First evidence for CP violation in charm decays at LHCb

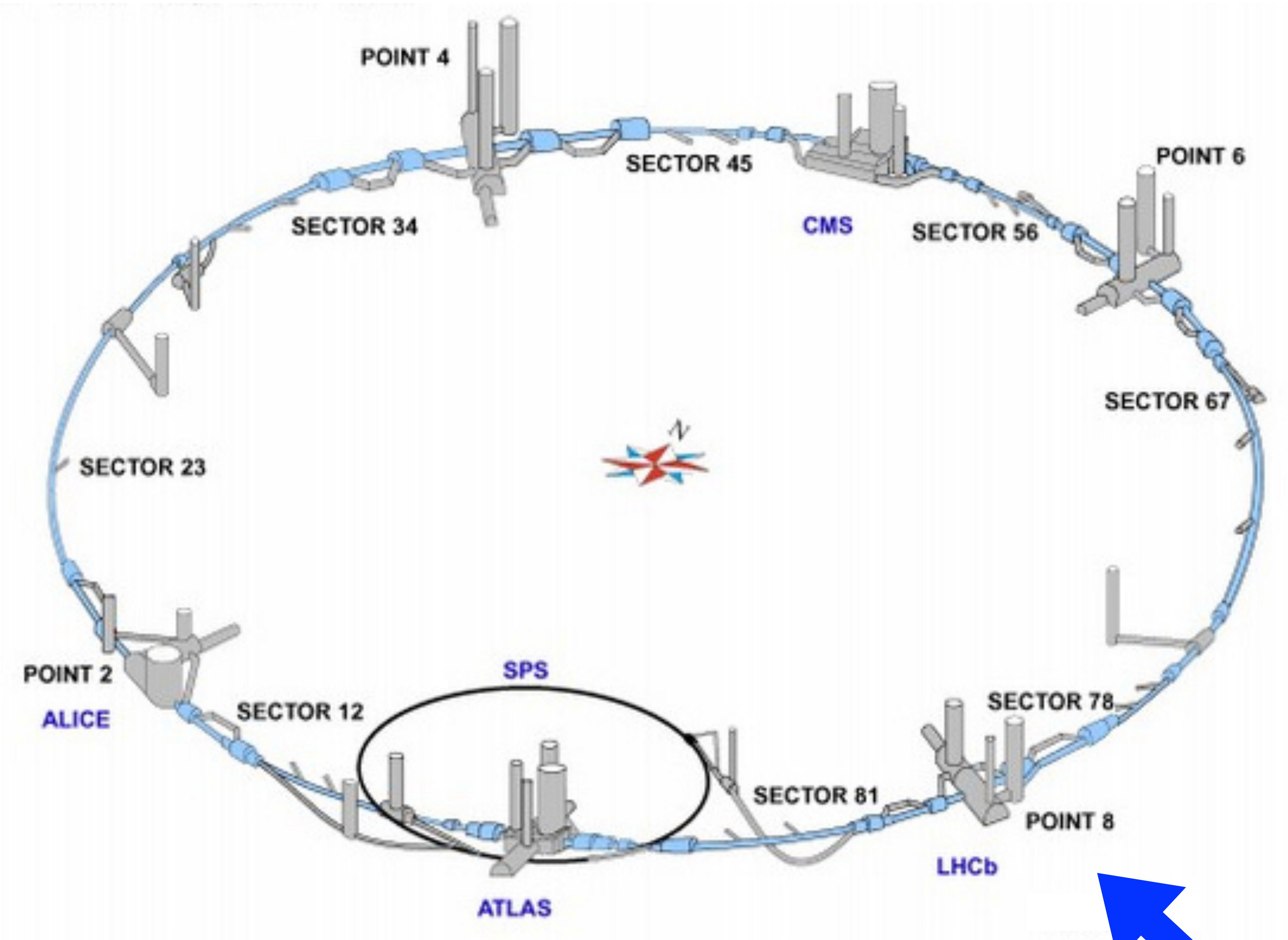
Mat Charles (Oxford)
on behalf of the LHCb collaboration

Overview

- Introduction to LHCb
- CP violation in charm
- Results of searches at LHCb:
  - 2010: y_{CP} and A_Γ in $D^0 \to K^- K^+$, $D^0 \to K^- \pi^+$
  - 2011: Time-integrated search for CPV in $D^0 \to K^- K^+$ vs $\pi^- \pi^+$
  - 2010: Search for CPV in $D^+ \to K^- K^+ \pi^+$ (if time allows)
- Conclusions

Introduction to LHCb

The LHC



POINT 4
SECTOR 45
CMS
POINT 6
SECTOR 34
SECTOR 56
SECTOR 67
SECTOR 23
POINT 2
ALICE
SPS
SECTOR 12
SECTOR 78
SECTOR 81
POINT 8
LHCb
ATLAS
N

Physics goals of LHCb

- Main strategy: indirect searches for NP in b, c decays.
  - Look for evidence of new, heavy particles in loop diagrams
  - Complementary to ATLAS/CMS direct searches
  - ... and a broader physics program too, e.g. forward electroweak
- Why heavy flavour?
  - In short: an excellent source of loop diagrams.
  - CP violation: SM CPV insufficient to explain baryogenesis
  - Rare decays: Tiny & precise SM predictions, enhanced by many NP models
- Why at the LHC?
  - Enormous $b\bar{b}$, $c\bar{c}$ cross-sections -- precision is the name of the game
  - Also: high momentum/boost great for time-dependent measurements

In our acceptance: $\sigma(c\bar{c})=1200\mu b$ and $\sigma(b\bar{b})=75\mu b$.
So in 1 fb^{-1} roughly 10^{12} $c\bar{c}$ and 10^{11} $b\bar{b}$ produced!

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

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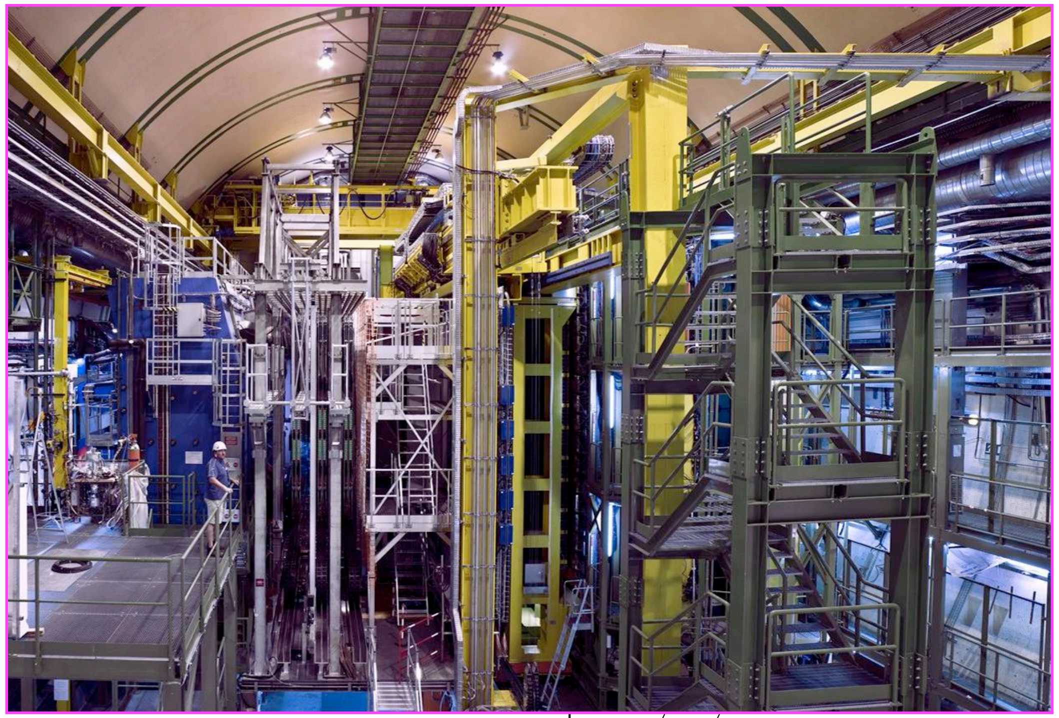
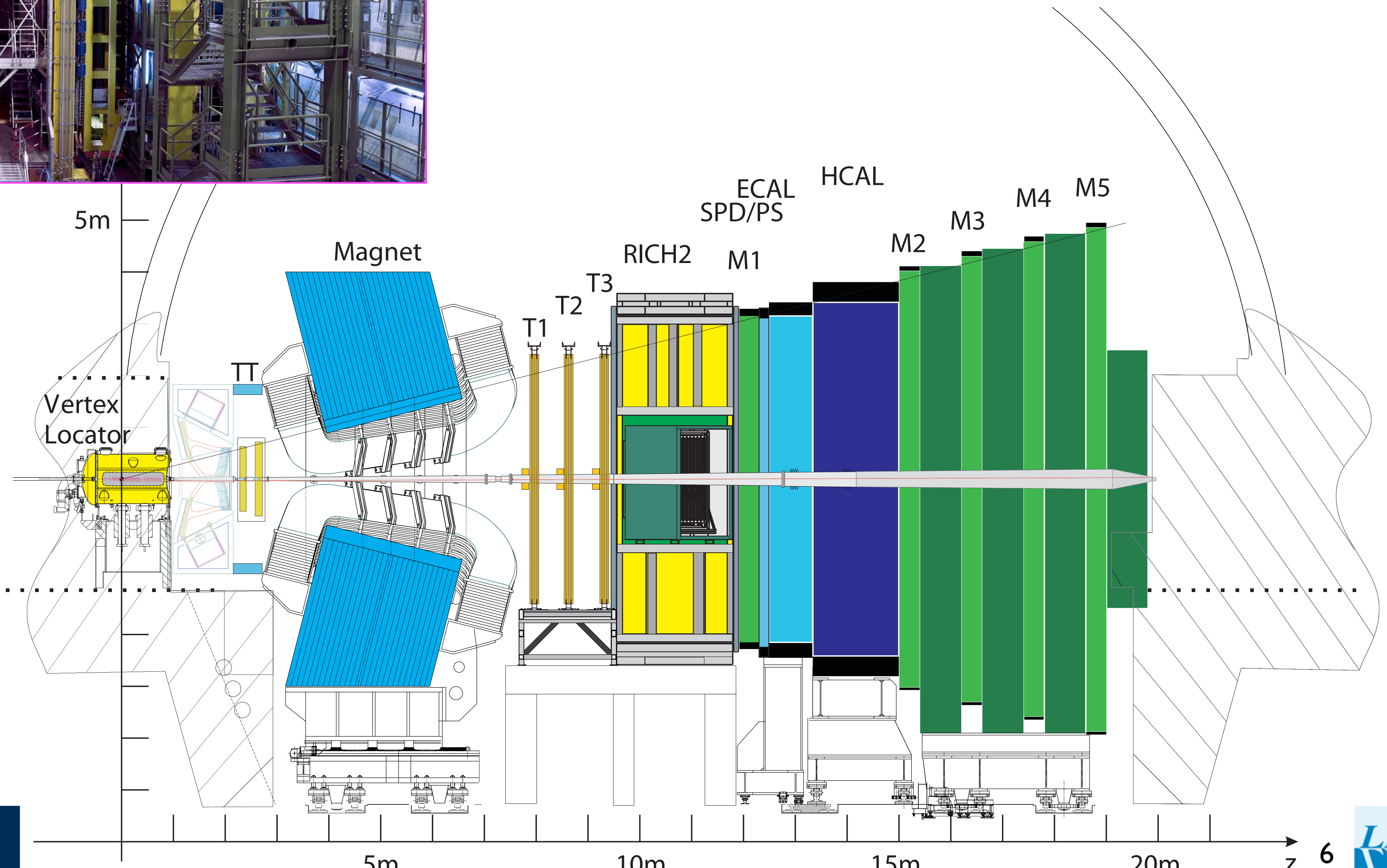
LHCb

The LHCb detector





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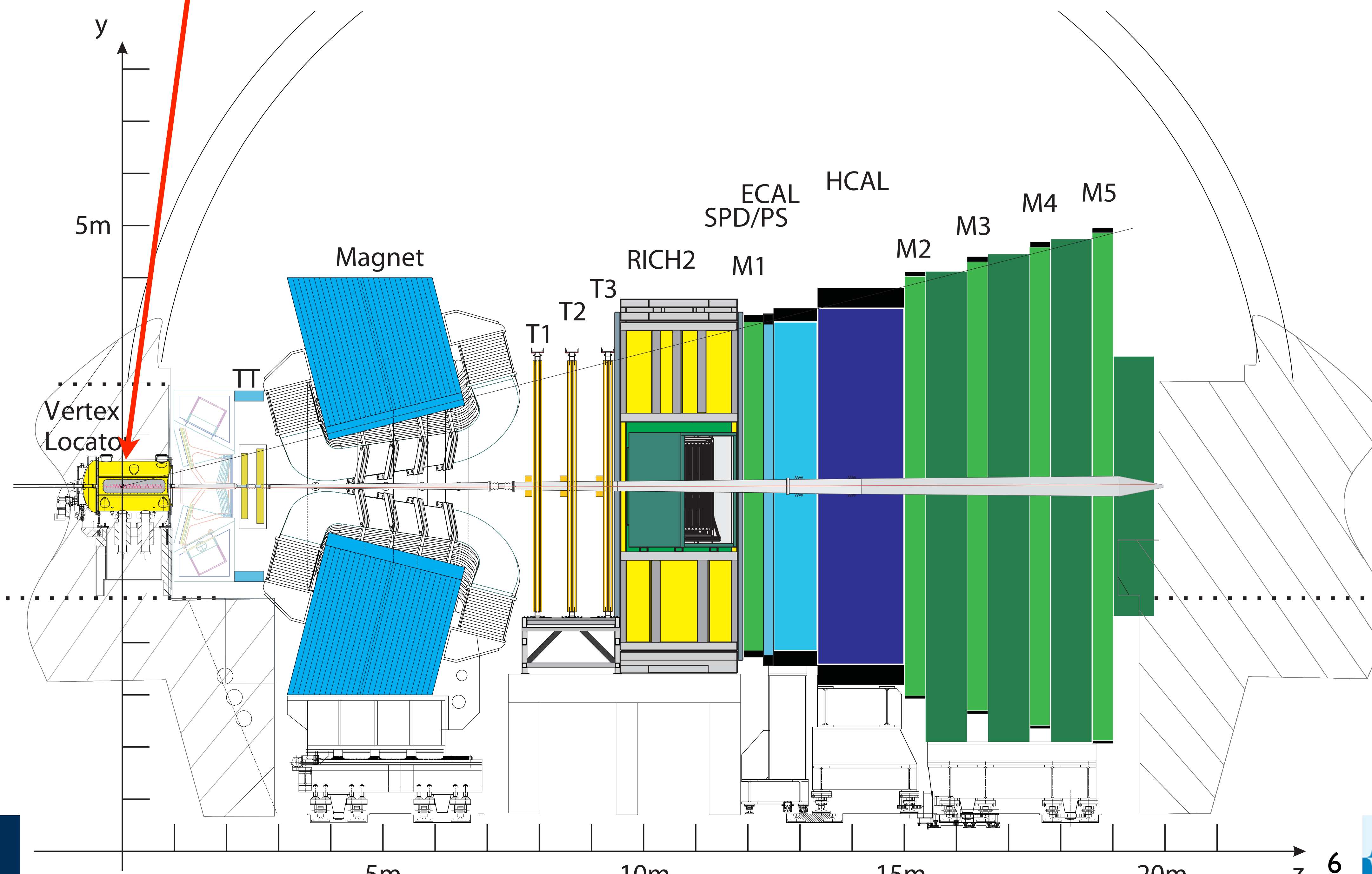
The LHCb detector

VELO: precision vertexing

42x2 silicon planes, strip pitch 40-100 μm

7mm from beam during data-taking; retracted during injection

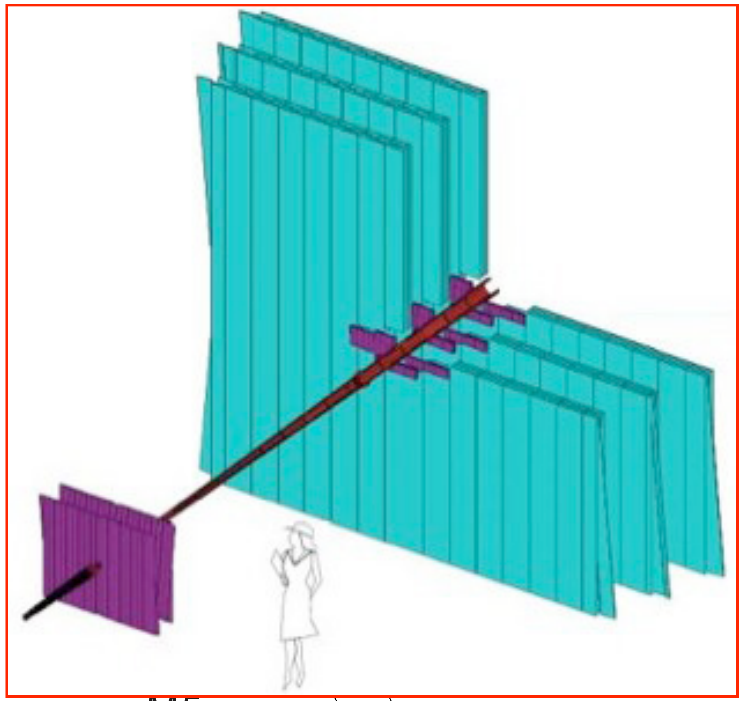


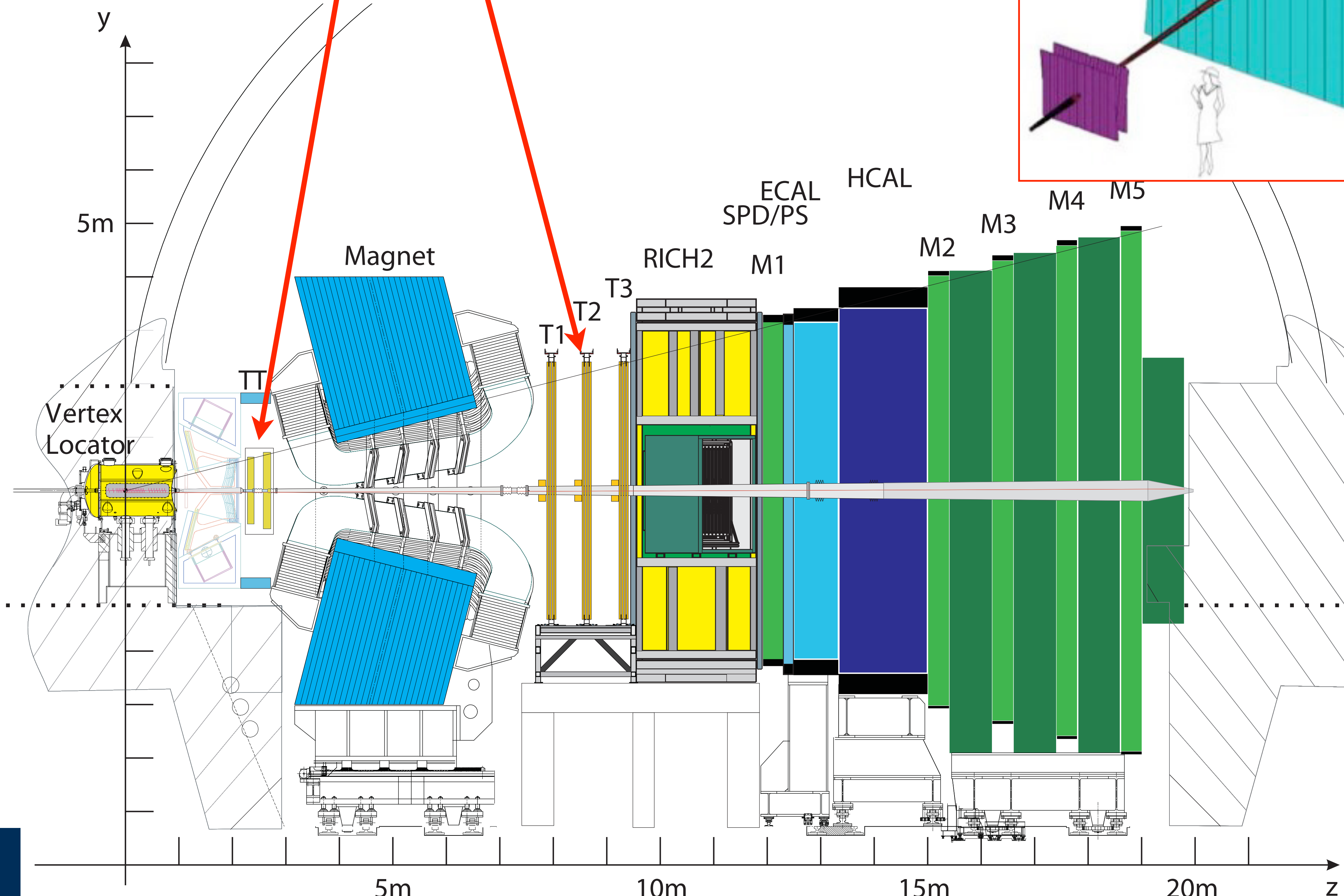
The LHCb detector

Tracker: momentum measurement

Stations upstream and downstream of magnet.

