Evidence for CP Violation in time integrated $D^0 \rightarrow hh$ Decays in LHCb

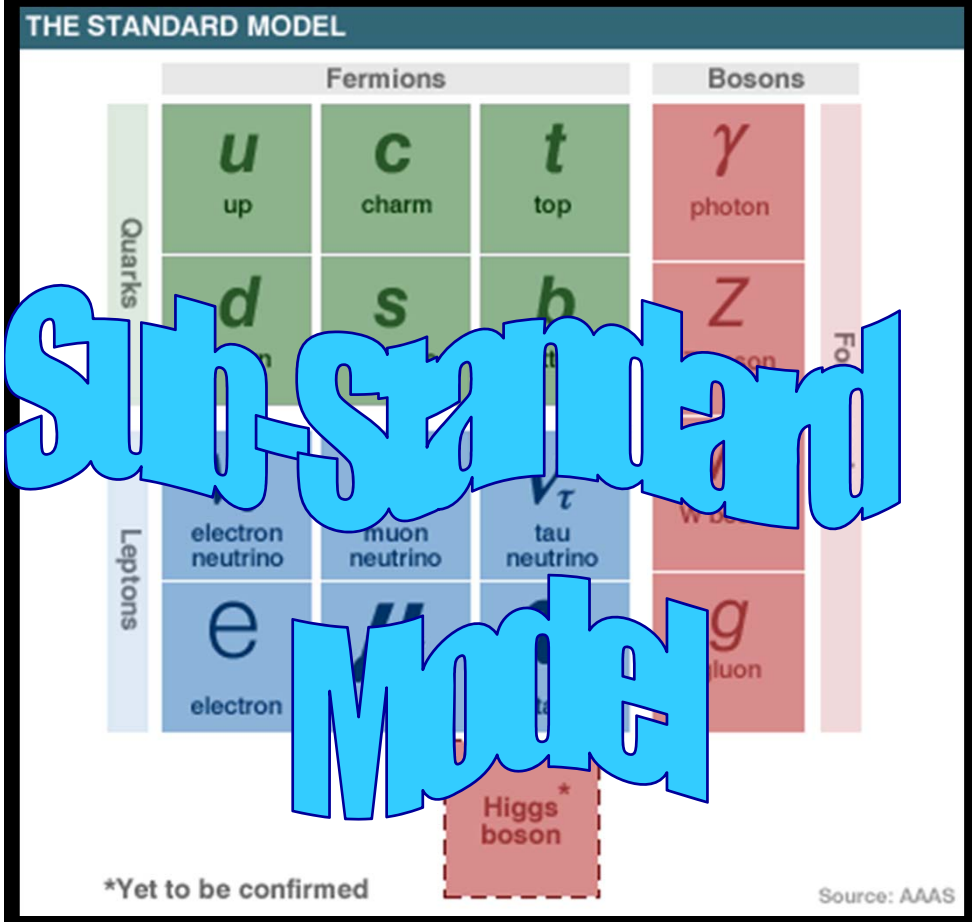
Steven Blusk

Syracuse University

Outline

- **Introduction: CKM Picture & CP Violation**
- **LHCb experiment**
- **Recent CP Violation Measurements in Charm**
- **Summary**

Introduction



- SM great success, but it "cannot" be the final word
- The case for New Physics is clear
  - Particle Physics
    - Hierarchy Problem and Unification with gravity
    - GR and Quantum theory
    - Origin of EWSB
    - Why 3 generations?
    - Masses & coupling constants
  - Cosmology
    - Dark Matter
    - Dark Energy
    - Cosmological constant problem
    - Baryon Asymmetry of the Universe
    - …

Decays involving quantum loops a great place to look for NP

CKM Formalism

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V \qquad \delta V = \begin{pmatrix} 0 & 0 & 0 \\ -iA^2\lambda^5\eta & 0 & 0 \\ A\lambda^5(\rho+i\eta)/2 & -A\lambda^4(1/2-\rho-i\eta) & 0 \end{pmatrix}$$

- All CPV phenomena attributable to a single complex phase in the CKM matrix with $\eta \neq 0$.
- Another consequence: Neutral mesons (K^0, D^0, B^0, B_s) mix via 2nd order weak interactions.

$$H = \begin{pmatrix} m & M_{12} \\ M_{12}^* & m \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

- M_{12} : off-shell (virtual) contributions
- Γ_{12} : on-shell (real) contributions
- Diagonalize → m_H, m_L, Γ_H, Γ_L

For example, in the B^0 sector:

$$|B_L\rangle = |B\rangle + \frac{q}{p}|\bar{B}\rangle \qquad |B_H\rangle = |B\rangle - \frac{q}{p}|\bar{B}\rangle$$

Mixing parameters: $x = \frac{m_H - m_L}{\Gamma}$ $\qquad y = \frac{\Gamma_L - \Gamma_H}{2\Gamma}$

If CP conserved: $\left|\frac{q}{p}\right| = 1$ $\qquad \Delta m = 2|M_{12}|$ $\qquad \Delta\Gamma = 2|\Gamma_{12}|$

CP Violation

- I: **CPV in mixing** ($|q/p| \neq 1$): Mass eigenstates cannot be CP eigenstates
  - $|q/p| = (1-\varepsilon_K)/(1+\varepsilon_K)$ Experimental result: $\varepsilon_K = 2.228\text{x}10^{-3}$.

Also: $$a_{sl} = \frac{\Gamma(\bar{B} \to X \ell^+ \nu) - \Gamma(B \to X \ell^- \nu)}{\Gamma(\bar{B} \to X \ell^+ \nu) - \Gamma(B \to X \ell^- \nu)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

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- II: **CPV in decay** ($|\bar{A}/A| \neq 1$): ≥2 amplitudes with different weak and strong phases.
  - $\text{Re}(\varepsilon'/\varepsilon) \sim 10^{-3}$, $B \to K\pi$ ..
  - γ from $B^- \to D^0 K^-$
  - Δa_{CP} in $D^0 \to KK, \pi\pi$ from LHCb (coming up shortly!)

CP Violation

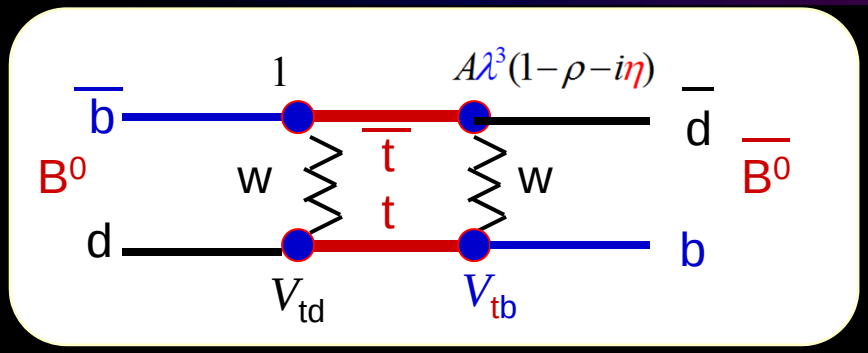
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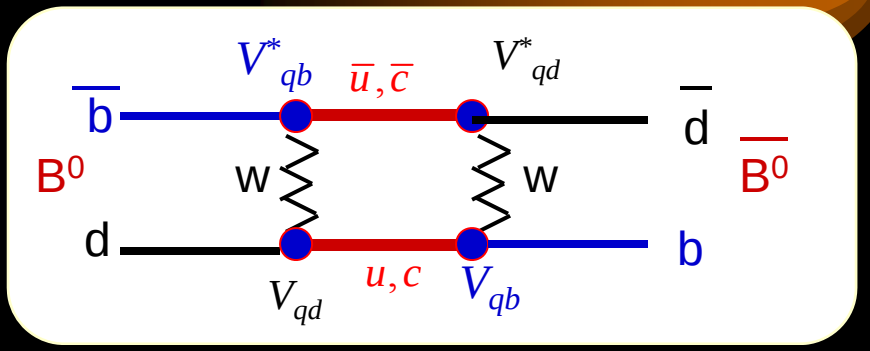
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- II: **CPV in decay** ($|\bar{A}/A| \neq 1$): Two amplitudes with different weak and strong phases.
  - $\text{Re}(\varepsilon'/\varepsilon) \sim 10^{-3}$, $B \to K\pi$ ..
  - Δa_{CP} in $D^0 \to KK, \pi\pi$ from LHCb (coming up shortly!)
  - γ from $B^- \to D^0 K^-$

- III: CPV in interference between decays with and without mixing,
  - Much attention in last 10-15 years
  - Clean extractions of weak phases when only 1 decay amplitude [$\sin(2\beta)$, $\sin(2\beta_s)$ …]

Mixing and CPV: B^0





$\Delta m_B \propto m_t^2 \lambda^6$, $\Gamma_d \sim m_b^5 \lambda^4$

→ $x = \Delta m_d / \Gamma_d \sim O(1)$

(Large Δm → large mixing rate)

$\Delta\Gamma \propto m_B^2 \lambda^6$

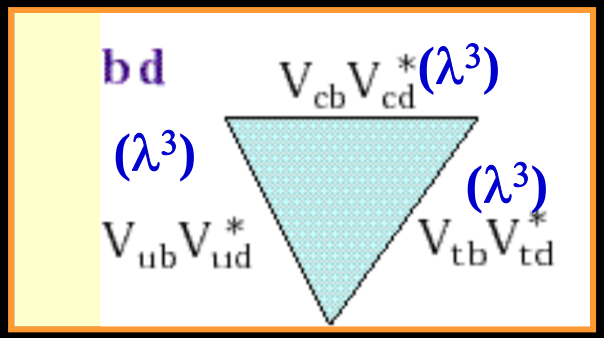
→ $\Delta\Gamma/\Delta m_d \sim O(m_B^2/m_t^2) \sim 10^{-3}$

→ $\Delta\Gamma/\Gamma$ small

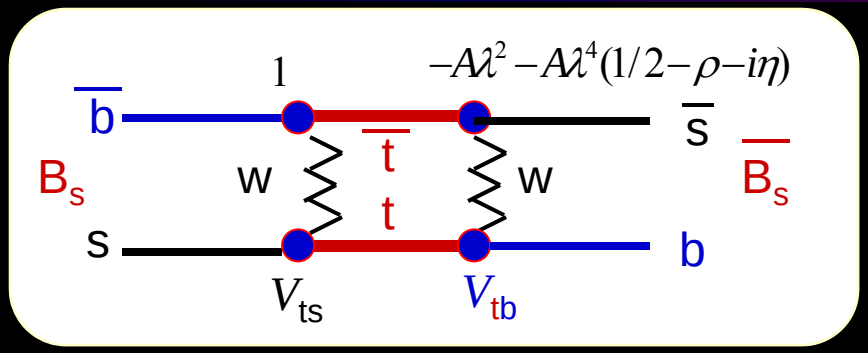
Mass eigenstates labeled by masses ("heavy"" and "light")

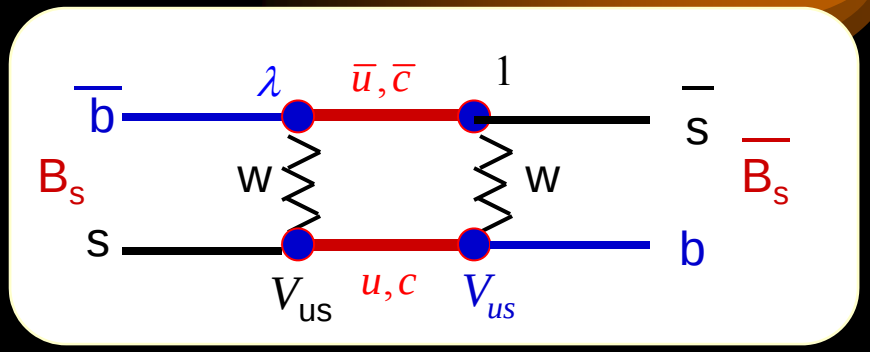
CP Violation:

- Large CPV in B^0 mixing: $\mathrm{Arg}(V_{td}) \sim \eta/(1-\rho)$
- Large direct CPV in selected decays.
  - $B^0 \rightarrow \pi\pi$, $K\pi$, etc
  - $B^- \rightarrow (\bar{D})K^-$, $(\bar{D}) \rightarrow KK$, $\pi\pi$, $K\pi$



Mixing and CPV: B_s





$\Delta m_{Bs} \propto m_t^2 \lambda^4$, $\Gamma_s \sim m_b^5 \lambda^4$

→ $\Delta m_s \sim 20 \Gamma_s$

(Very large mixing rate)

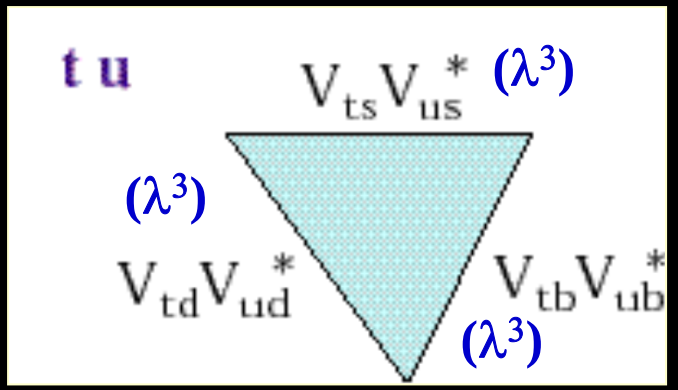
$\Delta\Gamma_s \propto m_B^2 \lambda^4$

