First evidence for CP violation in charm decays at LHCb

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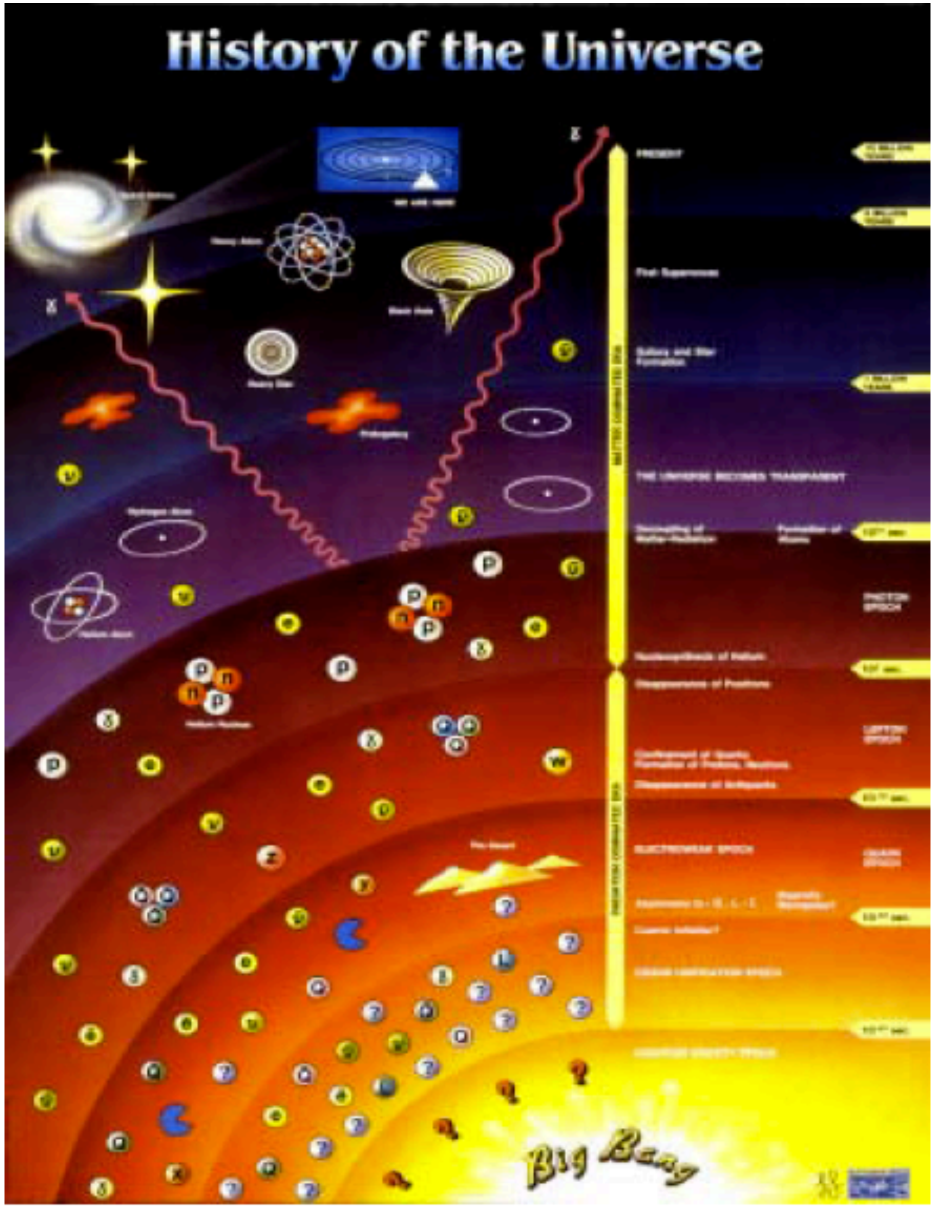
Reference: arXiv:1112.0938[hep-ex]

CP violation

The understanding of CP violation, and of flavour physics is particularly interesting since "New Physics" typically leads to new sources of flavour and CP violation

One of the key features of our Universe is the cosmological baryon asymmetry of $O(10^{-10})$

As was pointed out by Sakharov, the necessary conditions for the generation of such an asymmetry include also the requirement that elementary interactions violate CP



Discovery of CP violation

- In the weak interaction CP is not conserved
  - i.e. it means a non-invariance of the weak interactions with respect to a combined charge conjugation (C) and parity (P) transformation
- It was discovered for the first time through the observation of $K_L \rightarrow \pi^+\pi^-$ in 1964 by Cronin et al.

K_L decayed into $\pi^+\pi^-$ final state, forbidden by CP conservation

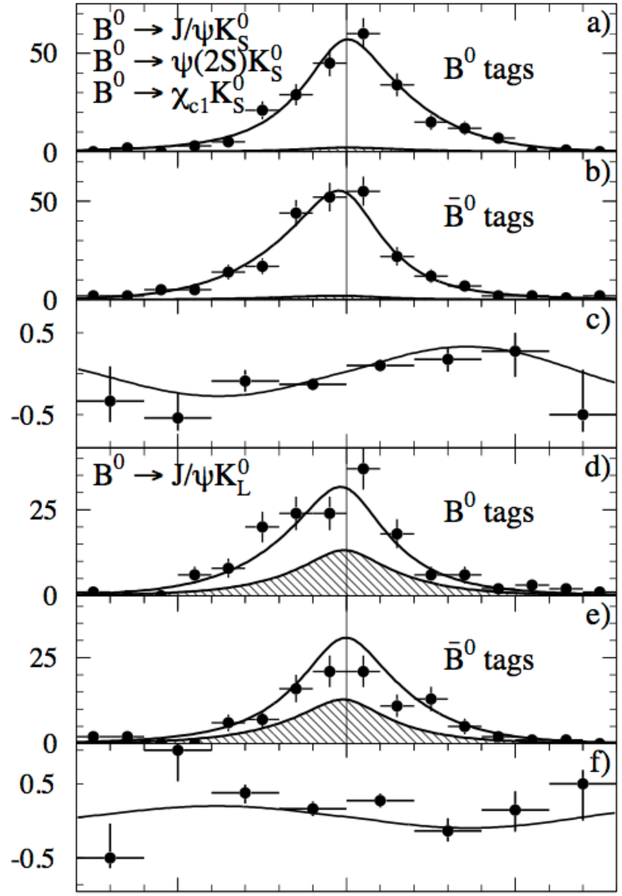

James Watson Cronin   Val Logsdon Fitch

Nobel prize 1980

Discovery CP violation in beauty

- About 40 years later, CP-violating effects were discovered in B meson decays using $B^0 \rightarrow J/\psi K_S$ by the BABAR and Belle Collaborations
- It was the first observation of CP violation outside the kaon system.
- In the summer of 2004, also an evidence of direct CP violation was observed in the $B^0 \rightarrow K^+\pi^-$ decay

BaBar example: sin2β measurement



hep-ex/0407057 hep-ex/0408100 hep-ex/0107013 hep-ex/0107061

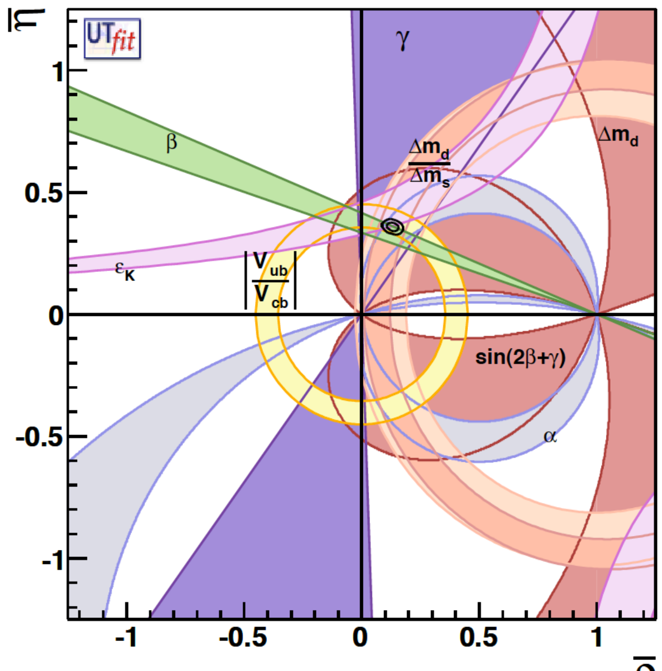
CKM matrix and Nobel Prize

A third family of quarks is necessary to accomodate CP violation in weak interactions

M. Kobayashi and T. Maskawa
CP Violation in the Renormalizable Theory of Weak Interaction
Prog. Theor. Phys. **49** (1973) 652
Cited 6231 times

2008:Nobel prize in physics

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"



…but don't forget Prof. Cabibbo

I have some favoured decays…

N. Cabibbo
Unitary Symmetry and Leptonic Decays
Phys. Rev. Lett. **10** (1963) 531
Cited 3399 times

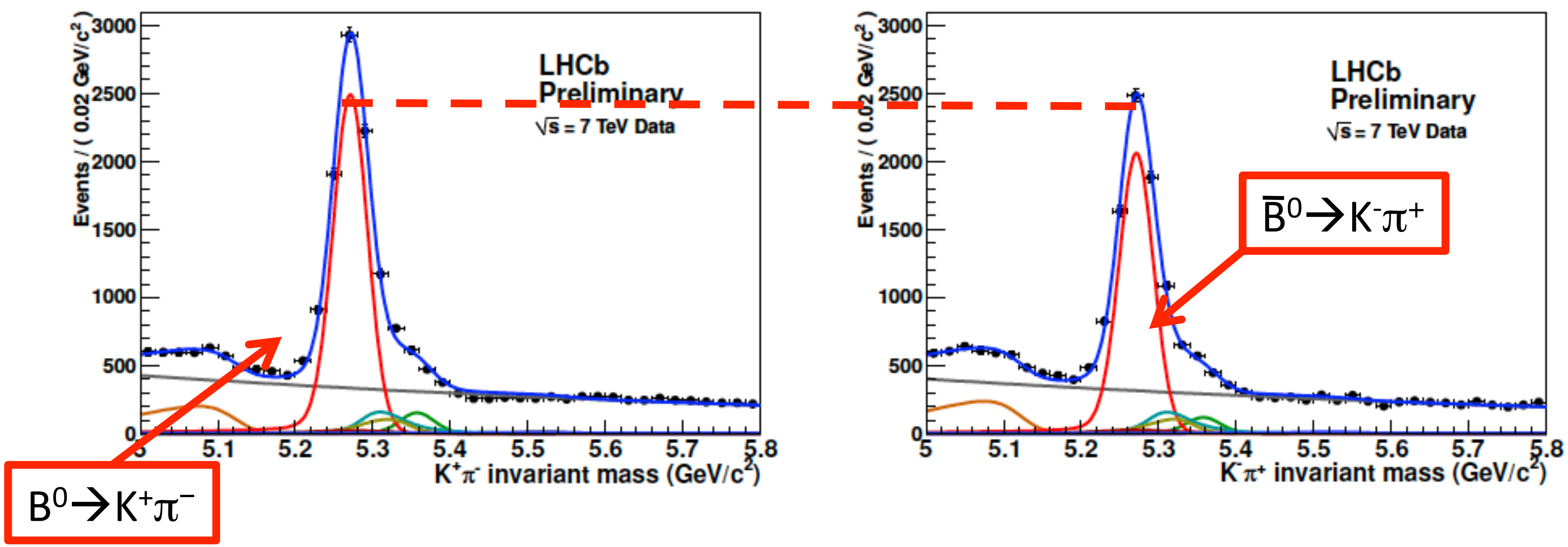
2010: Dirac Medal

for his **"fundamental contributions to the understanding of weak interactions and other aspects of theoretical physics"**

LHCb entered the scene

- In 2011 direct CP violation was observed in the $B^0 \rightarrow K^+\pi^-$ decay with a significance exceeding 5 standard deviation
- Also an evidence of direct CP violation was observed in the $B^0_s \rightarrow K^-\pi^+$ decay

LHCb-CONF-2011-042



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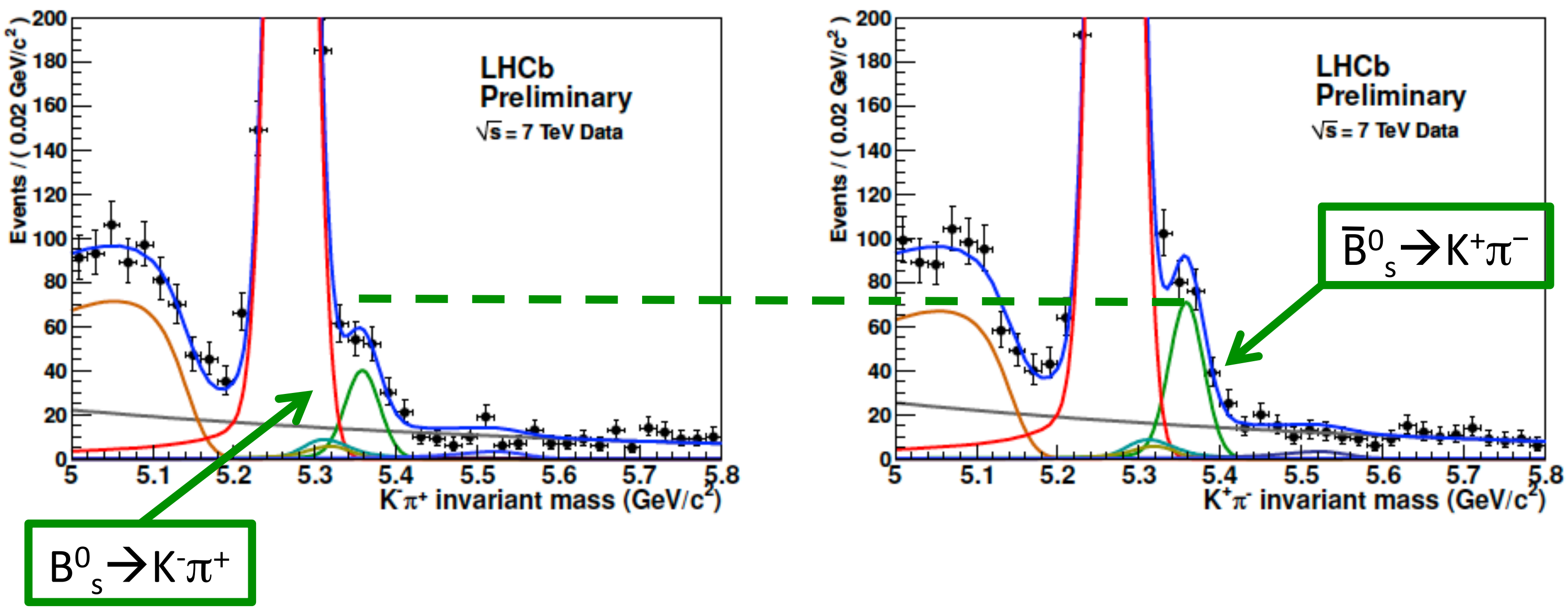


CP violation in charm

- So far CP violation has been observed in the area of down-quarks (s, b)
- CP violation in charm is the unique probe to the up-quark sector (inaccessible trough *t* or *u* quarks) → not yet observed
- Standard Model charm physics is CP conserving to first approximation (dominance of 2 generations)
- New Physics (NP) can enhance CP-violating observables

Unitary triangle for charm

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

(columns: d, s, b; rows: u, c, t)

CKM matrix

CP violation in charm

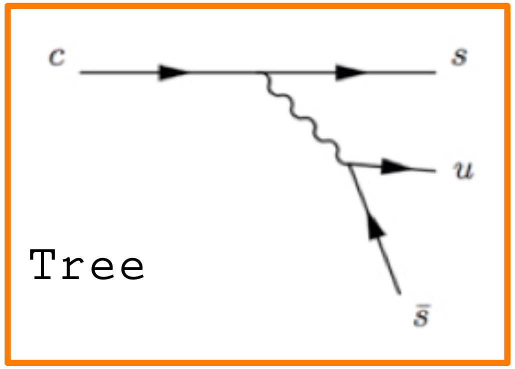
- 3 types of CP violation:
  - in mixing: rates of $D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$ differ → indirect
  - in decay: amplitudes for a process and its conjugate differ → direct
  - in interference between mixing and decay diagrams → indirect
- In the SM indirect CP violation expected to be very small and universal for CP eigenstates → $O(10^{-3})$
- Direct CP violation expected small as well
  - Negligible in Cabibbo-favoured modes (SM tree dominates everything)
  - In singly-Cabibbo-suppressed modes: up to $O(10^{-4} - 10^{-3})$ plausible
- Both can be enhanced by NP, in principle up to O(%)

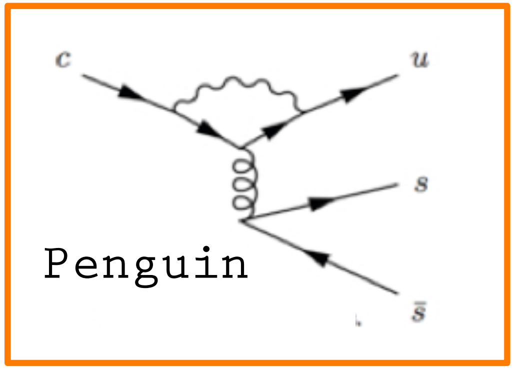
Bianco, Fabbri, Benson & Bigi, Riv. Nuovo. Cim 26N7 (2003)
Grossman, Kagan & Nir, PRD 75, 036008 (2007)
Bigi, arXiv:0907.2950

Bobrowski, Lenz, Riedl & Rorhwild, JHEP 03 009 (2010)
Bigi, Blanke, Buras & Recksiegel, JHEP 0907 097 (2009)

Where to look for CP violation?