Upstream & inner: silicon microstrips. Outer: drift chambers





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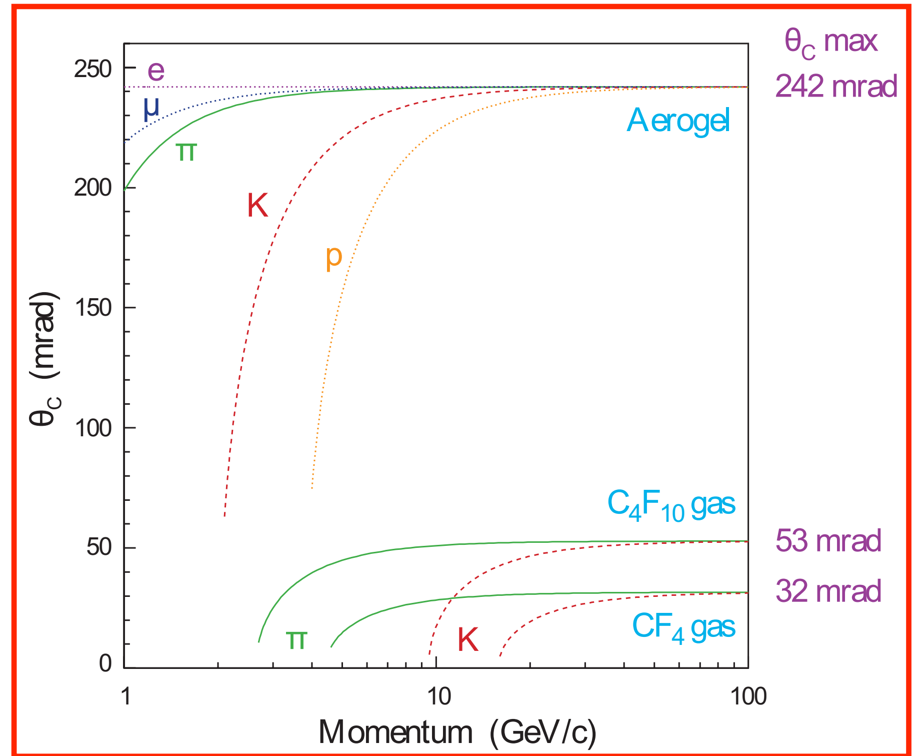
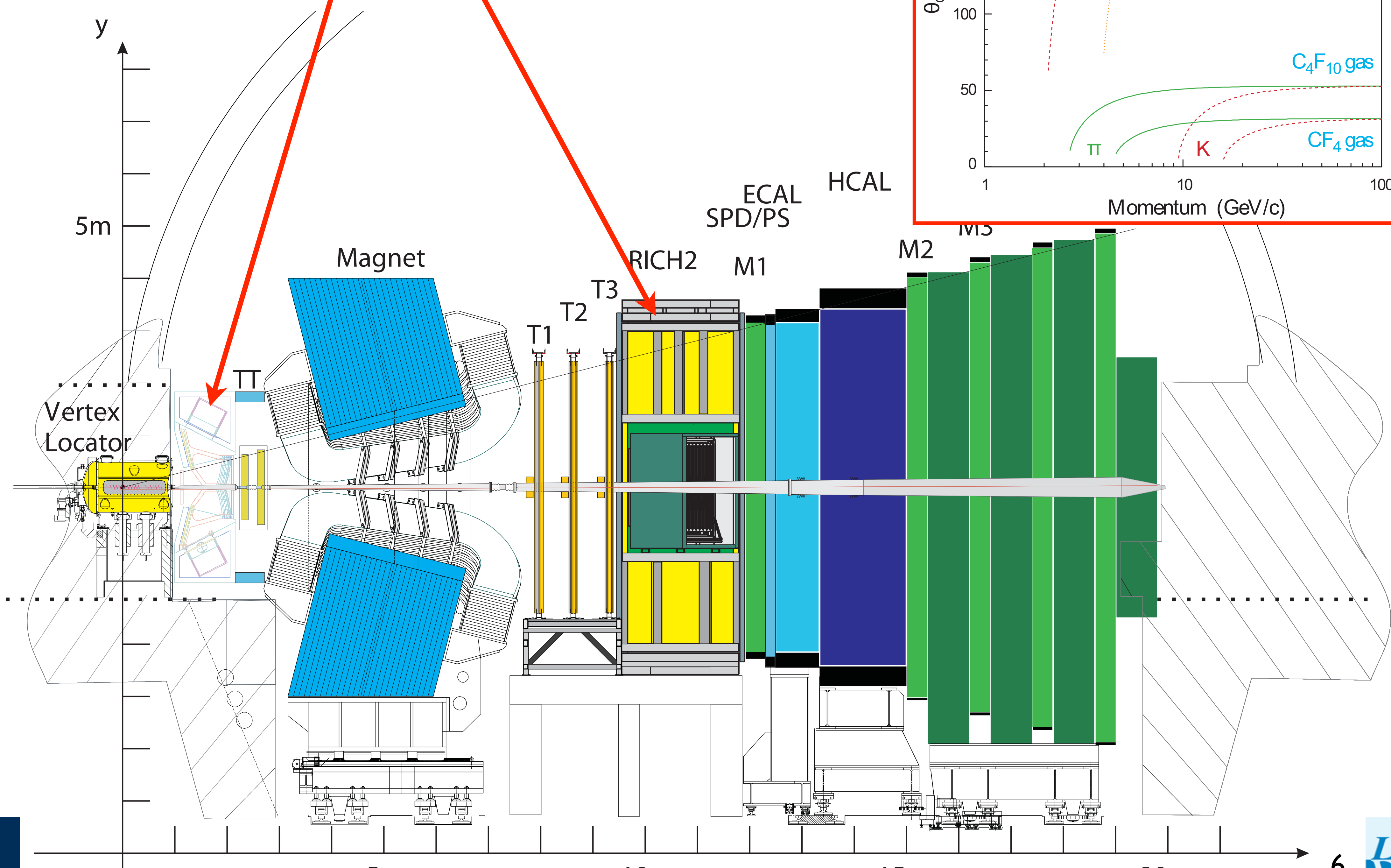
The LHCb detector

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



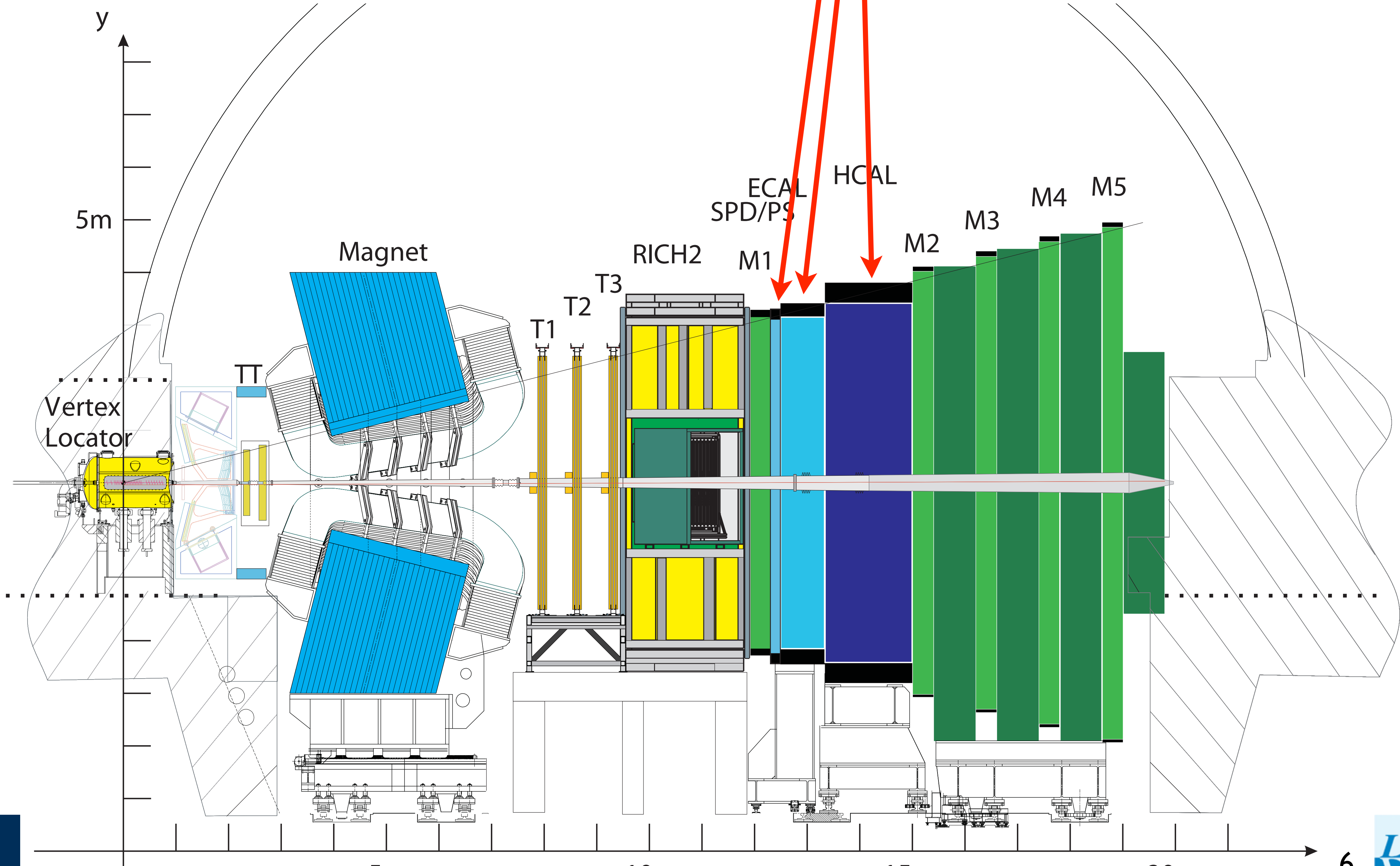


The LHCb detector

Calorimeters: trigger, photon/electron ID

Preshower + SPD + electromagnetic + hadronic calorimeters

Vital for hardware-level hadron triggering

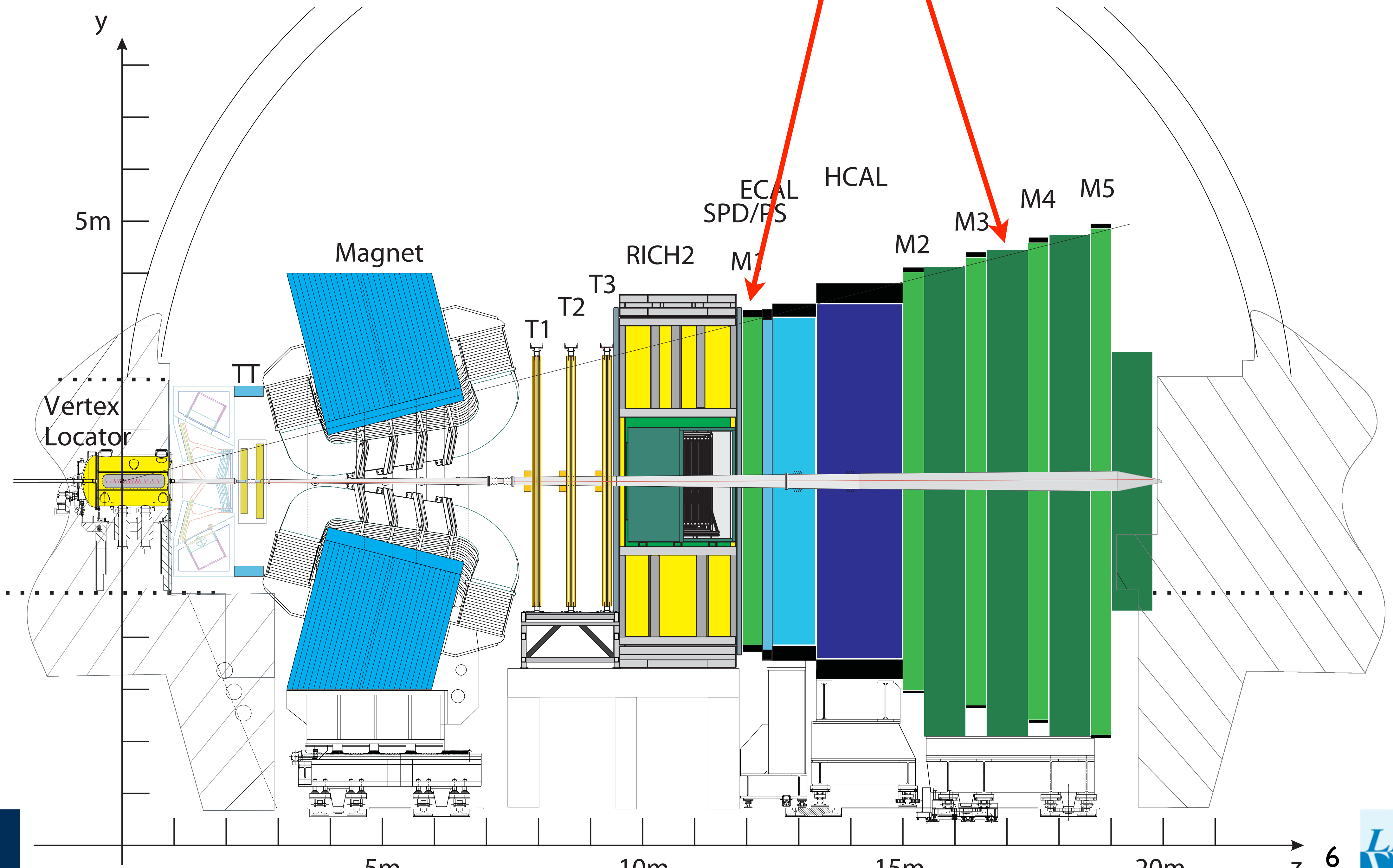


The LHCb detector

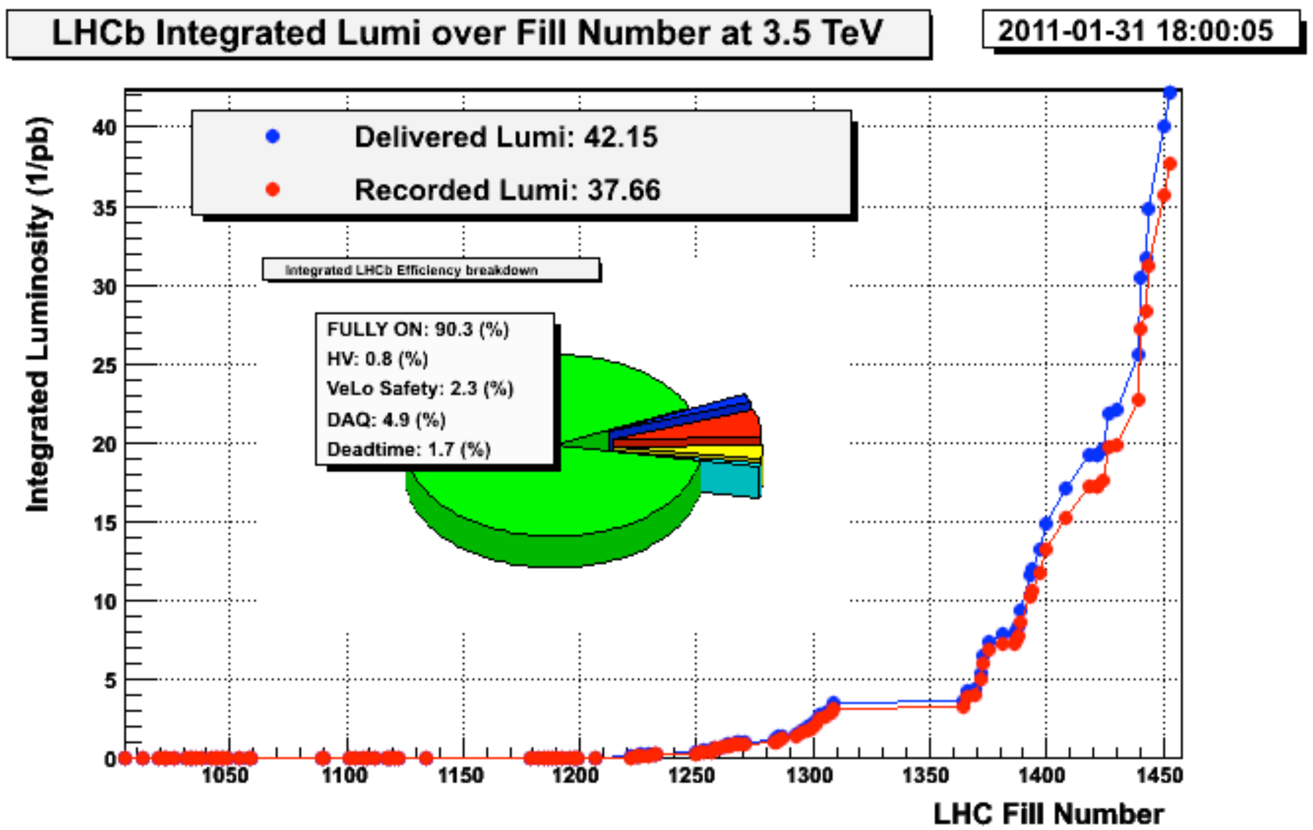
Muon stations: muon ID

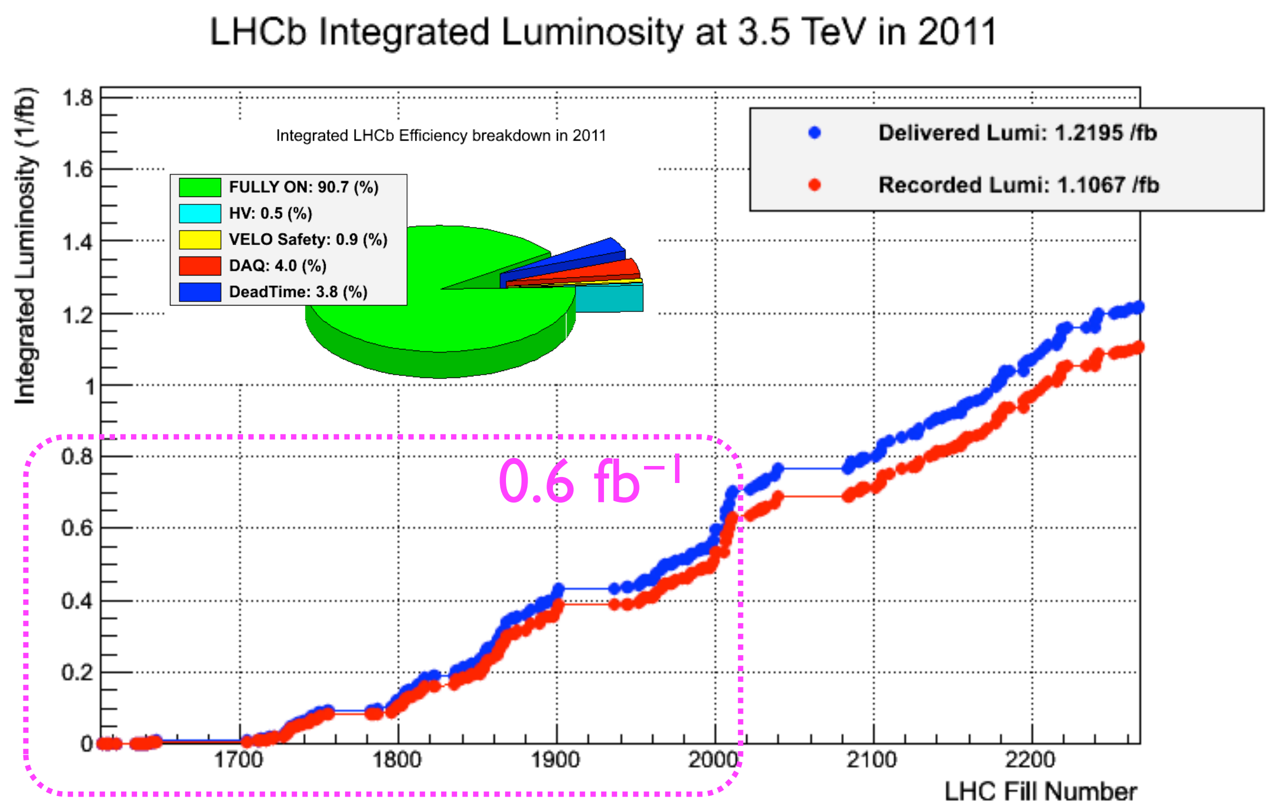
Five stations, used also in hardware trigger.

Excellent muon/pion separation (single hadron mis-ID rate 0.7% for Phys. Lett. B699 (2011) 330)



Data-taking





2010: 38 pb^{-1}

2011: 1 fb^{-1}

- Factor 30 more integrated luminosity in 2011
- Luminosity-leveling working nicely to control pile-up.

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The 2011 trigger (from a charm POV)

LHC bunch-crossing frequency
Max possible 40 MHz; actually ~15 MHz

10-15 MHz

L0: hardware trigger
Hadrons: require calorimeter 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, other triggers.

50 kHz

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

3 kHz

Storage
About 3 kHz total rate
of which about 1 kHz charm

After hardware trigger we already have 50% cc events (500 kHz).

No possibility of an inclusive charm trigger!

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

CP violation in charm

CP violation

- 3 types of CP violation:
  - In decay: amplitudes for a process and its conjugate differ
  - In mixing: rate of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ differ
  - In interference between mixing and decay diagrams

Direct

Indirect

- In the SM, indirect CP violation in charm is expected to be very small and universal between CP eigenstates
  - Perhaps $O(10^{-3})$ for CPV parameters => $O(10^{-5})$ for observables like A_Γ
- Direct CP violation can be larger in SM, very dependent on final state (therefore we must search wherever we can)
  - Negligible in Cabibbo-favoured modes (SM tree dominates everything)
  - In generic singly-Cabibbo-suppressed modes: up to $O(10^{-3})$ plausible
- Both can be enhanced by NP, in principle up to O(%)

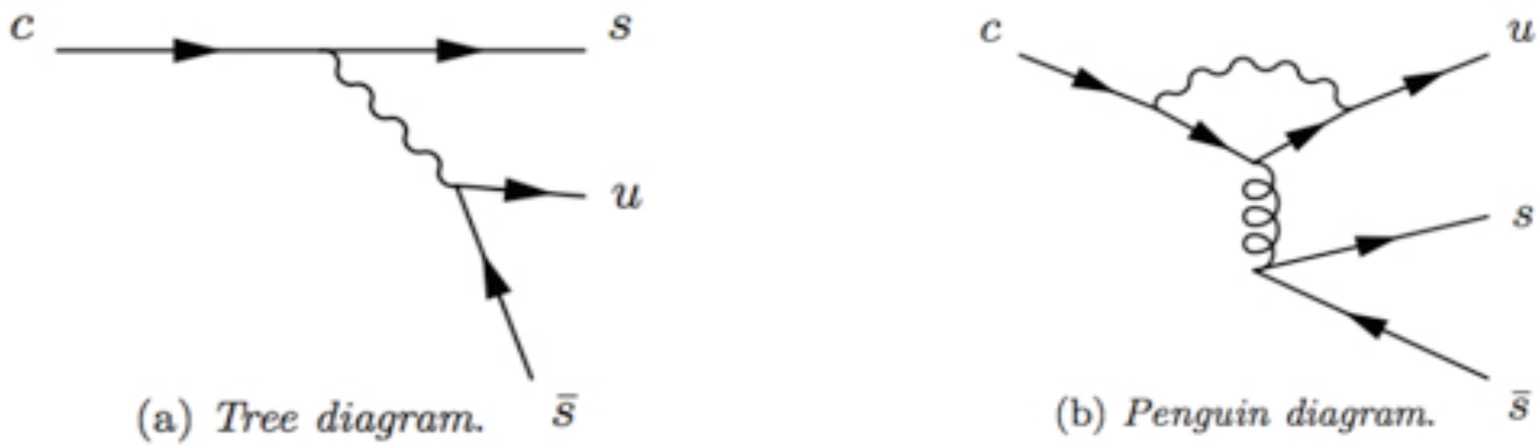
Bianco, Fabbri, Benson & Bigi, Riv. Nuovo. Cim 26N7 (2003)
Grossman, Kagan & Nir, PRD 75, 036008 (2007)
Bigi, arXiv:0907.2950

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

CPV in charm not seen previously

Where to look for direct CPV

- Remember: need (at least) two contributing amplitudes with different strong and weak phases to get CPV.
- Singly-Cabibbo-suppressed modes with gluonic penguin diagrams very promising
  - Several classes of NP can contribute
  - ... but also non-negligible SM contribution



(a) *Tree diagram.* (b) *Penguin diagram.*

And difference between $A_{CP}(D^0 \to K^+ K^-)$, $A_{CP}(D^0 \to \pi^+ \pi^-)$?

- Expectation from U-spin: $A^{dir}(KK) = -A^{dir}(\pi\pi)$ so $A_{CP}(KK) - A_{CP}(\pi\pi)$ maximal
- Conclusion could be softened by large U-spin violation in power corrections

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Grossman, Kagan & Nir, PRD 75, 036008 (2007)
For more on U-spin breaking, see arXiv:1202.3795 (Feldmann, Nandi, Soni)

LHCb

Mixing & indirect CPV with $D^0 \to K^- K^+, K^- \pi^+$

$38\ pb^{-1}$

arXiv:1112.4698 (submitted to JHEP)

See also: LHCB-CONF-2011-029, LHCB-CONF-2011-046, LHCB-CONF-2011-054

Standard mixing formalism

Mixing occurs for neutral mesons M^0 = K^0, D^0, B^0, $B_s{}^0$

Decompose into mass eigenstates $|M_{1,2}\rangle$:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \quad \text{for} \;\; |q|^2 + |p|^2 = 1$$

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

... and we can invert to get $|M^0(t)\rangle$ given $m_{1,2}$, $\Gamma_{1,2}$, q/p...

