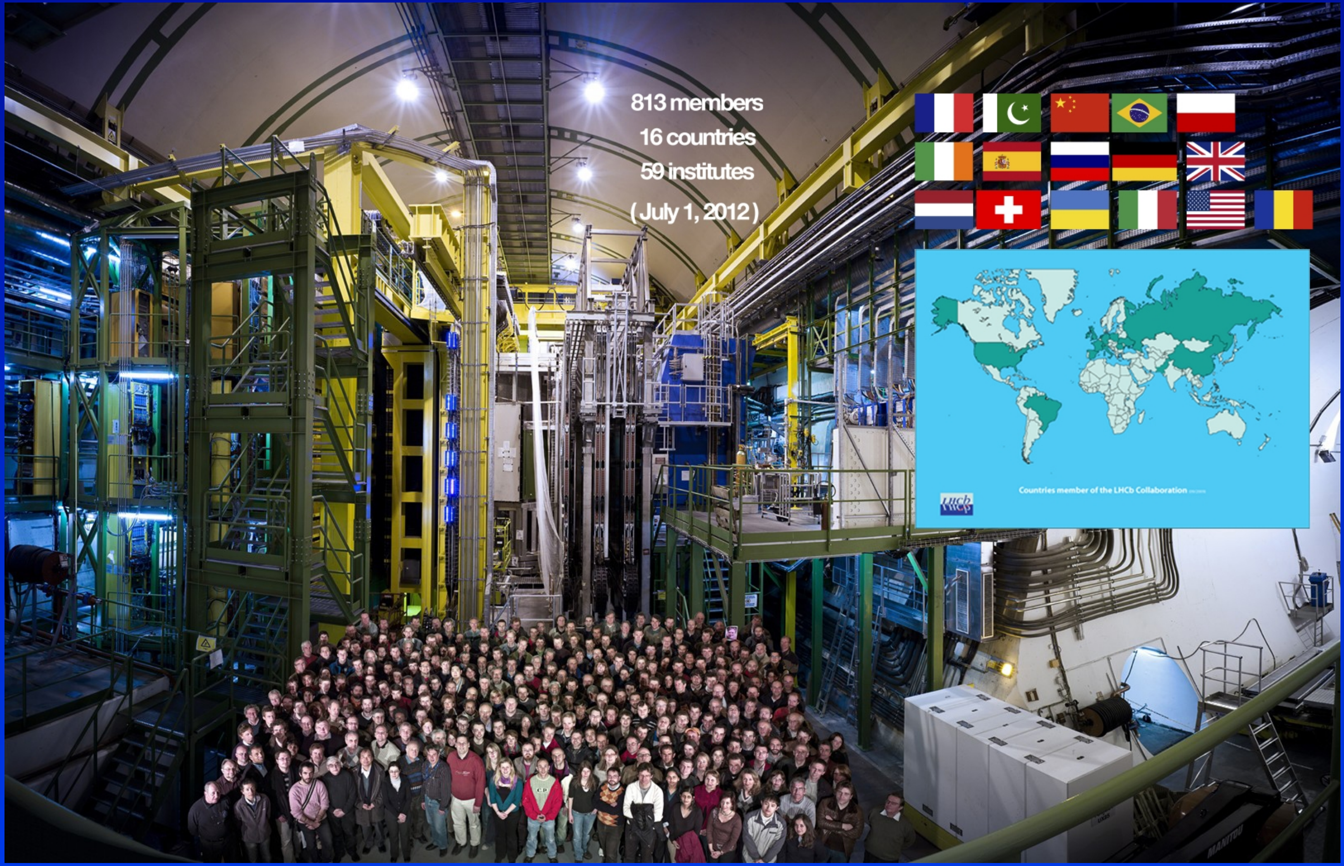
Heavy Quarks & Leptons 2014, Mainz

August 26th, 2014

Measurements of CPV and Mixing in Charm Decays



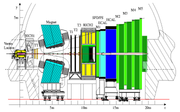
Jörg Marks, Heidelberg University
on behalf of the LHCb collaboration

LHCb – Charm Physics

- Search for evidence of physics beyond the Standard Model in CP violation and rare decays of charm and beauty hadrons
  - Indirect search, probe large mass scales via the study of virtual quantum loops of new particles
- Of all LHCb physics results focus here on mixing and CPV in Charm
  - Spectroscopy, production and charmed baryon states (D cross section (arXiv:1302.2864), X(3872) (arXiv:1112.5310), D mass (arXiv:1304.6865), J/ψ Pairs (arXiv:1407.4973), D_j decays (arXiv:1307.4556), D_{sj} decays (arXiv:1207.6016), Ξ_{cc}^{++} baryon (arXiv:1310.2538) , D^+ production asymmetry (arXiv:1208.3355) , $D_s^+ - D_s^-$ production asymmetry (arXiv:1205.0897))
  - Rare decays ($D^0 \to \mu^+\mu^-$ (arXiv:1305.5059) , $D^0 \to \pi^+\pi^-\mu^+\mu^-$ (arXiv:1310.2535) , $D_{(s)}^+ \to \pi^+\mu^+\mu^-$, $D_{(s)}^+ \to \pi^-\mu^+\mu^+$ (arXiv:1303.2614))

LHCb physics results are available in 209 papers submitted to journals and 118 conference notes.

https://cds.cern.ch/collection/LHCb%20Papers?ln=en
https://cds.cern.ch/collection/LHCb%20Conference%20Contributions?ln=en

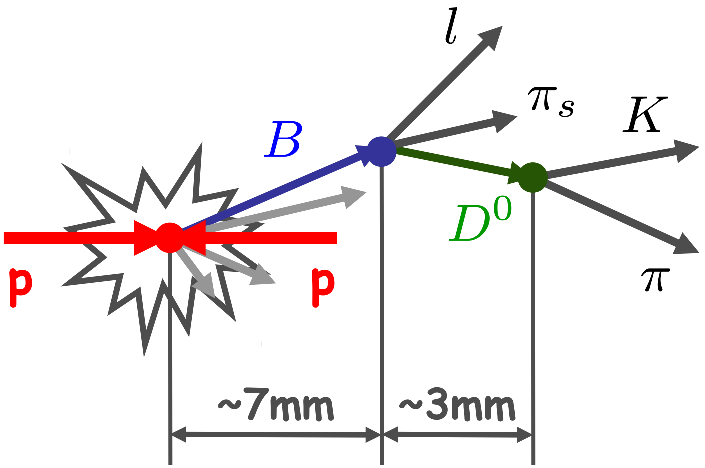


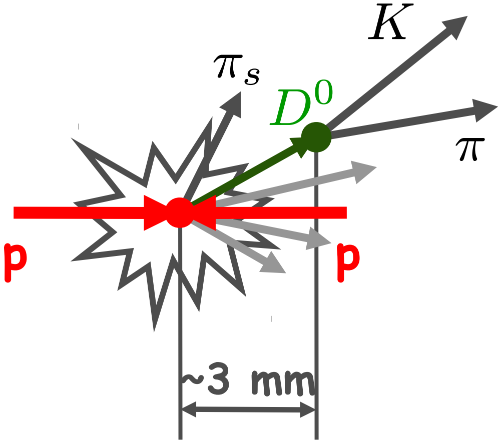
Charm Production at Hadron Colliders

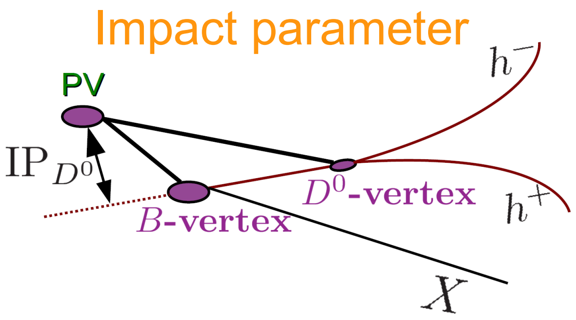
The large cross section for charm production at hadron colliders leads to $10^{12} c\bar{c}/fb^{-1}$ events within LHCb acceptance → world's largest c sample

- Prompt and secondary charm

$BR(B \to D^{*\pm} X) \approx 0.23$







PV resolution

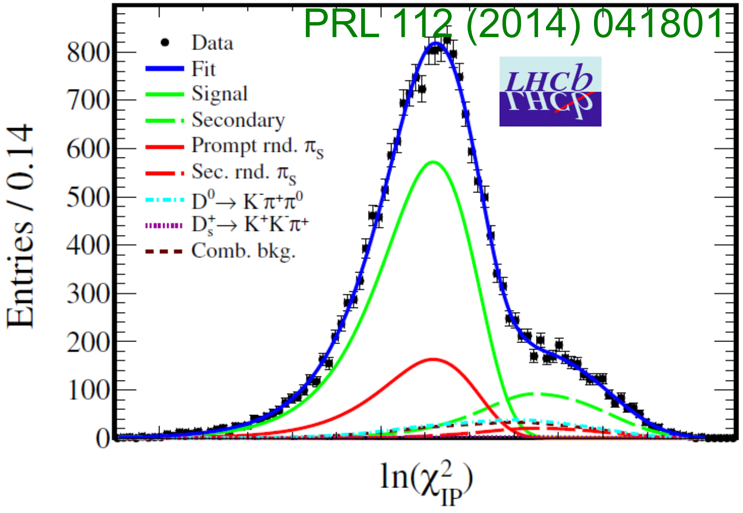
$\sigma_{x,y} \approx 11\ \mu m\,,\ N_{Tr} \approx 30$

$\sigma_z \approx 65\ \mu m\,,\ N_{Tr} \approx 30$

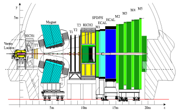
IP resolution, p_t > 2 GeV

$\sigma_{IP} \approx 22\ \mu m$

tagged $D^0 \to K^+K^-$

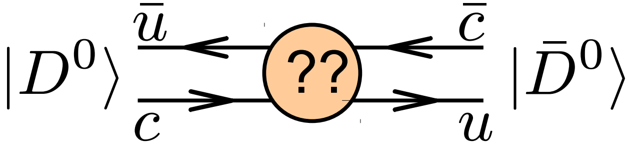


LHCb uses both charm samples



Mixing Formalism

Neutral D^0 mesons are created as flavour eigenstates of the strong interaction. They can mix through weak interactions.



- The time evolution is obtained by

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\right]\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

- The physical eigenstates are D$_1$ and D$_2$:

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

$$|D_{1,2}(t)\rangle = e^{-i(M_{1,2}-i\Gamma_{1,2}/2)t}|D_{1,2}(t=0)\rangle$$

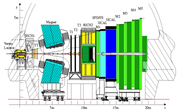
D_1 : CP even

D_2 : CP odd

- Define mass and lifetime differences of D$_1$ and D$_2$:

$$\boxed{x = \frac{\Delta M}{\Gamma} = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$



CP Violation in the D System

The only source of CP violation in SM is a single complex phase in the CKM matrix. CPV well established in Kaon and B meson systems.

For D mesons CP violating effects are predicted to be small $(\sim 10^{-3})$, therefore sizeable measurements of CPV hint for Physics beyond SM.

- CP violation in decay (direct CPV)

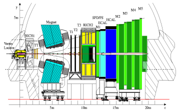
$$\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f}) \qquad |\mathcal{A}_f| \neq |\bar{\mathcal{A}}_f|$$

- CP violation in mixing (indirect CPV)

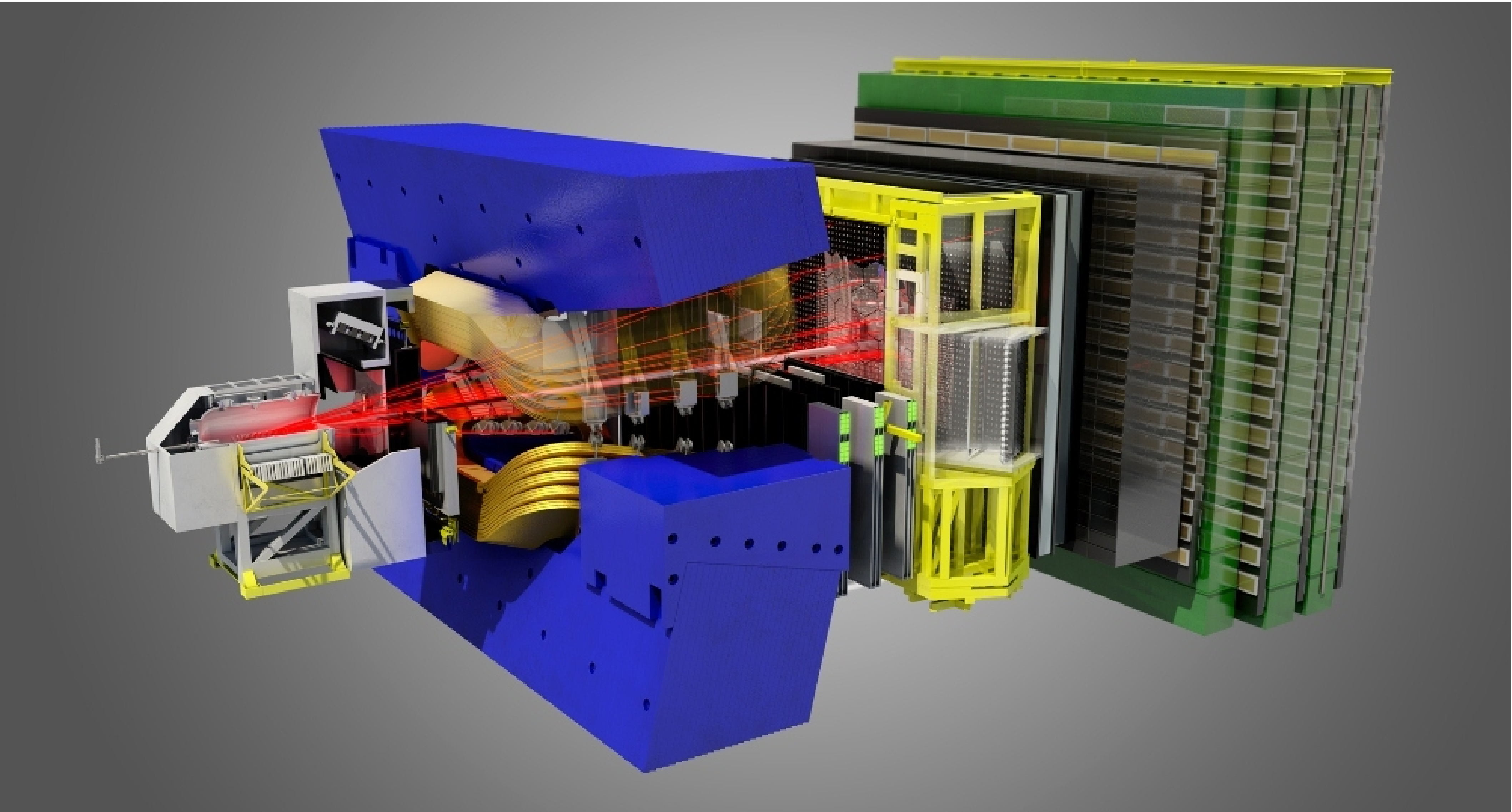
$$q/p = r_m \cdot e^{i\phi_M} \neq 1 \,, \qquad r_M \equiv |q/p| \quad \phi_M \equiv arg(q/p)$$

- CP violation in interference of mixing and decay (indirect CPV)

$$\phi_f \equiv arg\left[\frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}\right] \neq 0$$

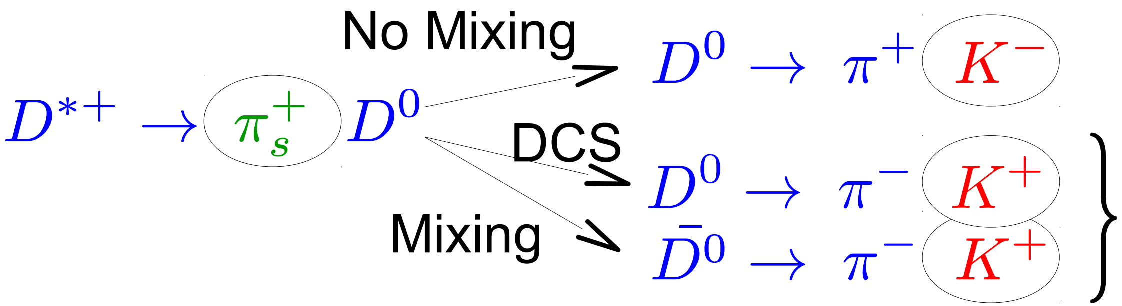


D^0 - $\overline{D}^0$ Mixing



Mixing in $D^0 \to K\pi$ Decays

- Event classes - flavour tagging at production and decay time



$D^{*+} \to \pi_s^+ \; D^0$

No Mixing: $D^0 \to \pi^+ K^-$

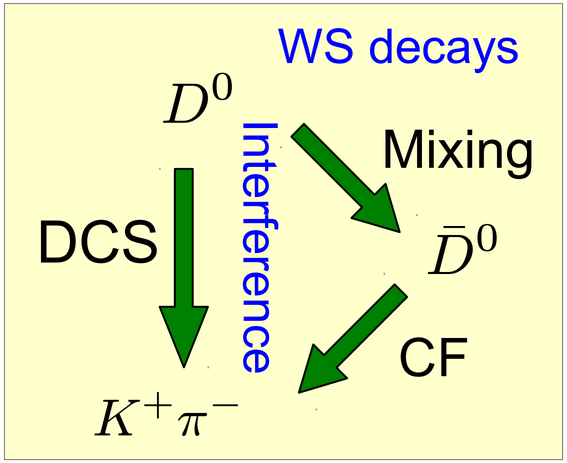
DCS: $D^0 \to \pi^- K^+$

Mixing: $\bar{D}^0 \to \pi^- K^+$

Right Sign Decay (RS)
no D^0 Mixing

Wrong Sign Decay (WS)
D^0 Mixing + DCS

- Time evolution of the WS decay rate



- assume CP conservation and $|x| \ll 1$; $|y| \ll 1$

$$T_{WS}(t) \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\, y'\, \Gamma t}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