→ $\Delta\Gamma_s/\Delta m_s \sim O(m_B^2/m_t^2) \sim 10^{-3}$

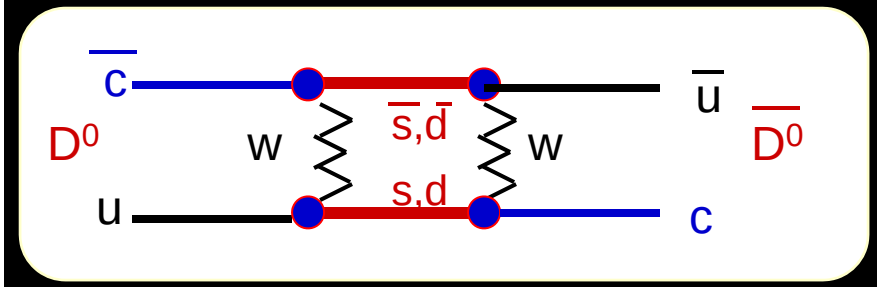
→ $\Delta\Gamma_s/\Gamma_s$ not small (~0.1)

CP Violation:

- Small B_s mixing: $\mathrm{Arg}(V_{ts}) \sim \eta\lambda^2$
- Large CPV in selected decays.
  - $B_s \rightarrow D_s K$



Mixing and CPV: D^0

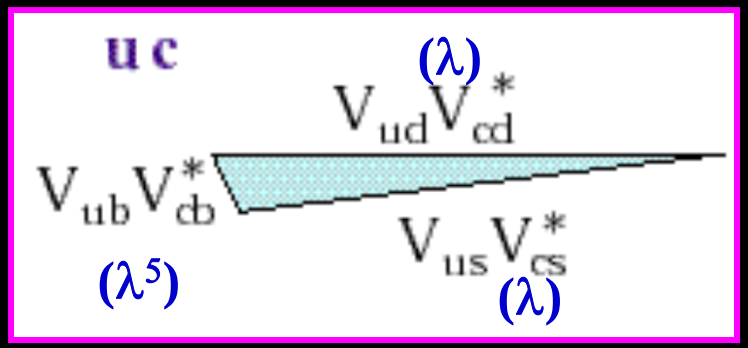


$\Delta m_D \sim (m_s^2 - m_d^2)/m_W^2$. Large GIM suppression..

(Very slow mixing)

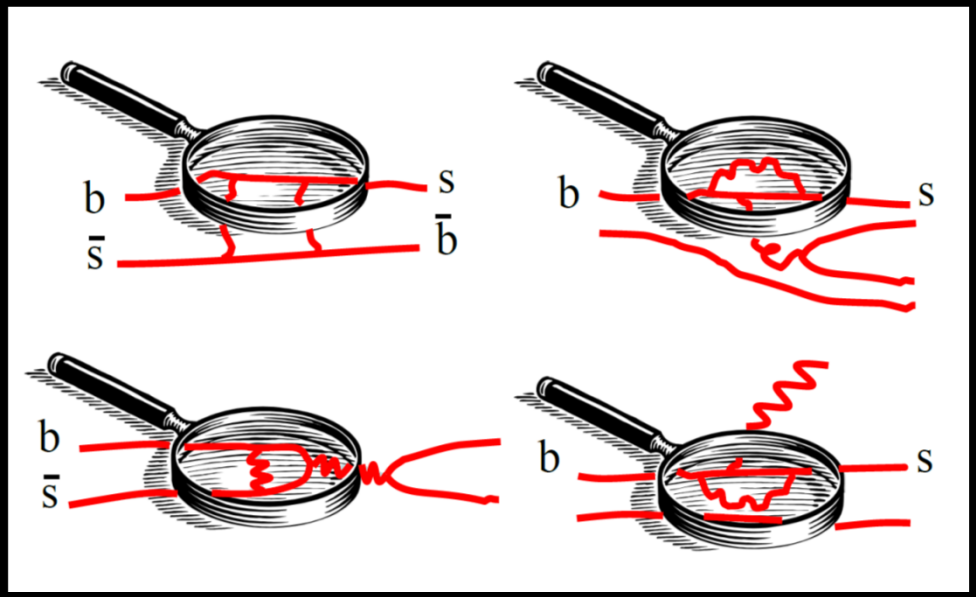
- Mixing parameters hard to compute (theoretically) due to long distance effects..
  - *Theory: x,y* in range 10^{-2} – 10^{-3}
  - CPV small, at the level 10^{-3}

- Here, aim is to uncover CPV at a level "significantly larger" than 10^{-3}.



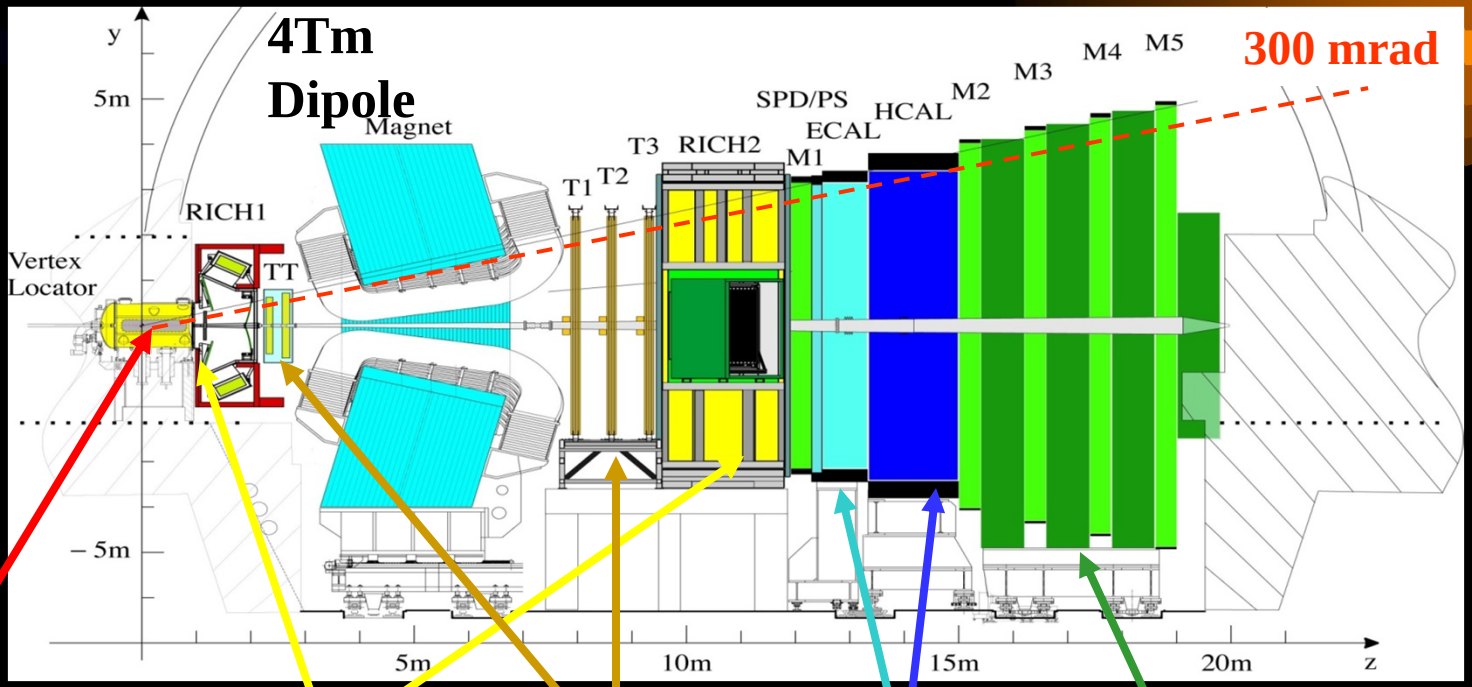
LHCb: Search for New Physics in Beauty & Charm

- Main aim of LHCb is to study a multitude of b- and c-hadron decays to search for inconsistencies in the CKM description of weak interactions.
  - Loop diagrams, rare decays, sensitive to NP



- Many other areas of exploration as well
  - Hidden valley, precision mass & lifetimes, new B decays, $\tau \rightarrow \mu\mu\mu$, X, Y, Z, Electroweak $W^{\pm}$, Z^0, etc

LHCb Detector



Vertex Detector

RICH counters π/K/p Identification

Tracking

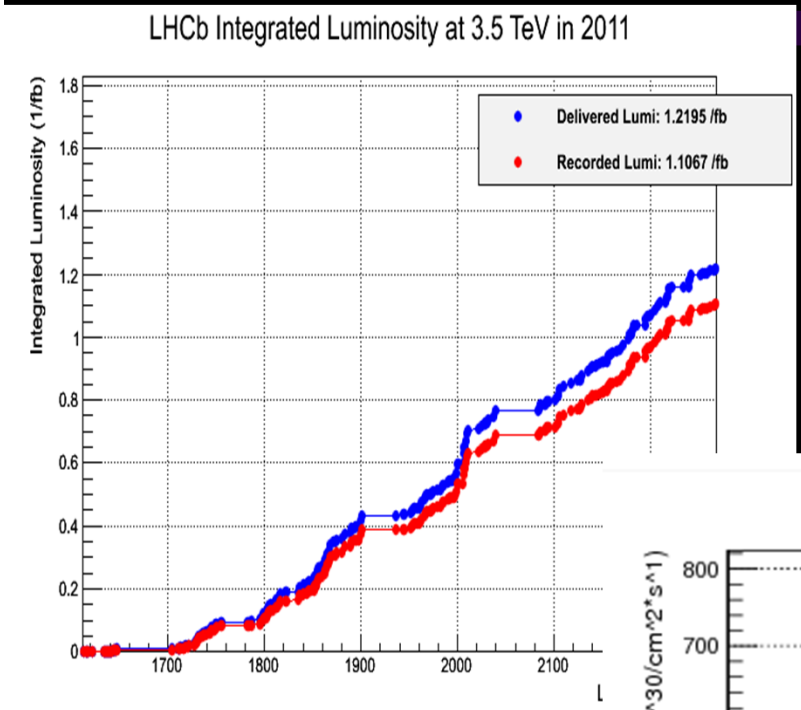
Calorimeters

Muon System

Key strengths of LHCb

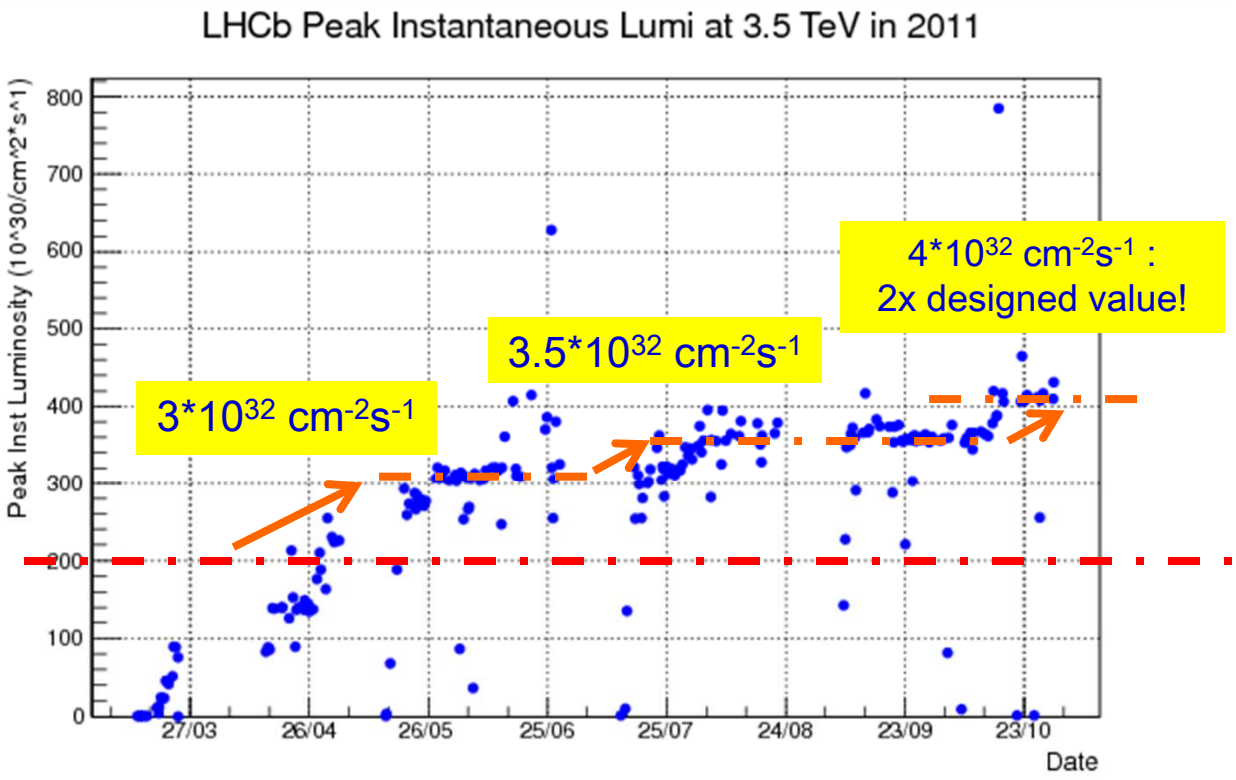
- ~5×10^{11} $b\bar{b}$/year.
- ~5×10^{12} $c\bar{c}$/year
- Highly flexible/large BW trigger (~2 kHz $b\bar{b}$, 1 kHz $c\bar{c}$)
- Excellent momentum resolution
- Ability to swap dipole polarity
- Precision vertexing
- Excellent PID