General time evolution:

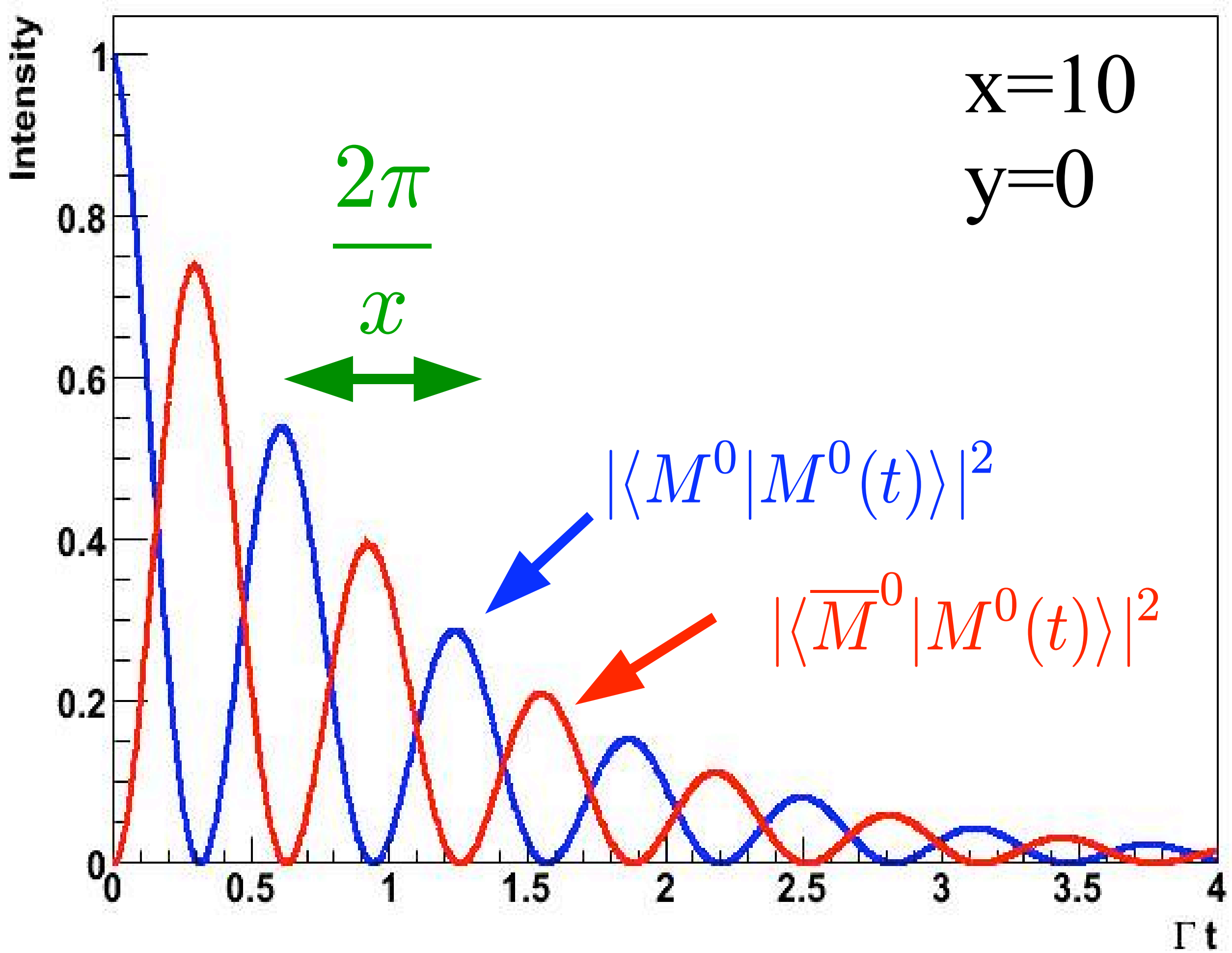
$$\boxed{\begin{aligned} |M(t)\rangle &= \frac{1}{2p}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) + e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right] \\ |\overline{M}(t)\rangle &= \frac{1}{2q}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right] \end{aligned}}$$

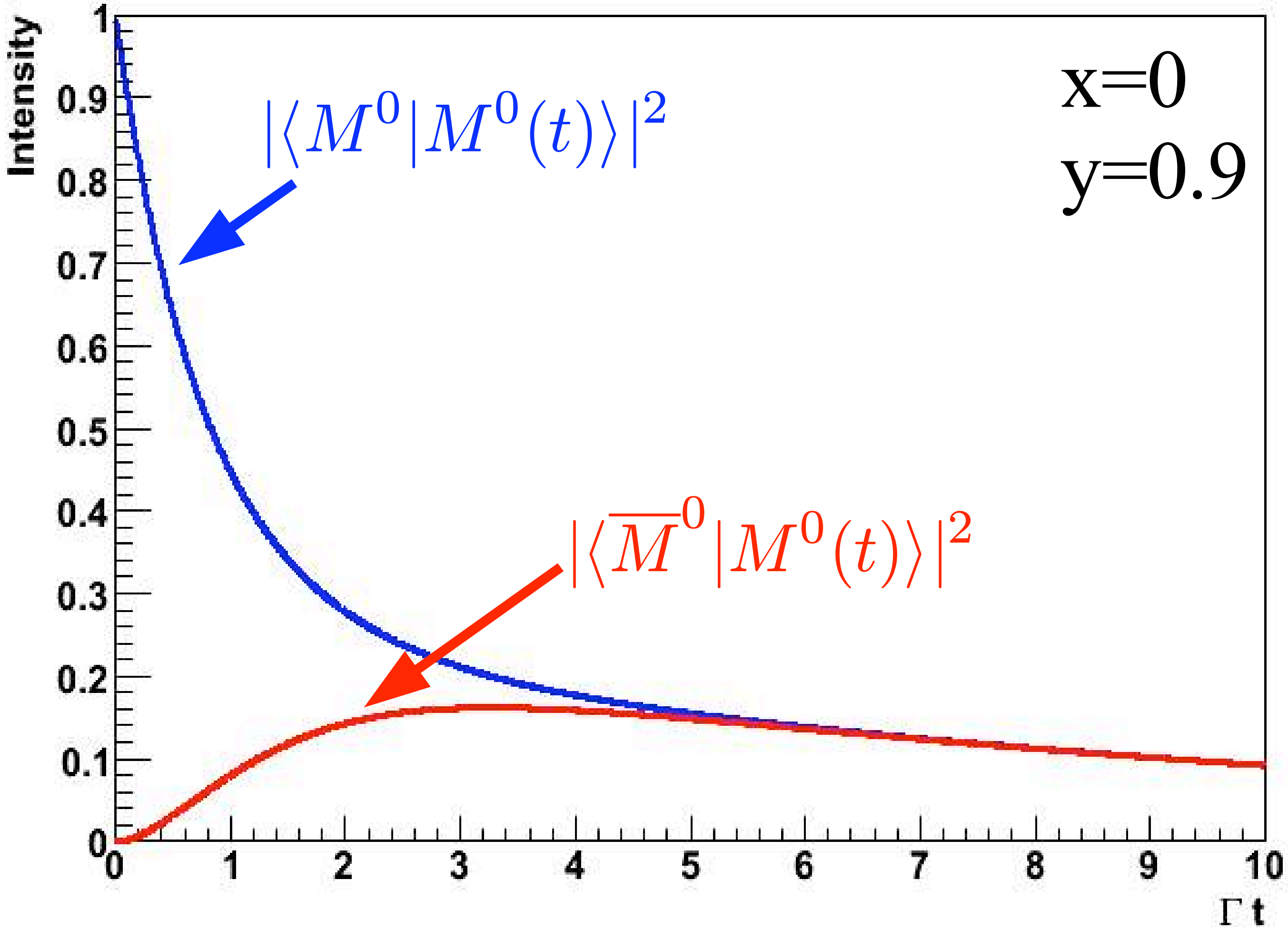
Cartoon of mixing

For convenience, define:

$$\boxed{\Gamma = \frac{\Gamma_2 + \Gamma_1}{2} \qquad x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}}$$

and $R_M = \dfrac{x^2 + y^2}{2}$

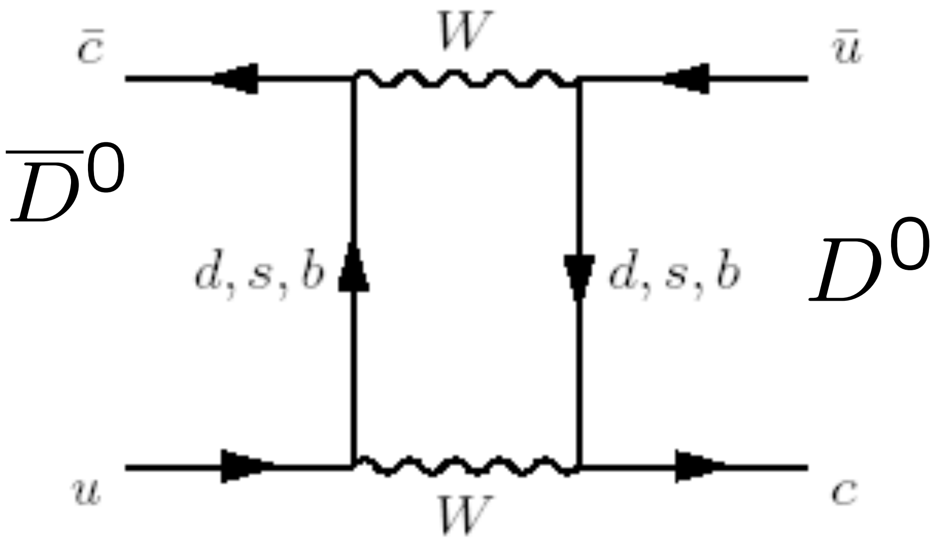




Mixing in charmed mesons

Charm mixing small compared to other mesons in SM:

Mixing via box diagram (short-range)



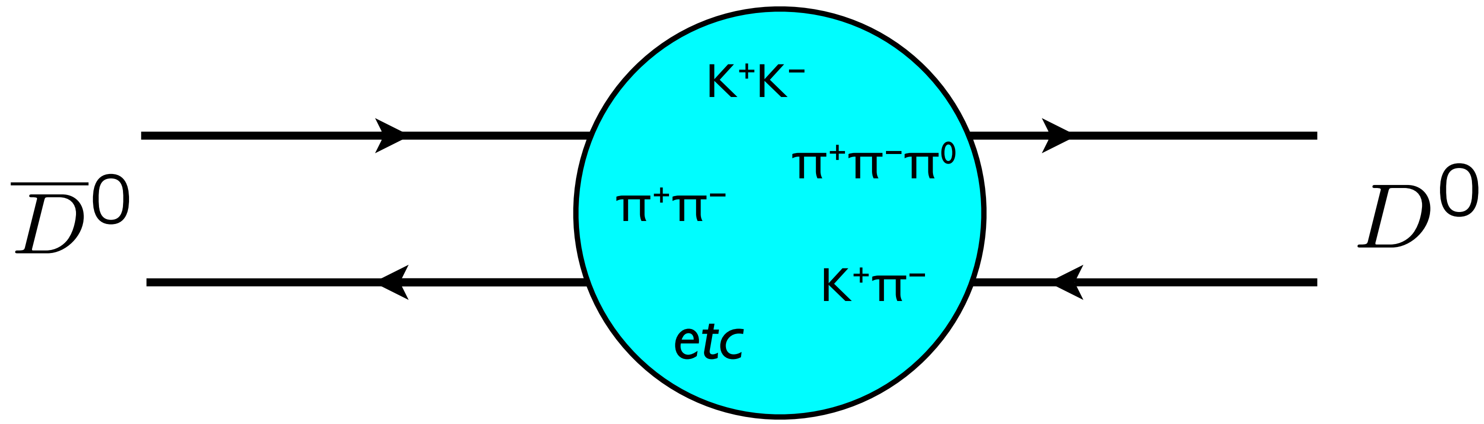
Contributes mainly to x

Intermediate b: CKM-suppressed
Intermediate d,s: GIM-suppressed

$$x \propto \frac{(m_s^2 - m_d^2)^2}{m_c^2} \sim 10^{-5}$$

Tiny!

Mixing via hadronic intermediate states (long-range)



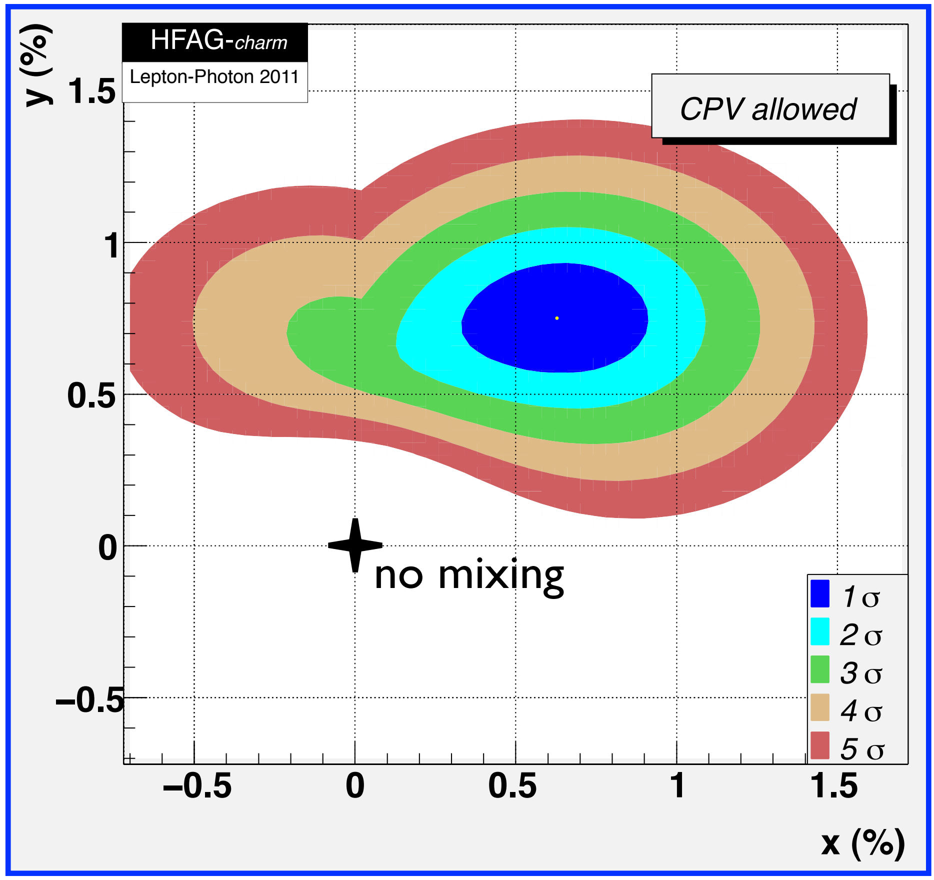
Non-perturbative; hard to predict SM contribution.

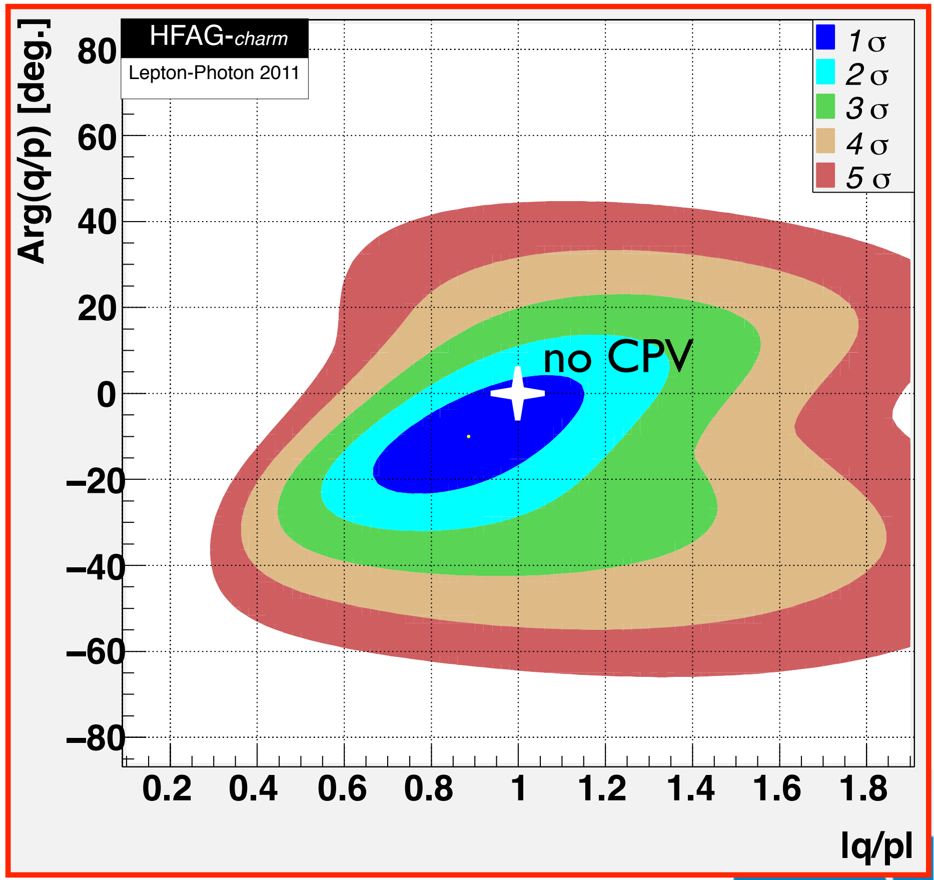
Currently: $|x| \leq 0.01$, $|y| \leq 0.01$ – less tiny!

e.g. PRD 69,114021 (Falk, Grossman, Ligeti, Nir & Petrov)

Mixing and indirect CPV

- D^0 mesons undergo mixing like K^0, B^0, B_s^0
- But unlike the others, D^0 mixing is small.
  - Mixing parameters x, y order of 10^{-2}
- First seen by BABAR & Belle in 2007
- Now well-established: HFAG average excludes no-mixing hypothesis by 10σ
- Smallness of mixing parameters makes CP asymmetries doubly small, e.g.





CP-violating terms << 10^{-2} in SM

$$2A_\Gamma = (|q/p| - |p/q|)\, y \cos\phi - (|q/p| + |p/q|)\, x \sin\phi$$

Mixing parameters $O(10^{-2})$

Observable asymmetry << 10^{-4} in SM

c.f. current world average from HFAG: $A_\Gamma = (0.123 \pm 0.248)\%$

Results discussed today

Define $y_{CP} = \dfrac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$

$D^0 \rightarrow K^- \pi^+$: Mixture of CP states

$D^0 \rightarrow K^- K^+$: CP-even eigenstate

y_{CP} related to y and CP parameters by:

$$y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$$

$A_M \neq 0$: CPV in mixing (asymmetry in R_M between D^0 and D^0)

$\cos\phi \neq 1$: CPV in interference between mixing and decay

CP observable A_Γ defined as:

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

$$2A_\Gamma = (|q/p| - |p/q|)\, y\cos\phi - (|q/p| + |p/q|)\, x \sin\phi$$

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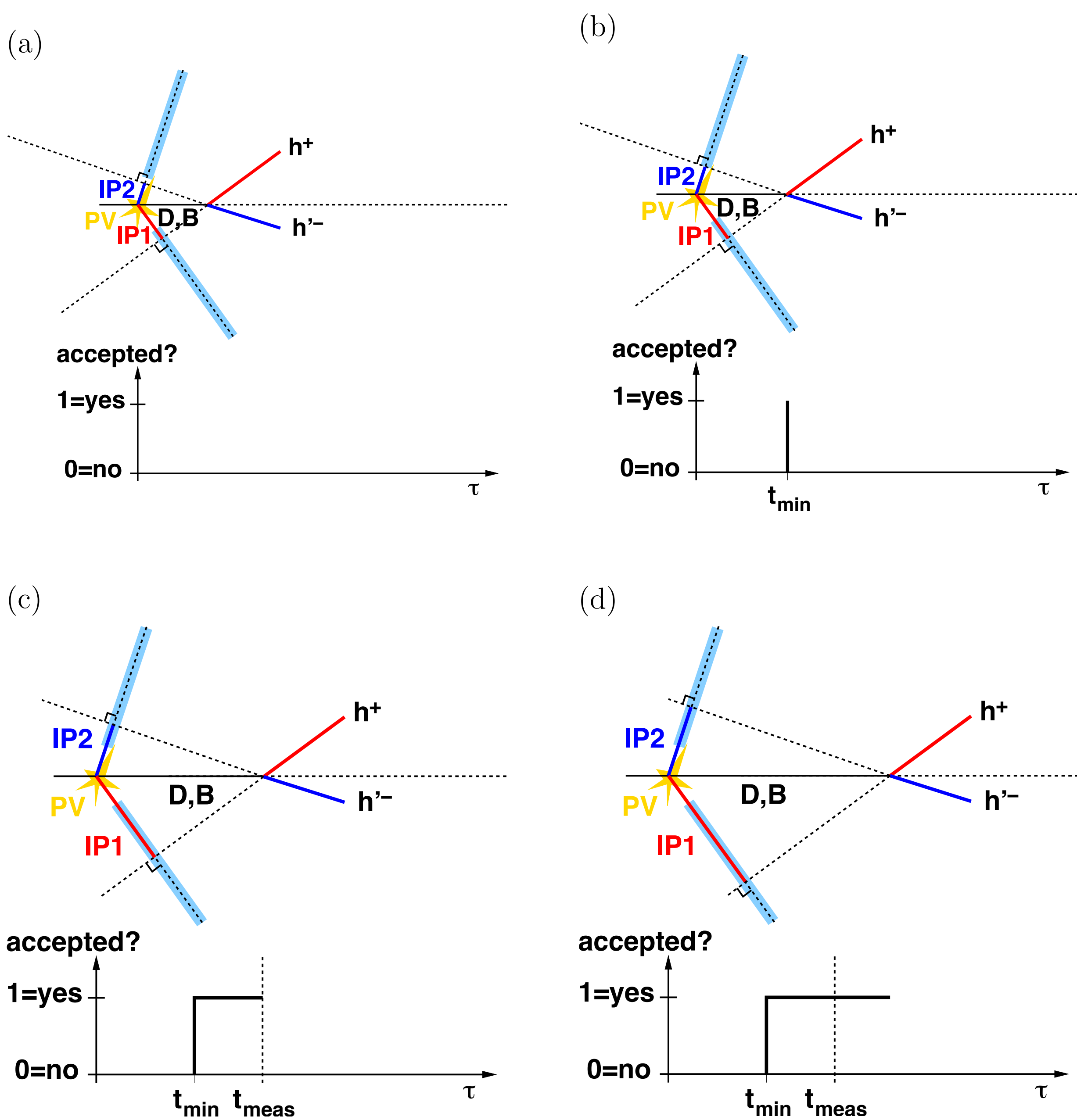
LHCb

Measuring y_{CP} and A_Γ at LHCb

- Two key challenges at a hadronic machine like LHCb
  - Background from secondary charm ($b \rightarrow c$ decays)
  - Lifetime-biasing trigger and selection
- But on the other hand, two big advantages:
  - Large boost => resolution < lifetime
  - Large production cross-section

Dealing with lifetime bias

- Swimming technique used at CDF (and DELPHI, and NA11)
- Ideally suited to LHCb where our software trigger can be recreated exactly offline.



Trying to measure how acceptance varies with lifetime candidate-by-candidate.

... so that we can pull it directly from the data instead of having to model it on signal MC.

Ideally, would shift D^0 decay vertex, but this is a nightmare (imagine trying to move VELO hits).

Instead, shift primary vertex in opposite sense (*nearly* the same thing; systematic for difference)

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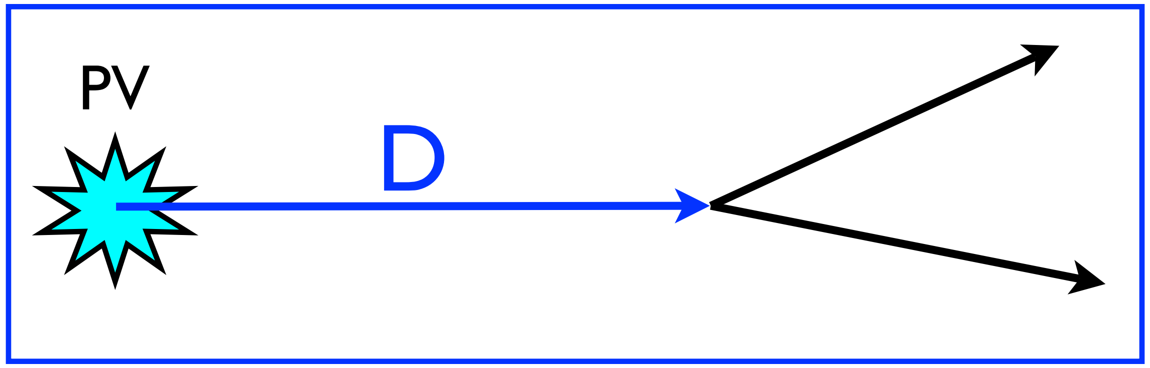
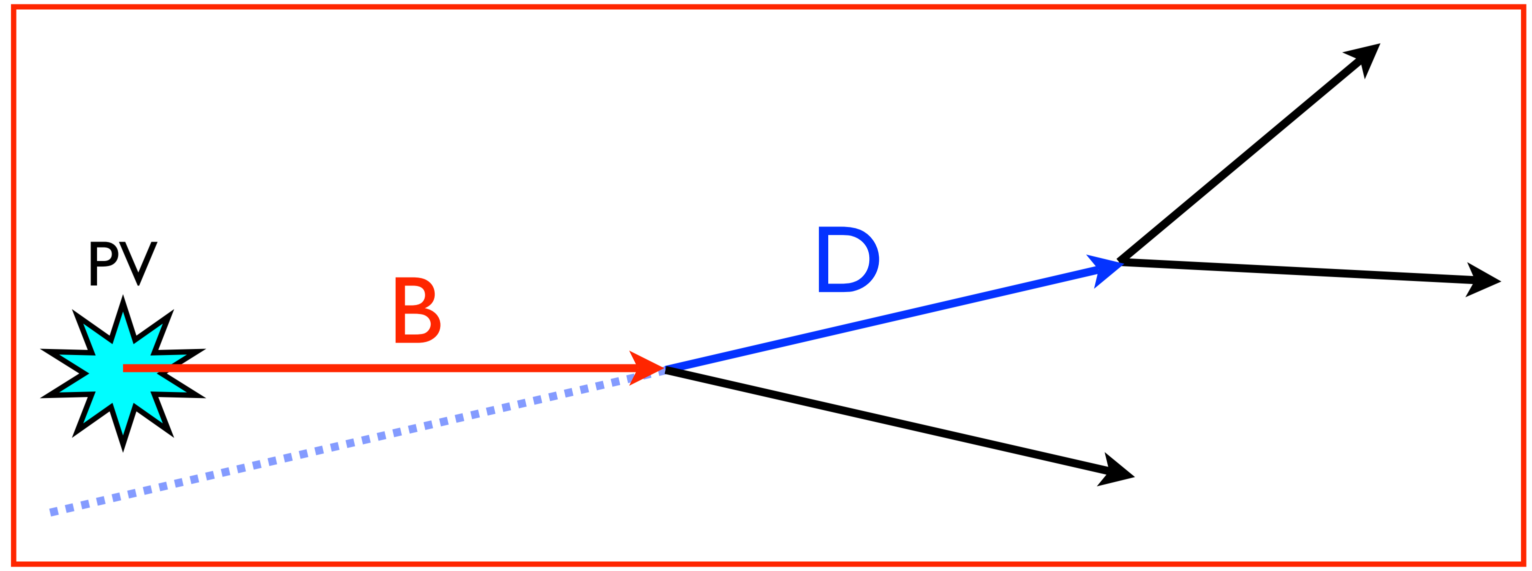
Prompt-secondary discrimination



