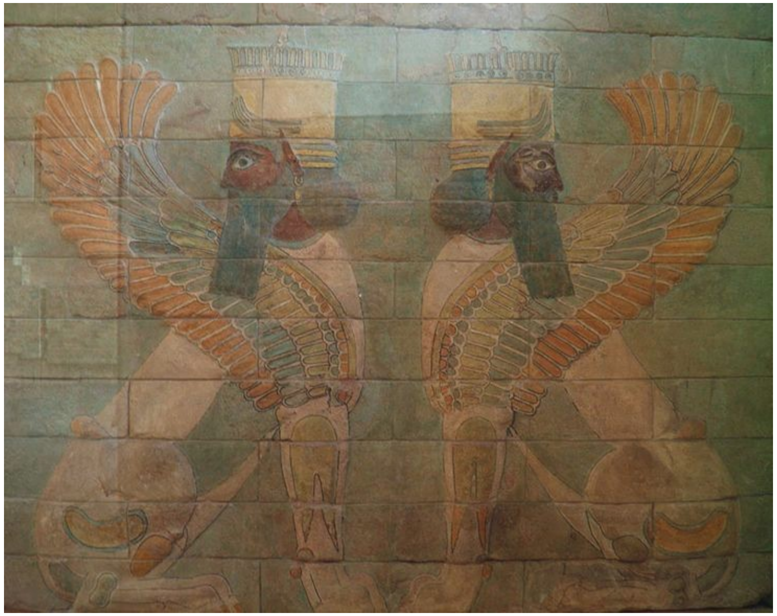


Charming physics

Tests of discrete symmetries and mixing phenomena in neutral charm meson systems at LHCb

Wojciech Krzemień

Seminar on Experimental Particle Physics

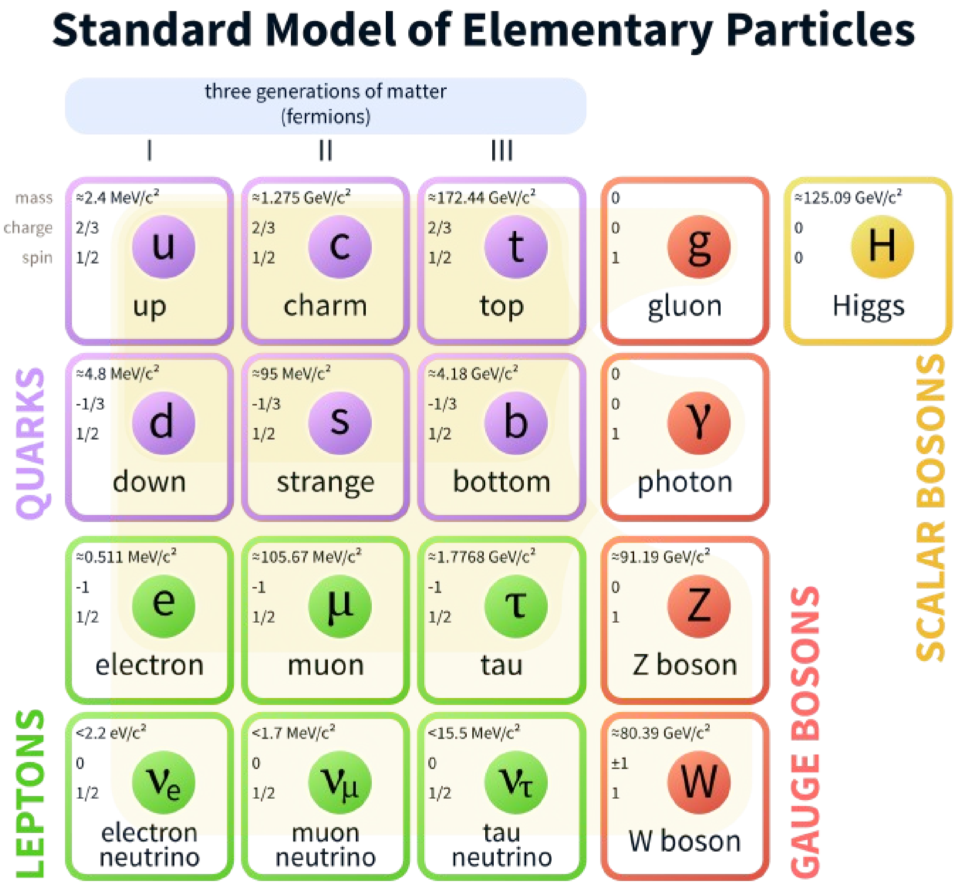
Kraków, 25.04 2022

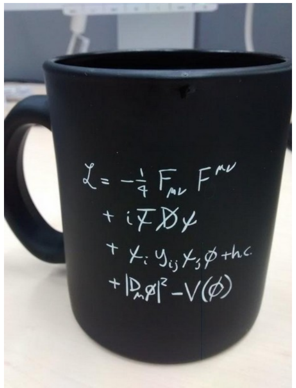
Outline

- Flavour mixing and CP violation formalism
- Charm @ LHCb detector
- Selected LHCb results in the charm sector
- Summary & Outlook

