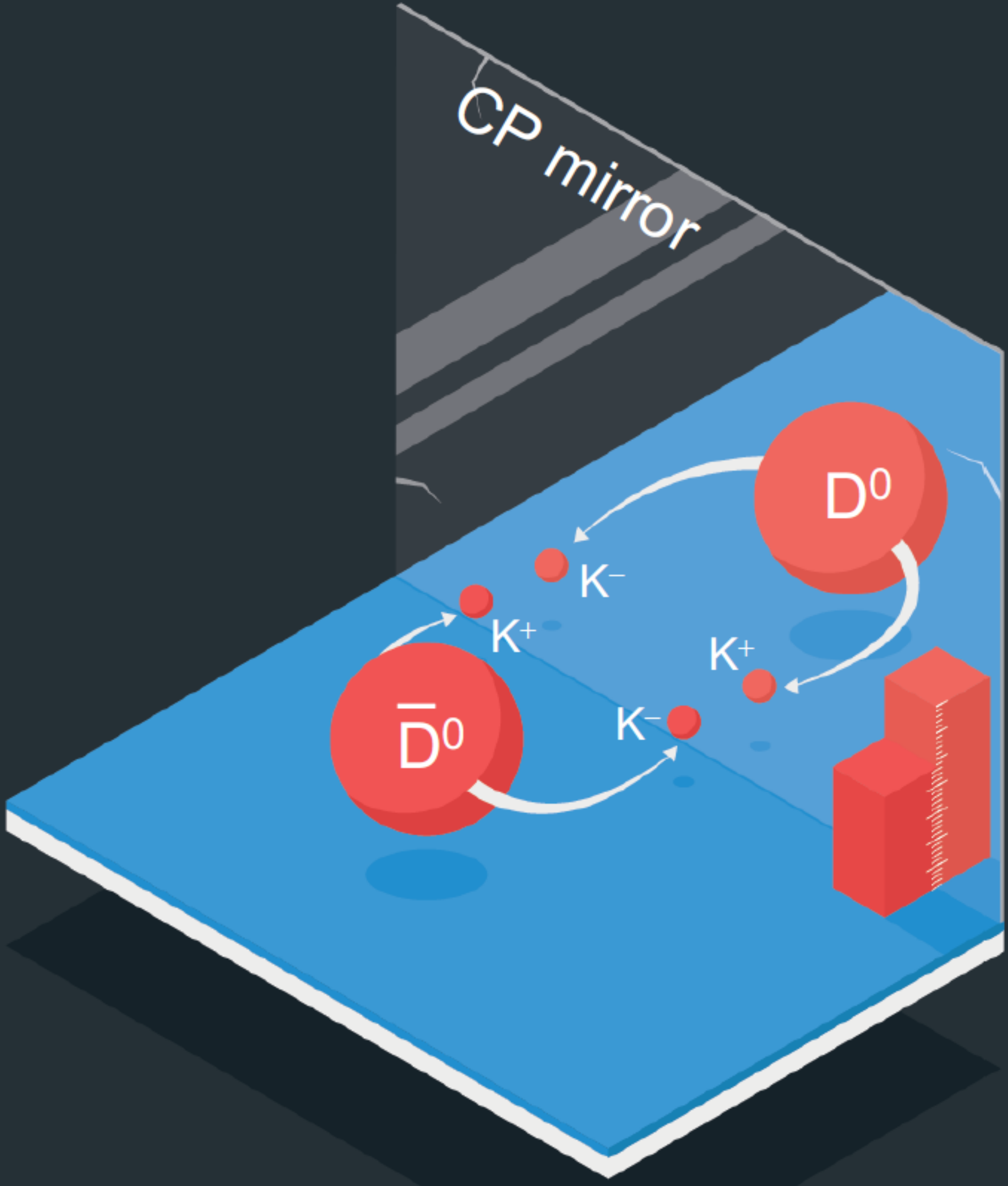
2nd Belle II Physics week

October 28–November 1, 2019
KEK, Tsukuba, Japan



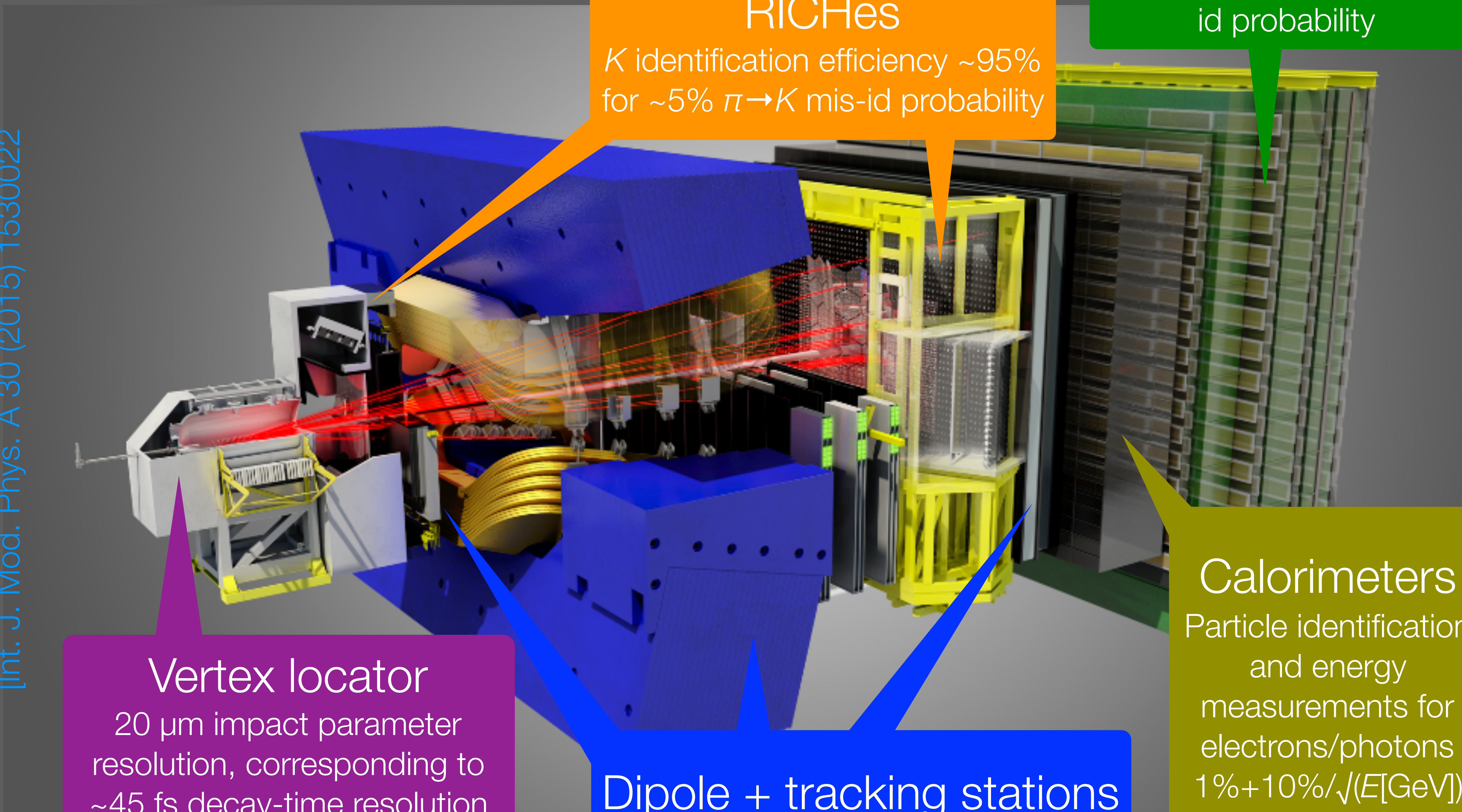
Charm physics at LHCb

(from the perspective of a former LHCb member that recently joined Belle II)

Angelo Di Canto

BROOKHAVEN NATIONAL LABORATORY

The beauty of the LHC



Muon stations
μ identification efficiency ~97% for 1-3% $\pi \rightarrow \mu$ mis-id probability

RICHes
K identification efficiency ~95% for ~5% $\pi \rightarrow K$ mis-id probability

Calorimeters
Particle identification and energy measurements for electrons/photons 1%+10%/$\sqrt{(E[\text{GeV}])}$

Vertex locator
20 μm impact parameter resolution, corresponding to ~45 fs decay-time resolution for *b*/*c* hadrons

Dipole + tracking stations
$\Delta p/p$ = 0.4-0.6% at 5-100 GeV/c

[Int. J. Mod. Phys. A 30 (2015) 1530022

Finally two concurrent ~~beauty~~ charm factories

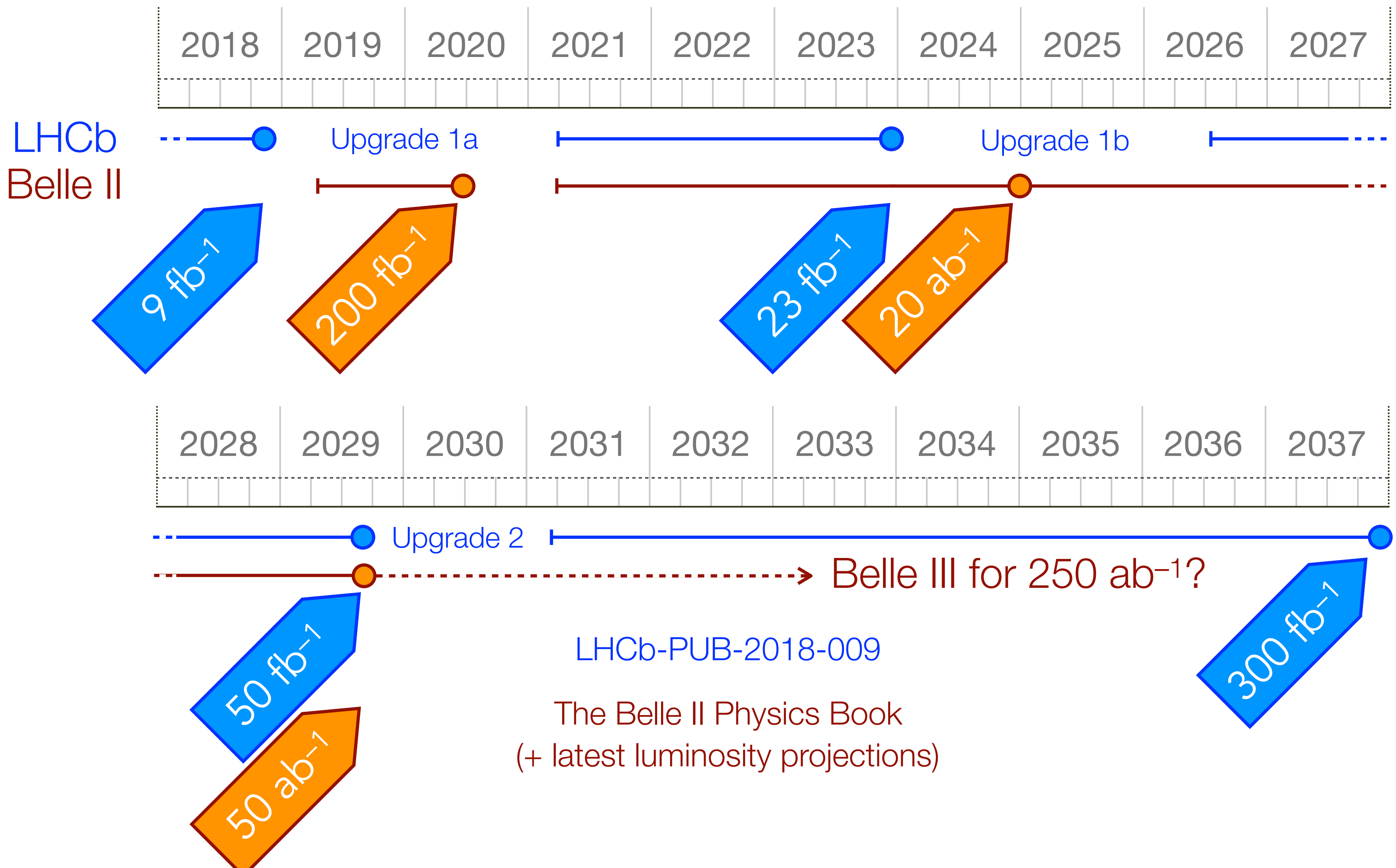
LHCb

- Huge advantage in production rate, but also large backgrounds — stringent online selections
- Superior decay-time resolution and access to larger decay times (boost)
- …but tricky efficiency effects (*e.g.* decay-time acceptance)

Belle II

- Cleaner environment allows for more generous selections — milder efficiency effects
- Better reconstruction of final states with neutrals/invisible particles
- Much easier separation between promptly produced charm and secondary (from-*B*) decays

Prospects of data collection



LHCb-PUB-2018-009

The Belle II Physics Book
(+ latest luminosity projections)

The rule of thumb

$$1\ fb^{-1} \sim 1\ ab^{-1}$$

@ LHCb @ Belle II

The rule of thumb

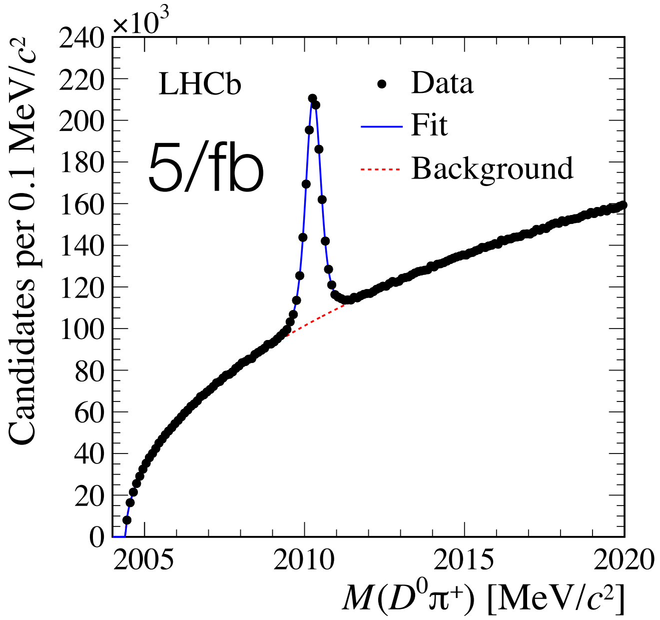
~~$1\ \mathrm{fb}^{-1} \sim 1\ \mathrm{ab}^{-1}$~~

~~@ LHCb~~ ~~@ Belle II~~

does not hold for charm

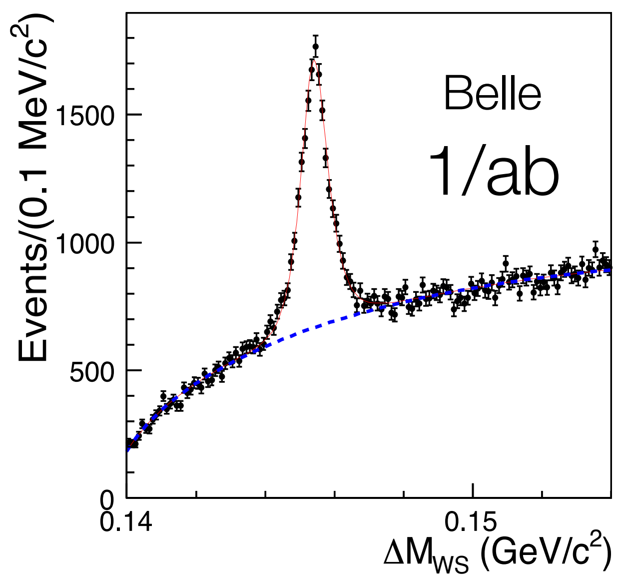
The rule of thumb

[PRD 97 (2018) 031101(R)]



$N/\mathcal{L}$~150k

[PRL 112 (2014) 111801]

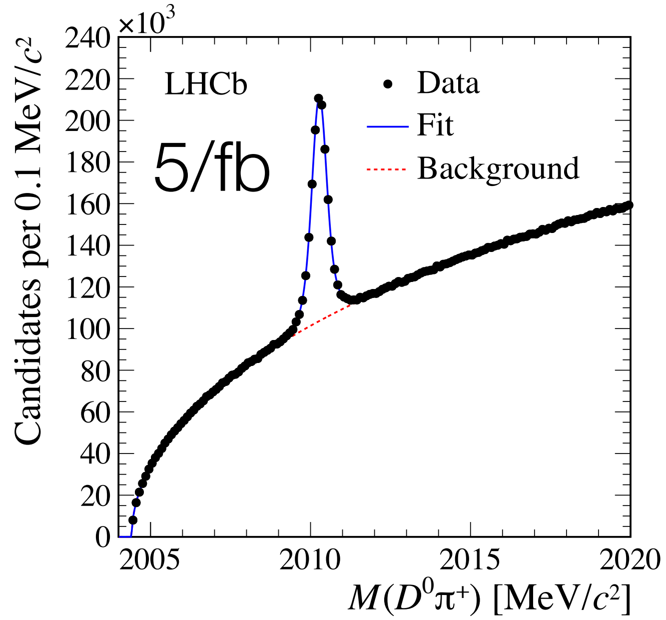


$N/\mathcal{L}$~10k

$$D^{*+} \rightarrow D^0(\rightarrow K^+\pi^-)\pi^+$$

The rule of thumb

[PRD 97 (2018) 031101(R)]



$N/\mathcal{L}$~150k

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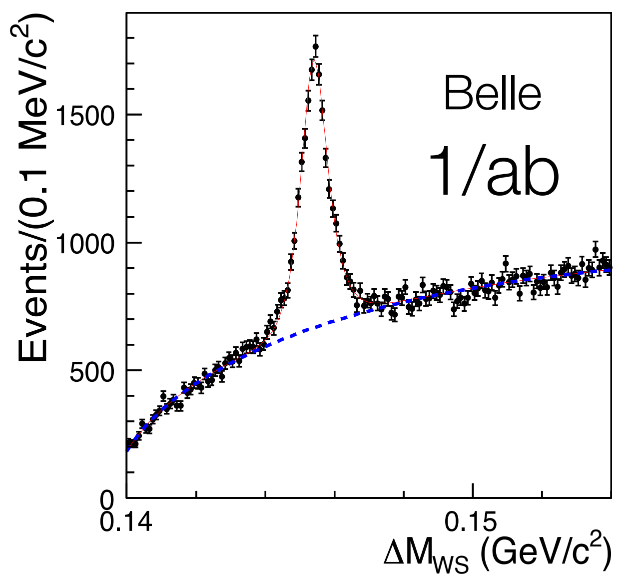


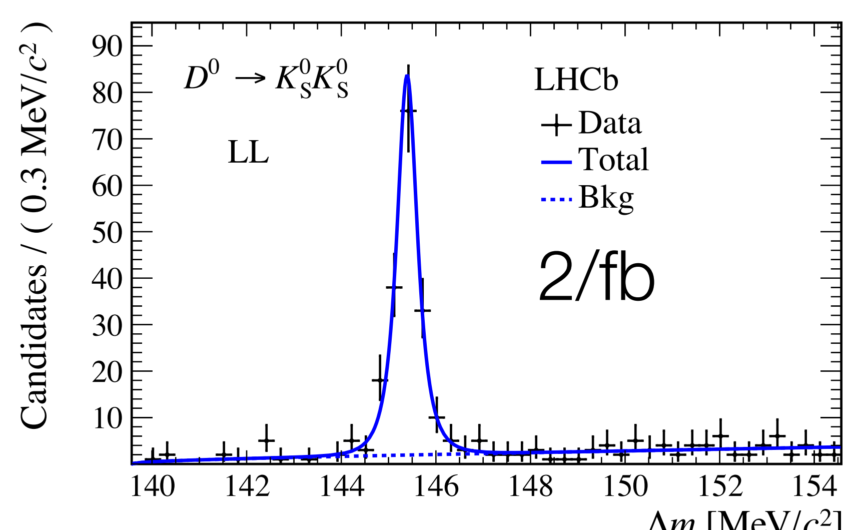
$N/\mathcal{L}$~10k

$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$

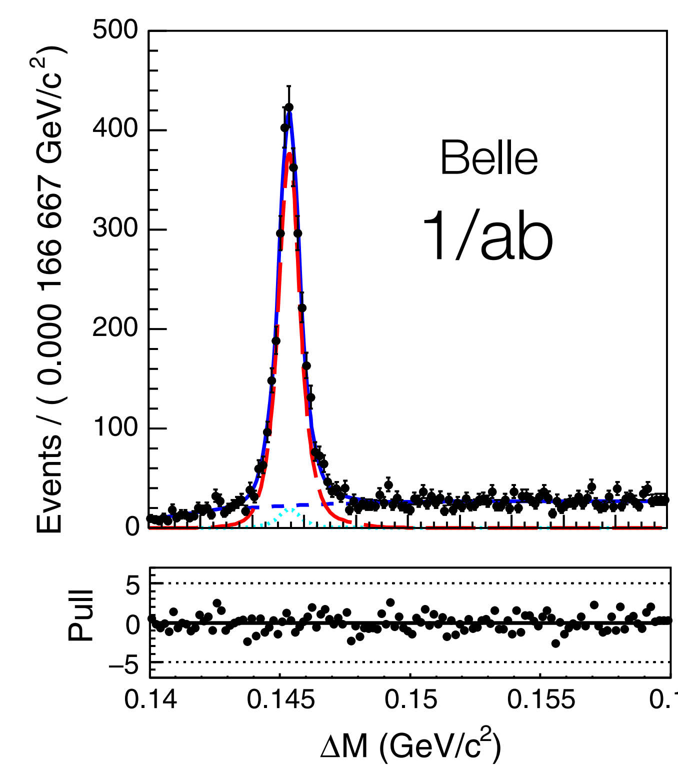
$N/\mathcal{L}$~5.4k

$D^{*+} \to D^0(\to K_S K_S)\pi^+$

$N/\mathcal{L}$~0.5k



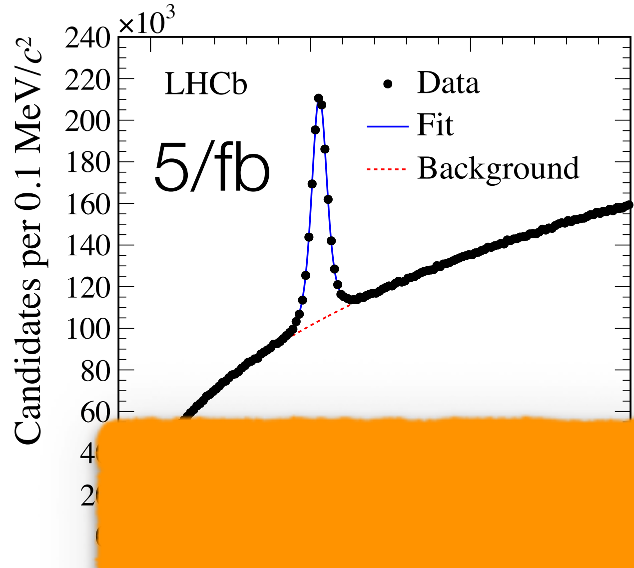
[JHEP 11 (2018) 048]



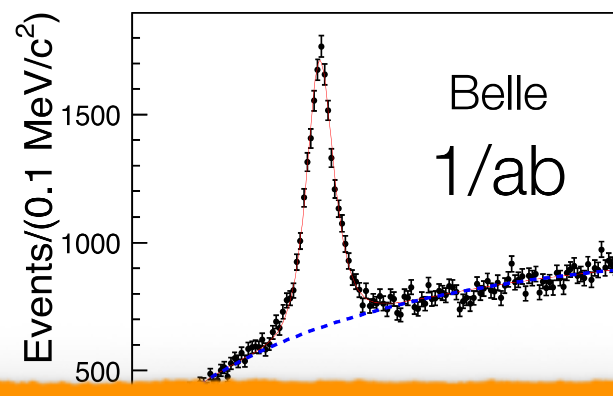
[PRL 119 (2017) 171801]

The rule of thumb

[PRD 97 (2018) 031101(R)]



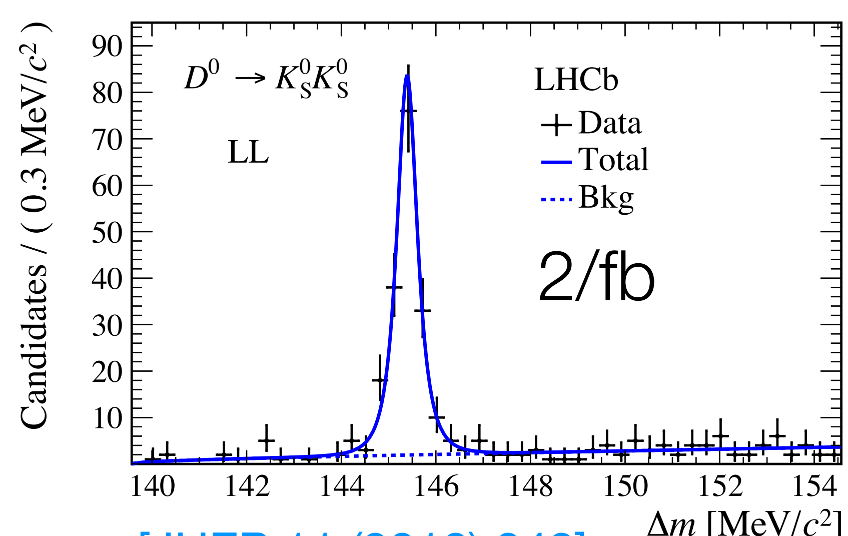
[PRL 112 (2014) 111801]



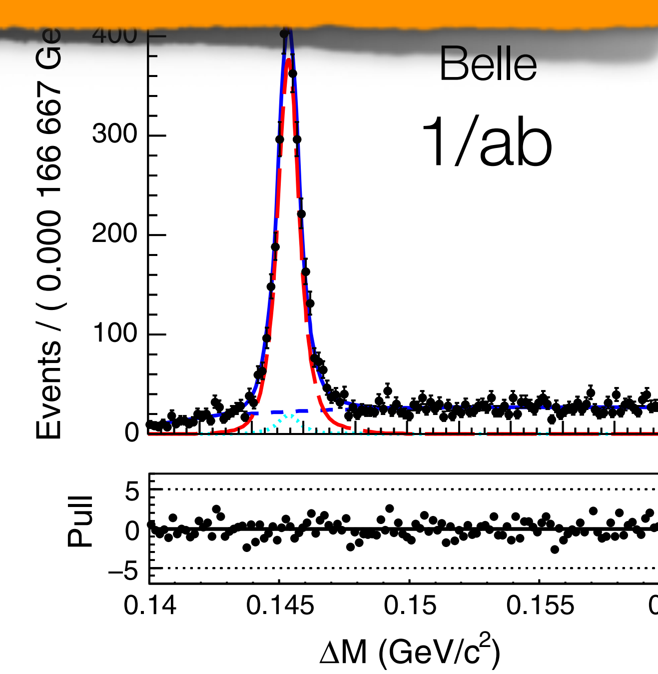
$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$

COMPLEMENTARITY

$D^{*+} \to D^0(\to K_S K_S)\pi^+$



[JHEP 11 (2018) 048]



[PRL 119 (2017) 171801]

Charm Physics program at LHCb

Mixing & *CPV*

- Time-dependent
  - $D^0 \to h^- h'^+$
  - $D^0 \to K_S h^- h^+$
- Time-integrated
  - ΔA_{CP}
  - $D^+ \to K_S h^+, \eta' h^+$
- Local *CPV* in multibody decays
- *CPV* in baryons
- …

Production & spectroscopy

- Cross sections
- Masses, lifetimes
- Amplitude analyses
- $D_{(s)J}$ states
- Charmed baryons
- Production asymmetries
- …

Rare decays

- LFV, LNV
  - $D^0 \to e^- \mu^+$
  - $D_{(s)} \to h^- \mu^+ \mu^+$
- FCNC
  - $D^0 \to \mu^- \mu^+$
  - $D^0 \to h^- h^+ \mu^- \mu^+$
  - $D_{(s)} \to h^+ \mu^- \mu^+$
- …

Charm Physics program at LHCb

Mixing & *CPV*

- Time-dependent
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Production & spectroscopy

- Cross sections
- Masses, lifetimes
- Amplitude analyses
- $D_{(s)J}$ states
- Charmed baryons
- Production asymmetries
- …

See Bostjan's talk on Monday

Rare decays

- LFV, LNV
  - $D^0 \to e^- \mu^+$
  - $D_{(s)} \to h^- \mu^+ \mu^+$
- FCNC
  - $D^0 \to \mu^- \mu^+$
  - $D^0 \to h^- h^+ \mu^- \mu^+$
  - $D_{(s)} \to h^+ \mu^- \mu^+$
- …

supplementary slides (if time allows)

Direct *CP* violation

What do we measure?

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

What do we really measure?

$$A(D^0 \to h^+h^-) = \frac{N(D^0 \to h^+h^-) - N(\overline{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\overline{D}^0 \to h^+h^-)}$$

What do we really measure?

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$$\approx A_{CP}(h^+h^-) + A_D + A_P$$

$A_{CP}(h^+h^-)$: The *CP* asymmetry we want to measure

A_D: Detection asymmetry of tagging particle (π^+ or μ^-) — D^0 final state does not contribute being charge symmetric

A_P: Production asymmetry of parent hadron (D^{*+} or $\bar{B}$)

What do we really measure?

$$A(D^0 \to h^+h^-) = \frac{N(D^0 \to h^+h^-) - N(\overline{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\overline{D}^0 \to h^+h^-)}$$

$$\approx A_{CP}(h^+h^-) + A_D + A_P$$

The *CP* asymmetry we want to measure

Detection asymmetry of tagging particle (π^+ or μ^-) — D^0 final state does not contribute being charge symmetric

Production asymmetry of parent hadron (D^{*+} or $\bar{B}$)

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A(K^+K^-) - A(\pi^+\pi^-)$$

What do we really measure?

$$A(D^0 \to h^+h^-) = \frac{N(D^0 \to h^+h^-) - N(\overline{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\overline{D}^0 \to h^+h^-)}$$

$$\approx A_{CP}(h^+h^-) + A_D + A_P$$

The *CP* asymmetry we want to measure

Detection asymmetry of tagging particle (π^+ or μ^-) — D^0 final state does not contribute being charge symmetric

Production asymmetry of parent hadron (D^{*+} or $\bar{B}$)

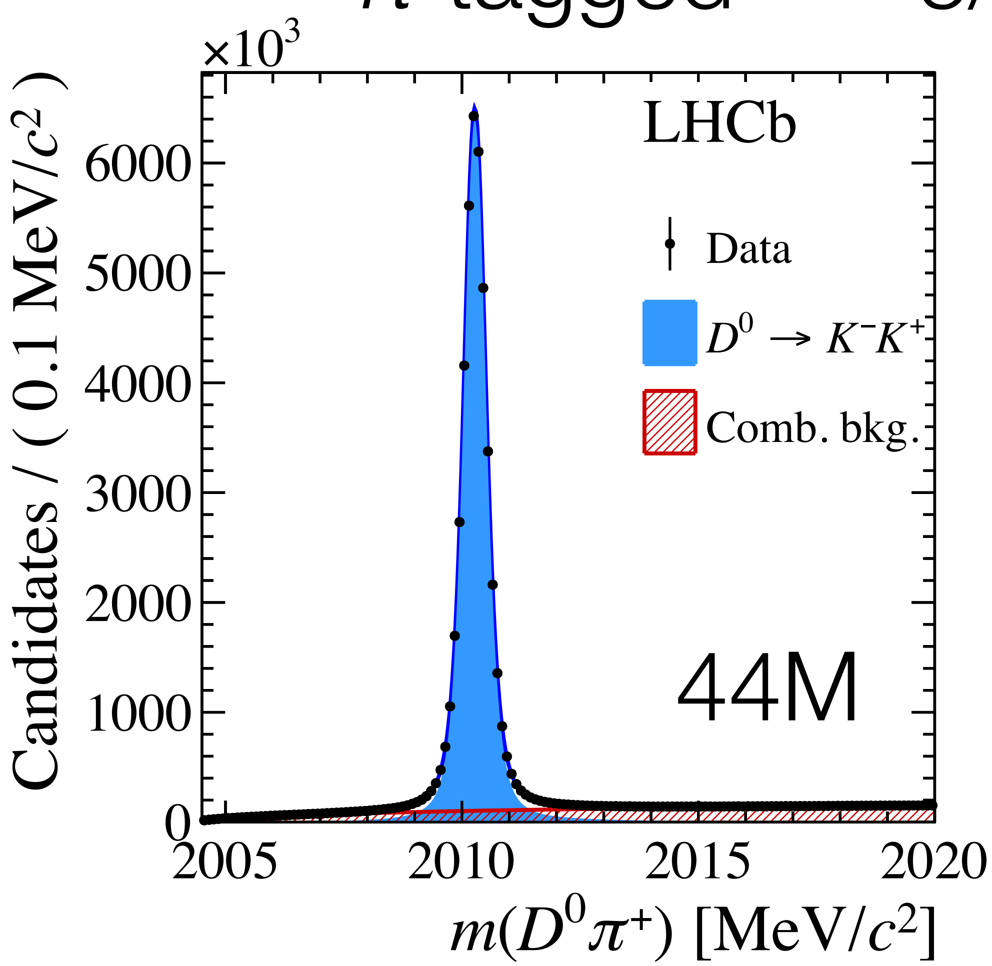
$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A(K^+K^-) - A(\pi^+\pi^-)$$

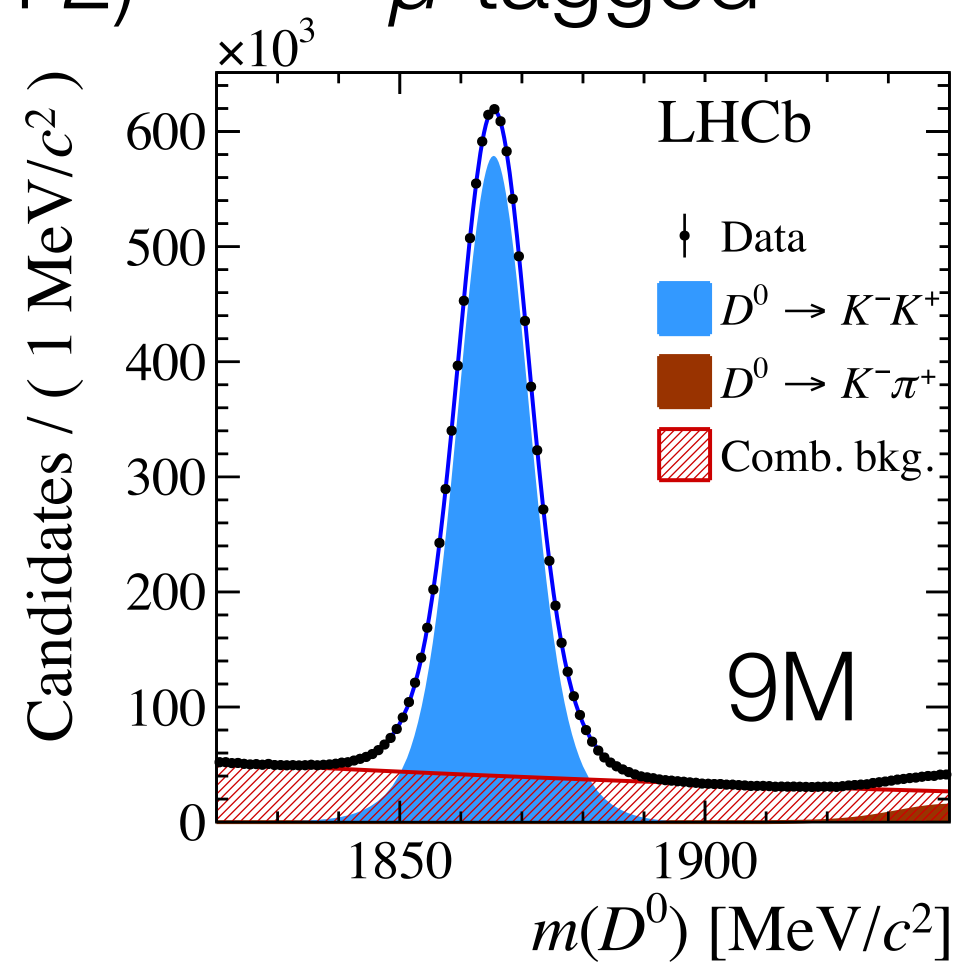
- In the limit of SU(3)/U-spin symmetry, $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ have same magnitude and opposite signs $\Longrightarrow$ in addition to be robust against experimental biases, ΔA_{CP} provides 2× enhanced sensitivity to *CP* violation

