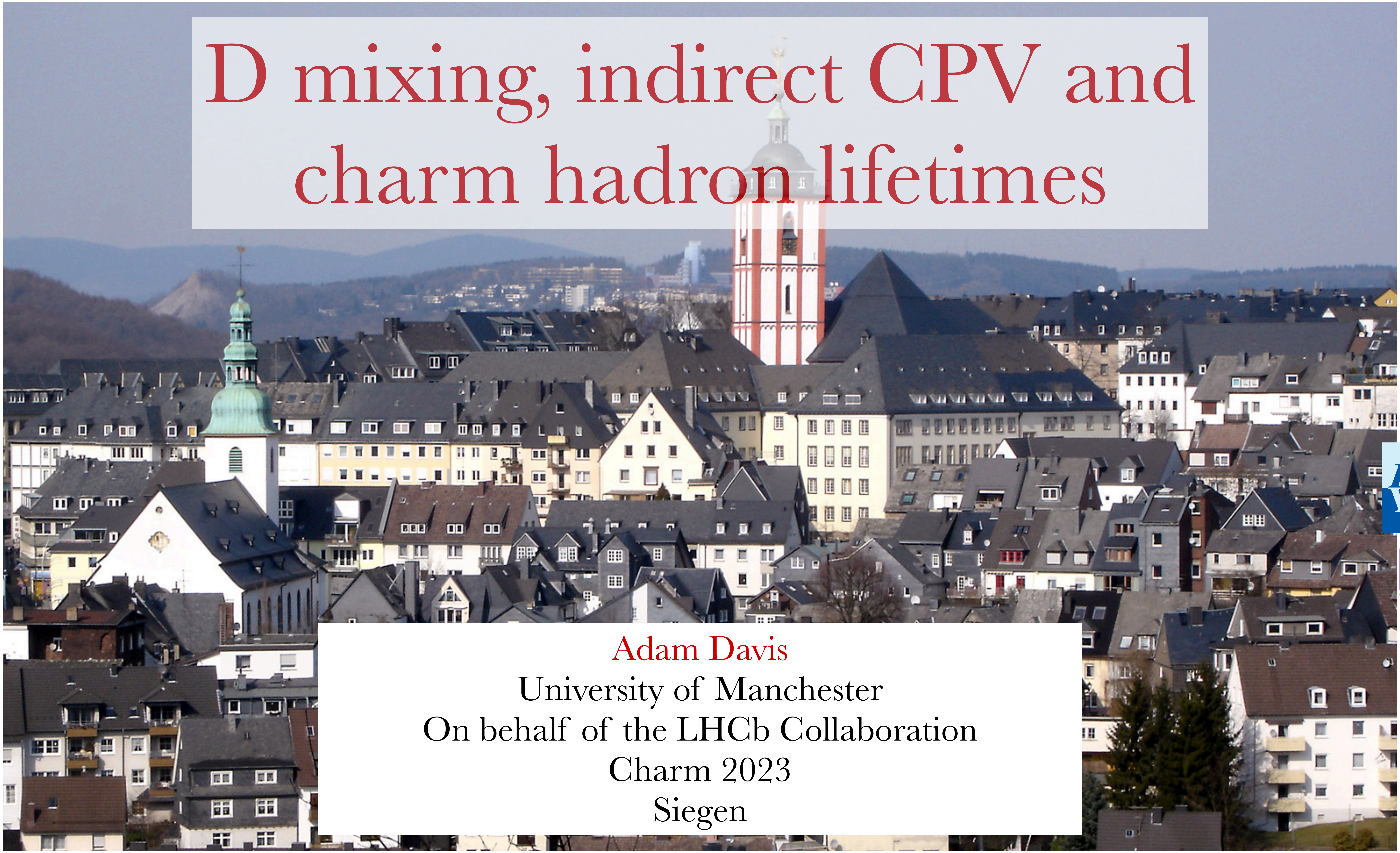


D mixing, indirect CPV and charm hadron lifetimes

Adam Davis
University of Manchester
On behalf of the LHCb Collaboration
Charm 2023
Siegen

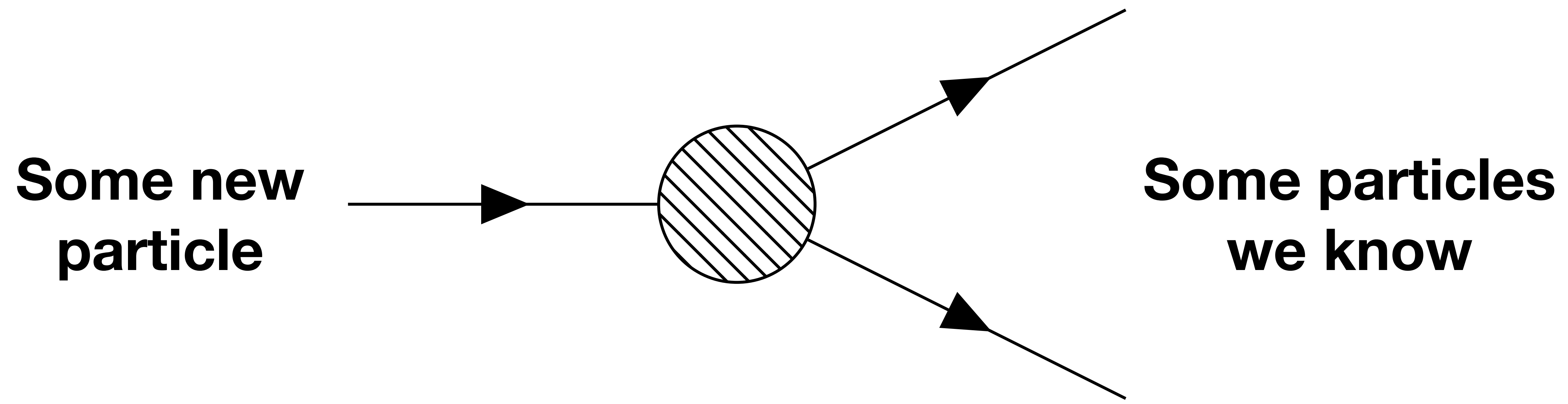
MANCHESTER 1824
The University of Manchester

Image: Bob Ionescu

Why do I care? The quest for new physics

Direct Searches

- Look *directly* for new particles produced



Why do I care? The quest for new physics

Direct Searches

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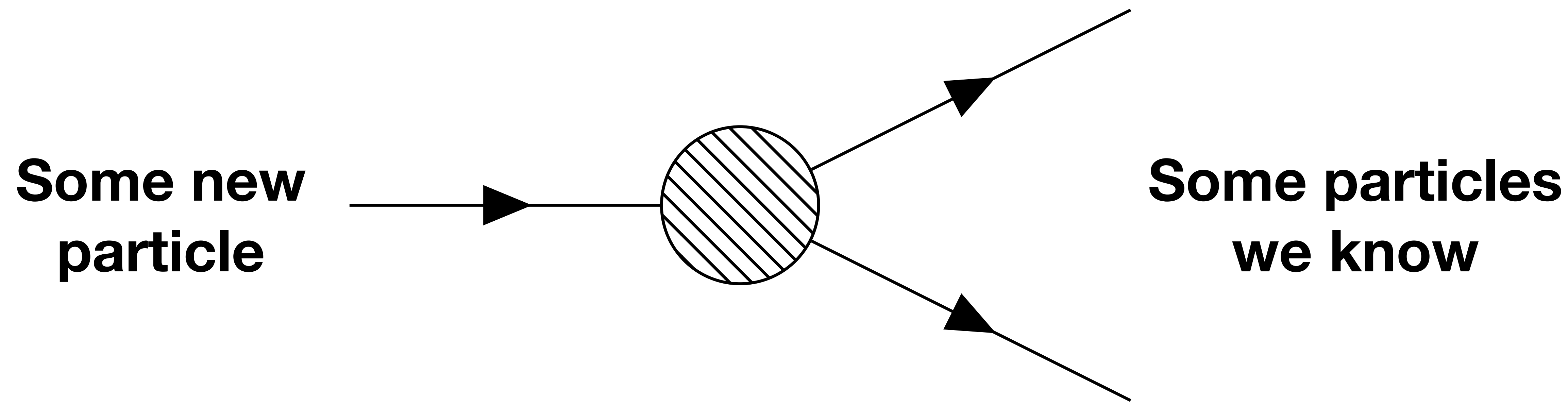
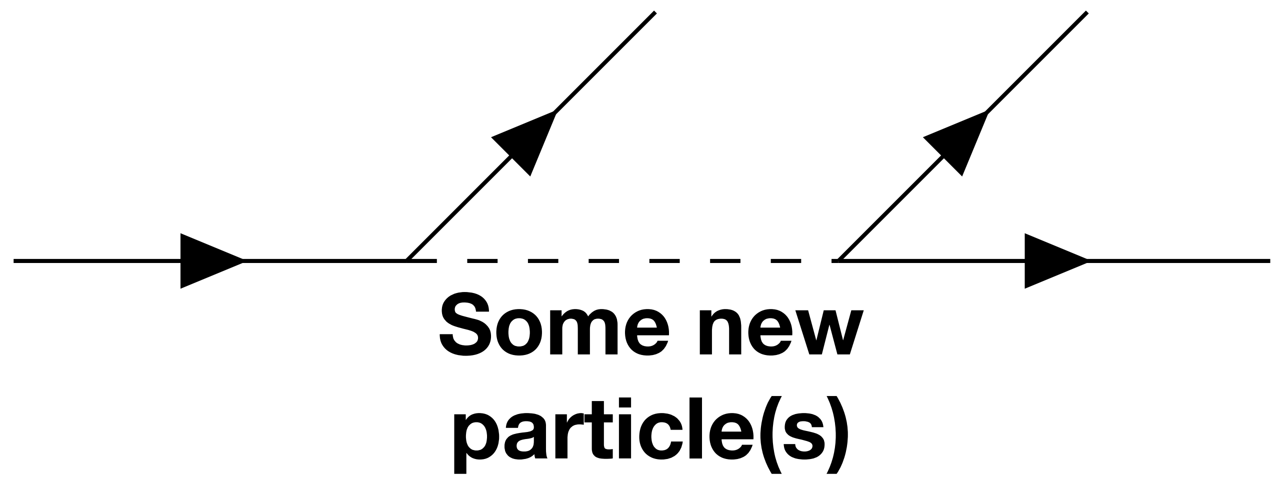


Indirect Searches

- Look for the *indirect* influence of unknown particles on calculable quantities



Each approach is complementary to the other

Why do I care? The quest for new physics

Direct Searches

s

Indirect Searches

- Look f own
  particl

Each approach is complementary to the other

Why do I care? The quest for new physics

Updates on the CKM matrix

testing the new-physics scale

M. Bona *et al.* (UTfit)
JHEP 0803:049,2008
arXiv:0707.0636

RGE

At the high scale
new physics enters according to its specific features

At the low scale
use OPE to write the most general effective Hamiltonian.
the operators have different chiralities than the SM
NP effects are in the Wilson Coefficients C

$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}$$

$$Q_1^{q_i q_j} = \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} ,$$
$$Q_2^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} ,$$
$$Q_3^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} ,$$
$$Q_4^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} ,$$
$$Q_5^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha} .$$

$$C_i(\Lambda) = \frac{F_i L_i}{\Lambda^2}$$

F_i: function of the NP flavour couplings
L_i: loop factor (in NP models with no tree-level FCNC)
Λ: NP scale (typical mass of new particles mediating $\Delta F=2$ processes)

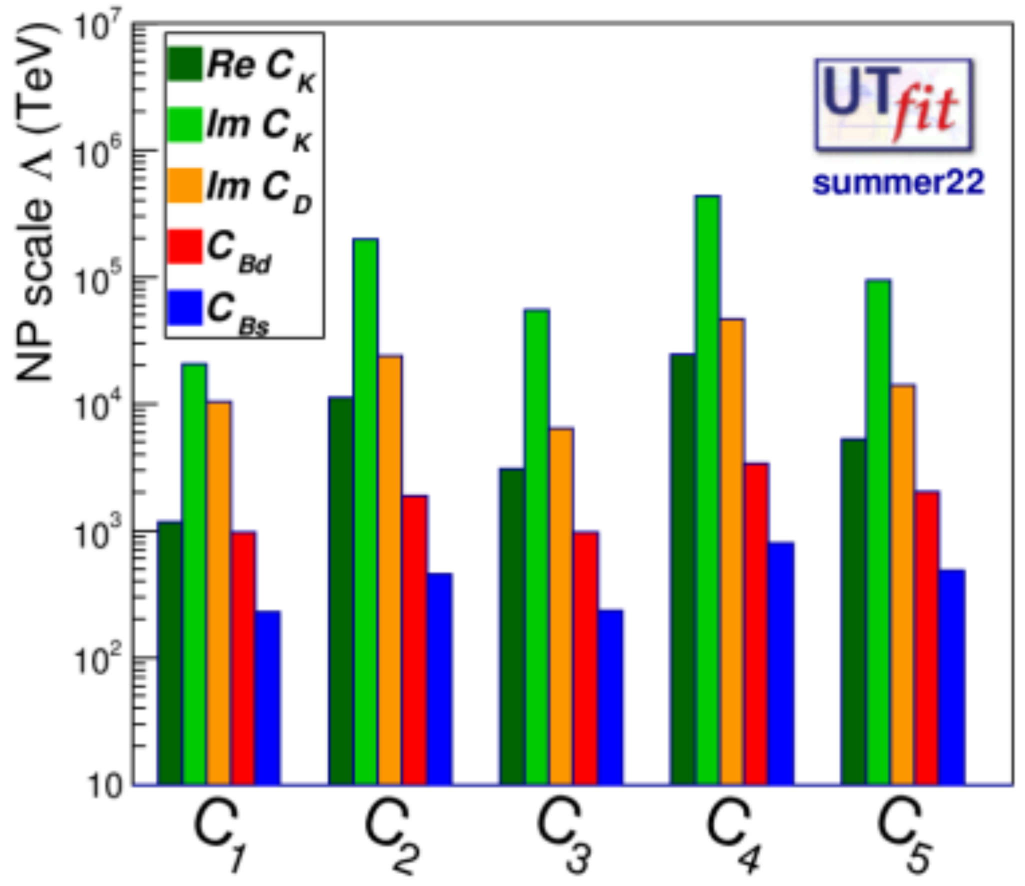
Marcella Bona

M. Bona
IPA 2022

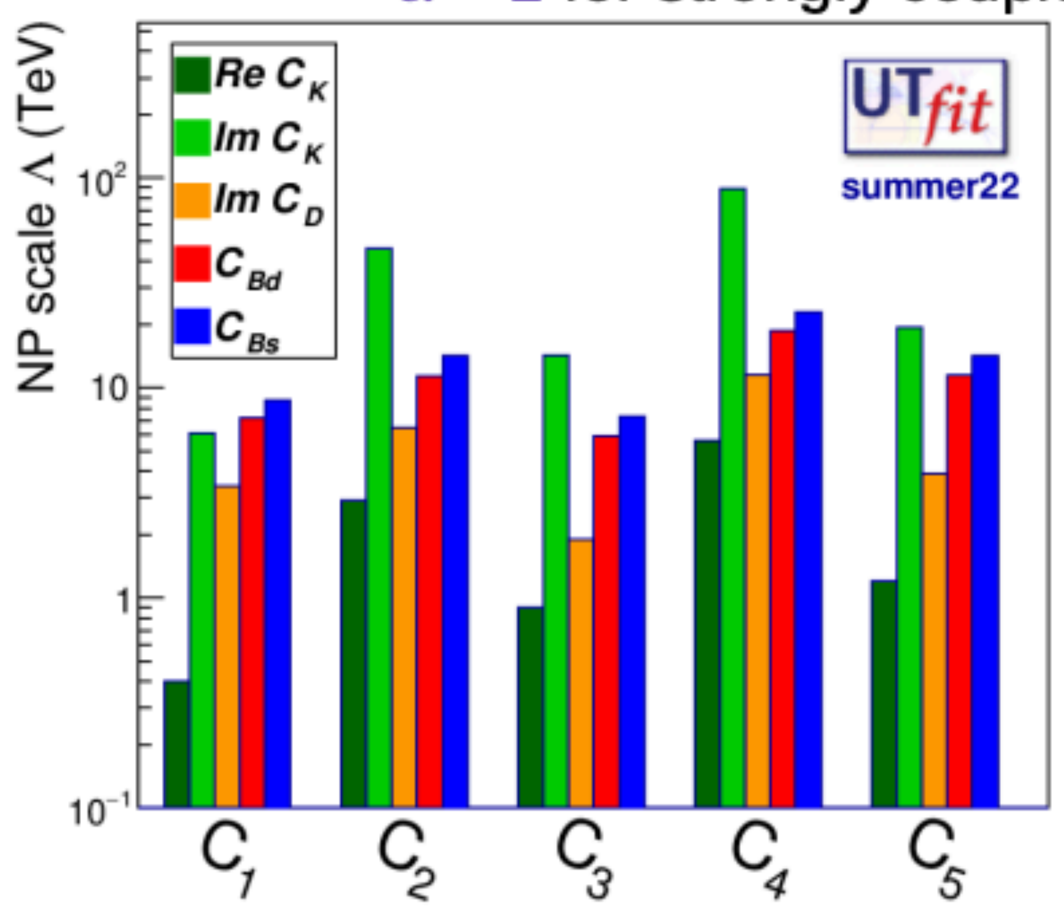
Updates on the CKM matrix

results from the Wilson coefficients

Generic: $C(\Lambda) = \alpha/\Lambda^2$,
$F_i \sim 1$, arbitrary phase
$\alpha \sim 1$ for strongly coupled NP



NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$,
$F_i \sim |F_{SM}|$, arbitrary phase
$\alpha \sim 1$ for strongly coupled NP



$\Lambda > 4.4\ 10^5$ TeV

Lower bounds on NP scale
(at 95% prob.)