- $\delta_{K\pi}$ is the strong phase between CF and DCS amplitudes ($D^0 \to K\pi$)

$$x' = \quad x\, cos\, \delta_{K\pi} + y\, sin\, \delta_{K\pi}$$
$$y' = -x\, sin\, \delta_{K\pi} + y\, cos\, \delta_{K\pi}$$

$$y'^2 + x'^2 = x^2 + y^2$$

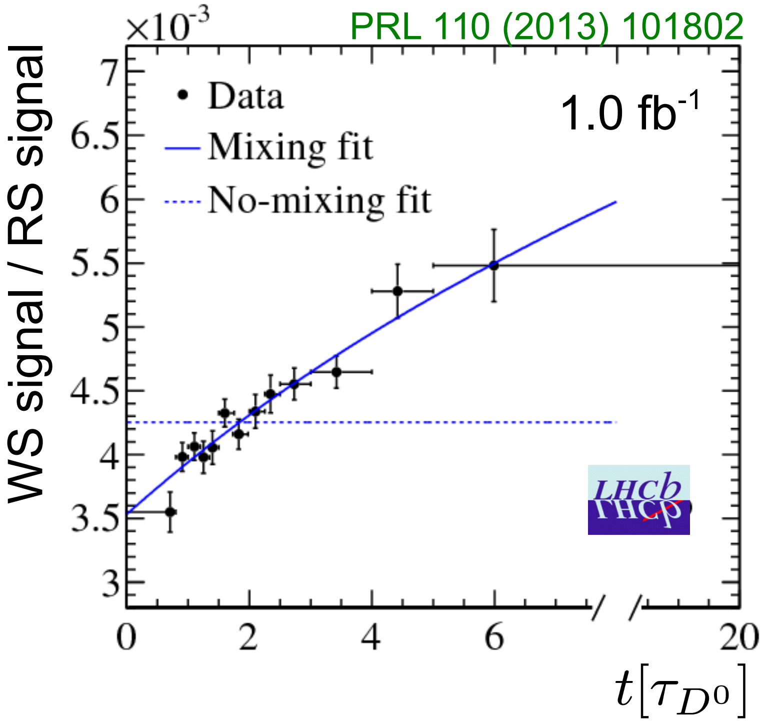
LHCb - t-dependent WS $D^0 \rightarrow K\pi$

- Measure the Number of WS and RS D^0 decays in 13 bins of the lifetime.

$$N_{RS}^{tot} = 5.3 \cdot 10^7 \qquad N_{WS}^{tot} = 2.3 \cdot 10^5 \qquad \text{(3.0 fb}^{-1}\text{)}$$

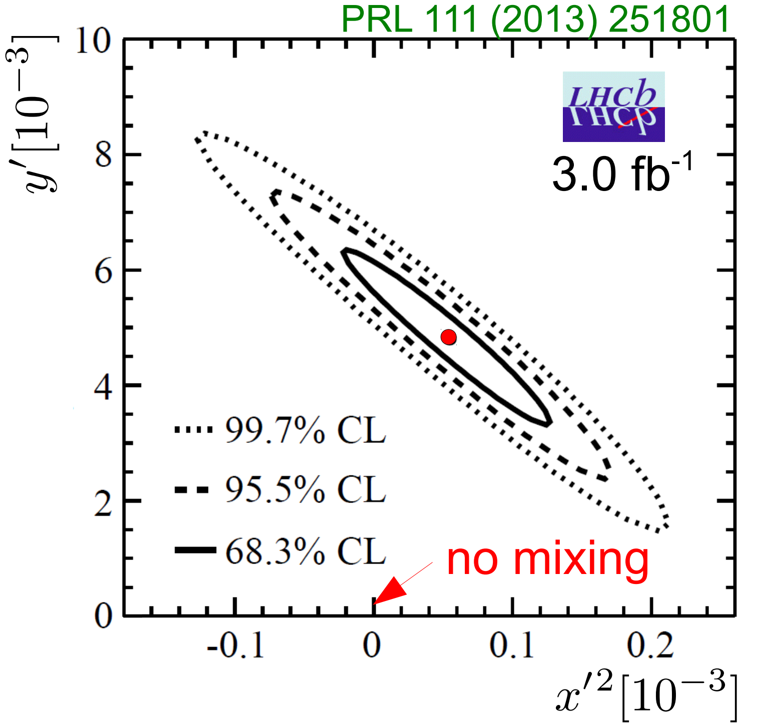
- Fit the $N_{WS}^{tot}/N_{RS}^{tot}$ vs the D^0 decay time

$$R(t) \propto e^{-\Gamma t}\left(R_D + \sqrt{R_D}\,y'\,\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right)$$



PRL 110 (2013) 101802

- Mixing Parameter



PRL 111 (2013) 251801

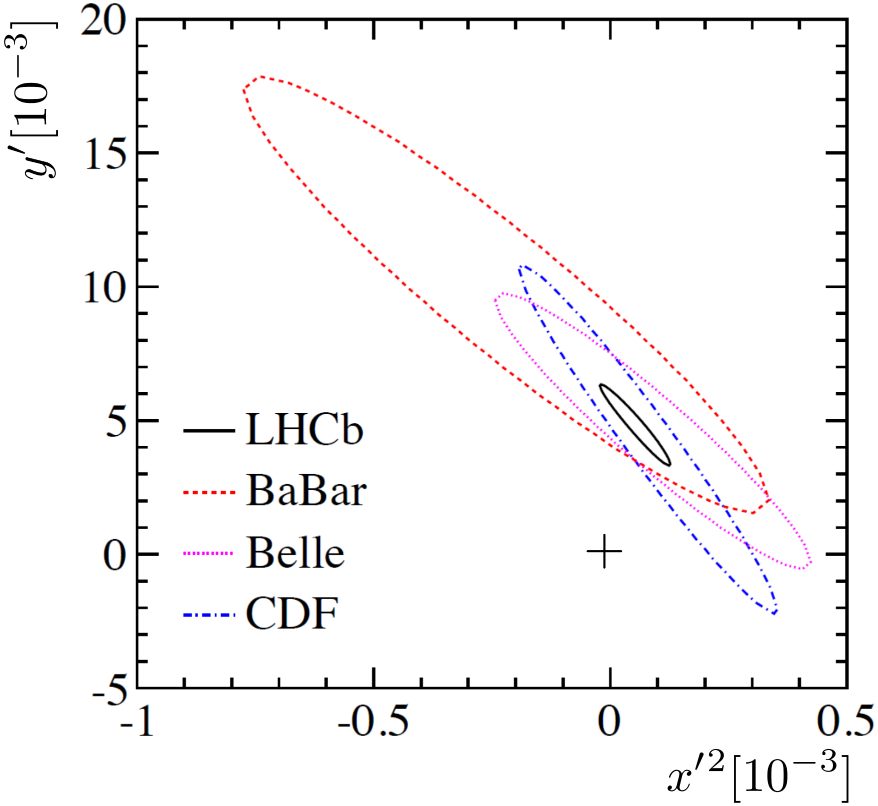
Errors include sys. uncertainties

$$R_D = (0.3568 \pm 0.0058 \pm 0.0033)\%$$
$$y' = (0.48 \pm 0.08 \pm 0.05)\%$$
$$x'^2 = (0.55 \pm 0.42 \pm 0.26)\%$$

WS $D^0 \to K\pi$ Mixing - Results

Comparison of recent mixing parameter measurements

1σ contours



	$R_D[10^{-3}]$	$y'[10^{-3}]$	$x'^2[10^{-3}]$
LHCb	3.568 ± 0.066	4.8 ± 1.0	0.055 ± 0.049
Belle	3.53 ± 0.13	4.6 ± 3.4	0.09 ± 0.22
BABAR	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
CDF	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18

PRL 111 (2013) 251801

PRL 98 (2007) 211802

PRL 112 (2014) 111801

PRL 111 (2013) 231802

CPV in WS $D^0 \to K\pi$

A determination of mixing parameters for D^0 and $\bar{D}^0$ gives access to CPV

PRL 111 (2013) 251801

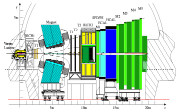
- Time dependent WS / RS rate for CPV

$$R^{\pm}(t) \propto e^{-\Gamma t}\left(R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm}\,\Gamma t + \frac{x'^{2\pm} + y'^{2\pm}}{4}|\frac{q}{p}|^2(\Gamma t)^2\right)$$

$$y'^{\pm} = |\frac{q}{p}|^{\pm 1}[y\, cos(\delta \pm \phi) \mp x\, sin(\delta \pm \phi)]$$

$$x'^{\pm} = |\frac{q}{p}|^{\pm 1}[x\, cos(\delta \pm \phi) \pm y\, sin(\delta \pm \phi)]$$

$$R_D^{\pm} = R_D(1 \pm A_D)$$



CPV in WS $D^0 \to K\pi$

A determination of mixing parameters for D^0 and $\bar{D}^0$ gives access to CPV

- Fit results

Direct and indirect *CP* violation		
R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf		$85.9/98$

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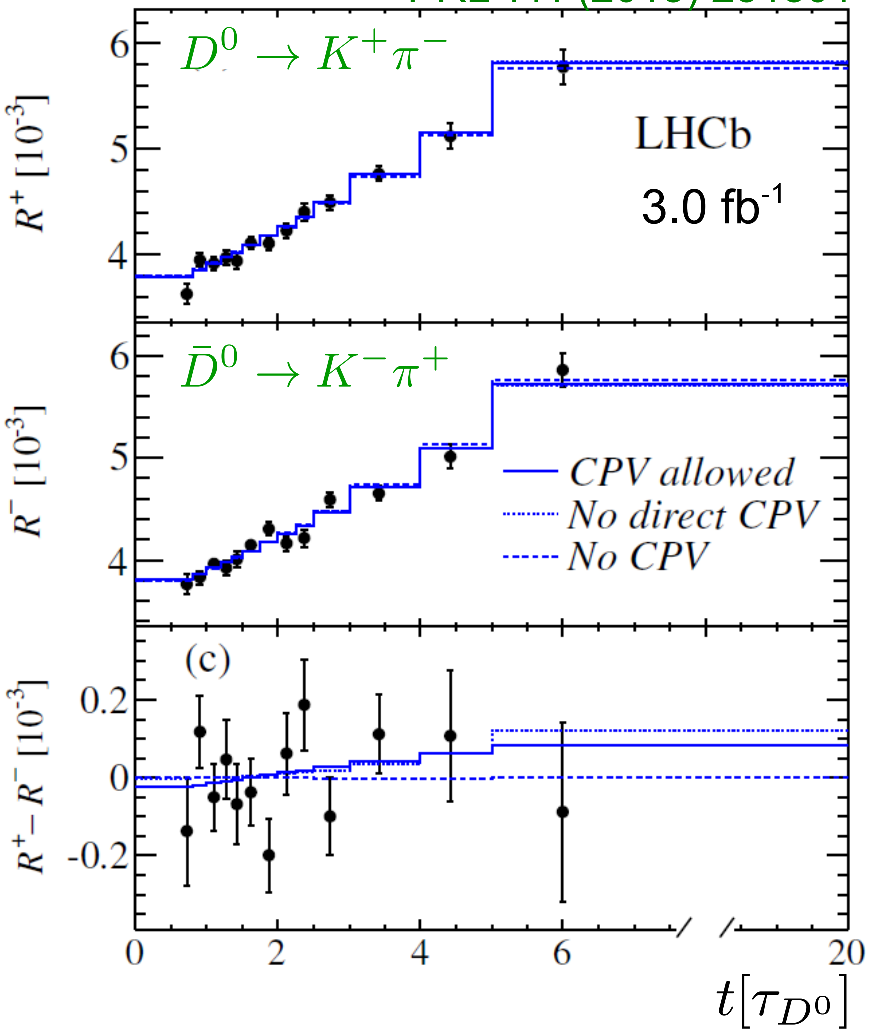
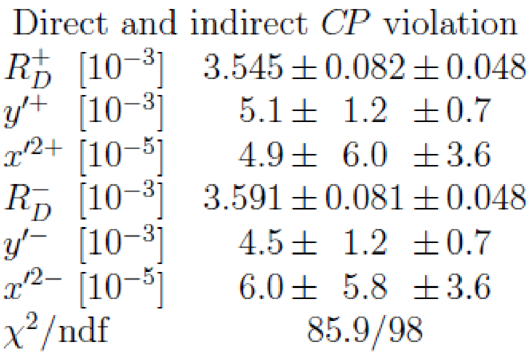