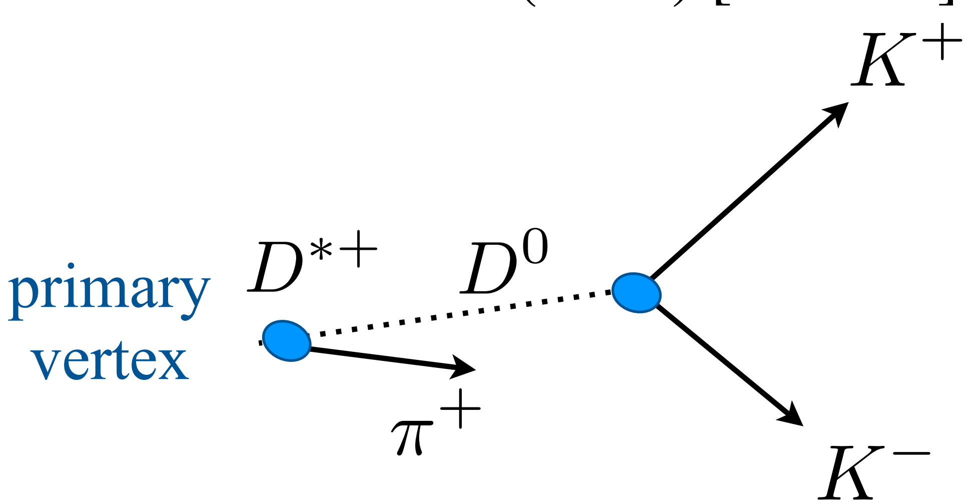
$D^0 \to h^+h^-$ decays at LHCb

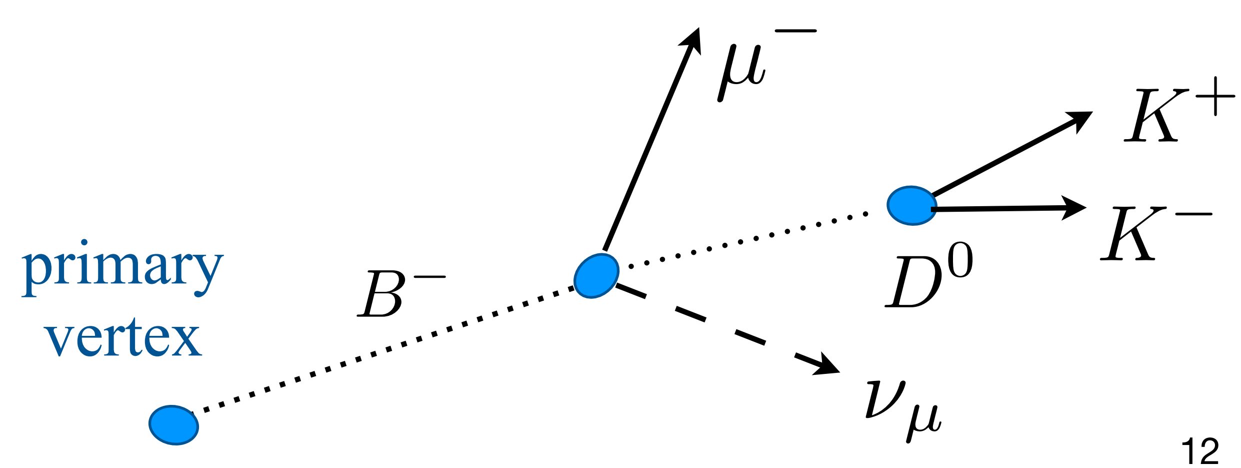
[PRL 122 (2019) 211803]

π tagged 6/fb (Run 2) μ tagged



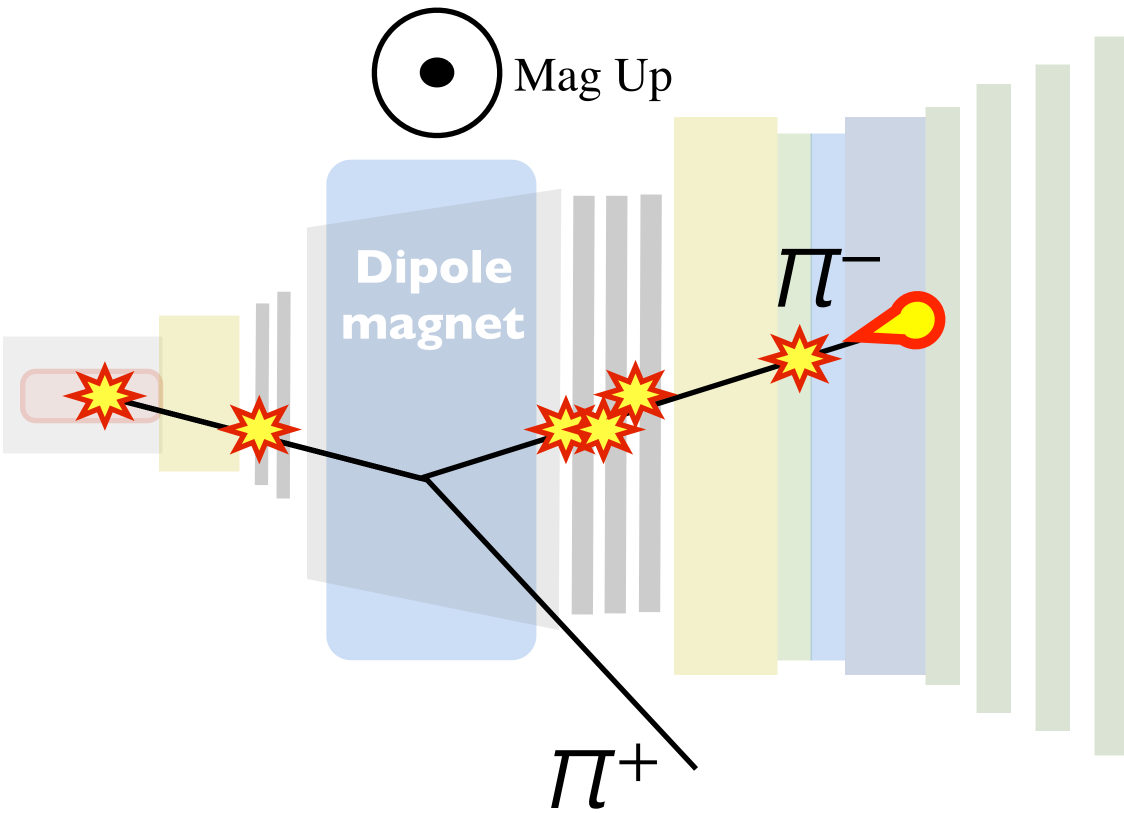




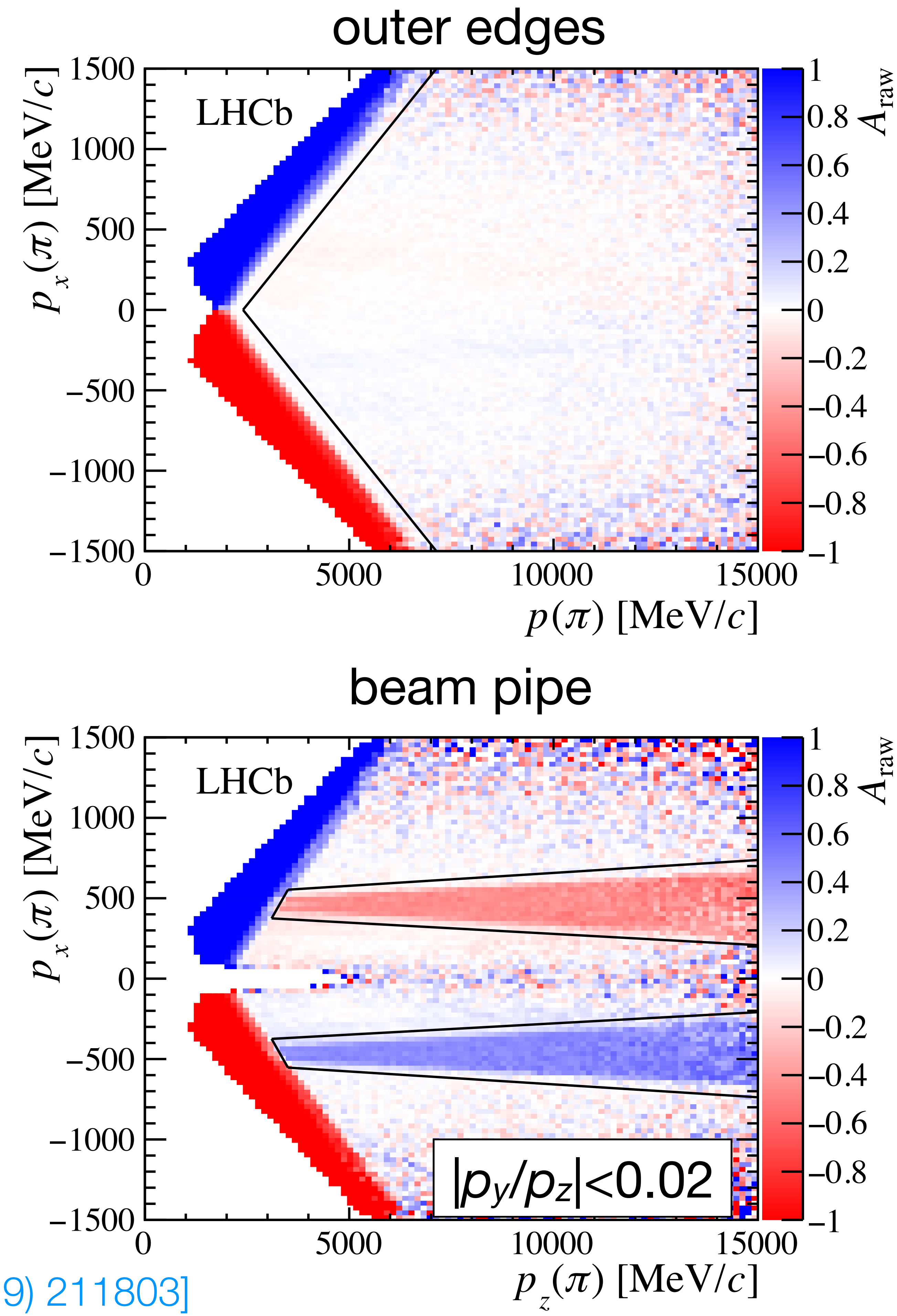


Fiducial requirements

- For specific regions of phase space, the soft pion of a given charge is kicked out of the detector acceptance by the magnetic field



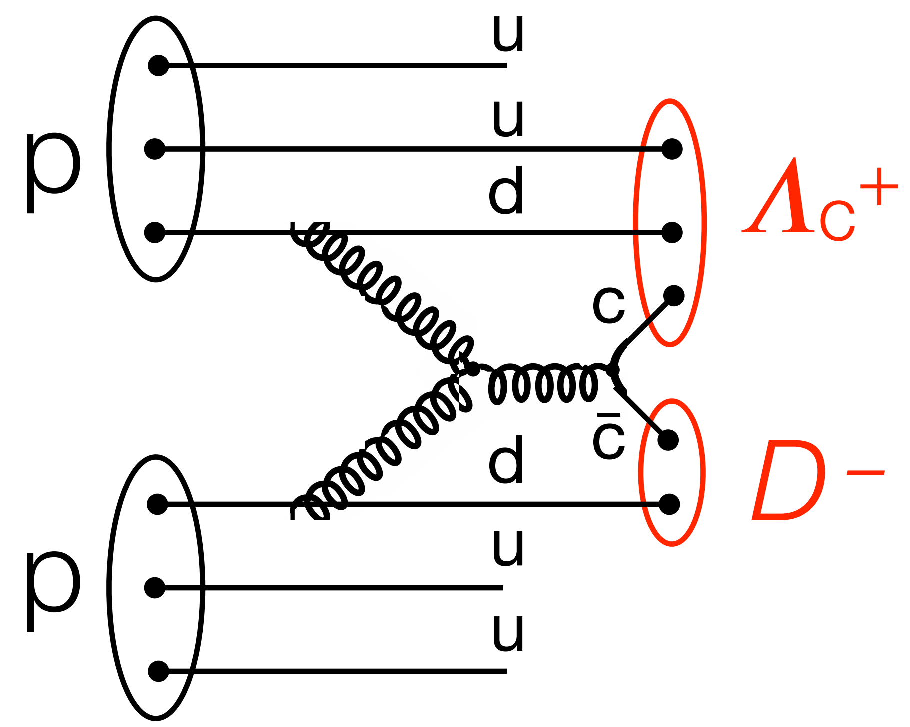
- $O(1)$ detection asymmetries break the linear decomposition of the raw asymmetry

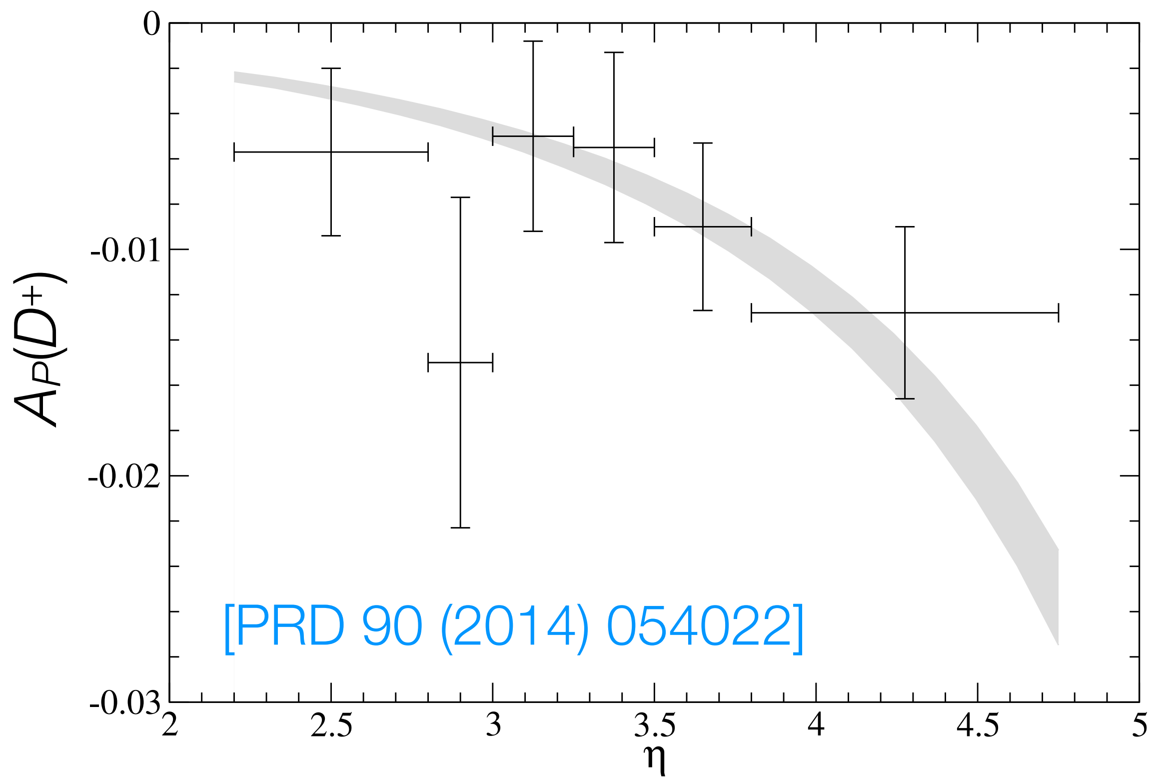


[PRL 122 (2019) 211803]

Production asymmetry

- In *pp* collision charm quarks are produced mostly through gluon fusion (which is charge symmetric)
- However, the c and the $\bar{c}$ quarks may “recombine” with some of the proton valence quarks (beam-drag effect) creating an asymmetric production of charm mesons or baryons
- The effect is enhanced in the forward region, where the charm pair is collinear with the protons’ direction

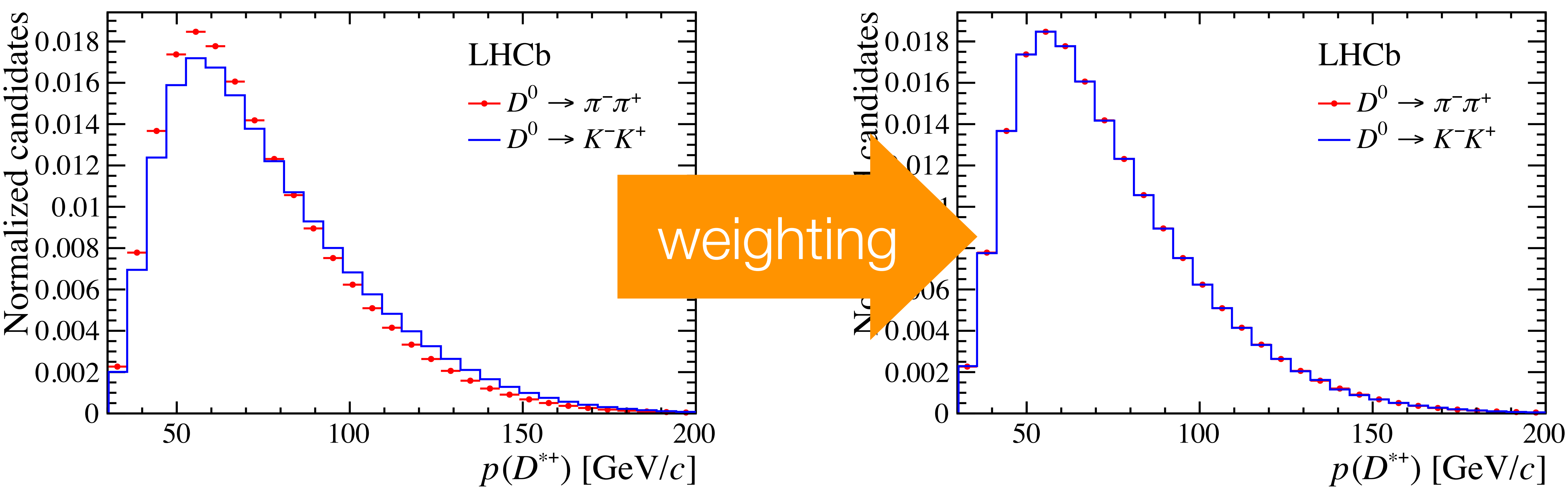




Kinematic weighting

[PRL 122 (2019) 211803]

- Detection and production asymmetries are expected to depend on kinematics
- Their cancelation may not be accurate if the kinematic distributions of the reconstructed $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ candidates differ
- Observed differences are removed through a weighting procedure — the resulting net effect on ΔA_{CP} is anyhow marginal (below 10^{-4})



Results

[PRL 122 (2019) 211803]

ΔA_{CP} [10^{-4}]

$-18.2 \pm$	3.2 (stat) $\pm$ 0.9 (syst)	π tagged (Run 2)
$-9 \pm$	8 (stat) $\pm$ 5 (syst)	μ tagged (Run 2)

Results

[PRL 122 (2019) 211803]

ΔA_{CP} $[10^{-4}]$	
$-18.2 \pm 3.2\,(\text{stat}) \pm 0.9\,(\text{syst})$	π tagged (Run 2)
$-9 \pm 8\,(\text{stat}) \pm 5\,(\text{syst})$	μ tagged (Run 2)
$-10 \pm 8\,(\text{stat}) \pm 3\,(\text{syst})$	π tagged (Run 1) [PRL 116 (2016) 191601]
$-14 \pm 16\,(\text{stat}) \pm 8\,(\text{syst})$	μ tagged (Run 1) [JHEP 07 (2014) 041]

Results

[PRL 122 (2019) 211803]

ΔA_{CP} [10^{-4}]	
-18.2 ± 3.2 (stat) ± 0.9 (syst)	π tagged (Run 2)
-9 ± 8 (stat) ± 5 (syst)	μ tagged (Run 2)
-10 ± 8 (stat) ± 3 (syst)	π tagged (Run 1) [PRL 116 (2016) 191601]
-14 ± 16 (stat) ± 8 (syst)	μ tagged (Run 1) [JHEP 07 (2014) 041]
-15.4 ± 2.9 (stat+syst)	combined

5.3σ deviation from zero

first observation of *CP* violation in charm

Now what?

- Measured value is in the ballpark of the standard model value
- Difficult to say if new physics is at play. Need better control of the QCD effects
- Experimentally look for *CP* violation in radiative decays, test isospin sum rules and SU(3) related modes
- Huge program of measurements, where Belle II role with neutrals will be crucial

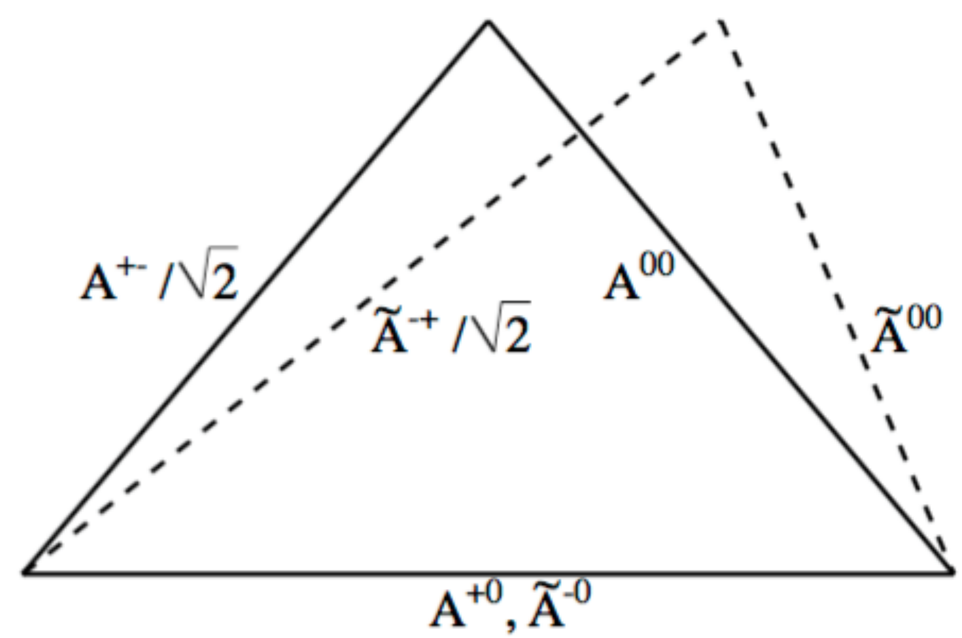
from Alexey's talk yesterday

- several final states possible, for D → $\pi^i \pi^k$

$$\frac{1}{\sqrt{2}}A^{+-} = A^{+0} - A^{00},$$
$$\frac{1}{\sqrt{2}}\overline{A}^{-+} = \overline{A}^{-0} - \overline{A}^{00},$$

Gronau, London
Bevan, Meadows

- others include D → $\pi\pi$, $\rho\pi$, $\rho\rho$



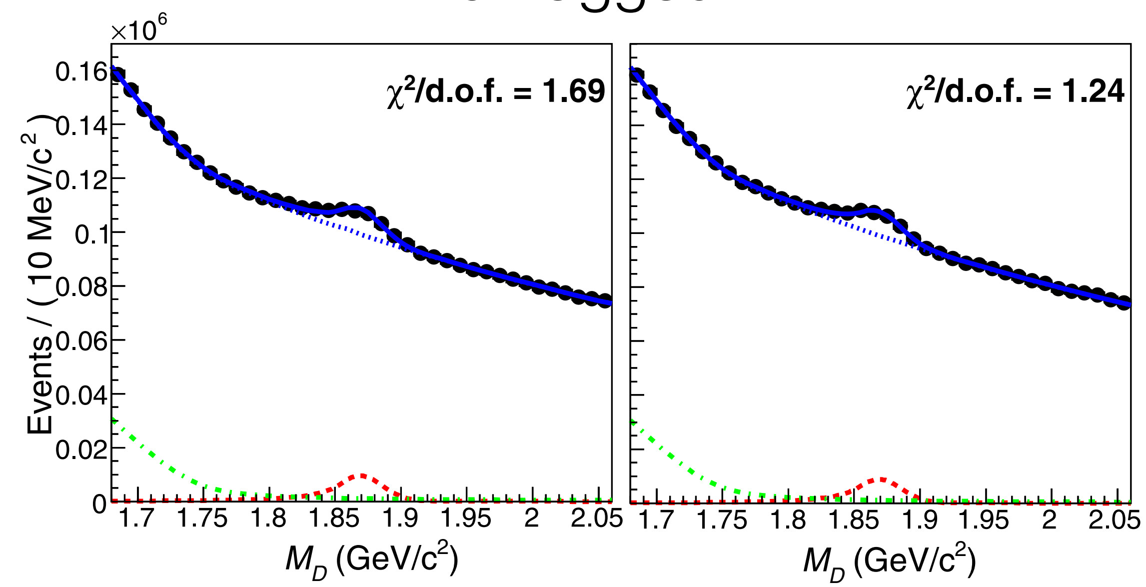
CP violation in $D^+ \to \pi^+\pi^0$ decays

- In the standard model ΔA_{CP} comes from ΔU=0 transitions
- *CP* violation in ΔU=1, *e.g.* in $D^+ \to \pi^+\pi^0$, would unambiguously be new physics
- Current best measurement from Belle (1/ab)

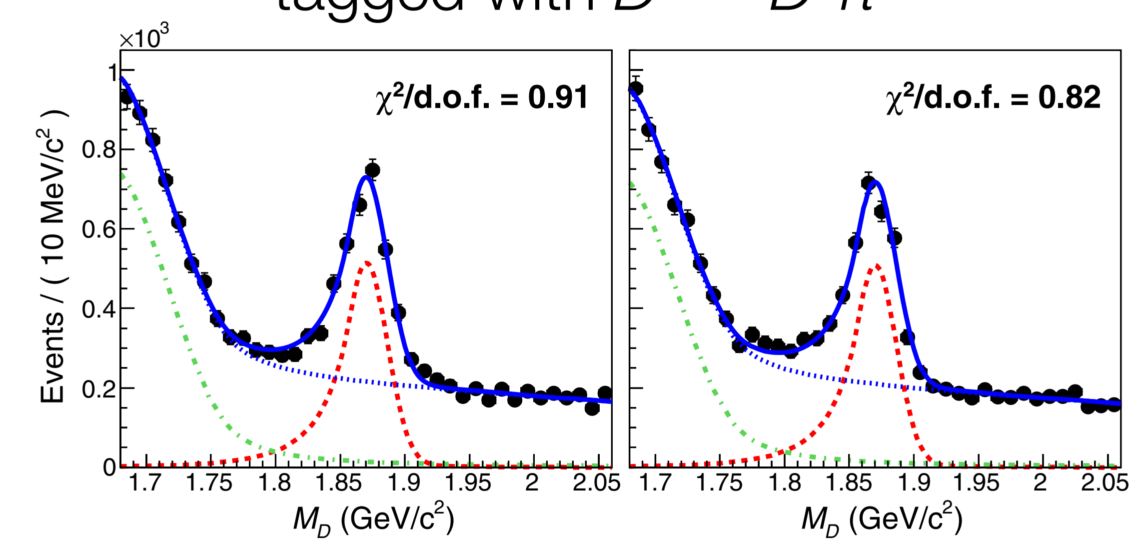
$$A_{CP} = (2.3 \pm 1.2 \pm 0.2)\%$$

- D^{*+} tagging crucial in suppressing the background
- Similar performances expected for Belle II. Sensitivity with 50/ab ~0.17%, maybe possible at LHCb but difficult

untagged



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



[PRD 97 (2018) 011101(R)]

Prospects for direct *CP* violation

LHCb-PUB-2018-009

The Belle II Physics Book

Decay mode	Current best sensitivity (stat + syst) [10^{-3}]		LHCb 300/fb (stat only) [10^{-3}]	Belle II 50/ab (stat+syst) [10^{-3}]
ΔA_{CP}	0.29	LHCb (9/fb)	0.03	0.6
$D^0 \to K^+K^-$	1.8	LHCb (3/fb)	0.07	0.3
$D^0 \to \pi^+\pi^-$	1.8	LHCb (3/fb)	0.07	0.5
$D^0 \to \pi^0\pi^0$	6.5	Belle (1/ab)	(?)	0.9
$D^0 \to K^+\pi^-$	9.1	LHCb (5/fb)	0.5	(4.0)
$D^0 \to K_S K_S$	15	Belle (1/ab)	2.8	2.1
$D_s \to K_S \pi^+$	18	LHCb (6.8/fb)	0.32	2.9
$D^+ \to K_S K^+$	0.76	LHCb (6.8/fb)	0.12	0.4
$D^0 \to \phi\gamma$	66	Belle (1/ab)	(?)	10
$D^0 \to \rho^0\gamma$	150	Belle (1/ab)	(?)	20
$D^+ \to \phi\pi^+$	0.49	LHCb (4.8/fb)	0.06	0.4
$D^+ \to \pi^0\pi^+$	13	Belle (1/ab)	(?)	1.7

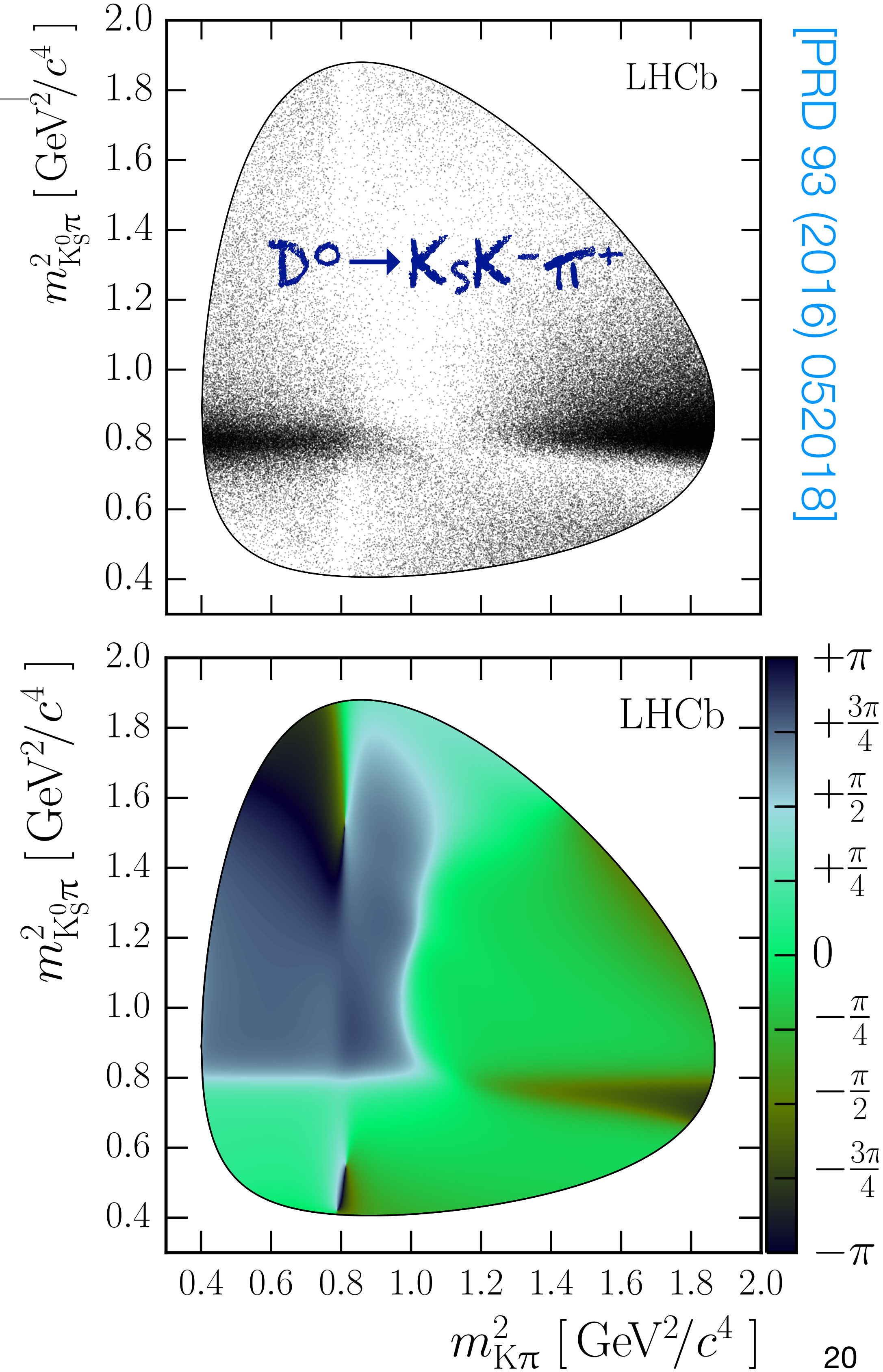
CPV in multi-body decays

- Enriched dynamics of multi-body decays allows to look for *CP* violation in subregions of the phase space
  - Additional sensitivity with respect to global asymmetries (which could average to zero for small values of δ)

$$A_{CP} \sim \sin\phi \sin\delta$$

  - Mostly insensitive to production and detection asymmetries
- Both model-dependent and model-independent measurements are possible
- 4-body final states give also access to *CP* violation in *P*-odd amplitudes (~cos δ)

μ tagged Run 1 (3/fb)

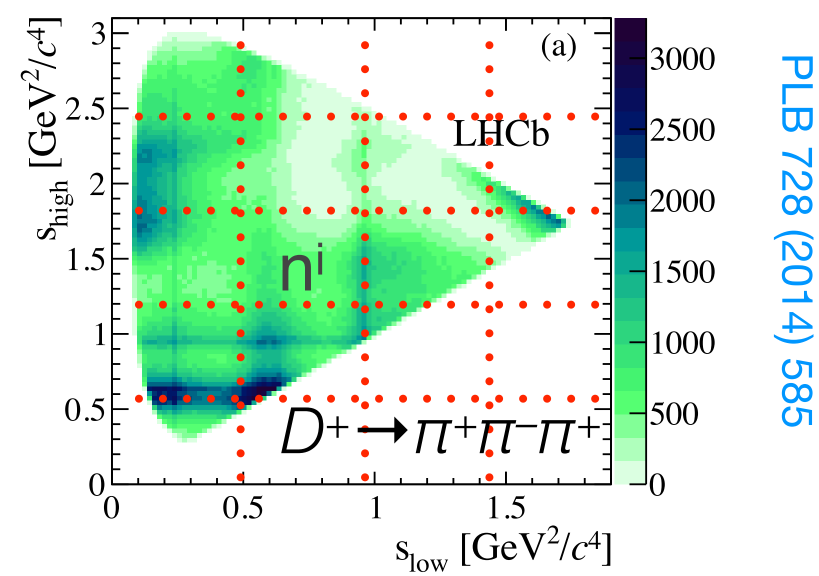


[PRD 93 (2016) 052018]

