Physics at the LHC - WS 2021-2022

CP violation in charm decays

Lecture 2/4 - Monday Jan 17th 2022

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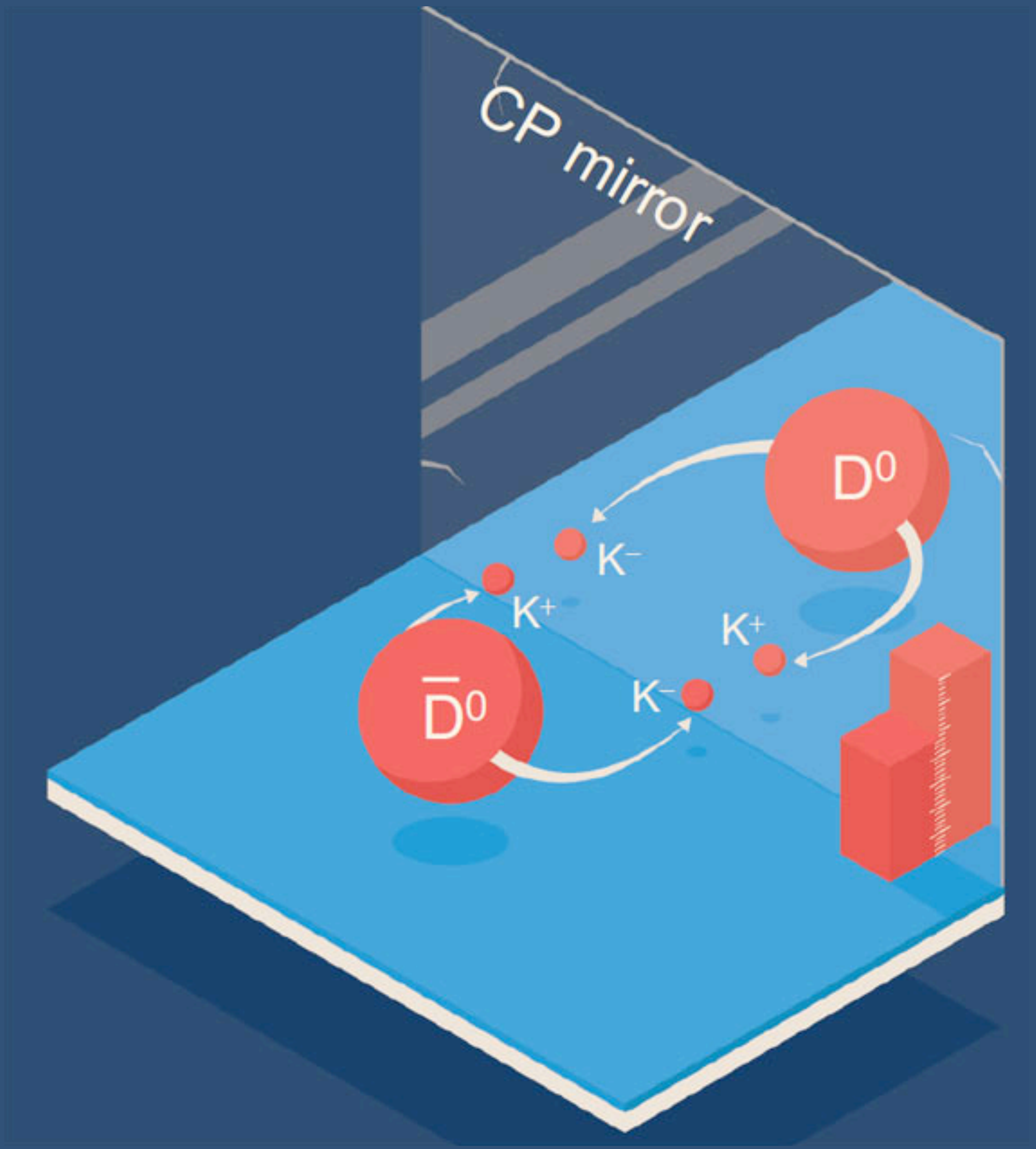
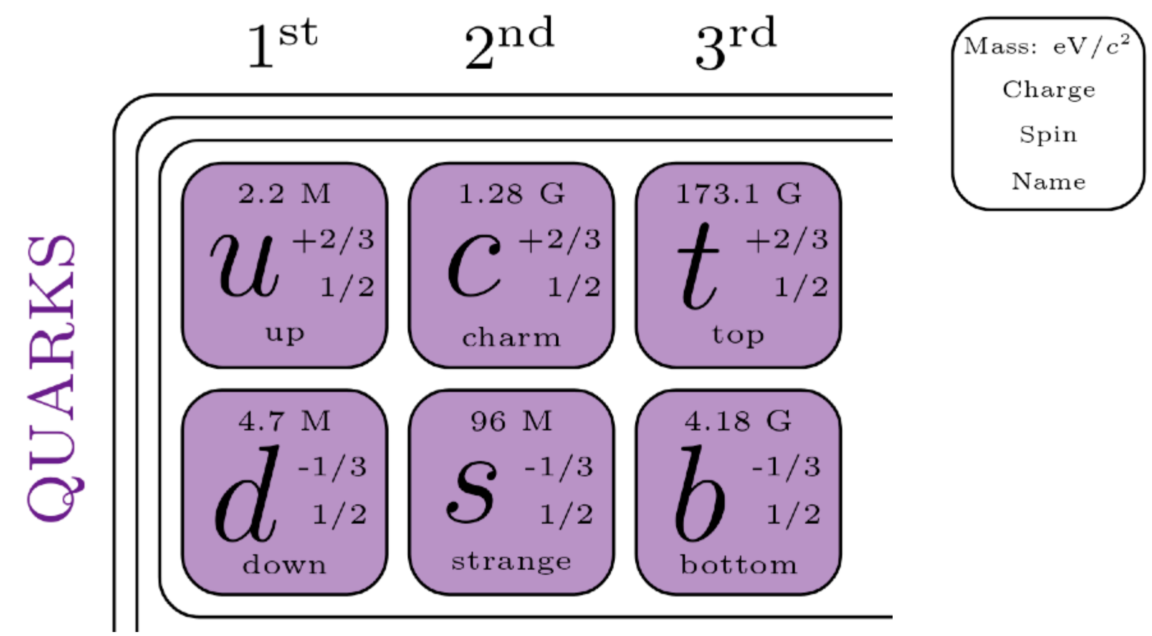
Largely inspired from
M.Williams LHCb StarterTalk



Charming physics

- Charm mesons

$?\bar{?}$ $\quad$ $c\bar{u}$: D^0 $\quad$ $c\bar{d}$: D^+ $\quad$ $c\bar{s}$: D_s^+ $\quad$ $c\bar{b}$: B_c^+ $\quad$ $\cancel{c\bar{t}}$



- Why study charm?
  - Decays by changing flavour
    → involves virtual heavy W
  - ~~Far from QCD scale~~
    ~~→ perturbative calculations~~
  - Contains up-type quark
    → provides unique probe of flavour structure
  - Complementary to studies in *B* and *K*
  - Often required input for *B* studies

	B^0	D^0
m [GeV]	5.28	1.86
τ [ps]	1.5	0.41

Charm at LHCb

$\sigma(pp \to b\bar{b}X)_{13\,\mathrm{TeV}} = 500\ \mu b \longrightarrow$ Very large rate of B

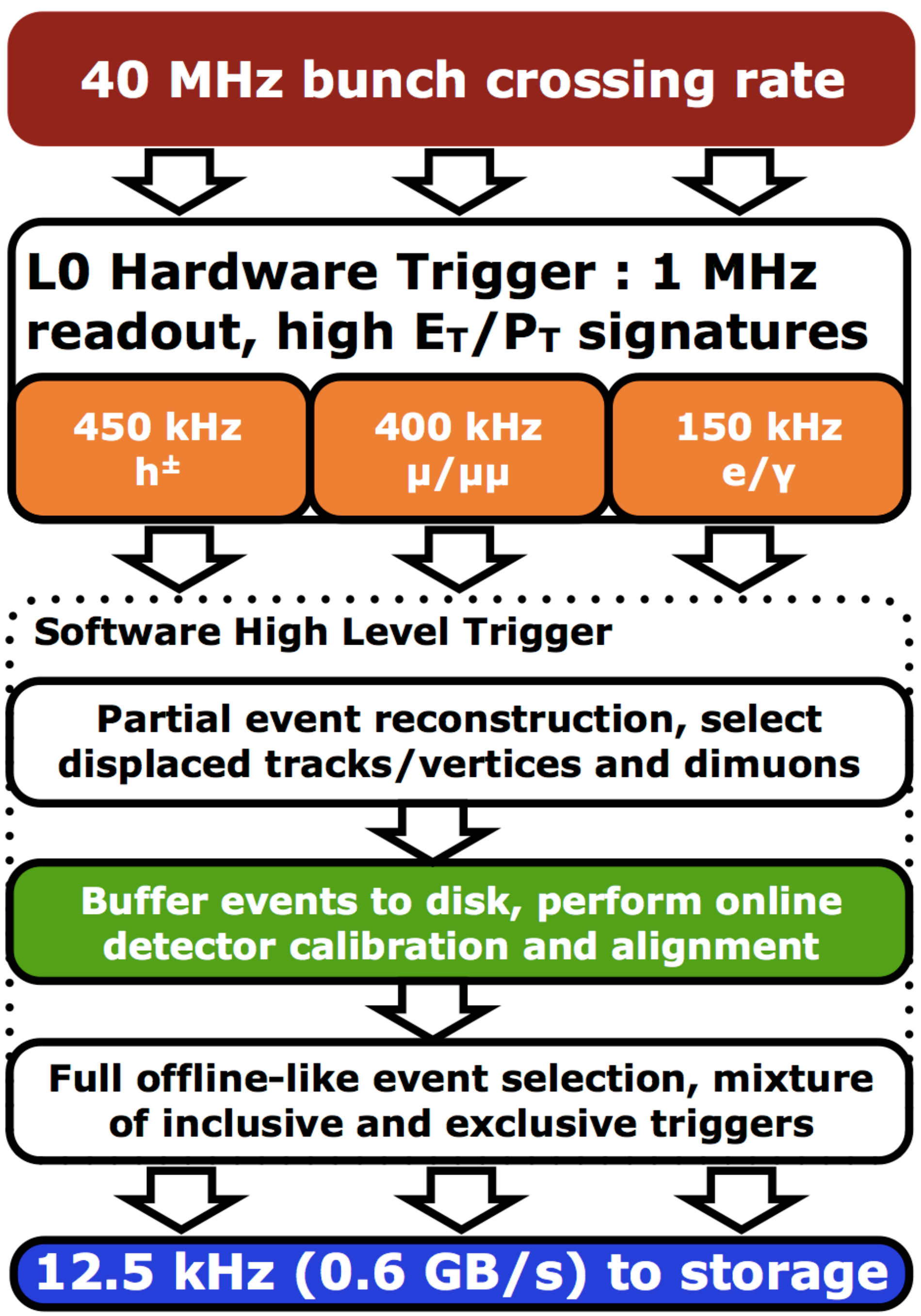
$\sigma(pp \to c\bar{c}X)_{13\,\mathrm{TeV}} = 20 \times \sigma(pp \to b\bar{b}X) \longrightarrow$ HUGE rate