2011 Data Taking

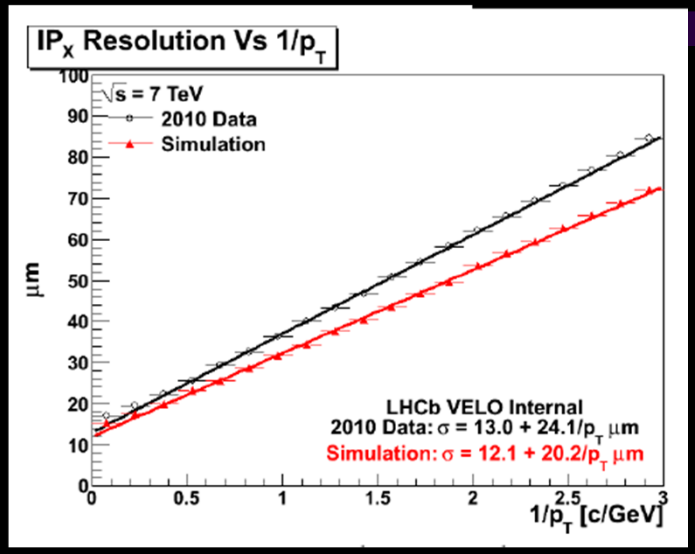


- In 2011, collected ~1 fb^{-1}, about a nominal LHC year for LHCb
- But, 50 ns bunch spacing

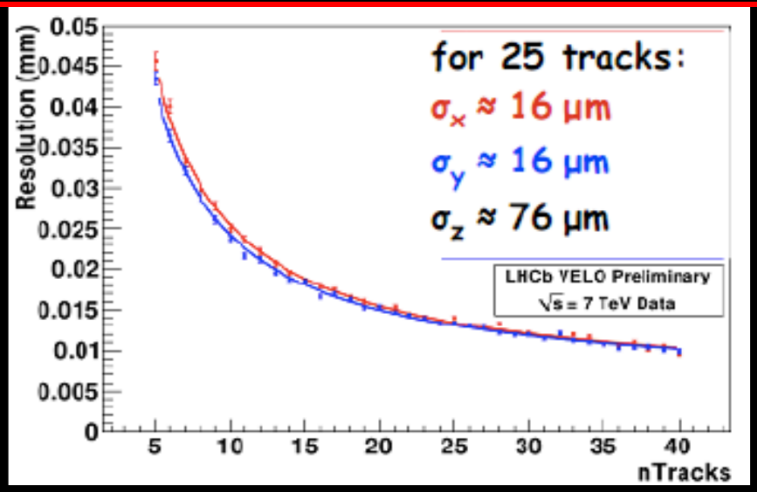
→ ~2X larger instantaneous lumi relative to design lumi