CPV in WS $D^0 \to K\pi$

A determination of mixing parameters for D^0 and $\bar{D}^0$ gives access to CPV

- Fit parameter



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χ^2/ndf		$85.9/98$

- CP violation parameters
  - CPV in mixing

$$0.75 < |q/p| < 1.24 \quad @\, 68.3\,\%\, CL$$

  - direct CPV of DCS component

$$A_D = \frac{R^+ - R^-}{R^+ + R^-} = (-0.7 \pm 1.9)\%$$

No indication for direct or indirect CPV

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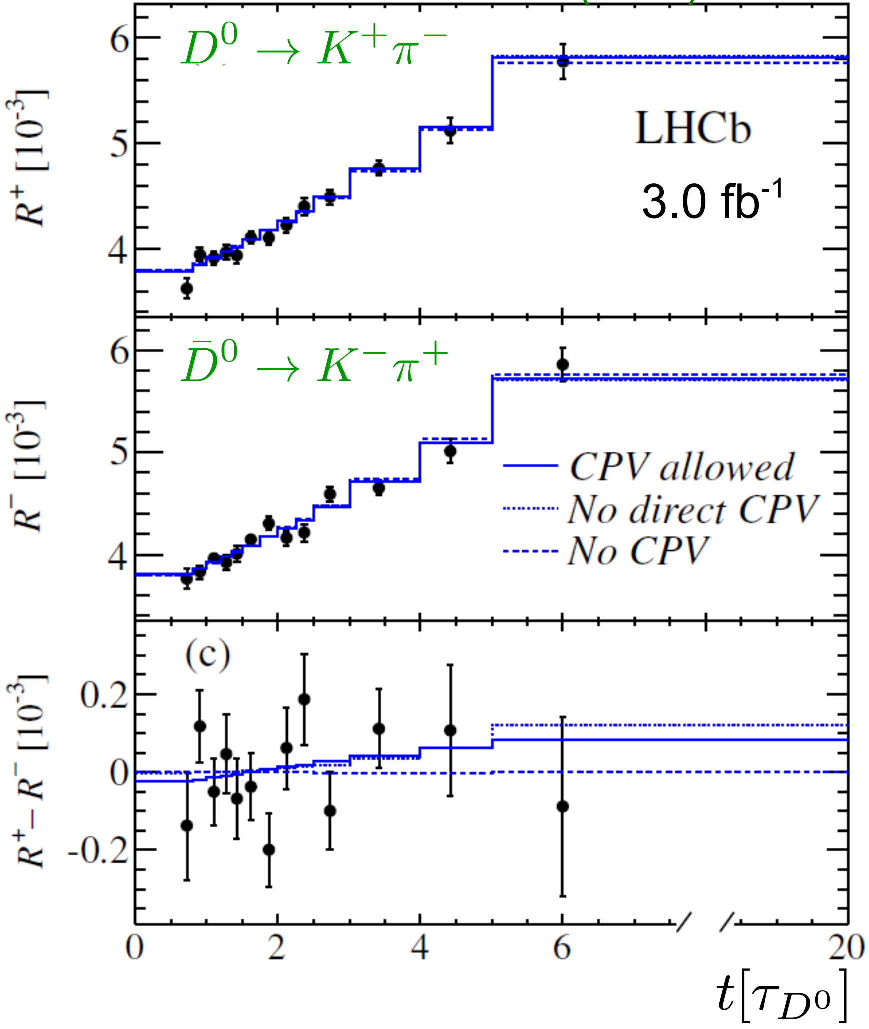
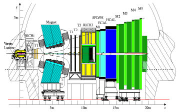
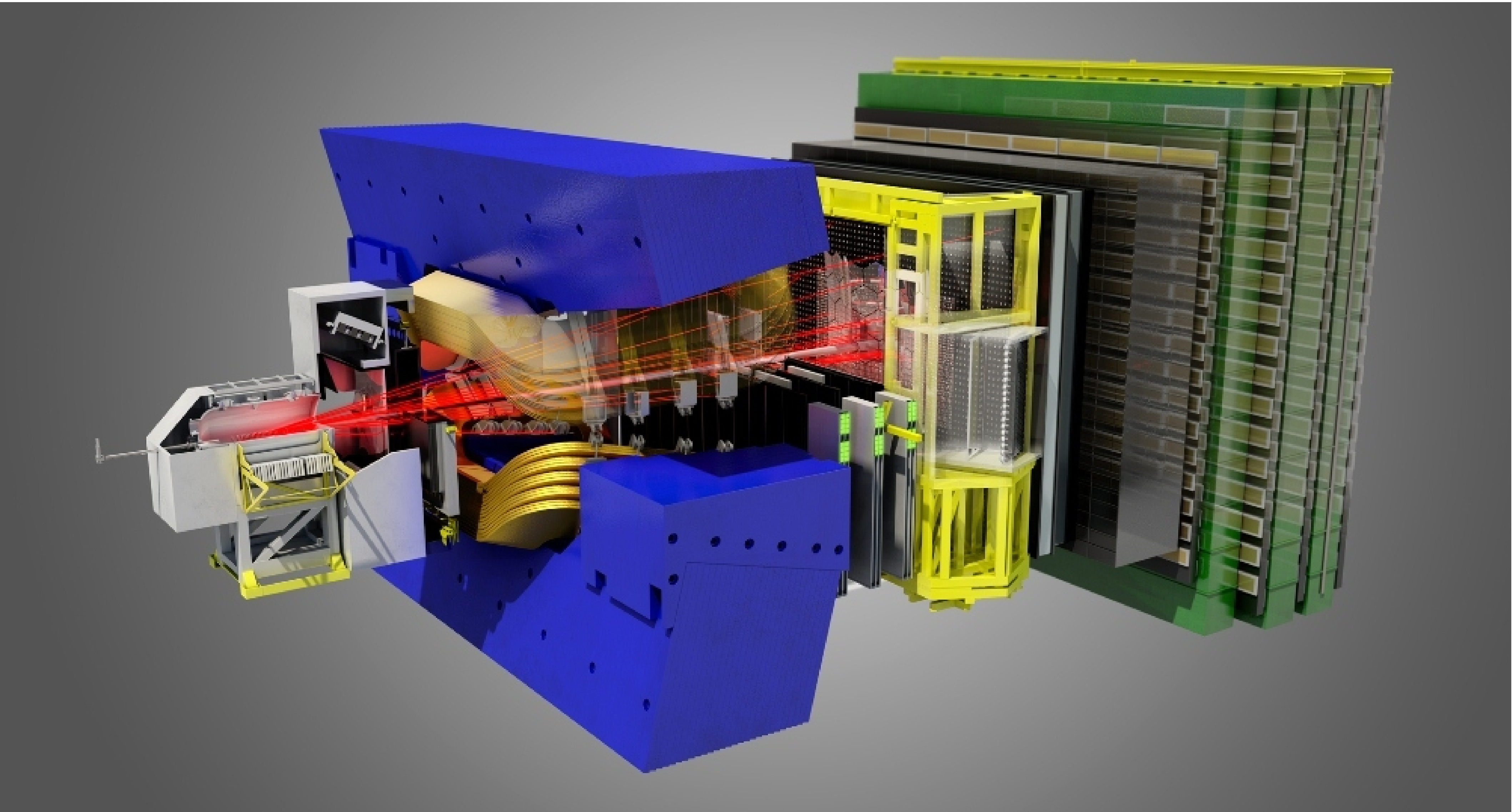




y_{CP} and A_{Γ}



y_{CP} and A_Γ - Introduction

- Decay time of D^0's is exponential with modifications due to mixing

$$\tau^{\pm} = \frac{\tau^0}{1+|q/p|(y\,cos\phi_f \mp x\,sin\phi_f)}$$

$\tau^{\pm}$: lifetime of D^0 ($\bar{\text{D}}^0$) → CP+ eigenstates

τ^0: lifetime of D^0 → CP mixed (CF)

- A lifetime difference between CP+ and CP mixed states gives access to mixing

$$y_{CP} = \frac{\tau^0}{\tau} - 1 = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = |q/p|(y\,cos\,\phi_f - x\,sin\,\phi_f)$$

$y_{CP} \neq 0 \quad \Rightarrow$ D^0-$\bar{\text{D}}^0$ mixing

$y_{CP} = y \quad \Leftarrow$ CP conservation

LHCb measurement for tagged $D^0 \rightarrow KK$ in 28 pb^{-1}:

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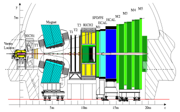
$$y_{cp} = (5.5 \pm 6.3\ (stat)\ \pm 4.1\ (sys)) \cdot 10^{-3}$$

- Test of CP violation

$$A_\Gamma = \frac{\tau^- - \tau^+}{\tau^- + \tau^+} \approx \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\ cos\ \phi_f - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\ sin\ \phi_f\right]$$

$A_\Gamma \neq 0 \quad \Rightarrow$

indirect CPV

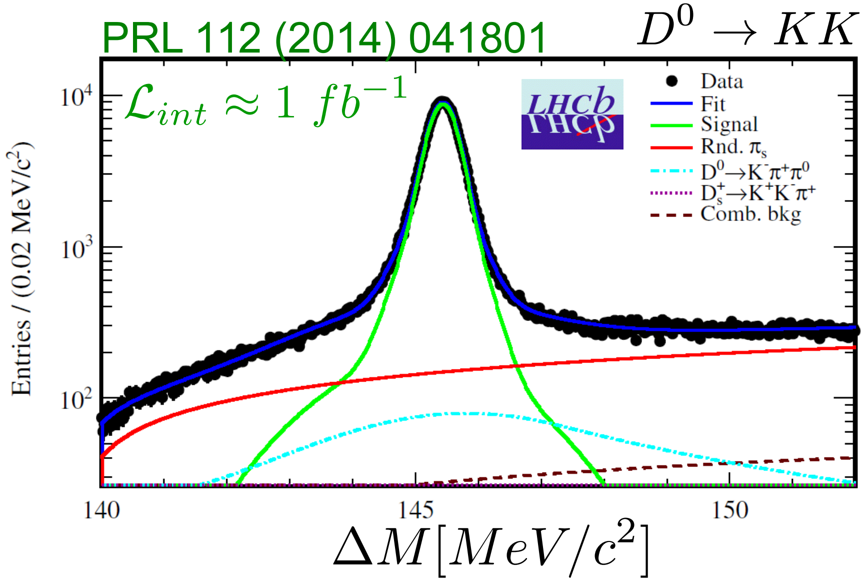


LHCb - A_Γ Measurement

- Measure lifetime asymmetry A_Γ with tagged $D^0 \to K^+K^-/\pi^+\pi^-$

$3.1M$ $1M$ events

PRL 112 (2014) 041801



Knowledge of the proper time acceptance dependence on the trigger and selection is needed.

- Recreate trigger decision while moving the PV along the D^0 momentum. Well suited for the LHCb software trigger.

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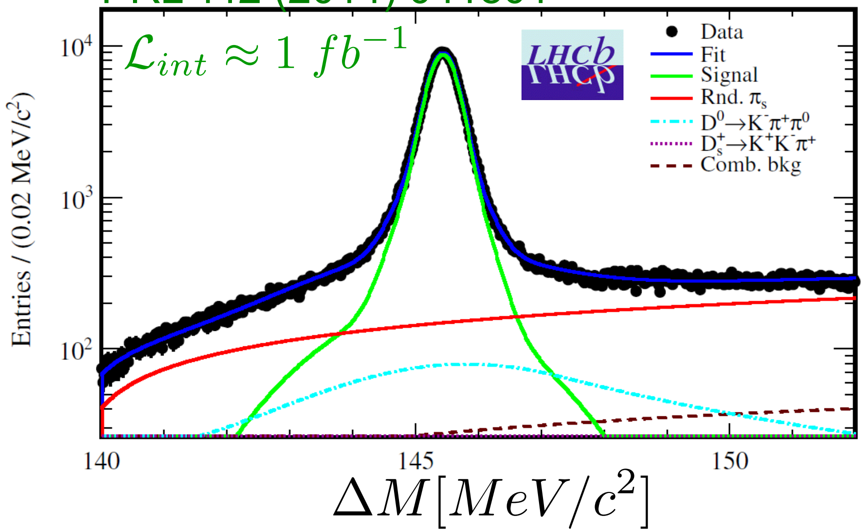
- Separation between prompt and secondary in $\chi^2(IP_D)$

LHCb - A_Γ Measurement

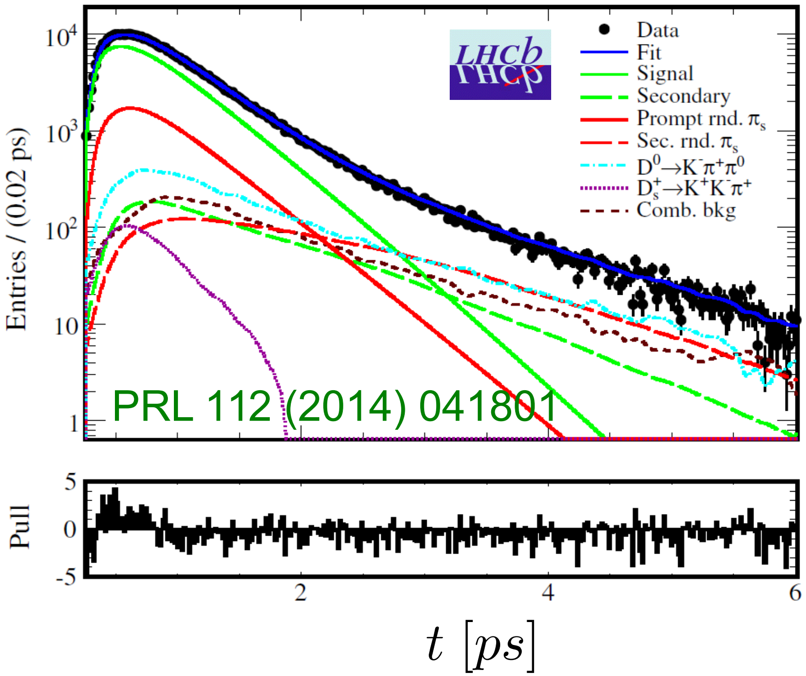
- Measure lifetime asymmetry A_Γ with tagged $D^0 \to K^+K^-/\pi^+\pi^-$

$3.1M$ $1M$ events

PRL 112 (2014) 041801 $D^0 \to KK$



$D^0 \to KK$



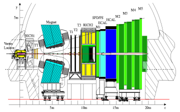
- World best measurement using $\mathcal{L}_{int} \approx 1\ fb^{-1}$

$$A_\Gamma(K^+K^-) = (-0.35 \pm 0.62 \pm 0.12) \cdot 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.33 \pm 1.06 \pm 0.14) \cdot 10^{-3}$$

No indirect CPV at the level of 0.1%

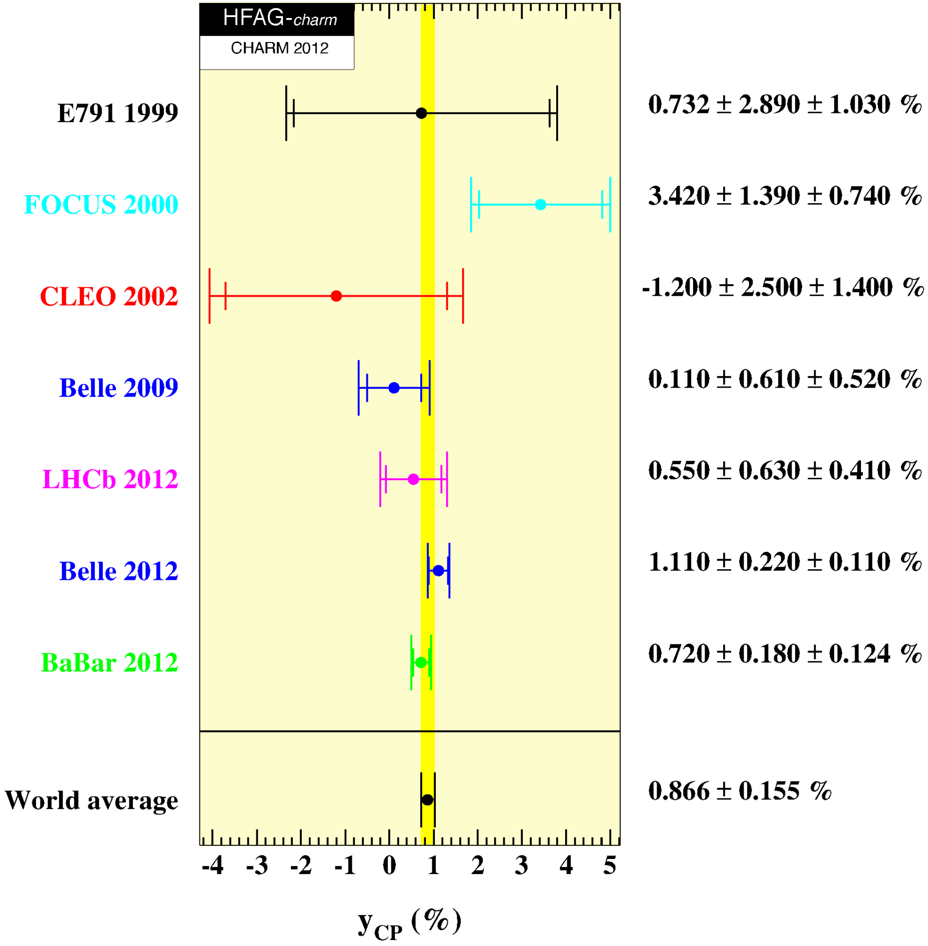
- Lifetime fit to obtain A_Γ
- Binned method, similar result

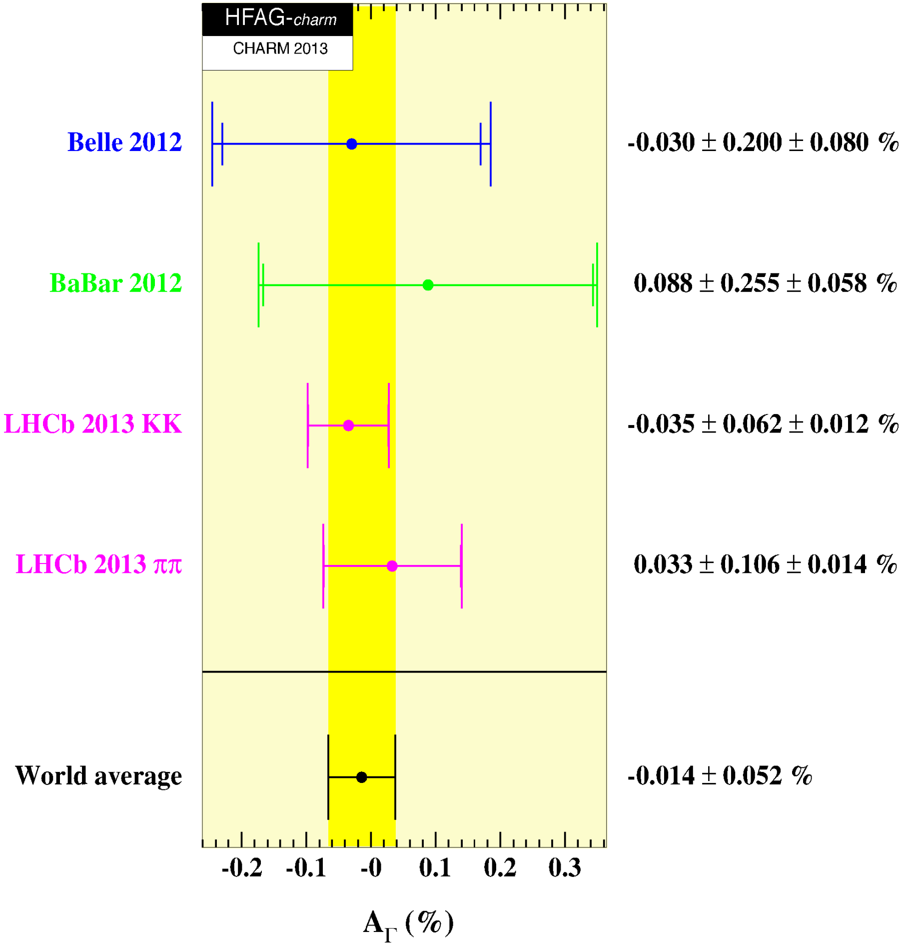
$$R(t) \approx \frac{N_{\bar{D}^0}}{N_{D^0}} \left(1 + \frac{2A_\Gamma}{\tau_{KK}} t\right) \frac{1 - e^{-\Delta t/\tau_{\bar{D}^0}}}{1 - e^{-\Delta t/\tau_{D^0}}}$$



Experimental Results – y_{CP} and A_Γ

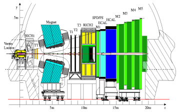
- Combined y_{CP} and A_Γ as averaged by the charm subgroup of HFAG



