Highlights of Recent Charm Results @ LHCb

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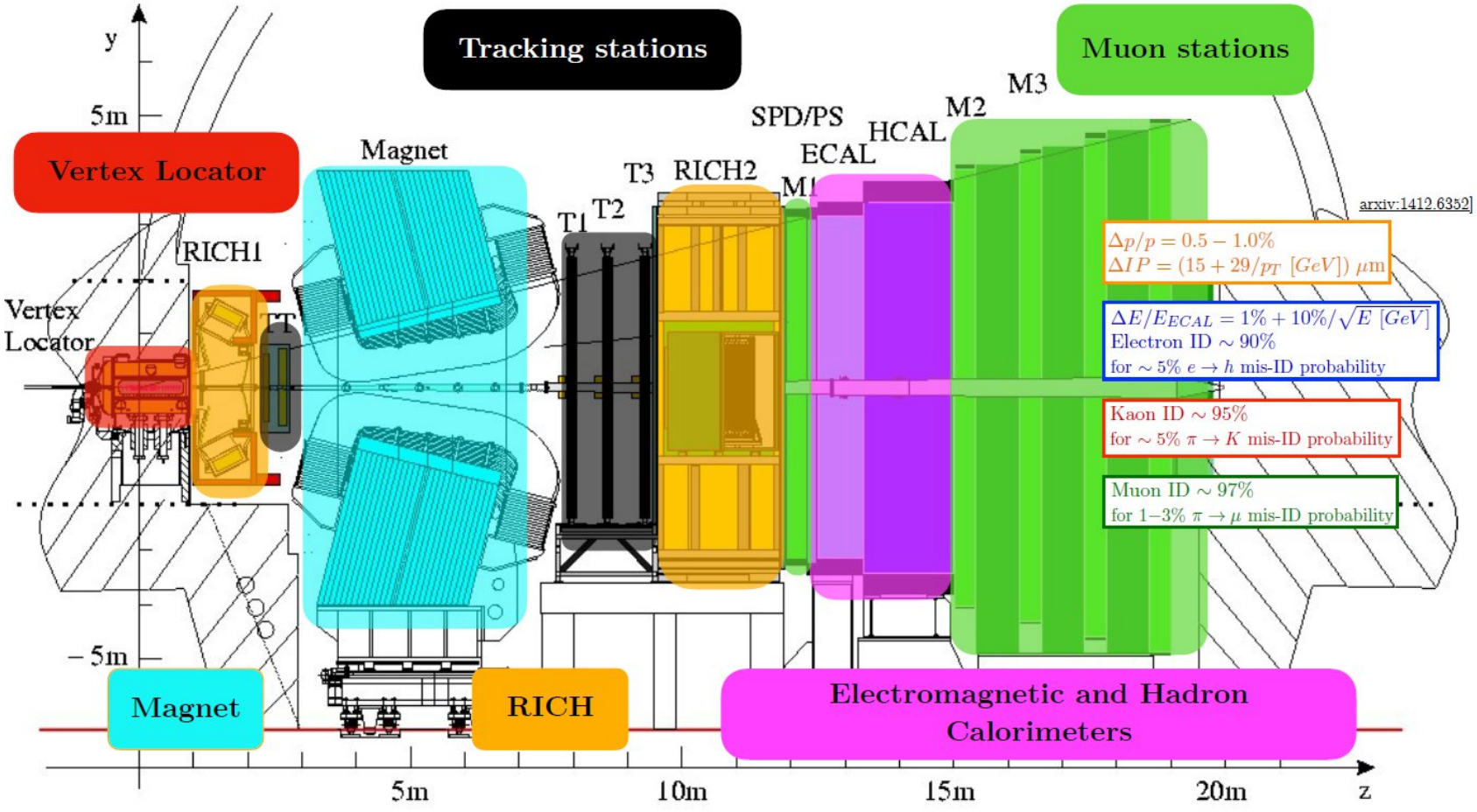
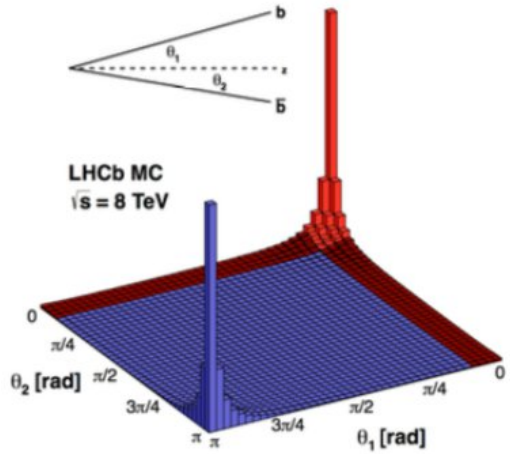
Outline

- LHCb as a charm factory
- Recent results on charm CPV
  - Mixing & CPV of $D^0 \to K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$
  - A_{CP} of $D^0 \to K_S^0 K_S^0$
  - A_{CP} of $D^+ \to \phi\pi^+$
- Recent results on rare charm decays
  - $\Lambda_c^+ \to p\mu^+\mu^-$
  - $D^0 \to hhe^+e^-$
- Other charm related results, such as spectroscopy (Ξ_{cc}^+, Ω_{cc}^+, Σ_c, D_{s1}), can be found here

LHCb in Runs 1-2 (2011-2018)

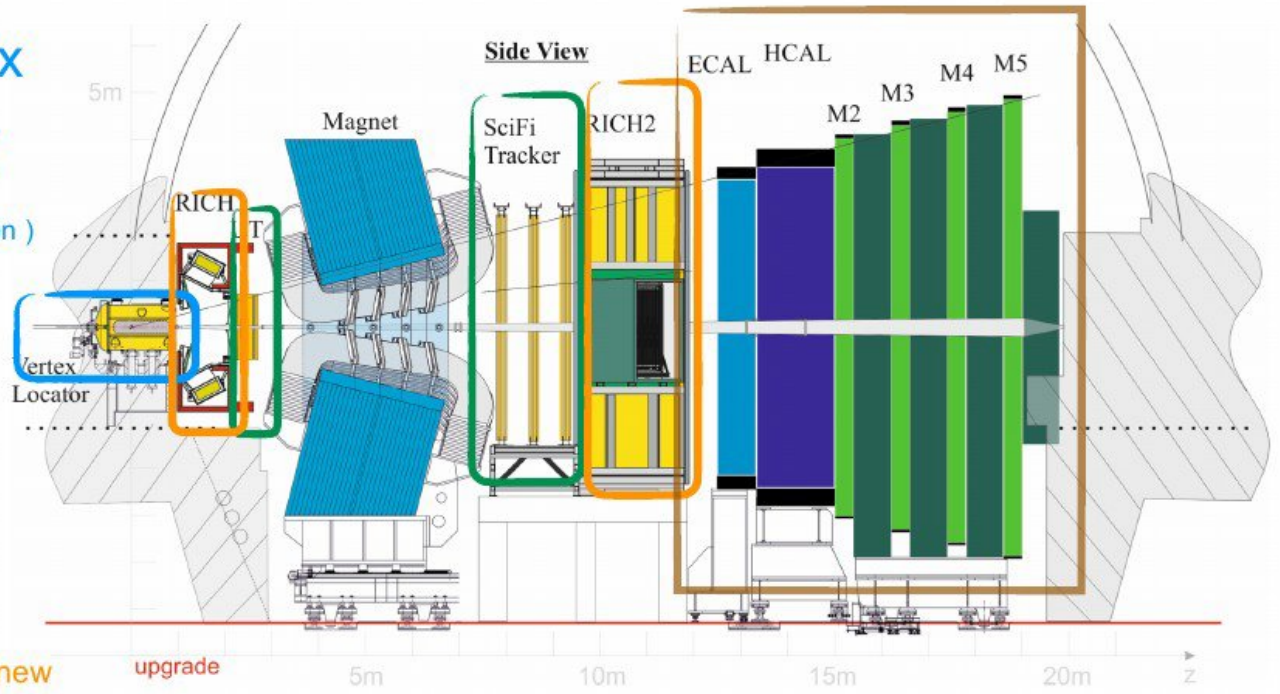




LHCb is designed and optimized for HF & CPV

LHCb in Run3 (2022-)

New Vertex detector (Si-microstrip-> Si-pixel, closer to beam, improved IP resolution)



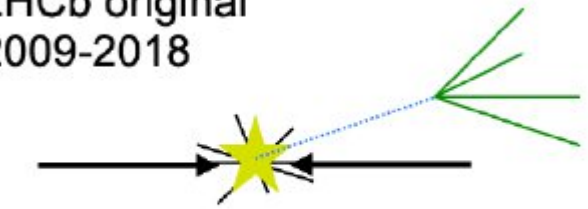
New PID detector, new photon detectors, readout + modified optics/mechanics

New tracking system (Si-strip + straw-tubes ->Scintillating fibres,+ Si-strip UT > granularity)