- Singly Cabibbo Suppressed (SCS) decays are an interesting sector for direct CPV searches
- Interference between Tree and Penguin can generate direct CP asymmetries
  - Several classes of NP can contribute
  - … but also non-negligible SM contribution





Time-integrated asymmetries in $D^0 \to hh$

Introduction to LHCb

LHC as a charm and beauty factory

Large production of charm and beauty

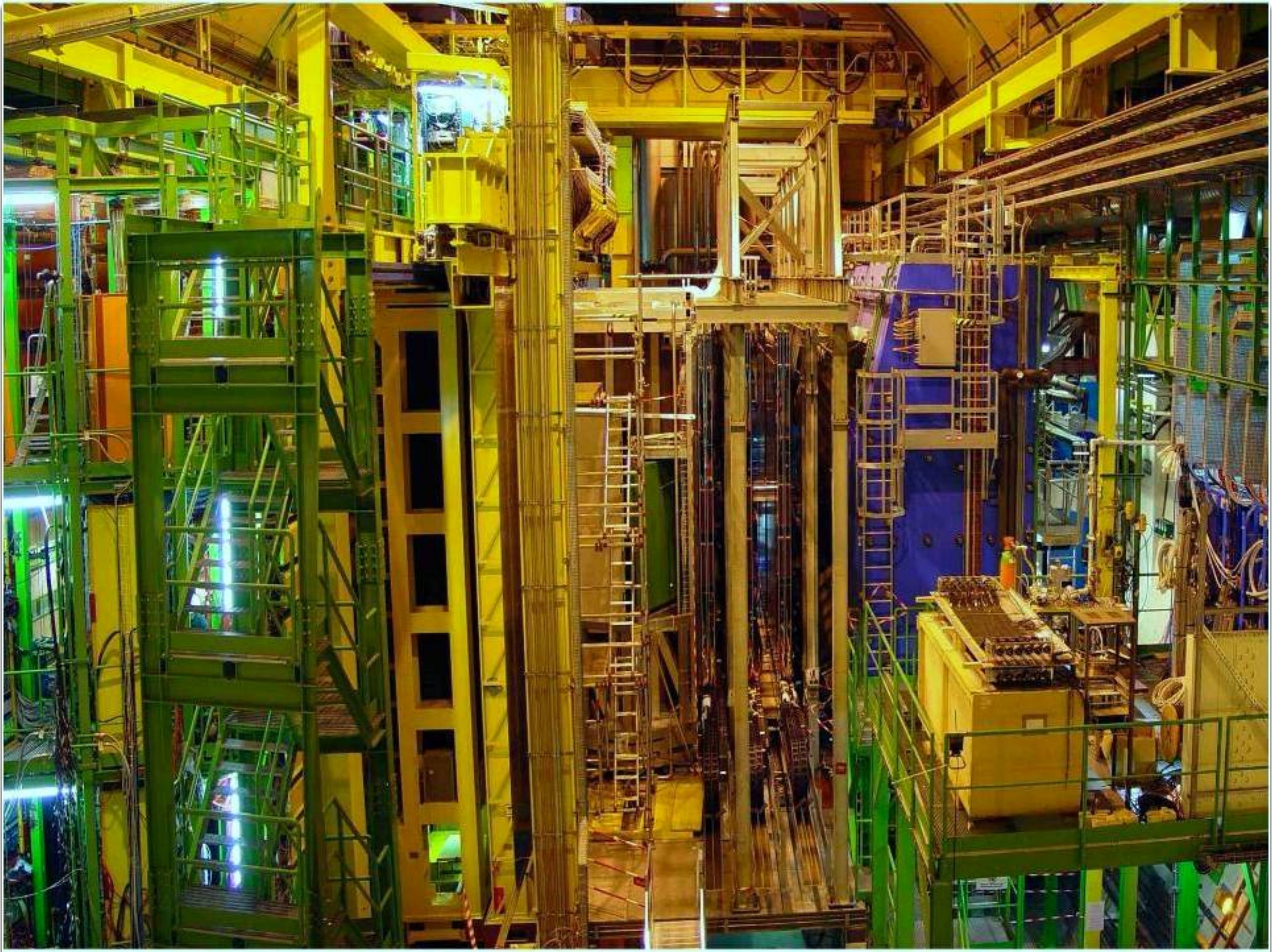
Cross sections at $\sqrt{s}$=7 TeV measured by LHCb:

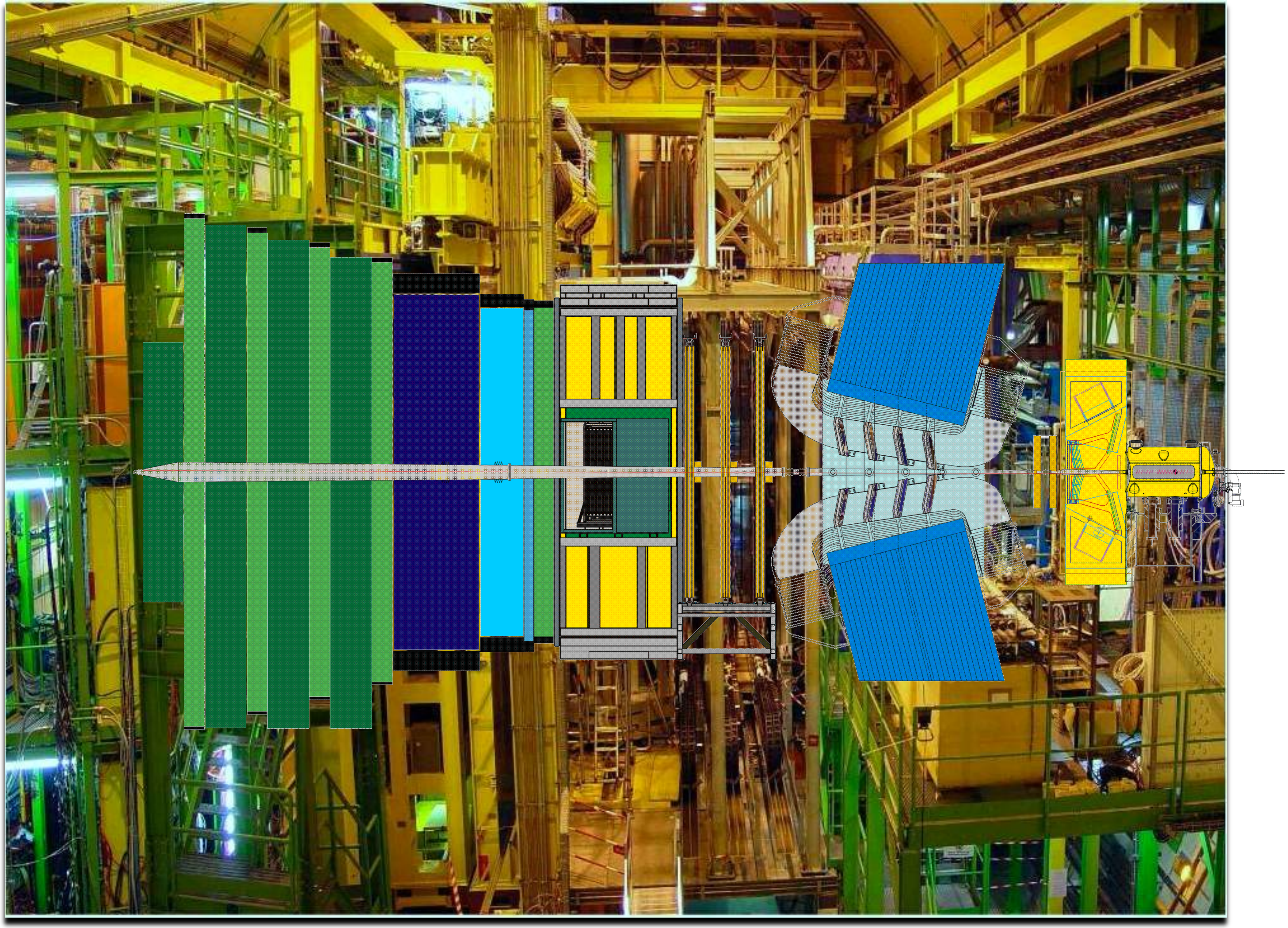
$\sigma_{b\bar{b}}(pp \rightarrow bbX) = (284 \pm 20 \pm 49)\mu b$

$\sigma_{c\bar{c}}(pp \rightarrow ccX) = (6.10 \pm 0.93) mb$

charm is ~20 times more abundant than beauty

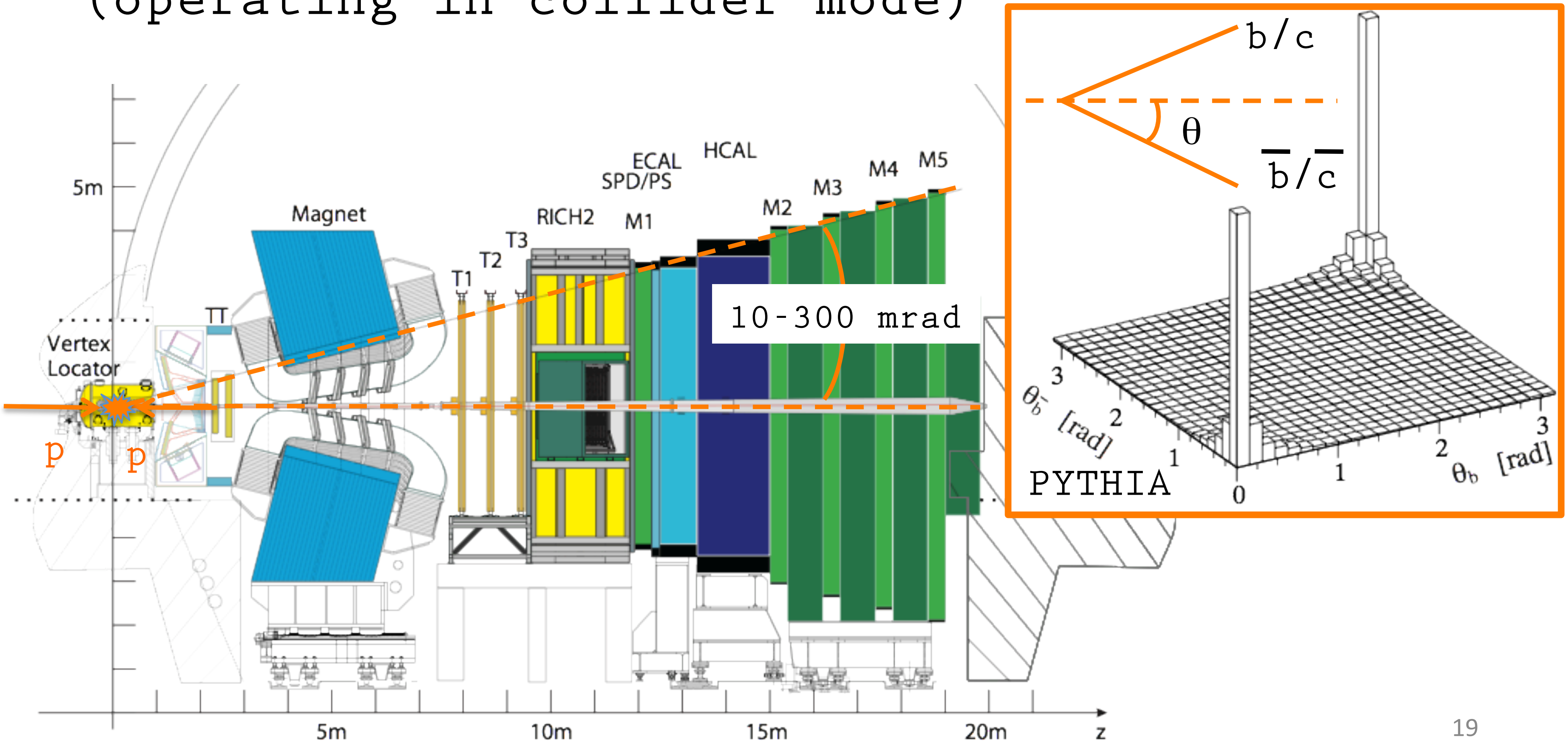
Phys. Lett. B694: 209-216, 2010
LHCb-CONF-2010-013





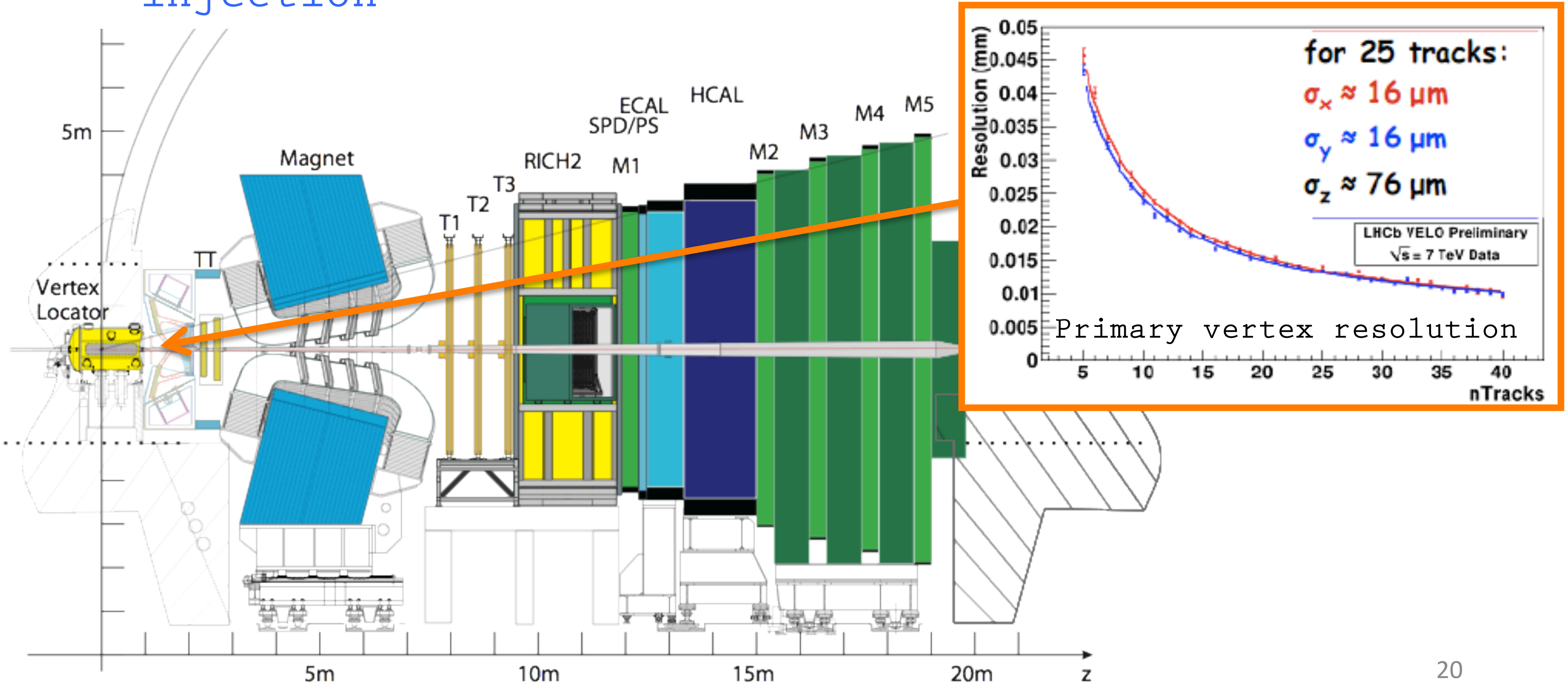
The LHCb detector

- Forward-peaked production of heavy quarks → LHCb designed as forward spectrometer (operating in collider mode)



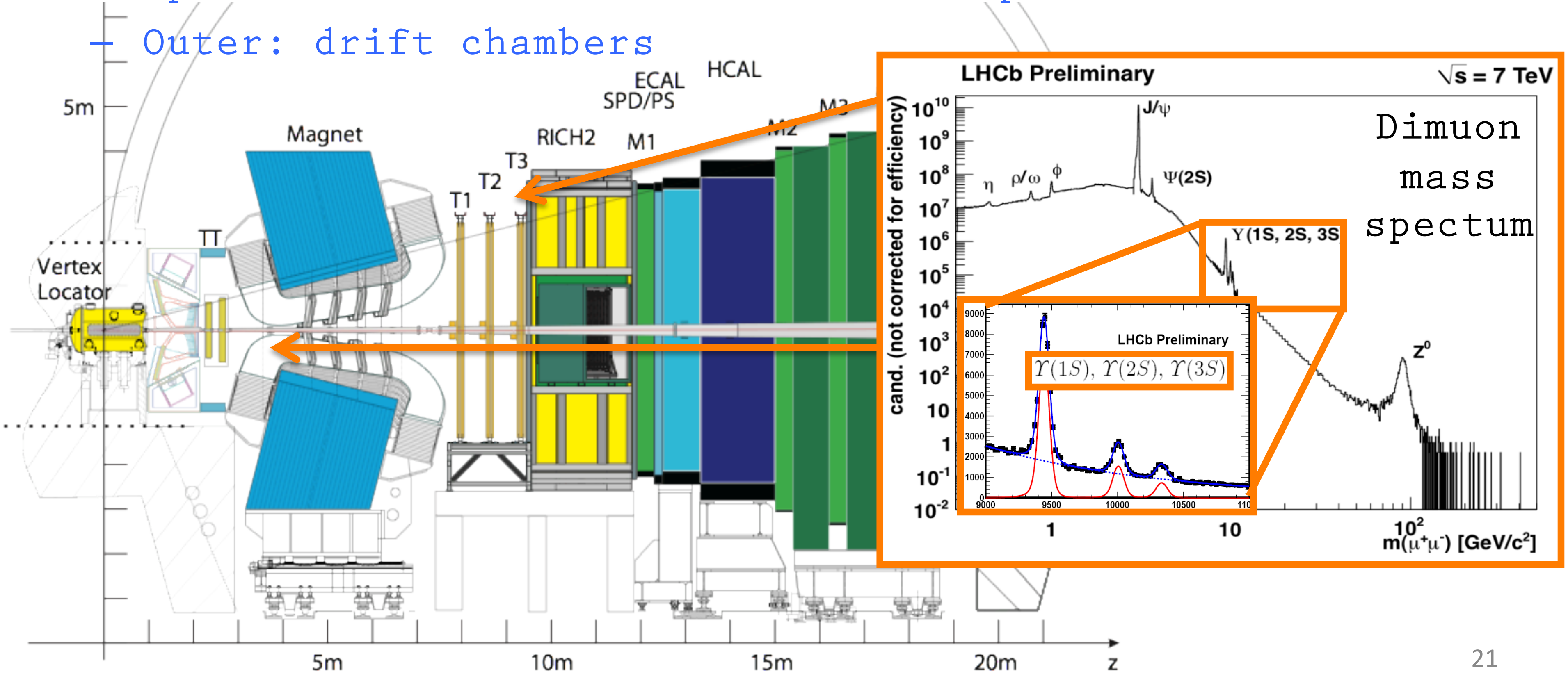
The LHCb detector

- VELO: precision vertexing
  - 42x2 silicon planes, strip pitch 40-100 μm
  - 7mm from beam during data-taking retracted during injection



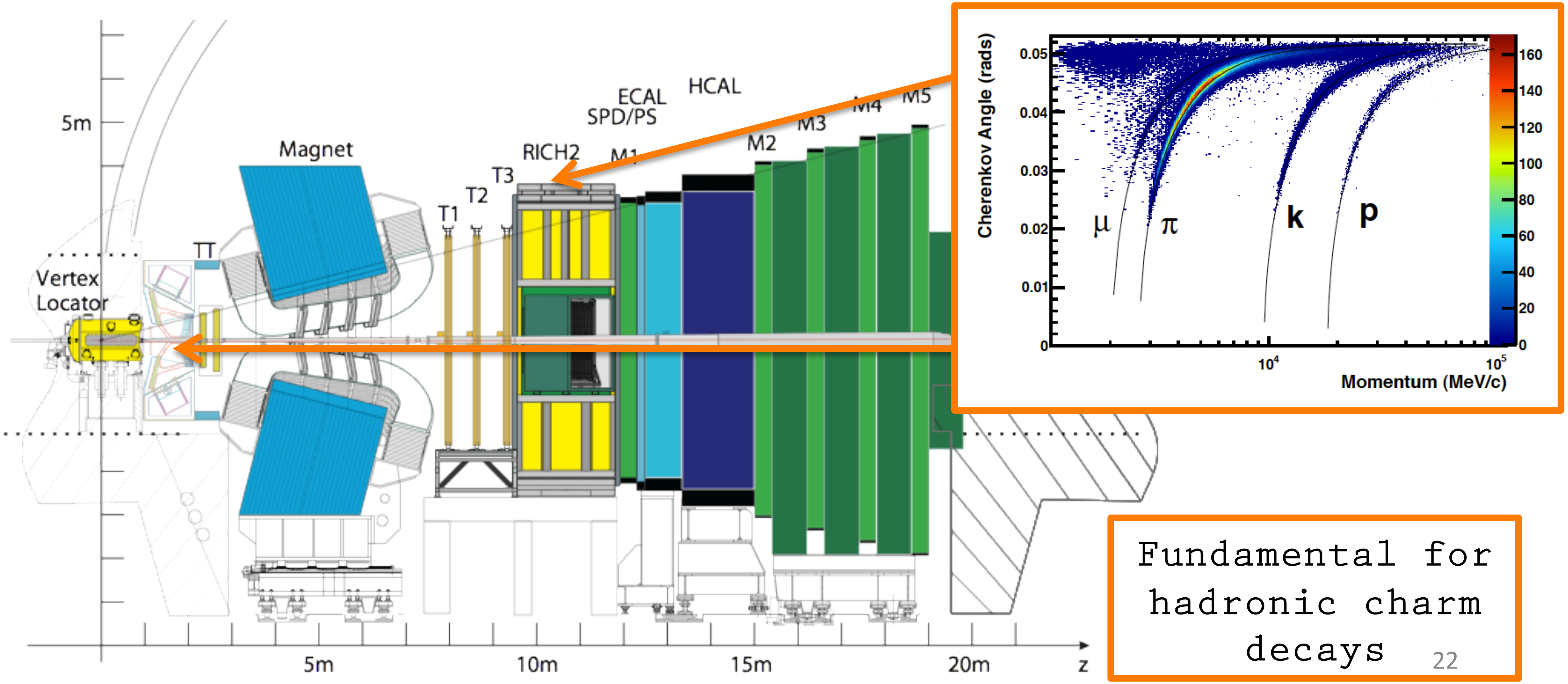
The LHCb detector

- TRACKER systems
  - Magnetic field reverse during data taking, integrated B field 4 Tm. Momentum resolution 0.4-0.6%
  - Stations upstream and downstream of magnet
  - Upstream & inner: silicon microstrips
  - Outer: drift chambers