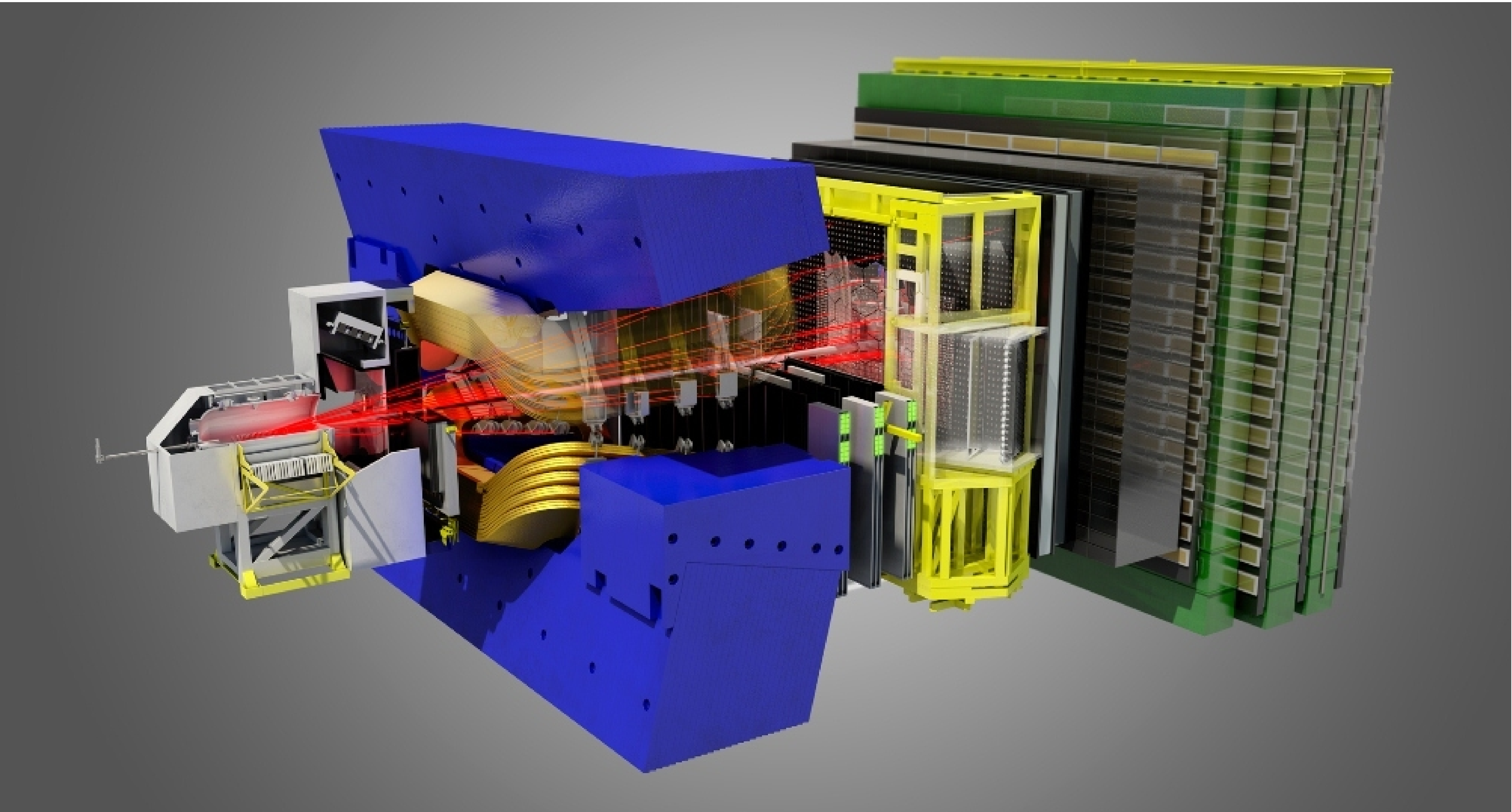


$$y_{CP} = (0.866 \pm 0.155)\%$$

$$A_\Gamma = (-0.014 \pm 0.052)\%$$



CP Asymmetries in twobody D Decays



t-integrated CPV in $D^0 \to K^+K^-/\pi^+\pi^-$

Use SCS 2-body D^0 decays to measure time integrated CP violating effects

- Access CP violation through asymmetry measurements

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)} = \underbrace{a_{CP}^{dir}(f)}_{\text{CPV in decay}} + \underbrace{\frac{t}{\tau} a_{CP}^{ind}}_{\text{CPV in mixing + interfer.}}$$

CP eigenstate

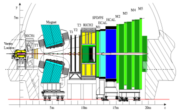
- Measure time integrated A_{CP} difference for $f = K^+K^-$ and $f = \pi^+\pi^-$

$$\Delta A_{CP} = A_{CP}^{raw}(K^+K^-) - A_{CP}^{raw}(\pi^+\pi^-)$$
$$\approx [a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)] + \frac{\Delta <t>}{\tau} a_{CP}^{ind}$$

  - Measurement of ΔA_{CP} with 2 independent data samples
    - $D^{*+} \to D^0\pi^+$ decays: published, $\int \mathcal{L} = 0.6 fb^{-1}$: PRL 108 (2012) 111602
      preliminary, $\int \mathcal{L} = 1 fb^{-1}$: LHCb-CONF-2013-003
    - $B \to D^0\mu^-\nu_\mu X$ decays: recently published, $\int \mathcal{L} = 3 fb^{-1}$: JHEP 07 (2014) 014

- Measure time integrated $A_{CP}(K^+K^-)$ with secondary D^0 sample

$$A_{CP}(K^+K^-) = A_{CP}^{raw}(K^+K^-) - A_{CP}^{raw}(K^-\pi^+) + A_D(K^-\pi^+)$$



Results – CPV in $D^0 \to h^+h^-$

- Secondary D^0 sample

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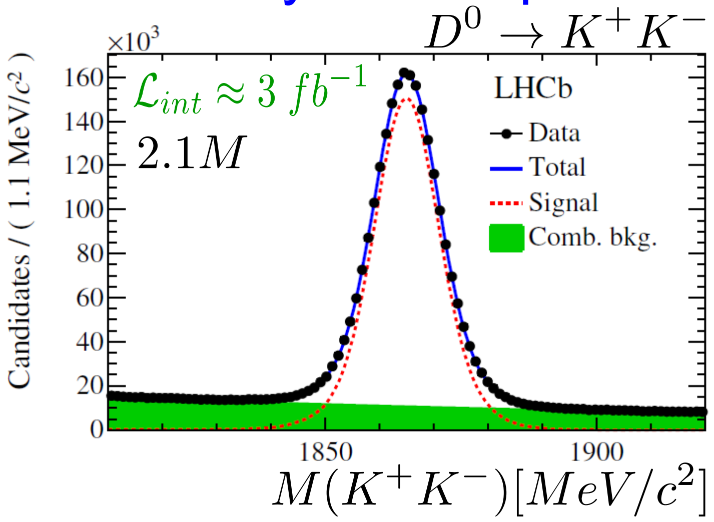
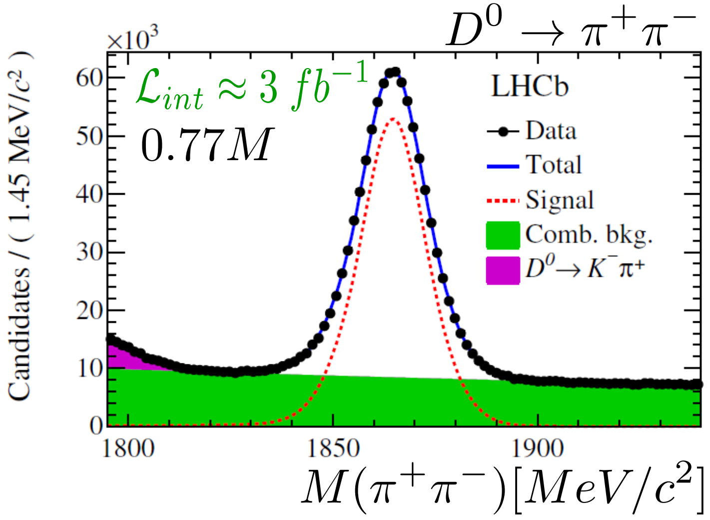


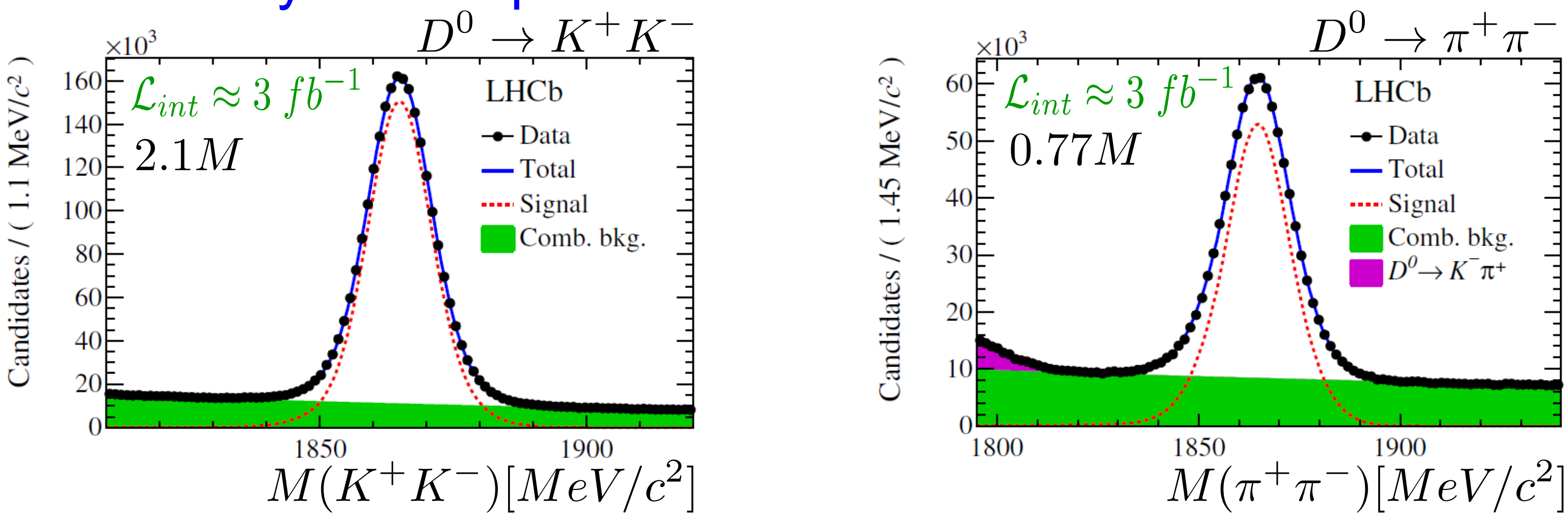


- $\Delta A_{CP} = (+0.14 \pm 0.16\,(stat) \pm 0.08\,(sys))\ \%$

Results – CPV in $D^0 \to h^+h^-$

- Secondary D^0 sample

JHEP 07 (2014) 014



- $\Delta A_{CP} = (+0.14 \pm 0.16\,(stat) \pm 0.08\,(sys))\ \%$
- To determine $A_{CP}(K^+K^-)$ need $A_D(K^-\pi^+)$

$$A_{CP}(K^+K^-) = A_{CP}^{raw}(K^+K^-) - A_{CP}^{raw}(K^-\pi^+) + A_D(K^-\pi^+)$$

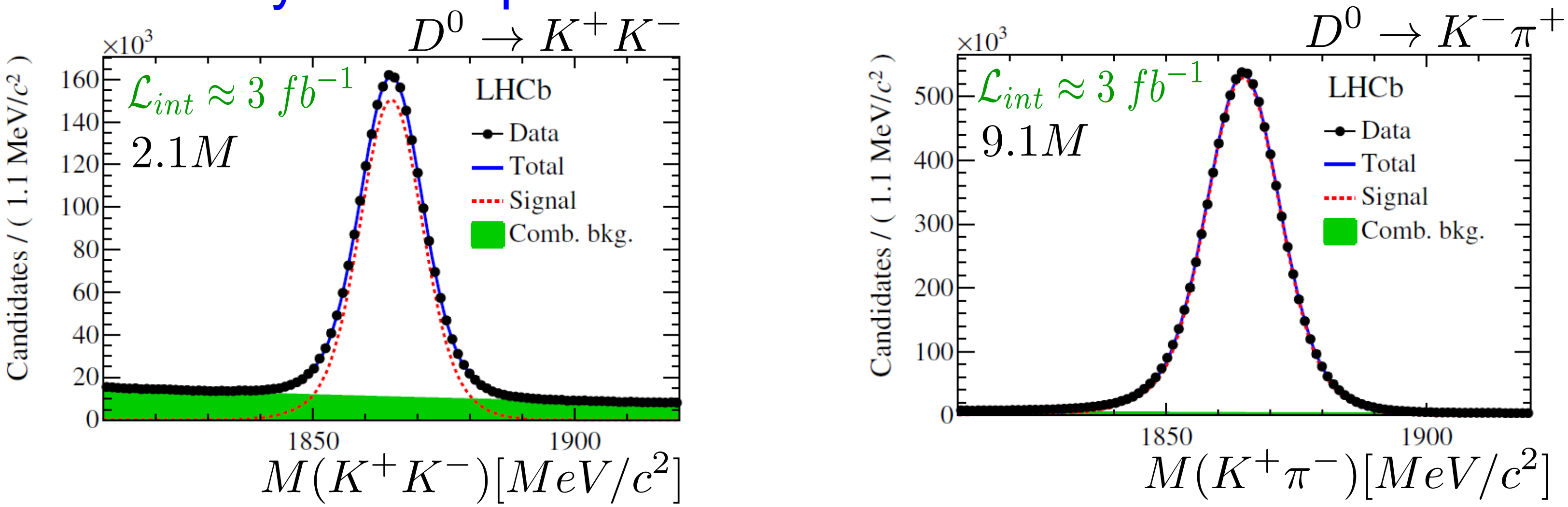
$$A_D(K^-\pi^+) = A_{CP}^{raw}(D^+ \to K^-\pi^+\pi^+) - A_{CP}^{raw}(D^+ \to \bar{K}^0\pi^+) - A_{K^0}$$

$$(0.054 \pm 0.014)\%$$

Results – CPV in $D^0 \rightarrow h^+h^-$

- Secondary D^0 sample

JHEP 07 (2014) 014



- $\Delta A_{CP} = (+0.14 \pm 0.16\,(stat) \pm 0.08\,(sys))\ \%$
- $A_{CP}(K^+K^-) = (-0.06 \pm 0.15\,(stat) \pm 0.10\,(sys))\ \%$

  $A_{CP}(\pi^+\pi^-) = (-0.20 \pm 0.19\,(stat) \pm 0.10\,(sys))\ \%$

  Most precise time integrated CP asymmetry measurements to date

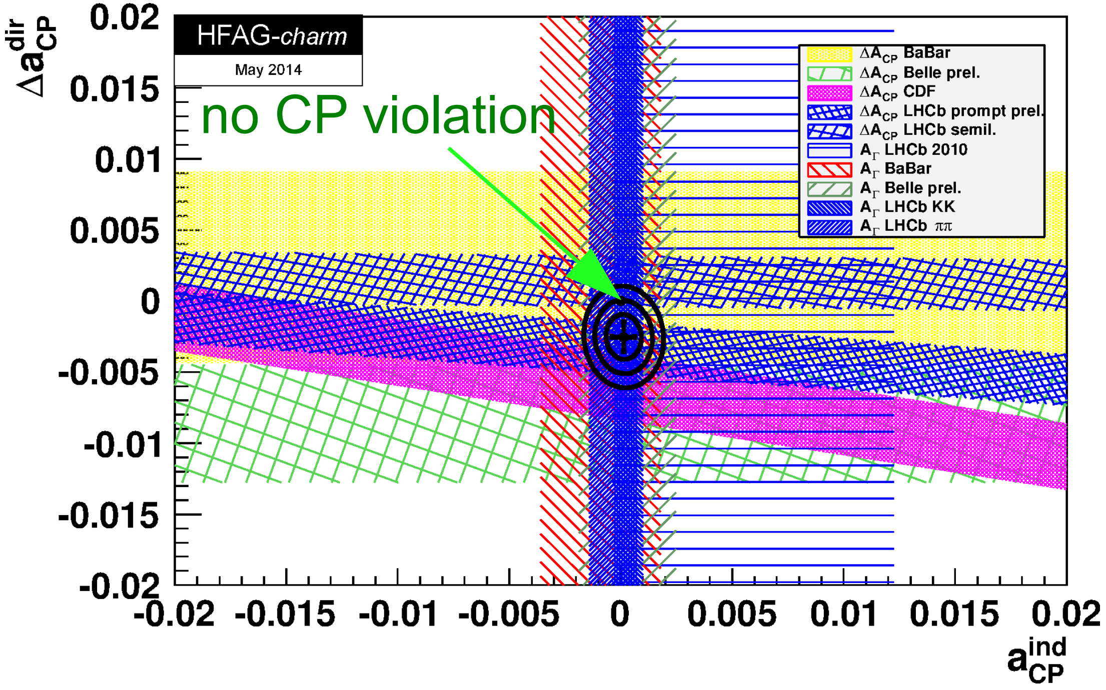
- D^*-tagged sample (preliminary)
  - $\Delta A_{CP} = (-0.34 \pm 0.15\,(stat) \pm 0.10\,(sys))\ \%$