$\Lambda > 95$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions
$\Lambda > 1.3\ 10^4$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions
$\Lambda > 2.9$ TeV

for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

Marcella Bona 36

Each approach is complementary to the other

The same slide from the last 2 presentations

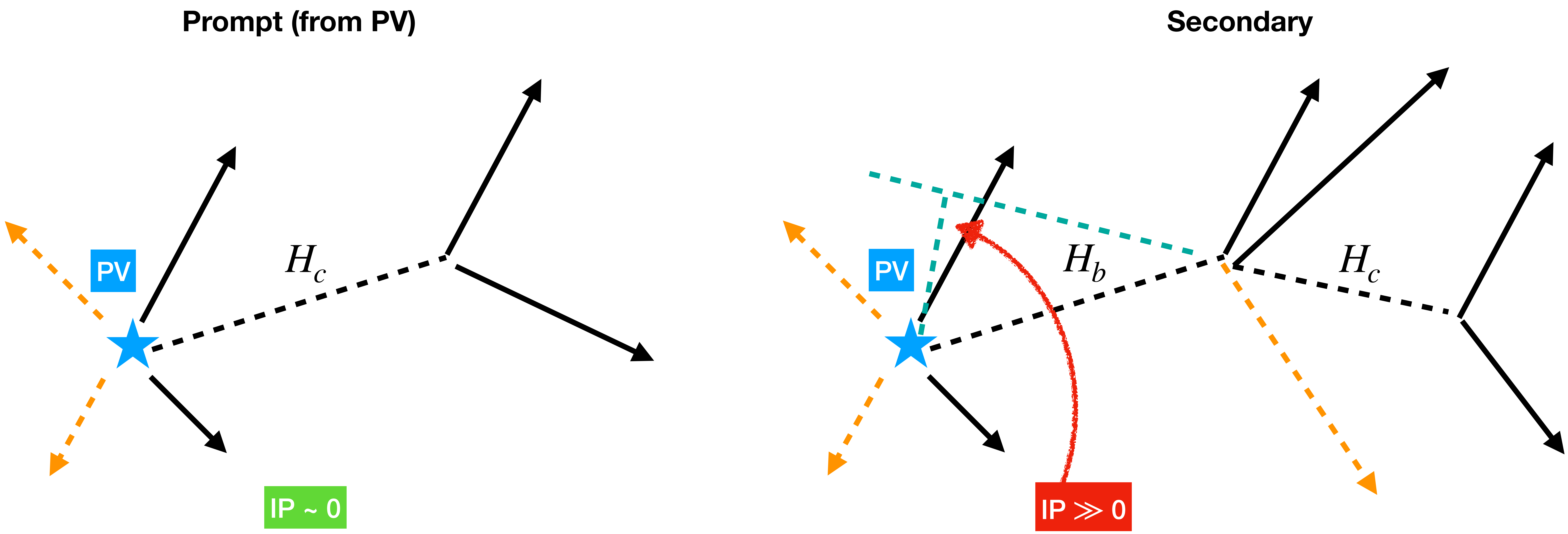
- Traditionally, mixing governed by 2x2 phenomenological Hamiltonian

$$\mathbf{H} = \mathbf{M} - i\mathbf{\Gamma}$$

- Diagonalized by $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, where p, q are complex numbers, $|p|^2 + |q|^2 = 1$
- Mixing defined by dimensionless parameters $x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$
- Indirect CPV encapsulated by $\left|\frac{q}{p}\right| \neq 1$, $\phi = \arg\left(\frac{q}{p}\right) \neq 0$
- Can access dispersive/absorptive parts directly with using $x_{12}, y_{12}, \phi_{12}$ and now ϕ_f^M and ϕ_f^Γ (PRD 103,053008(2021))
- Depending on final state, can define observables which are sensitive to these underlying parameters

Measurement strategies

- At LHCb, reconstruct decays in two specific ways

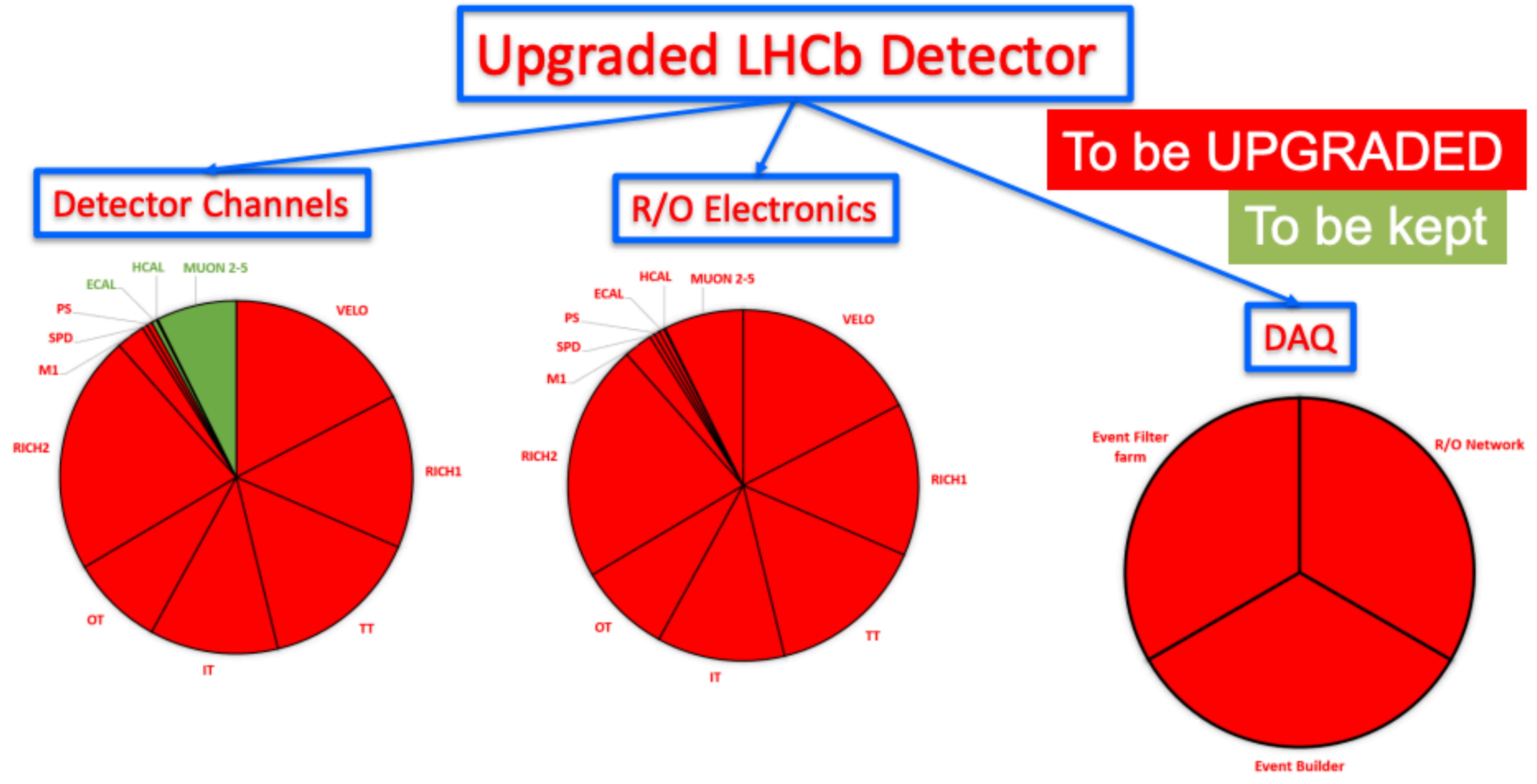


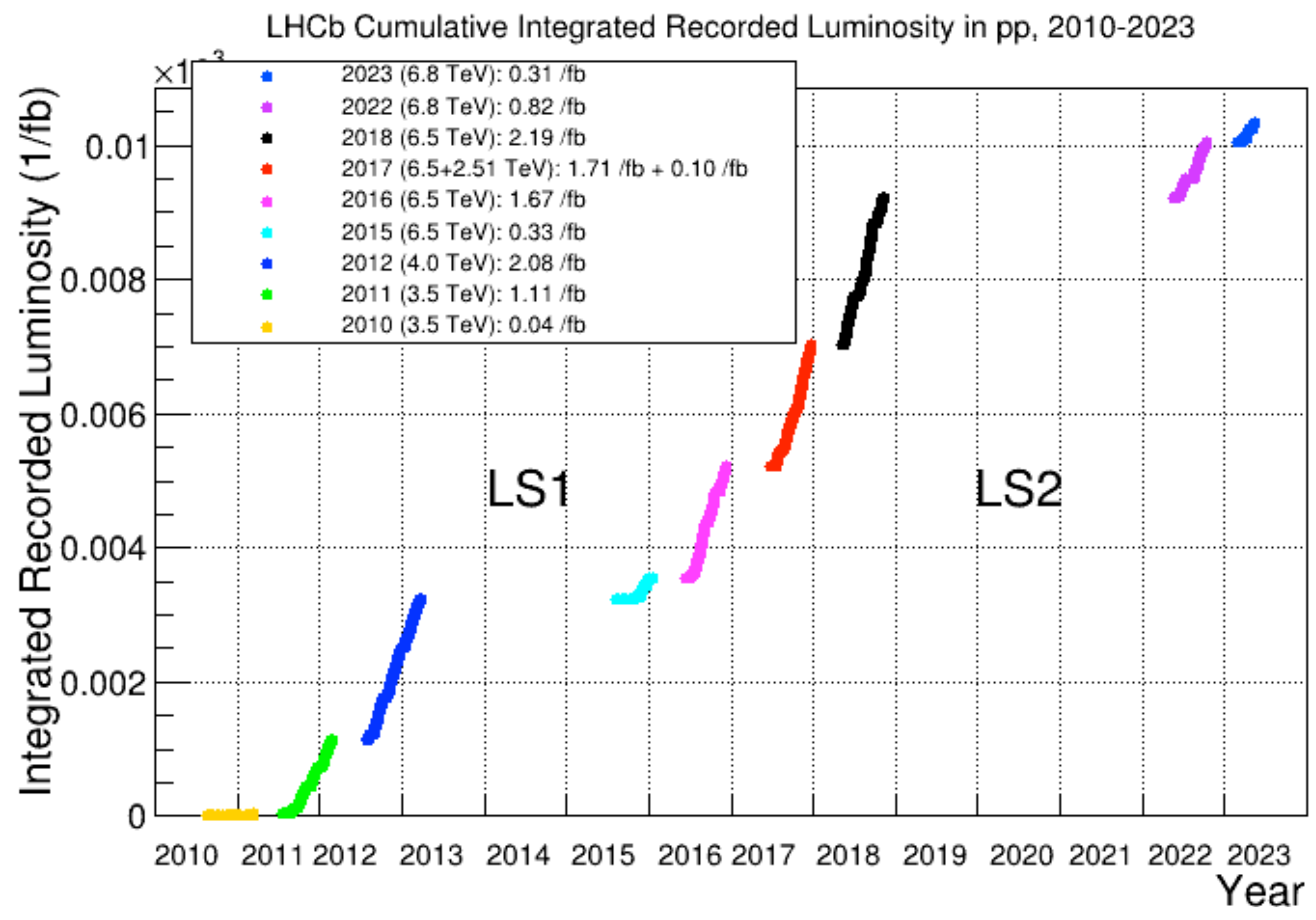
- In stark contrast to e^+e^- colliders

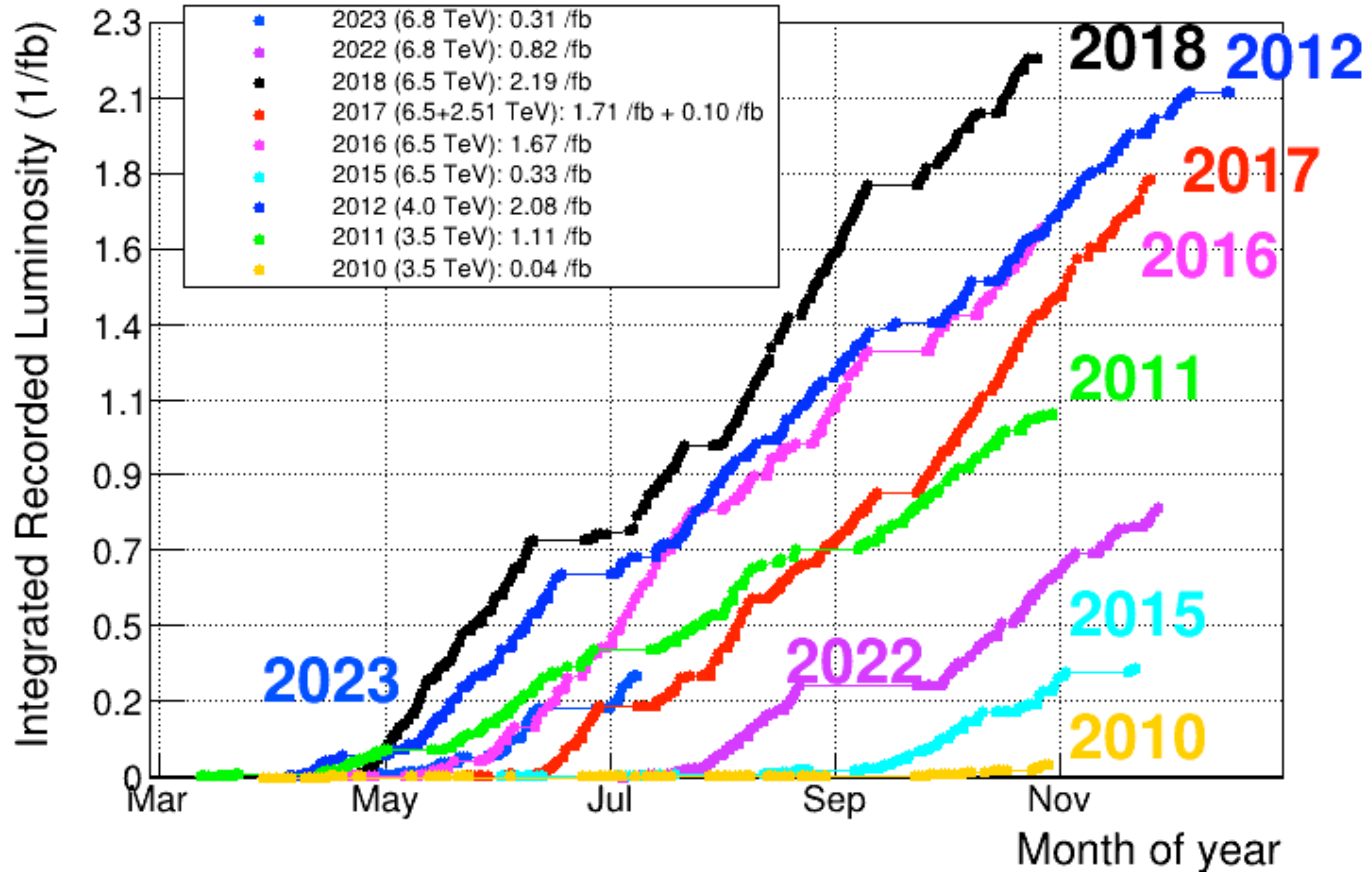
- Must account for cross-contamination between the two → lean on IP and related quantities to separate

The Data Samples

- Three major data-taking periods:
  - Run1 (2011-2012) - $\simeq 3\ \text{fb}^{-1}$
  - Run2 (2015-2018) - $\simeq 6\ \text{fb}^{-1}$
  - Run3 (Happening Now)
- Note, Run3 detector is brand new







