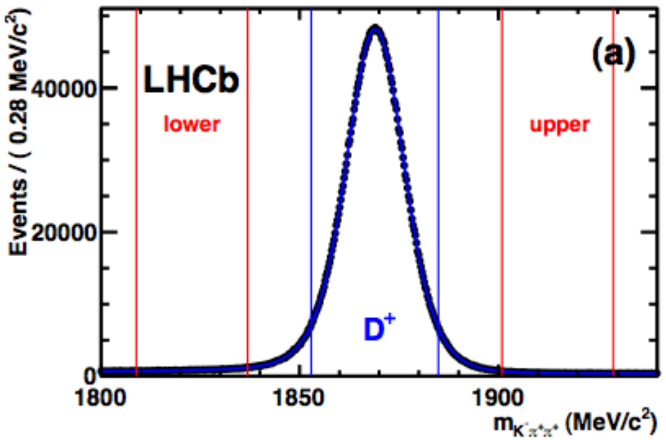
Yield of 400k in window
Purity of ≈91%



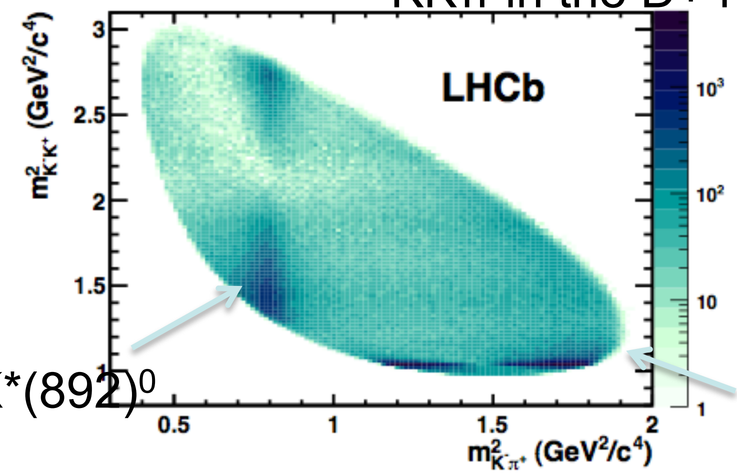
http://arxiv.org/abs/1110.3970
LHCb 35pb^{-1}

KKπ signal (D^+)
and control mode
(D_s^+)

Kππ control mode (D^+)
purity ~ 98%



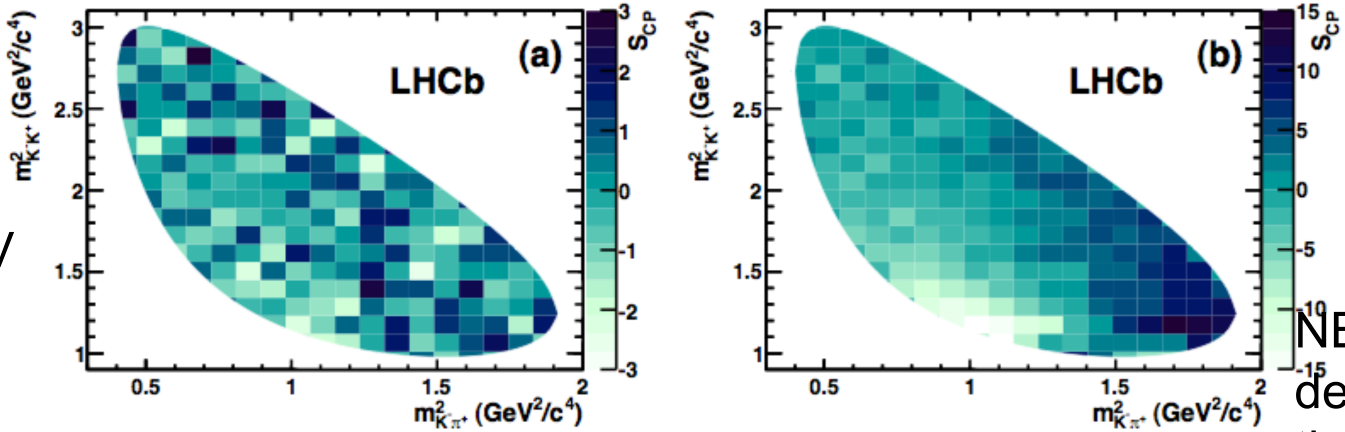
KKπ in the D+ mass window



K*(892)^0
φ(1020)

Sensitivity to NP

no CPV
p=5%



4^o in φ phase
p=10^{-100}!!