The LHCb detector

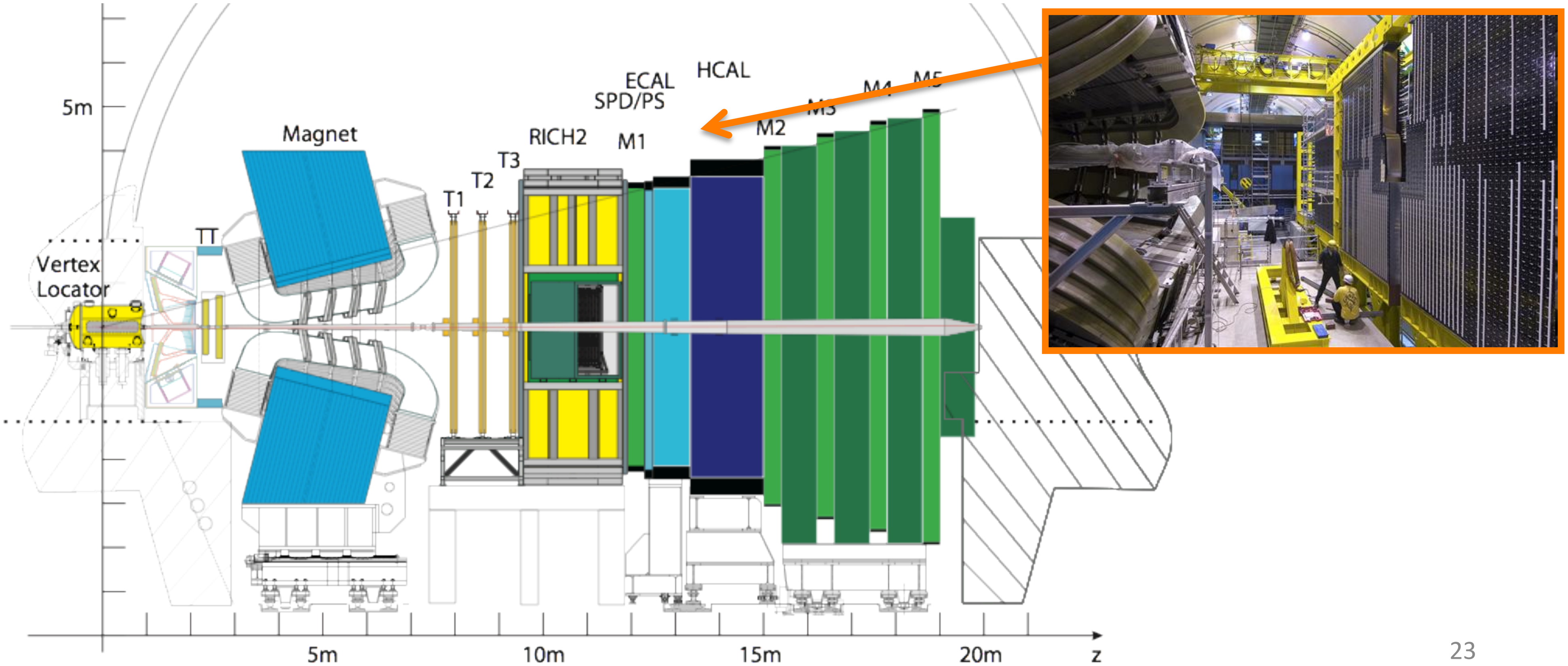
- RICH detectors: hadron ID
  - RICH1 uses aerogel and C_4F_{10} to cover 2-60 GeV/c
  - RICH2 uses CF_4 to cover 20-100 GeV/c
  - Excellent π/K/p separation up to 100 GeV/c



Fundamental for hadronic charm decays

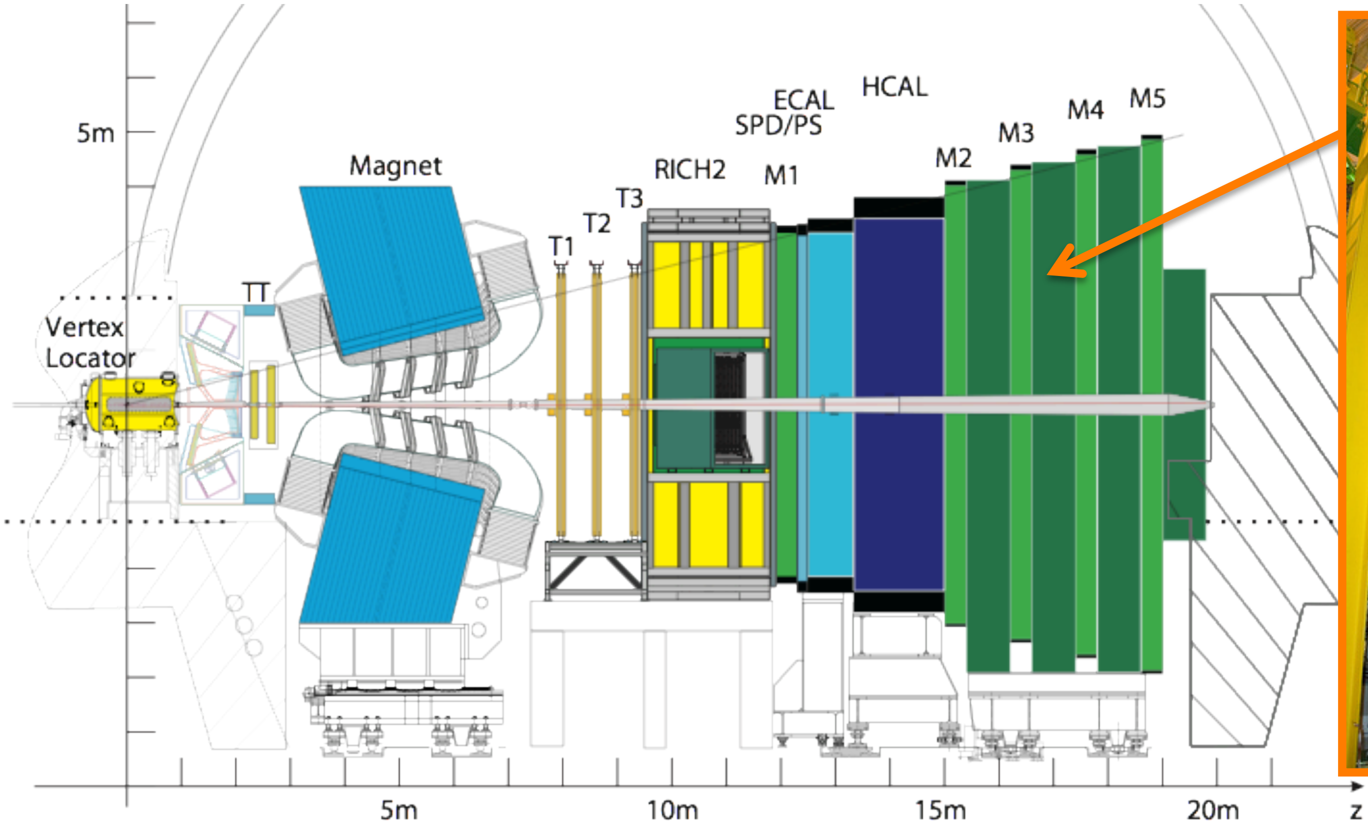
The LHCb detector

- CALORIMETERS: trigger, photon/electron ID
  - Preshower + SPD + electromagnetic + hadronic calorimeters
  - Vital for hardware-level hadron triggering



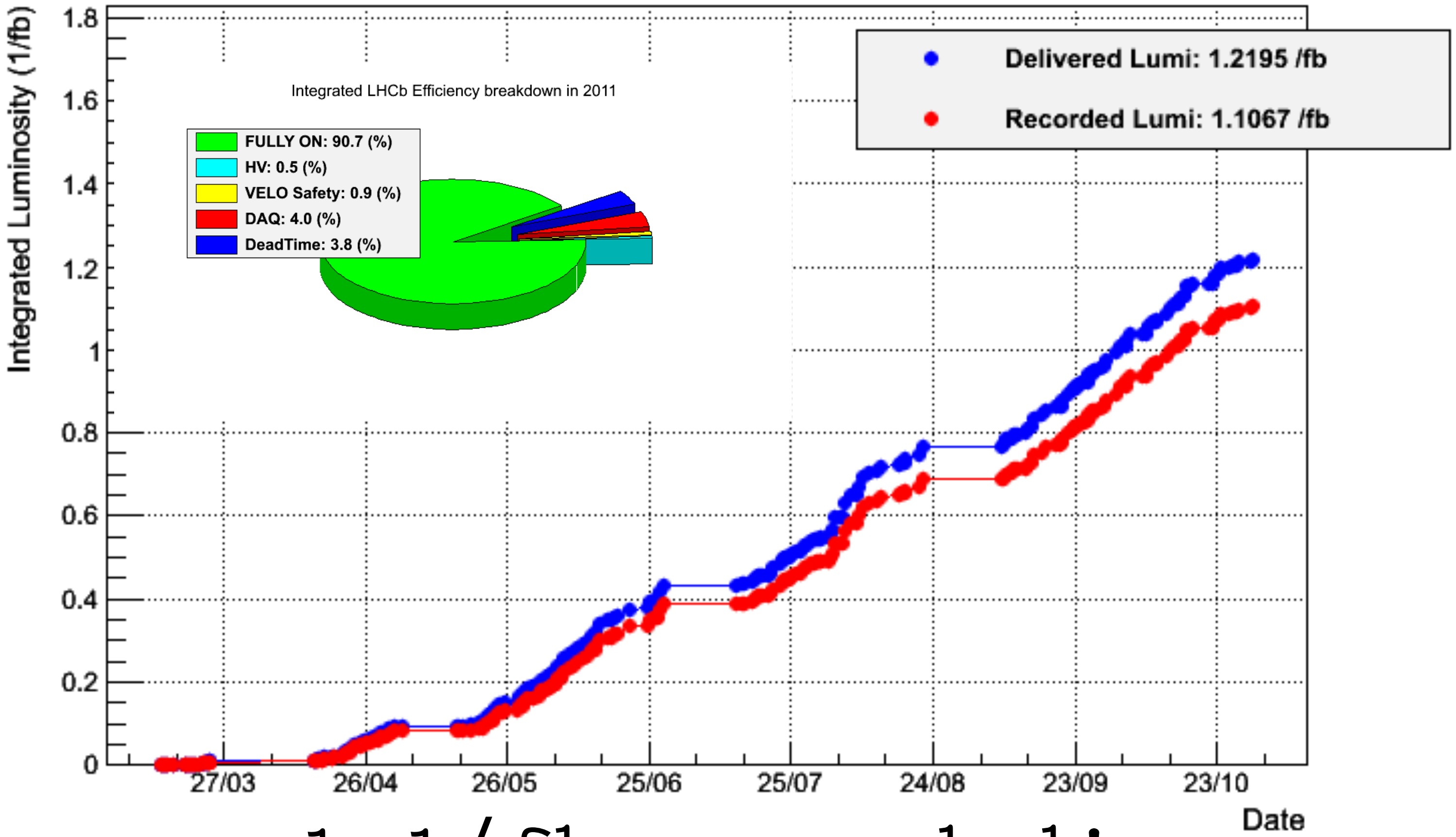
The LHCb detector

- MUON STATIONS: muon ID
  - Five stations, used also in hardware trigger.
  - Excellent muon/pion separation (single hadron mis-ID rate 0.7% Phys. Lett. B699 (2011) 330)



Data-taking

LHCb integrated Luminosity at 7 TeV in 2011



1.1/fb recorded!

Thanks LHC !

Data-taking

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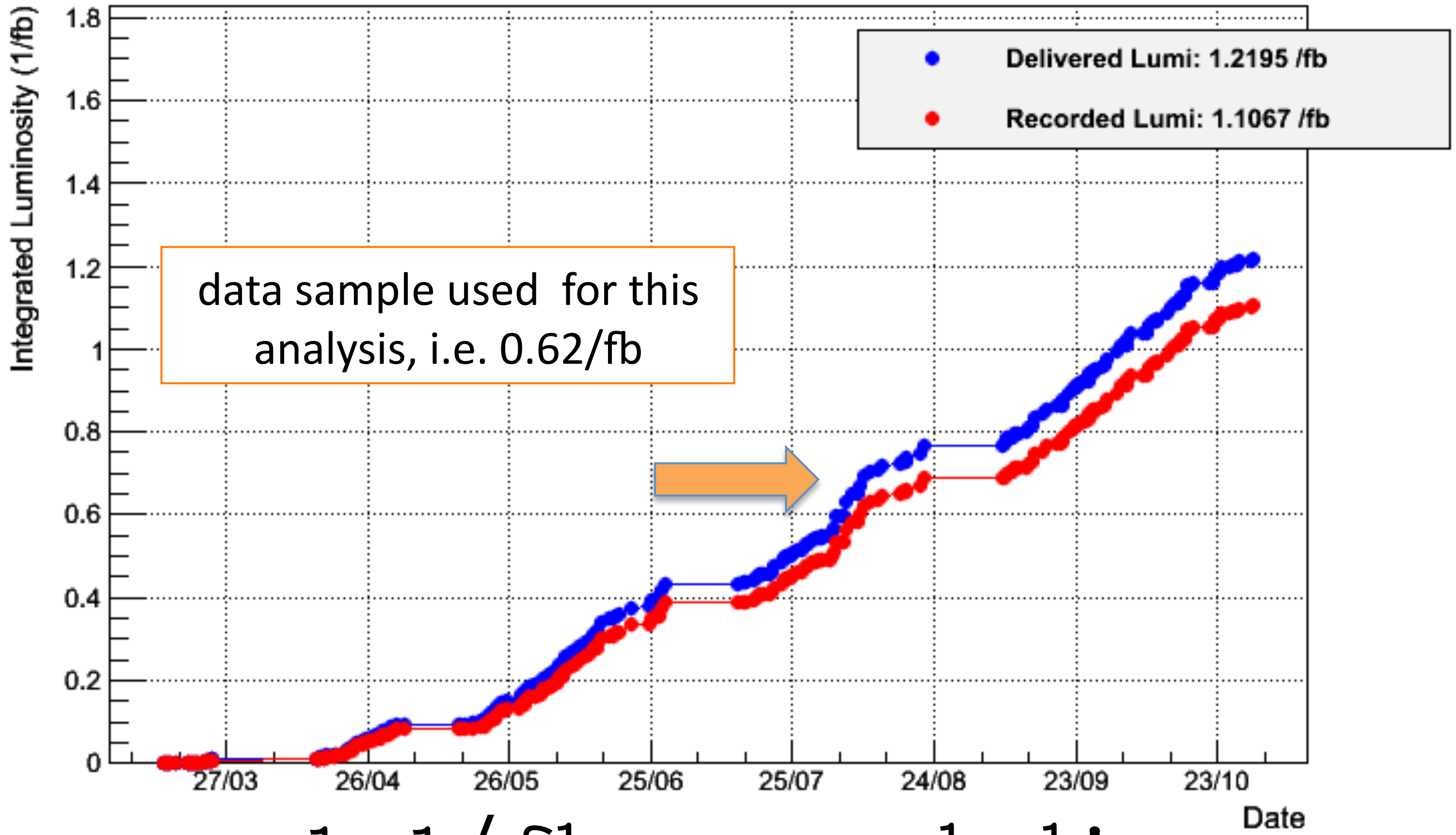

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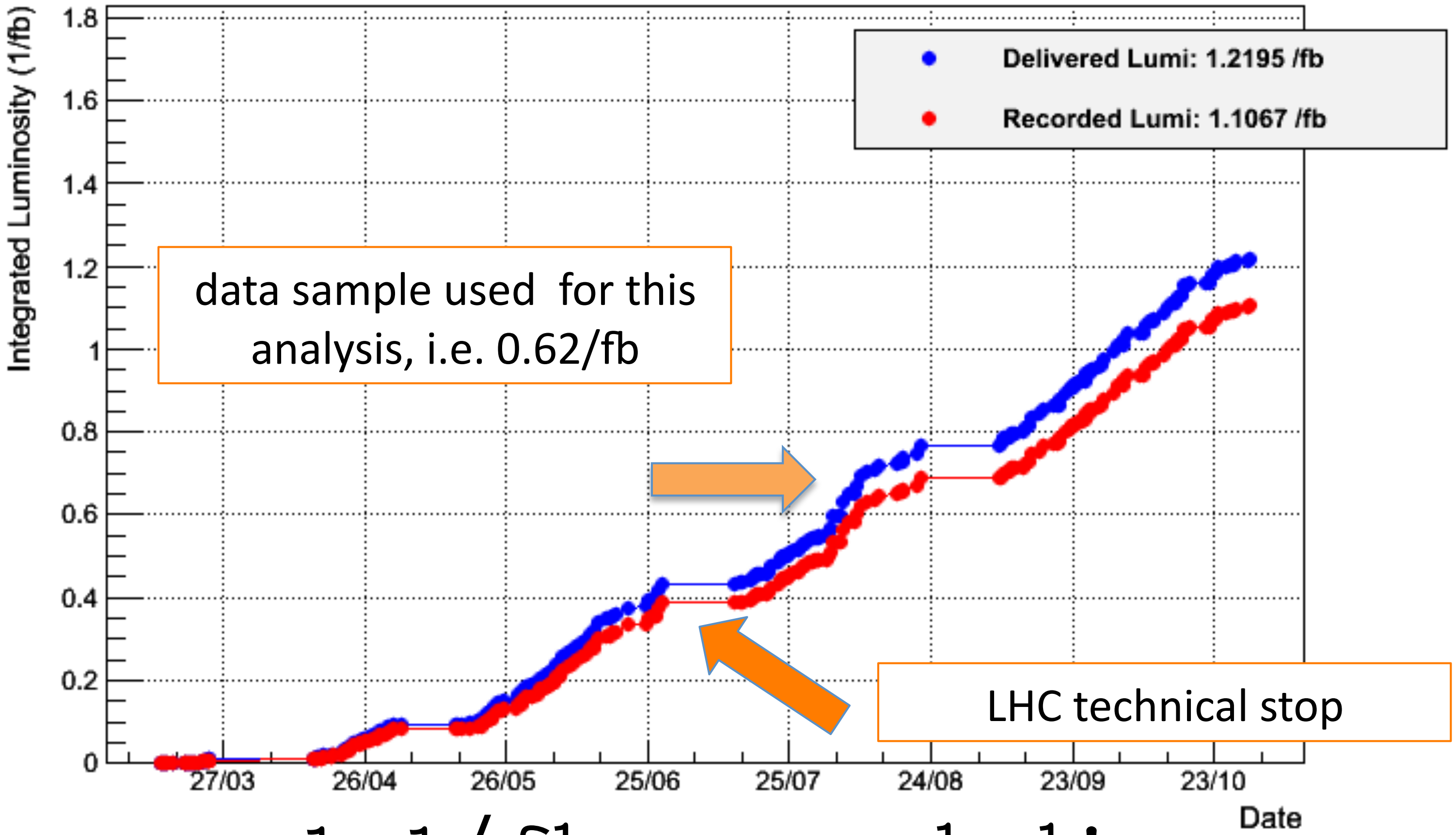
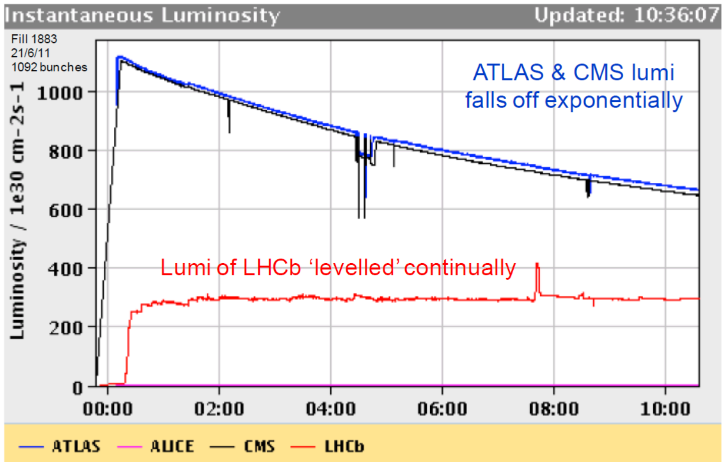


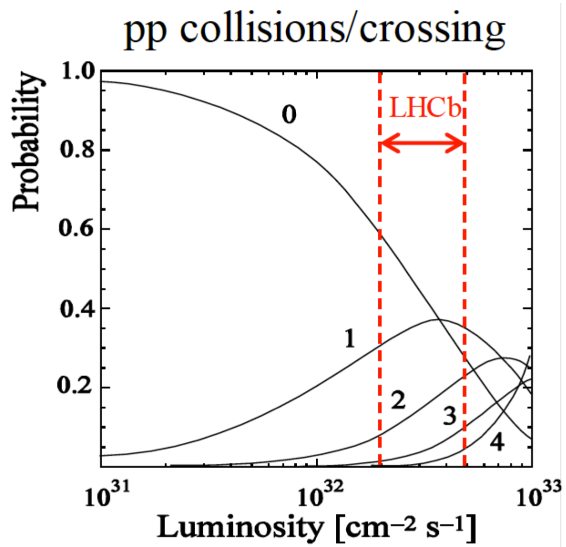
1.1/fb recorded!

Thanks LHC !