New read out

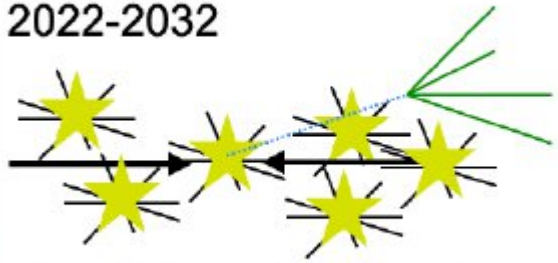
+ new DAQ/data centre

LHCb original 2009-2018



~1 pp collision per bunch-crossing

LHCb Upgrade I 2022-2032

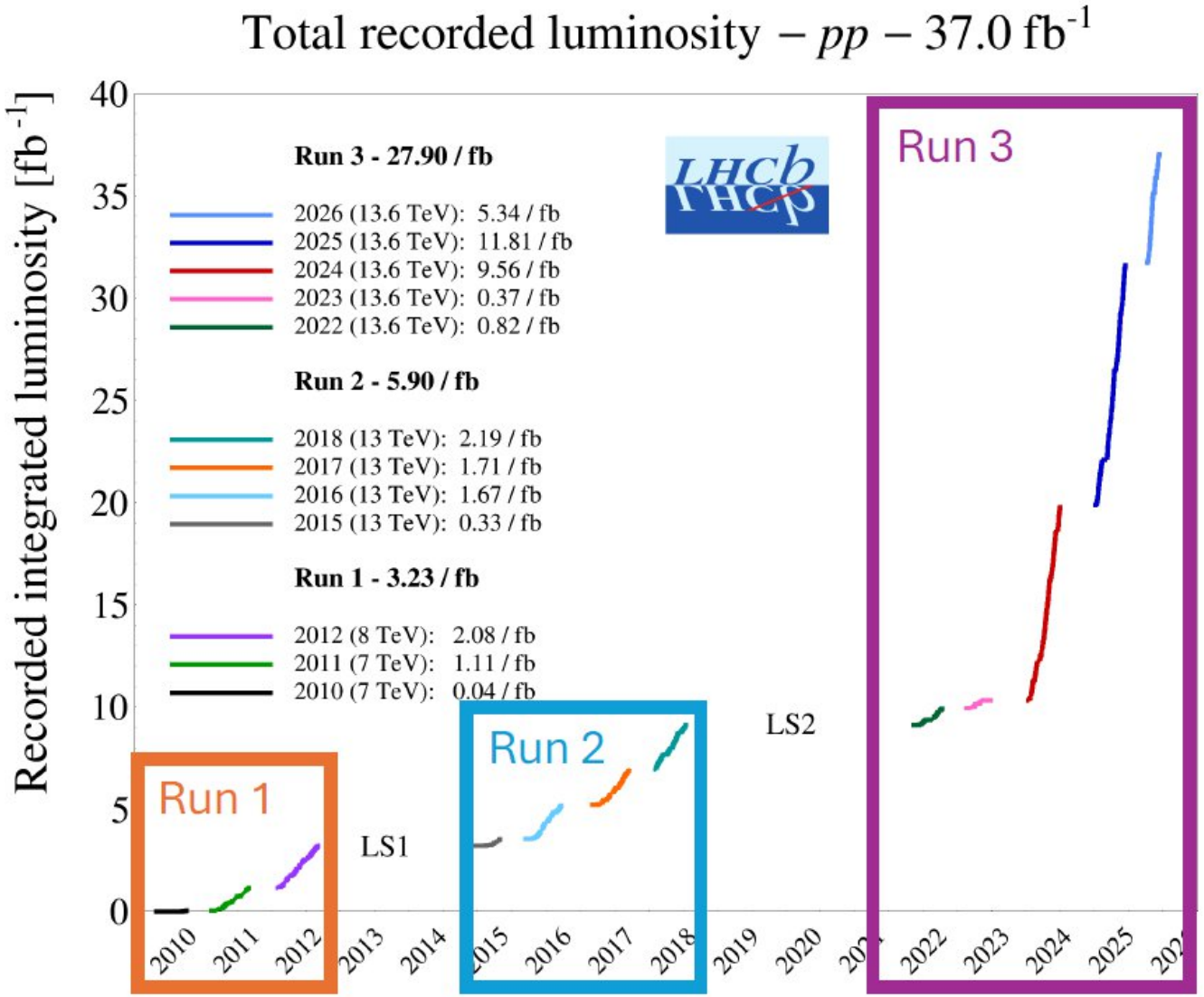


~6 pp collisions per bunch-crossing

Running with 5x higher instantaneous luminosity!

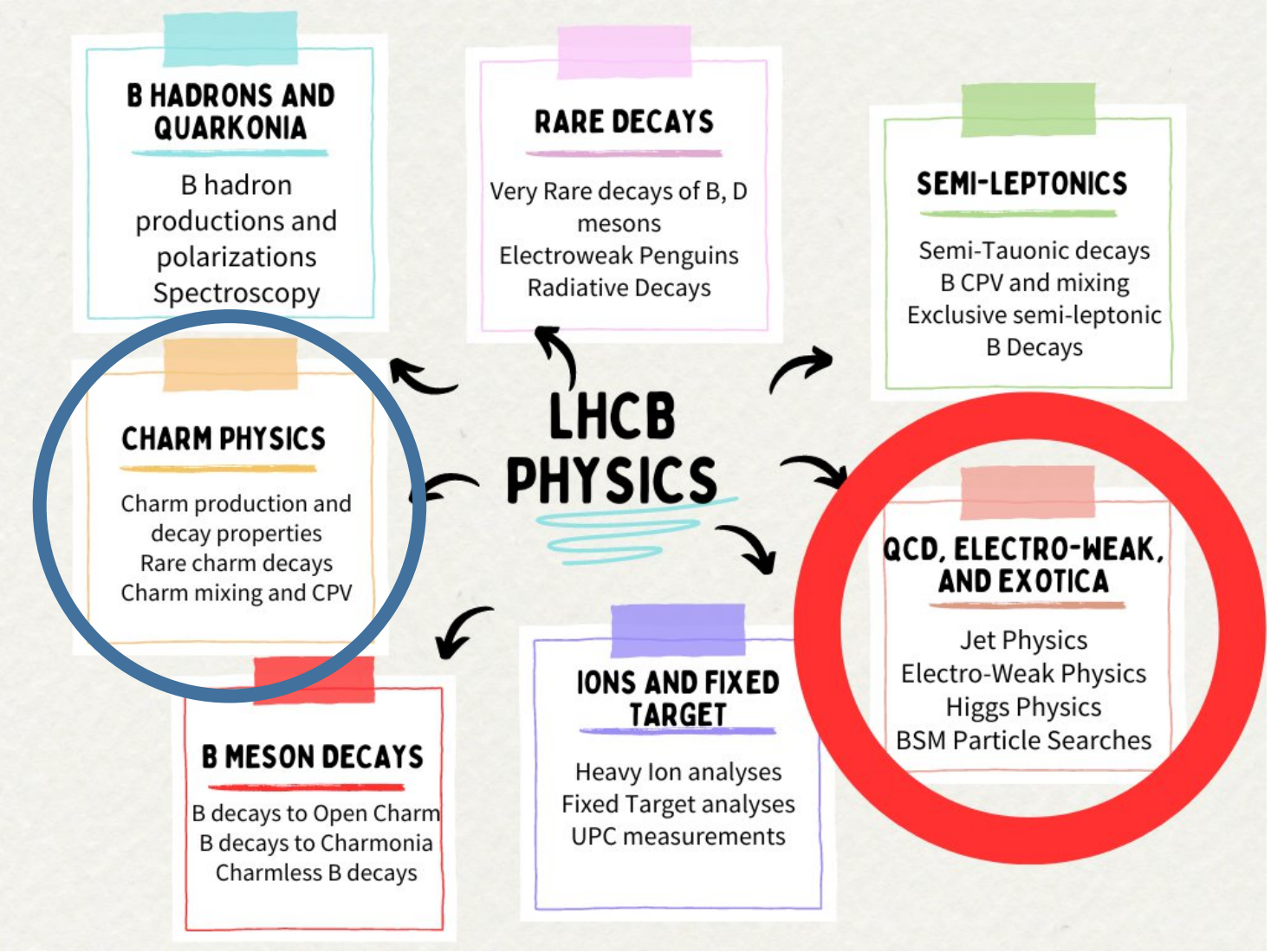
Excellent detector performance since 2024!