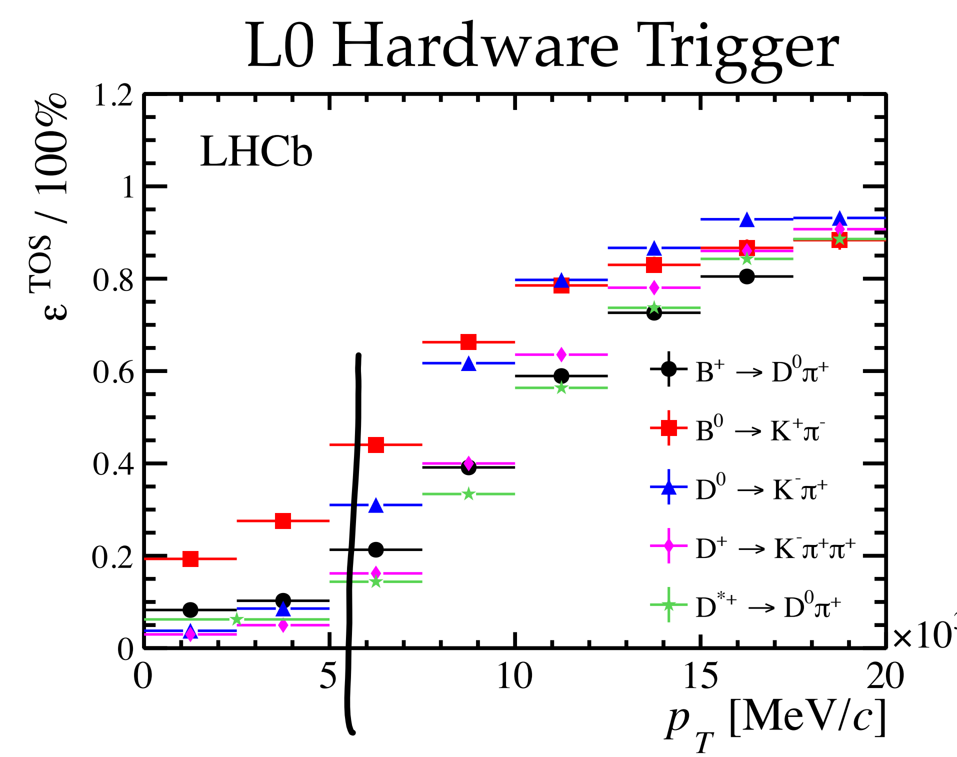
<u>RATE of D^0 at LHCb</u>

$$\frac{\sigma(pp \to D^0 X)^{LHCb}}{\sigma(pp \to X)} = \frac{2\ mb}{80\ mb} = \frac{1}{40}$$

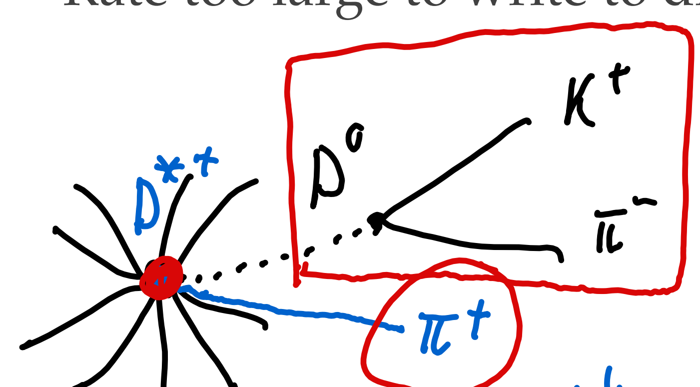
40 MHz $pp \Longrightarrow$ 1 MHz D^0 in LHCb

Triggering charm at LHCb



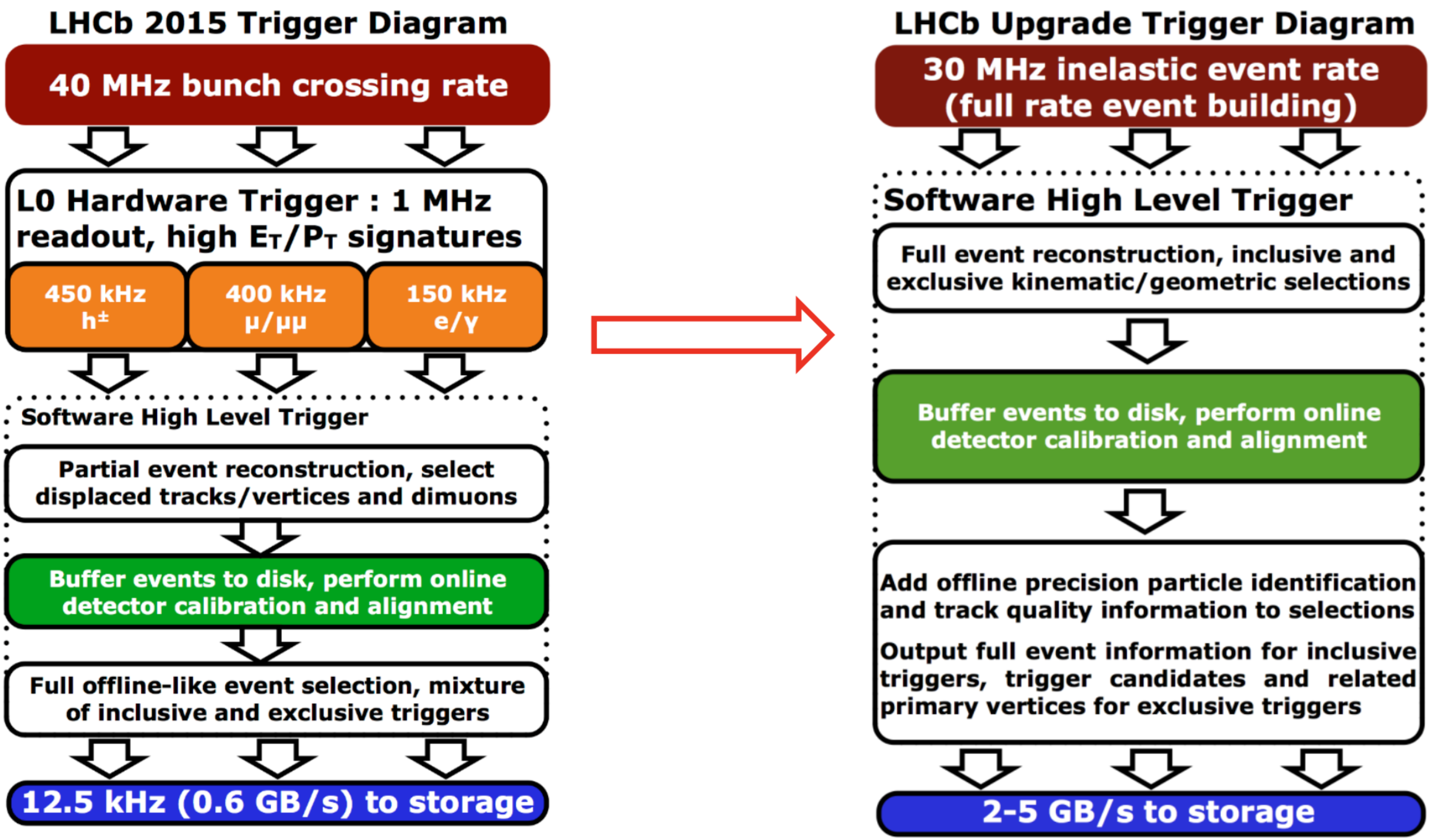


- **Software trigger**
  - Can use D^0 lifetime (IP of tracks, displaced vertex)
  - Rate too large to write to disk → **turbo stream**



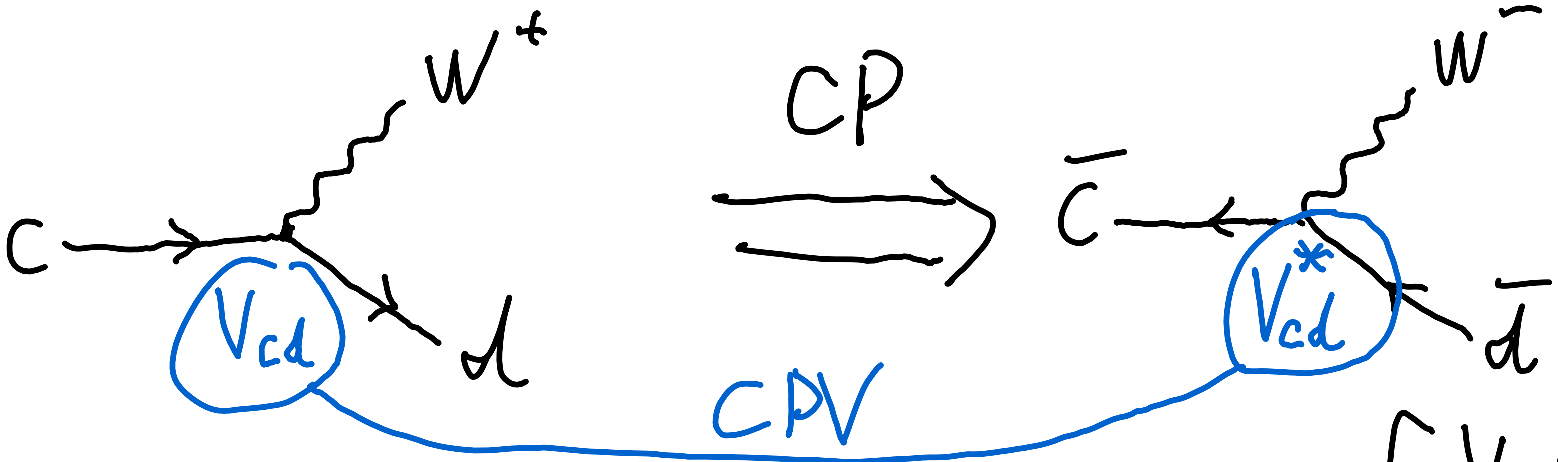
$pp \to D^{*+}X \to \pi^+ D^0$

LHCb Upgraded trigger



CP Violation

CPV in the Standard Model



transition Amplitude $\propto V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$