Running strategy

- LHCb has different runnings condition with respect to ATLAS and CMS
  - lower luminosity at the interaction point
- LHCb ran above its design luminosity
  - Average L~3×10^{32} $cm^{-2}s^{-1}$ (nominal 2×10^{32})
  - less bunches than nominal (50 ns bunch spacing)
- Need to cope with higher occupancies
  - More pile-up: average μ~1.5 (nominal 0.5)
  - Continuous, automatic adjustment of offset of colliding beams.





The trigger
(from charm point of view)

LHC bunch-crossing frequency
Max possible 40 MHz;
Visible collision 10 MHz

↓ 10 MHz

L0:hardware trigger
Hadrons: require cluster with high E_T
Also muon, electron triggers

↓ 1 MHz

HLT1:inclusive software trigger
Hadrons: require track with high IP,p_T
Also muon, electron and other triggers

↓ 50 kHz

HLT2:exclusive software trigger
Require fully reconstructed D^0,D^+,D_s^+

→ 3 kHz

Storage
About 3kHz total rate
1kHz charm

After hardware trigger we already have 50% $c\bar{c}$ events (500 kHz).

No possibility of an inclusive charm trigger!

Instead, we select useful/ reconstructable events from the most sensitive modes.

Time-integrated search for CPV in $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$

Time-integrated CP asymmetry
(what we measure at LHCb)

- We are looking for CP asymmetry defined as

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

with f=KK and f=ππ and

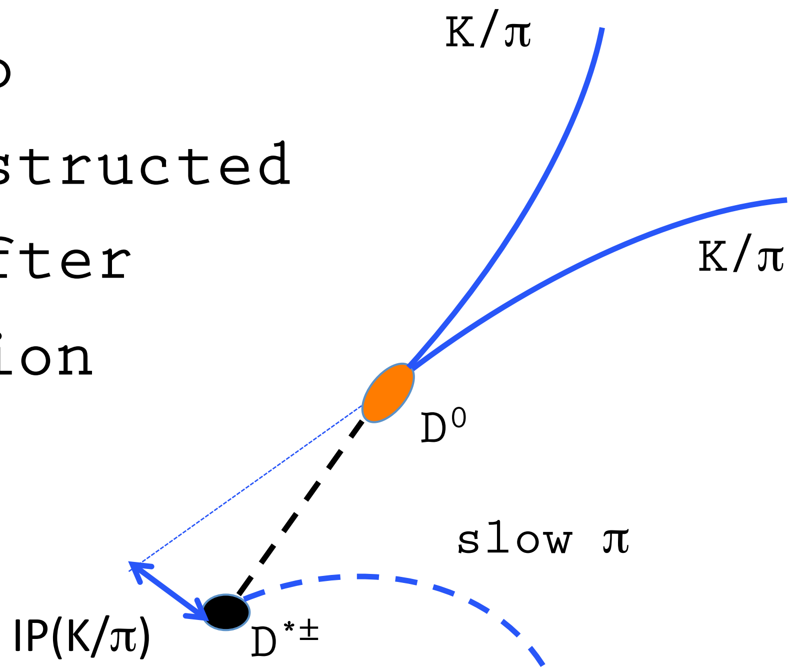
- The flavor of the initial state (D^0 or $\overline{D}^0$) is tagged by requiring a $D^{*+} \rightarrow D^0\pi^+_s$ decay, with the flavour determined by the charge of the slow pion (π^+_s)
- "slow" because of its lower average momentum (~5 GeV/c) with respect to the D^0 daughters (~30 GeV/c)

Time-integrated CP asymmetry
(what we measure at LHCb)

- The raw asymmetry for tagged D^0 decays to a final state f is given by

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

- where N(X) refers to the number of reconstructed events of decay X after background subtraction



Time-integrated CP asymmetry
(what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

Time-integrated CP asymmetry
(what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}) + A_{\rm P}(D^{*+})$$

- First order expansion assumes raw asymmetry not large
  - ... which is true: O(%)

Time-integrated CP asymmetry
(what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\mathrm{raw}}(f) = \boxed{A_{CP}(f)} + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

Physics CP asymmetry

Time-integrated CP asymmetry
(what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

Physics CP asymmetry

Detection asymmetry of D^0

Time-integrated CP asymmetry
(what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

Physics CP asymmetry

Detection asymmetry of D^0

Detection asymmetry of “slow” pions

Time-integrated CP asymmetry
(what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

- $A_{CP}(f)$: Physics CP asymmetry
- $A_{\mathrm{D}}(f)$: Detection asymmetry of D^0
- $A_{\mathrm{D}}(\pi_{\mathrm{s}})$: Detection asymmetry of “slow” pions
- $A_{\mathrm{P}}(D^{*+})$: Production asymmetry

- D/$\overline{\mathrm{D}}$ (as well as B/$\overline{\mathrm{B}}$) production asymmetries need to be taken into account in proton-proton interactions at LHC

Time-integrated CP asymmetry
(what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{D}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

Physics CP asymmetry

Detection asymmetry of D^0

Production asymmetry

Detection asymmetry of "slow" pions

- No detection asymmetry for D^0 decays to K^-K^+ or $\pi^-\pi^+$

Time-integrated CP asymmetry
(what we measure at LHCb)

- … if we take the raw asymmetry difference

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

- the production and the “slow” pion detection asymmetries will cancel

Experimental status
(individual A_{CP})

Year	Experiment	CP Asymmetry in the decay mode D0 to π+π-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2010	CDF	M.J. Morello (CDF Collab.), Preprint (CHARM 2010).	+0.0022 ± 0.0024 ± 0.0011
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 2008).	+0.0043 ± 0.0052 ± 0.0012
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
.	.	COMBOS average	+0.0020 ± 0.0022

Year	Experiment	CP Asymmetry in the decay mode D0 to K+K-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2011	CDF	A. Di Canto (CDF Collab.), Preprint (BEAUTY 2011).	-0.0024 ± 0.0022 ± 0.0010
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).	-0.0043 ± 0.0030 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	+0.0000 ± 0.0034 ± 0.0013
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.000 ± 0.022 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	-0.001 ± 0.022 ± 0.015
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.010 ± 0.049 ± 0.012
1995	CLEO	J.E. Bartelt et al. (CLEO Collab.), Phys. Rev. D 52, 4860 (1995).	+0.080 ± 0.061
1994	E687	P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).	+0.024 ± 0.084
.	.	COMBOS average	-0.0023 ± 0.0017

Dominated by CDF, especially for $D^0 \to \pi^+\pi^-$

K^+K^- and $\pi^+\pi^-$ values consistent with zero but have opposite sign.

ΔA_{CP} interpretation

- The physics asymmetry of each final state may be written at first order as[arXiv:1103.5785]

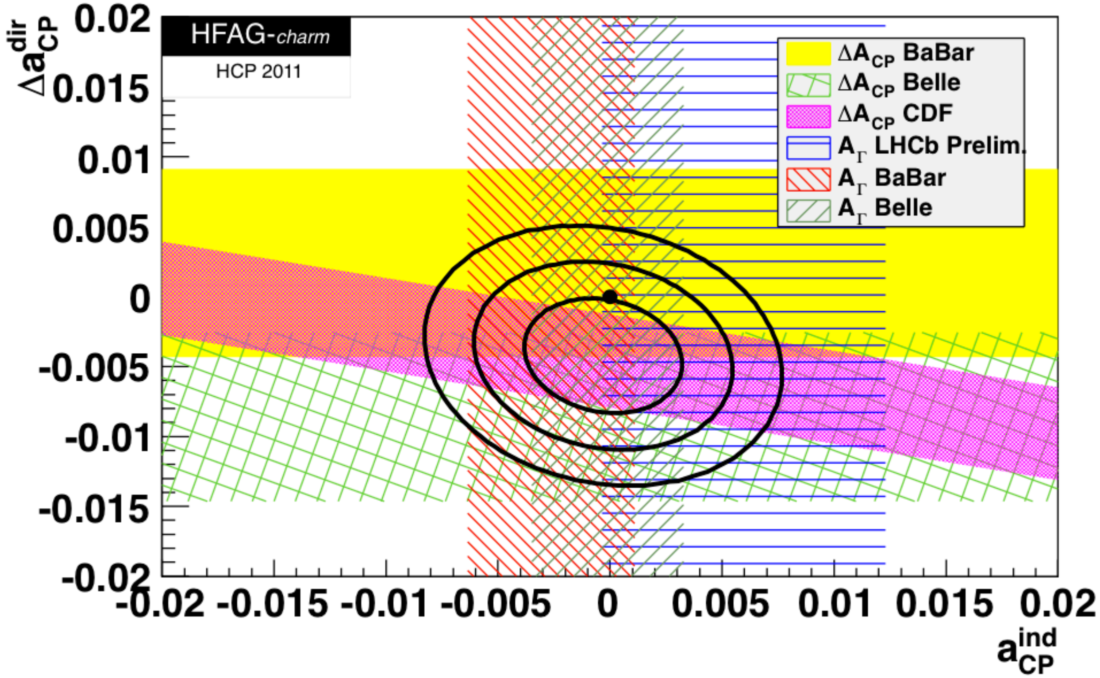
$$A_{CP}(f) \approx a_{CP}^{\rm dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{\rm ind}$$

  - $a^{dir}_{CP}(f)$ is the direct CP asymmetry in the decay
  - $\langle t \rangle$ is the average decay time→ experiment dependent
  - τ is the D^0 lifetime
  - $a^{ind}_{CP}(f)$ is the CP asymmetry due to the the mixing and/or the interference between mixing and decay
- To a good approximation $a^{ind}_{CP}(f)$ does not depend on the final state [**arXiv:0609178**], and so:

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

- In the limit of U-spin symmetry, $a^{dir}_{CP}(f)$ is equal in magnitude and opposite in sign for K^+K^- and $\pi^+\pi^-$
- Interpretation of ΔA_{CP} depends on experiment

Experimental status
(ΔA_{CP})



World average $\Delta a_{CP}{}^{dir}$
1.6σ from zero

HFAG combination

$$a_{CP}^{ind} = (-0.03 \pm 0.23)\%$$

$$\Delta a_{CP}^{dir} = (-0.42 \pm 0.27)\%$$

Consistency with NO CPV hypothesis: 28%

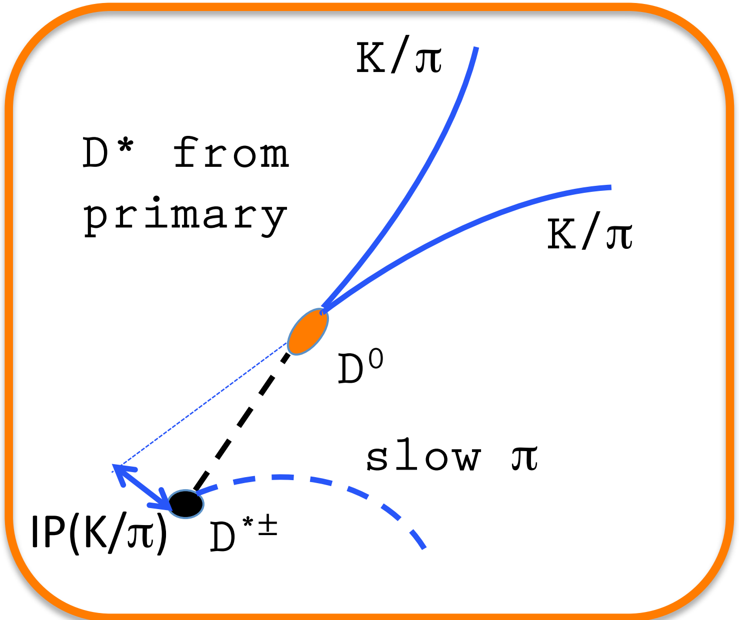
New CDF measurement
ΔA_{CP}=[-0.46±0.31±0.12]%
arXiv:1111.5023

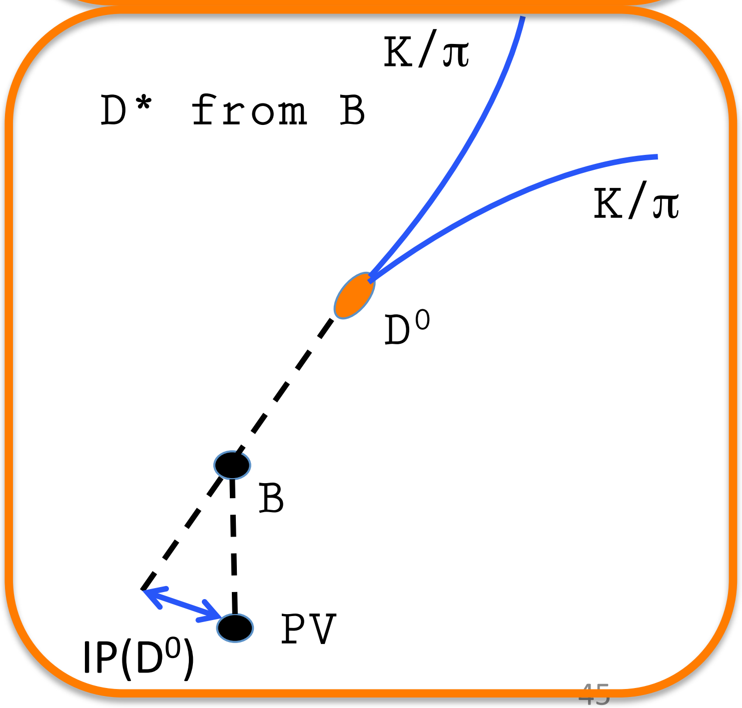
ΔA_{CP} extraction strategy

- ΔA_{CP} robust against systematics, however detector effect can induce different fake asymmetries for KK and ππ:
  - Dependence of $A_P(f)$ and $A_D(f)$ with respect to KK/ππ efficiency ratio
- Solution: divide data into bins of the variable (such that no correlation within bin) and treat each bin independently.
  - Divide data into kinematic bins of p_T of D^{*+}, η of D^{*+}, p of slow pion.
- Along similar lines:
  - split by magnet polarity (B field up/down)
  - split into left/right hemisphere (slow pion momentum points left/right of the bending plane)
  - split into two run groups (before & after technical stop)
- 216 independent measurements of ΔA_{CP}

Event selection

The following offline selection cuts have been applied on events which fired the software trigger explicitly on D^0 candidate:



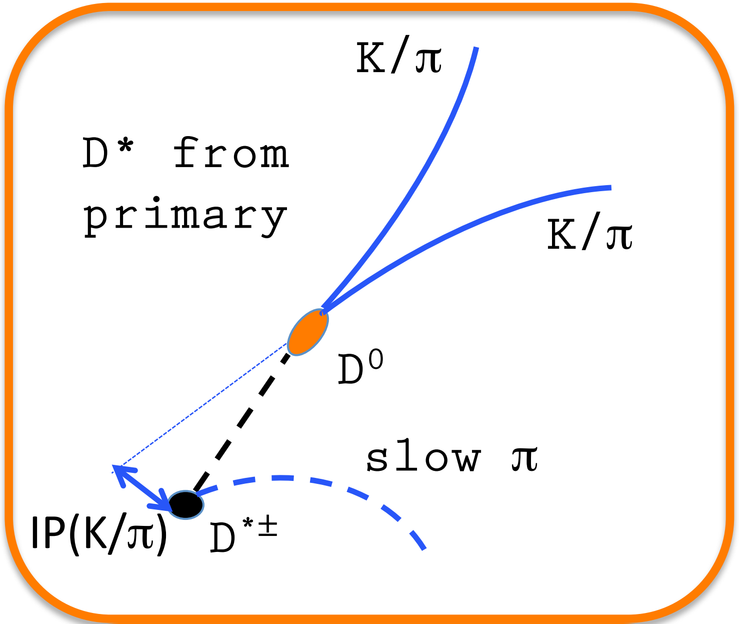


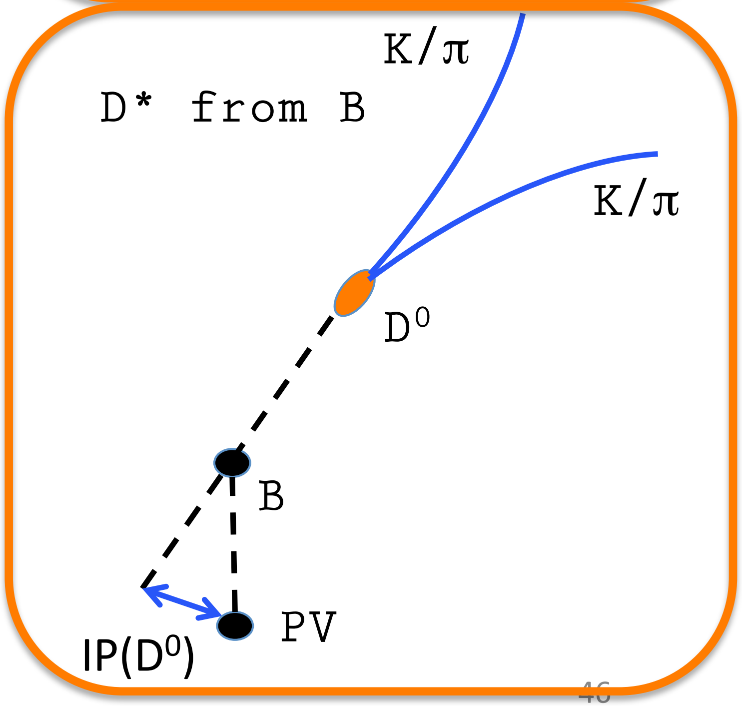
Event selection

The following offline selection cuts have been applied on events which fired the software trigger explicitly on D^0 candidate:

Track fit quality for all the tracks

D^0 and $D^{*\pm}$ vertex fit quality





Event selection

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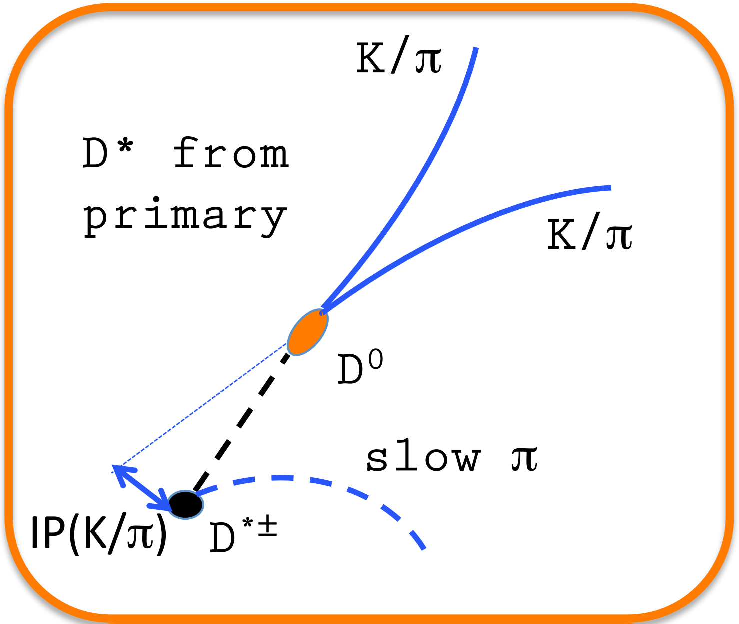
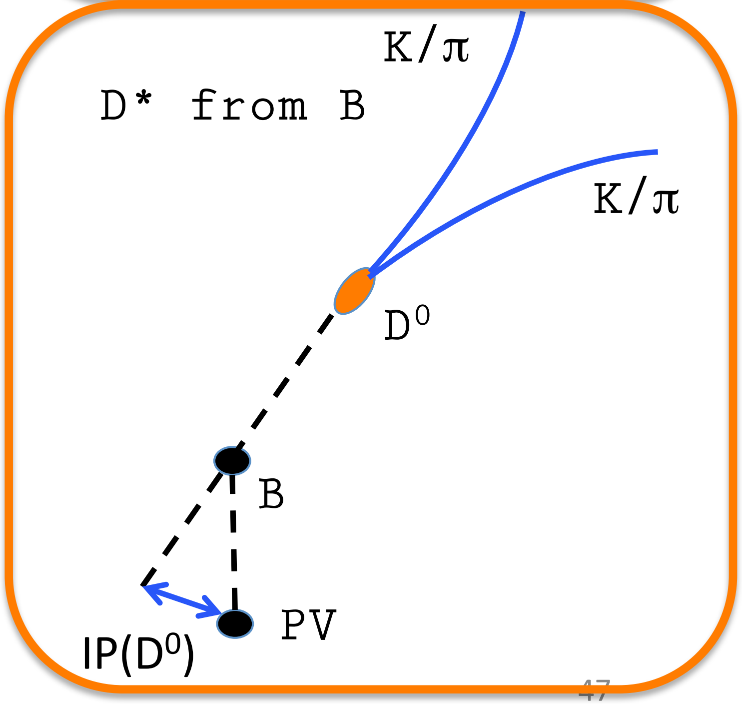
Track fit quality for all the tracks

