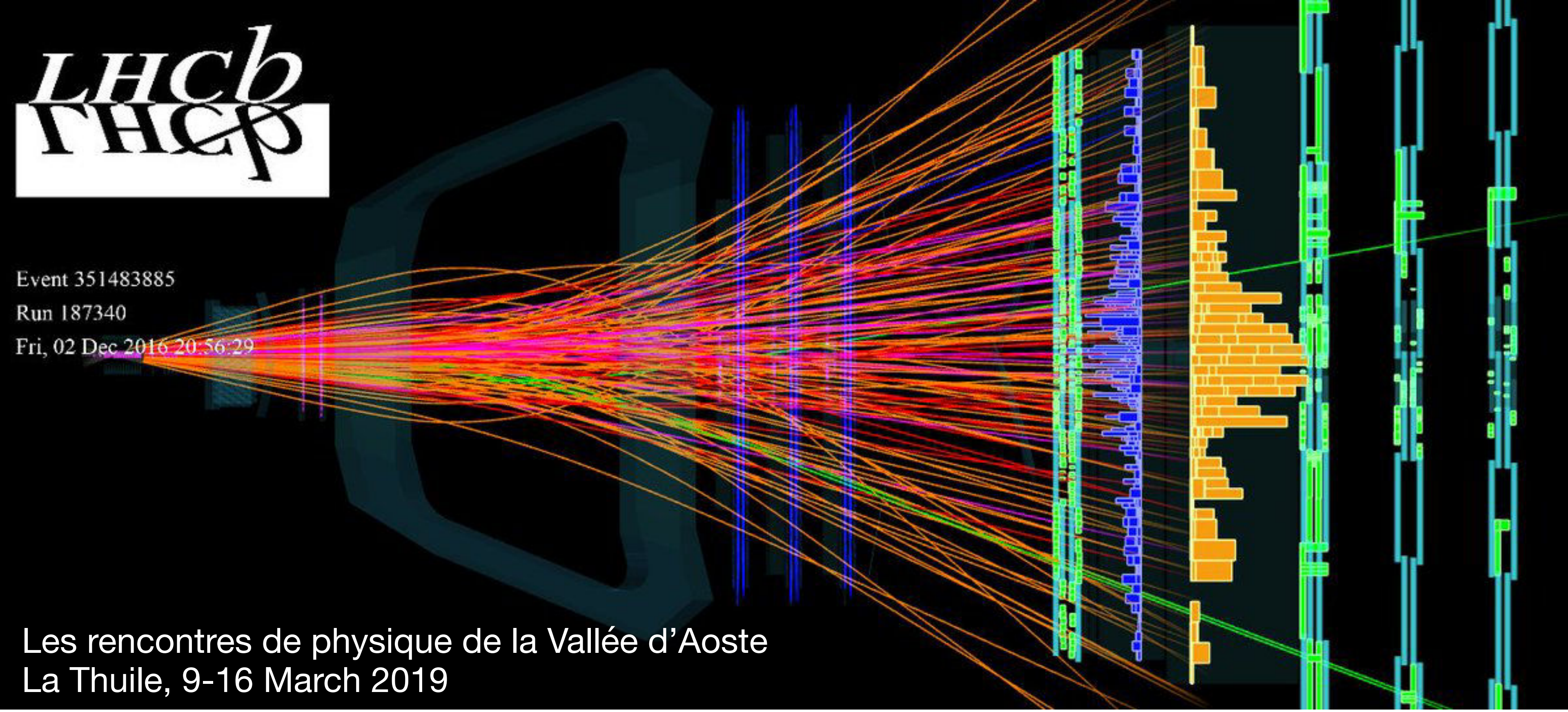

Les rencontres de physique de la Vallée d’Aoste
La Thuile, 9-16 March 2019

Mixing and CP violation in charm

Tommaso Pajero - Scuola Normale Superiore & INFN, Pisa
on behalf of LHCb collaboration

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Why charm physics?

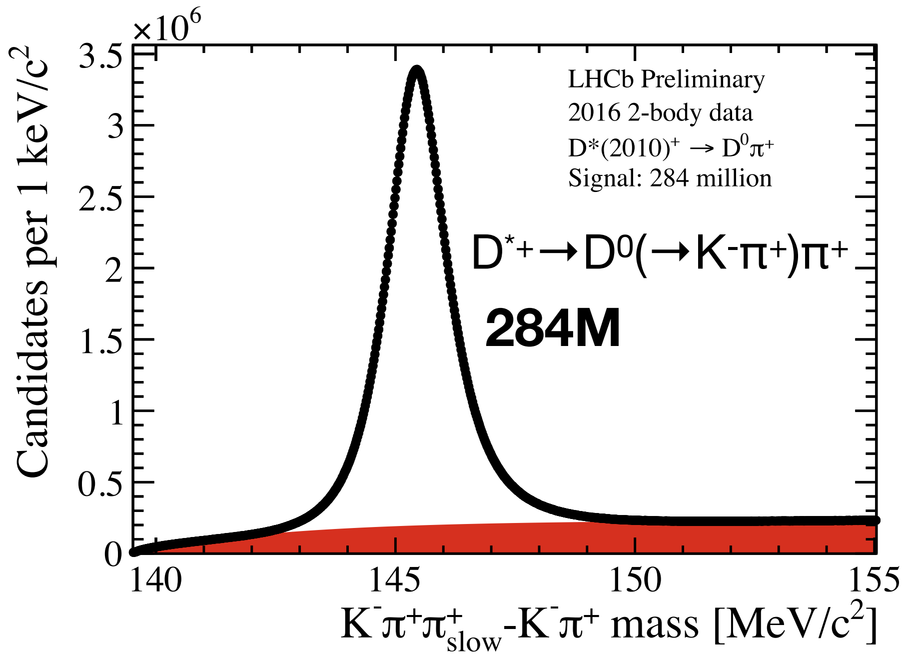
- A new source of CP violation (CPV) is needed to explain matter-antimatter asymmetry;
- CPV searches in charm **complementary** to those of K^0 and B mesons
  - up-type quarks involved.

- In the SM, CPV is expected to be **≤ 0.1—1%**:
  - CKM+GIM suppression;
  - large uncertainties owing to low-energy strong interactions;
  - **CPV not observed yet.**

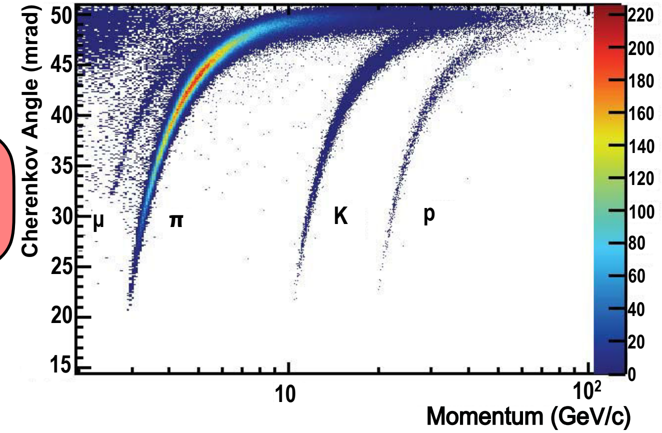
- At LHCb:

$\sigma(pp \to c\bar{c}X) \approx 2.4$ mb $(\sqrt{s} = 13$ TeV$)$

≈ 1 MHz $c\bar{c}$ pairs [JHEP 1603 (2016) 159]

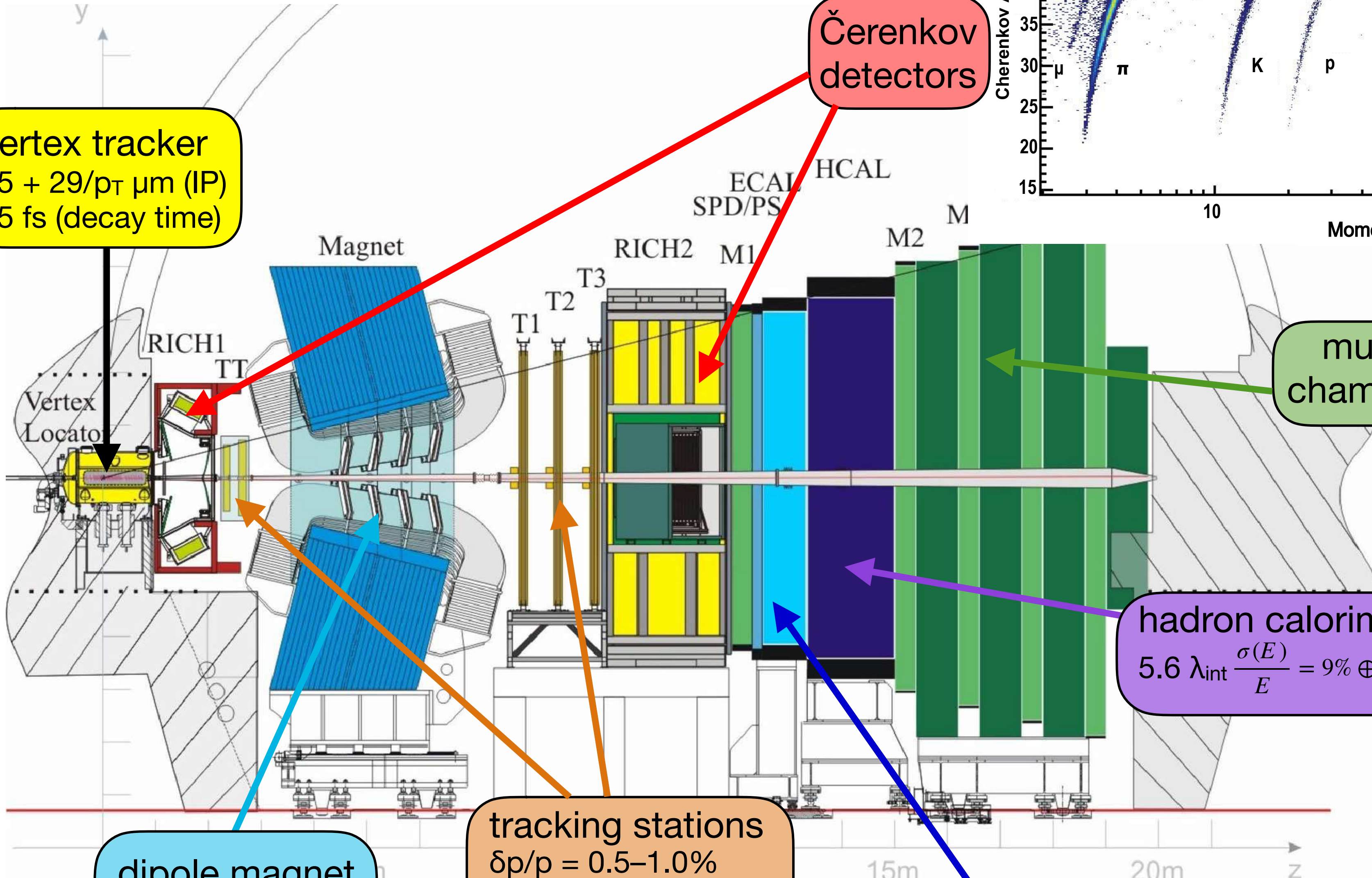


LHCb detector



Čerenkov detectors

vertex tracker
15 + 29/p_T μm (IP)
45 fs (decay time)



muon chambers

hadron calorimeter
5.6 λ_{int} $\frac{\sigma(E)}{E} = 9\% \oplus \frac{69\,\%}{\sqrt{E/GeV}}$

