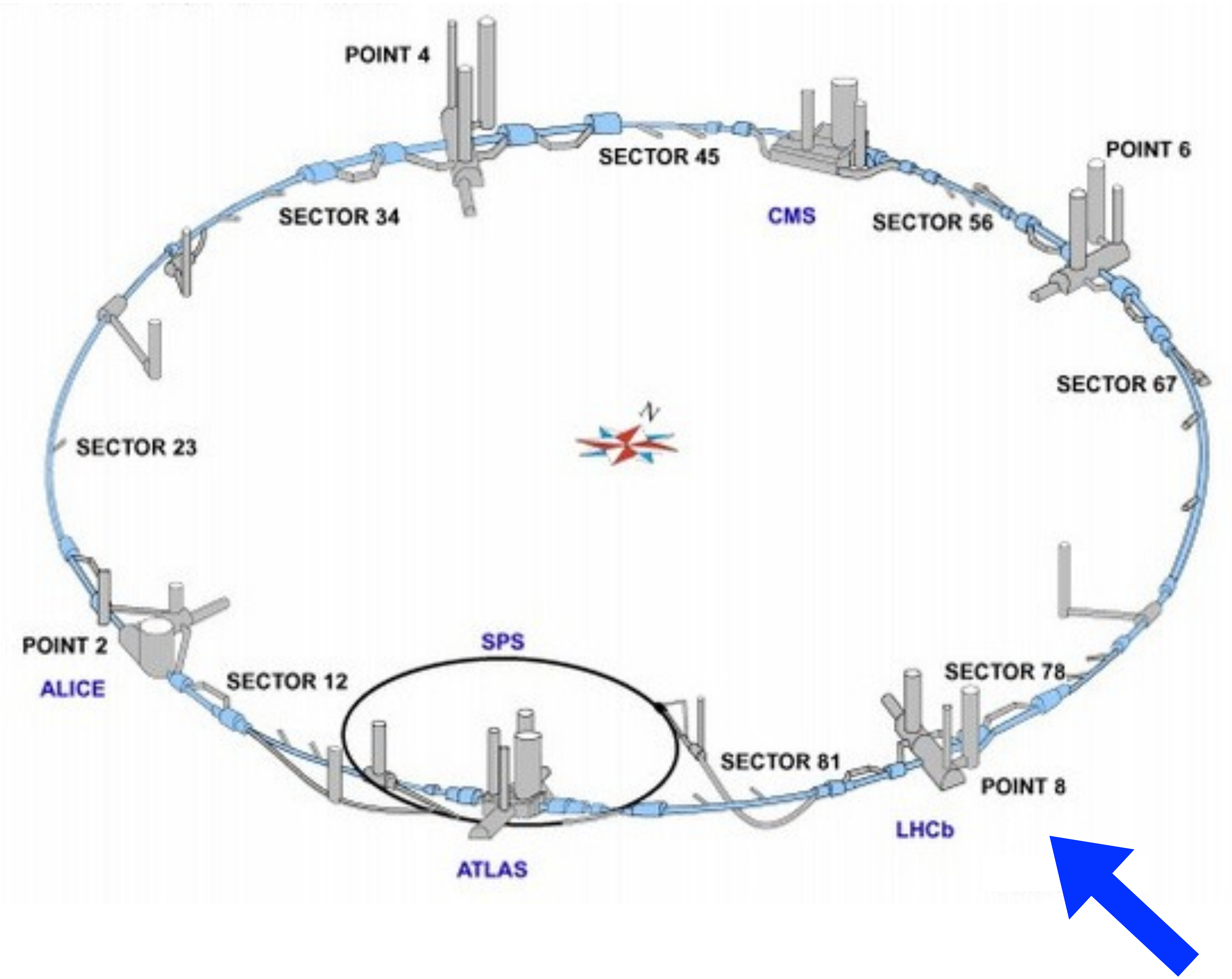
Charm physics at LHCb

Mat Charles (Oxford)

Introduction to LHCb

The LHC


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

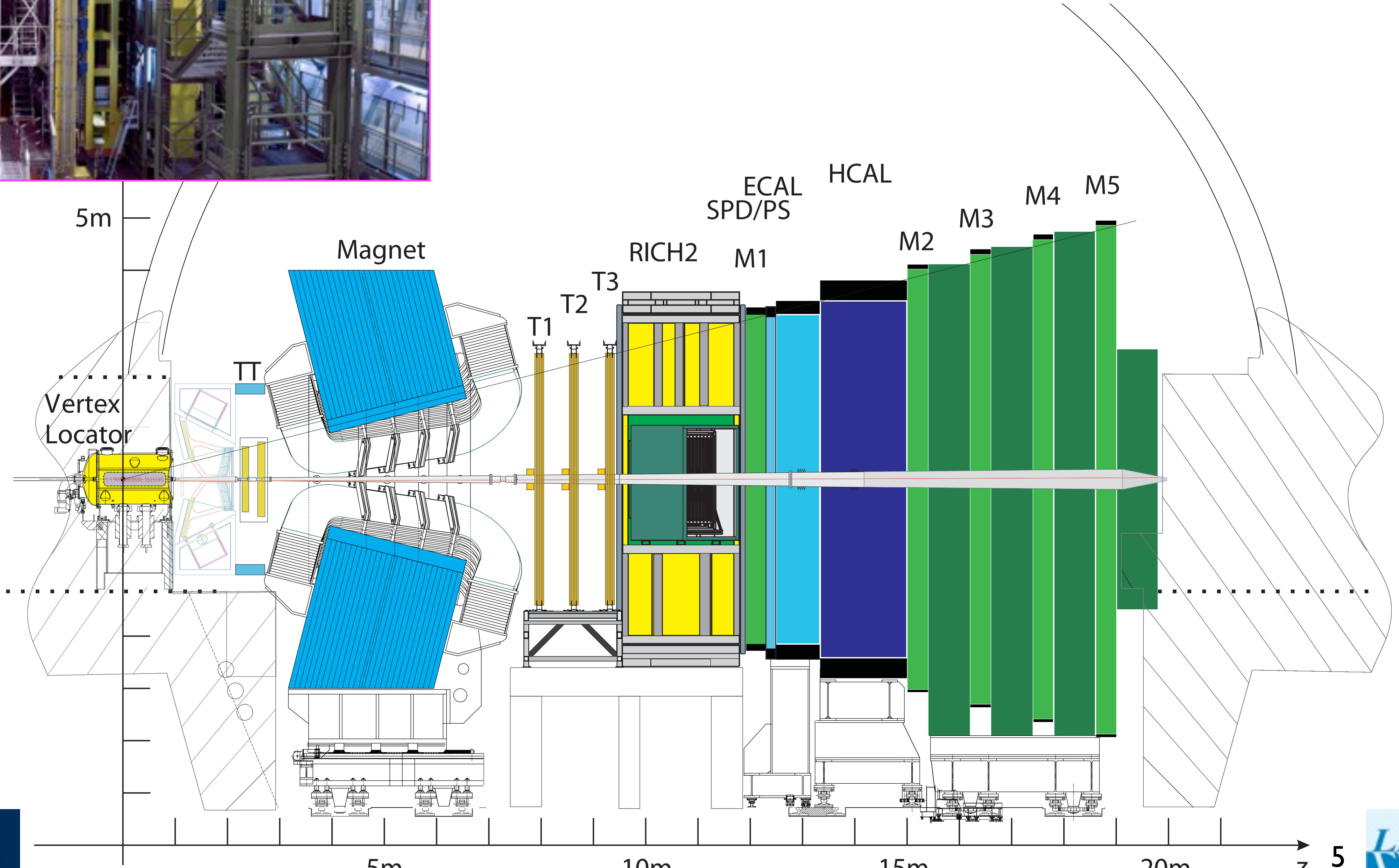
Physics goals of LHCb

- Main strategy: indirect searches for NP in b, c decays.
  - Look for evidence of new, heavy particles, mainly in loop diagrams
  - Complementary to direct searches at ATLAS and CMS
  - ... 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: $\sigma(c\bar{c})$=1200μb and $\sigma(b\bar{b})$=75μb.
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

The LHCb detector

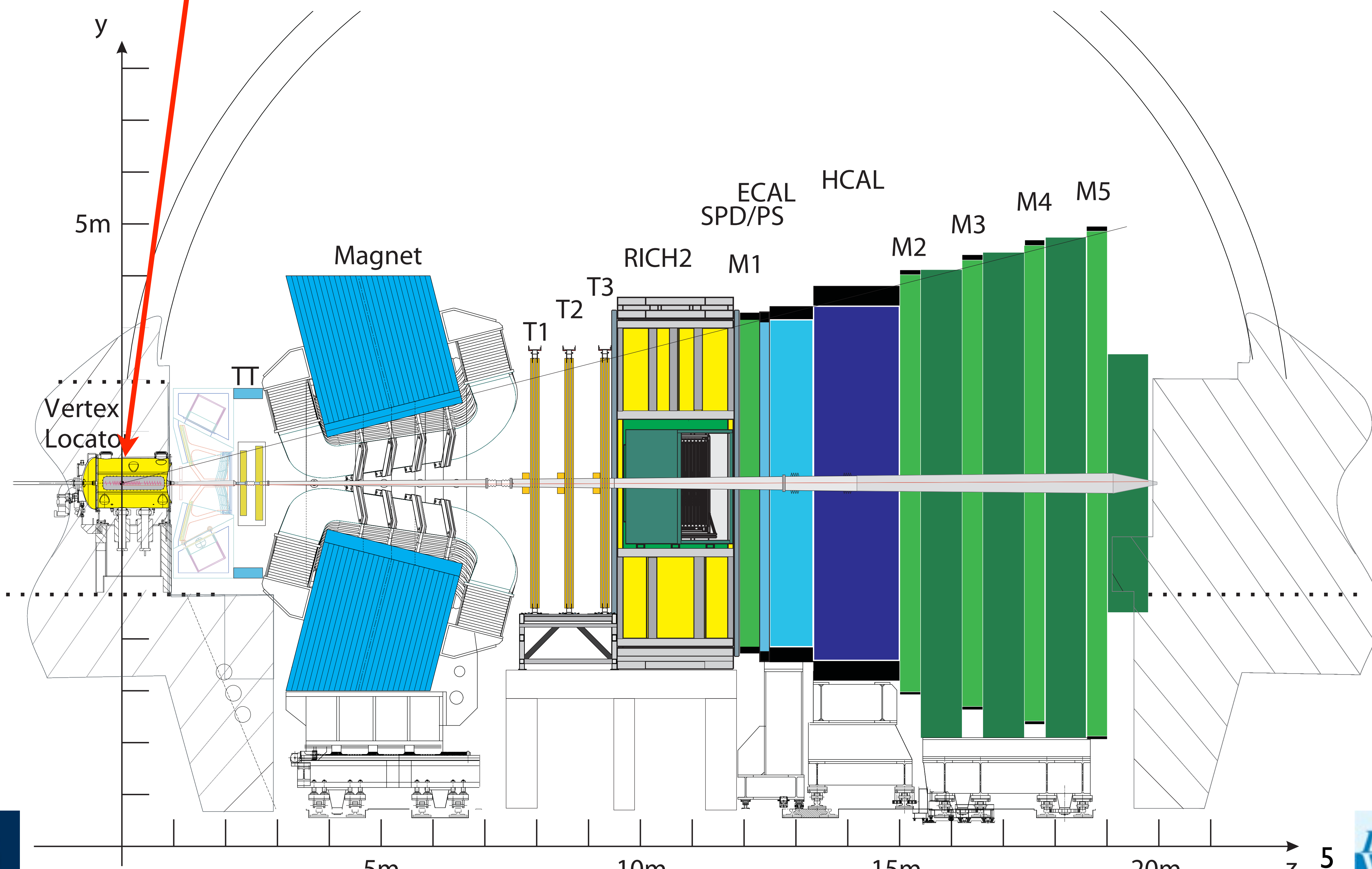


The LHCb detector

VELO: precision vertexing

42x2 silicon planes, strip pitch 40-100 μm

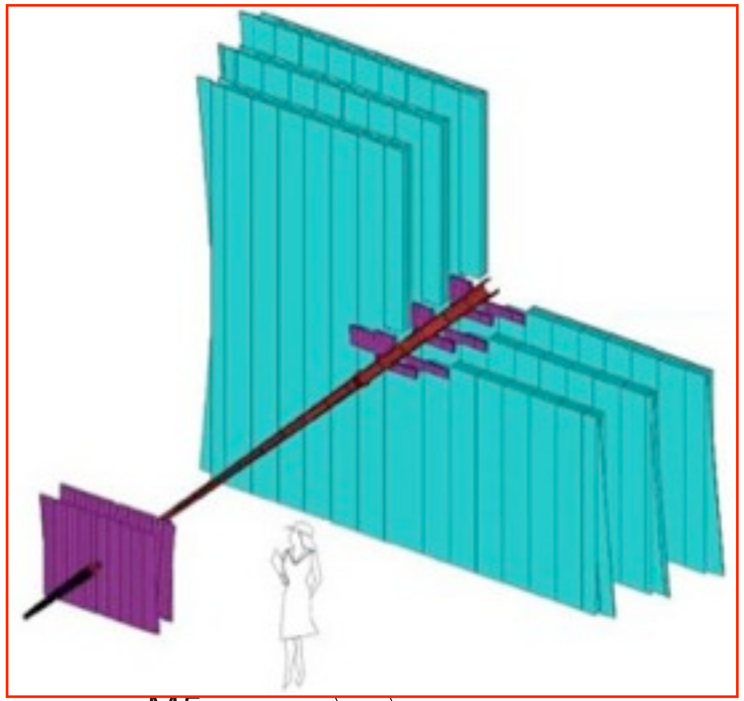
7mm from beam during data-taking; retracted during injection

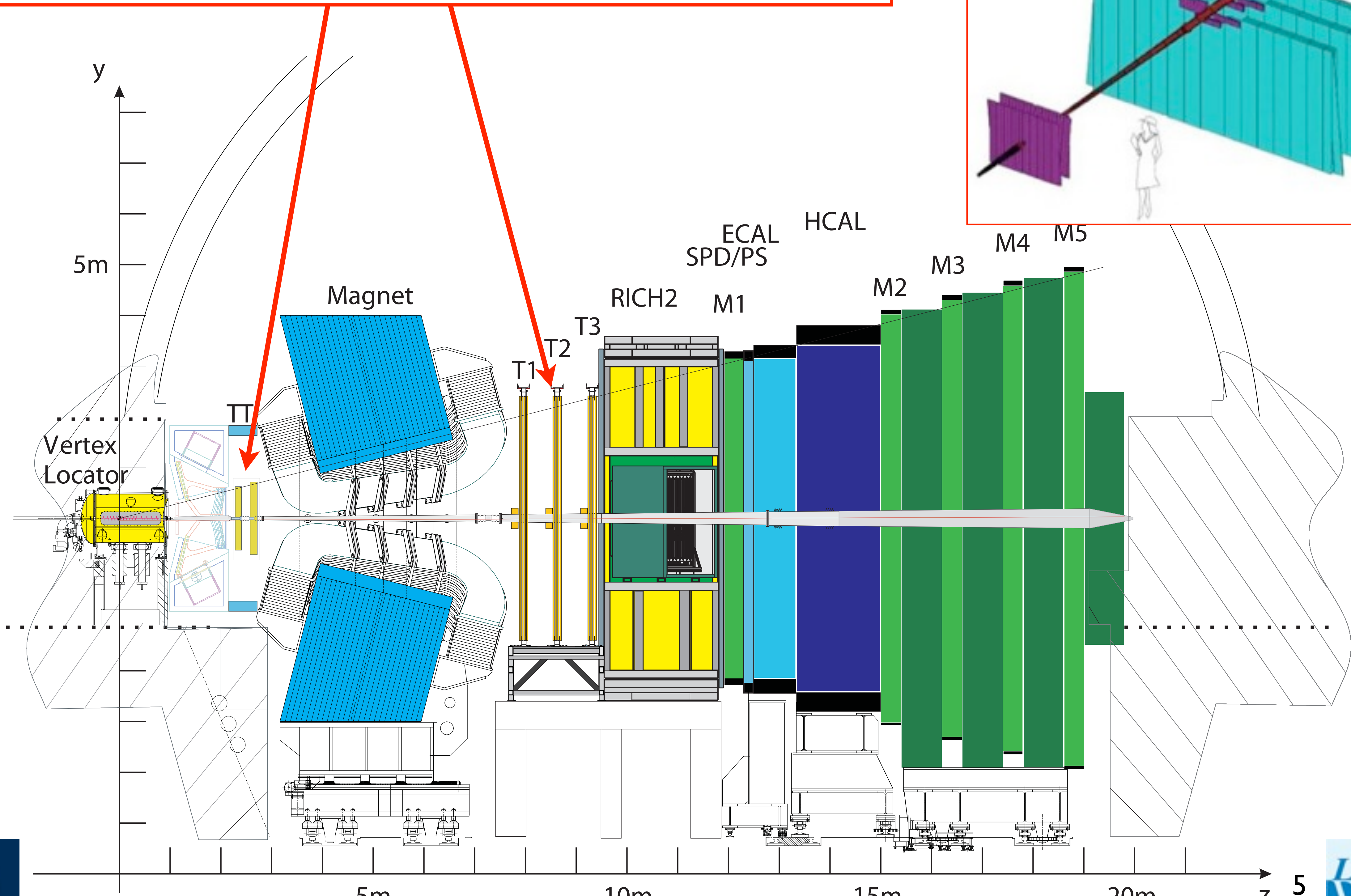


The LHCb detector

Tracker: momentum measurement

Stations upstream and downstream of magnet.
Upstream & inner: silicon microstrips. Outer: drift chambers

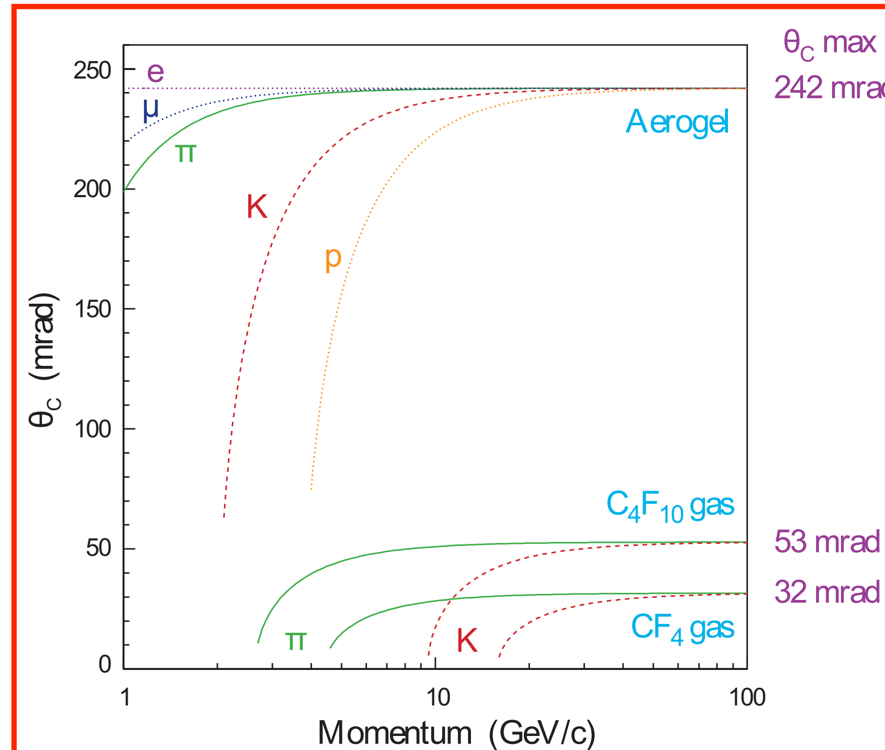


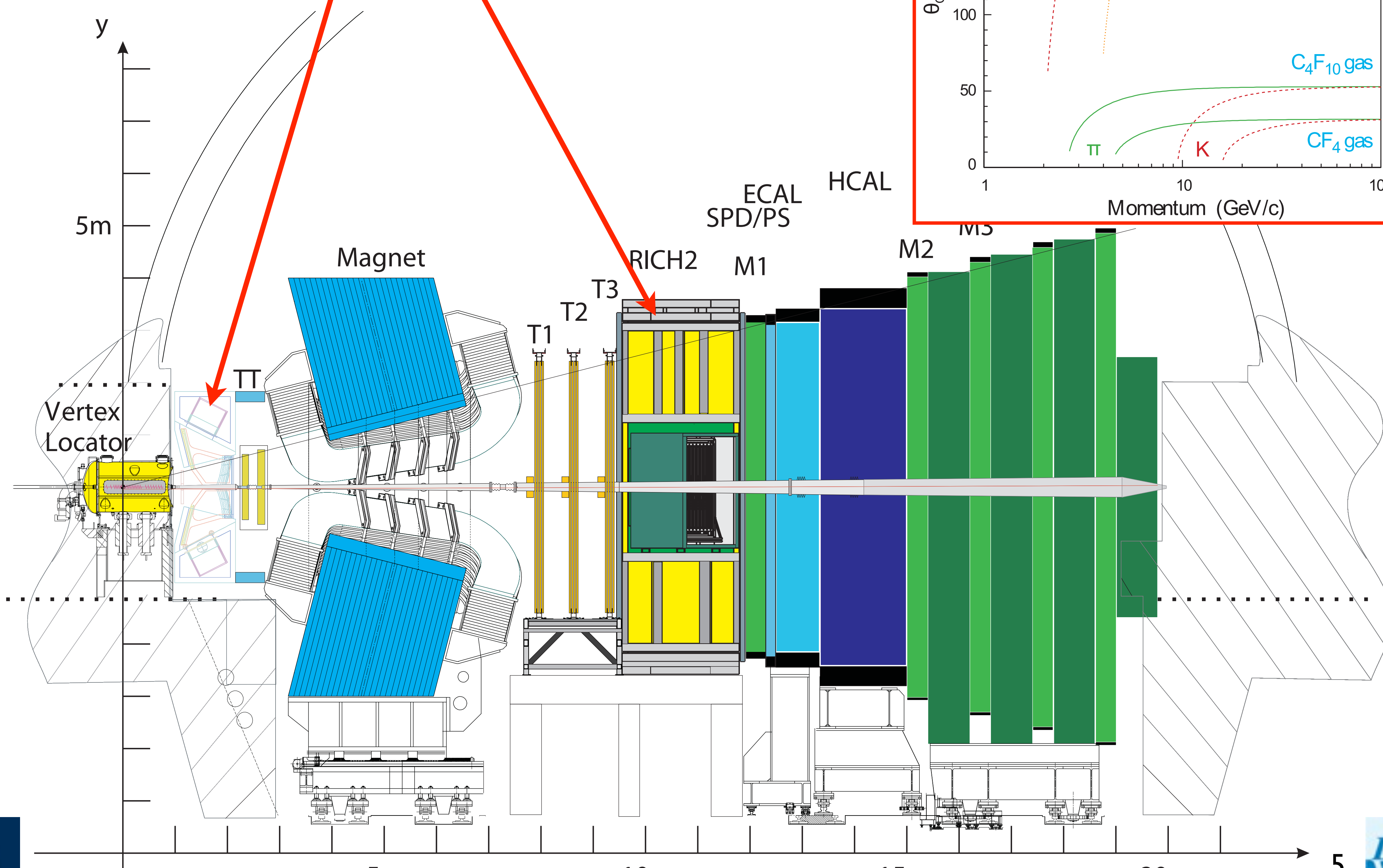


The LHCb detector

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



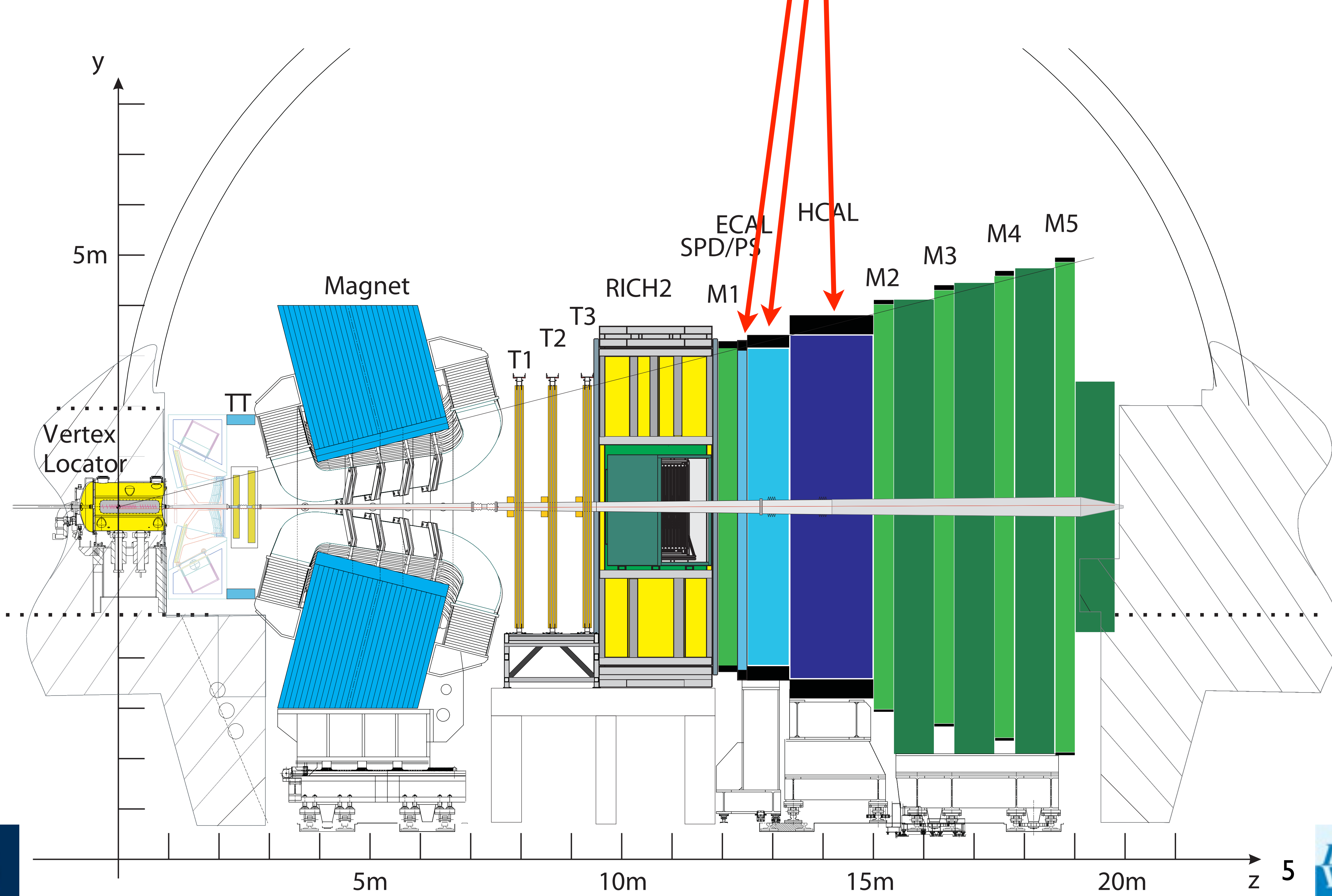


The LHCb detector

Calorimeters: trigger, photon/electron ID

Preshower + SPD + electromagnetic + hadronic calorimeters

Vital for hardware-level hadron triggering

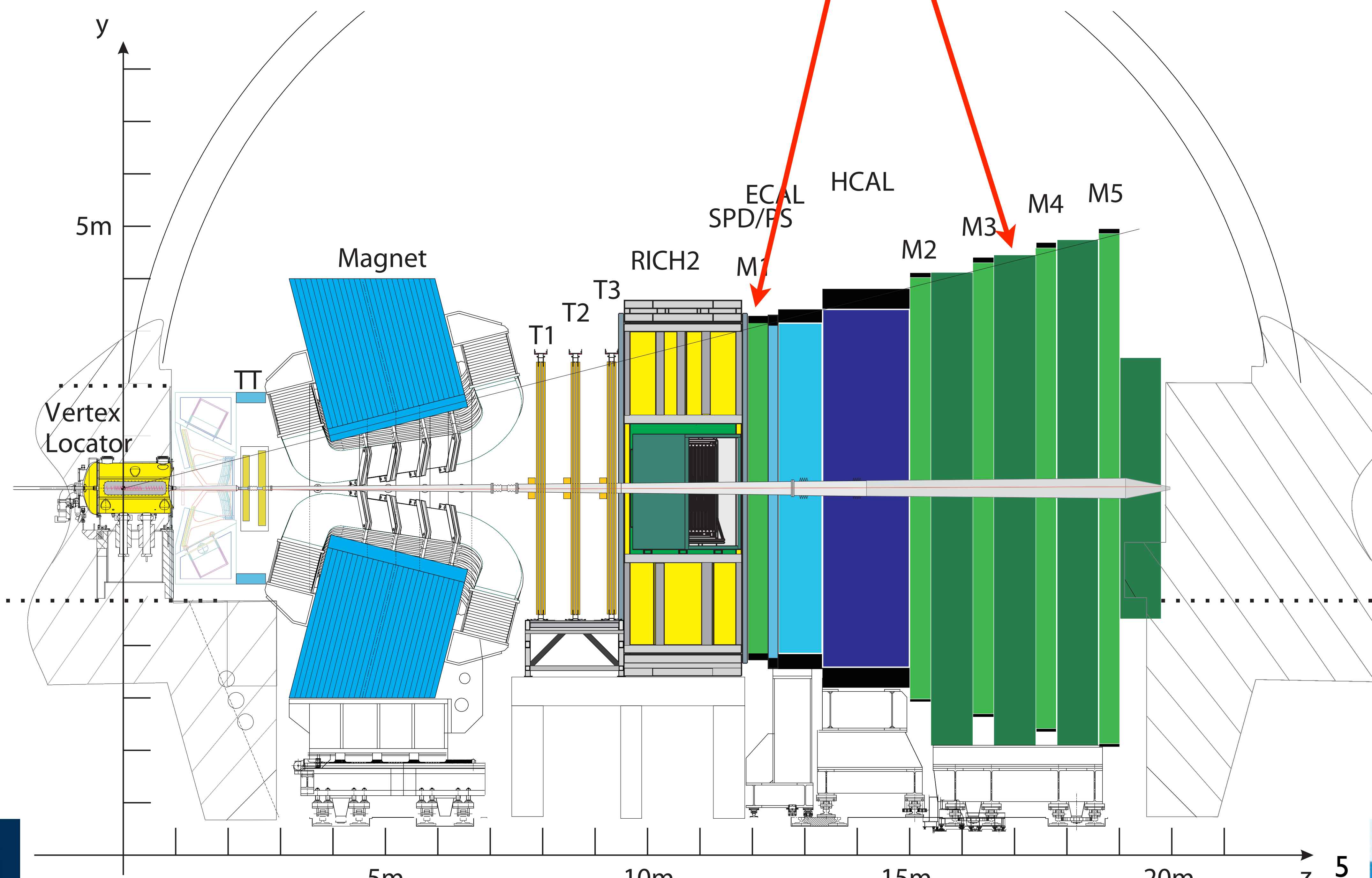


The LHCb detector

Muon stations: muon ID

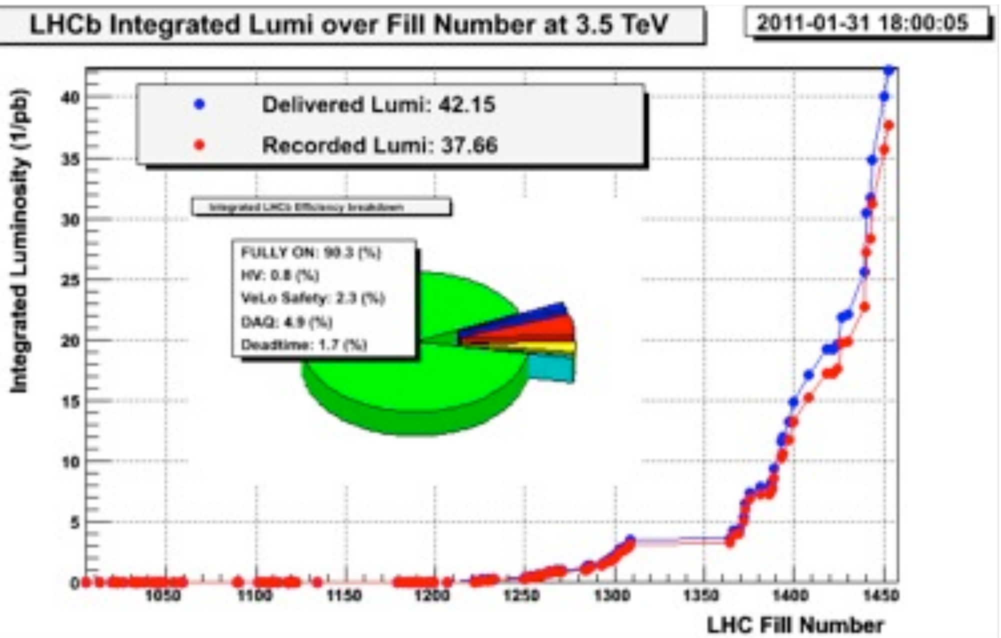
Five stations, used also in hardware trigger.