complex 3x3 rotation matrix

$\Rightarrow$ 3 mixing angles + 1 complex phase

3 QUARK GENER.

$\Downarrow$

CPV POSSIBLE

HISTORICALLY

History of CPV

- CPV in s quark

  K^0 mass eigenstates K_S^0, K_L^0

  $K_S \to \pi^+\pi^-$ CP-even

  $K_L \to \pi\pi\pi$ CP-odd

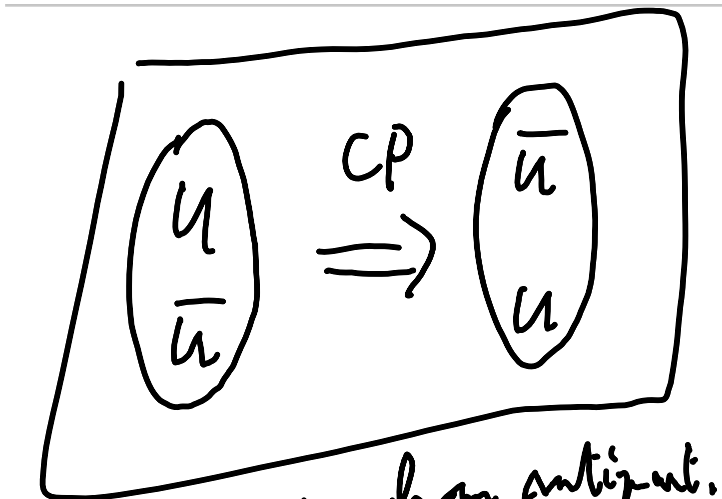
1964 Cronin and Fitch
0.4 % of $K_L \to \pi\pi$
mass eigenstates $\neq$ CP eigenstate
$\Rightarrow$ CPV

- CPV in b-quark

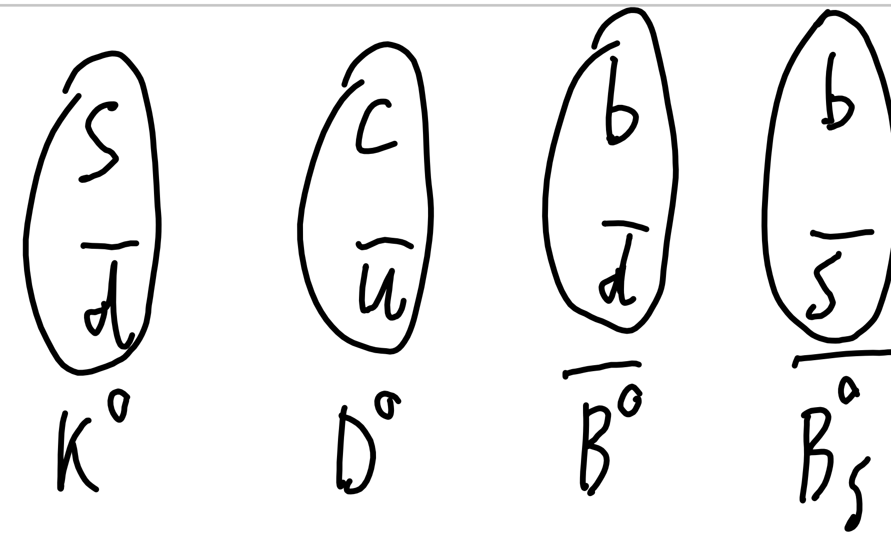
  2000s at B-factories
  decay-time dependent asymm $B^0/\bar{B}^0$

- CPV in c-quark $\Rightarrow$ 2019 at LHCb

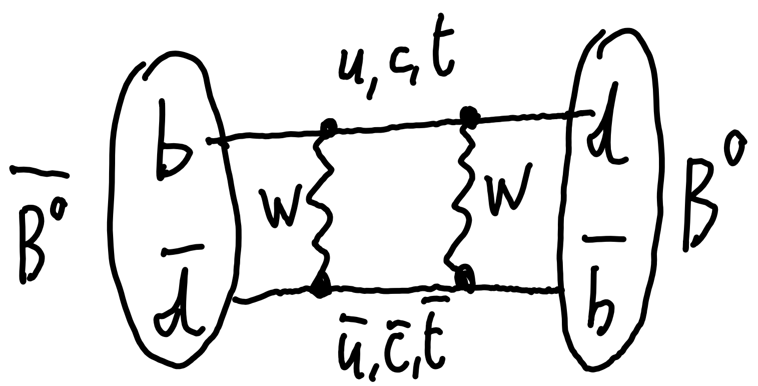
Neutral meson oscillations

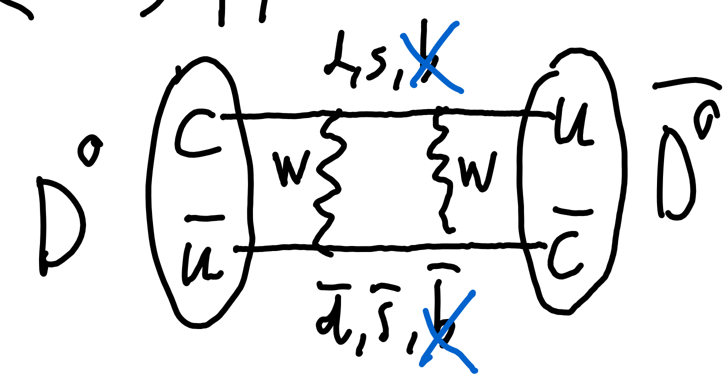


INDIST. from antipart.



$\Rightarrow$ can oscillate $\quad M^0 \longleftrightarrow \bar{M}^0$





$D^0 \leftrightarrow \bar{D}^0$ HIGHLY SUPPR.

- $V_{cb} V_{ub} << 1$
- d and s contr. cancel out $\quad m_d \sim m_s \quad$ (GIM)

3 types of CPV

1) CPV in decay $\qquad \Gamma(i \to f) \neq \Gamma(\bar{i} \to \bar{f})$

2) CPV in mixing $\qquad \Gamma(M^0 \to \bar{M}^0) \neq \Gamma(\bar{M}^0 \to M^0)$

3) CPV in interf. betw. mixing and decay

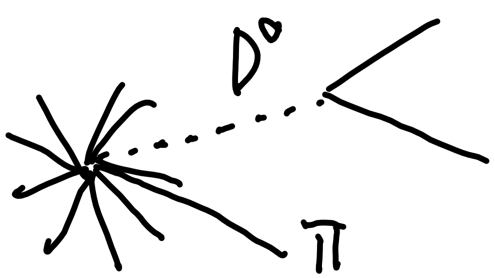
$$\Gamma\left(\begin{tikzcd} M^0 \arrow[r] \arrow[d, bend right] & f \\ \bar{M}^0 \arrow[ur] & \end{tikzcd}\right) \neq \Gamma\left(\begin{tikzcd} \bar{M}^0 \arrow[r] \arrow[d, bend right] & f \\ M^0 \arrow[ur] & \end{tikzcd}\right)$$