LHCb datasets

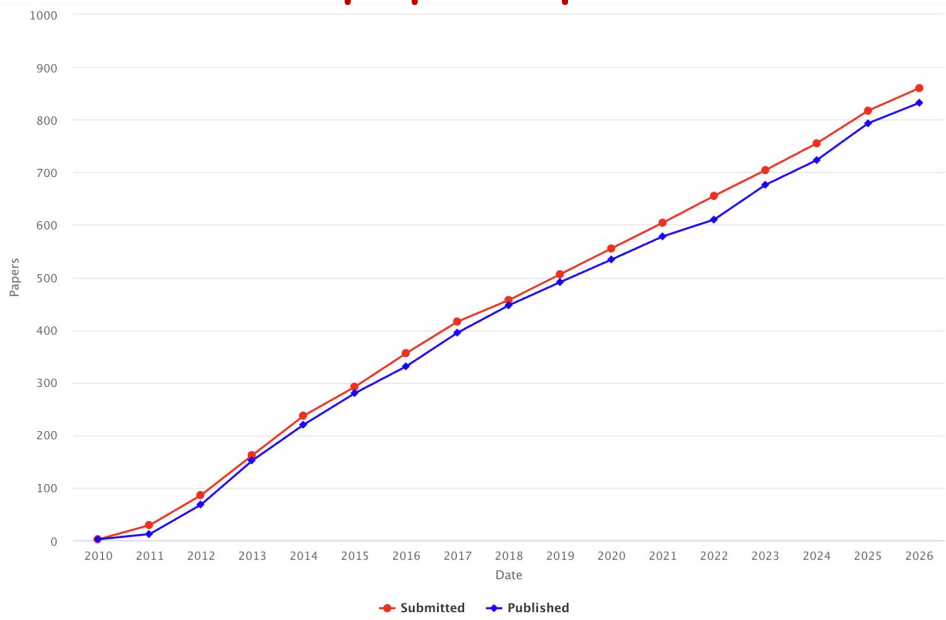


Most of recent LHCb results are still based on Runs 1-2 datasets

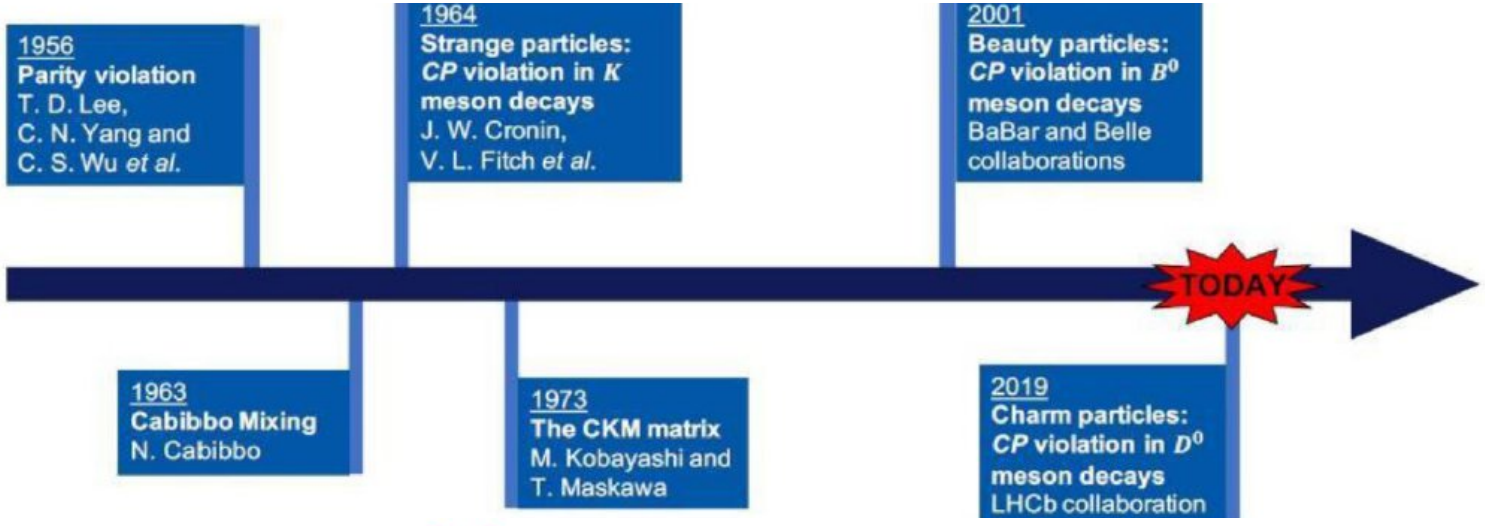
LHCb physics program

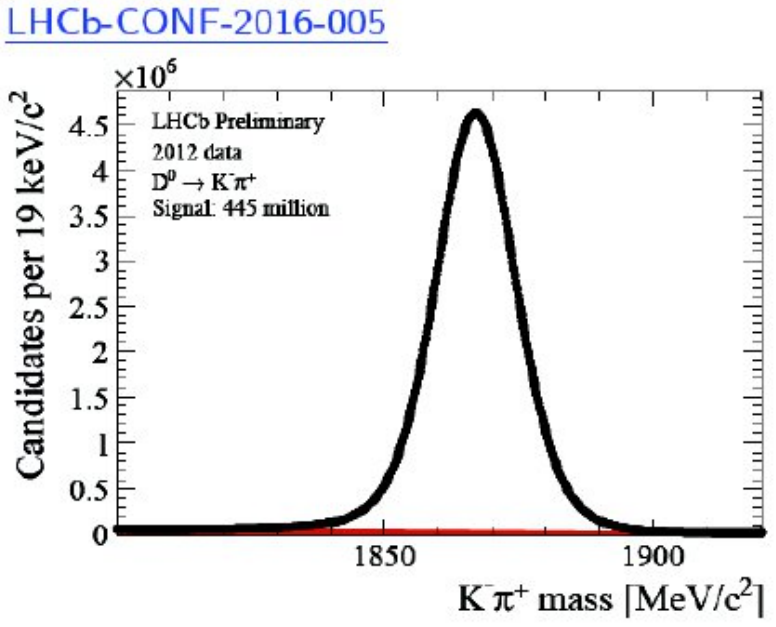


>800 papers published



LHCb as a charm factory





physicsworld 2019 Breakthrough of the Year

- LHCb acceptance: $2 < \eta < 5$ (forward region)
- Large production cross-section

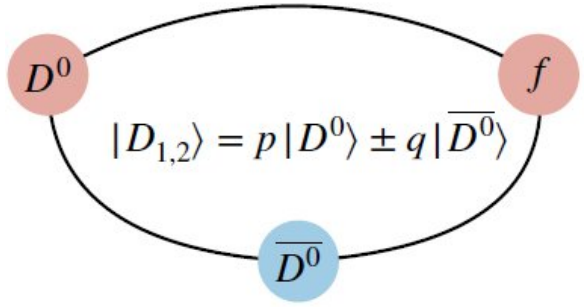
[JHEP 03 (2016) 159]

$$\sigma(pp \to c\bar{c}) = (2369 \pm 3 \pm 152 \pm 118)\,\mu b\,@\,13\,TeV$$

- More than 1 billion $D^0 \to K^-\pi^+$ collected by LHCb between 2011 and 2018
- Run2: Turbo stream from online reconstruction

[Comput. Phys. Commun. 208 (2016) 35]

Charm mixing & CPV

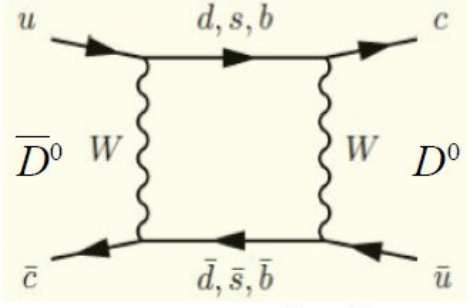


- Charm mixing – a well-established fact:
  - Mass eigenstates are related to their flavor eigenstates via $|D_{1,2}> \equiv p|D^0> \pm q|D^0>$, with $|q|^2 + |p|^2 \equiv 1$
  - Mixing parameters based on the mass and width differences: $x \equiv (m_2 - m_1)/\Gamma$, $y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$, with $\Gamma \equiv (\Gamma_2 + \Gamma_1)/2$
- *CP* violation contributions:
  - In decays: amplitudes for a process and its conjugate differ

Direct *CP* violation $\left|\frac{\overline{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \rightarrow a_{CP}^{dir} \approx -\frac{1}{2} A_d$

  - In mixing: rates of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ differ

Indirect *CP* violation $\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m \rightarrow a_{CP}^{ind} = -\frac{A_m}{2} y\cos\phi + x\sin\phi$



ϕ: *weak phase,*
A_m: *CPV from mixing*

  - In interference between mixing and decay diagrams

Unitarity triangle for charm

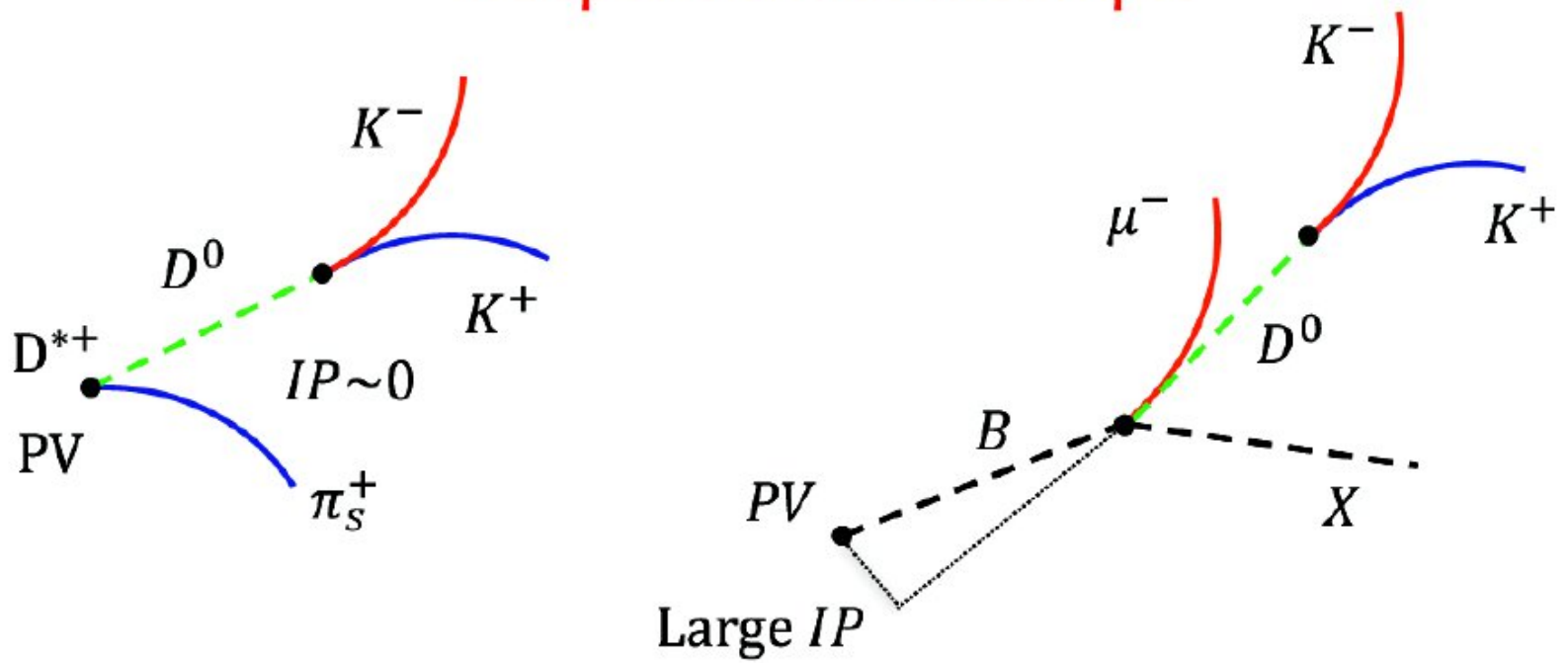
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$
$$\sim\lambda \quad \sim\lambda \quad \sim\lambda^5$$
$$\lambda = \sin(\theta_c) \sim 0.23$$