D^0 and $D^{*\pm}$ vertex fit quality

Transverse momentum of D^0 (p_T>2 GeV)





Event selection

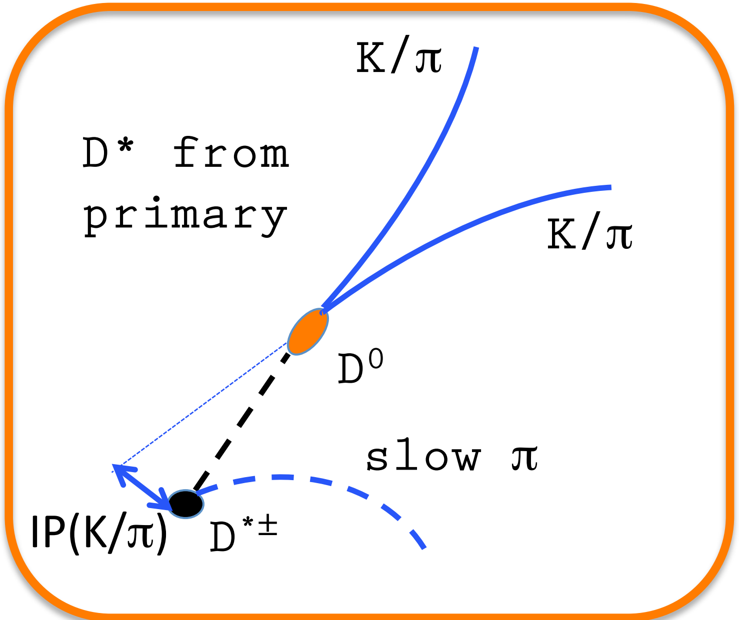
The following offline selection cuts have been applied on events which fired the software trigger explicitly on D^0 candidate:

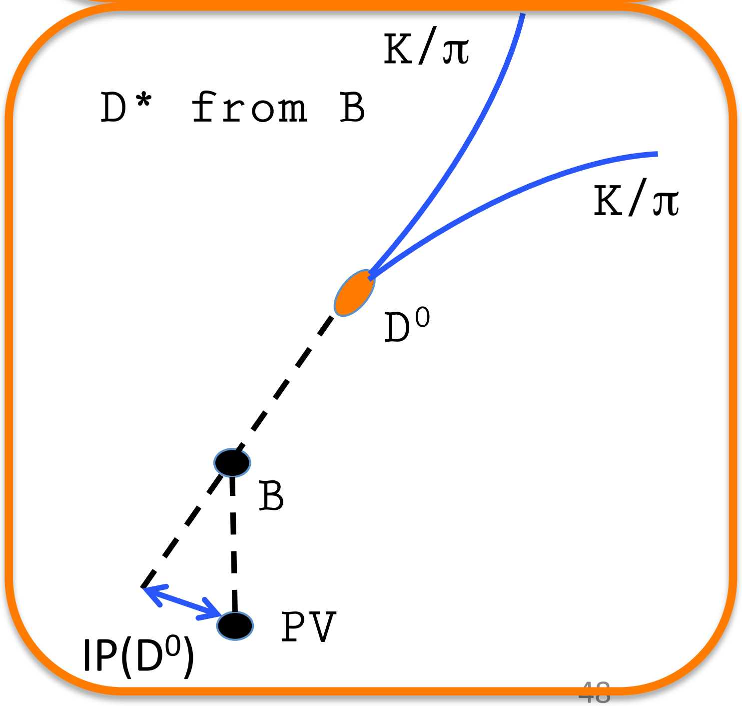
Track fit quality for all the tracks

D^0 and $D^{*\pm}$ vertex fit quality

Transverse momentum of D^0 (p_T>2 GeV)

Proper lifetime of D^0 (ct>100μm)





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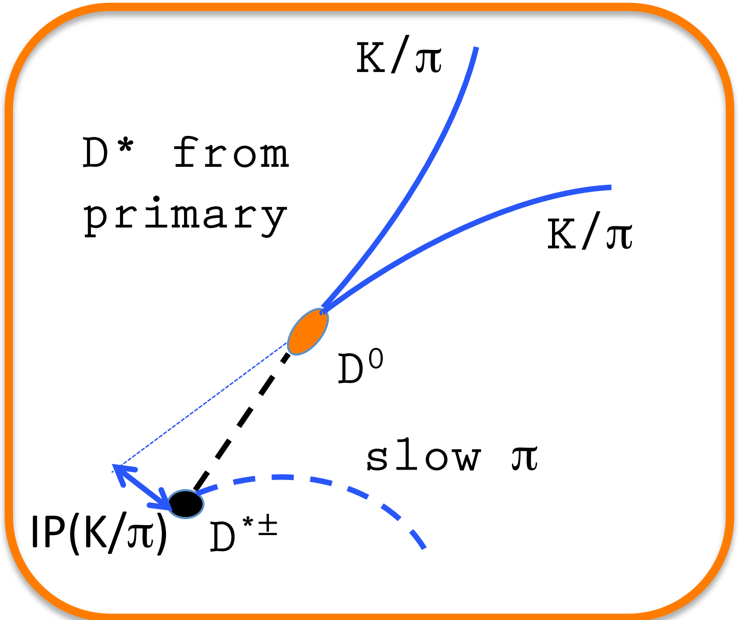

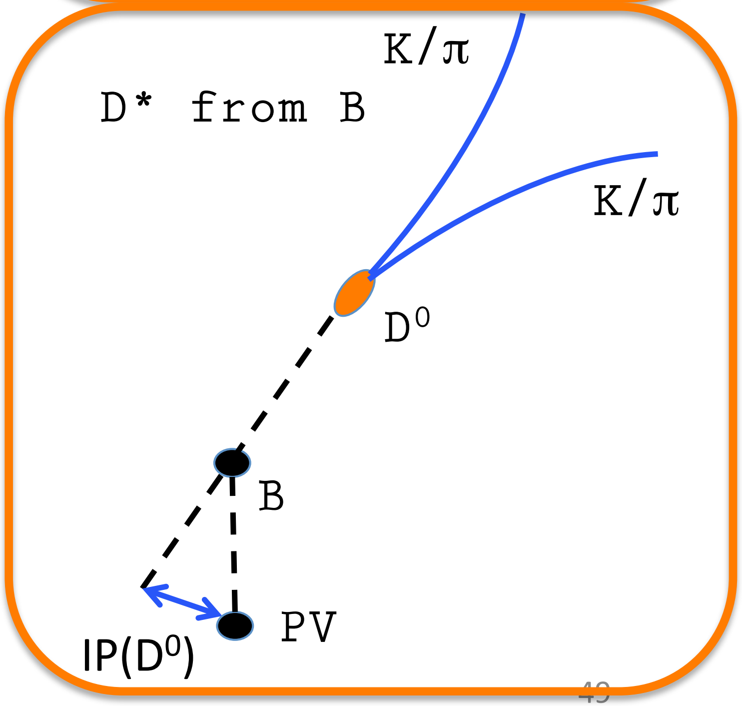

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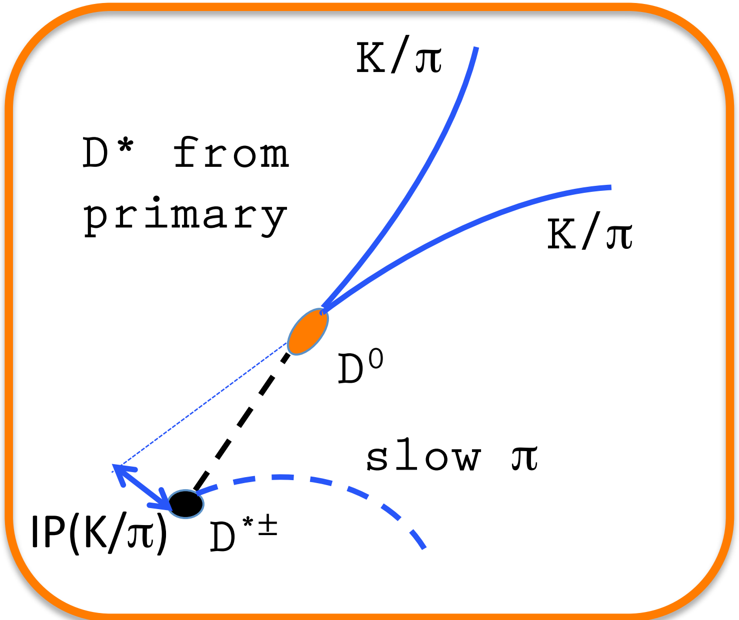
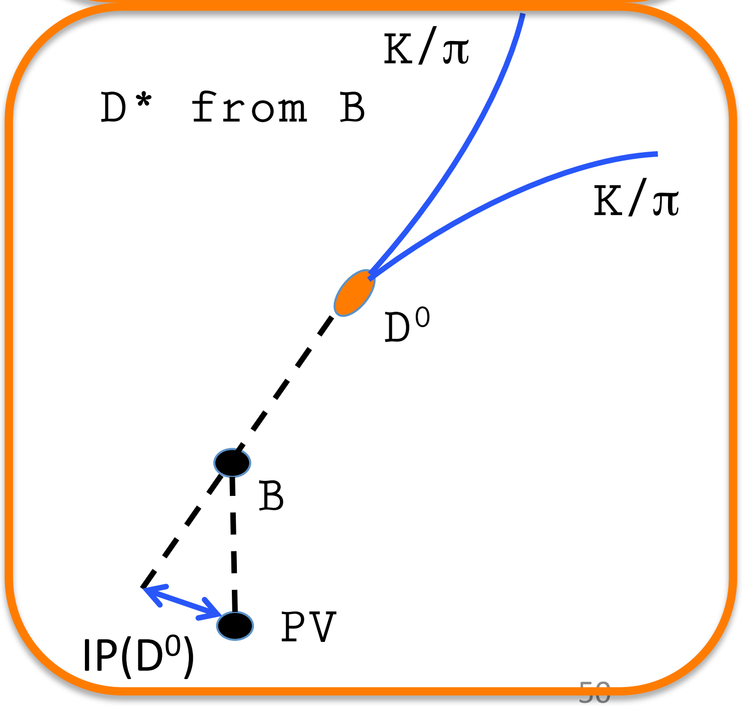
Angle between the D^0 momentum in the lab frame and its daughter momenta in the D^0 rest frame ($|\cos\theta|$ <0.9)

D^0 must point back to primary vertex (reject D^0 coming B)

→ 3% of B contamination after this cut

→ only lifetime measurements effected not ΔA_{CP}





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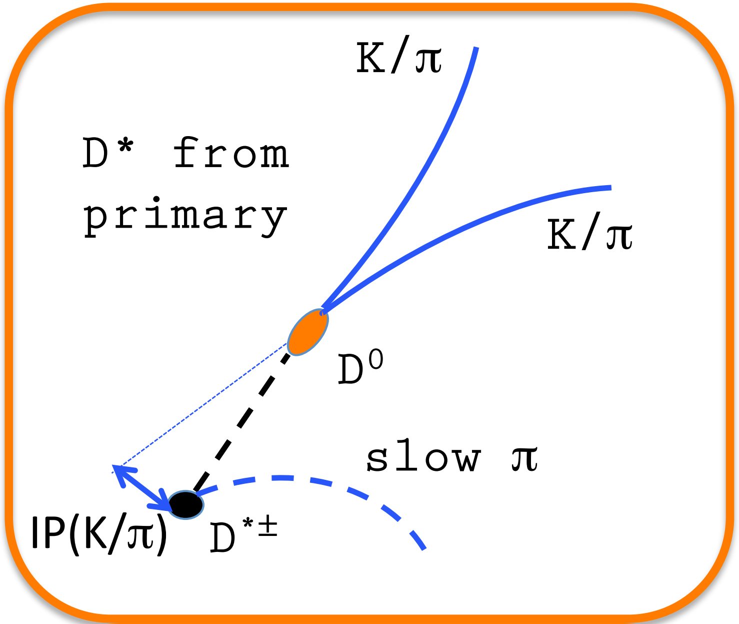

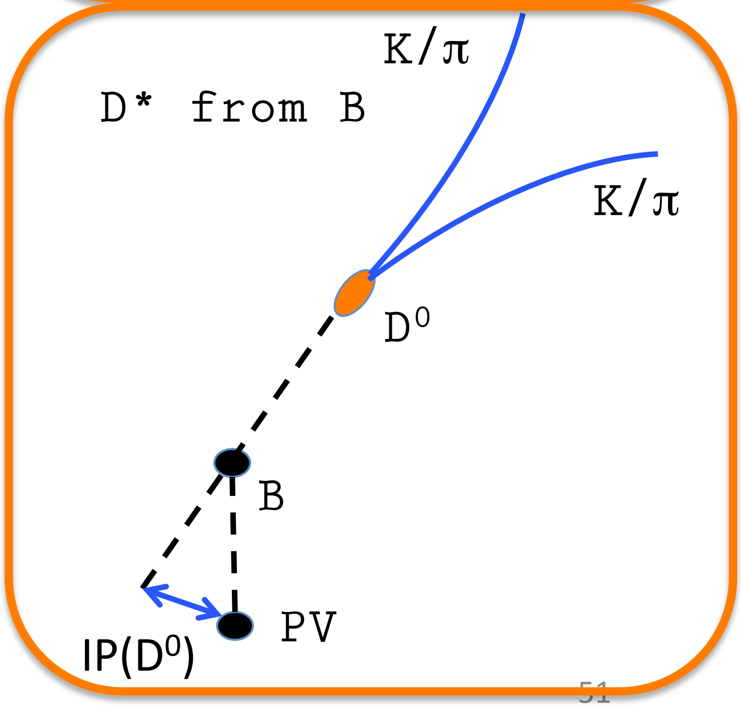

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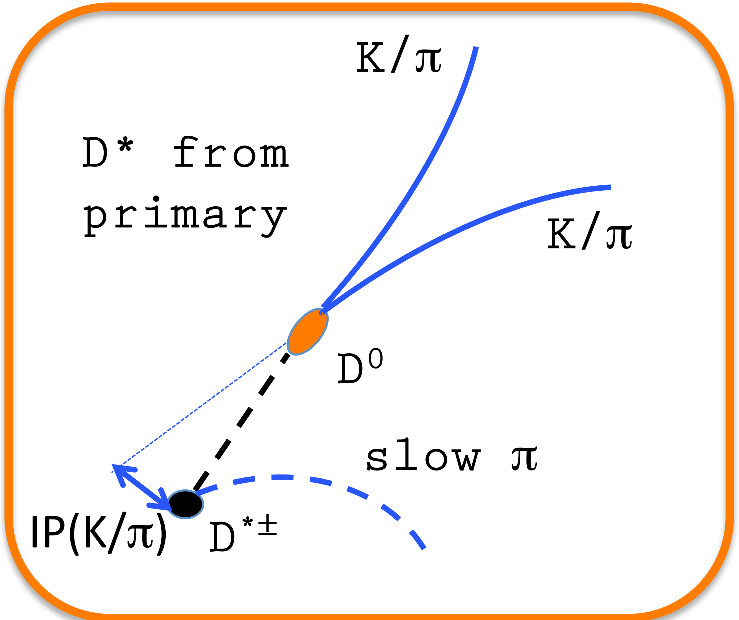

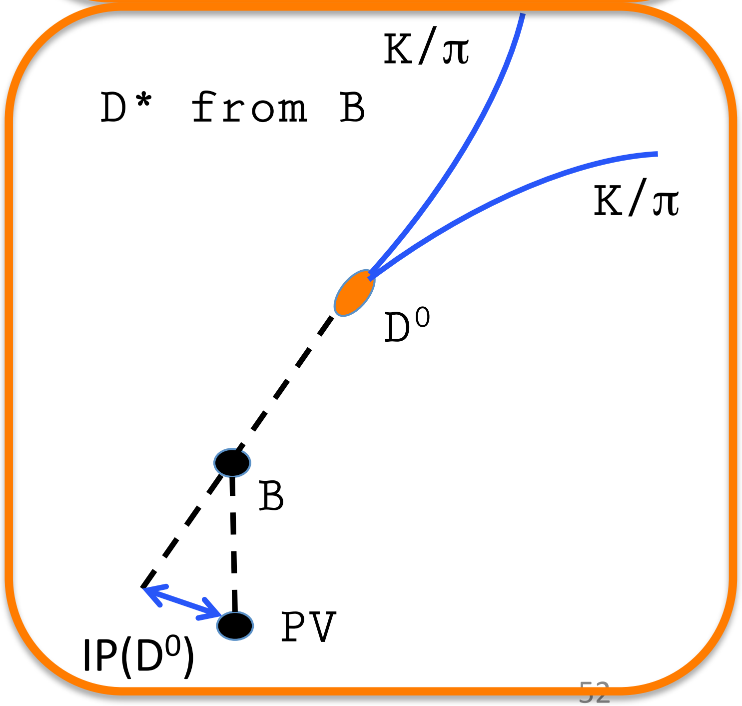

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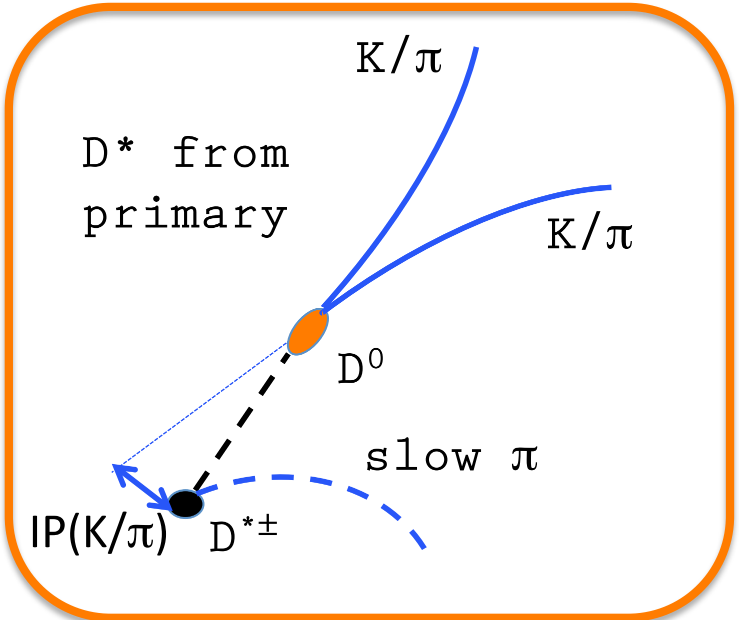