LHCb-CONF-2013-003

Consistent with no CP violation hypothesis

Results – CPV in $D^0 \to h^+h^-$

- HFAG averages



no CP violation

$$a_{CP}^{ind} = (-0.013 \pm 0.052)\ \%$$

$$\Delta a_{CP}^{dir} = (-0.253 \pm 0.104)\ \%$$

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

arXiv:1406.2624

- Search for direct CP asymmetry in SCS decays $D^\pm_{(s)} \to K^0_s h^\pm$, $(h = K, \pi)$

$$A_{CP}^{D^\pm_{(s)} \to K^0_s h^\pm} \equiv \frac{\Gamma(D^+_{(s)} \to K^0_s h^+) - \Gamma(D^-_{(s)} \to K^0_s h^-)}{\Gamma(D^+_{(s)} \to K^0_s h^+) + \Gamma(D^-_{(s)} \to K^0_s h^-)}$$

- Measured raw asymmetries contain pollution asymmetries

  $A_{CP}^{raw} \approx A_{CP} - A_D(h) + A_P(D^+_{(s)}) + A_{K^0}$

  mixing / CPV of K^0 and detection asymmetry K^0 : $A_{K^0} = (+0.07 \pm 0.02)\%$

  arXiv:1405.2797

  use CF modes $D^+ \to K^0_s \pi^+$, $D^+_s \to K^0_s K^+$

- Construct double difference to cancel detection and production asymmetries

$$A_{CP}^{DD} \approx [A_{CP}^{raw}(D^+_s \to K^0_s \pi^+) - A_{CP}^{raw}(D^+_s \to K^0_s K^+)] - [A_{CP}^{raw}(D^+ \to K^0_s \pi^+) - A_{CP}^{raw}(D^+ \to K^0_s K^+)] - 2A_{K^0} = A_{CP}^{D^\pm \to K^0_s K^\pm} + A_{CP}^{D^\pm_s \to K^0_s \pi^\pm}$$

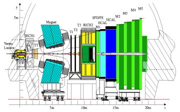
$$\boxed{A_{CP}^{D^\pm \to K^0_s K^\pm} + A_{CP}^{D^\pm_s \to K^0_s \pi^\pm} = (0.41 \pm 0.49 \pm 0.26)\%}$$

$\mathcal{L}_{int} \approx 3\ fb^{-1}$

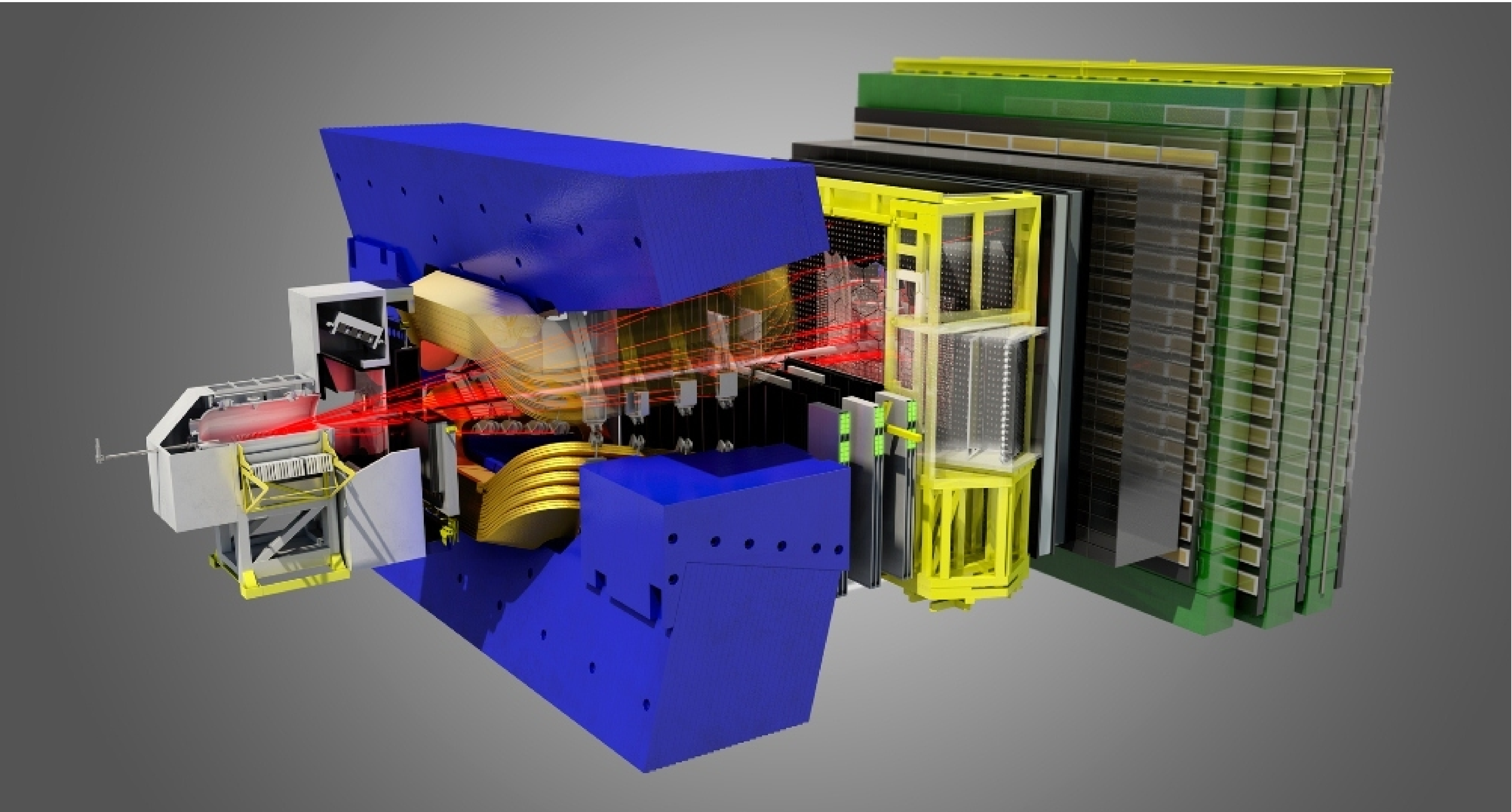
- Combine with CF $D^+_s \to \phi\pi^+$ to get CP asymmetries:

$$A_{CP}^{D^\pm \to K^0_s K^\pm} = (+0.03 \pm 0.17 \pm 0.14)\ \%$$
$$A_{CP}^{D^\pm_{(s)} \to K^0_s \pi^\pm} = (+0.38 \pm 0.46 \pm 0.17)\ \%$$

no CPV



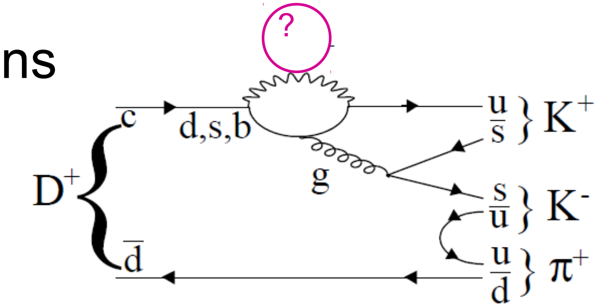
CP Violation in Multibody D Decays



CPV in multibody SCS Decays

- Single Cabbibo suppressed charm decays (SCS)
  - SCS decays are sensitive to CPV in $c \to uq\bar{q}$ transitions
    Contributions due to supersymmetric $\Delta C = 1$ QCD penguins could enter.
    → measurement of large CPV would be a sign of NP

Y. Grossman et al.
Phys. Rev. D75 036008 (2007)



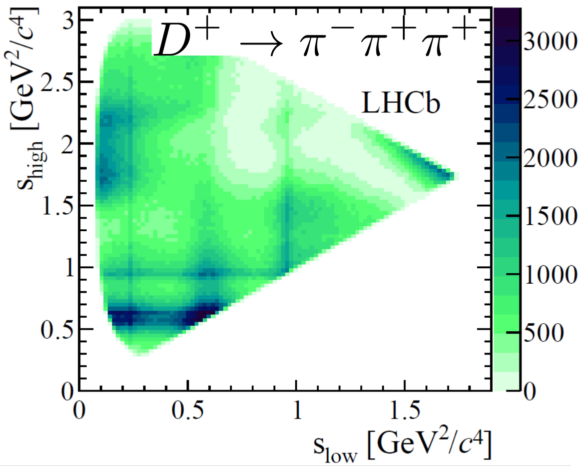
  - Search for CPV in SCS $D^+ \to \pi^+\pi^-\pi^+$, $D^0 \to \pi^-\pi^+\pi^-\pi^+$, $D^0 \to K^-K^+\pi^-\pi^+$
  - Decays from many resonances show strong phase variations in Phase Space
    → search for asymmetries in D and $\overline{\text{D}}$ in local areas of Phase Space

- Model independent Dalitz Plot analysis to look for local CP asymmetries

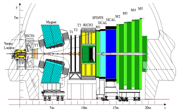
Significance of difference between corresponding Dalitz plot bins (a.k.a. Miranda method)
Phys. Rev. D80 096006 (2009)

$$S_{CP}^{i} = \frac{N(i) - \bar{N}(i)}{\sqrt{\alpha(N(i) + \bar{N}(i))}} \; , \; \alpha \equiv \frac{\sum N(i)}{\sum \bar{N}(i)}$$

- CPV if S_{CP}^{i} distribution nongaussian

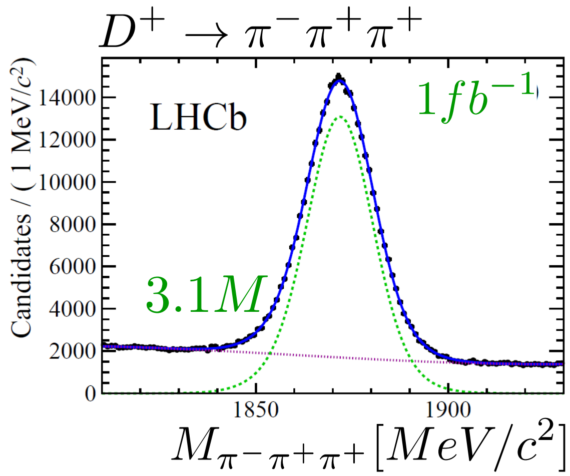


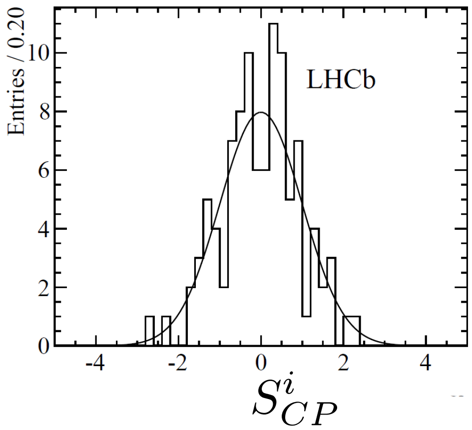
PLB 728 (2014) 585



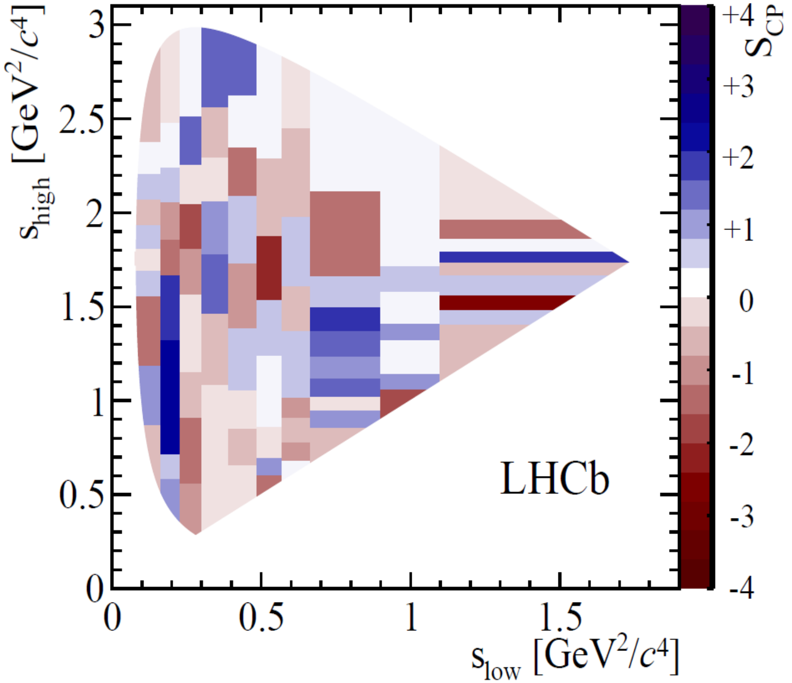
CPV in $D^+ \to \pi^-\pi^+\pi^+$ Decays

- Dalitz analysis of the SCS decay $D^+ \to \pi^-\pi^+\pi^+$





PLB 728 (2014) 585



- Test various uniform and adaptive binning schemes
- S^i_{CP} distributions agree with normal gaussian distribution (p-values 50 – 99 %)

- For SCS decays $D^0 \to \pi^-\pi^+\pi^-\pi^+$, $D^0 \to K^-K^+\pi^-\pi^+$ also no CP asymmetry found PLB 726 (2013) 623, not discussed here

CPV with T-odd Correlations

Search for CPV using T-odd correlations assuming CPT invariance

A. Datta and D. London
Int.J.Mod.Phys. A19 2505 (2004)

- Triple Products in $D \to VV$ are odd under T reversal

$$A_T = \frac{\Gamma_D(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3 > 0) - \Gamma_D(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3 < 0)}{\Gamma_D(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3 > 0) + \Gamma_D(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3 < 0)} \qquad \vec{v}_i = \{\vec{s}\,,\,\vec{p}\}$$

  - But FSI can produce $A_T \neq 0$

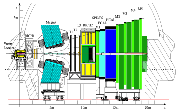
BABAR: PRD-RC 81 111103 (2010)

- Measure CPV observable $a_{CP}^{T-odd} = 1/2(A_T - \bar{A}_T)$ using triple products of final state particle momenta in $D^0 \to K^+K^-\pi^+\pi^-$ decays in D^0 $c.m.s.$
  - D^0 : $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ $\qquad A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)}$
  - $\bar{D}^0$: $\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$ $\qquad \bar{A}_T \equiv \frac{\Gamma_{\bar{D}^0}(-\bar{C}_T > 0) - \Gamma_{\bar{D}^0}(-\bar{C}_T < 0)}{\Gamma_{\bar{D}^0}(-\bar{C}_T > 0) + \Gamma_{\bar{D}^0}(-\bar{C}_T < 0)}$
  - Effective CPV differs depending on strong phase difference of the two interfering amplitudes $(\delta_1 - \delta_2)$

weak phases $\qquad$ strong phases

$$\mathcal{A}_{CP} \propto sin(\phi_1 - \phi_2) \cdot sin(\delta_1 - \delta_2) \qquad a_{CP}^{T-odd} \propto sin(\phi_1 - \phi_2) \cdot cos(\delta_1 - \delta_2)$$

a_{CP}^{T-odd} maximal for small $(\delta_1 - \delta_2)$



CPV - T-odd Cor. in $D^0 \to K^+K^-\pi^+\pi^-$

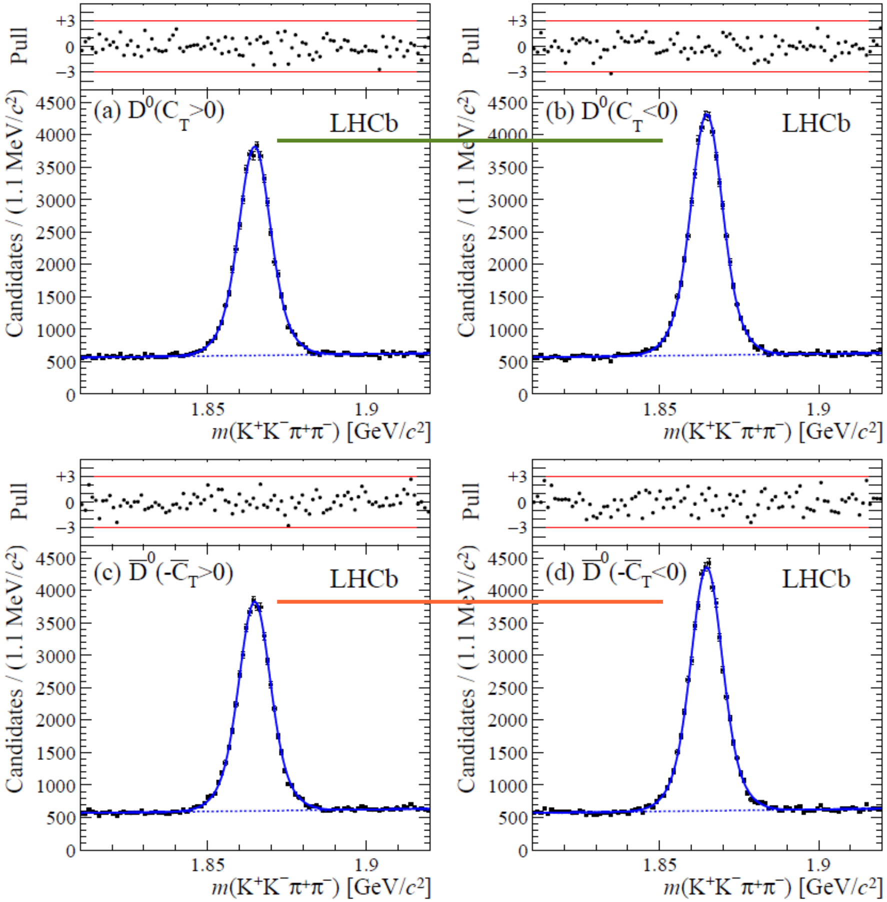
LHCb searches for CPV in 171 k secondary $D^0 \to K^+K^-\pi^+\pi^-$ decays using T-odd correlations with $3fb^{-1}$ of data

arXiv:1408.1299

- Measure phase space integrated T-odd observables and CP asymmetry

$$D^0 \;:\; A_T = (-7.18 \pm 0.41 \pm 0.13)\%$$

$$\bar{D}^0 \;:\; \bar{A}_T = (-7.55 \pm 0.41 \pm 0.12)\%$$



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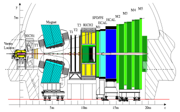
$$a_{CP}^{T-odd} = (0.18 \pm 0.29 \pm 0.04)\%$$