Prompt charm:

D points to primary vertex

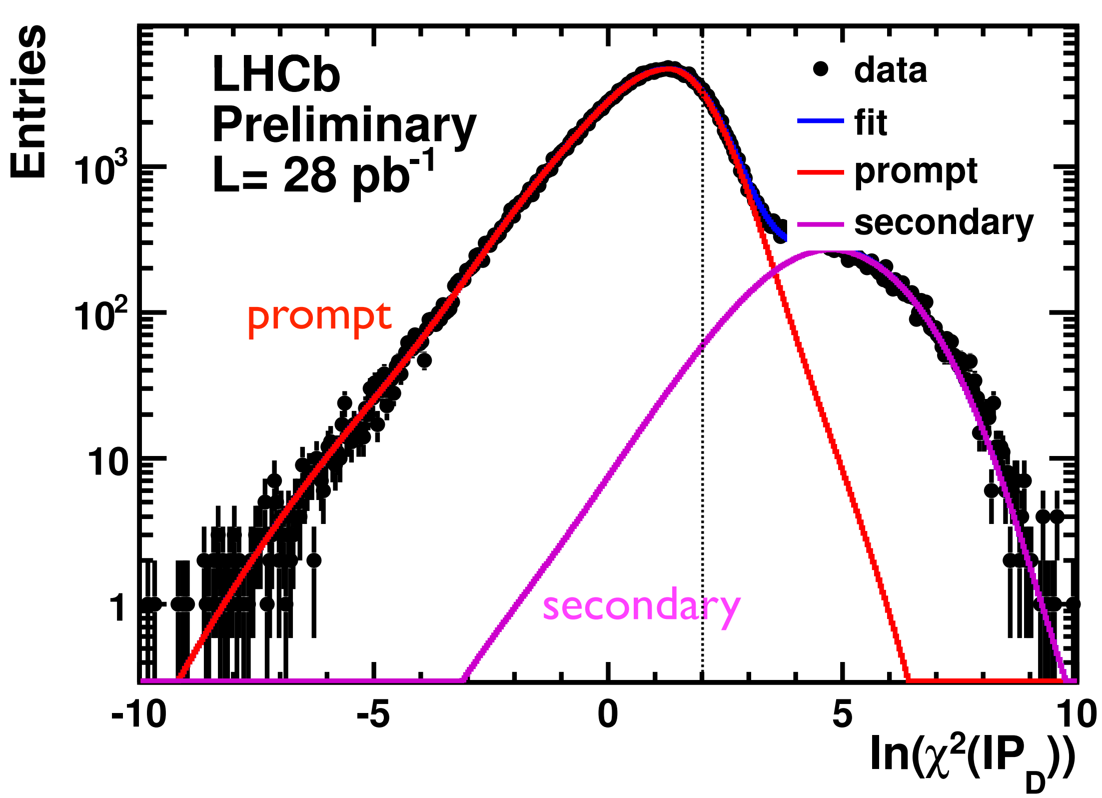
Daughters of D don't in general

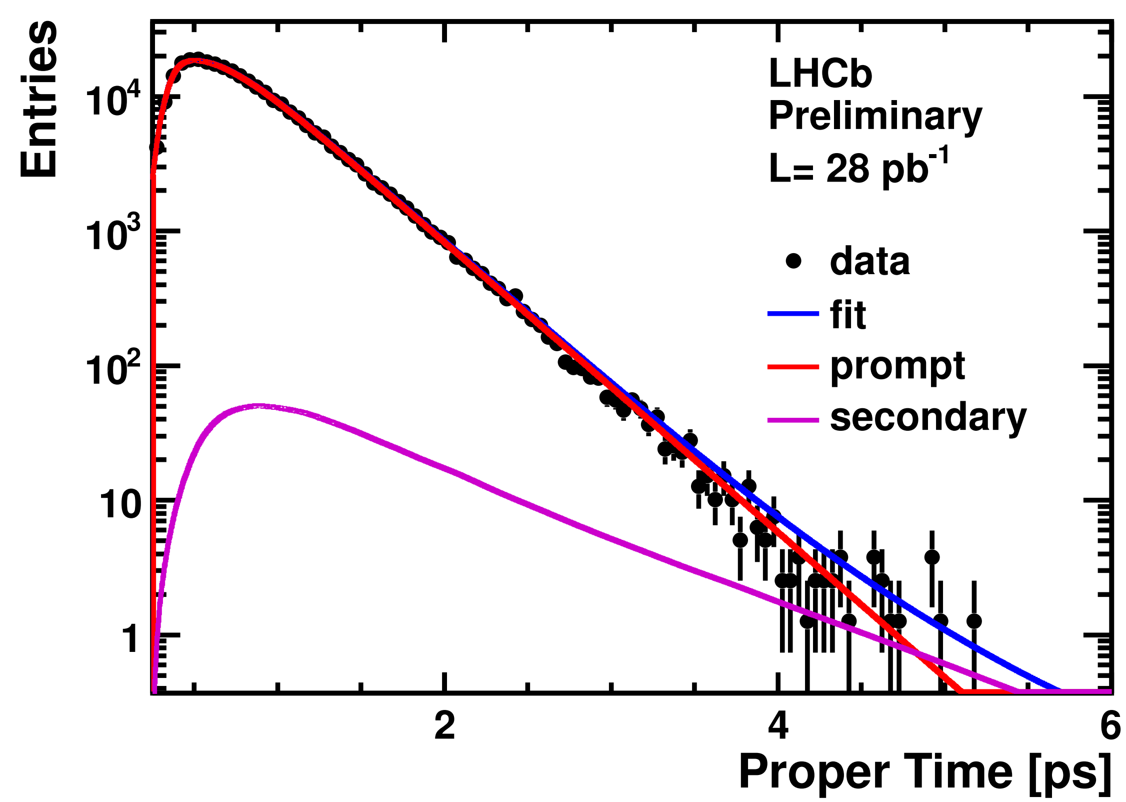


Secondary charm:

D doesn't point to PV in general

- Use impact parameter χ^2 to distinguish between these.
- 2D fit to (time, IP χ^2). 1D projections for tagged $D^0 \rightarrow K^- \pi^+$:





nb log y-axis

Cut of IPχ^2<2 applied in final fit to reduce secondary contamination

Results for y_{CP} in 2010 data

- Lifetime of $D^0 \rightarrow K^- \pi^+$: 410.2 ± 0.9 fs (stat err only)
  - Important test of the method. Compare to world-avg: 410.1 ± 1.5 fs
- $y_{CP} = (5.5 \pm 6.3 \pm 4.1) \times 10^{-3}$
- Dominant uncertainties from background.
  - Will be easier to control in 2011 after improvements to trigger
  - Statistical component in secondary charm uncertainty -- again, will improve with 2011 data.

Table 1: Summary of systematic uncertainties.

Effect	y_{CP} (10^{-3})
VELO length scale	negligible
Turning point bias	± 0.1
Turning point scaling	± 0.1
Combinatorial background	± 0.8
Proper-time resolution	± 0.1
Minimum proper-time cut	± 0.8
Maximum proper-time cut	± 0.2
Secondary charm background	± 3.9
Total	± 4.1

HFAG world avg: $y_{CP} = (1.107 \pm 0.217)\%$

Indirect CPV: A_Γ in 2010 data

$$
\begin{aligned}
A_\Gamma &\equiv \frac{\hat{\Gamma}(D^0 \to K^+K^-) - \hat{\Gamma}(\overline{D}^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^+K^-) + \hat{\Gamma}(\overline{D}^0 \to K^+K^-)} \\
&\approx \left(\frac{A_m}{2} y \cos\phi - x \sin\phi\right) \frac{1}{1 + y_{CP}} \\
&\approx \boxed{\frac{A_m}{2}} y \cos\phi - x \boxed{\sin\phi.}
\end{aligned}
$$

- $A_\Gamma = (-5.9 \pm 5.9 \pm 2.1) \times 10^{-3}$
- Systematic uncertainties smaller
  - Better cancellation since both final states use the same D^0 decay mode.
  - Again, background effects dominate and will improve with more data.

Table 1: Summary of systematic uncertainties.

Effect	A_Γ (10^{-3})
VELO length scale	negligible
Turning point bias	negligible
Turning point scaling	± 0.1
Combinatorial background	± 1.3
Proper time resolution	± 0.1
Minimum proper-time cut	± 0.1
Maximum proper-time cut	± 0.2
Secondary charm background	± 1.6
Total	± 2.1

HFAG world avg: $A_\Gamma = (0.123 \pm 0.248)\%$

Does not include recent Belle measurement of $A_{CP}(D^0 \to K_S\, \pi^0)$

Time-integrated asymmetries in $D^0 \to K^- K^+, \pi^- \pi^+$

$0.6\ \mathrm{fb}^{-1}$

arXiv:1112.0938
Accepted for publication in PRL

$D^0 \to K^+ K^-, \pi^+ \pi^-$ measurements

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).	$+0.0022 \pm 0.0024 \pm 0.0011$
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 2008).	$+0.0043 \pm 0.0052 \pm 0.0012$
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	$-0.0024 \pm 0.0052 \pm 0.0022$
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	$+0.019 \pm 0.032 \pm 0.008$
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	$+0.048 \pm 0.039 \pm 0.025$
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	$-0.049 \pm 0.078 \pm 0.030$
.	.	COMBOS average	$+0.0020 \pm 0.0022$

HFAG

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).	$-0.0024 \pm 0.0022 \pm 0.0010$
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).	$-0.0043 \pm 0.0030 \pm 0.0011$
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	$+0.0000 \pm 0.0034 \pm 0.0013$
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	$+0.000 \pm 0.022 \pm 0.008$
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	$-0.001 \pm 0.022 \pm 0.015$
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	$-0.010 \pm 0.049 \pm 0.012$
1995	CLEO	J.E. Bartelt et al. (CLEO Collab.), Phys. Rev. D 52, 4860 (1995).	$+0.080 \pm 0.061$
1994	E687	P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).	$+0.024 \pm 0.084$
.	.	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.

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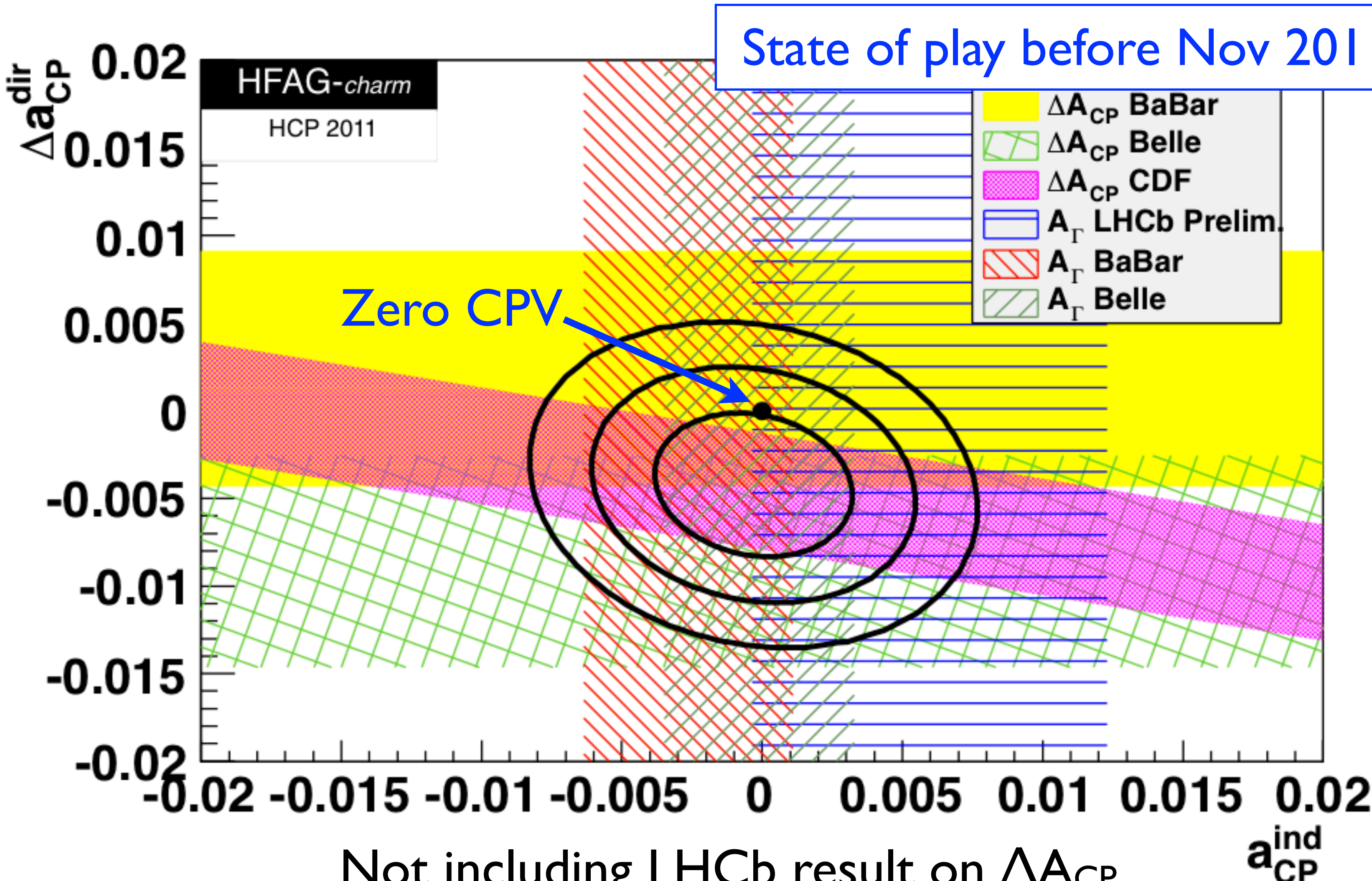
NB Updates of CDF result: arXiv:1111.5023, CDF-10784

LHCb

Indirect vs direct CP violation

- Both indirect & direct CPV can contribute.
- Indirect CPV is universal => cancels in A(KK)-A(ππ)...
  ... IF equal proper time acceptance for both (e.g. BABAR, Belle)
- If not equal, residual contribution: $A^{ind}[<t_{KK}>-<t_{\pi\pi}>]/\tau_0$



Not including LHCb result on ΔA_{CP}

Consistency with no CPV hypothesis: 28%

$$a^{\rm ind}_{CP} = (-0.03 \pm 0.23)\%$$

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

World avg ΔA_{CP} negative and (if no indirect CPV) about 1.6σ from zero.

See: CDF, arXiv:1111.5023
See also: Bigi, Paul & Recksiegel, JHEP05 089 (2011)

Formalism

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

physics CP asymmetry

Detection asymmetry of D^0

Detection asymmetry of soft pion

Production asymmetry

- ... so when we take $A_{RAW}(f)^* - A_{RAW}(f')^*$ the production and soft pion detection asymmetries will cancel. Moreover...
- No detector asymmetry for D^0 decays to $(K^+ K^-)$, $(\pi^+ \pi^-)$

... i.e. all the D^*-related production and detection effects cancel.

This is why we measure the CP asymmetry difference: very robust against systematics.

Shorthand: $\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$

Assumptions

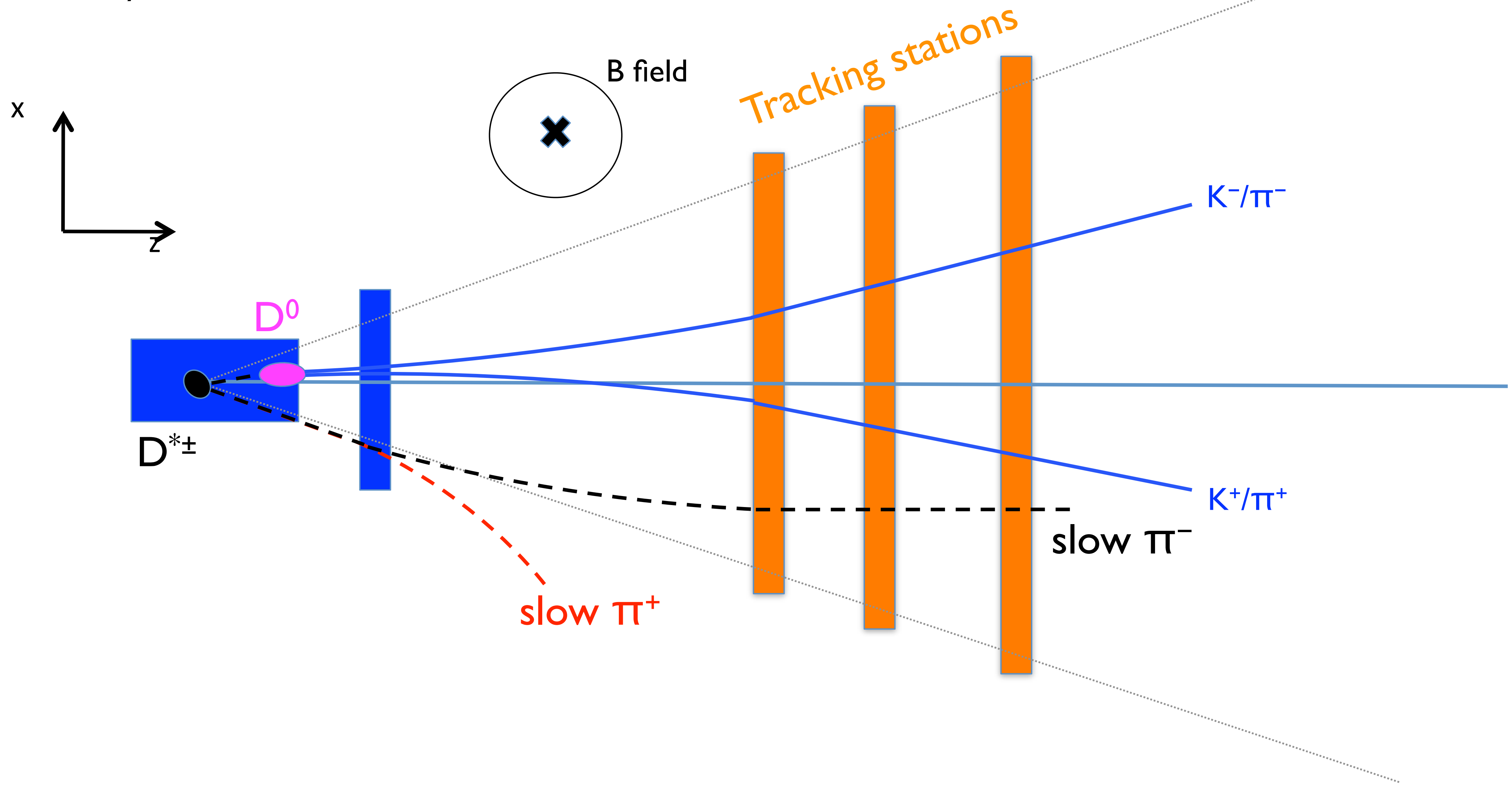
- Double-difference robust against systematics.
- In order to break the formalism, you need a detector effect that induces different fake asymmetries for KK and ππ.
- Two known mechanisms:
  - Correlation between KK/ππ efficiency ratio and D^{*+}/D^{*-} asymmetry (from production or soft pion efficiency)
    - e.g. correlated variation of A_P and A_D with kinematics (p_t, η)
    - Solution: divide data into bins of the variable (such that no correlation within bin) and treat each bin independently.
  - Asymmetric peaking background different between KK, ππ
    - Comes from mis-reconstructed $D^{*+} \rightarrow D^0 \pi^+$
    - This is a small effect at LHCb due to excellent hadron ID: from D^0 mass sidebands, size of peaking background O(1%) of signal... and background asymmetry O(%) so effect $O(10^{-4})$
- First-order expansion assumes raw asymmetry not large.
  - ... which is true: O(%).

Selection

- Kinematic and geometrical selection cuts, including:
  - Track fit quality for all three tracks
  - D^0 and D^{*+} vertex fit quality
  - Transverse momentum of D^0: $p_T > 2$ GeV/c
  - Proper lifetime of D^0: $ct > 100$ μm
  - Decay angle of D^0 decay: $\cos\theta_h < 0.9$
  - D^0 must point back to primary vertex (IP $\chi^2 < 9$)
  - D^0 daughter tracks must not point back to primary vertex
  - Hard kaon/pion hadron ID cuts imposed with RICH information
  - Fiducial cuts to exclude edges where B-field causes large D^{*+}/D^{*-} acceptance asymmetry
- Software trigger required to fire explicitly on the D^0 candidate.
- D^0 mass window: 1844 --1884 MeV/c^2 (few slides' time)

Fiducial cuts: cartoon of detector

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



- B-field breaks symmetry between D^{*+} and D^{*-}

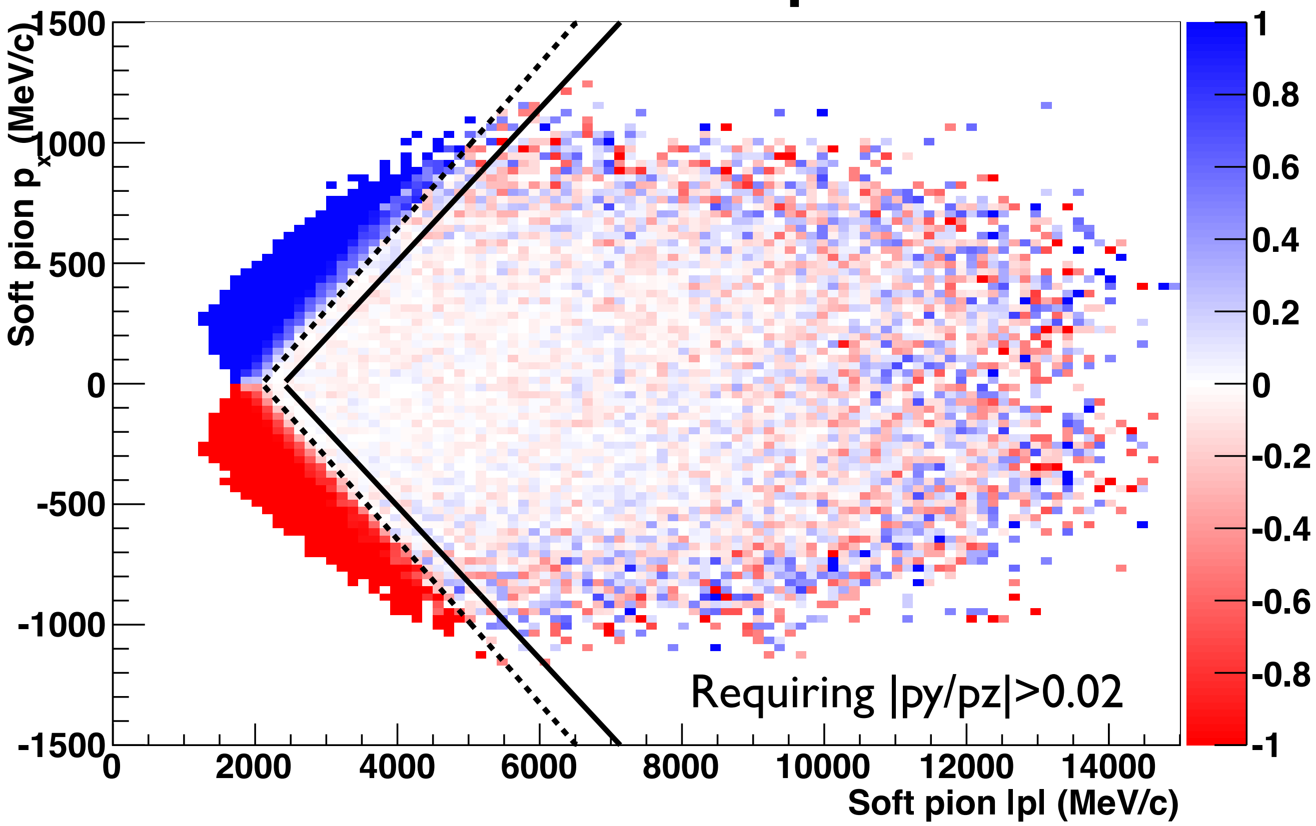
Fiducial cuts

- ∃ regions of kinematic space where one charge of slow pion winds up inside acceptance but other does not.
  - Main example: edges of acceptance (prev. slide)
  - Also downstream beampipe
- Result: large local raw asymmetries.
- These are independent of the D^0 decay mode but:
  - break the assumption that raw asymmetries are small
  - risk of second-order effects if bin includes border region where raw asymmetry is changing rapidly *and* ratio of efficiencies of ($D^0 \to K^- K^+$) vs ($D^0 \to \pi^- \pi^+$) is also varying
- Therefore exclude them.