Predicted by SM:

- W, Z boson
- gluon
- c and t quarks
- Higgs boson





Predicted by SM:

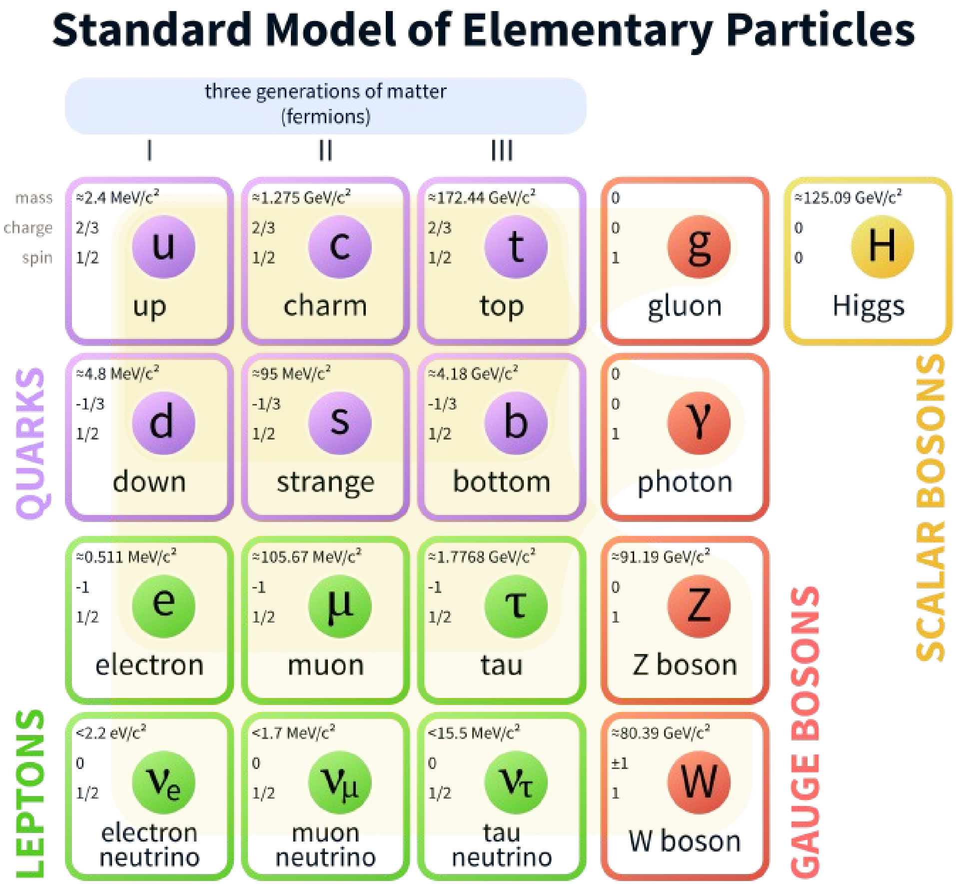
- W, Z boson
- gluon
- c and t quarks
- Higgs boson

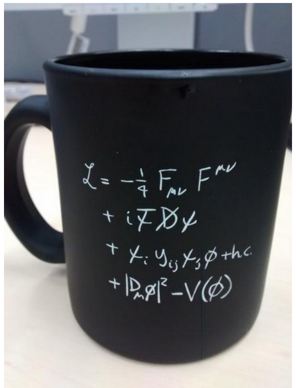
However several unresolved questions:

- Quark mass hierarchy problem
- Matter-antimatter asymmetry
- Dark matter / dark energy
- Neutrino mass