Search for "local" *CP* violation across Dalitz plot

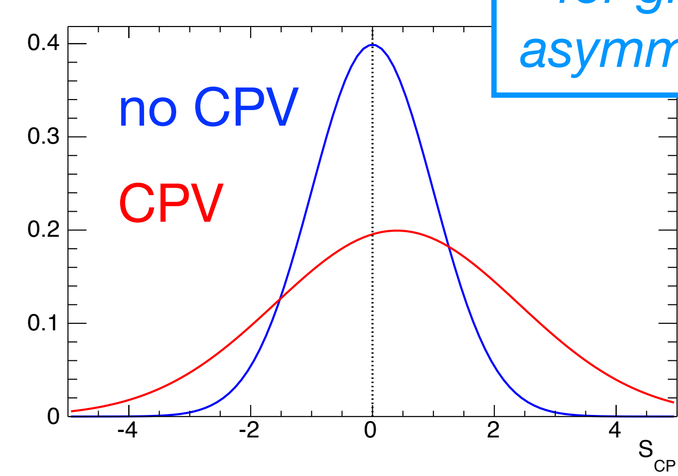
- Compute local *CP* asymmetry in different bins of the Dalitz plot
- In absence of *CP* violation, the distribution of local asymmetry is Gaussian with zero mean and unit variance
- Get *p*-value from $\chi^2 = \sum_i \left(S^i_{\rm CP}\right)^2$
- Test several binning schemes (same number of events/same strong phase) to enhance sensitivity

Binned (a.k.a. Miranda) method



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

to account for global asymmetries $\alpha = \frac{N(D^+)}{N(D^-)}$



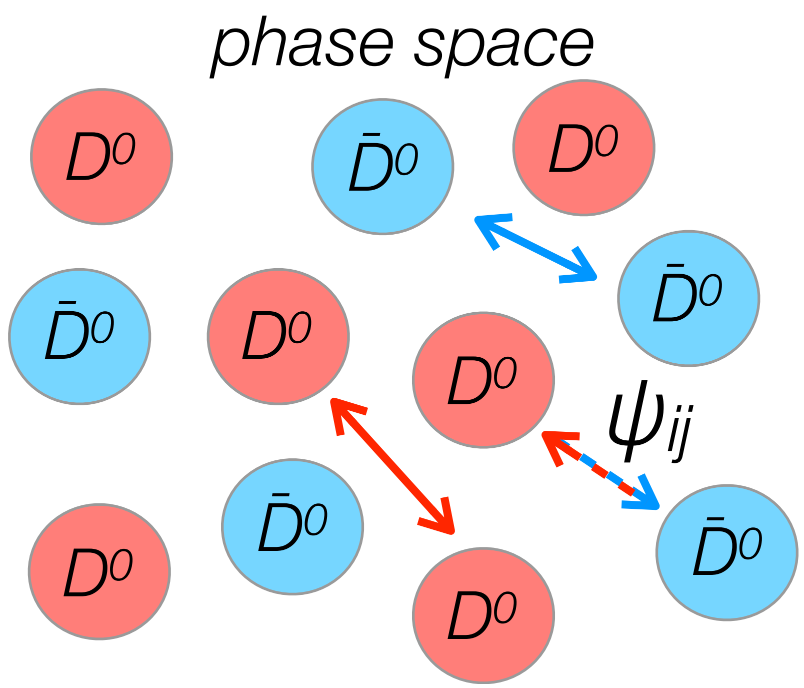
Local CPV in $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays

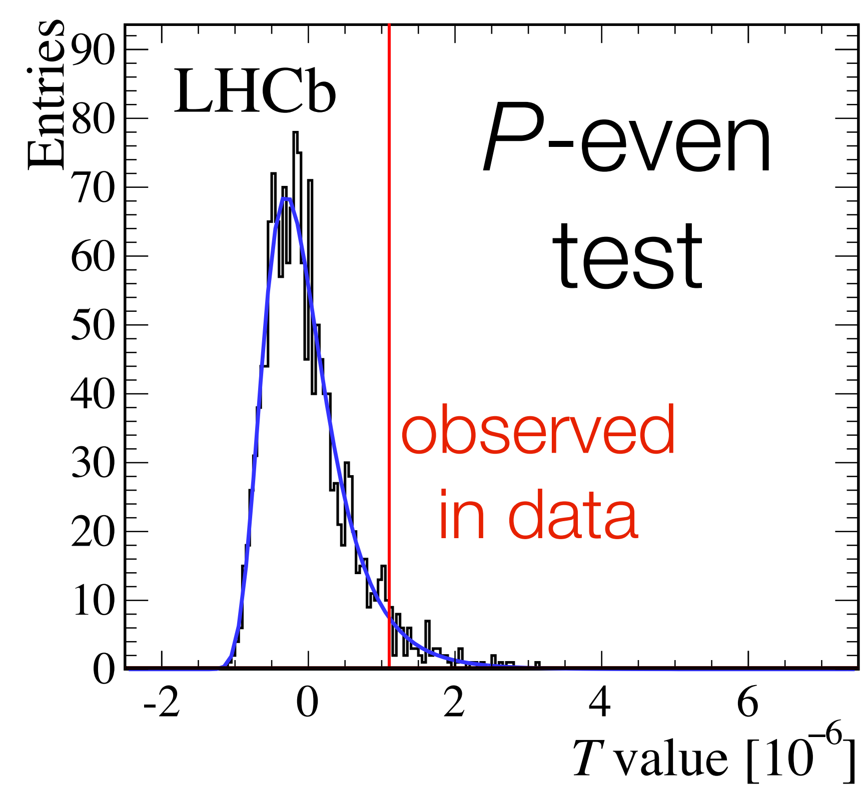
[PLB 769 (2017) 345]

- Statistical comparison of two distributions based on distance in phase space between pairs of particles

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}},$$

- Compare with T distribution of no CP-violation case (randomize D flavor)
- Consistent with CP symmetry (in P-even amplitudes)





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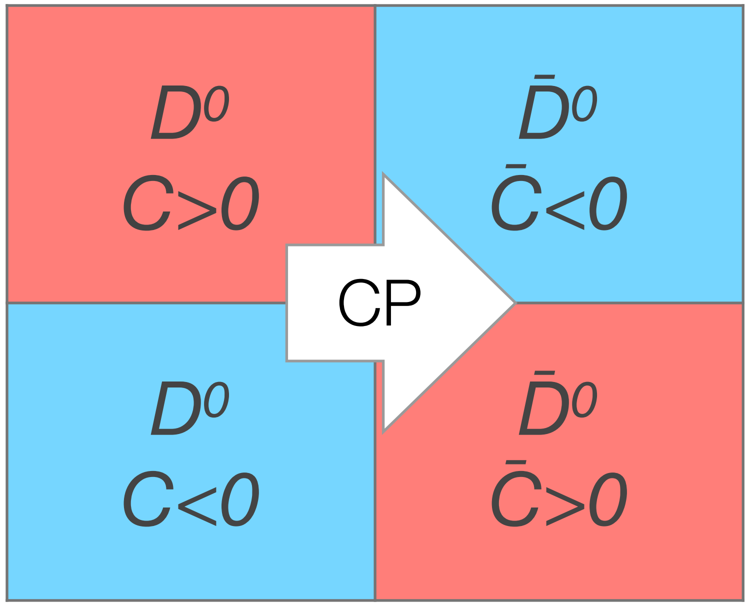
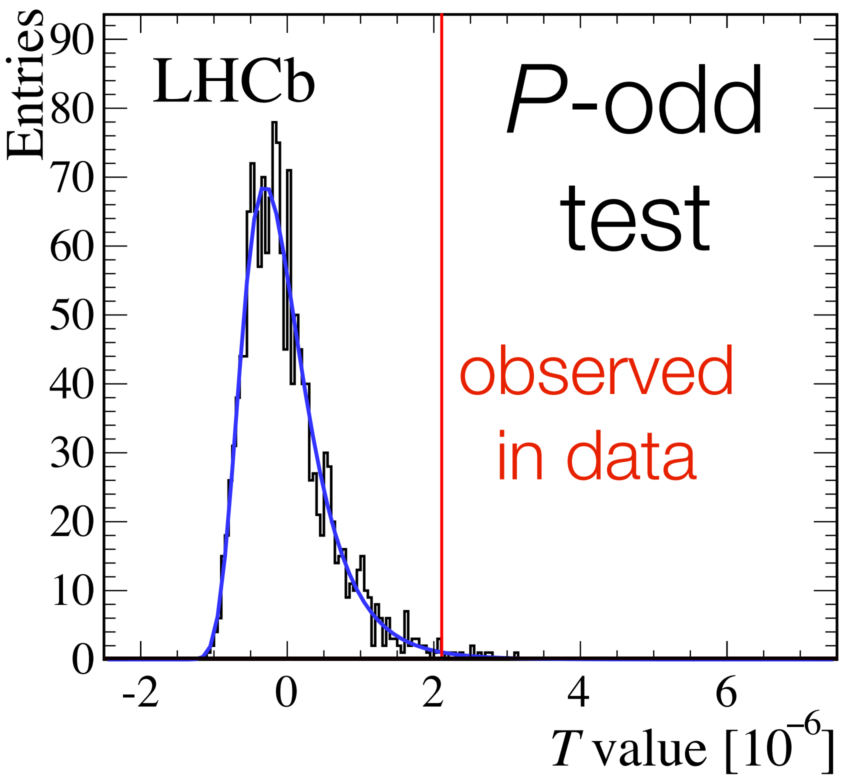
- Compare with T distribution of no CP-violation case (randomize D flavor)
- Use triple product to access P-odd CP violation

$$C = \vec{p}_{\pi^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$
$$\bar{C} = \vec{p}_{\pi^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

- Results is marginally consistent with CP symmetry (2.7σ)





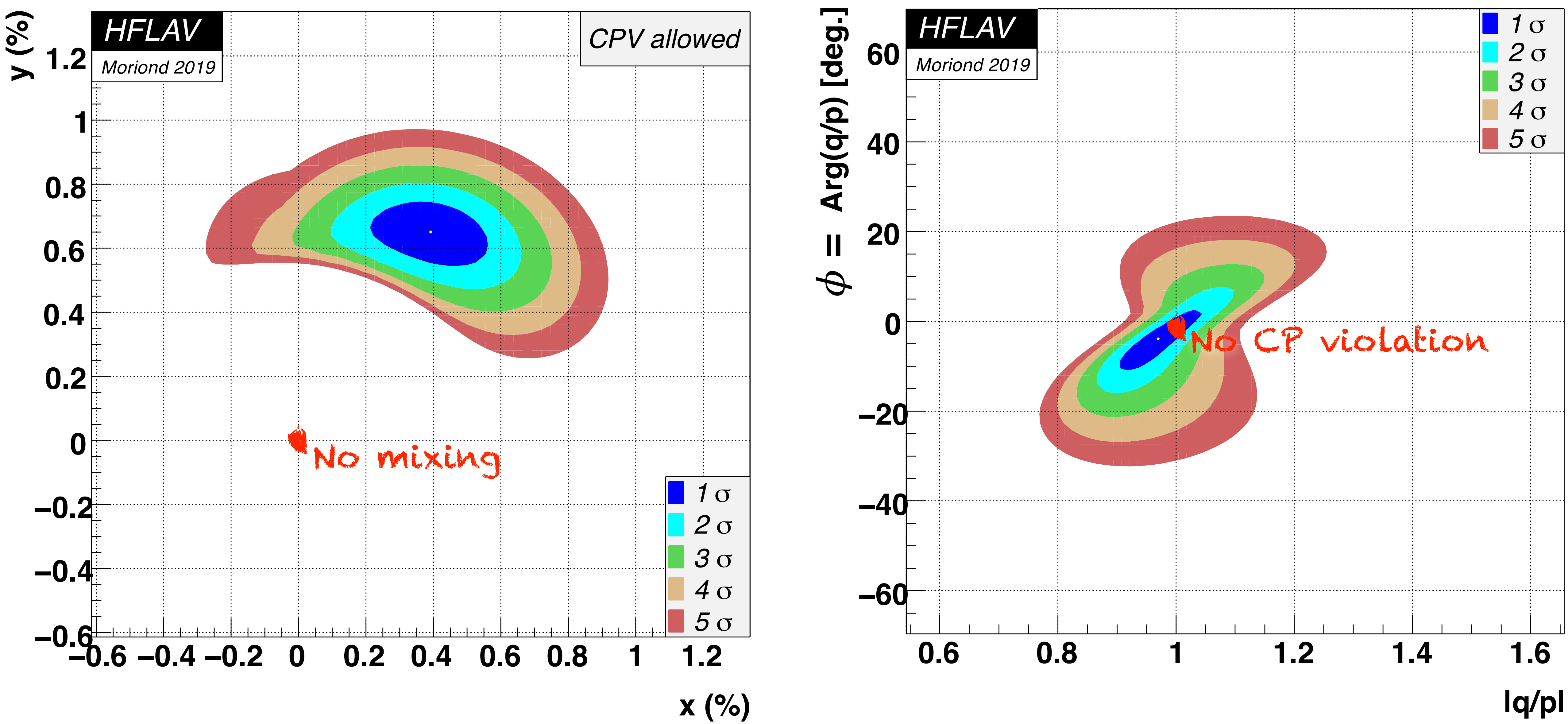
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$x = (m_1 - m_2)/\Gamma$$

$$y = (\Gamma_1 - \Gamma_2)/2\Gamma$$

Mixing-induced *CP* violation

Experimental status



$$x = (3.9 \ {}^{+1.1}_{-1.2}) \times 10^{-3}$$

$$y = (6.51 {}^{+0.63}_{-0.69}) \times 10^{-3}$$

$$|q/p| = 0.969 {}^{+0.050}_{-0.045}$$

$$\phi = (-3.9 {}^{+4.5}_{-4.6})^{\circ}$$

[PRD 97 (2018) 031101(R)]

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

$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-|t)}{\Gamma(D^0 \to K^-\pi^+|t)} \approx R_D + \sqrt{R_D}y' \left(\frac{t}{\tau}\right) + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

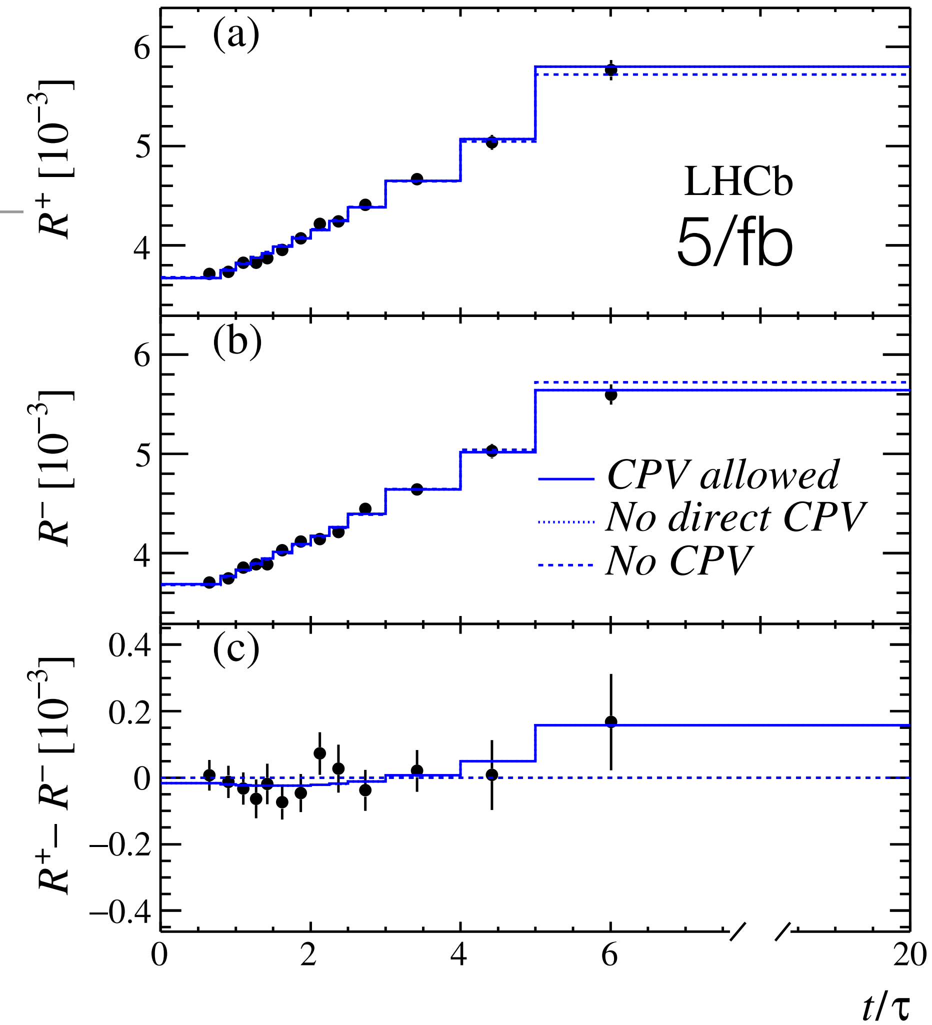
- The latest analysis from LHCb (5/fb) measures

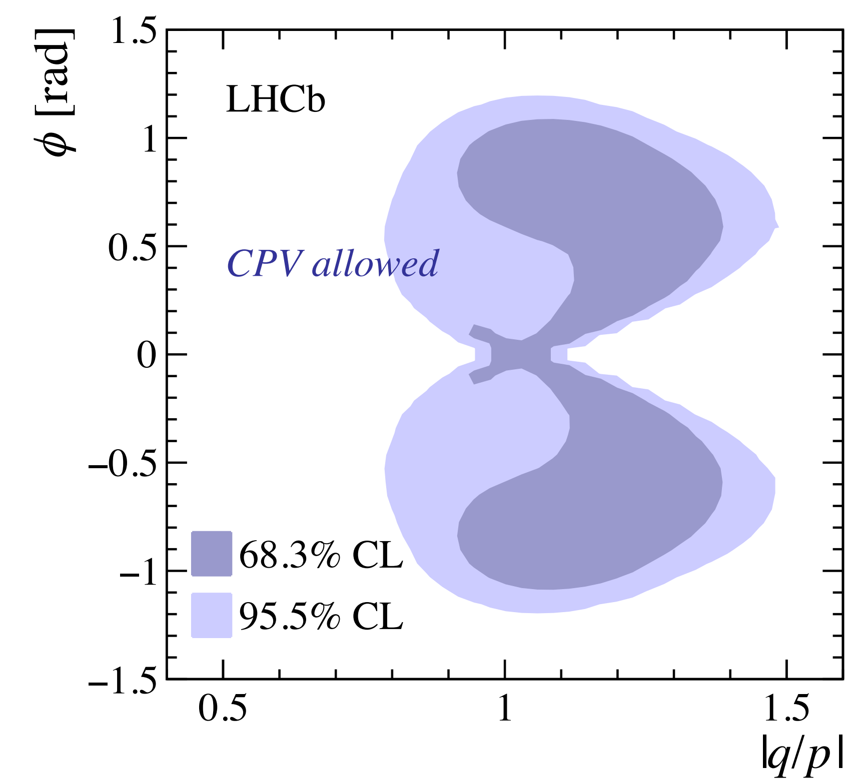
$$x'^2 = (3.9 \pm 2.7) \times 10^{-5}$$
$$y' = (5.28 \pm 0.52) \times 10^{-3}$$

and provides stringent bounds on direct *CPV* in DCS decays and *CPV* in mixing

$$1.00 < |q/p| < 1.35 \text{ @ } 68\% \text{ CL}$$

- Belle II sensitivity with 50/ab not sufficient to compete with LHCb 9/fb



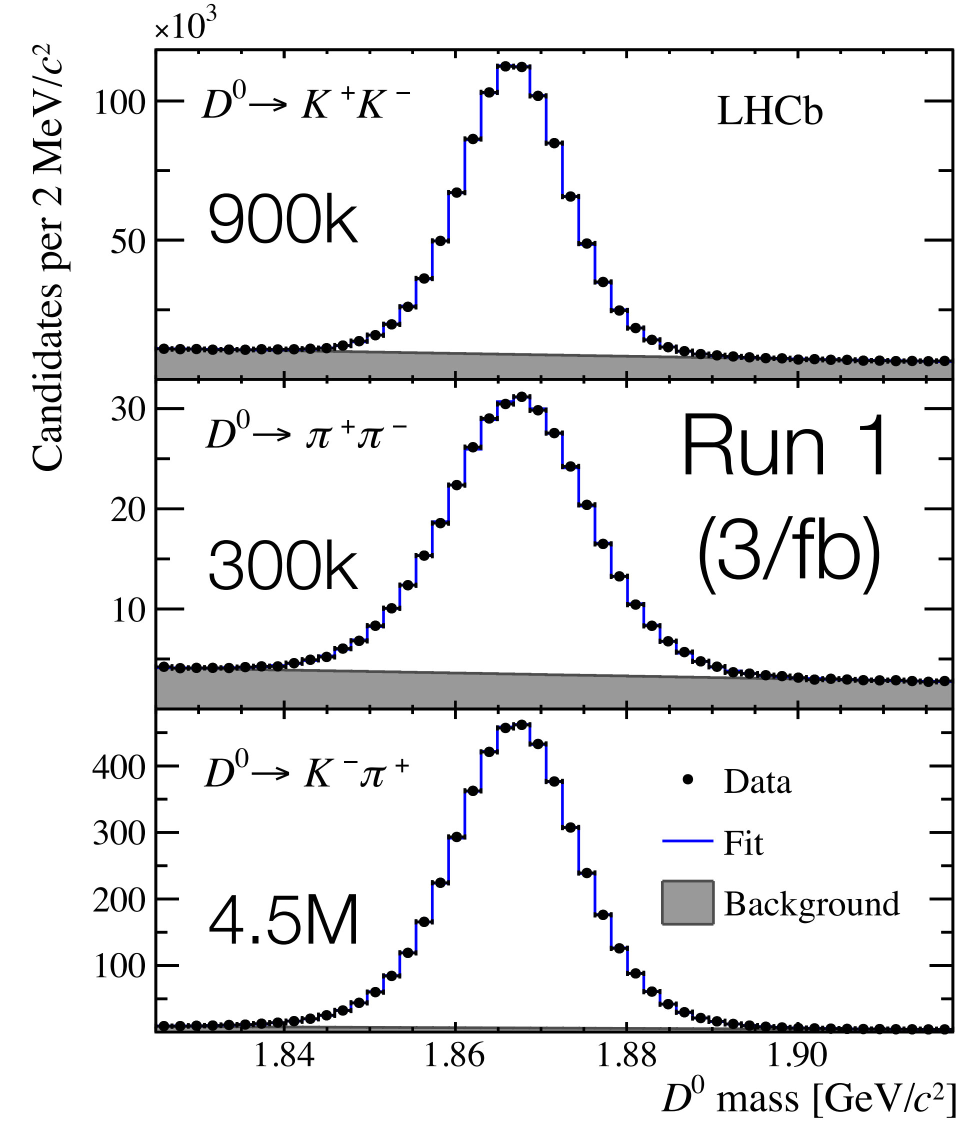


Measurement of y_{CP}

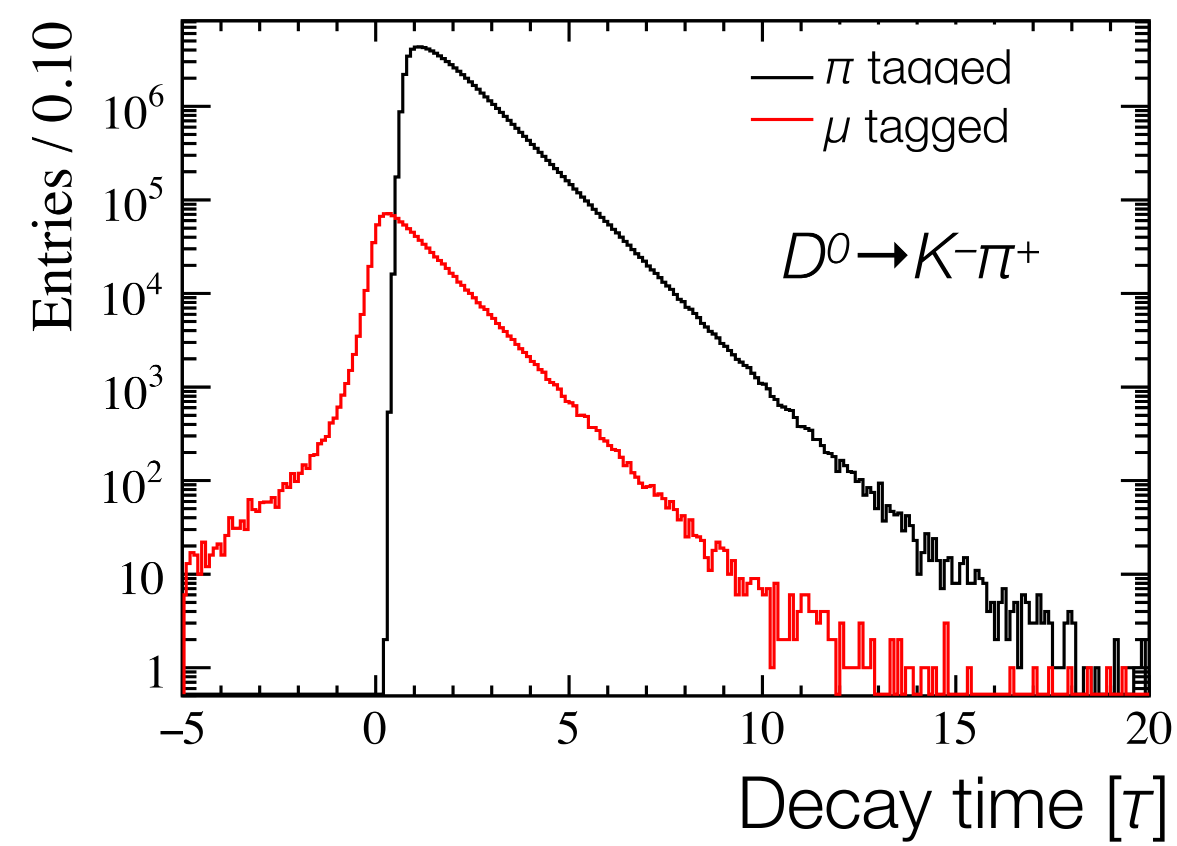
- Effective lifetime of decays to *CP*-even final state (relative to *CP*-mixed)

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

- Equal to *y* in case of *CP* symmetry
- Use μ-tagged decays to reduce biases on D^0 decay time
- Result with Run 1 data is as precise as the world average
- If LHCb does not manage to analyze the π-tagged sample, could be a measurement where Belle II can compete



[PRL 122 (2019) 011802]



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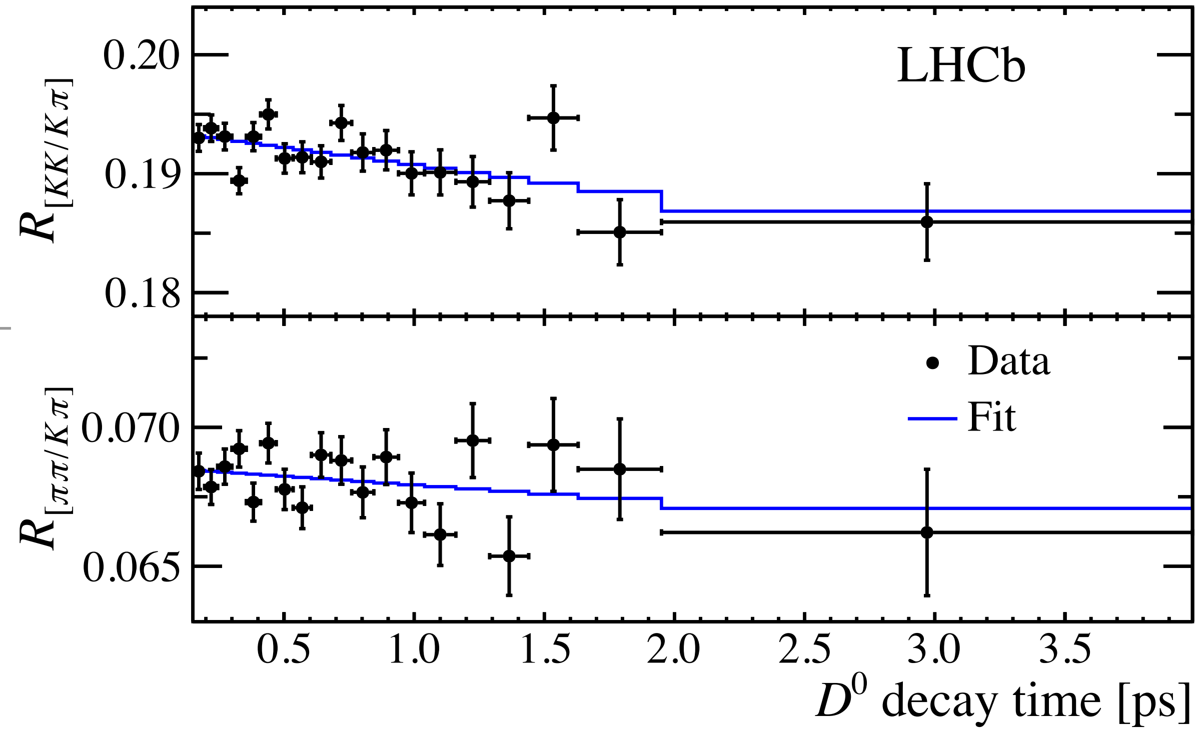
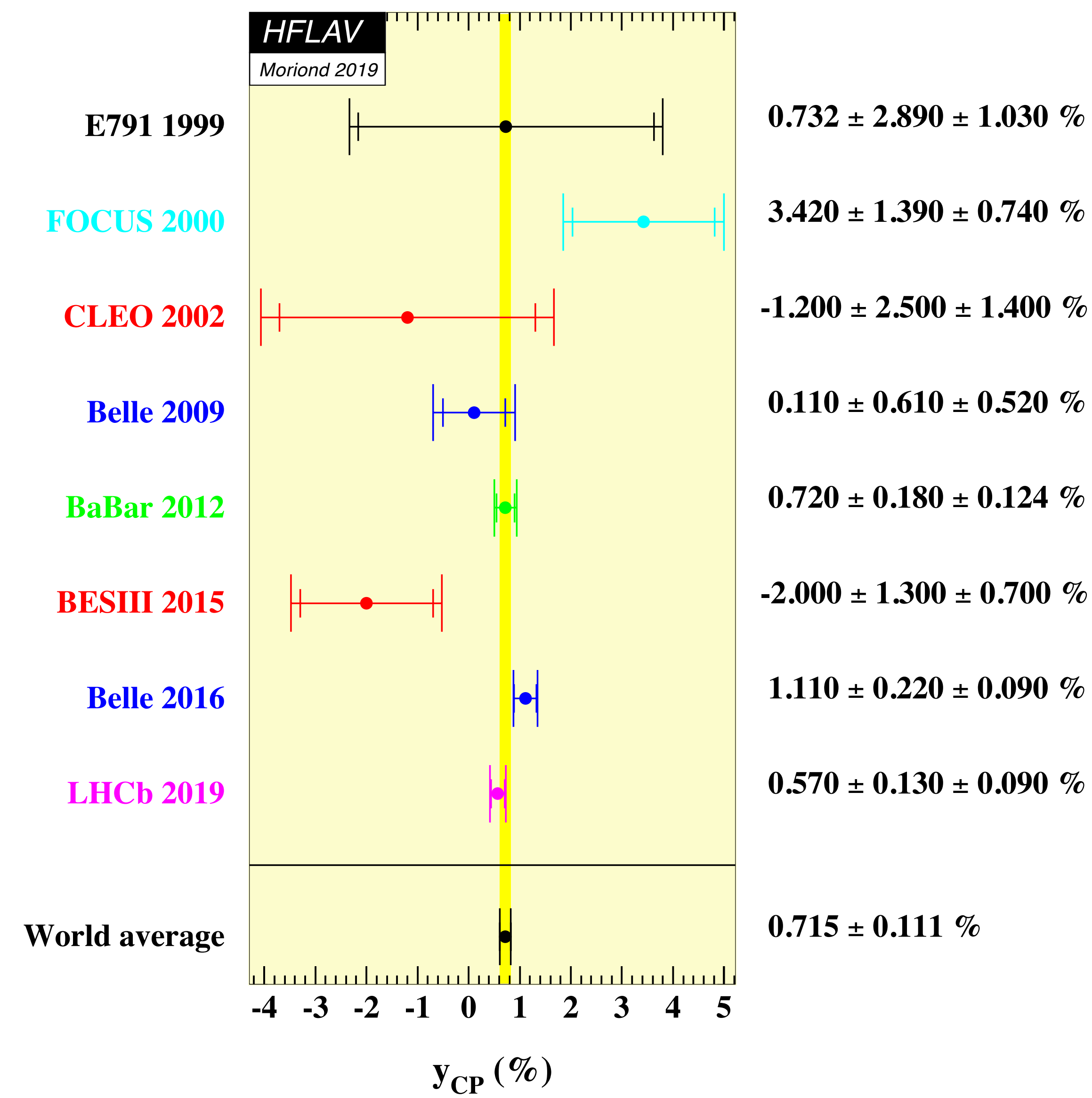


[PRL 122 (2019) 011802]



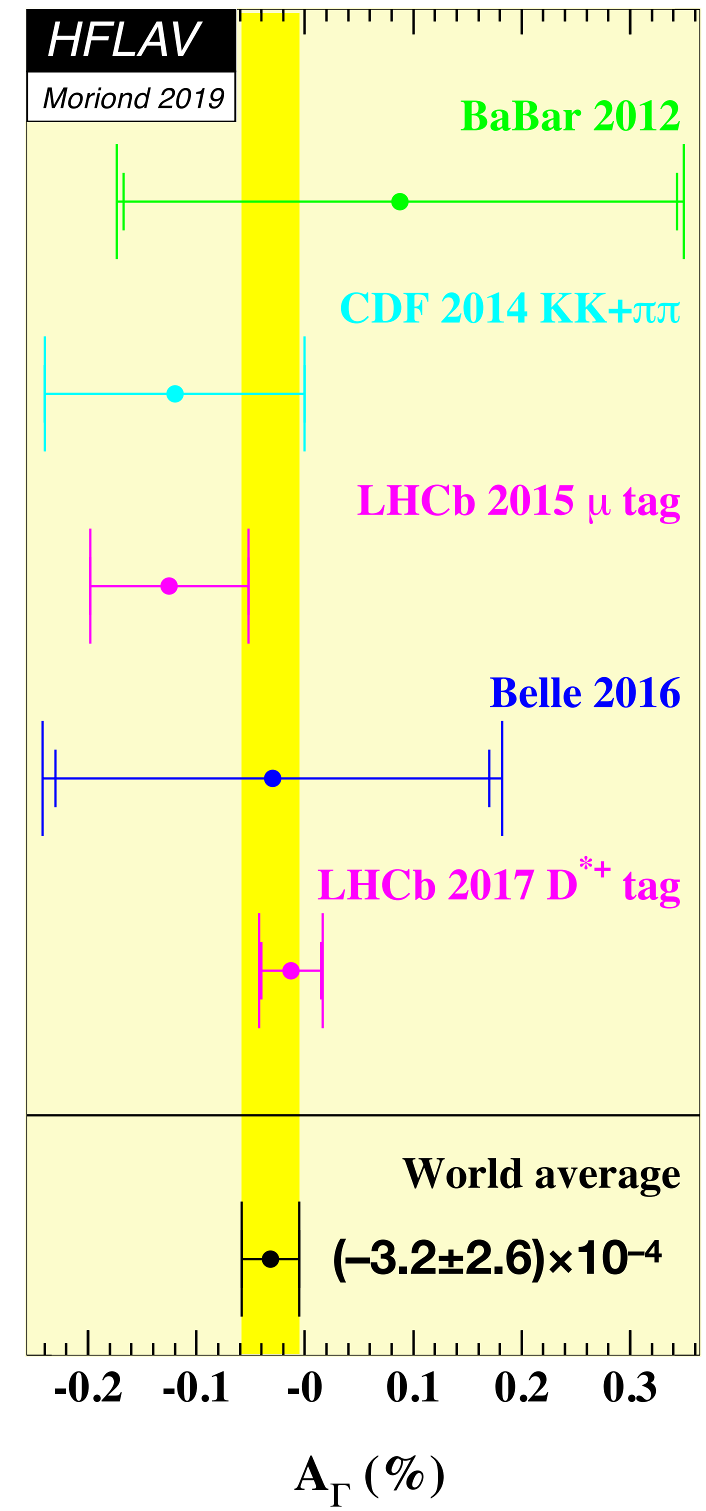
Time-dependent CP asymmetry in $D^0 \to h^+h^-$