Vertex and Tracking Performance

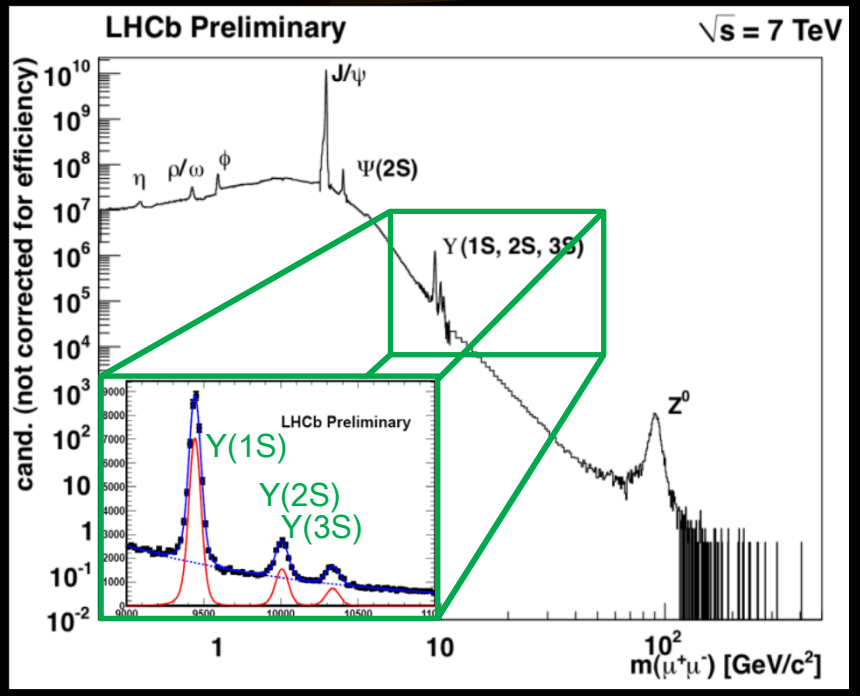


Vertex resolution



Primary vertex resolution ~16 μm

Momentum resolution

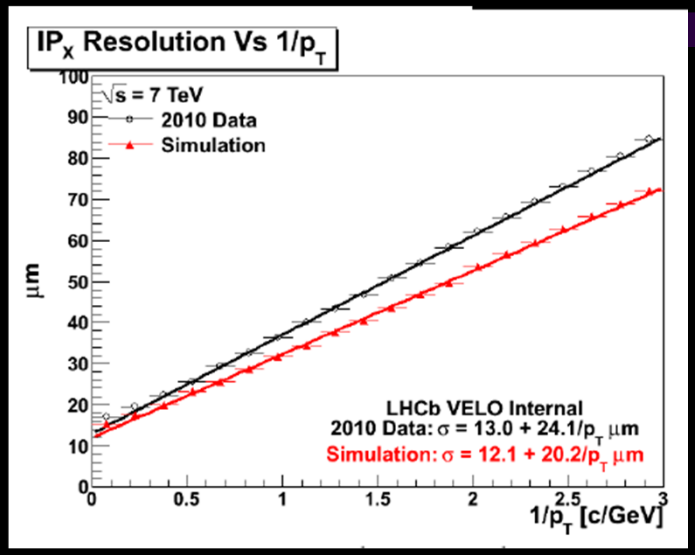


Accurate field map and alignment

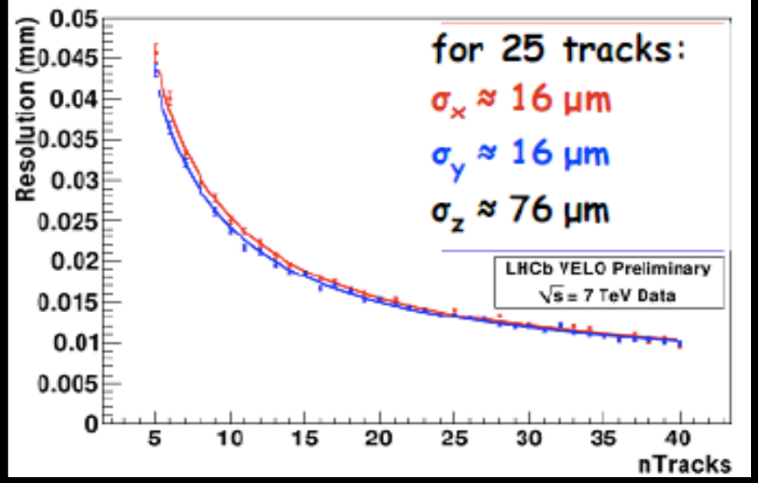
Momentum resolution: 0.4% - 0.6%

Mass resolution: J/ψ = 13 MeV

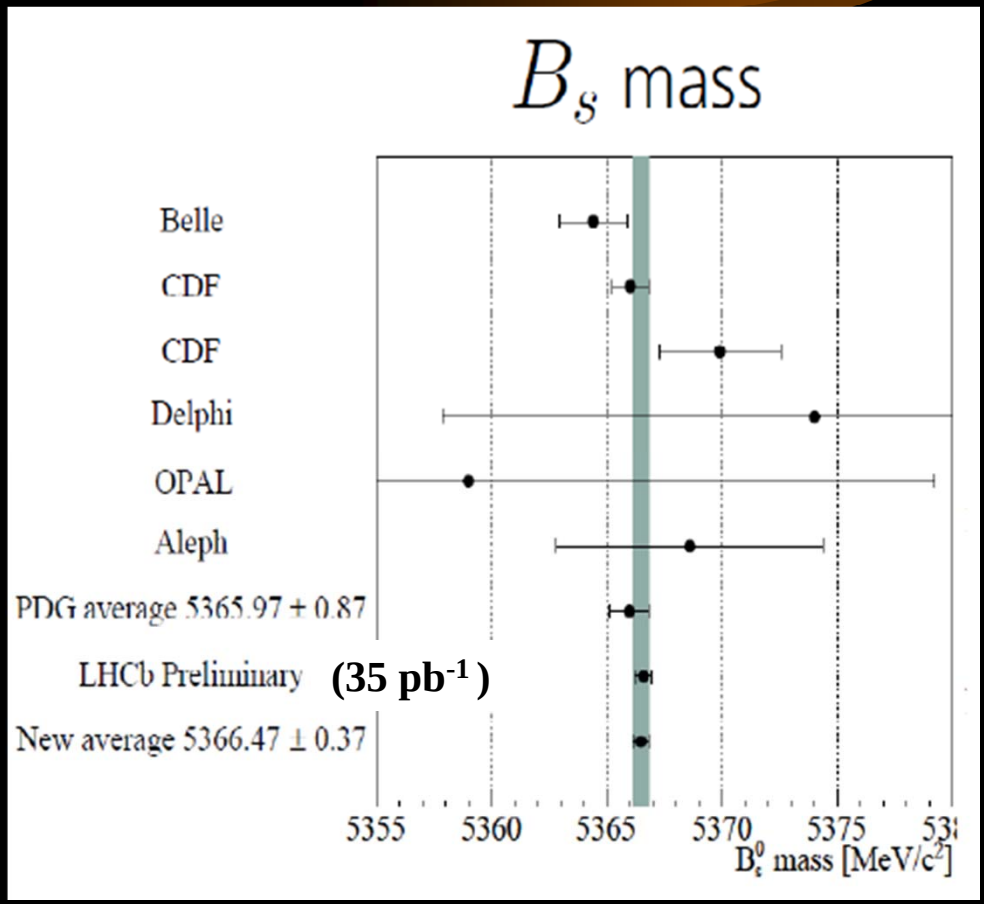
Vertex and Tracking Performance



Vertex resolution

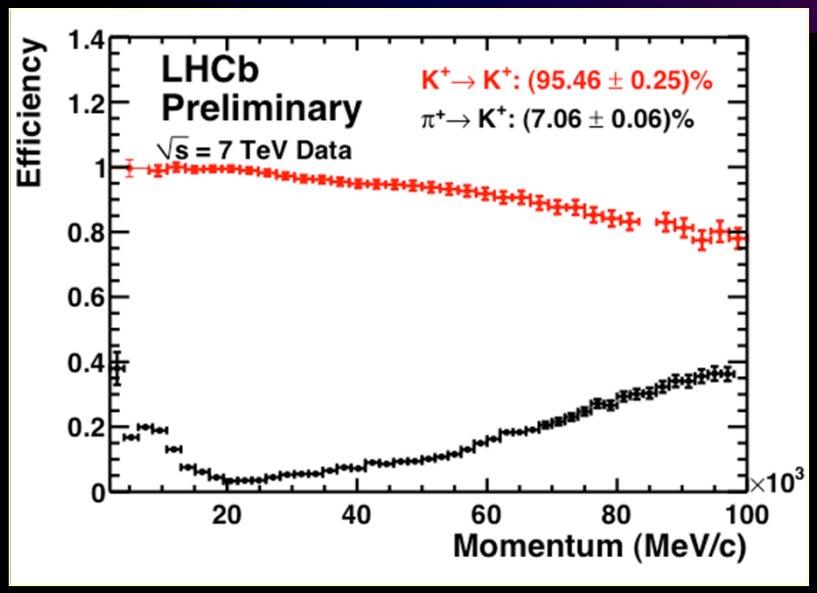


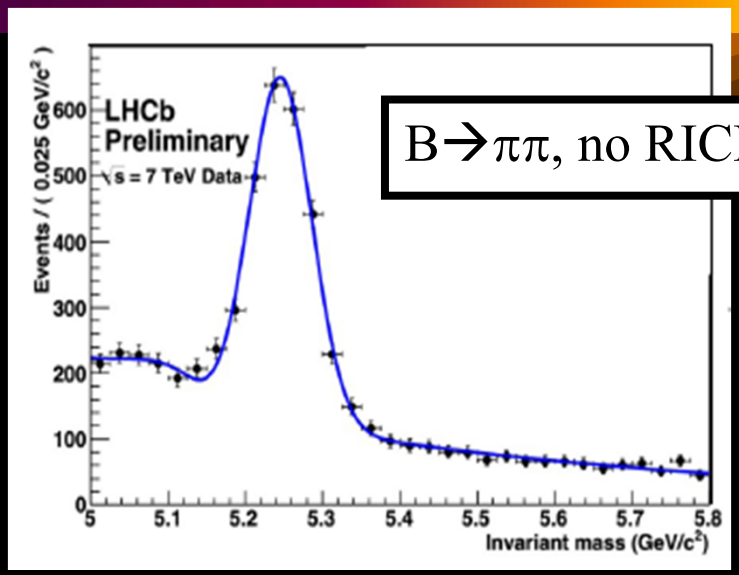
Primary vertex resolution ~16 μm



~2X more precise B_s mass than WA
Same for Λ_b

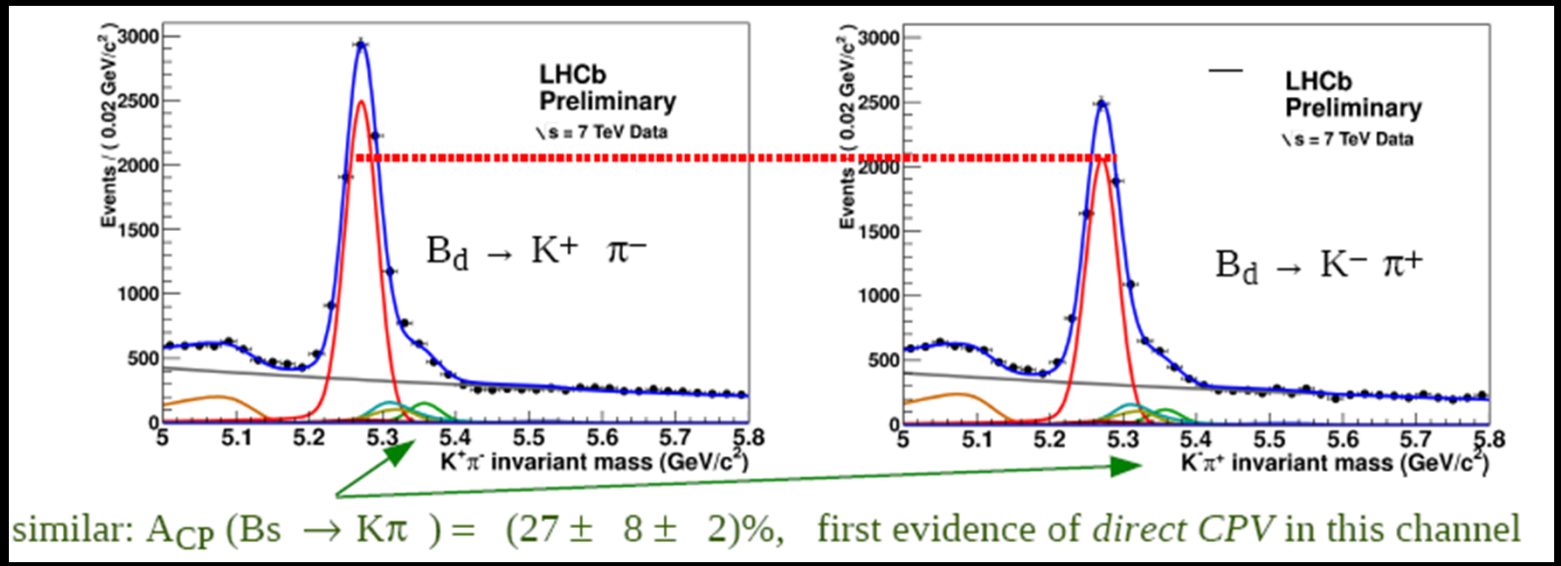
RICH Performance - K/π Separation





B→ππ, no RICH

With RICH: A_{CP} (B^0→Kπ) = - 0.088 ± 0.011 ± 0.008



similar: A_{CP} (Bs → Kπ) = (27 ± 8 ± 2)%, first evidence of *direct CPV* in this channel

Charm Physics

- Probing CPV in charm:
  - Time-dependent WS decays
  - Time-dependent $D^0 \rightarrow K_s \pi\pi$
  - Lifetimes in CP eigenstates
  - **CP asymmetries (CS decays)**

CPV in Charm - Lifetimes

- In D^0 decays : $x, y \sim 0.01 - 0.001$ (Let's take $f_{cp} = K^+K^-$), then:

$$\Gamma_{D^0\to KK}(t) = |A_{KK}|^2 e^{-\Gamma t}\left(1 - R_m(y\cos\phi - x\sin\phi)\Gamma t\right)$$

$$\Gamma_{\overline{D^0}\to KK}(t) = |A_{KK}|^2 e^{-\Gamma t}\left(1 - R_m^{-1}(y\cos\phi + x\sin\phi)\Gamma t\right)$$

$R_m = \left|\frac{q}{p}\right|$ ϕ = rel. phase between q/p and A_{KK}

- Each can be re-expressed as an exponential with modified widths (τ's)

$$\overline{\Gamma}_{D^0\to KK} = \Gamma\left(1 + R_m(y\cos\phi - x\sin\phi)\Gamma t\right) \qquad \overline{\Gamma}_{\overline{D^0}\to KK} = \Gamma\left(1 + |q/p|(y\cos\phi + x\sin\phi)\Gamma t\right)$$

- **Lifetimes in CP Eigenstates**

Expt Underlying params

$$y_{CP} \equiv \frac{\overline{\Gamma}_{D^0\to KK} + \overline{\Gamma}_{\overline{D^0}\to KK}}{2\Gamma} - 1 = \frac{\tau_{K\pi}}{\tau_{KK}} - 1 \approx \frac{y}{2}\left(R_m + \frac{1}{R_m}\right)\cos\phi - \frac{x}{2}\left(R_m - \frac{1}{R_m}\right)\sin\phi$$

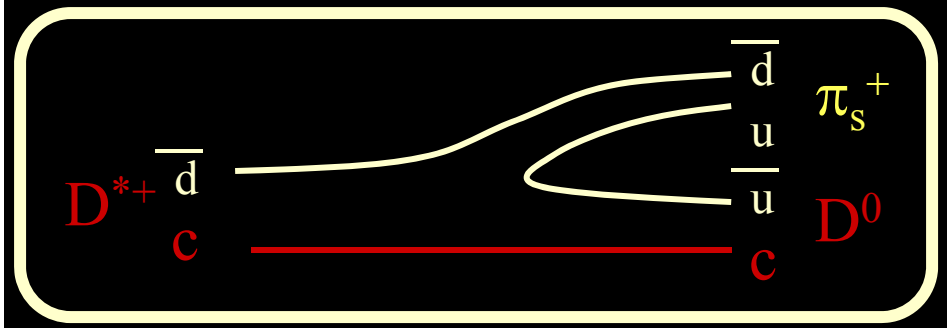
If $R_m \to 1$, $\phi = 0 \Rightarrow y_{CP} = y$
$y_{CP} \neq y \Rightarrow$ indirect CPV

$$A_\Gamma \equiv \frac{\overline{\Gamma}_{D^0\to KK} - \overline{\Gamma}_{\overline{D^0}\to KK}}{2\Gamma_D} = \frac{\tau_{\overline{D^0}\to KK} - \tau_{D^0\to KK}}{\tau_{\overline{D^0}\to KK} + \tau_{D^0\to KK}} \approx \frac{y}{2}\left(R_m - R_m^{-1}\right)\cos\phi - \frac{x}{2}\left(R_m + R_m^{-1}\right)\sin\phi$$

If $A_\Gamma \neq 0 \Rightarrow$ indirect CPV (ignores small direct CPV contribution)

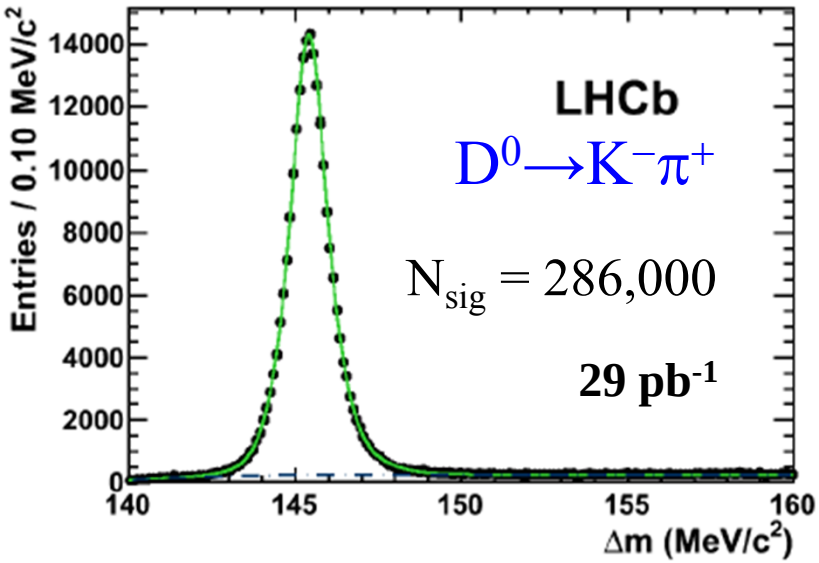
$D^{*\pm} \to \pi^{\pm} \overline{D}^0$, $\overline{D}^0 \to K^+K^-$, $K^-\pi^+$

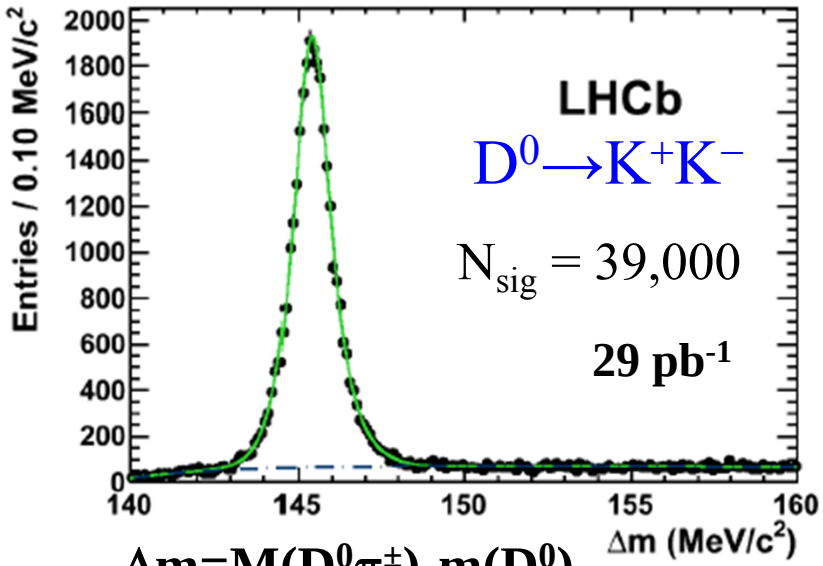
arXiv:1112.4698 submitted to JHEP; 2010 data (29 pb^{-1})





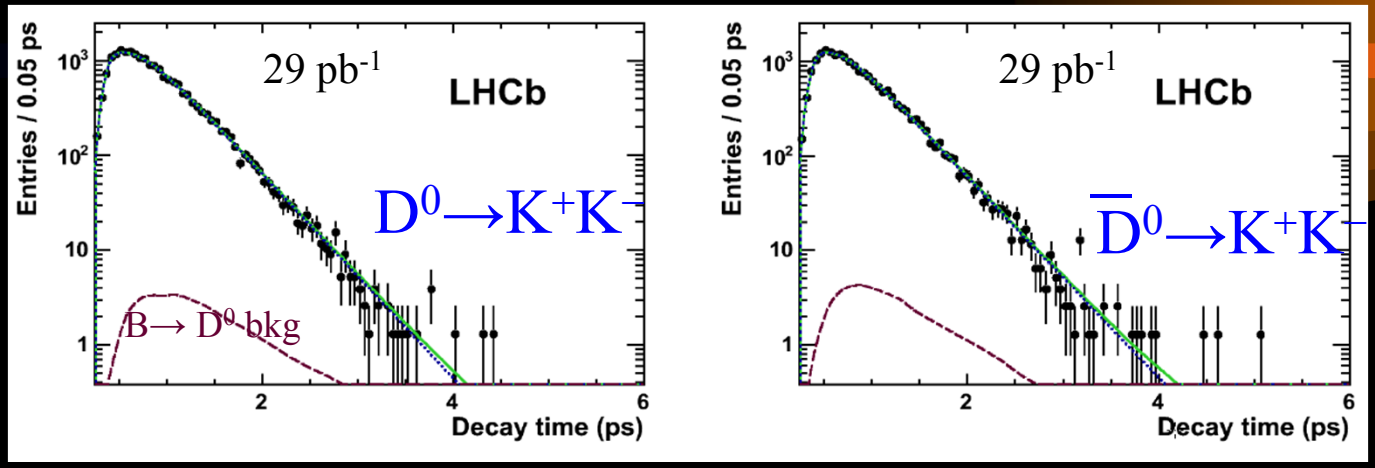
- Charge of the π_s tags the D^0 flavor
- D^{*+} detection also helps the background suppression





$\Delta m = M(D^0\pi^{\pm}) - m(D^0)$

Charm mixing and CPV via effective lifetimes



Experiment	y_{cp} (10^{-3})	A_Γ (10^{-3})
LHCb	5.6±6.3±4.1	-5.9±5.9±2.1
BaBar[1,2]	11.2±2.2±1.8	2.6±3.6±0.8
Belle[3]	13.1±3.2±2.5	0.1±3.0±1.5
HFAG y_{CP} Average	11.07±2.17	1.23 ± 2.48

[1] PRD78,01105(2008)
[2] PRD80,071103(2009)
[3] PRL 98,211803(2007)

HFAG fit for y: $(6.3 \pm 2.0)\times10^{-3}$

$y_{CP} \approx y \rightarrow$ No clear evidence for indirect CPV $\quad A_\Gamma \approx 0$

- First measurements at a hadron collider.
- Not yet competitive with e^+e^-. With 2011 data [1.1 fb^{-1}] $\sigma_{stat}(y_{cp}) \sim 1\times10^{-3}$. Will soon have most sensitive measurements.
- Expected statistical errors on A_Γ with 5 fb^{-1} (upgraded LHCb 50 fb^{-1}) ~4×10^{-4} (1×10^{-4})

Evidence of Direct CPV in D^0 decays

Particle Physics Blog

Monday, 14 November 2011

LHCb has evidence of new physics! Maybe.