Expected CPV very small in charm
- Effectively 2-generation system
- 3rd generation and CPV enter through loops

D^0 production at LHCb

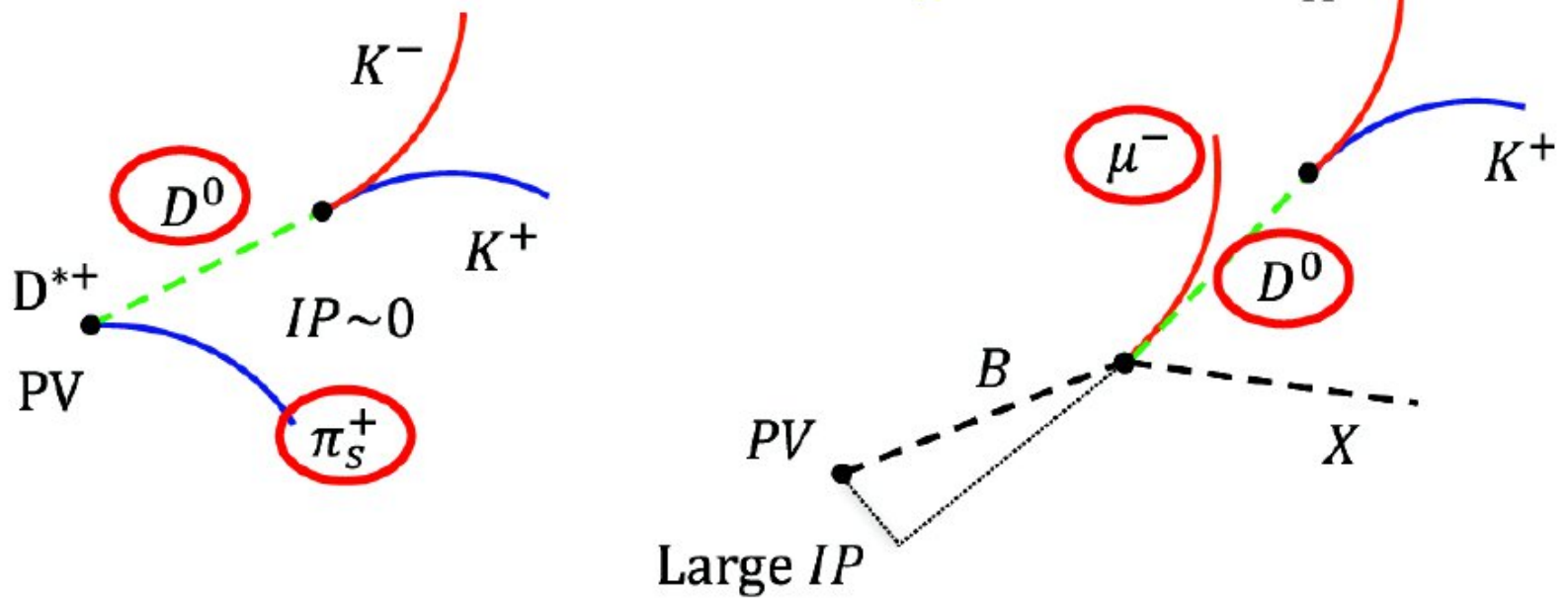
Two mechanisms of D^0 production

Independent data sample



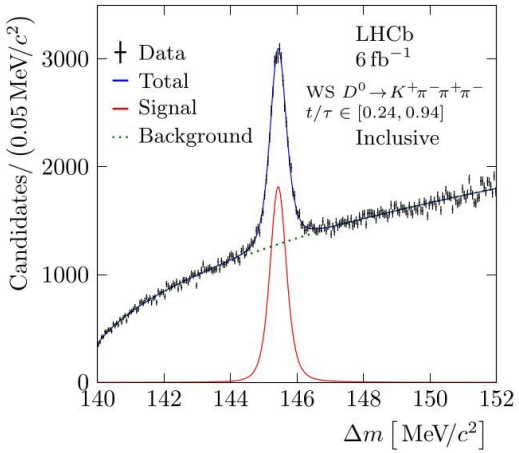
D^0 flavor tagging at LHCb

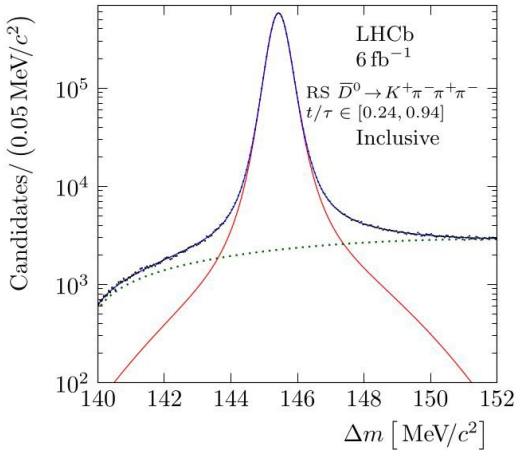
Experimentally we can tag D^0 flavour at production by means of the charge of the muon and the soft pion



Mixing and CPV with $D^0 \to K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$

- Using full Run2 6 fb^{-1} data
- Based on $D^0 \to K^-\pi^+\pi^-\pi^+$ (RS) and $D^0 \to K^+\pi^-\pi^+\pi^-$ (WS) decays
- D^0 tagged via $D^{*+} \to D^0\pi_s^+$
- Data split into 4 PHSP bins with binning shared with CKM phase γ measurement
- Fit to extract κ and δ constraining mixing parameters x and y from global fit
- Alternative fit to extract CPV & mixing parameters constraining κ and δ from external inputs including BESIII



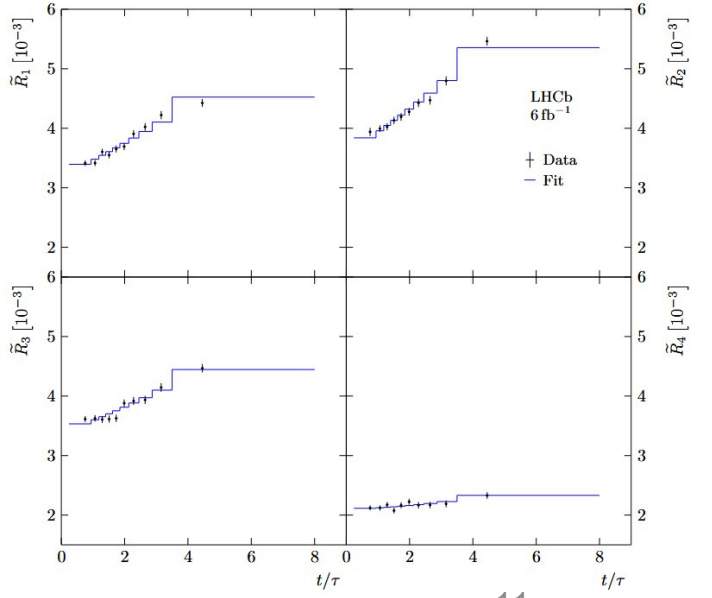


$$y' \equiv y\cos\delta - x\sin\delta$$

$$R(t) \equiv \frac{\Gamma[D^0 \to K^+\pi^-\pi^+\pi^-](t)}{\Gamma[D^0 \to K^-\pi^+\pi^-\pi^+](t)} \approx$$

$$\approx r^2 - r\kappa y'\frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$

$$\kappa e^{i\delta} \equiv \langle\cos\delta_l\rangle + i\langle\sin\delta_l\rangle$$