- Small D^0-$\bar{D}^0$ mixing rate implies that time-dependent CP asymmetries can be approximated as

$$A_{CP}(h^+h^-) \approx a_{CP}^{\mathrm{dir}}(h^+h^-) - \frac{t}{\tau} A_\Gamma$$

- Mixing-induced CP violation results in a nonzero value of the linear term

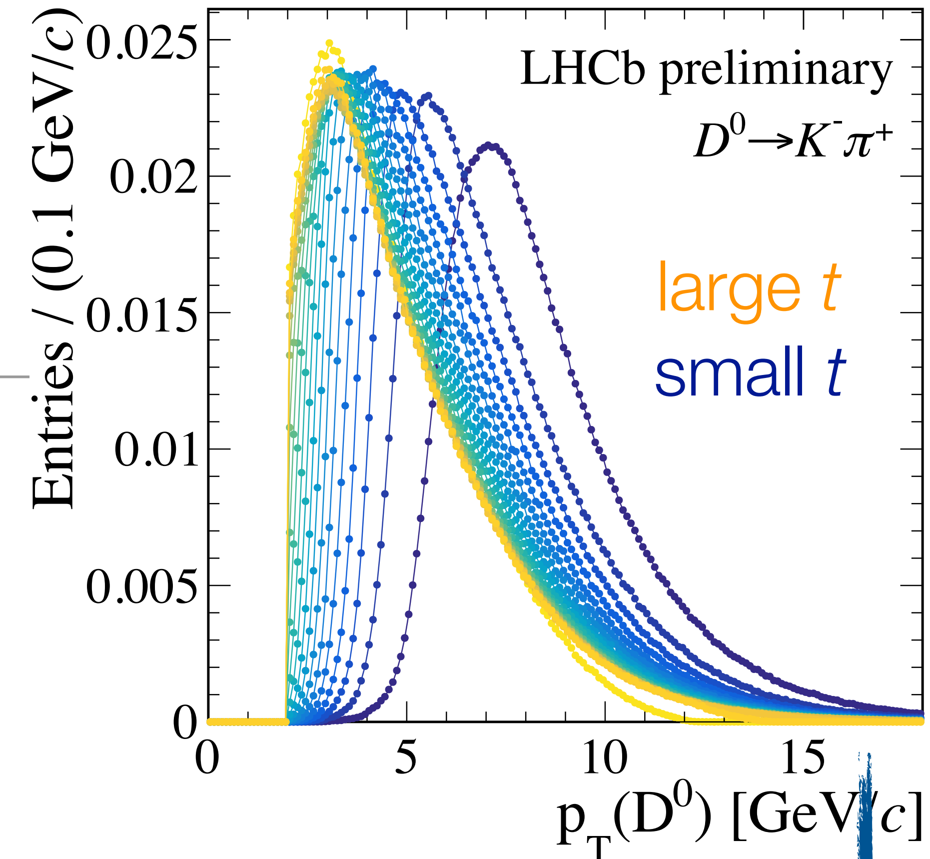
- Standard model expectation is at least one order of magnitude below the current experimental sensitivity



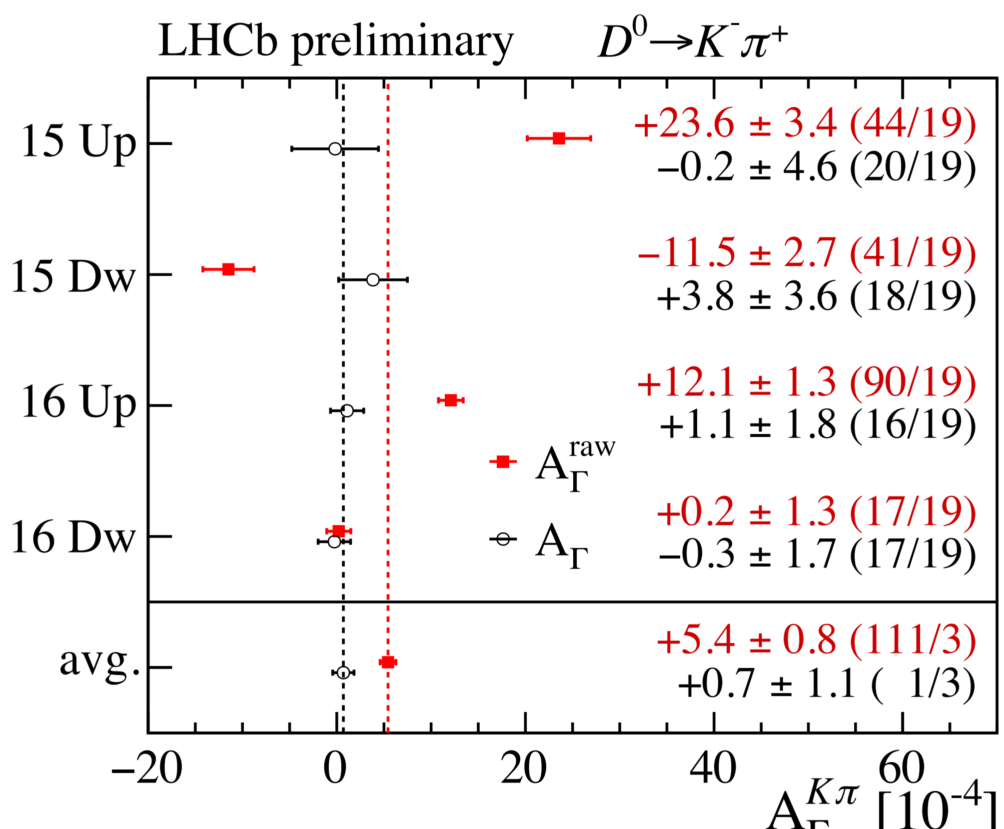
Detection asymmetries

- Time-dependent detection asymmetries studied with large-yield samples of $D^0 \to K^- \pi^+$ decays

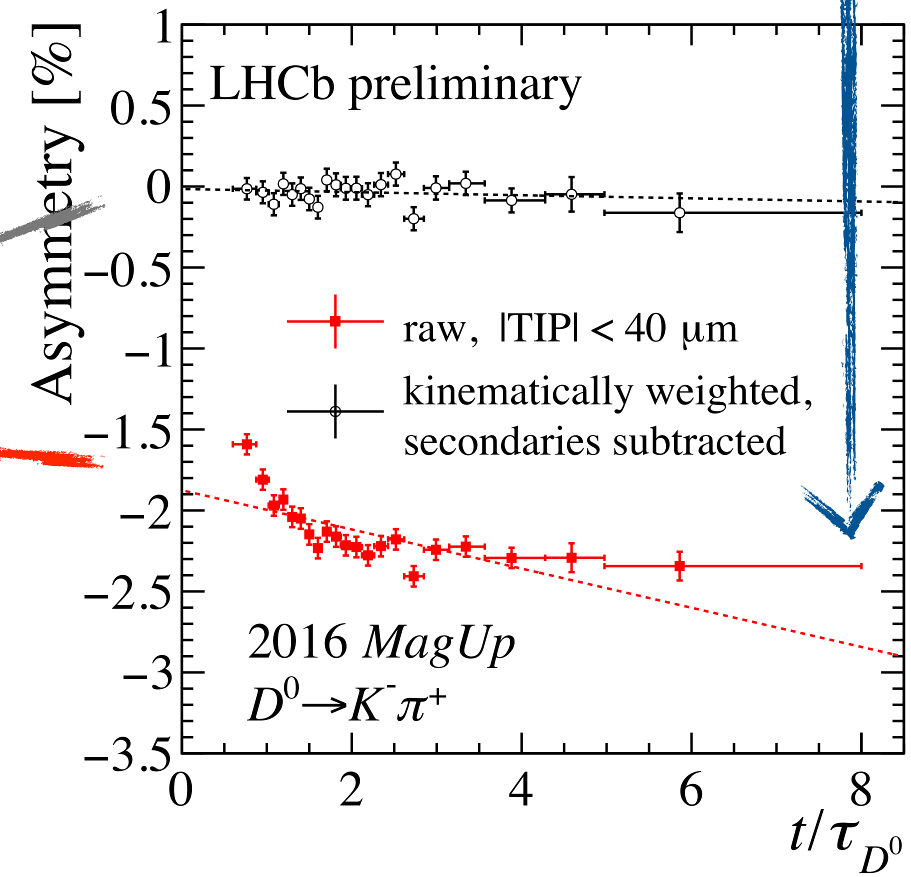
- Removed by equalizing the 3D momentum distributions of D^0 and $\bar{D}^0$ candidates (separately for data-taking period and magnet polarity)



p-dependent asymmetries and (*p*, *t*) correlations induce *t*-dependent asymmetries



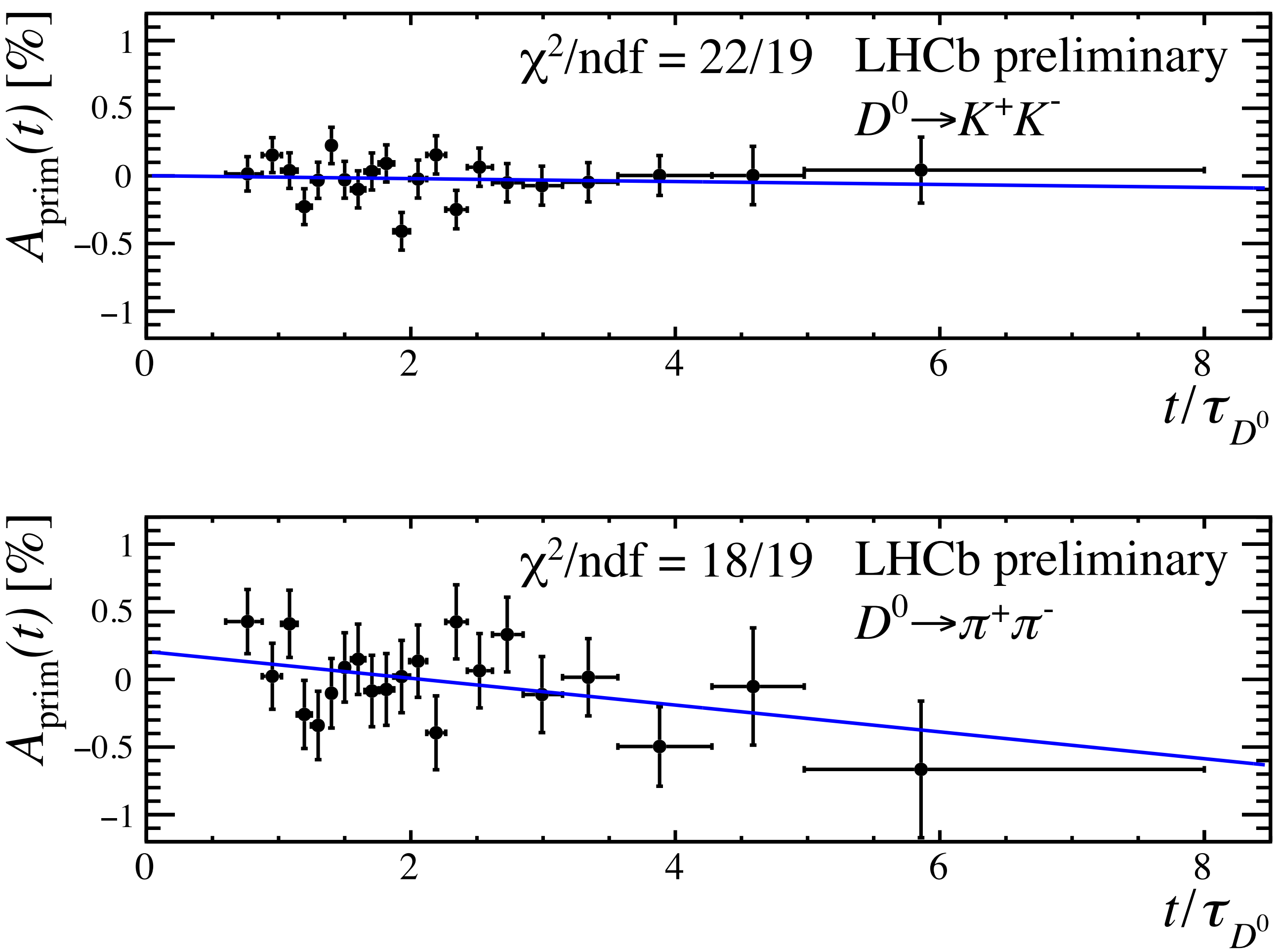
[LHCb-CONF-2019-001]



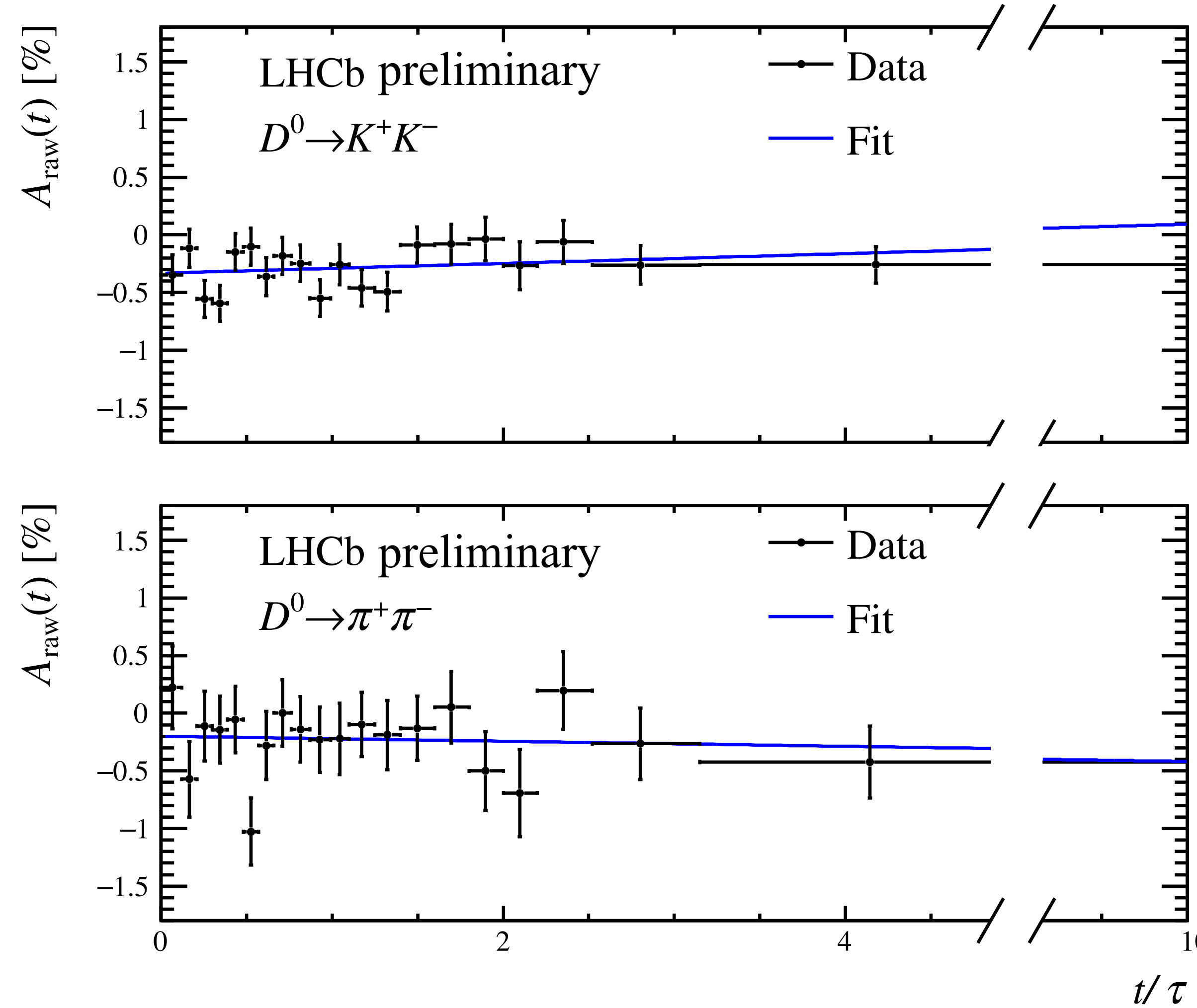
Time-dependent *CP* asymmetry in $D^0 \rightarrow h^+h^-$

π tagged 1.9/fb (Run 2)

[LHCb-CONF-2019-001]



NEW μ tagged 5.4/fb (Run 2)

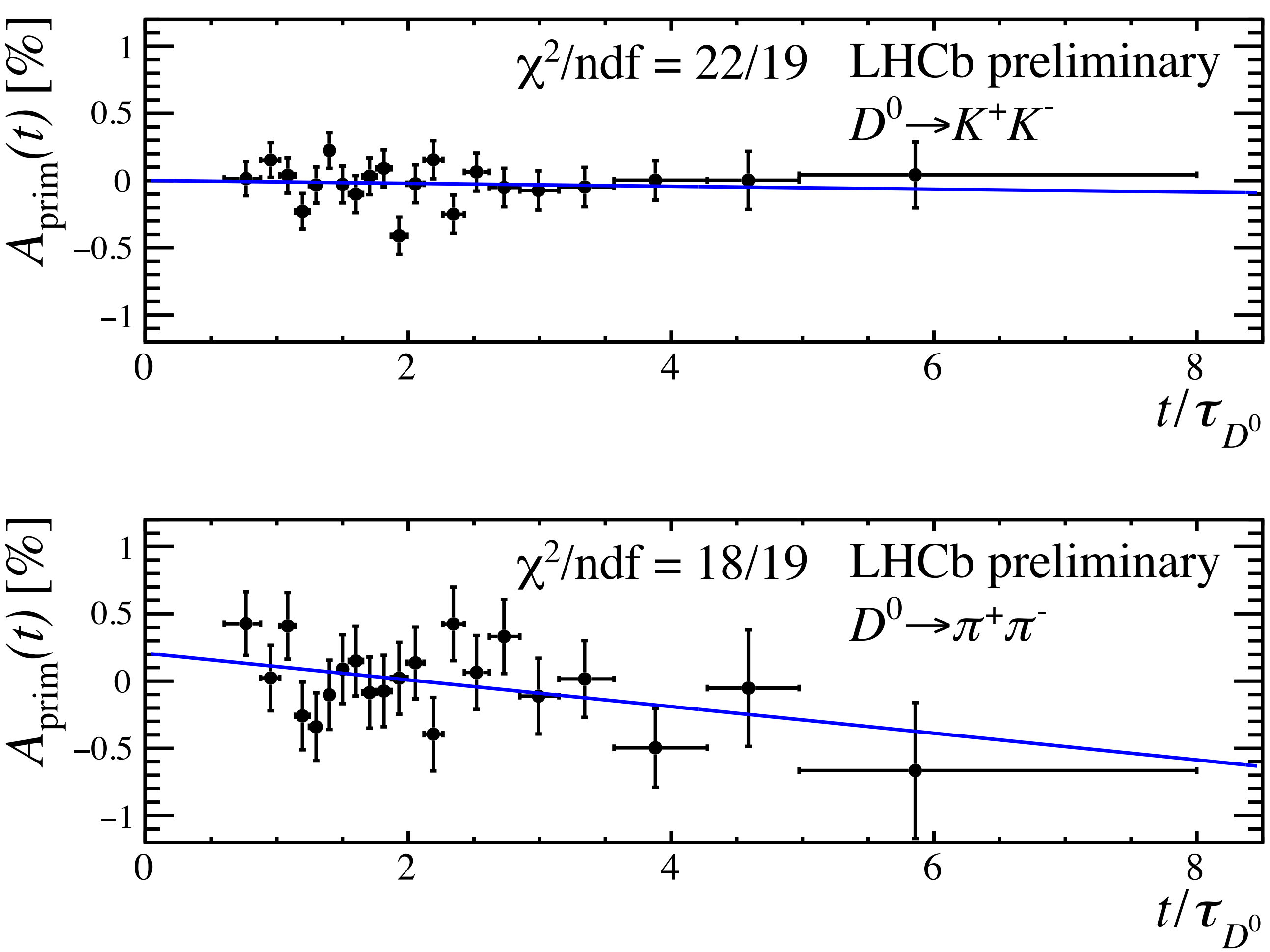


[LHCb-PAPER-2019-032 (in preparation)]

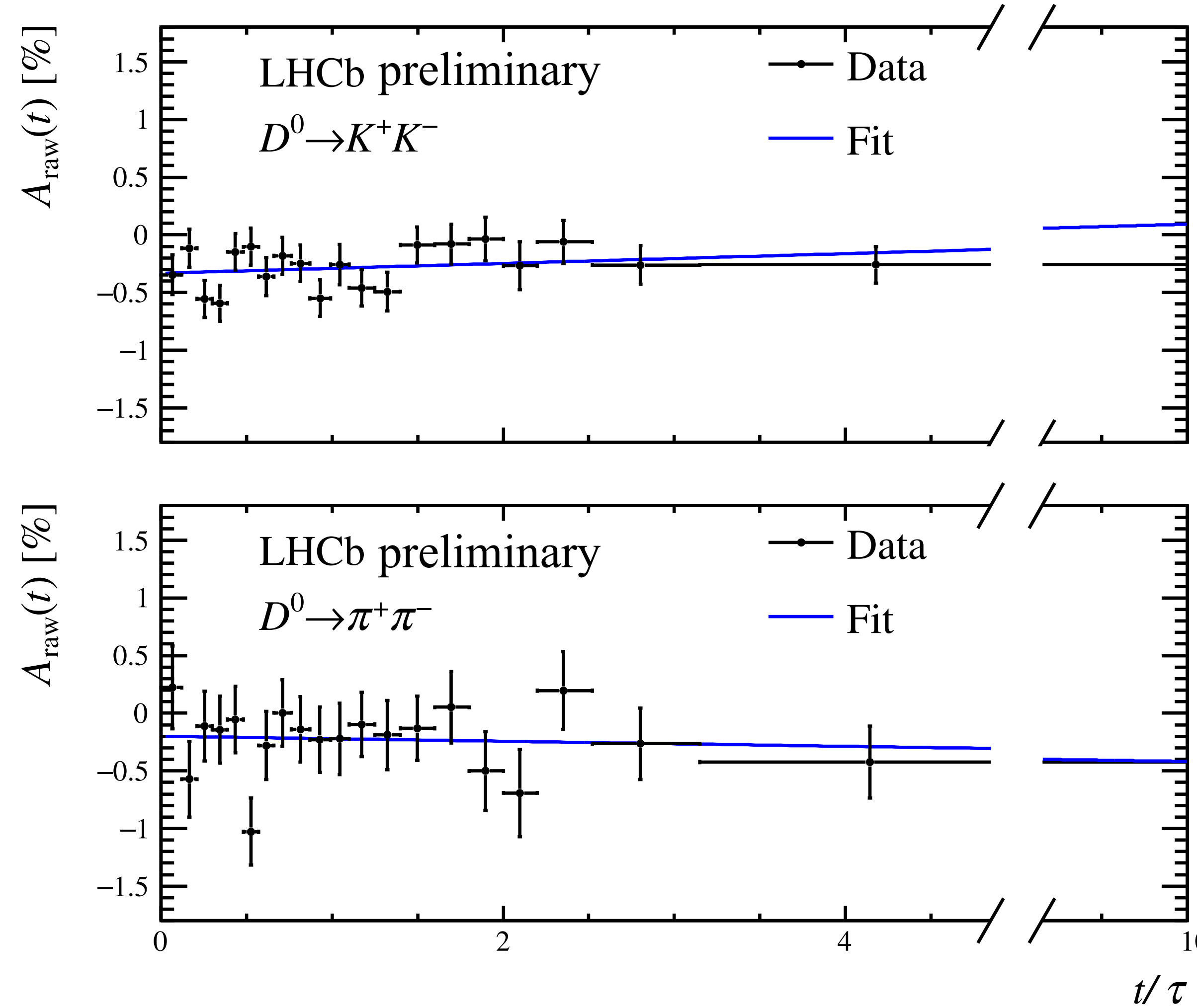
Time-dependent *CP* asymmetry in $D^0 \to h^+h^-$

π tagged 1.9/fb (Run 2)

[LHCb-CONF-2019-001]



NEW μ tagged 5.4/fb (Run 2)



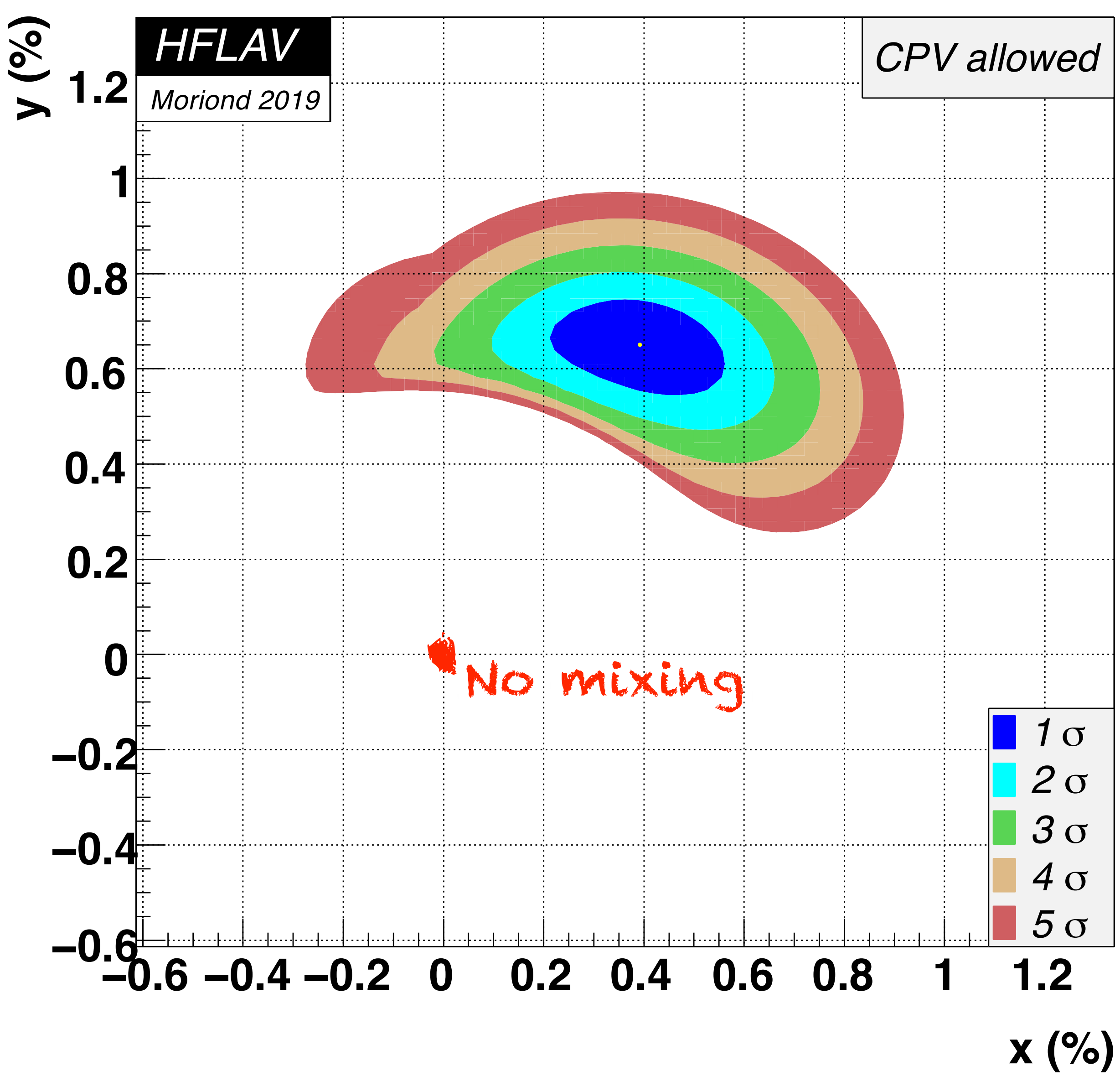
[LHCb-PAPER-2019-032 (in preparation)]

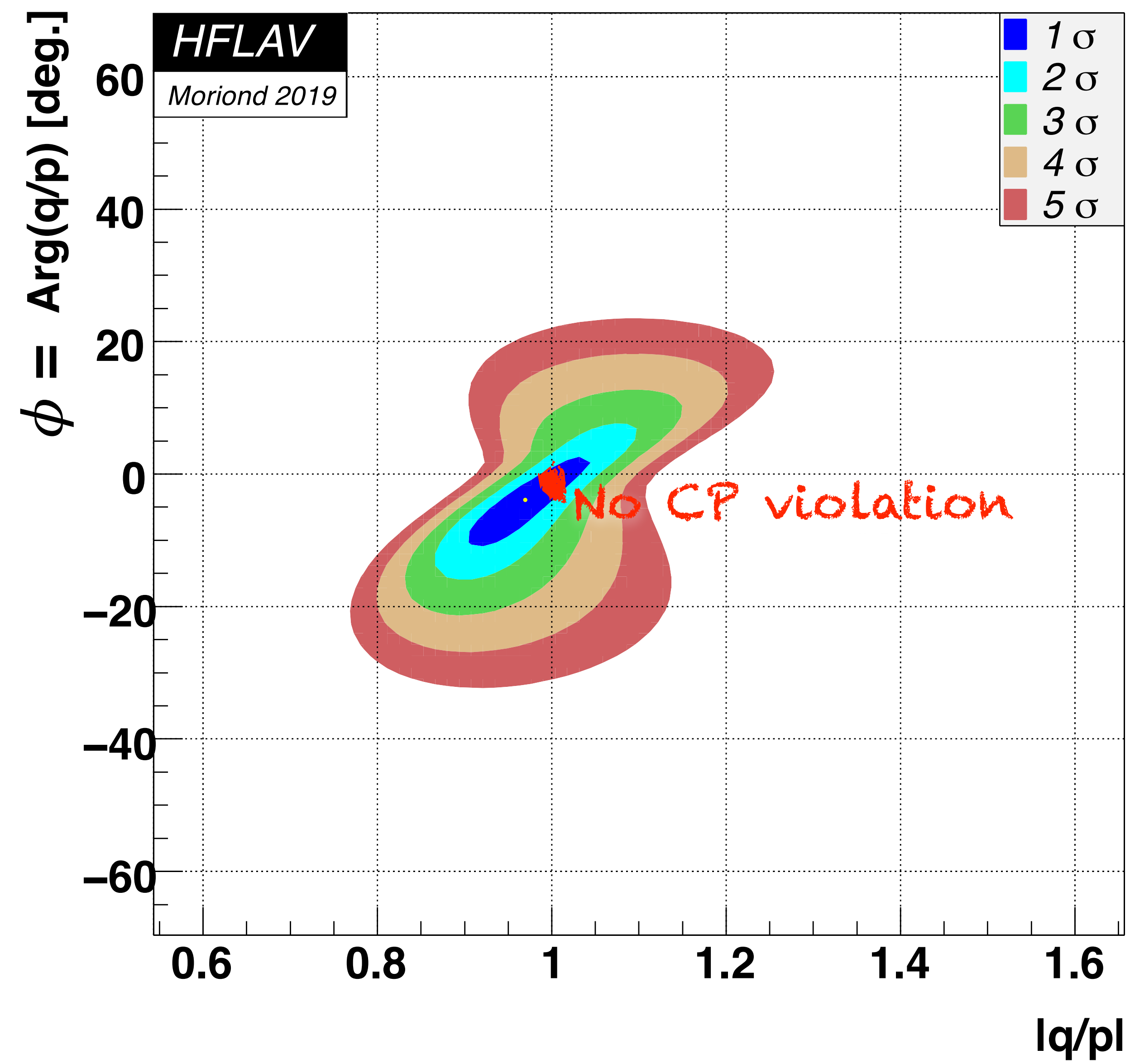
- Averaging the four samples and combining with Run 1 [PRL 118 (2017) 261803, JHEP 04 (2015) 043]

PRELIMINARY

$$A_\Gamma = [-1.1 \pm 1.7\ (\text{stat}) \pm 0.5\ (\text{stat})] \times 10^{-4}$$