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

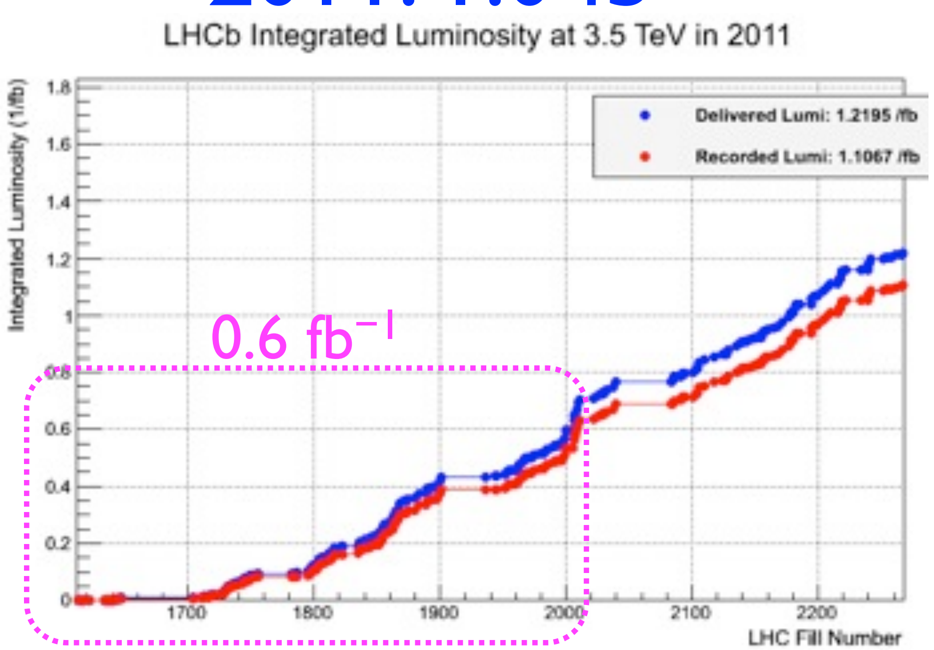


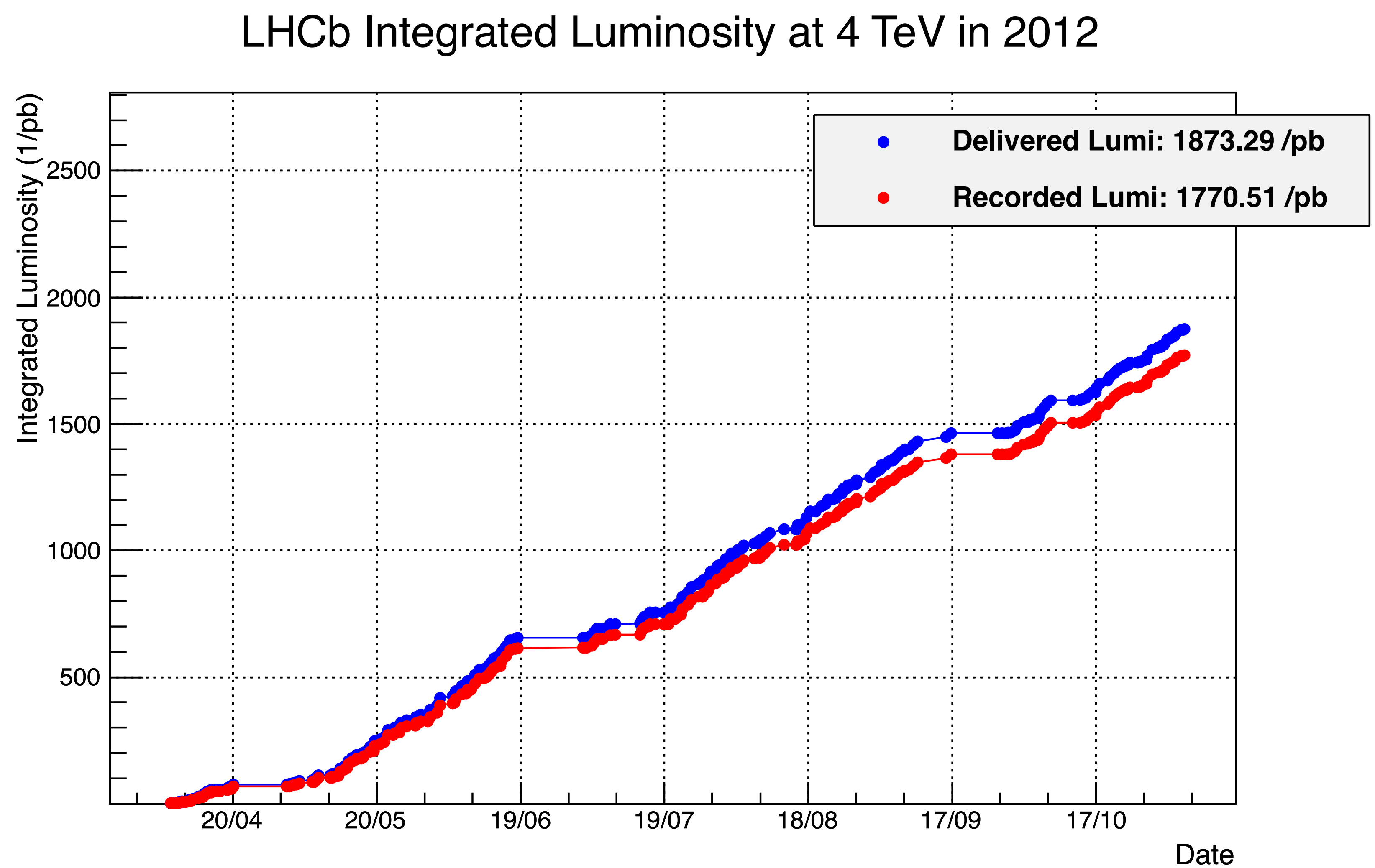
Data-taking

2010: 38 pb^{-1}



2011: 1.0 fb^{-1}





2012: 2.1 fb^{-1}

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.

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LHCb's charm physics programme

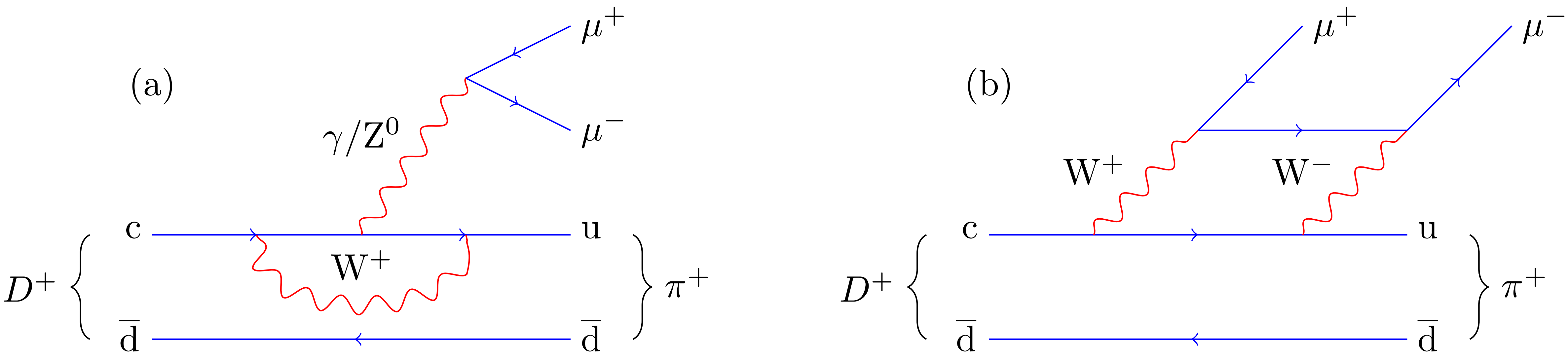
Charm physics at LHCb

- Too many things to cover them all!
- Main activities:
  - Very rare decays
  - Mixing & time-dependent CP violation
  - Time-integrated CP violation
  - Hadronic physics -- production, spectroscopy

Very rare decays

Search for $D^+ \rightarrow \pi^+ \mu^- \mu^+$

- FCNC in charm suppressed by GIM mechanism
- Expected BR tiny: few x 10^{-9} in SM



- Can be enhanced by new physics, e.g. RPV SUSY

[4] S. Fajfer, S. Prelovsek, and P. Singer, *Rare charm meson decays $D \to P\, l^+ l^-$ and $c \to u\, l^+ l^-$ in SM and MSSM*, Phys. Rev. **D64** (2001) 114009, arXiv:hep-ph/0106333.

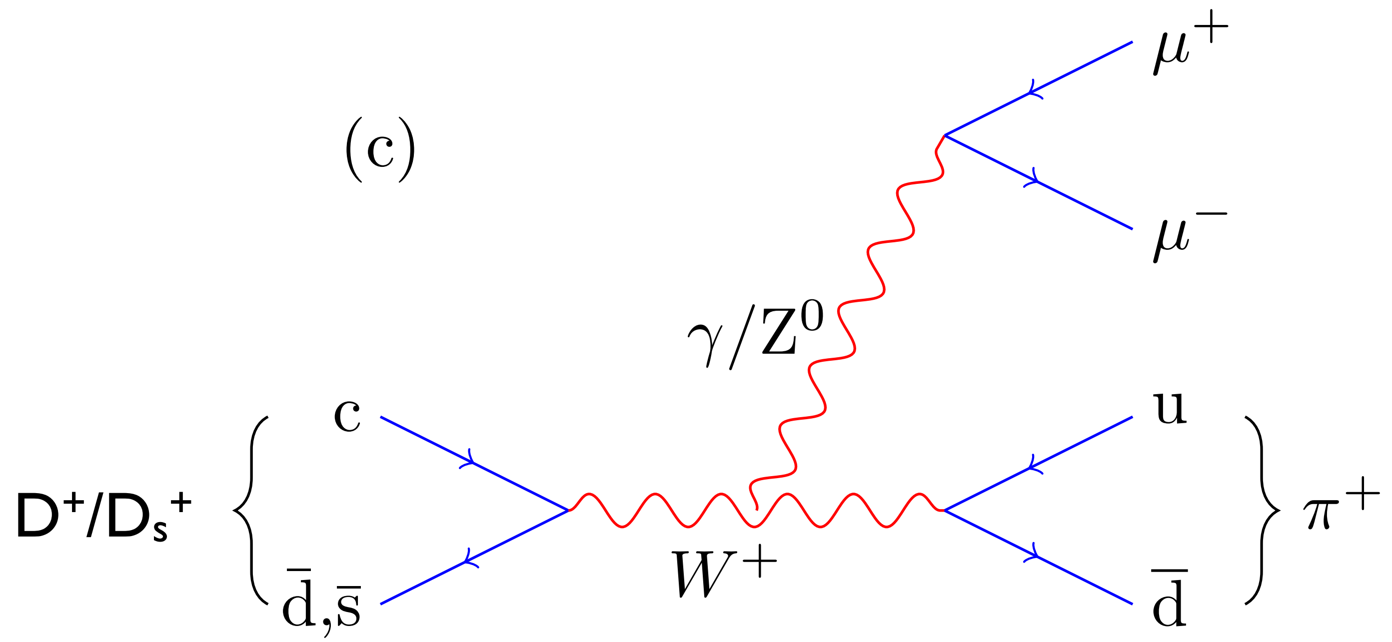
[5] S. Fajfer, N. Kosnik, and S. Prelovsek, *Updated constraints on new physics in rare charm decays*, Phys. Rev. **D76** (2007) 074010, arXiv:0706.1133.

[6] A. Paul, I. I. Bigi, and S. Recksiegel, *On $D \to X_u\, l^+ l^-$ within the Standard Model and frameworks like the littlest Higgs model with T parity*, Phys. Rev. **D83** (2011) 114006, arXiv:1101.6053.

[7] M. Artuso *et al.*, *B, D and K decays*, Eur. Phys. J. **C57** (2008) 309, arXiv:0801.1833.

Search for $D^+ \to \pi^+ \mu^- \mu^+$

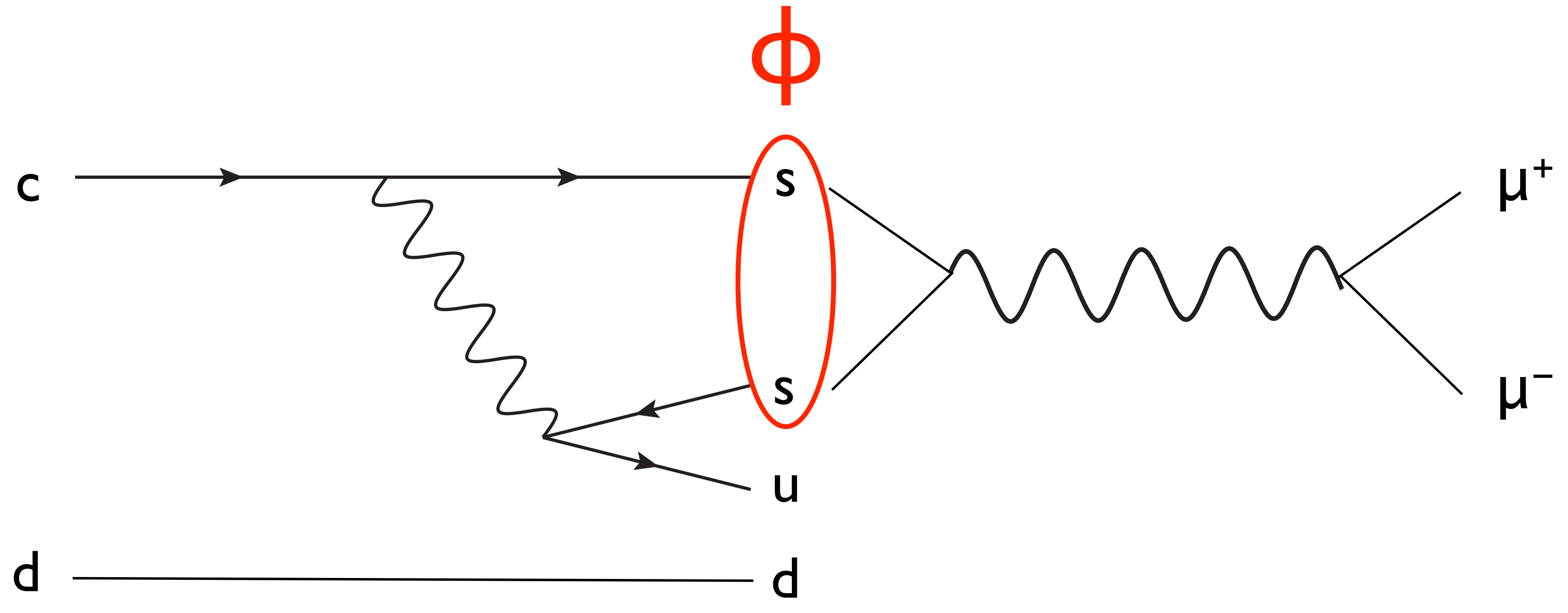
- Complication: contributions from weak annihilation -- not FCNC, but also suppressed.



- Solution: use $D_s^+ \to \pi^+ \mu^- \mu^+$ as control channel:
  - weak annihilation diagram is also present and without CKM suppression ($|V_{cs}|^2$ vs $|V_{cd}|^2$)
  - FCNC diagrams absent

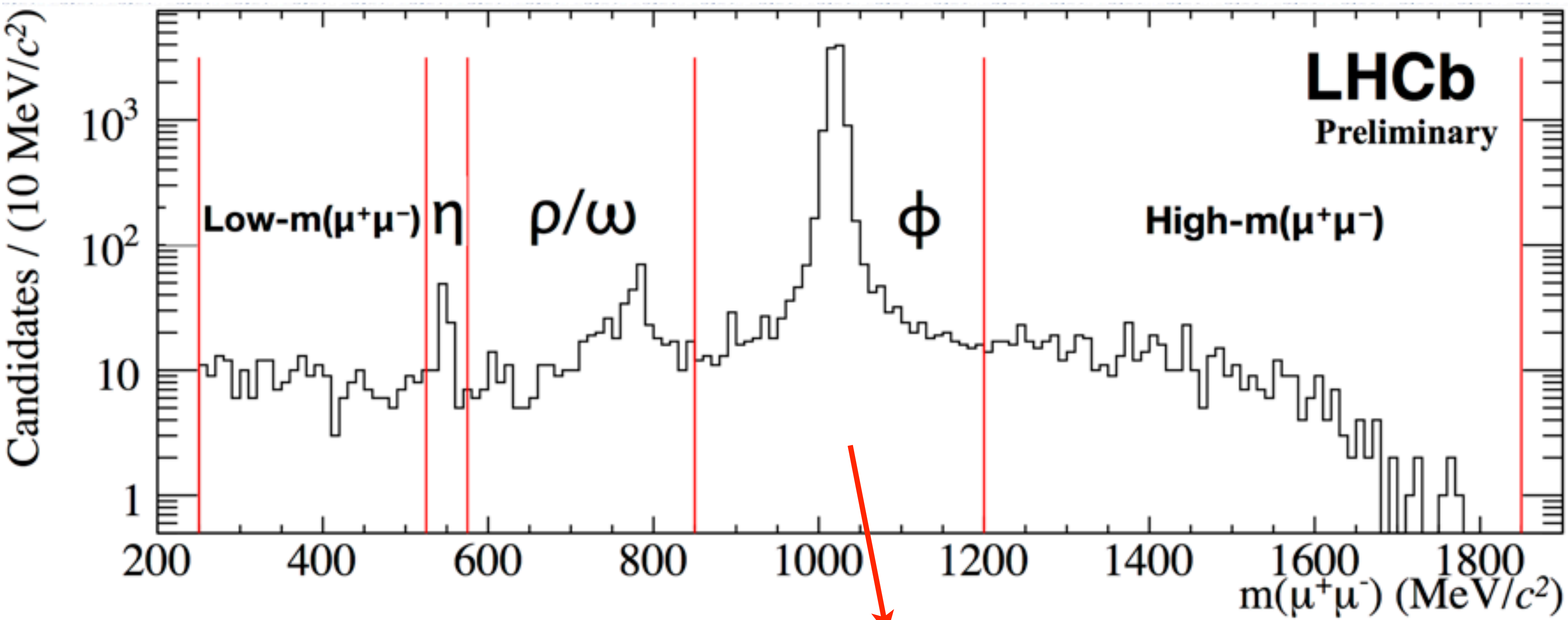
Search for $D^+ \rightarrow \pi^+ \mu^- \mu^+$

- Complication: contributions from long-range processes, e.g.

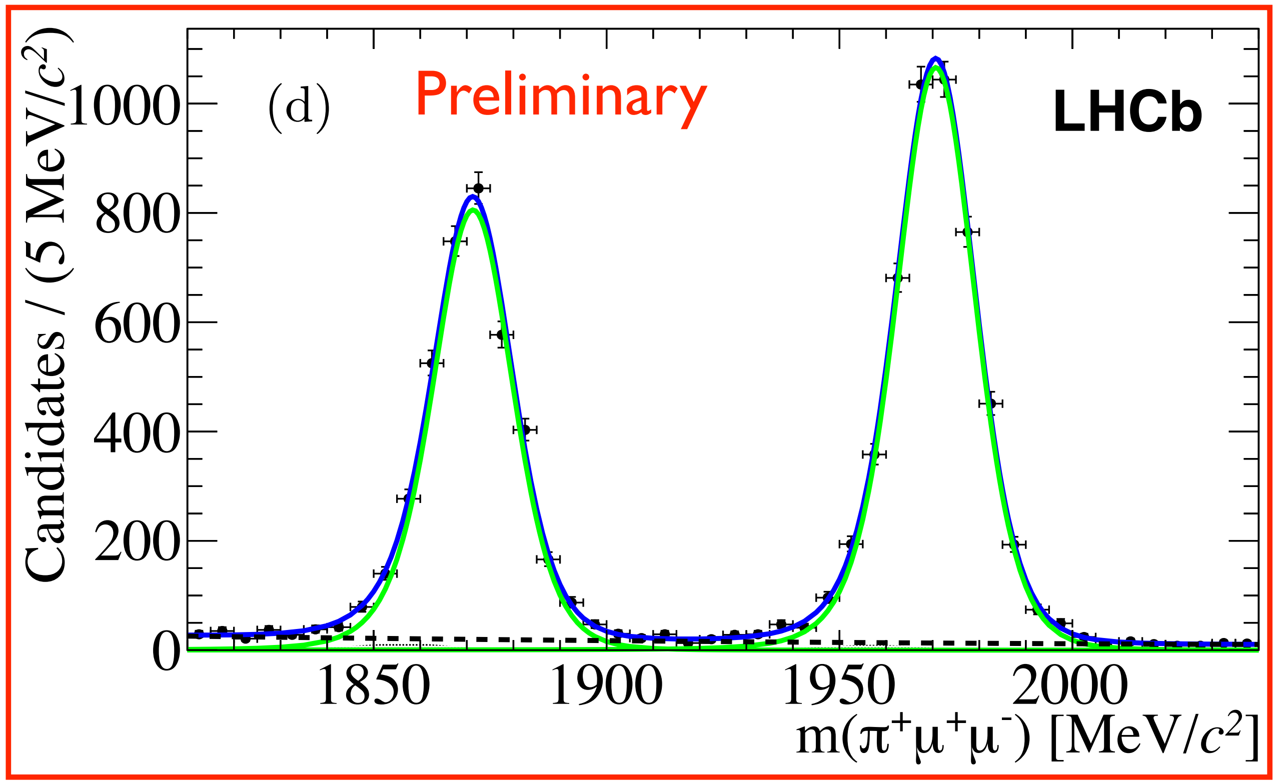


- Solution: search in regions of $m(\mu^+\mu^-)$ away from resonances.
- Bonus: these modes provide built-in normalization.

Search for $D^+ \to \pi^+ \mu^- \mu^+$



Beautiful!



LHCb-PAPER-2012-051
(in preparation)

Search for $D^+ \to \pi^+ \mu^- \mu^+$

- Complication: double-misID of $D^+/D_s^+ \to \pi^+ \pi^- \pi^+$
- Solution:
  - Suppress with muon PID -- misID rate $O(10^{-2} \times 10^{-2})$
  - Get the shape from data -- look for $D^+/D_s^+ \to \pi^+ \pi^- \pi^+$ without muon ID, then reconstruct under $\pi\mu\mu$ mass hypothesis
  - Include it in the fit...

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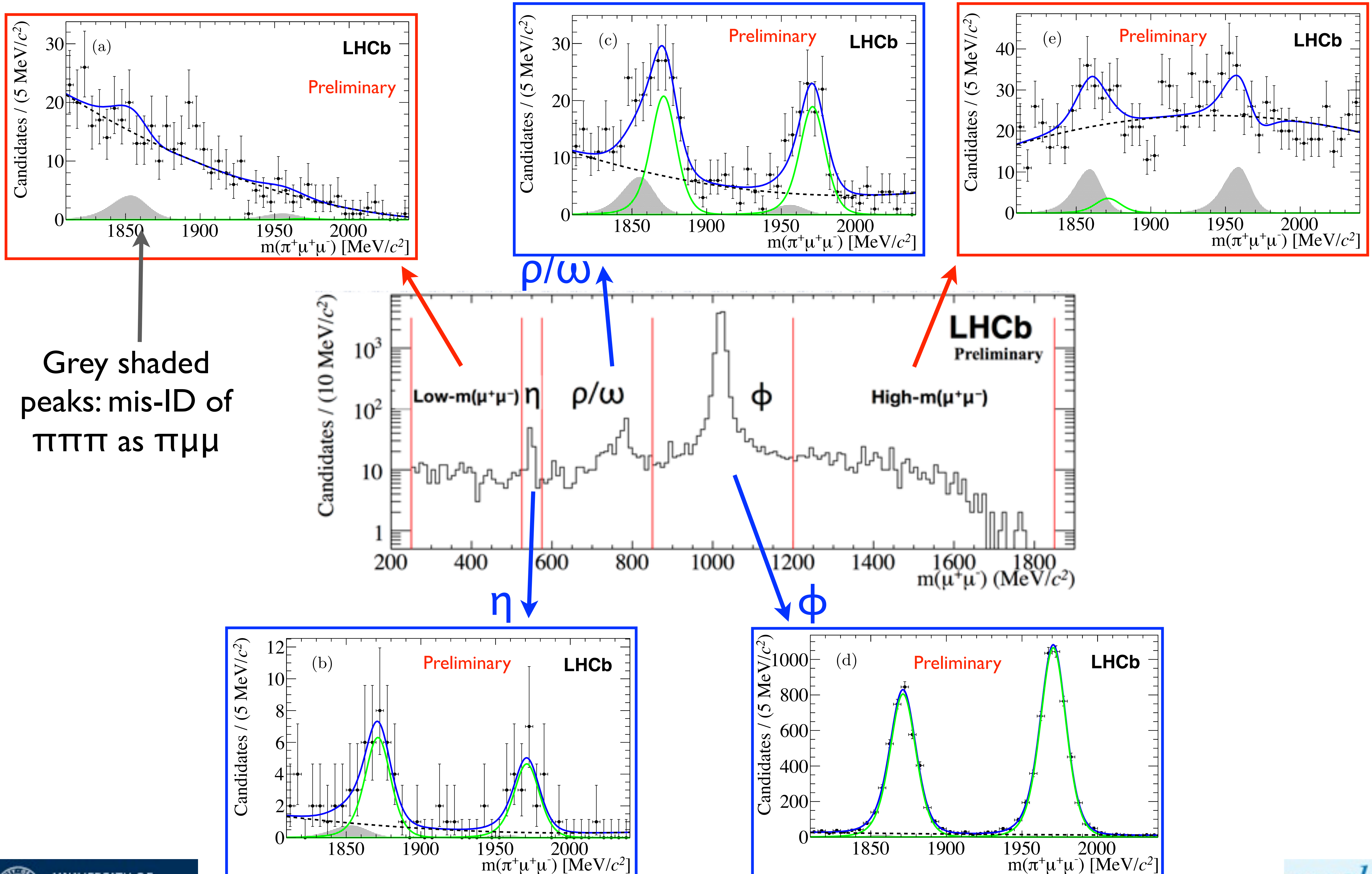
Search for $D^+ \to \pi^+ \mu^- \mu^+$



LHCb-PAPER-2012-051 (in preparation)

Search for $D^+ \to \pi^+ \mu^- \mu^+$

- Simultaneous fit to
  - all $m(\mu\mu)$ regions of $D^+ \to \pi^+ \mu^- \mu^+$
  - equivalent regions in $D^+ \to \pi^+ \pi^- \pi^+$ (fixes mis-ID shape)
- Signal yields in non-resonant regions consistent with zero.
- Extrapolate to full phase space and quote CLs UL on branching ratios relative to $D^+ \to \phi\pi^+$:

Preliminary

Decay	Bin	90% [$\times 10^{-8}$]	95% [$\times 10^{-8}$]	p-value
$D^+ \to \pi^+\mu^+\mu^-$	low-$m(\mu^+\mu^-)$	2.0	2.5	0.742
	high-$m(\mu^+\mu^-)$	2.6	2.9	0.415
	Total	7.3	8.3	0.417
$D_s^+ \to \pi^+\mu^+\mu^-$	low-$m(\mu^+\mu^-)$	6.9	7.7	0.777
	high-$m(\mu^+\mu^-)$	16.0	18.6	0.414
	Total	41.0	47.7	0.416

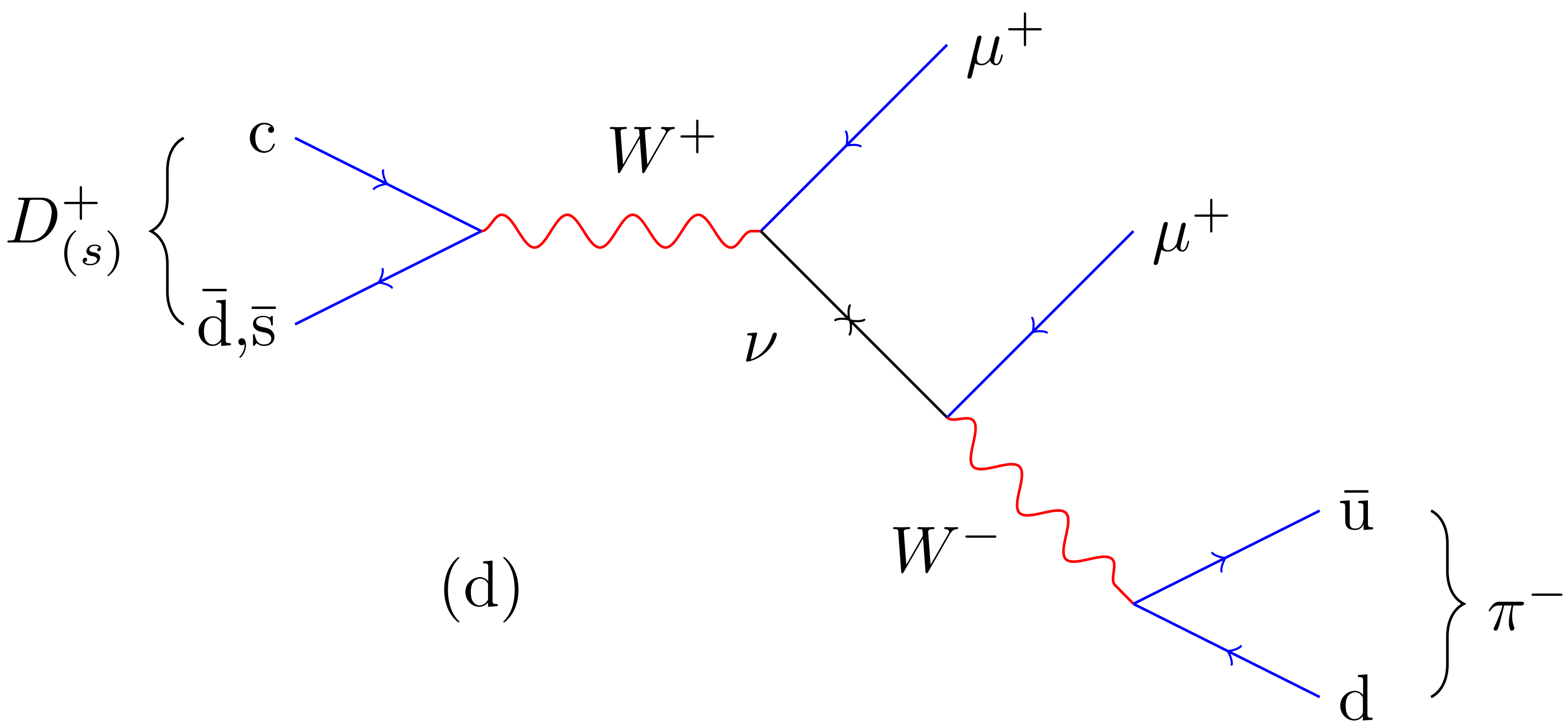
Previous best limit (D0): 3.9×10^{-6} (90% C.L.)