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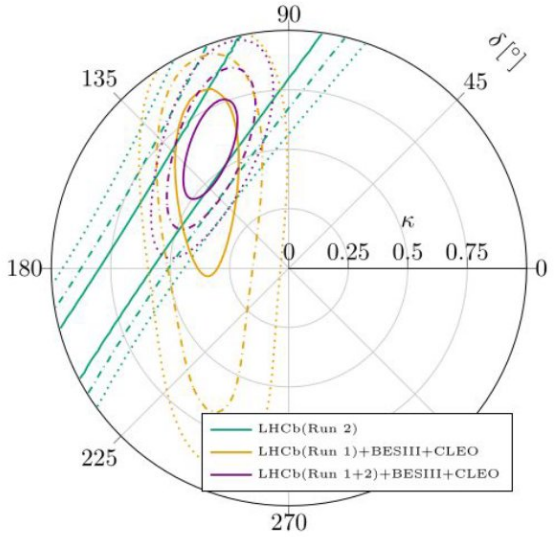
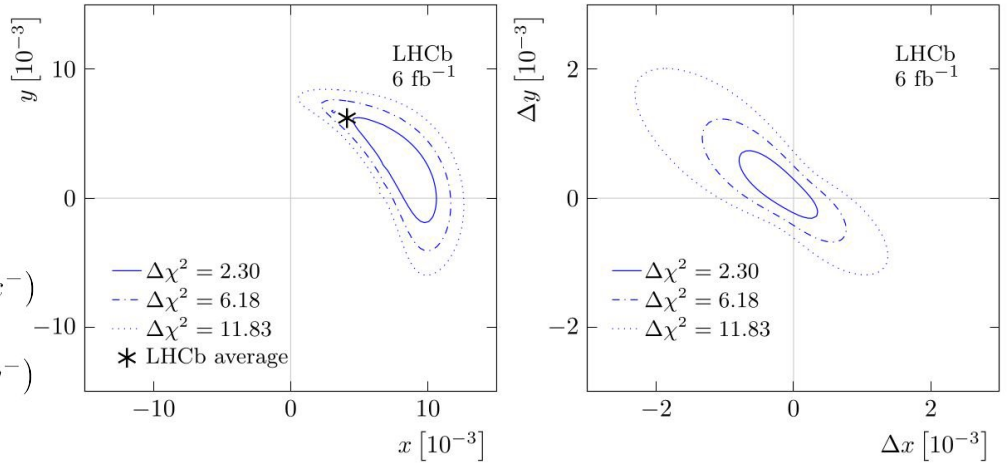


- ✓ Significantly improved precision on hadronic parameters
- ✓ Important input for γ measurement with $B^- \to K^- D^0(K\pi\pi\pi)$

$$\Delta x = \frac{1}{2}\left(x^+ - x^-\right)$$

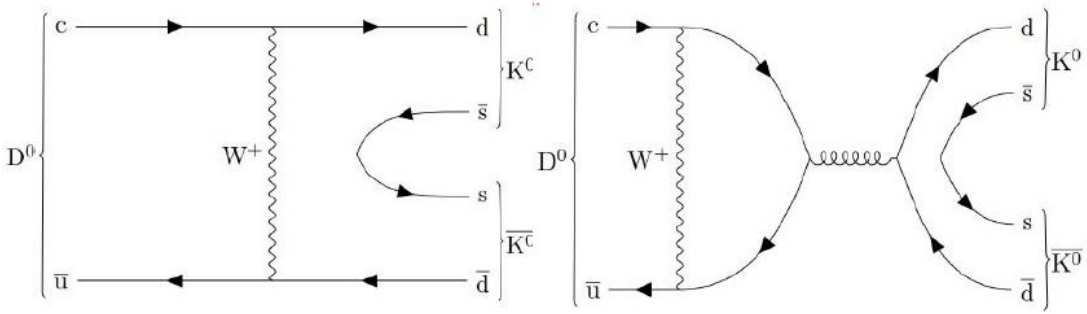
$$\Delta y = \frac{1}{2}\left(y^+ - y^-\right)$$

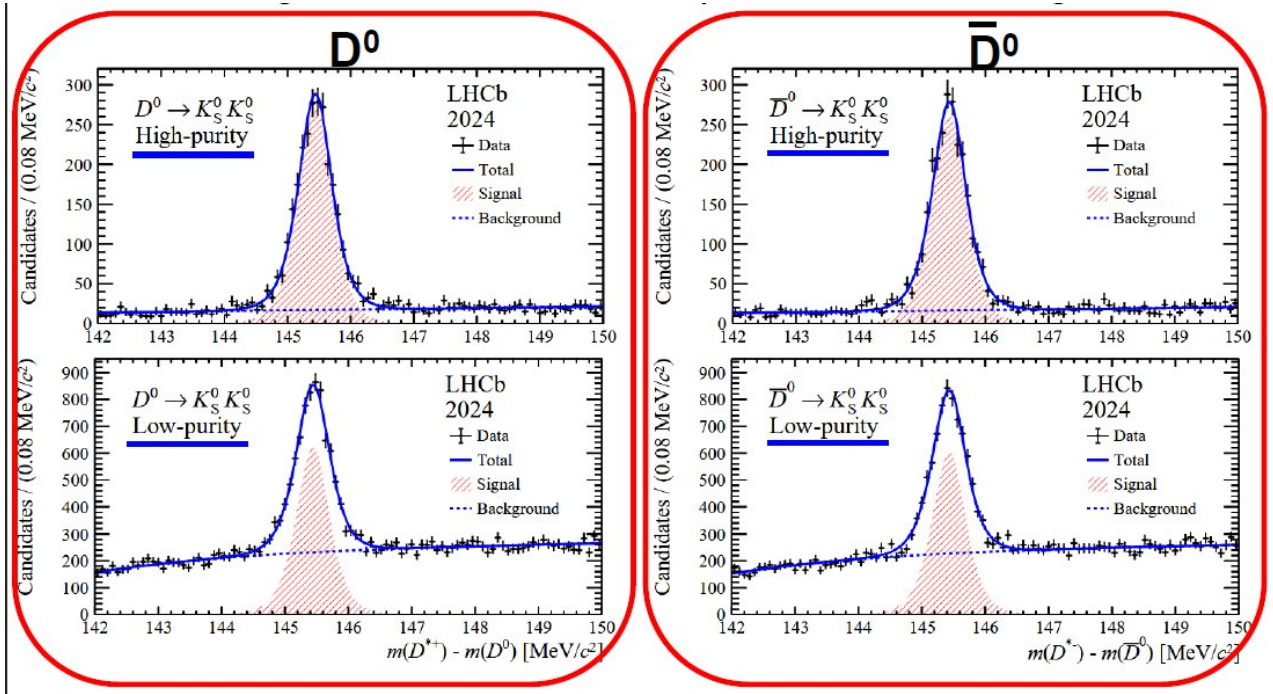


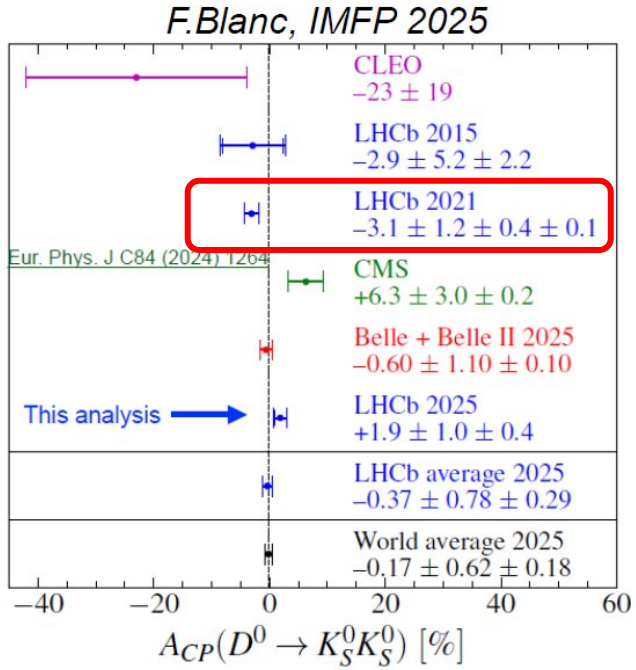
One of the most precise measurements of Δx and Δy

CPV in $D^0 \to K^0_S K^0_S$

- Using Run3 (2024) 6.2 fb^{-1} data
- D^0 tagged via $D^{*+} \to D^0 \pi^+_s$
- $D^0 \to K^0_S \pi^+ \pi^-$ as control mode
- Two categories with low/high purites according to kNN classifier:







~3x efficiency wrt Run2 due to dedicated Hlt1 selection on K^0_S

$$\mathcal{A}^{CP}(K^0_S K^0_S) = (1.86 \pm 1.04 \pm 0.41)\%$$

Most precise single measurement of this quantity to date

arXiv:2607.20276

CPV in $D^+ \to \phi\pi^+$

- Using full Run2 6 fb^{-1}data
- $D^+ \to K^0_S\pi^+$ used to cancel nuisance asymmetry
- Time-dependent analysis in bins of $\tau(K^0_S)$ to model K^0_S asymmetry that accouts for interference of CF/DCS decays:
- Result:

$$A_{CP}(D^+ \to \phi\pi^+) = (0.1 \pm 4.9 \pm 2.4) \times 10^{-4}$$

$$A^s(D^+ \to \phi\pi^+) = A^s_{\rm P}(D^+) + A^s_{\rm D}(\pi^+) + a_{CP}(D^+ \to \phi\pi^+),$$

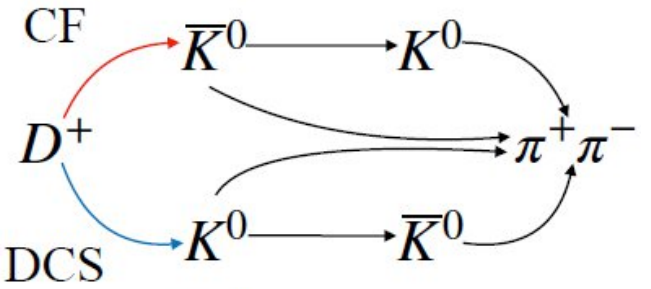
$$A^s(D^+ \to K^0_S\pi^+) = A^s_{\rm P}(D^+) + A^s_{\rm D}(\pi^+) + A^s_{\rm D}(K^0_S),$$