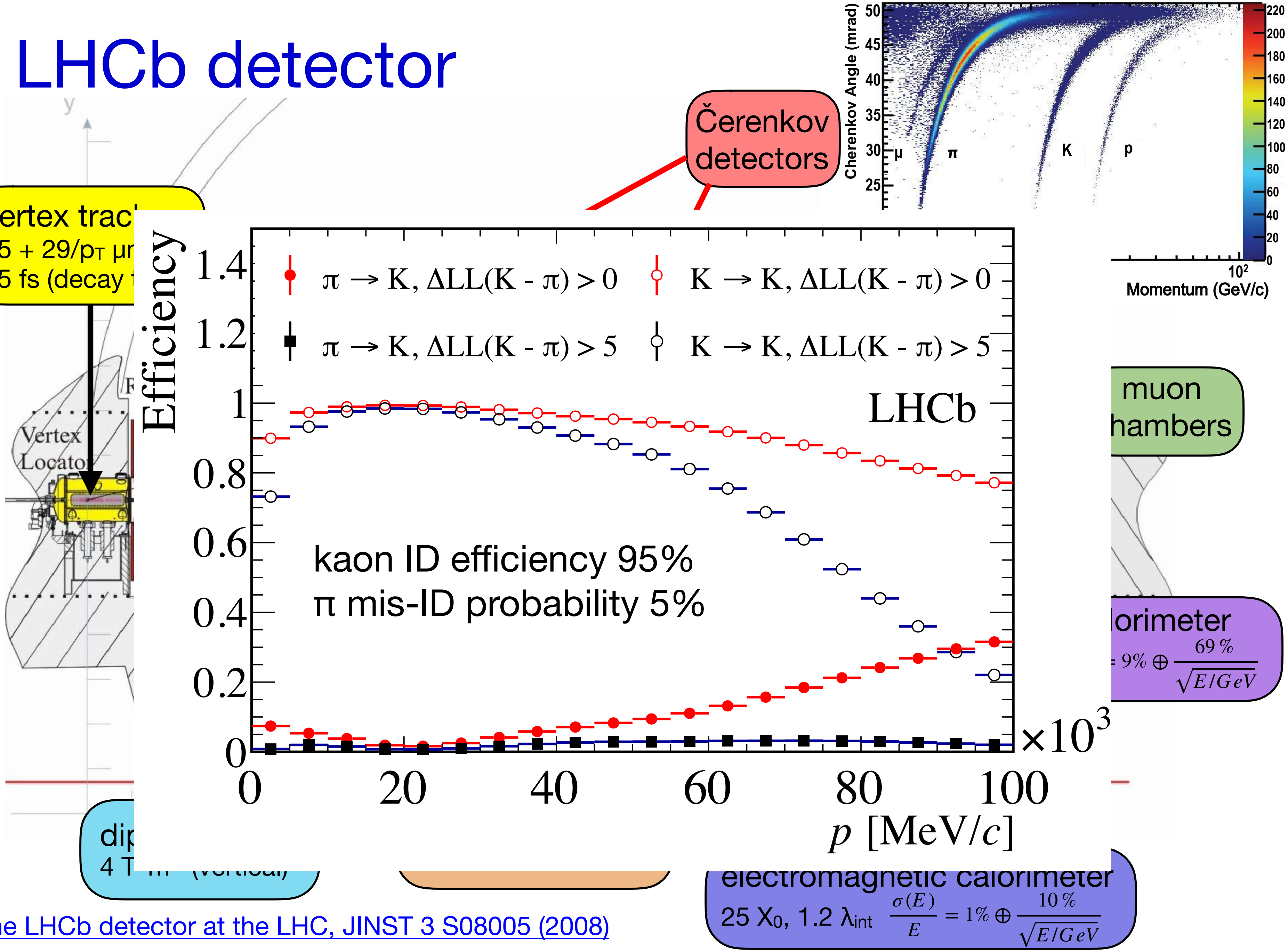
dipole magnet
4 T·m (vertical)

tracking stations
δp/p = 0.5–1.0%
for p = 20–200 GeV/c

electromagnetic calorimeter
25 X_0, 1.2 λ_{int} $\frac{\sigma(E)}{E} = 1\% \oplus \frac{10\,\%}{\sqrt{E/GeV}}$

The LHCb detector at the LHC, JINST 3 S08005 (2008)

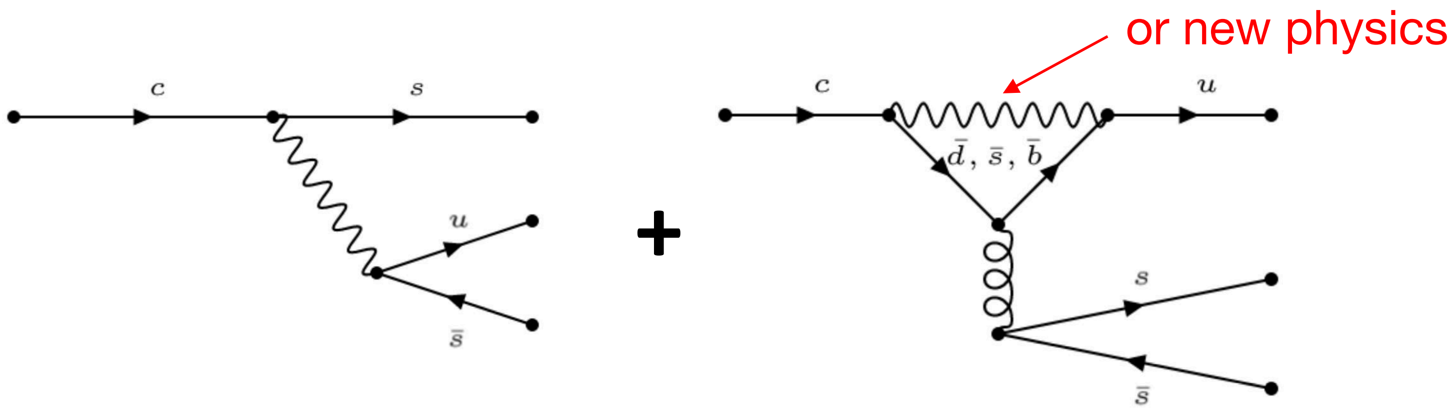
LHCb detector



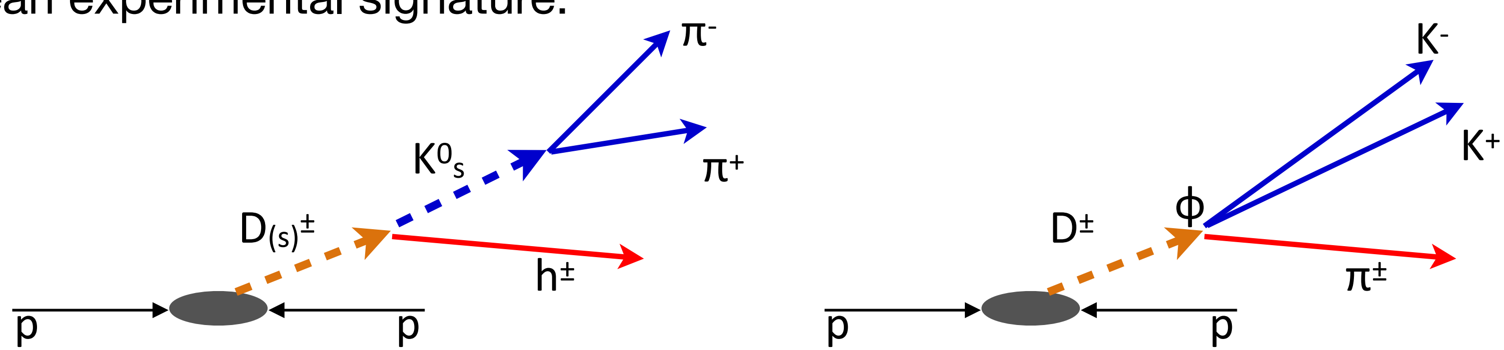
[The LHCb detector at the LHC, JINST 3 S08005 (2008)]

Direct CPV in $D_s^+ \to K^0_S\pi^+$, $D^+ \to K^0_S K^+$, $D^+ \to \phi\pi^+$

- They are all **Cabibbo-suppressed** (CS) decays: [arXiv.1903.01150]
  - **CPV ≤ O(10^{-3})** expected from the interference between tree and penguin amplitudes;
  - **sensitive to QCD penguin and chromomagnetic dipole operators** beyond the SM [PRD 75, 036008];