Two orders of magnitude better!

LHCb-PAPER-2012-051 (in preparation)

Search for $D^+ \to \pi^- \mu^+ \mu^+$

- LFV decay forbidden in the SM
- ... but can occur via Majorana neutrino:

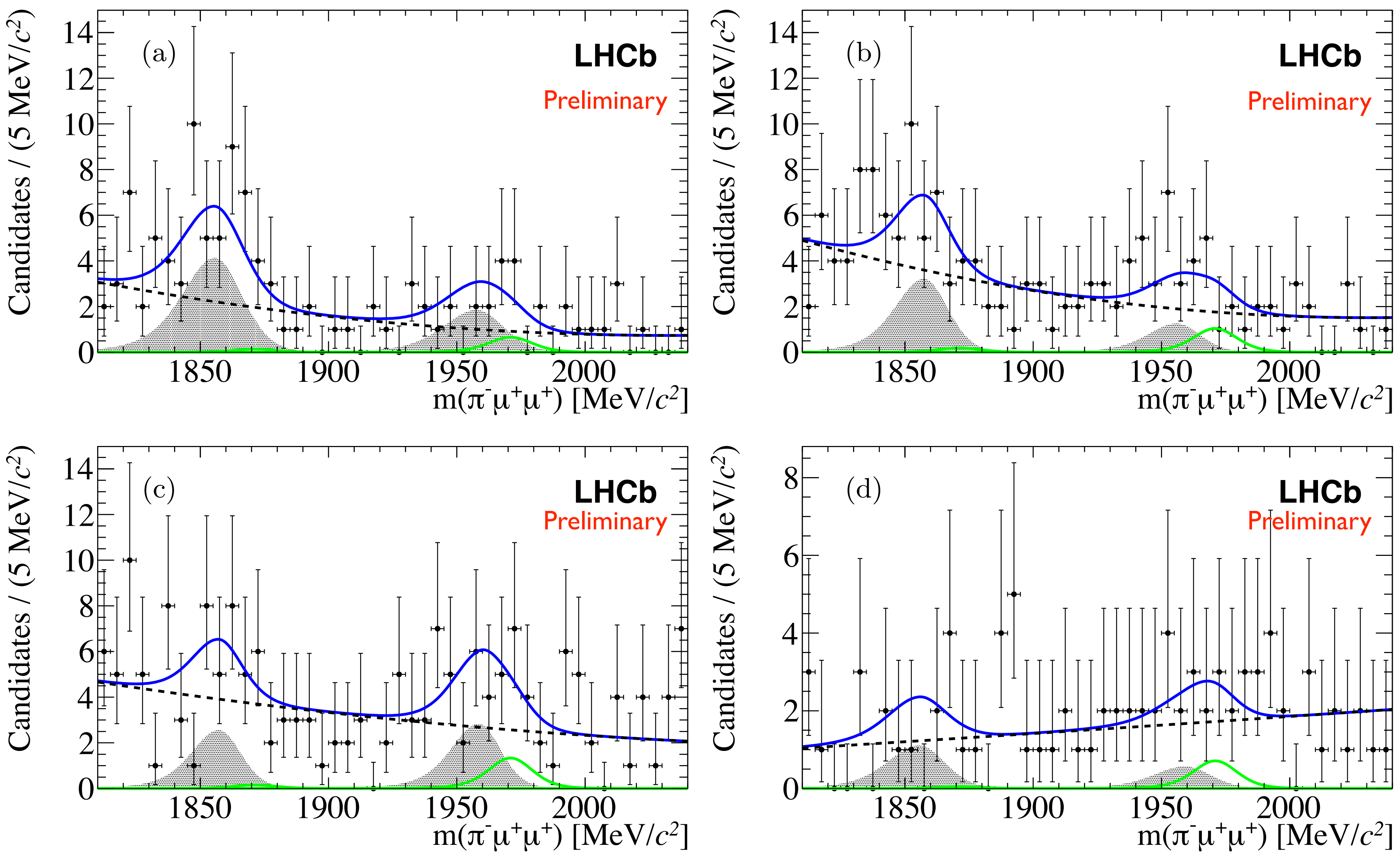


No pesky SM/resonance backgrounds this time, just $\pi \to \mu$ mis-ID.

Previous limit from BABAR for D^+ (D_s^+): $\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 2(14) \times 10^{-6}$ (90% C.L.)

Search for $D^+ \to \pi^- \mu^+ \mu^+$

- Fits in four Dalitz plot regions:



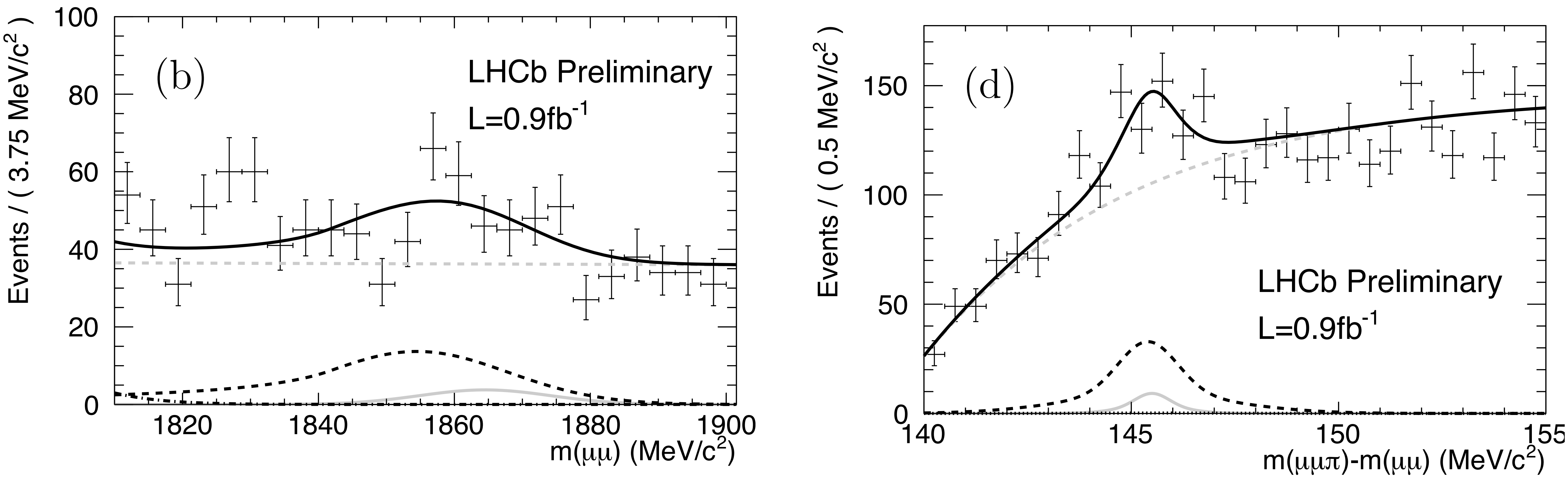
Preliminary

$$\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 2.5 \times 10^{-8} \text{ at } 95\% \text{ C.L.}$$

$$\mathcal{B}(D_s^+ \to \pi^- \mu^+ \mu^+) < 14.1 \times 10^{-8} \text{ at } 95\% \text{ C.L.}$$

Two orders of magnitude better than previous limit!

Search for $D^0 \to \mu^+ \mu^-$



Dashed line: tagged $D^0 \to \pi^+ \pi^-$
Almost invisible light grey line: $D^0 \to \mu^+ \mu^-$ (consistent with zero)

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < \begin{cases} 1.3 \times 10^{-8} \text{at } 95\% \text{ C.L.} \\ 1.1 \times 10^{-8} \text{at } 90\% \text{ C.L.} \end{cases}$$

Preliminary

Mixing and CP violation

Standard mixing formalism

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

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

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

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

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

General time evolution:

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

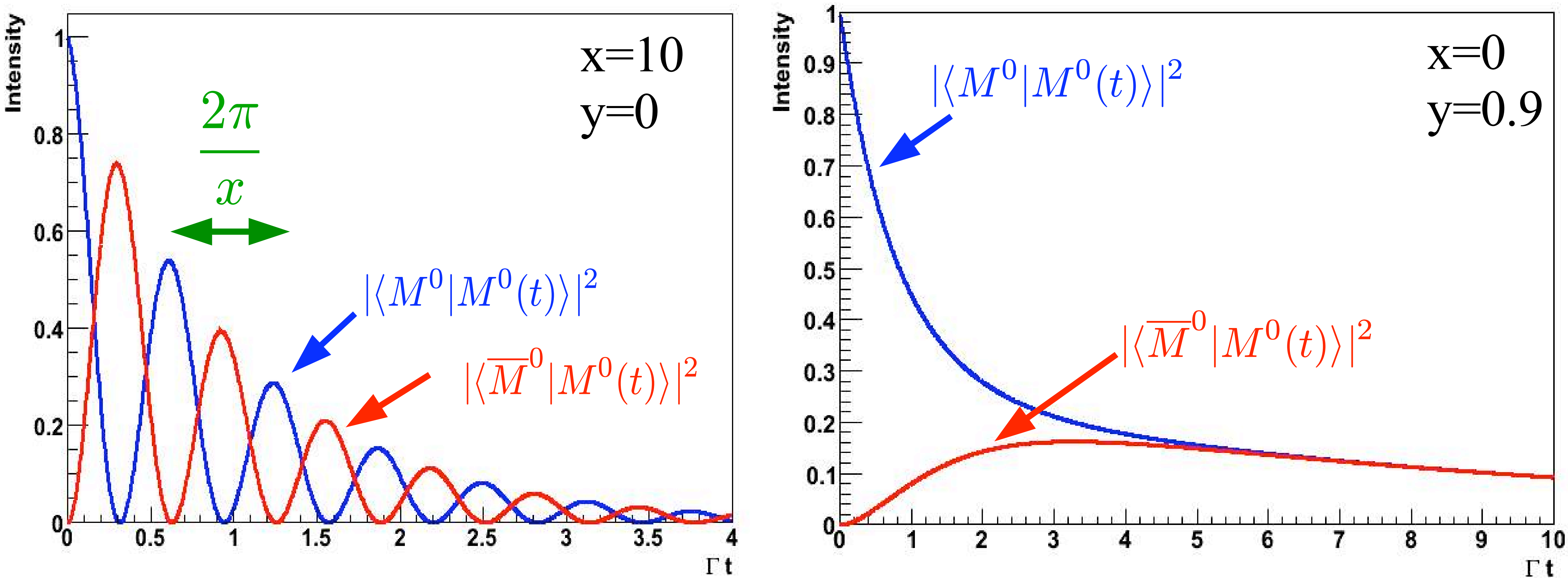
$$|\overline{M}(t)\rangle = \frac{1}{2q}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right]$$

Cartoon of mixing

For convenience, define:

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

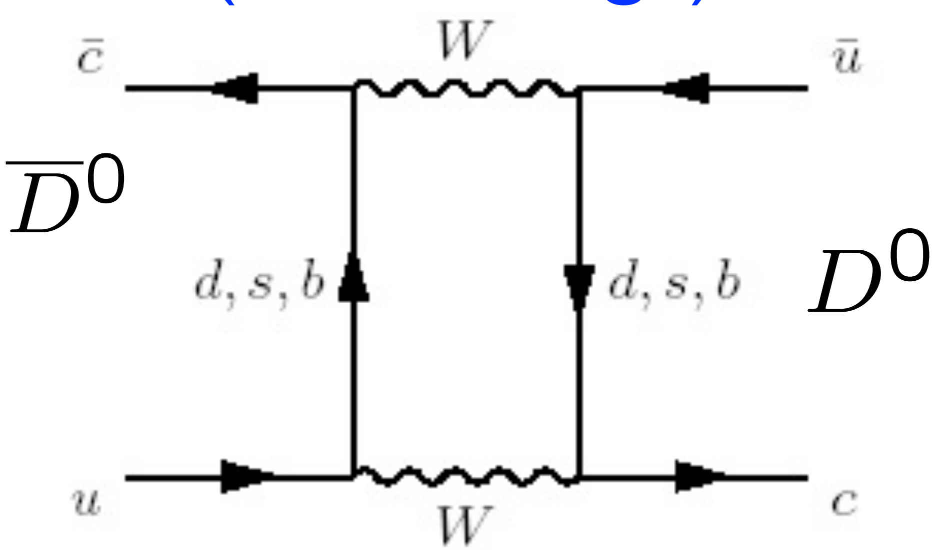
and $R_M = \dfrac{x^2 + y^2}{2}$



Mixing in charmed mesons

Charm mixing small compared to other mesons in SM:

Mixing via box diagram (short-range)



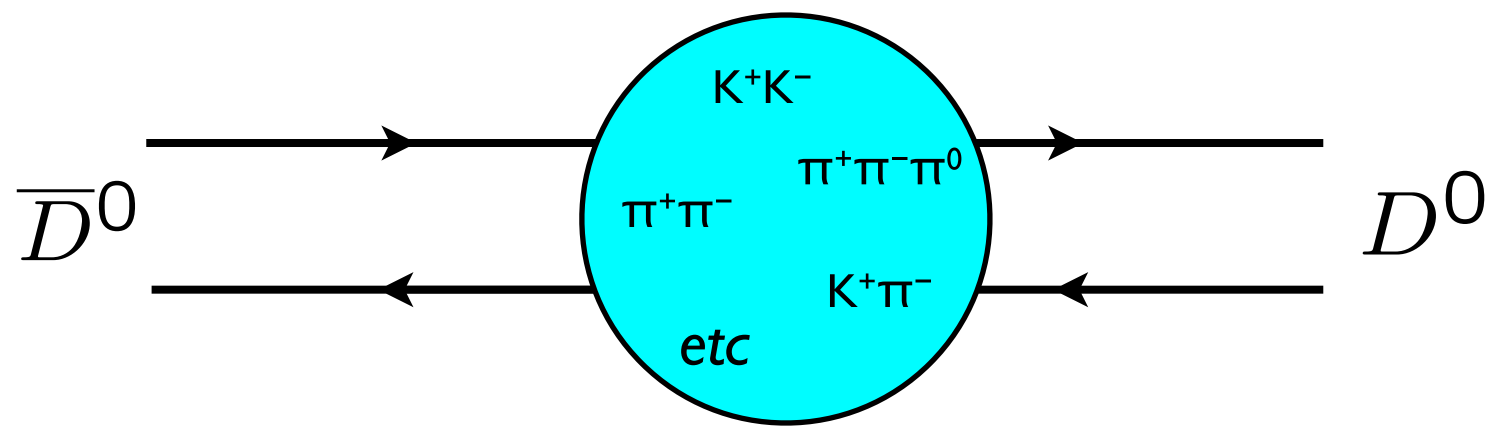
Contributes mainly to x

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)

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CP violation

- 3 types of CP violation:
  - In decay: amplitudes for a process and its conjugate differ
  - In mixing: rate of $D^0 \rightarrow \overline{D}^0$ and $\overline{D}^0 \rightarrow D^0$ 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(%)

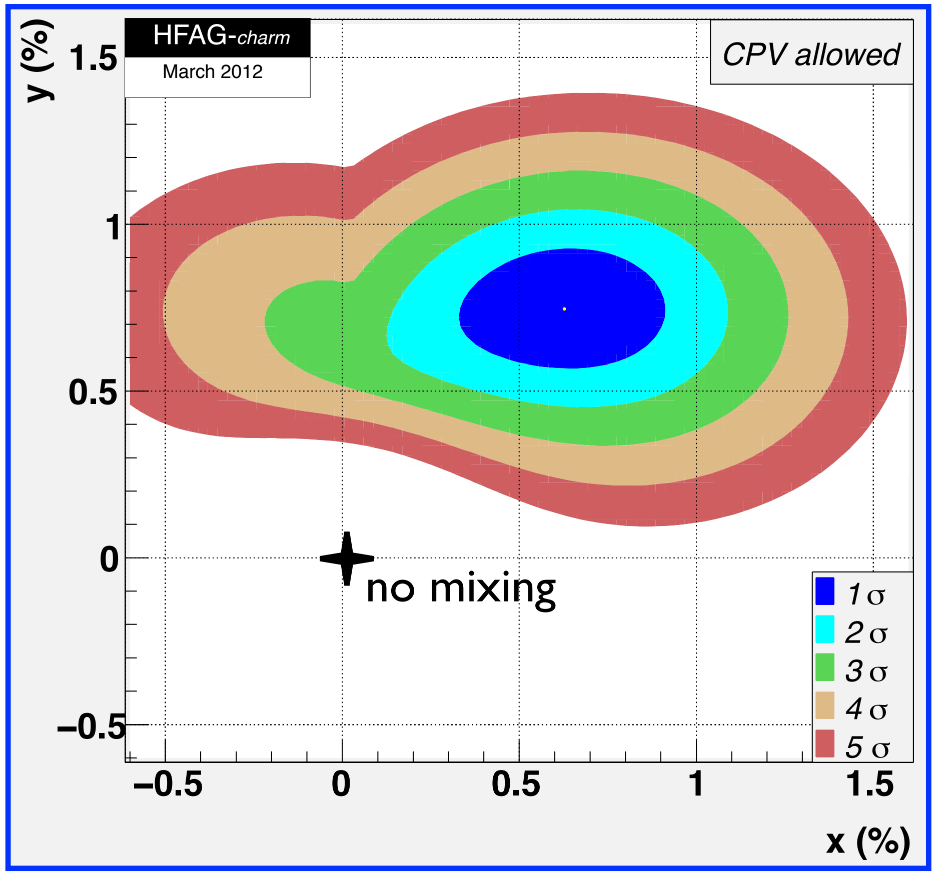
Bianco, Fabbri, Benson & Bigi, Riv. Nuovo. Cim 26N7 (2003)
Grossman, Kagan & Nir, PRD 75, 036008 (2007)
Bigi, arXiv:0907.2950

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

CPV in charm not observed yet

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.

(neglecting direct CPV)

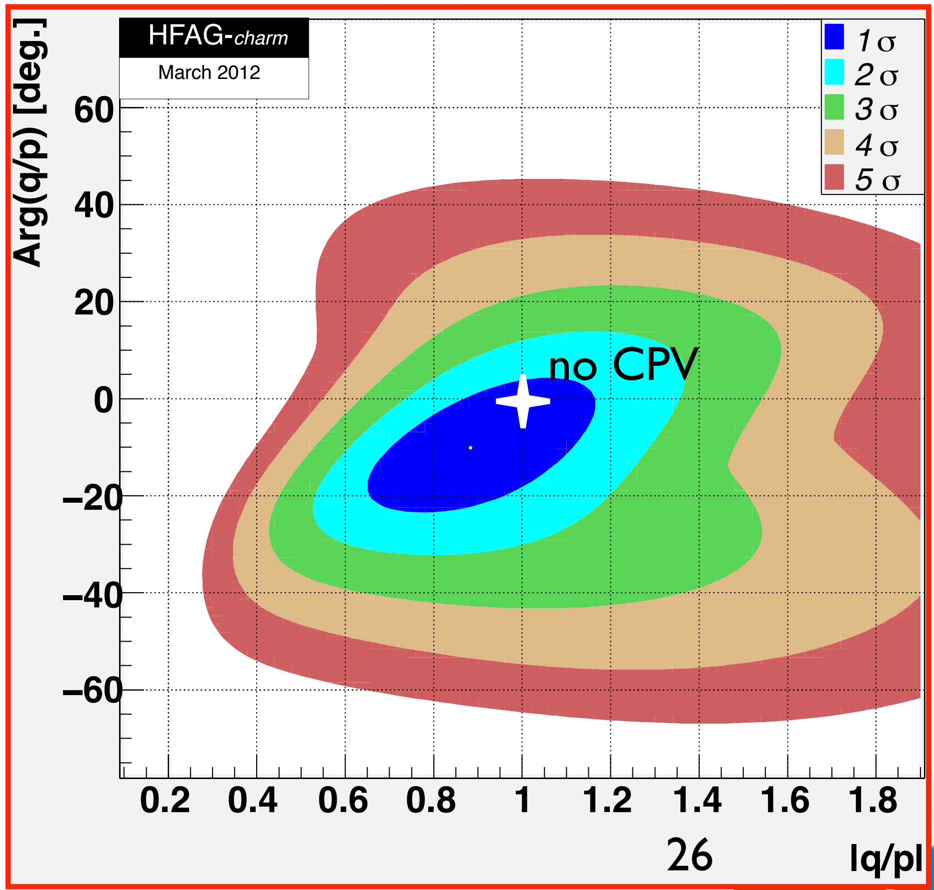
CP-violating terms << 10^{-2} in SM

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

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

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

c.f. current world average from HFAG: $A_\Gamma = (0.026 \pm 0.231)\%$



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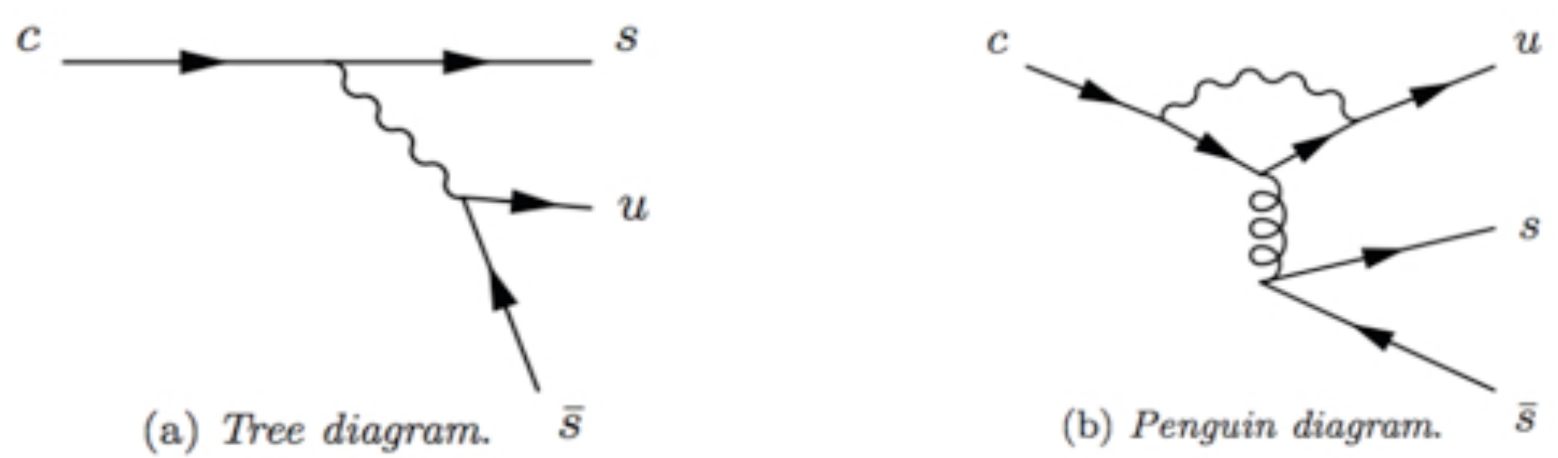
Where to look for direct CPV

- 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.*

- Small CPV from tree-penguin interference:

$$A_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})} = 2\, r_f \,\sin\phi_f\, \sin\delta_f$$

Weak phase difference (ϕ_f)

Strong phase difference (δ_f)

Ratio of penguin/tree amplitudes (r_f)

Grossman, Kagan & Nir, PRD 75, 036008 (2007)

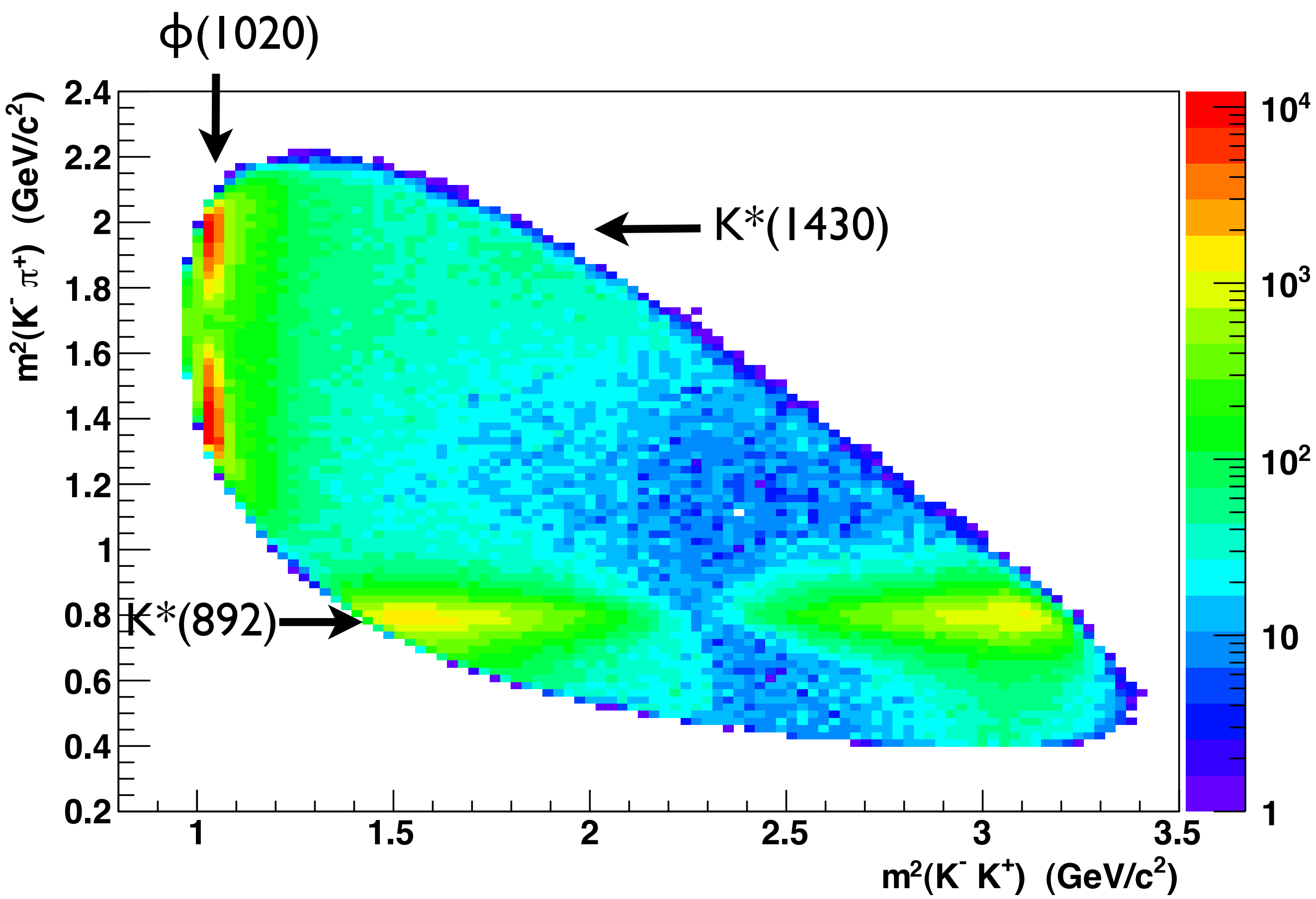
Direct CPV at LHCb

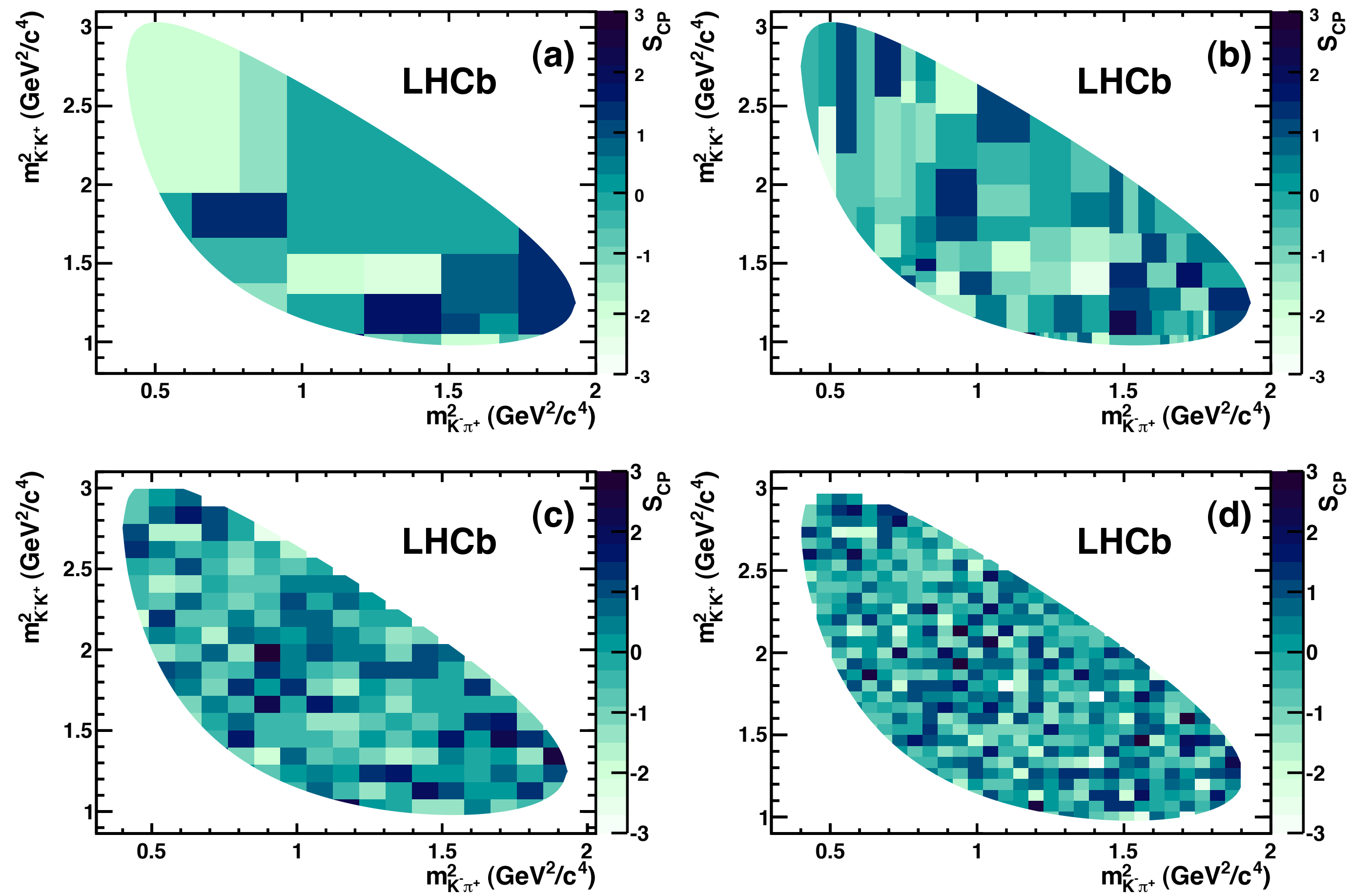
- Looking for time-integrated asymmetries.
- Main experimental challenge: separating real CP asymmetry from nuisance asymmetries:
  - Production asymmetry of D vs Dbar
  - Efficiency asymmetry of f vs fbar

$$A_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})}$$

- Solution 1: construct observables where these effects cancel or are irrelevant
  - Asymmetry differences: $\Delta A_{CP} = A(D^0 \to K^+ K^-) - A(D^0 \to \pi^+ \pi^-)$
  - Distribution asymmetries in multibody decays:
    - $D^+ \to K^- K^+ \pi^+$ Phys. Rev. D 84, 112008 (2011)
    - $D^0 \to \pi^+ \pi^- \pi^+ \pi^-$ LHCb-CONF-2012-019
- Solution 2: measure these effects and remove them at source.
  - π^+/π^- efficiency asymmetry Phys. Lett. B 713 186 (2012)
  - D_s^+, D^+ production asymmetries arXiv:1210.4112 (LHCb-PAPER-2012-026)