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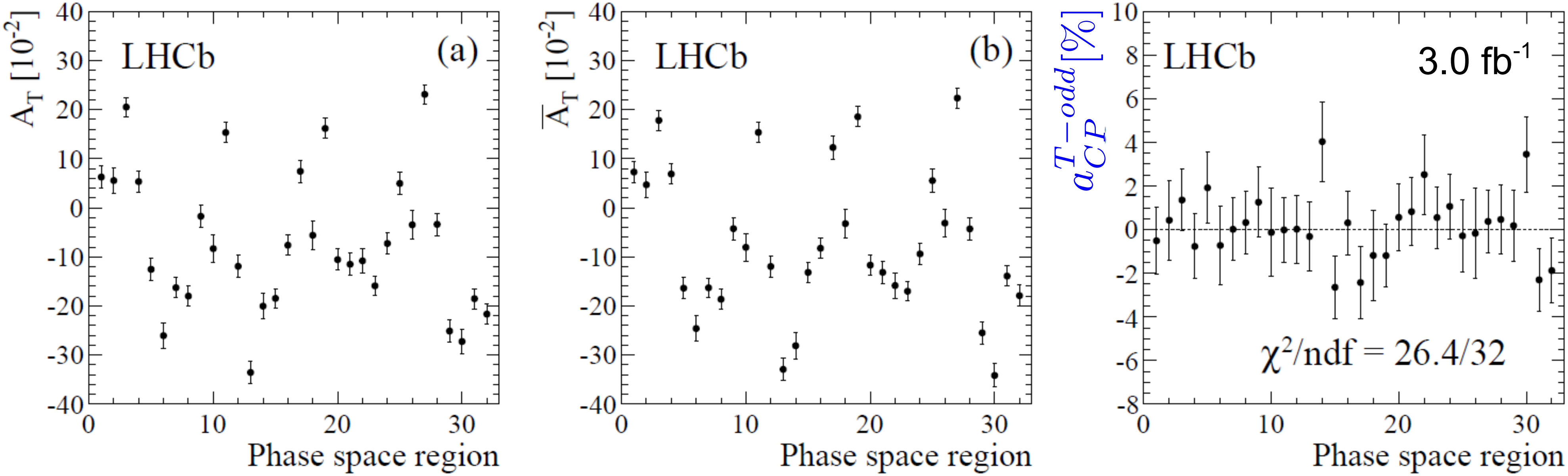
$$a_{CP}^{T-odd} = (0.18 \pm 0.29 \pm 0.04)\%$$

- Variations of T-odd variable with phase space cancelling in a_{CP}^{T-odd}



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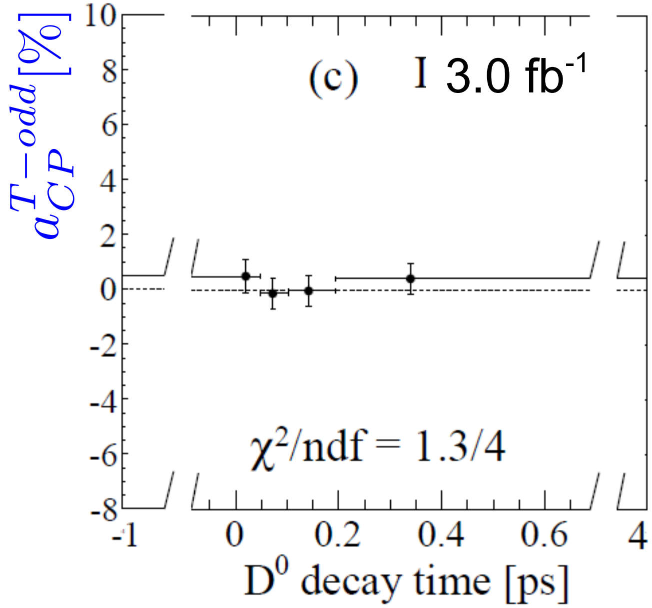
$$a_{CP}^{T-odd} = (0.18 \pm 0.29 \pm 0.04)\%$$

- Variations of T-odd variable with phase space cancelling in a_{CP}^{T-odd}

- No variations with τ_{D^0} which excludes effects of indirect CPV

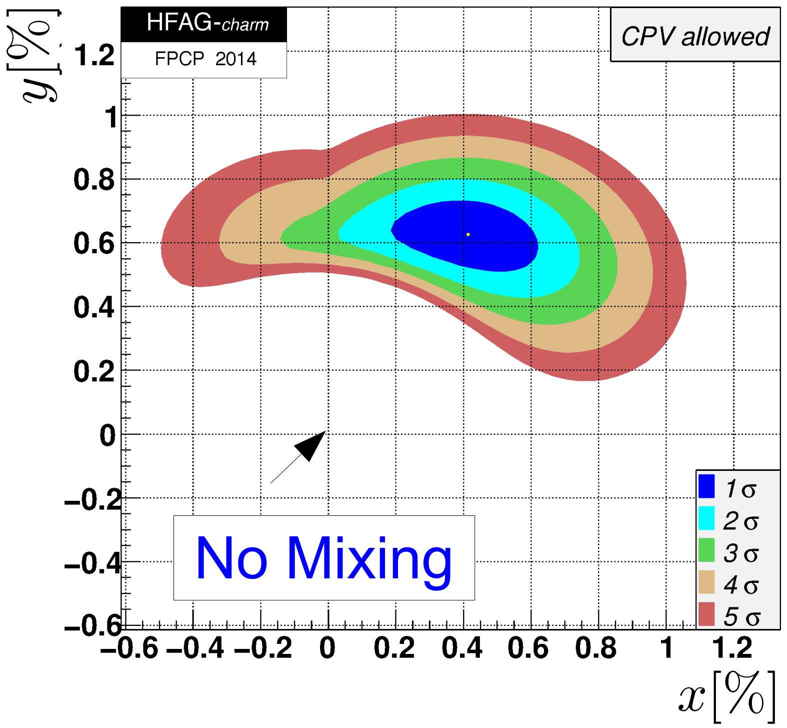
- Precision on a_{CP}^{T-odd} significantly improved

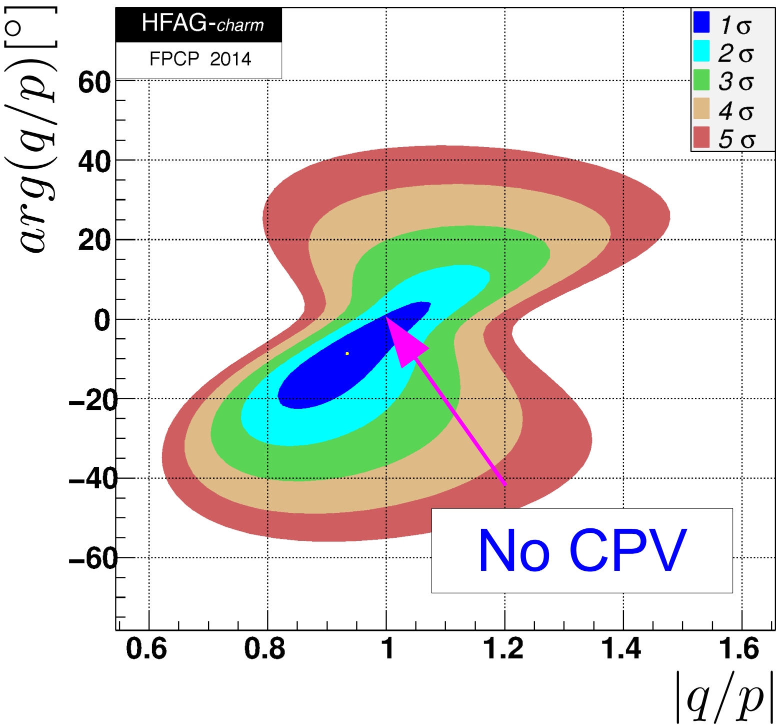
No evidence of CP asymmetry



Summary

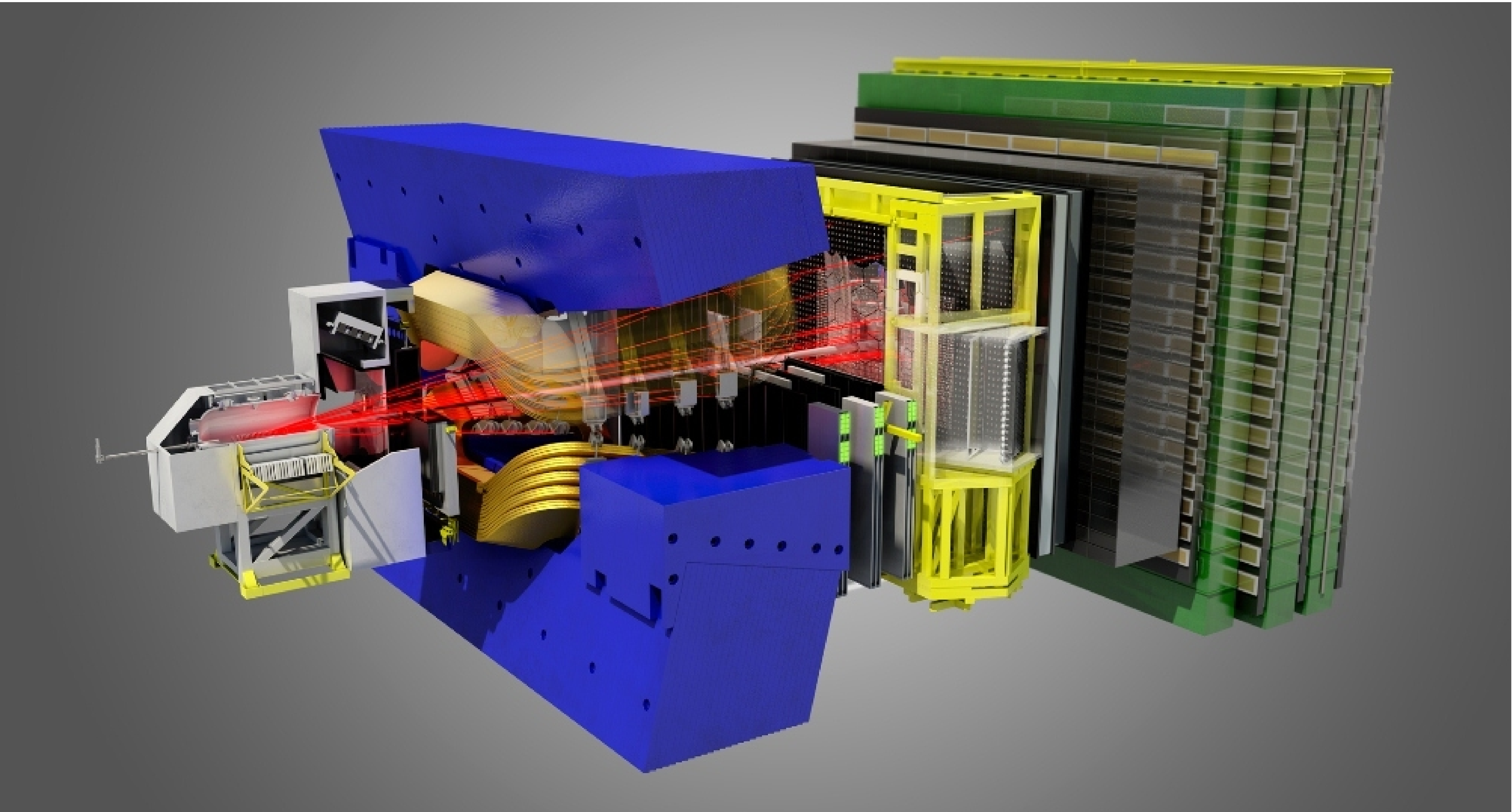
- LHCb takes the fine results of the B factories and Tevatron in charm physics to an even higher precision to allow for comparison with SM predictions.





- LHCb is still analyzing data of Run I with Run II lurking at the doorstep, thus more exciting results are to be expected.

Back up



LHC – b and c Quark Production

The LHC is also a heavy flavour factory

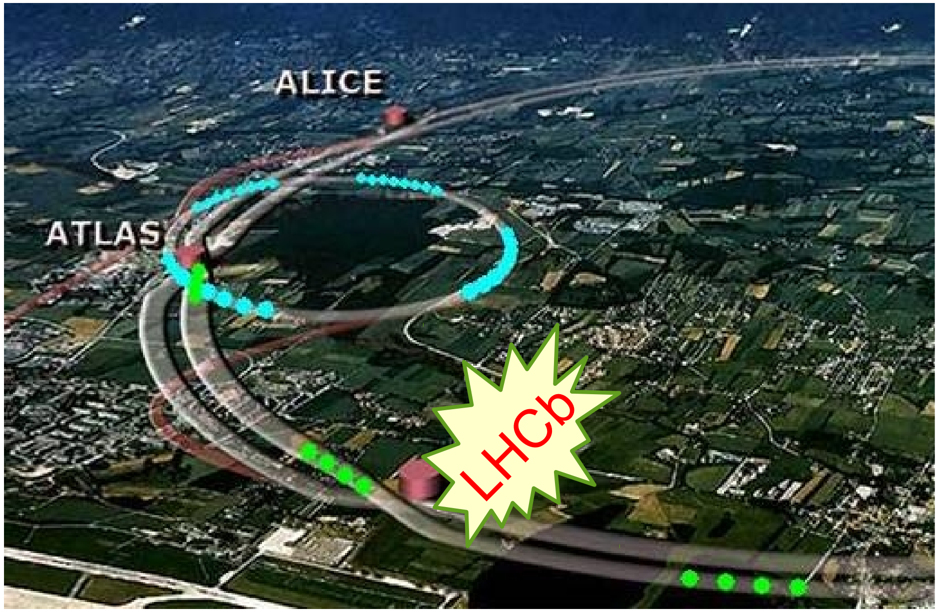
$$\sigma(\sqrt{s} = 7\,TeV\,,\, pp \rightarrow c\bar{c}X) \approx 6\ mb$$

Phys. Lett. B 694, 209 (2010)

$$\sigma(\sqrt{s} = 7\,TeV\,,\, pp \rightarrow b\bar{b}X) \approx 0.3\ mb$$

Nucl. Phys. B 871, (2013)

LHC – b and c Quark Production



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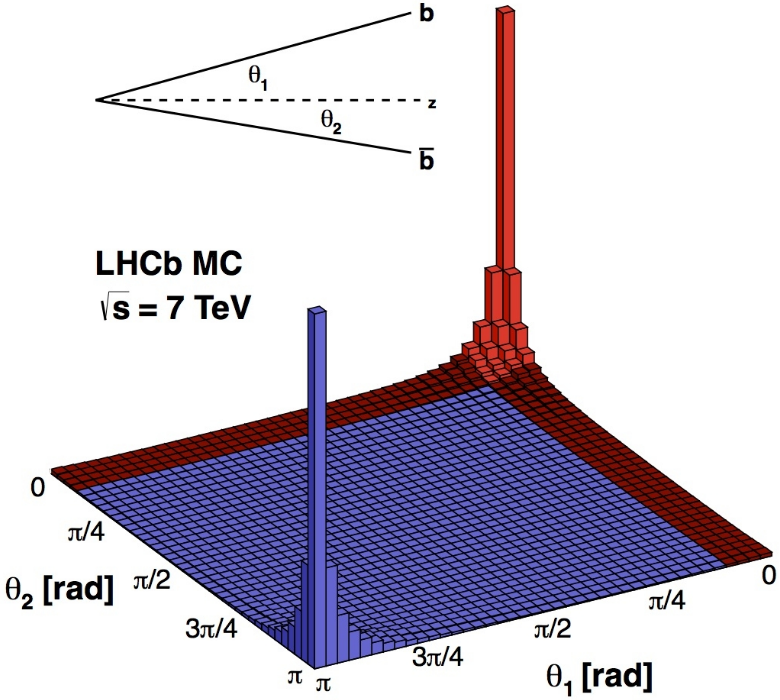
Phys. Lett. B 694, 209 (2010)

$$\sigma(\sqrt{s} = 7\,TeV\,,\,pp \to b\bar{b}X) \approx 0.3\;mb$$

Nucl. Phys. B 871, (2013)