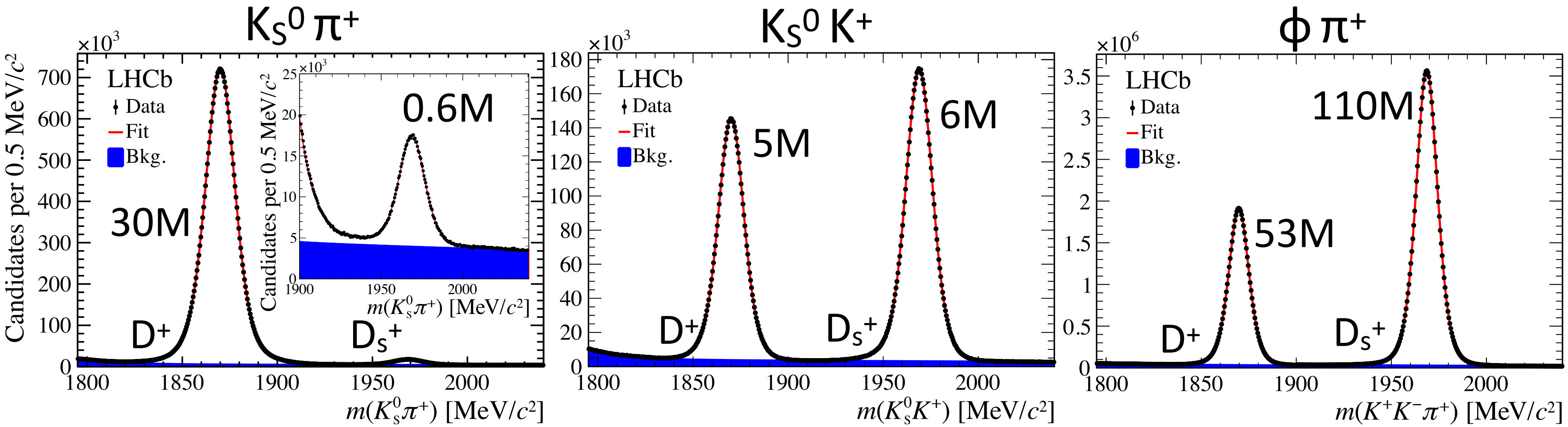
- Clean experimental signature:



Data sample

[arXiv.1903.01150]

- Run-2 data, 2015-2017, 3.8 fb^{-1}



- ***Raw asymmetry*** between the measured yields:

$$A_{\rm raw}(D^+_{(s)} \to f) = \frac{N(D^+_{(s)} \to f) - N(D^-_{(s)} \to \bar{f})}{N(D^+_{(s)} \to f) + N(D^-_{(s)} \to \bar{f})}$$

$$= A_{CP}(D^+_{(s)} \to f) + A_{\rm P}(D^+_{(s)}) + A_{\rm D}(f)$$

production asymmetry

detection asymmetry

Removal of spurious asymmetries

[arXiv.1903.01150]

- Use raw asymmetries of Cabibbo-favoured (CF) $D_{(s)}^+$ decays:
  - CPV negligible for CF decays;
  - kinematics of CF sample weighted to that of the CS one to cancel out precisely production and detection asymmetries.

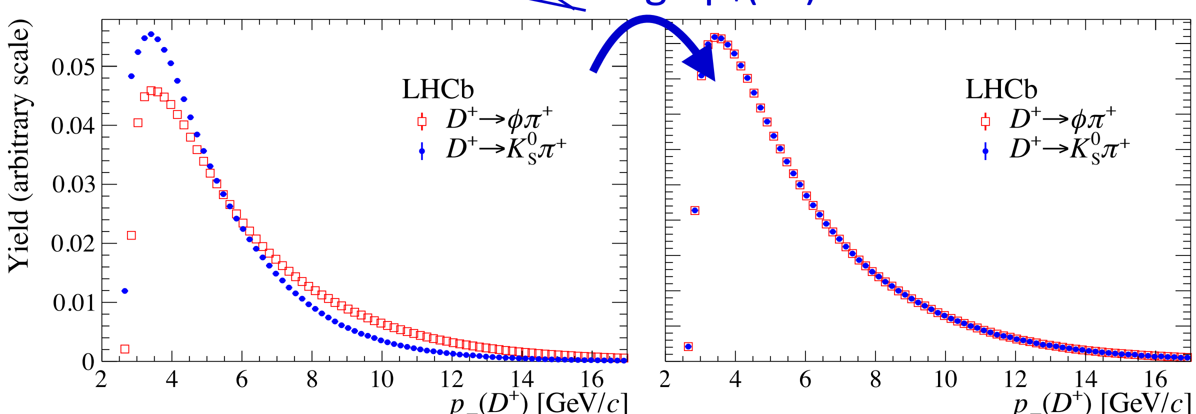
$$A_{CP}(D_s^+ \to K_S^0\pi^+) = [A(D_s^+ \to K_S^0\pi^+) - A_{\rm D}(K^0)] - A(D_s^+ \to \phi\pi^+)$$

$$A_{CP}(D^+ \to K_S^0K^+) = [A(D^+ \to K_S^0K^+) - A_{\rm D}(\bar{K}^0)] - [A(D^+ \to K_s^0\pi^+) - A_{\rm D}(\bar{K}^0)]$$
$$-[A(D_s^+ \to K_S^0K^+) - A_{\rm D}(\bar{K}^0)] + A(D_s^+ \to \phi\pi^+)$$

$$A_{CP}(D^+ \to \phi\pi^+) = A(D^+ \to \phi\pi^+) - [A(D^+ \to K_s^0\pi^+) - A_{\rm D}(\bar{K}^0)]$$

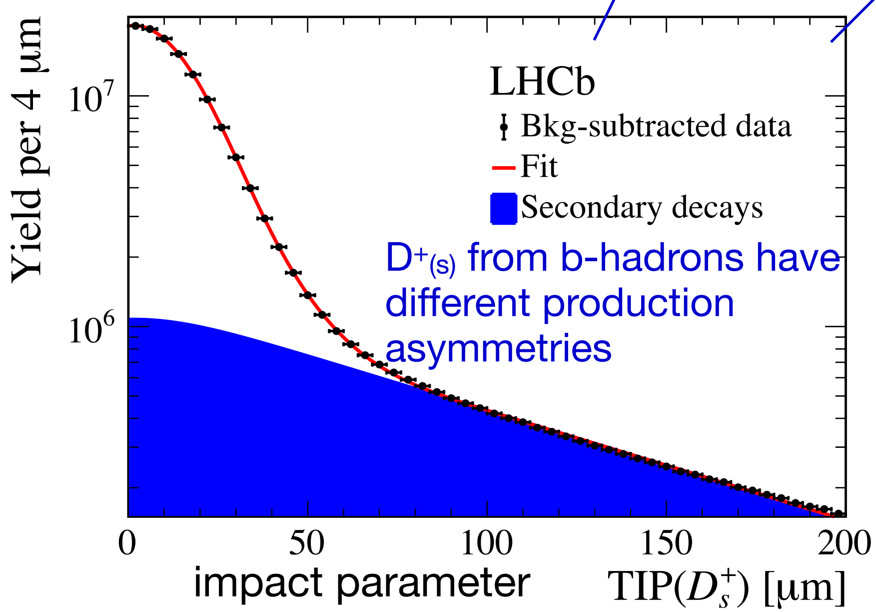
weigh $p_T(D^+)$

$A_{\rm D}(K^0) = -A_{\rm D}(\bar{K}^0)$ is the detection asymmetry of neutral kaons, calculated from the matter distribution of LHCb detector (also including CPV in K^0 mixing)
[JHEP 1407 (2014) 041]

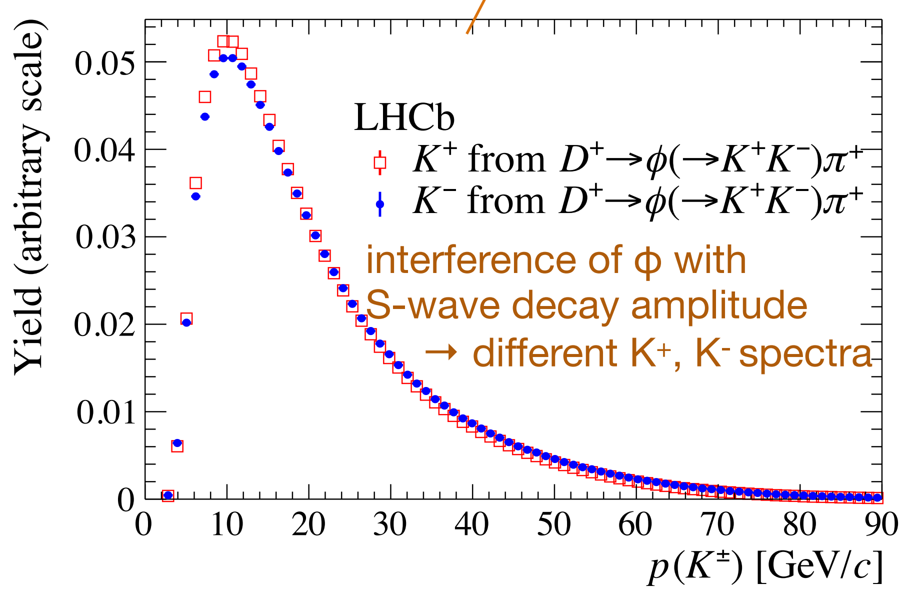


Systematic uncertainties (in 10^{-3}) [arXiv.1903.01150]

Source	$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+)$	$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+)$	$\mathcal{A}_{CP}(D^+ \to \phi\pi^+)$
Fit model	0.39	0.44	0.24
Secondary decays	0.30	0.12	0.03
Kinematic differences	0.09	0.09	0.04
Neutral kaon asymmetry	0.05	0.05	0.04
Charged kaon asymmetry	0.08	0.09	0.15
Total	0.51	0.48	0.29



impact parameter in the transverse plane



Results

[arXiv.1903.01150]

- LHCb Run 2, 2015-2017 (3.8 fb^{-1} @13 TeV):

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.3\ \pm 1.9\ \pm 0.5\ ) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65 \pm 0.48) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.05 \pm 0.42 \pm 0.29) \times 10^{-3}$$

- Average with LHCb 2011-2012 results (1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV) [JHEP 06(2013)112], [JHEP 10 (2014) 025]:

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.6\ \pm 1.7\ \pm 0.5\ ) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.03 \pm 0.40 \pm 0.29) \times 10^{-3}$$