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





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

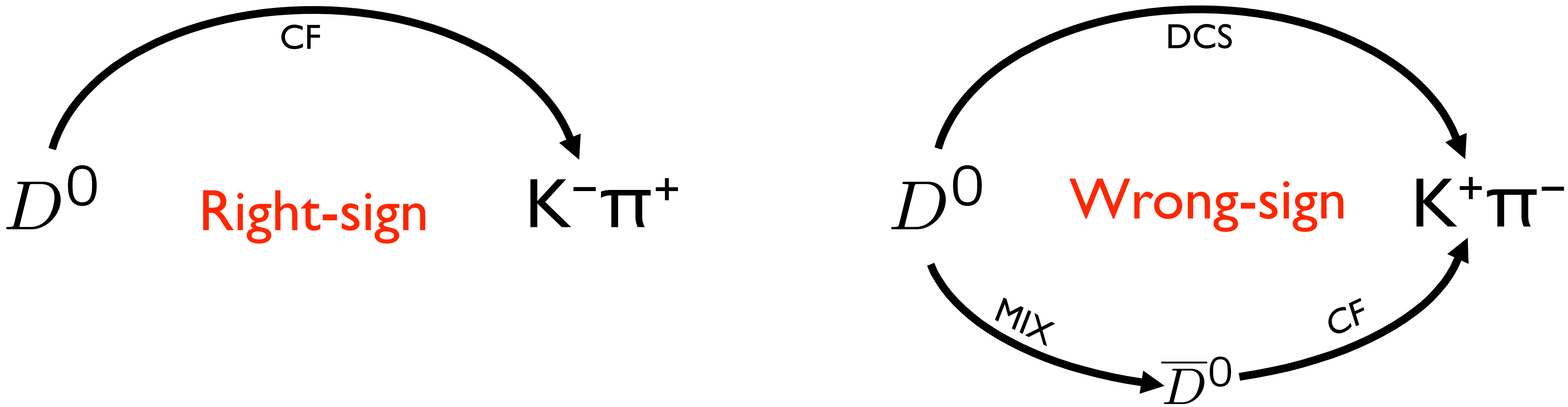
Phys. Rev. D 84, 112008 (2011)

Mixing in $D^0 \to K^+ \pi^-$

arXiv:1211.1230

Accepted for publication in PRL

Mixing in $D^0 \to K^+ \pi^-$



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

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

Measure time-dependent wrong-sign / right-sign ratio:

$$R(t) \approx R_D + \sqrt{R_D}\, y' \,\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2,$$

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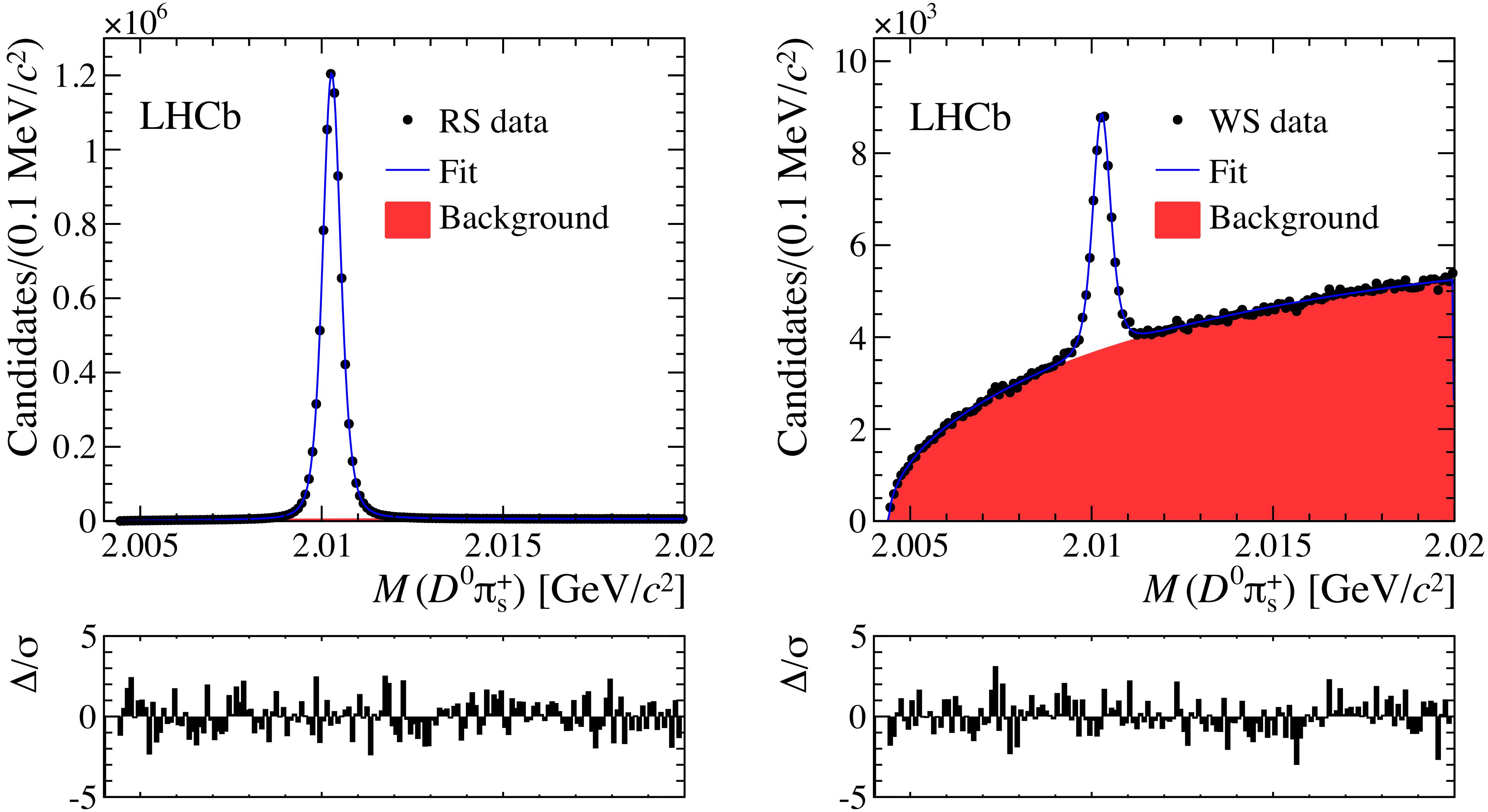
LHCb

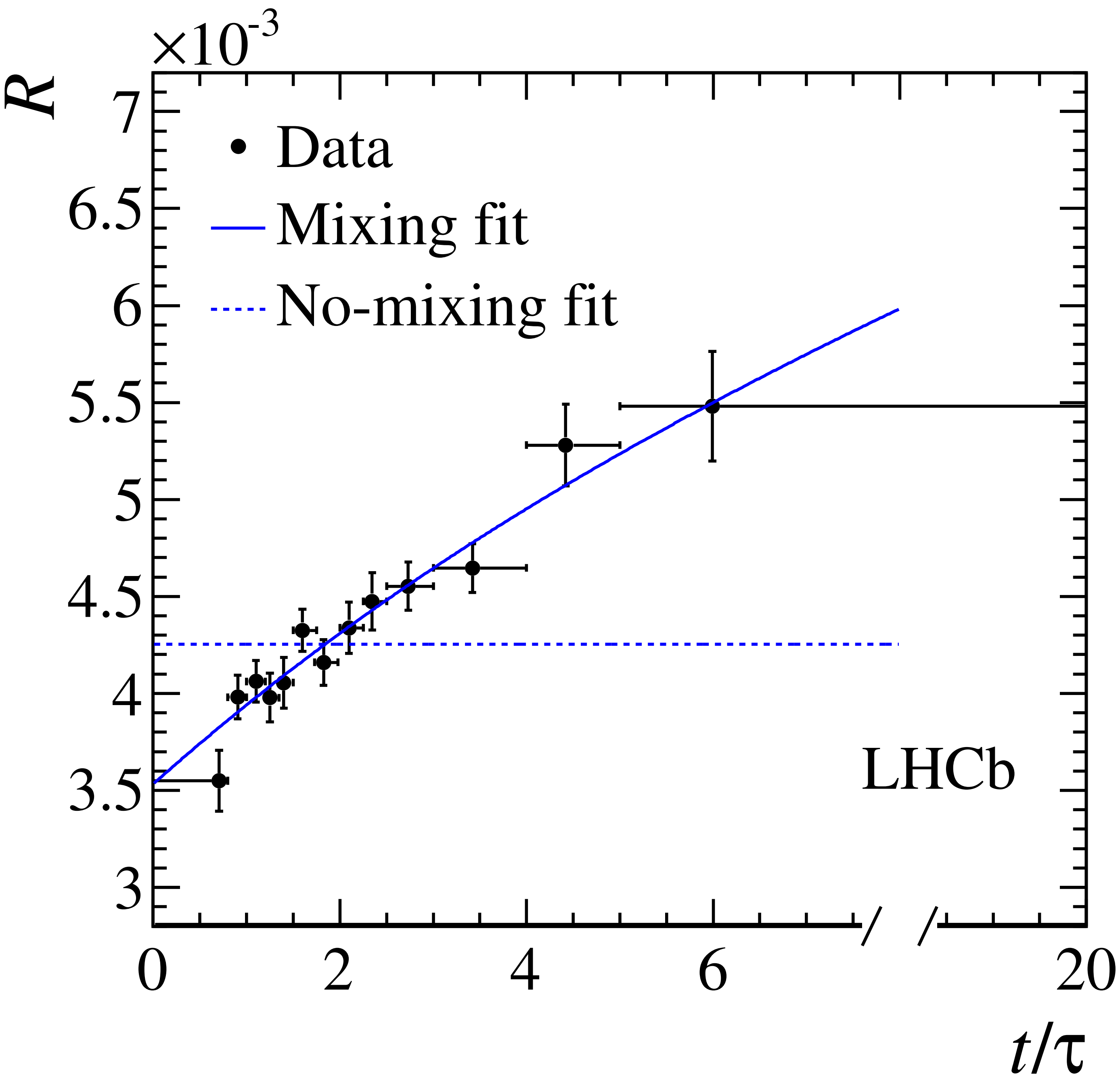
Mixing in $D^0 \to K^+ \pi^-$



Right-sign Wrong-sign

- Plots above show entire data sample.
- Now divide into bins of proper decay time and fit each...

Mixing in $D^0 \to K^+ \pi^-$

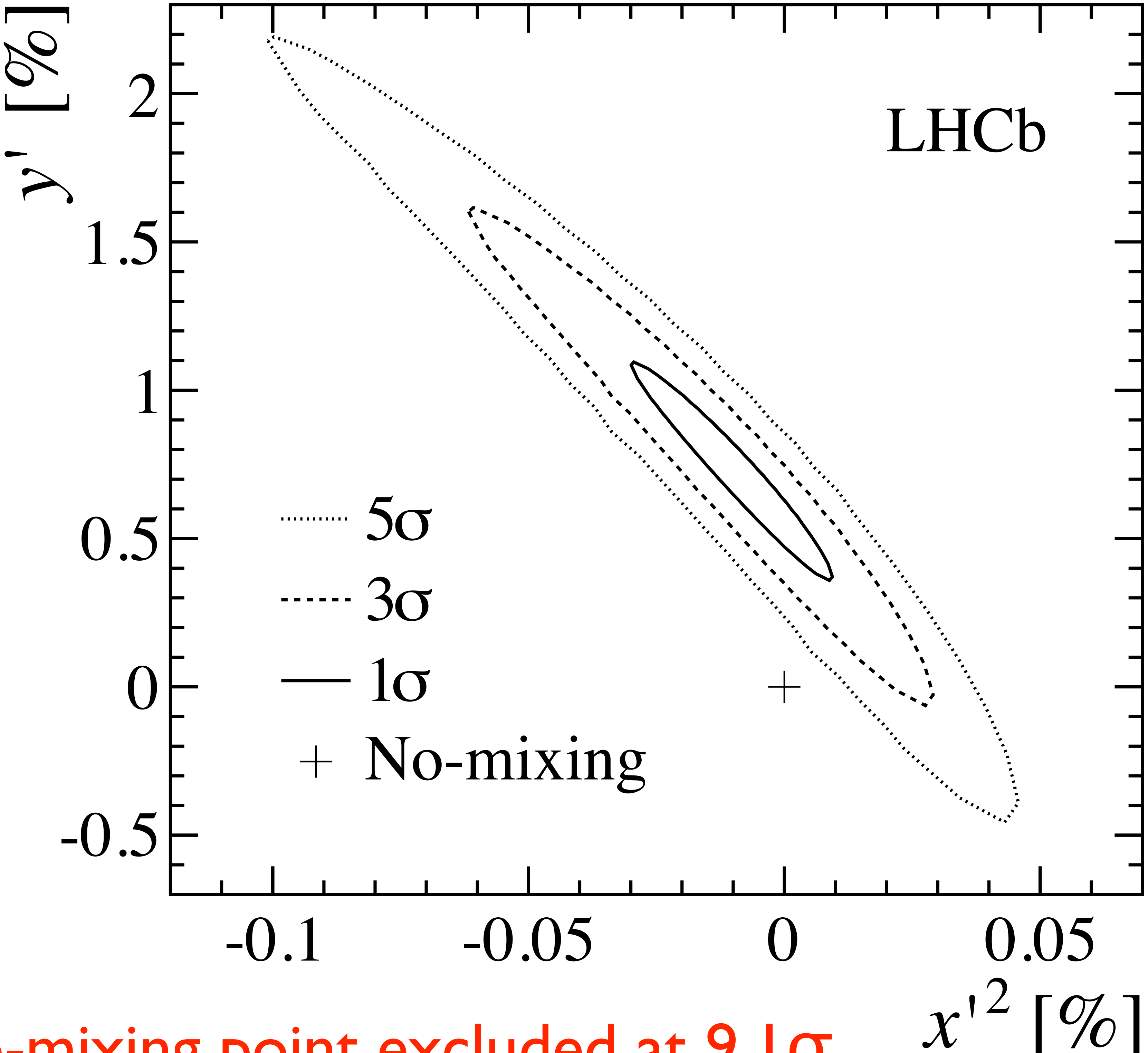


Mixing very obvious by eye: ratio is not constant!

Fit type (χ^2/ndf)	Parameter	Fit result (10^{-3})
Mixing (9.5/10)	R_D	3.52 ± 0.15
	y'	7.2 ± 2.4
	x'^2	-0.09 ± 0.13
No mixing (98.1/12)	R_D	4.25 ± 0.04

Fit results in table -- but that's not the whole story. Parameters are correlated...

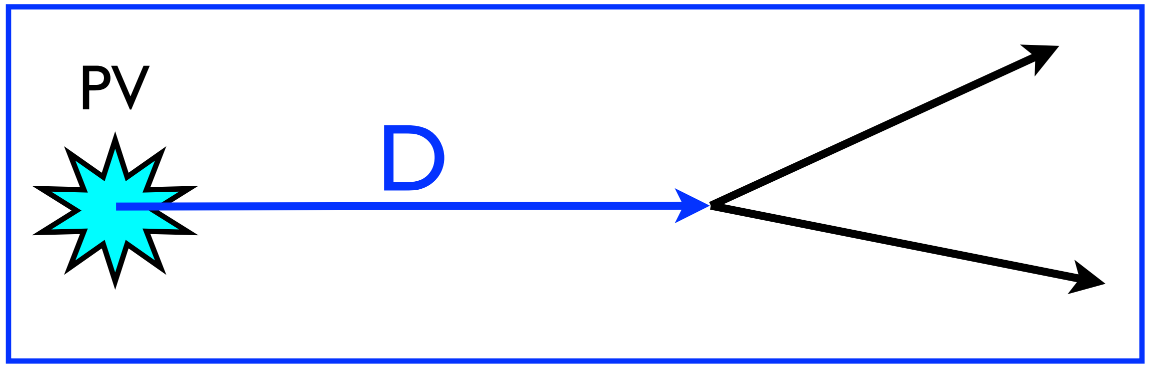
Mixing in $D^0 \to K^+ \pi^-$



No-mixing point excluded at 9.1σ.

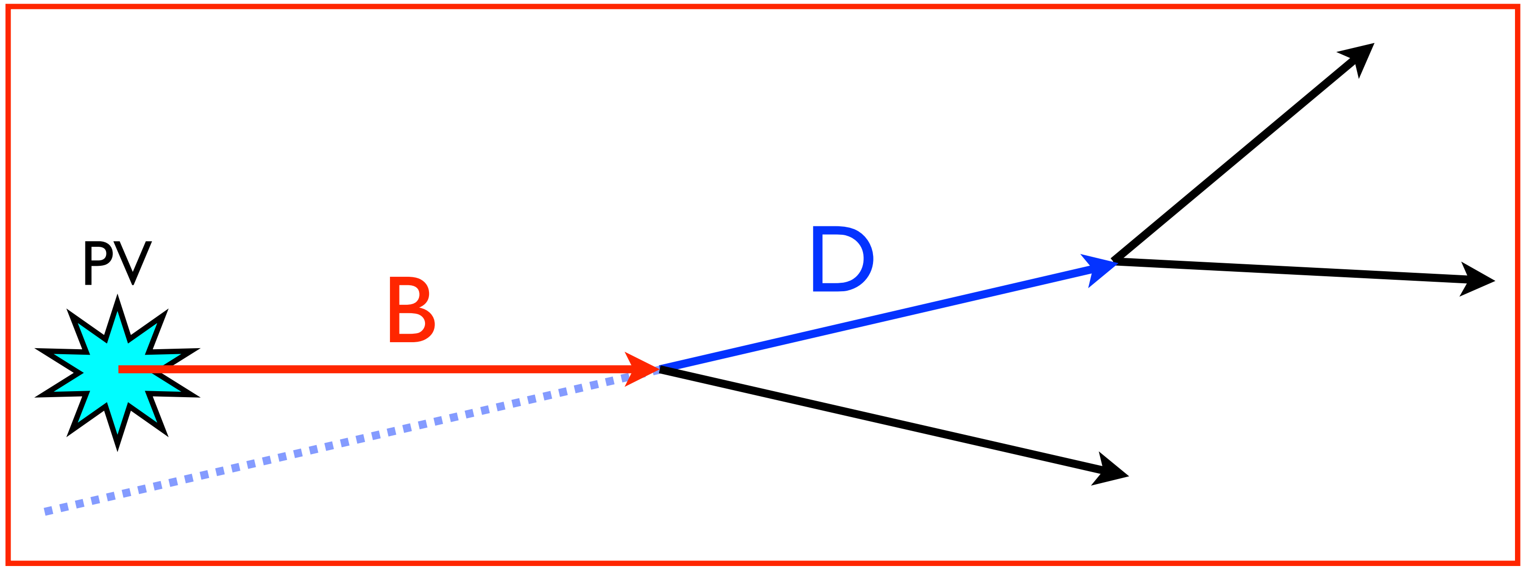
arXiv:1211.1230

Mixing in $D^0 \to K^+ \pi^-$



Prompt charm:

D points to primary vertex
Daughters of D don't in general



Secondary charm:

D doesn't point to PV in general

- One experimental issue we had to worry about: contamination from B decays ("secondary charm")
- Suppressed with pointing requirement: D^0 IPχ^2 to PV < 9
- Surviving secondaries are from short-lived B decays, so bias is small -- and partly cancels in WS/RS ratio. Bounded from above and included as systematic.

$$0 \leqslant \Delta_B(t) \leqslant f_B^{\mathrm{RS}}(t)\left[1 - \frac{R_D}{R(t)}\right]$$

arXiv:1211.1230

Secondary fraction $f_B^{RS}(t)$ varies from (0.0±0.5)% at t=0 up to (14±5)% at high lifetimes.

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

$0.6\ fb^{-1}$

PRL 108 (2012) 111602
arXiv:1112.0938

My timing is lousy...

LHC Seminar

New results on CP violation in the charm sector

by Jeroen Van Tilburg (Ruprecht-Karls-Universitaet Heidelberg (DE))

Tuesday, March 12, 2013 from **11:00** to **12:00** (Europe/Zurich)
at CERN (503-1-001 - Council Chamber)

Description The difference in CP violation between the $D0 \to K+K-$ and $D0 \to \pi+\pi-$ decays (ΔACP) has emerged as an interesting observable to search for matter-antimatter asymmetries in the charm sector. By taking the difference between the two modes, most of the asymmetries induced by the detector or coming from the production mechanism cancel. A previous LHCb measurement, using 0.6 fb–1 of data, gave 3.5σ evidence for CP violation in the charm sector, which was further strengthened by results from the CDF and Belle collaborations. We present an update of the ΔACP measurement, consisting of two independent analyses, both using the full 2011 data set of 1.0 fb–1. In the first, the initial flavour of the D meson (D0 or D0-bar) is inferred from the charge of the slow pion in the decay $D^{*}+ \to D0\pi+$, as in the previous publication. The second uses D mesons produced in semileptonic B decays, where the charge of the associated muon provides the tag.

Webcast Please note that this event will be available *live* via the **Webcast Service**.

Material: Poster

Organised by M. Mangano, C. Lourenco, G. Unal......................... **Tea and Coffee will be served at 10h30**

- Today you just get the old result, I'm afraid.

$A(D^0 \to K^+ K^-) - A(D^0 \to \pi^+ \pi^-)$

- Ideal: uncorrelated measurements of the two asymmetries.
- For practical reasons, LHCb measures difference between CP asymmetries (see next slide)
- Natural worry: are we also cancelling CP asymmetry?
- Naive expectation from U-spin: $A_{dir}(KK) = -A_{dir}(\pi\pi)$, i.e. difference is 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

Formalism

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

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 D^0 detector asymmetry for decays to $(K^+ K^-)$, $(\pi^+ \pi^-)$

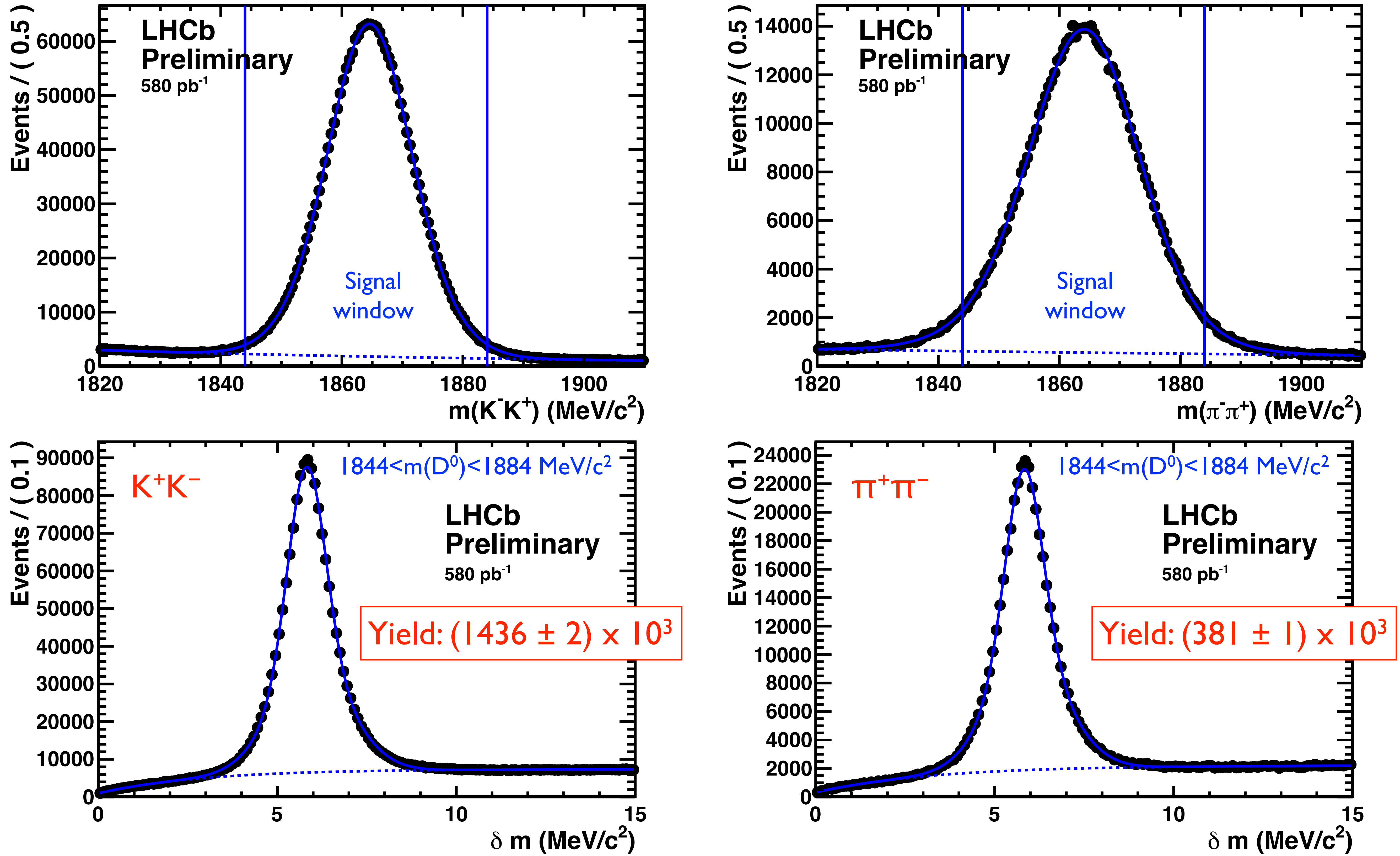
... i.e. all the D^*-related production and detection effects cancel.

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

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

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}

Result & systematics

Source	Uncertainty
Fiducial requirement	0.01%
Peaking background asymmetry	0.04%
Fit procedure	0.08%
Multiple candidates	0.06%
Kinematic binning	0.02%
Total	0.11%

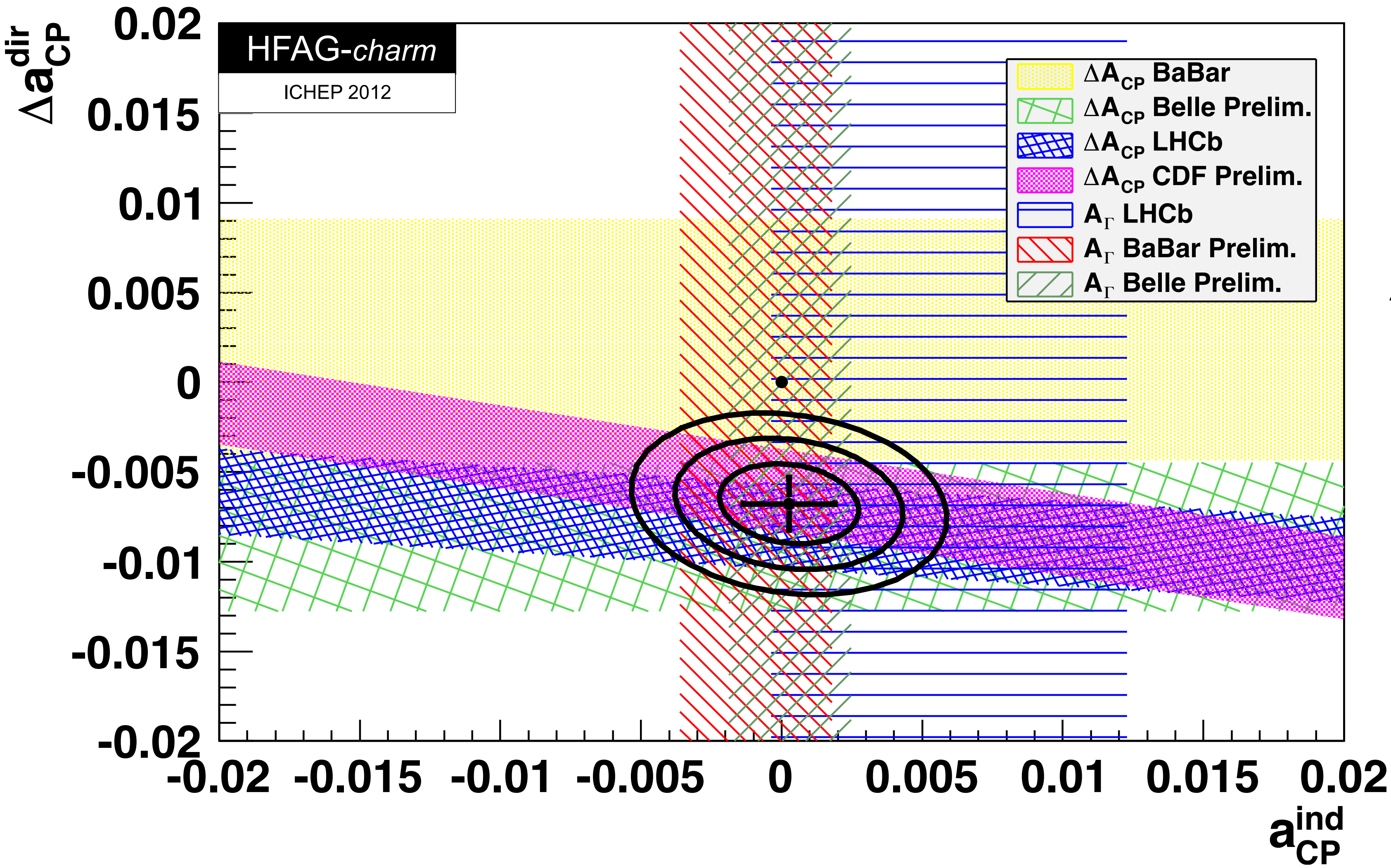
$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})]\,\%$$

Significance: 3.5 σ

Skipping a bunch of subtleties, e.g. kinematic correlations.