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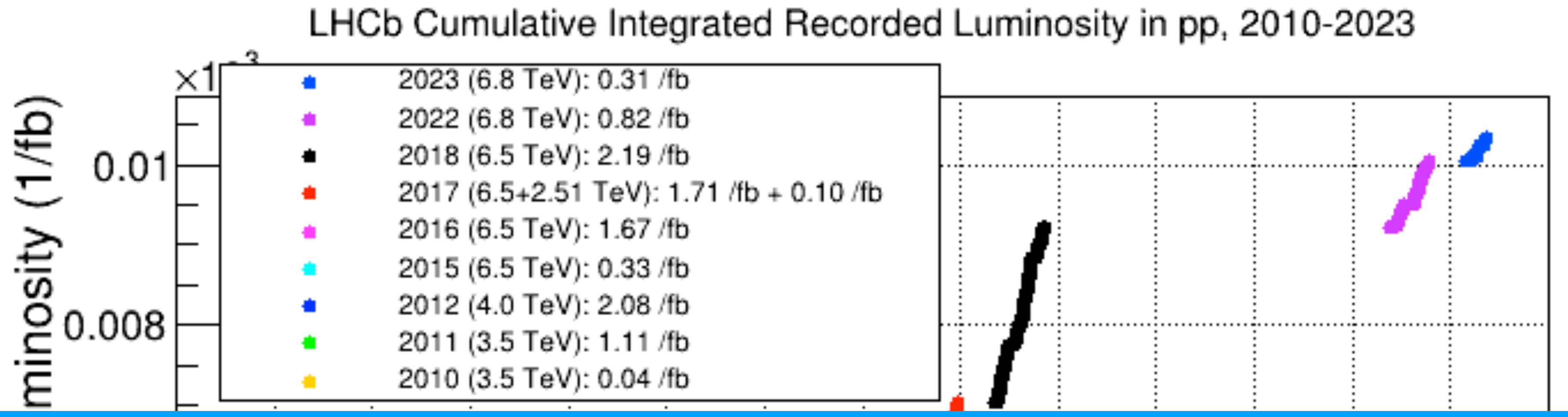
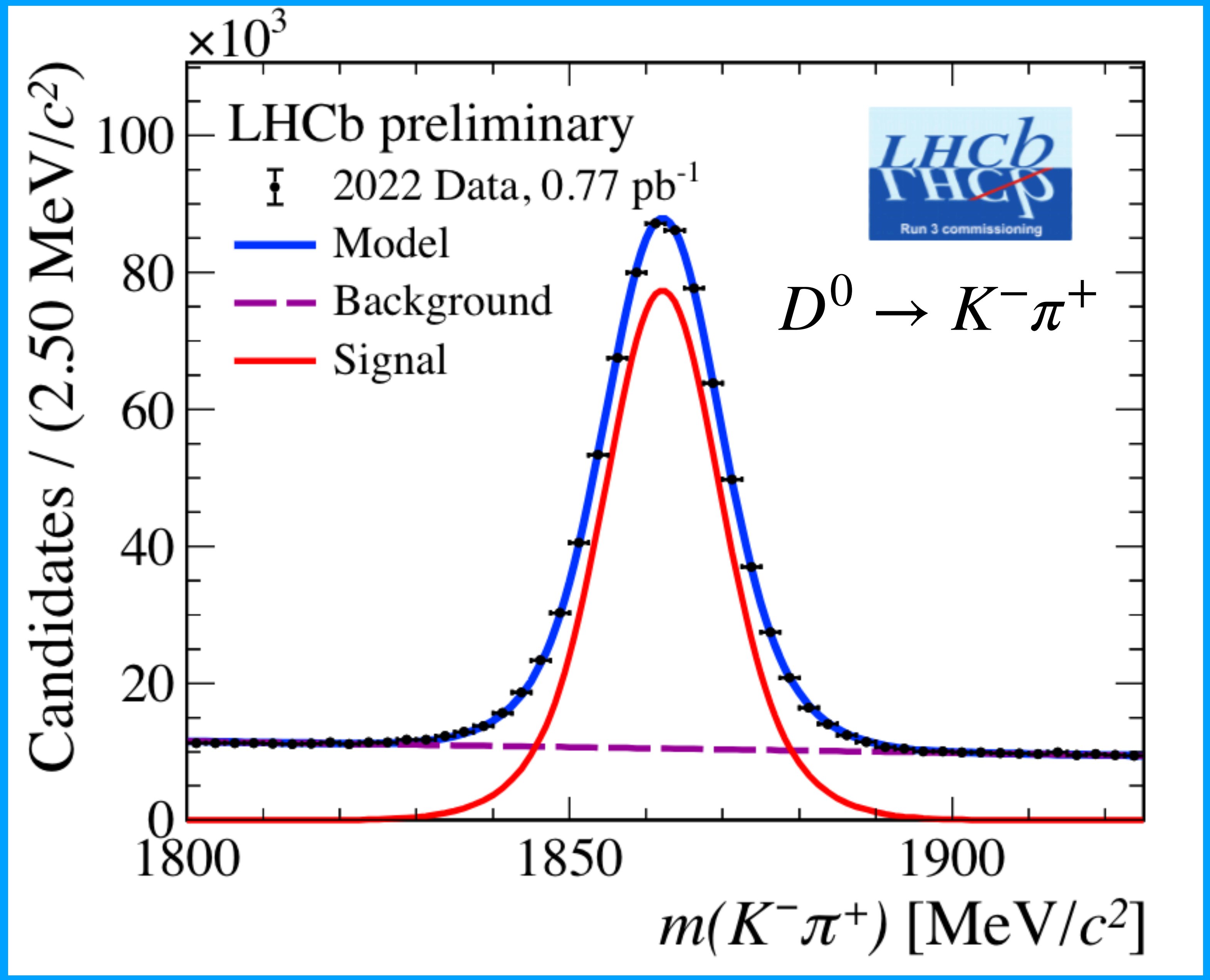
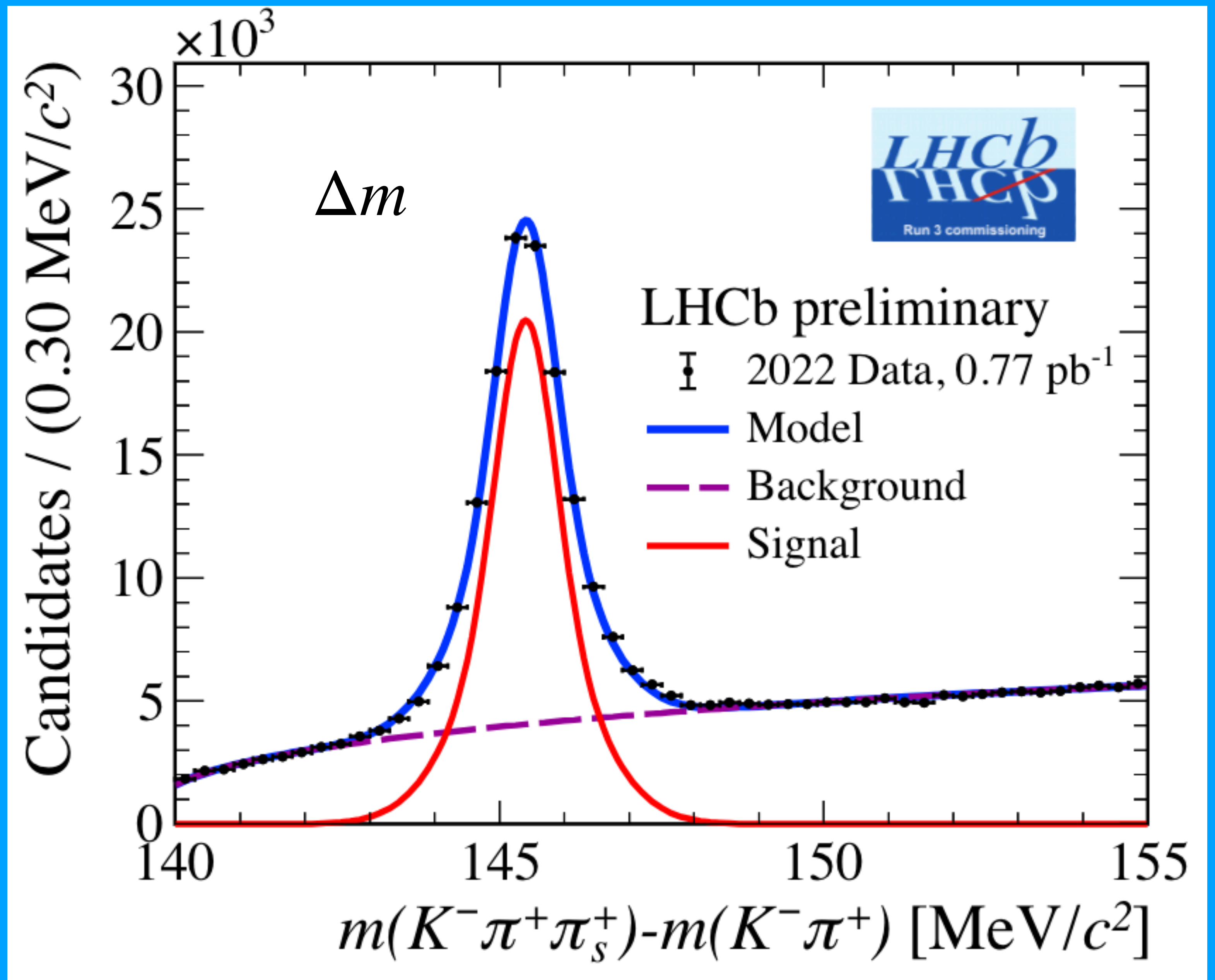
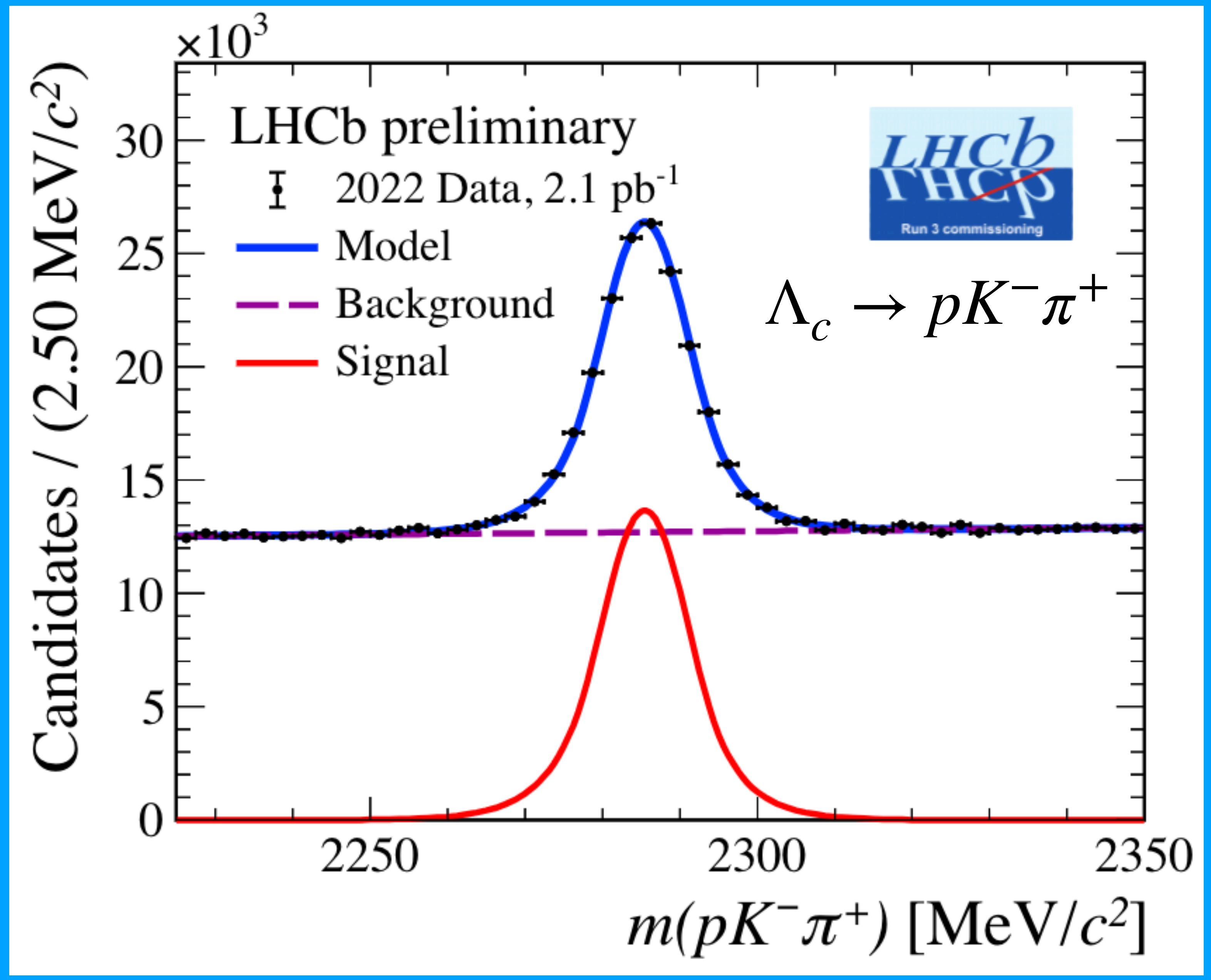


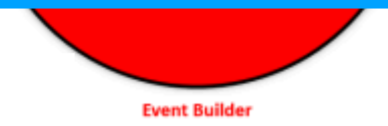
Charm hadrons already visible in Run3 data samples!
Commissioning is ongoing
[LHCb-FIGURE-2023-011]()

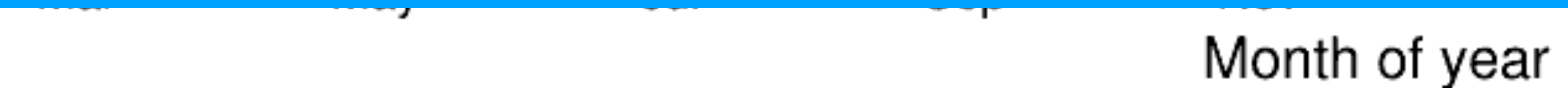






See talk by G. Tuci





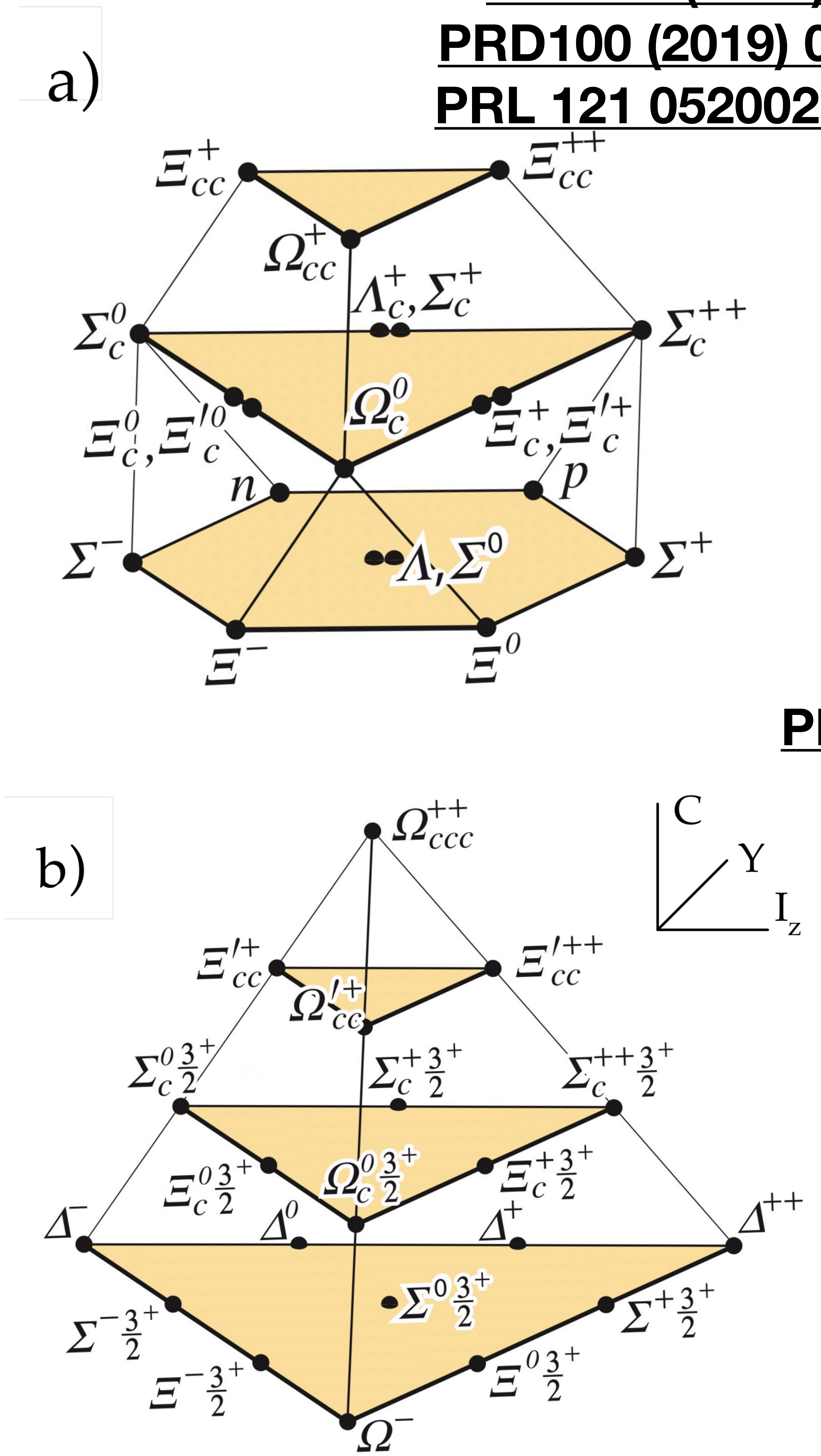
Baryon Lifetime Measurements

SciB 67 (2022) 479
PRD100 (2019) 032001
PRL 121 052002 (2018)

- To date, LHCb has upended conventional knowledge about charmed baryon lifetimes → precision tests of HQET, etc