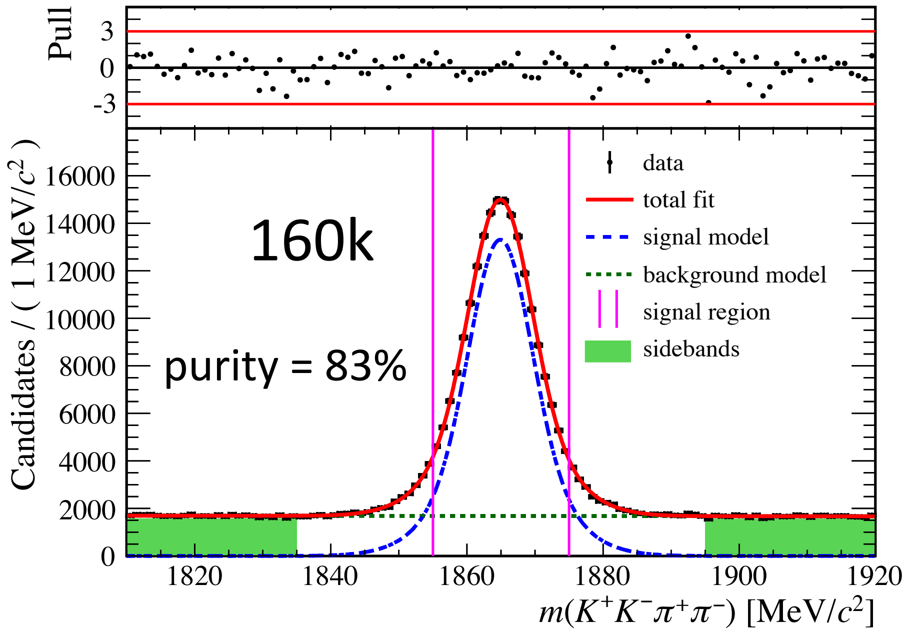
- No evidence of CPV;
- **most precise measurements of these quantities to date.**

CPV with amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$

[JHEP 1902 (2019) 126]

- **Cabibbo-suppressed** decay with rich resonant structure;
- strong phases vary along 5D phase space;
  - enhanced sensitivity to CPV;
- precise amplitude model needed to **measure the CKM angle γ in $B^- \to D^0(\to K^+K^-\pi^+\pi^-)K^-$** decays [PLB 647 (2007) 400-404].

- Run 1 data sample (2011-2012, 3 fb^{-1});
- D^0 flavour from $B \to D^0\mu^-X$.
- Selection designed to get efficiency as flat as possible as a function of phase space;
  - trigger on μ^-.



50x statistics w.r.t. previous best measurement from Cleo-c [JHEP 1705 (2017) 143]

Fit strategy

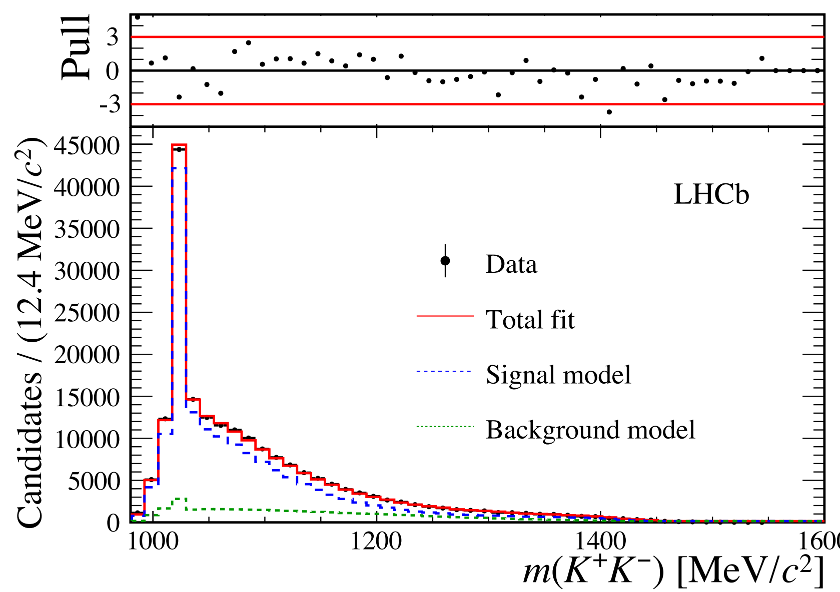
[JHEP 1902 (2019) 126]

- Unbinned 5D maximum likelihood fit;
  - amplitude model developed on $D^0 + \bar{D}^0$ sample (blind analysis);
  - efficiency from MC;
  - isobar model:

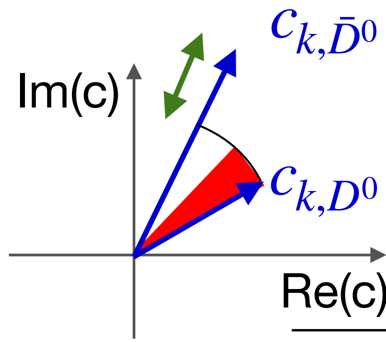
$$S(\mathbf{x};\mathbf{c}) = \left| \sum_{k=1}^{N} \mathbf{c_k A_k(x)} \right|^2$$

	KK	$\pi\pi$	$K\pi$	$KK\pi$	$K\pi\pi$
$J^P = 0^+$	$a_0(980)$ $f_0(980)$ $f_0(1370)$	$f_0(980)$ $f_0(1370)$	$K_0^*(1430)$		
$J^P = 1^+$				$a_1(1260)$	$K_1(1270)$ $K_1(1400)$
$J^P = 1^-$	$\phi(1020)$	$\rho(770)$ $\omega(782)$ $\rho(1450)$	$K^*(892)$ $K^*(1680)$		$K^*(1410)$ $K^*(1680)$
$J^P = 2^+$	$f_2(1270)$ $a_2(1320)$	$f_2(1270)$	$K_2^*(1430)$		$K_2^*(1430)$

  - in principle >130 decay chains might contribute;
  - start from a minimal model with dominant amplitudes only;
  - add amplitudes one-by-one until no improvement in the description of data is obtained.
- 26 amplitudes pinpointed;
- $\chi^2/\text{ndf} = 9242/8121 = 1.14$



Results



[JHEP 1902 (2019) 126]

$$A_{|c_k|} = \frac{|c_k|_{D^0} - |c_k|_{\bar{D}^0}}{|c_k|_{D^0} + |c_k|_{\bar{D}^0}} \qquad \Delta\arg(c_k) = \frac{\arg(c_k)_{D^0} - \arg(c_k)_{\bar{D}^0}}{2}$$

first 4 components account for > 80% of the fit fractions

decreasing contributions

Amplitude	$A_{\lvert c_k\rvert}$ [%]	$\Delta\arg(c_k)$ [%]	$A_{\mathcal{F}_k}$ [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	0 (fixed)	0 (fixed)	$-1.8 \pm 1.5 \pm 0.2$
$D^0 \to K_1(1400)^+K^-$	$-1.4 \pm 1.1 \pm 0.2$	$1.3 \pm 1.5 \pm 0.3$	$-4.5 \pm 2.1 \pm 0.3$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$1.9 \pm 1.1 \pm 0.3$	$-1.2 \pm 1.3 \pm 0.3$	$2.0 \pm 1.8 \pm 0.7$
$D^0 \to K_1(1270)^+K^-$	$-0.4 \pm 1.0 \pm 0.2$	$-1.1 \pm 1.4 \pm 0.2$	$-2.6 \pm 1.7 \pm 0.2$
$D^0 \to [K^*(892)^0\bar{K}^*(892)^0]_{L=0}$	$-1.3 \pm 1.3 \pm 0.3$	$-1.7 \pm 1.5 \pm 0.2$	$-4.3 \pm 2.2 \pm 0.5$
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.2 \pm 1.3 \pm 0.3$	$1.4 \pm 1.5 \pm 0.2$	$2.6 \pm 2.2 \pm 0.4$
$D^0 \to [K^*(892)^0\bar{K}^*(892)^0]_{L=1}$	$-0.4 \pm 1.7 \pm 0.2$	$3.7 \pm 2.0 \pm 0.2$	$-2.6 \pm 3.2 \pm 0.3$
$D^0 \to K_1(1270)^-K^+$	$2.6 \pm 1.7 \pm 0.4$	$-0.1 \pm 2.1 \pm 0.3$	$3.3 \pm 3.5 \pm 0.5$
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$3.5 \pm 2.5 \pm 1.5$	$-5.5 \pm 2.6 \pm 1.6$	$5.1 \pm 5.1 \pm 3.1$
$D^0 \to K_1(1400)^-K^+$	$0.2 \pm 2.9 \pm 0.7$	$2.5 \pm 3.5 \pm 1.0$	$-1.3 \pm 6.0 \pm 1.0$
$D^0 \to [K^*(1680)^0\bar{K}^*(892)^0]_{L=0}$	$4.0 \pm 2.7 \pm 0.8$	$-5.4 \pm 2.8 \pm 0.8$	$6.2 \pm 5.2 \pm 1.5$
$D^0 \to [\bar{K}^*(1680)^0K^*(892)^0]_{L=1}$	$-0.4 \pm 2.1 \pm 0.3$	$0.4 \pm 2.1 \pm 0.3$	$-2.5 \pm 3.9 \pm 0.4$
$D^0 \to \bar{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$2.1 \pm 2.0 \pm 0.6$	$-1.8 \pm 2.2 \pm 0.3$	$2.4 \pm 3.7 \pm 1.1$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$0.8 \pm 1.9 \pm 0.3$	$-1.2 \pm 2.0 \pm 0.5$	$-0.1 \pm 3.3 \pm 0.5$
$D^0 \to [K^*(892)^0\bar{K}^*(892)^0]_{L=2}$	$-0.6 \pm 2.5 \pm 0.4$	$0.6 \pm 2.6 \pm 0.4$	$-3.0 \pm 5.0 \pm 0.7$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$3.8 \pm 3.1 \pm 0.7$	$-0.5 \pm 3.9 \pm 0.7$	$5.8 \pm 6.1 \pm 0.8$
$D^0 \to [K^*(1680)^0\bar{K}^*(892)^0]_{L=1}$	$1.6 \pm 2.8 \pm 0.5$	$0.7 \pm 3.0 \pm 0.4$	$1.3 \pm 5.3 \pm 0.6$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$4.6 \pm 4.1 \pm 0.6$	$9.3 \pm 3.3 \pm 0.6$	$7.5 \pm 8.5 \pm 1.1$
$D^0 \to a_0(980)^0f_2(1270)^0$	$1.6 \pm 3.6 \pm 0.7$	$-7.3 \pm 3.3 \pm 0.8$	$1.5 \pm 7.2 \pm 1.3$
$D^0 \to a_1(1260)^+\pi^-$	$-4.4 \pm 5.6 \pm 3.7$	$9.3 \pm 6.1 \pm 1.3$	$-10.6 \pm 11.7 \pm 7.0$
$D^0 \to a_1(1260)^-\pi^+$	$-3.4 \pm 7.0 \pm 1.9$	$-5.8 \pm 5.6 \pm 4.3$	$-8.7 \pm 13.7 \pm 2.9$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$2.1 \pm 5.2 \pm 0.8$	$-12.2 \pm 5.5 \pm 0.6$	$2.4 \pm 11.0 \pm 1.4$
$D^0 \to [K^*(1680)^0\bar{K}^*(892)^0]_{L=2}$	$5.2 \pm 7.1 \pm 1.9$	$-5.6 \pm 8.1 \pm 1.3$	$8.5 \pm 14.3 \pm 3.5$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$11.7 \pm 6.0 \pm 1.9$	$4.8 \pm 6.2 \pm 1.1$	$21.3 \pm 12.5 \pm 2.8$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$2.7 \pm 6.7 \pm 1.7$	$0.9 \pm 6.0 \pm 1.7$	$3.6 \pm 13.3 \pm 3.0$
$D^0 \to [K^*(892)^0\bar{K}_2^*(1430)^0]_{L=1}$	$3.9 \pm 5.2 \pm 1.0$	$6.8 \pm 6.4 \pm 1.4$	$6.1 \pm 10.8 \pm 1.8$