BBC Mobile

NEWS SCIENCE

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15 November 2011 Last updated at 07:18 ET

LHC reveals hints o particle decays

By Jason Palmer

Science and technology reporter, BBC News



LHC-beauty, or LHCb, is an enormous detector designed to examine CP violation

the reference frame

Veritas

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monday, november 14, 2011 ...

LHCb reports a new source of CP-violation

Well, just another 3-sigma hint that may go away

Mat Charles of Oxford gave a talk at HCP 2011 in Paris in which he reported a surprising result by LHCb at CERN based on 0.58/fb of their

who is lumo?



Luboš Motl
Pilsen, Czech Republic

View my complete profile

LHC Luminosity 30-Oct-2011: peak = 3650/pb/s total d

ations About Science with Theoretical Physicist Matt Strassle

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← Expanding the Dimensions Articles

A Notable Discrepancy at the LHCb Experiment

Posted on November 16, 2011 | Leave a comment

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BSM CPV in LHCb at HCP11

Beyond standard model CP violation has been reported by Mat Charle for the LHCb collaboration at the Hadron Collider Physics conference

A Quantum Diaries Survivor

Private thoughts of a physicist and chessplayer

CP Violation In Charm Decays: 3.5 Sigma From LHCb!

By Tommaso Dorigo | November 15th 2011 05:59 AM | 16 comments | Print | E-mail | Track Comments

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Today I wish to briefly discuss a recent important measurement produced by the LHCb collaboration, a measurement of CP

A Quantum Diaries Su

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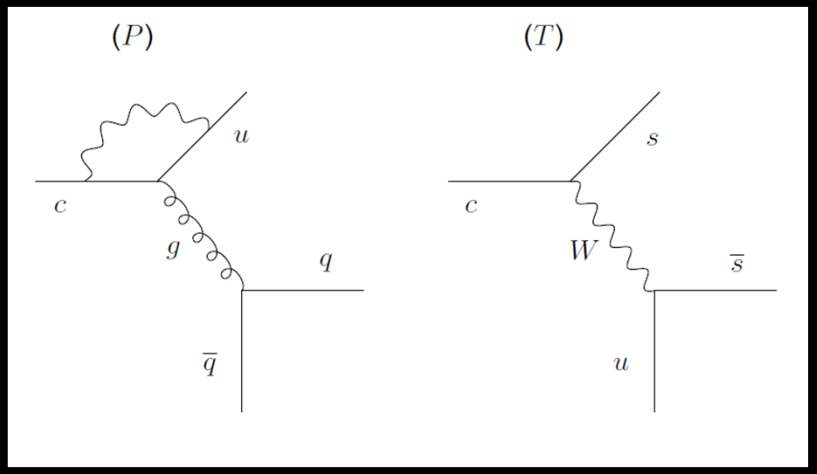
New Physics at LHC? An Anomaly in CP Violation

by Sean

Here in the Era of 3-Sigma Results, we tend to get excited about hints of new physics that eventually end up going away. That's okay — excitement is cheap, and eventually one of these results is going to stick and end up changing physics in a dramatic way. Remember that "3 sigma" is the minimum standard required for physicists to take a new result at all seriously; if you want to

Direct CPV in $D^0 \to K^+K^-, \pi^+\pi^-$

- Singly CS D decays receive extra penguin amplitudes that generally have a different weak phase.
- To get direct CPV, need a different strong phase as well.



$$A_f = A(1 + r_f e^{i(\delta+\phi_f)})$$
$$\bar{A}_f = A(1 + r_f e^{i(\delta-\phi_f)})$$

$$r_f = \left|\frac{V_{cb}V_{ub}}{V_{cs}V_{us}}\right| \times \left|\frac{P - T_d}{T_s - T_d}\right|$$

T_s = leading tree
T_d = exchange
P = penguin

By CKM factors, $r_f \sim 6\text{x}10^{-4}$

Since: $a_f^d = 2r_f \sin\phi \sin\delta_f$ expect direct CPV ~ 10^{-3}

(will depend on P/T, but "natural" level would be P/T ~ 0.1)

Y. Grossman, A. Kagan, Y. Nir arXiv:0609178v1

- The SM cannot account for asymmetries that are significantly larger than $\mathcal{O}(10^{-4})$. Thus, CP violation from new physics must be playing a role if an asymmetry is observed with present experimental sensitivities $[\mathcal{O}(0.01)]$.

CPV in time integrated $D^0 \to K^+K^-,\ \pi^+\pi^-$

Recall, time dependent decay rates

$$\Gamma(t) = |A_f|^2 e^{-\Gamma t}\left(\begin{array}{l}(1+|\lambda_f|^2)\cosh(y\Gamma t)+(1-|\lambda_f|^2)\cos(x\Gamma t)\\ +\left(2\,\mathrm{Re}\,\lambda_f\right)\sinh(y\Gamma t)-\left(2\,\mathrm{Im}\,\lambda_f\right)\sin(x\Gamma t)\end{array}\right)$$

$$\bar{\Gamma}(t) = |\bar{A}_f|^2 e^{-\Gamma t}\left(\begin{array}{l}(1+|\lambda_f^{-1}|^2)\cosh(y\Gamma t)+(1-|\lambda_f^{-1}|^2)\cos(x\Gamma t)\\ +\left(2\,\mathrm{Re}\,\lambda_f^{-1}\right)\sinh(y\Gamma t)-\left(2\,\mathrm{Im}\,\lambda_f^{-1}\right)\sin(x\Gamma t)\end{array}\right)$$

$$A_f = A(1+r_f e^{i(\delta+\phi_f)})$$
$$\bar{A}_f = A(1+r_f e^{i(\delta-\phi_f)})$$

In the limit $x, y, r_f \ll 1$

$$\langle a_{CP}\rangle = \frac{\Gamma_{D^0\to f}(t)-\Gamma_{\bar{D}^0\to f}(t)}{\Gamma_{D^0\to f}(t)+\Gamma_{\bar{D}^0\to f}(t)} \cong a_f^d + \langle a_f^m(t)\rangle + \langle a_f^i(t)\rangle$$

Indirect CPV

Direct CPV $a_f^d = 2r_f \sin\phi \sin\delta_f$

$$\langle a_f^i(t)\rangle = \eta_{CP}\frac{x}{2}\left(\frac{\langle t\rangle}{\tau}\right)\left(R_m + R_m^{-1}\right)\sin\phi$$

$$\langle a_f^m(t)\rangle = -\eta_{CP}\frac{y}{2}\left(\frac{\langle t\rangle}{\tau}\right)\left(R_m - R_m^{-1}\right)\cos\phi$$

In mixing + Interference between direct and mixed decay) $= A_\Gamma$

$$A_{CP} \approx a_{CP}^{dir} - A_\Gamma \frac{\langle t\rangle}{\tau}$$

Raw CP asymmetry is sensitive to both direct & indirect CPV

What do we measure ?

For any D^*-tagged decay $D^0 \to f$:

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

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

- $A_{CP}(f)$: physics CP asymmetry
- $A_D(f)$: Detection asymmetry of D^0
- $A_D(\pi_s)$: Detection asymmetry of soft pion
- $A_P(D^{*+})$: Production asymmetry

For a two-body decay of a spin-0 particle to a self-conjugate final state, no D^0 detector efficiency asymmetry, i.e.

$A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$

Then:

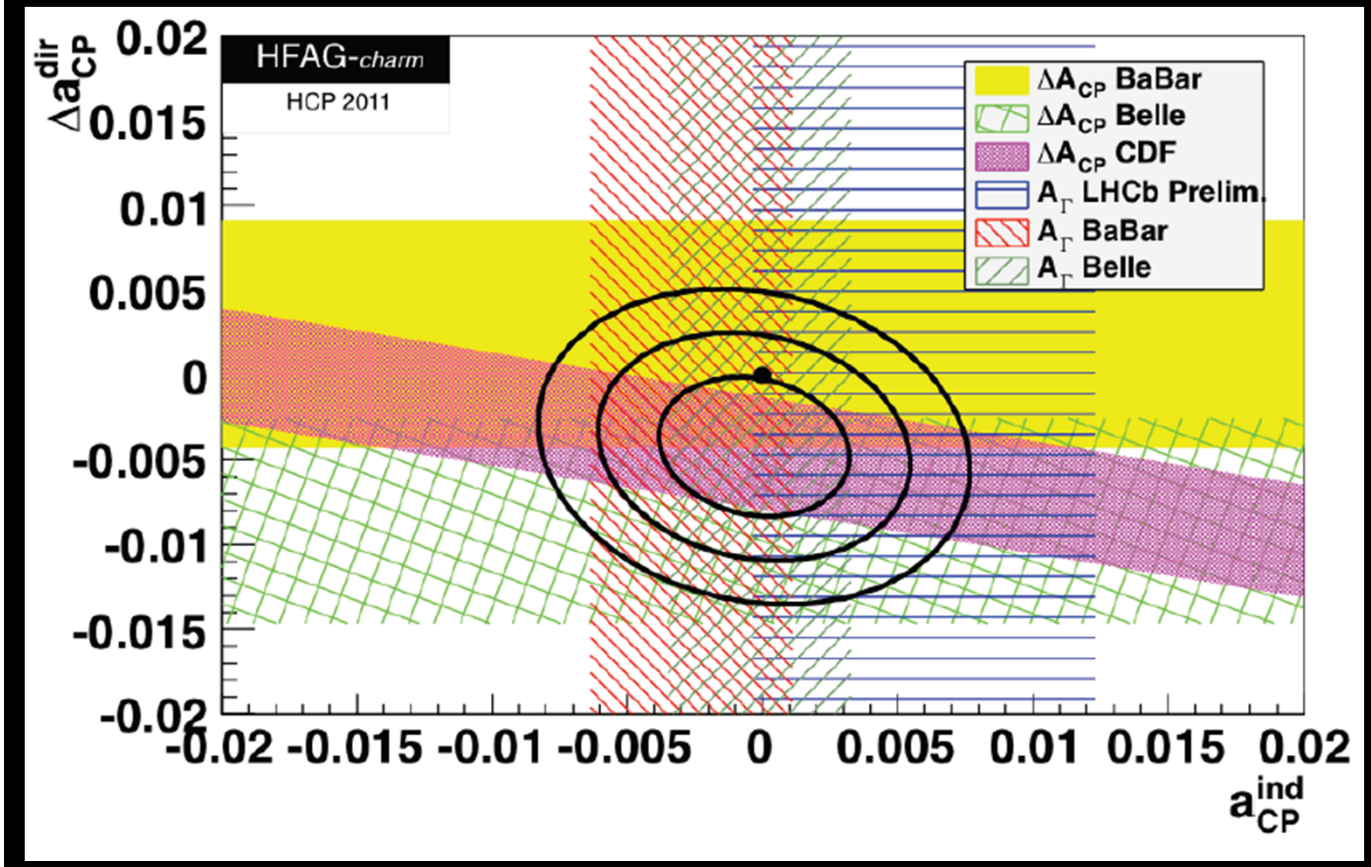
$$\begin{aligned} A_{RAW}(K^-K^+)^* &= A_{CP}(K^-K^+) + A_D(\pi_s) + A_P(D^{*+}) \\ A_{RAW}(\pi^-\pi^+)^* &= A_{CP}(\pi^-\pi^+) + A_D(\pi_s) + A_P(D^{*+}) \\ \Rightarrow A_{RAW}(K^-K^+)^* - A_{RAW}(\pi^-\pi^+)^* &= A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \end{aligned}$$

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

- Difference in asymmetry much more robust against systematic uncertainties
- Expect direct CP asymmetry to be opposite sign for KK and ππ (V_{cd} and V_{us} have phase diff of π)

Δa_{CP} previous measurements

- Different measurements are sensitive to different combinations of direct and indirect asymmetries



HFAG averages:

$\Delta a_{CP}^{dir}=(-0.42\pm0.27)\%$

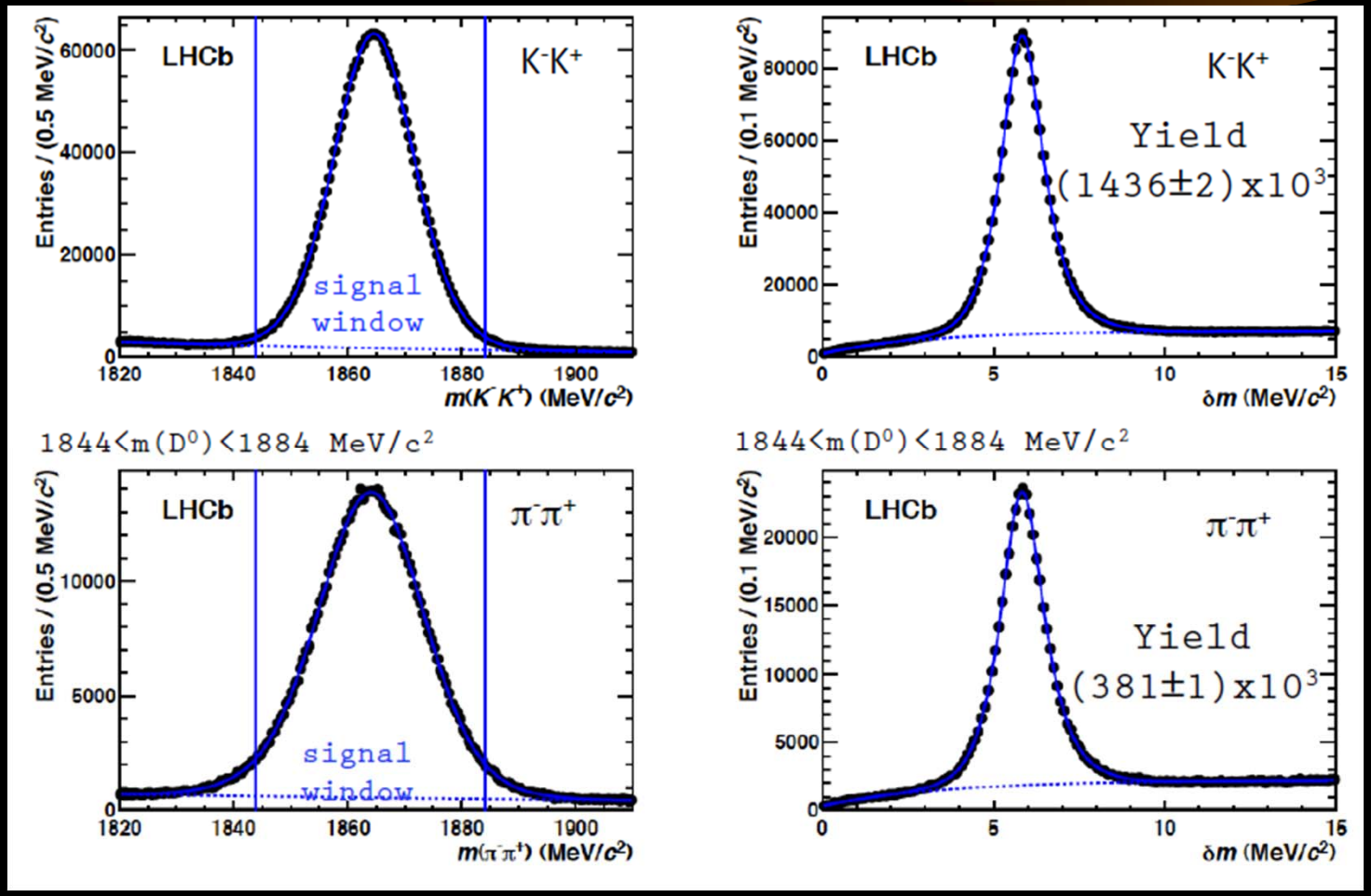
1.6σ away from zero

$a_{CP}^{ind}=(-0.03\pm0.23)\%$

Recent CDF measurement
$\Delta A_{CP}=[-0.46\pm0.31\pm0.12]\%$
arXiv:1111.5023

Data Sample

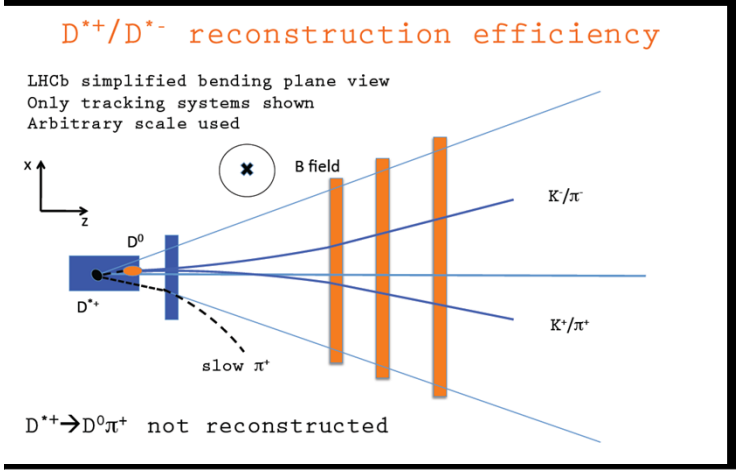
- Based on 60% of 2011 data

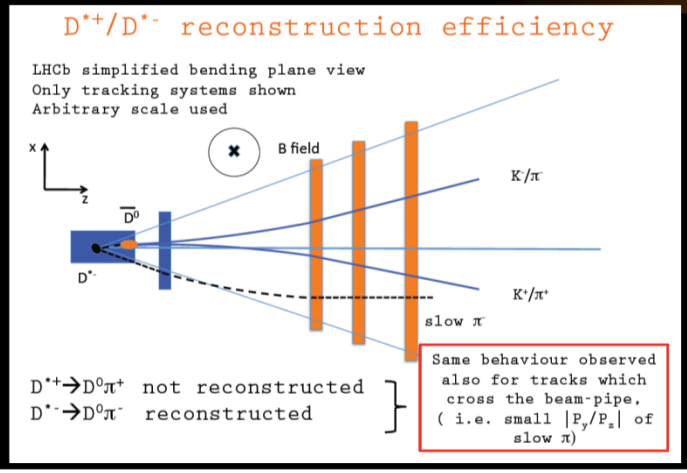


$\delta m = M(D^0\pi^\pm) - m(D^0) - M(\pi^\pm)$

Fiducial Cuts

Certain regions of the detector are only accessible to D^{*+} or D^{*-}, depending on polarity of the field… Up to 100% asymmetry!

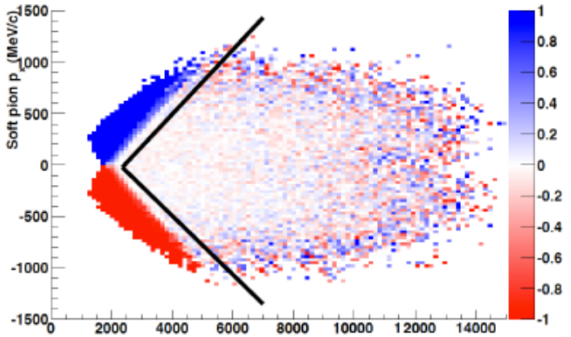




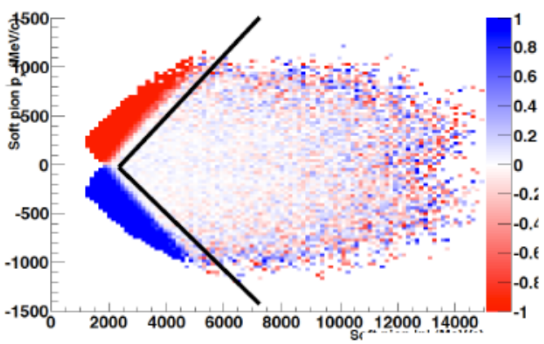
Raw asymmetry of $D^{*+}\rightarrow D^0(KK)\pi^+$ and cc in the (P_x,P) plane of slow pion

$P_x(\pi_s)$

D^{*+}/D^{*-} B field up



B field down

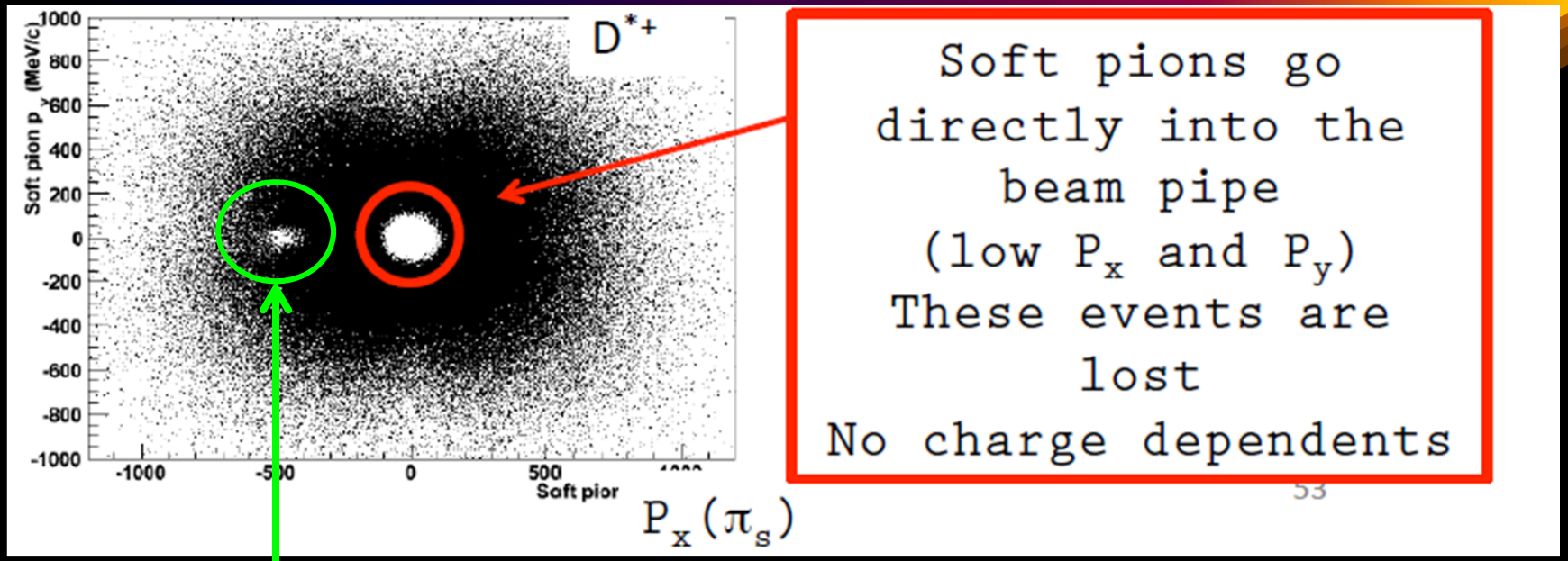


$|p_y/p_z|>0.02$

We veto these Regions to avoid possible small second order effects.

75% of events retained after fiducial selection

Additional fiducial subtleties

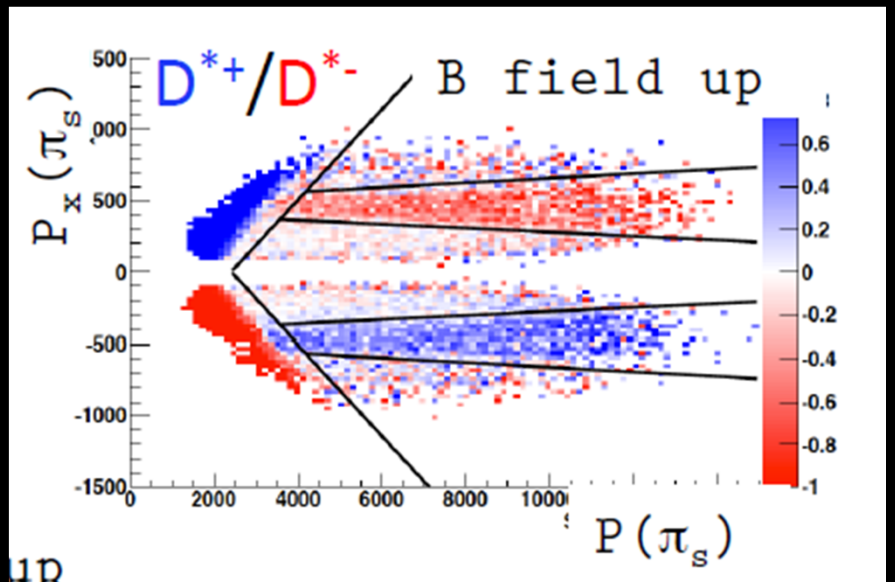


Soft pions go directly into the beam pipe (low P_x and P_y) These events are lost

No charge dependents

π^+ curves into the beampipe region in the downstream tracking chambers!

Require $|p_y/p_z|>0.02$



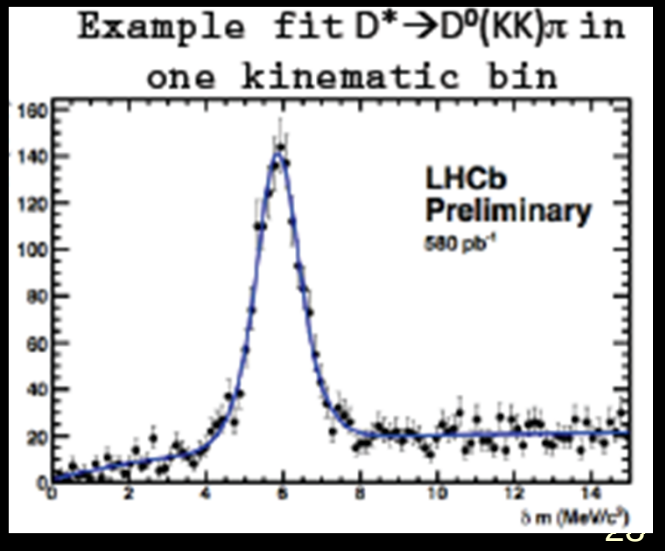
Determination of ΔA_{CP} in LHCb

Fit $\delta m = M(D^0\pi^\pm) - m(D^0) - M(\pi^\pm)$ to count number of candidates for each D^0 flavor.

- To suppress possible 2nd order detector asymmetries between KK and ππ divide the data into bins of:
  - $p_T(D^*)$, $\eta(D^*)$, p(slow π)
  - magnet polarity (up/down)
  - runs before/after technical stop

– fit δm in each bin separately, then average.