  - $\tau_{SL}(\Xi_c^+) = 456.8 \pm 3.5 \pm 2.9 \pm 3.1$ fs
  - $\left.\begin{array}{l}\tau_{prompt}(\Omega_c^0) = 276.5 \pm 13.4 \pm 4.4 \pm 0.7 \text{ fs} \\ \tau_{SL}(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2 \text{ fs}\end{array}\right\} \tau(\Omega_c^0) = 274.5 \pm 12.4$ fs
  - $\tau_{prompt}(\Xi_{cc}^{++}) = 256^{+24}_{-22} \pm 14$ fs
  - $\tau_{SL}(\Lambda_c^+) = 203.5 \pm 1.0 \pm 1.3 \pm 1.4$ fs (Noting 2022 BelleII Measurement)
  - $\left.\begin{array}{l}\tau_{prompt}(\Xi_c^0) = 148.0 \pm 2.3 \pm 2.2 \pm 0.2 \text{ fs} \\ \tau_{SL}(\Xi_c^0) = 154.5 \pm 1.7 \pm 1.6 \pm 0.1 \text{ fs}\end{array}\right\} \tau(\Xi_c^0) = 152.0 \pm 2.0$ fs

- Challenged previous measurements, and upended conventional understanding



PDG

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SciB 67 (2022) 479
PRD100 (2019) 032001
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- Challenged previous measurements, and upended conventional understanding

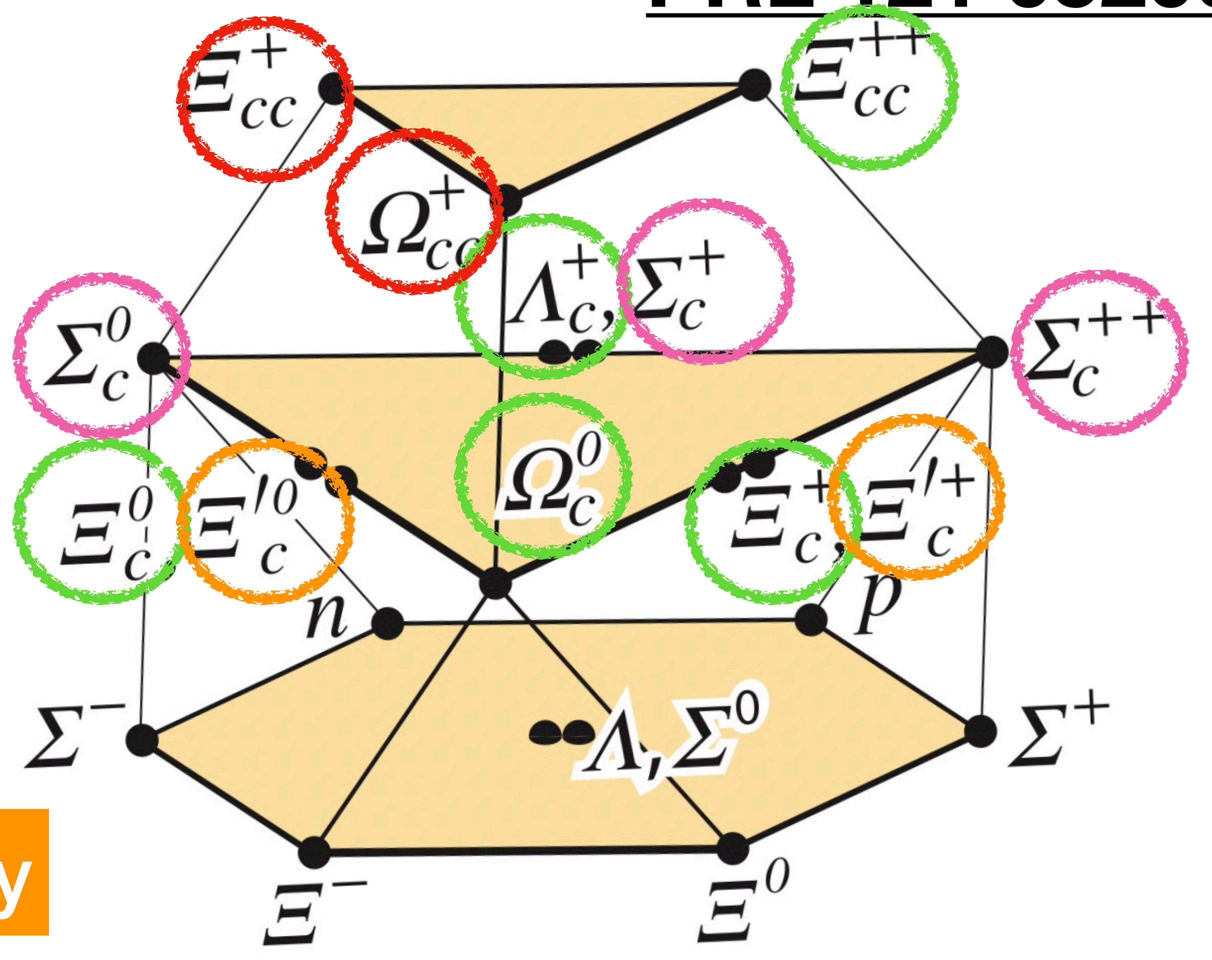
Measured by LHCb

Decay Strongly

Decay Electromagnetically

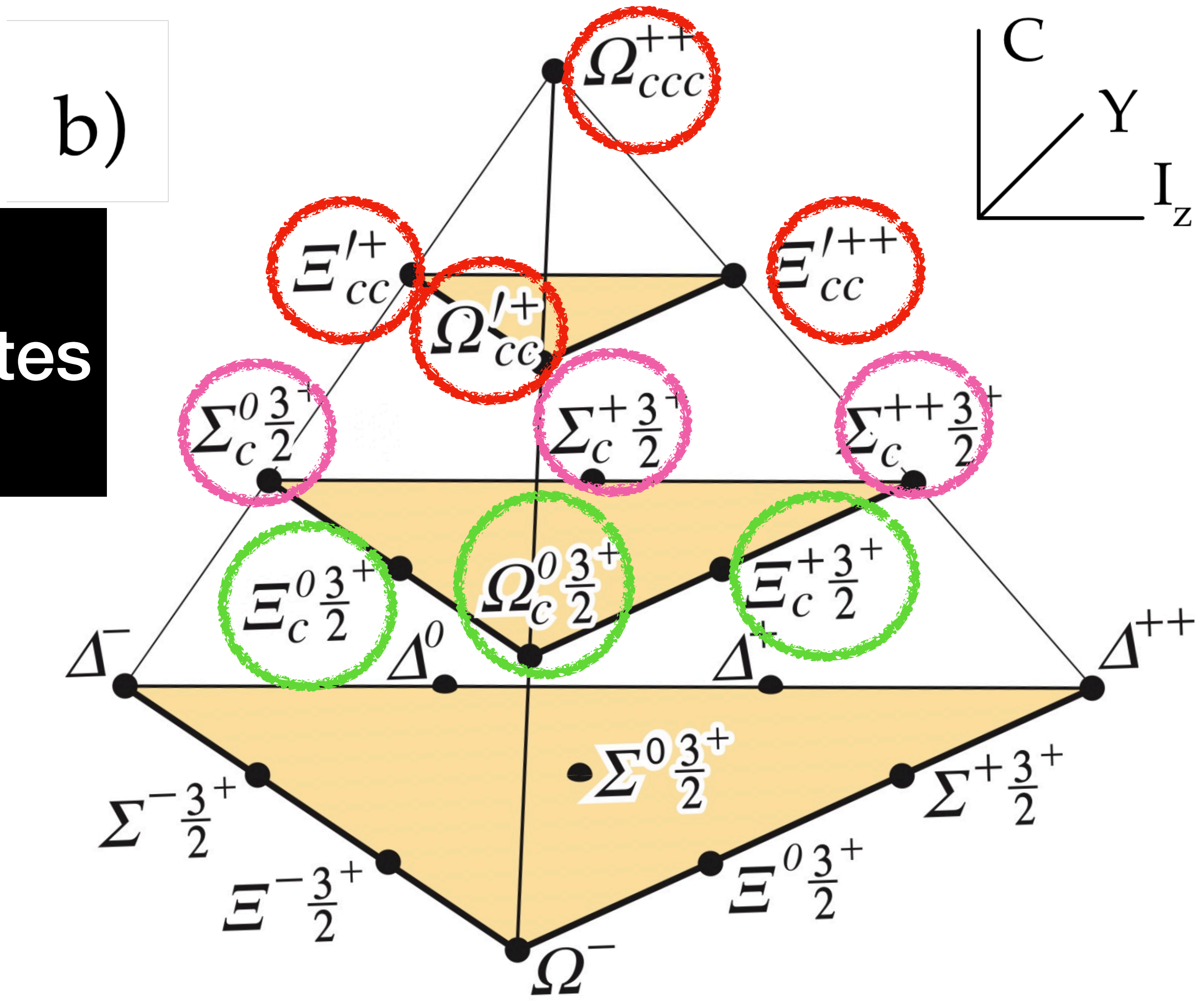
Observed

Not yet observed



Opportunities!
Will require observation of missing states first

PDG



From Lifetimes to Time Dependent CPV

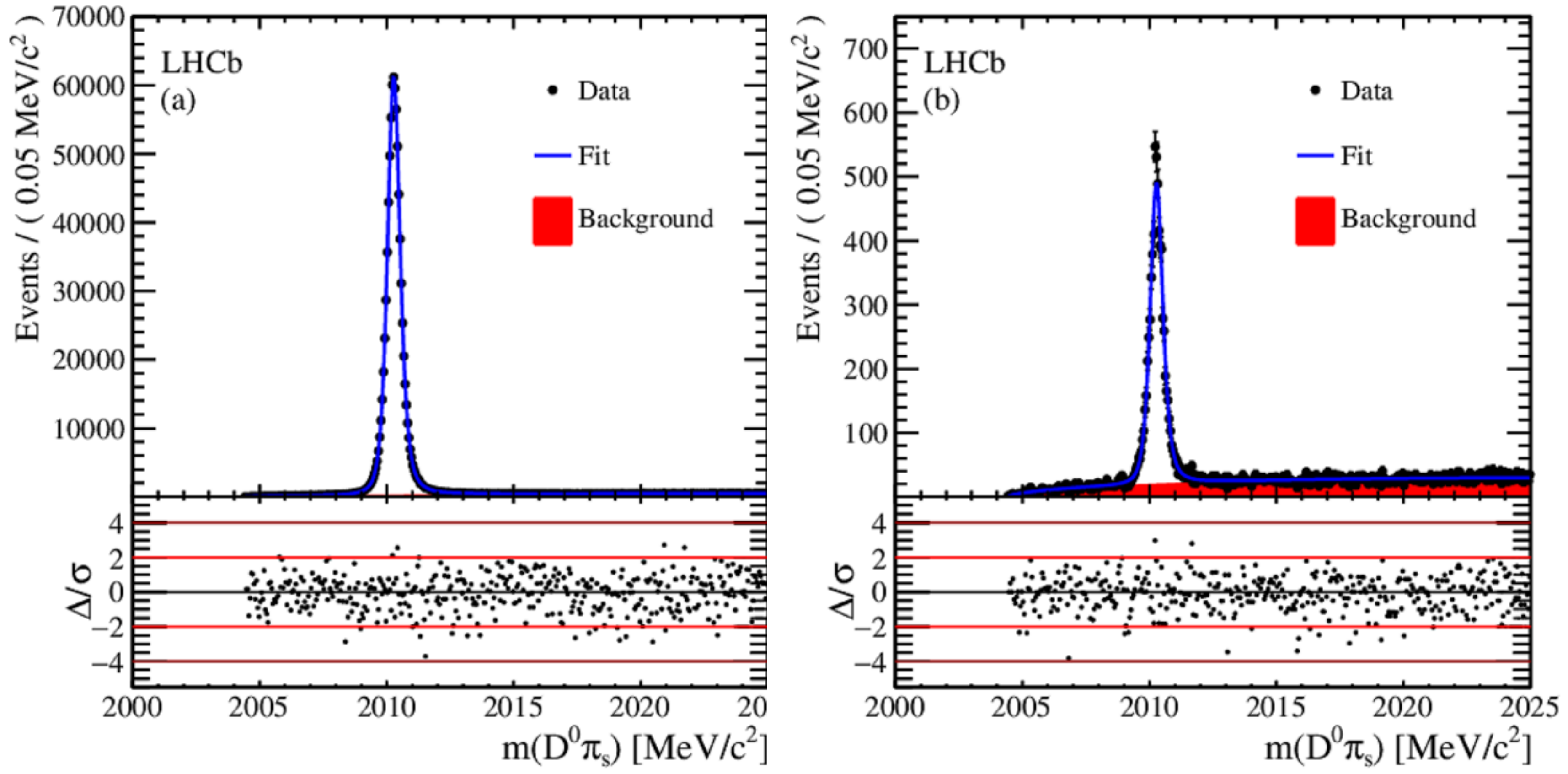
- Measurements of CP asymmetries require information on nuisance asymmetries

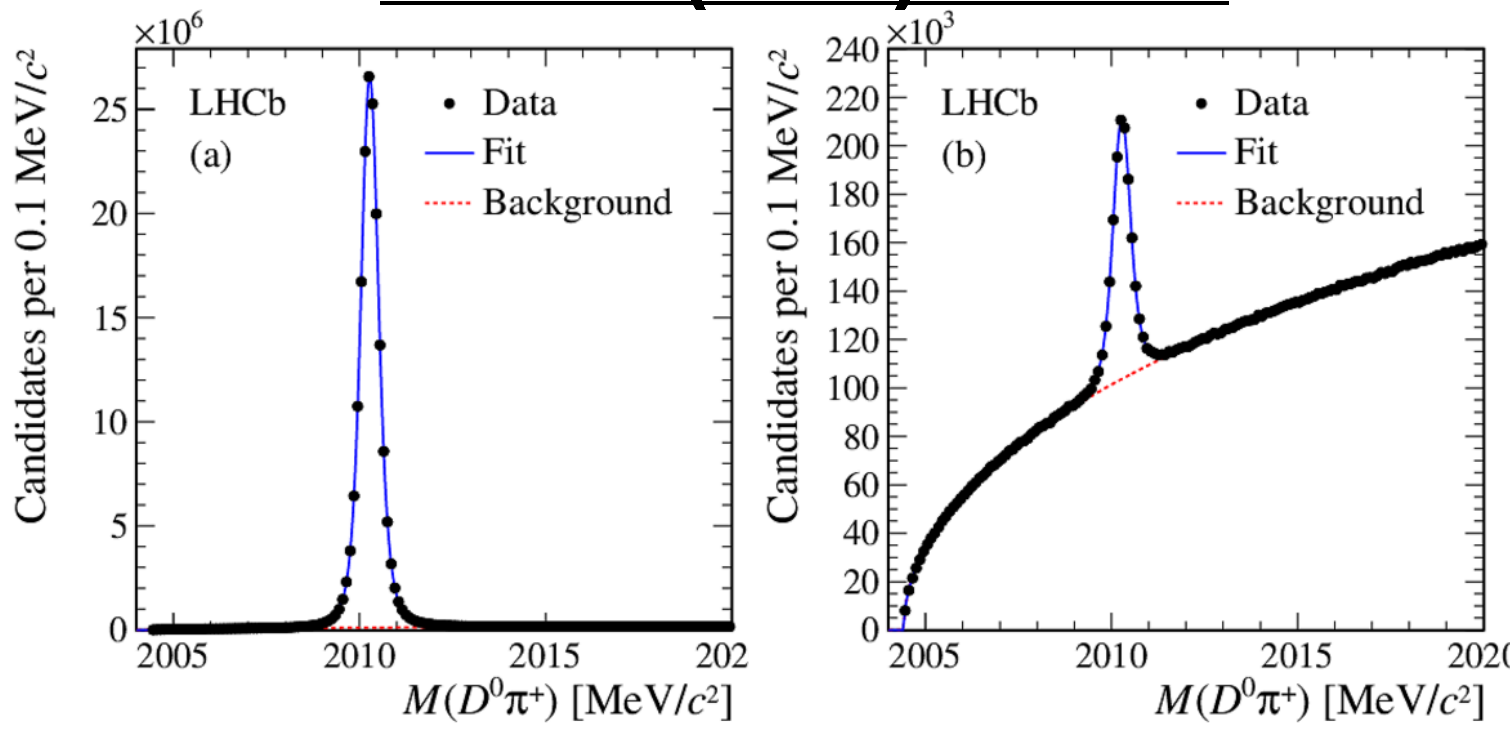
$$A_{raw} \simeq A_{CP} + A_{prod} + A_{det} + A_{trigger} + \mathcal{O}(A^3)$$

  - Detection asymmetries: E.g. response of detector to K^+ can differ from K^-
  - Production asymmetries: At time of production, can produce more D^0 than $\overline{D}^0$ (pp collisions)
- Control of these asymmetries requires essentially a dedicated analysis per physics result

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

PRD97 (2018) 031101
PRD95 (2017) 052004





- Responsible for first-ever single experiment observation of Mixing in D^0

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

- Current measurements:
  - Prompt: Run1+2015+2016
  - Doubly-Tagged: Run1

- Statistic dominated. Dominant systematic in prompt is secondary overlap, in DT is in-depth knowledge of detection asymmetry