NB: on the total decay asymmetry the effect would be 0.1%!!

toys using CLEO-c model

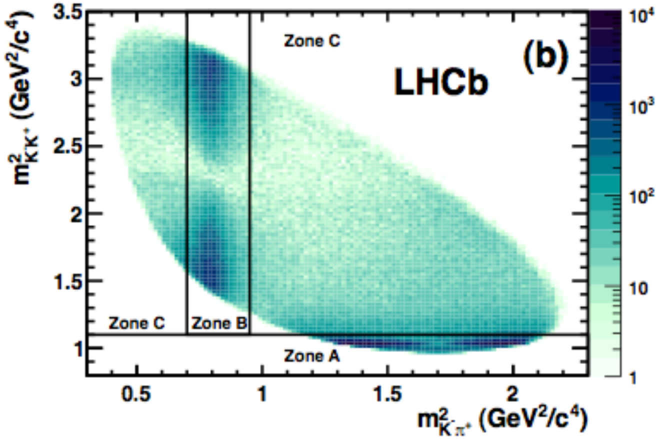
CPV	Adaptive I		Adaptive II	
	$p(3\sigma)$	$\langle S \rangle$	$p(3\sigma)$	$\langle S \rangle$
no CPV	0	0.84σ	1%	0.84σ
6° in $\phi(1020)$ phase	99%	7.0σ	98%	5.2σ
5° in $\phi(1020)$ phase	97%	5.5σ	79%	3.8σ
4° in $\phi(1020)$ phase	76%	3.8σ	41%	2.7σ
3° in $\phi(1020)$ phase	38%	2.8σ	12%	1.9σ
2° in $\phi(1020)$ phase	5%	1.6σ	2%	1.2σ
6.3% in $\kappa(800)$ magnitude	16%	1.9σ	24%	2.2σ
11% in $\kappa(800)$ magnitude	83%	4.2σ	95%	5.6σ

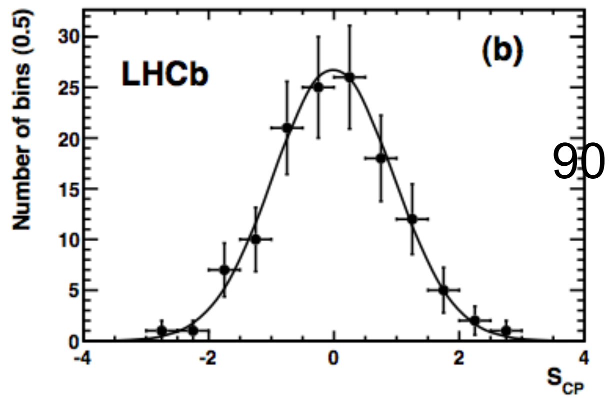
- With no CPV, method does not produce a signal (good!)
- If we do see a signal, it will mean big CPV and thus new physics.