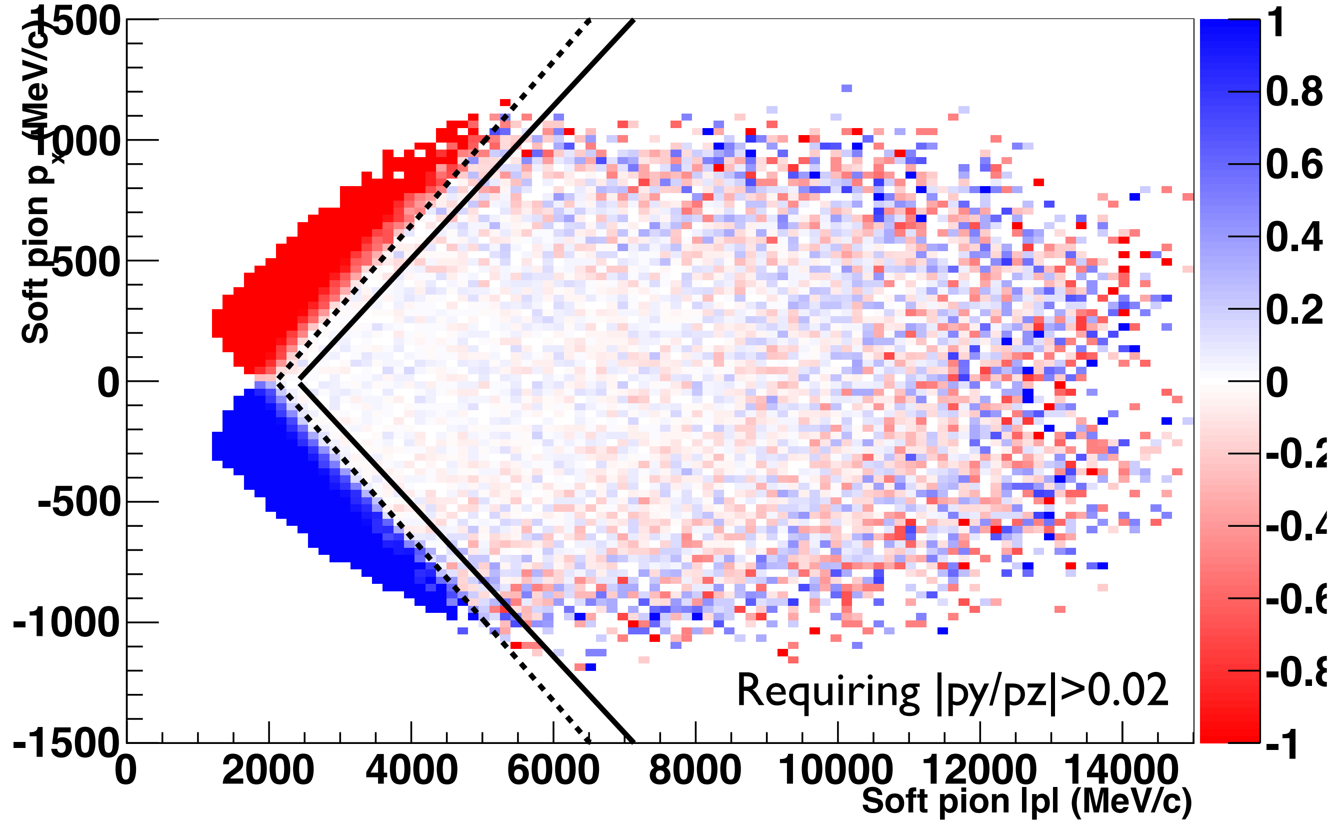
Fiducial cuts: edge region

Raw asymmetry of $D^{*\pm} \rightarrow D^0(K^-K^+)\,\pi^+$ in the $(p_x, |p|)$ plane of the tagging slow pion:

B-field up



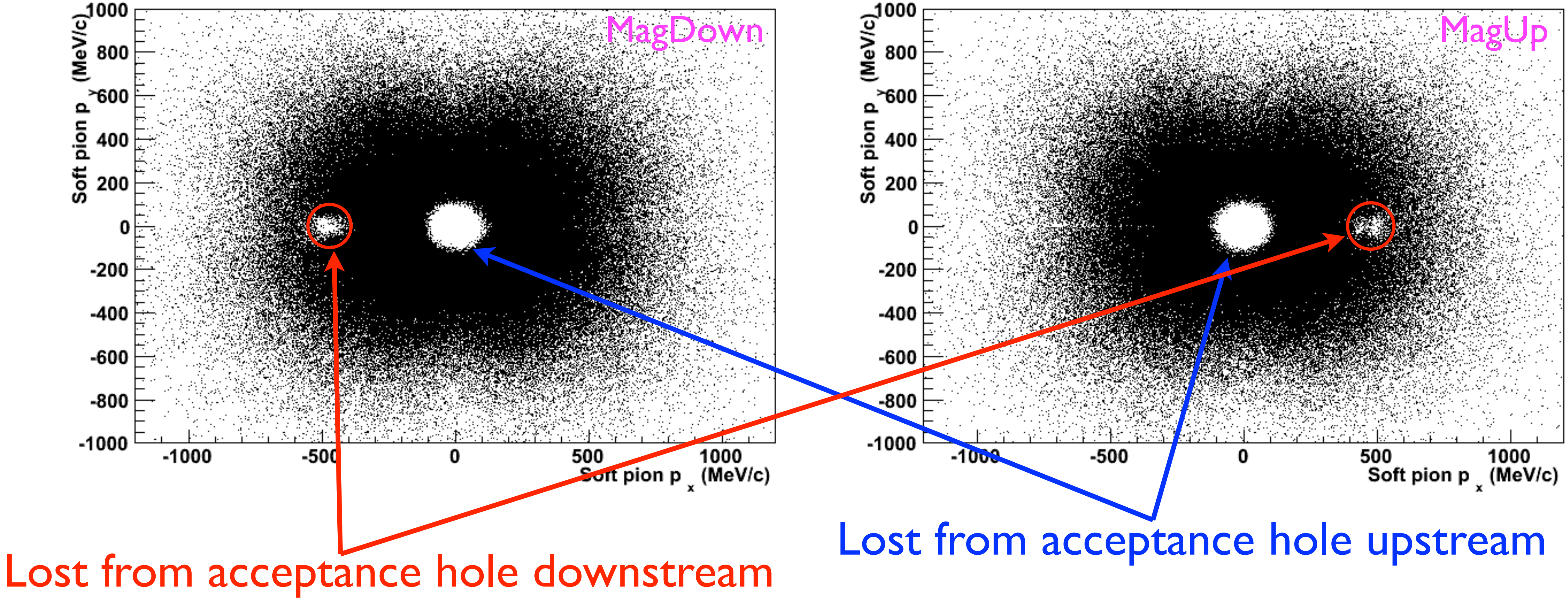
B-field down



- Solid line: fiducial cuts applied
- Dotted line: looser cuts used for crosscheck.

Fiducial cuts: downstream beampipe

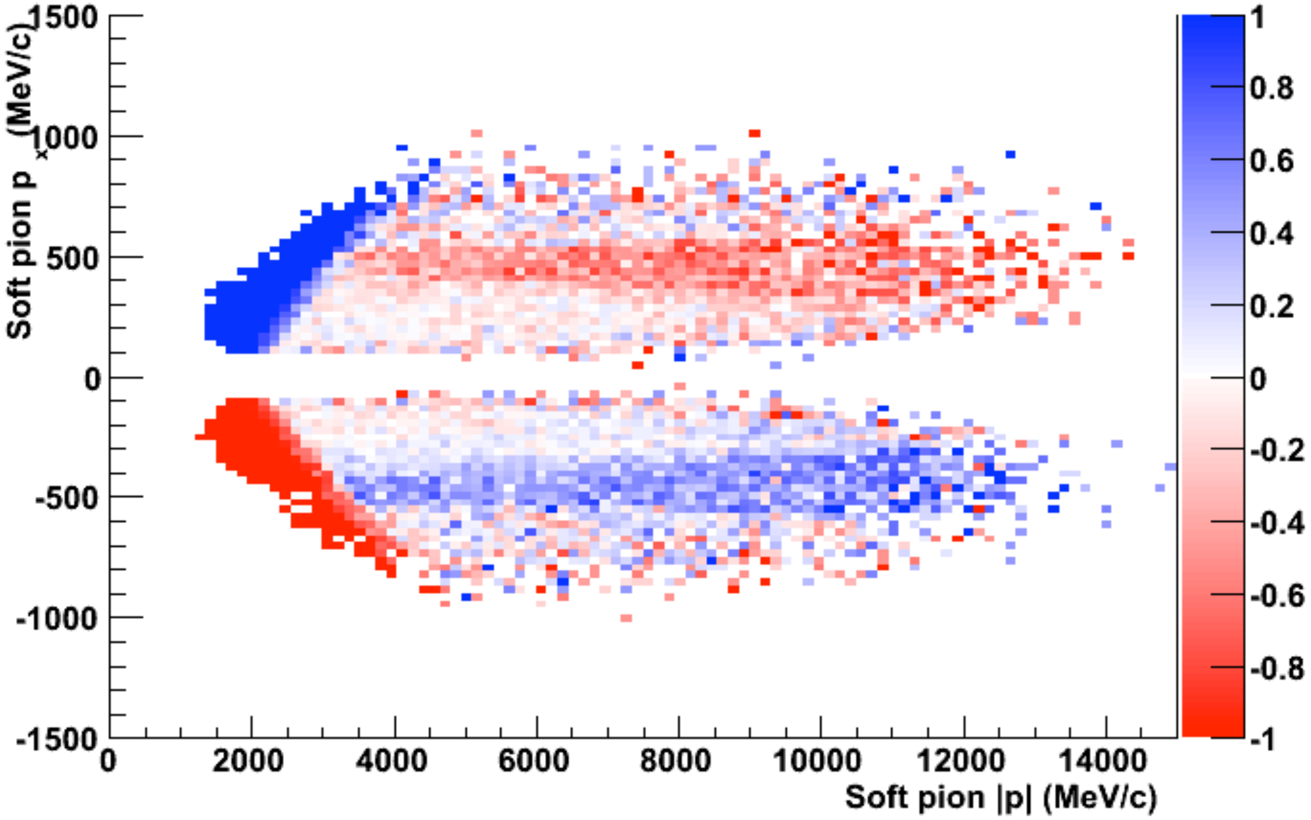
Plot slot pion p_y vs p_x (D^{*+} only):

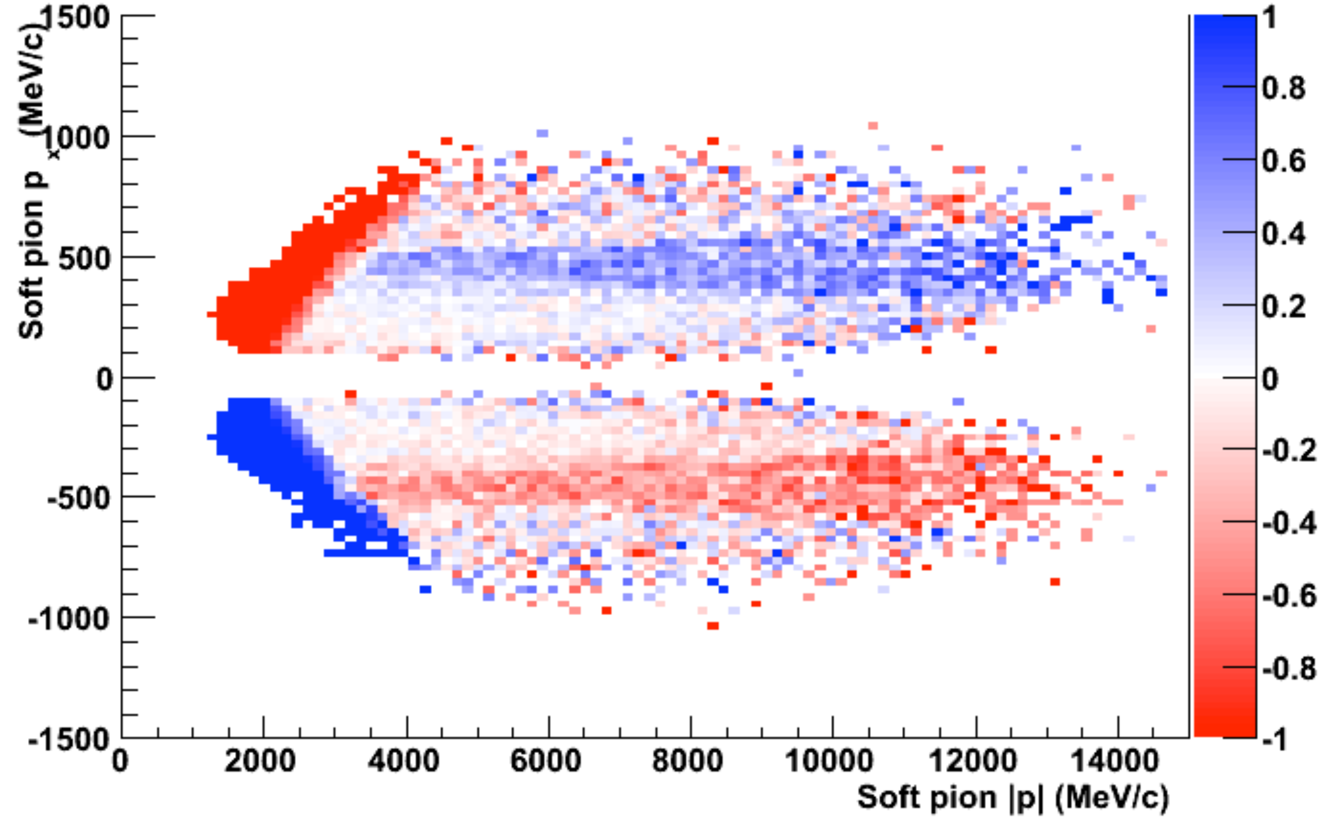


- Upstream acceptance is charge-independent
- Downstream acceptance has left-right asymmetry

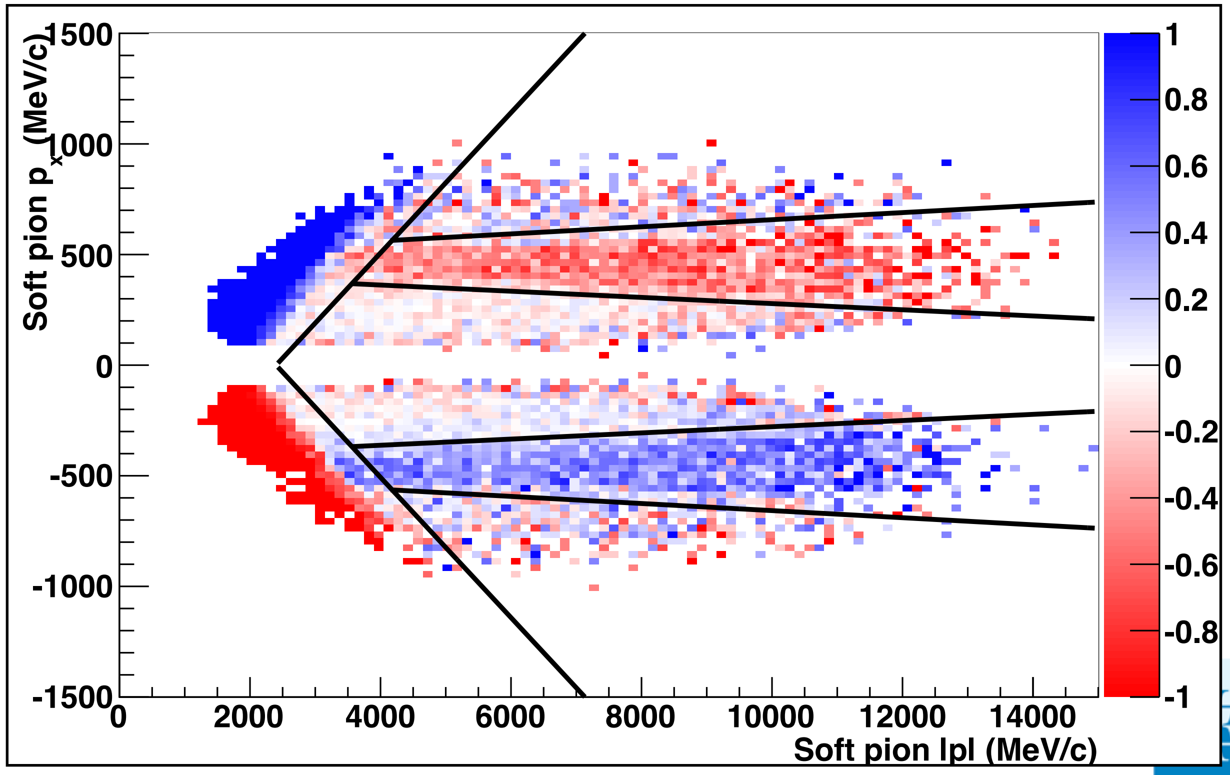
Fiducial cuts: downstream beampipe

Raw asymmetry plots again, this time requiring $|p_y/p_z|<0.02$:



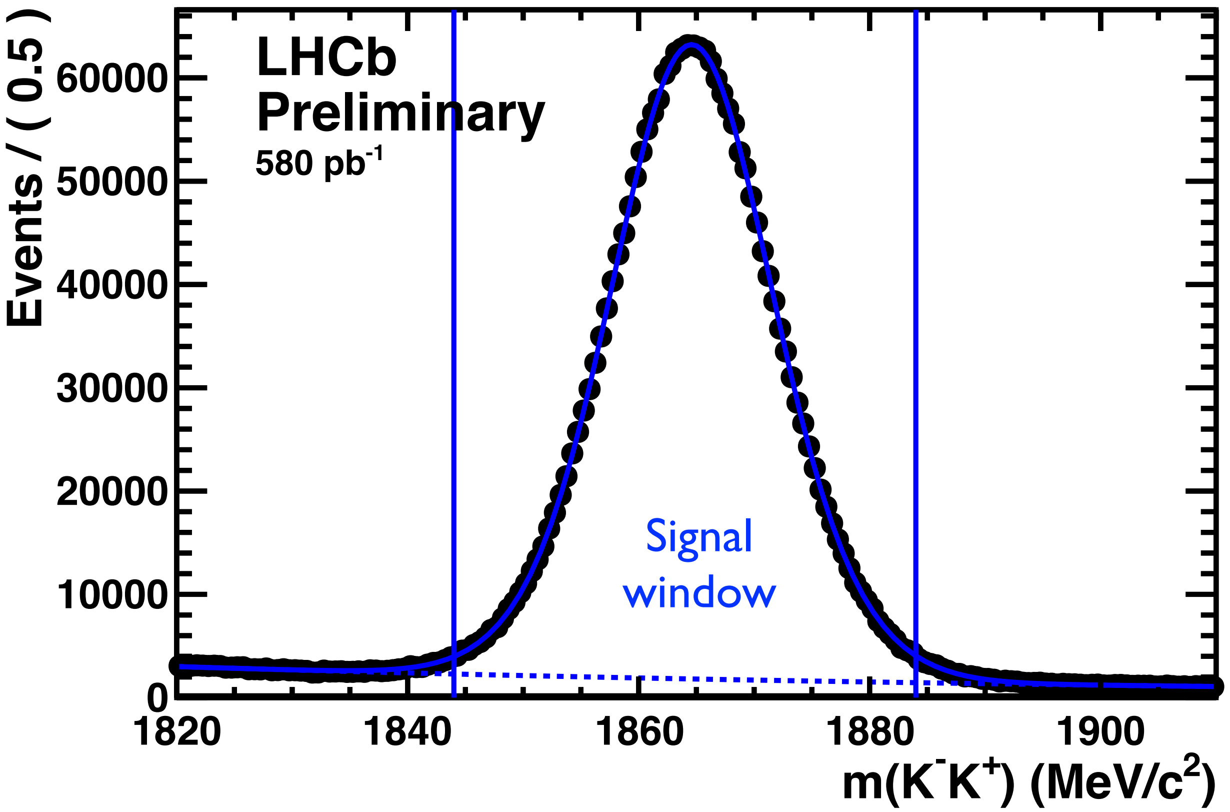


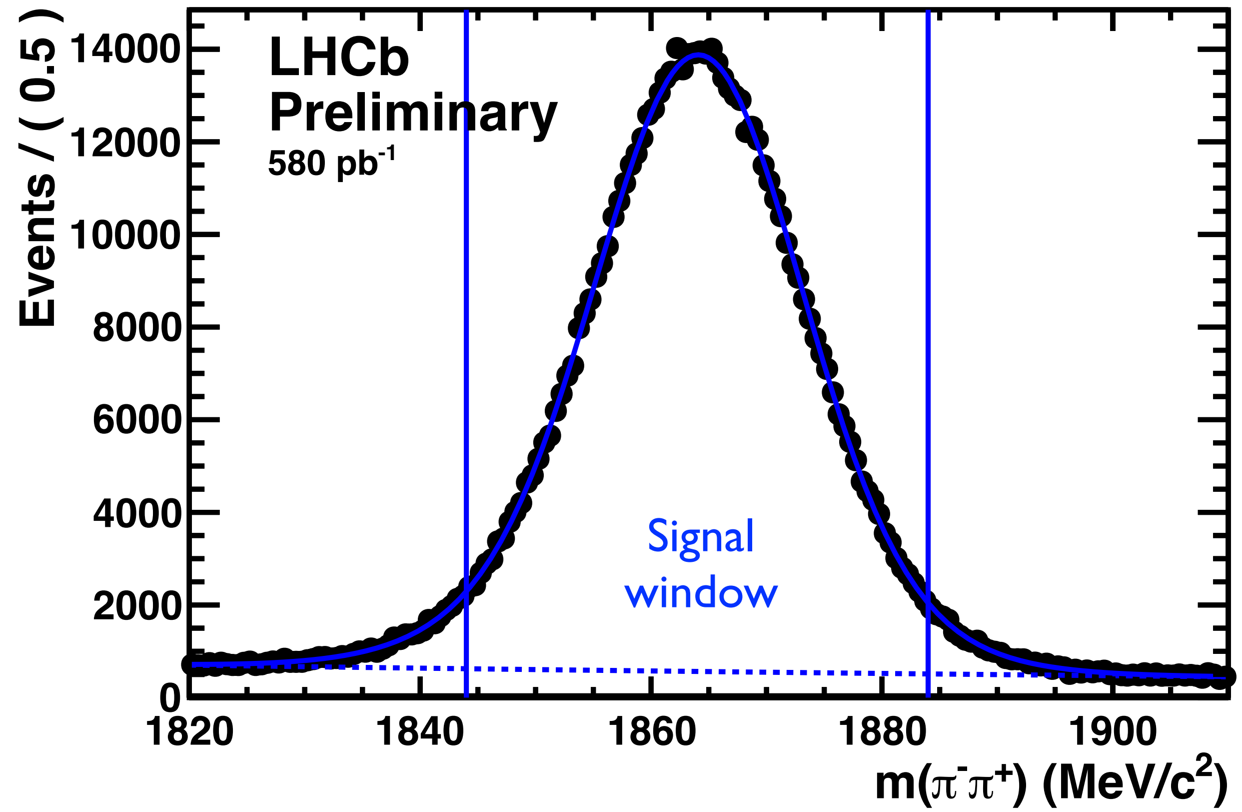
- Very clear effect.
- Impose cuts to remove this region too:
  - Only applied for $|p_y/p_z|<0.02$