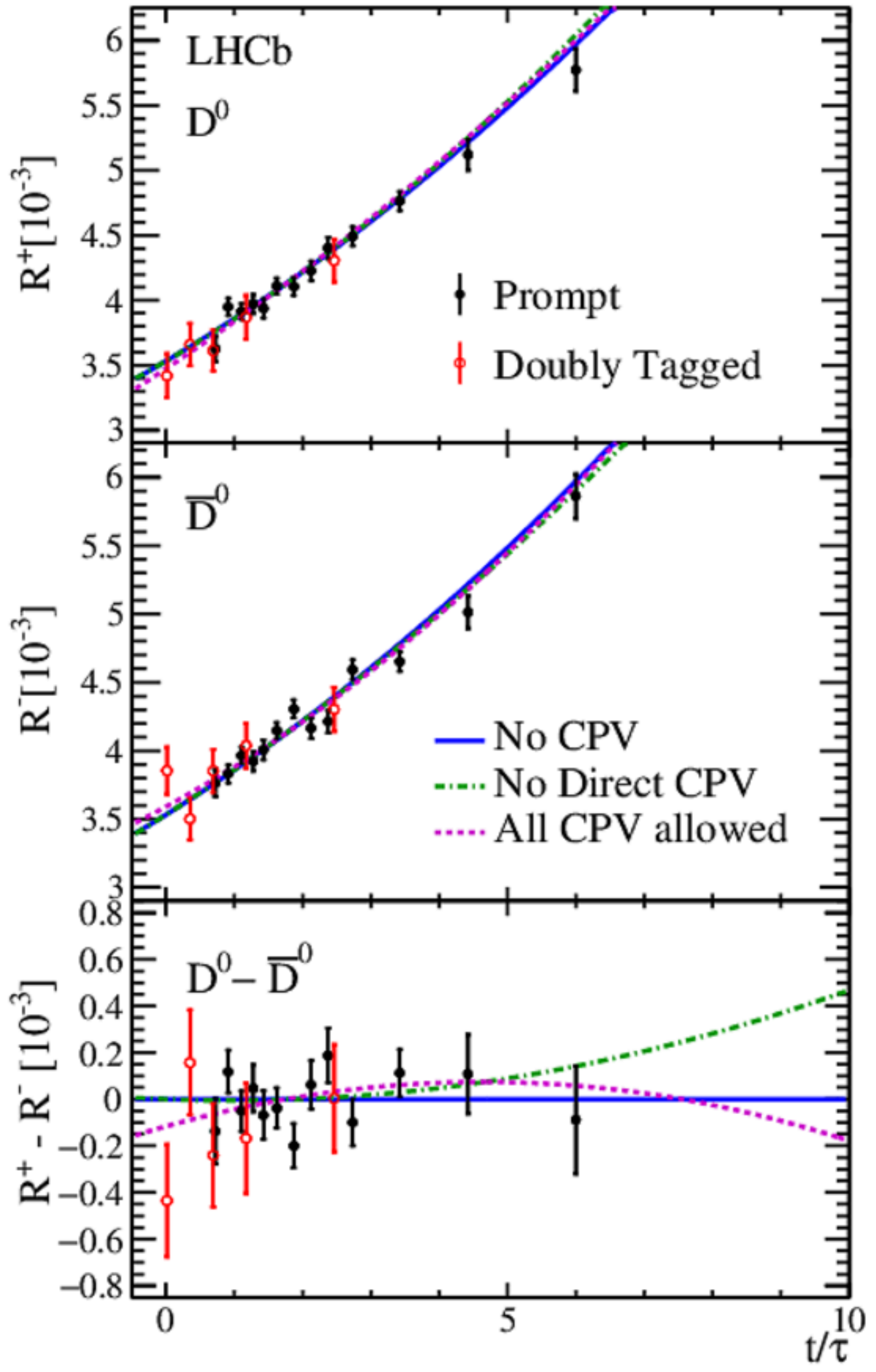
- Legacy updates soon - watch this space

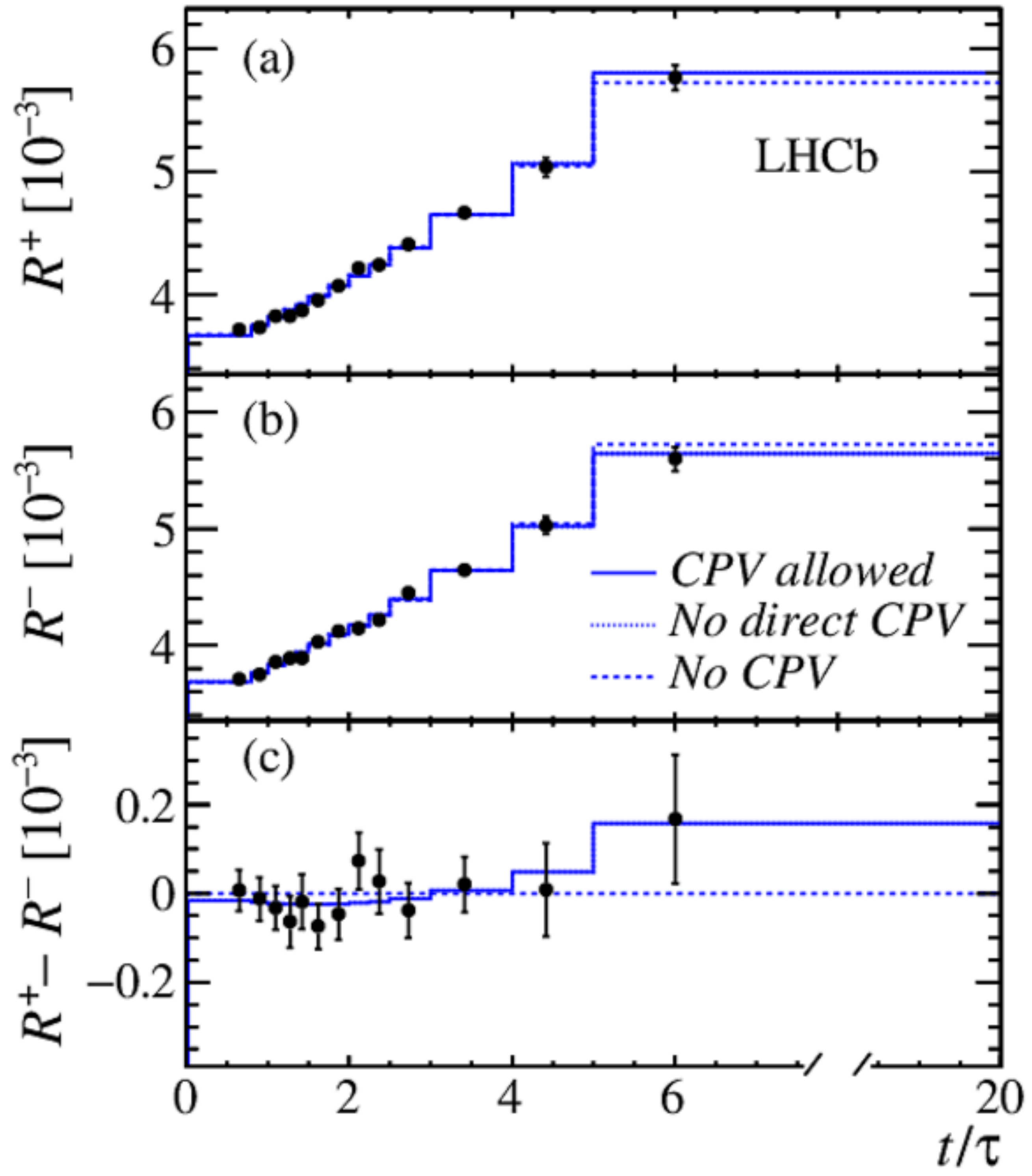
Prompt

Parameter	Value
R_D^+	$3.454 \pm 0.040 \pm 0.020$
y'^+	$5.01 \pm 0.64 \pm 0.38$
$(x'^+)^2$	$0.061 \pm 0.032 \pm 0.019$
R_D^-	$3.454 \pm 0.040 \pm 0.020$
y'^-	$5.54 \pm 0.64 \pm 0.38$
$(x'^-)^2$	$0.016 \pm 0.033 \pm 0.020$

DT

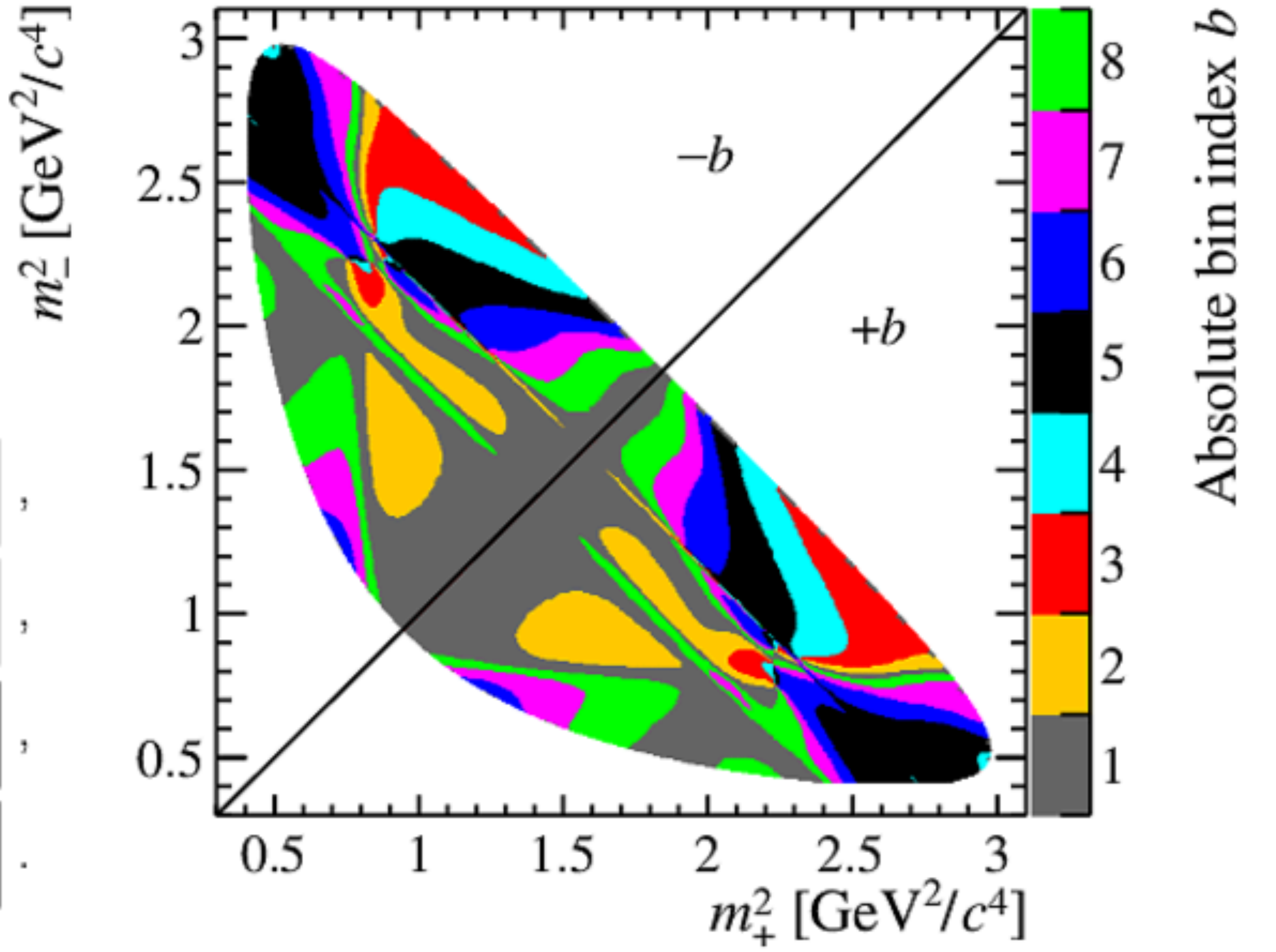
$R_D^+[10^{-3}]$	$3.38 \pm 0.15 \pm 0.06$
$(x'^+)^2[10^{-4}]$	$-0.19 \pm 4.46 \pm 0.31$
$y'^+[10^{-3}]$	$5.81 \pm 5.25 \pm 0.32$
$R_D^-[10^{-3}]$	$3.60 \pm 0.15 \pm 0.07$
$(x'^-)^2[10^{-4}]$	$0.79 \pm 4.31 \pm 0.38$
$y'^-[10^{-3}]$	$3.32 \pm 5.21 \pm 0.40$
χ^2/ndf	4.5/4





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

LHCb-PAPER-2022-020
PRL 127, (2021) 111801



- Can perform a similar analysis with $D^0 \to K^0_s\pi^+\pi^-$ by splitting into bins of constant strong phase ("Bin-flip" method), with a slightly different time dependence

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

$$R_{bj}^{\pm} \approx \frac{r_b + r_b\frac{\langle t^2\rangle_j}{4}\operatorname{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle t^2\rangle_j}{4}|z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \operatorname{Re}[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{\langle t^2\rangle_j}{4}\operatorname{Re}(z_{CP}^2 - \Delta z^2) + r_b\frac{\langle t^2\rangle_j}{4}|z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \operatorname{Re}[X_b(z_{CP} \pm \Delta z)]}$$

- Measure $x_{CP}, y_{CP}, \Delta X, \Delta Y (A_\Gamma)$

- Prompt, SL(2016-2018) + combination

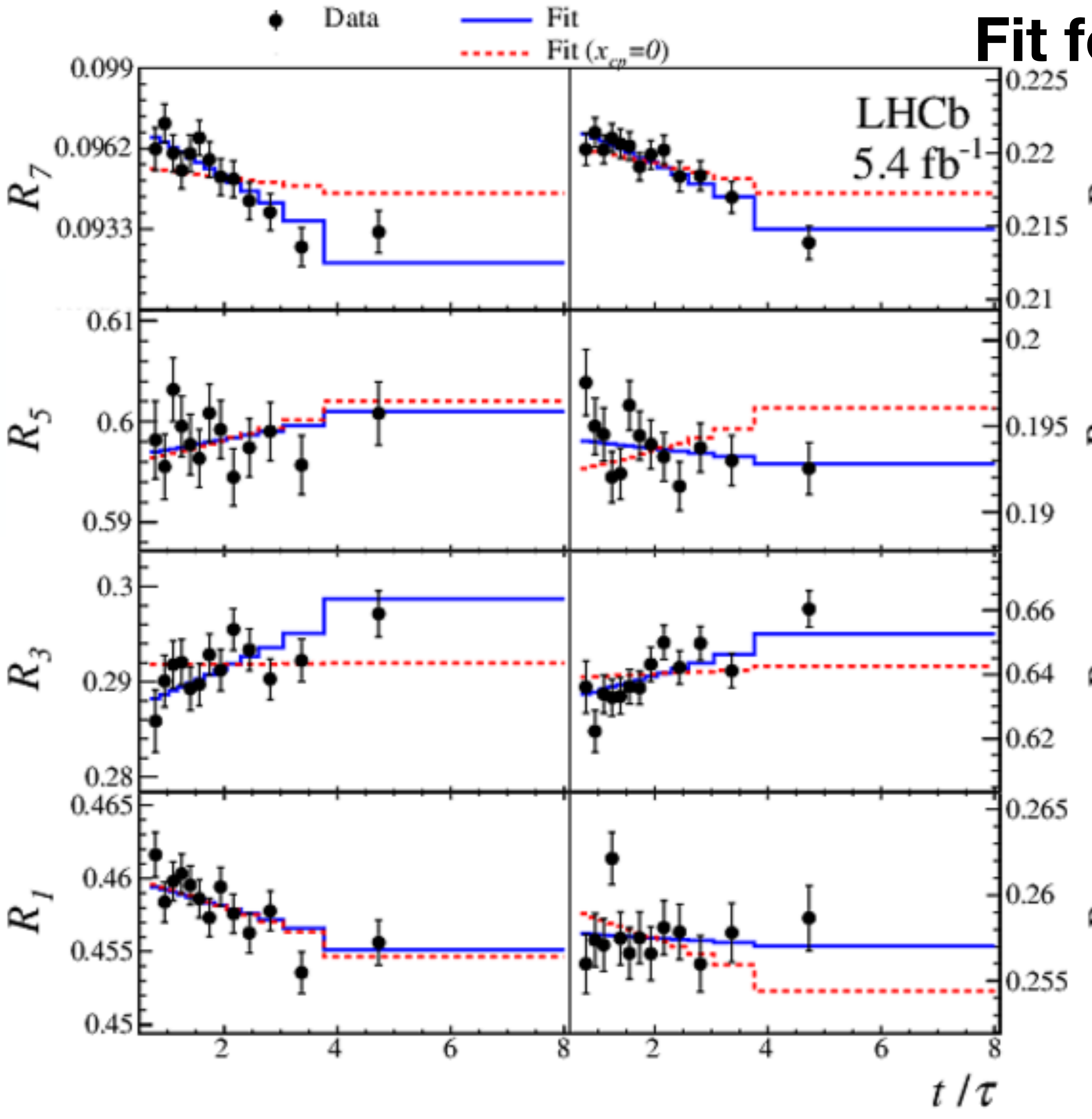
$$\begin{aligned}
x_{CP} &= (\ \ 3.97 \pm 0.46 \pm 0.29) \times 10^{-3},\\
y_{CP} &= (\ \ 4.59 \pm 1.20 \pm 0.85) \times 10^{-3},\\
\Delta x &= (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3},\\
\Delta y &= (\ \ 0.20 \pm 0.36 \pm 0.13) \times 10^{-3},
\end{aligned}$$

x_{CP} = [4.29 ± 1.48(stat) ± 0.26(syst)] × 10^{-3},
y_{CP} = [12.61 ± 3.12(stat) ± 0.83(syst)] × 10^{-3},
Δx = [−0.77 ± 0.93(stat) ± 0.28(syst)] × 10^{-3},
Δy = [3.01 ± 1.92(stat) ± 0.26(syst)] × 10^{-3}.