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: $A^{ind}[\langle t_{KK}\rangle - \langle t_{\pi\pi}\rangle]/\tau_0$



$$a_{CP}^{\rm ind} = (+0.027 \pm 0.163)\%$$

$$\Delta a_{CP}^{\rm dir} = (-0.678 \pm 0.147)\%$$

Current world avg

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

Charm at LHCb

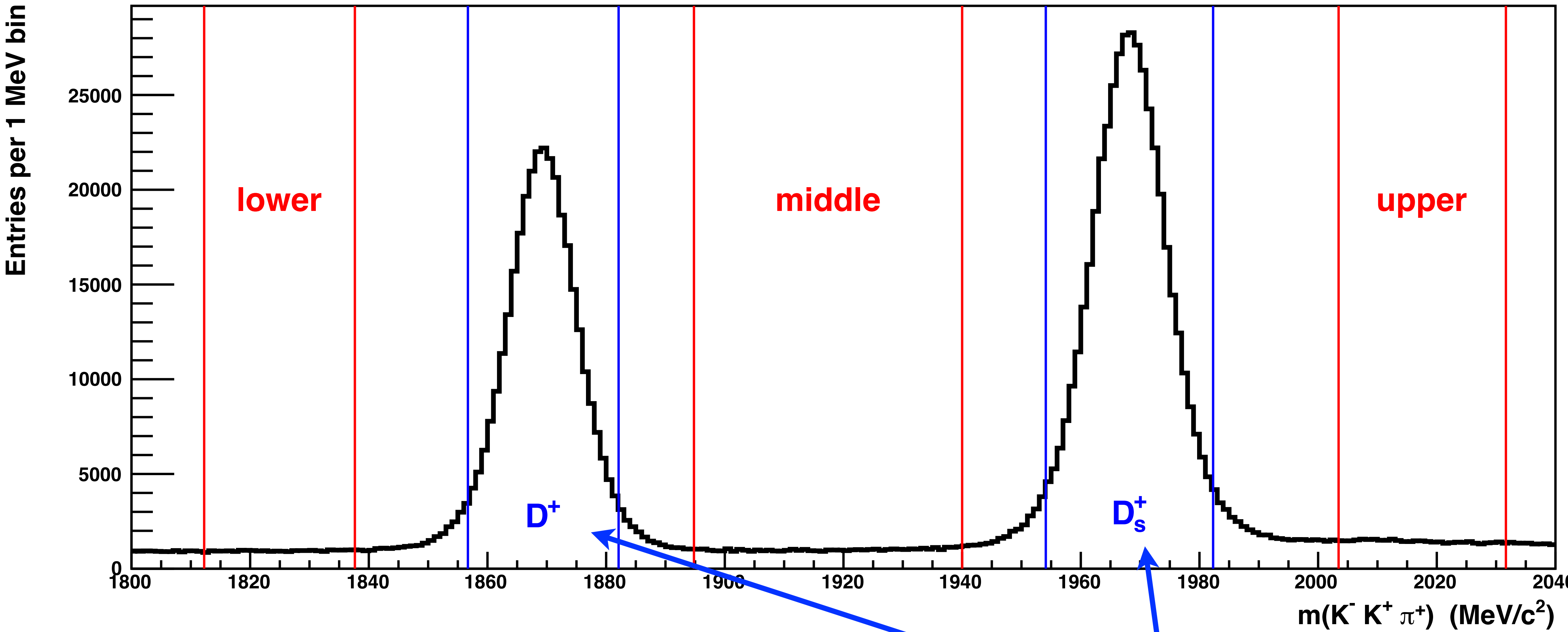
- Lots going on!
- I couldn't show you everything...
  - Production studies -- single & double charm; asymmetries
  - Spectroscopy, recent results in D_{sJ}
  - More CPV and mixing studies (including 4-body decays)
- ... but I hope you got a flavour.
- LHCb's real strengths (POV of an ex-BaBarian):
  - Huge statistics (at least for all-charged final states)
  - Fantastic hadron and muon PID
  - Great precision on lifetimes, vertices
- Systematics are a challenge, especially for charm
  - because of the production environment
  - because of the very large samples
- ... but we are making steady progress. Interesting times!

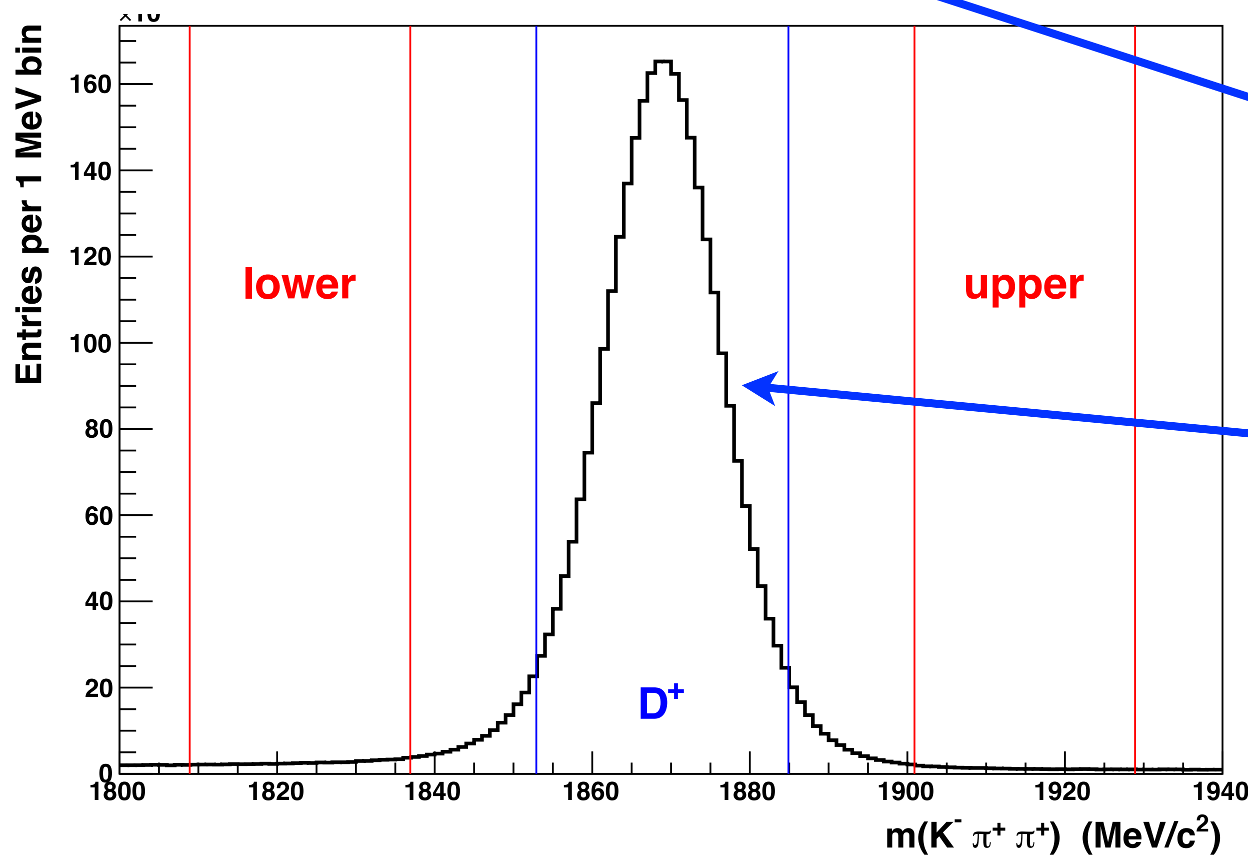
$D^+ \to K^- K^+ \pi^+$

38 pb^{-1}

Phys. Rev. D 84, 112008 (2011)

Mass spectra after selection





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.

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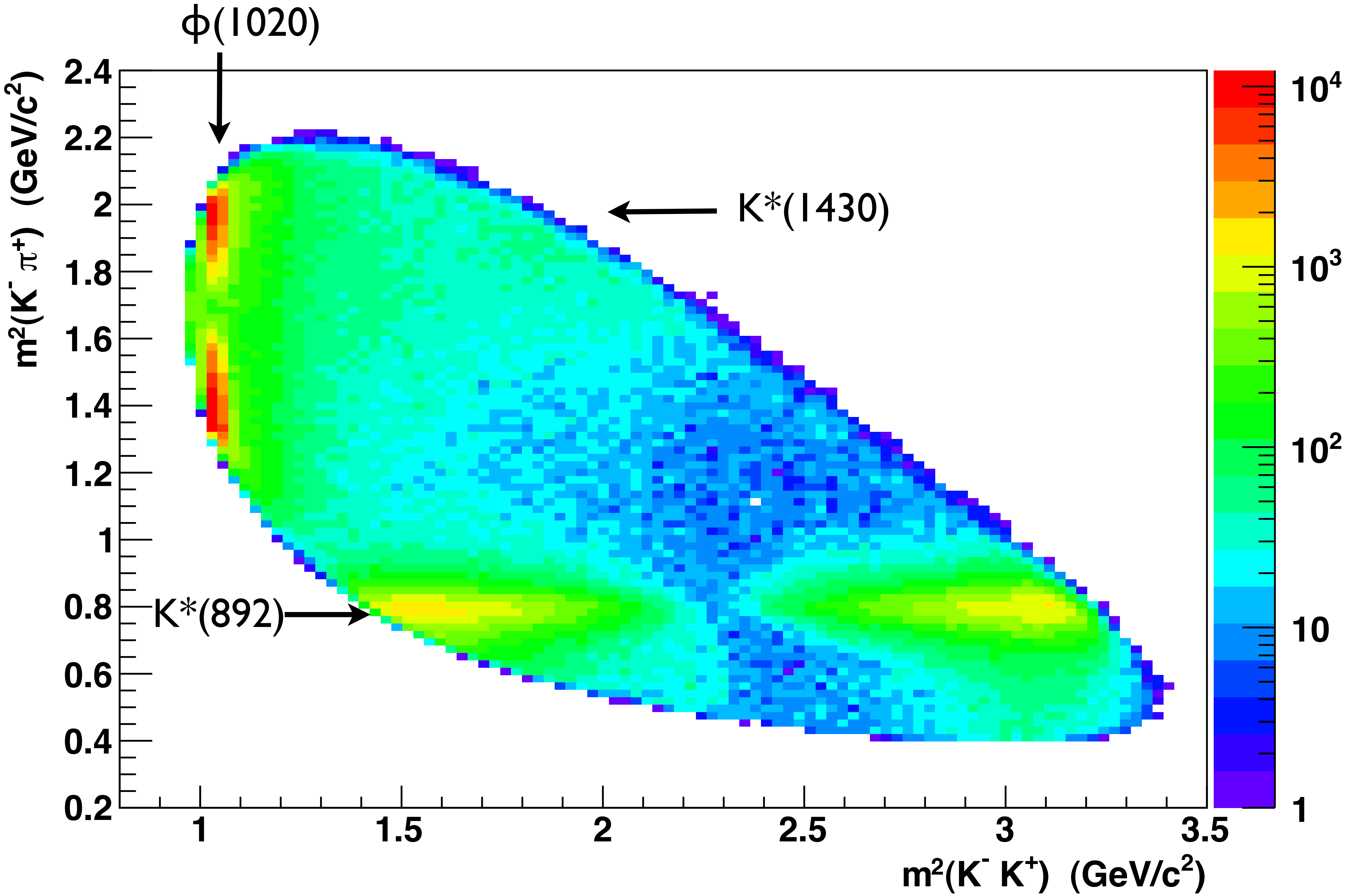
The Dalitz plot

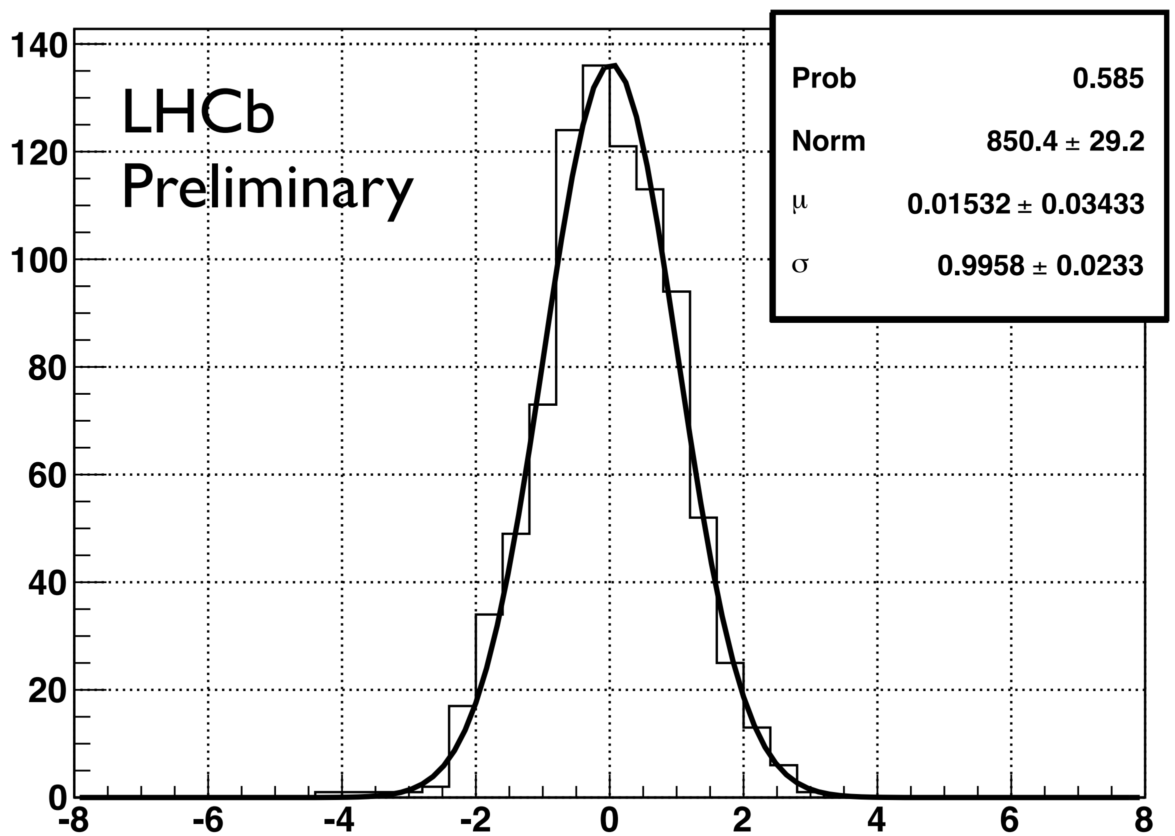
- First, here is the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot with LHCb data:



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 $D^+ \to K^- \pi^+ \pi^+$ control mode follows prediction very nicely.

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

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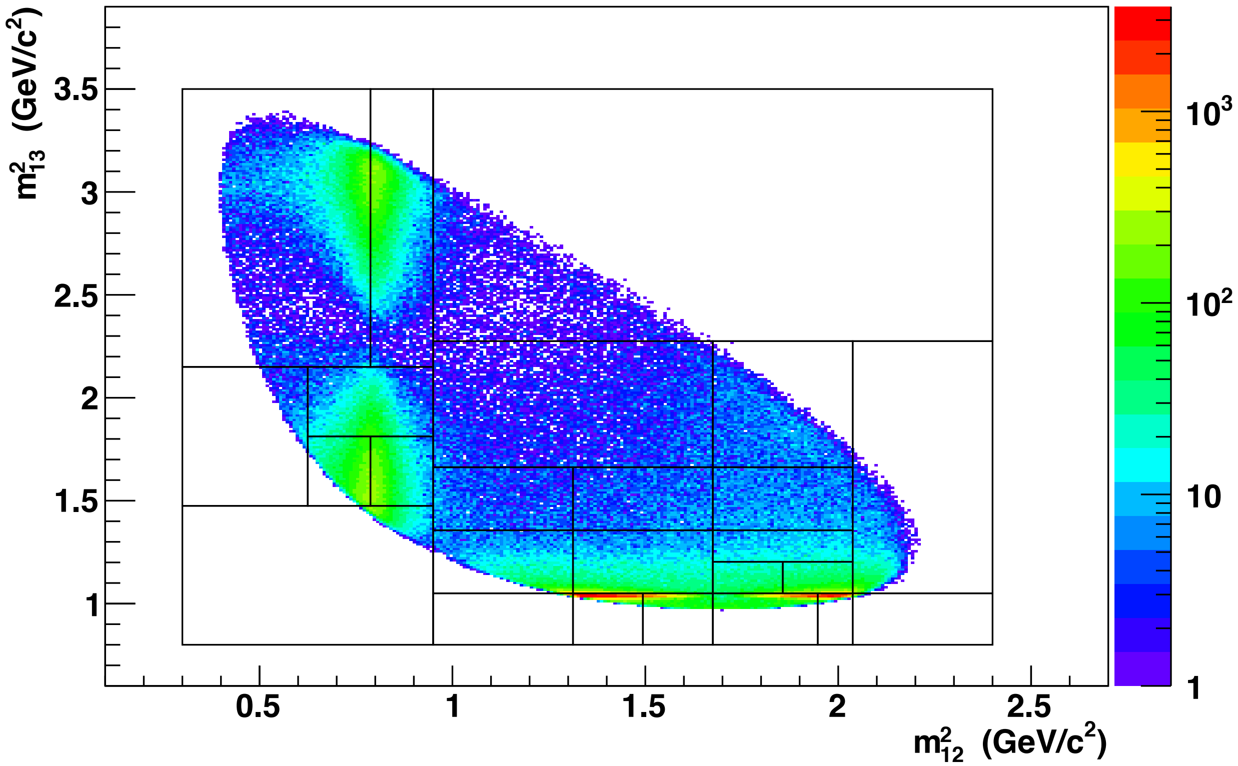
$D_s^+ \rightarrow K^- K^+ \pi^+$ control mode



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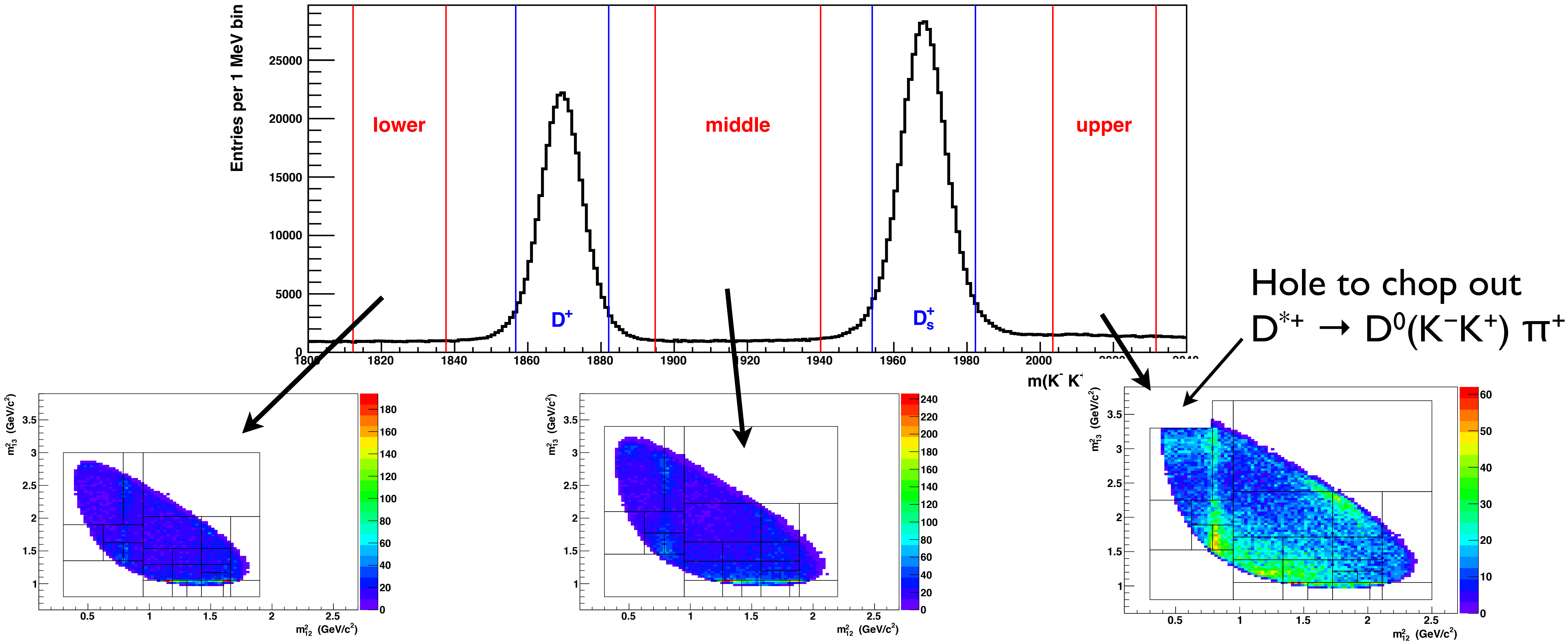
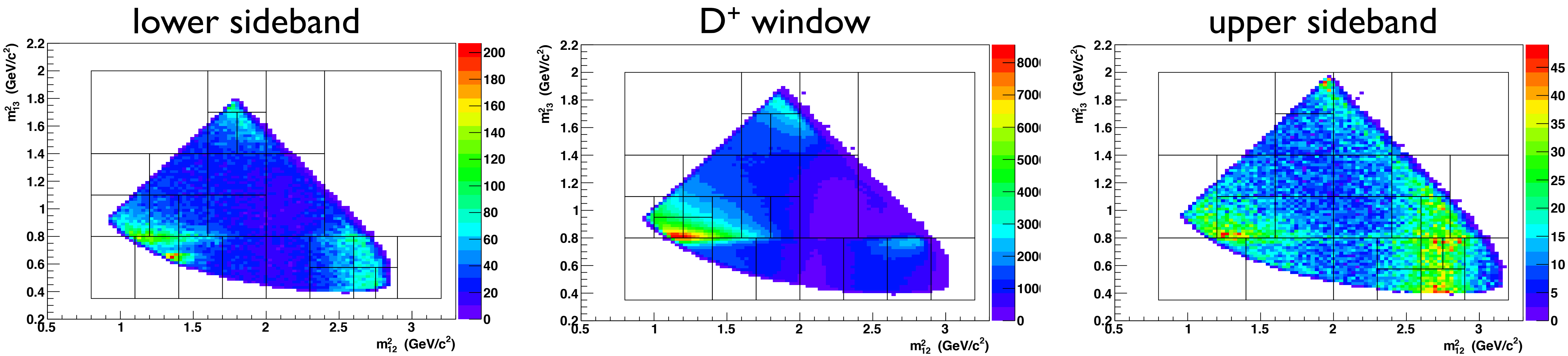
Other $K^- K^+ \pi^+$ control modes



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!

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



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%

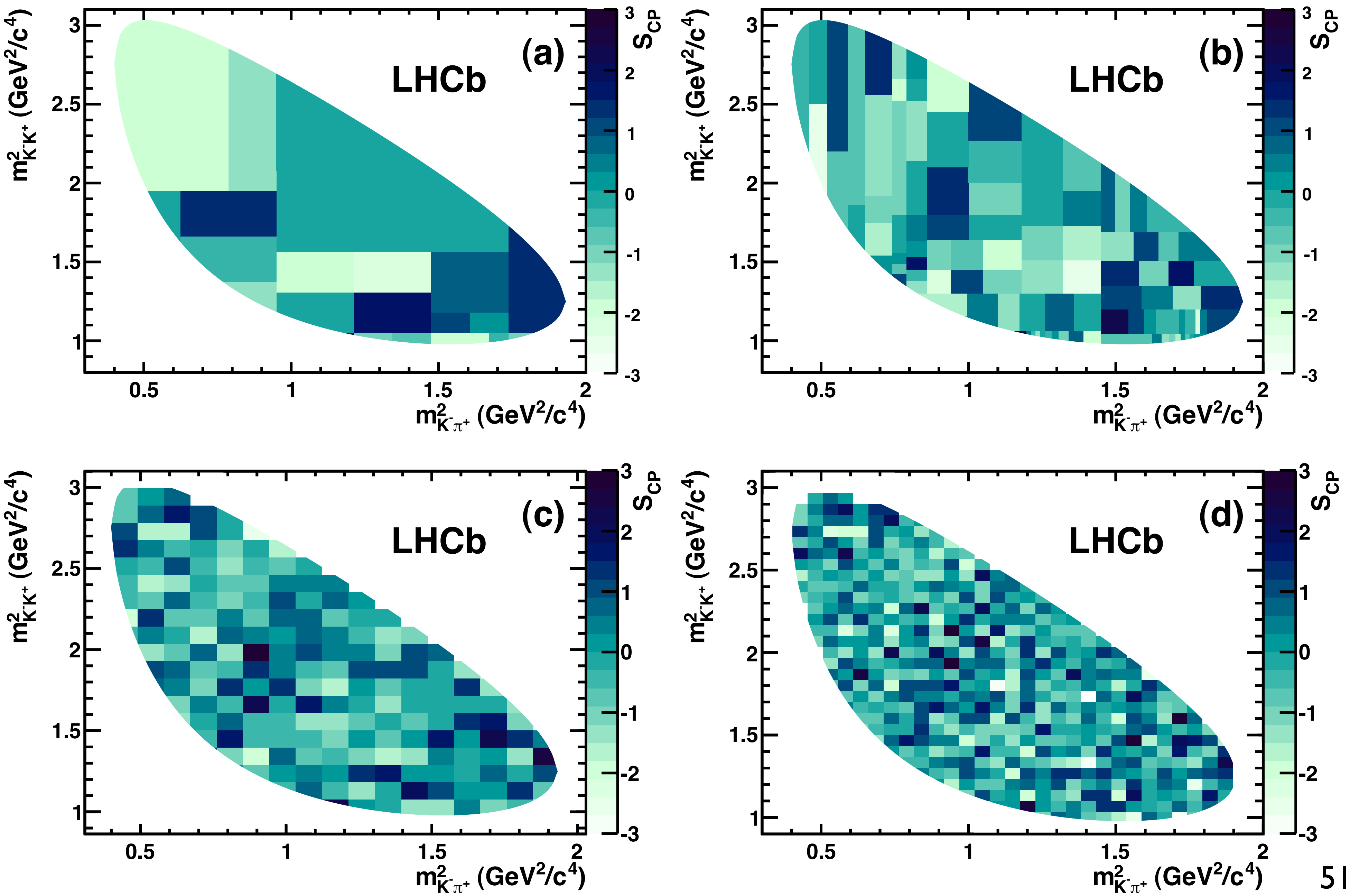
- $D^+ \rightarrow K^- \pi^+ \pi^+$ behaves amazingly well. Remember:
  - there is a mechanism for a fake asymmetry that doesn't apply to the signal mode (kaon efficiency)
  - the statistics are 10x larger than in the signal mode

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}



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fin

From Phys.Rev. D54 (1996) 4445 (Agashe & Graesser)

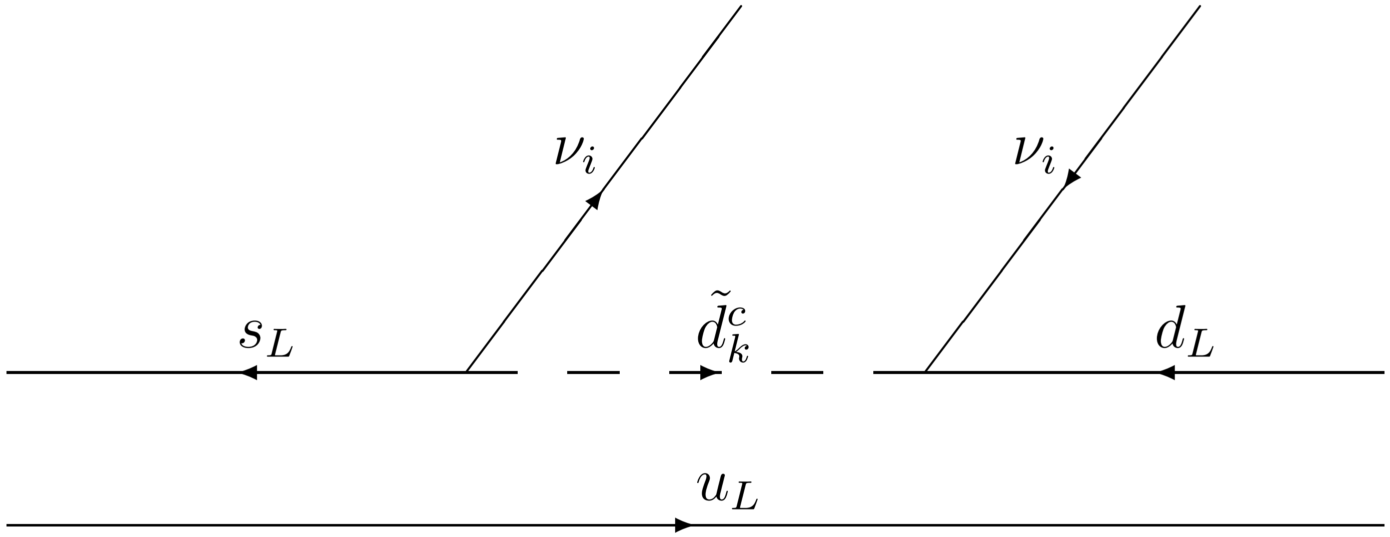


Figure 2: $R\!\!\!/_p$ contribution to $K^+ \to \pi^+ \nu \bar{\nu}$ with one $\lambda'_{ijk} \neq 0$.

