Charm Physics at Hadron Machines

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on behalf of the

LHCb collaboration

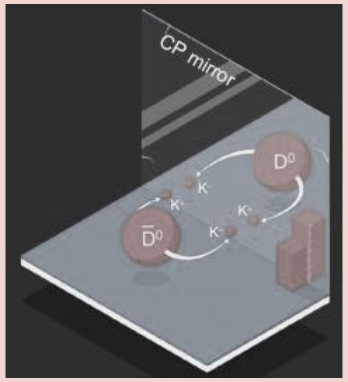
9 June 2020

LHCb

Charm Physics at LHC(b)*

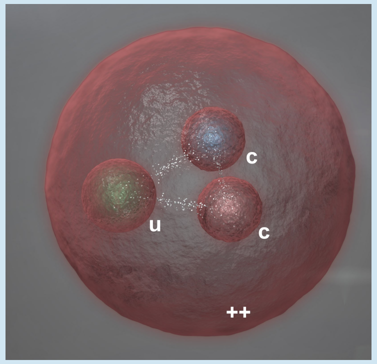
Mixing and CPV

- Meson oscillations
- Time-integrated CPV
- Time-dependent CPV
- CPV in baryons
- …



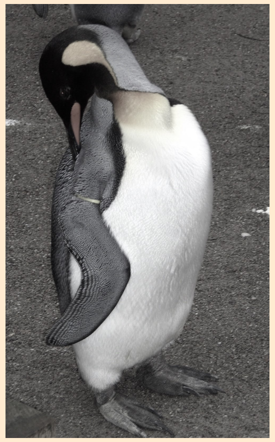
Production and decay properties

- Doubly charmed baryons
- Charm production [see Yanxi's talk Wed 10:15]
- Excited charm baryons [see Roberta's talk Wed 13:00]
- …



Rare decays

- Flavour-changing neutral current processes
- Lepton-flavour, lepton-number violation
- …

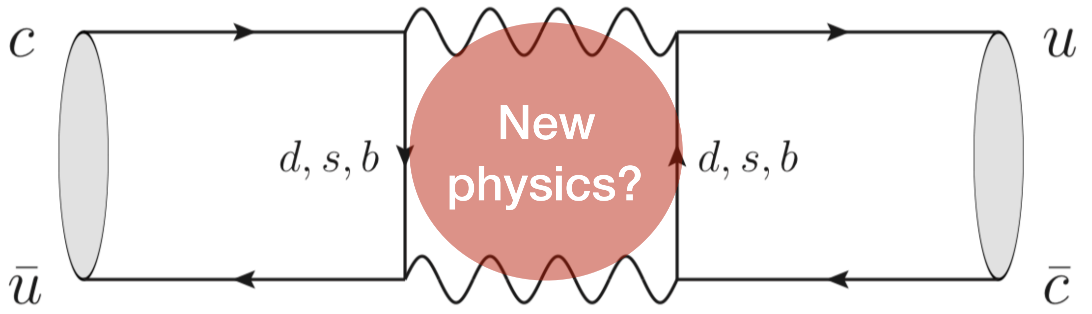


*only LHCb analyses discussed in this talk, for results on charm hadron production and spectroscopy (including LHCb, CMS and ALICE results) see Yanxi's and Roberta's talks tomorrow 10:15 and 13:00.

Why care about Charm?

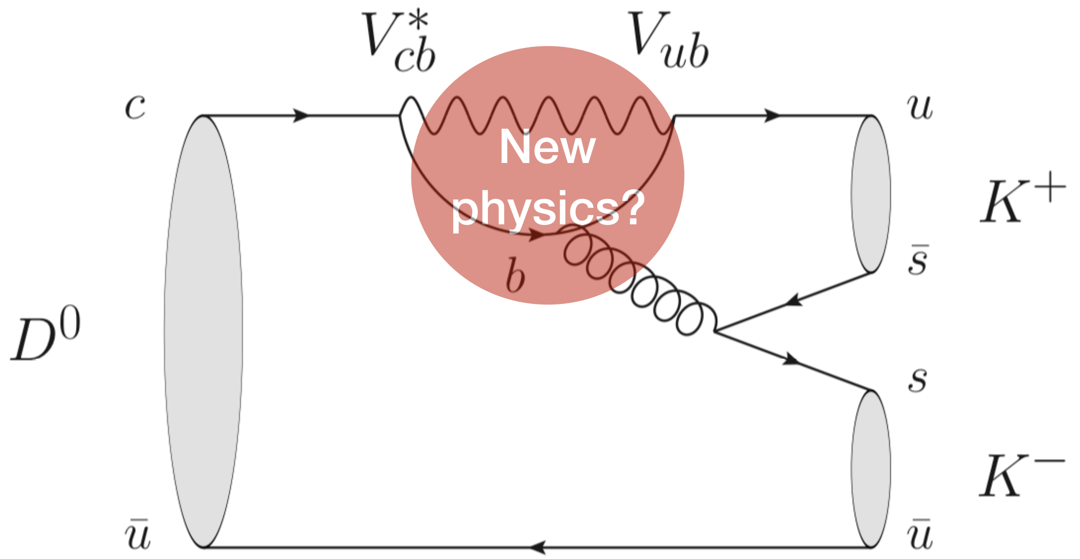
Unique:

- Only bound system made of up-type quarks, complementary sensitivity to BSM couplings wrt to K and $B_{(s)}$ decays
- $m_c \sim 1.3$ GeV/c^2 makes theoretical predictions hard, but allows for insights into QCD from a different perspective



Discovery tool:

- All processes involving quantum-loops are highly suppressed in the SM
  - Charm meson oscillation probability very low
  - CP violating effects tiny ($\lesssim \mathcal{O}(10^{-3})$)
  - Rare decays extremely rare ($\lesssim \mathcal{O}(10^{-9})$)



room for new physics to show up!

Charming beauty detector

JINST3(2008)S08005
Int.J.Mod.Phys.A30(2015)no.07 1530022

- Large production cross-sections of charm hadrons at LHCb

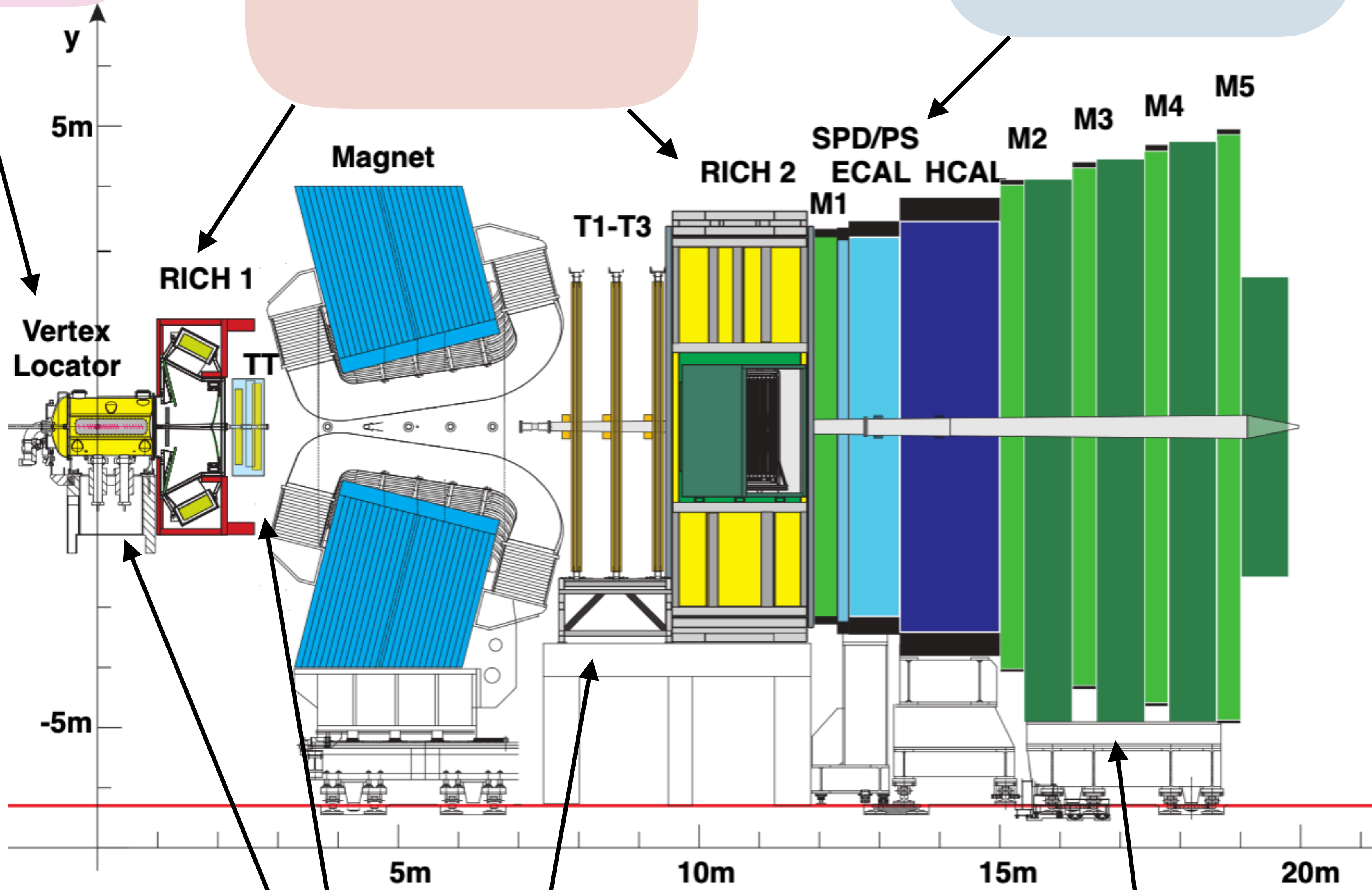
$$\sigma(pp \to c\bar{c}X) \approx 2.4 \text{ mb}$$
$$\sim 20 \times \sigma(pp \to b\bar{b}X)$$

$@\sqrt{s} = 13\text{TeV}$

JHEP03(2016)159

- Collected 9 fb^{-1} of data at 7, 8 and 13 TeV

enormous yields available



Vertexing

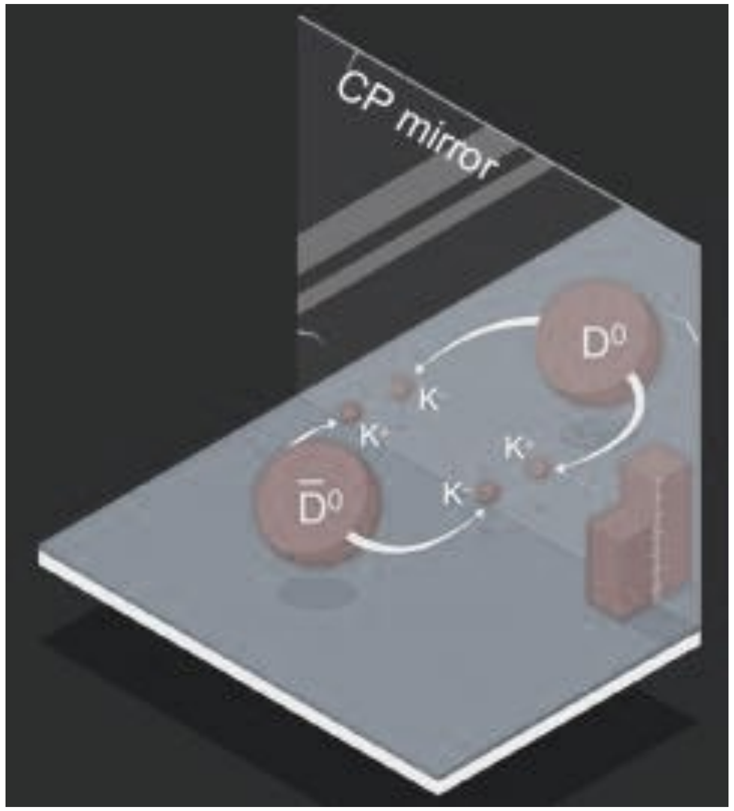
Particle Identification

Calorimetry

Tracking

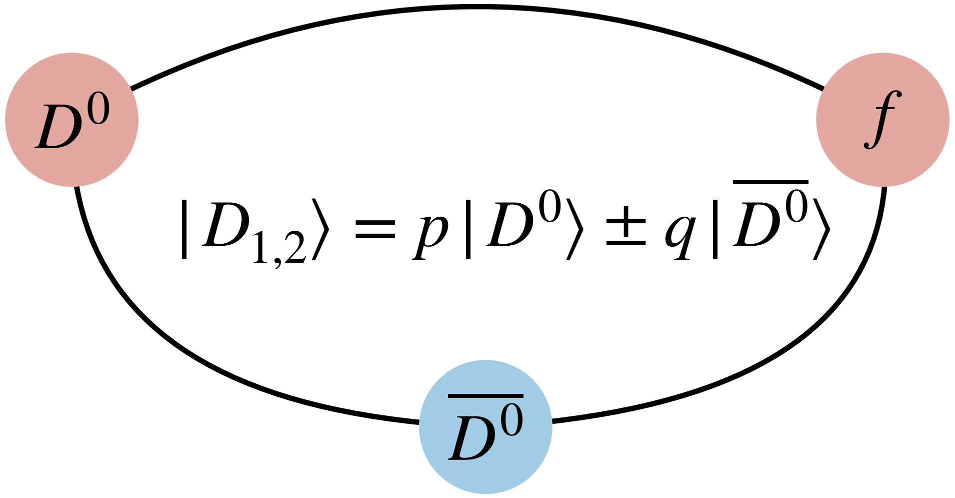
Muon System

Mixing & CPV



Charm mixing & CPV

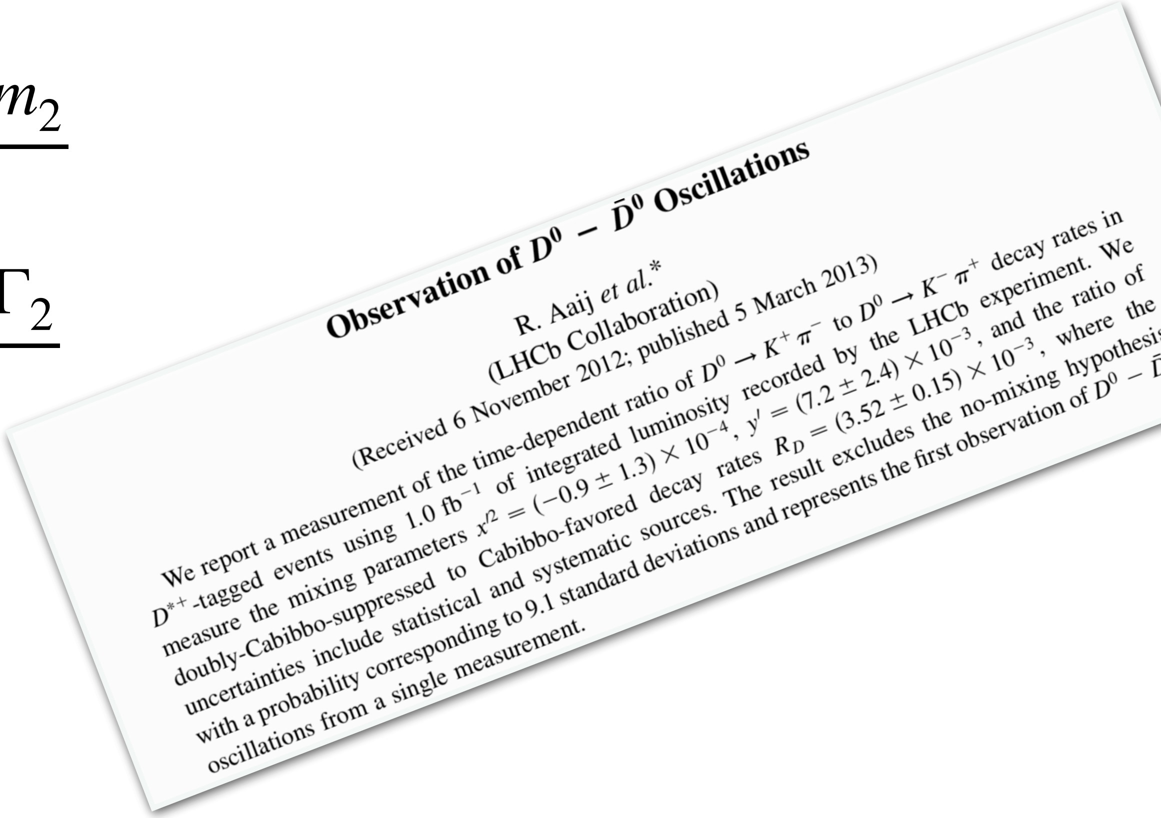
- Measurements of mixing (x, y) and CPV $(A_{CP}, |q/p|, \phi)$ parameters



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

$$x = \frac{m_1 - m_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$



Observation of $D^0 - \bar{D}^0$ Oscillations

R. Aaij *et al.**
(LHCb Collaboration)
(Received 6 November 2012; published 5 March 2013)

We report a measurement of the time-dependent ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ decay rates in
D^{*+}-tagged events using 1.0 fb^{-1} of integrated luminosity recorded by the LHCb experiment. We
measure the mixing parameters $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$, $y' = (7.2 \pm 2.4) \times 10^{-3}$, and the ratio of
doubly-Cabibbo-suppressed to Cabibbo-favored decay rates $R_D = (3.52 \pm 0.15) \times 10^{-3}$, where the
uncertainties include statistical and systematic sources. The result excludes the no-mixing hypothesi
with a probability corresponding to 9.1 standard deviations and represents the first observation of $D^0 - \bar{D}$
oscillations from a single measurement.

- CPV in the decay $\left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| \neq 1$
- CPV in mixing $\left|\frac{q}{p}\right| \neq 1$
- CPV in interference between mixing and decay

$$\phi_f = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \approx arg\left(\frac{q}{p}\right) \neq 0$$

We are in the post-mixing & post-CPV-observation phase, but…

$x \neq 0$? $\left|\frac{q}{p}\right| \neq 1$? $\phi \neq 0$?