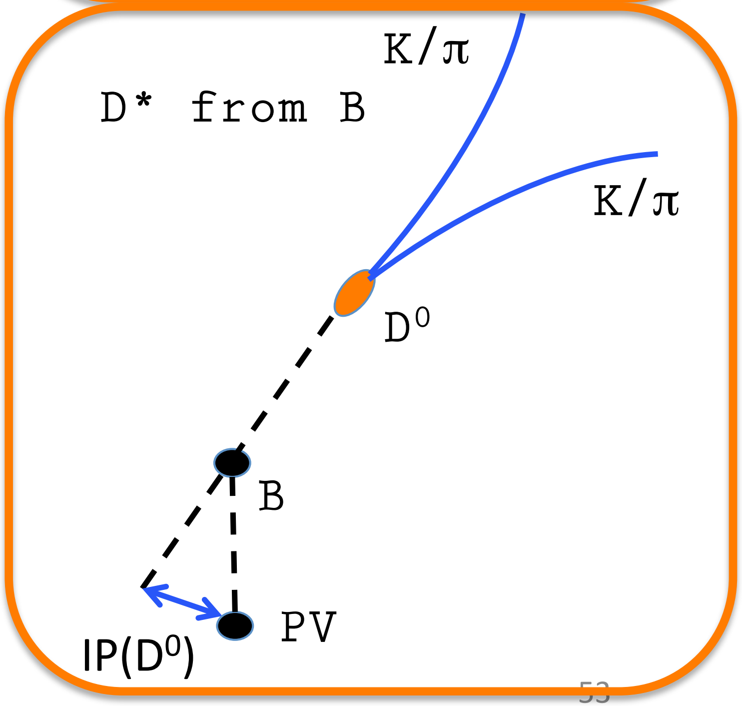

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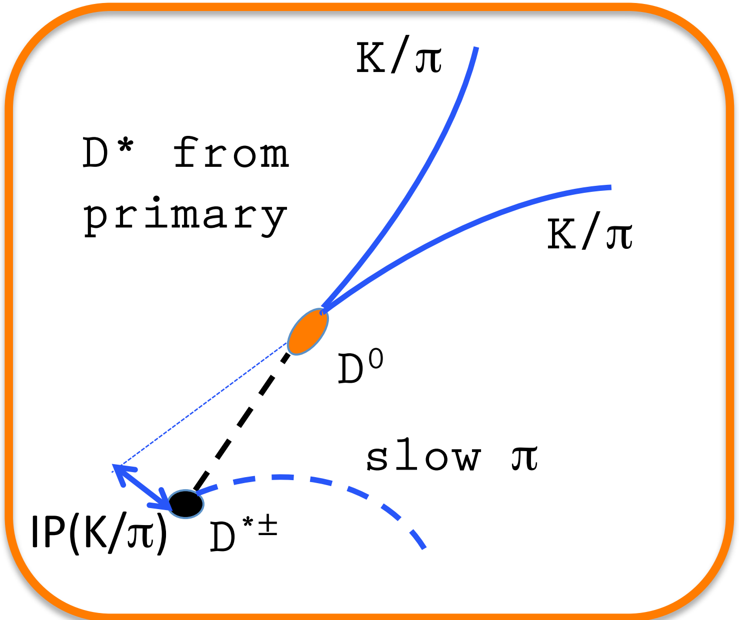
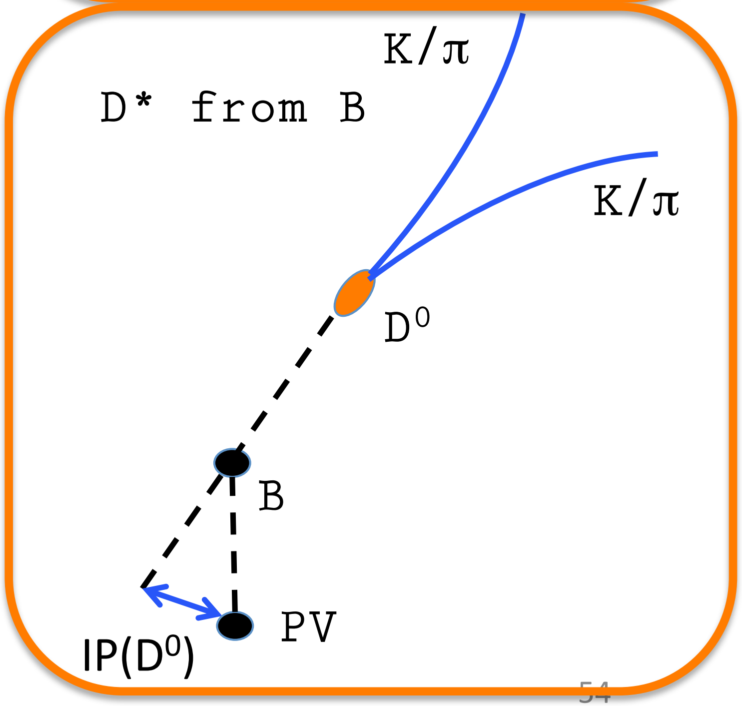
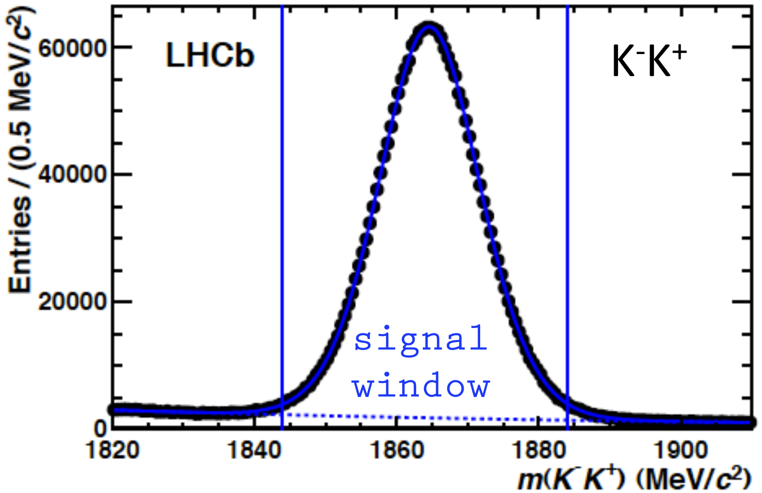
D^0 mass window ($1844 < m(D^0) < 1884$ MeV/c^2)

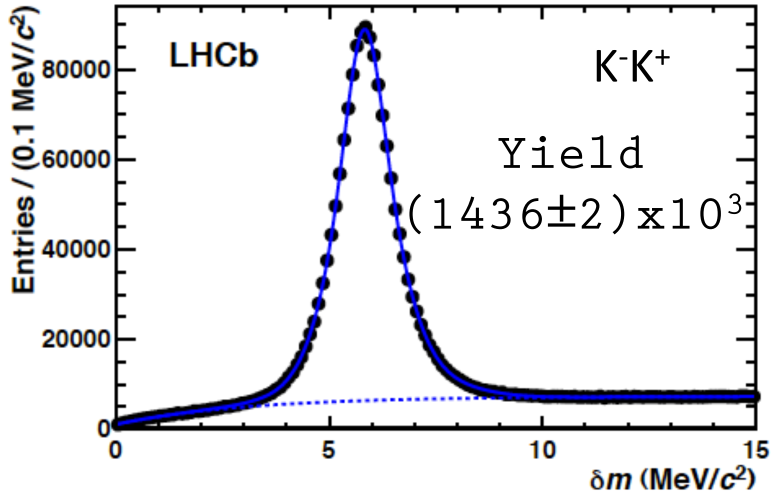




Mass spectra

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





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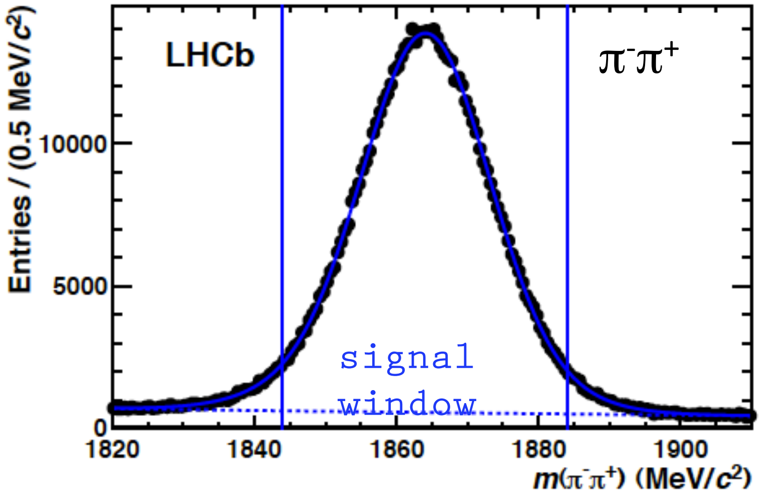
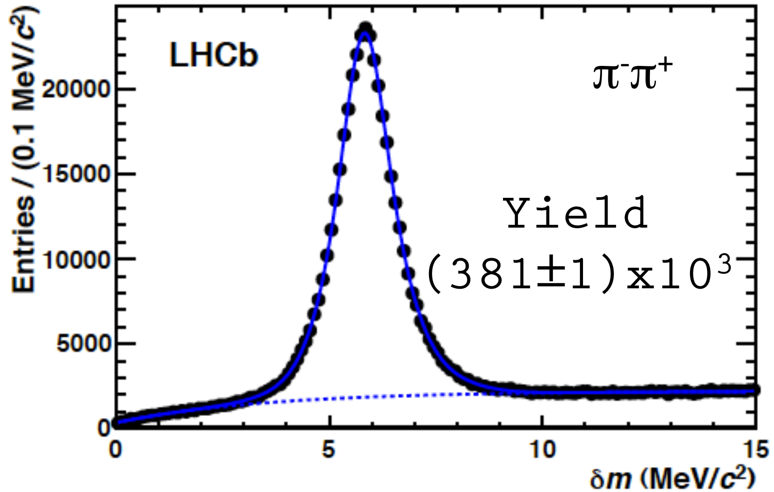


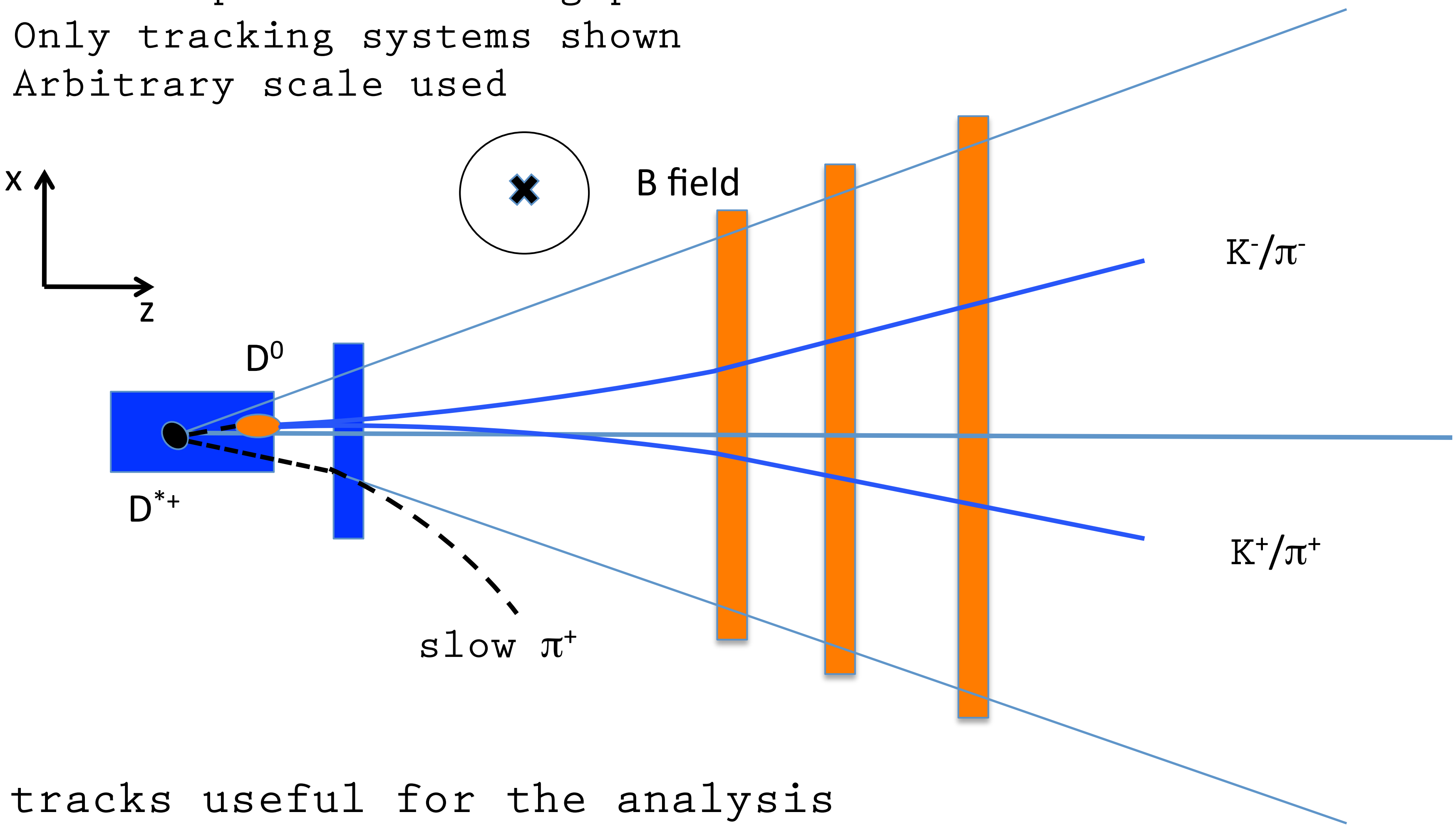


Peaking background

- Mis-reconstructed D^{*+} decays that peaks in δm but not $m(D^0)$, i.e.:
  - $D^{*+} \rightarrow D^0(K^- \pi^+ \pi^0)\pi^+$, where the π^0 is missing and the π^- is mis-reconstructed as K or proton
  - Semi-leptonic D^0 decays
- Background studied on δm from the D^0 sidebands, upper and lower, after signal-subtraction, leaving the component that does not peak in $m(D^0)$.
- Estimated to be 1% both for KK and $\pi\pi$.
- Systematic evaluated with toy studies injecting peaking background with a level and asymmetry from this study.

D^{*+}/D^{*-} reconstruction efficiency

LHCb simplified bending plane view
Only tracking systems shown
Arbitrary scale used



tracks useful for the analysis
must cross all the tracking
station

D^{*+}/D^{*-} reconstruction efficiency

LHCb simplified bending plane view
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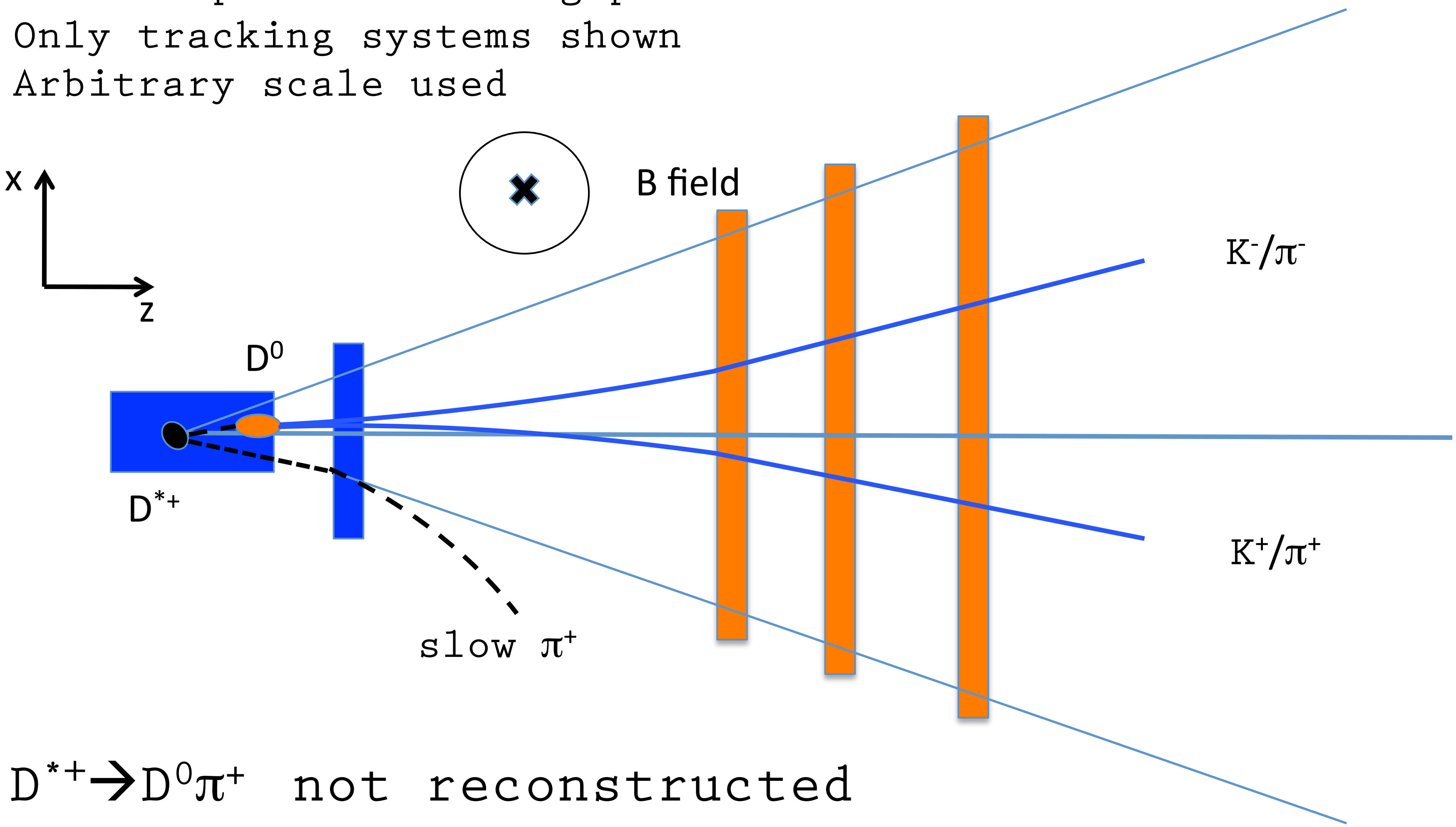

$D^{*+} \rightarrow D^0\pi^+$ not reconstructed

D^{*+}/D^{*-} reconstruction efficiency

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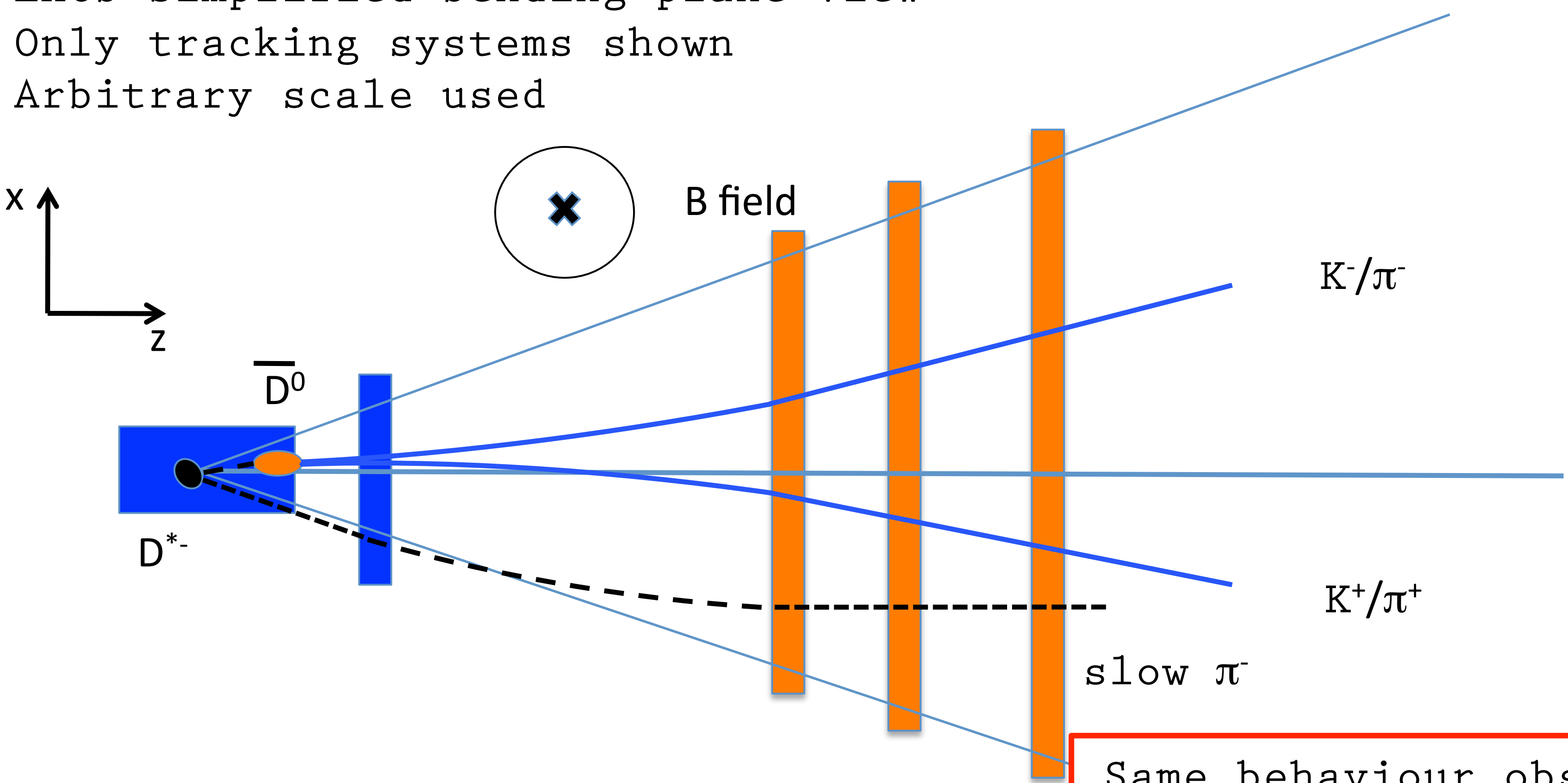


$D^{*+} \rightarrow D^0\pi^+$ not reconstructed
$D^{*-} \rightarrow D^0\pi^-$ reconstructed

Same behaviour observed also for tracks which cross the beam-pipe, (i.e. small $|P_y/P_z|$ of slow π)

Fiducial cuts

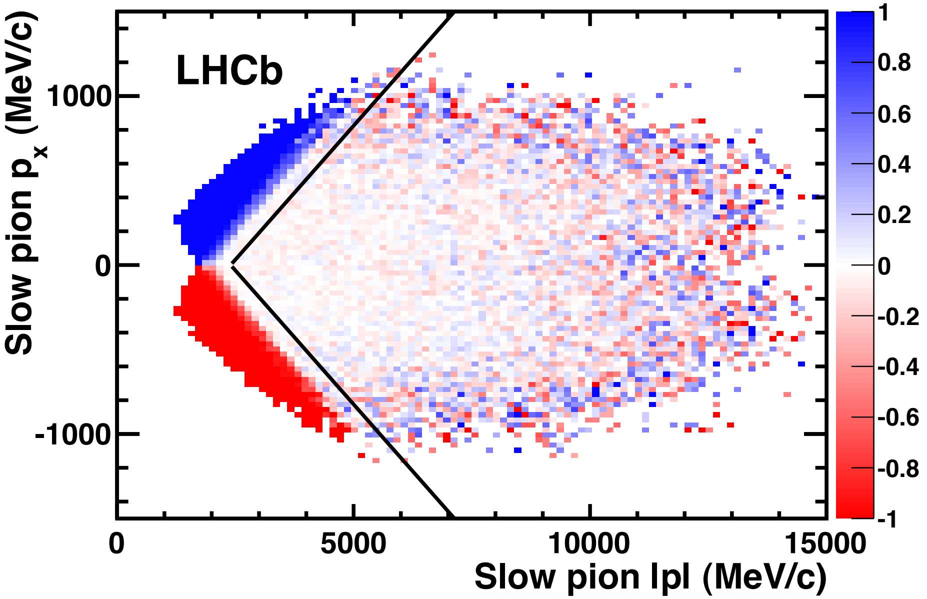
- There are regions of phase space where only D^{*+} or only D^{*-} is kinematically possible.
  - this causes large value of A_{CP}^{Raw} up to 100% in the edges regions where only D^{*+} or D^{*-} is reconstructed
- This asymmetry is independent of the D^0 decay modes but it breaks the assumption that the raw asymmetries are small
- and it carries a risk of second-order systematic effects if the ratio of efficiencies of $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ varies in the affected region.