- $b\bar{b}\,/\,c\bar{c}$ pairs are mainly produced in forward / backward direction

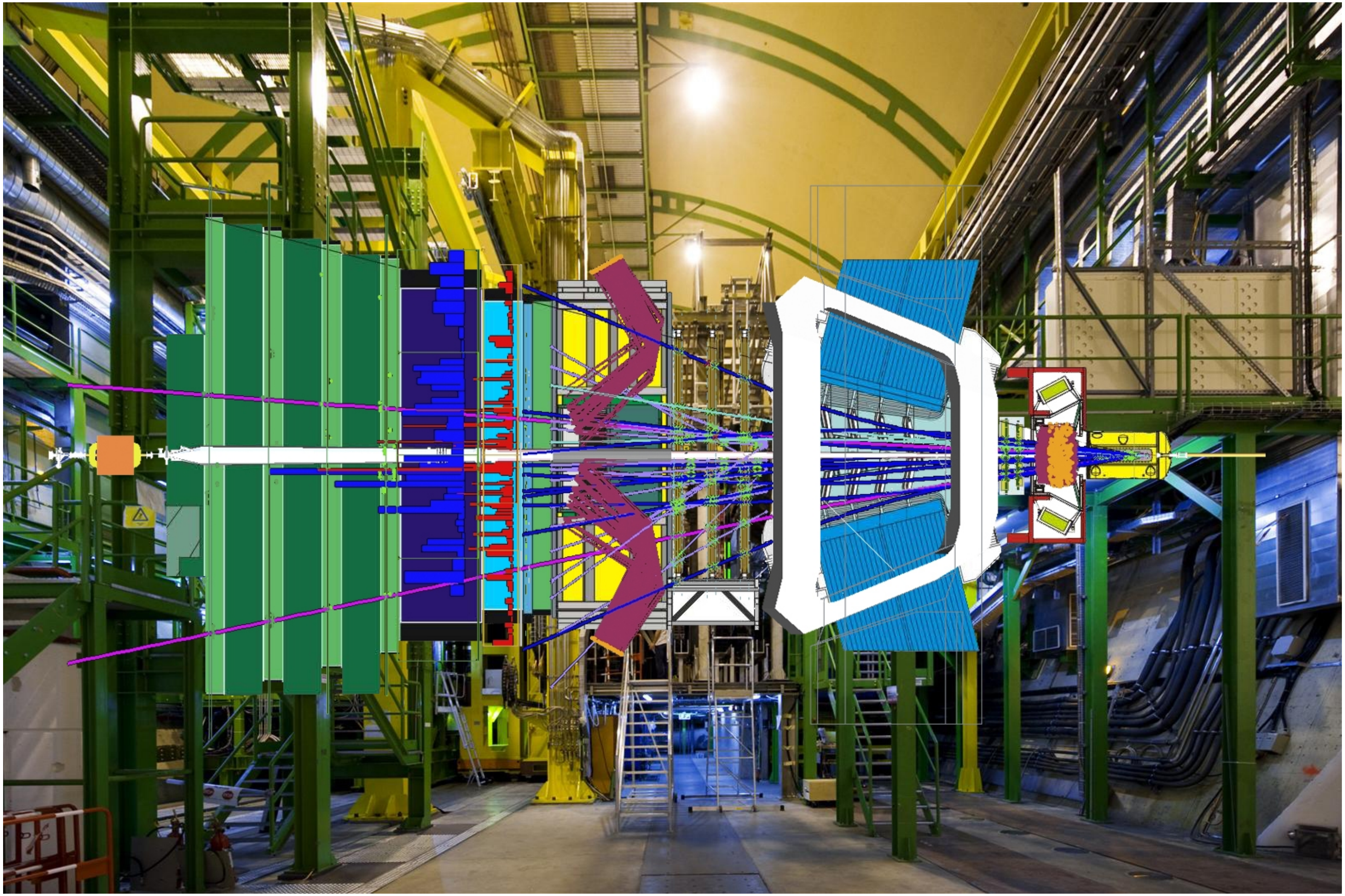


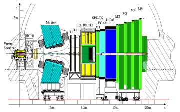
LHCb → forward spectrometer

LHCb Detector

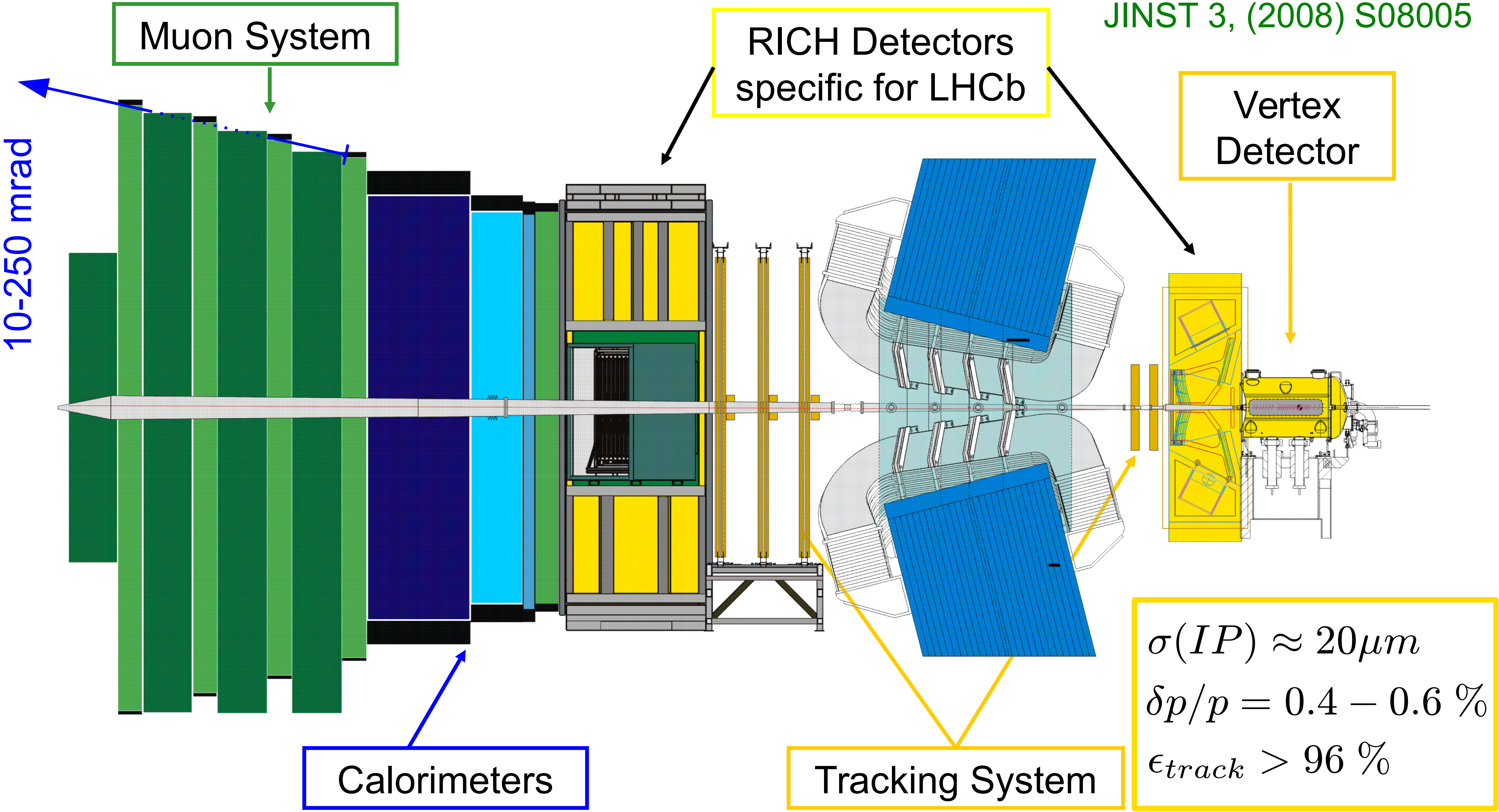
LHCb Detector

10-250 mrad





LHCb Experimental Setup



JINST 3, (2008) S08005

10-250 mrad

Muon System

RICH Detectors specific for LHCb

Vertex Detector

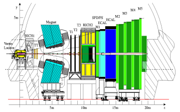
Calorimeters

Tracking System

$\sigma(IP) \approx 20\mu m$

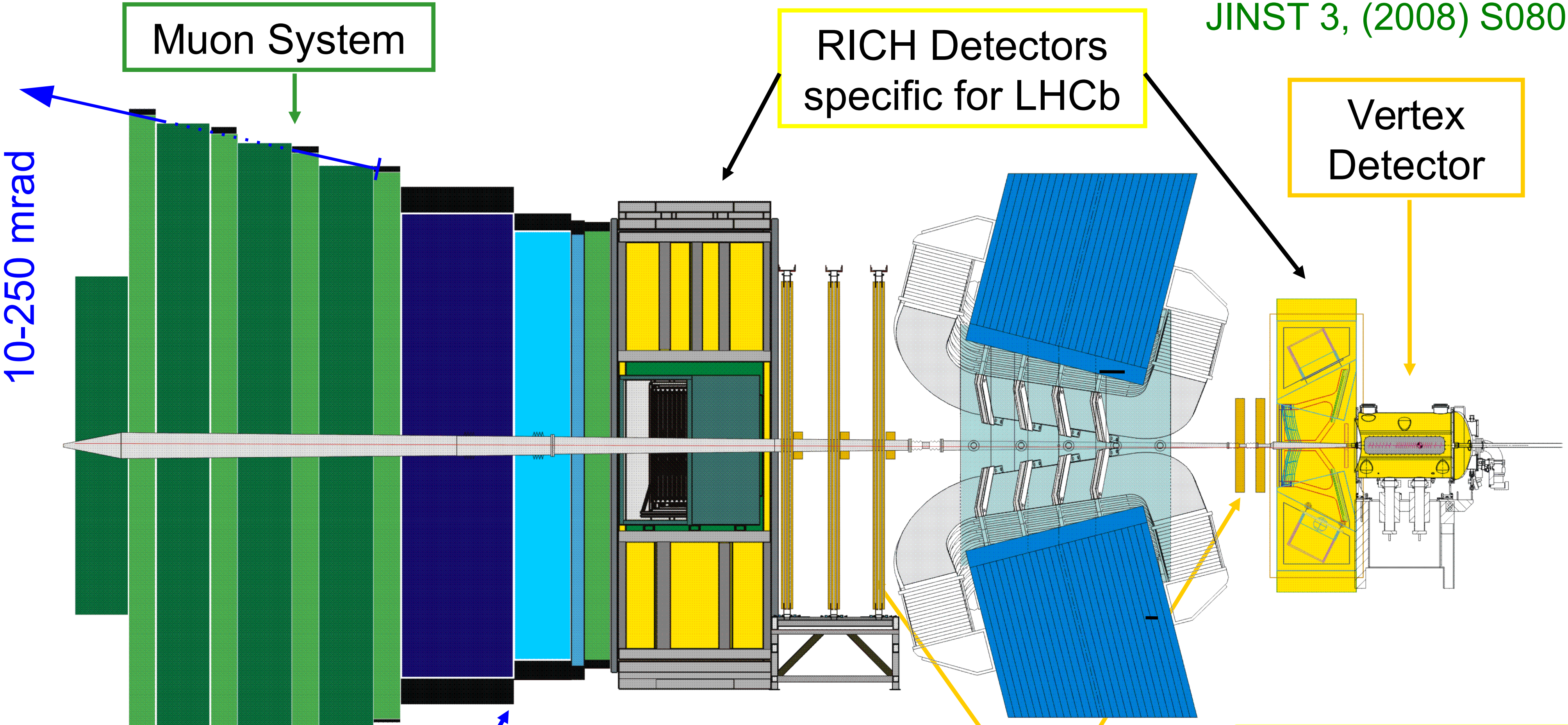
$\delta p/p = 0.4 - 0.6\ \%$

$\epsilon_{track} > 96\ \%$



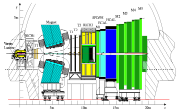
LHCb Experimental Setup

JINST 3, (2008) S08005

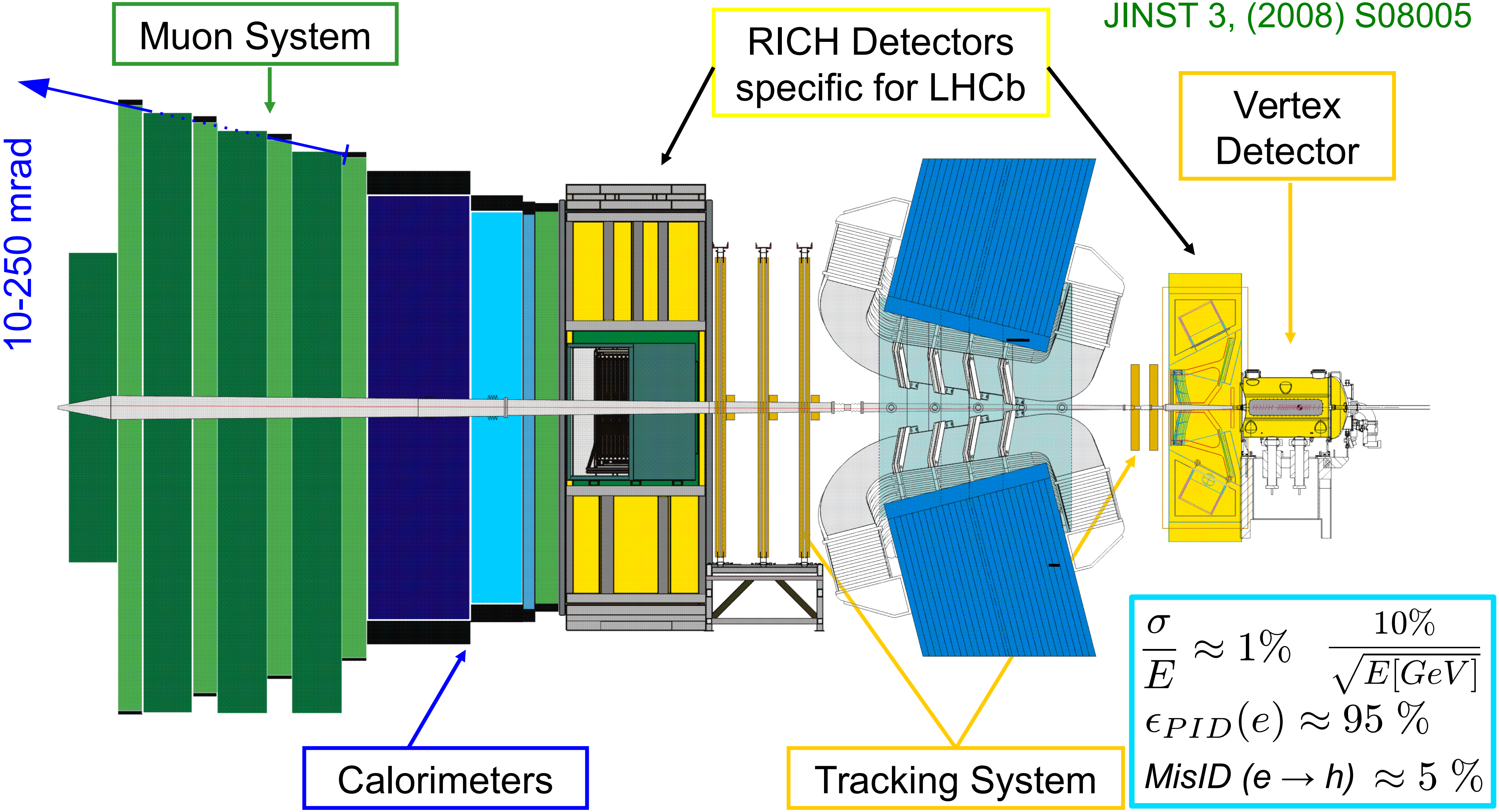


$\epsilon_{PID}(K) \approx 95\ \%$

MisID $(K \to \pi) \approx 5\ \%$



LHCb Experimental Setup



JINST 3, (2008) S08005

Muon System

RICH Detectors specific for LHCb

Vertex Detector

10-250 mrad

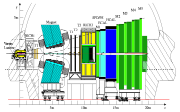
Calorimeters

Tracking System

$$\frac{\sigma}{E} \approx 1\% \quad \frac{10\%}{\sqrt{E[GeV]}}$$

$$\epsilon_{PID}(e) \approx 95\ \%$$

MisID ($e \rightarrow h$) $\approx 5\ \%$



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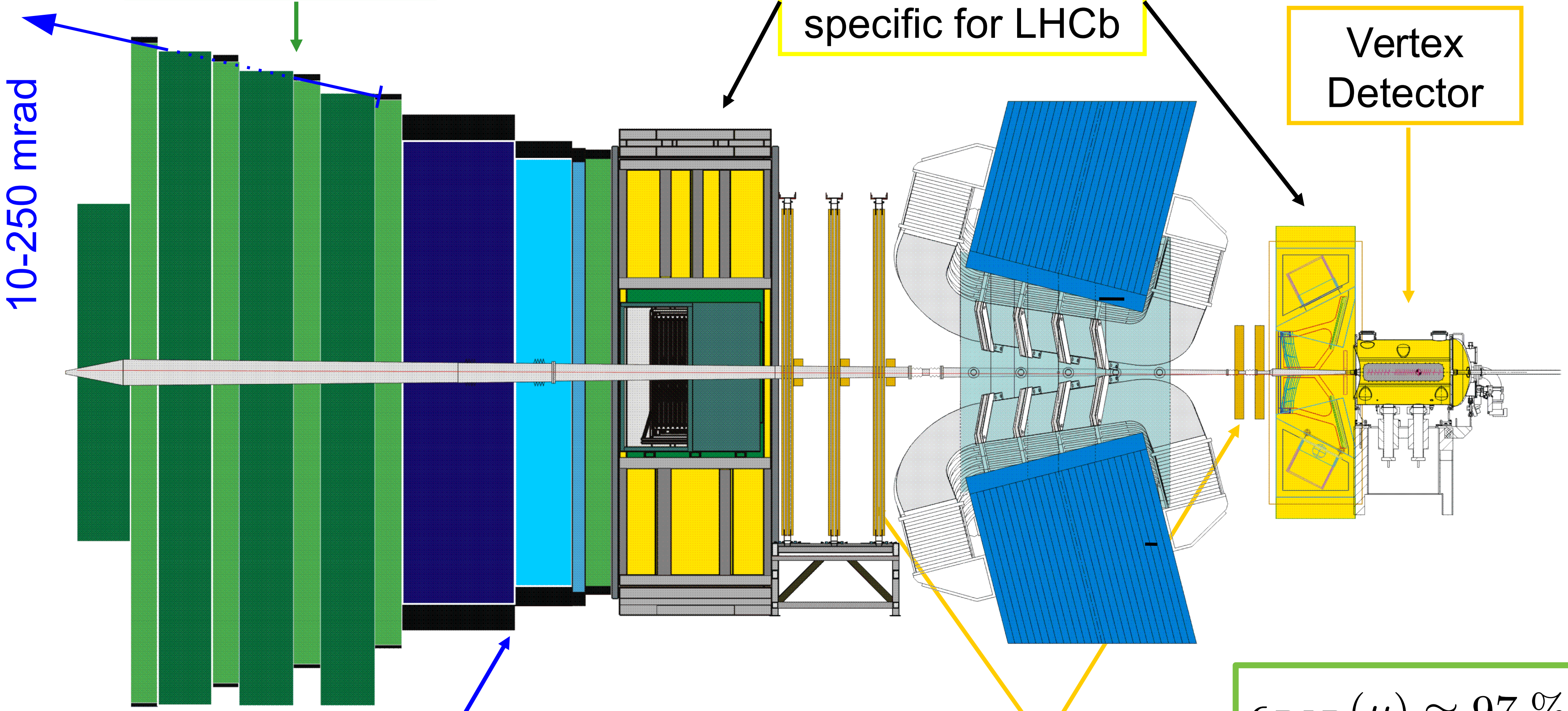


Muon System

RICH Detectors specific for LHCb

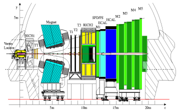
Vertex Detector

Calorimeters

Tracking System

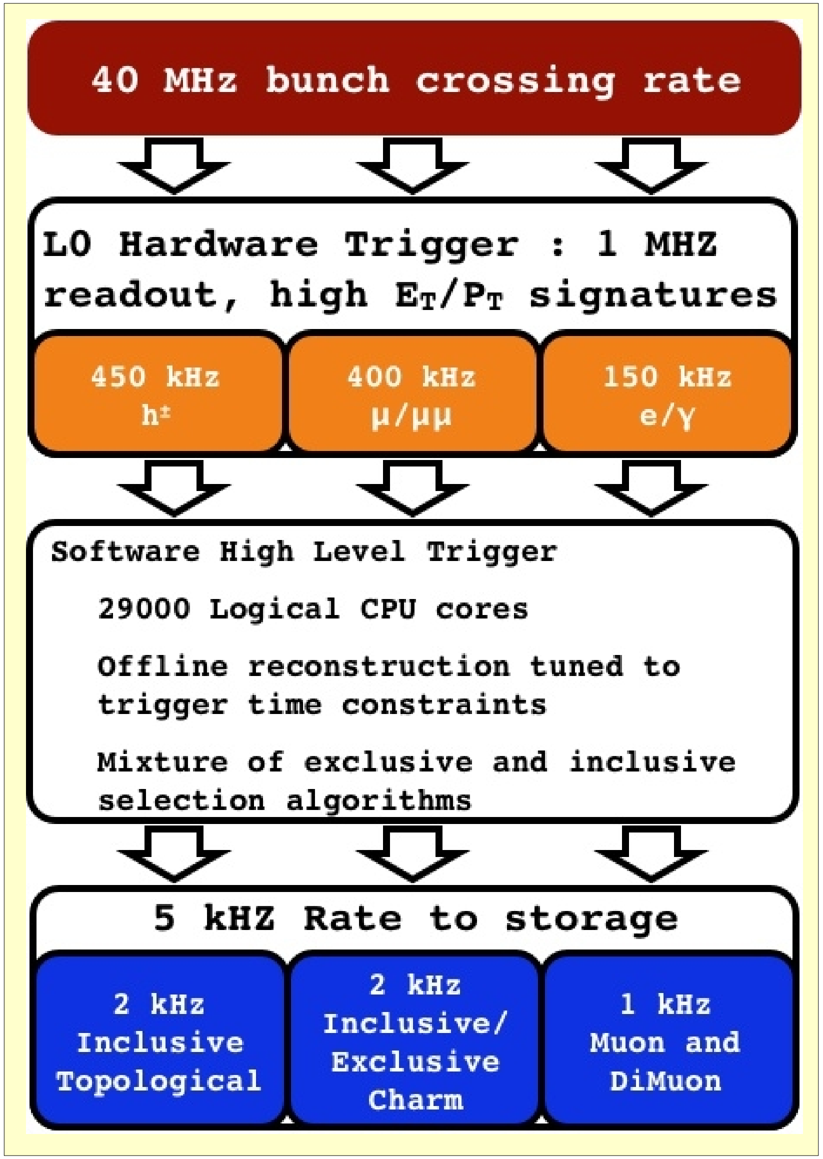
$\epsilon_{PID}(\mu) \approx 97\ \%$

MisID $(\pi \to \mu) \approx 3\ \%$



LHCb - Trigger Overview

- Hardware Trigger based on VELO, Calorimeter- and Muonsystem
  - Select on p_T objects: $h, \mu, \mu\mu, e^{\pm}, \gamma, \pi^0$
  - Obtain p-p interaction and multiplicity info
- Two level software trigger based on partly / fully reconstructed objects with all detector information
  - Confirm L0 trigger using reconstr. and combined detector info
  - Select on a single track with high p_T and displaced vertices using VELO