No evidence of mixing induced CPV, sizeable BSM effects possible

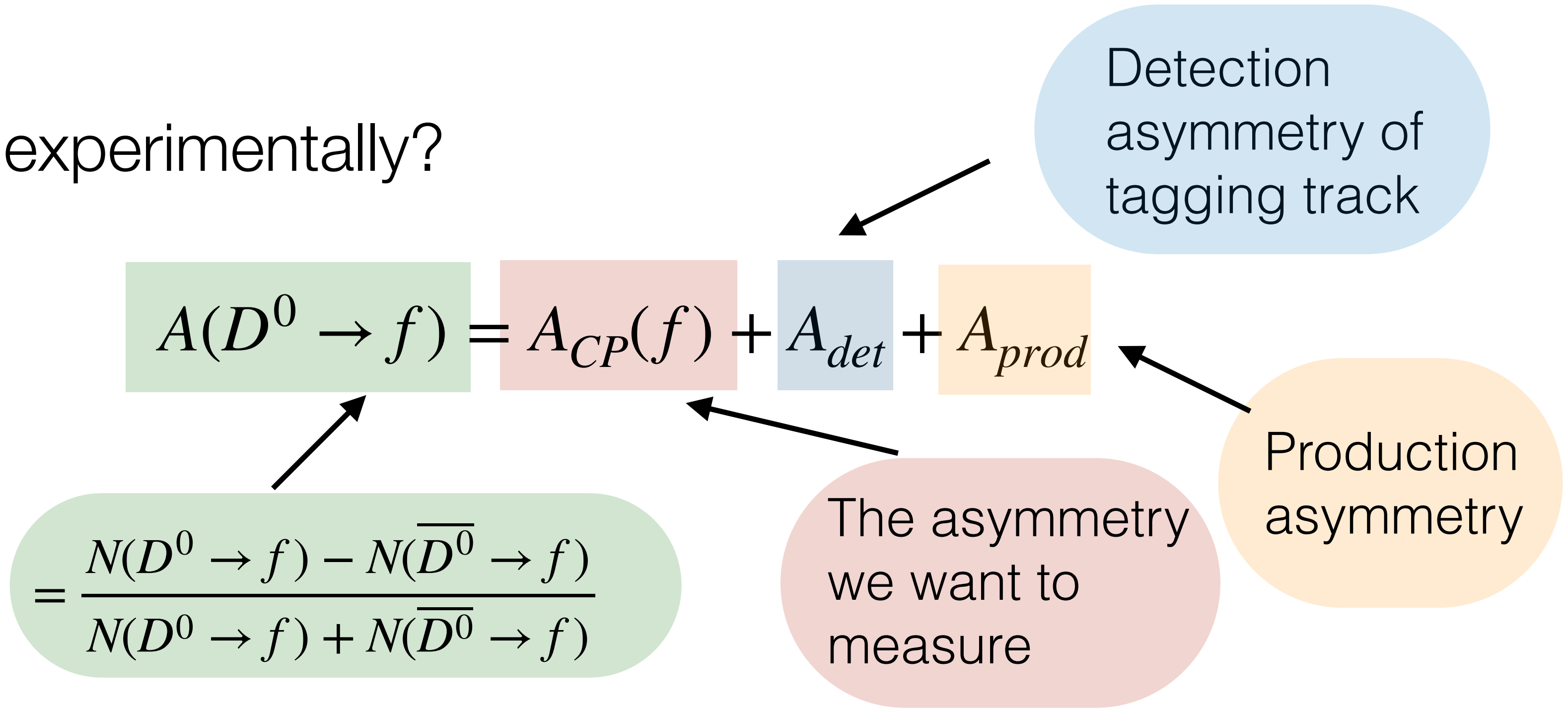
Observation of CP violation in charm

PRL122(2019)211803

- Measurement of decay-time integrated CP asymmetries in $D^0 \to K^+K^-, \pi^+\pi^-$

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

- How experimentally?



$$A(D^0 \to f) = A_{CP}(f) + A_{det} + A_{prod}$$

Detection asymmetry of tagging track

Production asymmetry

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

The asymmetry we want to measure

- Compute the difference of measured raw asymmetries ΔA_{CP}, in the limit of SU(3) symmetry

$$A_{CP}^{SM}(K^+K^-) = -A_{CP}^{SM}(\pi^+\pi^-) \approx \mathcal{O}(10^{-4} - 10^{-3})$$

arXiv:1112.5451

$$\boxed{\begin{aligned}\Delta A_{CP} &= A(K^+K^-) - A(\pi^+\pi^-) \\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\end{aligned}}$$

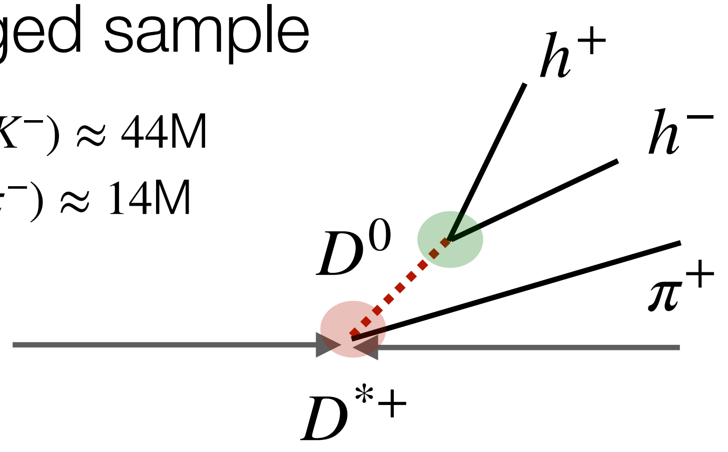
*mainly sensitive to CPV in the decay (=direct CPV)

Observation of CP violation in charm

PRL122(2019)211803

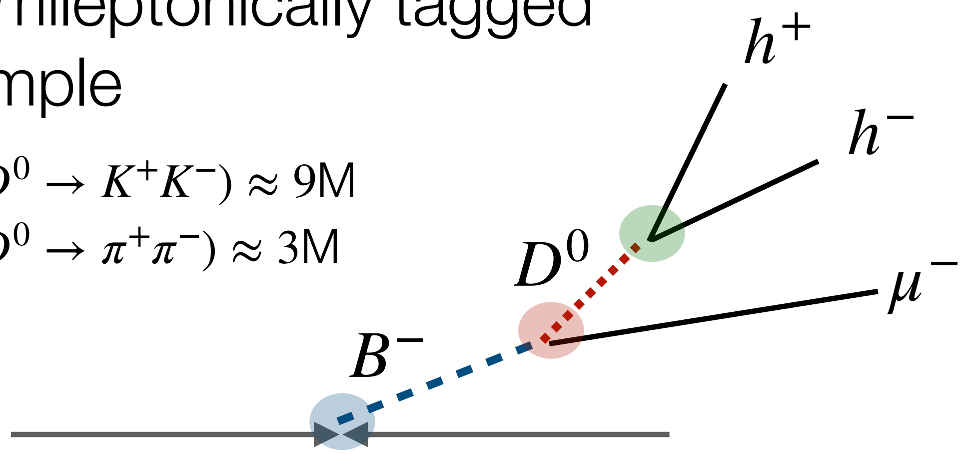
- Analyse full Run2 (6fb^{-1}) data set
  - Pion tagged sample

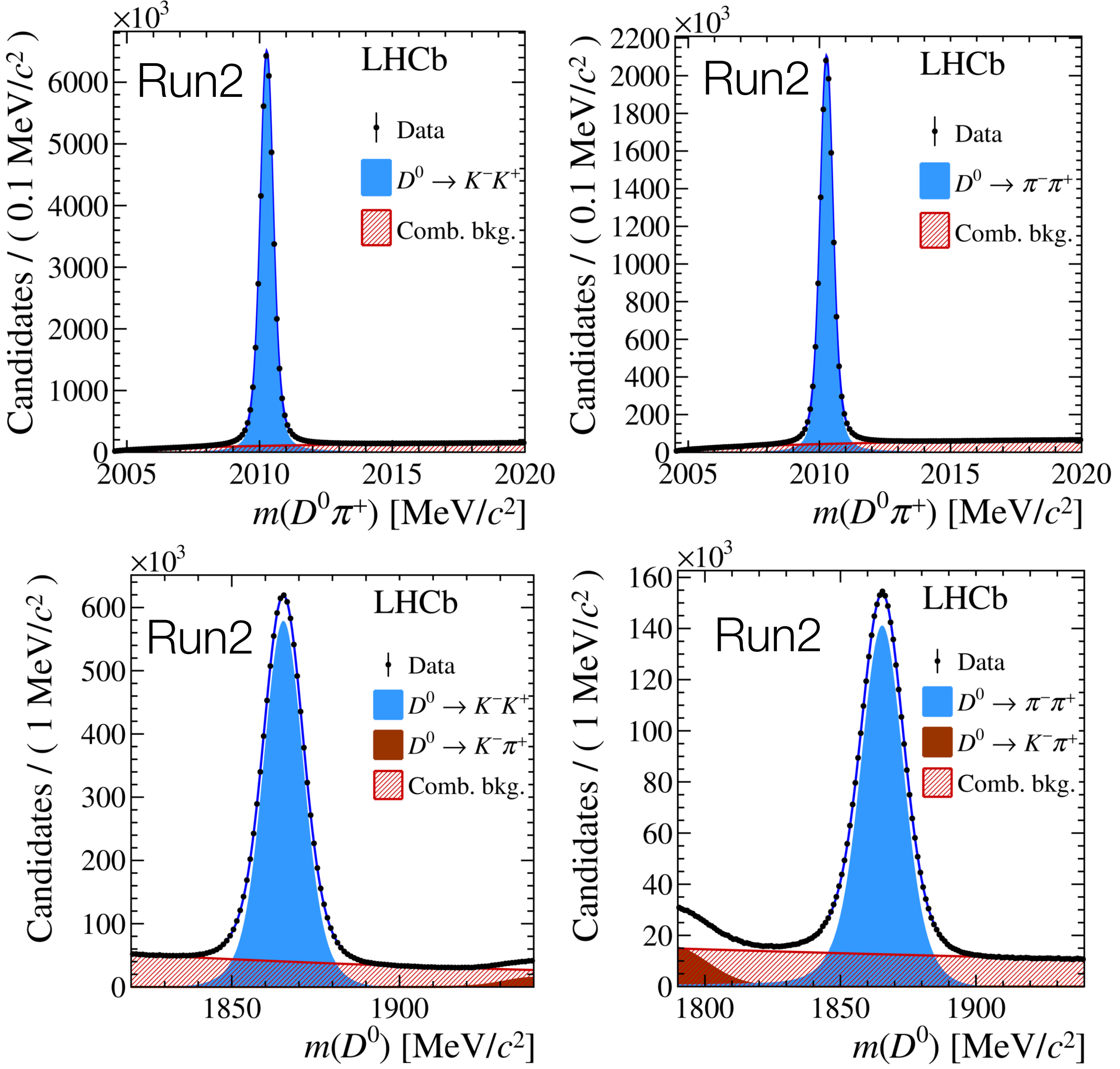
    $N(D^0 \to K^+K^-) \approx$ 44M
    $N(D^0 \to \pi^+\pi^-) \approx$ 14M



  - Semileptonically tagged sample

    $N(D^0 \to K^+K^-) \approx$ 9M
    $N(D^0 \to \pi^+\pi^-) \approx$ 3M





Combination Run1 and Run2 results:

$$\Delta A_{CP} = [-15.4 \pm 2.9)] \times 10^{-4}$$

PRL122(2019211803, JHEP07(2014)041, PRL116(2016)191601

5.3σ deviation
from zero,
first observation!

arXiv:1812.07638

Compatible with SM!(?)

Additional measurements will help to clarify the picture, e.g. $A_{CP}(K^+K^-)$, $A_{CP}(\pi^+\pi^-)$,….

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

PRD101(2020)012005

- Measurement of A_Γ in $D^0 \to K^+K^-, \pi^+\pi^-$ decays

$$A_\Gamma(f) = \frac{\hat{\tau}(\overline{D}^0 \to f) - \hat{\tau}(D^0 \to f)}{\hat{\tau}(\overline{D}^0 \to f) + \hat{\tau}(D^0 \to f)}$$

$$\approx -x\phi_f + y(|q/p| - 1) - yA_{CP}^{decay}(f)$$

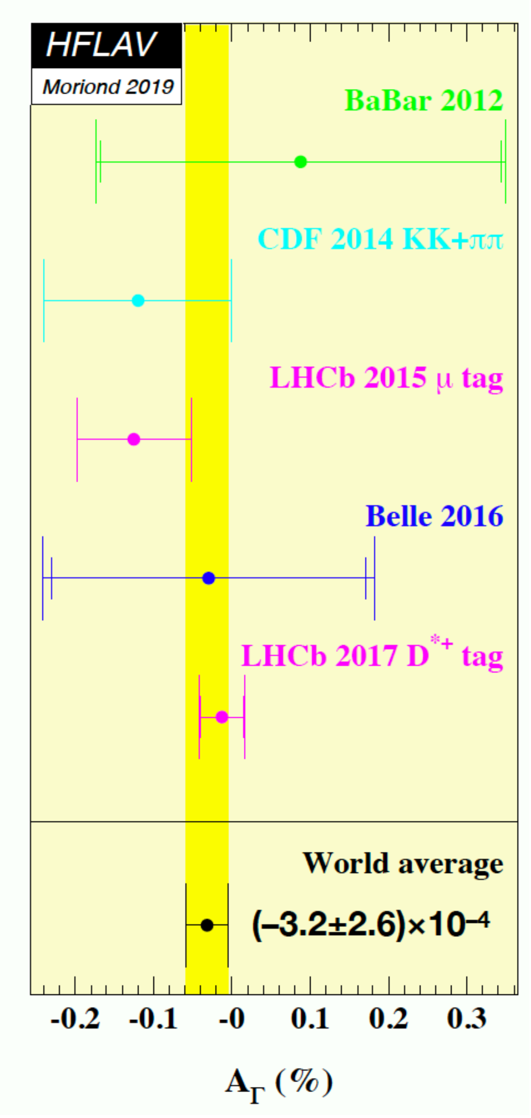
~arg(q/p)

$<10^{-5}$

A_Γ probes CPV in mixing and interference of decay with and w/o mixing

$$A_\Gamma^{SM} \approx 2 \times 10^{-5}$$

arXiv:2001.07207
arXiv:2001.04079



- How experimentally?

$$A(t) = \frac{N(D^0(t) \to f) - N(\overline{D}^0(t) \to f)}{N(D^0(t) \to f) + N(\overline{D}^0(t) \to f)} = A_{CP}(t) + A_{det} + A_{prod}$$

~independent of t ?

$$A_{CP}(t) = A_{CP}^{decay} - \frac{t}{\tau}A_\Gamma$$

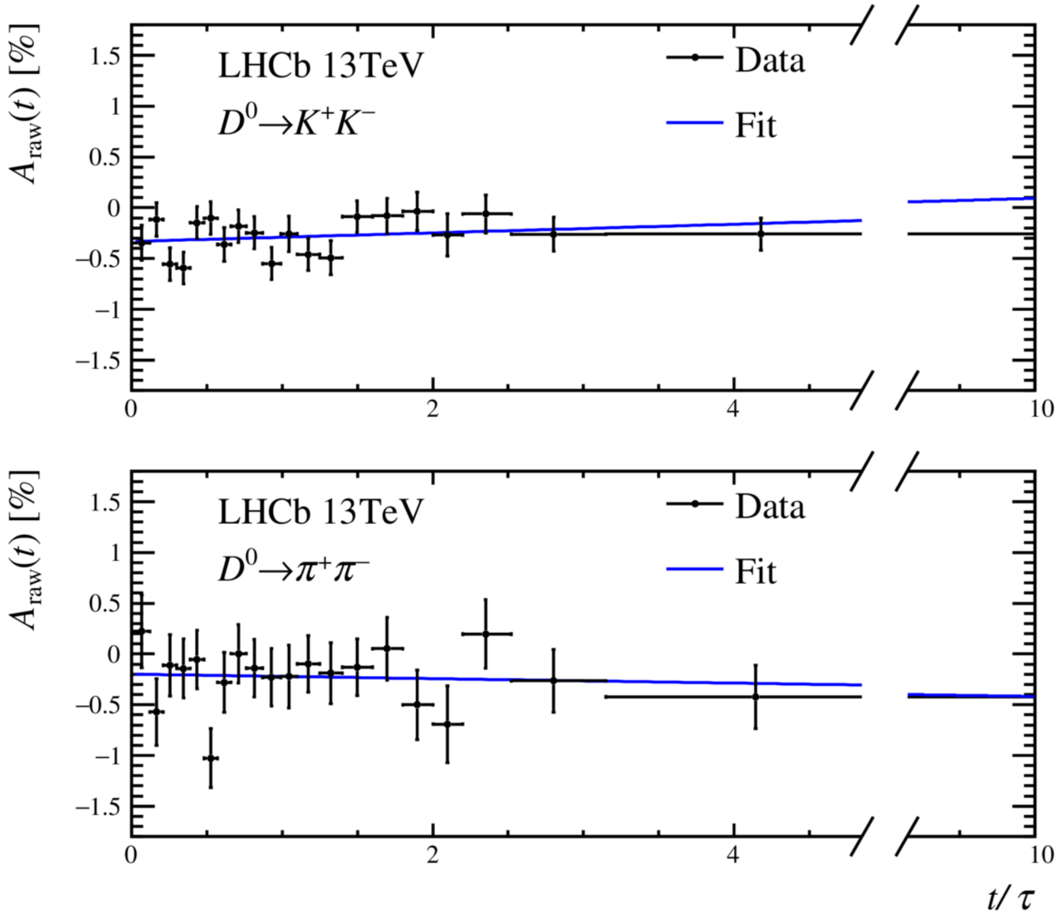
independent of t

t-dependent!

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

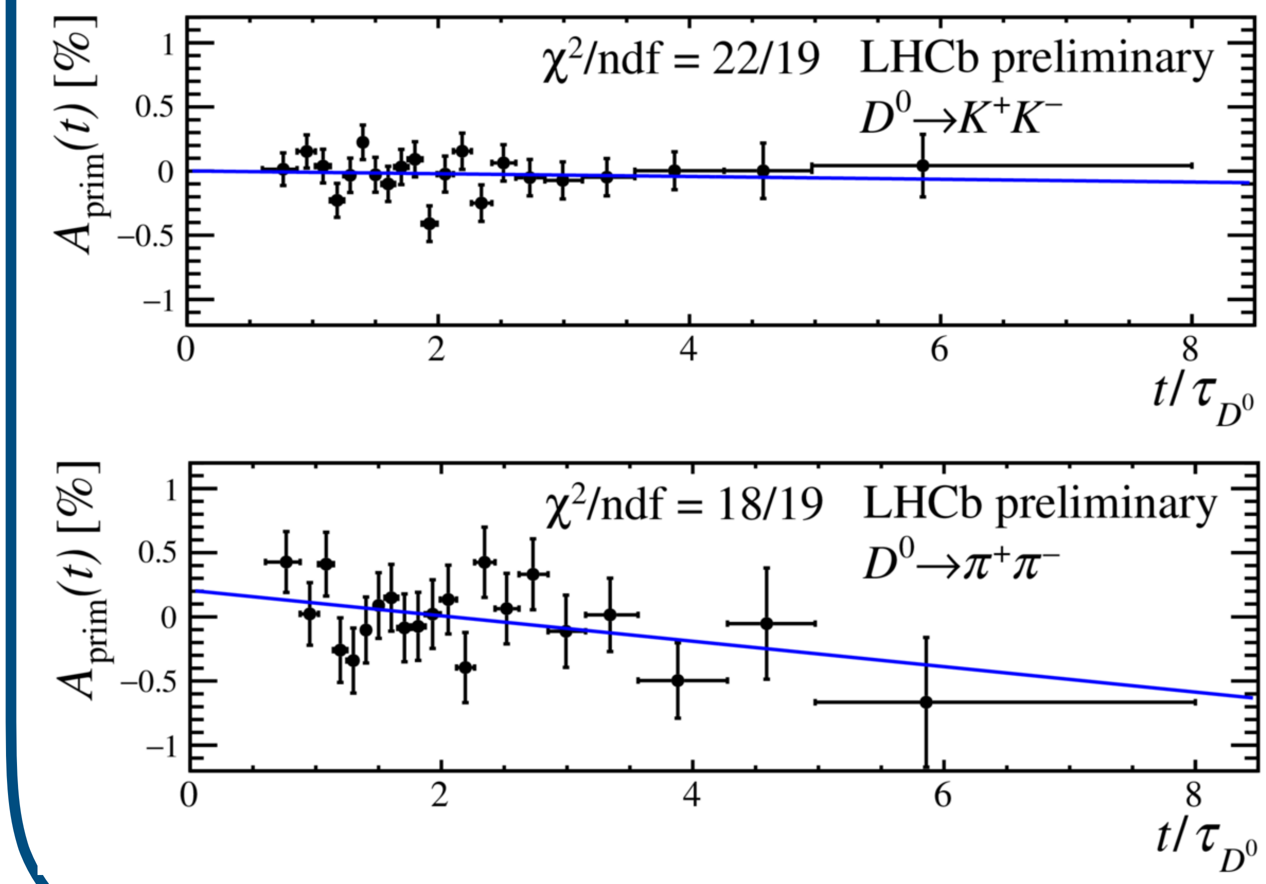
semileptonically tagged sample 5.4 fb^{-1} (Run 2)

PRD101(2020)012005



pion tagged sample 1.9 fb^{-1} (Run 2)

LHCb-CONF-2019-001



Averaging the four samples and combining with Run1 results:

PRL118(2017)261803,JHEP04(2015)043

Preliminary

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

Analysis of full (pion tagged) Run2 data still to come!