Charm flavour tagging

$D^0 \to K^-\pi^+$ $\quad \bar{D}^0 \to K^+\pi^-$ $\quad$ self tagging

$D^0 \to K^+K^-$ $\quad \bar{D}^0 \to K^-K^+$ $\Rightarrow$ flv. tagging

PROMPT CHARM

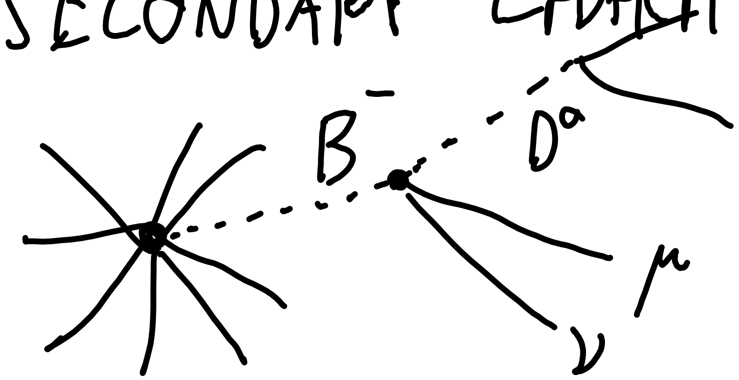


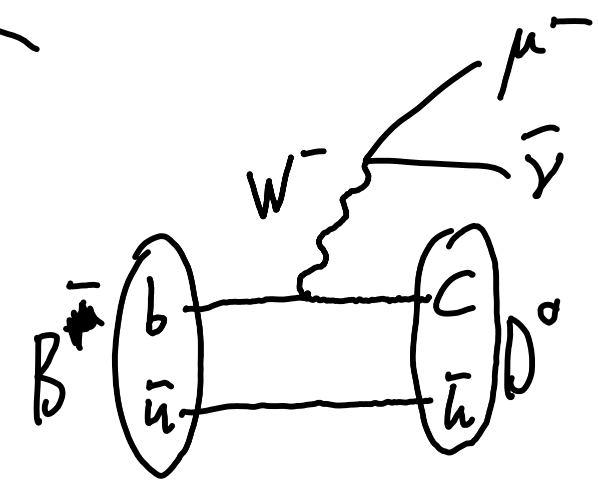
$pp \to D^{*+} \to D^0 \pi^+_{tag}$

$pp \to D^{*-} \to \bar{D}^0 \pi^-_{tag}$

- Higher rate
- lifetime biasing

SECONDARY CHARM





$pp \to B^- \to D^0 \mu^- \bar{\nu}$

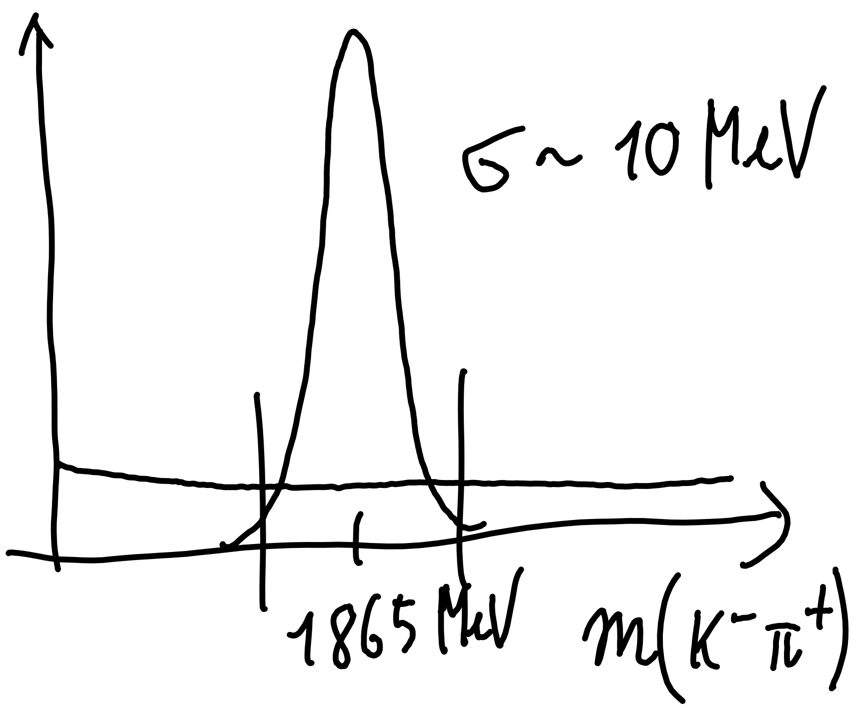
$pp \to B^+ \to \bar{D}^0 \mu^+ \nu$

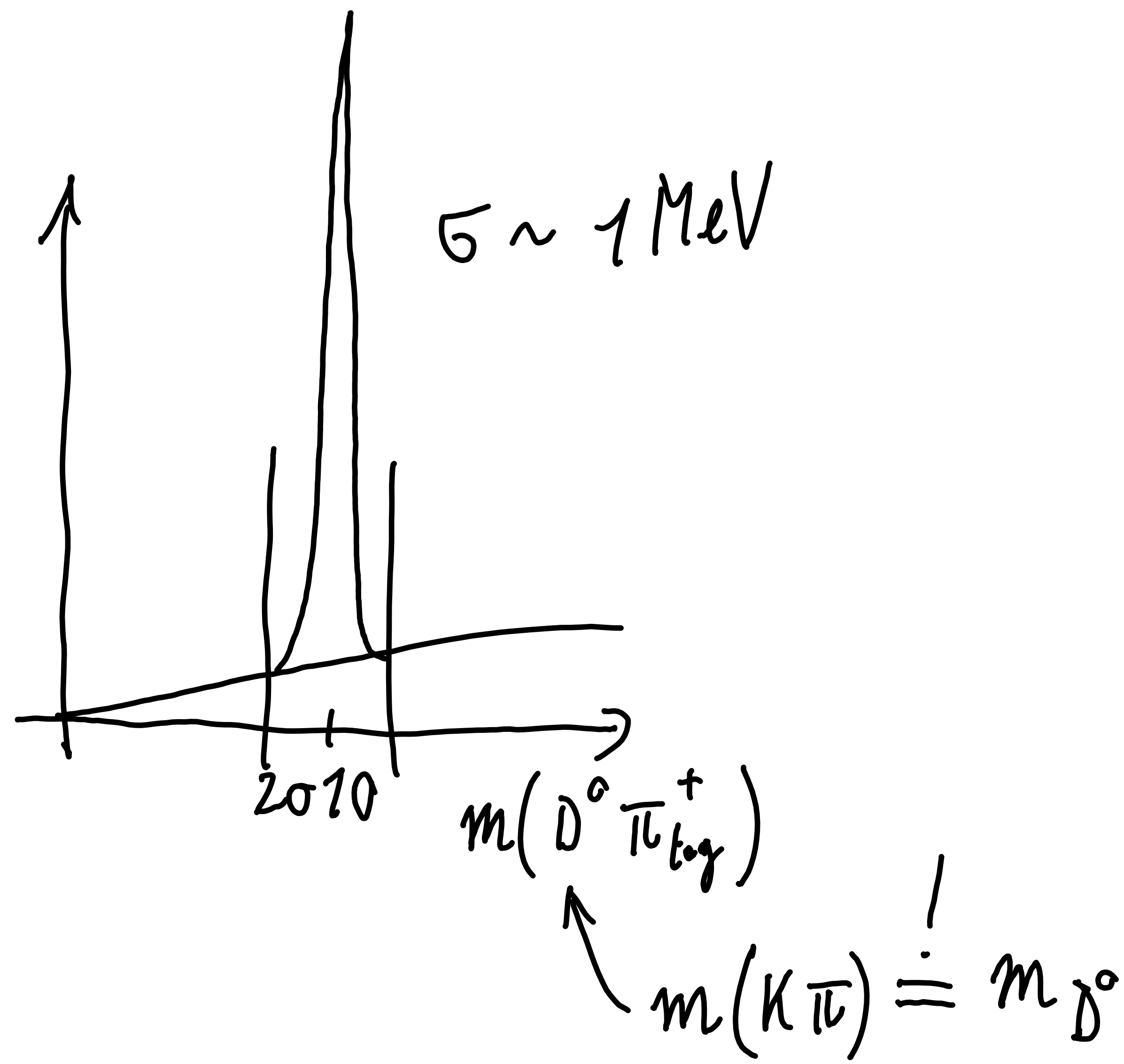
- lifetime unbiased
- background to PROMPT CHARM