Experimental status





$$x = (3.9 \ {}^{+1.1}_{-1.2}\ ) \times 10^{-3}$$

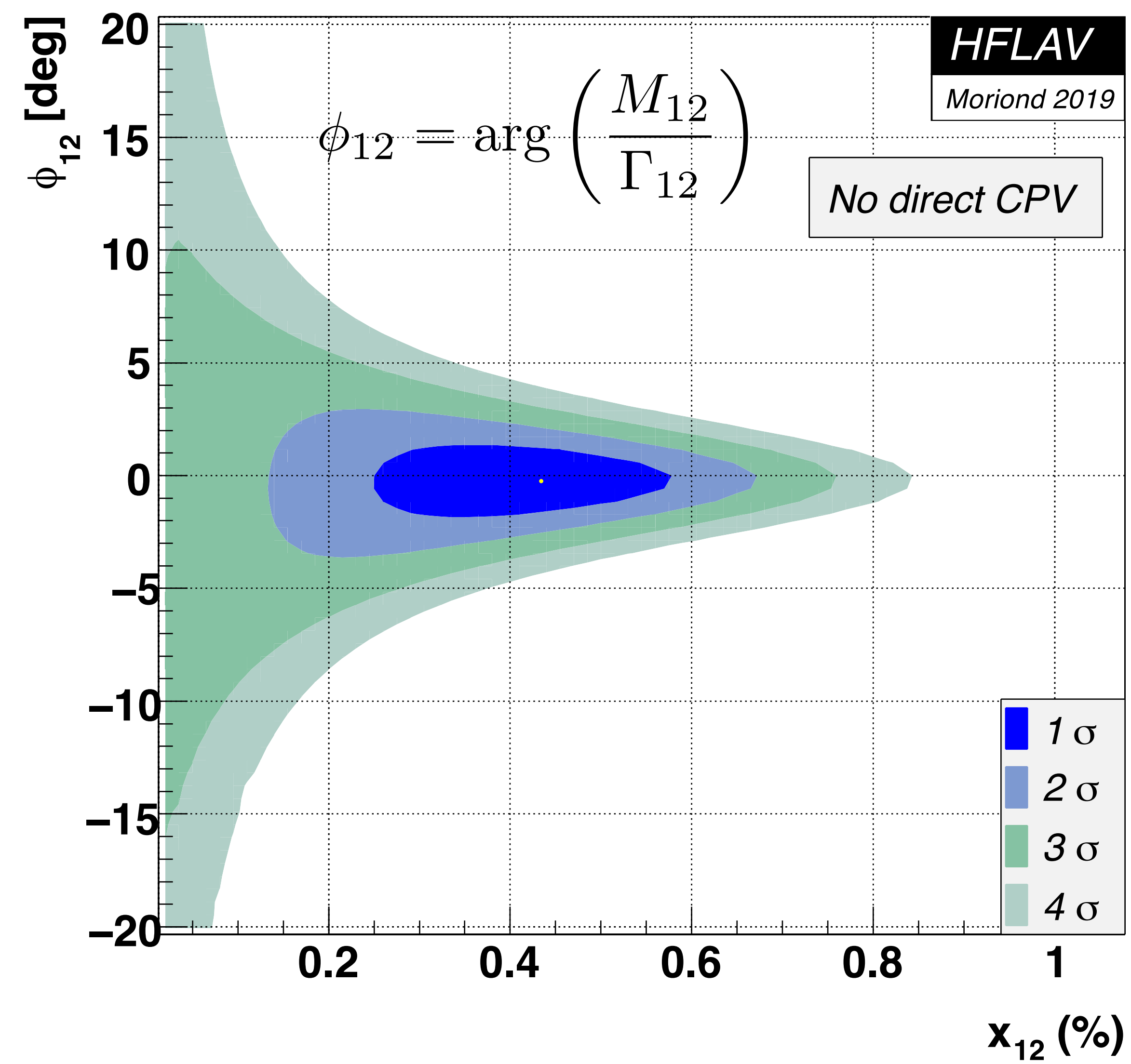
$$y = (6.51 {}^{+0.63}_{-0.69}) \times 10^{-3}$$

$$|q/p| = 0.969 {}^{+0.050}_{-0.045}$$

$$\phi = (-3.9 {}^{+4.5}_{-4.6})^{\circ}$$

x is the key

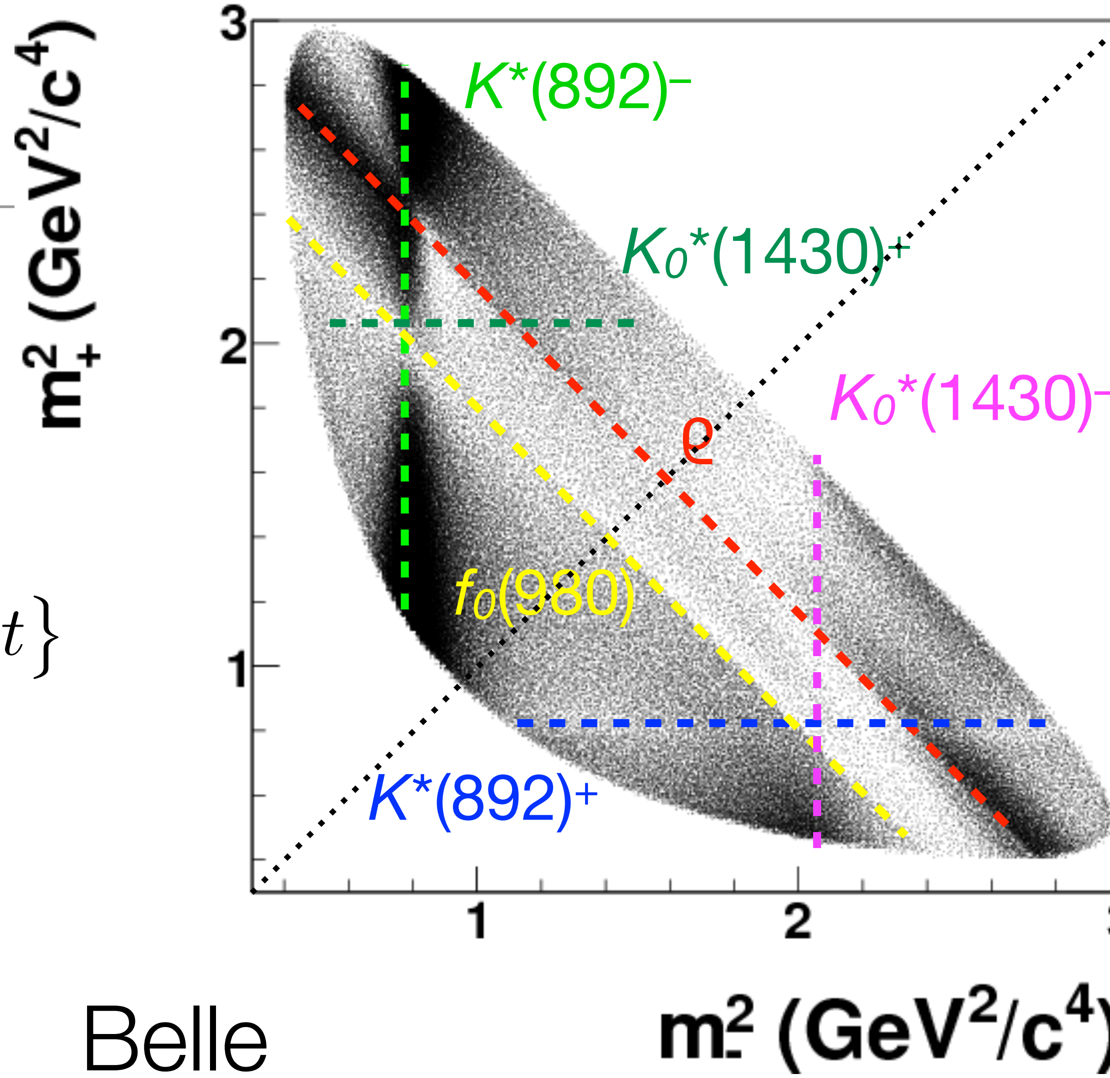
- Experimental sensitivity to the *CP*-violation in mixing limited by the knowledge of $x_{12} \approx x$
  - $A_\Gamma \approx -x_{12} \sin\phi_{12}$ (superweak approx.)
  - Available mixing measurements are mostly based on decays to two-body final states ($y_{CP} \approx y$, $y' \approx y$)
  - Need more measurements with multi-body final states



$$\phi_{12} = (-0.25\,^{+\,0.99}_{-\,0.96})^\circ$$

Mixing with $D^0 \to K_S \pi^+ \pi^-$

[PRD 89 (2014) 091103]



- Multiple interfering amplitudes enhance the sensitivity to mixing

$$\mathcal{P}_{D^0} \propto e^{-\Gamma t}\{|\mathcal{A}_{D^0}|^2 - \mathrm{Re}[\mathcal{A}^*_{D^0}\mathcal{A}_{\overline{D}^0}(y+ix)]\Gamma t\}$$

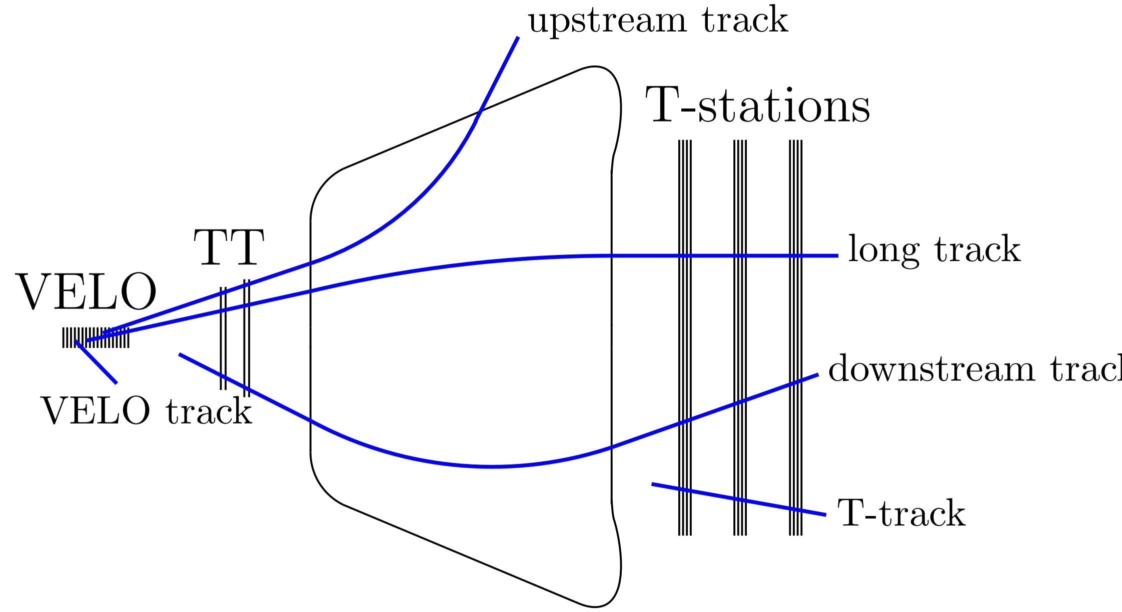
- Requires a time-dependent Dalitz-plot analysis
- Pioneered by CLEO in 2005, then followed by *B* factories with larger yields
- Belle 1/ab result has been for long the best determination of *x* available

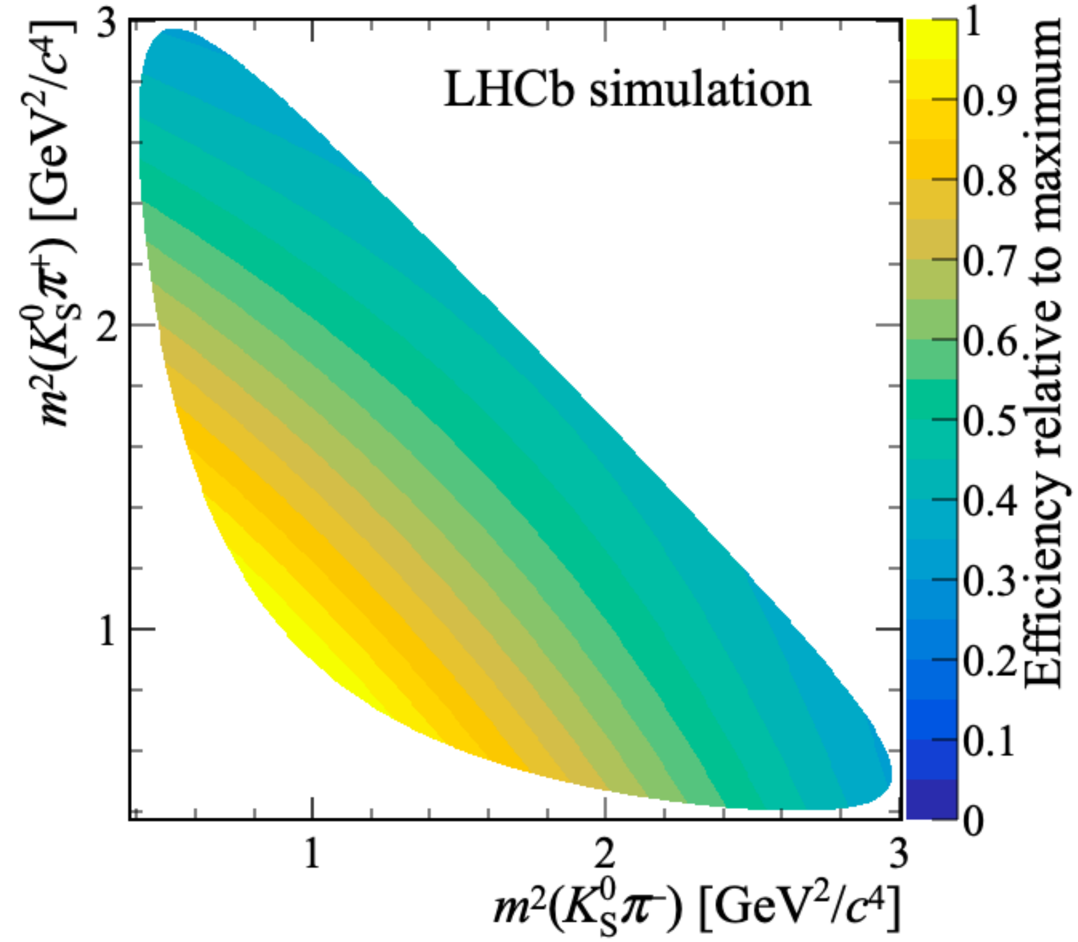
Belle

Fit type	Parameter	Fit result
No CPV	$x(\%)$	$0.56 \pm 0.19^{+0.03}_{-0.09}{}^{+0.06}_{-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04}_{-0.08}{}^{+0.06}_{-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.07}$
	$\|q/p\|$	$0.90^{+0.16}_{-0.15}{}^{+0.05}_{-0.04}{}^{+0.06}_{-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

$D^0 \to K_S \pi^+ \pi^-$ at LHCb

- $K_S \to \pi^+\pi^-$ are difficult to reconstruct in LHCb
  - In the early stages of the trigger only K_S decaying inside the VELO ($t < 0.5\ \tau_{K_S}$) can be reconstructed
  - Trigger relies mostly on the two pions from the D^0 decay $\Longrightarrow$ non-uniform efficiency over the Dalitz plot (which is also correlated with the D^0 decay time)
- Could be overcome using μ-tagged D^0 decays $\Longrightarrow$ reduced efficiency and larger background levels
- A time-dependent amplitude analysis is very challenging at LHCb



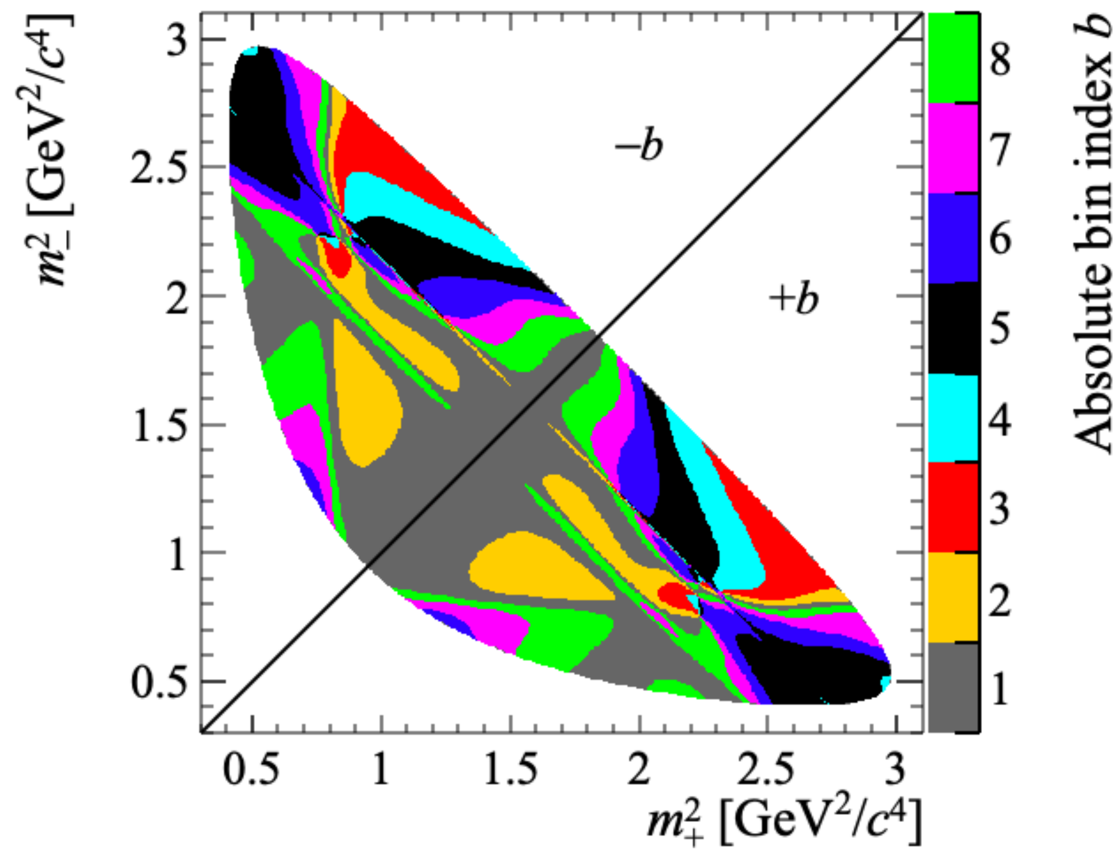


[PRL 122 (2019) 231802]

$D^0 \to K_S \pi^+ \pi^-$ with a model-independent approach

- Avoid amplitude analysis by integrating over Dalitz-plot bins with constant strong-phase variation

$$\mathcal{P}_{D^0} \propto e^{-\Gamma t}\left[F_b - \sqrt{F_b F_{-b}}(c_b\, y - s_b\, x)\Gamma t\right]$$



- Constrain hadronic parameters (c_b, s_b) using measurements with quantum-correlated $D^0\bar{D}^0$ pairs, *i.e.* at CLEO and BESIII

$$F_b = \int_b |\mathcal{A}_{D^0}|^2 dm_+^2 dm_-^2$$

$$c_b - i s_b \propto \int_b \mathcal{A}^*_{D^0} \mathcal{A}_{\bar{D}^0} dm_+^2 dm_-^2$$

Bin-flip method

Open Access

Novel method for measuring charm-mixing parameters using multibody decays

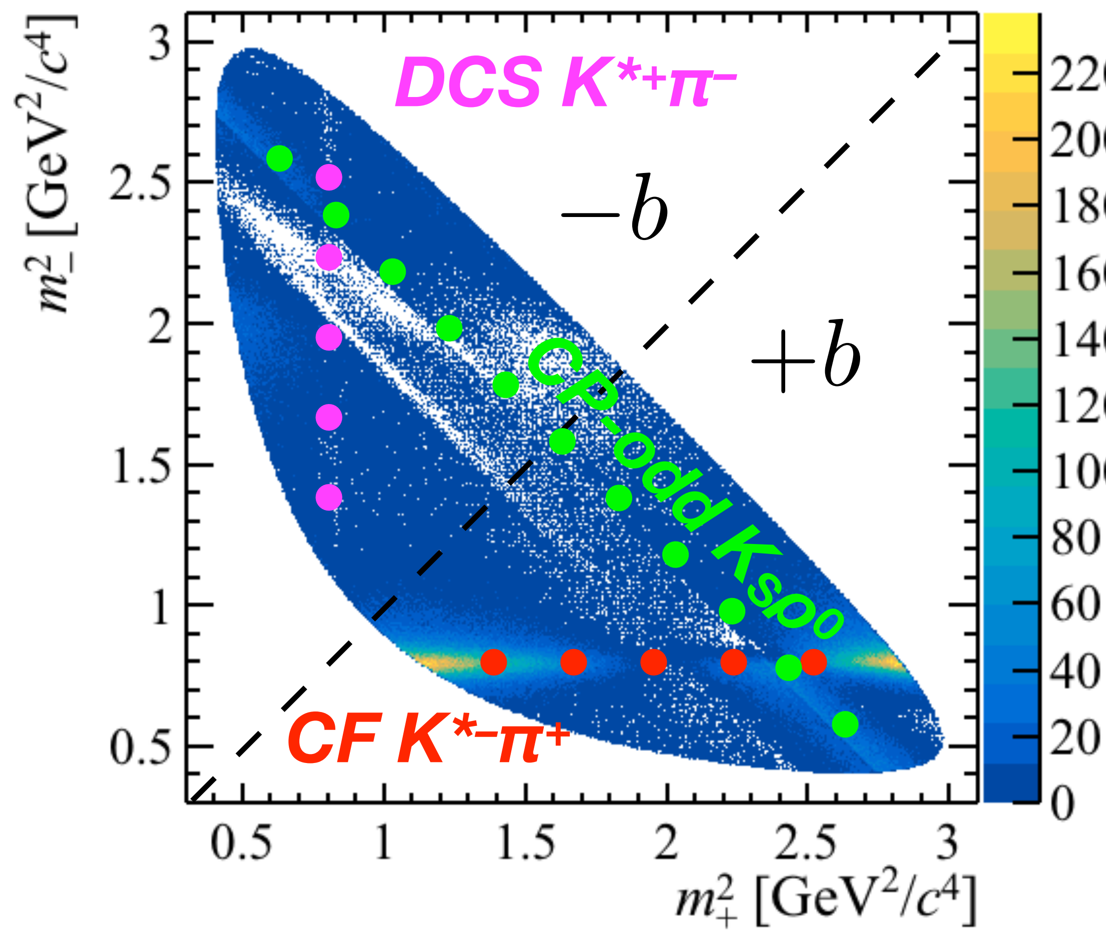
A. Di Canto, J. Garra Ticó, T. Gershon, N. Jurik, M. Martinelli, T. Pilař, S. Stahl, and D. Tonelli

Phys. Rev. D **99**, 012007 – Published 16 January 2019

[PRD 99 (2019) 012007]

- Inspired by the WS $D^0 \to K\pi$ analysis: ratio of events in bin $-b$ to events in bin b to suppress effects due to non-uniform efficiency variations and enhance sensitivity to *x*

$$R_b \approx r_b - \sqrt{r_b}\left[(1-r_b)c_b\, y - (1+r_b)s_b\, x\right]\Gamma t$$



$$r_b = \frac{F_{-b}}{F_b}$$

- Mixing parameters from simultaneous fit to all bins. Split in D^0 and $\bar{D}^0$ to access also indirect *CP* violation

- Model-independent and completely data driven

- Comes with the price of degraded sensitivity to mixing effects from *CP*-even/odd amplitudes (*i.e.* to *y*)

Bin-flip method

[PRD 99 (2019) 012007]

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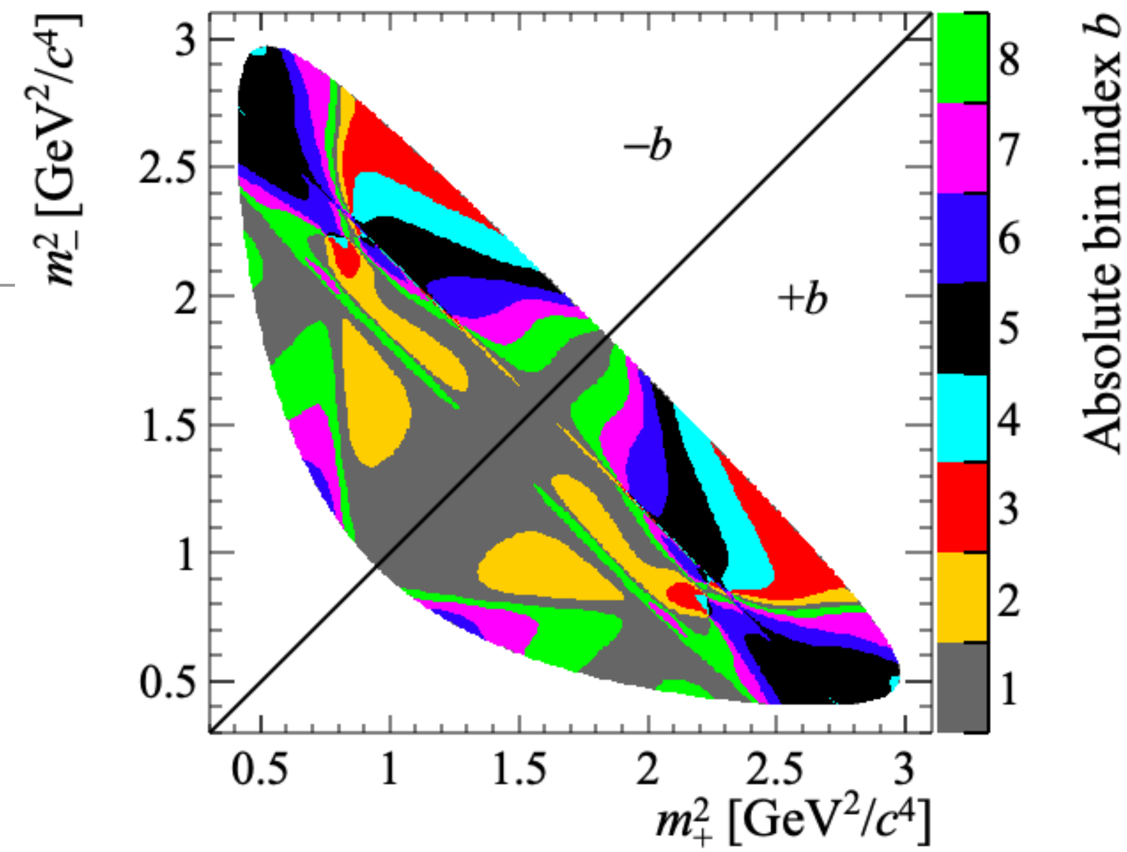
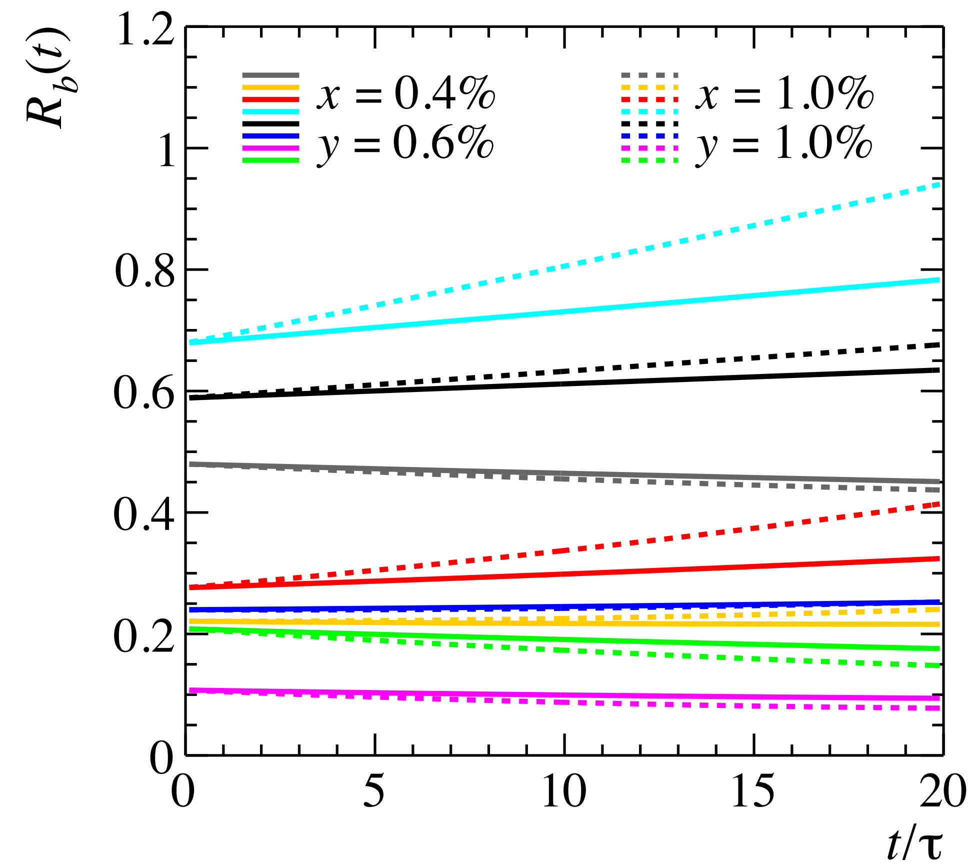
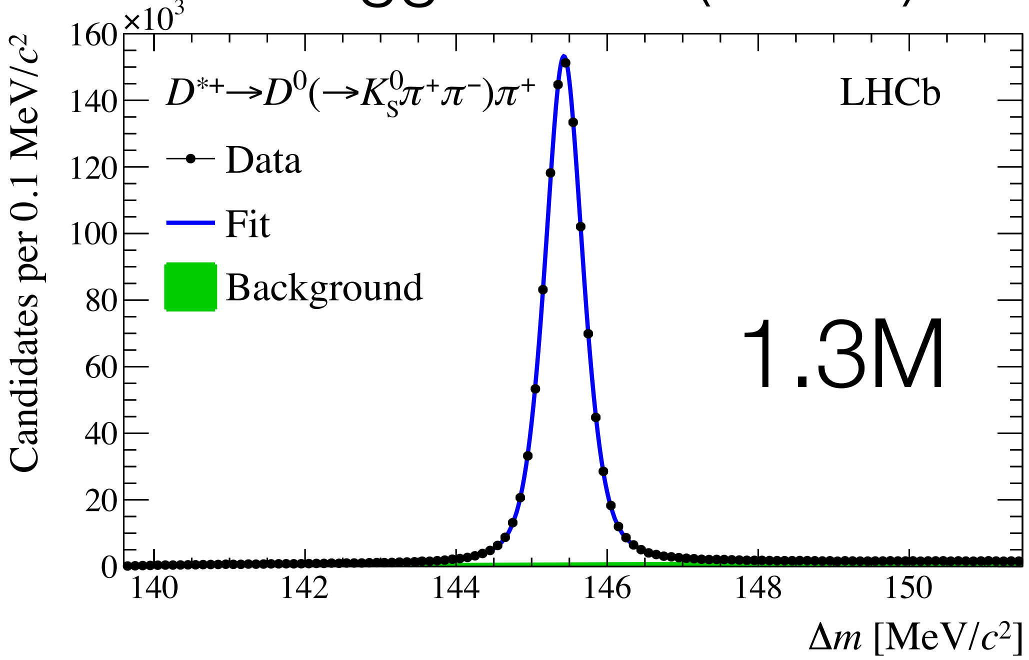




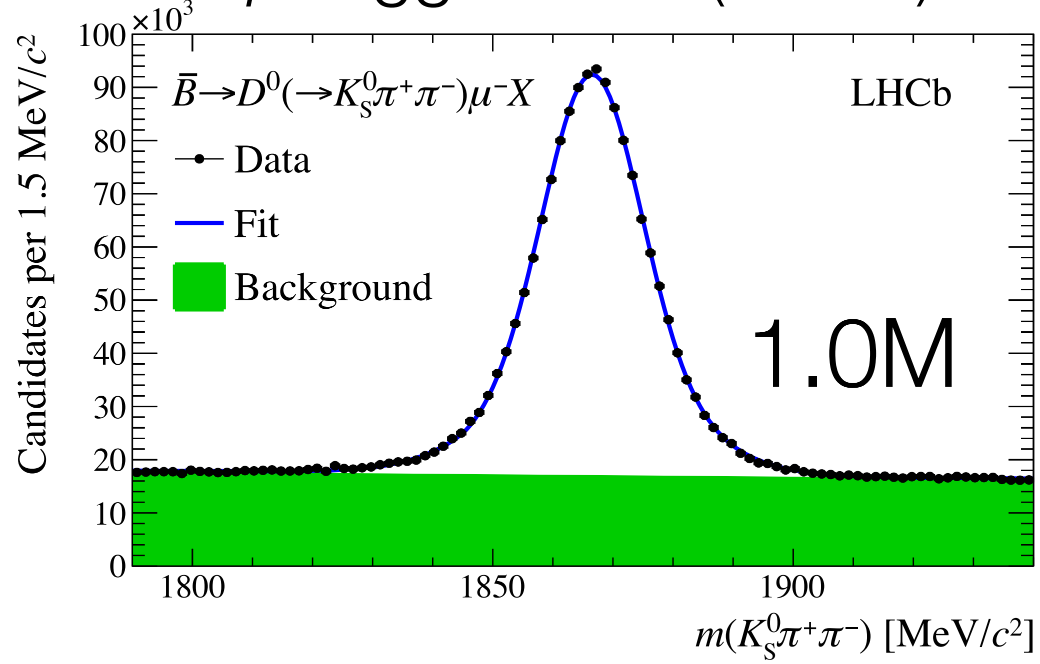
Bin-flip $D^0 \to K_S\pi^+\pi^-$ at LHCb

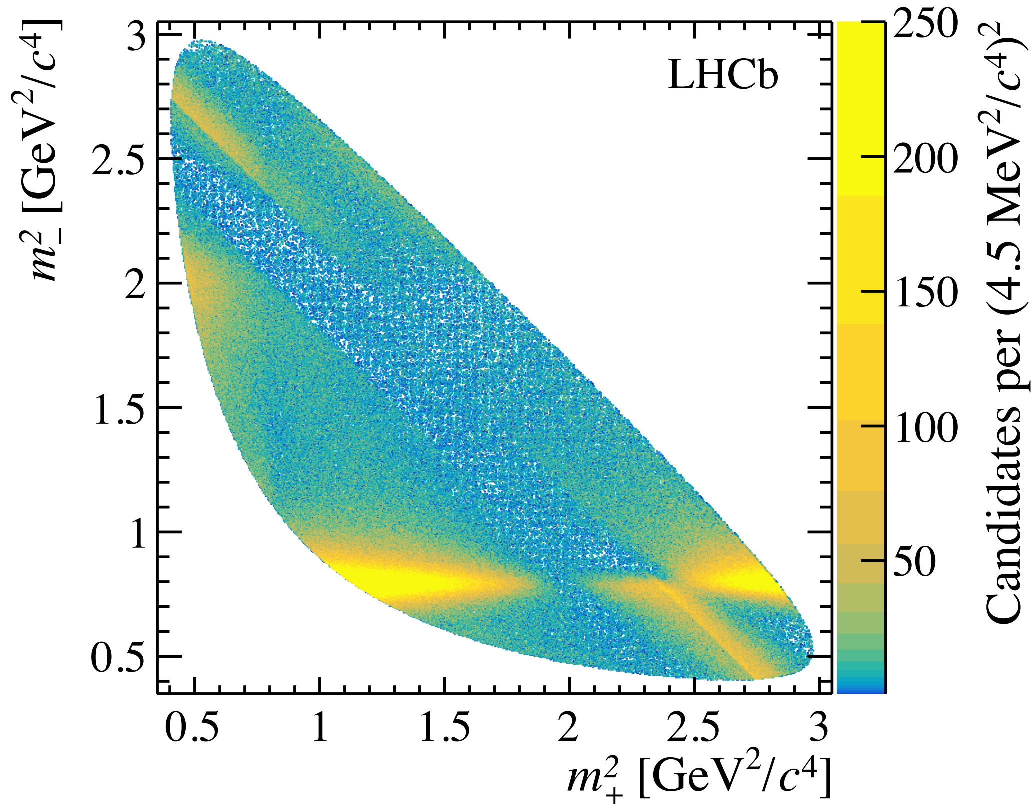
[PRL 122 (2019) 231802]

π tagged 2/fb (Run 1)