Mixing and CPV with $D^0 \to K_s\pi^+\pi^-$

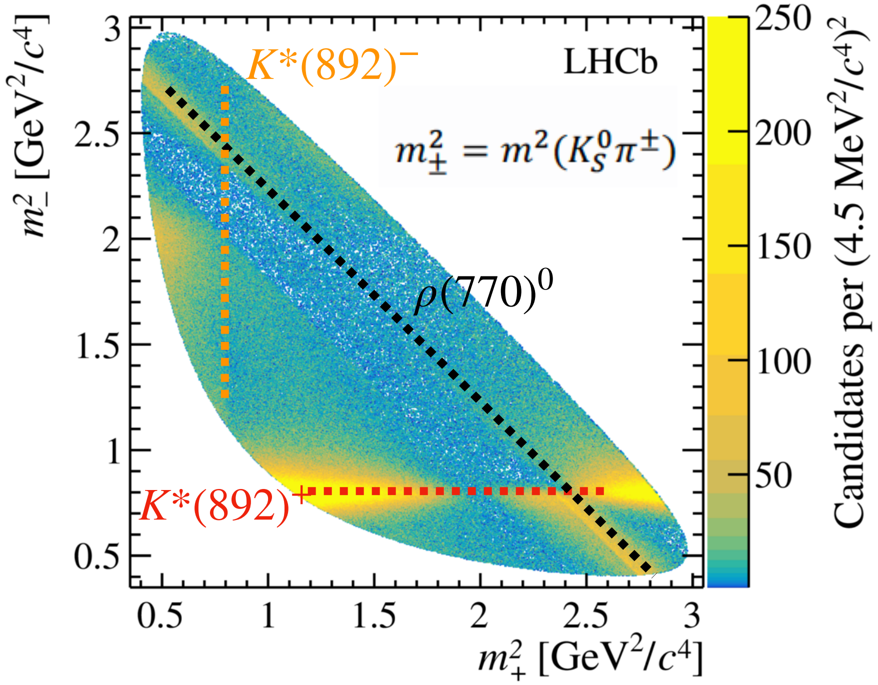
PRD99(2019)012007

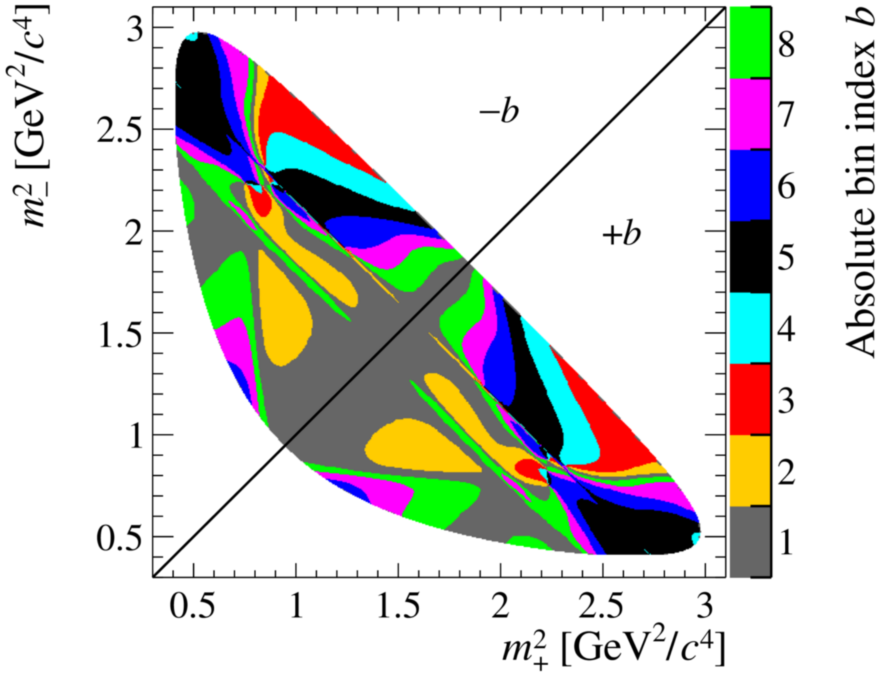
- Multiple interfering amplitudes in $D^0 \to K_s\pi^+\pi^-$ decays enhance sensitivity to mixing
  - Bin the Dalitz plot to avoid amplitude analysis in bins with approximately constant strong phase difference (Bin-Flip method)
  - Measure ratio of signal yields in bin -b and +b

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

PRD99(2019)012007

  - Hadronic parameters c_b, s_b constraint using measurements with quantum correlated $D^0\overline{D^0}$ pairs (CLEO, BESIII)
  - Mixing parameters from simultaneous fit to all bins, access to CPV by splitting in D^0 and $\overline{D^0}$



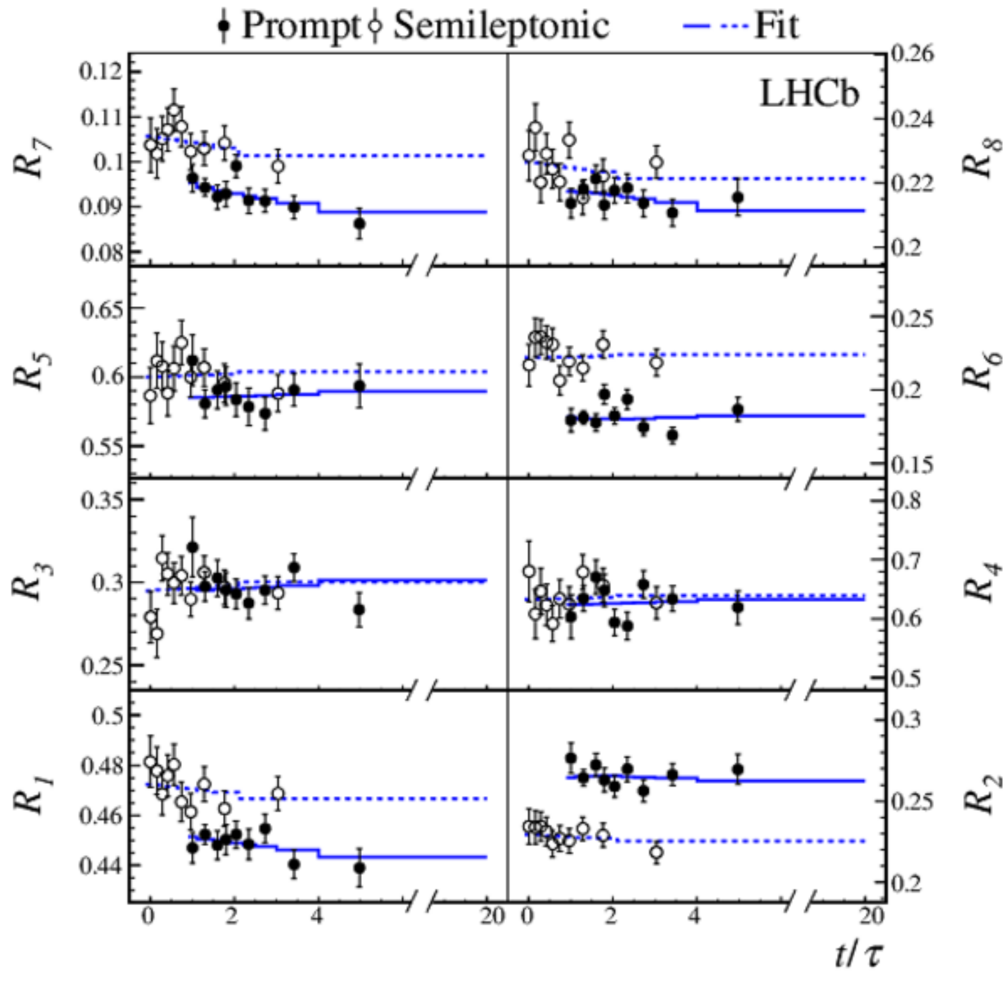


Mixing and CPV with $D^0 \to K_s\pi^+\pi^-$

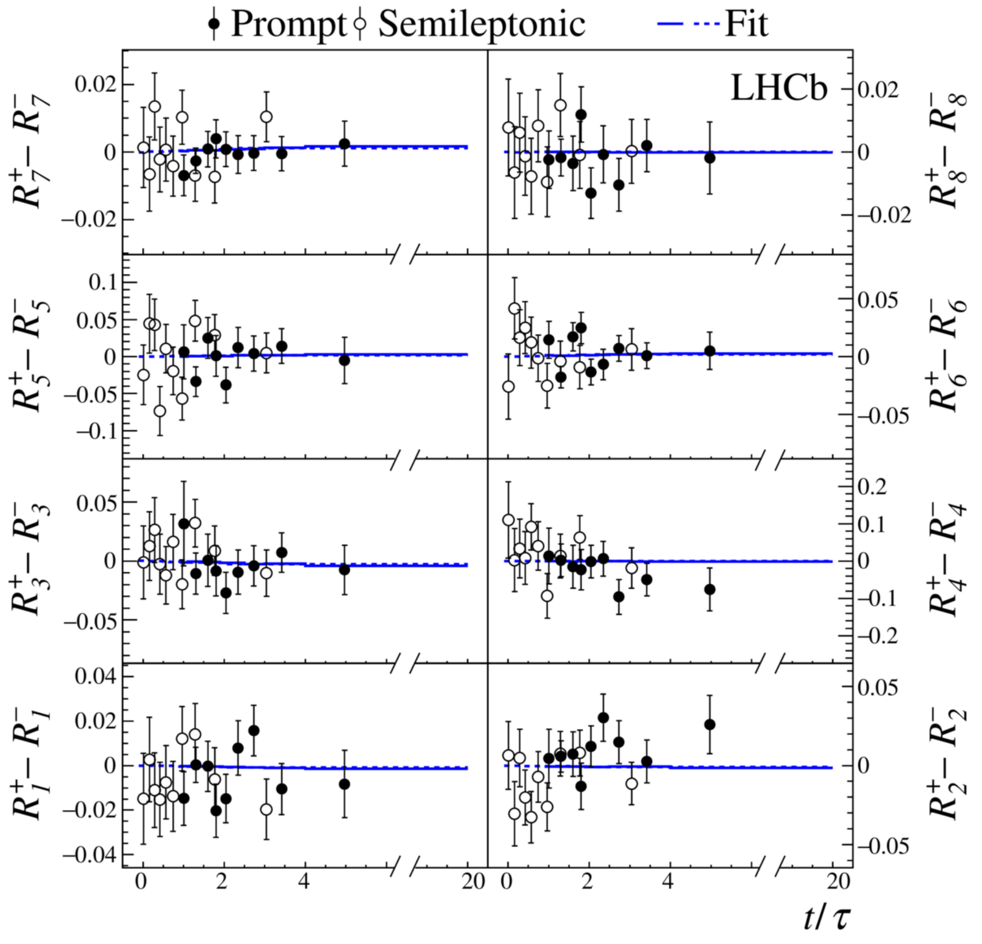
PRL122(2019)231802

- LHCb analysed semileptonically (1M) and pion tagged (1.3M) samples (3/fb Run1)

combined D^0 and $\overline{D^0}$ decays
(measure mixing parameters)



D^0 and $\overline{D^0}$ decays separated
(measure mixing induced CPV)



Mixing and CPV with $D^0 \to K_s\pi^+\pi^-$

PRL122(2019)231802

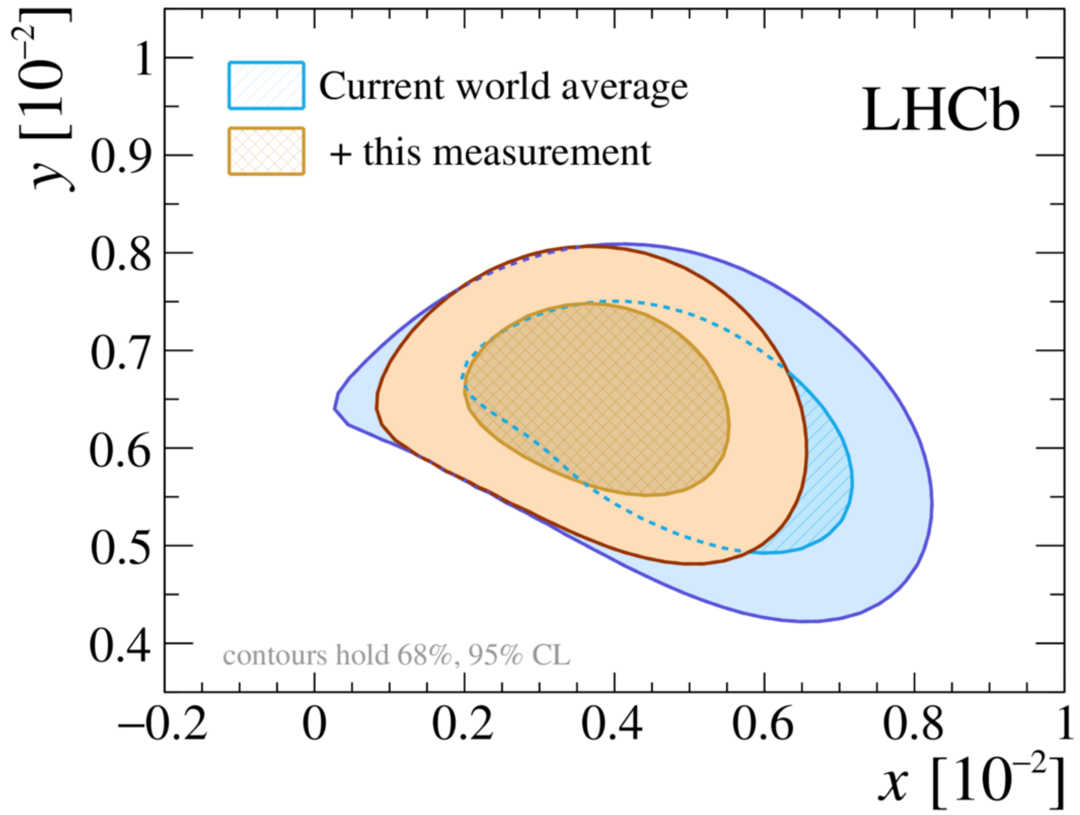
Parameter	Value	95.5% CL interval
$x\ [10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
$y\ [10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p\rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

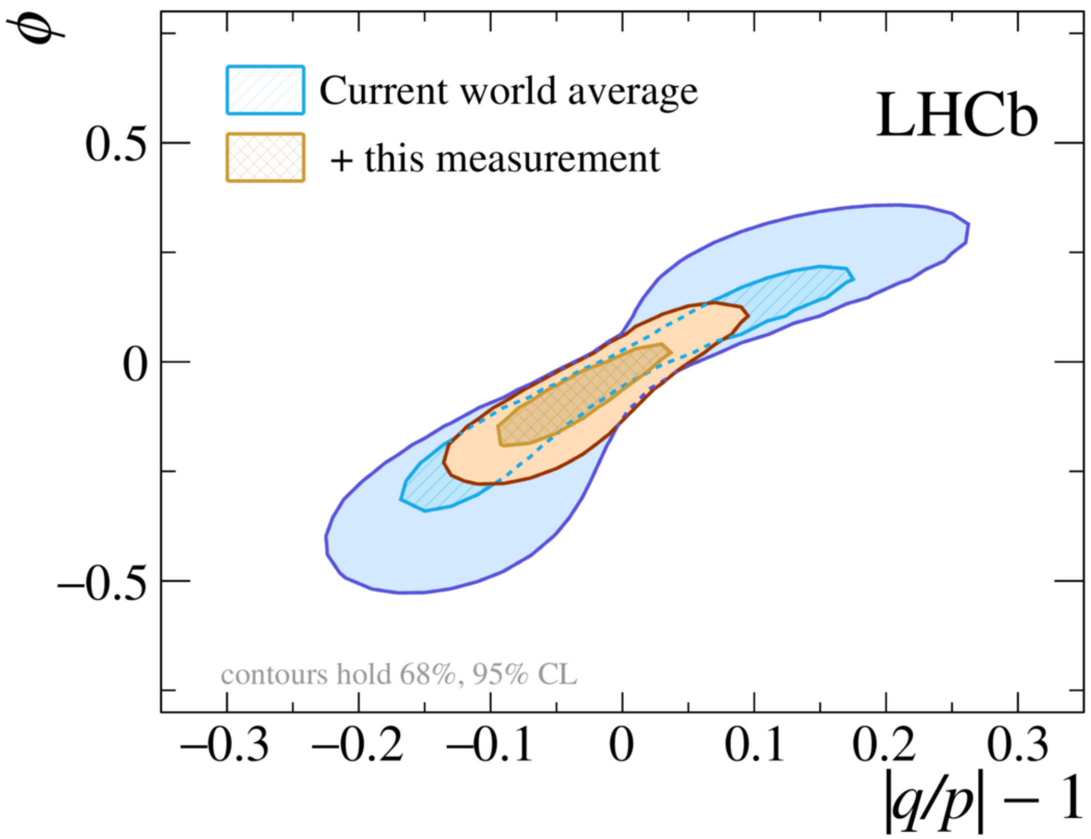
today's most precise measurement of x, $\left|\frac{q}{p}\right|$, ϕ

New WA results in first evidence for nonzero (positive) value of x

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

Analysis of full Run2 data set on the way!



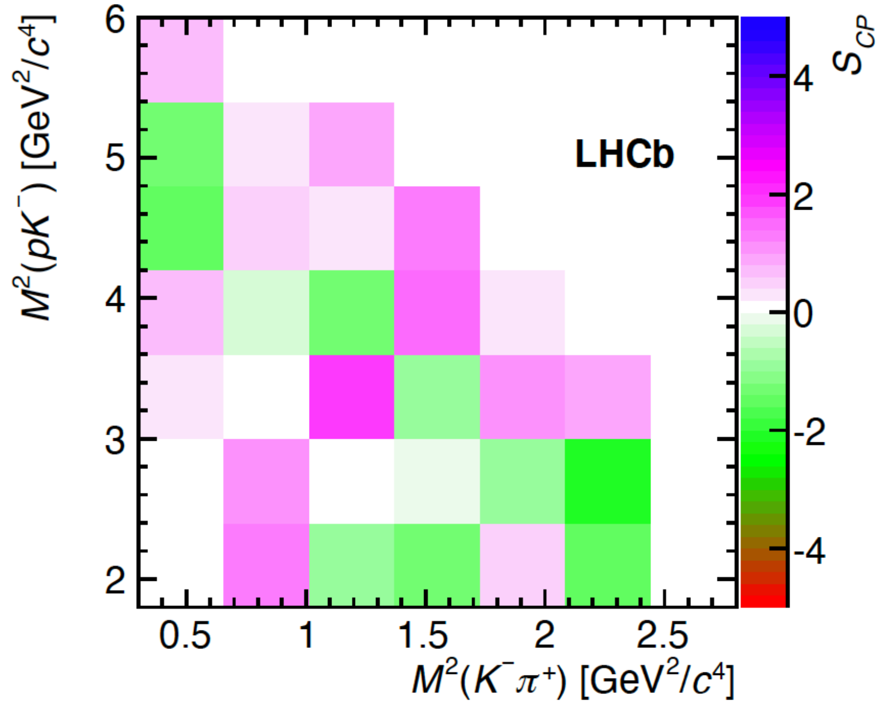


Search for CPV in $\Xi_c^+ \to pK^-\pi^+$

NEW

arXiv:2006.03145

- Searches for CPV in charmed baryon largely unexplored, search for CPV using model-independent techniques in the Dalitz plot



- Analyse full Run1 (3fb^{-1}) data set (~0.25M Ξ_c^+ candidates)
  - A sample of 2M $\Lambda_c^+ \to pK^-\pi^+$ is used for validation

$$S_{CP}^i = \frac{n_+^i - \alpha n_-^i}{\alpha\sqrt{n_+^i + n_-^i}} \qquad \alpha = \frac{n_+}{n_-} = 1.029 \pm 0.004 \qquad \begin{array}{l} n_+ = n(\Xi_c^+) \\ n_- = n(\Xi_c^-) \end{array}$$

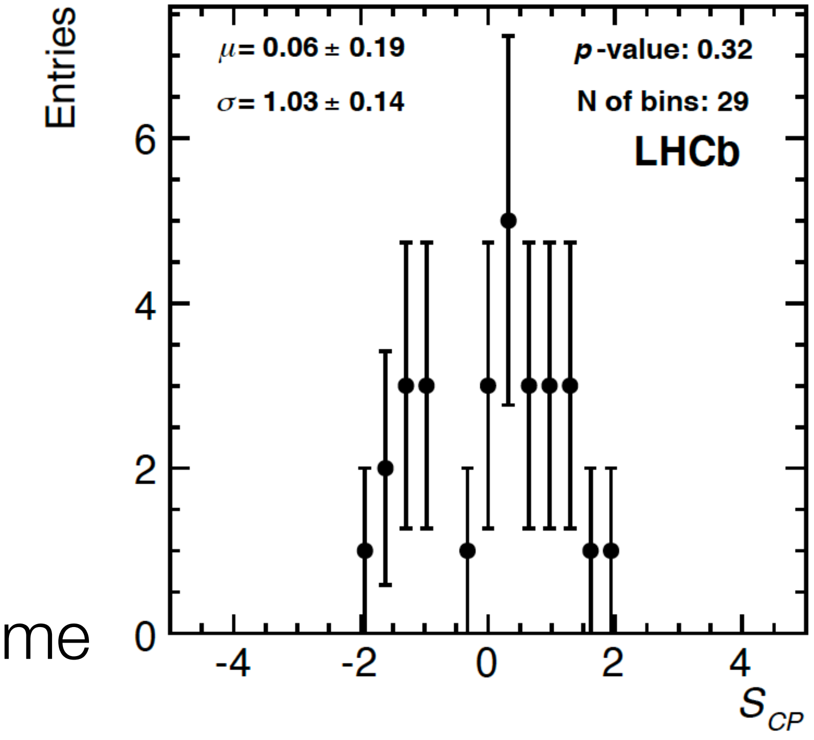
- If no CPV the S_{CP}^i are gaussian distributed with zero mean and width of unity

$$\boxed{\chi^2 = \sum (S_{CP}^i)^2}$$

exclude CP conservation if $p < 3 \times 10^{-7}$ (n_{dof}=n_{bins}-1)

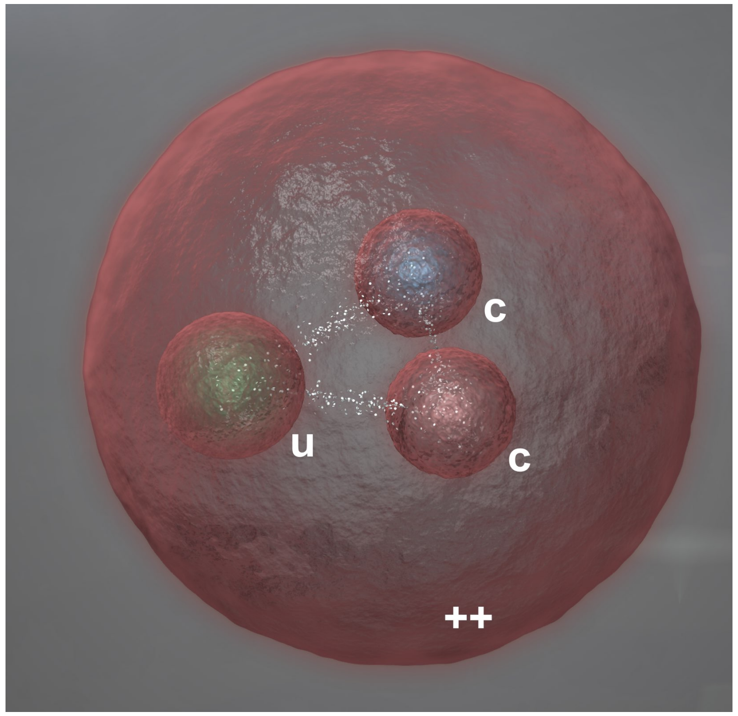
consistent with no evidence for CPV!