Selecting prompt charm

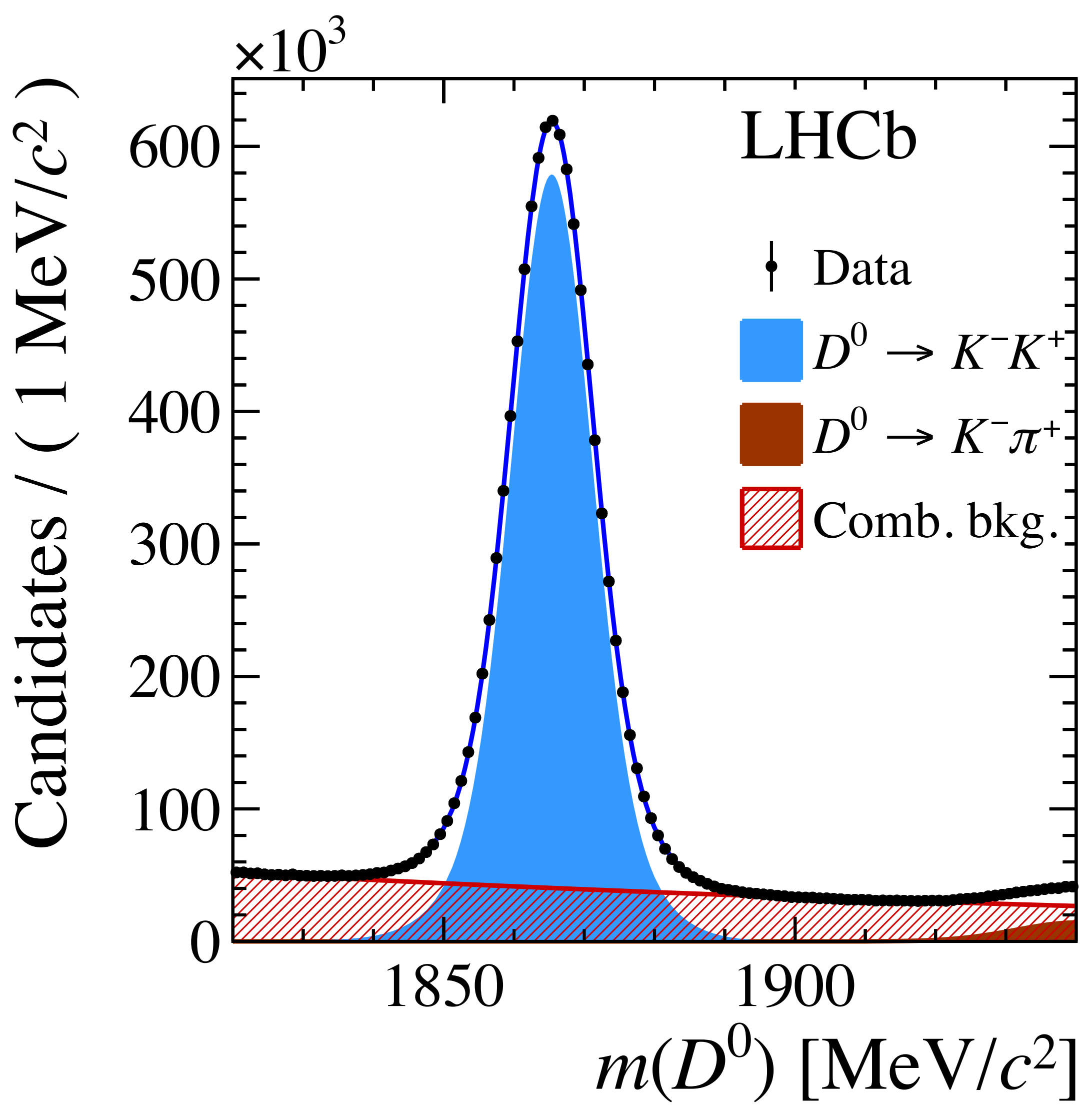
$D^{*+} \to D^0 \pi^+_{tag}$

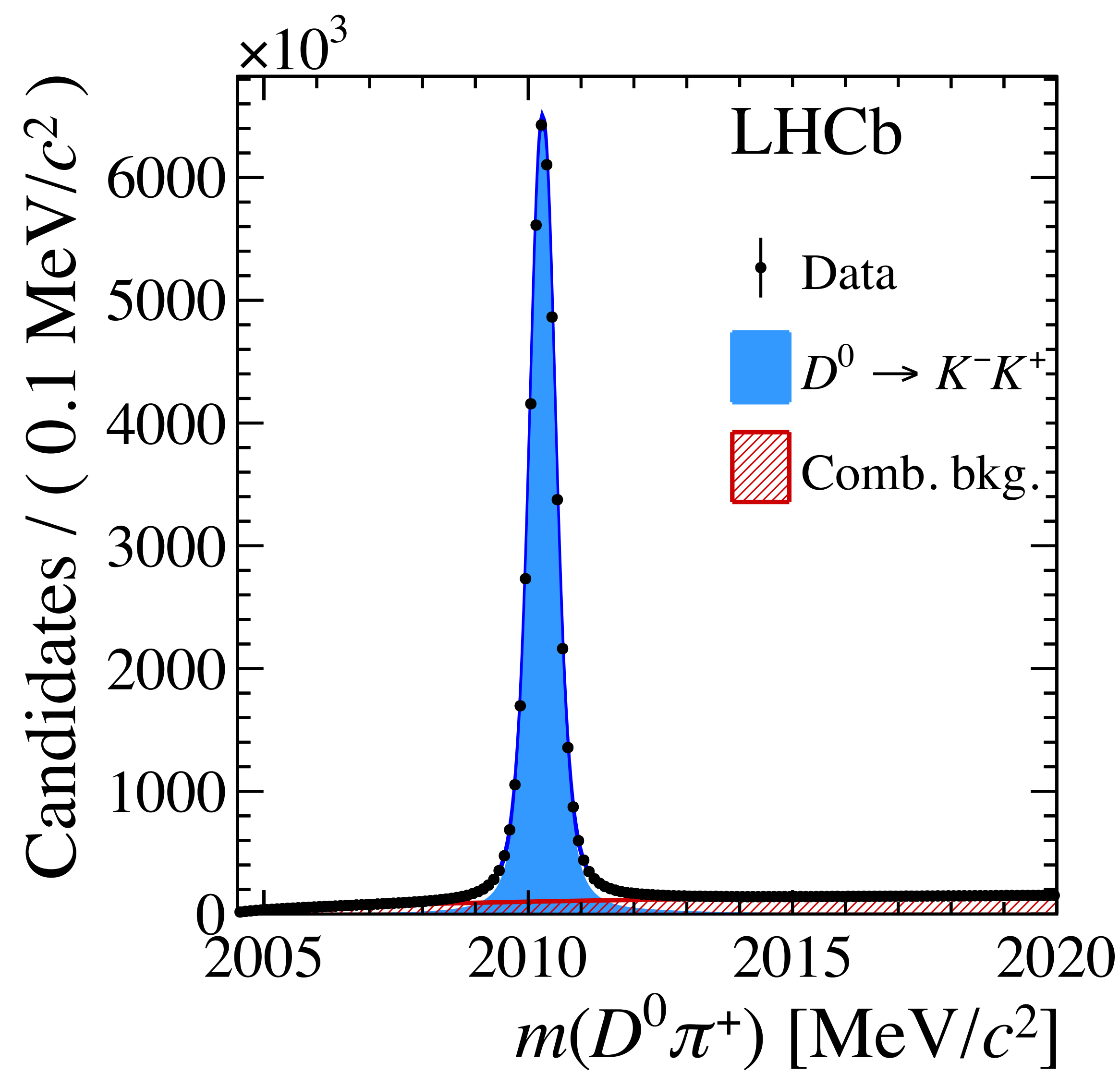
$D^0 \to K^-\pi^+, \; K^+K^-, \; \pi^+\pi^-$





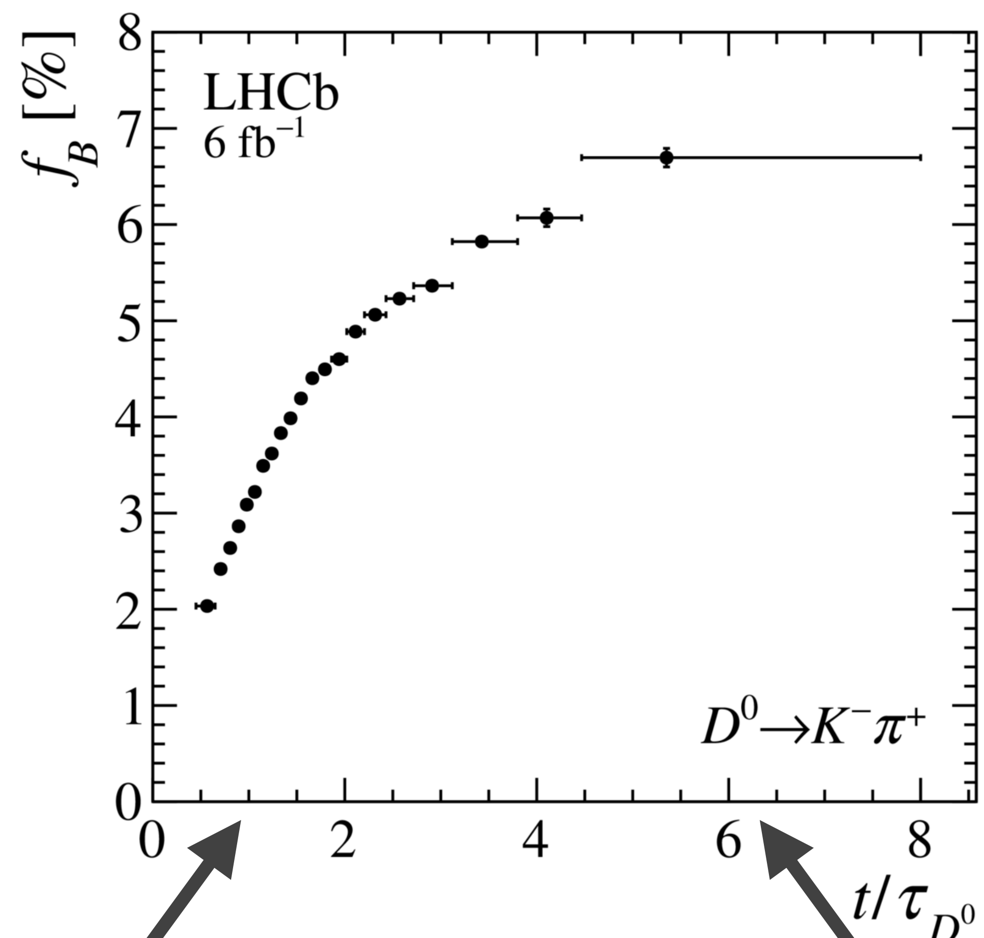
Selecting prompt charm

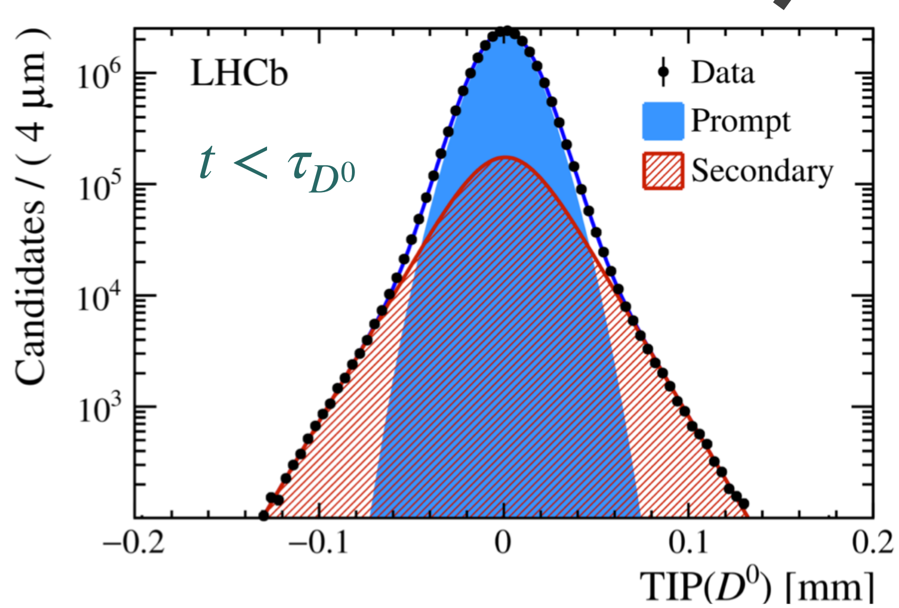


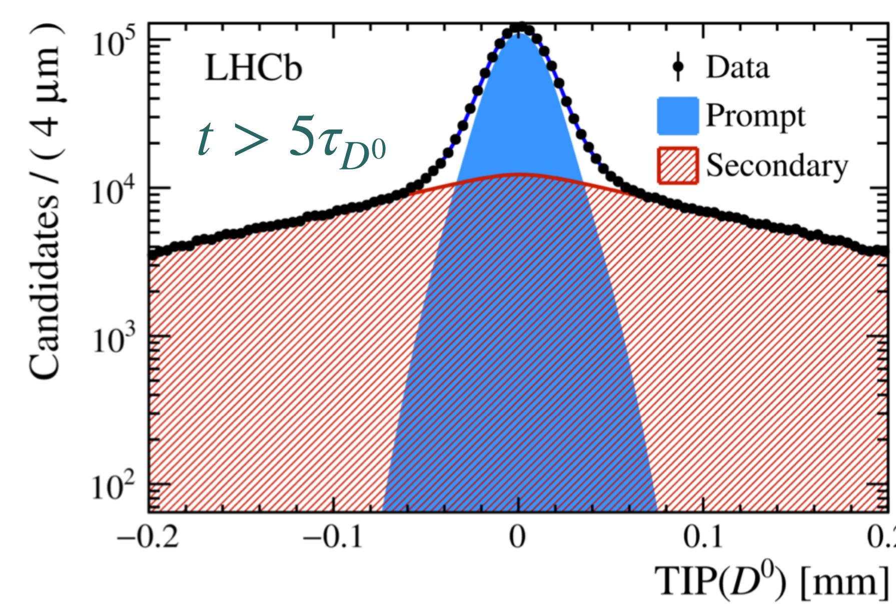


Background from $B \to D$

- Irreducible background from displaced D^0 production in B decays
  - Background rate will depend on D^0 decay time
  - Cannot be suppressed completely
  - Studied and modelled as a function of decay time