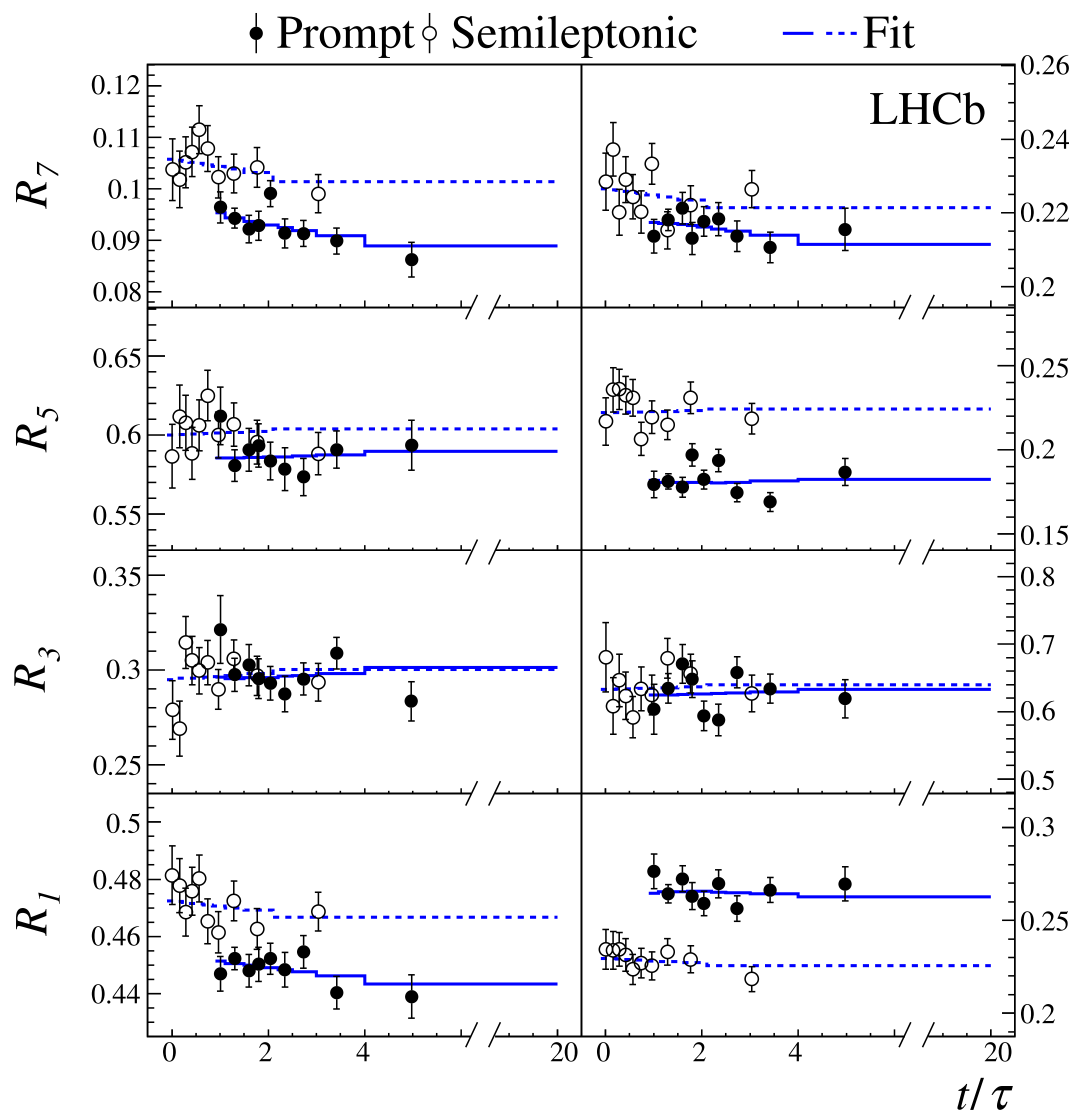
μ tagged 3/fb (Run 1)

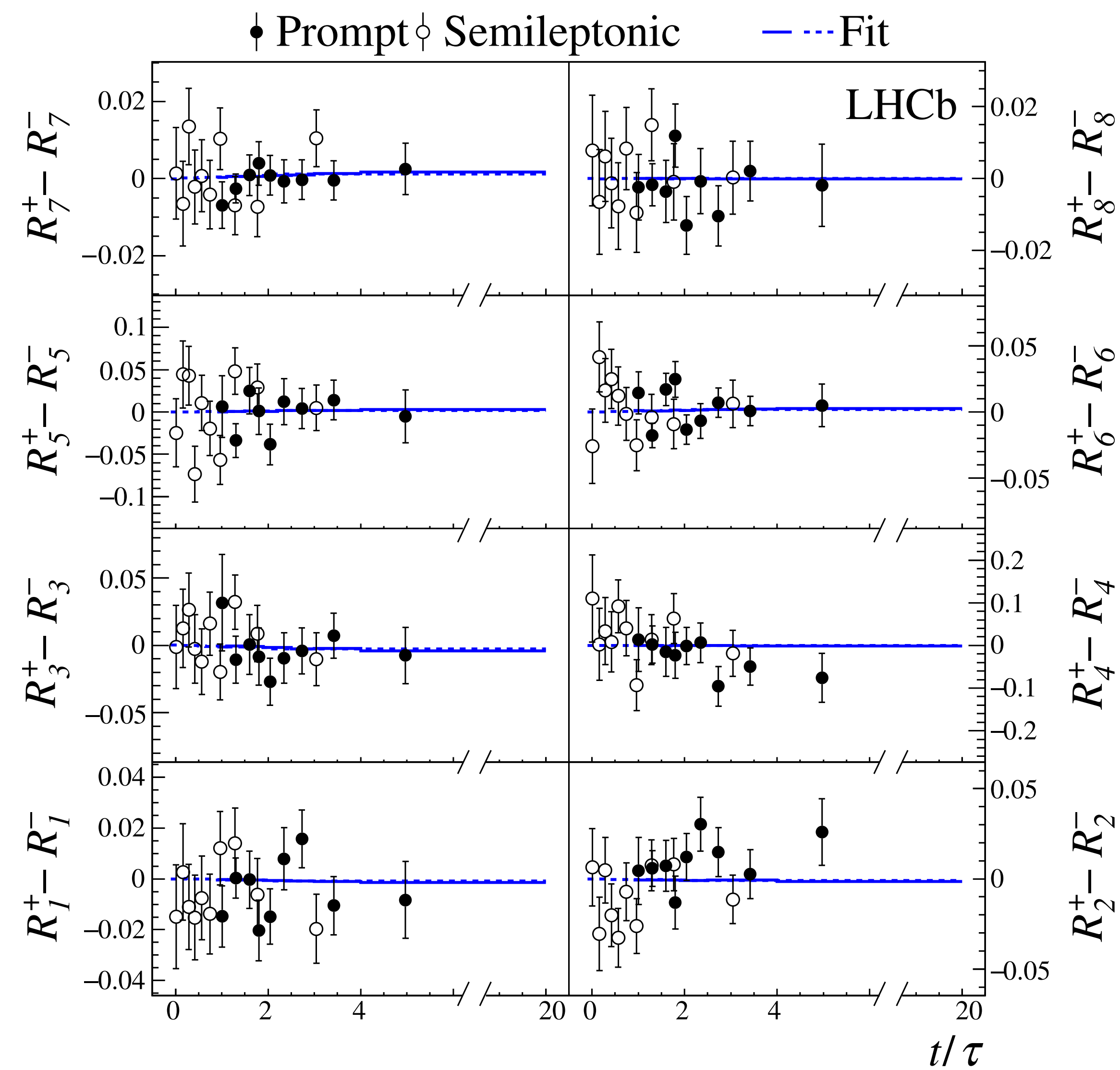




Bin-flip $D^0 \to K_S\pi^+\pi^-$ at LHCb

[PRL 122 (2019) 231802]

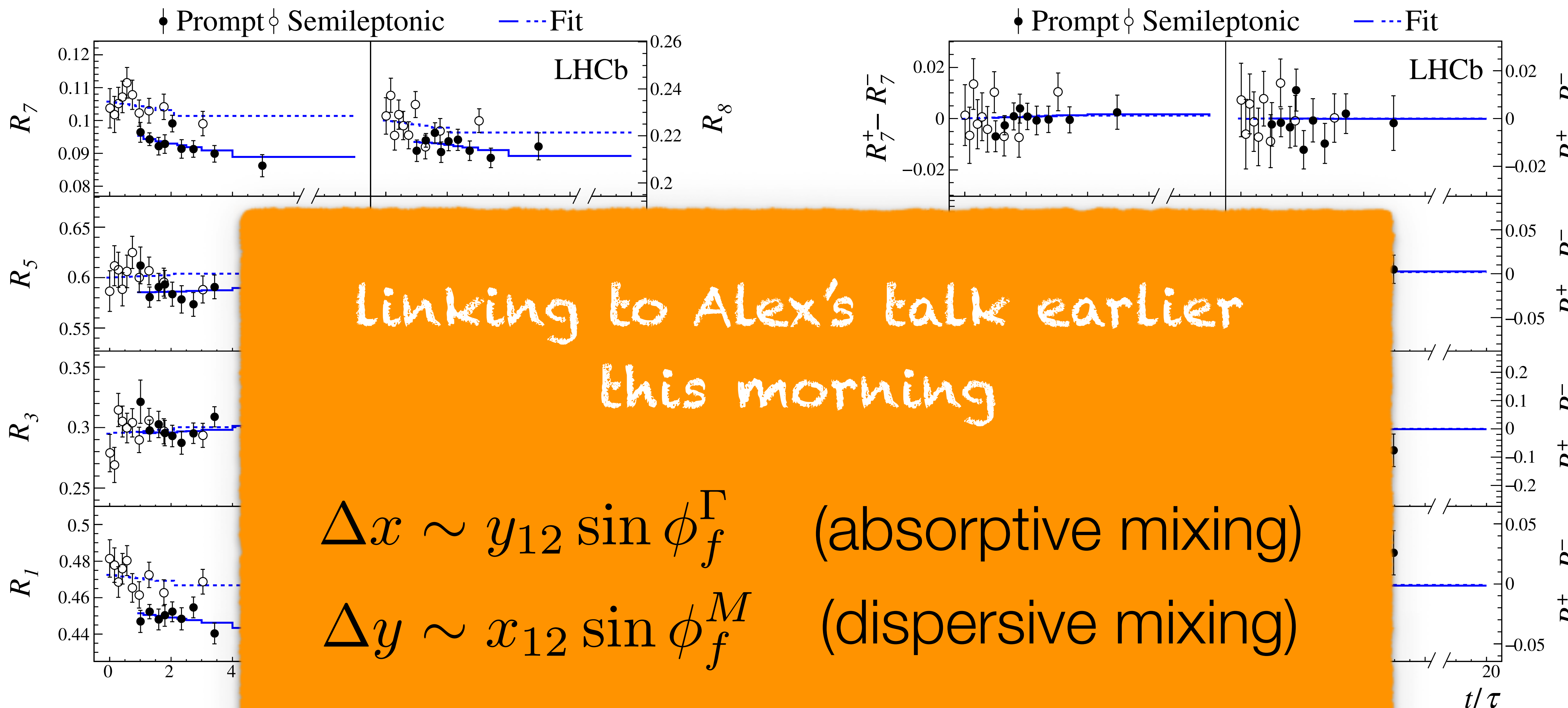




Parameter	Value $[10^{-3}]$	Stat. correlations y_{CP}	Stat. correlations Δx	Stat. correlations Δy	Syst. correlations y_{CP}	Syst. correlations Δx	Syst. correlations Δy
x_{CP}	$2.7 \pm 1.6 \pm 0.4$	-0.17	0.04	-0.02	0.15	0.01	-0.02
y_{CP}	$7.4 \pm 3.6 \pm 1.1$		-0.03	0.01		-0.05	-0.03
Δx	$-0.53 \pm 0.70 \pm 0.22$			-0.13			0.14
Δy	$0.6 \pm 1.6 \pm 0.3$						

Bin-flip $D^0 \to K_S \pi^+ \pi^-$ at LHCb

[PRL 122 (2019) 231802]



linking to Alex's talk earlier this morning

$$\Delta x \sim y_{12} \sin \phi_f^{\Gamma} \quad \text{(absorptive mixing)}$$

$$\Delta y \sim x_{12} \sin \phi_f^{M} \quad \text{(dispersive mixing)}$$

Parameter	Value $[10^{-3}]$	Stat. correlations y_{CP}	Stat. correlations Δx	Stat. correlations Δy	Syst. correlations y_{CP}	Syst. correlations Δx	Syst. correlations Δy
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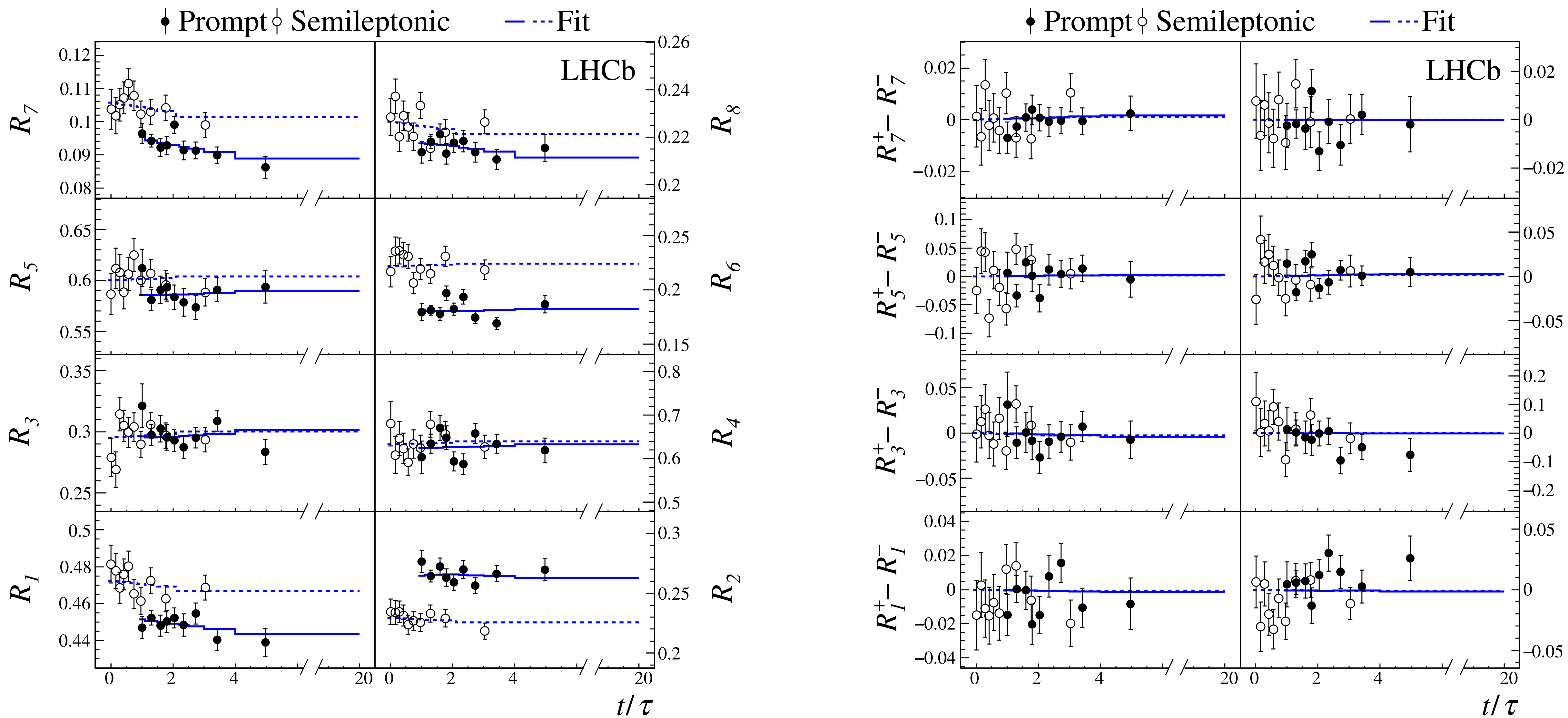
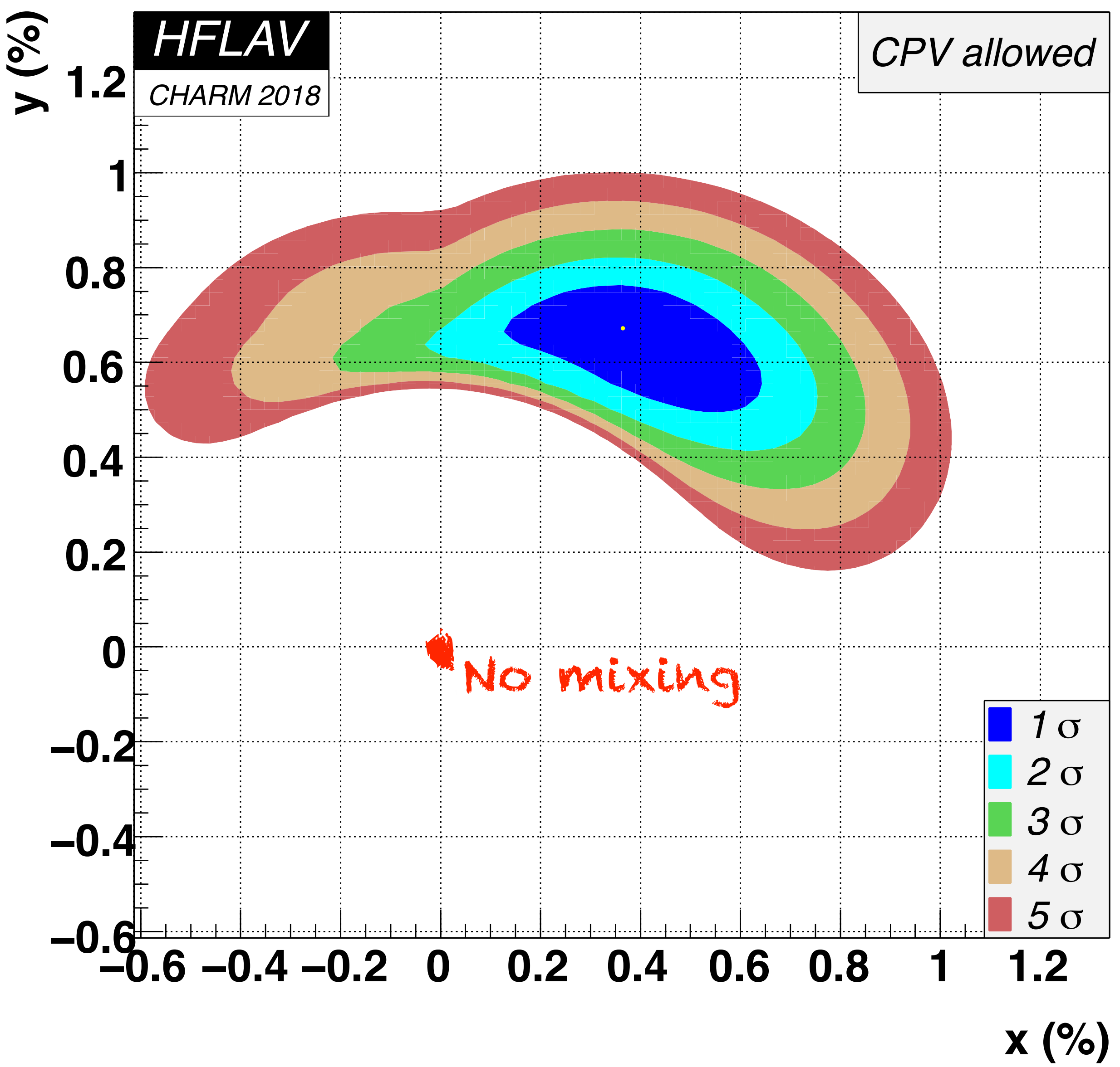
Bin-flip $D^0 \to K_S\pi^+\pi^-$ at LHCb

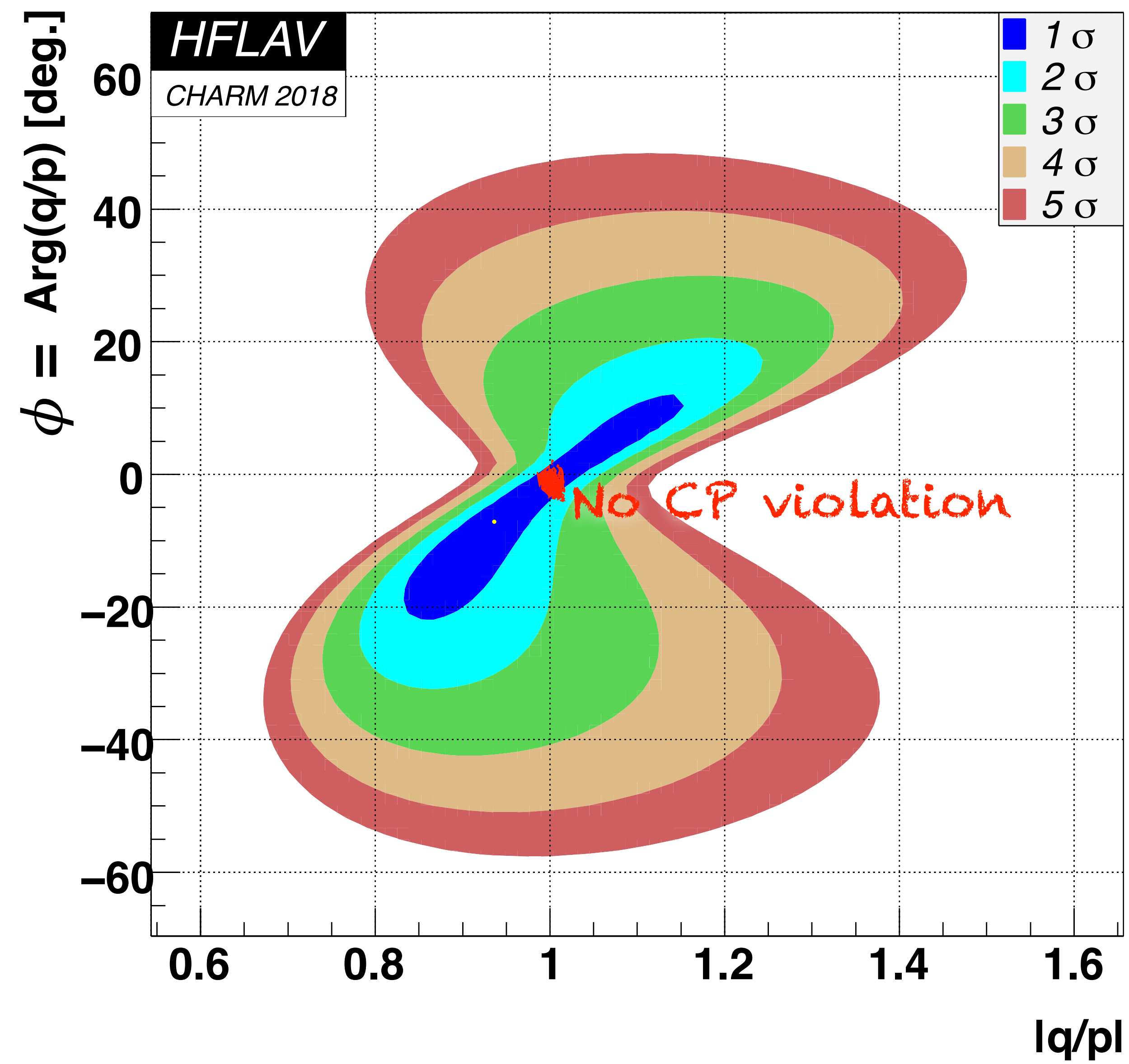
[PRL 122 (2019) 231802]



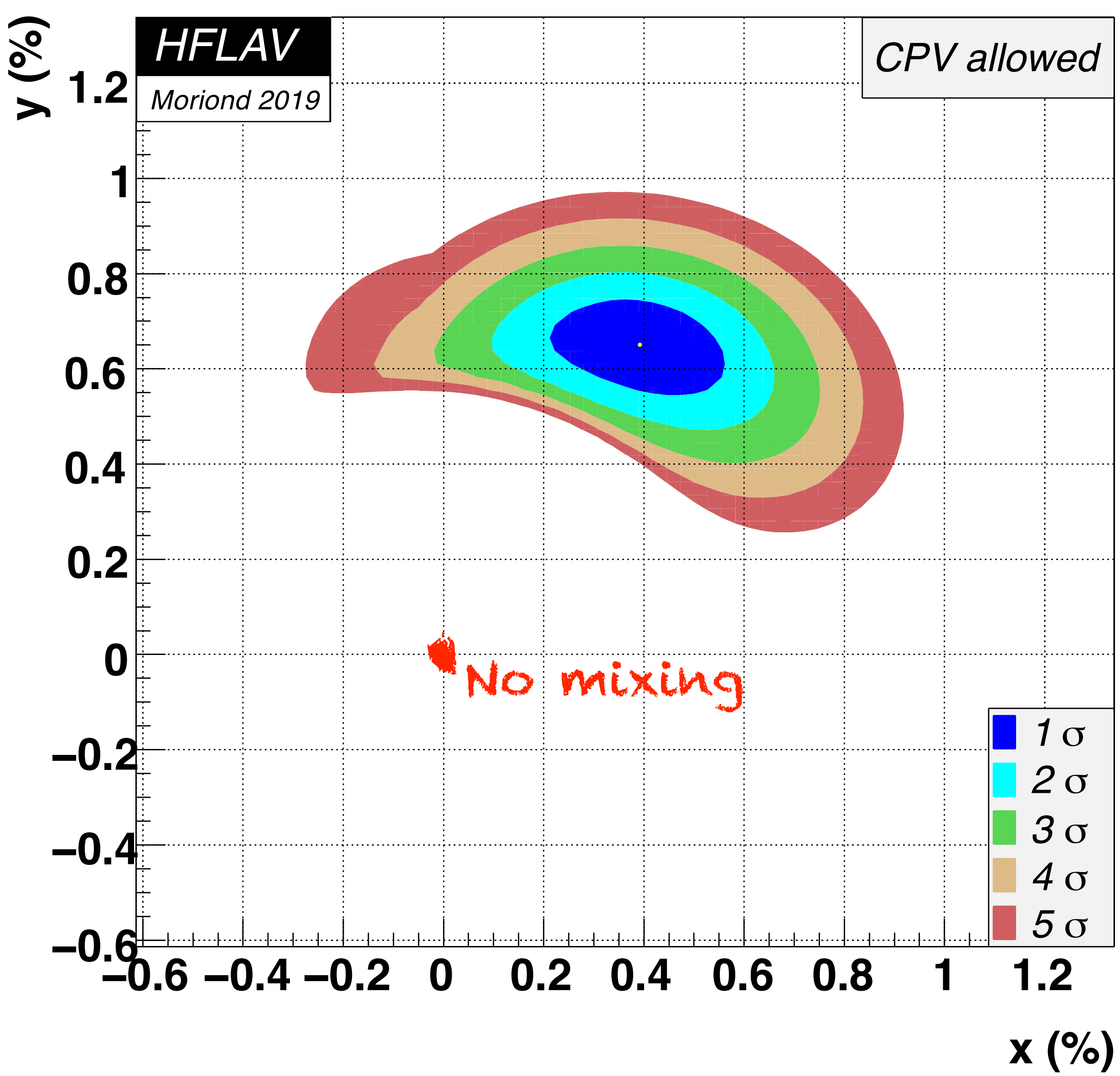
Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p\rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

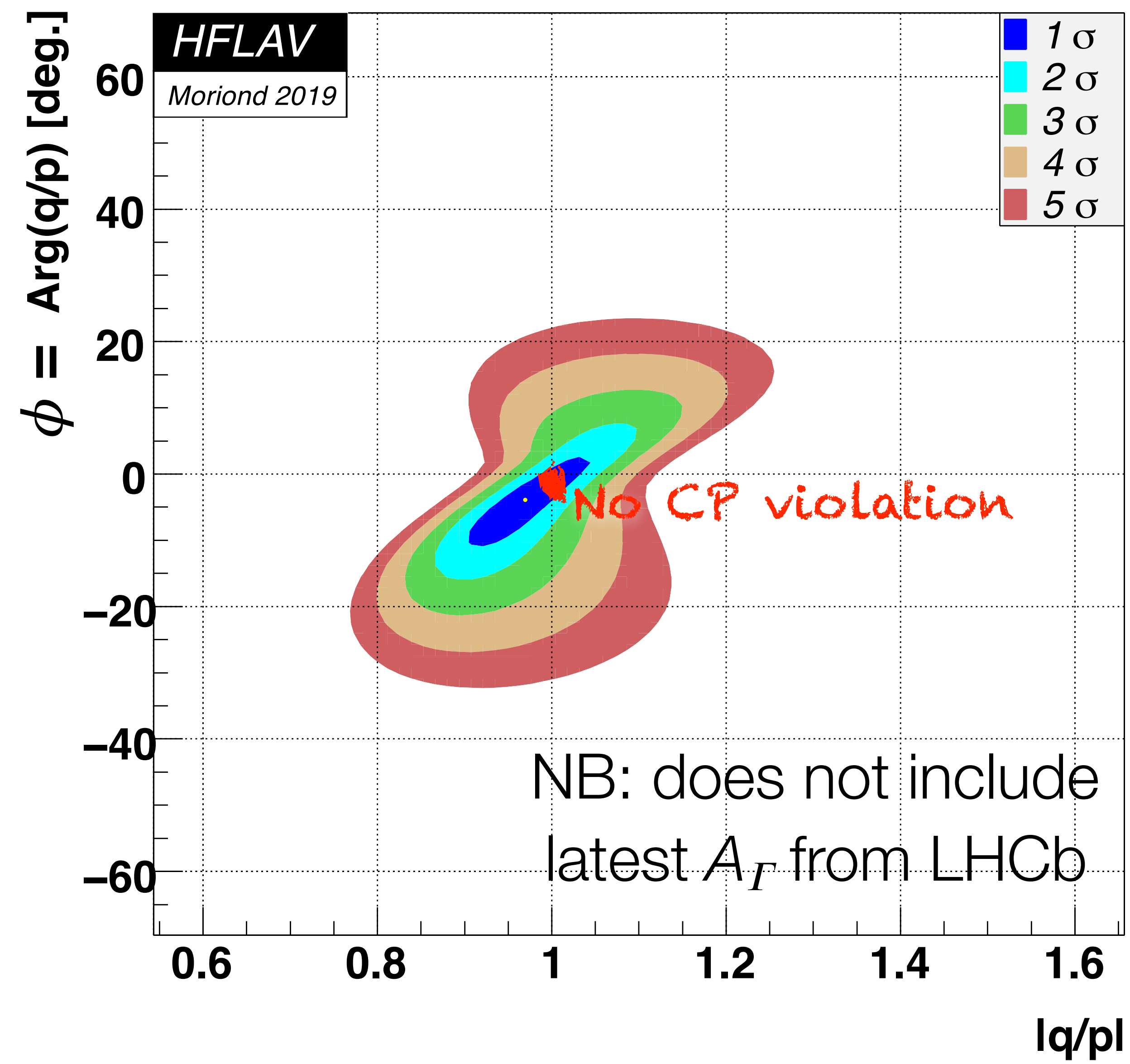
Impact on world average



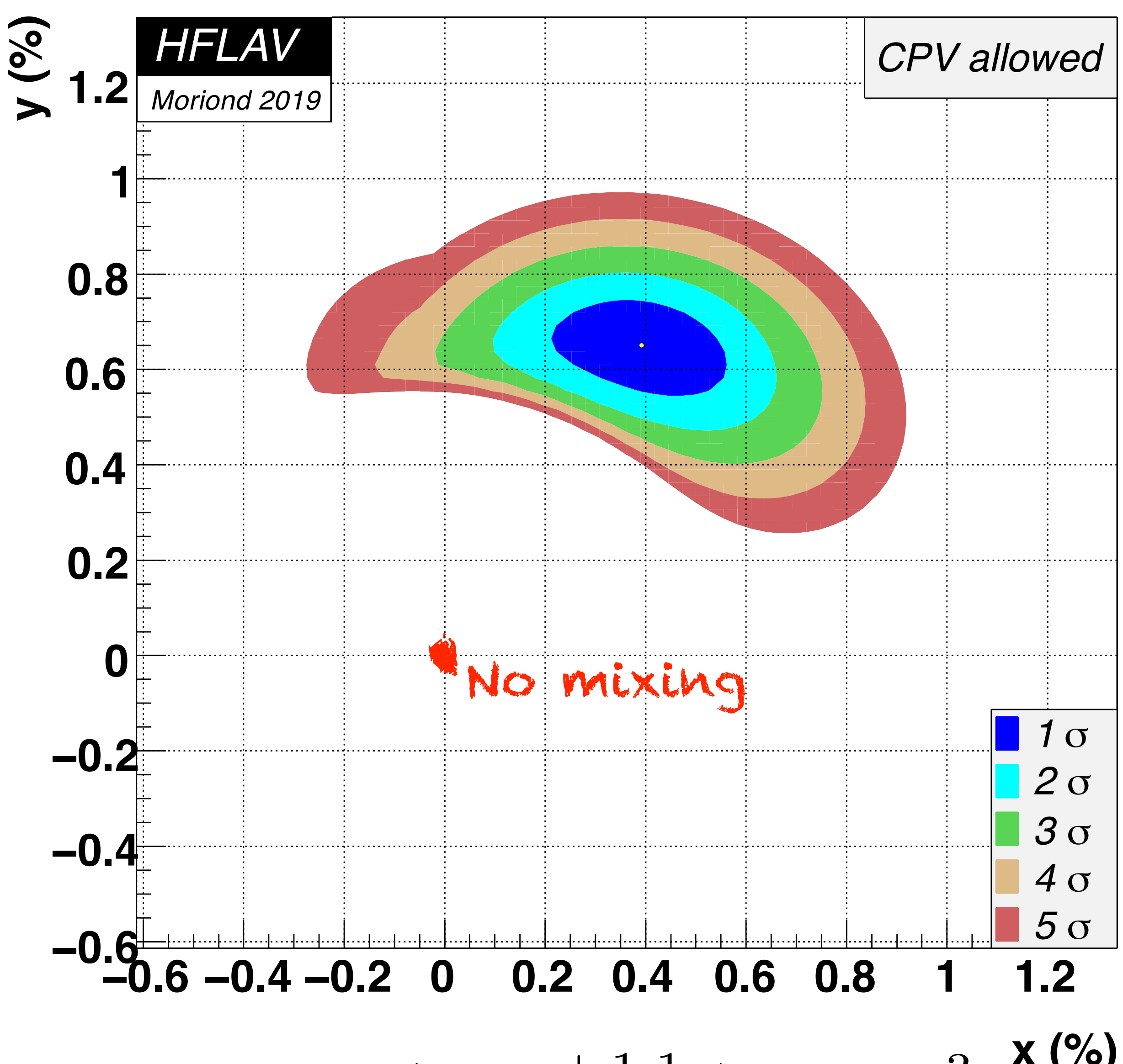


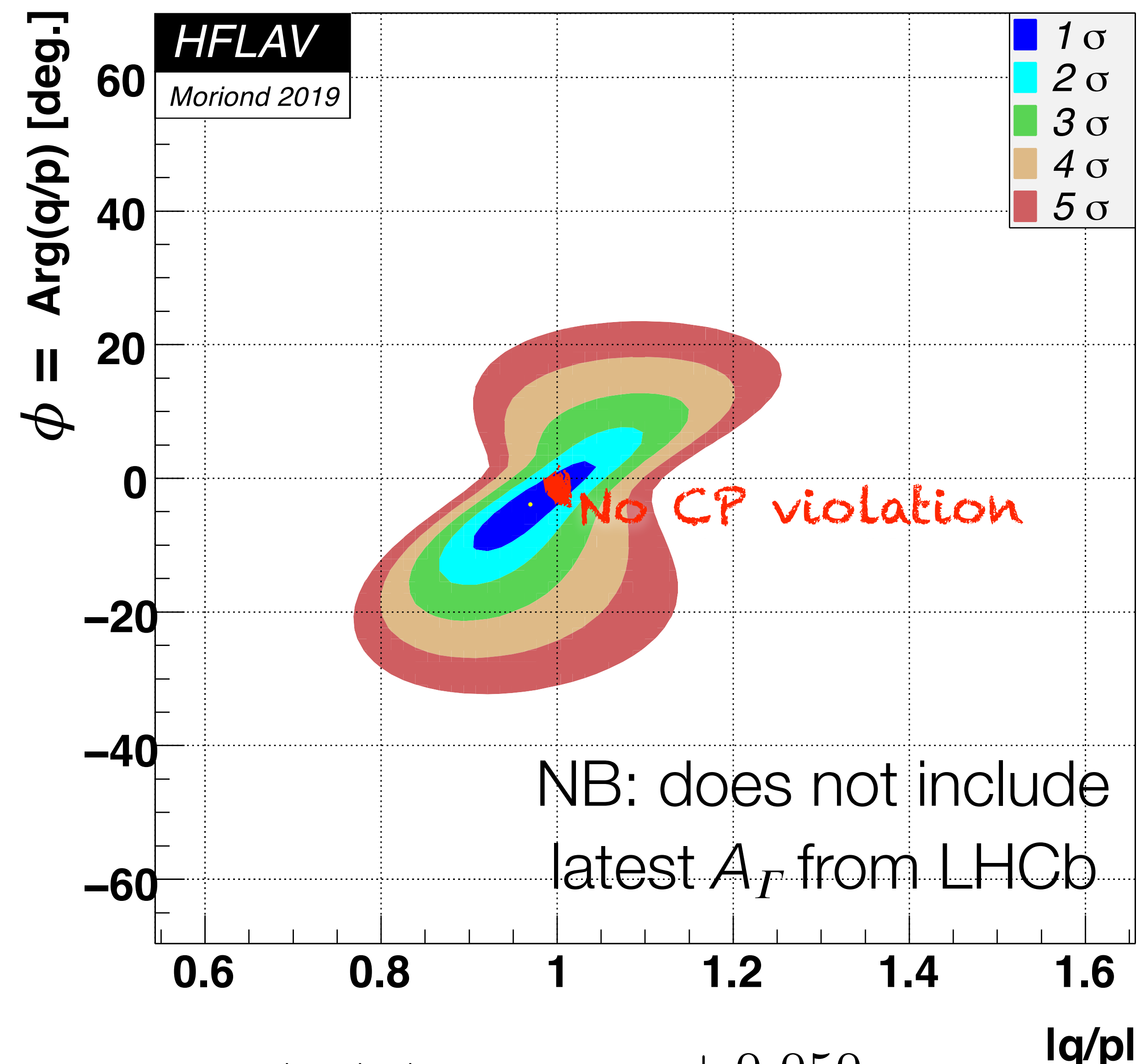
Impact on world average





Impact on world average





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$$|q/p| = 0.969\,{}^{+0.050}_{-0.045}$$

$$\phi = (-3.9\,{}^{+4.5}_{-4.6})^\circ$$

first evidence for nonzero (positive) value of *x*

Prospects for $D^0 \to K_S \pi^+ \pi^-$

- In Run 1+2 LHCb has collected ~36M π-tagged $D^0 \to K_S \pi^+ \pi^-$ decays and ~10M μ-tagged decays
  - Expected sensitivity (my own extrapolation, not official)