Fit fraction definition:

$$\mathcal{F}_k = \frac{\int |c_k A_k(\boldsymbol{x})|^2 \mathcal{R}_4(\boldsymbol{x}) d^5\boldsymbol{x}}{\int |\sum_{\ell=1}^{N} c_\ell A_\ell(\boldsymbol{x})|^2 \mathcal{R}_4(\boldsymbol{x}) d^5\boldsymbol{x}}$$

4 body phase space

No evidence of CPV for any amplitudes;

- **σ = 1% — 15%**
- resolution improves dramatically w.r.t. Cleo-c (50x statistics) [JHEP 1705 (2017) 143]

Conclusions

- Could not cover all results since last La Thuile:
  - $A_{CP}(D^0 \to K_s^0 K_s^0)$ with 2015-2016 data [JHEP 11 (2018) 048];
  - Angular and CP asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$ with 2011-2016 data [PRL 121 (2018) 091801];
  - measurement of CPV parameter y_{CP} with 2011-2012 data [PRL 122, 011802];
  - **new measurement of Δm of D^0 eigenstates in $D^0 \to K^0_s\pi^+\pi^-$ with bin-flip method** [arXiv:1903.03074].

Julián García Pardiñas' talk tomorrow

Nathan Jurik's talk tomorrow

- Enormous yields at LHC and dedicate LHCb detector **inaugurated the era of high-precision CPV measurements in charm**;
  - we are **now approaching the SM predictions for CPV, $\leq O(10^{-3})$**;
  - measurements are currently not limited by systematic uncertainties despite O(10M) data samples.

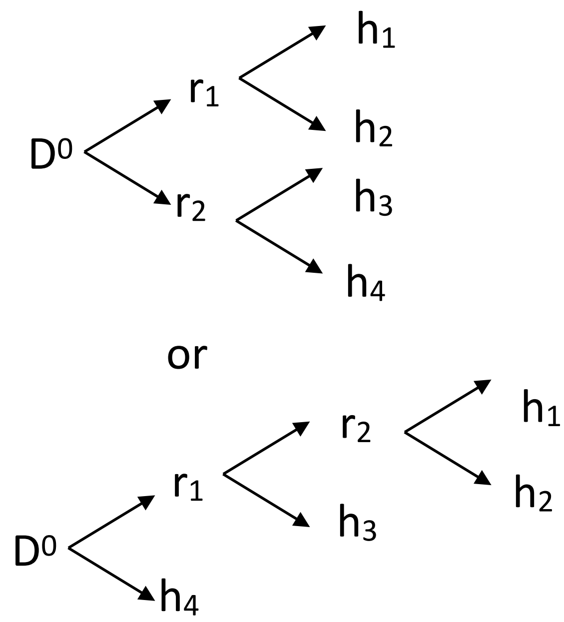
Backup slides

$D^0 \to K^+K^-\pi^+\pi^-$: fit model

[JHEP 1902 (2019) 126]

- Resonances considered for the isobar model [PRD 11 (1975) 3165], [Phys.Rev. 123 (1961), 333-376]

	KK	$\pi\pi$	$K\pi$	$KK\pi$	$K\pi\pi$
$J^P = 0^+$	$a_0(980)$ $f_0(980)$ $f_0(1370)$	$f_0(980)$ $f_0(1370)$	$K_0^*(1430)$		
$J^P = 1^+$				$a_1(1260)$	$K_1(1270)$ $K_1(1400)$
$J^P = 1^-$	$\phi(1020)$	$\rho(770)$ $\omega(782)$ $\rho(1450)$	$K^*(892)$ $K^*(1680)$		$K^*(1410)$ $K^*(1680)$
$J^P = 2^+$	$f_2(1270)$ $a_2(1320)$	$f_2(1270)$	$K_2^*(1430)$		$K_2^*(1430)$



$$S(\mathbf{x};\mathbf{c}) = \left| \sum_{\mathbf{k}=1}^{\mathbf{N}} \mathbf{c_k} \mathbf{A_k}(\mathbf{x}) \right|^2$$

signal is a coherent sum of decay chains

- Relativistic Breit-Wigner, Flatté and K-matrix formalism for the lineshapes;
- covariant formalism for the spin factors.

$D^0 \to K^+K^-\pi^+\pi^-$: amplitude model results

- Results averaged over D^0 flavour:

$$S(\mathbf{x};\mathbf{c}) = \left|\sum_{k=1}^{N} \mathbf{c_k A_k(x)}\right|^2$$

- Fit fraction definition:

$$\mathcal{F}_k = \frac{\int |c_k A_k(\boldsymbol{x})|^2 \mathcal{R}_4(\boldsymbol{x}) d^5\boldsymbol{x}}{\int |\sum_{\ell=1}^{N} c_\ell A_\ell(\boldsymbol{x})|^2 \mathcal{R}_4(\boldsymbol{x}) d^5\boldsymbol{x}}$$

where $R_4(x)$ is the 4-body phase space factor.

first 4 amplitudes account for > 80% of the fit fractions

decreasing contributions ↓

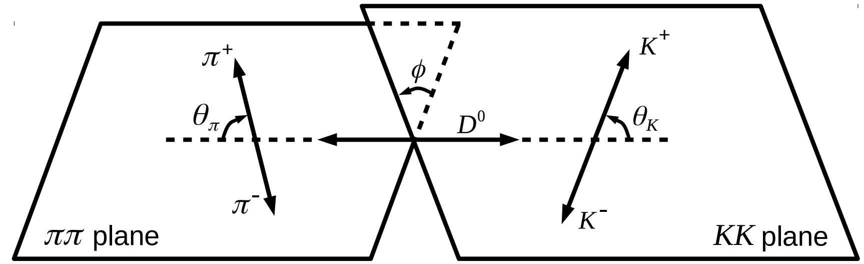
Amplitude	$\|c_k\|$	$\arg(c_k)$ [rad]	Fit fraction [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	1 (fixed)	0 (fixed)	$23.82 \pm 0.38 \pm 0.50$
$D^0 \to K_1(1400)^+K^-$	$0.614 \pm 0.011 \pm 0.031$	$1.05 \pm 0.02 \pm 0.05$	$19.08 \pm 0.60 \pm 1.46$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$0.282 \pm 0.004 \pm 0.008$	$-0.60 \pm 0.02 \pm 0.10$	$18.46 \pm 0.35 \pm 0.94$
$D^0 \to K_1(1270)^+K^-$	$0.452 \pm 0.011 \pm 0.017$	$2.02 \pm 0.03 \pm 0.05$	$18.05 \pm 0.52 \pm 0.98$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=0}$	$0.259 \pm 0.004 \pm 0.018$	$-0.27 \pm 0.02 \pm 0.03$	$9.18 \pm 0.21 \pm 0.28$
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.359 \pm 0.036 \pm 0.624$	$0.44 \pm 0.02 \pm 0.03$	$6.61 \pm 0.15 \pm 0.37$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=1}$	$0.249 \pm 0.005 \pm 0.017$	$1.22 \pm 0.02 \pm 0.03$	$4.90 \pm 0.16 \pm 0.18$
$D^0 \to K_1(1270)^-K^+$	$0.220 \pm 0.006 \pm 0.011$	$2.09 \pm 0.03 \pm 0.07$	$4.29 \pm 0.18 \pm 0.41$
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$0.120 \pm 0.003 \pm 0.018$	$-2.49 \pm 0.03 \pm 0.16$	$3.14 \pm 0.17 \pm 0.72$
$D^0 \to K_1(1400)^-K^+$	$0.236 \pm 0.008 \pm 0.018$	$0.04 \pm 0.04 \pm 0.09$	$2.82 \pm 0.19 \pm 0.39$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=0}$	$0.823 \pm 0.023 \pm 0.218$	$2.99 \pm 0.03 \pm 0.05$	$2.75 \pm 0.15 \pm 0.19$
$D^0 \to [\overline{K}^*(1680)^0K^*(892)^0]_{L=1}$	$1.009 \pm 0.022 \pm 0.276$	$-2.76 \pm 0.02 \pm 0.03$	$2.70 \pm 0.11 \pm 0.09$
$D^0 \to \overline{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$1.379 \pm 0.029 \pm 0.373$	$1.06 \pm 0.02 \pm 0.03$	$2.41 \pm 0.09 \pm 0.27$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$1.311 \pm 0.031 \pm 0.018$	$0.54 \pm 0.02 \pm 0.02$	$2.29 \pm 0.08 \pm 0.08$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=2}$	$0.652 \pm 0.018 \pm 0.043$	$2.85 \pm 0.03 \pm 0.04$	$1.85 \pm 0.09 \pm 0.10$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$0.049 \pm 0.001 \pm 0.004$	$-1.71 \pm 0.04 \pm 0.37$	$1.49 \pm 0.09 \pm 0.33$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=1}$	$0.747 \pm 0.021 \pm 0.203$	$0.14 \pm 0.03 \pm 0.04$	$1.48 \pm 0.08 \pm 0.10$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$0.762 \pm 0.035 \pm 0.068$	$1.17 \pm 0.04 \pm 0.04$	$0.98 \pm 0.09 \pm 0.05$
$D^0 \to a_0(980)^0f_2(1270)^0$	$1.524 \pm 0.058 \pm 0.189$	$0.21 \pm 0.04 \pm 0.19$	$0.70 \pm 0.05 \pm 0.08$
$D^0 \to a_1(1260)^+\pi^-$	$0.189 \pm 0.011 \pm 0.042$	$-2.84 \pm 0.07 \pm 0.38$	$0.46 \pm 0.05 \pm 0.22$
$D^0 \to a_1(1260)^-\pi^+$	$0.188 \pm 0.014 \pm 0.031$	$0.18 \pm 0.06 \pm 0.43$	$0.45 \pm 0.06 \pm 0.16$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$0.160 \pm 0.011 \pm 0.005$	$0.28 \pm 0.07 \pm 0.03$	$0.43 \pm 0.05 \pm 0.03$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=2}$	$1.218 \pm 0.089 \pm 0.354$	$-2.44 \pm 0.08 \pm 0.15$	$0.33 \pm 0.05 \pm 0.06$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$0.195 \pm 0.015 \pm 0.035$	$2.95 \pm 0.08 \pm 0.29$	$0.27 \pm 0.04 \pm 0.05$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$1.388 \pm 0.095 \pm 0.257$	$1.71 \pm 0.06 \pm 0.37$	$0.18 \pm 0.02 \pm 0.07$
$D^0 \to [K^*(892)^0\overline{K}_2^*(1430)^0]_{L=1}$	$1.530 \pm 0.086 \pm 0.131$	$2.01 \pm 0.07 \pm 0.09$	$0.18 \pm 0.02 \pm 0.02$
		Sum of fit fractions	$129.32 \pm 1.09 \pm 2.38$
		χ^2/ndf	$9242/8121 = 1.14$