Nuisance asymmetries

$$A_{CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

We measure:

$$A_{raw} = \frac{N - \bar{N}}{N + \bar{N}}$$

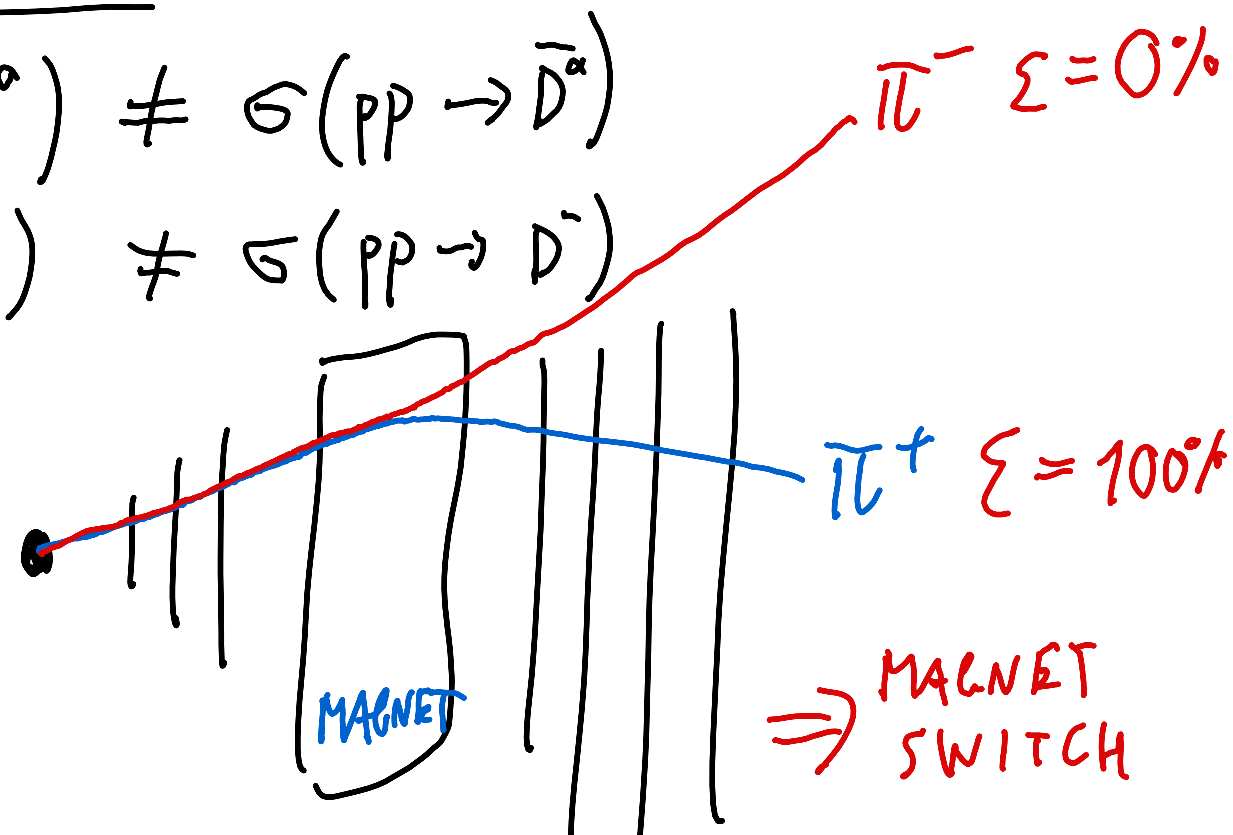
SOURCES OF NUISANCE ASYMM

- PRODUCTION $\quad \sigma(pp \to D^0) \neq \sigma(pp \to \bar{D}^0)$

  $\sigma(pp \to D^+) \neq \sigma(pp \to D^-)$

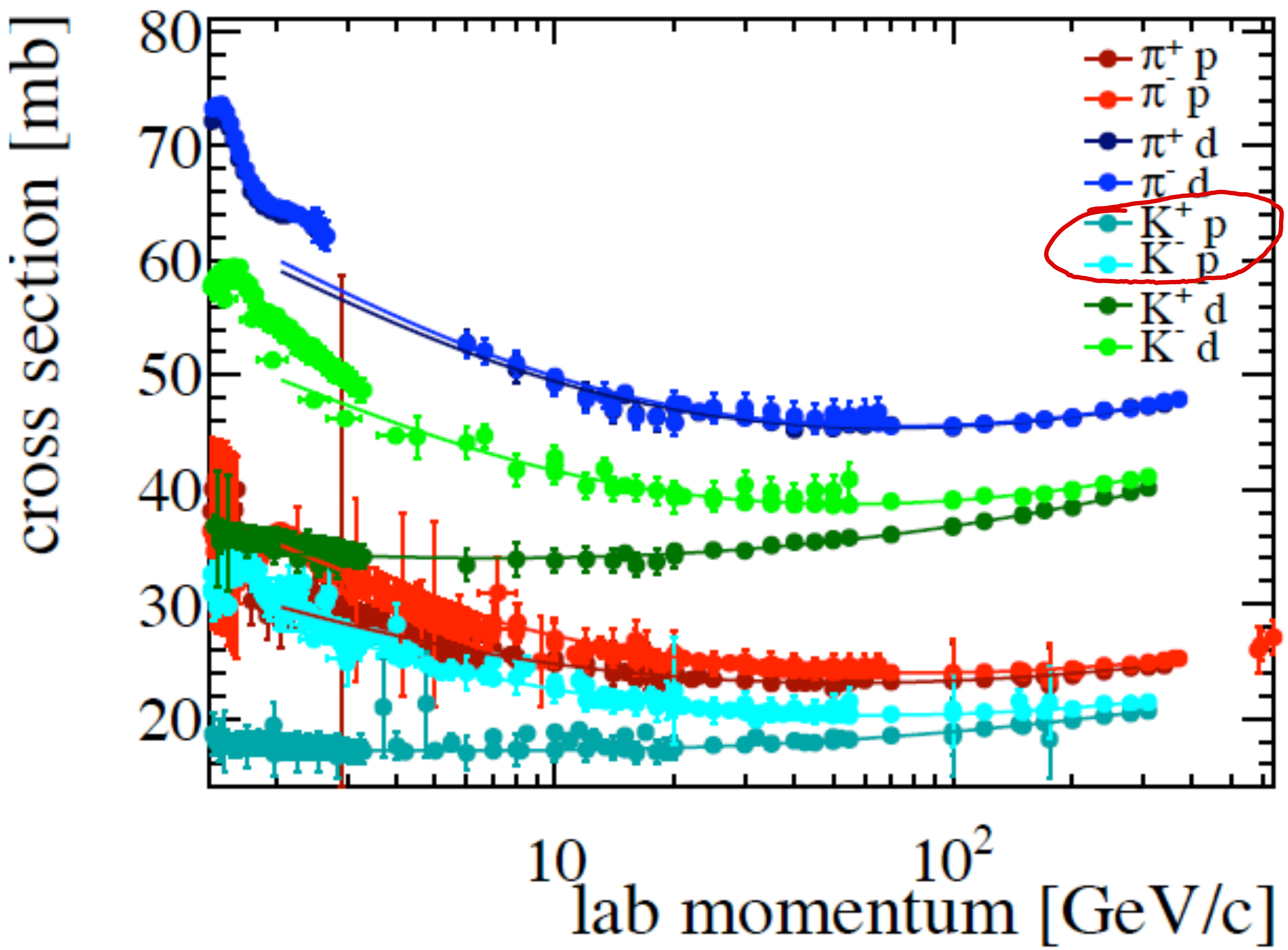
- DETECTOR

$$\varepsilon(K^+) \neq \varepsilon(K^-)$$



$\Rightarrow$ MAGNET SWITCH

Nuisance asymmetries



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

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

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

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

CPV discovery in charm

The discovery mode

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

$D^0 \to \pi^+ \pi^-$

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

$pp \to D^{*+} \to D^0 \pi^+_{tag}$

$pp \to D^{*-} \to \bar{D}^0 \pi^-_{tag}$

$pp \to B \to D^0 \mu^+ \bar{\nu} X$

$pp \to B \to \bar{D}^0 \mu^- \nu X$

$$A_{raw}(KK) = A_{CP}(KK) + A_{prod}(D^*, B) + A_{det}(\pi^\pm_{tag}, \mu^\pm_{tag})$$

$$A_{raw}(\pi\pi) = A_{CP}(\pi\pi) + A_{prod}(D^*, B) + A_{det}(\pi_{tag}, \mu_{tag})$$

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

$$\text{U-spin} \Rightarrow A_{CP}(KK) = -A_{CP}(\pi\pi)$$

THEORY

Time dependence

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)}$$

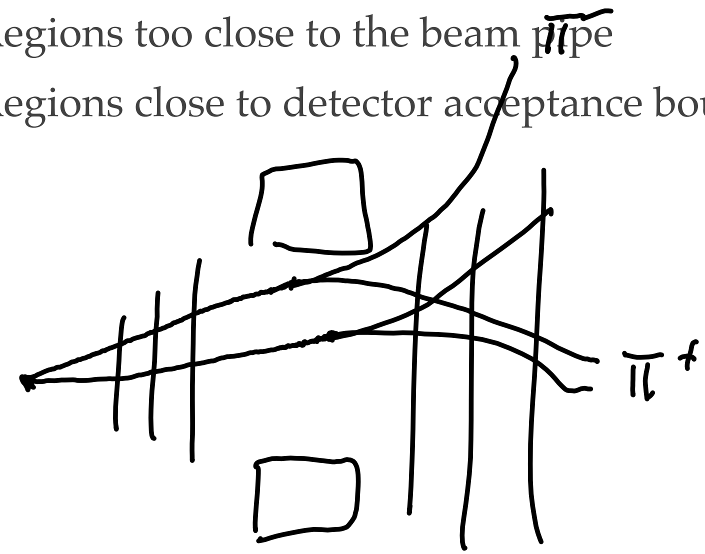
DIRECT CPV, MIXING CPV, INTERFERENCE CPV