Ds→KKπ control mode

LHCb 35pb-1

CF mode → expect no CPV





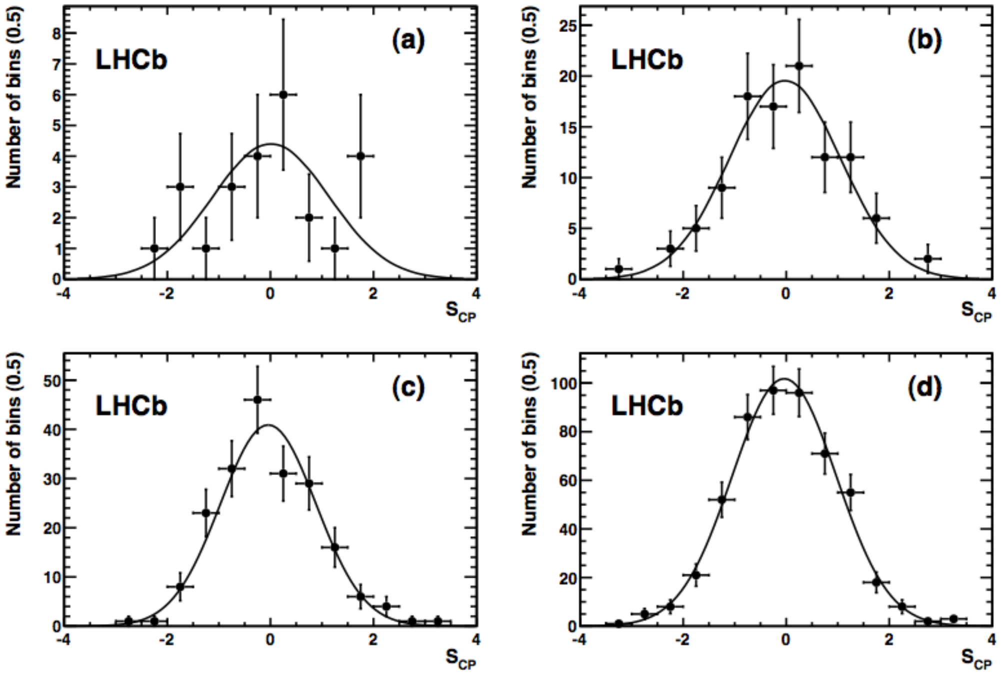
900 uniform bins

bins	Zone A	Zone B	Zone C
300	20.1	25.3	14.5
100	41.7	84.6	89.5
30	66.0	62.5	24.6

p-Values

Results for D→KKπ

Binning	Fitted mean	Fitted width	χ^2/ndf	p-value (%)
Adaptive I	0.01 ± 0.23	1.13 ± 0.16	32.0/24	12.7
Adaptive II	-0.024 ± 0.010	1.078 ± 0.074	123.4/105	10.6
Uniform I	-0.043 ± 0.073	0.929 ± 0.051	191.3/198	82.1
Uniform II	-0.039 ± 0.045	1.011 ± 0.034	519.5/529	60.5



No evidence for CP violation in the 2010 dataset

LHCb 35pb^{-1}

$\Delta A_{CP}=A_{CP}(D^0\rightarrow KK)-A_{CP}(D^0\rightarrow \pi\pi)$

$$A_{RAW}(f) \equiv \frac{N(D^0 \to f) - N(\overline{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\overline{D}^0 \to \bar{f})}$$

$$A_{RAW}(f)^* \equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \overline{D}^0(\bar{f})\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \overline{D}^0(\bar{f})\pi^-)}$$

$$\begin{aligned} A_{RAW}(f) &= \boxed{A_{CP}(f)} + \boxed{A_D(f)} + \boxed{A_P(D^0)} \\ A_{RAW}(f)^* &= \boxed{A_{CP}(f)} + \boxed{A_D(f)} + \boxed{A_D(\pi_s)} + \boxed{A_P(D^{*+})} \end{aligned}$$

physics CP asymmetry

Detection asymmetry of D^0

Detection asymmetry of soft pion

Production asymmetry

For a two-body decay of a spin-0 particle to a self-conjugate final state, no D^0 detector efficiency asymmetry, $A(K^-K^+) = A(\pi^-\pi^+) = 0$

Look at difference in CP asymmetry between KK and ππ: very robust against systematics

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

$A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ receive contributions from both indirect CPV (universal) and direct CPV (final state dependent) → taking the difference we are sensitive (almost) only to the direct CPV contribution