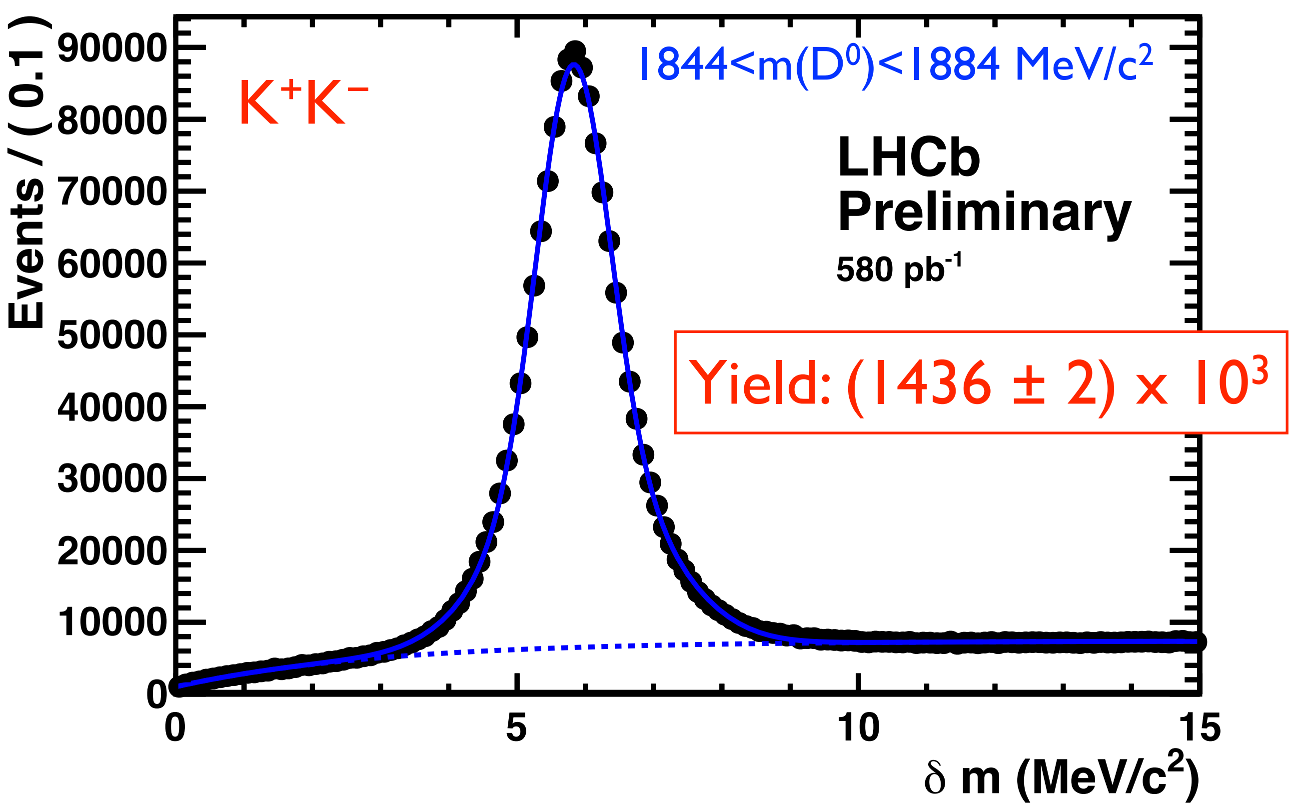


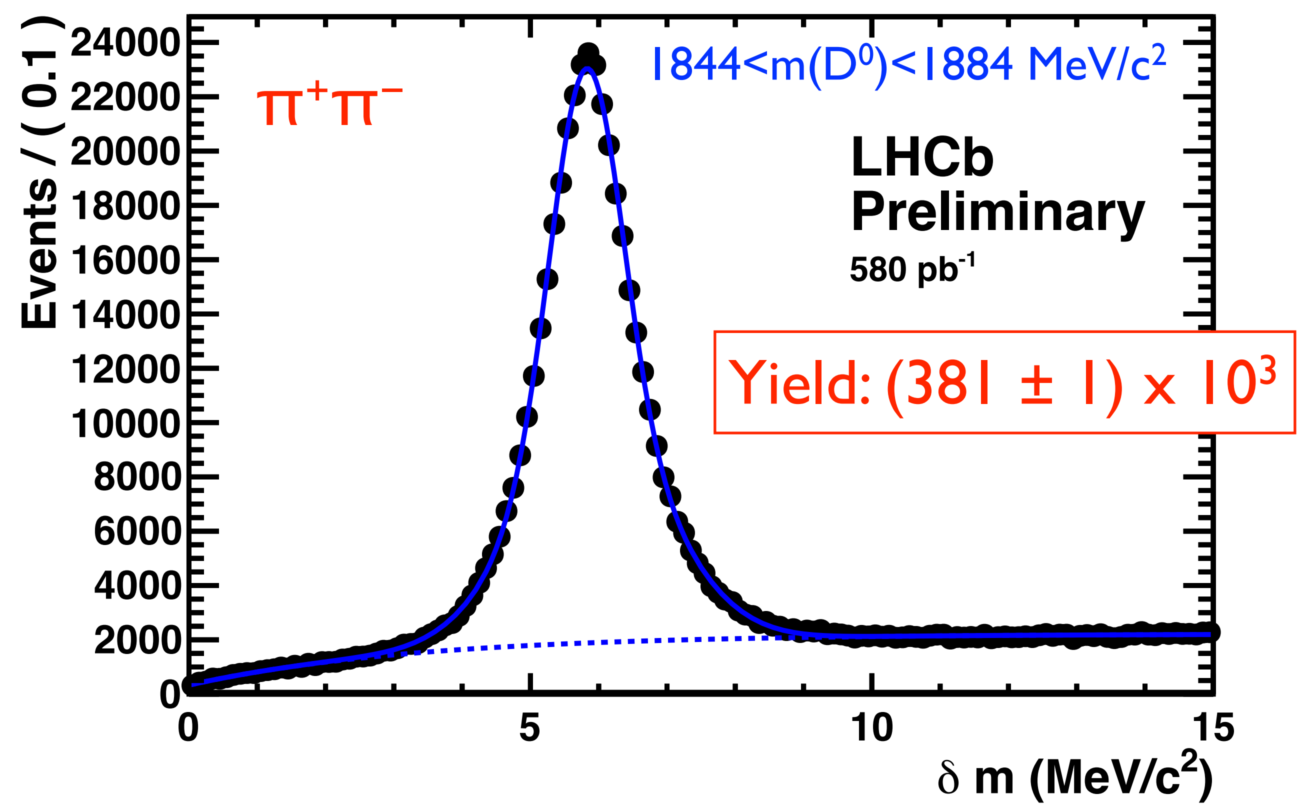
Mass spectra

Showing D^0 candidate mass for D^{*+} candidates within $0<\delta m<15$ MeV/c^2; $\delta m = m(D^0\,\pi^+) - m(D^0) - m(\pi^+)$









For illustration; not used in calculating ΔA_{CP}

Kinematic binning

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

Fit procedure

- Use 1D fits to mass difference $\delta m = m(D^0\pi^+) - m(D^0) - m(\pi^+)$
- Signal model: double-Gaussian convolved with asymmetric tail:

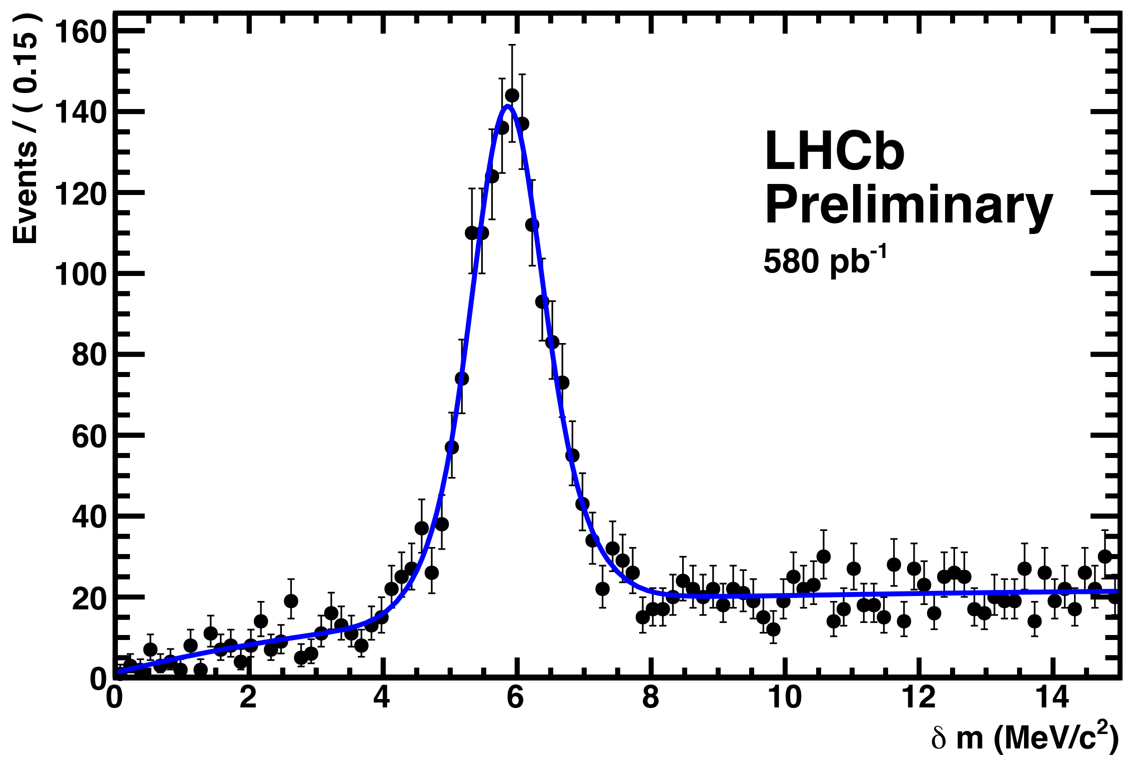
$$g(\delta m) = [\Theta(\delta m' - \mu)\, A(\delta m' - \mu)^s] \otimes G_2(\delta m - \delta m'; f_{\rm core}, \sigma_{\rm core}, \sigma_{\rm tail})$$

Phys. Lett. B 633 (2006) 309; LHCb-PUB-2009-031

- D^{*+} and D^{*-} are allowed to have different mass and resolution.
  - ... though $f_{\rm core}$ and $(\sigma_{\rm core}/\sigma_{\rm tail})$ are shared
- Background model:

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

δm_0 fixed from fit to high-statistics $D^0 \to K^-\pi^+$ channel
Special handling of tricky cases (single Gaussian for low-statistics bins, background parameters loosened in some kinematic regions).



Example fit (first kinematic bin of first run block, magnet polarity up, $D^0 \to K^+K^-$)

Consistency for ΔA_{CP} among individual fits: χ^2/NDF=211/215 (56%)
Stat error: 0.21% absolute

Systematic uncertainties

- Kinematic binning: 0.02%
  - Evaluated as change in ΔA_{CP} between full 54-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: 3.5 σ

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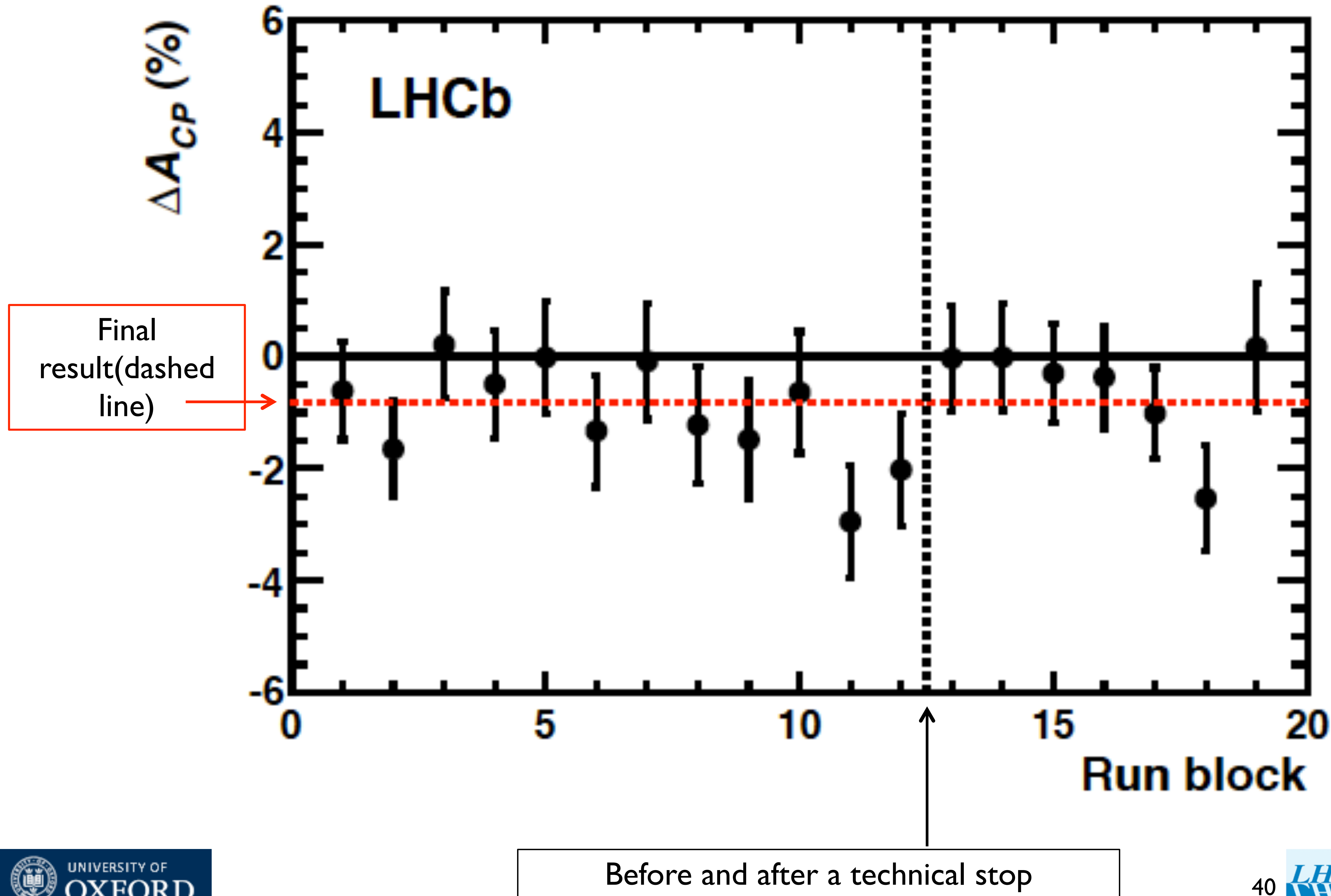
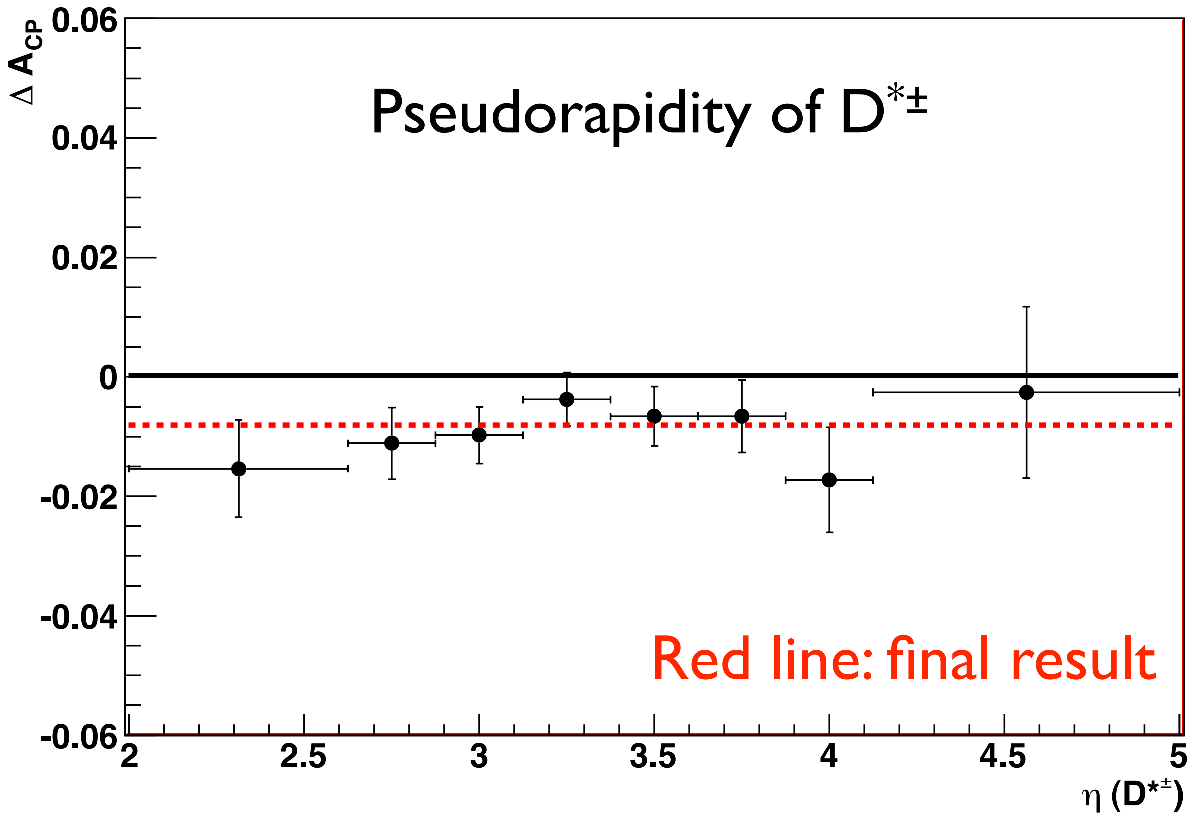
Further crosschecks

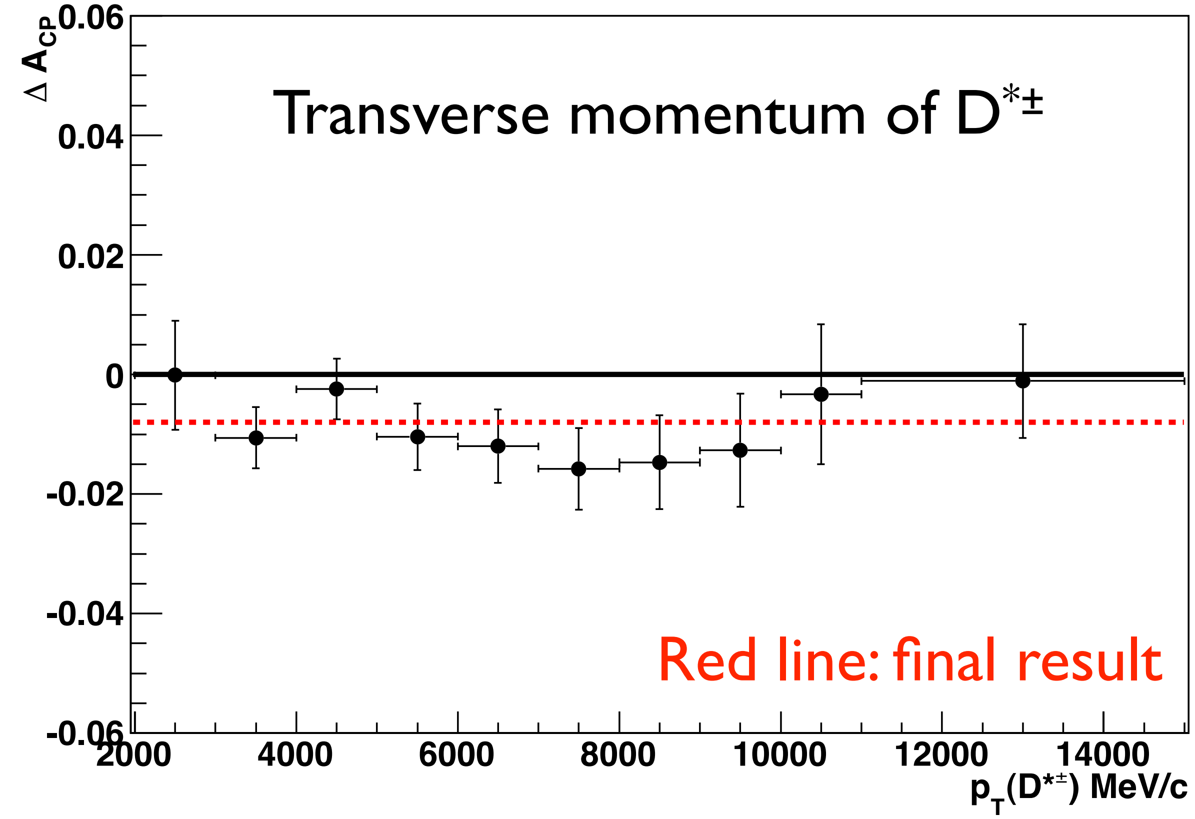
- Numerous crosschecks carried out, including:
  - Electron and muon vetoes on the soft pion and on the D^0 daughters
  - Different kinematic binnings
  - Stability of result vs time
  - Toy MC studies of fit procedure, statistical errors
  - Tightening of PID cuts on D^0 daughters
  - Stability with kinematic variables
  - Variation with event track multiplicity
  - Use of other signal, background lineshapes in the fit
  - Use of alternative offline processing (skimming/stripping)
  - Internal consistency between subsamples of data
- All variation within appropriate statistical/systematic uncertainties.

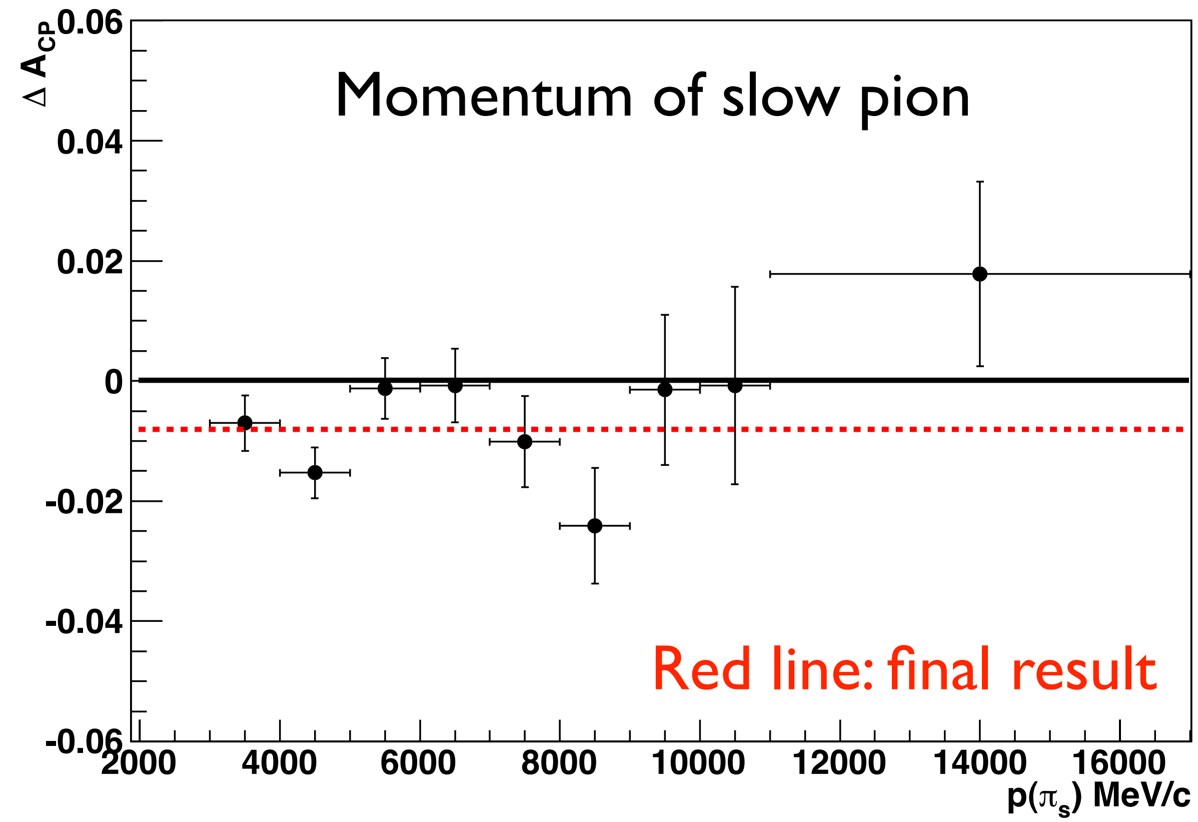
Stability vs time



Stability with kinematic variables







- No evidence of dependence on relevant kinematic variables.