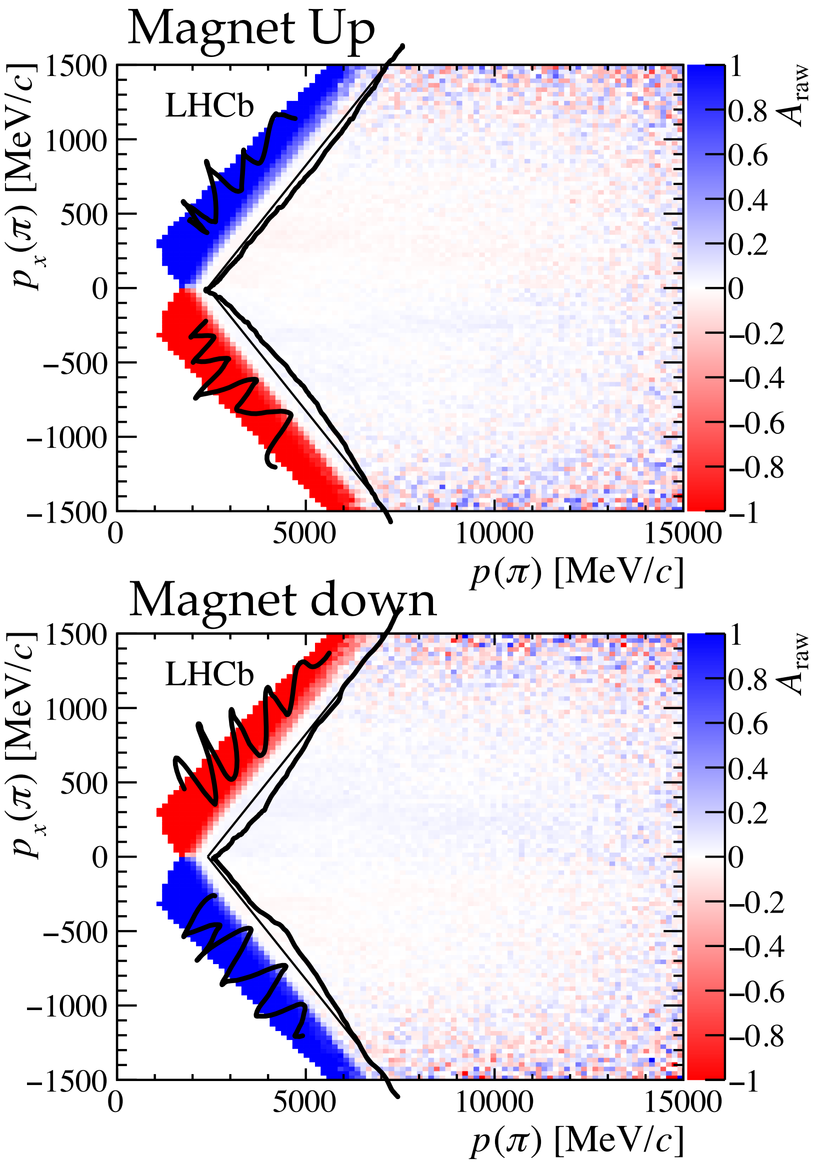
$$A_{CP}(f) \approx a^{dir}_{CP}(f) - \frac{\langle t(f)\rangle}{\tau(D^0)} A_\Gamma(f)$$

$$\Delta A_{CP}(f) \equiv A_{CP}(KK) - A_{CP}(\pi\pi) \approx \Delta a^{dir}_{CP} - \frac{\Delta\langle t\rangle}{\tau(D^0)} A_\Gamma(f)$$

Fiducial region

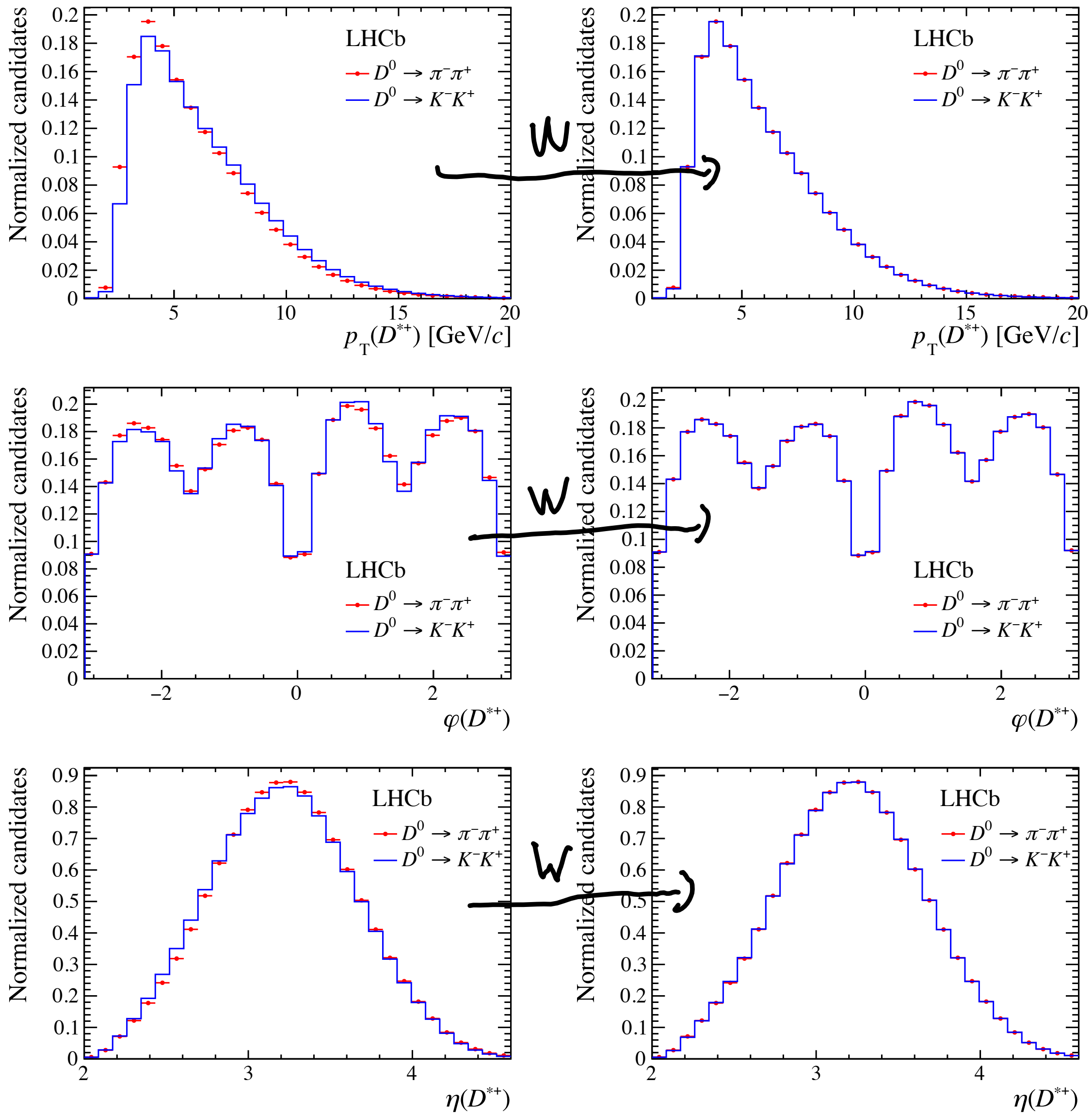
- Detection asymmetry of $\pi^{\pm}_{\text{tag}}$
  - Cancels in $\Delta A_{CP} = A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-)$
  - Cancels when switching magnet polarity
- Does not cancel perfectly
  - Remove region with large det. asymmetry
    - Regions too close to the beam pipe
    - Regions close to detector acceptance boundaries