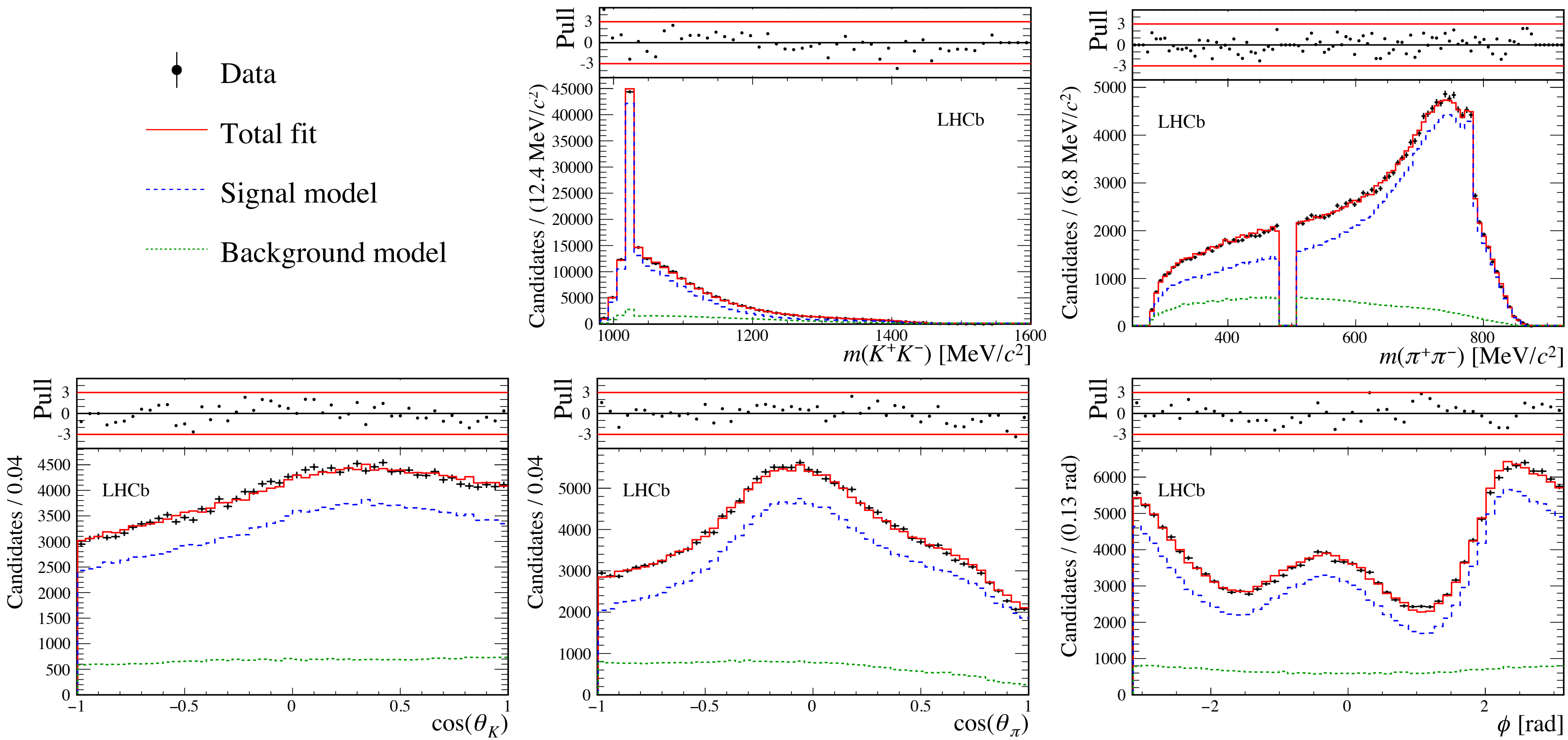
[JHEP 1902 (2019) 126]

$D^0 \to K^+K^-\pi^+\pi^-$: fit projections

[JHEP 1902 (2019) 126]

- Use the Cabibbo-Maksymowicz variables [PRL 137 (1965) B438-B443]





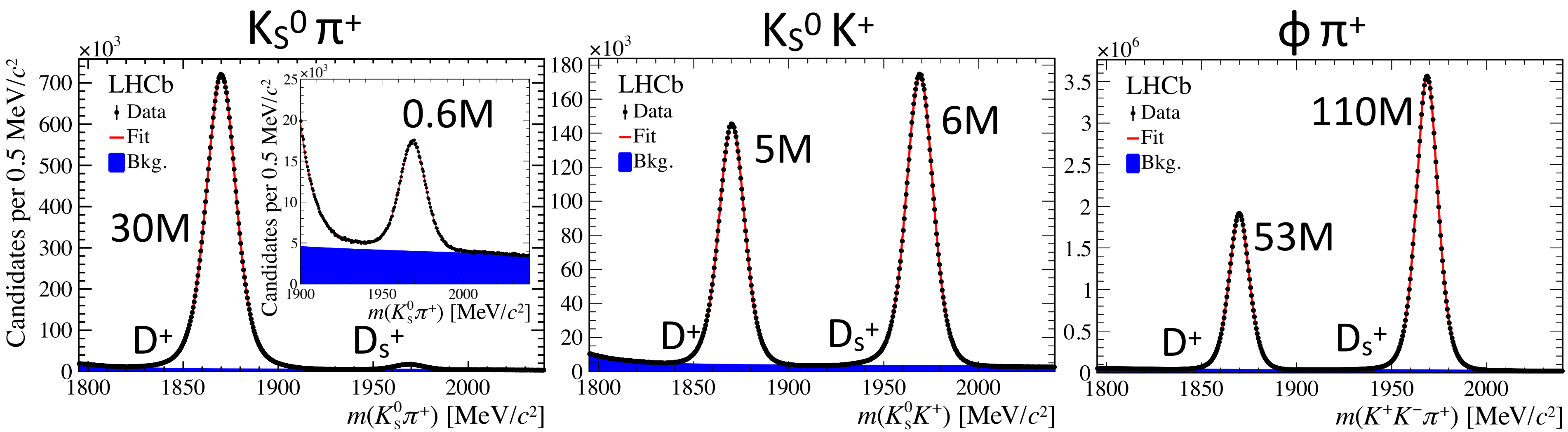
$D^0 \to K^+K^-\pi^+\pi^-$: systematics

[JHEP 1902 (2019) 126]

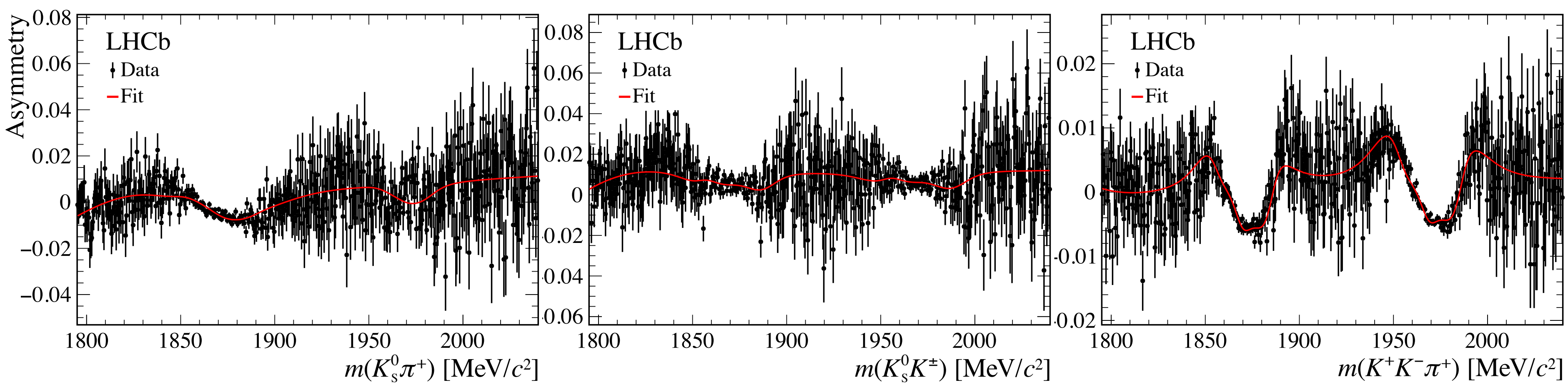
- Selection efficiency (discrepancies between MC and data);
- background description;
- relativistic Breit-Wigner -> Gounaris Sakurai for the $\rho(770)^0$;
- $K\pi$ K-matrix description -> LASS lineshape;
- compare various solutions of KK and $\pi\pi$ K-matrix description;
- uncertainty in PDG masses and widths of the resonances;
- D^0 flavour mistag (prob ≈ 0.5%);
- kaon detection asymmetry;
- add additional amplitudes;
- use $K^*(1410)^0$ instead of $K^*(1680)^0$;
- add additional 5 decay chains in addition to the 26 fitted ones;
- add $D^0 \to \rho(1450)^0\rho(1450)^0$ in D-wave.