Uncertainty ($\times 10^{-3}$)	x_{CP}	y_{CP}	Δx	Δy
CLEO inputs	0.3	1.0	0.07	0.13
Data statistics	0.4	0.8	0.16	0.34
Total	0.5	1.3	0.18	0.39

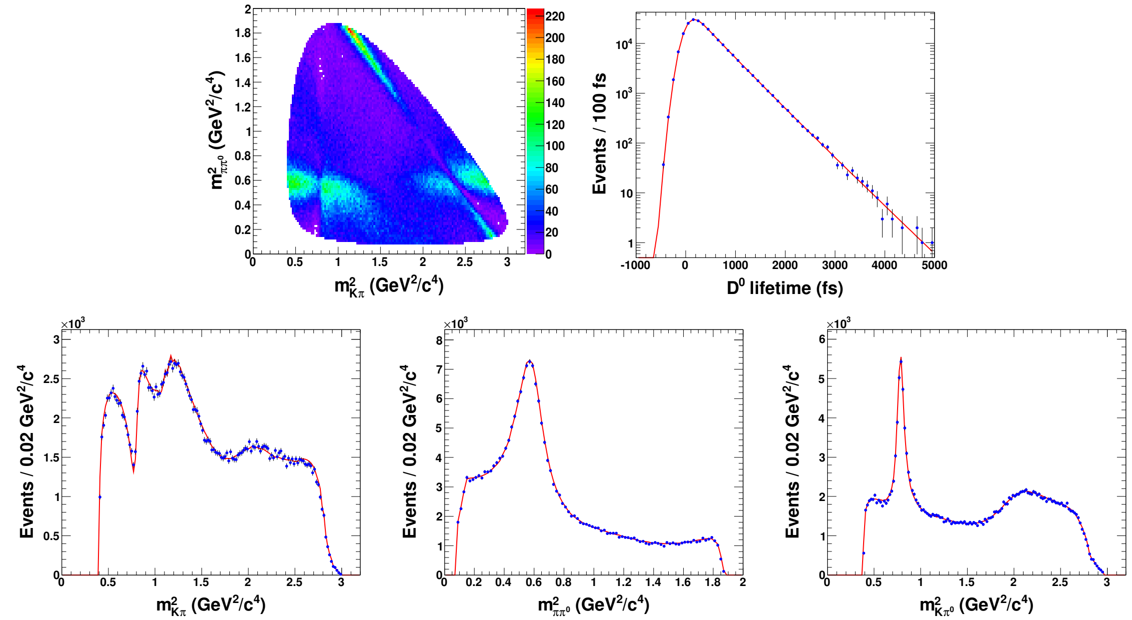
- Belle II will collect ~50M (π-tagged) decays with 50/ab. Difficult to compete if LHCb keeps same efficiency in the Upgrade
- Can Belle II do $D^0 \to K_L \pi^+ \pi^-$? (it is being considered for $\gamma/\phi 3$)

More multibodies

- Lots of other promising final states not yet explored/fully exploited experimentally: *e.g.* $D^0 \to K^+\pi^-\pi^0$, $D^0 \to K_S\pi^+\pi^-\pi^0$, $D^0 \to K^+\pi^-\pi^+\pi^-$, …

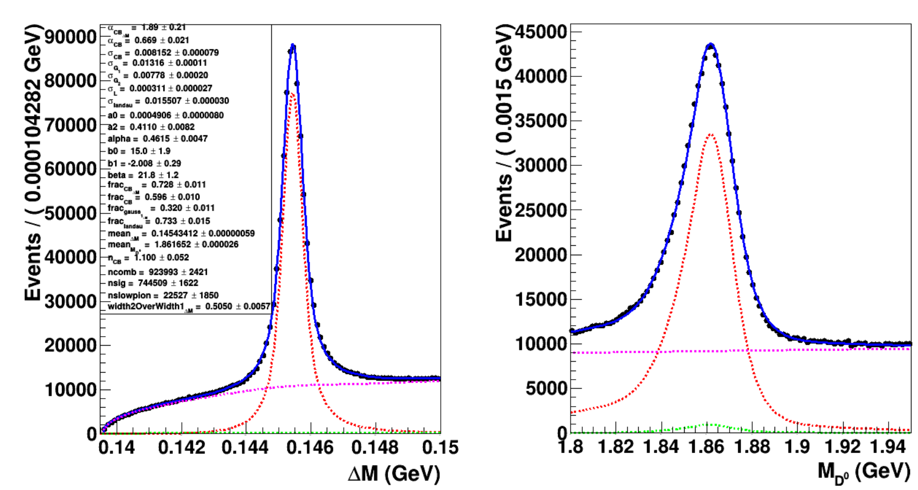
- Model-independent analyses would have to rely on BESIII measurements of the strong-phase parameters

[arXiv:1808.10567]



~225k $D^0 \to K^+\pi^-\pi^0$
expected at Belle II (50/ab)
$\sigma(x'' \approx x) \sim 0.5\times10^{-3}$

[PRD 95 (2017) 091101]



~750M $D^0 \to K_S\pi^+\pi^-\pi^0$
at Belle (1/ab)

Summary

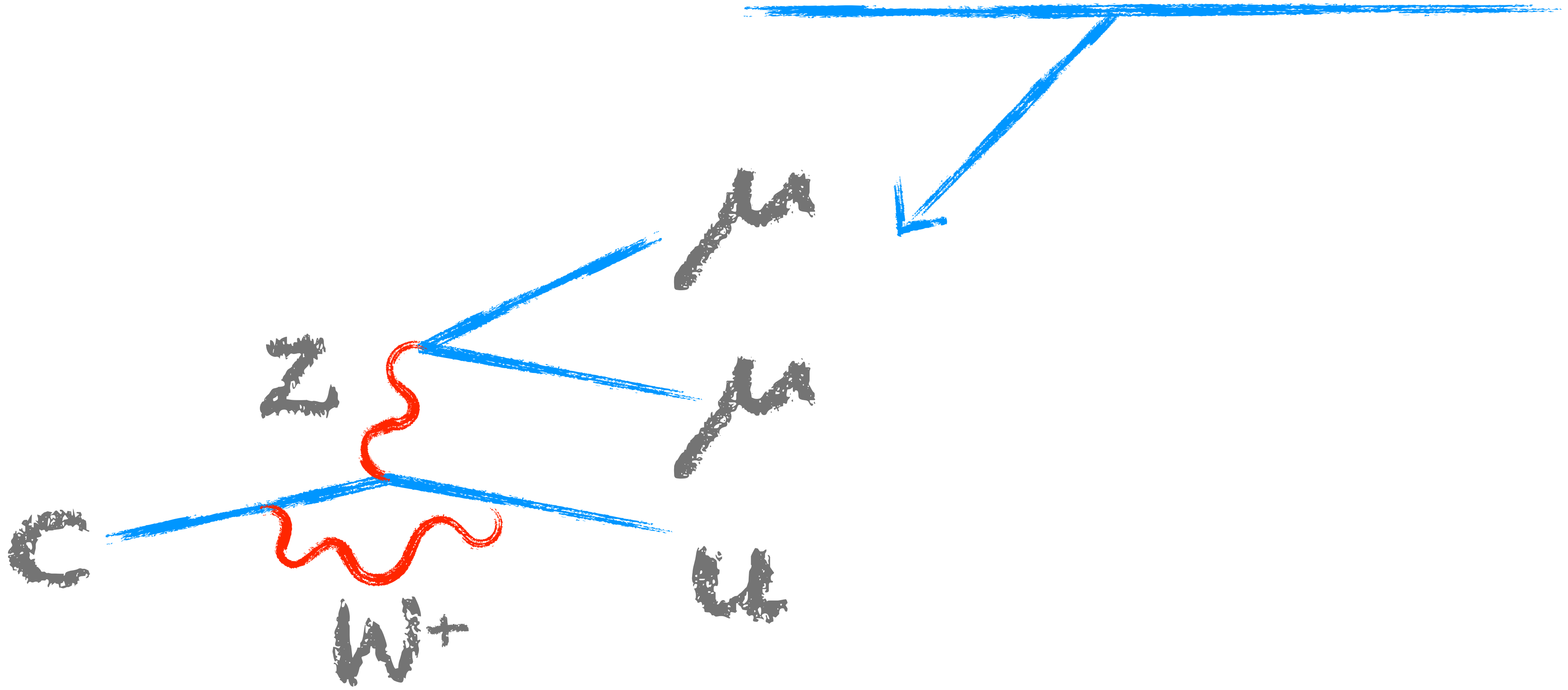
- Observed (direct) *CP* violation in charm decays
  - Measured asymmetry seems consistent with standard model, although predictions suffer from large uncertainties due to strong-interaction effects
  - Additional searches for *CP* violation in different decay modes can help to clarify the picture, together with improved theory calculations
- Yet no signs for mixing-induced *CP* violation. Precision still ~10× larger than naive standard model expectation, so plenty of room for new physics
- Huge experimental progress expected in the next decade(s) at LHCb and Belle II (with valuable inputs from BESIII) if we fully exploit the excellent complementarity between the two experiments

“Charm is the new beauty!”

Charm is more valuable than beauty. You can resist beauty, but you can't resist charm.

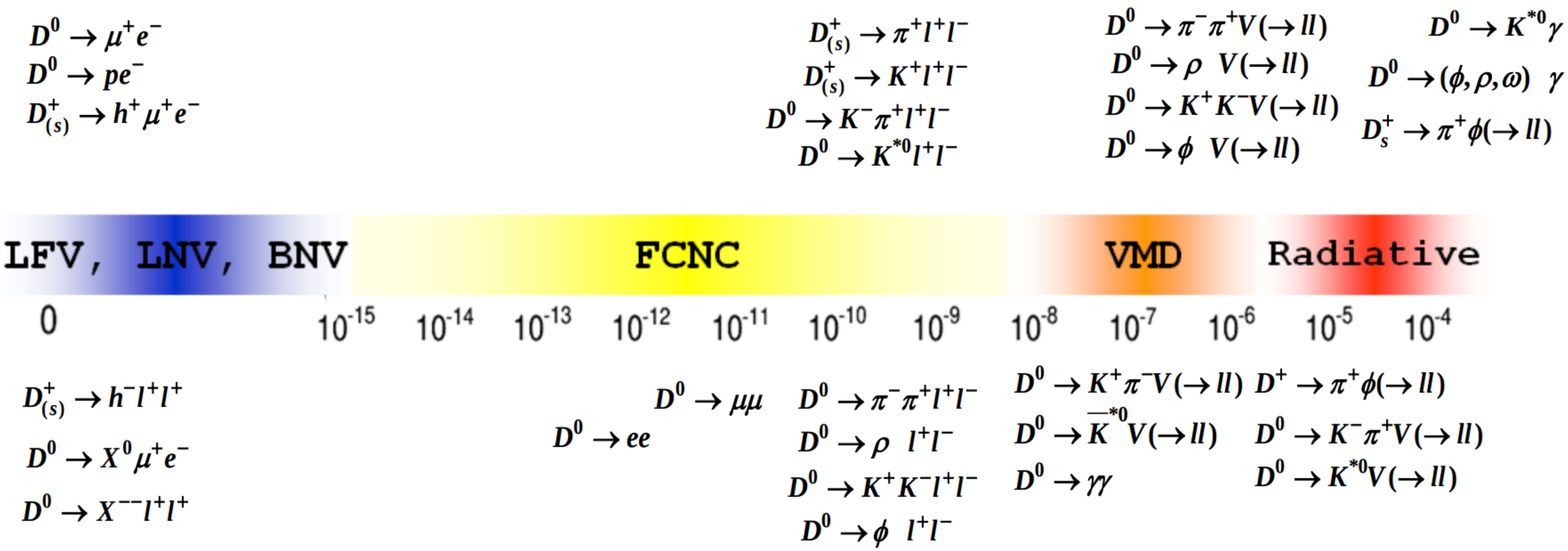
— *Audrey Tautou* —

Supplementary slides on rare charm decays



Rare charm decays at LHCb

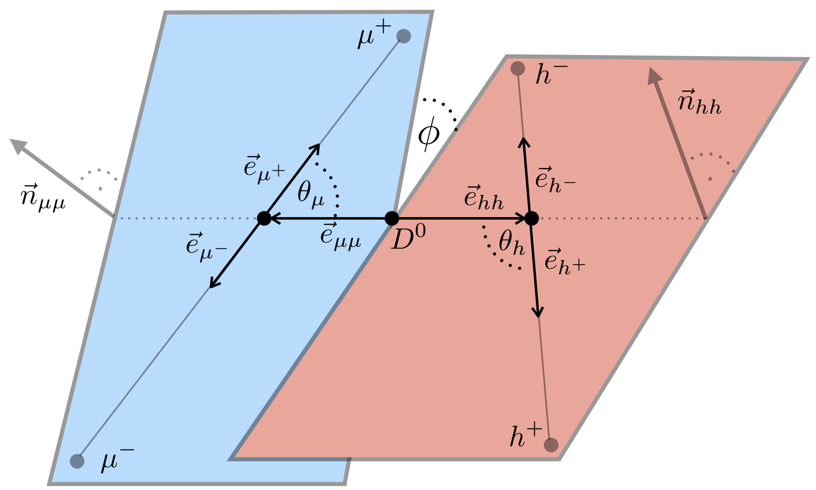
- A rainbow of different physics, ranging from forbidden to (not-so-rare) radiative decays



- So far LHCb focused mostly on final states with 2 muons:
  - Best limit on $D^0 \to \mu^+\mu^-$ [PLB 725 (2013) 15], $D_{(s)} \to \pi^+\mu^+\mu^-$, $\pi^-\mu^+\mu^+$ [PLB 724 (2013) 203], $D^0 \to h^+h^-\mu^+\mu^-$ [PLB 728 (2014) 234], $D^0 \to e^+\mu^-$ [PLB 754 (2016) 167], $\Lambda_c \to p\mu^+\mu^-$ [PRD 97 (2018) 091101]
  - First observation of $D^0 \to K^-\pi^+V(\to\mu^+\mu^-)$ [PLB 757 (2016) 558], $K^+K^-V(\to\mu^+\mu^-)$, $\pi^+\pi^-V(\to\mu^+\mu^-)$ [PRL 119 (2017) 181805, PRL 121 (2018) 091801], $\Lambda_c \to pV(\to\mu^+\mu^-)$ [PRD 97 (2018) 091101]

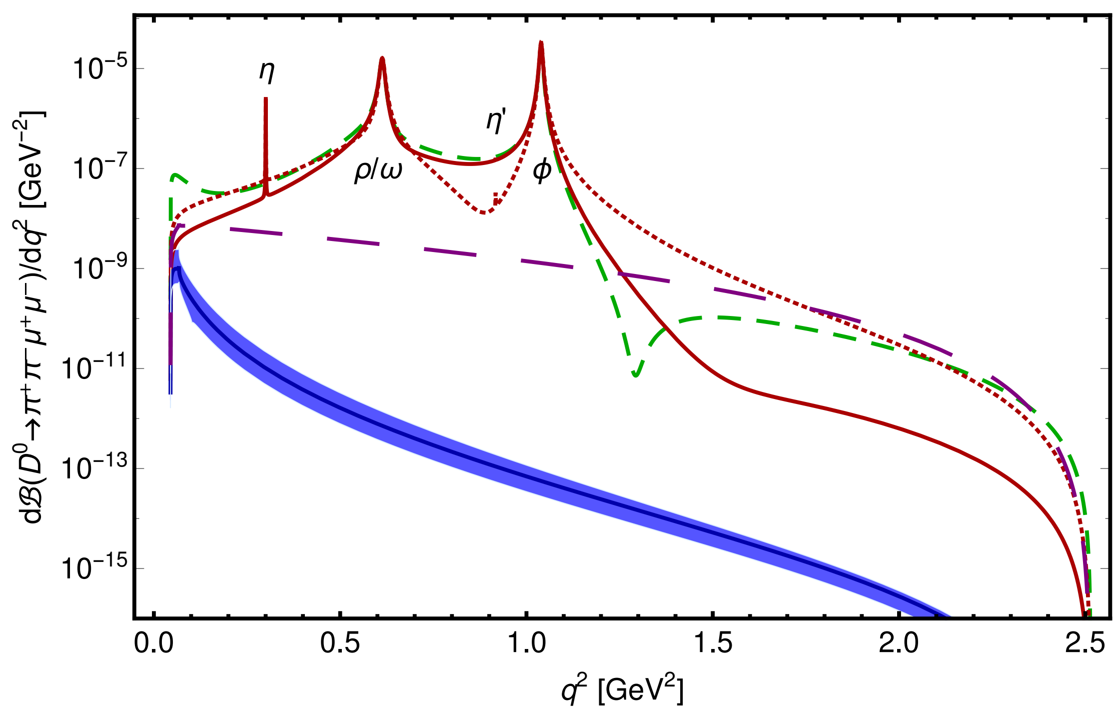
The richness of $D^0 \to h^+h^-\mu^+\mu^-$ decays

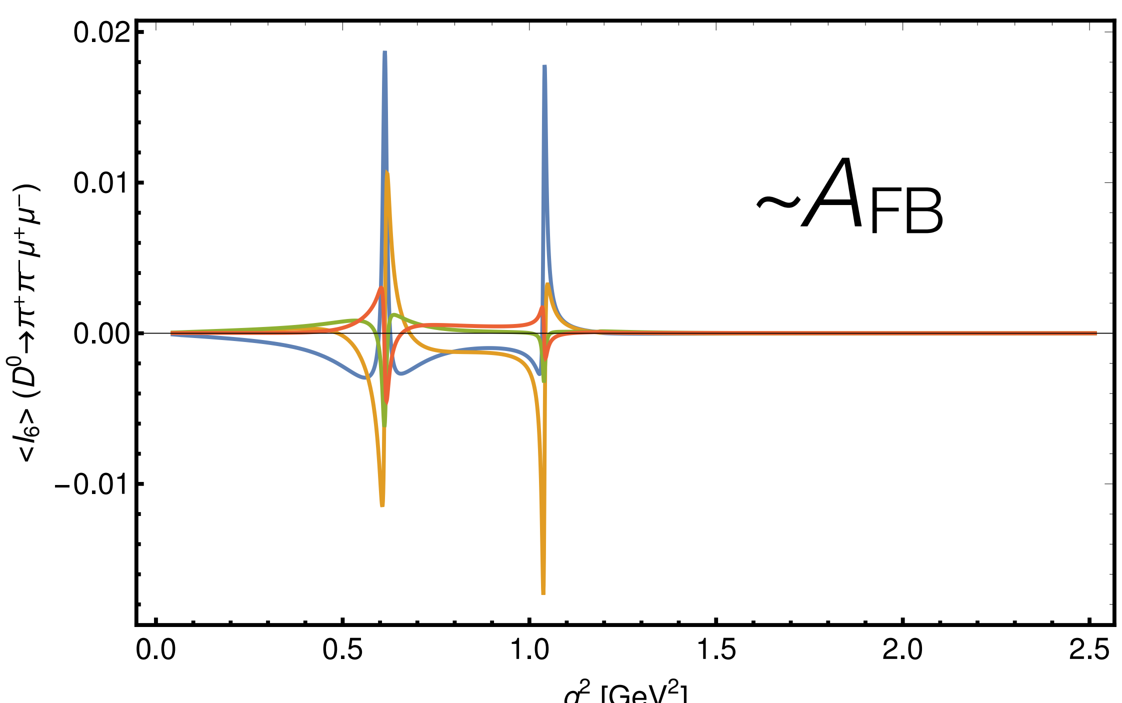
- Overwhelming contribution from long-distance amplitudes proceeding through intermediate vector resonances in the dimuon spectrum
- Such penalty is overly compensated by the rich and diverse dynamics of multibody decays



  - Access to angular and *CP* asymmetries can greatly increase sensitivity to short-distance physics
  - O(1%) asymmetries may be generated by NP [JHEP 04 (2013) 135, PRD 87 (2013) 054026, PRD 98 (2018) 035041]

[PRD 98 (2018) 035041]

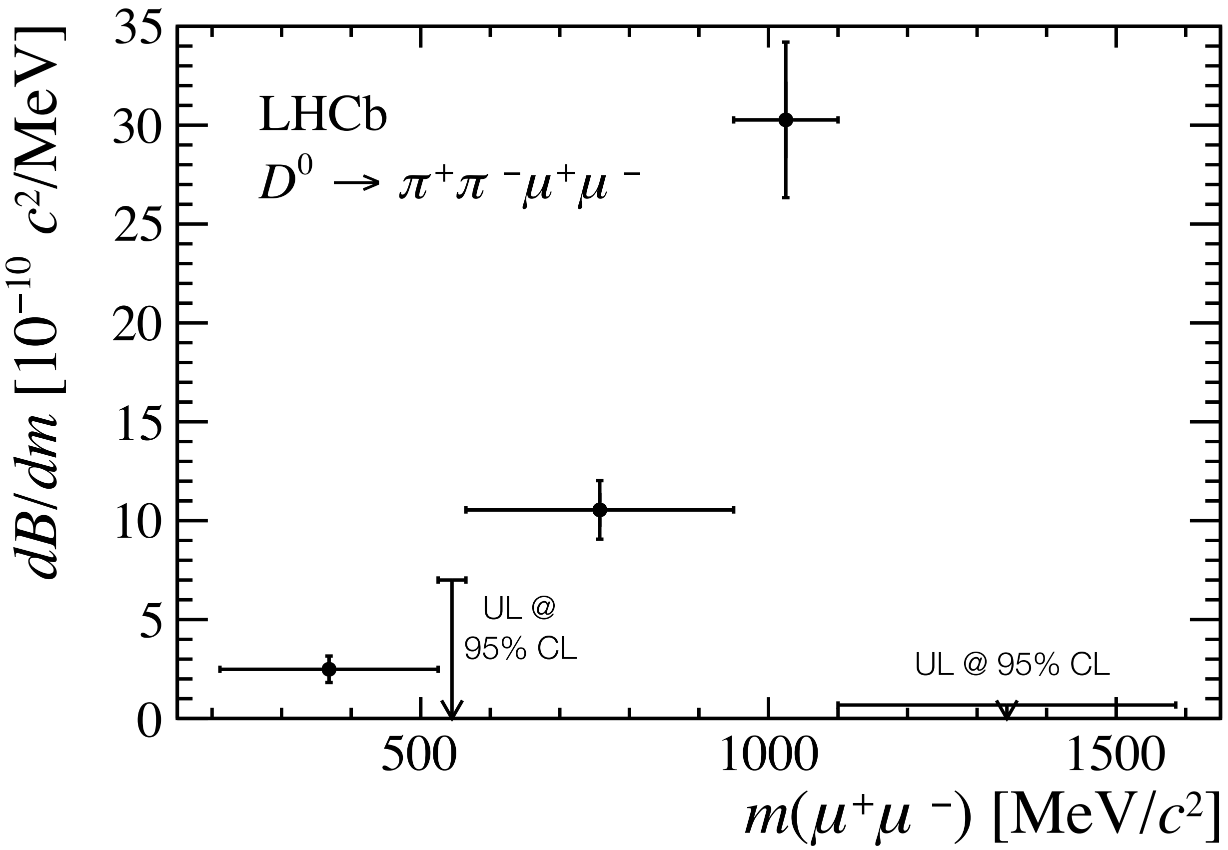


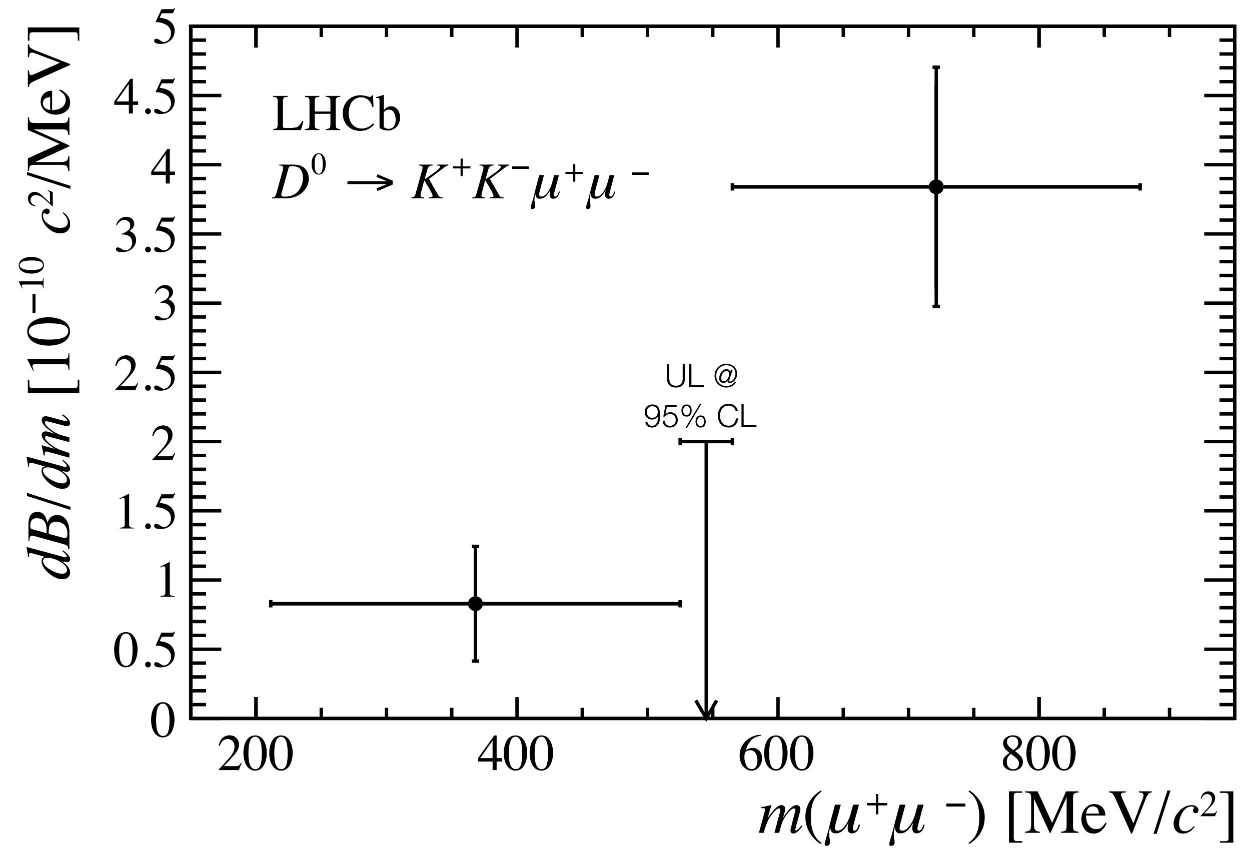


$D^0 \to h^+h^-\mu^+\mu^-$: branching fraction

Run 1 (2/fb)

[PRL 119 (2017) 181805]





- Rarest charm-hadron decays ever observed:

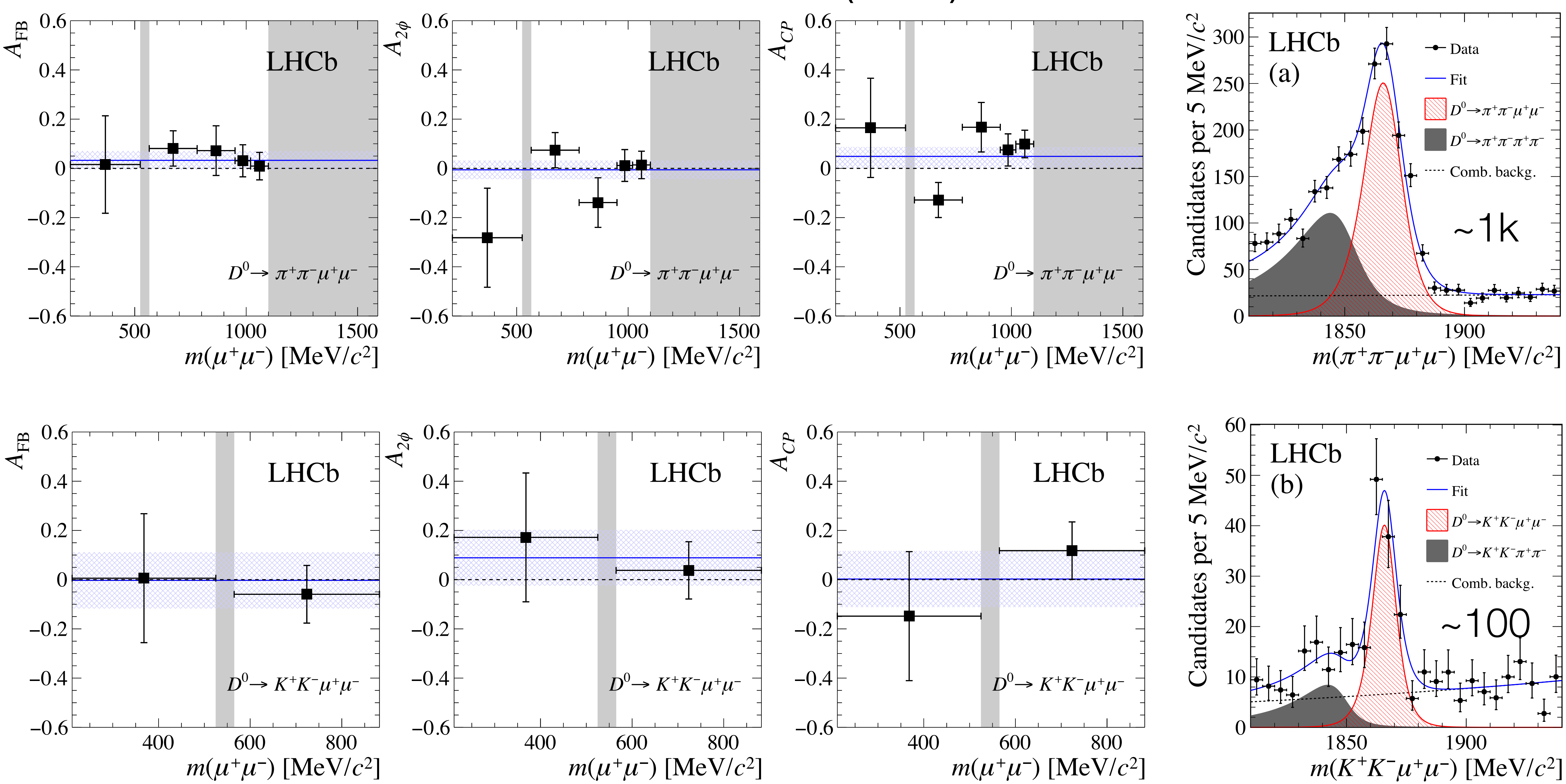
$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

where the uncertainties are statistical, systematic and due to the BF of the normalization decay

$D^0 \to h^+h^-\mu^+\mu^-$: angular and CP asymmetries

Run 1+2 (5/fb)



[PRL 121 (2018) 091801]

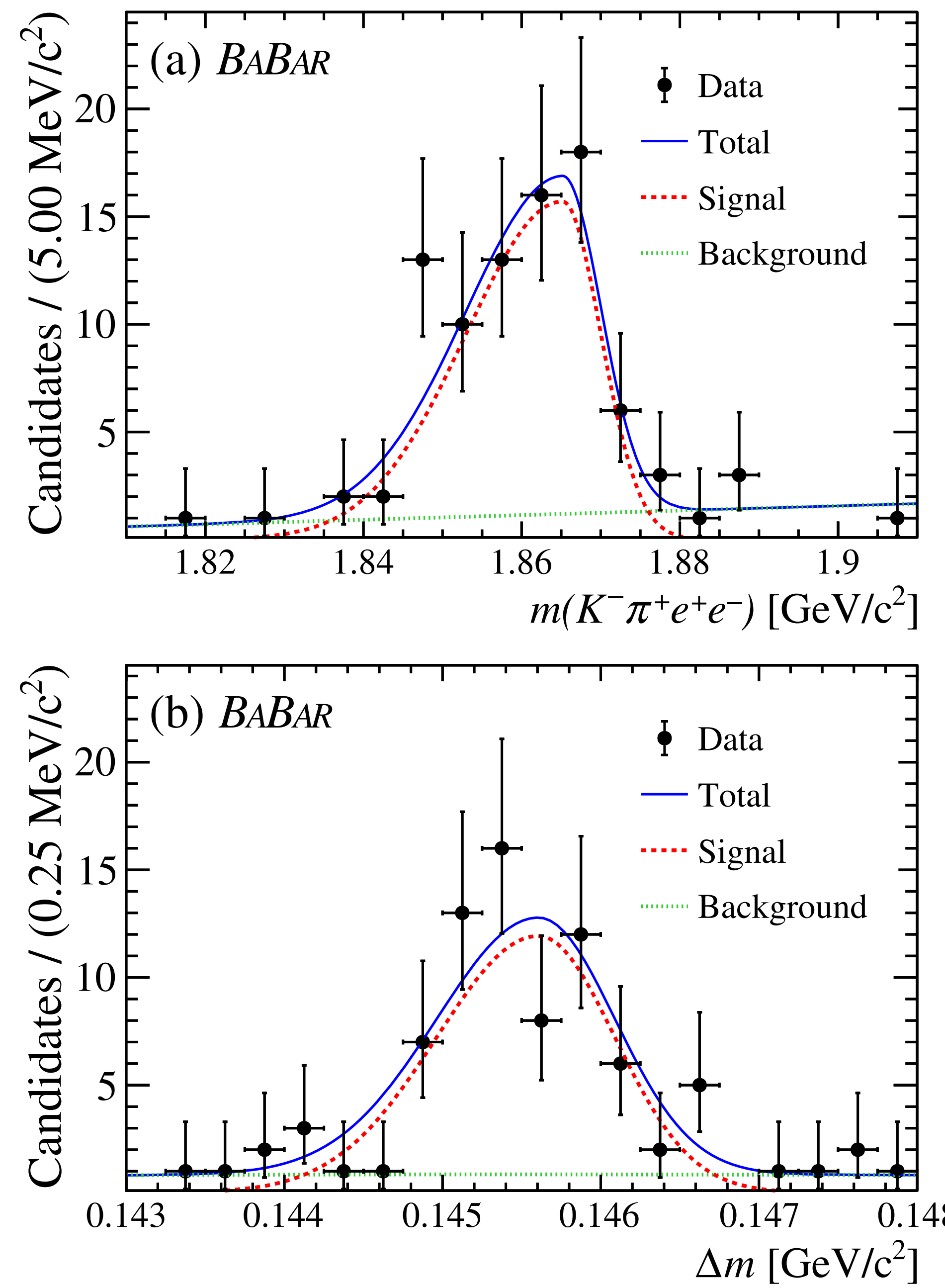
Which final states for Belle II?