- Measured p-value 32%



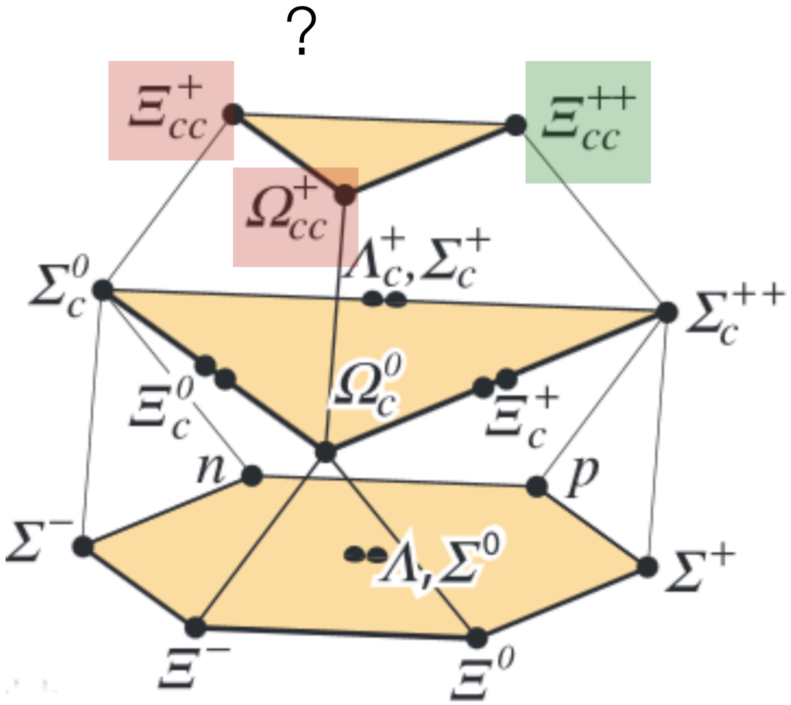
- Alternative (unbinned) k-nearest neighbour method gives same result

Production & decay properties



Doubly Charmed baryons

- Triggered a lot of attention in the last ~3 years
  - Discovery of Ξ_{cc}^{++} in decays to $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ final states PRL119(2017)112001 PRL121(2018)162002
  - First measurement of Ξ_{cc}^{++} production in pp collision Chin. Phys. C44(2020)022001
  - First measurement of the lifetime $\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(stat) \pm 0.014(sys)$ps PRL121(2018)052002

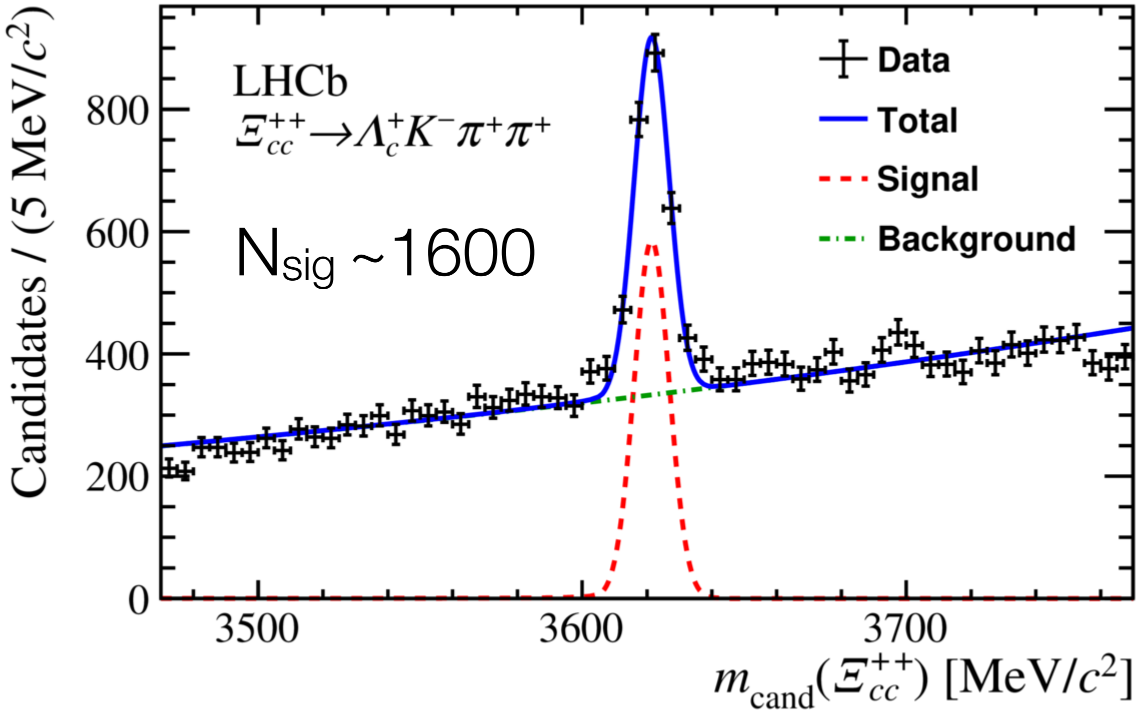


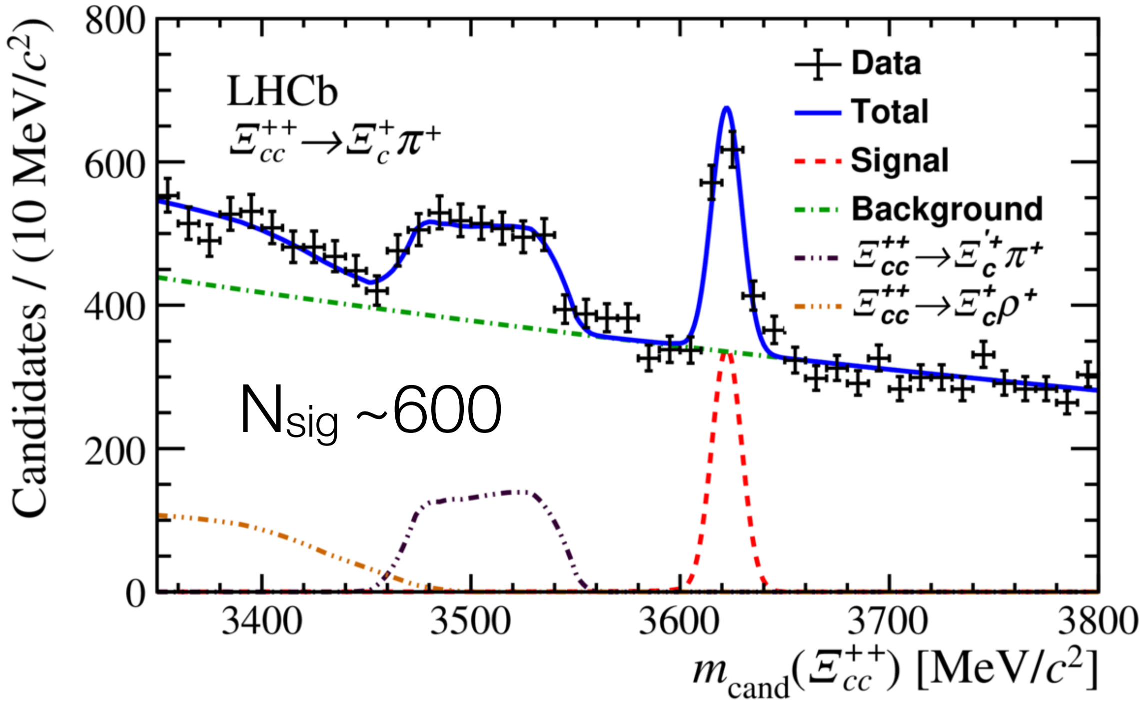
- And now?
  - Further precision measurements of Ξ_{cc}^{++} properties
  - Search for singly charged Ξ_{cc}^+ and Ω_{cc}^+, which have not been seen at hadron colliders and b-factories
    - SELEX reported observation of the decays $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \rightarrow p D^+ K^-$ using a charged hyperon beam at $m(\Xi_{cc}^+) = [3518.7 \pm 1.7]$ MeV/c^2 ($\tau < 33$ fs$@90CL$)

PRL89(2002)112001
PLB628(2005)18

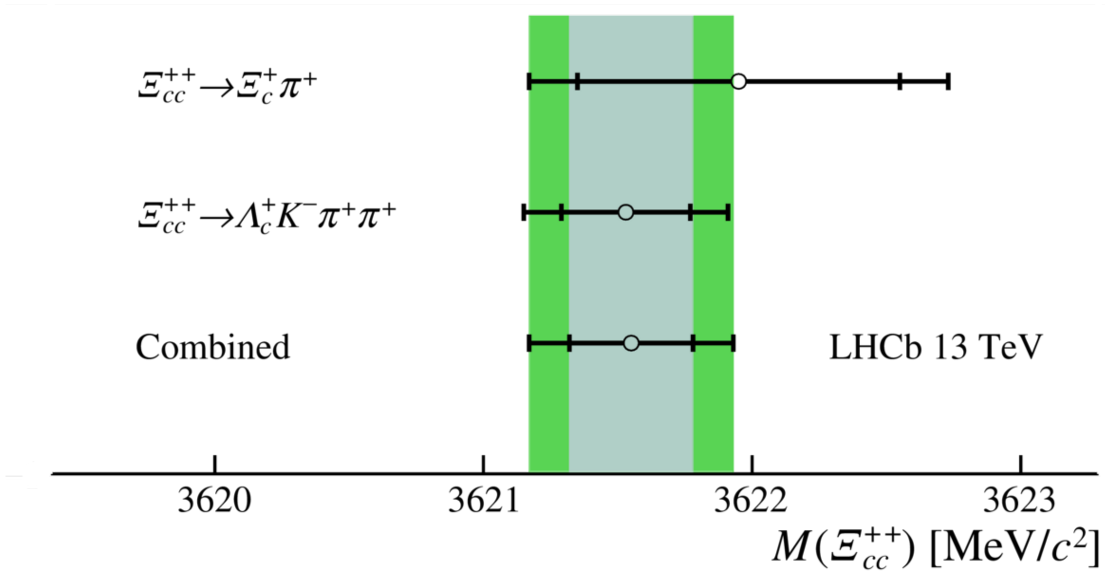
Mass measurement of Ξ_{cc}^{++}

JHEP02(2020)049





- Analyse Run 2 pp collision data (5.6/fb)
- Ξ_{cc}^{++} candidates are reconstructed via the decay modes $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ (~600 signals)



Combined results word's most precise value

$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23(stat) \pm 0.30(syst)$ MeV/c^2

Search for singly charged Ξ_{cc}^{+}

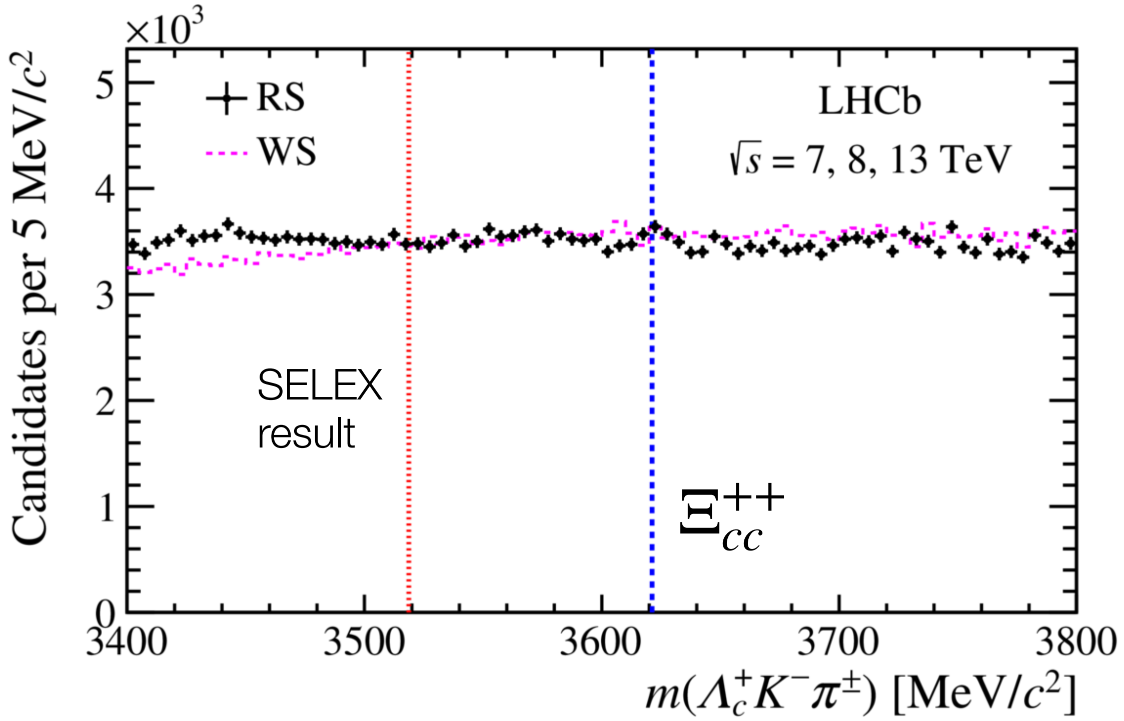
Sci. China Phys. Mech. Astron. 63 (2020) 221062

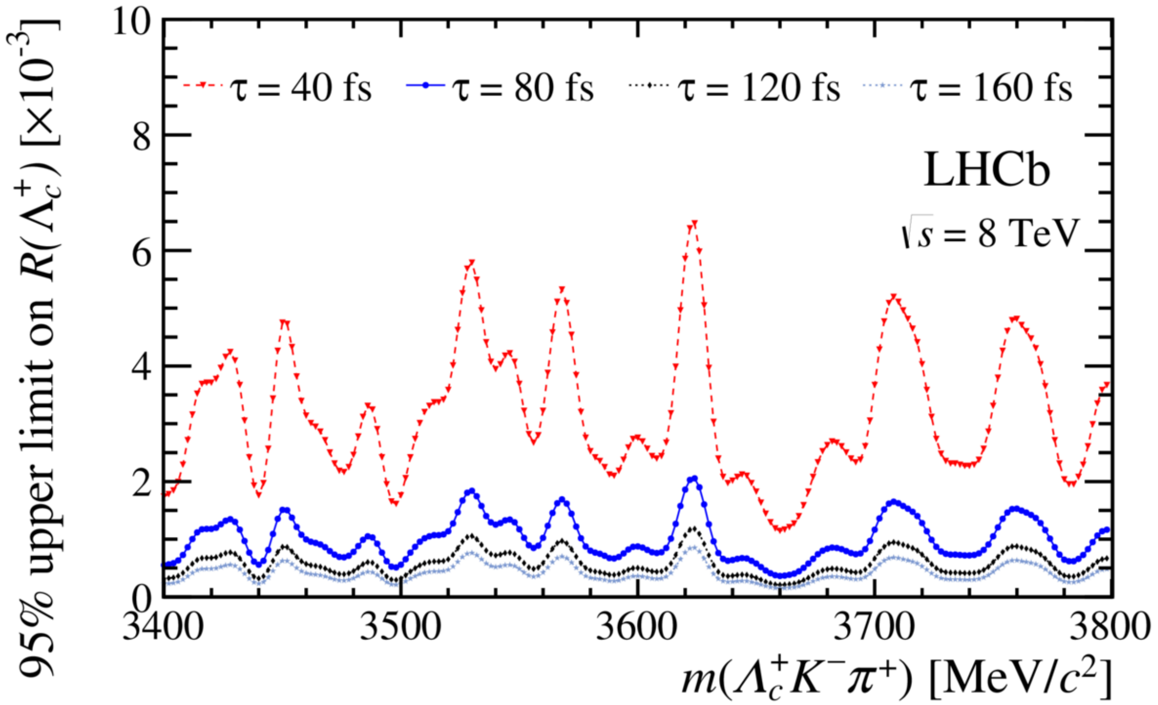
- Analyse full Run1 and Run2 data set (9/fb)
- Search for Ξ_{cc}^{+} decays to final state $\Lambda_c^+ K^- \pi^+$ (SELEX observation channel)
- Mass search window from $[3.4 - 3.8] GeV/c^2$
- No significant signal found
- Set limits on the production ratios for different lifetime hypotheses

$$\mathcal{R}(\Lambda_c^+) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$$

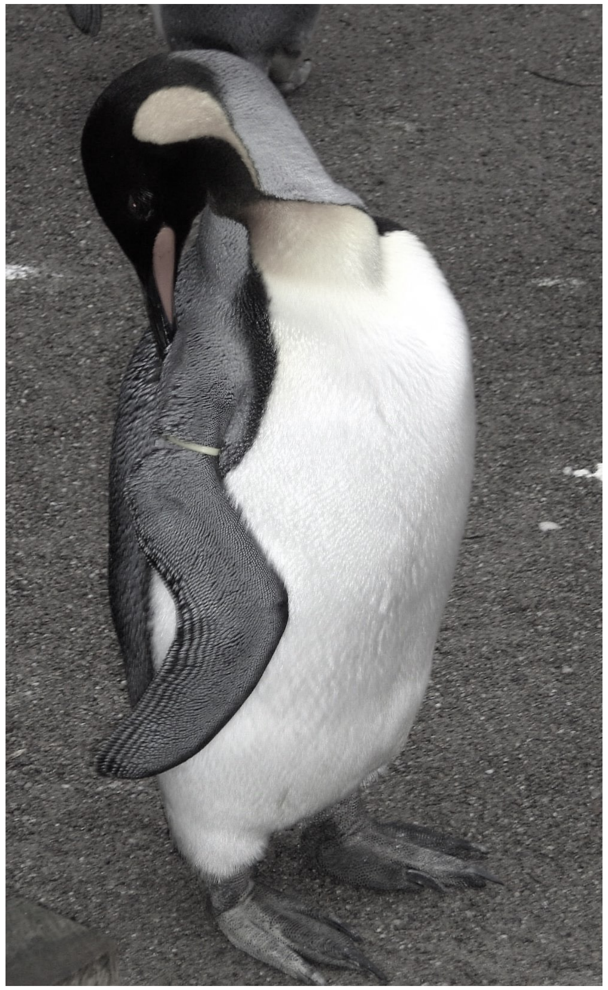
$$\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$

We will extend our searches to different final states soon!