Mass spectra

http://arxiv.org/abs/1112.0938

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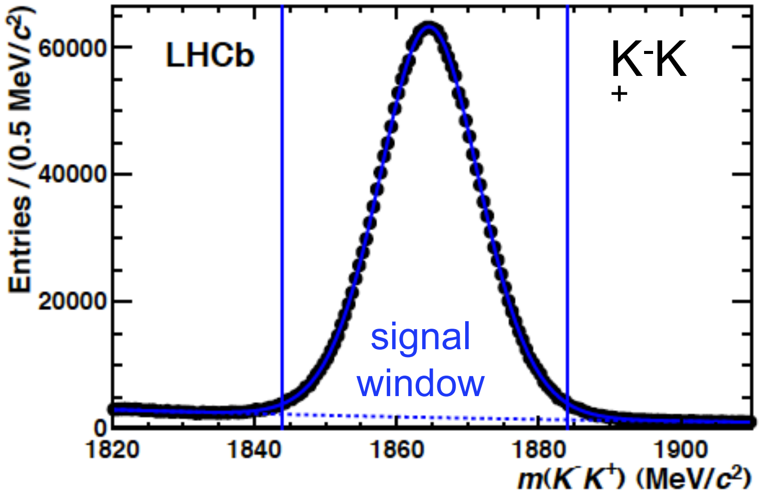
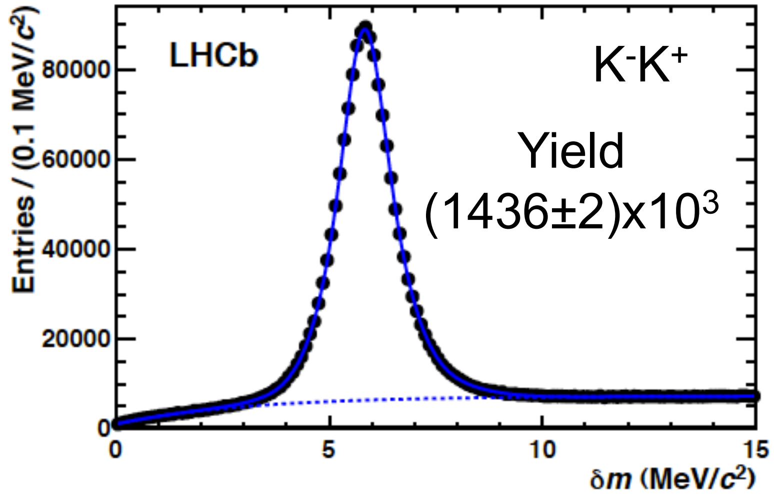
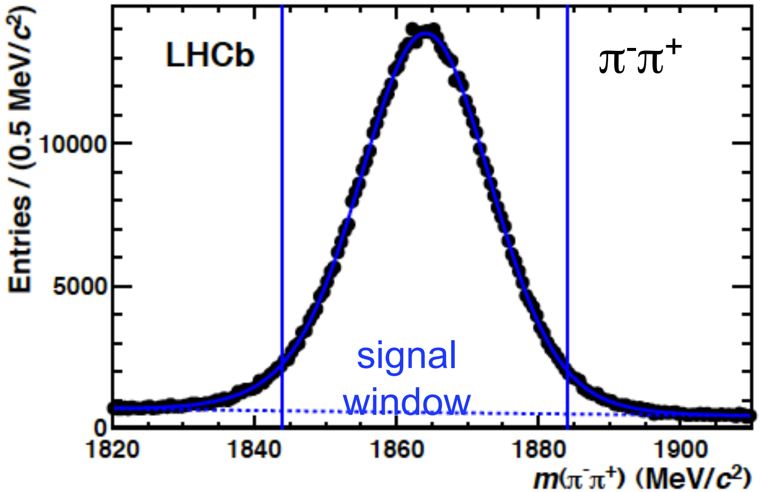
$\delta m = m(h^+h^-\pi^+) - m(h^+h) - m(\pi^+)$