Direct CPV in $D_s^+ \to K^0_S \pi^+$, $D^+ \to K^0_S K^+$, $D^+ \to \phi\pi^+$

[arXiv.1903.01150]

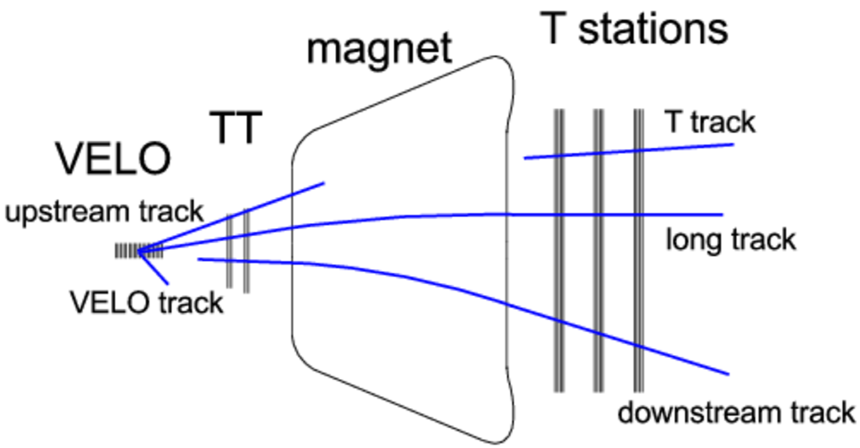


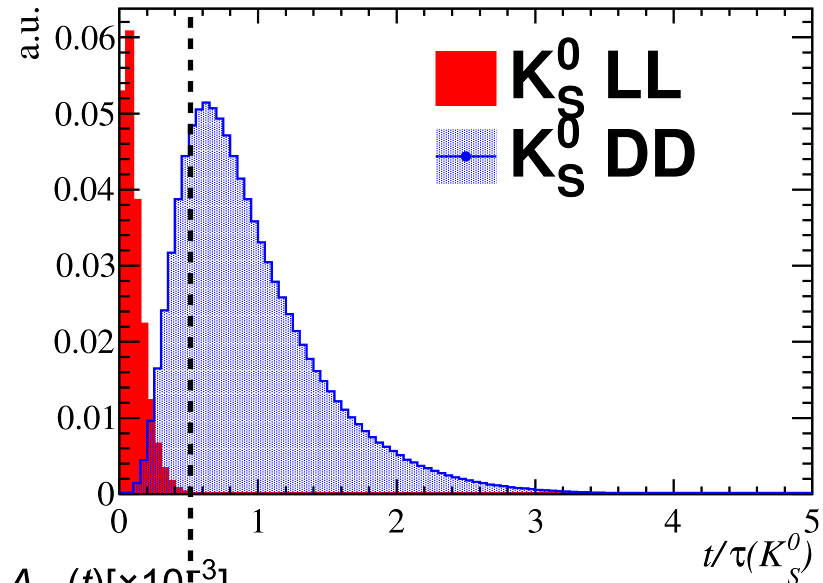
Projections of raw asymmetries:



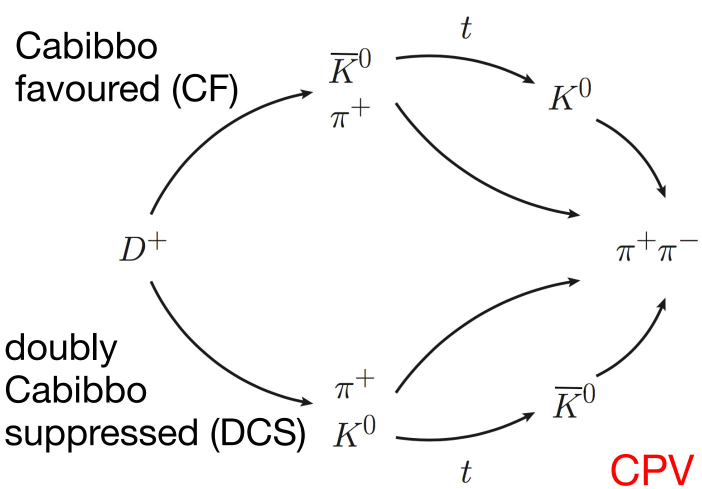
CPV in Cabibbo-favoured $D_{(s)}^+ \to K^0_S h^+$ decays

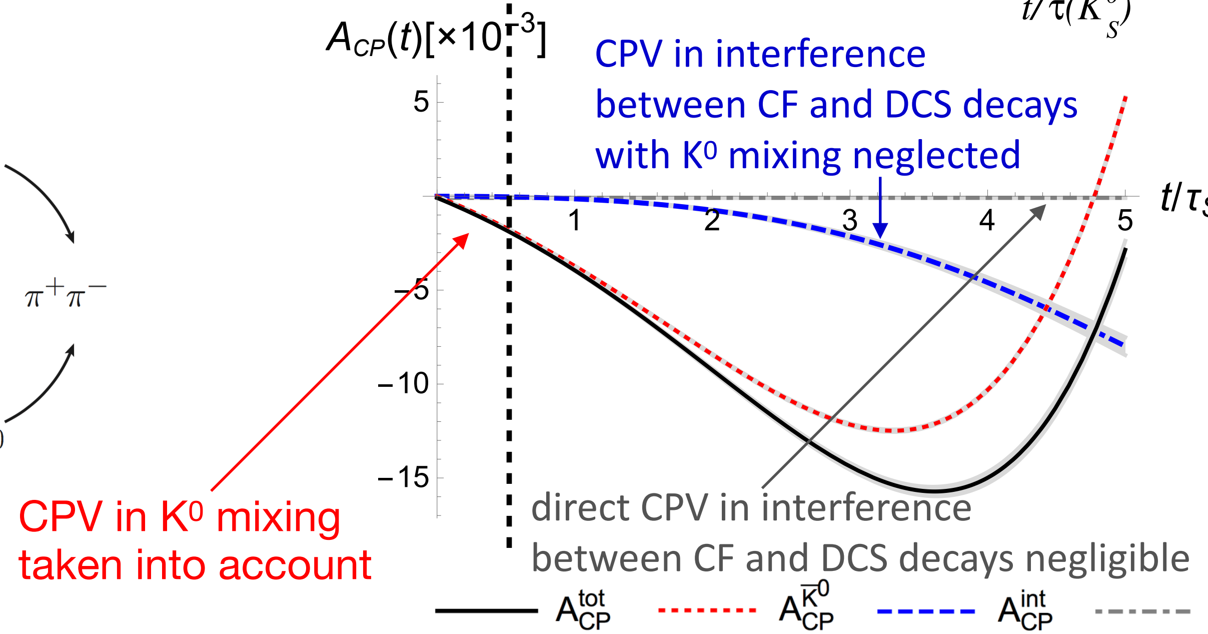
- K_S^0 reconstructed with two $\pi^+\pi^-$ long tracks





[LHCb-ANA-2013-055]

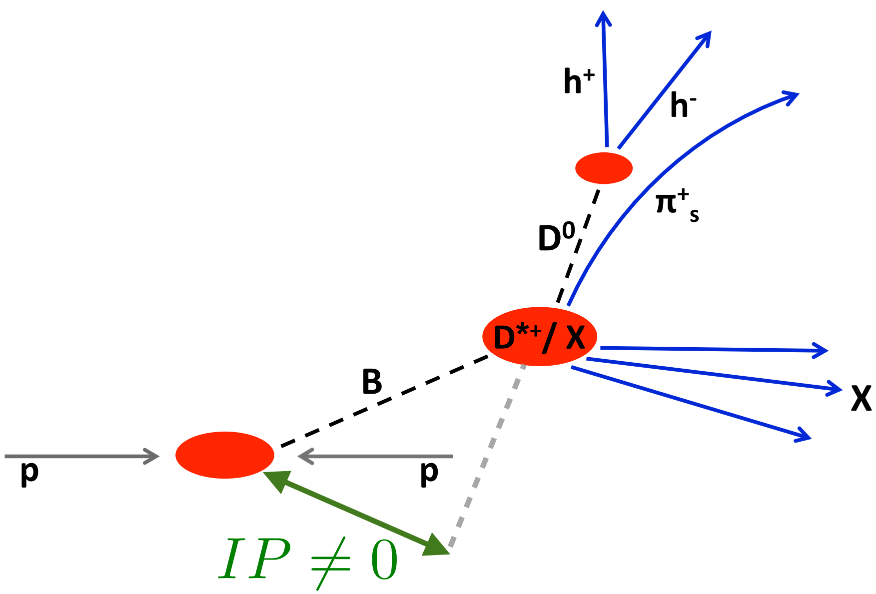




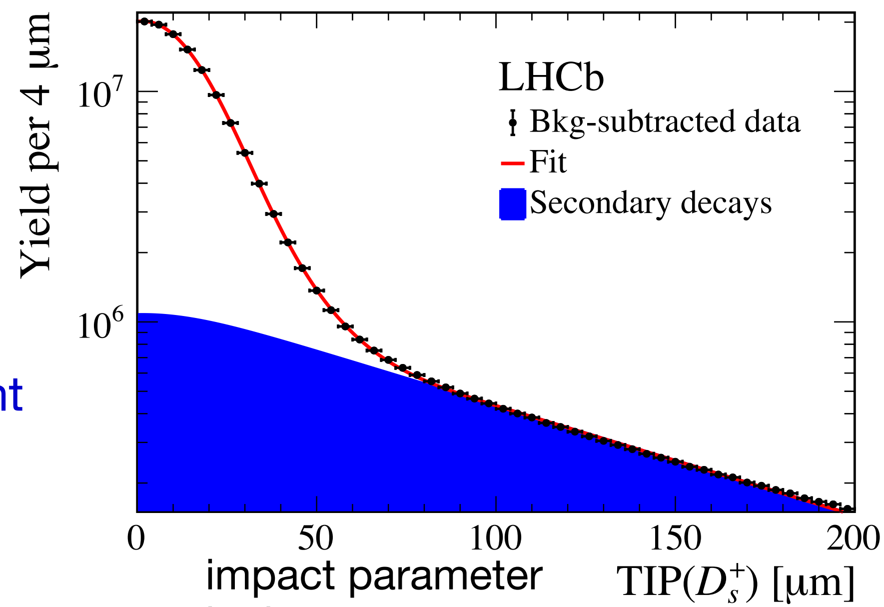
[PRL 119 (2017) 181802]