Fiducial cuts

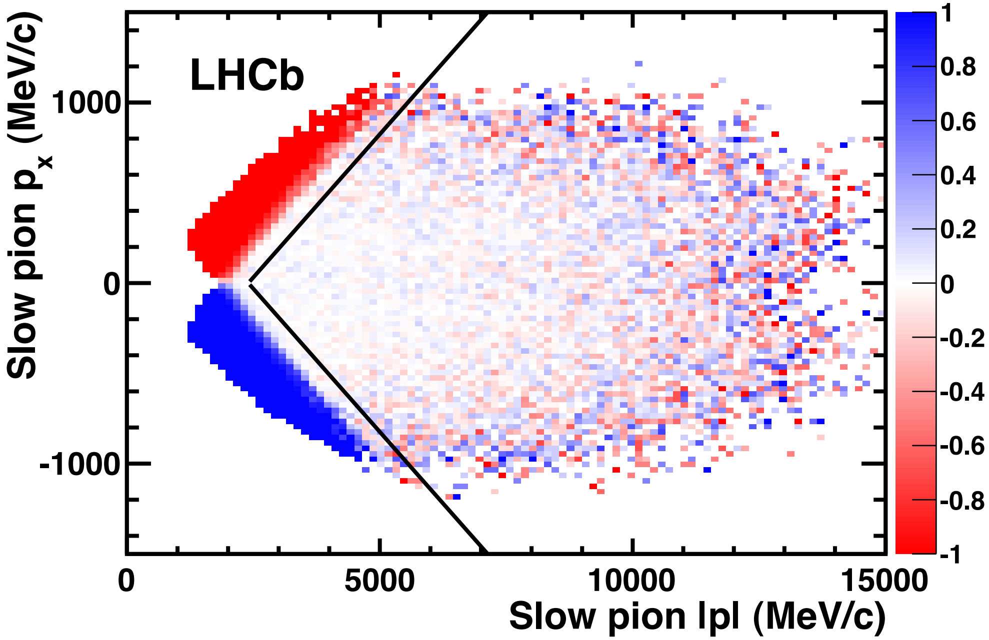
- The edge regions are therefore excluded with cuts in the slow pion(P_x,P) plane.

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

B field up



B field down



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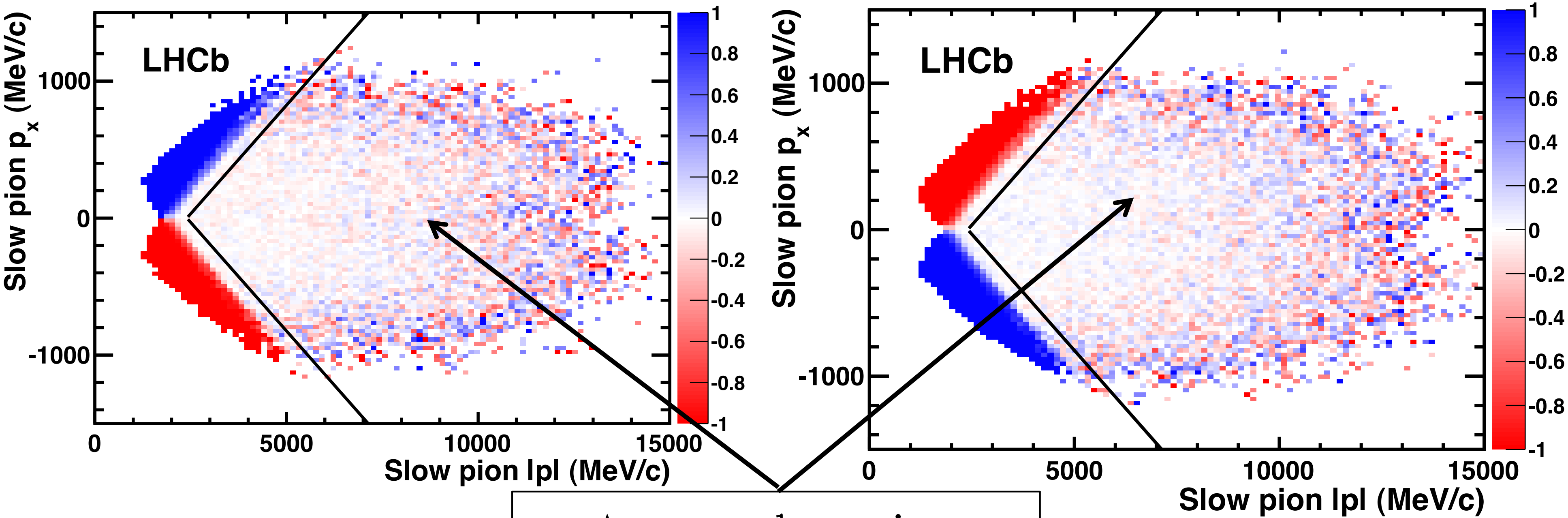

Accepted region
reject 25% of events

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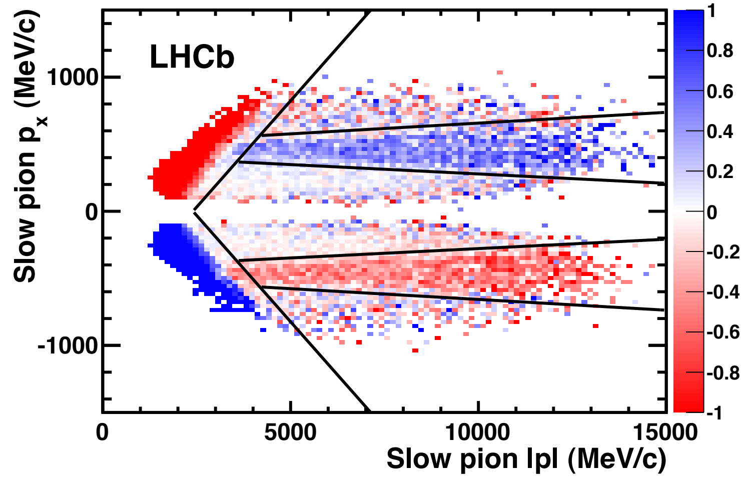
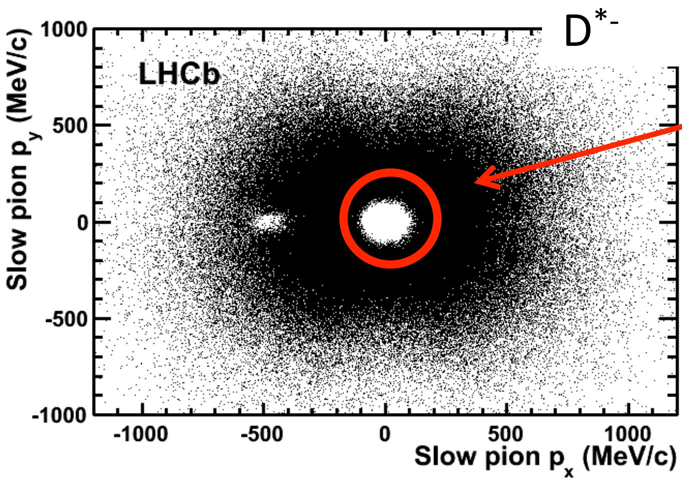
Raw asymmetry of
$D^{*+} \rightarrow D^0(KK)\pi^+$ + cc in the (P_x,P) plane of slow pion

$|P_y/P_z|$(slow π)<0.2
beam pipe region



B field down



Soft pions go directly into the beam pipe
(low P_x and P_y)
These events are lost
No charge dependents

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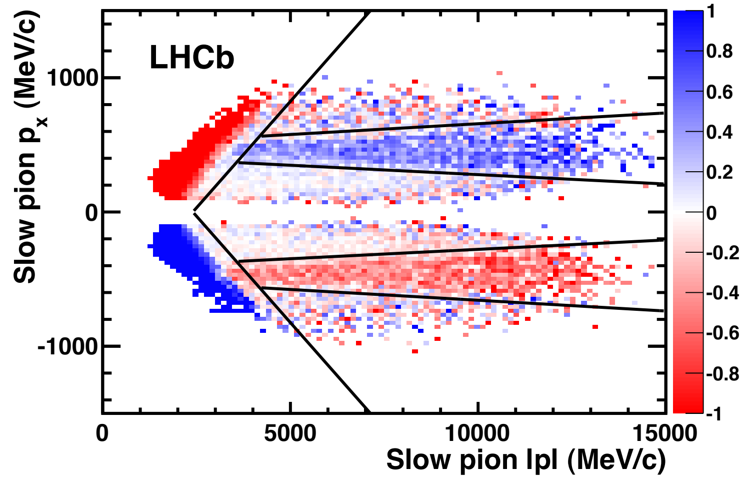

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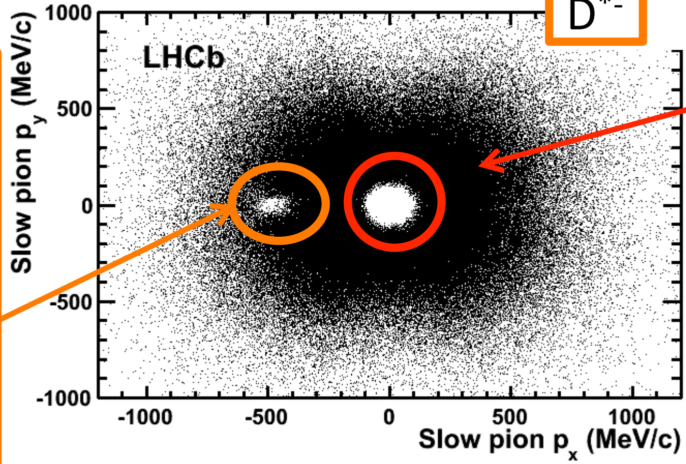

Soft pions swept through the beam pipe where there is no tracking station These events are lost
Charged dependent

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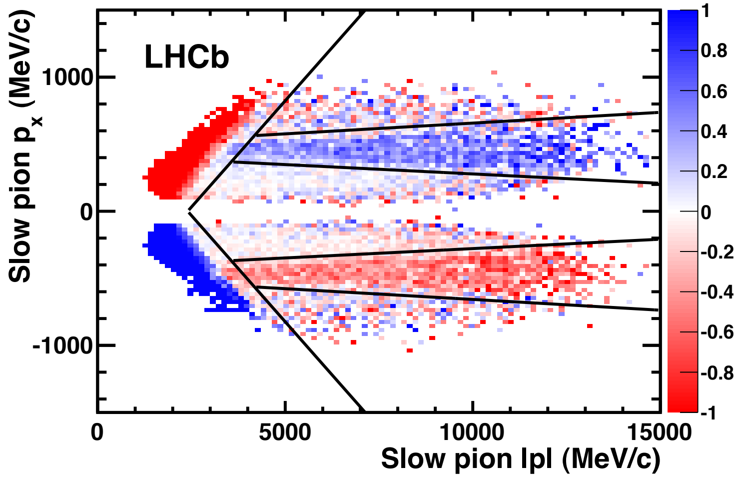
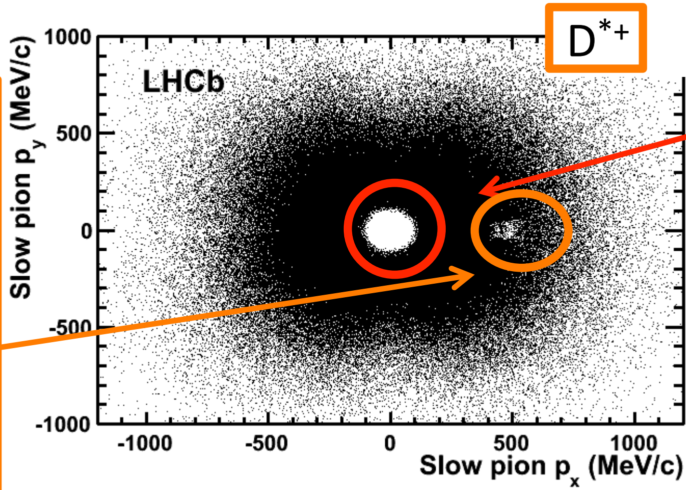


B field down



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Fit procedure

- Use 1D fits to mass difference

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

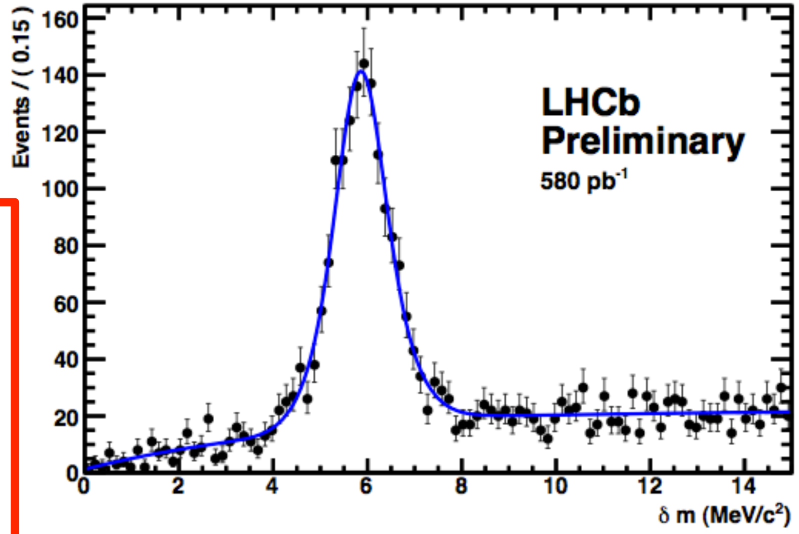
- Signal model: double-Gaussian convolved with a function accounting for the asymmetric tail:

$$B(\delta m; s) = \Theta(\delta m)\, \delta m^s$$

- Background model:

$$h(\delta m) = B\left[1 - \exp\left(-\frac{\delta m - \delta m_0}{c}\right)\right]$$

Example fit $D^* \to D^0(KK)\pi$ in one kinematic bin



Consistency for ΔA_{CP} among 216 kinematic bins:
$\chi^2/NDF = 211/215$
(χ^2 prob. 56%)

A weighted average of the kinematic bins yields the result
$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.})]\%$

Further cross checks

- Numerous crosschecks carried out, including:
  - Electron and muon vetoes on the soft pion and on the D0 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, etc)

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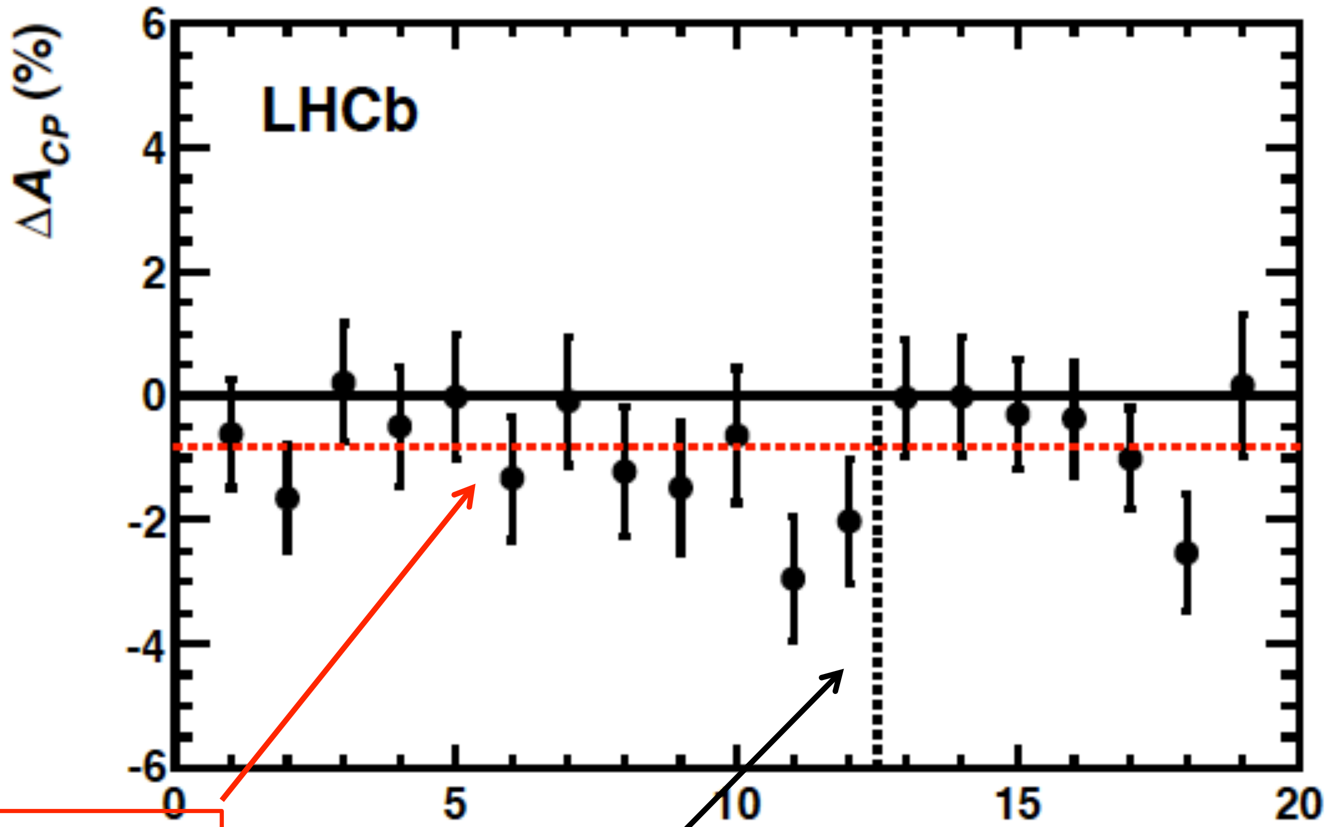
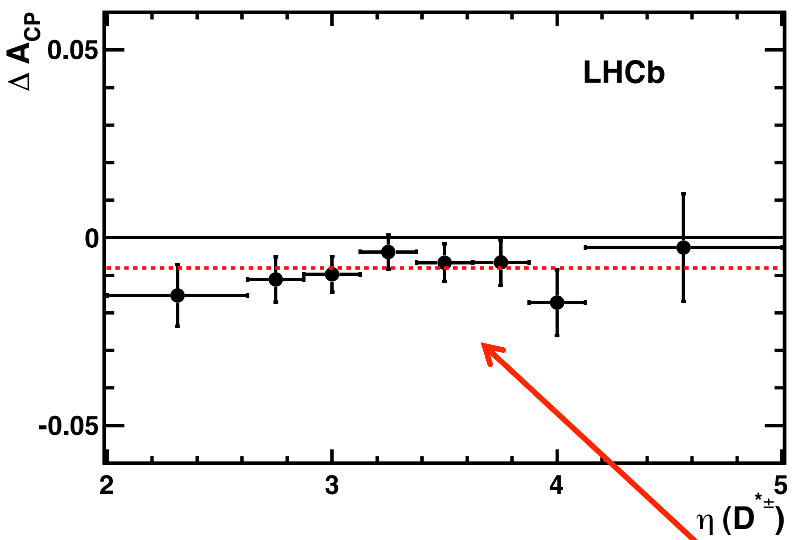
Stability of result vs data-taking runs