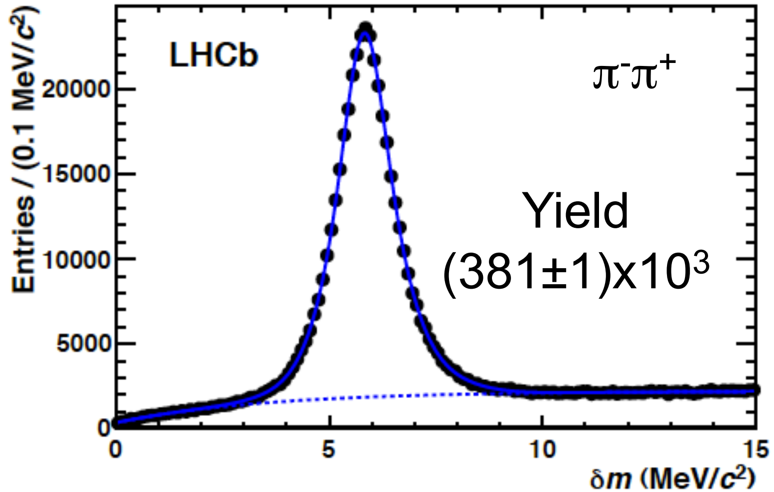




$1844 < m(D^0) < 1884$ MeV/c^2

$1844 < m(D^0) < 1884$ MeV/c^2





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Kinematic binning

- **Kinematic binning needed to suppress second-order effects** of correlated asymmetries e.g. correlated variation of A_P and A_D with kinematics (pt, η of soft π)
  - Divide data into kinematic bins of (pT of D*+, η of D*+, p of soft pion, left/right hemisphere) -- 54 bins
  - Along similar lines:
    - split by magnet polarity (field pointing up, pointing down)
    - split into two run groups (before & after technical stop)
  - Fit final states $D^0 \to K^+ K^-$ and $\pi^+ \pi^-$ separately => 432 independent fits.

Result

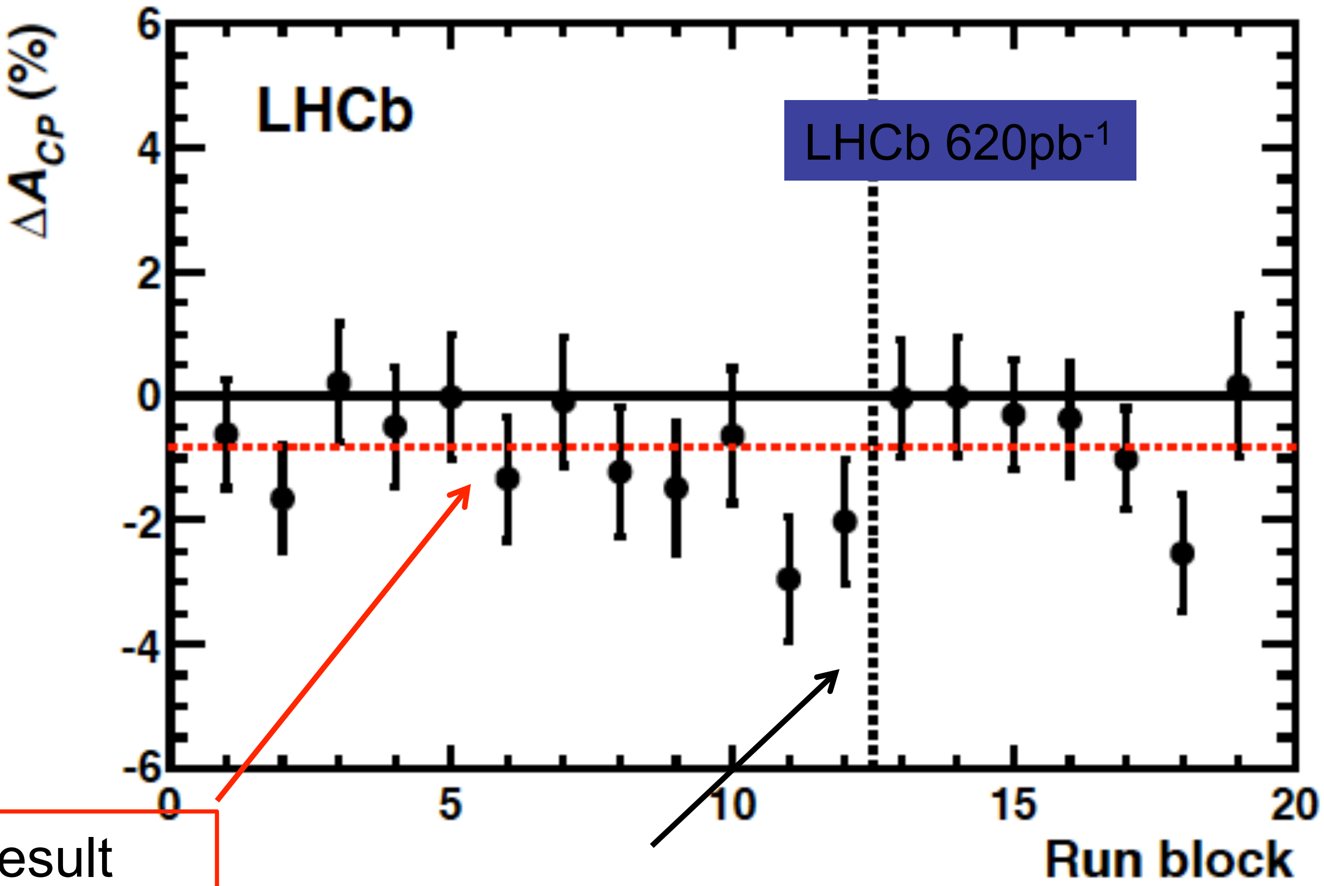
$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})]\,\%$$