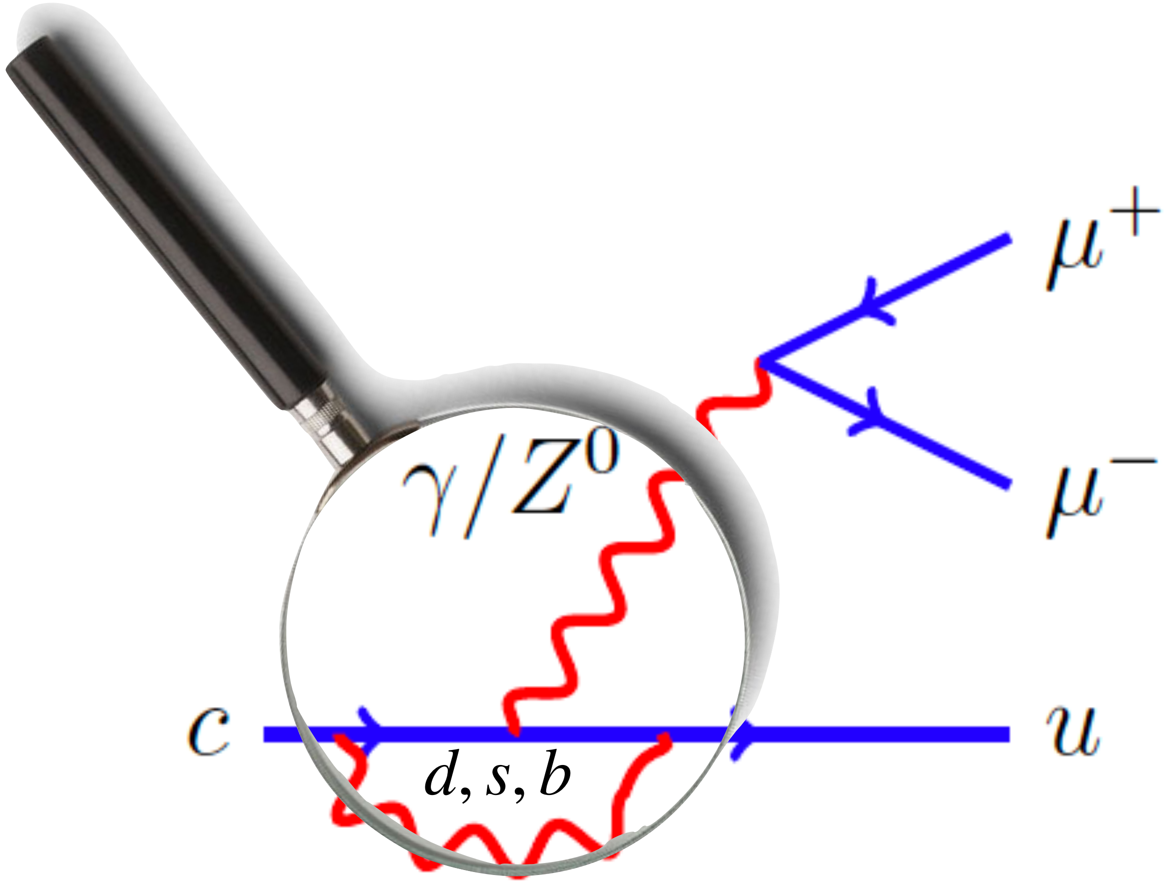
Rare decays

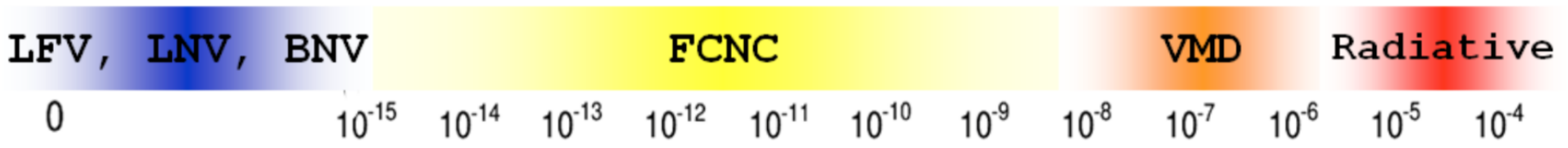


Rare decays

- Mainly investigation of processes involving FCNC $c \to u\ell\ell$ transitions

- Covering a very large variety of analyses
  - BF measurements
  - Angular+CP asymmetries
  - Searches for forbidden/extremely rare modes





Searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons

LHCB-PAPER-2020-007-001(in preparation)

NEW

LFV, LNV, LNV & LFV

$D^+_{(s)} \to \pi^+\mu^\pm e^\mp$

$D^+_{(s)} \to K^+\mu^\pm e^\mp$

$D^+ \to K^-\mu^+e^+$

$D^+_{(s)} \to \pi^-\mu^+e^+$

$D^+_{(s)} \to \pi^-e^+e^+$

$D^+_{(s)} \to \pi^-\mu^+\mu^+$

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

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

FCNC

$D^+_{(s)} \to \pi^+e^+e^-$

$D^+_{(s)} \to \pi^+\mu^+\mu^-$

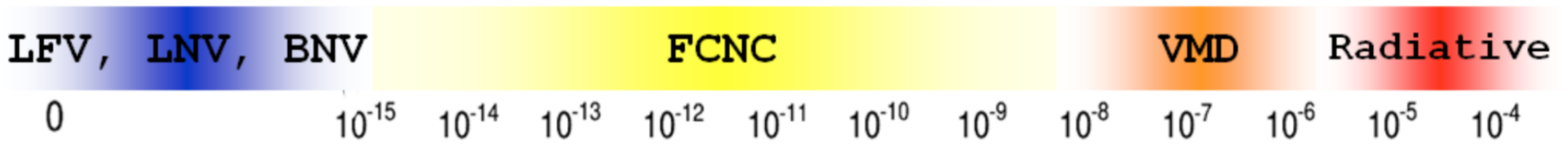
$D^+_{(s)} \to K^+e^+e^-$

$D^+_{(s)} \to K^+\mu^+\mu^-$

Resonance dominated

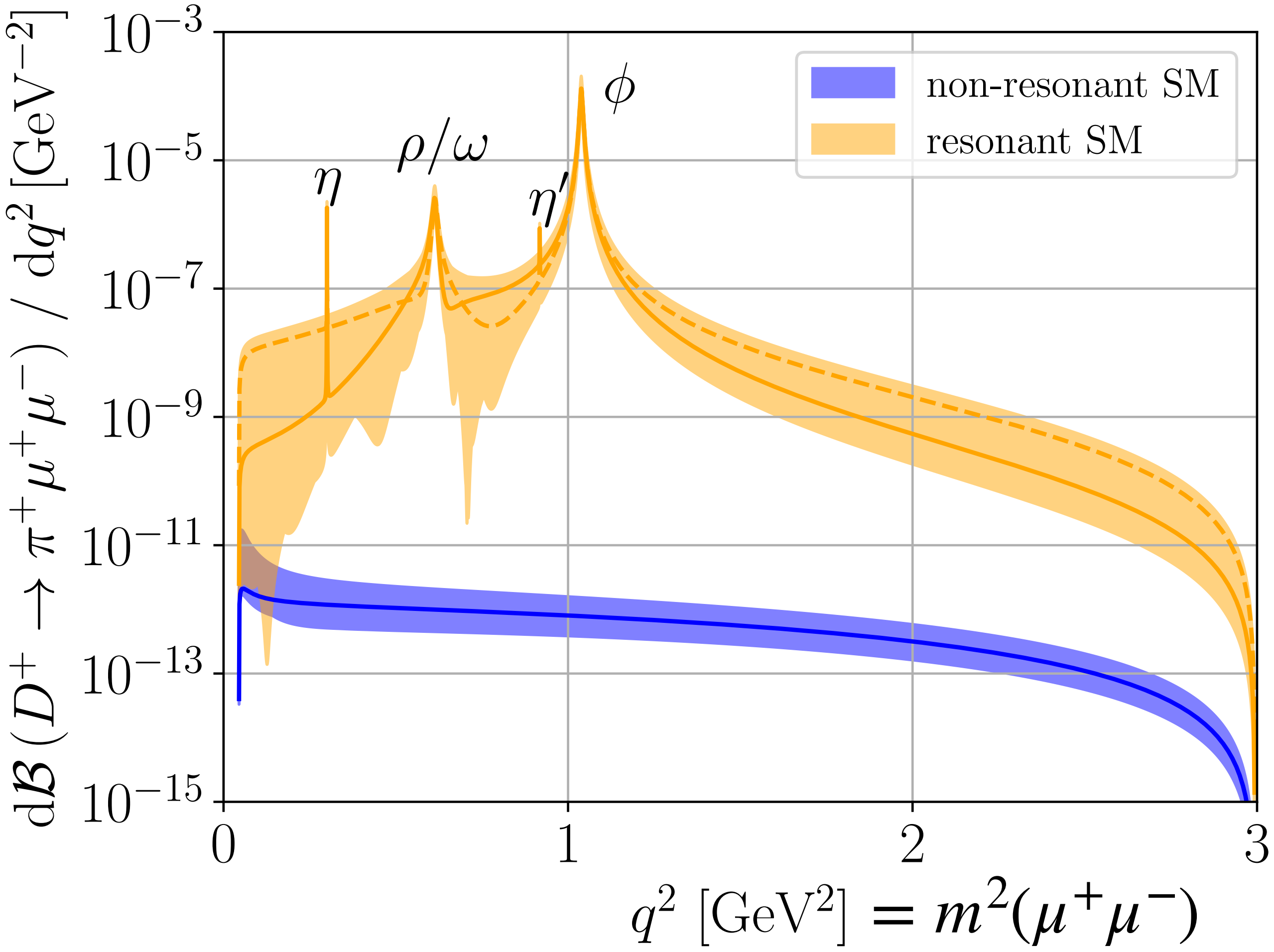
$D^+_{(s)} \to \pi^+\phi(\mu^+\mu^-)$

$D^+_{(s)} \to K^+\phi(e^+e^-)$



Search for the rare decays $D^0 \to hl^{\pm}l^{(\prime)\mp}$

- Non-forbidden decay modes are dominated by intermediate resonances
- BSM enhancement in regions away from resonances possible
- Forbidden modes clear null-tests of the SM



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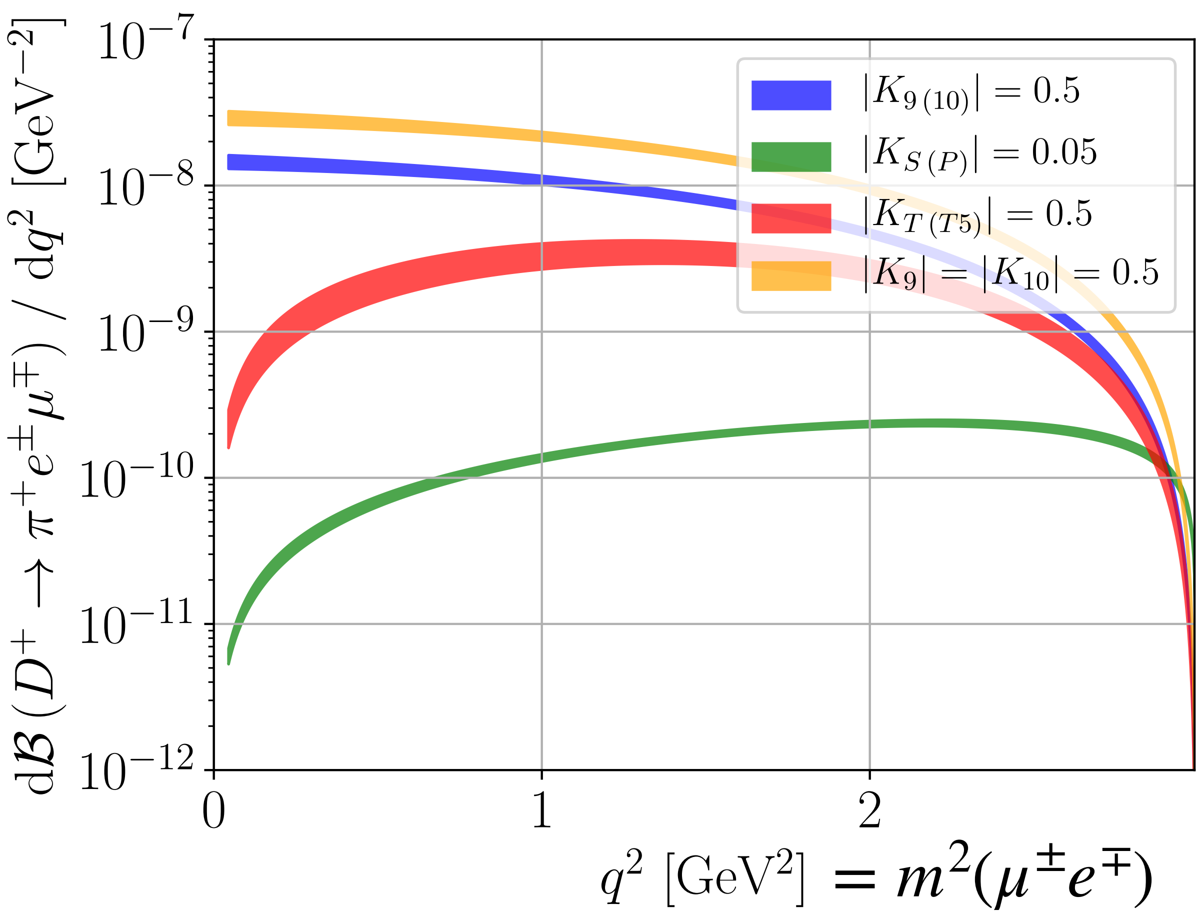

EPJ C80(202)65

Search for the rare decays $D^0 \to h l^{\pm} l^{(\prime)\mp}$

- Non-forbidden decay modes are dominated by intermediate resonances
- BSM enhancement in regions away from resonances possible
- Forbidden modes clear null-tests of the SM

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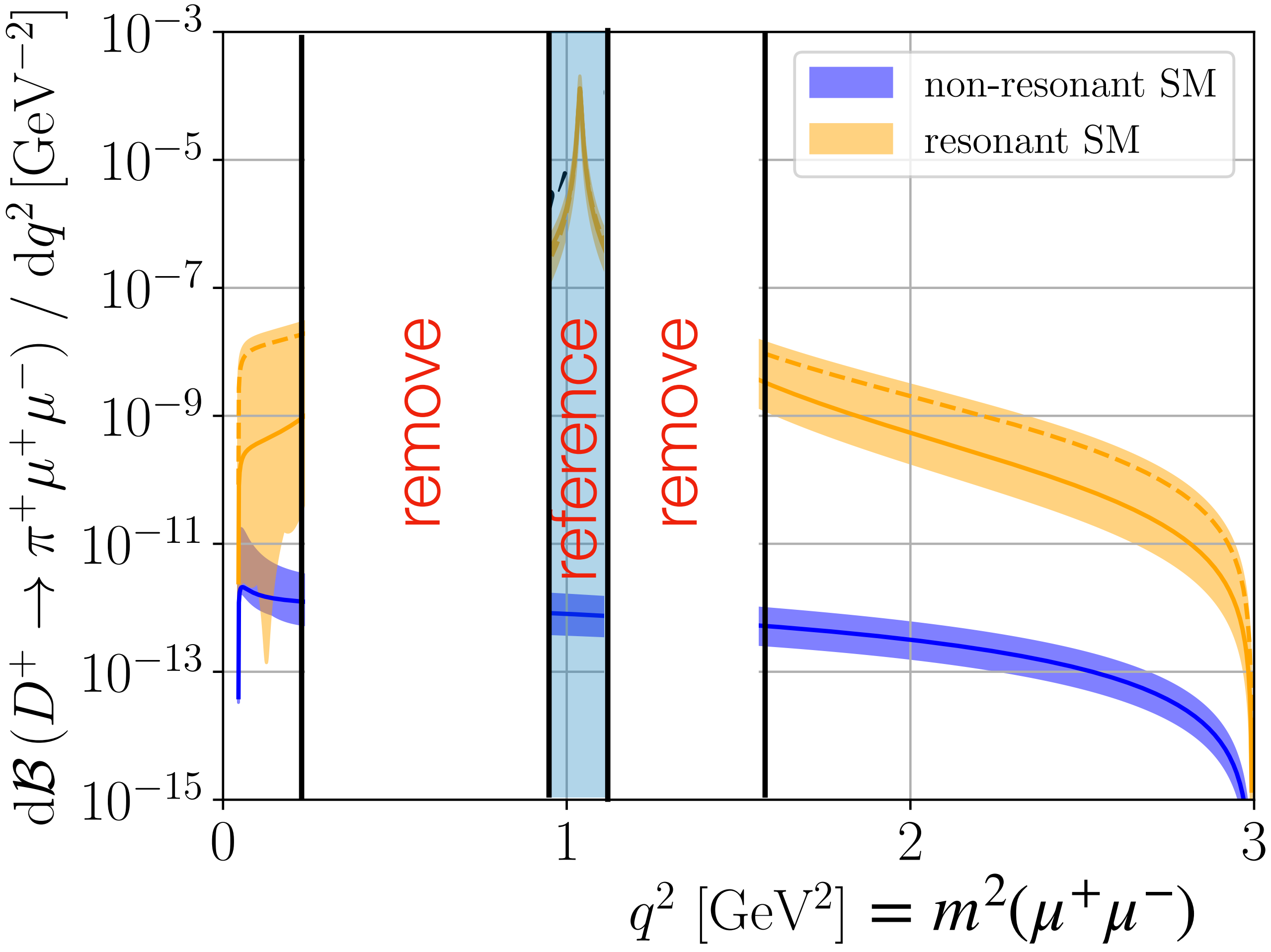

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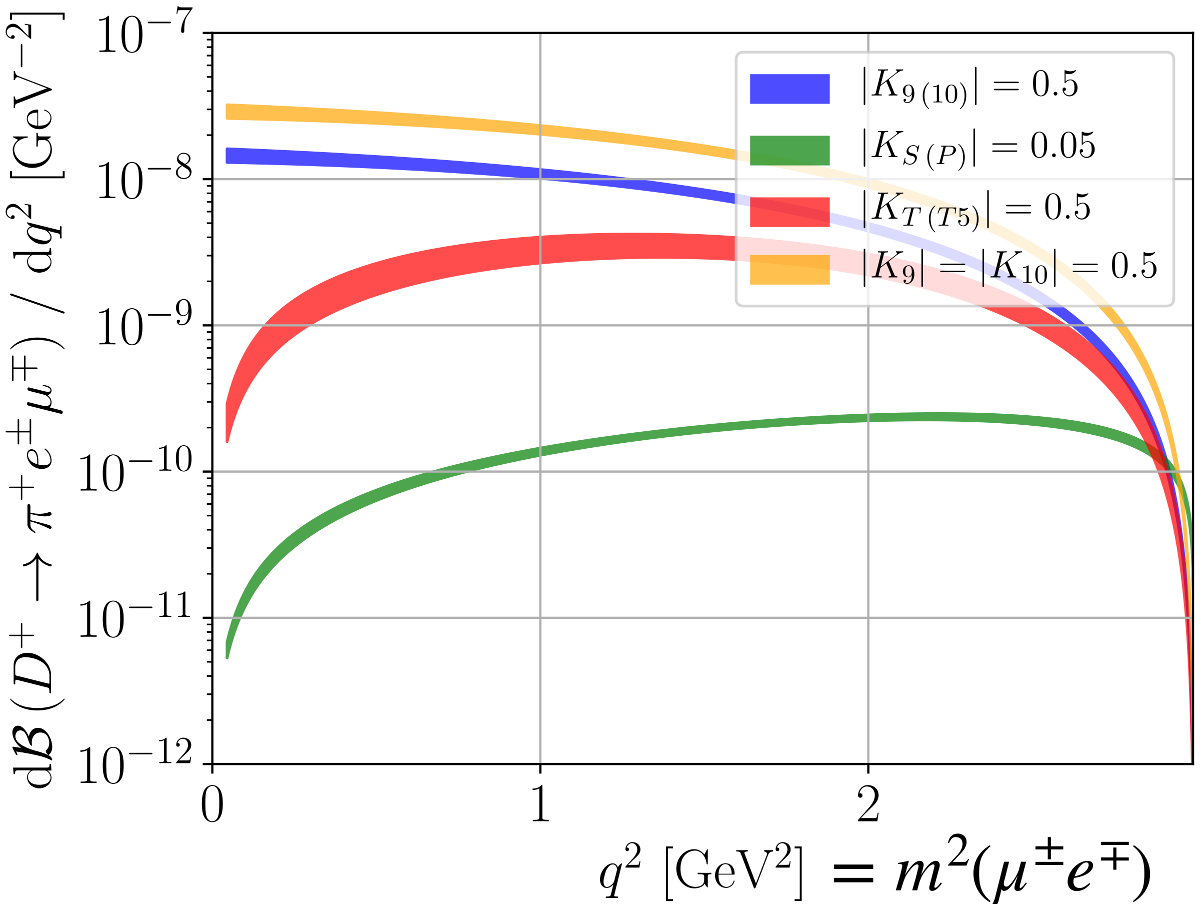


Search for the rare decays $D^0 \to hl^{\pm}l^{(\prime)\mp}$

LHCB-PAPER-2020-007-001

- How experimentally?