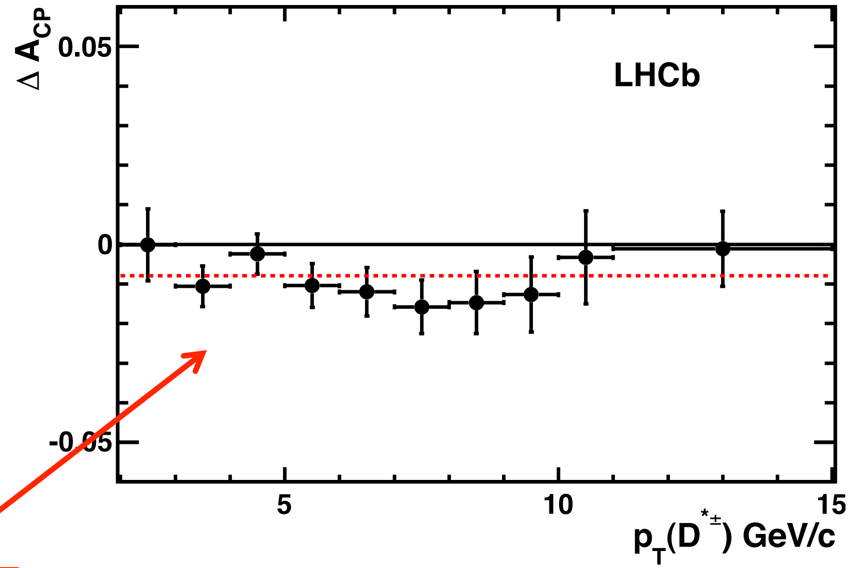


Final result (dashed line)

Before and after a technical stop

Stability of result on relevant kinematic variables





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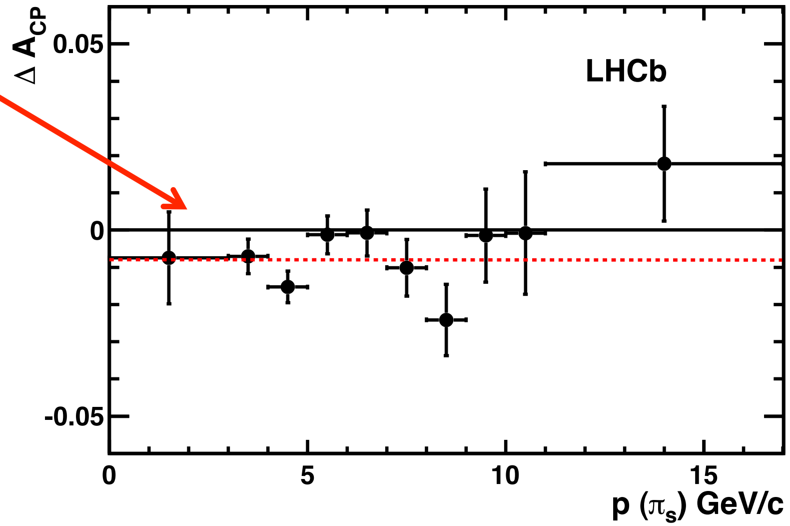


No evidence of dependence on relevant kinematic variables

Tightening of PID cuts on D^0 daughters

- The measurement is repeated with progressively more restrictive RICH particle identification requirements, finding values

tight PID cut

$$(-0.88 \pm 0.26)\%$$

tight++ PID cut

$$(-1.03 \pm 0.31)\%$$

- consistent with the baseline result

Internal consistency between subsamples

- Disjoint subsamples of data split according
  - to magnet polarity
  - the sign of P_x of the tagging slow pion
  - whether the data were taken before or after the technical stop.
- The χ^2 probability for consistency among the subsamples is 45% (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%)

Systematic uncertanties

- 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%

Result

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

Significance: 3.5σ

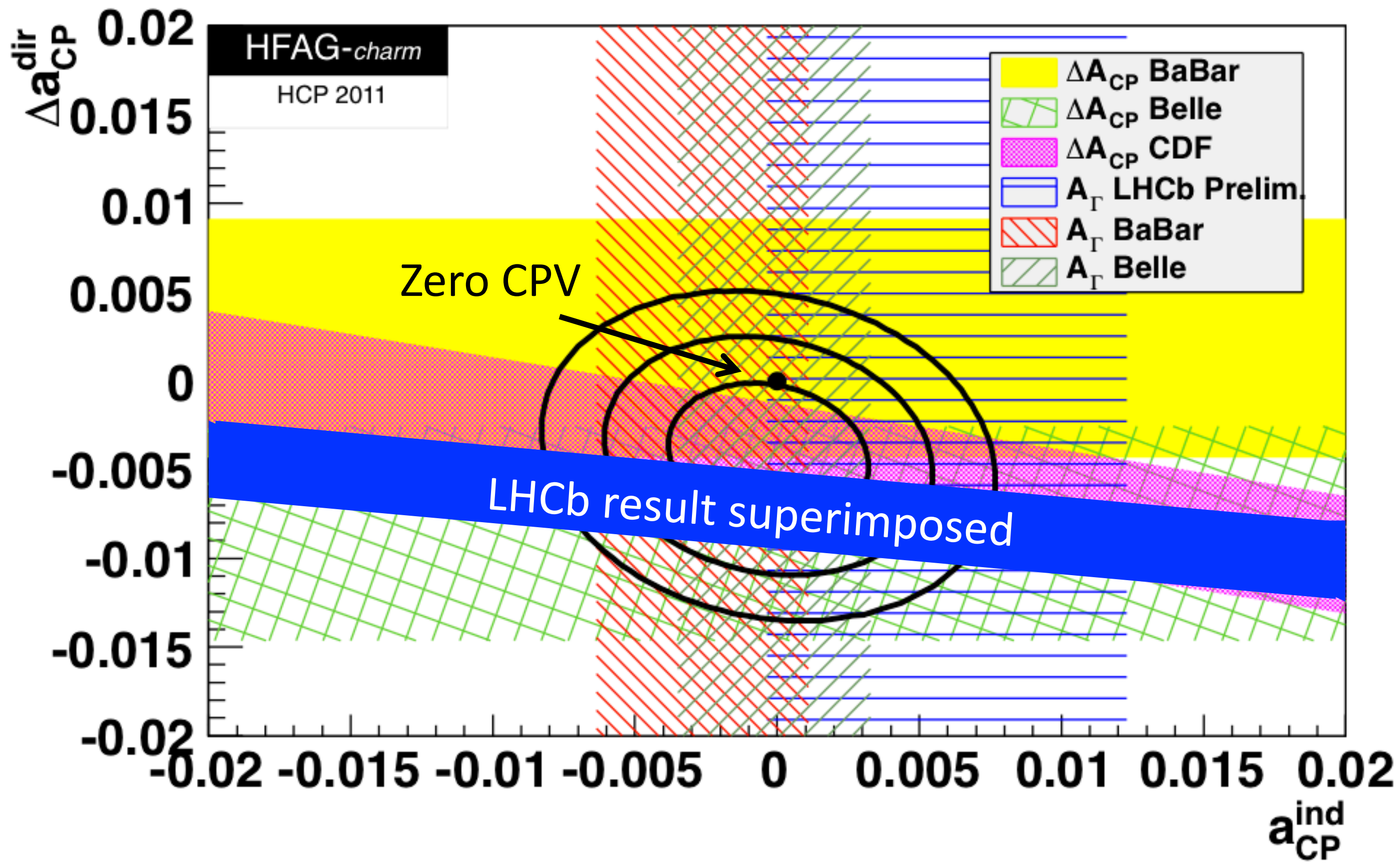
Interpretation: lifetime acceptance

- Lifetime acceptance differs between $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$
  - e.g. smaller opening angle => short-lived $D^0 \rightarrow K^+K^-$ more likely to fail cut requiring daughters not to point to PV than $D^0 \rightarrow \pi^+\pi^-$
- Need this to compute how much indirect CPV could contribute.
- Background-subtracted average decay time of D^0 candidates passing the selection is measured for each final state, and the fractional difference with respect to world average D^0 lifetime is obtained:

$$\Delta\langle t\rangle/\tau = [9.83 \pm 0.22(\text{stat.}) \pm 0.19(\text{syst.})]\,\%$$

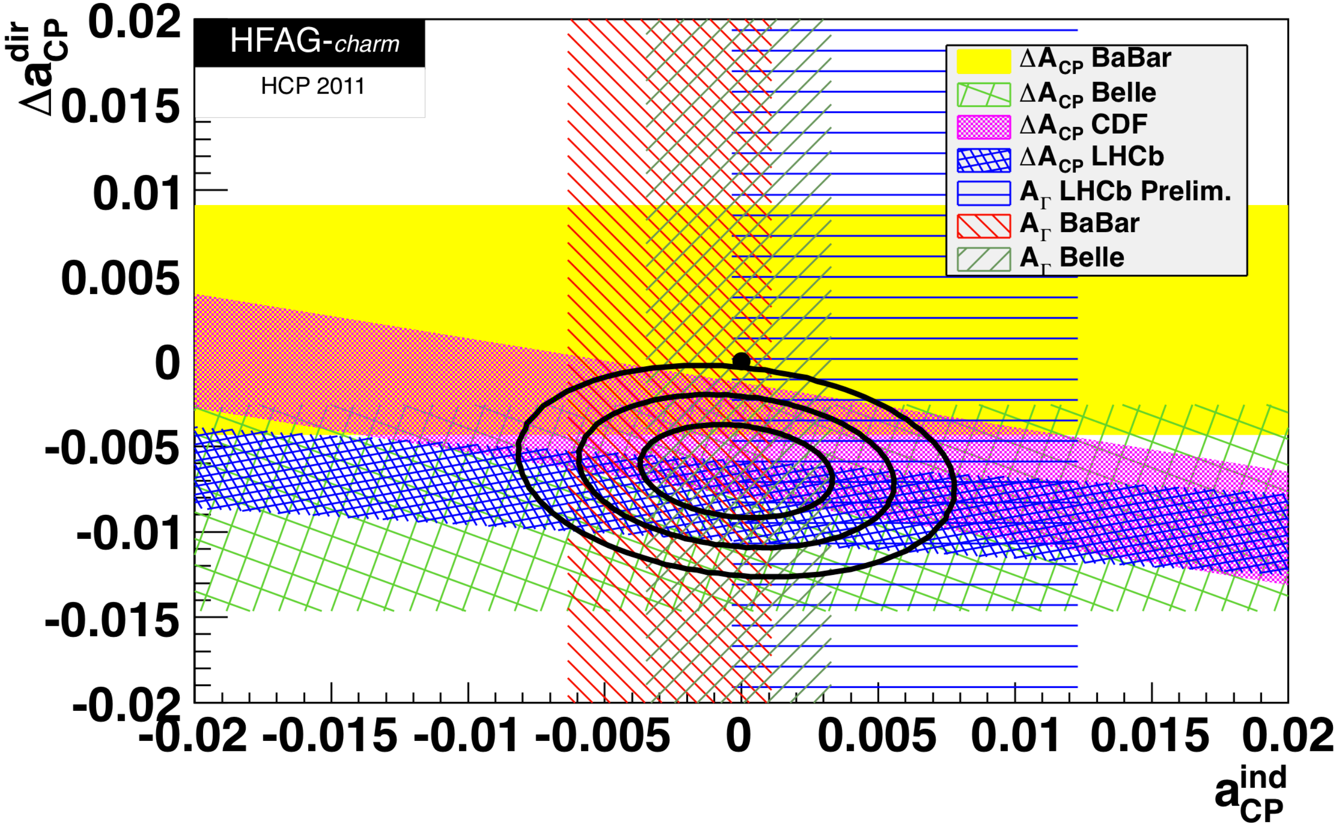
- Systematics:
  - world-average D^0 lifetime 0.04%
  - fraction of charm from B-hadron decays 0.18%
  - background-subtraction procedure 0.04%
- Remind: $\Delta A_{CP} = [a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\text{ind}}$
- ... so indirect CP violation mostly cancel

Comparison with the world average



LHCb measurement, interpreted assuming no a_{CP}^{ind}, is consistent with HFAG averages based on previous results (1.1 sigma)

New HFAG combination
(with LHCb result)



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

Consistency with NO CP violation: 0.15%

Prospects

- Current measurement of ΔA_{CP} performed with 60% of 2011 recorded sample
  - To establish whether this result is consistent with the SM will require the analysis of more data (work in progress, as well as improved theoretical understanding
- Measure ΔA_{CP} with D^0 from B semileptonics decays
- Look for direct CPV in other SCS modes, especially 3 body ones
- In addition to direct CPV search, perform time dependent measurements to look for indirect CPV, i.e. A_Γ and studies of $D^0 \to K_S hh$

Summary

First evidence of CP violation in charm sector

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

Significance 3.5σ (incl. statistical and systematic uncertainties)

Our value is consistent with HFAG average (1σ)

Magnitude of central value larger than current SM expectation ... but charm is notoriously difficult to pin down theoretically

Looking forward to more data and many new charming results!

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Magnitude of central value larger than current SM expectation ... but charm is notoriously difficult to pin down theoretically

Looking forward to more data and many new charming results!

Summary

First evidence of CP violation in charm sector

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

Significance 3.5σ (incl. statistical and systematic uncertainties)

Our value is consistent with HFAG average (1σ)

Magnitude of central value larger than current SM expectation ... but charm is notoriously difficult to pin down theoretically

Looking forward to more data and many new charming results!

A look at the future

also for the charm particles ?

Backup

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

arXiv 1110.3970

Results of fit with a Gaussian to S^i_{CP} distribution

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 of 38 pb^{-1}

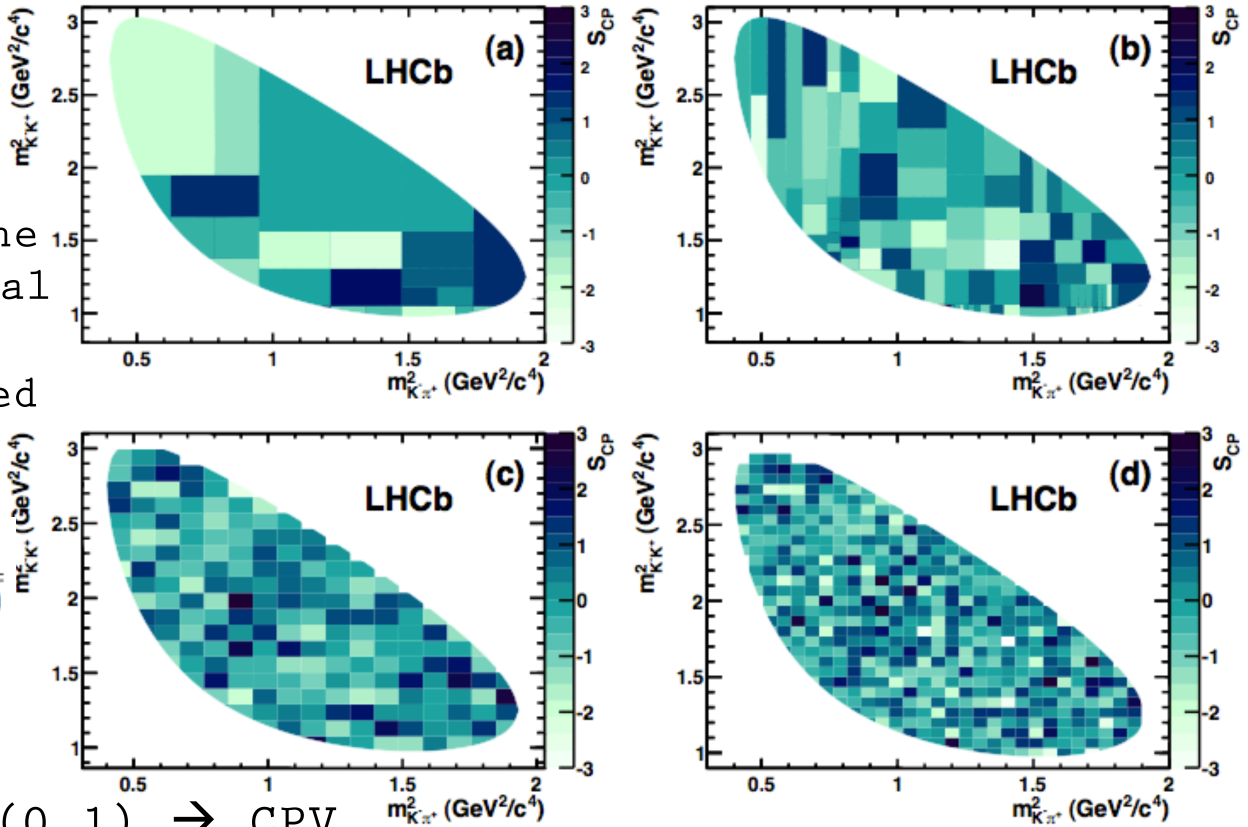
Preliminary: 2010 data, 38 pb^{-1}

Strategy: for each bin in the Dalitz plot, a local CP asymmetry variable is defined

arXiv: 0905.4233,0802.4035

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

$$\alpha = \frac{N_{tot}(D^+)}{N_{tot}(D^-)}$$



If S^i_{CP} is not G(0,1) → CPV

Search for time-dependent CPV

LHCb-CONF-2011-54
LHCb-CONF-2011-46

- Search CP vialotion in mixing involves two observables

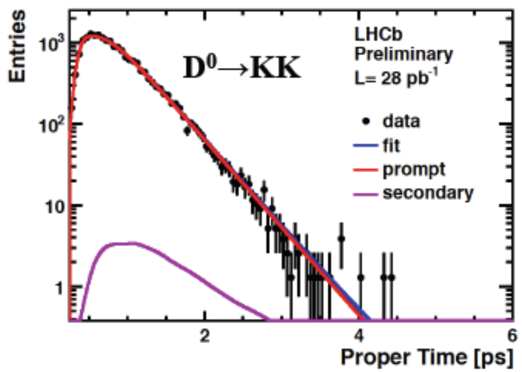
$$y_{CP} \equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^-\pi^+)} - 1$$

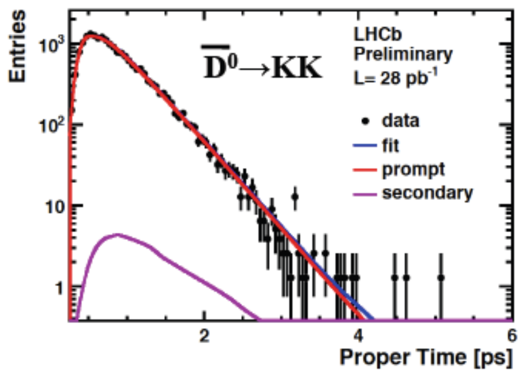
→ D^0 mixing well establish, $y_{CP} \neq y$
→ indirect CP violation
$y = (7.5 \pm 1.2) \times 10^{-3}$ HFAG

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

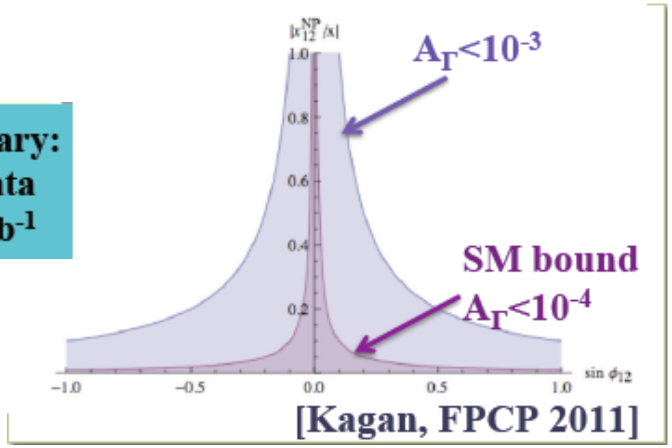
→ non-zero value of A_Γ → indirect CP violation

- where the flavour of $D^0 \to K^-K^+$ is determined from the sign of $D^{*\pm}$





Preliminary: 2010 data $L=28\ pb^{-1}$



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

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