- Electron modes to test LFU: *e.g.* $D_{(s)} \to h^+e^+e^-$, $D^0 \to h^-h^+e^+e^-$ $D^0 \to \pi^0 e^+e^-$, …
  - First observation of $D^0 \to K^-\pi^+e^+e^-$ at BaBar with 0.5/ab

$$\mathcal{B}(D^0 \to K^-\pi^+[e^+e^-]_{\rho^0/\omega}) = (4.0 \pm 0.5) \times 10^{-6}$$

- Radiative and neutrals: *e.g.* $D^0 \to V^0\gamma$, $D^0 \to \gamma\gamma$, $D_{(s)} \to K\pi\pi\gamma$, …

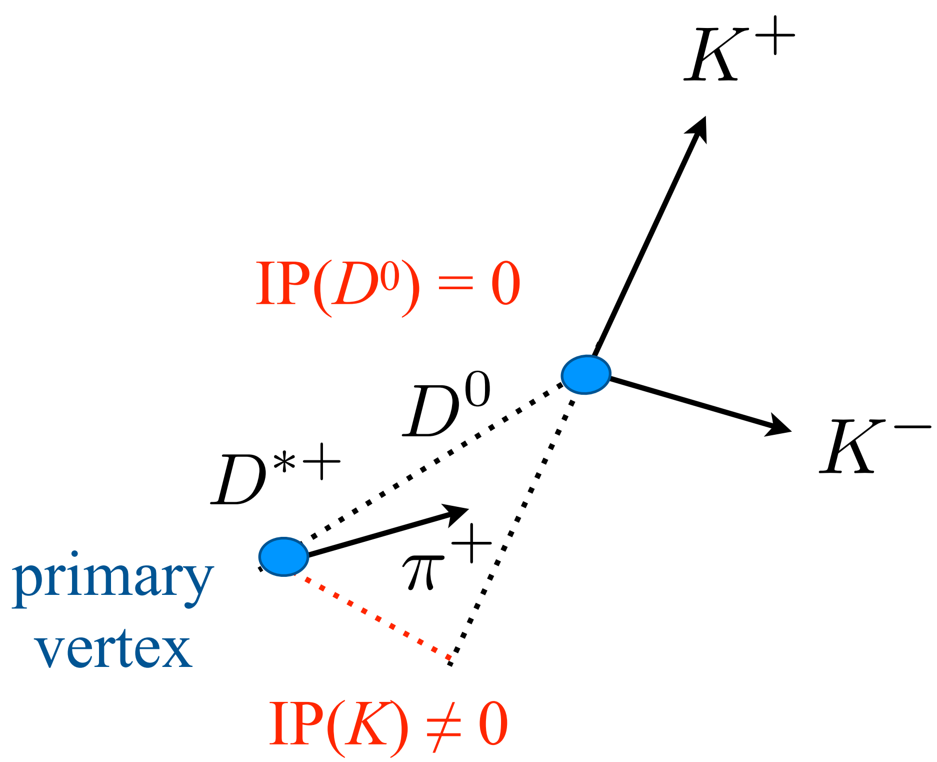
[PRL 122 (2019) 081802]

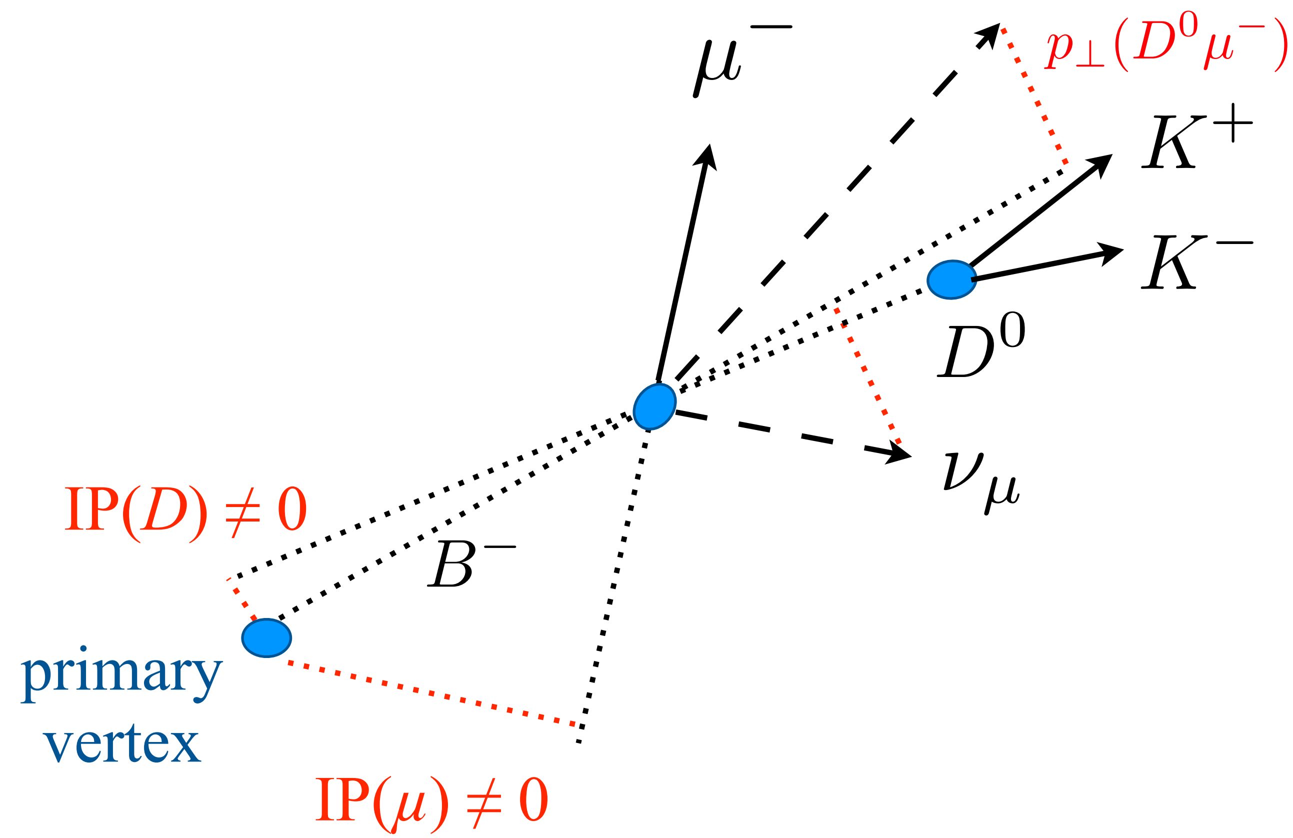


Backup slides

$D^0 \to h^+h^-$ decays at LHCb

$$m_{\rm corr} = \sqrt{m^2(D^0\mu^-) + p_\perp(D^0\mu^-)^2} + p_\perp(D^0\mu^-)$$





- Prompt charm (π tagged): well identified kaons/pions forming a displaced secondary vertex, paired with low-momentum pion to form a D^{*+} vertex that coincides with the primary vertex

- From semileptonic B decays (μ tagged): well identified and displaced muon paired with D^0 candidate, requirement on corrected mass to (partly) compensate for undetected neutrino

Systematic uncertainties

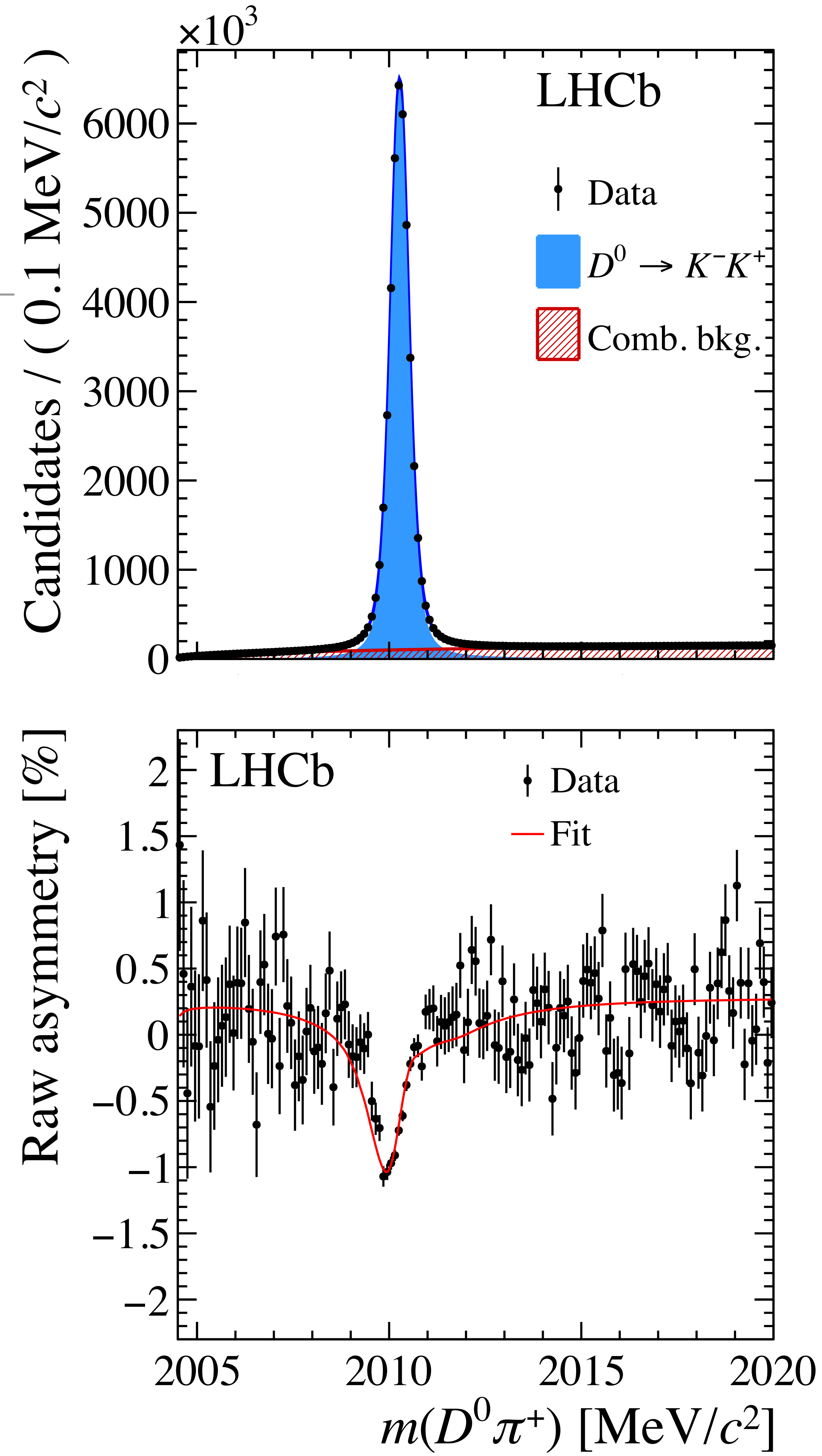
[PRL 122 (2019) 211803]

[10^{-4}]

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

Fit model

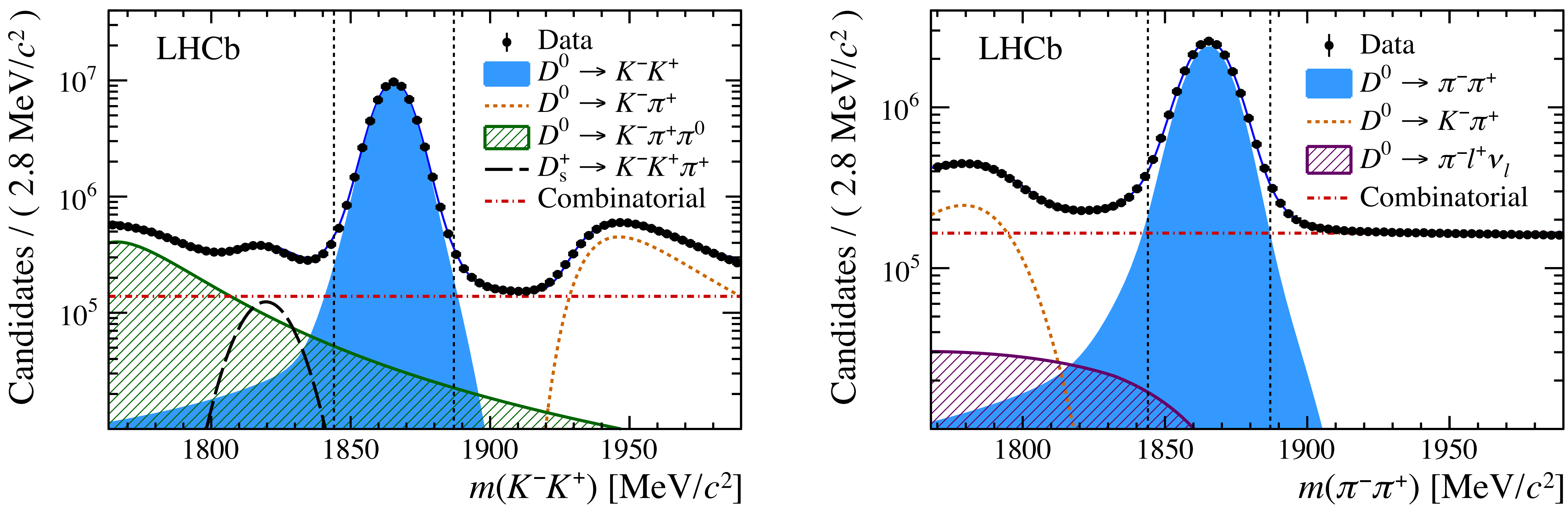
- Mass model with O(10M) candidates is never perfect
- Impact on asymmetries is generally marginal
- However, mass shapes may also be charge asymmetric (momentum scale/resolution is slightly asymmetric)
- Tested a variety of alternative models, bias on signal asymmetry estimated using pseudoexperments



[PRL 122 (2019) 211803]

Peaking background

[PRL 122 (2019) 211803]

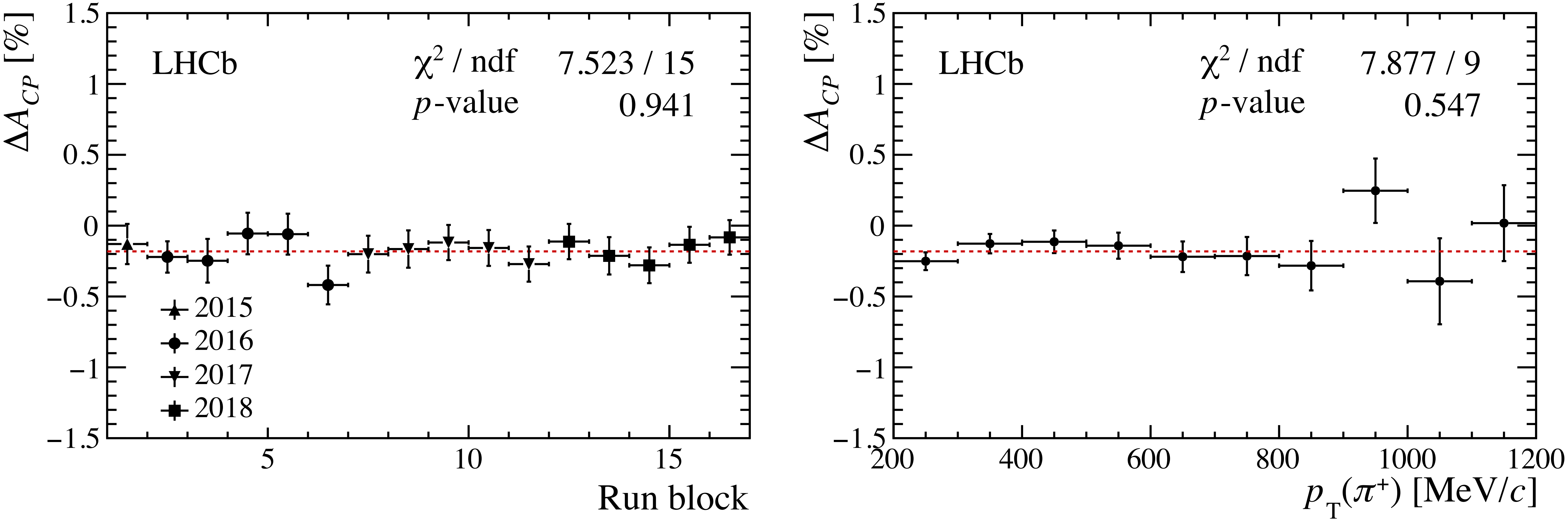


- Backgrounds due to $D^{*+} \to D^0\pi^+$ decays, where the D^0 is mis- or partially reconstructed would peak in $m(D^0\pi^+)$
- Bias on signal asymmetry estimated by measuring backgrounds asymmetry and contamination in the D^0-mass signal region

Consistency checks

[PRL 122 (2019) 211803]

- Measured value of ΔA_{CP} studied as a function of several variables (*e.g.*, magnet polarity, data-taking period, kinematics)



- No evidence found for unexpected dependences

Interpretation of ΔA_{CP}

- The time-integrated asymmetry receives contribution from *CP* violation in the decay amplitudes (direct) and in D^0-$\bar{D}^0$ mixing (indirect)

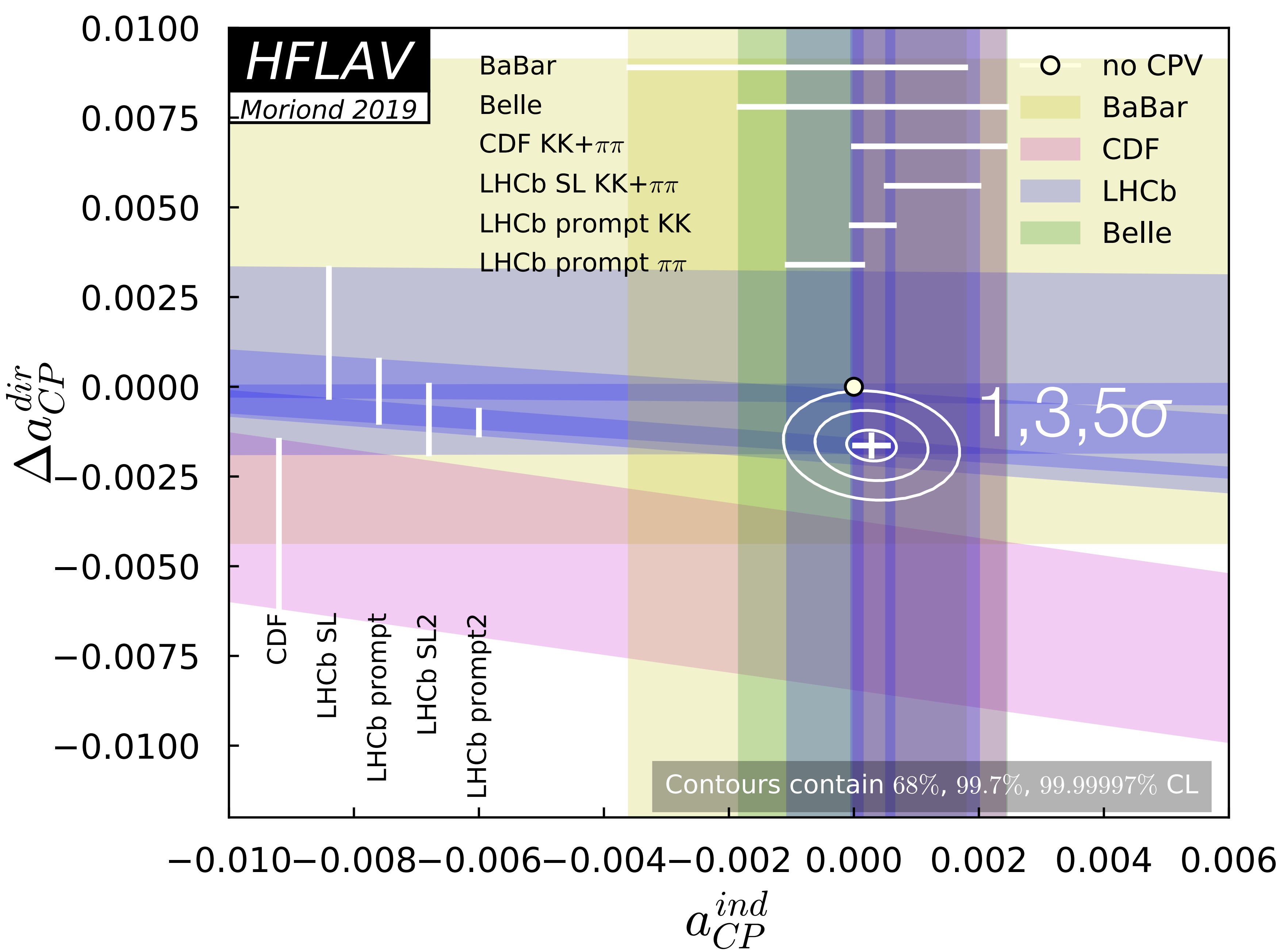
$$A_{CP}(h^+h^-) \approx a_{CP}^{\mathrm{dir}}(h^+h^-) + \frac{\langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}$$

- Indirect contribution is to a good approximation independent of the decay mode

- Since $\Delta\langle t \rangle \sim 0.1\tau$, ΔA_{CP} is mostly a measurement of direct *CP* violation

$$\Delta A_{CP} \approx \Delta a_{CP}^{\mathrm{dir}} + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}$$

Experimental status of CP violation in $D^0 \to h^+h^-$



$$\Delta a_{CP}^{\mathrm{dir}} = (-16.4 \pm 2.8) \times 10^{-4}$$

$$a_{CP}^{\mathrm{ind}} = (\quad 2.8 \pm 2.6) \times 10^{-4}$$

Individual asymmetries at LHCb

Run 1 (3/fb)
[PLB 767 (2017) 177]

- Use large samples of Cabibbo-favored $D^0 \to K^- \pi^+$, $D^+ \to K^- \pi^+ \pi^+$ and $D^+ \to \bar{K}^0 \pi^+$ decays (where no *CPV* is expected) to cancel detector and production asymmetries

Removes production asymmetry and tag μ/π detection asymmetry

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

$$A_D(K^-\pi^+) = A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) - A(K^0)$$

Removes D^+ production asymmetry and π^+ detection asymmetry

Correction for *CPV* in neutral kaon system and for different interaction with matter

$$A_{CP}(D^0 \to K^+K^-) = (1.4 \pm 1.5 \pm 1.0) \times 10^{-3}$$

$$A_{CP}(D^0 \to \pi^+\pi^-) = (2.4 \pm 1.5 \pm 1.1) \times 10^{-3}$$

Neutral kaons asymmetry

[CERN-THESIS-2014-274]

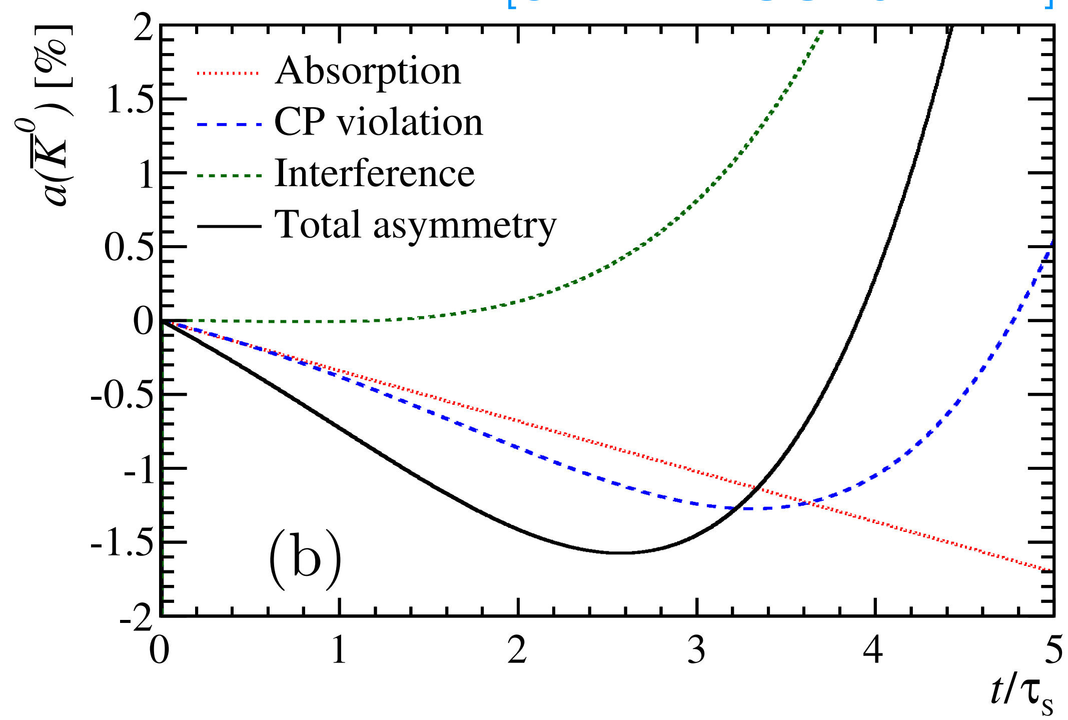
- Neutral kaons violates *CP* and their mixing can be affected by material interactions (*i.e.* regeneration of K_S in K_L beams)

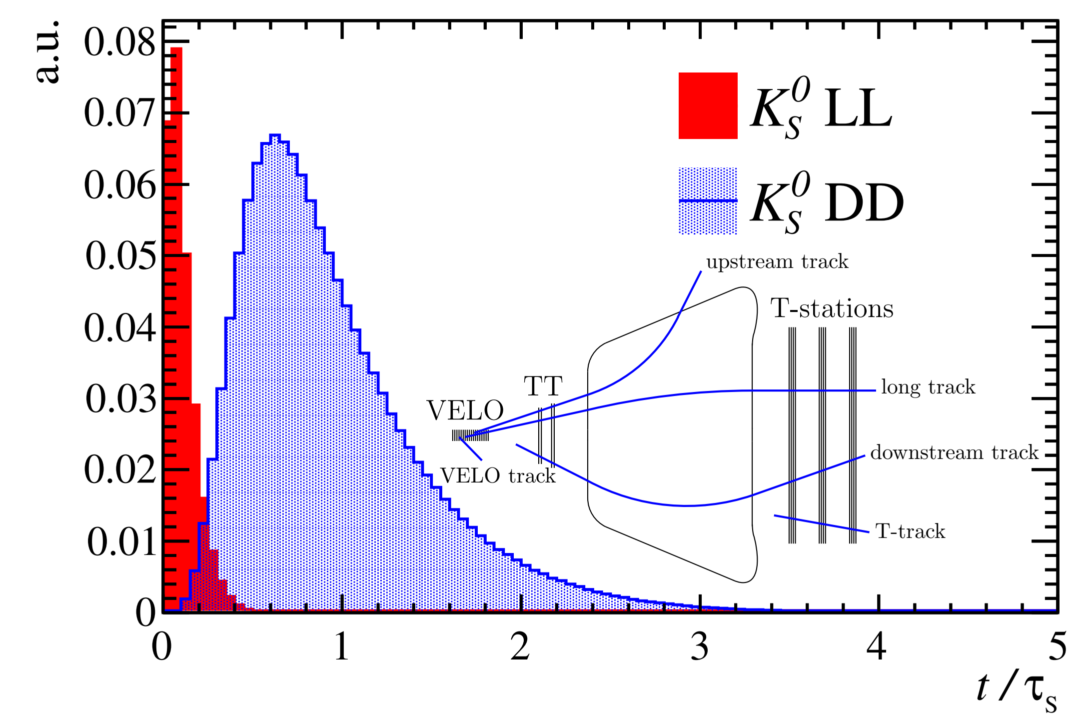
- Both effects lead to tiny detection asymmetries when using K_S that decay in the VELO (LL)

$$A(K_S \text{ LL}) = (-0.73 \pm 0.05)\times10^{-3}$$
$$A(K_S \text{ DD}) = (-6.2 \pm 0.3)\times10^{-3}$$

- Uncertainty limited by the knowledge of the detector material — if not under control, may impact the ultimate precision

- *CP* asymmetries with one K_S mesons in the final state are currently limited to LL candidates (~1/3 of reconstructed decays)





Phase-space binning

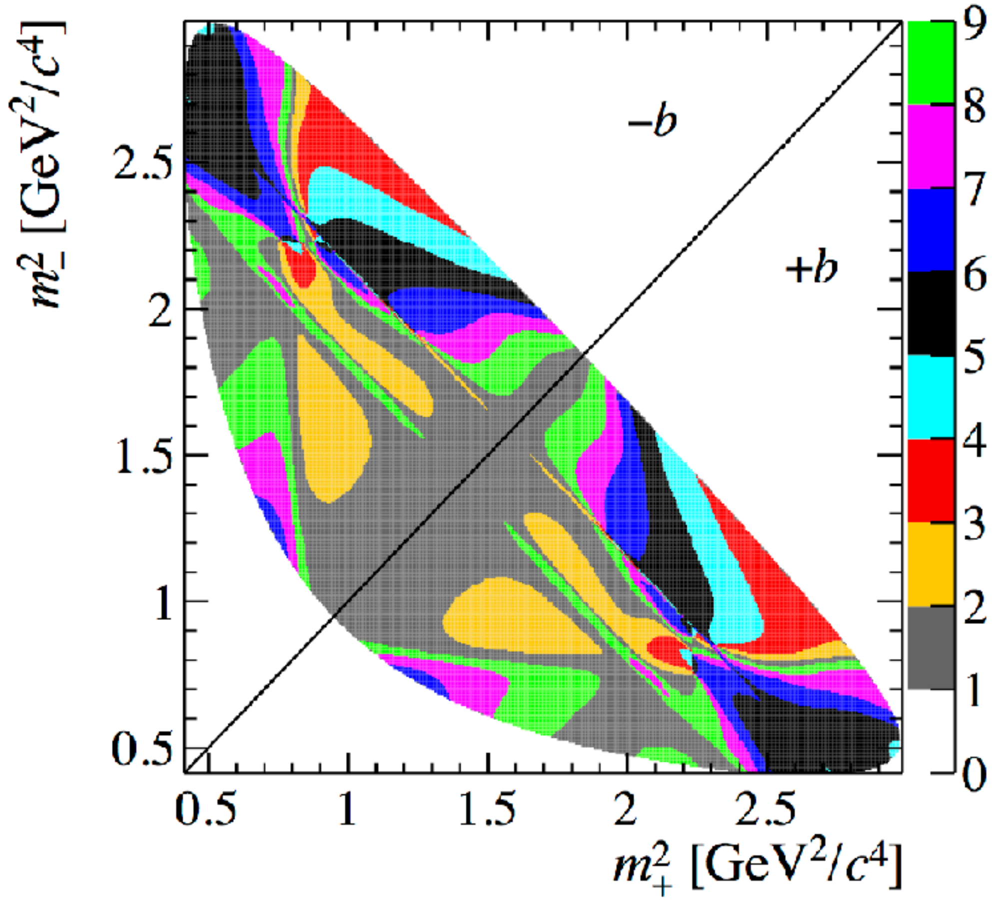
$$c_b \equiv \frac{1}{\sqrt{F_b F_{-b}}} \int_b dm_+^2 dm_-^2 \, |A_f(m_+^2, m_-^2)| \, |A_f(m_-^2, m_+^2)| \cos[\Delta\delta(m_+^2, m_-^2)], \qquad (26)$$

$$s_b \equiv \frac{1}{\sqrt{F_b F_{-b}}} \int_b dm_+^2 dm_-^2 \, |A_f(m_+^2, m_-^2)| \, |A_f(m_-^2, m_+^2)| \sin[\Delta\delta(m_+^2, m_-^2)], \qquad (27)$$

where $\Delta\delta(m_+^2, m_-^2) = \delta(m_+^2, m_-^2) - \delta(m_-^2, m_+^2)$ and $\delta(m_+^2, m_-^2)$ is the phase of $A_f(m_+^2, m_-^2)$.

$$2\pi(b - 3/2)/n < \Delta\delta(m_+^2, m_-^2) < 2\pi(b - 1/2)/n, \quad b = 1, ..., n.$$

b	c_b	s_b
1	$0.655 \pm 0.036 \pm 0.042$	$-0.025 \pm 0.098 \pm 0.043$
2	$0.511 \pm 0.068 \pm 0.063$	$0.141 \pm 0.183 \pm 0.066$
3	$0.024 \pm 0.140 \pm 0.080$	$1.111 \pm 0.131 \pm 0.044$
4	$-0.569 \pm 0.118 \pm 0.098$	$0.328 \pm 0.202 \pm 0.072$
5	$-0.903 \pm 0.045 \pm 0.042$	$-0.181 \pm 0.131 \pm 0.026$
6	$-0.616 \pm 0.103 \pm 0.072$	$-0.520 \pm 0.196 \pm 0.059$
7	$0.100 \pm 0.106 \pm 0.124$	$-1.129 \pm 0.120 \pm 0.096$
8	$0.422 \pm 0.069 \pm 0.075$	$-0.350 \pm 0.151 \pm 0.045$



[PRD 82 (2010) 112006]

Sensitivity study

[PRD 99 (2019) 012007]

- Generated 1M signal-only $D^0 \to K_S \pi^+ \pi^-$ decays using the BaBar amplitude model and compared sensitivity to *x* and *y* with different analysis methods (all other nuisance parameters fixed)

Analysis method	$\sigma(x)$	$\sigma(y)$
Model-dependent	0.11%	0.10%
Original model-independent	0.20%	0.18%
Bin-flip model-independent	0.15%	0.29%

- Bin-flip method gives better sensitivity to *x* than the original model-independent method

- Similar ratios of sensitivities hold for the *CP*-violation parameters when fitting D^0 and $\overline{D}^0$ decays separa

$$x \longrightarrow x^{\pm} = x_{CP} \pm \Delta x$$

$$y \longrightarrow y^{\pm} = y_{CP} \pm \Delta y$$

A new parametrization

[PRD 99 (2019) 012007]

$$z_{CP} \pm \Delta z = -(q/p)^{\pm 1}(y + ix)$$

$$x_{CP} = -\Im(z_{CP}) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta x = -\Im(\Delta z) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$y_{CP} = -\Re(z_{CP}) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta y = -\Re(\Delta z) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$