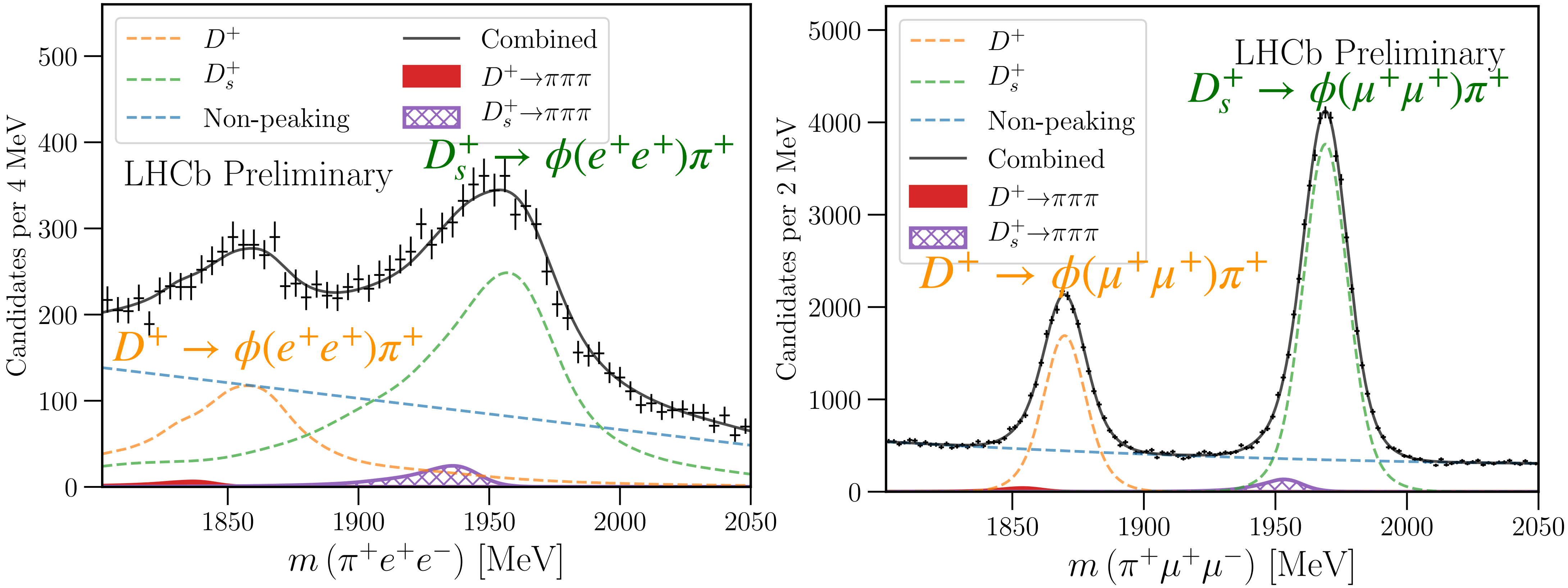
$$\mathcal{B}(D^+_{(s)} \to h\ell\ell) = \frac{N(D^+_{(s)} \to h\ell\ell)}{N(D^+_{(s)} \to h\phi(\to \ell\ell))} \cdot \frac{\epsilon(D^+_{(s)} \to h\phi(\to \ell\ell))}{\epsilon(D^+_{(s)} \to h\ell\ell)} \cdot \mathcal{B}(D^+_{(s)} \to h\phi(\to \ell\ell))$$

determination through maximum likelihood fits

mainly from simulations, data driven methods when possible

external input

- Resonant reference channels (Run2, 1.7fb^{-1})



Search for the rare decays $D^0 \rightarrow h l^{\pm} l^{(\prime)\mp}$

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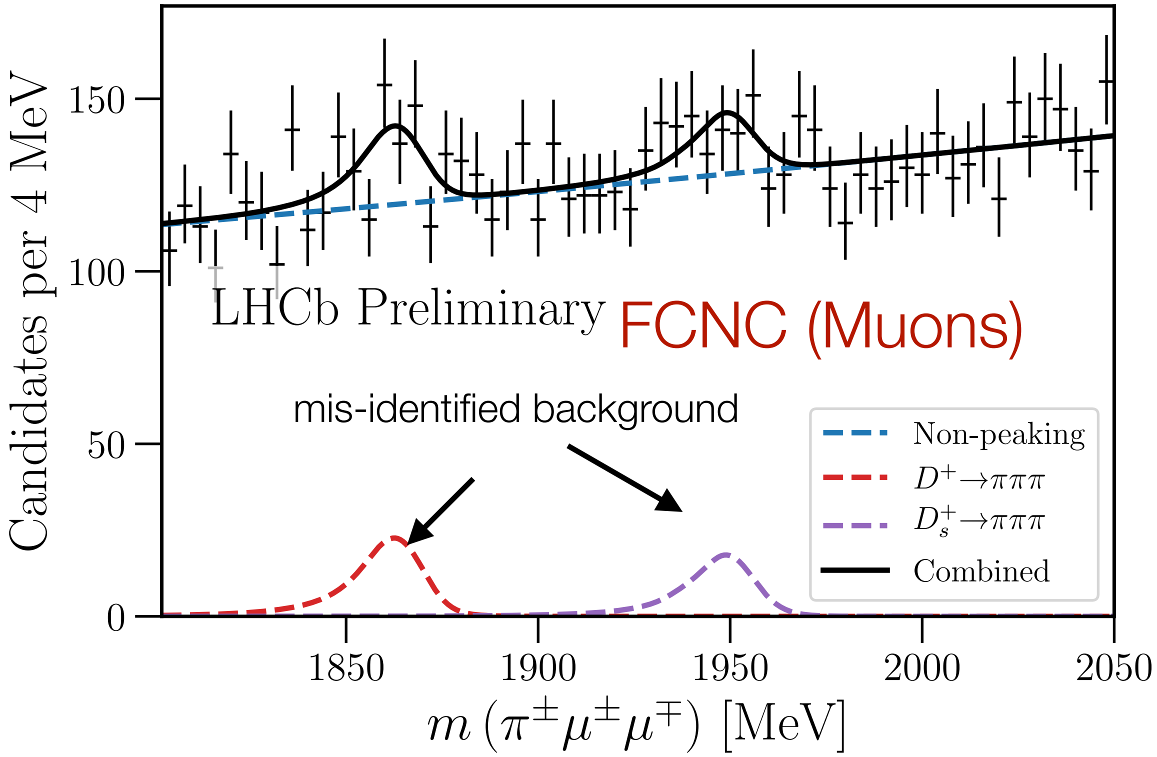
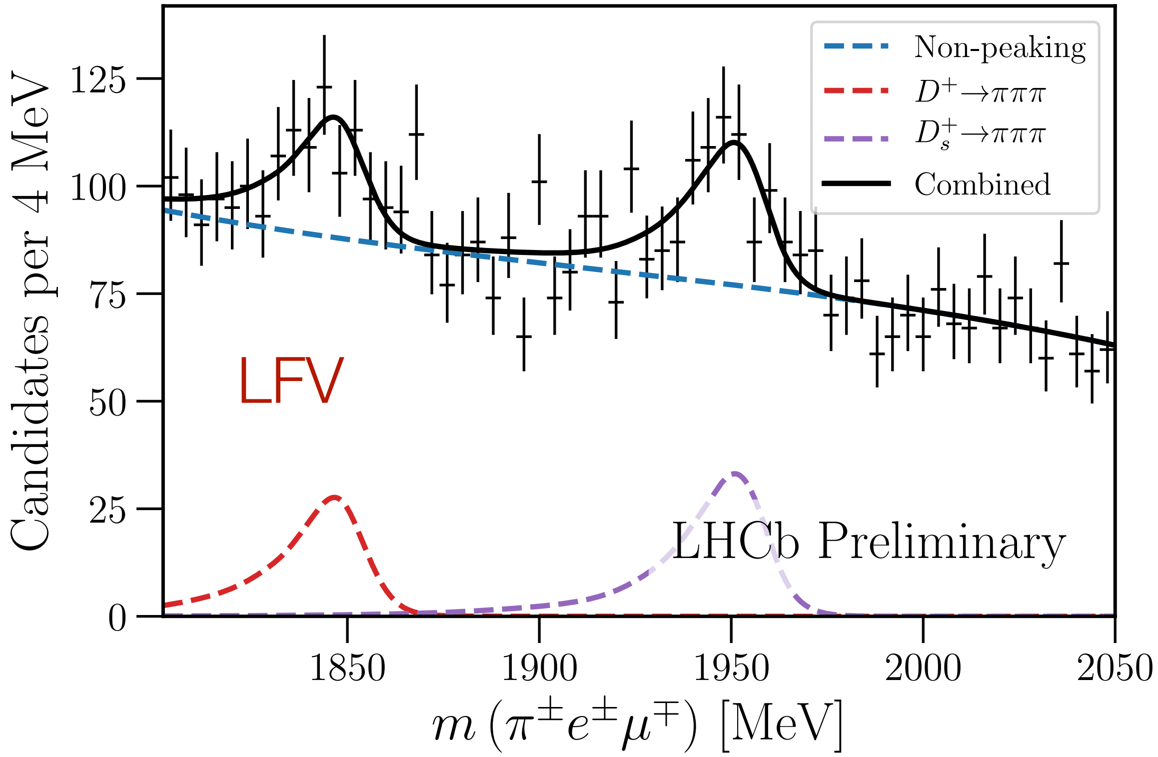
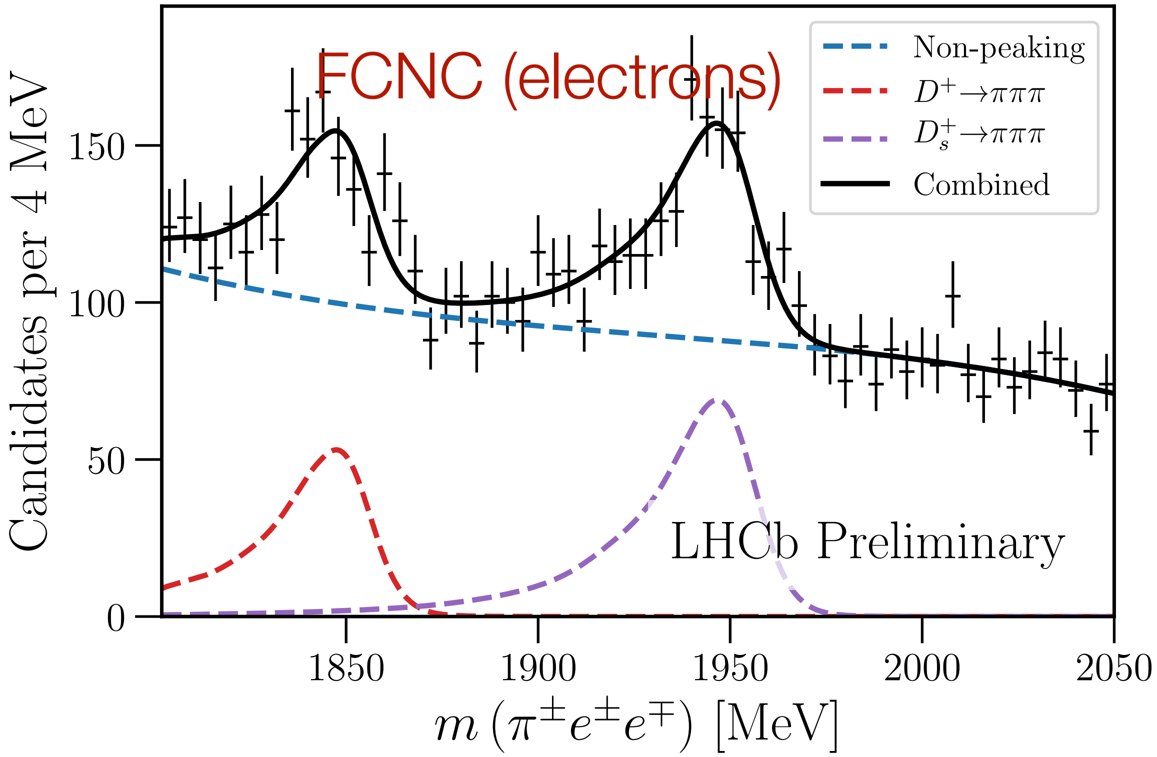
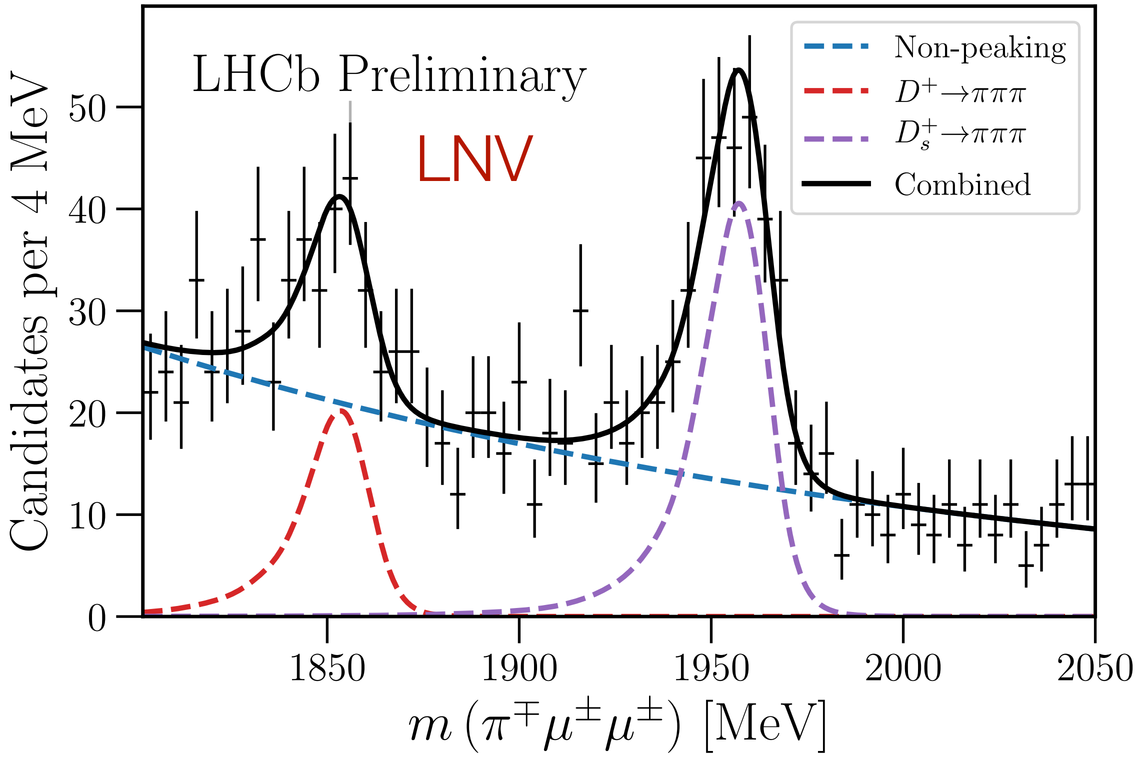








- All mass spectra well described by background only hypothesis

Search for the rare decays $D^0 \rightarrow hl^{\pm}l^{(\prime)\mp}$

LHCB-PAPER-2020-007-001

- No significant signal found, upper limits on the BFs $\mathcal{O}(10^{-8} - 10^{-7})$
- Improved limits by several orders of magnitude

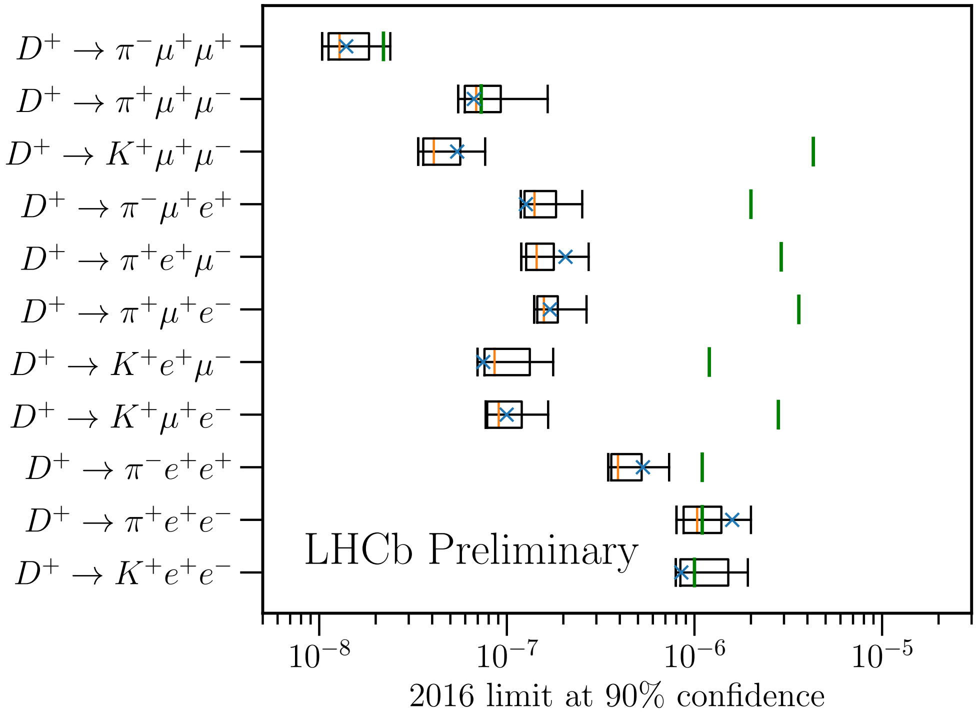
*tabulated version in backup

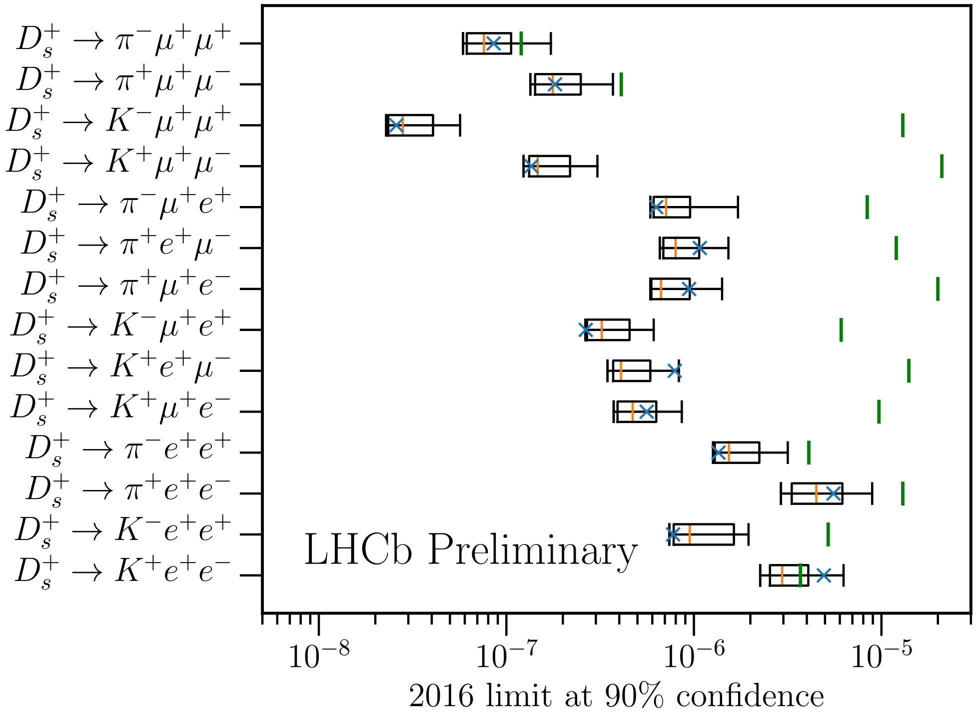
previous best limit

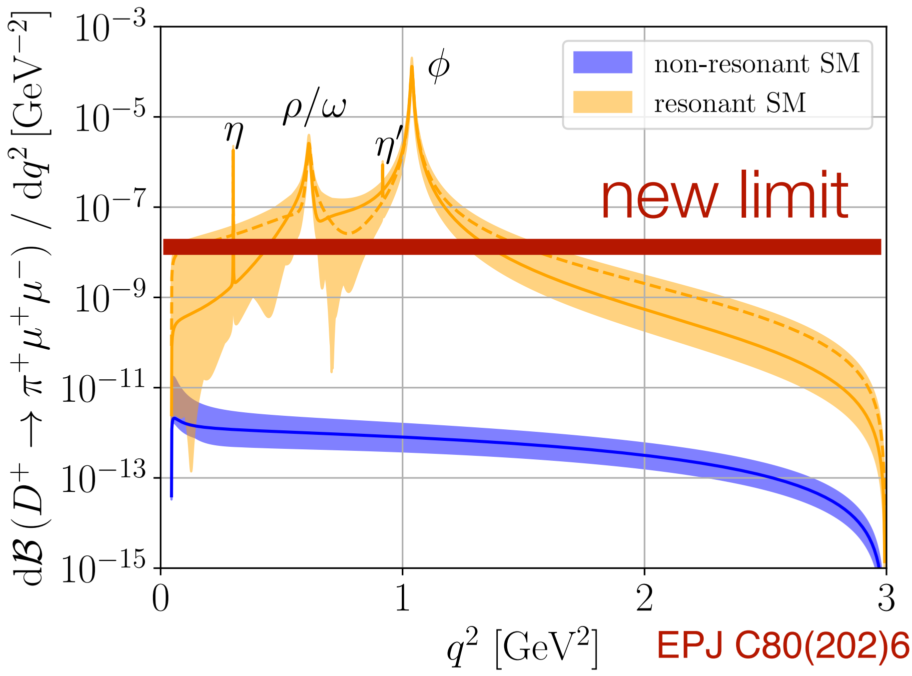
observed limit

expected limit

with 1σ and 2σ intervals







EPJ C80(202)65

We come close to SM expectation of resonant contributions for some modes

Analysis of full Run2 data still to come

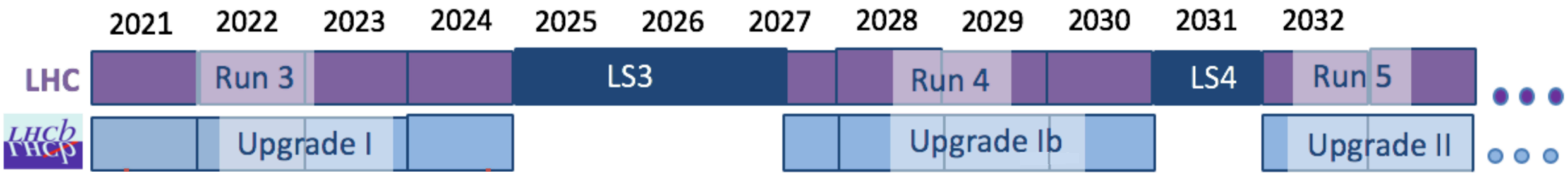
Future prospects

Short term future:

- We are working on fully exploiting the total Run2 data set (9/fb)
  - Many of the measurements shown today are expected to be updated soon (A_Γ, $D^0 \to K_S\pi^+\pi^-$, $D^0 \to h\ell^+\ell^-$, ...)
  - Plus many updates of analyses not shown today, such as $A_{CP}(K^+K^-)$, $D^0 \to \mu^+\mu^-$, further searches for Ξ_{cc}^+ and Ω_{cc}^+ , ...