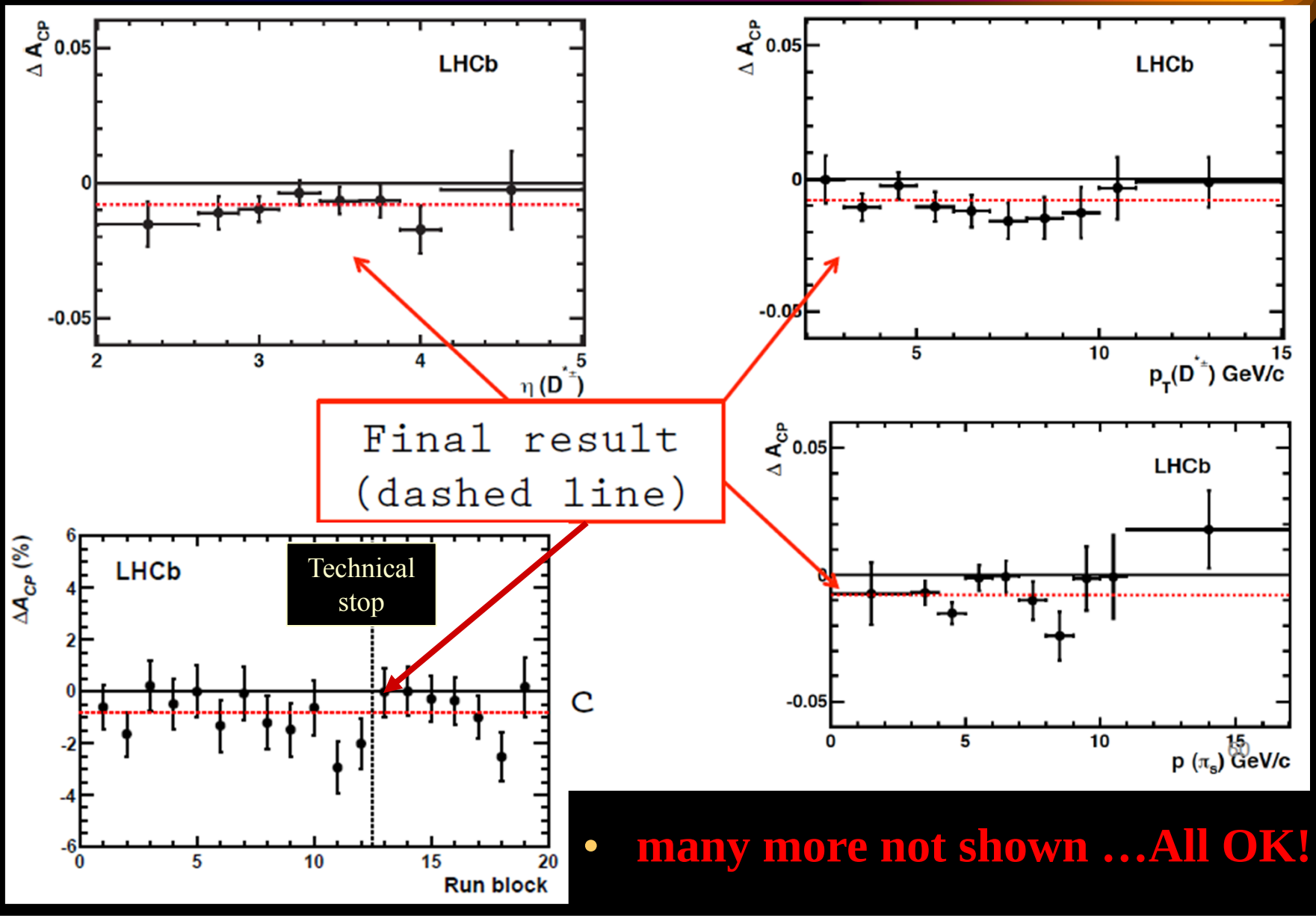
- All together 432 fits to δm distributions; 216 independent measurements of ΔA_{CP}
  - good consistency among bins: χ^2/NDF=211/215 (CL=56%)
  - average $\Delta A_{CP} = 0.82 \pm 0.21(stat)\%$



Systematic Uncertainties

- Kinematic binning: 0.02%
  - Evaluated as change in ΔA_{CP} between full 216-bin kinematic binning and "global" analysis with just one giant bin.
- Fit procedure: 0.08%
  - Evaluated as change in ΔA_{CP} between baseline and not using any fitting at all (just sideband subtraction in δm for KK and $\pi\pi$ modes)
- Peaking background: 0.04%
  - Evaluated with toy studies injecting peaking background with a level and asymmetry set according to D^0 mass sidebands (removing signal tails).
- Multiple candidates: 0.06%
  - Evaluated as mean change in ΔA_{CP} when removing multiple candidates, keeping only one per event chosen at random.
- Fiducial cuts: 0.01%
  - Evaluated as change in ΔA_{CP} when cuts are significantly loosened.
- Sum in quadrature: 0.11% small!

ΔA_{CP} : additional cross checks



- **many more not shown …All OK!**

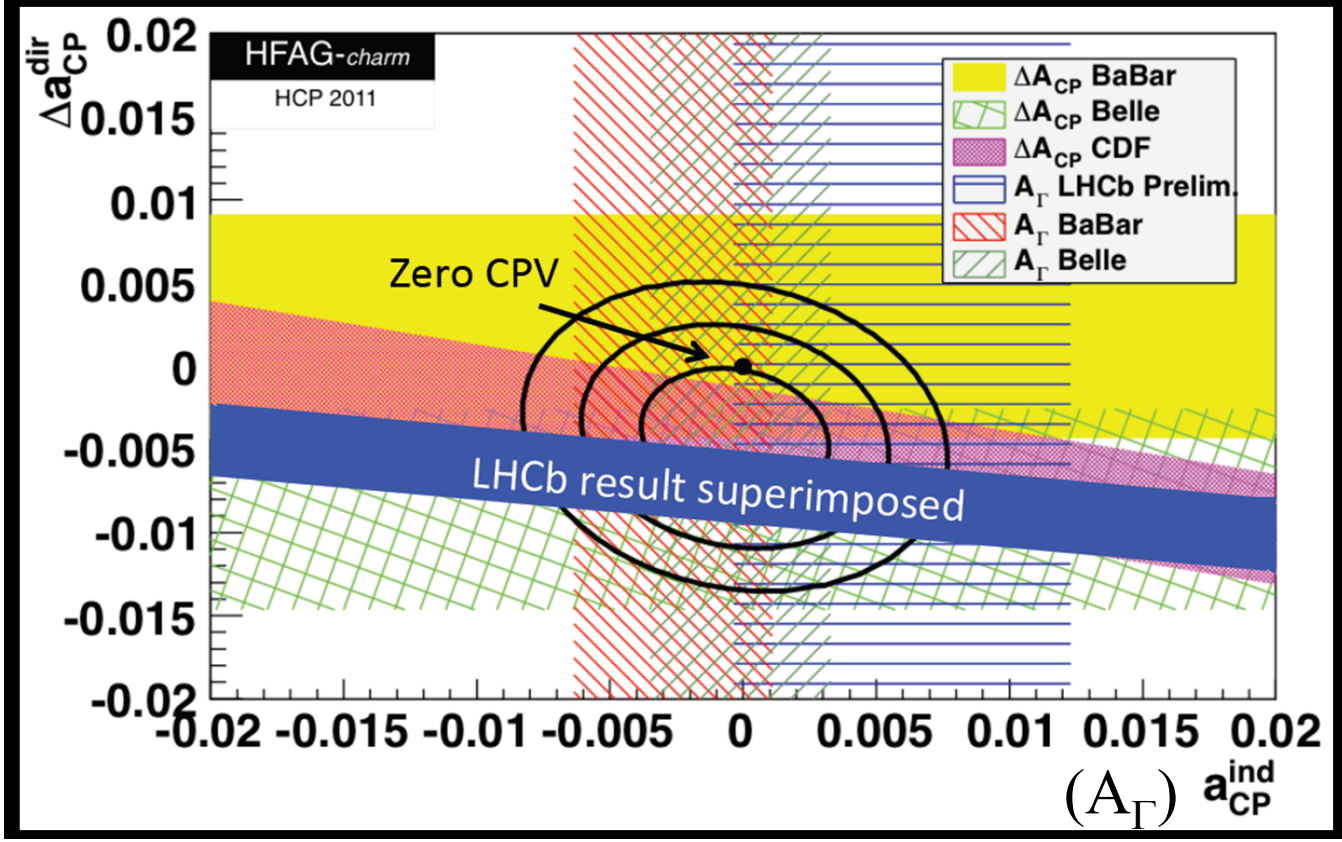
ΔA_{CP} Results

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (0.82 \pm 0.21 \pm 0.11)\%$$
$$= a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-) + (0.098 \pm 0.002 \pm 0.001)a_{CP}^{ind}$$

9.8% = difference in average decay time for KK and ππ final states

Our result is consistent with the previous measurements (~1.1σ) but more precise

3.5σ away from no CPV



HFAG averages including LHCb:

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

3.6σ away from zero

$a_{CP}^{ind} = (-0.02 \pm 0.23)\%$

Probability no CPV: 0.15%

A_{CP} in $B \rightarrow D^0 X \mu\nu$

- Large inclusive μ sample
- Charge of μ tags the D flavor
- Orthogonal to prompt D* analysis

$$A_{RAW}(f)^* = \frac{N(B \rightarrow D^0(f)\mu^+\nu_\mu) - N(B \rightarrow \overline{D}^0(\bar{f})\mu^-\overline{\nu}_\mu)}{N(B \rightarrow D^0(f)\mu^+\nu_\mu) + N(B \rightarrow \overline{D}^0(\bar{f})\mu^-\overline{\nu}_\mu)}$$

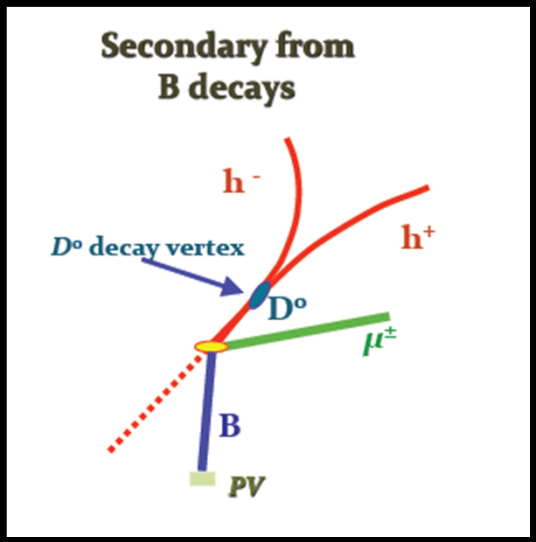
$$A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\mu) + A_P(B) + A_{CP}(B)$$

Physics CP asymmetry

Detection asymmetry of D^0 and of muon

Production asymmetry

B CP asymmetry



- Taking difference between $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$, unwanted production and detection asymmetries cancel.
- Expect stat. error ~0.3% with 2011 data sample (1.1 fb^{-1}).

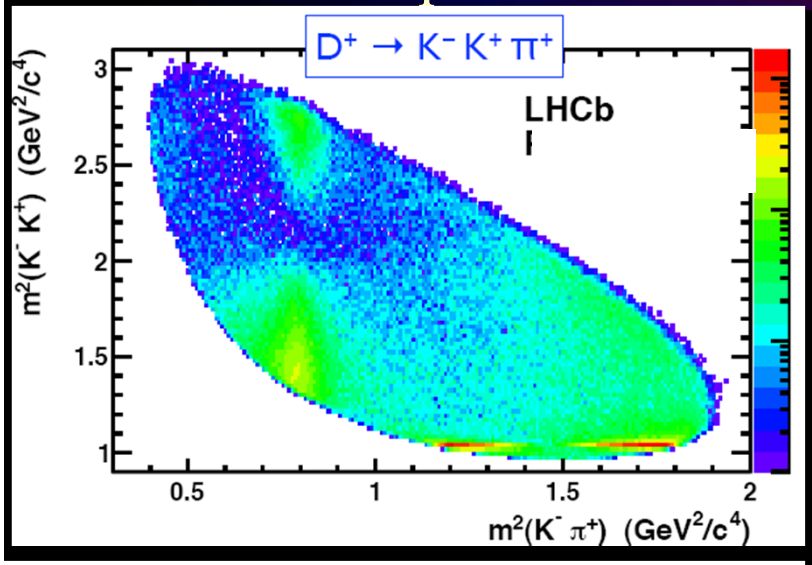
CPV in Charged D decays

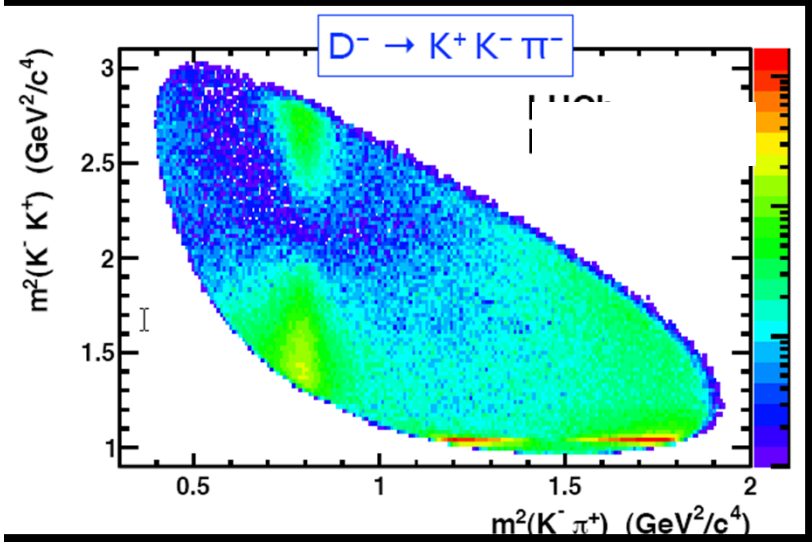
- Searching for CPV in charged D decays ensures, if you see it, it's direct CPV (no mixing).
- Contributing amplitudes must have both a weak and strong phase difference.
- CS $D^+ \rightarrow h^+h^-h^+$ good since:
  - natural variation of strong phase across the Dalitz plot, all but guarantees a strong phase difference.
  - Can look at asymmetry across the Dalitz plot
  - Strength of LHCb for fully charged final states.