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Consistency among subsamples

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	$(-0.82 \pm 0.21)\%$	$211/215(56\%)$

- Split by:
  - Before/after technical stop (about 60% of data before)
  - Magnetic field polarity
  - Charge of slow pion
- Consistency among subsamples: X^2/NDF = 6.7/7 (45%)

Interpretation: lifetime acceptance

- Lifetime acceptance differs between $D^0 \to K^+ K^-, \pi^+ \pi^-$
  - e.g. smaller opening angle => short-lived $D^0 \to K^+ K^-$ more likely to fail cut requiring daughters not to point to PV than $\pi^+ \pi^-$
- Need this to compute how much indirect CPV could contribute.
- Fit to background-subtracted samples passing the full selection, correcting for ~ 3% secondary charm, and extract:

$$\frac{\Delta\langle t\rangle}{\tau} = \frac{\langle t_{KK}\rangle - \langle t_{\pi\pi}\rangle}{\tau} = [9.83 \pm 0.22(\mathrm{stat.}) \pm 0.19(\mathrm{syst.})]\,\%$$

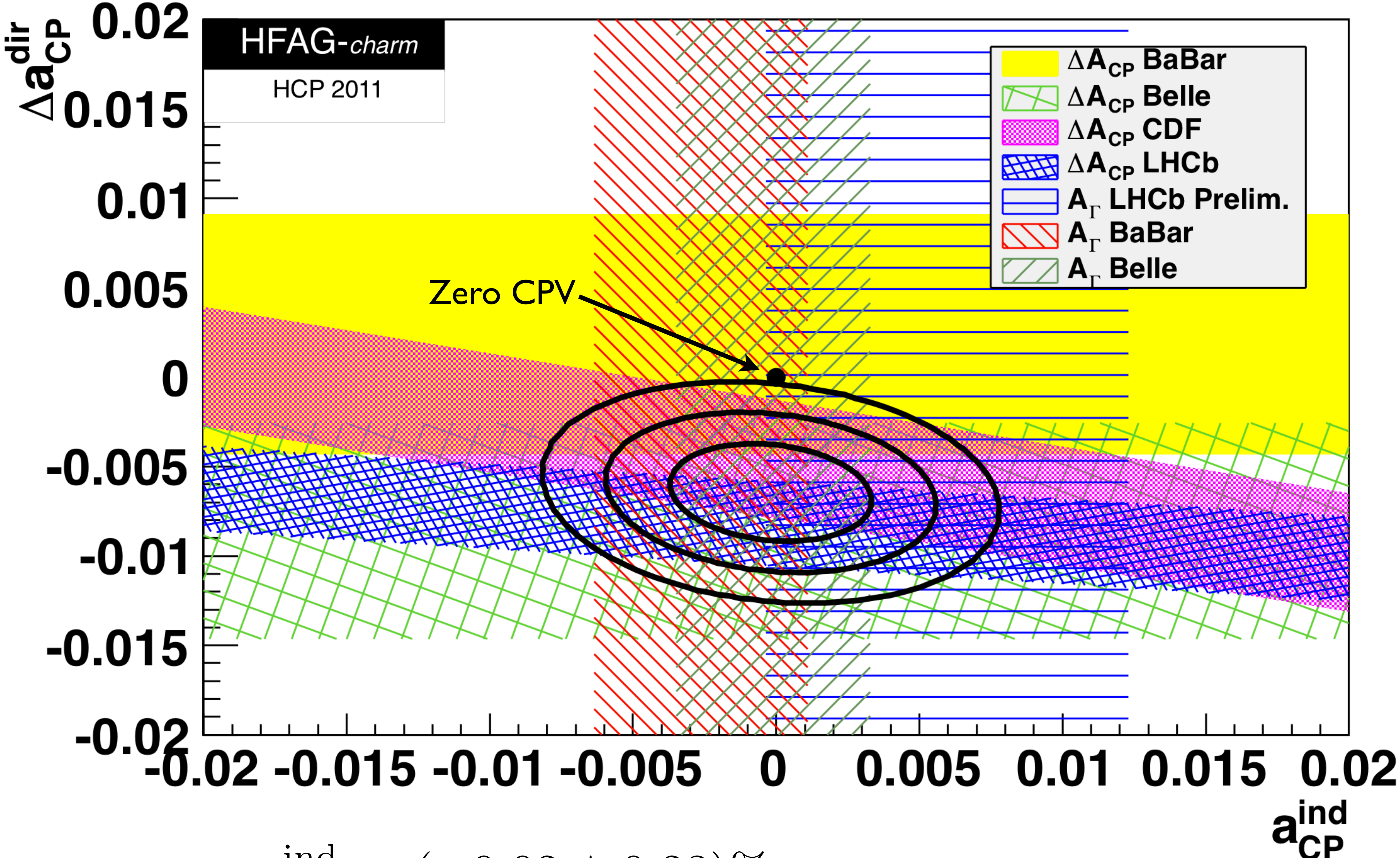
Systematics: secondary charm fraction (0.18%), world average D^0 lifetime (0.04%), background-subtraction procedure (0.04%)

- ... so indirect CP violation contribution mostly cancels.

LHCb value (−0.82 ± 0.21 ± 0.11)% consistent with HFAG average of non-LHCb results given our time-acceptance (approx 1.2σ)

$$a_{CP}^{\mathrm{ind}} = (-0.03 \pm 0.23)\%$$
$$\Delta a_{CP}^{\mathrm{dir}} = (-0.42 \pm 0.27)\%$$

World avg including LHCb result



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

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

Consistency with no CPV: 0.15%

New result from CDF at La Thuile

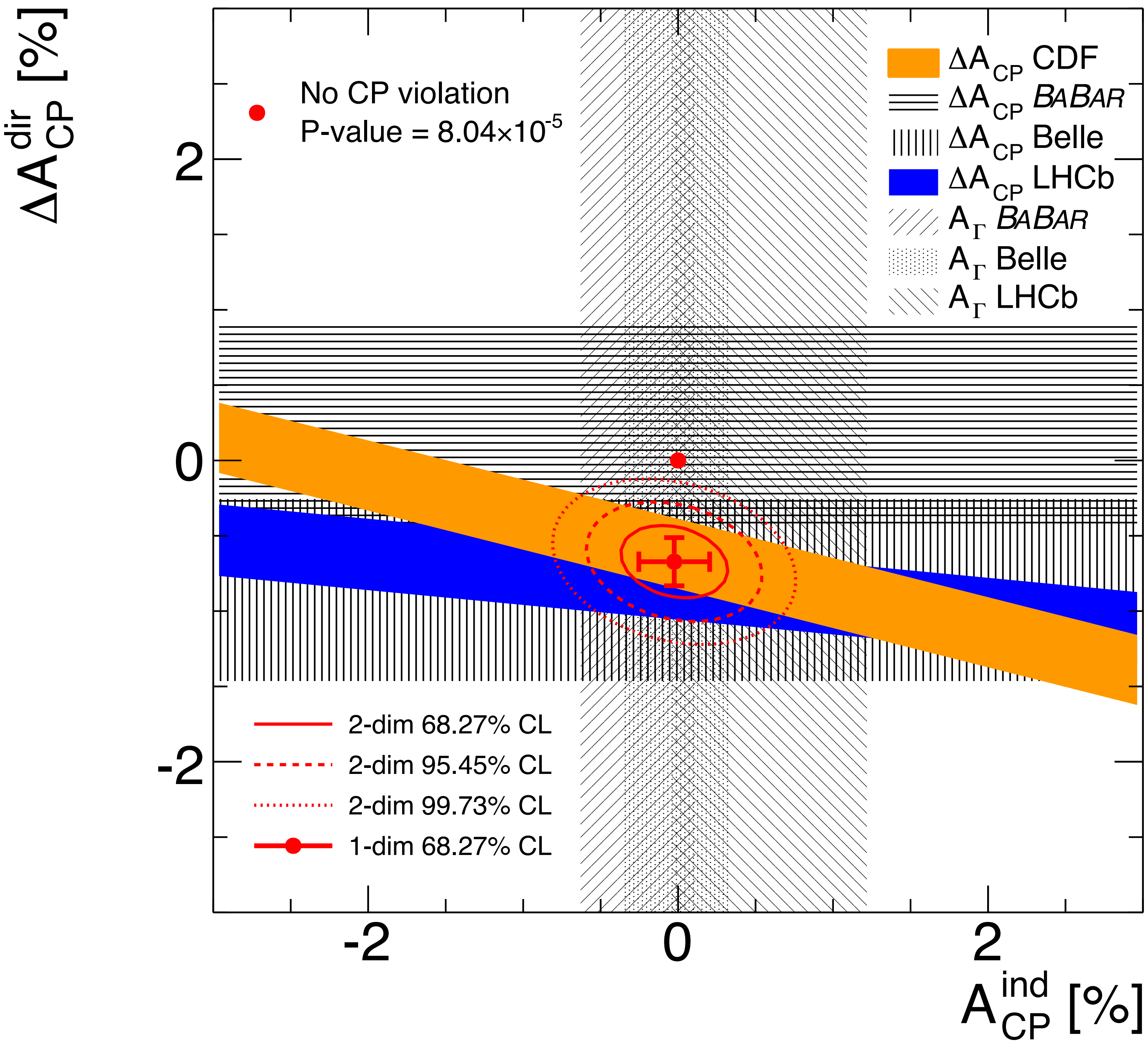
$$\Delta A_{CP} = [-0.62 \pm 0.21(\text{stat.}) \pm 0.10(\text{syst.})]\ \%$$ CDF note 10784

- Result on 9.7/fb of data
- Fully consistent with LHCb result (less than 1σ apart)
- CDF result 2.7σ away from no-CPV hypothesis.
- CDF fit to all experimental results:

$$A_{CP}^{\text{dir}} = (-0.67 \pm 0.16)\ \%$$

$$A_{CP}^{\text{ind}} = (-0.02 \pm 0.22)\ \%$$

(3.8σ from no CPV)



What next?

- Lots of work needed on both experimental & theoretical sides.
- This measurement: 0.6/fb.
  - Already ~ 1/fb on tape -- will extend to this.
  - Expect another O(1/fb) in 2012 before long shutdown
  - ... with improved charm trigger efficiency
- Independent measurements with other tagging methods (esp. semileptonic B decays)
- Look for direct CPV in other SCS charm decays, esp. 3-body modes
- Further measurements of indirect CPV

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Isidori, Kamenik, Ligeti, Perez (arXiv:1111.4987); Brod, Kagan, Zupan (arXiv:1111.5000)

First evidence of CP violation in charm.

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

38 pb^{-1}

Phys. Rev. D 84, 112008 (2011)

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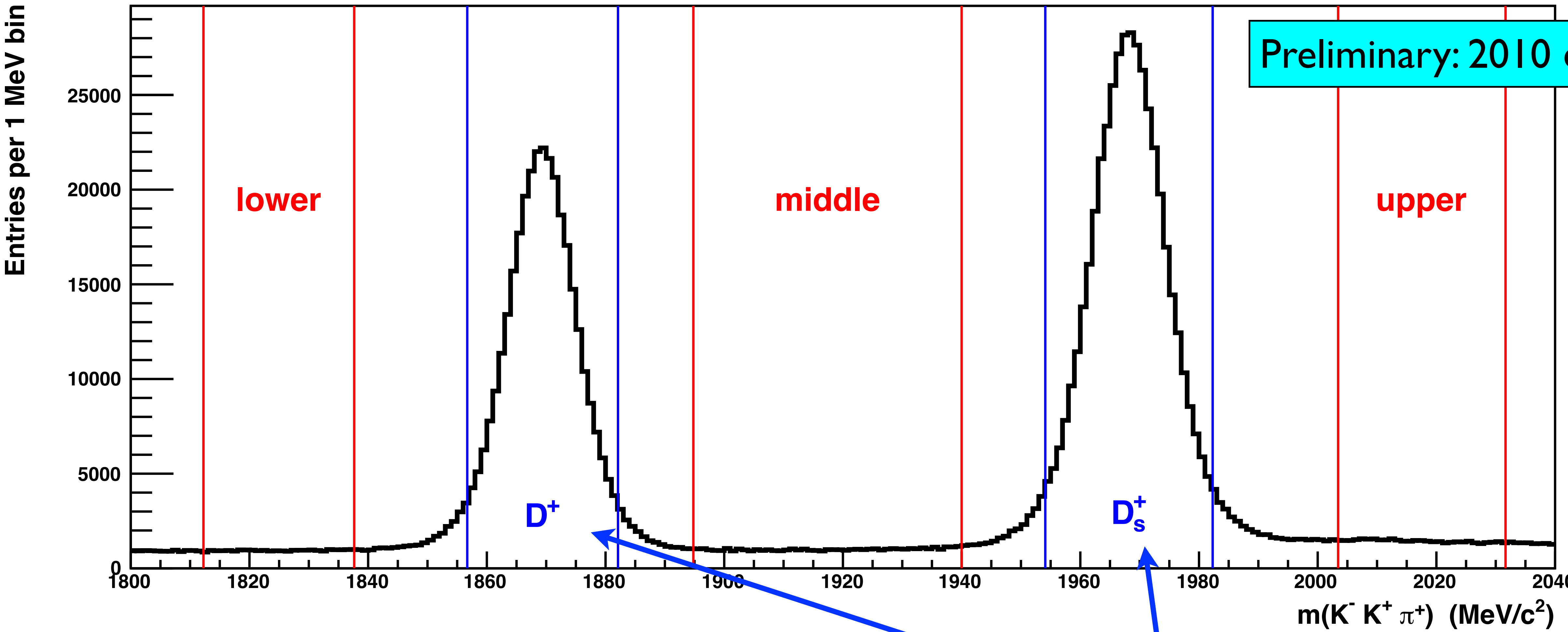
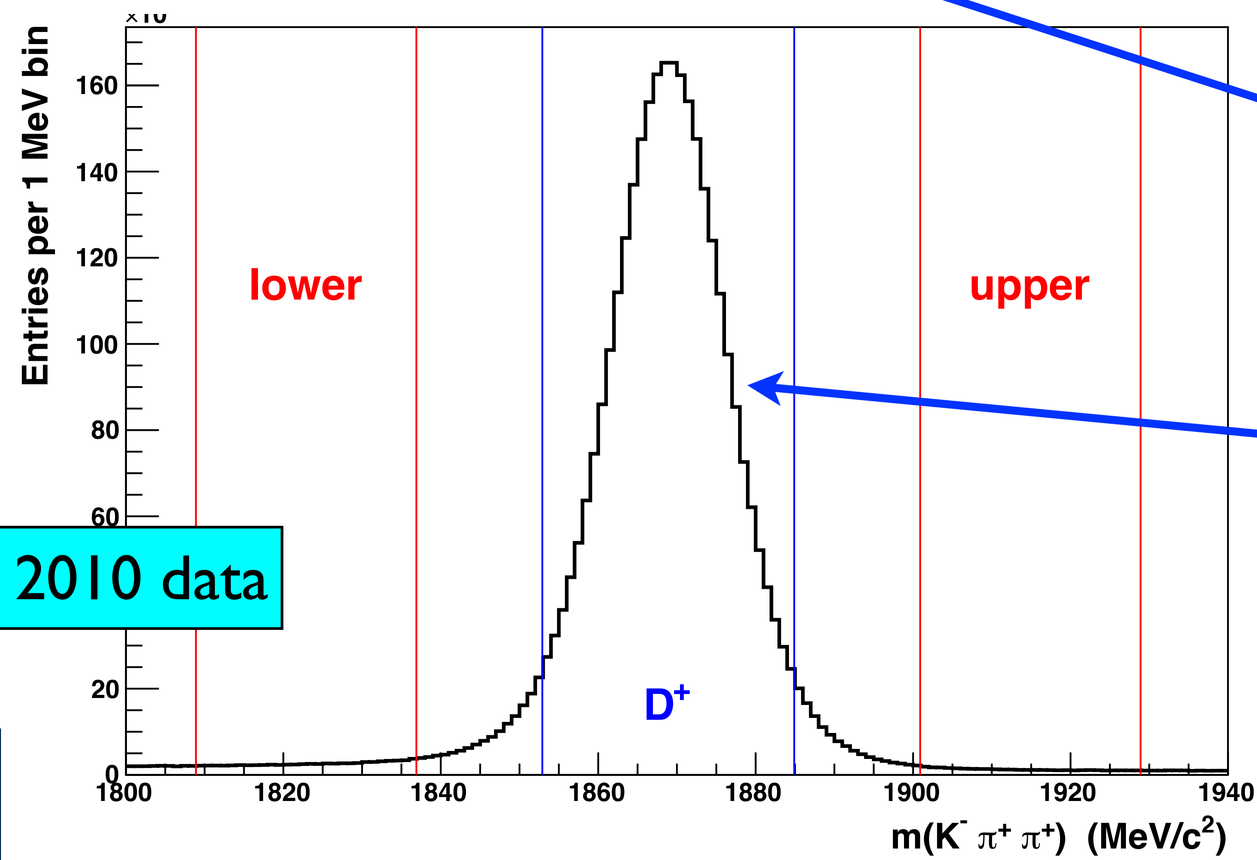
Mass spectra after selection





Preliminary: 2010 data

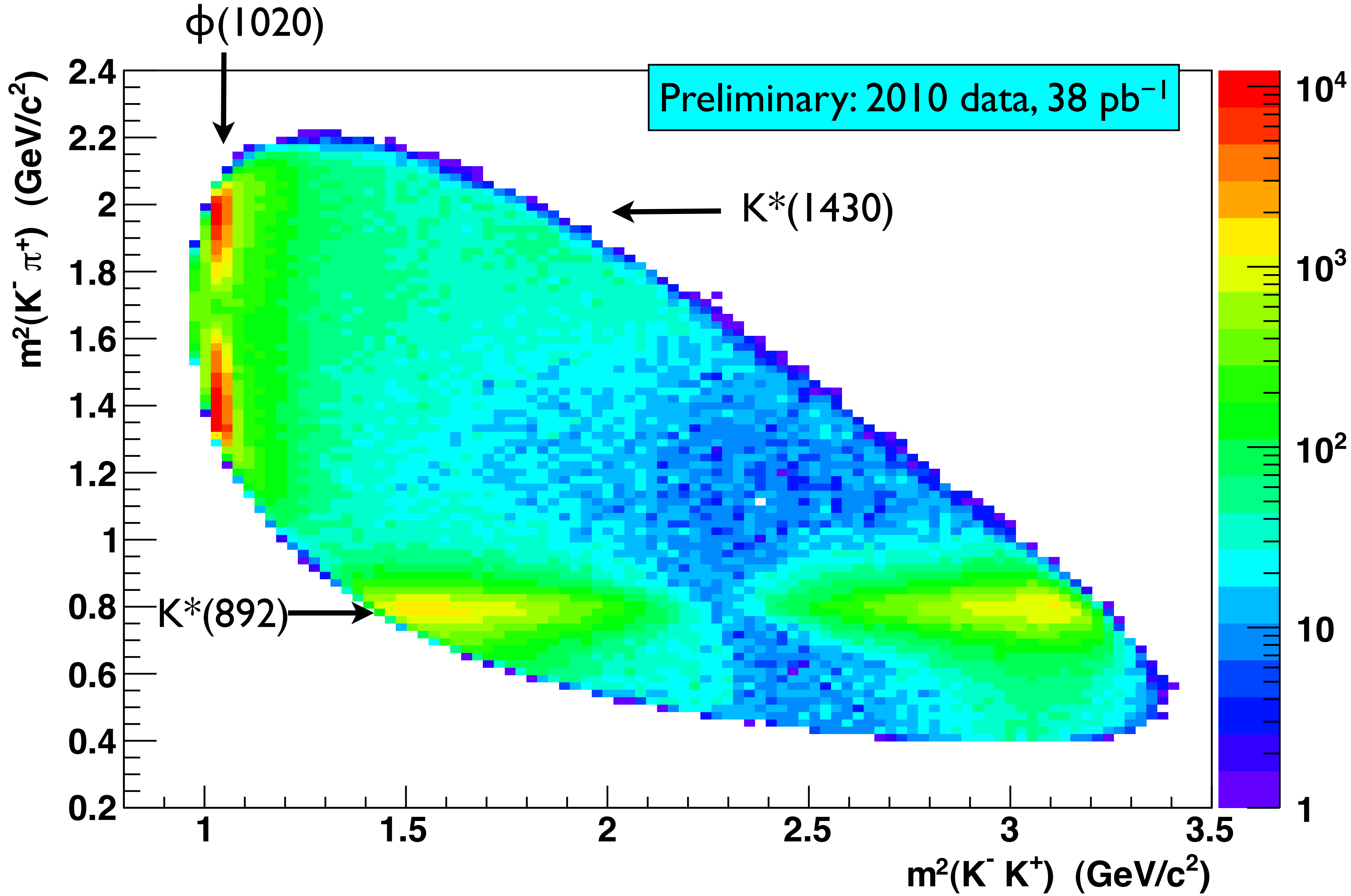
KKπ signal (D^+) and control mode (D_s^+) purity ~ 90%. Signal yield ~ 370k.

Kππ control mode (D^+) purity ~ 98%

About 6/pb omitted from these mass spectra for technical reasons, but still used in analysis.

The Dalitz plot

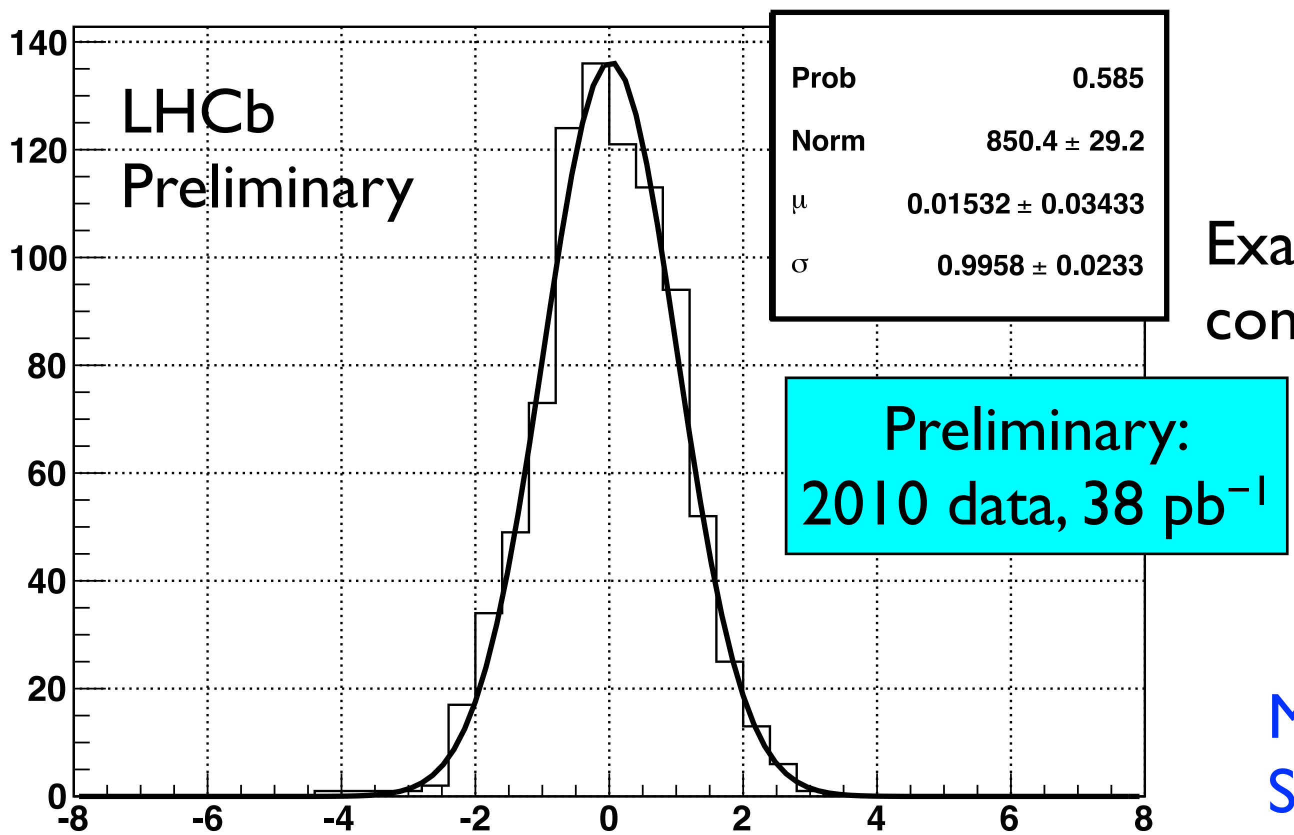
- First, here is the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot with LHCb data:



Technique

- Model-independent search for CPV in Dalitz plot distribution
- Compare binned, normalized Dalitz plots for D^+, D^-
  - Production asymmetry etc cancels completely after normalization.
  - Efficiency asymmetries that are flat across Dalitz plot also cancel.
- Method based on "Miranda" approach -- asymmetry significance
  - In absence of asymmetry, values distributed as Gaussian(μ=0, σ=1)
  - Figure of merit for statistical test: sum of squares of Mirandas is a χ^2.

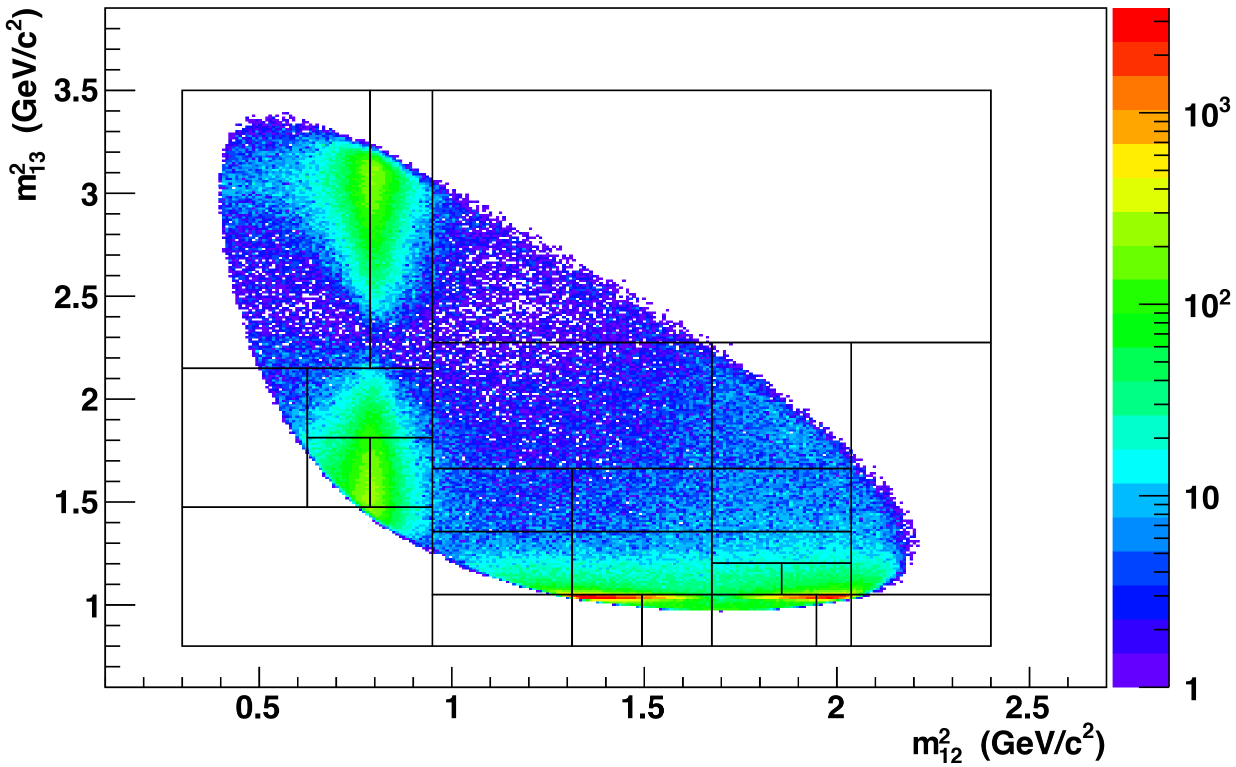
NDF = (#bins−1) → p-value



Example: distribution for $D^+ \rightarrow K^- \pi^+ \pi^+$ control mode follows prediction very nicely.