From Phys.Rev.D76:074010,2007 (Fajfer, Kosnik & Prelovsek)

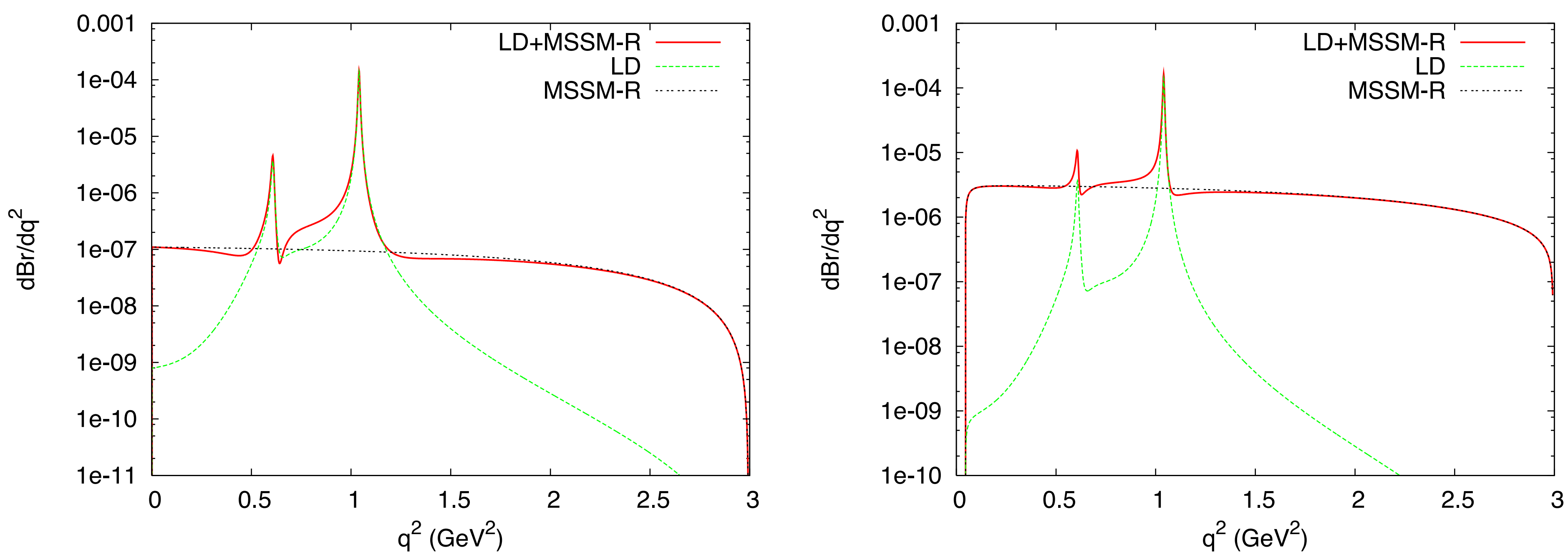


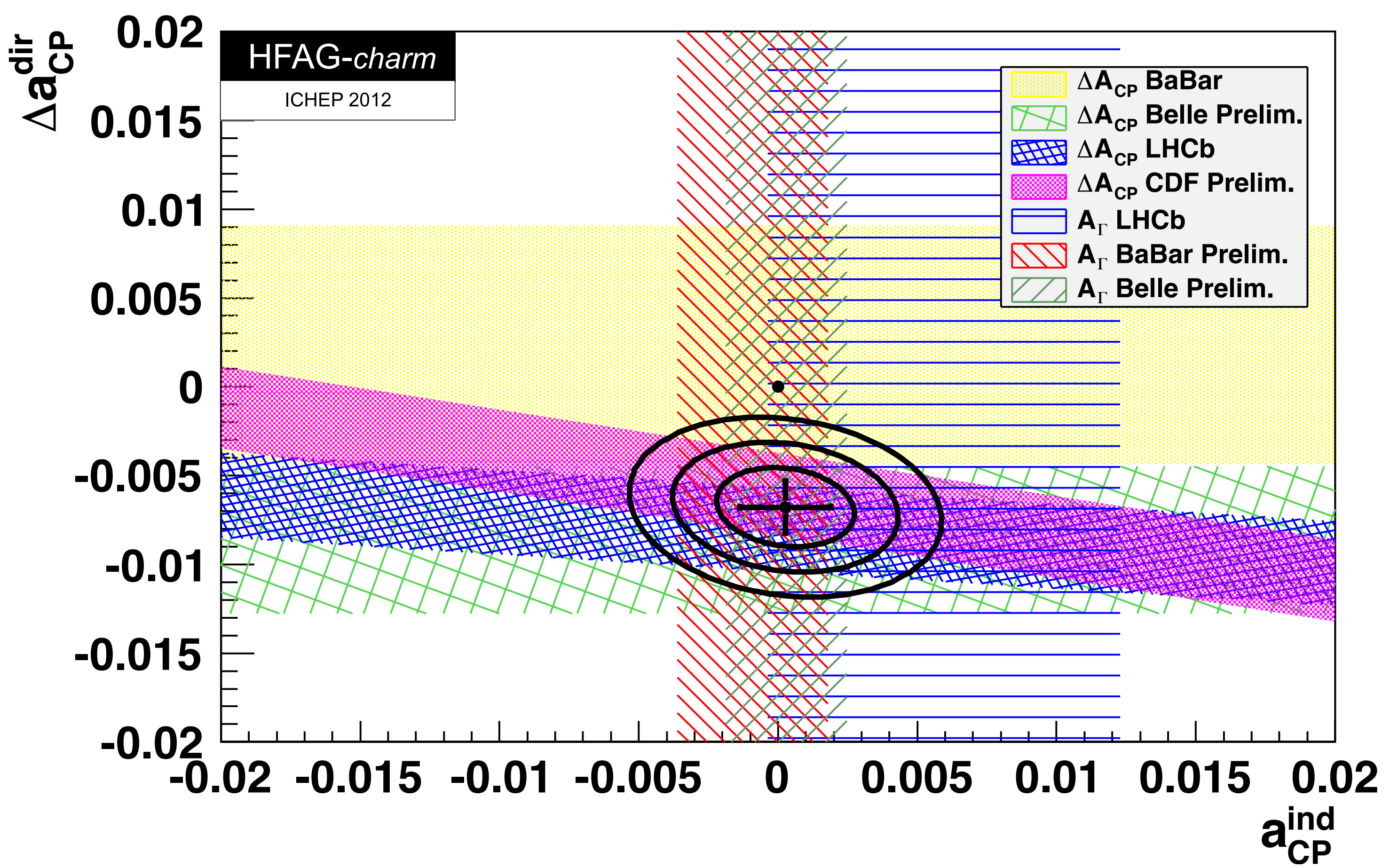
Figure 2: Distributions of the maximal branching ratios in the MSSM$R\!\!\!/$ model for the decay modes $D^+ \to \pi^+ e^+ e^-$ (left) and $D^+ \to \pi^+ \mu^+ \mu^-$ (right). Full line represents the combined LD and SD contributions, and it corresponds to the experimental upper bound $BR(D^+ \to \pi^+ \mu^+ \mu^-) = 8.8 \times 10^{-6}$ on the right plot.

Interpretation

- Is there something there?
- If so, is it SM?
- If not, what could it be?

Is there something there?

- Effect seen by LHCb, CDF, Belle with similar central values and significance between 2 and 3½ σ
- Smells interesting, but we are not yet at discovery level.



CDF: Phys.Rev. D85 (2012) 012009
CDF: Phys.Rev.Lett. 109 (2012) 111801
LHCb: Phys. Rev. Lett. 108 (2012) 111602
Belle preliminary (976/fb)

$$\Delta a_{CP}^{\rm dir} = (-0.678 \pm 0.147)\,\%$$

p-value for no CPV: 0.002%

Is it SM?

- Theory consensus: it can be accommodated.
- Contributions from penguin & tree:

$$A_f = A(D^0 \to f) = A_f^T\, e^{+i\phi_f^T}\, \left[1 + r_f e^{i(\delta_f + \phi_f)}\right]$$

$$\overline{A}_f = A(\overline{D}^0 \to f) = A_f^T\, e^{-i\phi_f^T}\, \left[1 + r_f e^{i(\delta_f - \phi_f)}\right]$$

$$\Rightarrow a_f^{\mathrm{dir}} = 2\, r_f \sin\phi_f \sin\delta_f$$

- Key question: how large can r_f be?

Grossman, Kagan & Nir, PRD 75, 036008 (2007)

ΔA_{CP} in the SM

- Clue: odd pattern of BRs, e.g. $D^0 \to K^+K^- > D^0 \to \pi^+\pi^-$
  [Brod, Grossman, Kagan, Zupan -- JHEP 1210 (2012) 161]

$$\mathcal{B}(D^0 \to \pi^+\pi^-) = (1.401 \pm 0.027) \times 10^{-3}$$
$$\mathcal{B}(D^0 \to K^+K^-) = (3.96 \pm 0.08) \times 10^{-3}$$

PDG

- Single mechanism can explain both effects: unusually large penguin amplitude.
  - Remember $\Delta A_{CP} \sim |A(KK)| + |A(\pi\pi)| \propto r_f$
  - Penguin amplitude appears with opposite sign in BRs:

$$\begin{aligned}
A(\bar{D}^0 \to K^+\pi^-) &= V_{cs}V_{ud}^* T(1 - \tfrac{1}{2}\epsilon'_{1T}),\\
A(\bar{D}^0 \to \pi^+\pi^-) &= -V_{cs}V_{us}^*\left[T(1 + \tfrac{1}{2}\epsilon_{1T}) - P_{\rm break}(1 - \tfrac{1}{2}\epsilon_{sd}^{(2)})\right]\\
&\quad - V_{cb}^* V_{ub}(T/2(1 + \tfrac{1}{2}\epsilon_{1T}) + P(1 - \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to K^+K^-) &= V_{cs}V_{us}^*\left[T(1 - \tfrac{1}{2}\epsilon_{1T}) + P_{\rm break}(1 + \tfrac{1}{2}\epsilon_{sd}^{(2)})\right]\\
&\quad - V_{cb}^* V_{ub}(T/2(1 - \tfrac{1}{2}\epsilon_{1T}) + P(1 + \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to \pi^+K^-) &= V_{cd}V_{us}^* T(1 + \tfrac{1}{2}\epsilon'_{1T}).
\end{aligned}$$

Brod et al, Phys.Rev. D86 (2012) 014023

See also e.g. Bhattacharya et al, Phys. Rev. D 85, 054014
Feldmann et al, JHEP 1206 (2012) 007

ΔA_{CP} beyond the SM

- But still room for NP here:
  - SM estimates rather uncertain
  - We haven't explained WHY the penguin amplitudes are large
- Suppose that effect is real and that SM doesn't saturate it. What else could contribute?
- Generically, can look at which operators would give the right enhancement without violating flavour bounds:

$$\mathcal{H}^{\text{eff}-\text{NP}}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_i C_i^{\text{NP}} Q_i + \text{h.c.}$$

Allowed	Ajar	Disfavored
$Q_{7,8}\,,\ Q'_{7,8}\,,$	$Q_{1,2}^{(c-u,8d,b,0)}\,,$	$Q_{1,2}^{s-d}\,,\ C_{5,6}^{(s-d)\prime}\,,$
$\forall f\ Q_{1,2}^{f\prime}\,,\ Q_{5,6}^{(c-u,b)\prime}$	$Q_{5,6}^{(0)}\,,\ Q_{5,6}^{(8d)\prime}$	$C_{5,6}^{s-d,c-u,8d,b}$

Table III: List of $|\Delta c| = 1$ operators grouped according to whether they can contribute to Δa_{CP} at a level comparable to the central value of the measurement, given the constrains from $D - \bar{D}$ mixing and ϵ'/ϵ.

Dipole operators -- esp. chromo-magnetic dipole -- good candidates.

Isidori, Kamenik, Ligeti, Perez (arXiv:1111.4987)

ΔA_{CP} beyond the SM

- Many papers looking at implications for particular models
  - Too many to go through here! See slides by Kamenik at CKM 2012, and the references therein
- For example, very thorough discussion on SUSY by Giudice, Isidori & Paradisi in JHEP 04 (2012) 060
  - Requires large left-right squark mixing
  - Implications for flavour structure in SUSY models (e.g. consistent with split families)

What next?

- More to do on both experimental & theoretical sides.
- This measurement: 0.6/fb.
  - From 2011: 1/fb on tape -- now reprocessed.
  - Expect total of O(2/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
- Pin down mixing parameters x, y

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

$38\ pb^{-1}$

JHEP 04 (2012) 129
arXiv:1112.4698

Recap

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

$D^0 \rightarrow K^- \pi^+$: 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:

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

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

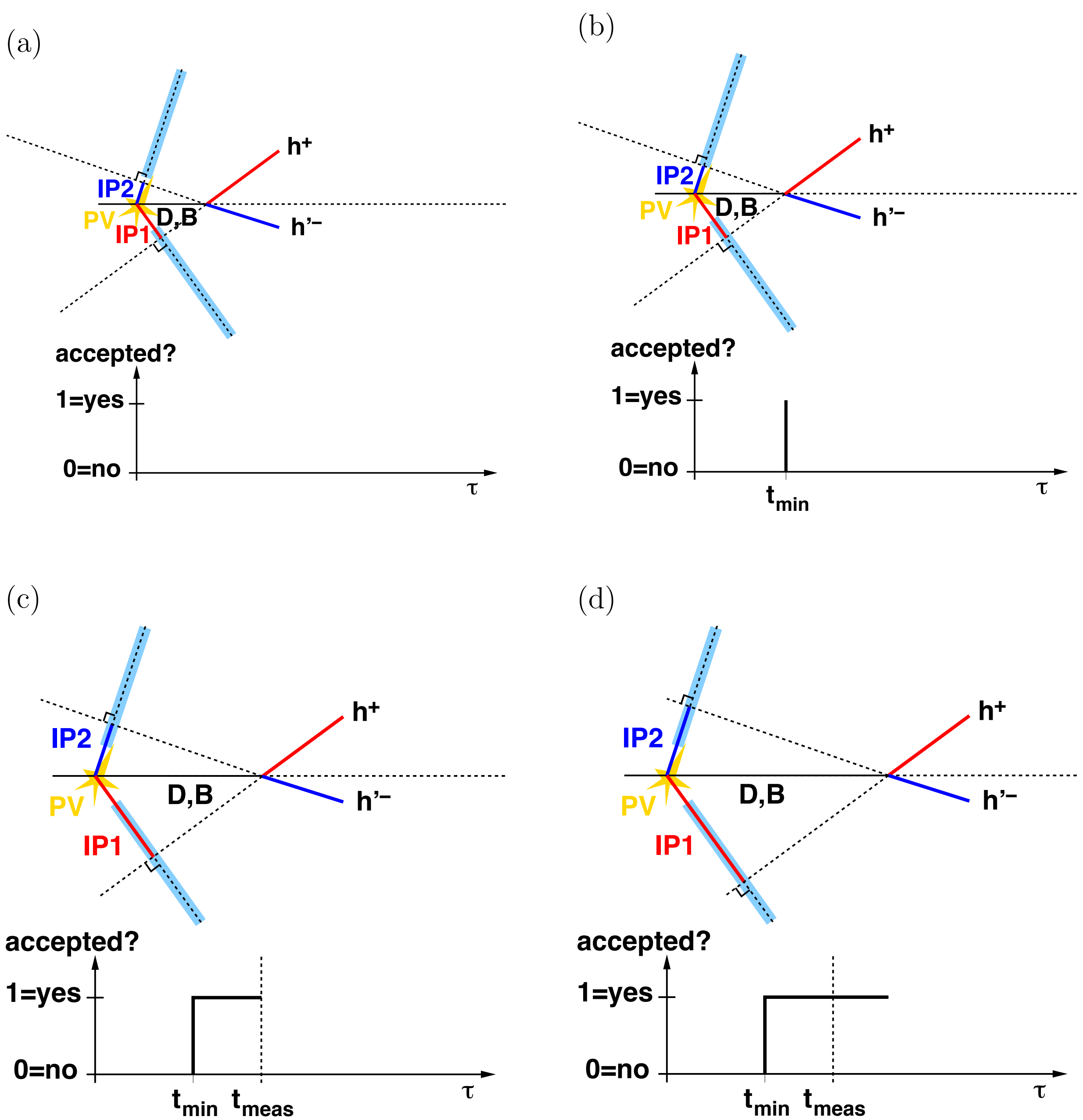
(neglecting direct CPV)

Measuring y_{CP} and A_Γ at LHCb

- Two key challenges at a hadronic machine like LHCb
  - Background from secondary charm ($b \to c$ 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.



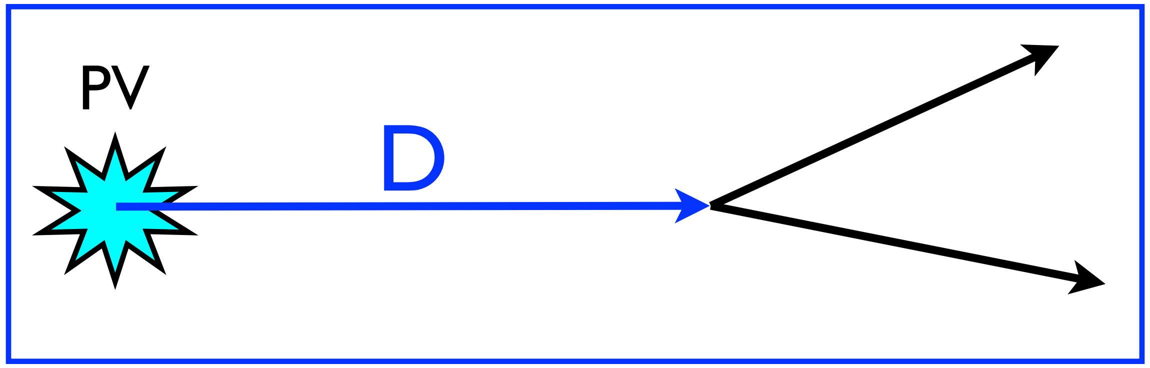
Trying to measure how acceptance varies with lifetime candidate-by-candidate.

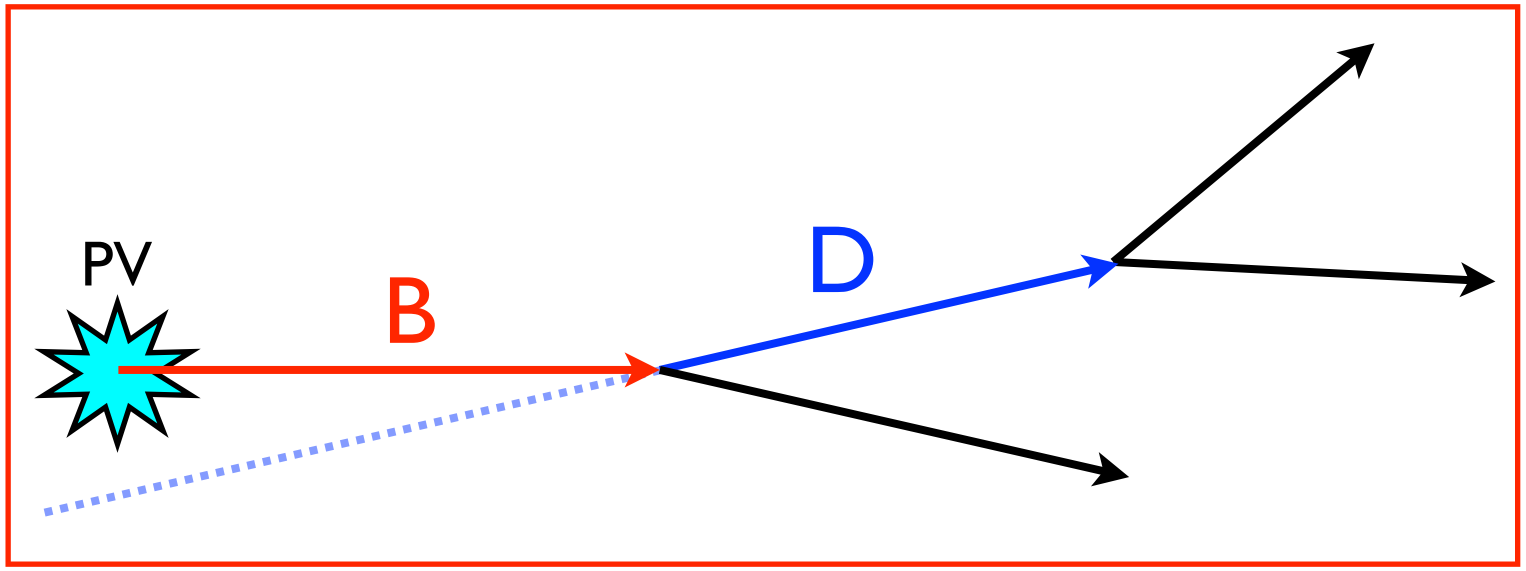
... so that we can pull it directly from the data instead of having to model it on signal MC.

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)

Prompt-secondary discrimination





Prompt charm:

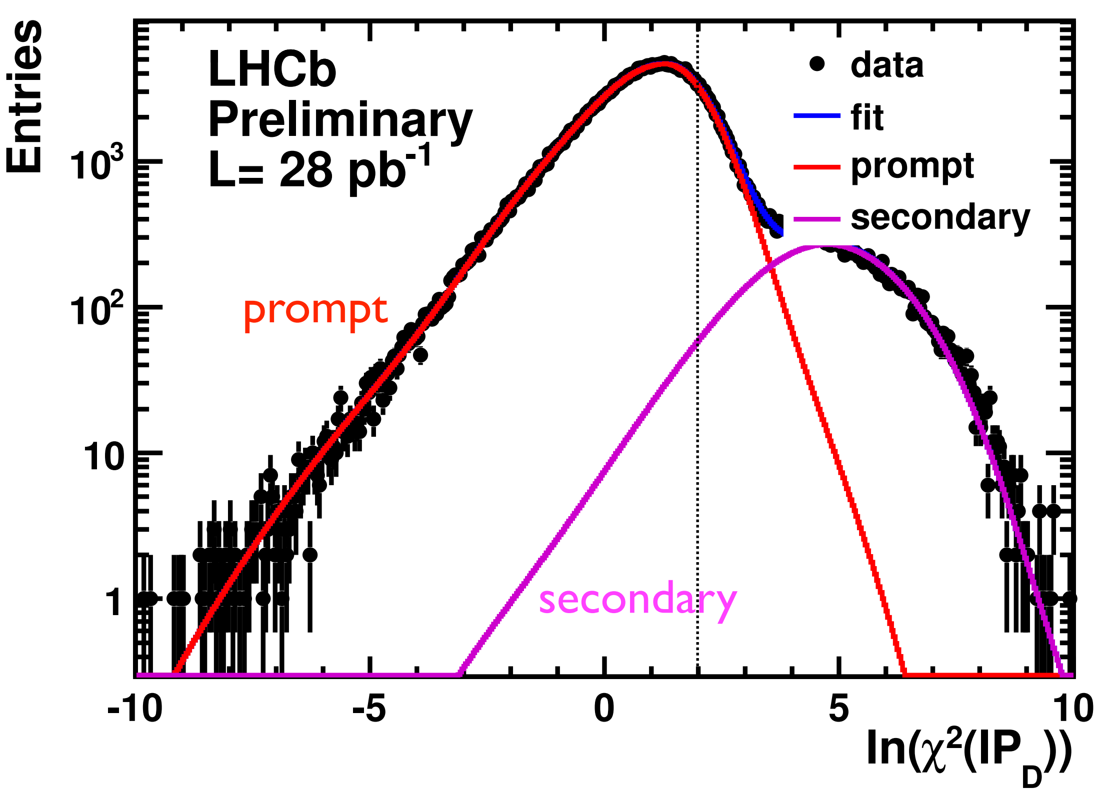
D points to primary vertex

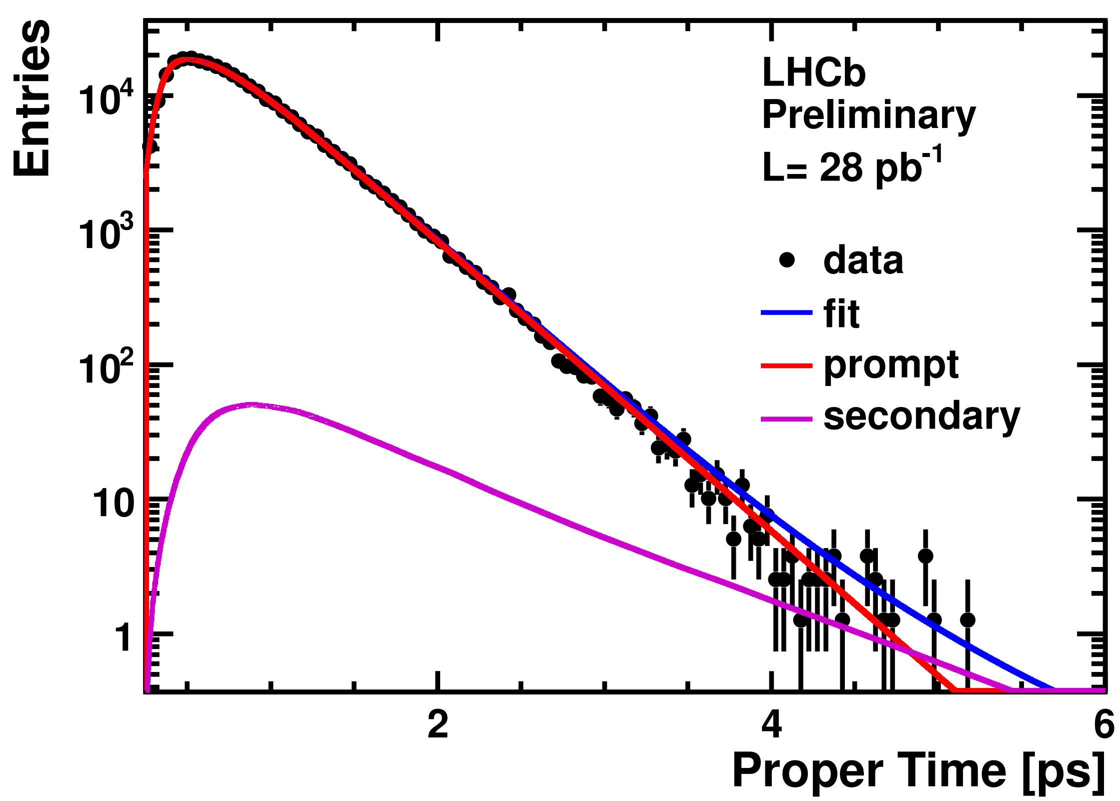
Daughters of D don't in general

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 IPX^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.

Effect	A_Γ (10^{-3})	y_{CP} (10^{-3})
Decay-time acceptance correction	0.1	0.1
Decay-time resolution	0.1	0.1
Minimum decay-time cut	0.1	0.8
Maximum decay-time cut	0.2	0.2
Combinatorial background	1.3	0.8
Secondary-like background	1.6	3.9
Total	2.1	4.1

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HFAG world avg: $y_{CP} = (1.064 \pm 0.209)\%$

LHCb

Indirect CPV: A_Γ in 2010 data

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

$$\approx \left(\frac{A_m}{2} y \cos\phi - x \sin\phi\right) \frac{1}{1 + y_{CP}}$$

$$\approx \frac{A_m}{2} y \cos\phi - x \sin\phi.$$

- $A_\Gamma = (-5.9 \pm 5.9 \pm 2.1) \times 10^{-3}$
- 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.

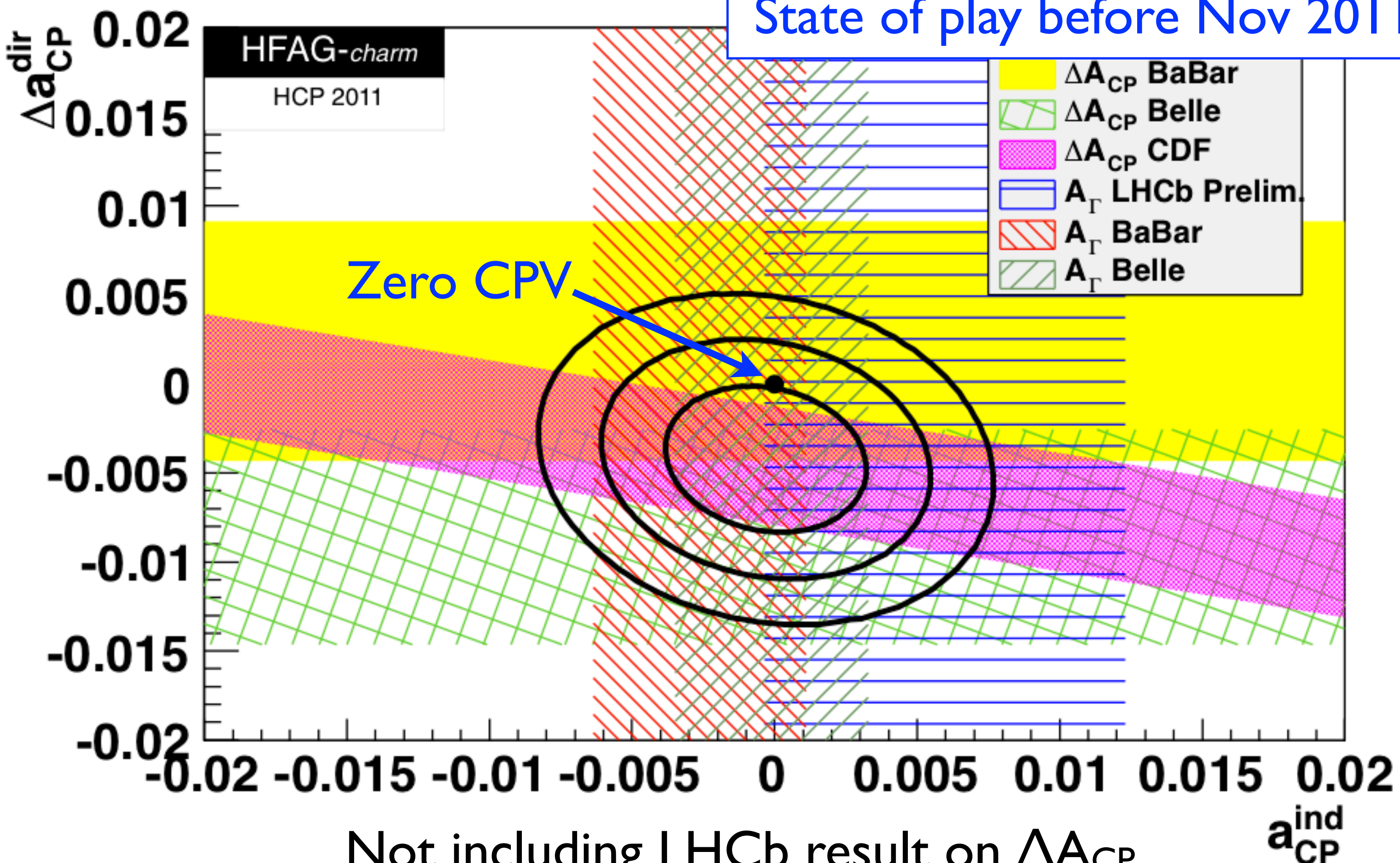
Effect	A_Γ (10^{-3})
Decay-time acceptance correction	0.1
Decay-time resolution	0.1
Minimum decay-time cut	0.1
Maximum decay-time cut	0.2
Combinatorial background	1.3
Secondary-like background	1.6
Total	2.1

HFAG world avg: $A_\Gamma = (0.026 \pm 0.231)\%$

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: $A^{ind}[\langle t_{KK}\rangle - \langle t_{\pi\pi}\rangle]/\tau_0$

State of play before Nov 2011



Not including LHCb result on ΔA_{CP}

Consistency with no CPV hypothesis: 28%

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

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

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)

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(%).