Long(er) term future:

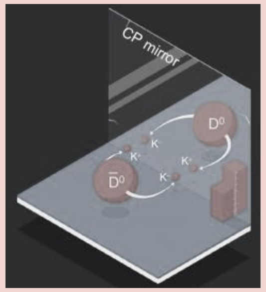
- Upgrade I is ongoing, plan to collect up to 50fb^{-1} by ~2030
  - The vast majority of our measurements are limited by the statistical precision



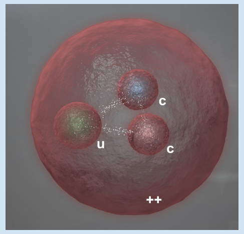
- Upgrade II is in preparation, eventually plan to collect up to 300fb^{-1} by ~2038
- Projections for specific modes can be found in CERN-PUB-LHCC-2018-027

Summary

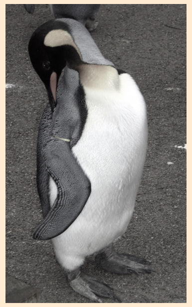
- First observation of CPV, fruitful discussions about its interpretation
- First evidence of non-zero mass difference of neutral D meson eigenstates
- Upper limits on indirect CPV are shrinking towards SM prediction, still one order of magnitude room for NP



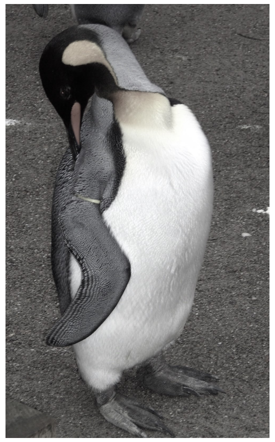
- Doubly Charmed baryon saga puzzling, still no hints for Ξ_{cc}^{+} at LHC, precision measurements of Ξ_{cc}^{++} have started
- Important results on spectroscopy and production from LHCb, CMS, ALICE not shown today [Roberta's and Yanxi's talks tomorrow]

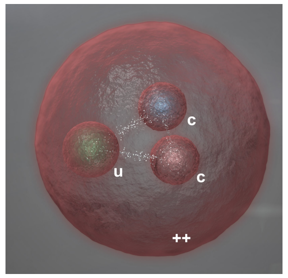


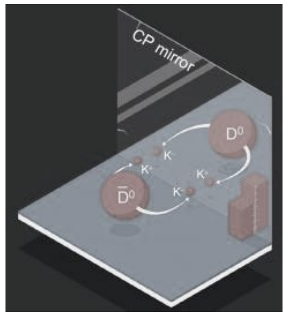
- Limits on rare and forbidden decays pushed down by orders of magnitudes
- Many more results are soon to come with full Run2 data set, including CPV in rare/radiative decays and angular distributions



Supplemental







Prospects selected measurements (I)

CERN-PUB-LHCC-2018-027

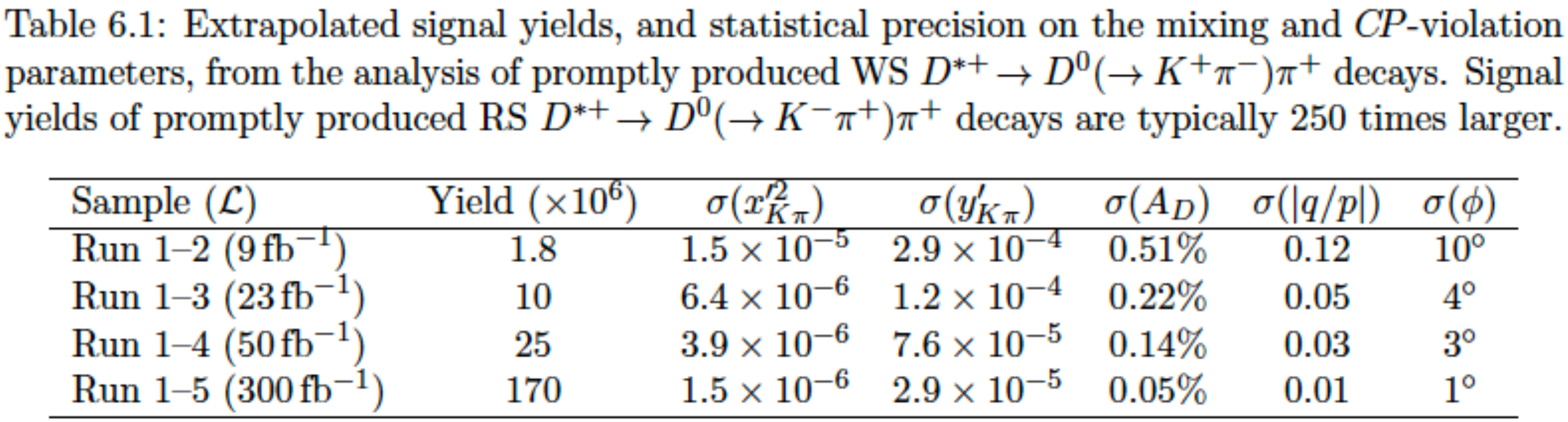


Table 6.1: Extrapolated signal yields, and statistical precision on the mixing and *CP*-violation parameters, from the analysis of promptly produced WS $D^{*+} \rightarrow D^0(\rightarrow K^+\pi^-)\pi^+$ decays. Signal yields of promptly produced RS $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ decays are typically 250 times larger.

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'^2_{K\pi})$	$\sigma(y'_{K\pi})$	$\sigma(A_D)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 ($9\,\text{fb}^{-1}$)	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1–3 ($23\,\text{fb}^{-1}$)	10	6.4×10^{-6}	1.2×10^{-4}	0.22%	0.05	4°
Run 1–4 ($50\,\text{fb}^{-1}$)	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	3°
Run 1–5 ($300\,\text{fb}^{-1}$)	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

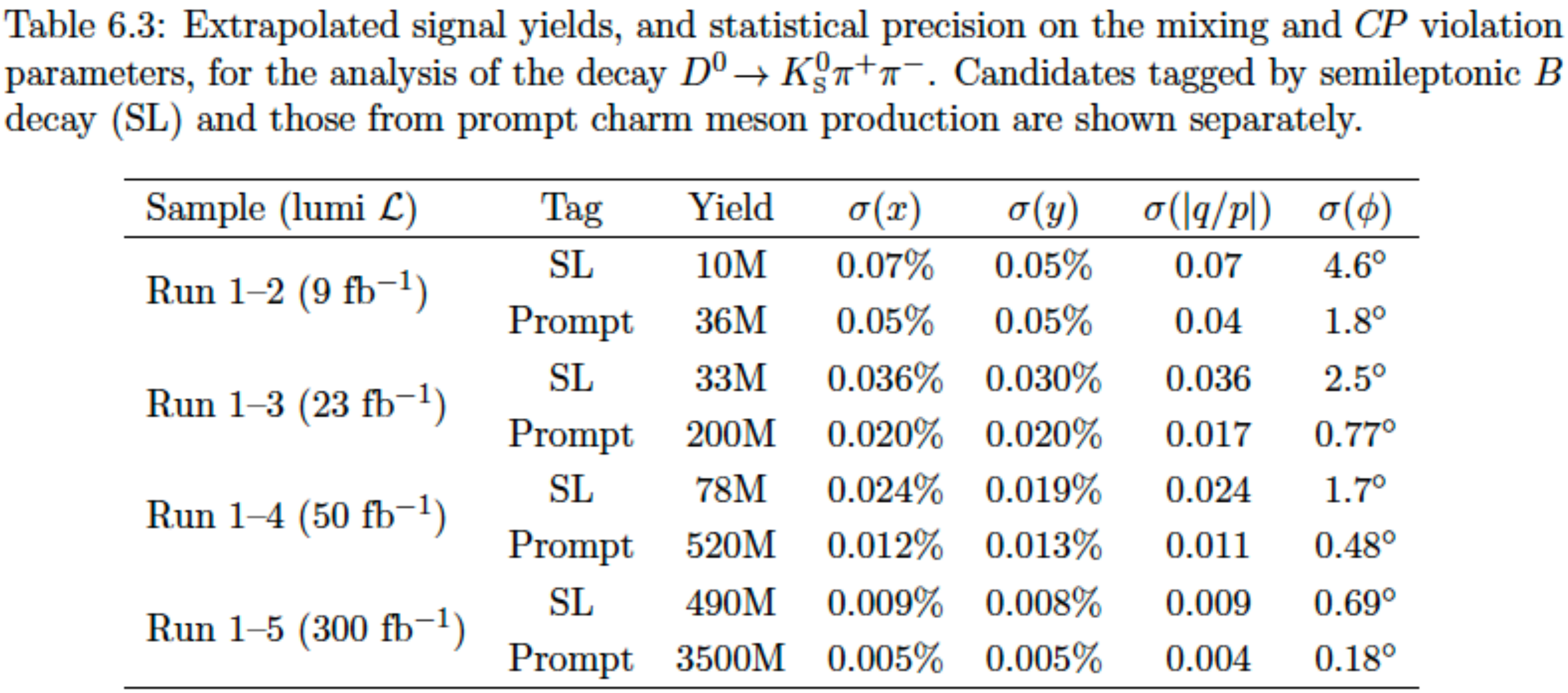


Table 6.3: Extrapolated signal yields, and statistical precision on the mixing and *CP* violation parameters, for the analysis of the decay $D^0 \rightarrow K^0_S\pi^+\pi^-$. Candidates tagged by semileptonic *B* decay (SL) and those from prompt charm meson production are shown separately.

Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

Prospects selected measurements (II)

CERN-PUB-LHCC-2018-027

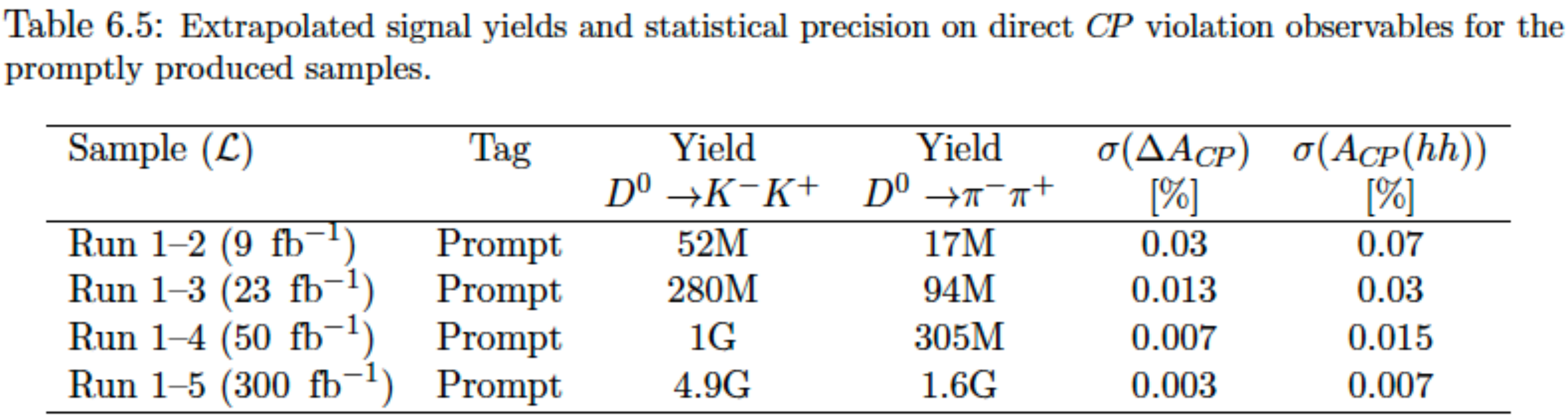


Table 6.5: Extrapolated signal yields and statistical precision on direct *CP* violation observables for the promptly produced samples.

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^-K^+$	Yield $D^0 \to \pi^-\pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

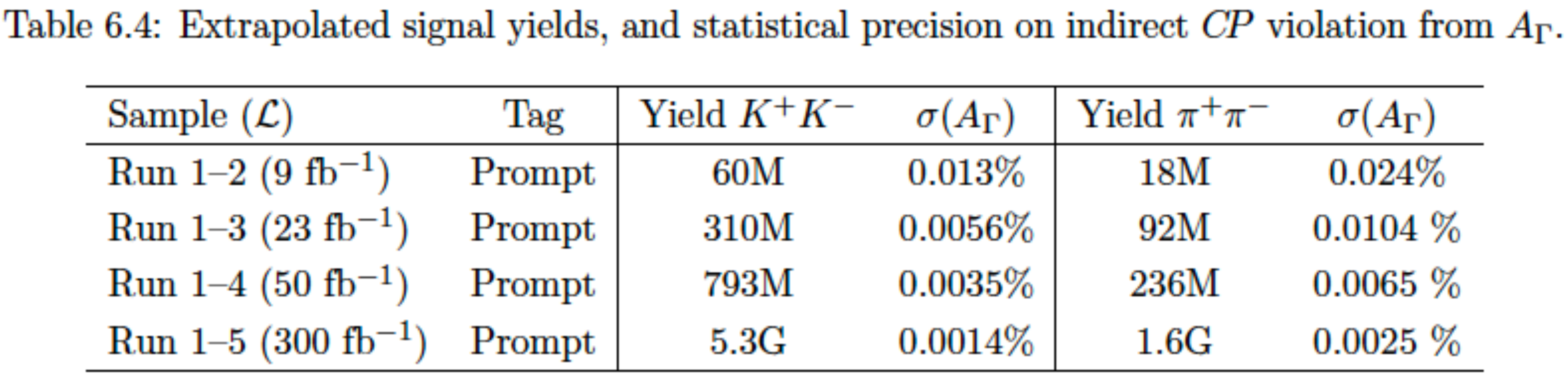


Table 6.4: Extrapolated signal yields, and statistical precision on indirect *CP* violation from A_Γ.

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

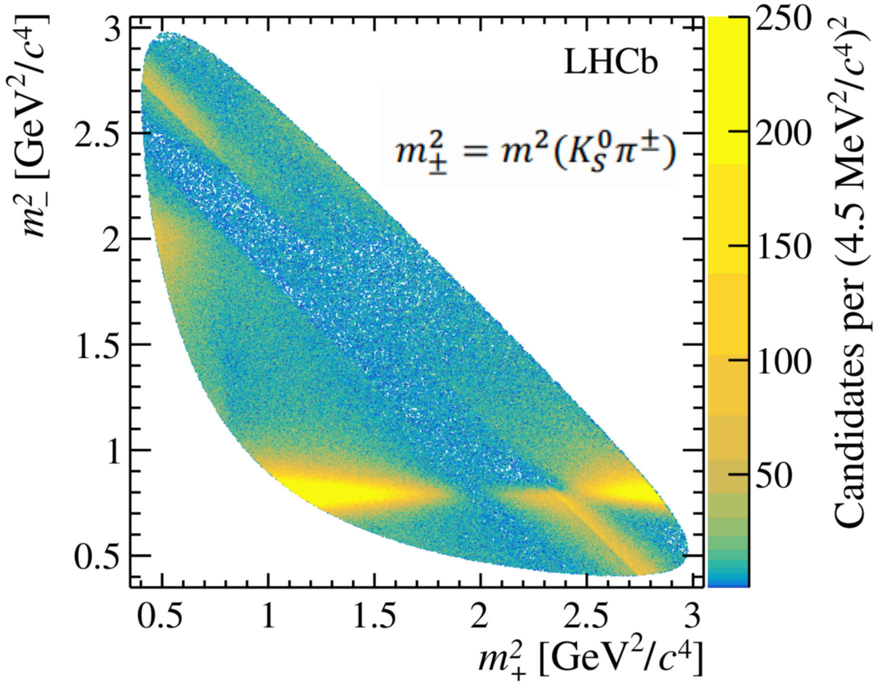
Mixing and CPV with $D^0 \to K_s\pi^+\pi^-$

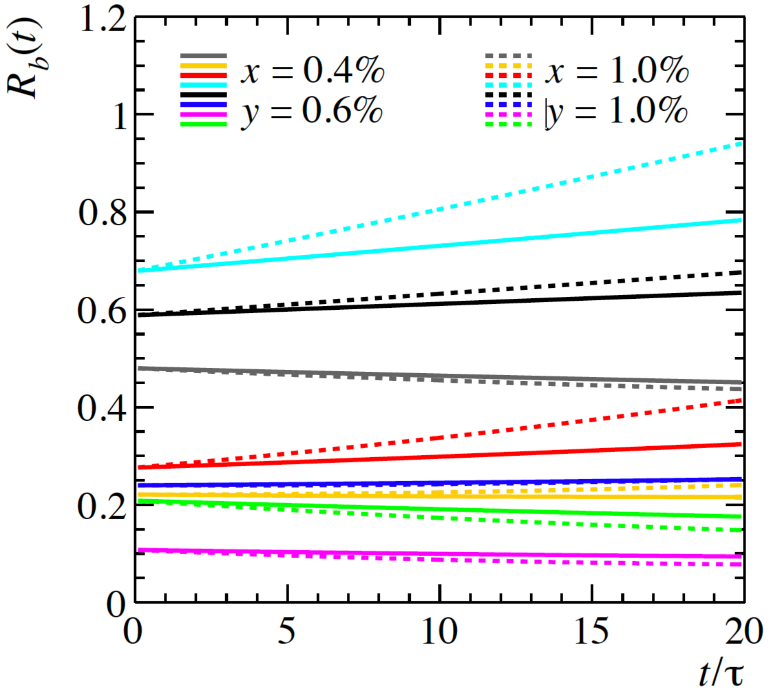
PRD99(2019)012007

- Multiple interfering amplitudes in $D^0 \to K_s\pi^+\pi^-$ decays enhance sensitivity to mixing
  - Bin the Dalitz plot to avoid amplitude analysis in bins with approximately constant strong phase difference (Bin-Flip method)
  - Measure ratio of signal yields in bin -b and +b

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

  - Hadronic parameters constraint using measurements with quantum correlated $D^0\overline{D^0}$ pairs (CLEO, BESIII)
  - Mixing parameters from simultaneous fit to all bins, access to CPV by splitting in D^0 and $\overline{D^0}$





Search for singly charged Ξ_{cc}^{+}

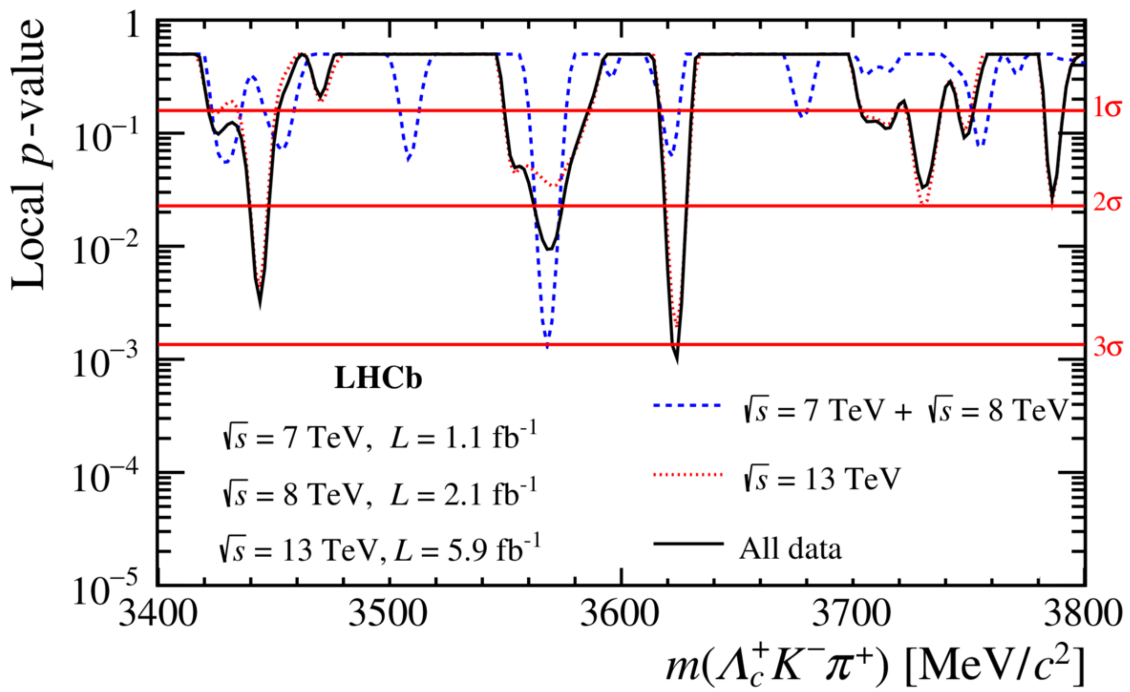
Sci. China Phys. Mech. Astron. 63 (2020) 221062