Search for CPV in $D^+ \to K^+K^-\pi^+$

2010 data: 38 pb^{-1}

arXiv 1110.3970, 2010 data (38 pb^{-1})

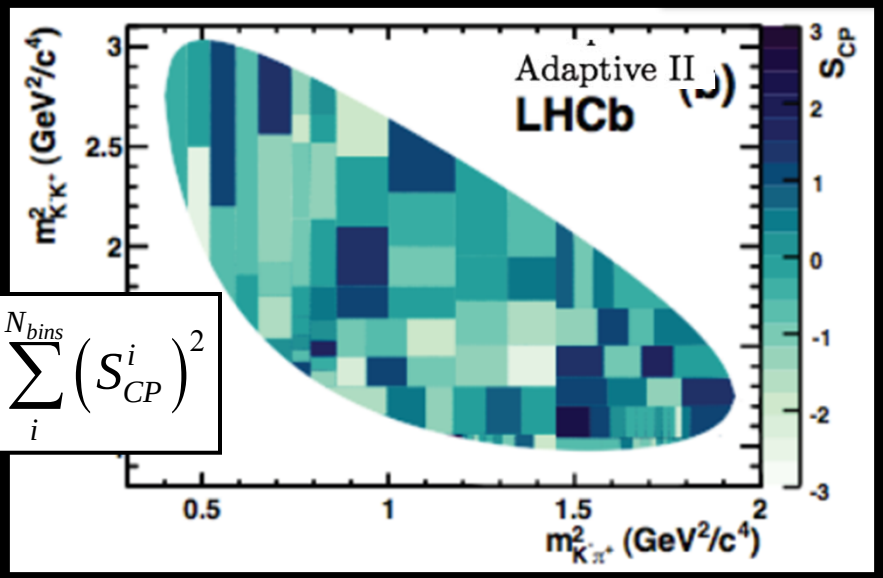




No evidence for direct CPV with 2010 data

For each bin of Dalitz plot calculate standard deviation from no CP:

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



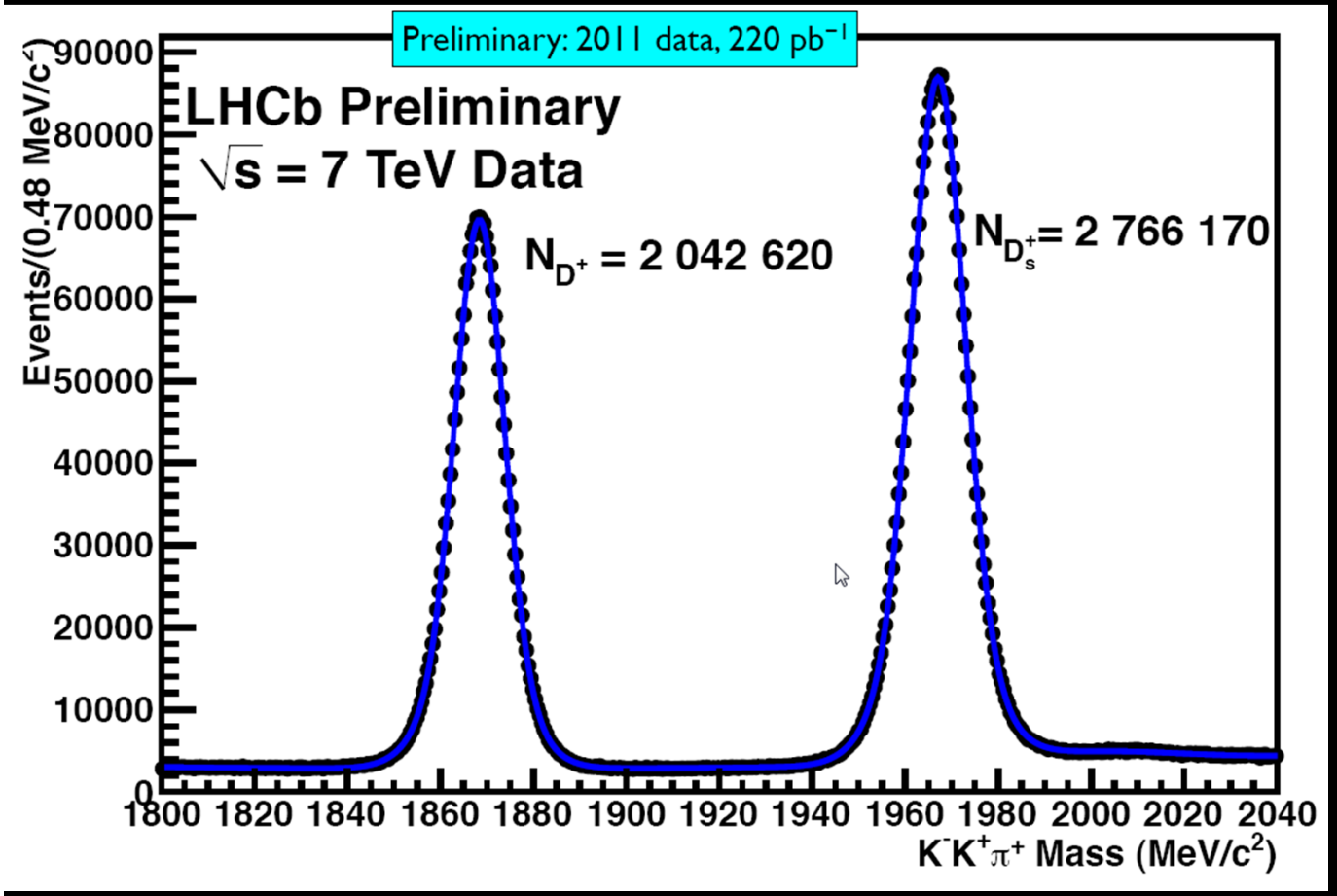
$$\chi^2 = \sum_i^{N_{bins}} \left(S^i_{CP}\right)^2$$

mean=0 ? σ=1 ? p high ?

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

Looking ahead for CPV in $D^+ \to K^-K^+\pi^+$

1/5 of 2011 data (0.22 fb^{-1})



2010 data: 0.04 fb-1

D+ 370 000

Signal purity 91 %

LHCb (0.22 fb^{-1})

D^+ 2 042 620 events

CLEO-c (0.8 fb^{-1})

D^+ 19 000 84%

BABAR (80 fb^{-1})

D^+ 43 000 66%

Summary

- Lots of excitement about charm physics lately, in great part due to a large measured CP asymmetry in $D^0 \rightarrow KK, \pi\pi$.
- We eagerly anticipate analysis of the full 2011 data sample (~40% more data), and a doubling of Lint in 2012. Expect statistical error to shrink almost in half.
- Many other charm measurements being pursued, but have not had time to discuss them.
  - $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K_s\pi\pi$, K_sKK (Linear sensitivity to *x* and *y*)
  - $D_{(s)} \rightarrow K_sh^+$
  - Mixing with DCS $D^0 \rightarrow K\pi$
  - …

Backup

CP Violation in Mixing & Decay

- Consider final states accessible to both P^0 and $\overline{P}^0$. Let's assume it's a CP eigenstate, for ease

$$\lambda_f = -\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$

$$\Gamma(t) = |A_f|^2 e^{-\Gamma t}\left(\begin{array}{l}(1+|\lambda|^2)\cosh(y\Gamma t)+(1-|\lambda|^2)\cos(x\Gamma t)\\ +(2\,\mathrm{Re}\,\lambda)\sinh(y\Gamma t)-(2\,\mathrm{Im}\,\lambda)\sin(x\Gamma t)\end{array}\right)$$

— Direct decay

— Mixing + decay (DCPV if $|\lambda| \neq 1$)

— Interference between mixing + decay

- In B^0 decays: $\Delta\Gamma/\Gamma$ small →

$$\Gamma(t) \Rightarrow |A_f|^2 e^{-\Gamma t}\left((1+|\lambda|^2+\left((1-|\lambda|^2\right)\cos(\Delta m t)-(2\,\mathrm{Im}\,\lambda)\sin(\Delta m t)\right)$$

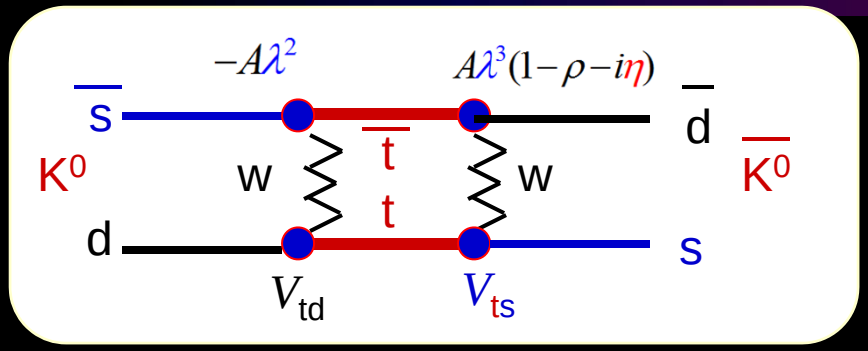
$$a_{CP} = \frac{\Gamma(t)-\bar{\Gamma}(t)}{\Gamma(t)+\bar{\Gamma}(t)} = \frac{(1-|\lambda|^2)\cos(\Delta m t)-(2\,\mathrm{Im}\,\lambda)\sin(\Delta m t)}{(1+|\lambda|^2)} \xrightarrow{|\lambda|=1} \sin(2\phi)\sin(\Delta m t)$$

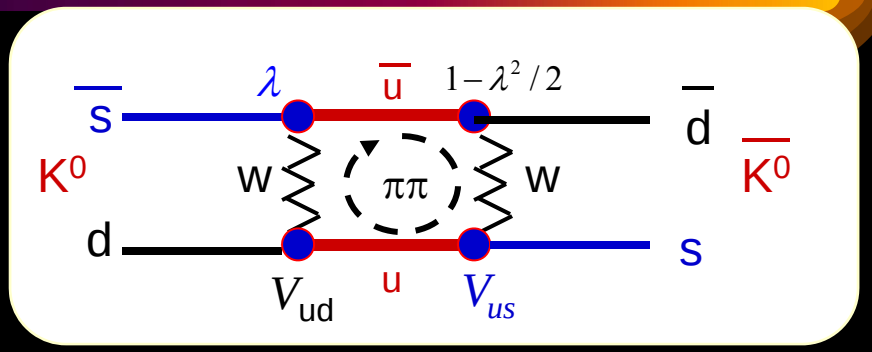
- In B_s decays: $y=\Delta\Gamma_s/2\Gamma_s \sim 0.1$ not too small …. Keep all 4 terms

- In D^0 decays : x,y ~ 0.01 – 0.001, can expand , e.g $D^0 \rightarrow KK$…

$$\Gamma_{D^0\to KK}(t) = |A_{KK}|^2 e^{-\Gamma t}\left(1-|q/p|(y\cos\phi - x\sin\phi)\Gamma t\right)$$

Mixing and CPV: K^0





$\Delta m_K \propto m_t^2 \lambda^{10} << \Gamma_K \sim O(\lambda^4)$

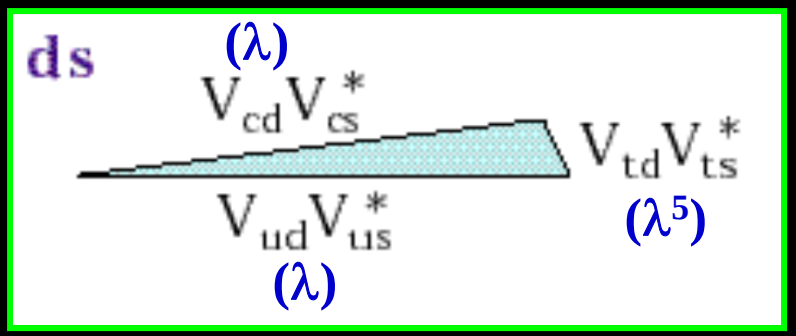
→ **Slow mixing rate.**

Γ_{12} large $\propto \lambda^4$

→ $\tau(K_S) << \tau(K_L)$

Mass eigenstates labeled by lifetimes ("short"" and "long")

CP Violation: Kaon decays described almost by first two generations, which are ~real → Small CPV



- (Indirect) CPV in mixing $\varepsilon_k \sim 10^{-3}$
- Direct CPV, $\varepsilon' \sim 10^{-3}\,\varepsilon$
- Long distance effects make lead to large uncertainties in CKM params