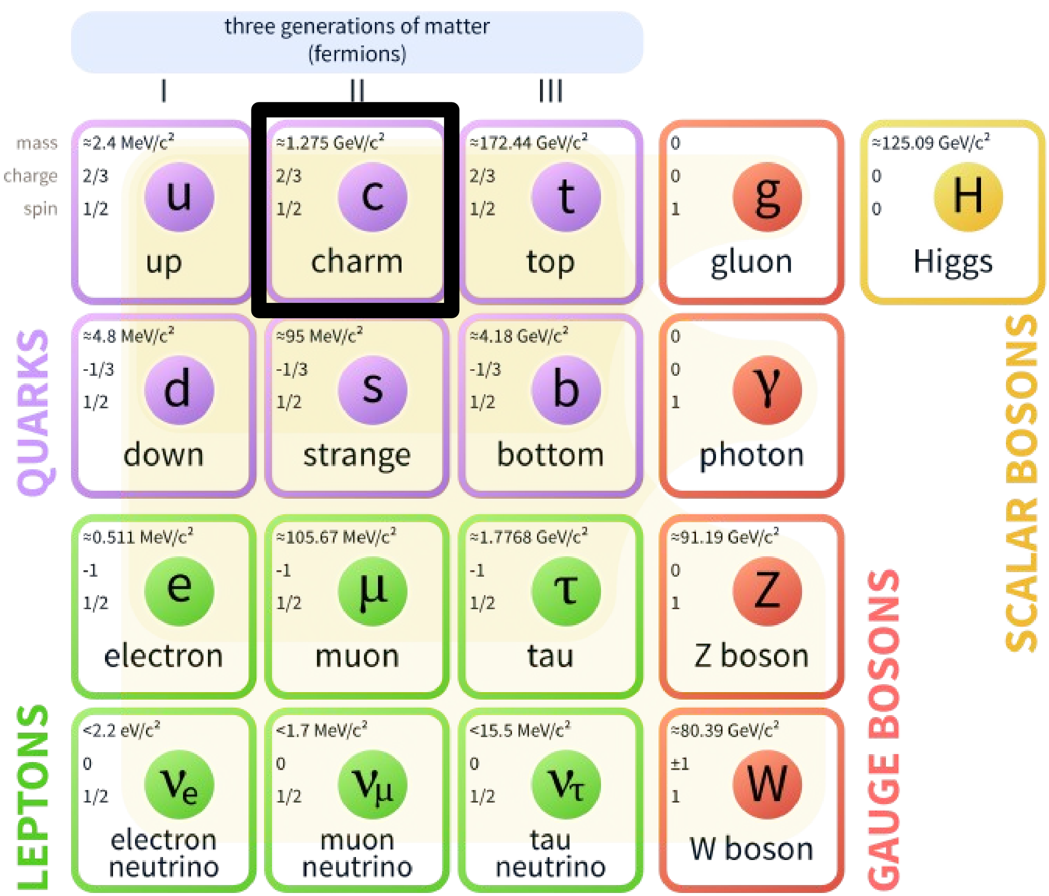
- ...
- How to incorporate gravity forces

Looking for SM “holes” to reveal “hidden” New Physics phenomena


Standard Model of Elementary Particles

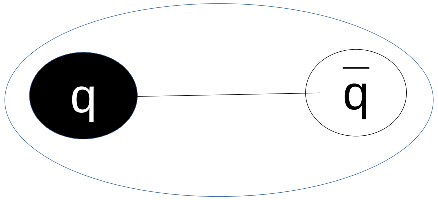


Standard Model of Elementary Particles



three generations of matter (fermions)

	I	II	III		
mass charge spin	≈2.4 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈172.44 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c^2 0 0 H Higgs
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
	≈0.511 MeV/c^2 -1 1/2 e electron	≈105.67 MeV/c^2 -1 1/2 μ muon	≈1.7768 GeV/c^2 -1 1/2 τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS



Flavour neutral mesons

K_0 ($d\bar{s}$)
- m ~= 0.5 GeV/c^2

B_0 ($d\bar{b}$)
- m ~= 5 GeV/c^2

B_S ($s\bar{b}$)
- m ~= 5.4 GeV/c^2

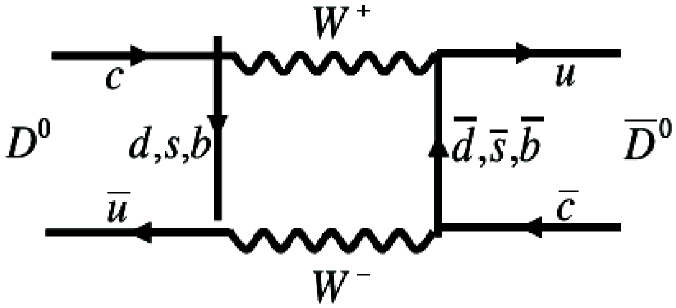
D_0 ($c\bar{u}$)
- m ~= 1.9 GeV/c^2

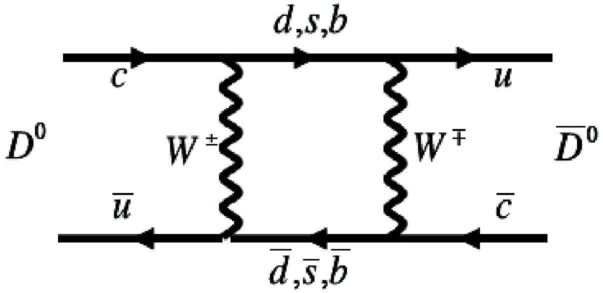
Charming physics

Flavour mixing

Flavour neutral mesons mixing

Weak interactions do not conserve the flavour





Flavour neutral mesons mixing

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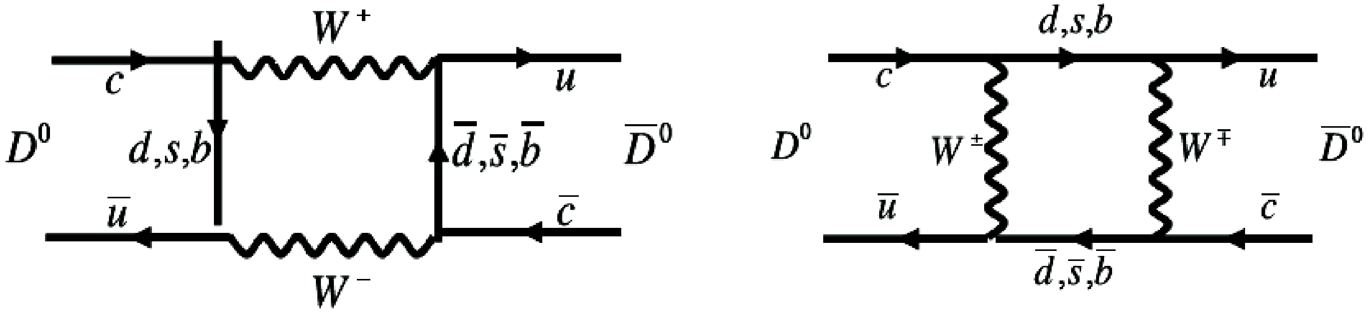
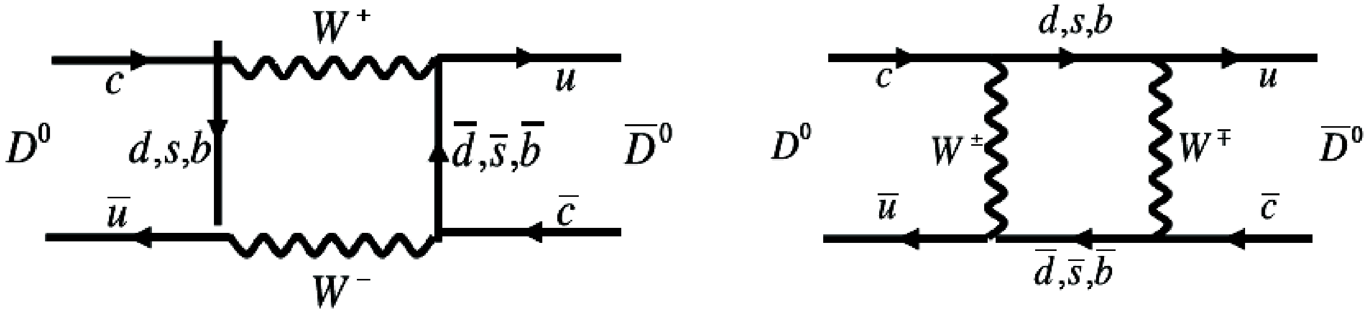