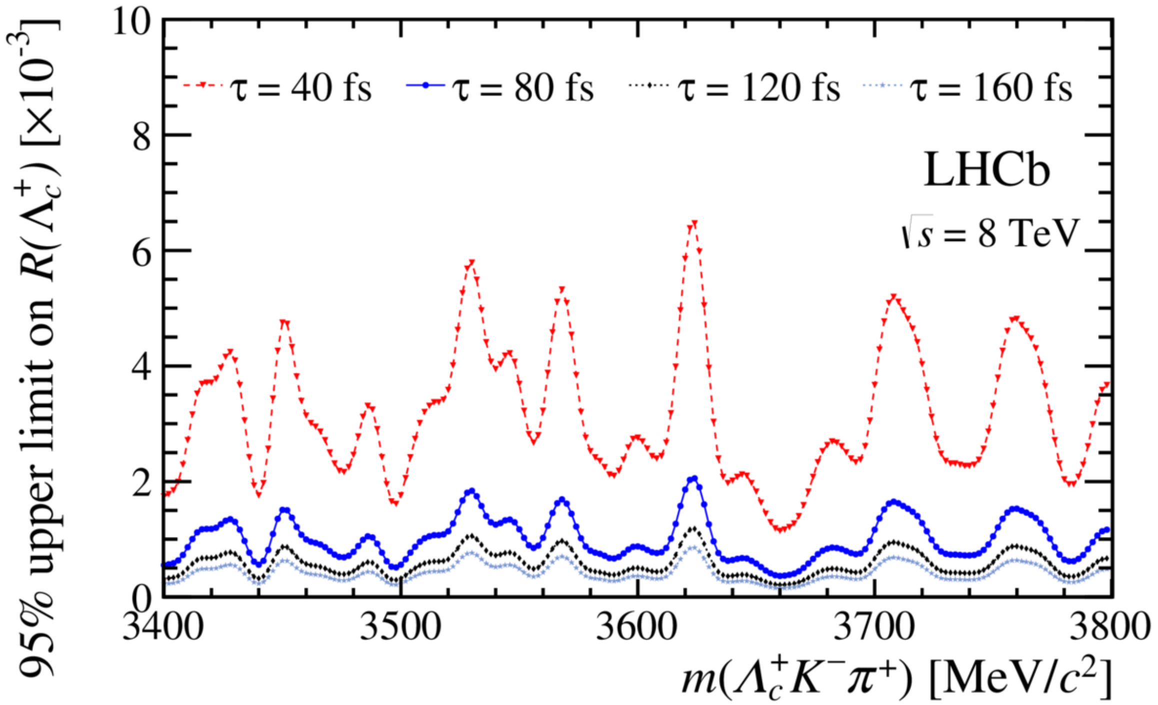
- Analyse full Run1 and Run2 data set (9/fb)
- Search for Ξ_{cc}^{+} decays to final state $\Lambda_c^+ K^- \pi^+$ (SELEX observation channel)
- Mass search window from $[3.4 - 3.8] GeV/c^2$
- No significant signal found
- Set limits $\mathcal{O}(10^{-4} - 10^{-3})$ on the production ratios for different lifetime hypotheses

$$\mathcal{R}(\Lambda_c^+) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$$

$$\mathcal{R}(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$

We will extend our searches to different final states soon!



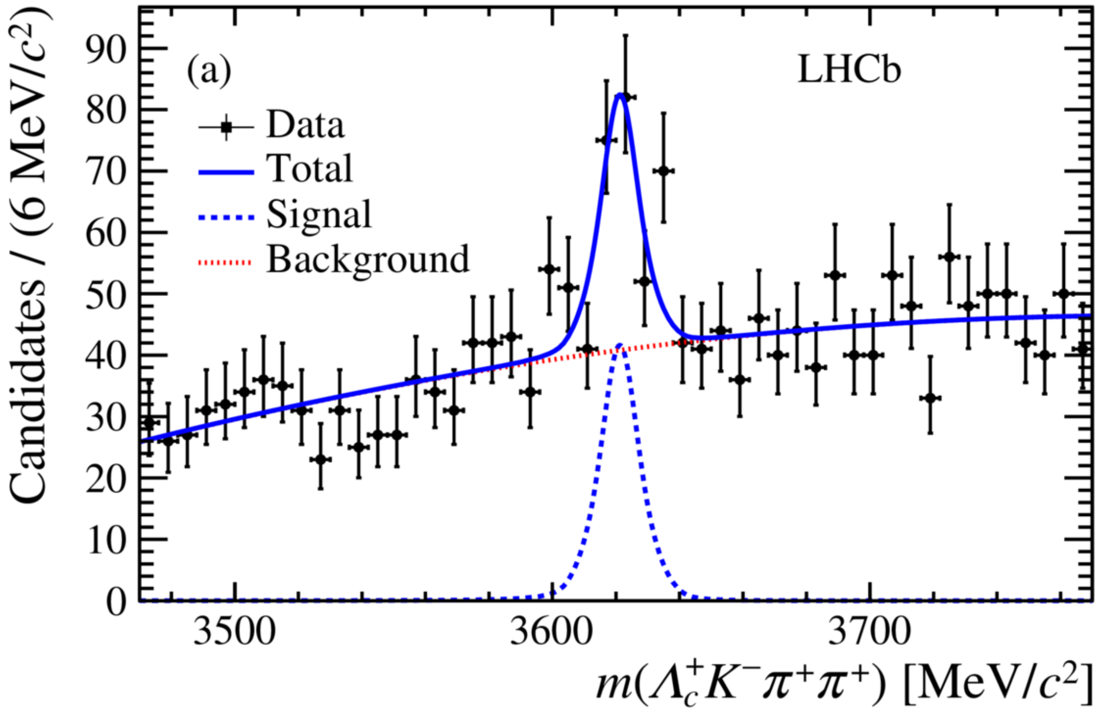


Production measurement of Ξ_{cc}^{++}

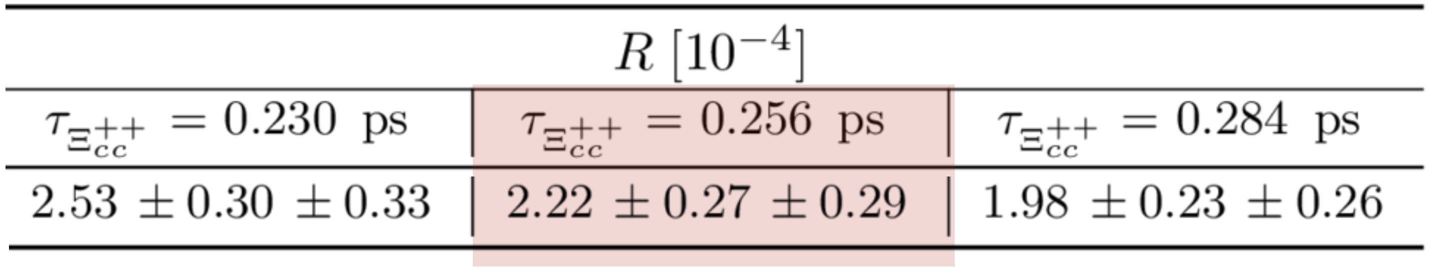
Chin. Phys. C44(2020)022001

- Analyse Run2 pp collision data set (1.7/fb) at $\sqrt{s} = 13$TeV

$$\boxed{R \equiv \frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)}}$$



- Measurement in the range $4 < p_T < 15GeV$ and $2.0 < \eta < 4.5$



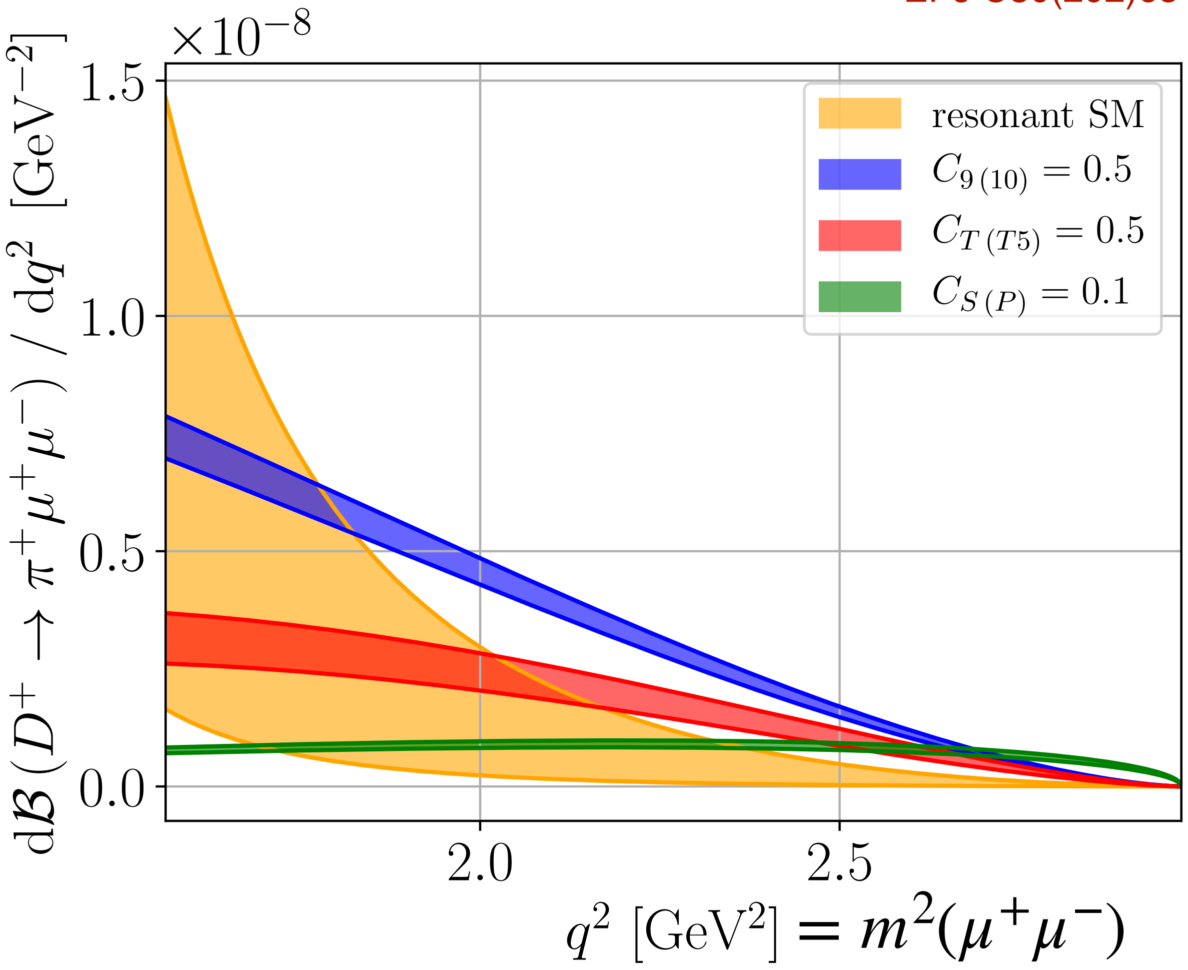
$R\ [10^{-4}]$		
$\tau_{\Xi_{cc}^{++}} = 0.230$ ps	$\tau_{\Xi_{cc}^{++}} = 0.256$ ps	$\tau_{\Xi_{cc}^{++}} = 0.284$ ps
$2.53 \pm 0.30 \pm 0.33$	$2.22 \pm 0.27 \pm 0.29$	$1.98 \pm 0.23 \pm 0.26$

First measurement of the production of doubly charmed baryons in pp collisions

Search for the rare decays $D^0 \rightarrow hl^{\pm}l^{(')\mp}$

- Non-forbidden decay modes are dominated by intermediate resonances
- BSM enhancement in regions away from resonances possible
- Forbidden modes clear null-tests of the SM

EPJ C80(202)65



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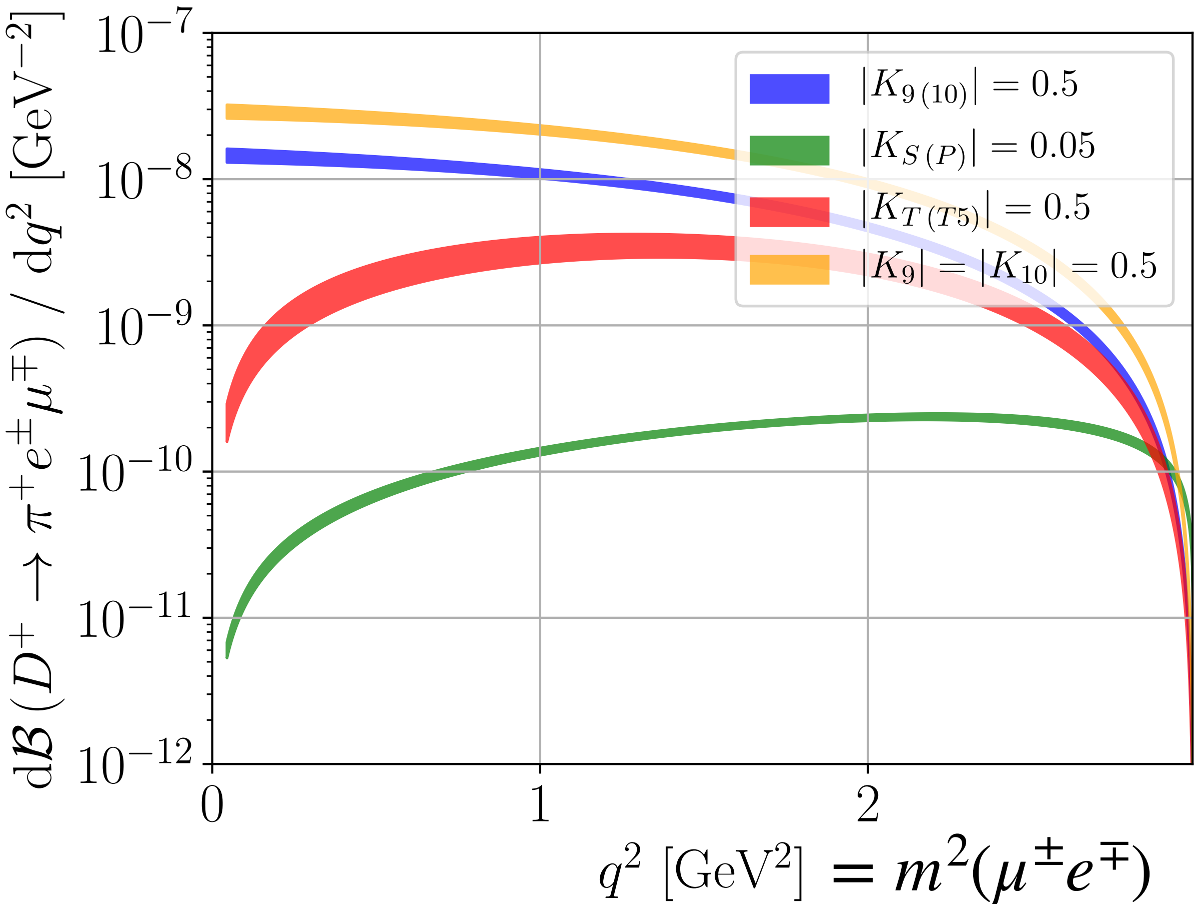
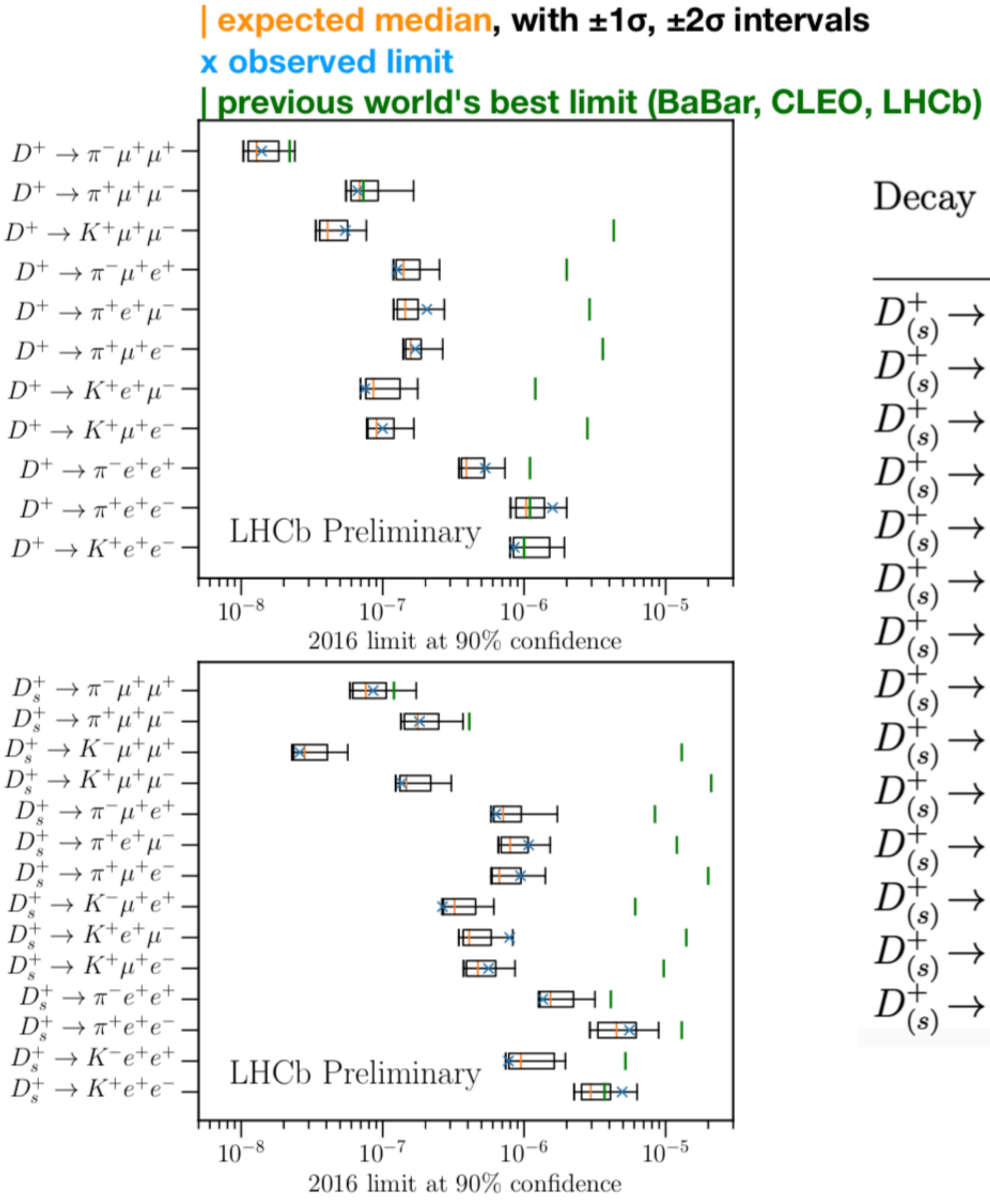


Search for the rare decays $D^0 \to h l^{\pm} l^{(\prime)\mp}$

LHCB-PAPER-2020-007-001

- No significant signal found, upper limits on the BFs $\mathcal{O}(10^{-8} - 10^{-7})$
- Improved limits by several orders of magnitude, we come close to SM expectation of resonant contributions for some modes



Decay	Branching fraction upper limit $[10^{-9}]$				Improvement	
	D^+		D_s^+			
	90 % CL	95 % CL	90 % CL	95 % CL	D^+	D_s^+
$D^+_{(s)} \to \pi^+\mu^+\mu^-$	67	74	180	210	1.1	2.3
$D^+_{(s)} \to \pi^-\mu^+\mu^+$	14	16	86	96	1.6	1.4
$D^+_{(s)} \to K^+\mu^+\mu^-$	54	61	140	160	79.0	150.0
$D^+_{(s)} \to K^-\mu^+\mu^+$	-	-	26	30	-	500.0
$D^+_{(s)} \to \pi^+e^+\mu^-$	210	230	1100	1200	14.0	11.0
$D^+_{(s)} \to \pi^+\mu^+e^-$	220	220	940	1100	16.0	21.0
$D^+_{(s)} \to \pi^-\mu^+e^+$	130	150	630	710	16.0	13.0
$D^+_{(s)} \to K^+e^+\mu^-$	75	83	790	880	16.0	18.0
$D^+_{(s)} \to K^+\mu^+e^-$	100	110	560	640	28.0	17.0
$D^+_{(s)} \to K^-\mu^+e^+$	-	-	260	320	-	23.0
$D^+_{(s)} \to \pi^+e^+e^-$	1600	1800	5500	6400	0.7	2.3
$D^+_{(s)} \to \pi^-e^+e^+$	530	600	1400	1600	2.1	3.0
$D^+_{(s)} \to K^+e^+e^-$	850	1000	4900	5500	1.2	0.8
$D^+_{(s)} \to K^-e^+e^+$	-	-	770	840	-	6.7

Analysis of full Run2 data still to come