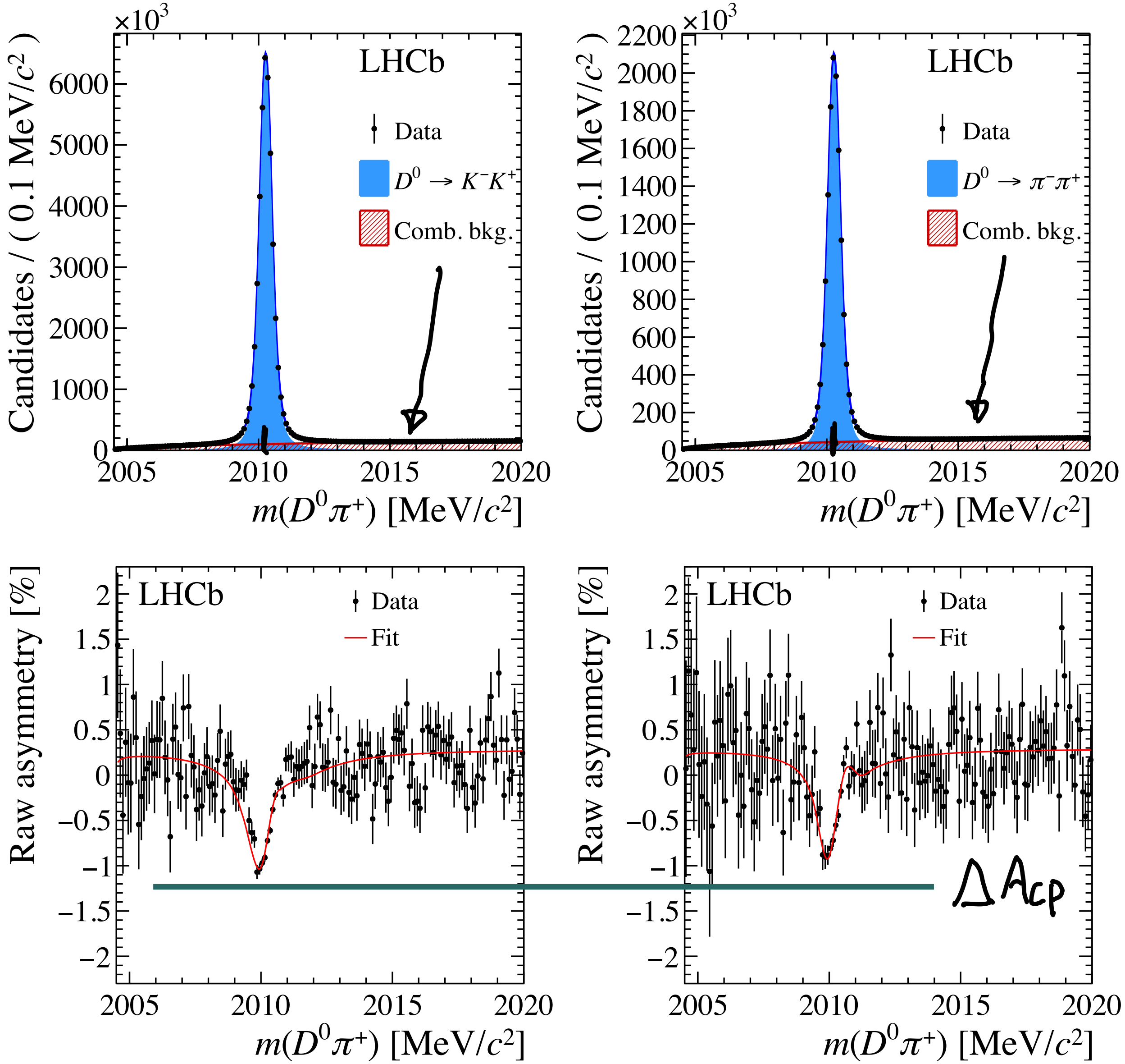
Kinematic reweighting

- Production (D^{*+} and B) and detection ($\pi^{\pm}_{\mathrm{tag}}$ and $\mu^{\pm}$) asymmetries depend on kinematic
- Match kinematics of D^{*+} and B in K^+K^- and $\pi^+\pi^-$
  - First subtract background using mass fit
  - Match distributions with per-event weights
  - Match 3D distribution of p_{T}, ϕ, η



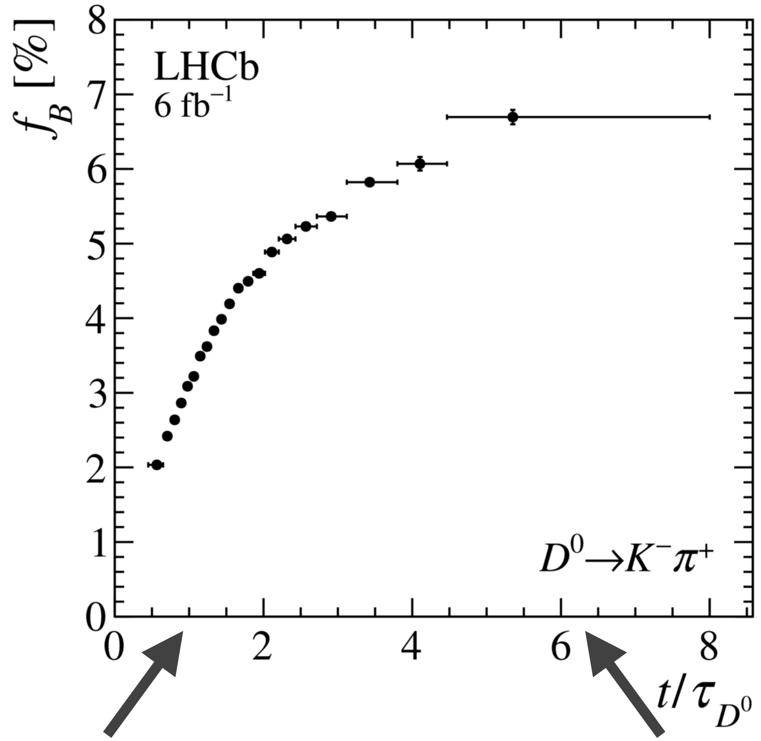
Measurement of ΔA_{CP}

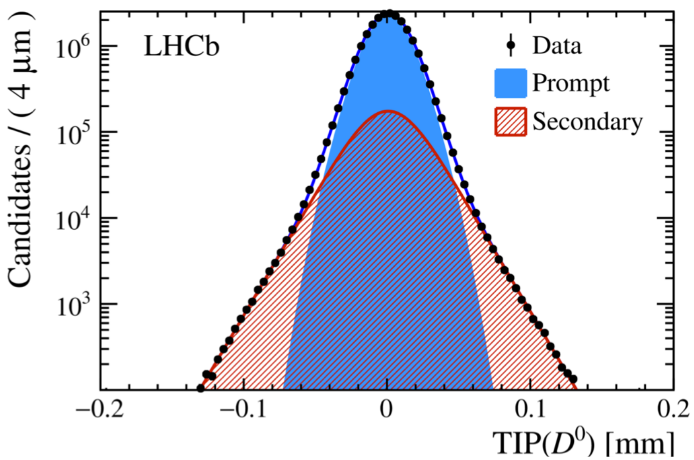
$D^{*+} \to D^0 \pi^+$

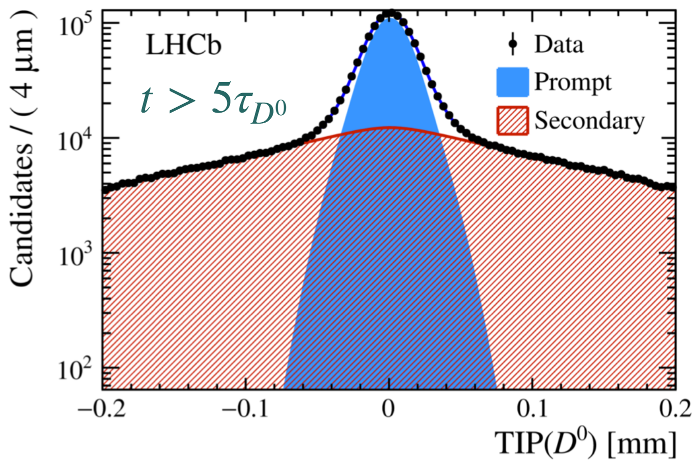


Pollution from secondary D

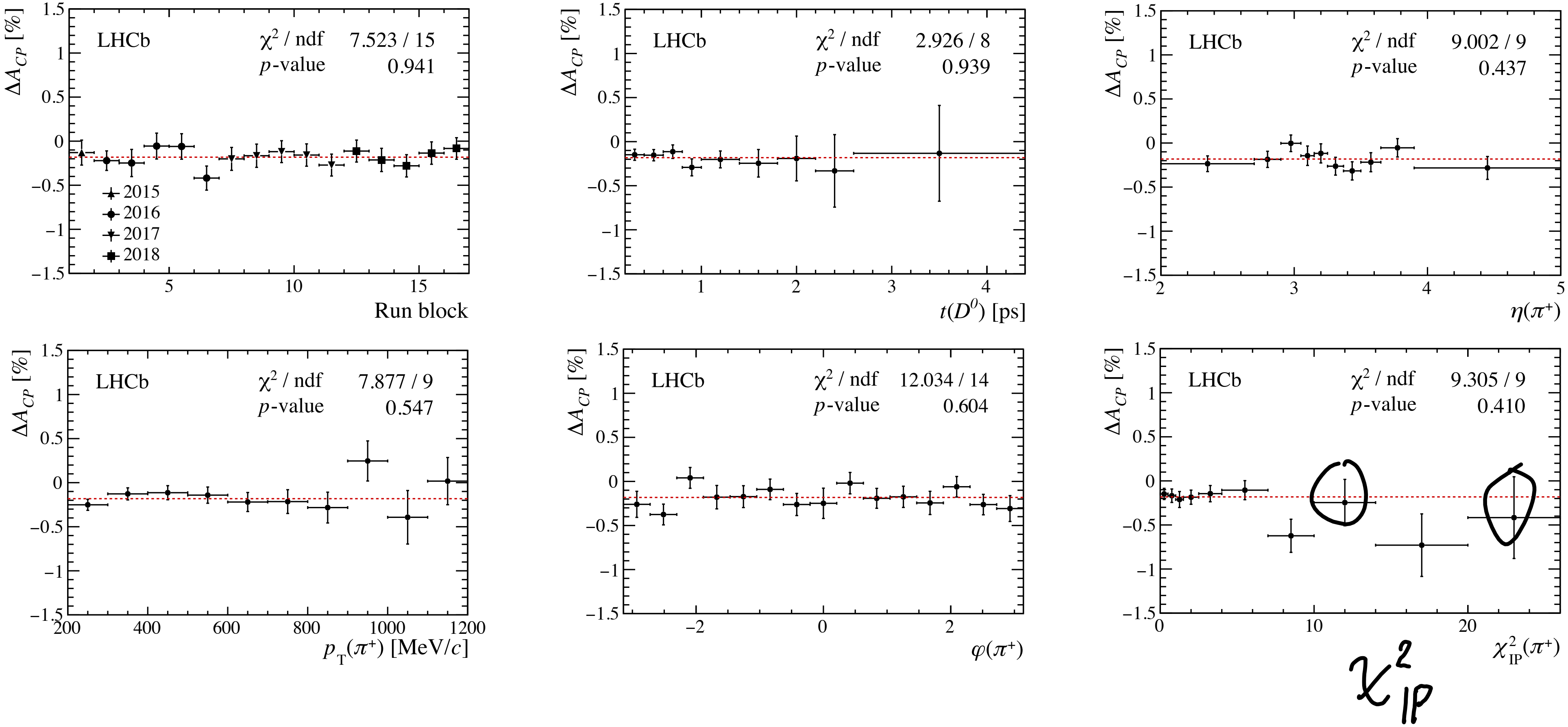
- Small fraction (f_B) of secondary D^0 in prompt D^0 sample
- Can induce a (small) bias in ΔA_{CP}
- Measure yield and asymmetry of secondary in bins of decay time







Crosschecks



Results

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

+ previous measurements

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}, \quad \Rightarrow 5.3\sigma$$

- Can also get $\Delta a_{CP}^{\text{dir}}$

$$\Delta a_{CP}^{dir} \approx \Delta A_{CP} + \frac{\Delta\langle t\rangle}{\tau(D^0)} A_\Gamma$$

$$A_\Gamma = (-2.8 \pm 2.8) \times 10^{-4}$$

$$= (-15.7 \pm 2.9) \times 10^{-4}$$

$$\frac{\Delta\langle t\rangle}{\tau(D^0)}^{\mu\text{-tag}} = -0.003 \pm 0.001$$

$$\frac{\Delta\langle t\rangle}{\tau(D^0)}^{\pi\text{-tag}} = 0.135 \pm 0.002$$