Flavour states are not eigenvectors of the full Hamiltonian

$$\frac{\partial}{\partial t}|\Phi >= H|\Phi >$$

Flavour neutral mesons mixing

Weak interactions do not conserve the flavour



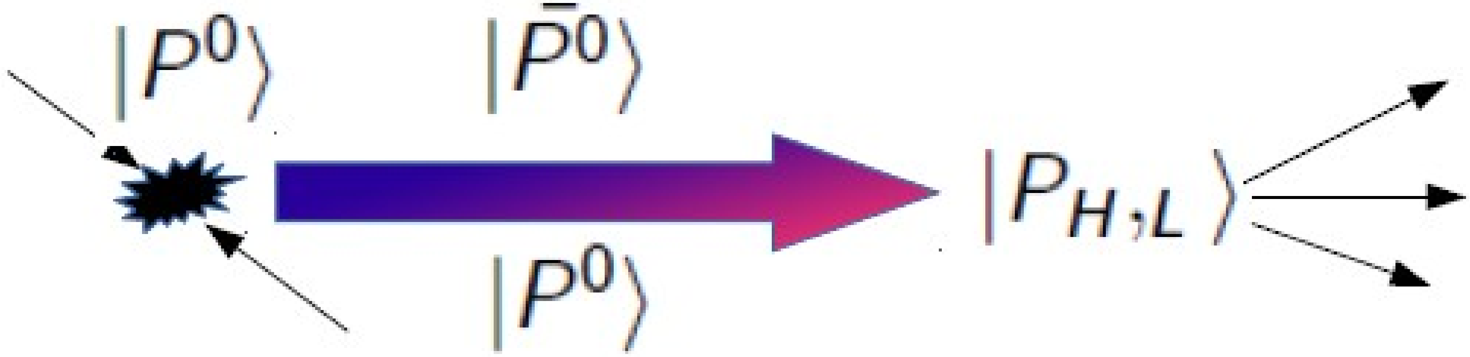
Flavour states are not eigenvectors of the full Hamiltonian

$$\frac{\partial}{\partial t}|\Phi>=H|\Phi>$$

Mass eigenstates expressed as a superposition of flavour eigenstates :

$|D_{1,2}\rangle = p|\mathrm{D}^0\rangle \pm q|\bar{\mathrm{D}}^0\rangle$ $|p|^2+|q|^2=1$ *p, q* are complex

Flavour neutral mesons mixing



Weisskopf-Wigner approach

$$|\Phi >= a(t)|P^0 > +b(t)|\bar{P^0} > \tag{1}$$

$$\frac{\partial}{\partial t}|\Phi >= H|\Phi >, \tag{2}$$

- effective 2x2 Hamiltonian,
- time-independent,
- non-diagonal elements change flavour,
- non-Hermitian since decays outside of the $|P^0 >, |\bar{P^0} >$ subspace,

$$H = M - \frac{i}{2}\Gamma, \tag{3}$$

M and Γ are hermitian matrices (mass and decay matrix, respectively).

Weisskopf-Wigner approach II

$$\begin{aligned}|P_L\rangle &= p|\mathrm{P}^0\rangle + q|\overline{\mathrm{P}}^0\rangle \\ |P_H\rangle &= p|\mathrm{P}^0\rangle - q|\overline{\mathrm{P}}^0\rangle \ ,\end{aligned} \tag{4}$$

$$\frac{q^2}{p^2} = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}} \tag{5}$$

- Conservation of CP or T: $|\frac{q}{p}| = 1$

Flavour neutral mesons mixing II

Probabilities of mixing:

$\Pr[P^0 \rightarrow P^0] \sim e^{-\Gamma t}\,(\cosh(y\Gamma t) + \cos(x\Gamma t))$

$\Pr[P^0 \rightarrow \overline{P}^0] \sim e^{-\Gamma t}\,|q/p|^2\,(\cosh(y\Gamma t) - \cos(x\Gamma t))$

Mixing parameters:

$$\boxed{x = \frac{\Delta m}{\Gamma}} \qquad \Delta\Gamma = \Gamma_1 - \Gamma_2$$