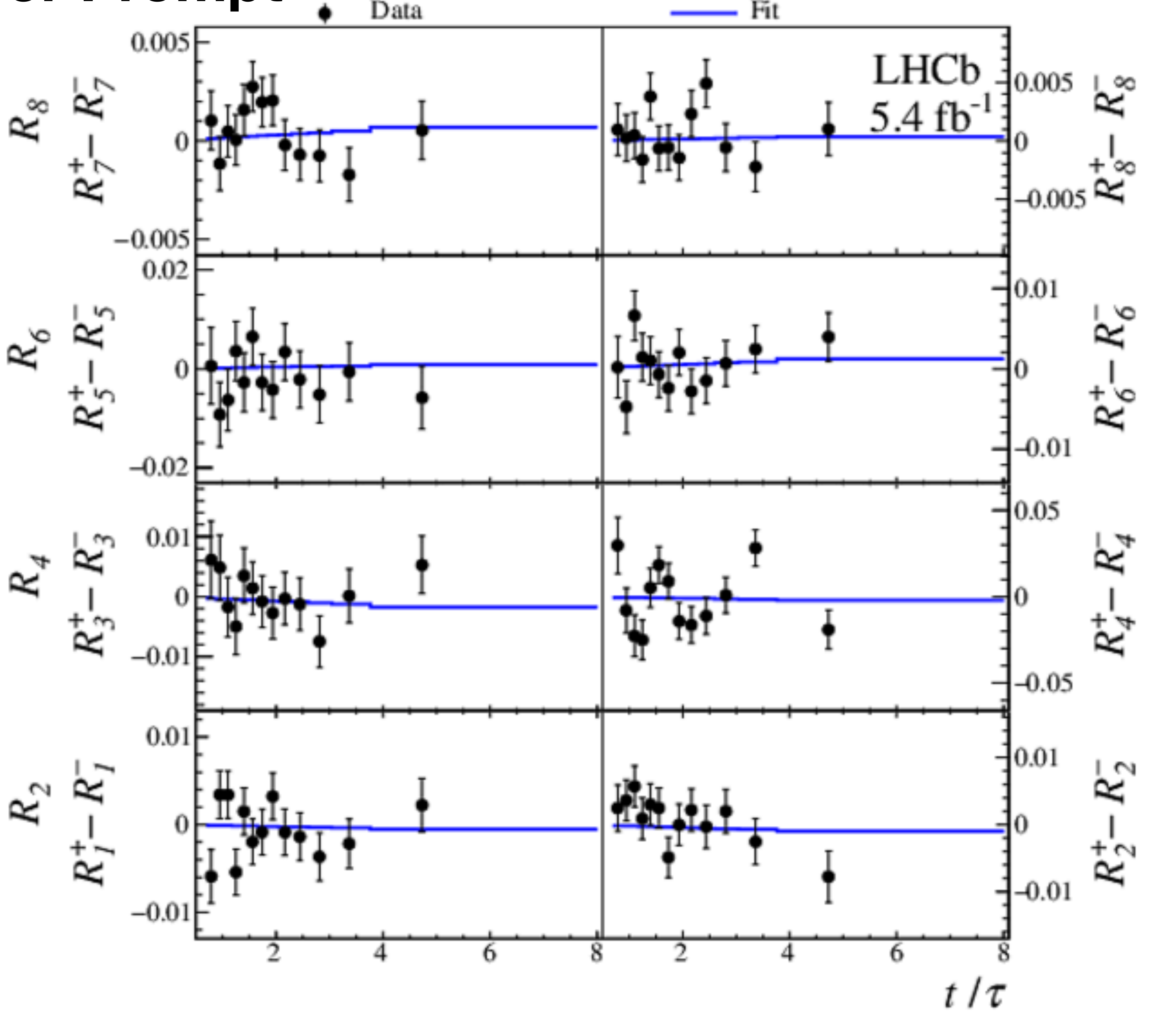
- Statistics limited

- Dominant systematic: $D^0\mu$ tagging (SL) and resolution from detector effects (Prompt)

- First ever measurement of non-zero x

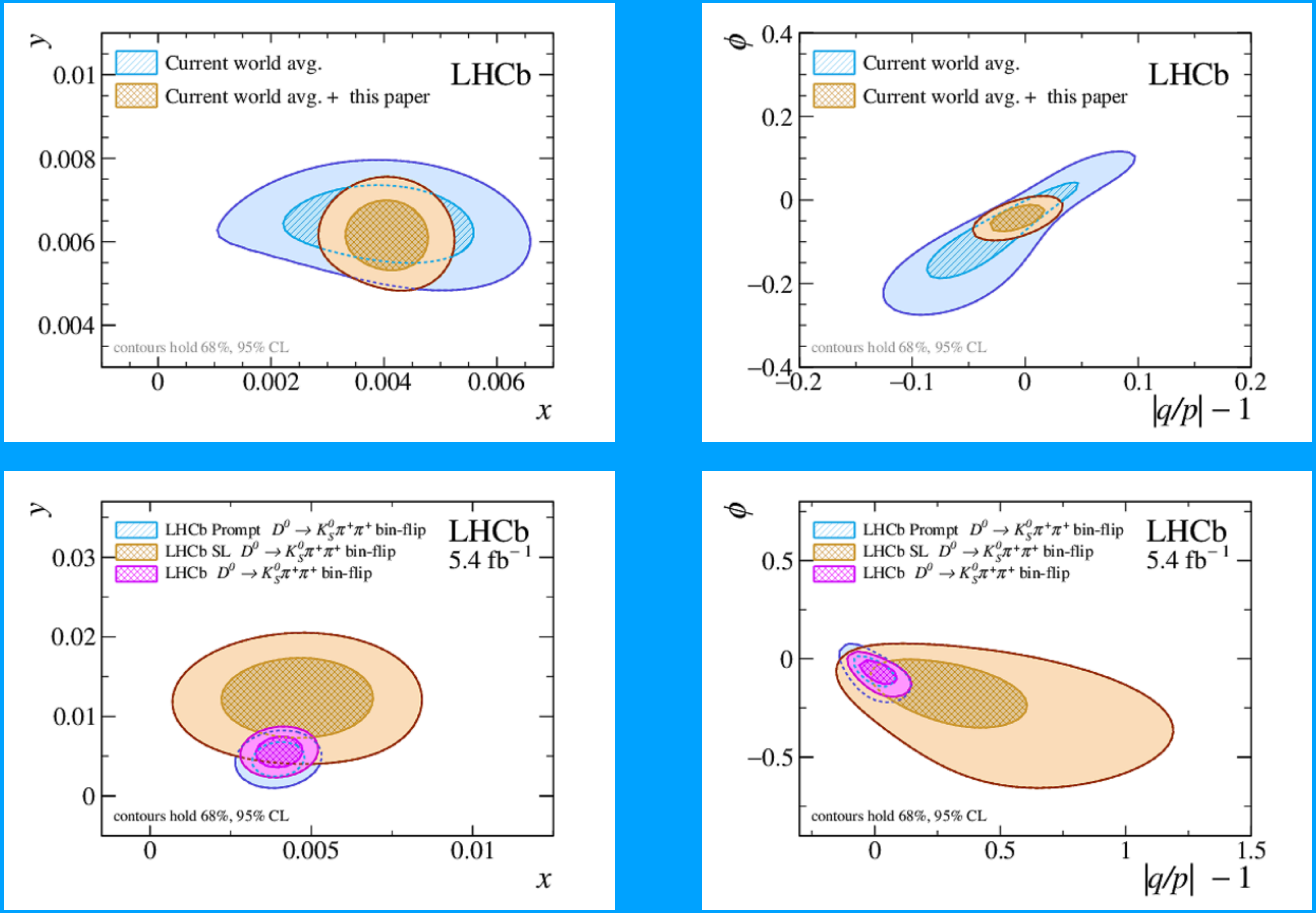


Fit for Prompt



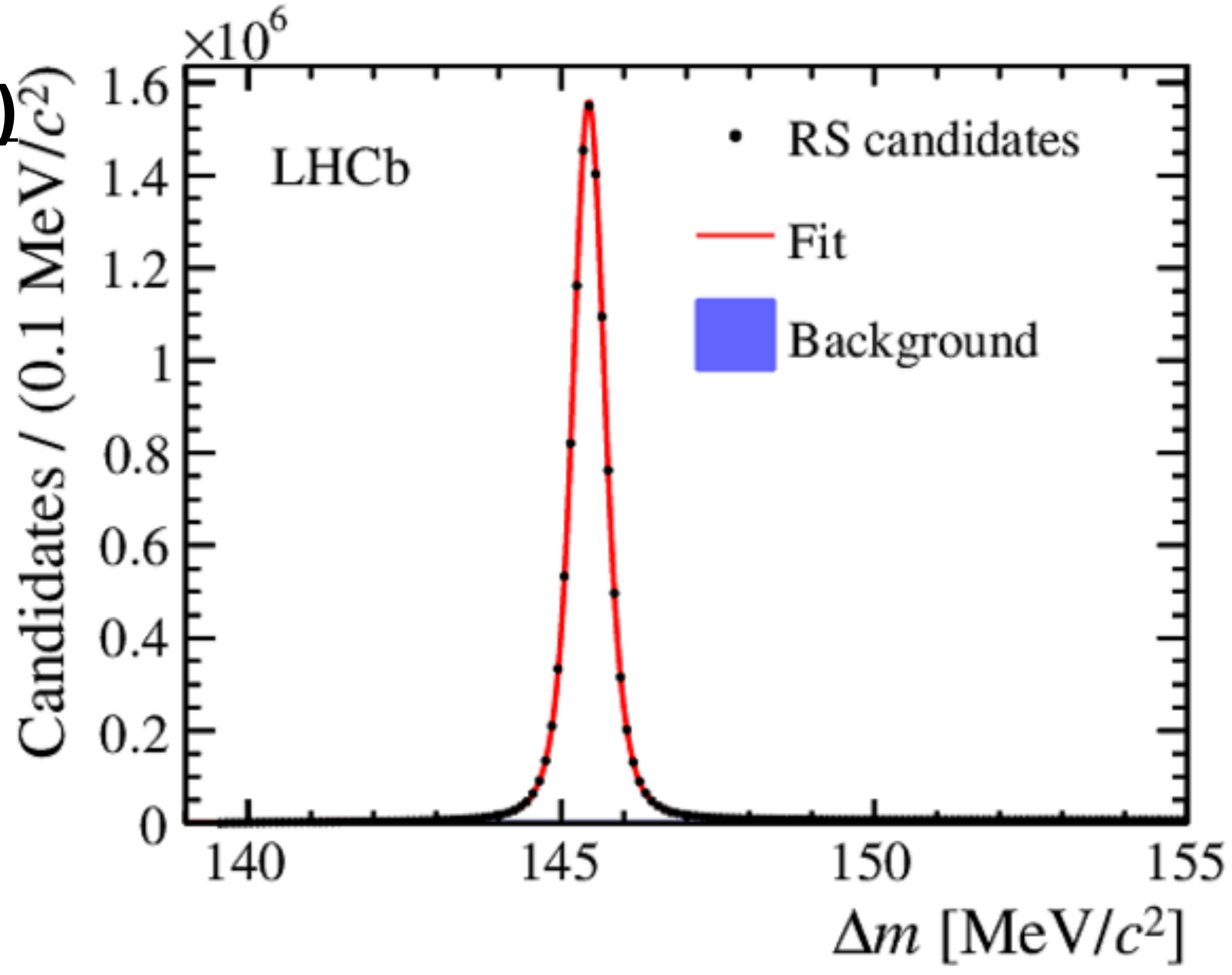
Mixing/CPV in $D^0 \to K^0\pi^+\pi^-$

Huge impact on World Average at time of publication



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

PRL 116, 241801 (2016)



- Motivation: Necessary for extraction of γ from $B \to D^0 K$ decays

- Time dependence described by

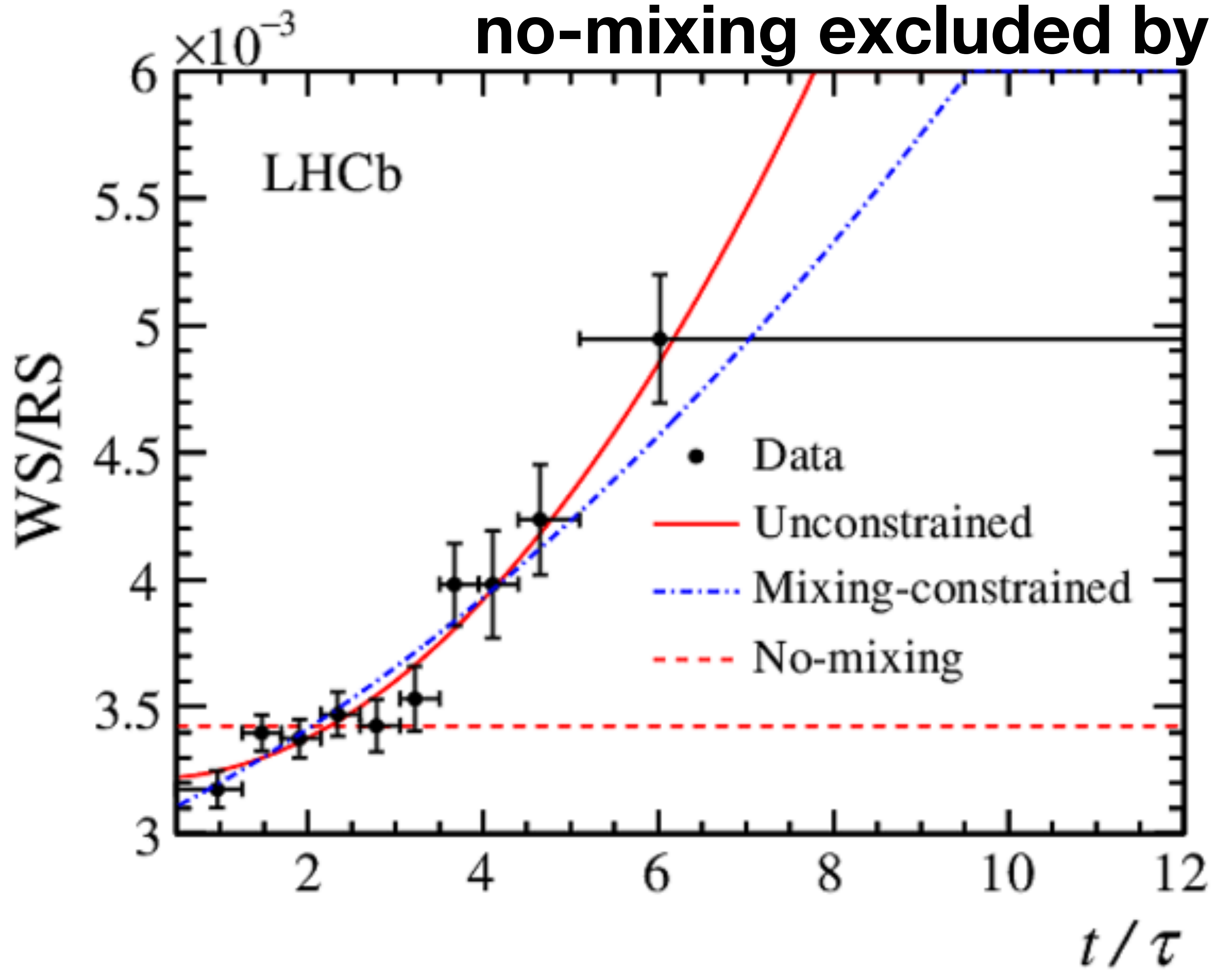
$$R(t) \simeq (r_D^{K3\pi})^2 - r_D^{K3\pi} R_D^{K3\pi} y'_{K3\pi} \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$