significance 3.5σ

LHCb 620pb^{-1}

expected stat error with 5fb^{-1} → 4×10^{-4}

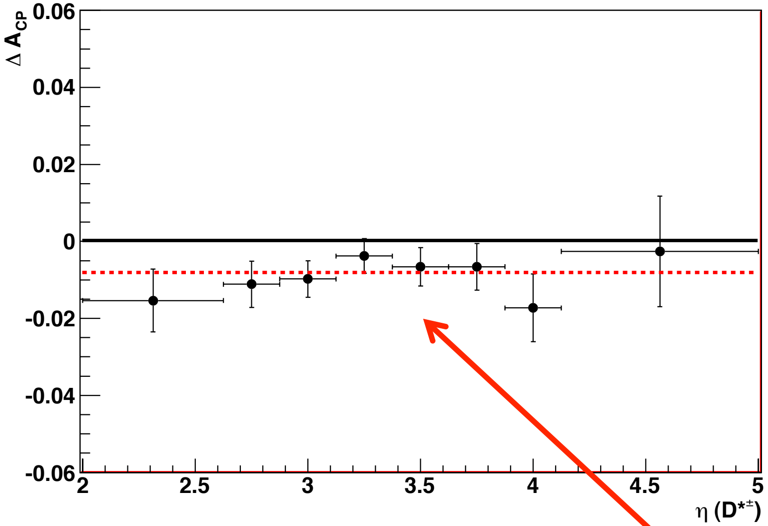
Stability of result vs data-taking runs

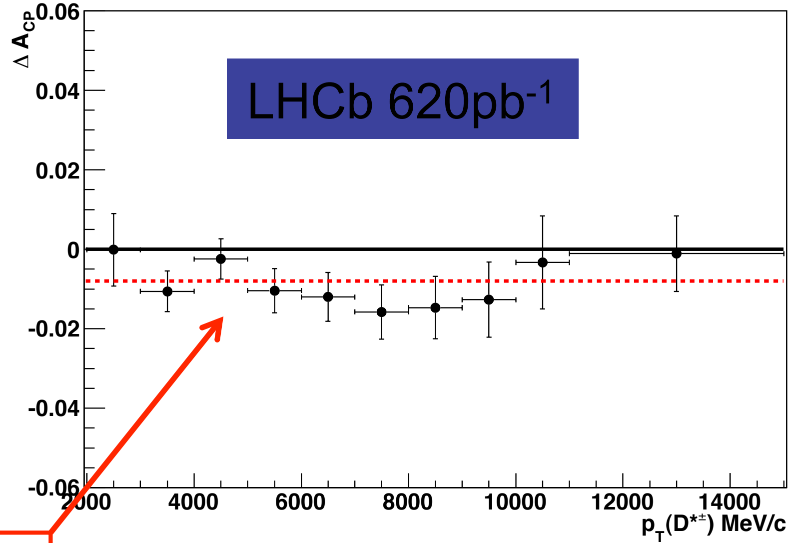


Final result (dashed line)