$$\boxed{y = \frac{\Delta\Gamma}{2\Gamma}} \qquad \Delta m = m_1 - m_2$$

Flavour neutral mesons mixing II

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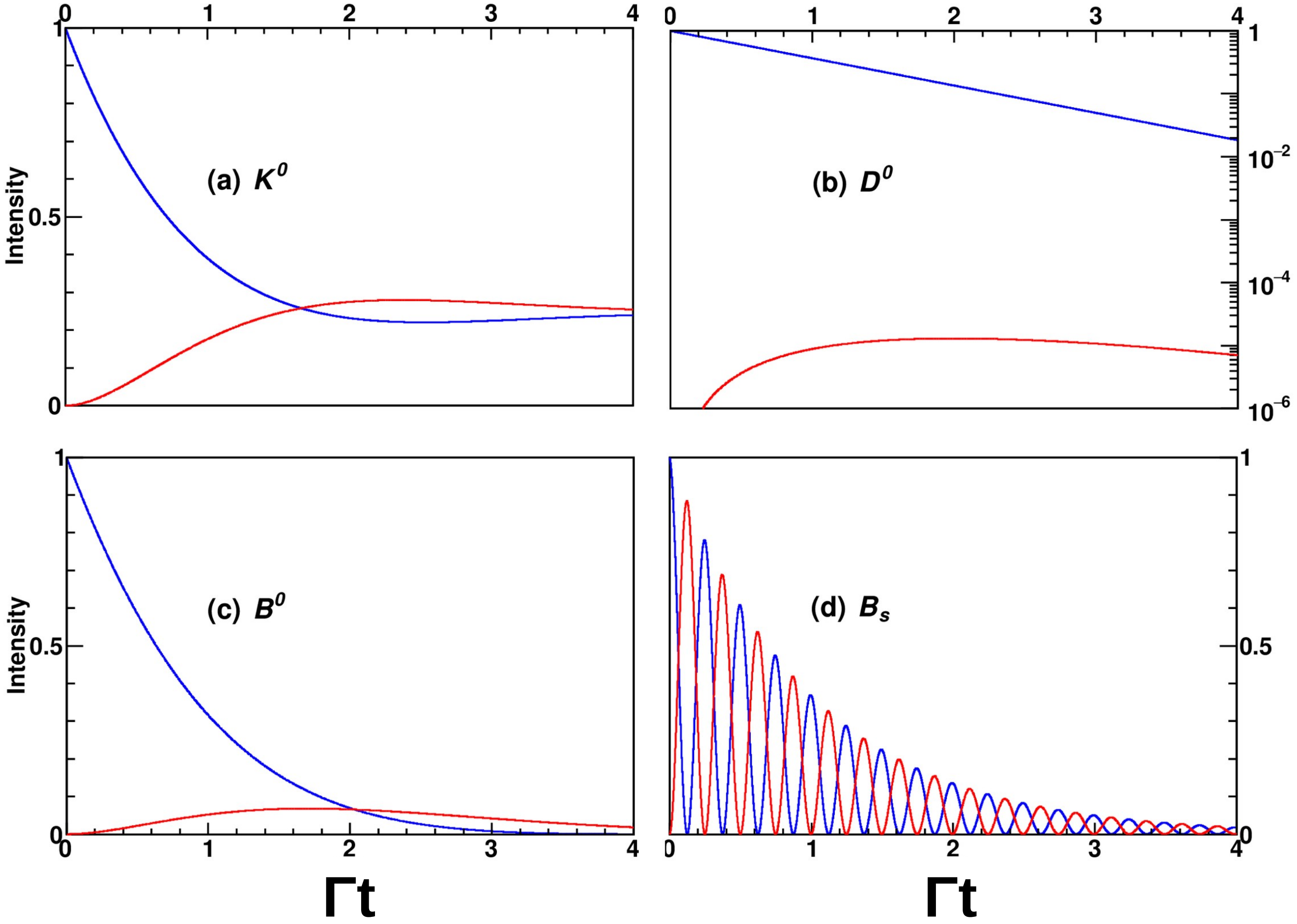


D^0 very slow:
$x \approx 0.001$, $y \approx 0.001$

K^0 slow:
$X \approx -0.95$, $y = 0.99$

B^0 fast:
$x \approx 0.78$, $y < 0.01$

B^0_s the fastest:
$x \approx 26.1$, $y \approx 0.15$

Symmetries

Symmetries in physics

Role of symmetries:

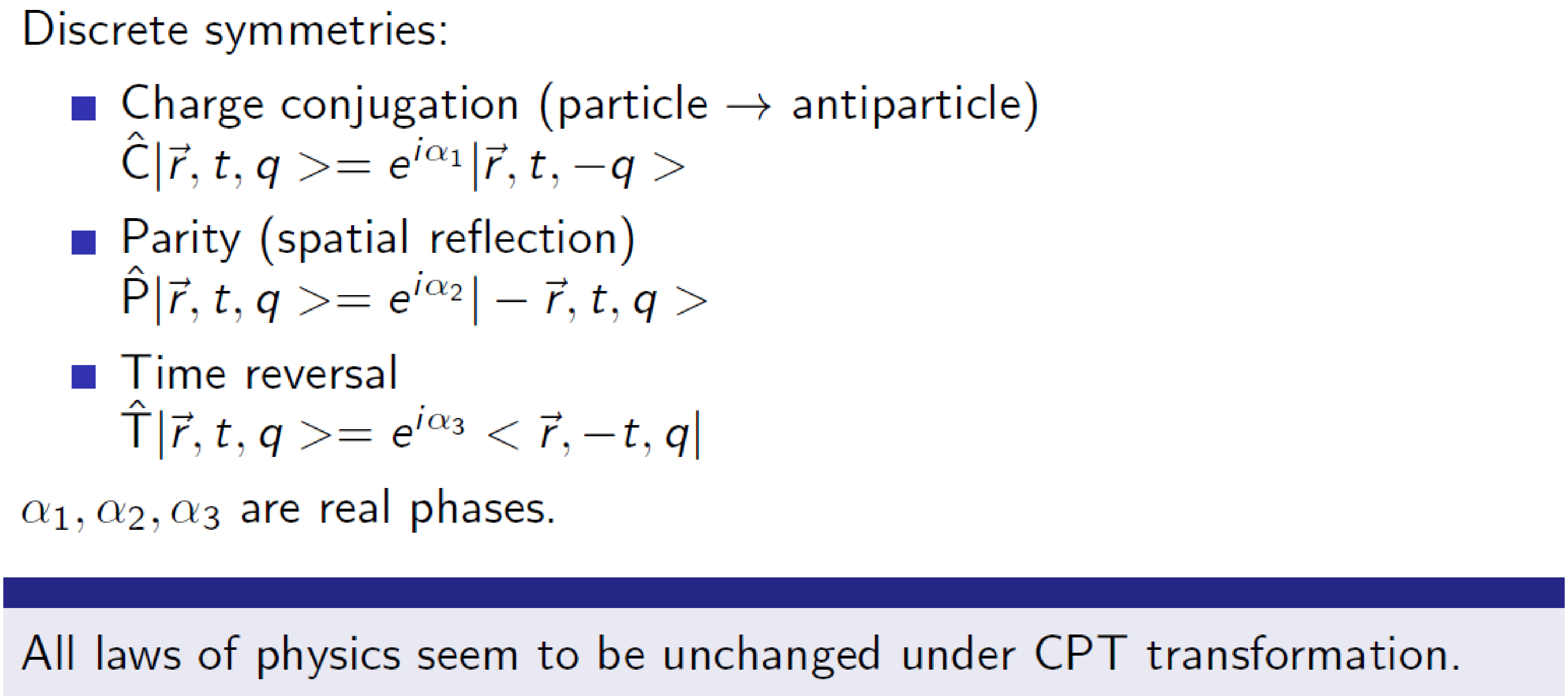
- Simplify the description of phenomena,
- Relation between symmetries and conservation of laws (e.g. Noether theorem),
- Symmetry as a methodological indication,
- Symmetries constraining dynamical laws,
- Symmetry breaking e.g. chiral fields, origin of mass, flavour physics

  ...

It is only slightly overstating the case to say that physics is the study of symmetry

P.W. Anderson, Science, New Series, Vol.177,no.4047 (1972) 393-396

C, P and T transformations



Discrete symmetries:

- Charge conjugation (particle → antiparticle)
  $\hat{C}|\vec{r}, t, q >= e^{i\alpha_1}|\vec{r}, t, -q >$
- Parity (spatial reflection)
  $\hat{P}|\vec{r}, t, q >= e^{i\alpha_2}|-\vec{r}, t, q >$
- Time reversal
  $\hat{T}|\vec{r}, t, q >= e^{i\alpha_3} < \vec{r}, -t, q|$

$\alpha_1, \alpha_2, \alpha_3$ are real phases.

All laws of physics seem to be unchanged under CPT transformation.

- C,P, CP, T symmetries broken by the weak interactions
- CP symmetry violation needed to explain matter-antimatter puzzle

History of CP violation discoveries

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

TODAY

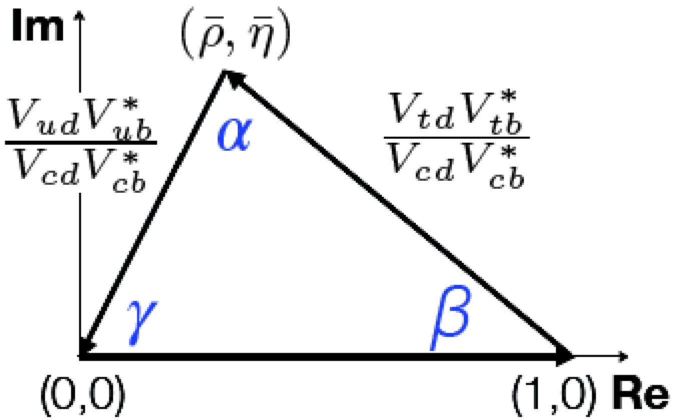
“Today” ~ presented 21.03 2019 at Moriond conference.

CP violation in Standard Model

- In SM, CPV is accommodated in weak interactions

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



Unitarity Triangle

(1st and 3rd CKM columns)

- The η is the only source of CPV in the SM.