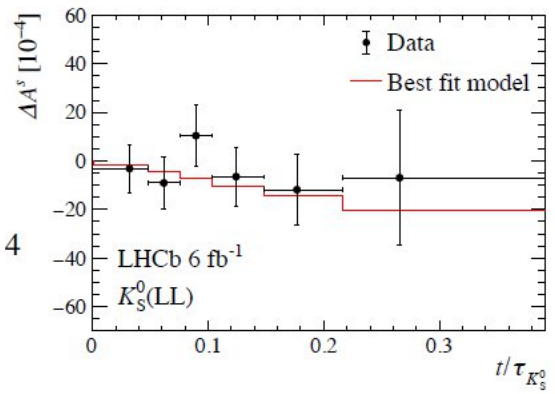
$$\Delta A^s \equiv A^s(D^+ \to K^0_S\pi^+) - A^s(D^+ \to \phi\pi^+) \approx A^s_{\rm D}(K^0_S) - a_{CP}(D^+ \to \phi\pi^+).$$

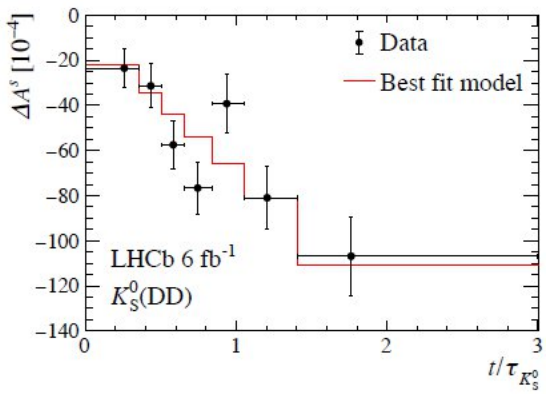
$$r_\pi e^{i(\delta_\pi+\phi)} = \frac{\mathscr{A}(DCS)}{\mathscr{A}(CF)}$$

$D^+ \to \overline{K}^0\pi^+$ CF decay

$D^+ \to K^0\pi^+$ DCS decay







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CPV in $D^+ \to \phi\pi^+$

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- $D^+ \to K^0_S\pi^+$ used to cancel nuisance asymmetry
- Time-dependent analysis in bins of $\tau(K^0_S)$ to model K^0_S asymmetry that accouts for interference of CF/DCS decays:
- Result:

$$A_{CP}(D^+ \to \phi\pi^+) = (0.1 \pm 4.9 \pm 2.4) \times 10^{-4}$$

- Model-independent ULs on strong parameters provided for the first time in a collider experiment!
  - Compatible with FAT predictions

$$A^s(D^+ \to \phi\pi^+) = A^s_{\rm P}(D^+) + A^s_{\rm D}(\pi^+) + a_{CP}(D^+ \to \phi\pi^+),$$

$$A^s(D^+ \to K^0_S\pi^+) = A^s_{\rm P}(D^+) + A^s_{\rm D}(\pi^+) + A^s_{\rm D}(K^0_S),$$

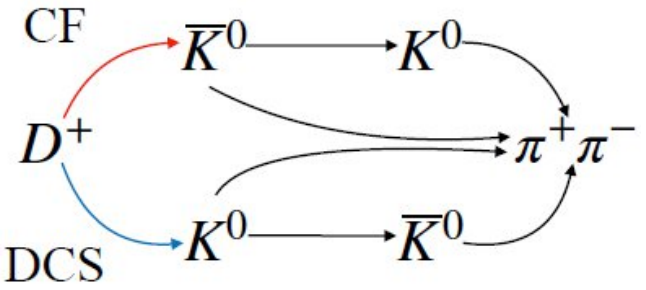
$$\Delta A^s \equiv A^s(D^+ \to K^0_S\pi^+) - A^s(D^+ \to \phi\pi^+)$$

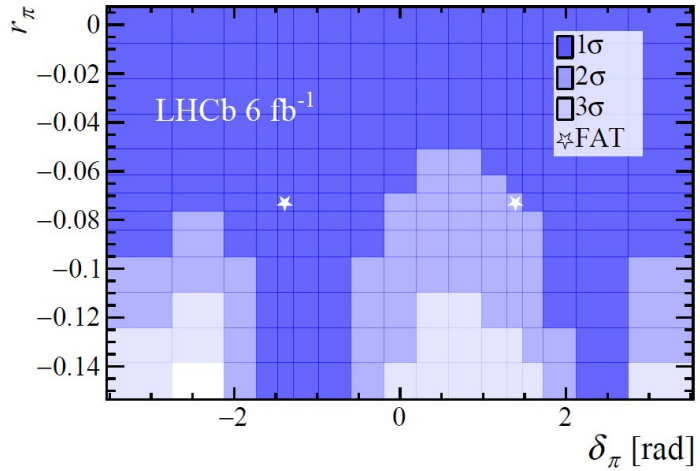
$$\approx A^s_{\rm D}(K^0_S) - a_{CP}(D^+ \to \phi\pi^+).$$

$$r_\pi e^{i(\delta_\pi+\phi)} = \frac{\mathscr{A}(DCS)}{\mathscr{A}(CF)}$$

$D^+ \to \overline{K}^0\pi^+$ CF decay

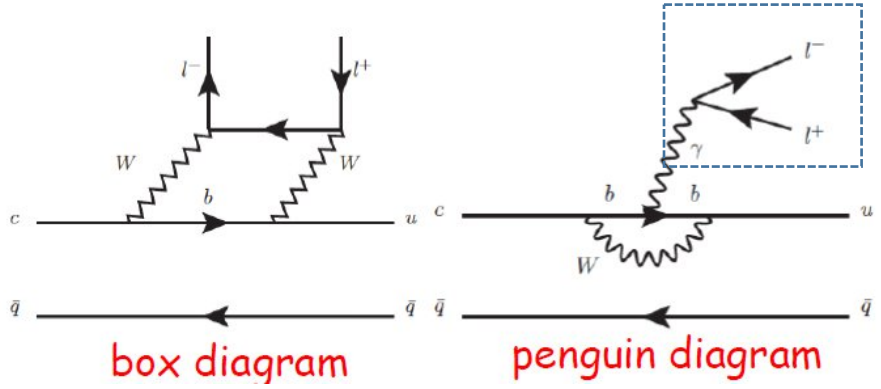
$D^+ \to K^0\pi^+$ DCS decay

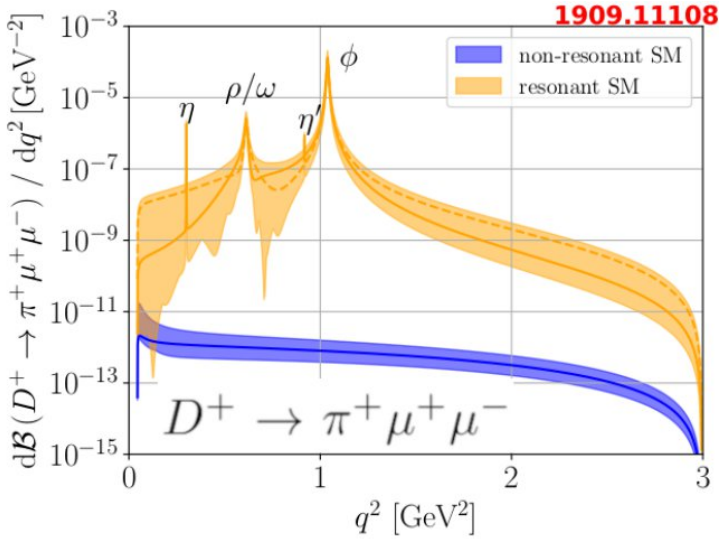


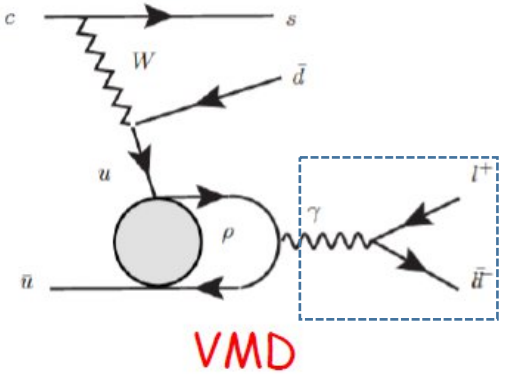


Flavor Changing Neutral Currents in charm

- $c \to u\ell\ell$ processes forbidden at tree level in SM, only allowed in loop and box diagrams
  - Strongly suppressed due to GIM cancellation:
  - Expected SM BF ~O(10^{-9})
  - NP might manifest in the loops
- $D \to X\ell^+\ell^-$ dominated by Long-Distance contributions
  - Vector Meson Dominance (VMD)
  - BF ~O(10^{-6}) for $D \to X\ell^+\ell^-$