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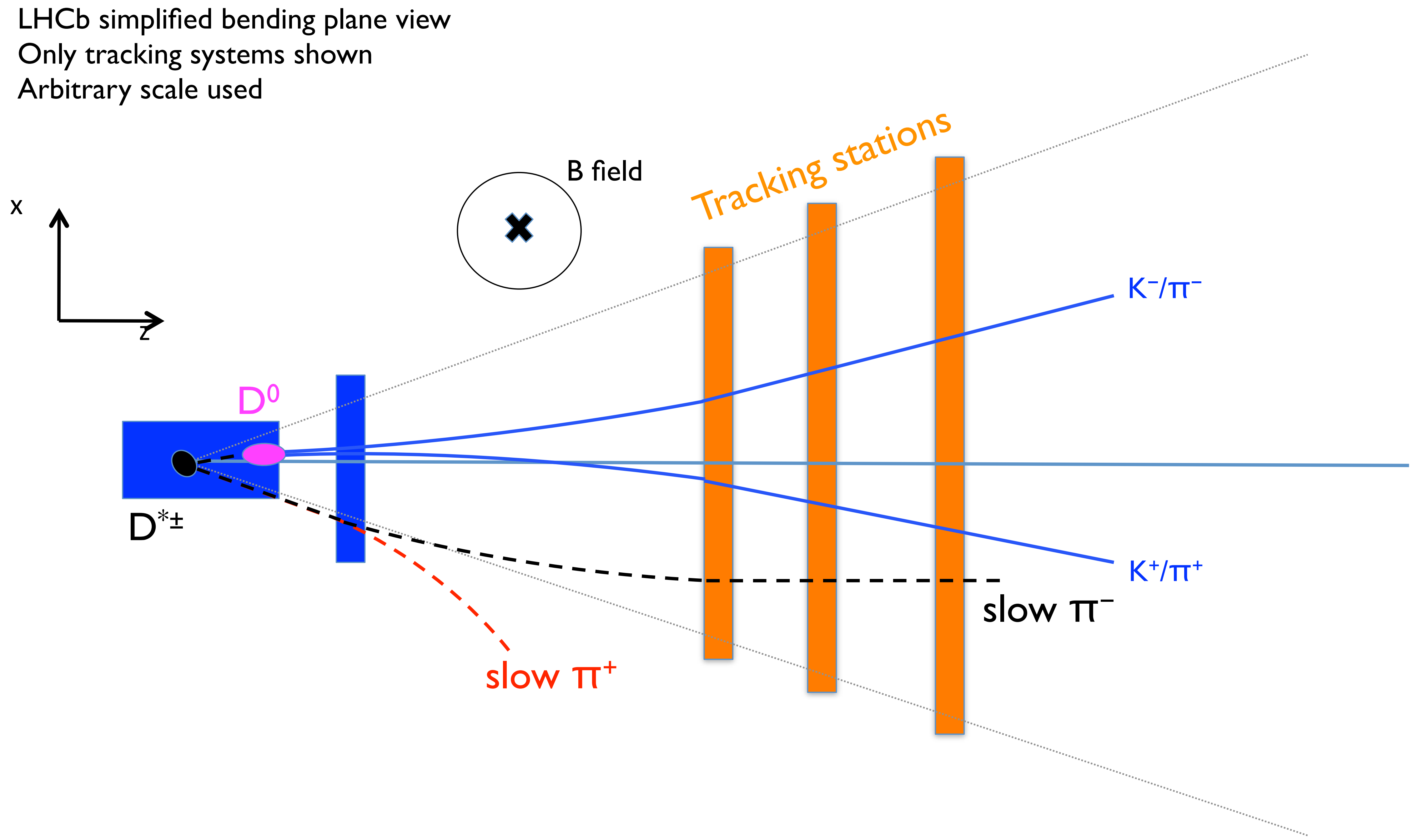
LHCb

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



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

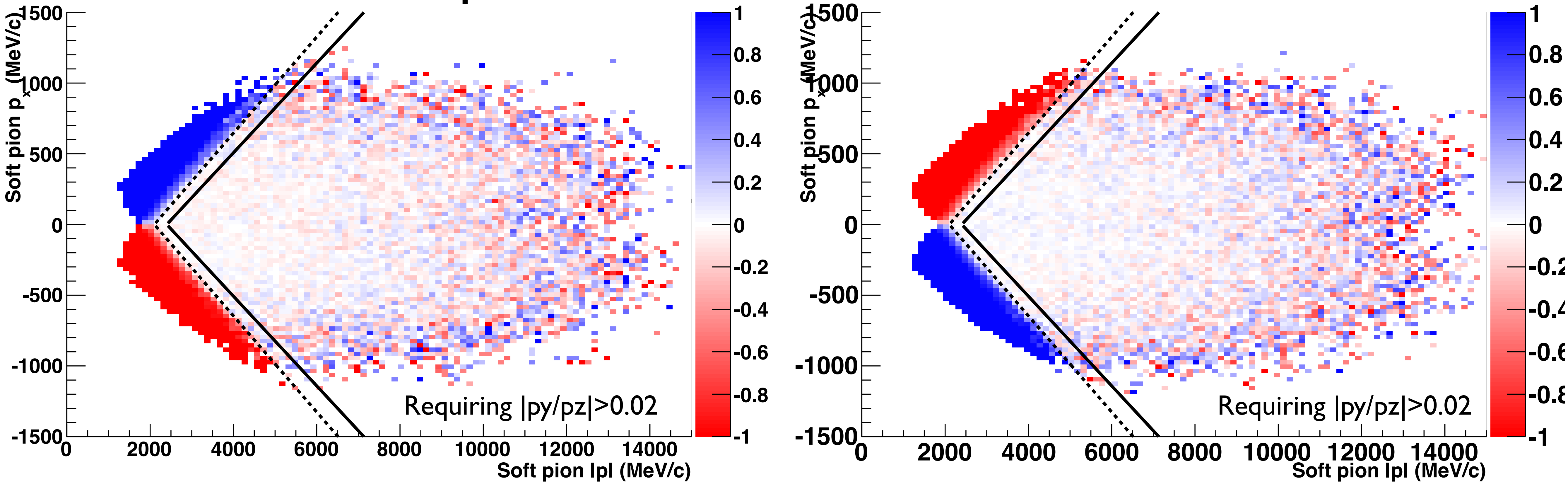
Fiducial cuts

- ∃ 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:

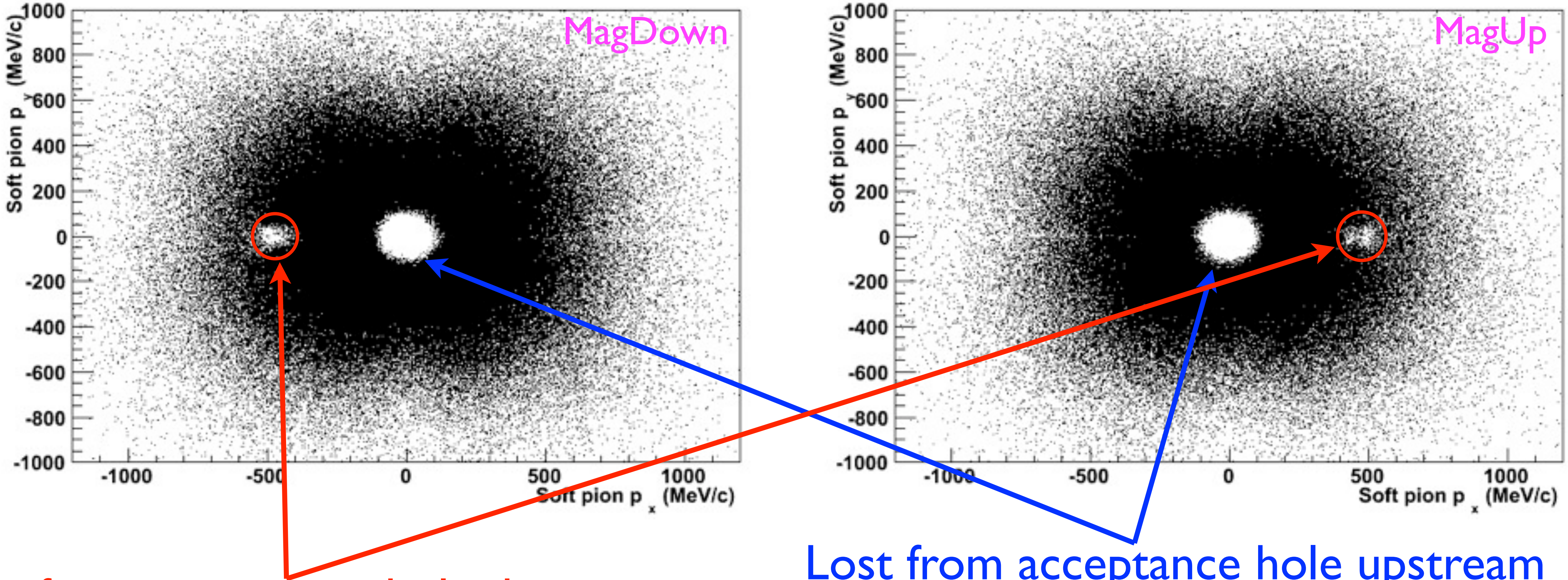
B-field up B-field down



- 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

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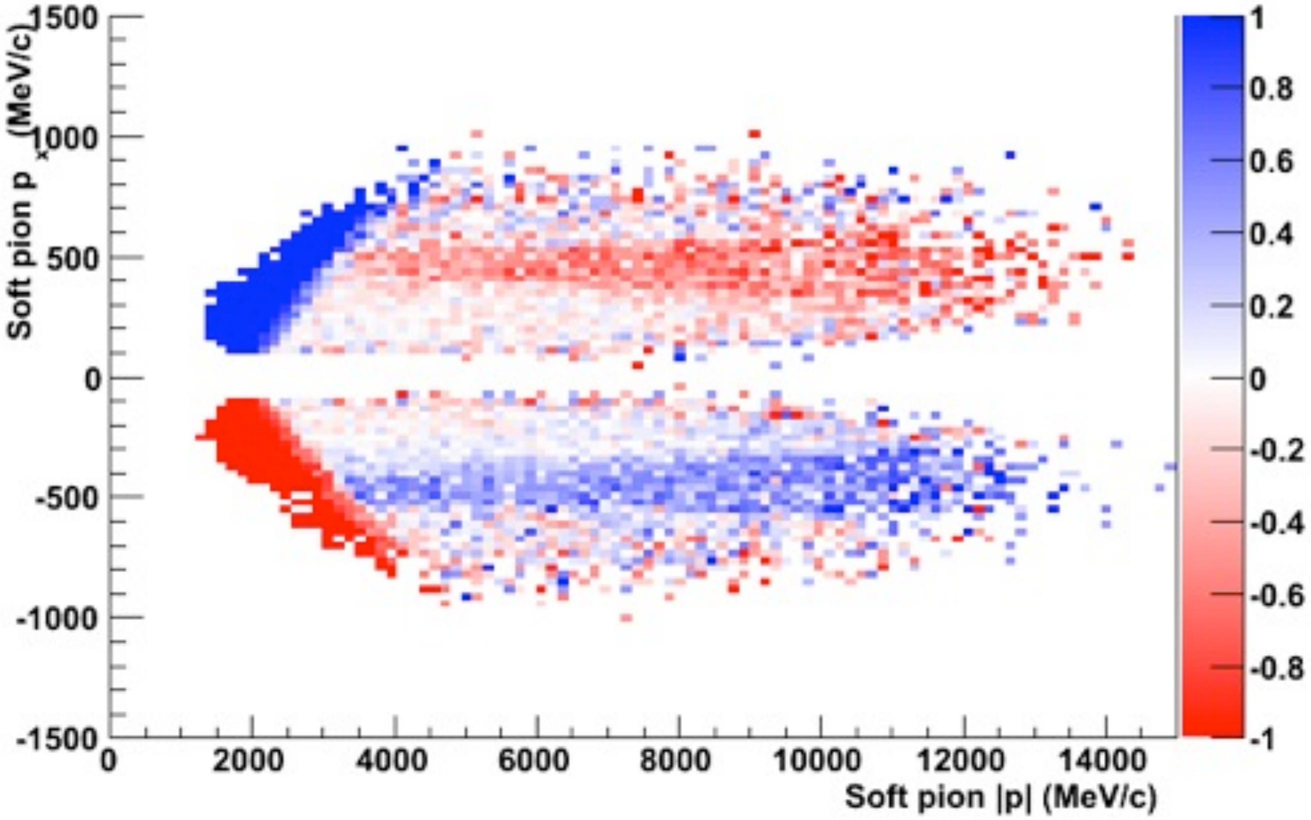
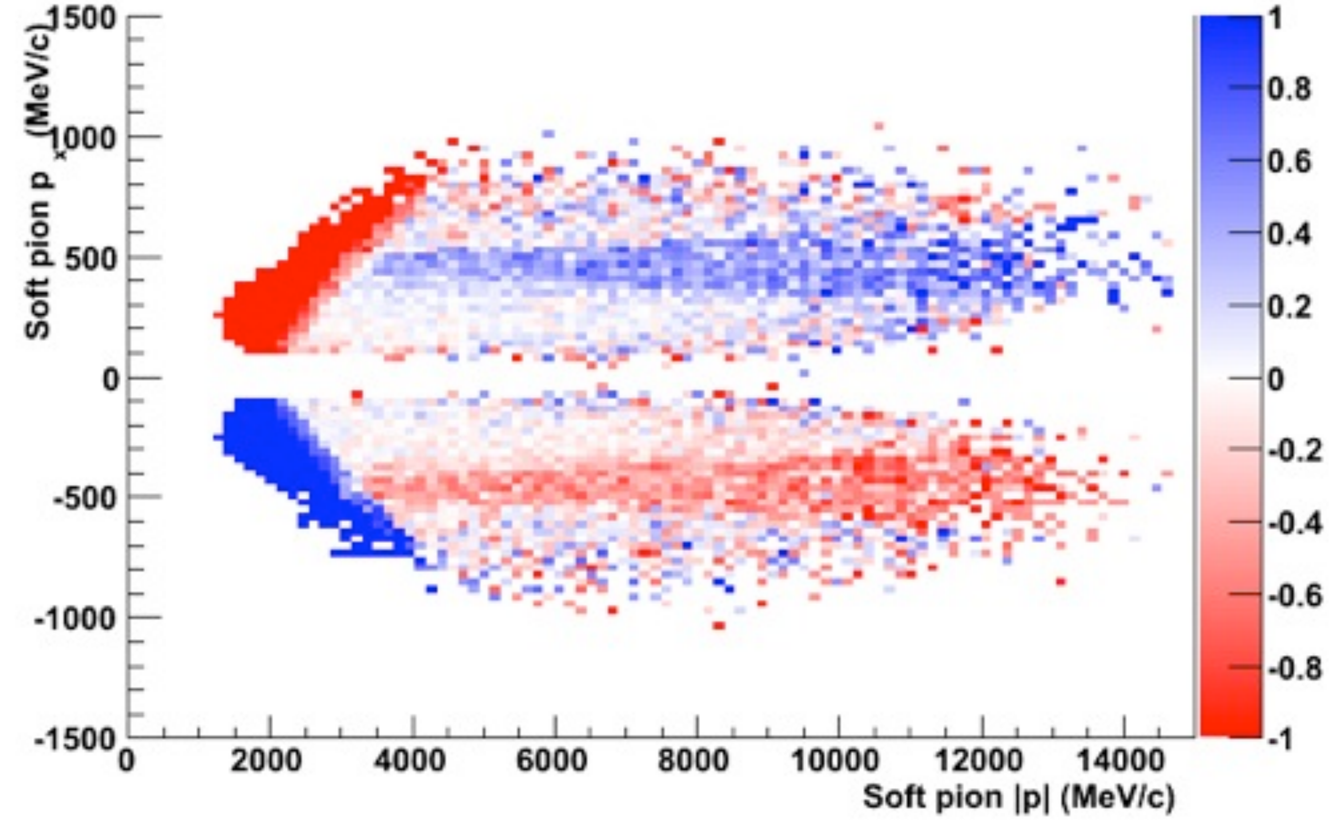
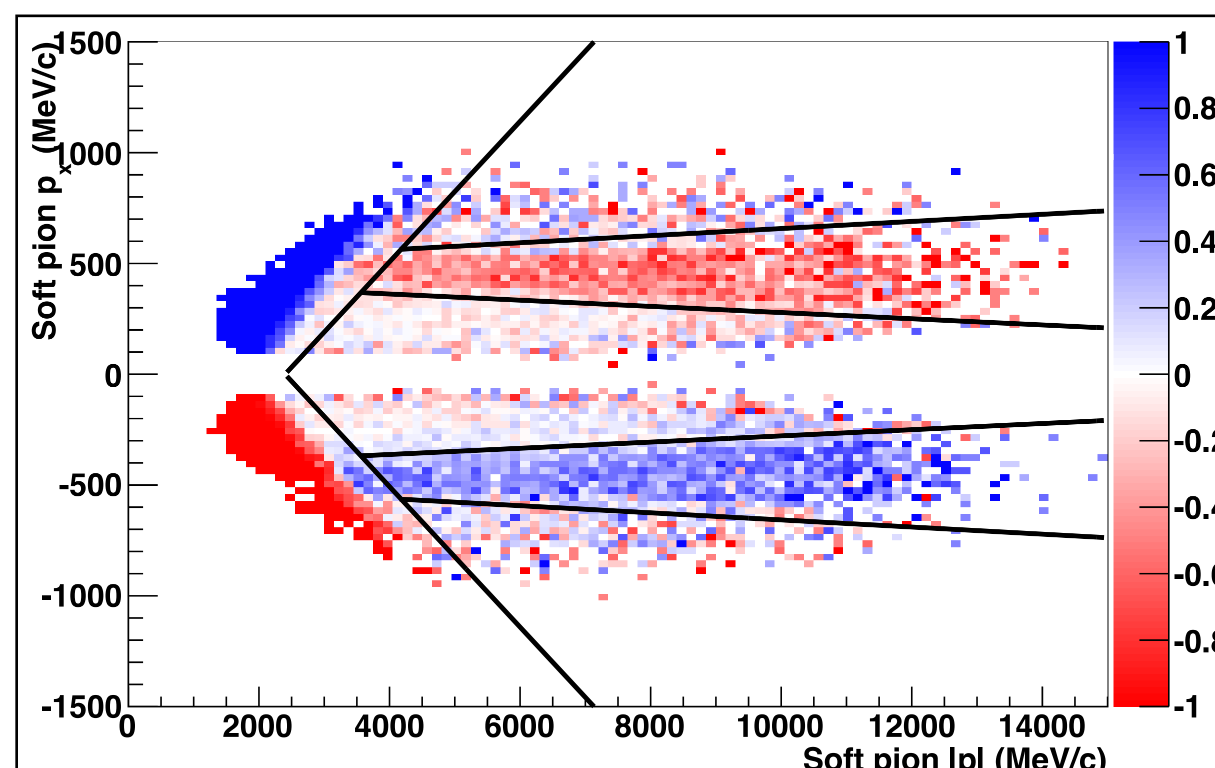
Fiducial cuts: downstream beampipe

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 $|p_y/p_z|<0.02$



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:

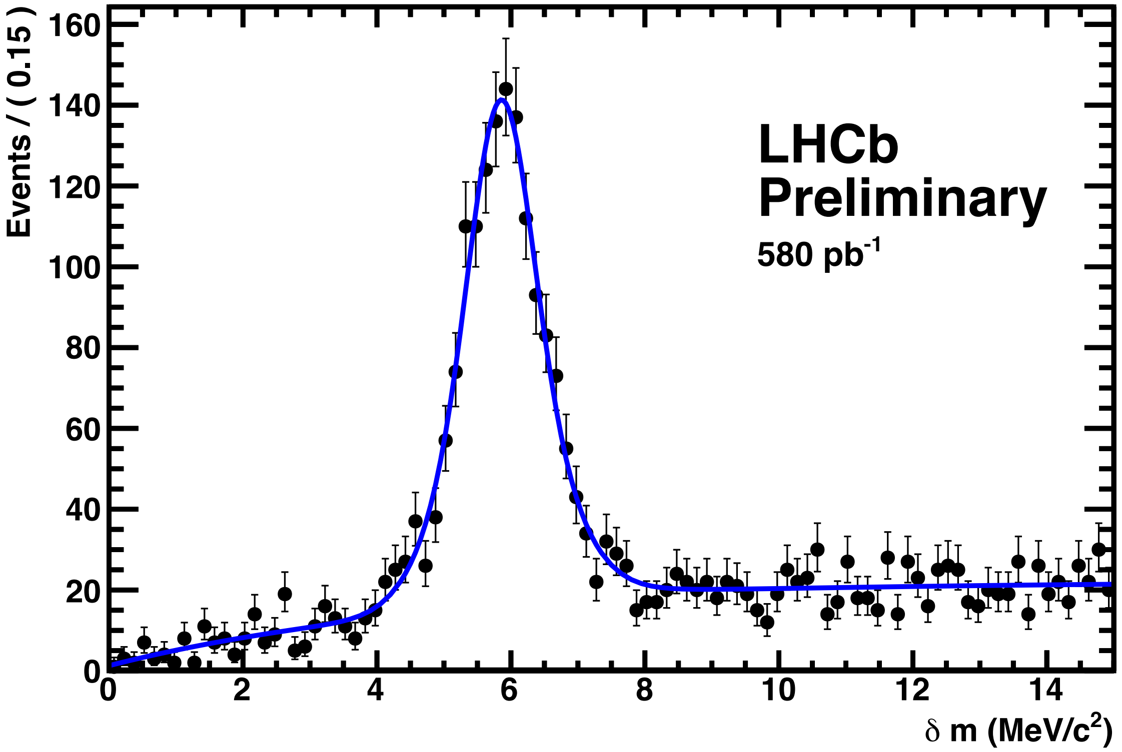
$$g(\delta m) = [\Theta(\delta m' - \mu)\, A(\delta m' - \mu)^s] \otimes G_2(\delta m - \delta m'; f_{\rm core}, \sigma_{\rm core}, \sigma_{\rm tail})$$

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

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

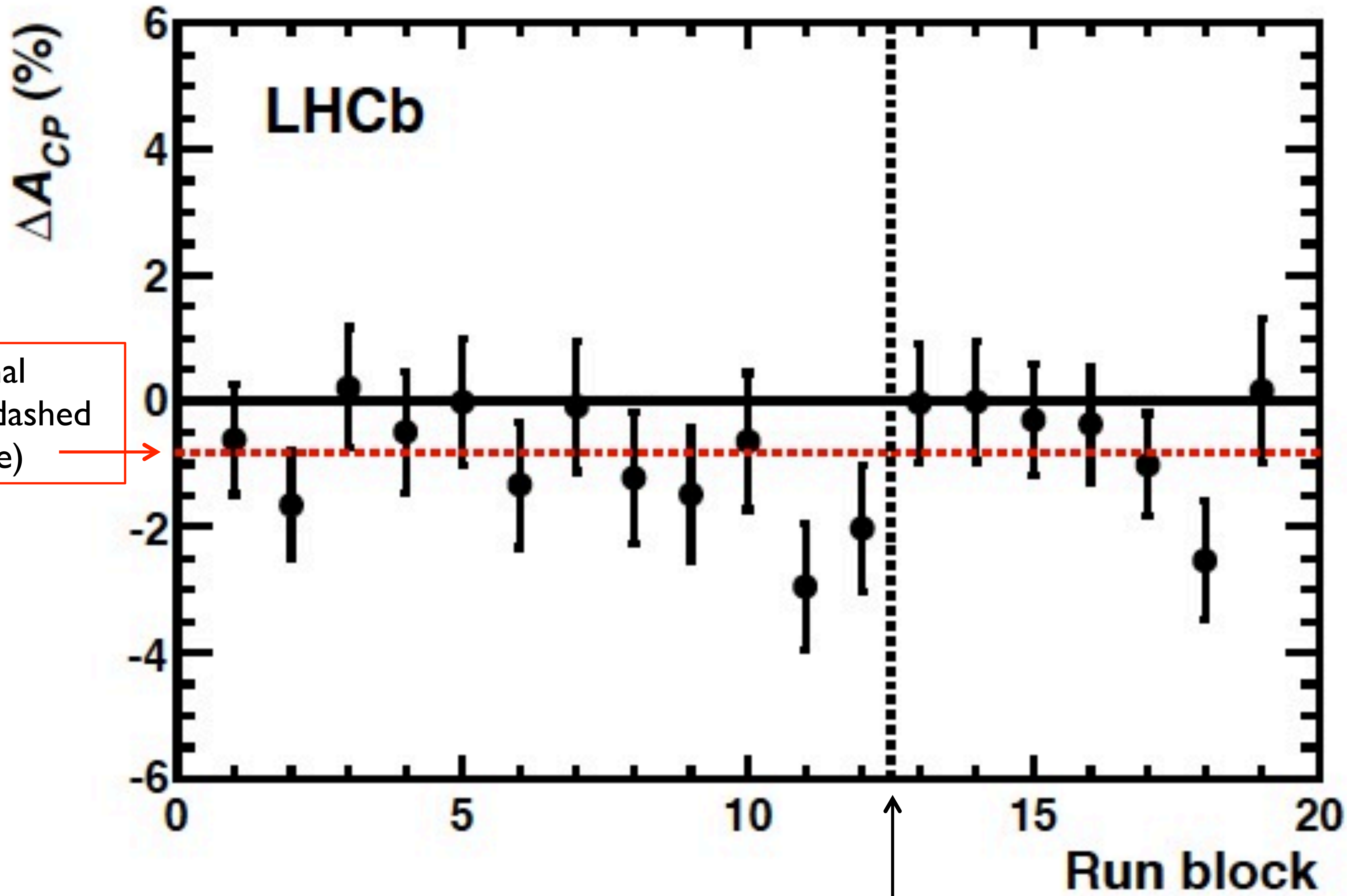
Systematic uncertainties

- 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 ππ 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%

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.

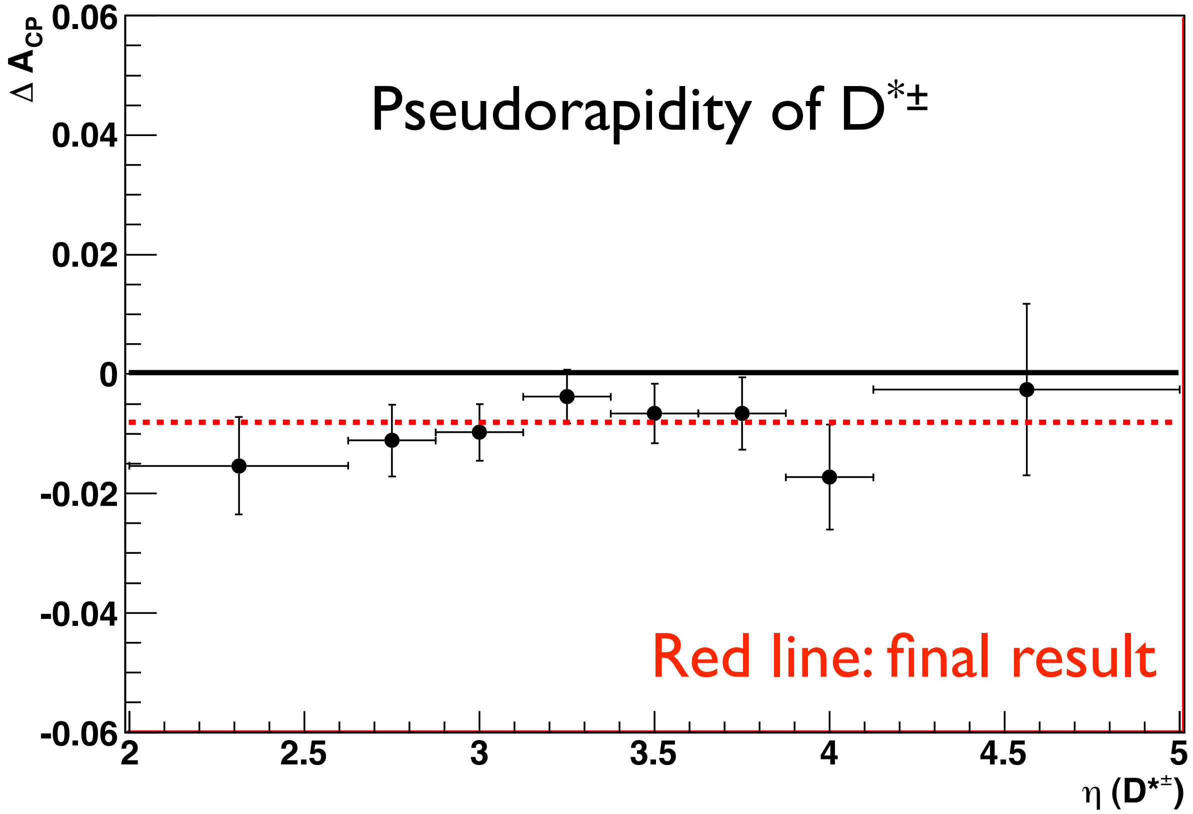
Stability vs time

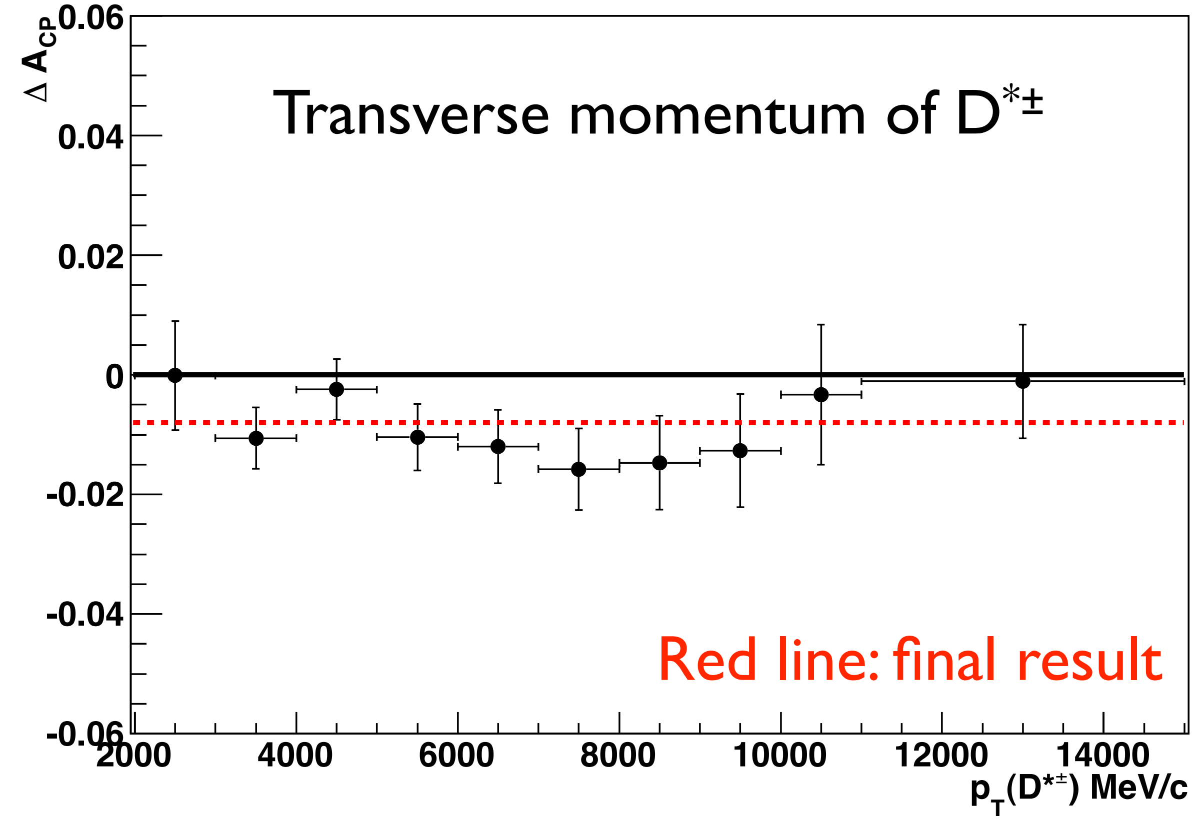


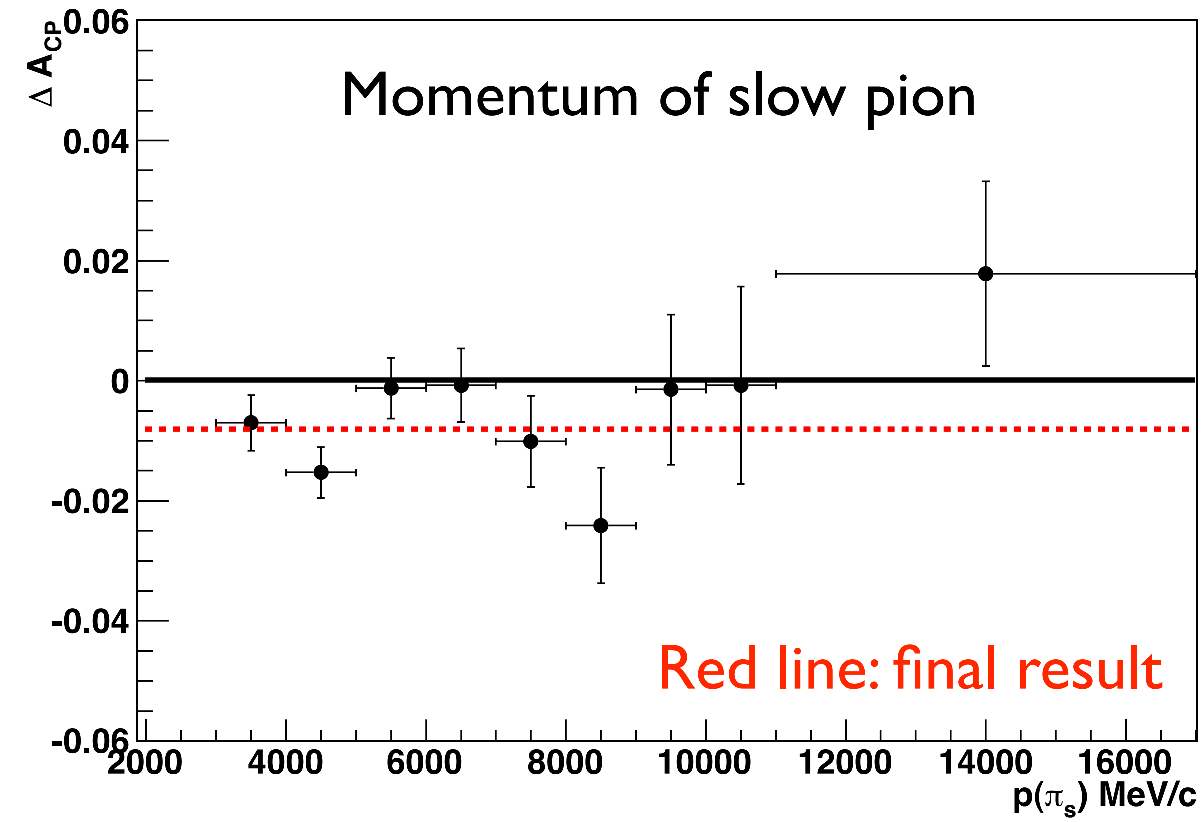
Final result(dashed line)

Before and after a technical stop

Stability with kinematic variables







- No evidence of dependence on relevant kinematic variables.