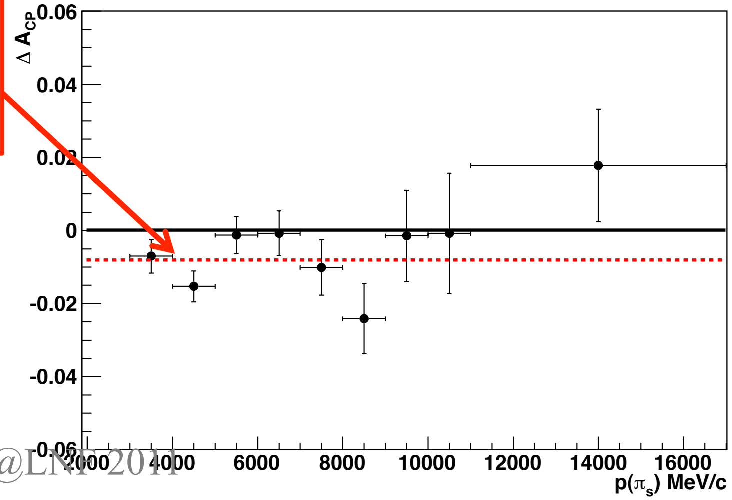
Before and after a technical stop

Stability of result on relevant kinematic variables



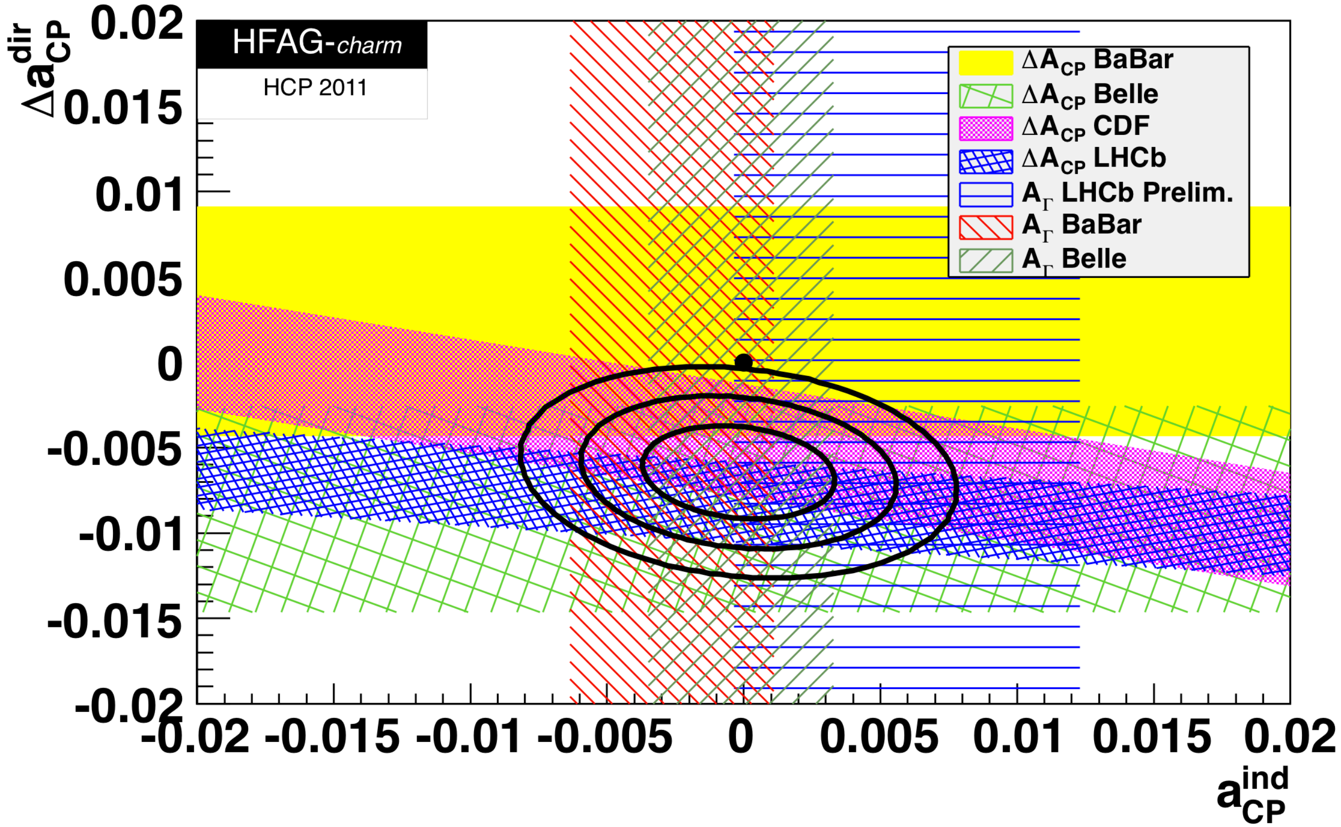


Final result(dashed line)