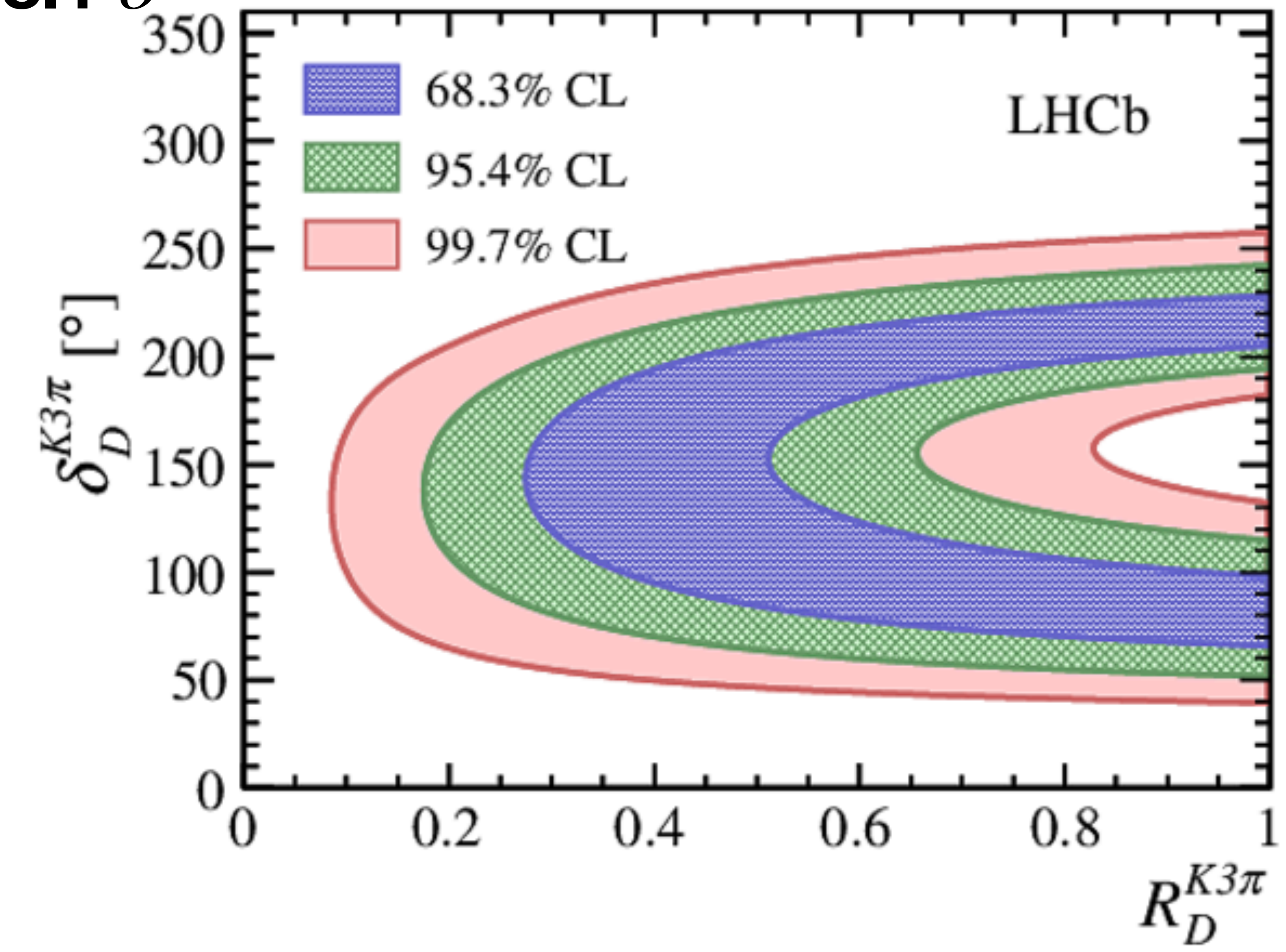
$R_D^{K3\pi} e^{i\delta_D^{K3\pi}} = \langle \cos\delta \rangle + i\langle \sin\delta \rangle$

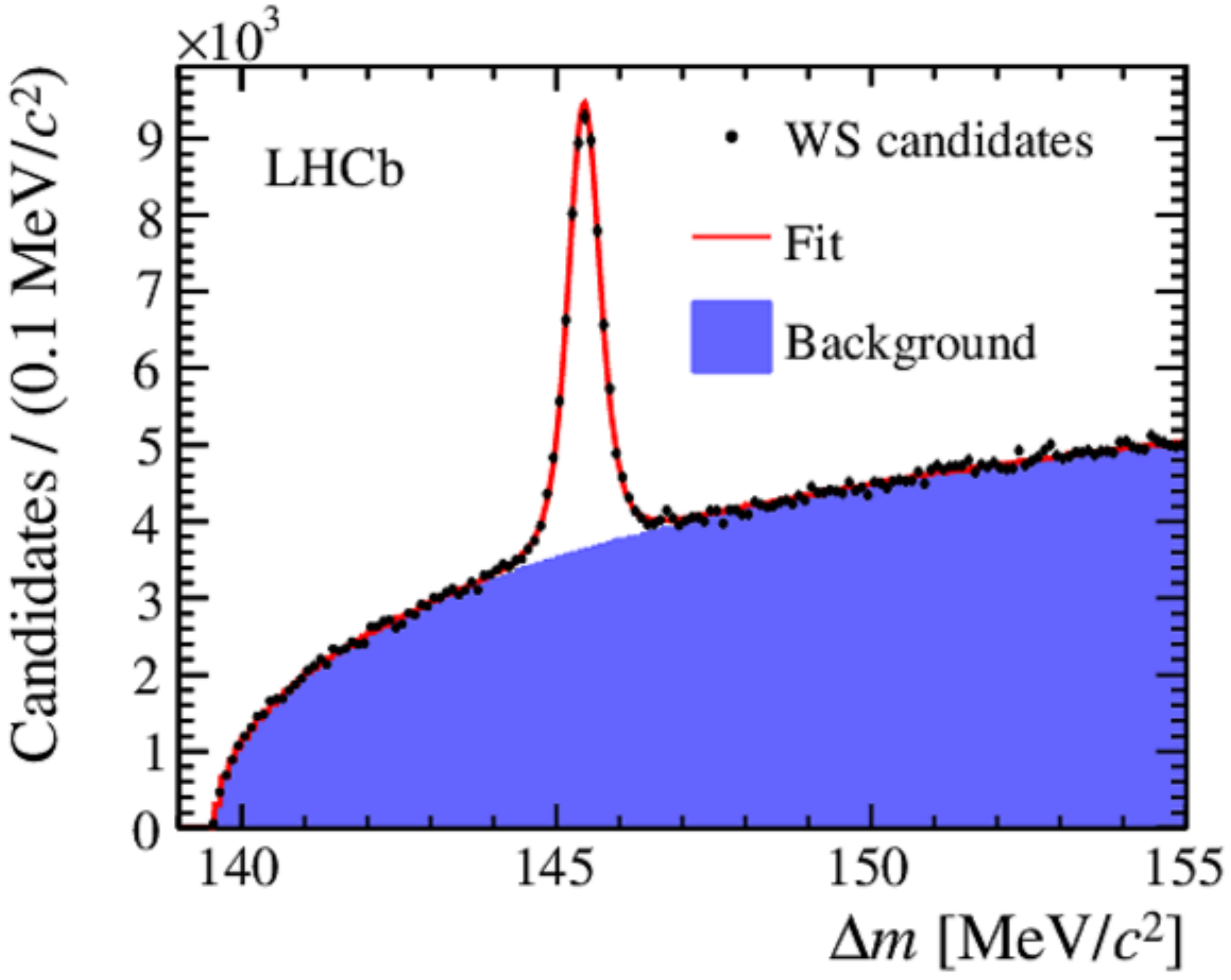
$y'_{K3\pi} = y\cos\delta_D^{K3\pi} - x\sin\delta_D^{K3\pi}$

- Can use world average of x, y to extract $r_D^{K3\pi}, R_D^{K3\pi}, \delta_D^{K3\pi}$

no-mixing excluded by 8.1 σ







Prompt Run1 only → stay tuned

A_Γ or ΔY

PRD104 (2021) 072010
JHEP04(2015)043
PRL 118 (2017) 261803
PRD 101 (2020) 012005

- Can express the CP asymmetry to CP eigenstates as

- $$A_{CP}(t) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} \simeq A_{CP}^{dir} + \frac{t}{\tau} A_{CP}^{ind} + \mathcal{O}\left(\left(\frac{t}{\tau}\right)^2\right)$$

$-A_\Gamma$ or $\Delta Y \simeq - x_{12} \sin \phi_f^M - y_{12} a_f^d$

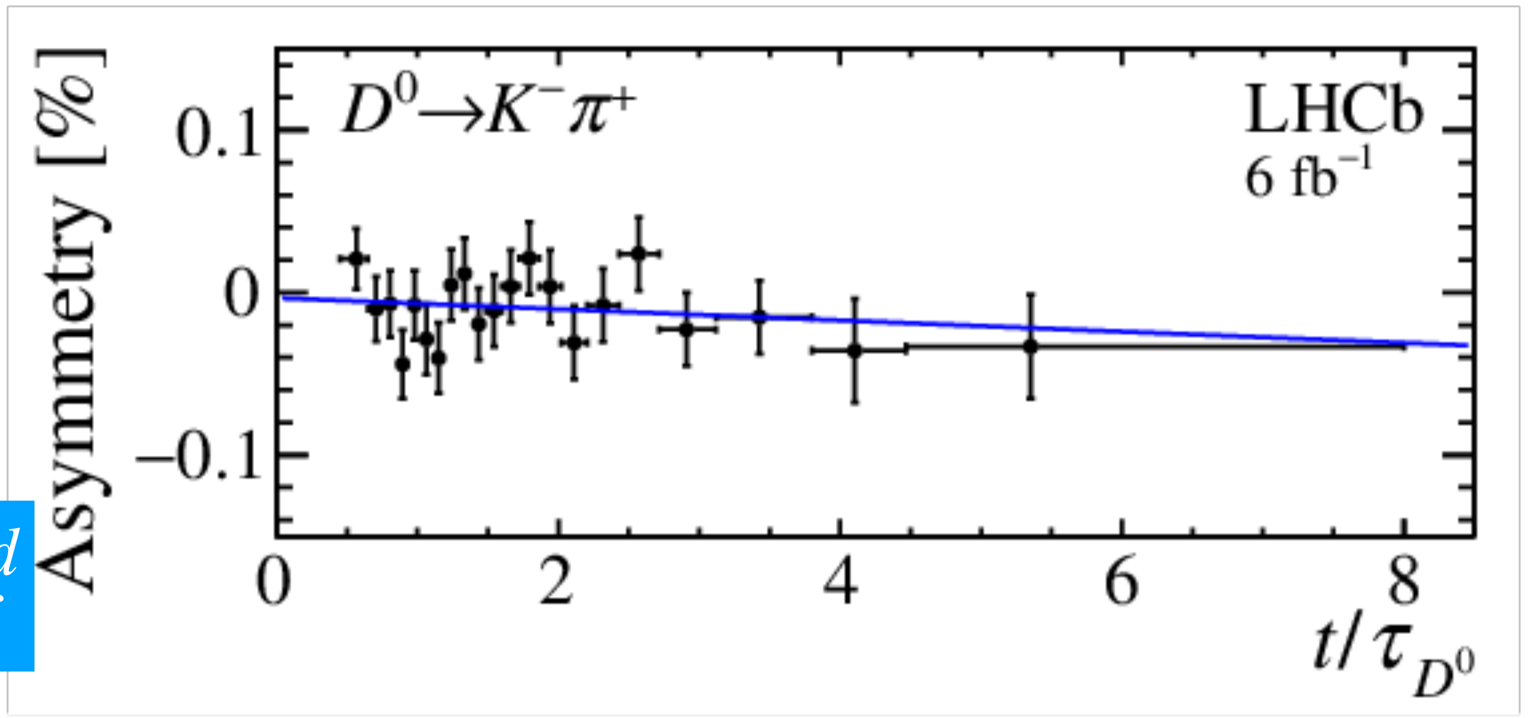
- Can be expressed as the difference between effective lifetimes → measure slope of time dependent CP asymmetry

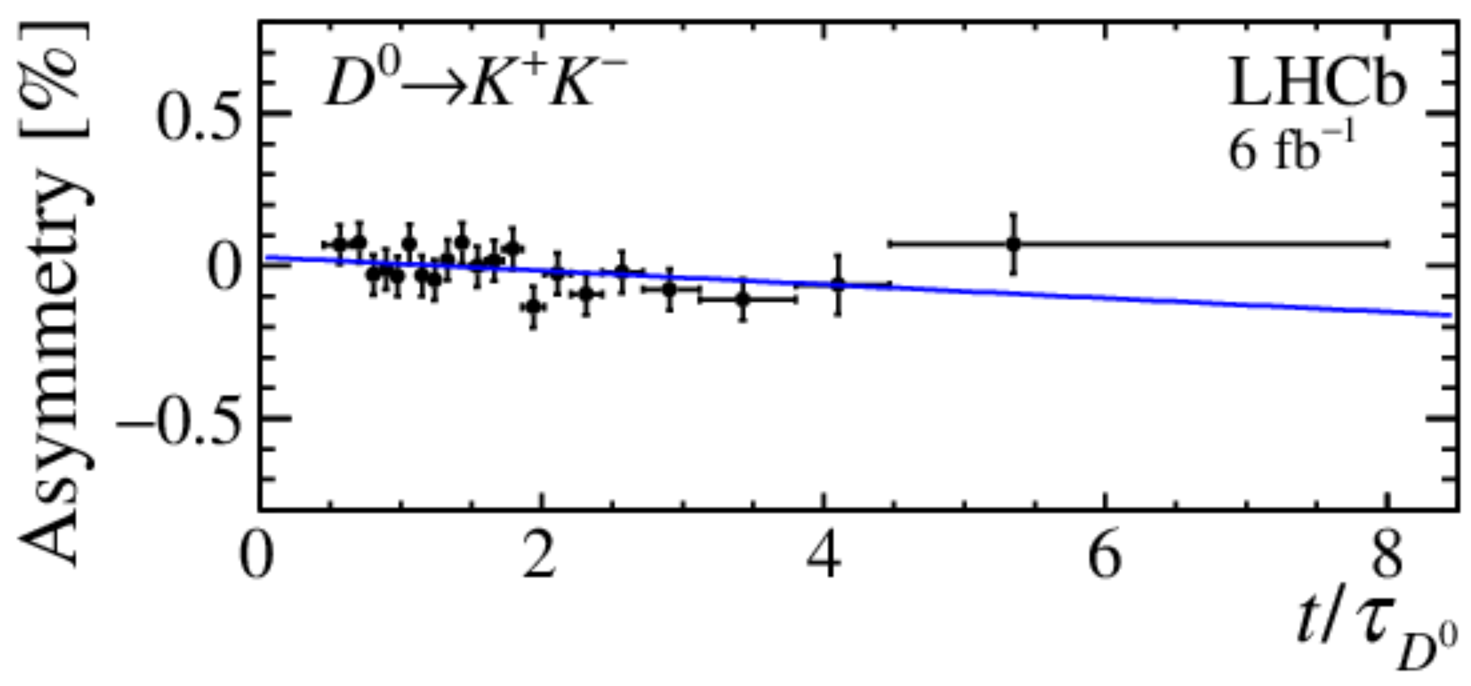
- Samples: Prompt Run 2, Evaluate using $D^0 \to K^- \pi^+$ for special treatment of kinematic dependent nuisance asymmetries.

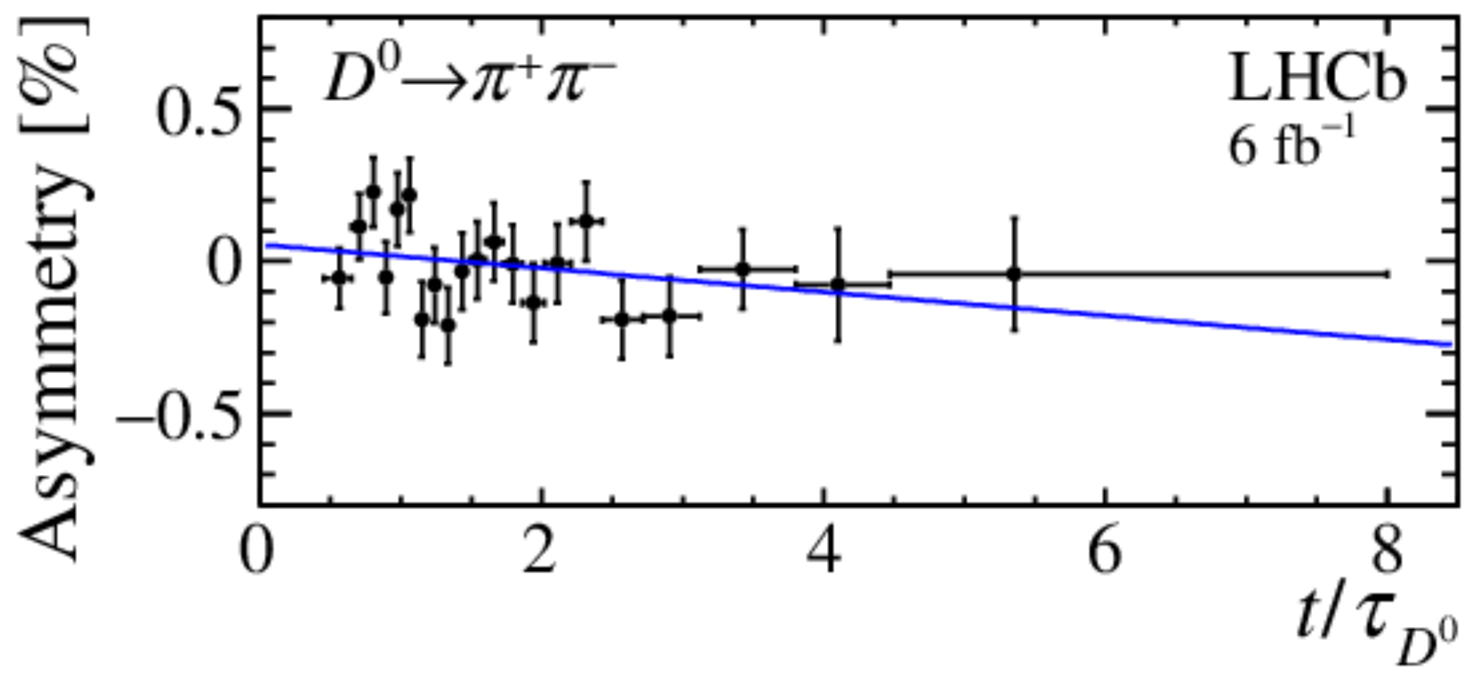
$$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$$