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:

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

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) →

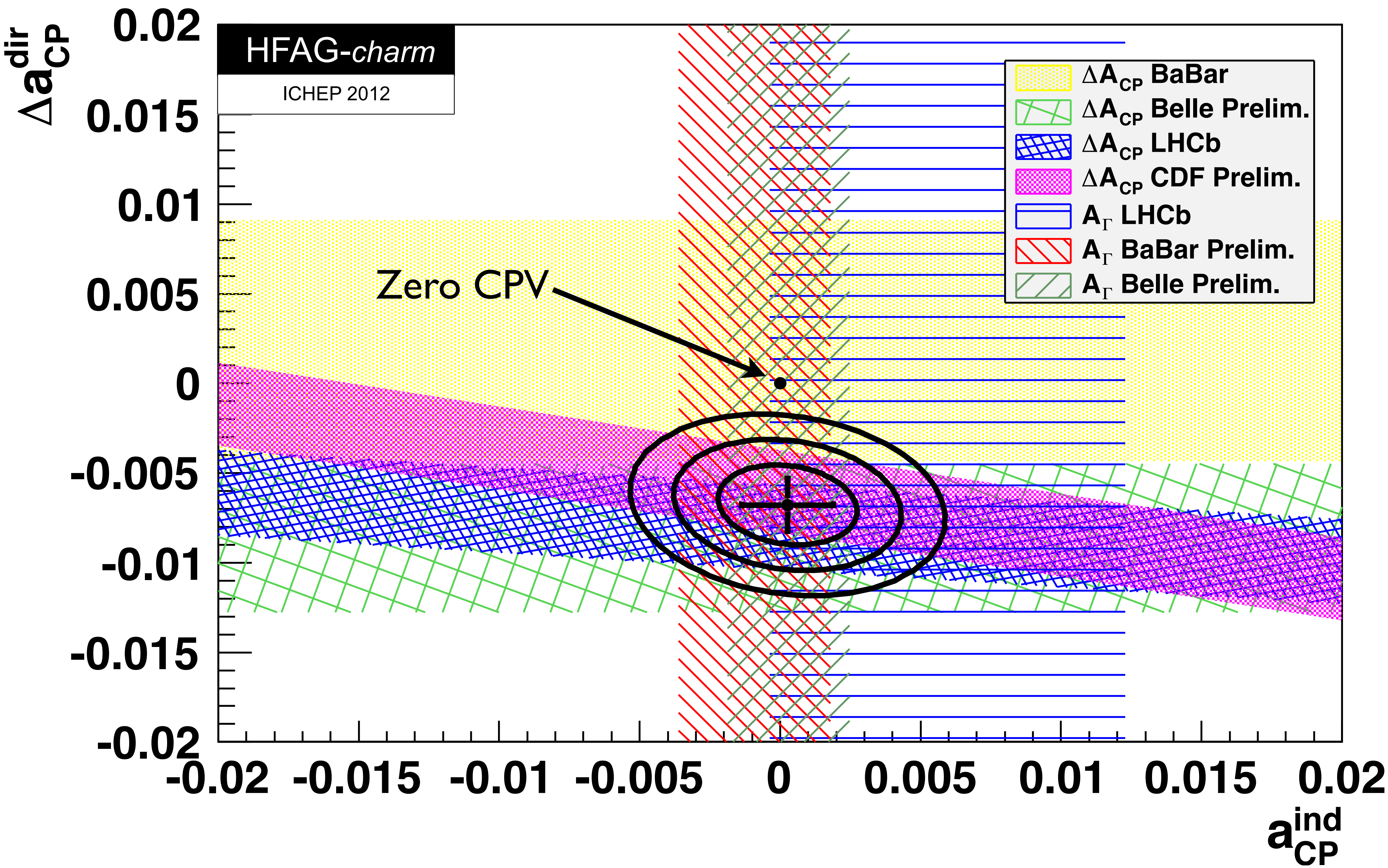
$$a_{CP}^{\text{ind}} = (-0.03 \pm 0.23)\%$$
$$\Delta a_{CP}^{\text{dir}} = (-0.42 \pm 0.27)\%$$

Current world average

Including recent results:

Belle (prelim.) $\Delta A_{CP} = (-0.87 \pm 0.41 \pm 0.06)\%$

CDF $\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$ Phys.Rev.Lett. 109 (2012) 111801



$a_{CP}^{\rm ind} = (+0.027 \pm 0.163)\%$

$\Delta a_{CP}^{\rm dir} = (-0.678 \pm 0.147)\%$

Consistency with no CPV: 0.002%

$D^0 \to \mu\mu$

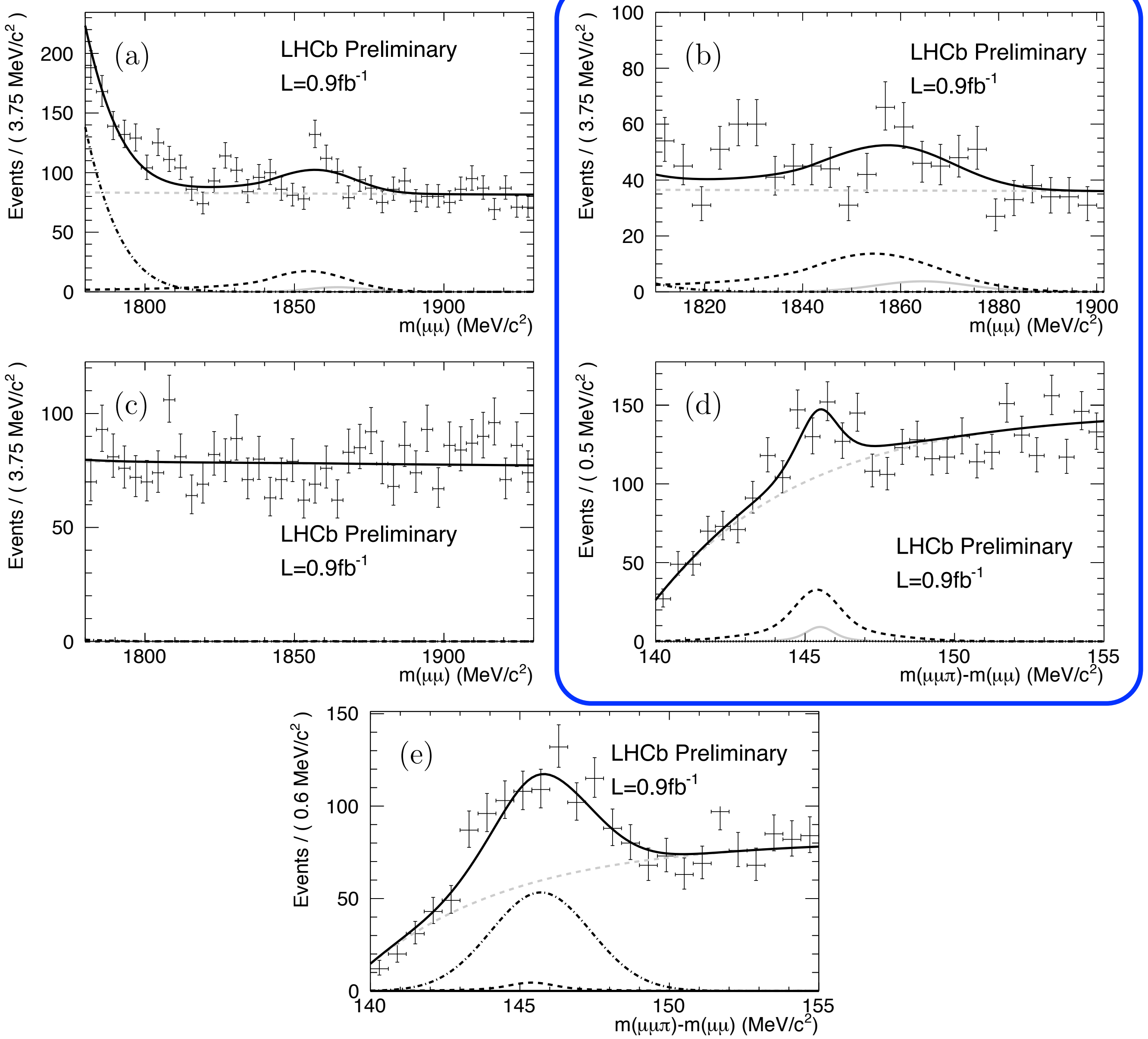
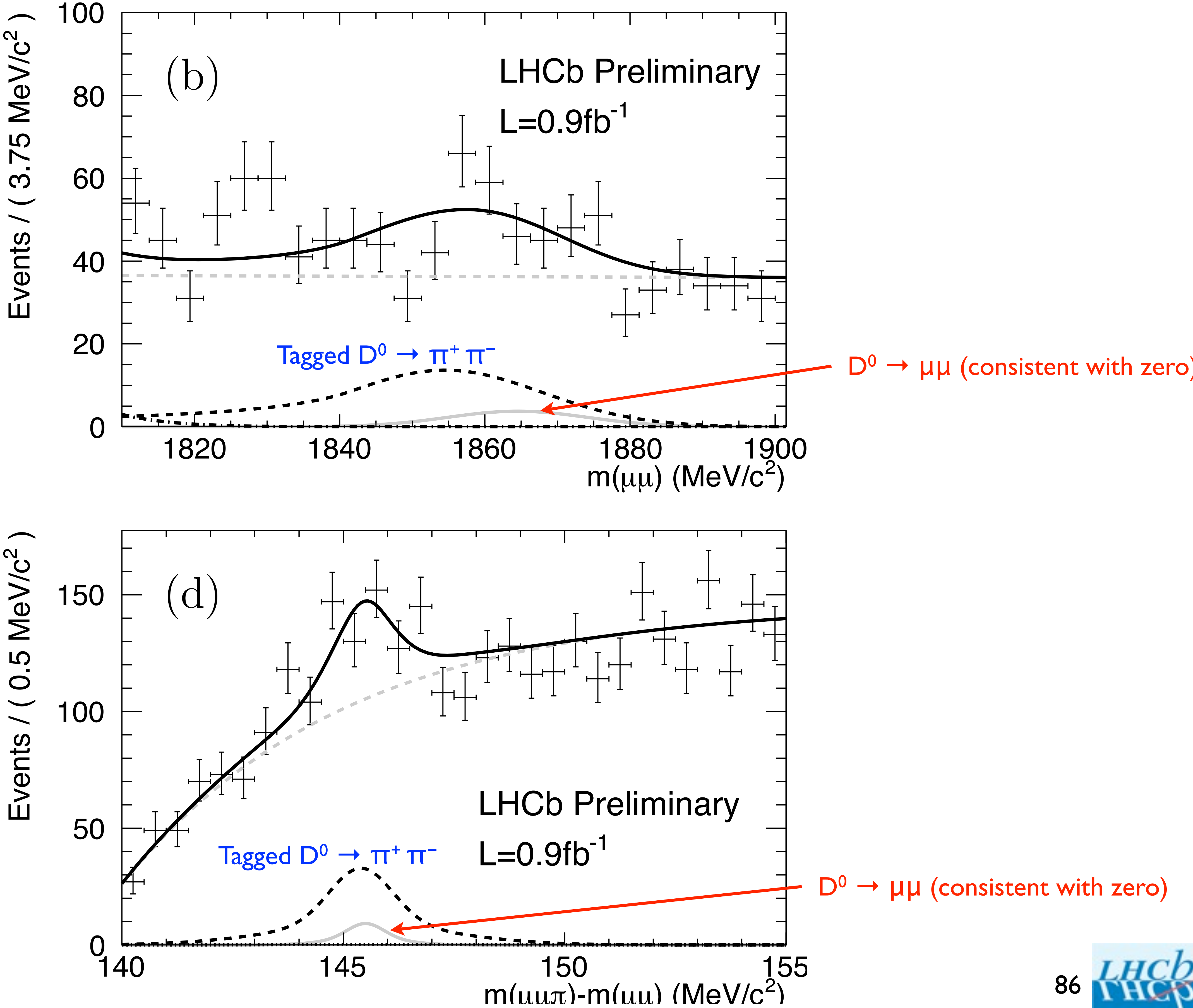


Figure 8: Distribution of (a) the $\mu\mu$ invariant masses with Δm in the range 142-149 MeV/c^2, (b) in the range 144-147 MeV/c^2 and (c) in the range 150-155 MeV/c^2. In (d) the distribution of Δm in the range 1820-1885 MeV/c^2 and in (e) in the range 1780-1810 MeV/c^2 of the $\mu\mu$ invariant mass is shown. Superimposed are the projections of the two-dimensional unbinned maximum likelihood fit. The curves represent the full fit function (continuous black line), the $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+$contribution (dashed dark grey line), the combinatorial background (dashed light grey line), the $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$contribution (dotted line) and the signal $D^{*+} \to D^0(\to \mu^+\mu^-)\pi^+$contribution (continuous light grey line).

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < \begin{cases} 1.3 \times 10^{-8} \text{at } 95\% \text{ C.L.} \\ 1.1 \times 10^{-8} \text{at } 90\% \text{ C.L.} \end{cases}$$

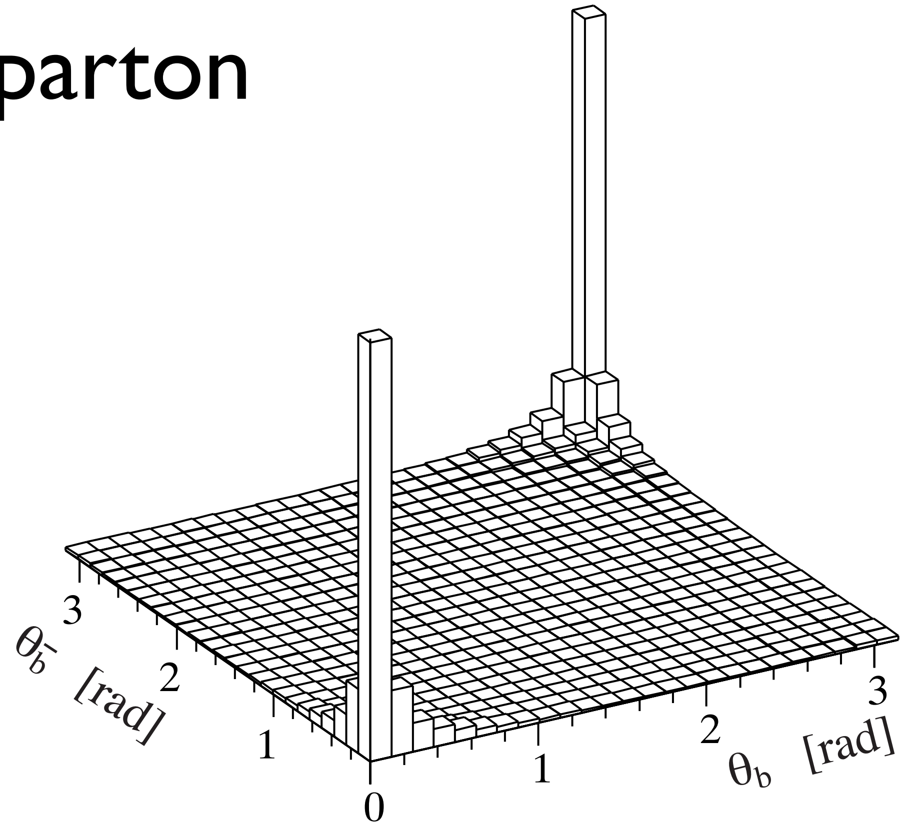
$D^0 \to \mu\mu$

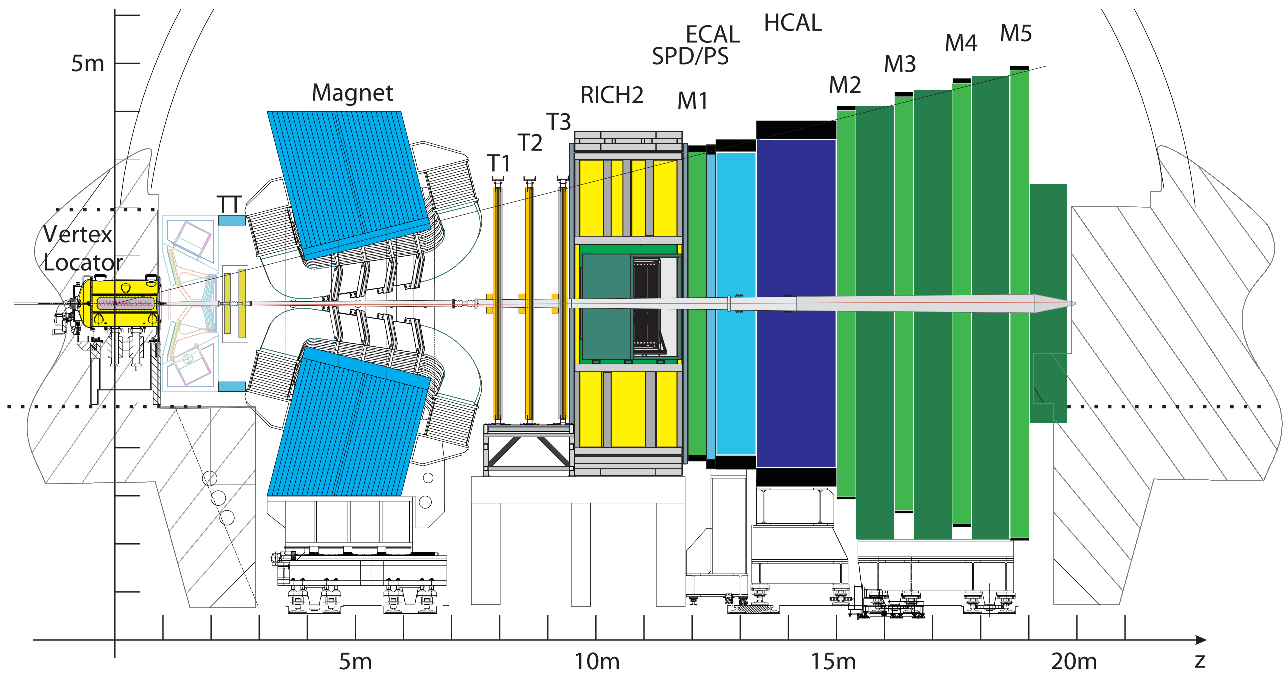
LHCb-CONF-2012-005

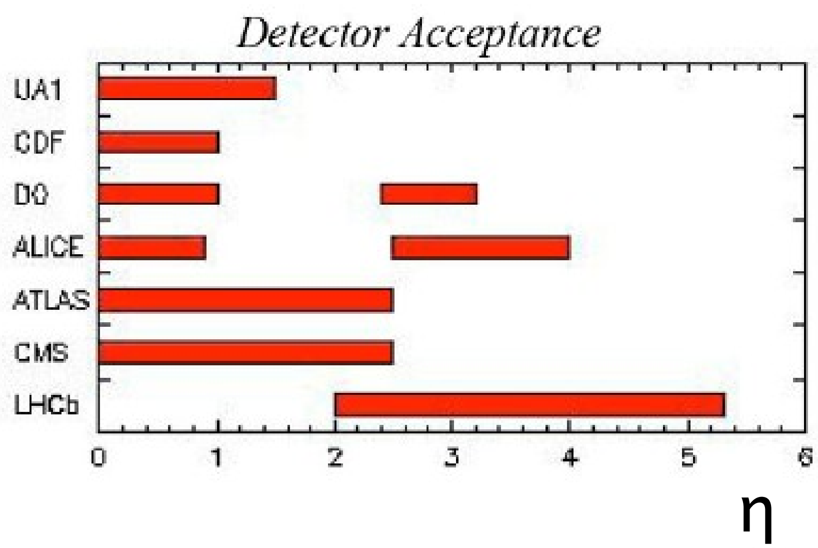


Heavy flavour production at the LHC

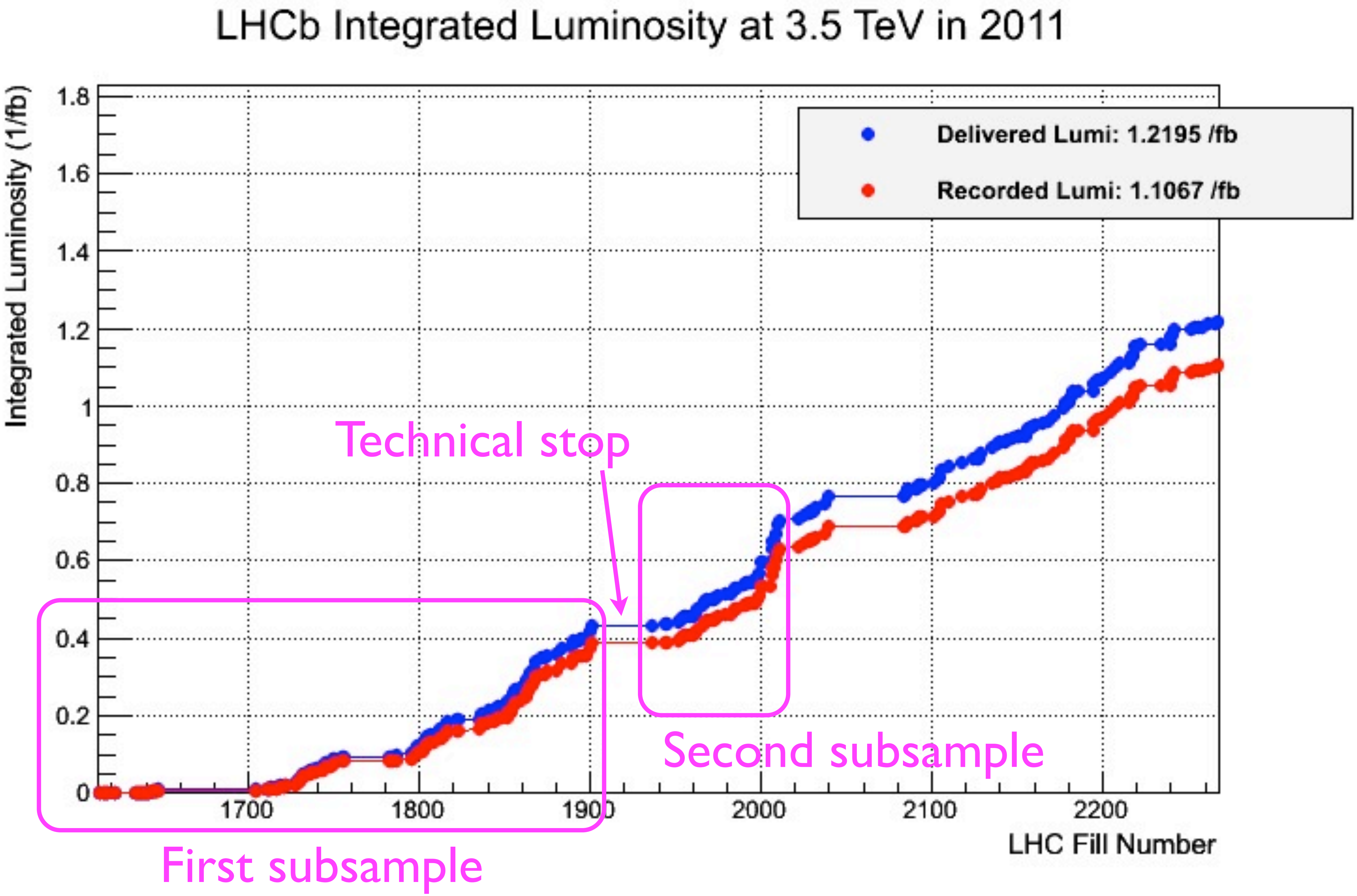
- b and c are light compared to $\sqrt{s}$ = 7 TeV
- Dominant production: one hard + one soft parton
- Therefore $q\bar{q}$ produced with large boost in far forward (or far backward) region
- This drives the LHCb layout: we instrument just the forward region
  - Instrumenting backward region would have increased statistical power by $\sqrt{2}$ but cost by $\gg 2$







Integrated luminosity



Showing online luminosity (not final calibration)

Can the SM stretch?

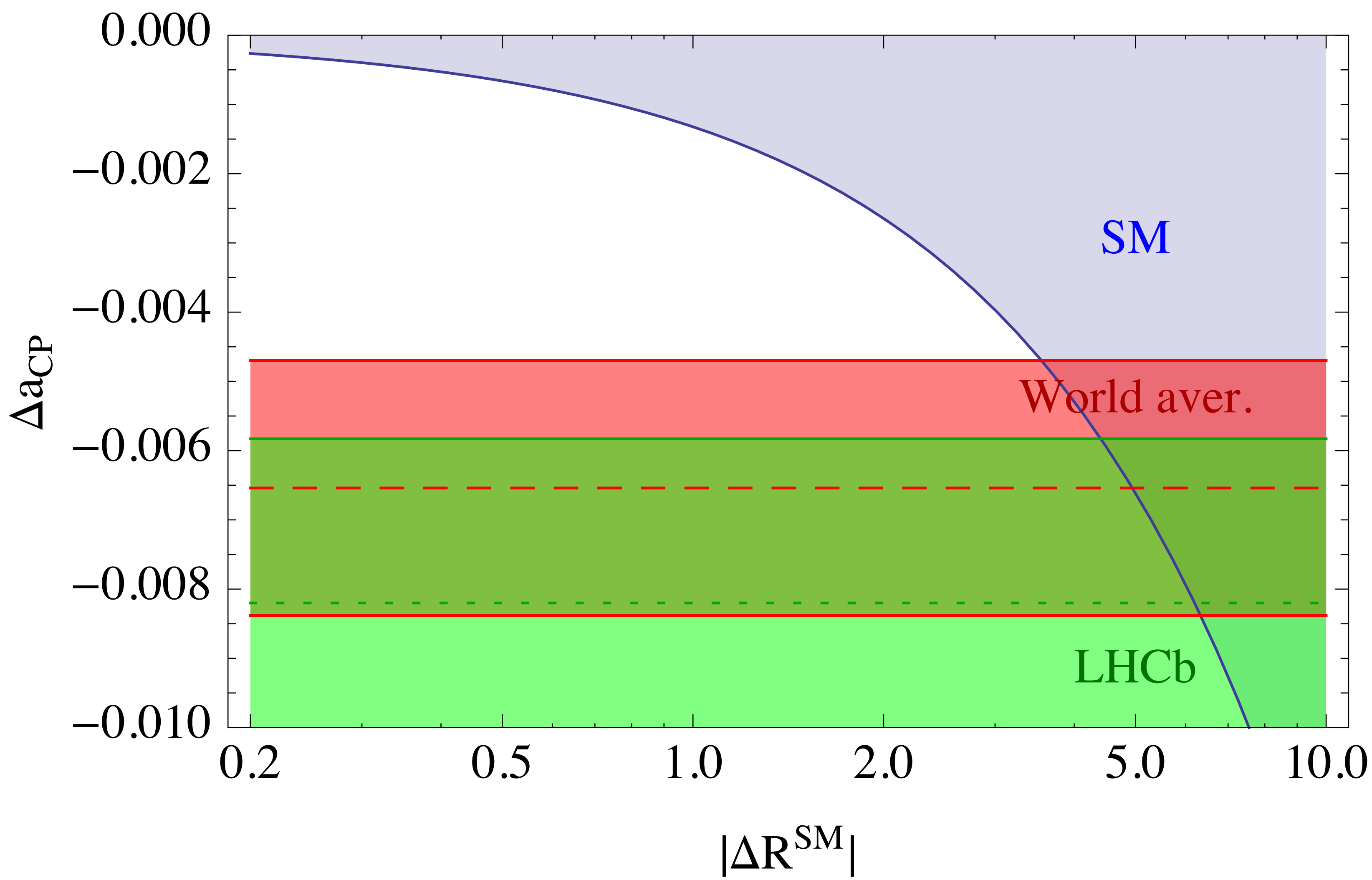


Figure 1: Comparison of the experimental Δa_{CP} values with the SM reach as a function of $|\Delta R^{\rm SM}|$.

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

arXiv:1111.4987v1 (Isidori, Kamenik, Ligeti, Perez)

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

Three contributions with different lifetime dependence:

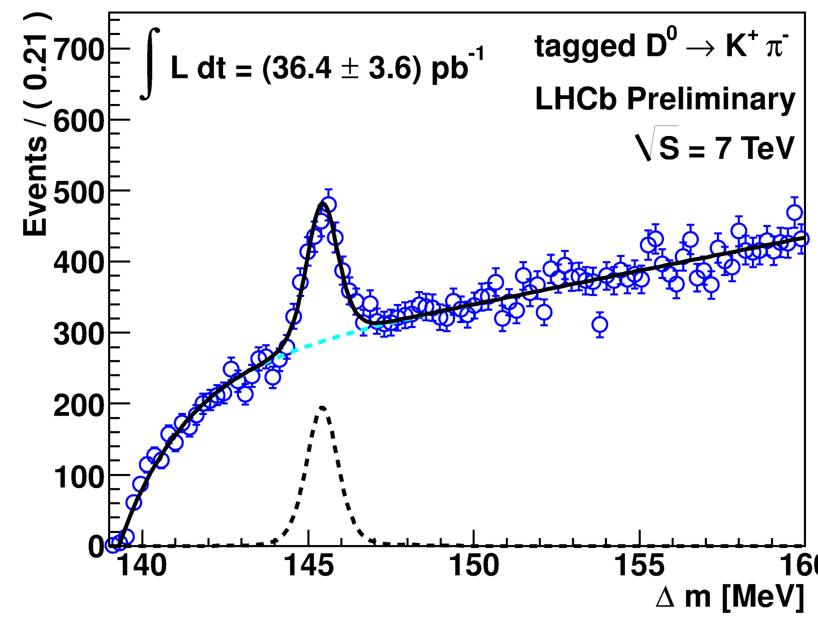
$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}(\Gamma t)}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}} \right)$$

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

Cross-check consistent with PDG average.