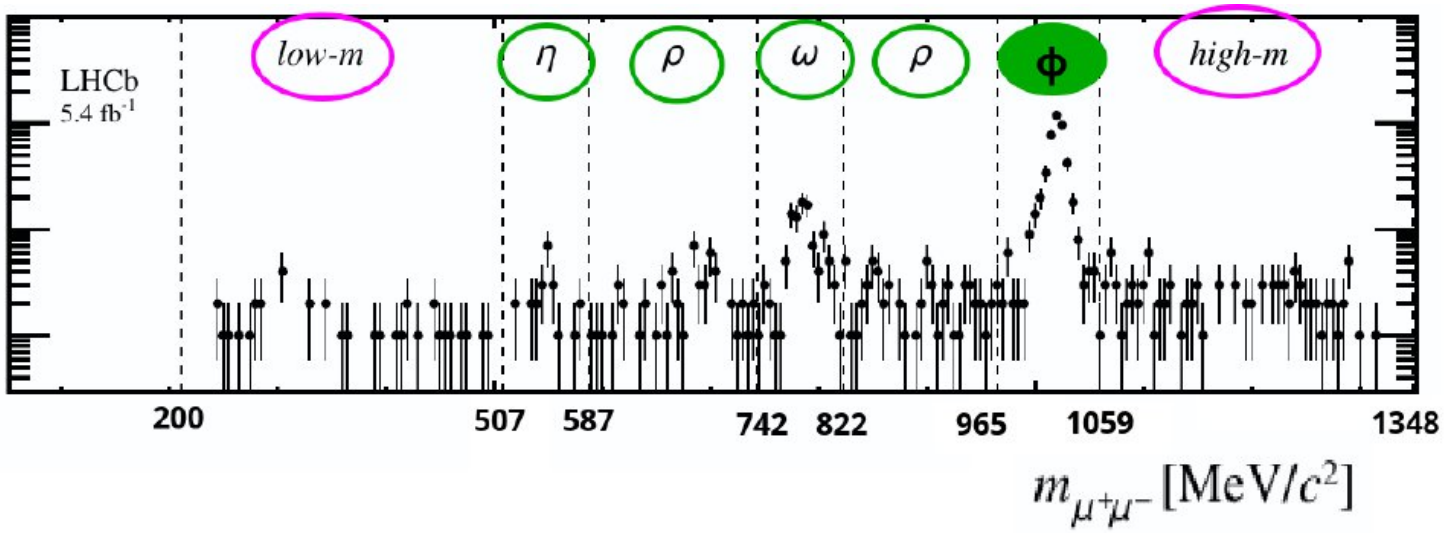


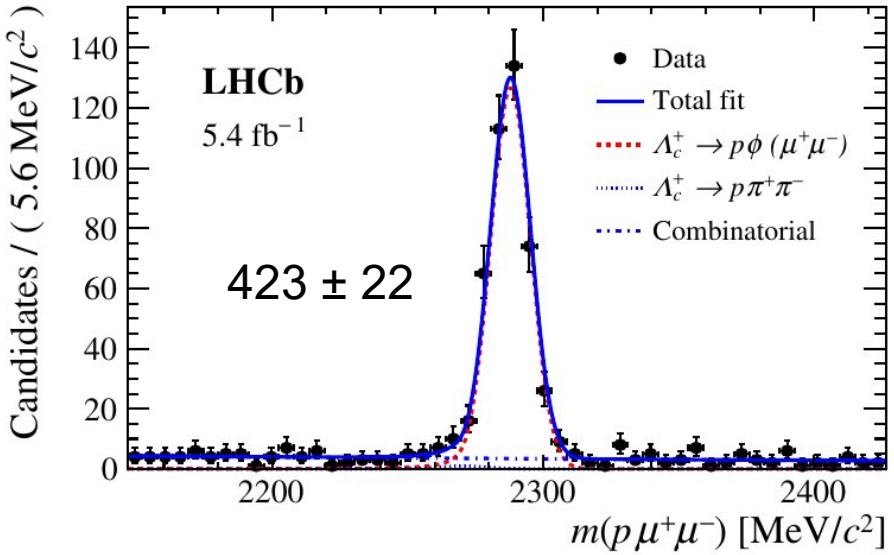




Search for $\Lambda_c^+ \to p\mu^+\mu^-$

- Based on Run2 5.4 fb^{-1} dataset
- Signals searched for in 6 dimuon mass regions
- Normalized to ϕ resonant region





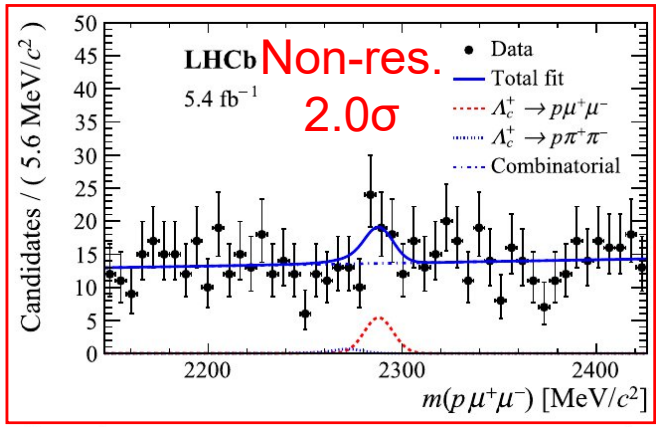
Search for $\Lambda_c^+ \to p\mu^+\mu^-$

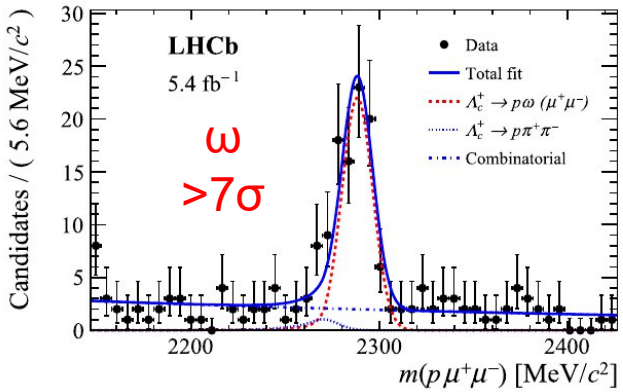
- BFs measured in different resonant regions:

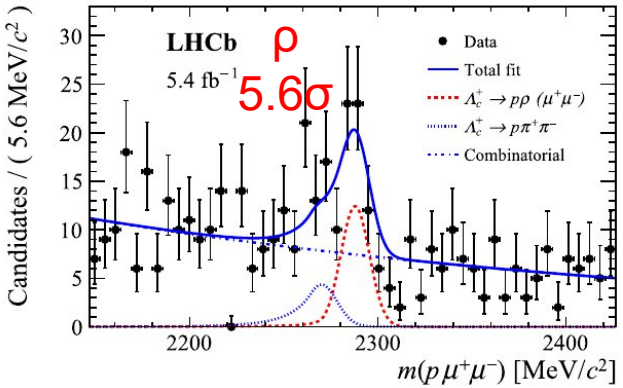
$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23(\text{stat}) \pm 0.73(\text{syst}) \pm 2.79(\text{ext})) \times 10^{-4}$$
$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34(\text{stat}) \pm 0.14(\text{syst}) \pm 0.24(\text{ext})) \times 10^{-3}$$
$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69(\text{stat}) \pm 0.23(\text{syst}) \pm 0.34(\text{ext})) \times 10^{-3}$$

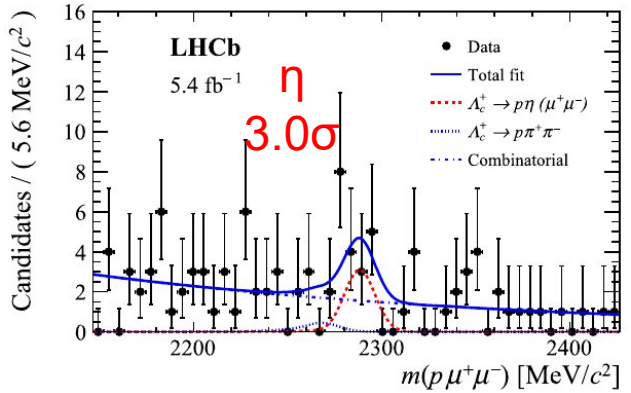
- Most stringent limit set on non-resonant BF:

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9\ (3.2) \times 10^{-8} \quad \text{at}\ \ 90\%\ (95\%)\ \text{CL.}$$