Secondary decays

[arXiv.1903.01150]



$D^+_{(s)}$ from b-hadrons have different production asymmetries

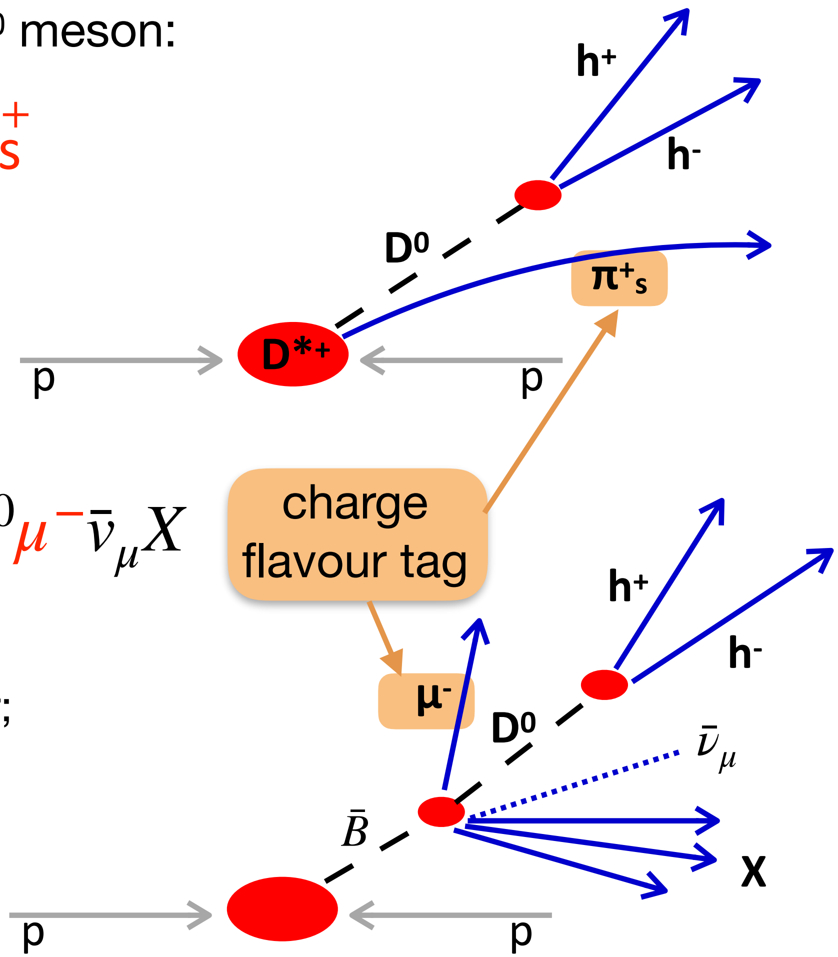


impact parameter
in the transverse plane

Tagging strategies at LHCb

To identify the flavour at production of the D^0 meson:

- **Prompt tag**: strong decay $D^{*+} \to D^0 \pi_S^+$
  - larger production cross section;
  - tight trigger cut on D^0 flight distance and h^+, h^- impact parameters to improve S/B;
  - low trigger efficiency at low decay times;
  - D^0 points at the primary vertex (PV).



- **Semileptonic tag**: weak decay $\bar{B} \to D^0 \mu^- \bar{\nu}_\mu X$
  - lower production cross section;
  - no need to cut on D^0 flight distance;
  - all D^0 decay times collected by the trigger;
  - total yield ≈ 25% of prompt one;
  - D^0 does not necessarily point at PV.

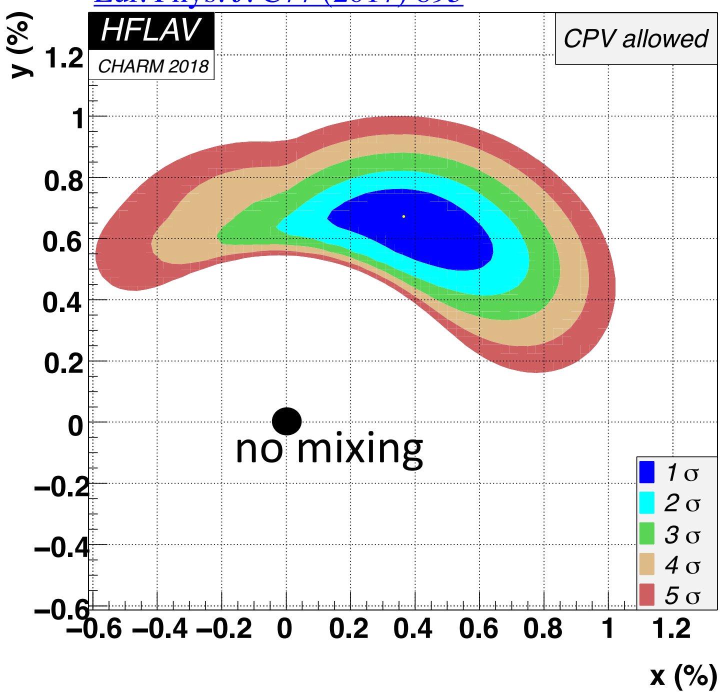
- **Double-tag**: $\bar{B} \to [D^0 \pi_S^+]_{D^{*+}} \mu^- \bar{\nu}_\mu X$
  - highest purity;
  - lowest yield.

Mixing and indirect CPV in charm

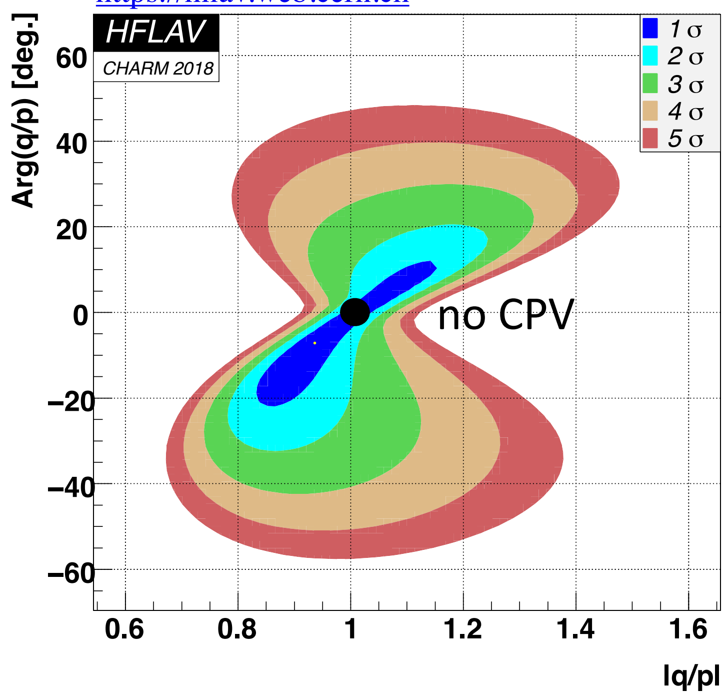
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$ mass eigenstates

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

Eur. Phys. J. C77 (2017) 895



https://hflav.web.cern.ch

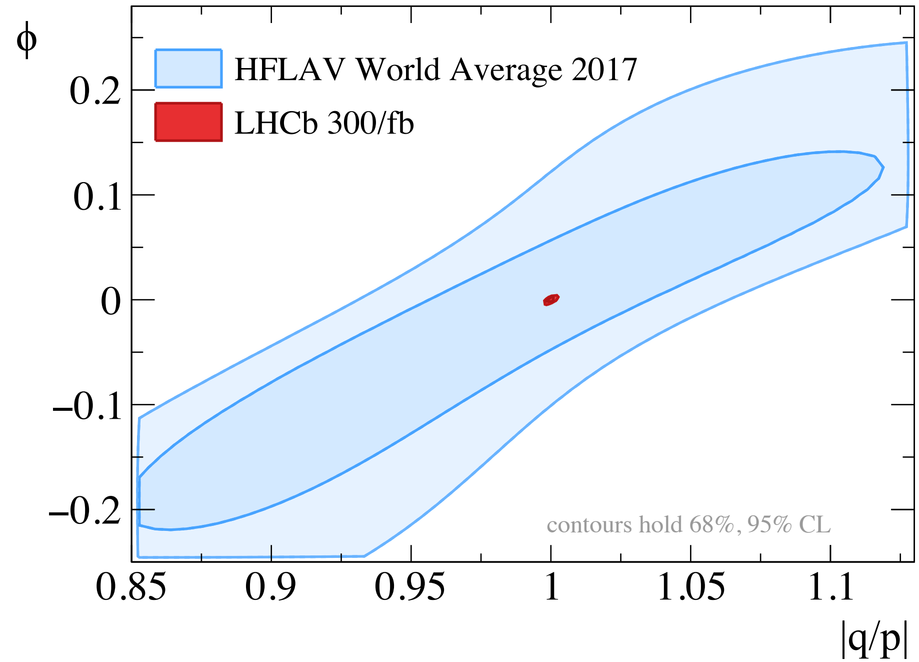


$$\phi = \arg(M_{12}/\Gamma_{12})$$

LHCb Upgrade II

Assumptions:

- x2 of hadron trigger efficiency (no hardware trigger + new magnet stations);
- current LHCb performance is maintained in Upgrade II conditions;
- statistical uncertainty only (with $1/\sqrt{N}$ scaling).



[Opportunities in Flavour Physics at the HL-LHC and HE-LHC [arXiv:1812.07638]]
[Physics case for an LHCb Upgrade II [arXiv:1808.08865]]