Miranda paper: Phys. Rev. D80 (2009) 096006
See also BaBar: Phys.Rev. D78:051102 (2008)

$D_s^+ \to K^- K^+ \pi^+$ control mode



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

- For MagUp: χ^2/NDF = 16.0 / 24 (88.9%)
- For MagDown: χ^2/NDF = 31.0 / 24 (15.5%)
- Combined*: χ^2/NDF = 26.2 / 24 (34.4%)
- Great! No evidence of any fake asymmetry in control mode.

* To combine: take weighted average of measured asymmetry in each bin, then its evaluate significance. Also tried simple merge of events; gives almost identical result.

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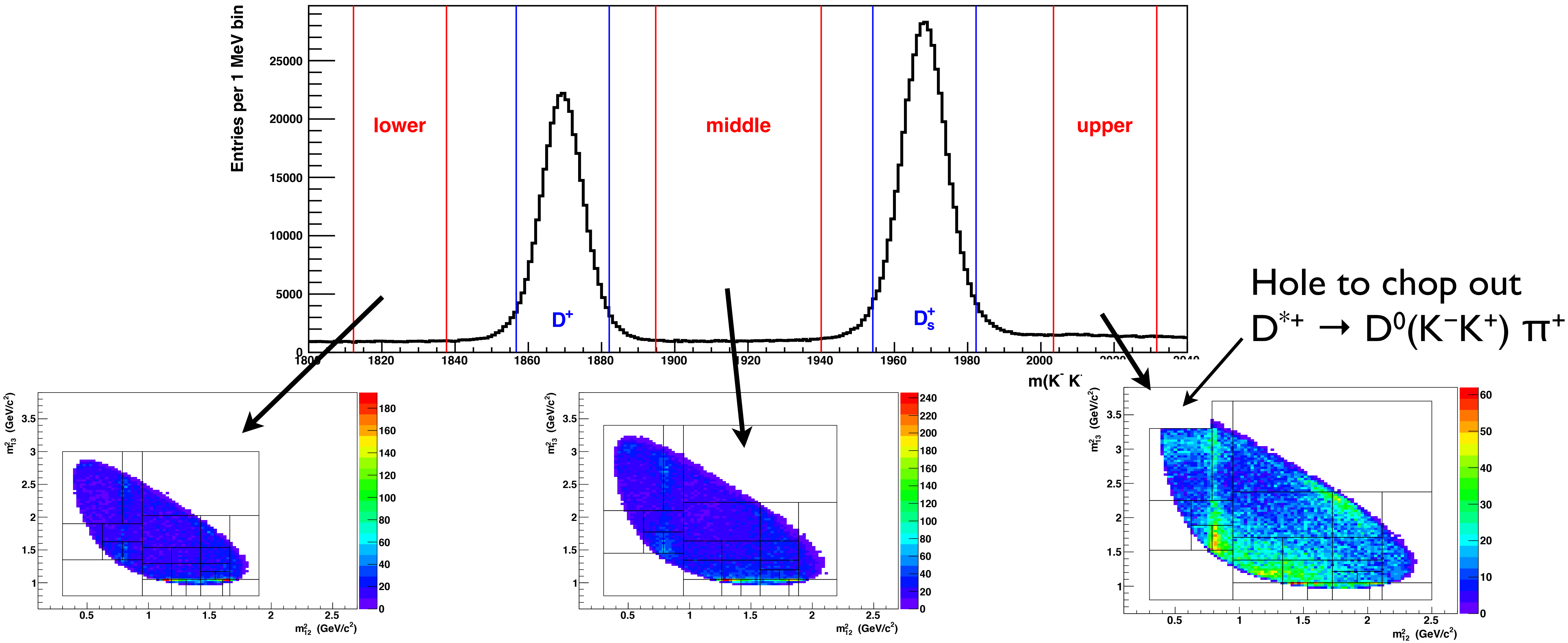
Other $K^- K^+ \pi^+$ control modes



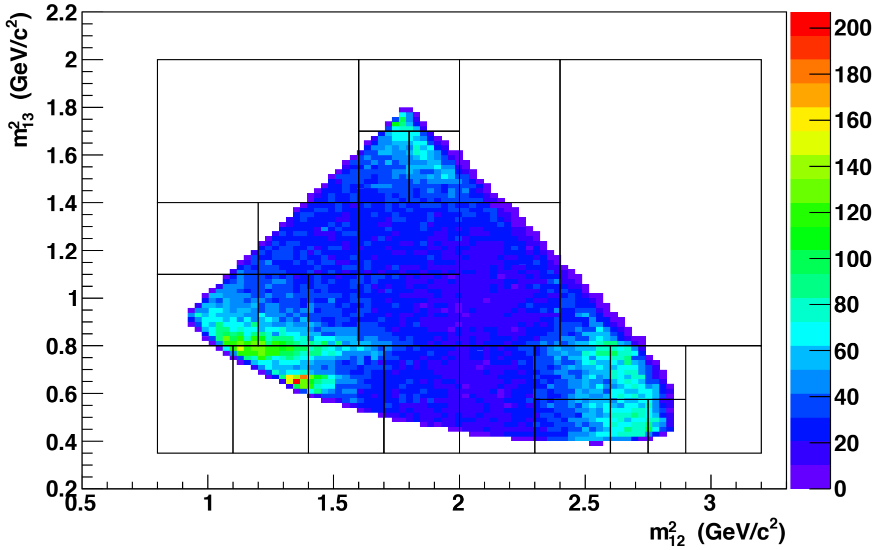
Window	MagUp	MagDown	Combined
lower sideband	32.7%	10.1%	8.7%
middle sideband	31.4%	27.7%	50.8%
D_s^+ window	88.9%	15.5%	34.4%
upper sideband	1.3%	50.7%	26.5%

Sidebands around the D^+ signal peak look completely fine!

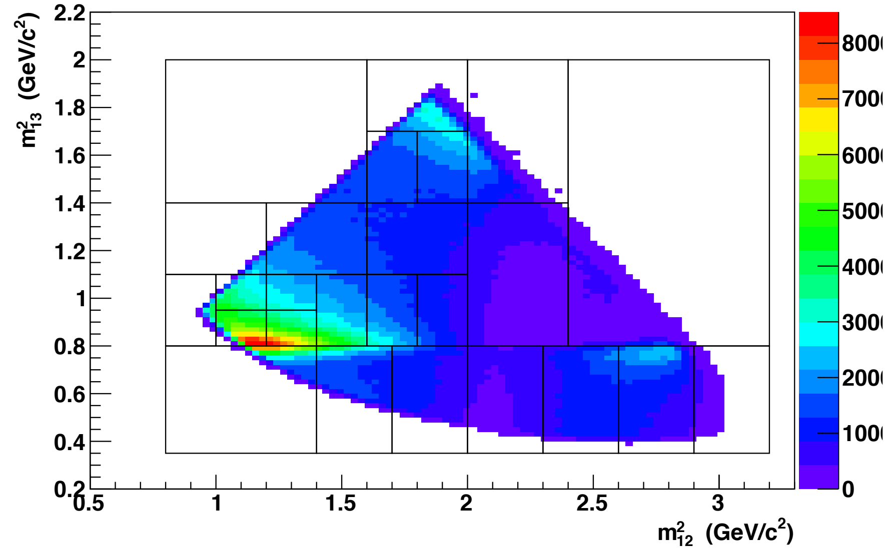
Preliminary: 2010 data, 38 pb^{-1}

$K^- \pi^+ \pi^+$ control modes

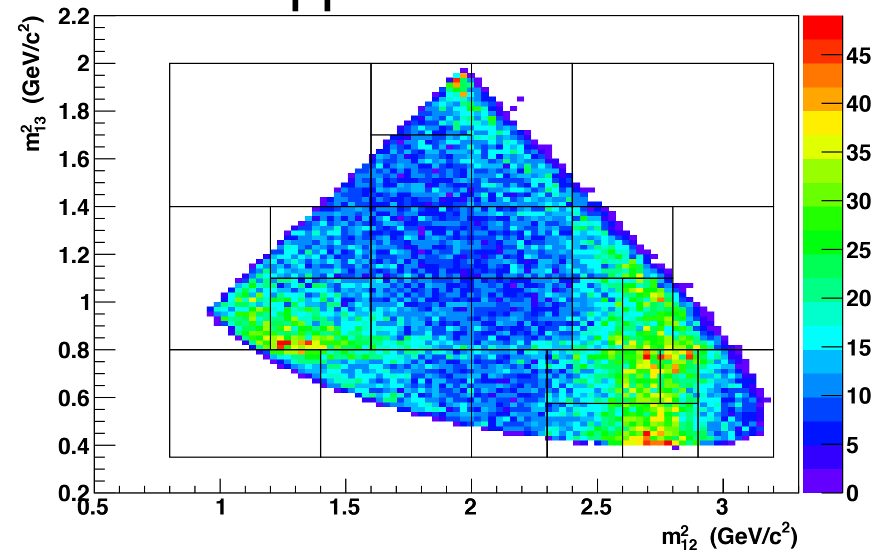
lower sideband



D^+ window



upper sideband



Window	MagUp	MagDown	Combined
lower sideband	99.7%	18.2%	91.0%
D^+ window	49.2%	0.15%	9.2%
upper sideband	66.2%	56.1%	35.3%

Preliminary
2010 data, 38 pb^{-1}

- $D^+ \rightarrow K^- \pi^+ \pi^+$ behaves amazingly well. Remember:
  - there is a mechanism for a fake asymmetry that doesn't apply to the signal mode (kaon efficiency)
  - the statistics are 10x larger than in the signal mode

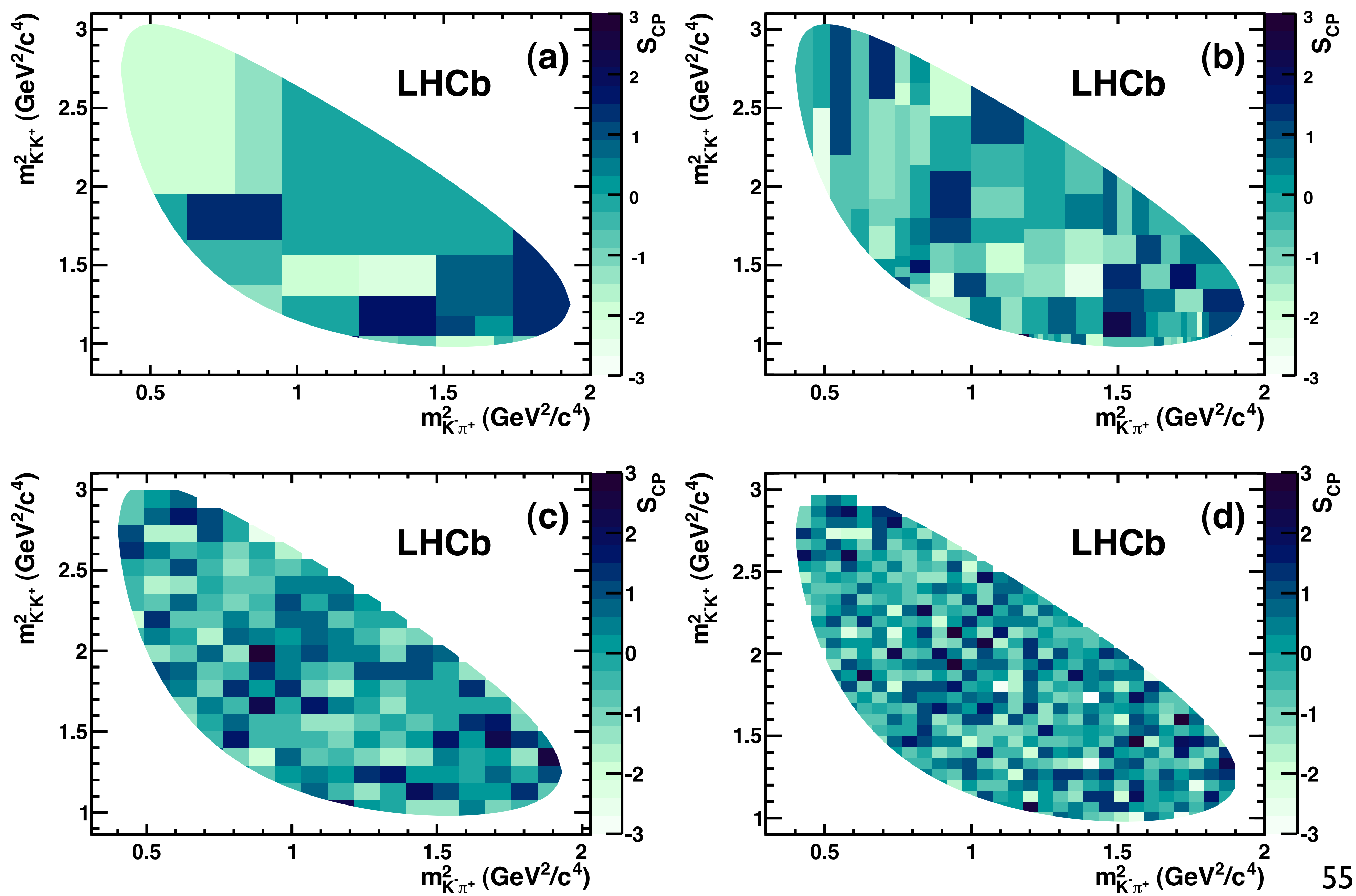
Method of comparing normalized Dalitz plots very robust against systematic effects.

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

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}



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First evidence of CP violation in charm.

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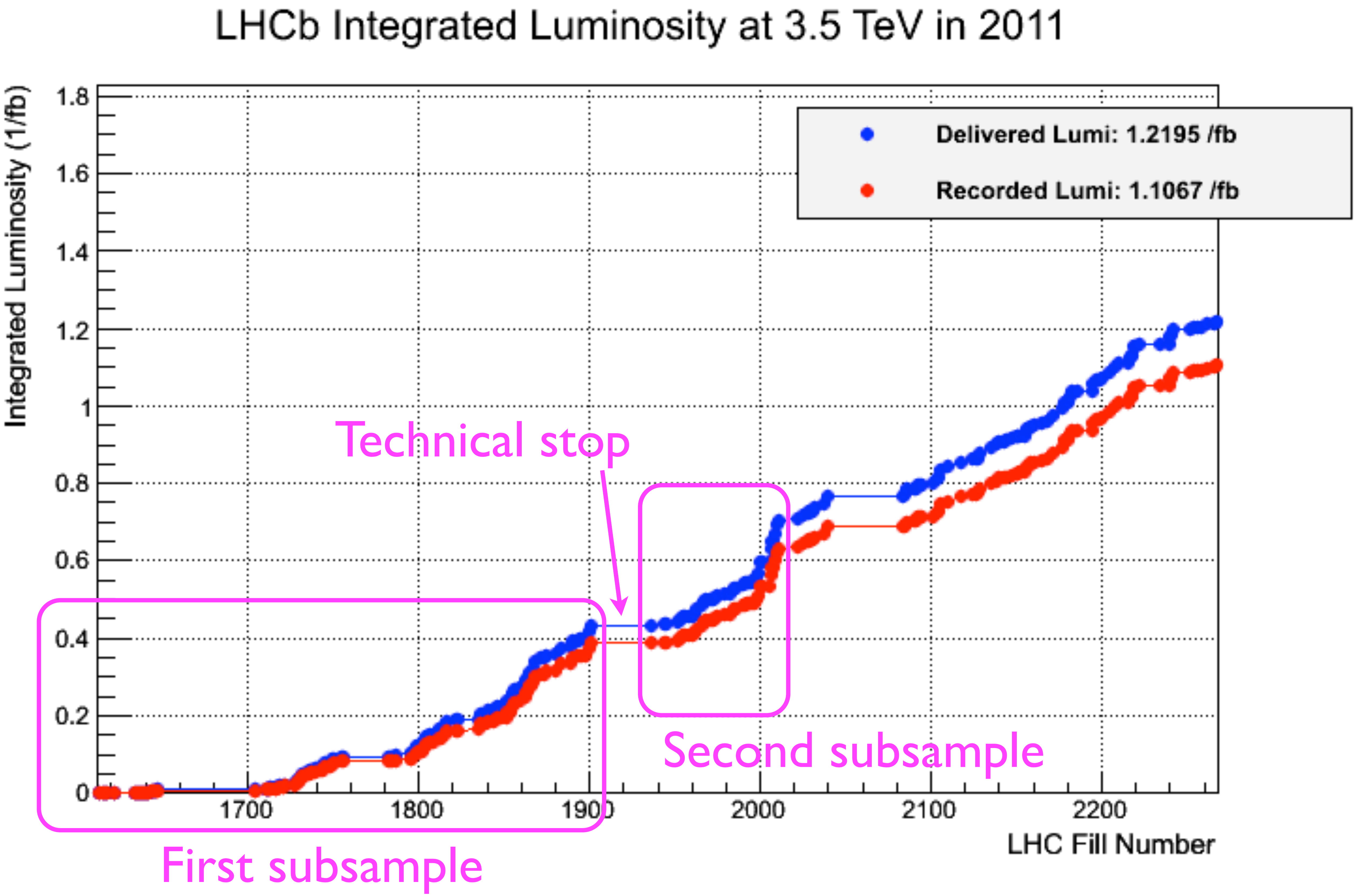
Isidori, Kamenik, Ligeti, Perez (arXiv:1111.4987); Brod, Kagan, Zupan (arXiv:1111.5000)

First evidence of CP violation in charm.

fin

Integrated luminosity



Showing online luminosity (not final calibration)

Can the SM stretch?

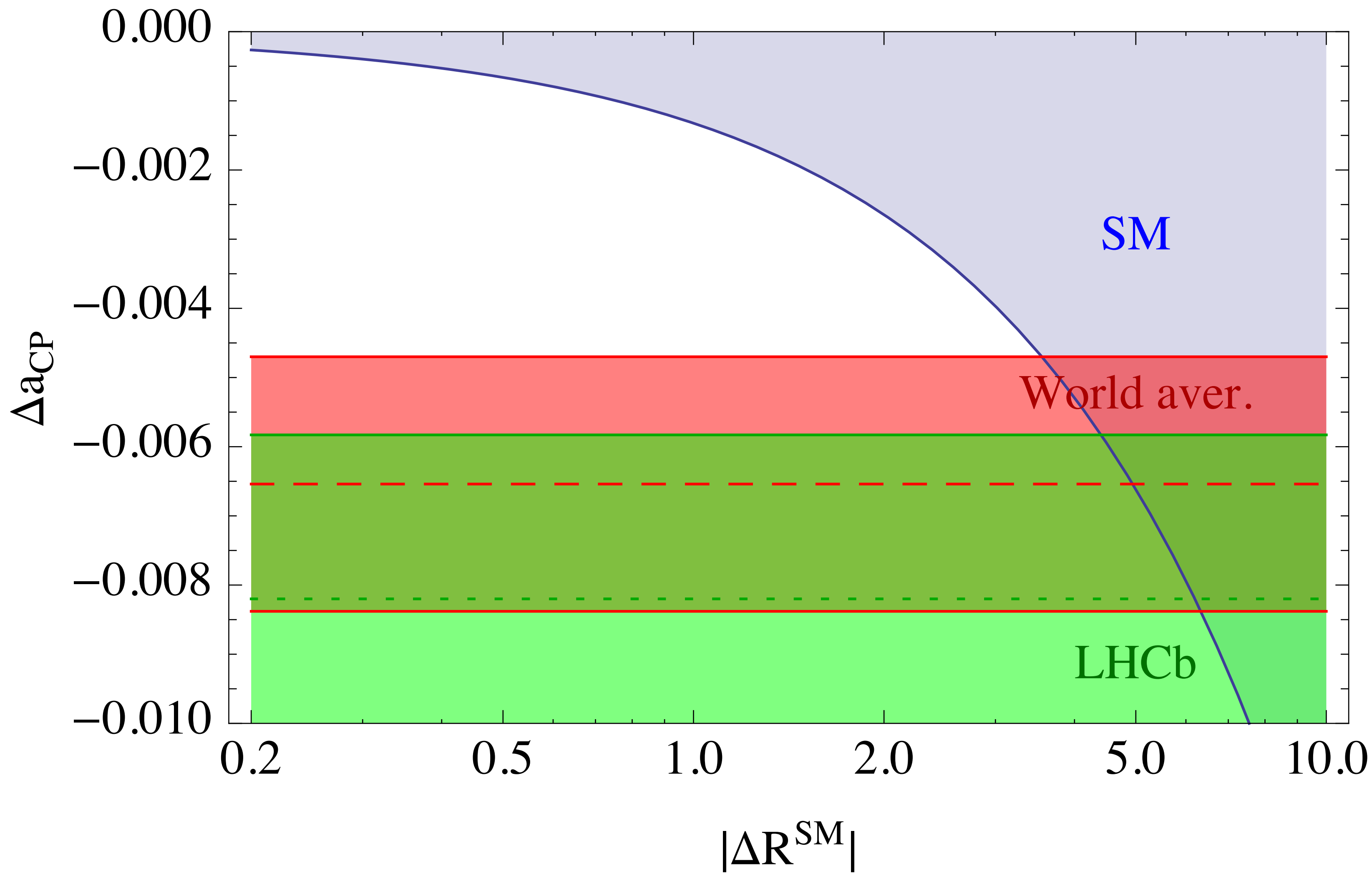


Figure 1: Comparison of the experimental Δa_{CP} values with the SM reach as a function of $|\Delta R^{\rm SM}|$.

- Well above naive expectation... but not excluded from first principles.

Time-integrated wrong-sign $D^0 \rightarrow K\pi$

Three contributions with different lifetime dependence:

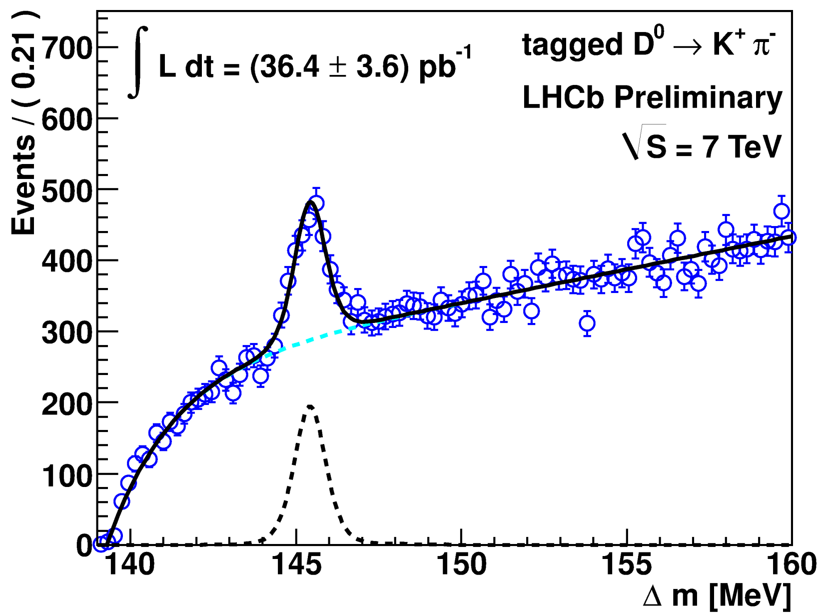
$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}(\Gamma t)}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

[Limit of |x| ≪ 1, |y| ≪ 1, and no CPV.]

Our lifetime acceptance is not flat => affects relative weighting.

- Start with raw WS/RS time-integrated ratio.
- Determine our efficiency(t) using PDG D0 lifetime as input
- Determine correction using HFAG mixing parameters as input
- Compute lifetime-acceptance-corrected WS/RS ratio.

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



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

Cross-check consistent with PDG average.