No evidence of dependence on relevant kinematic variables

New HFAG combination
(with LHCb result)



$$a_{CP}^{ind} = (-0.02 \pm 0.23)\% \qquad \Delta a_{CP}^{dir} = (-0.65 \pm 0.18)\%$$

Consistency with NO CP violation: 0.15%

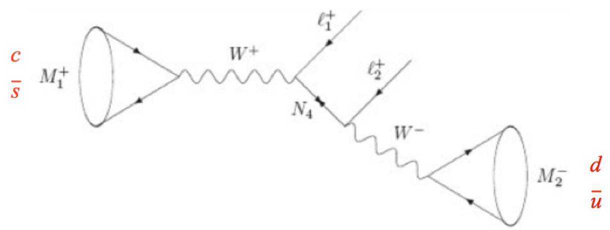
(the slanted bands due to lifetime acceptances)

Other channels under study

- Beyond updating with 2011 statistics (>30x 2010) the above mentioned analyses of 2010 data and updating to the $1fb^{-1}$ statistics the ΔA_{CP} analysis, we have under study:
  - Direct CPV in $D^+ \rightarrow K^0_S h$
  - Direct CPV in Dalitz plot if $D^0 \rightarrow \pi\pi\pi\pi$
  - T-odd correlations in $D^0 \rightarrow KK\pi\pi$
  - Direct CPV in Dalitz plot in other 3-body Singly-Cabibbo-Suppressed D+ and D_s^+ decays
  - The golden channel: Mixing and CPV with time dependent Dalitz analysis $D^0 \rightarrow K^0_S hh$
  - We are also investigating tagging charm from semi-leptonic b decays
  - Direct CPV $\Lambda_c \rightarrow p\pi\pi$
  - CPV in $\Lambda_c \rightarrow \Lambda\pi$, ΛK
- Main limitation: manpower…!

The charm RD measurements

- **LHCb is well suited for measurements with muons in the final state**, a bit less with e- (bremsstrahlung, modest resolution ECAL)
- High efficiency triggering on muons in LHCb
- **Three main channels are being investigated**:
  - $D \rightarrow \mu\mu$ FCNC, best limit Belle $1.7 \cdot 10^{-7}$ @ 90% C.L.
    - SM predicts, even including a long range term $<10^{-13}$
  - $D_{(s)}^{+} \rightarrow \pi\mu\mu$ with SS muons → forbidden in SM, sensitive to Majorana neutrinos



present limits on the order of 10^{-6} for D^+ modes and 10^{-5} for D_s^+ modes

  - $D_{(s)}^{+} \rightarrow \pi\mu\mu$ with OS muons → FCNC, sensitive to RPV SUSY → need to study $\mu\mu$ invariant mass distribution to exclude regions of long range contributions
- Analyses with 2011 data in preparation

Conclusion

- LHCb has a very rich charm physics program ranging from mixing/CPV to rare decays and spectroscopy, mostly with decays to charged particles in the final state
- **With 2011 data (1fb^{-1}) we already have the world highest statistics in many channels**
- We expect to collect 5fb^{-1} up to 2017 (phase 1) and 50fb^{-1} (2019-2029?) with the upgrade
- **For many years to come, at least until 2018, LHCb will be (together with BES3) the leading experiment in the field**: statistical sensitivity to many observables such to rule out NP contributions (e.g. some channels sensitive direct CPV)
- Still systematics such as production asymmetries in CPV and lifetime acceptance have to be treated with care and more new ideas on that need to be developed
- In general, we have not tried yet to address channels with neutrals in the final state but things are starting, though it is not guaranteed it will be competitive.
- **Most channels with neutrinos and π^0's remain peculiar to the e^+e^- machines**