  - Use reconstructed objects for exclusive and inclusive selections with clear signature
- In 2012 wrote 5 kHz to storage thanks to deferred trigger processing of up to 25% of data



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures

450 kHz $h^{\pm}$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

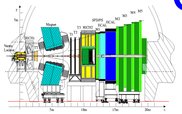
Mixture of exclusive and inclusive selection algorithms

5 kHZ Rate to storage

2 kHz Inclusive Topological

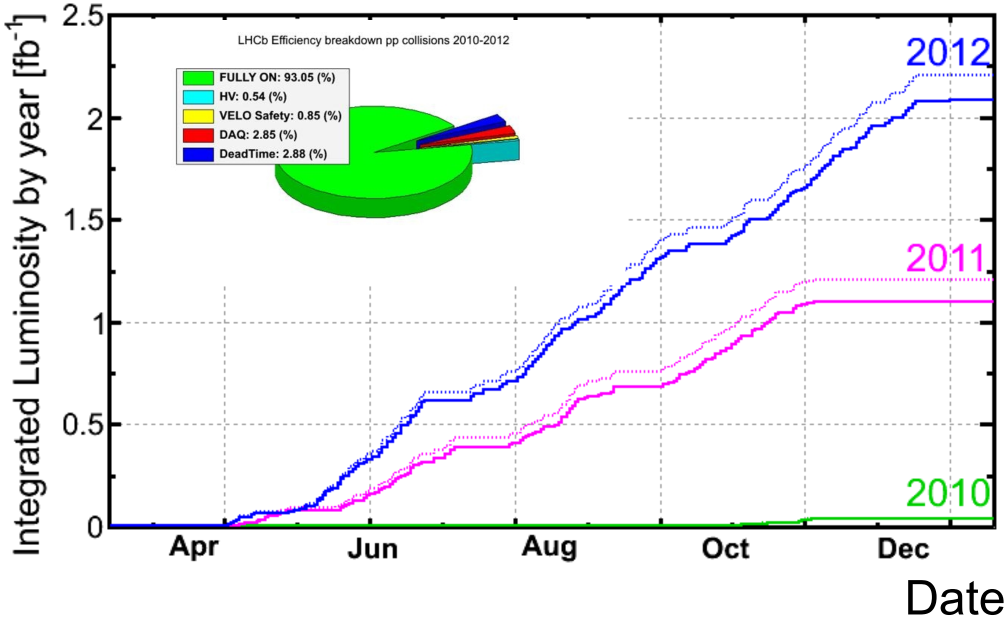
2 kHz Inclusive/ Exclusive Charm

1 kHz Muon and DiMuon

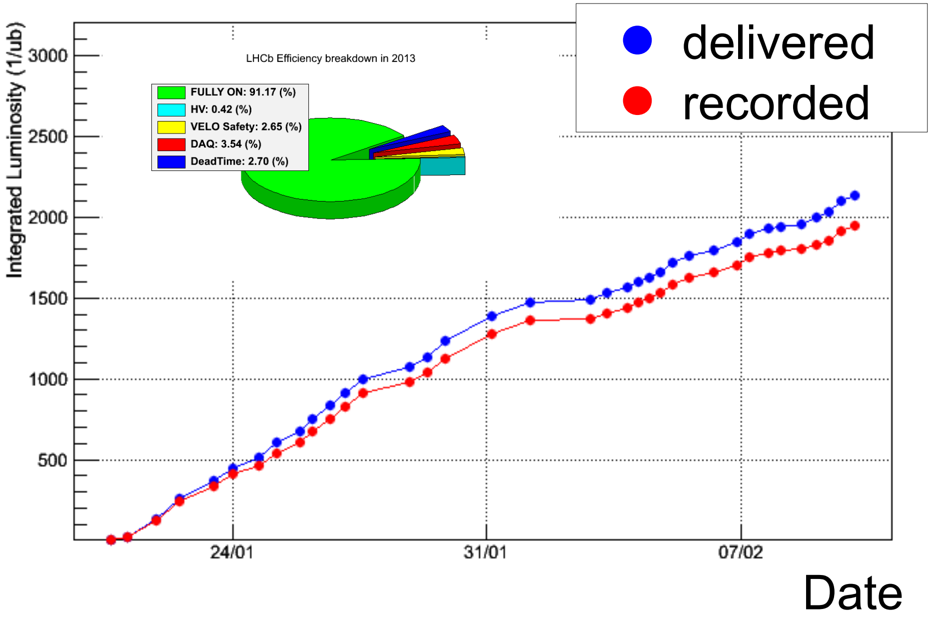


Operations in 2011 / 2012

- ➢ p-p at 3.5 / 4 TeV

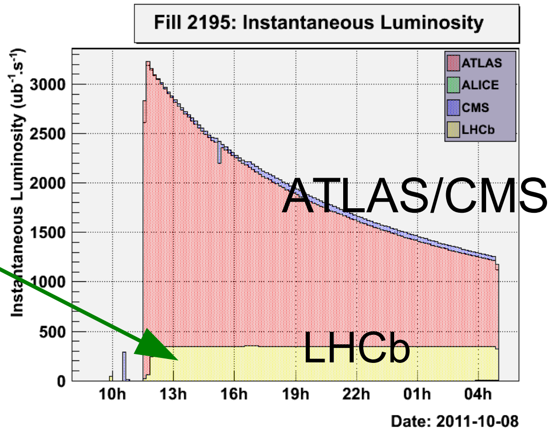


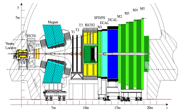
- ➢ p-Pb at $\sqrt{s_{NN}} = 5$ TeV in 2013



- LHCb operates with high efficiency
- Take data at constant instantaneous luminosity rate: $\mathcal{L} \approx 4 \times 10^{32}\, cm^{-2} s^{-1}$

  (factor 2 larger than design luminosity)
- Visible pp interactions per bunch crossing μ = 1.7 (50 ns bunch spacing)





LHCb - Lifetime Acceptance

JHEP 04 (2012) 129

Knowledge of the proper time acceptance dependence on the trigger and selection is needed.

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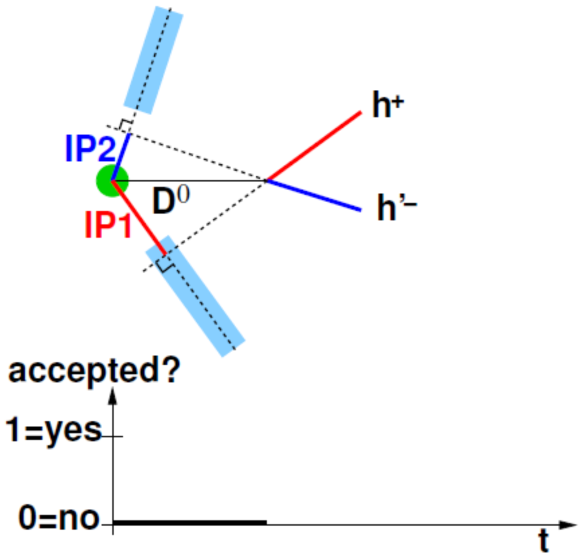
- Recreate trigger decision while moving the PV along the D^0 momentum. Well suited for the LHCb software trigger.



Initially the IP for this D^0 lifetime is still below trigger threshold.

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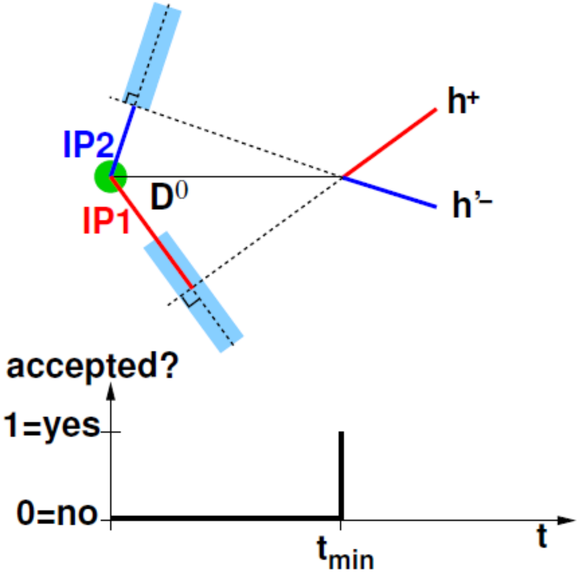

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Moving the PV and recreating the IP info yields a D^0 lifetime t_{min} which creates a trigger.

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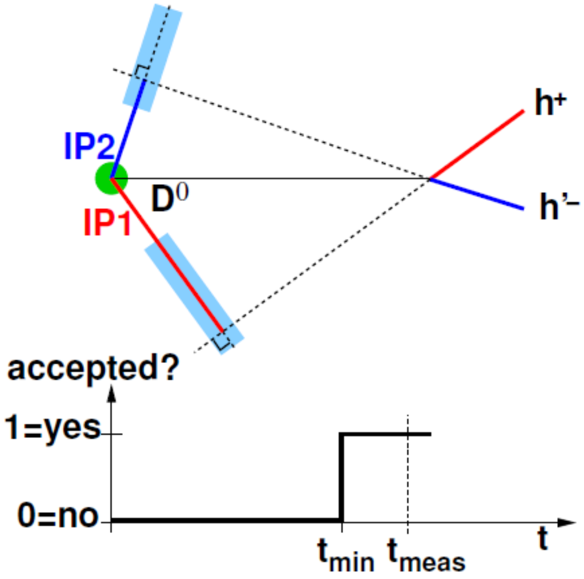

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t_{meas} is reached.

Similar procedure can be applied for other selection criteria.