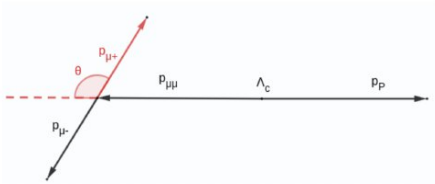






$\Lambda_c^+ \to p\mu^+\mu^-$: CPV & angular asymmetries

- Asymmetries in ϕ region compatible with SM prediction and conservation of P and CP symmetry



$$A_{FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

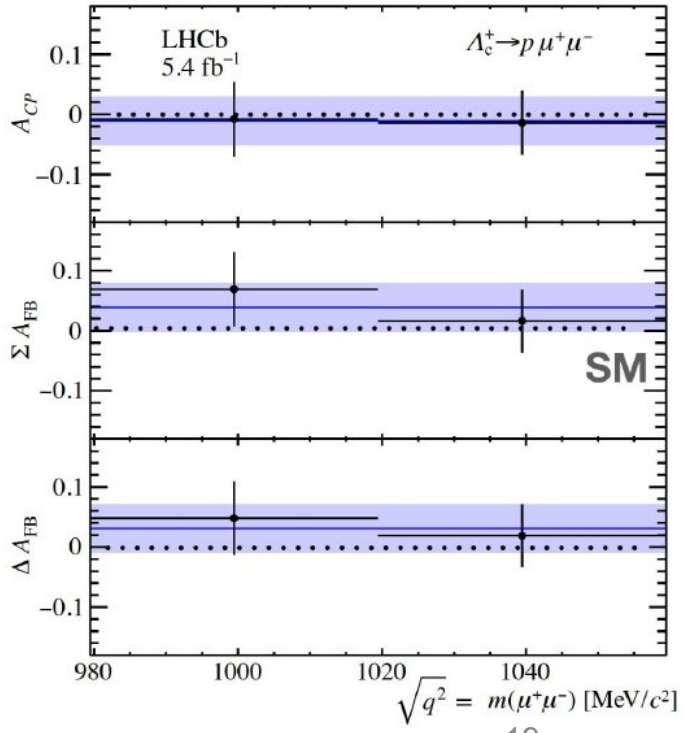
$$A_{CP} = \frac{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) - \Gamma(\Lambda_c^- \to \bar{p}\mu^+\mu^-)}{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) + \Gamma(\Lambda_c^- \to \bar{p}\mu^+\mu^-)}$$

$$\Sigma A_{\rm FB}^{CP} \equiv 1/2 \cdot \left[A_{\rm FB}^{\Lambda_c^+} + A_{\rm FB}^{\bar{\Lambda}_c^-}\right]$$

$$\Delta A_{\rm FB}^{CP} \equiv 1/2 \cdot \left[A_{\rm FB}^{\Lambda_c^+} - A_{\rm FB}^{\bar{\Lambda}_c^-}\right]$$

Dimuon-mass integrated

	Stat.	Sys.
$A_{CP} = (-1.1 \pm 4.0 \pm 0.5)\%$		
$\Sigma A_{\rm FB} = (\ 3.9 \pm 4.0 \pm 0.6)\%$		
$\Delta A_{\rm FB} = (\ 3.1 \pm 4.0 \pm 0.4)\%$		



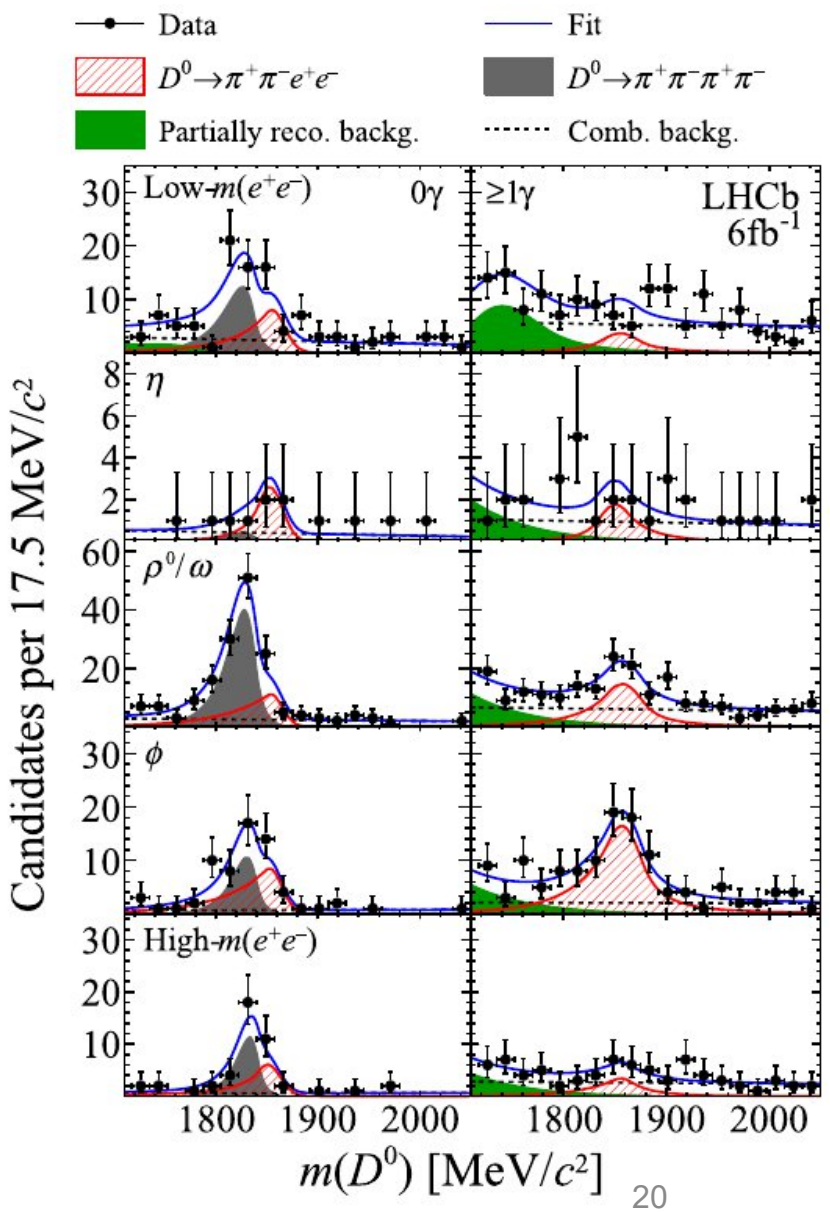
Search for $D^0 \to \pi^+\pi^- e^+ e^-$

- Based on Run2 6 fb^{-1} dataset
- Signals searched for in 5 dielectron mass regions
- First observation in ρ/ω & ϕ regions

$m(e^+e^-)$ region	[MeV/c^2]	Yield	$\mathcal{S}$
	$D^0 \to \pi^+\pi^- e^+ e^-$		
Low mass	$2m_\mu$–525	37 ± 13	2.8σ
η	525–565	10 ± 7	1.6σ
ρ^0/ω	565–950	97 ± 21	5.5σ
ϕ	950–1100	100 ± 18	8.1σ
High mass	> 1100	30 ± 11	2.9σ

- Total BF: $\mathcal{B}(D^0 \to \pi^+\pi^-[e^+e^-]_{m(e^+e^-)>2m_\mu})$

$$= (13.3 \pm 1.7 \pm 1.7 \pm 1.8) \times 10^{-7}$$

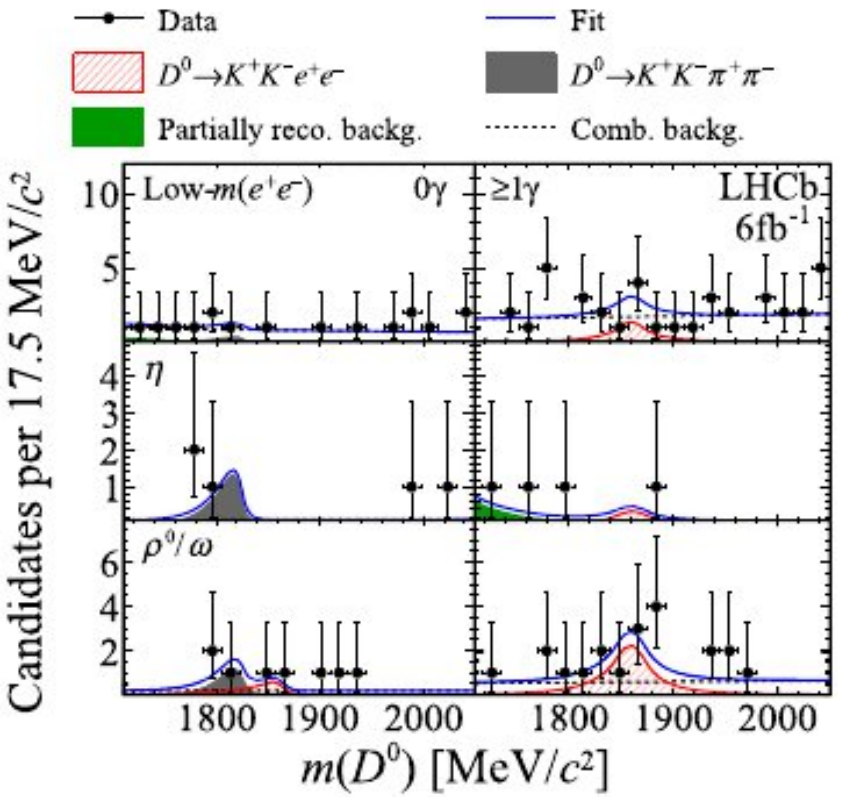


Search for $D^0 \to K^+K^-e^+e^-$

- Based on Run2 6 fb^{-1} dataset
- Signals searched for in 3 dielectron mass regions

$m(e^+e^-)$ region	[MeV/c^2]	Yield	$\mathcal{S}$
	$D^0 \to K^+K^-e^+e^-$		
Low mass	$2m_\mu$–525	4 ± 8	1.2σ
η	525–565	1 ± 2	1.1σ
ρ^0/ω	> 565	12 ± 7	2.2σ

- BF upper limits of O(10^{-7}) are set in different regions



Similar study performed by BELLE(II) yielding less stringent limits
[PRD 112 (2025) L071101]

Summary

- LHCb: essentially a charm factory
  - World's leading role in measuring charm mixing & CPV, and searching for rare charm decays
  - Close cooperation with BESIII important for precision improvement
- For now, most of charm results are still Run2 based
- A huge Run3 data sample now available for analysis, with a new detector & improved triggering
  - Possible observation of CPV in mixing, or in charm baryon?
  - Run3 results are showing up, stay tuned!
- And we will have Run4 and Upgrade-II
  - 50 fb-1 by 2033, > 300 fb-1 by 2041 for LHCb