- Combined with previous measurements for Legacy Result

$$\Delta Y_{KK} = (-0.3 \pm 1.3 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{\pi\pi} = (-3.6 \pm 2.4 \pm 0.4) \times 10^{-4}$$
$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{KK} - \Delta Y_{\pi\pi} = (3.3 \pm 2.7 \pm 0.2) \times 10^{-4}$$







y_{CP}

PRD 105, 092013

- Can re-write the effective decay widths relative to Cabibbo Favoured $D^0 \to K^-\pi^+$ as

- $y^f_{CP} = \dfrac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)}{2\Gamma} - 1 = y_{12} \cos \phi^{\Gamma}_f$

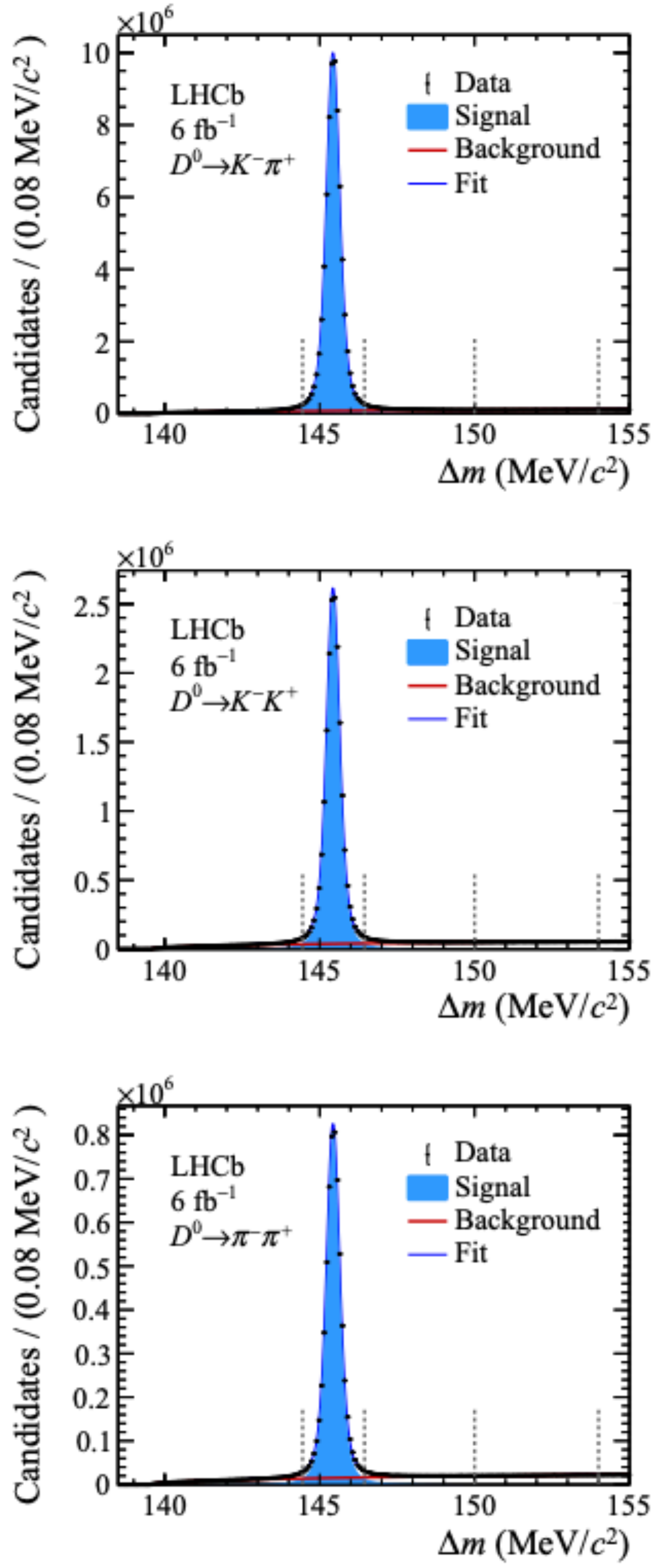
- However, should no longer neglect $D^0 \to K^-\pi^+$ influence (JHEP 2022, 162 (2022)), hence

- $\dfrac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\overline{D}^0 \to f)}{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\overline{D}^0 \to K^+\pi^-)} - 1 \simeq y^f_{CP} - y^{K\pi}_{CP} \simeq y(1 + \sqrt{R_D})$

- Hence, measure $R^f(t) = \dfrac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y^f_{CP} - y^{K\pi}_{CP})t/\tau} \dfrac{\epsilon(f,t)}{\epsilon(K^-\pi^+, t)}$, using prompt decays in full Run2 dataset, accounting for secondary contamination

$$y^{\pi\pi}_{CP} - y^{K\pi}_{CP} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$
$$y^{KK}_{CP} - y^{K\pi}_{CP} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$

Largest systematic is background modelling/understanding



Zum Einkaufen Gehen

Measurement	Run 1	Run 2	Run 1/2 Legacy	Run 3
WS Mixing/CPV	Prompt + DT	Prompt Run1 +2015/16	Stay Tuned	
DACP	Prompt + SL	Prompt+SL (+Discovery)	Prompt+SL (+Discovery)	
ACP(KK)	Prompt+SL	Prompt+SL	Prompt+SL	
ΔY	Prompt + SL	Prompt + SL	Prompt + SL	
$D^0 \to K_S^0 \pi^+ \pi^-$	Model Dependent	Bin Flip (Prompt + SL)		
$D^0 \to K^\pm \pi^\mp \pi^+ \pi^-$	Prompt	Stay Tuned		
yCP	SL	Prompt		
$D^0 \to \pi^+ \pi^- \pi^0$				
$D^0 \to K^+ K^- \pi^+ \pi^-$				
$D^0 \to K_S^0 h h'$				
...				

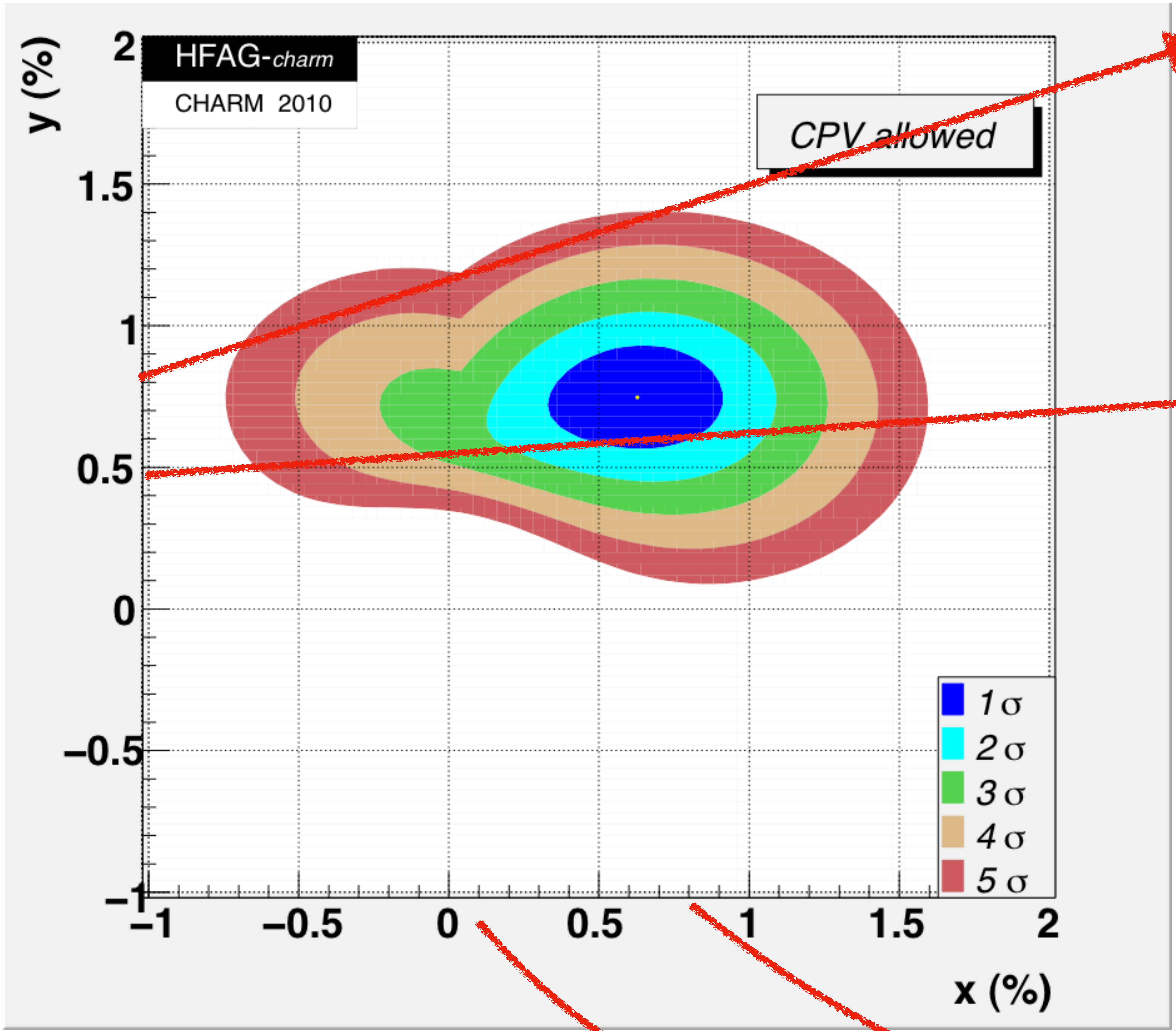
See
E. Gersabeck

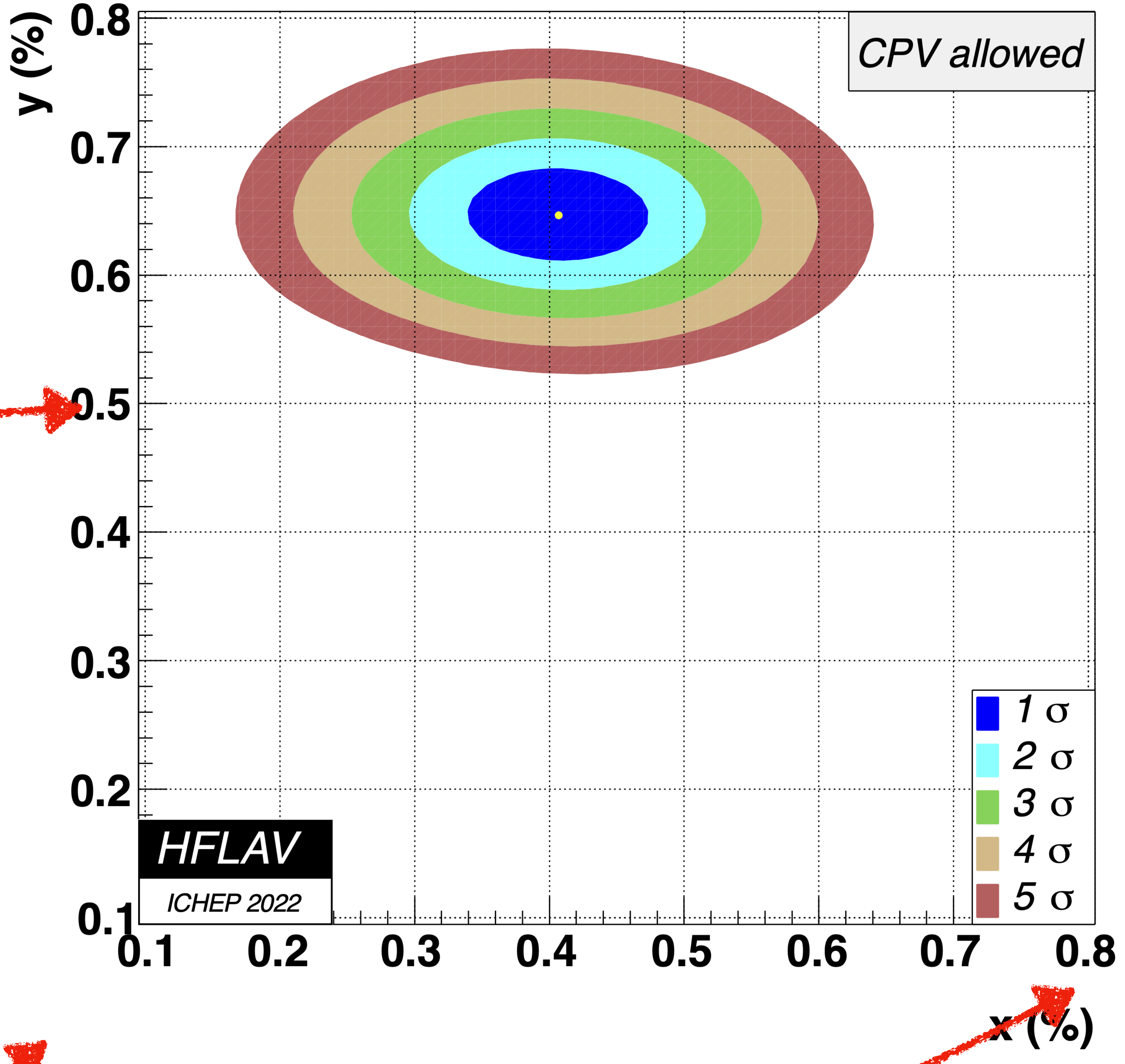
Stay
Tuned

Stay
Tuned

Conclusion

- LHCb has collected the largest sample of Charm hadrons in the world. With it, we have
  - Up-ended conventions on charm baryon lifetimes
  - Pushed the boundaries on Mixing and indirect CPV searches
  - Are testing theory with unprecedented precision
- Run3 is now - we shall see what the future holds


HFAG-charm
CHARM 2010
CPV allowed
y (%)
x (%)
1 σ
2 σ
3 σ
4 σ
5 σ

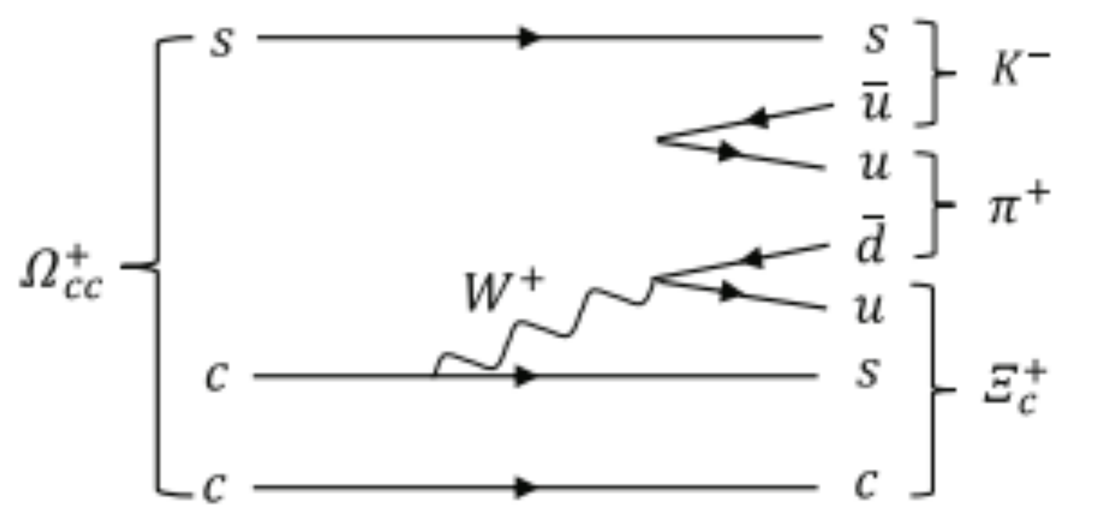

CPV allowed
y (%)
x (%)
HFLAV
ICHEP 2022
1 σ
2 σ
3 σ
4 σ
5 σ


HFAG-charm
CHARM 2010
1 σ
2 σ
3 σ
4 σ
5 σ
Arg(q/p) [deg.]
80
60
40
20
0
−20
−40
−60
−80
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
|q/p|
HFLAV
ICHEP 2022
1 σ
2 σ
3 σ
4 σ
5 σ
Arg(q/p) [degrees]
10
5
0
−5
−10
−0.1
−0.05
0
0.05
0.1
|q/p|-1

Backup

Search for Ω_{cc}^{+} LHCb-PAPER-2021-011

Sci. China Phys. Mech. Astron. 64 (2021) 101062



- Search with 2016-2018 data in decay mode $\Omega_{cc}^{+} \to \Xi_{c}^{+} K^{-} \pi^{+}$
- Multivariate selection (BDT) trained to reduce combinatorial background
- Local significance: 3.2σ, Global: 1.8σ
- Upper limits set on $\sigma \times \mathscr{B}$ at 1.1×10^{-1} to 0.5×10^{-2} for $\tau \in [40{,}200]$ fs