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

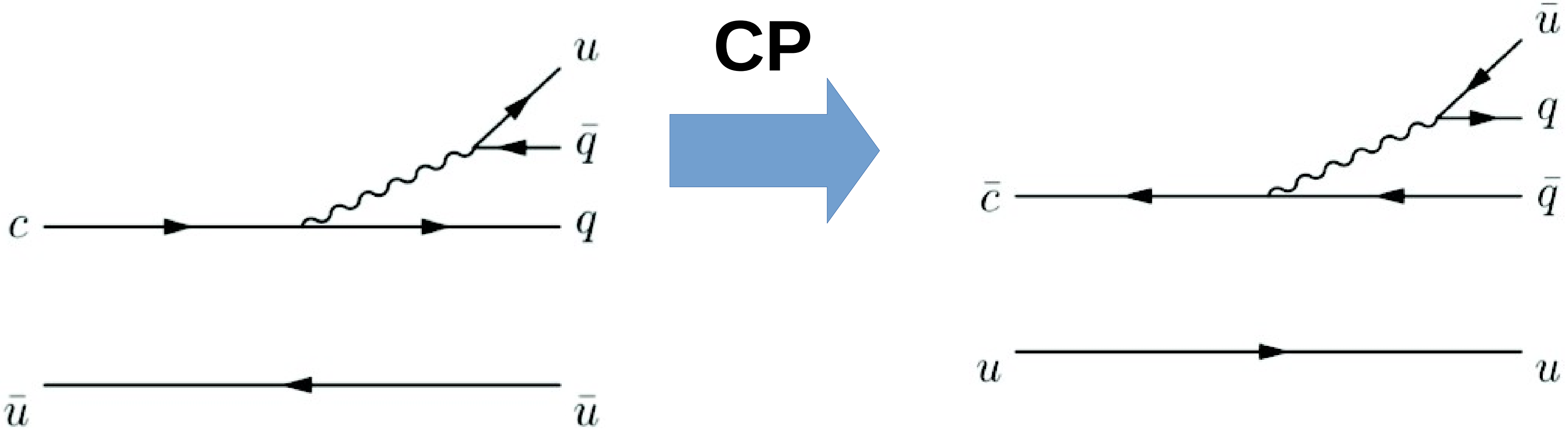
Over-constrain unitarity triangle apex coordinates for a stringent test of SM:

  - CP violation measurements give angles
  - CP conserving measurements give sides

CP violation in decay

$A = |A|\, e^{i\theta}\, e^{i\delta}$

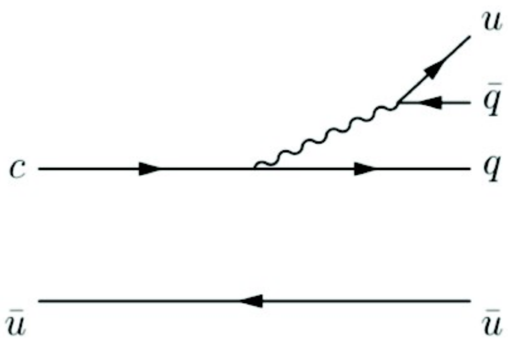
$\bar{A} = |A|\, e^{i\theta}\, e^{-i\delta}$



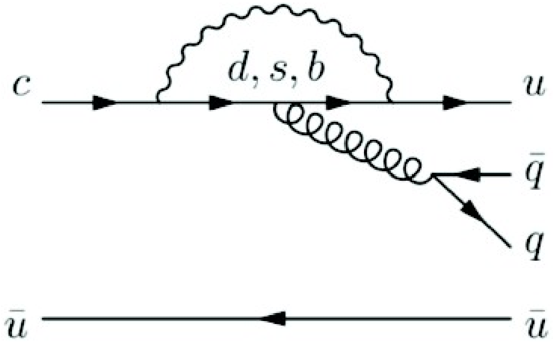
- θ – strong phase
- δ – weak phase

$$|A|^2 - |\bar{A}|^2 = 0$$

CP violation in decay

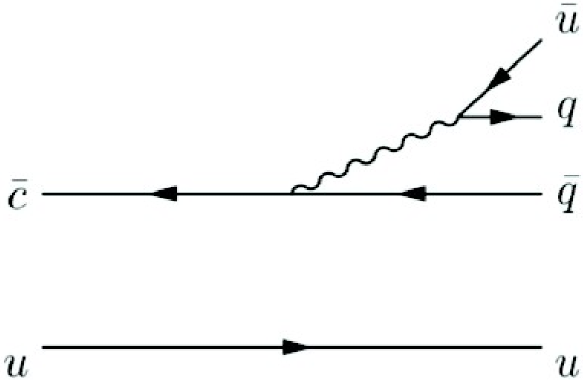


$A_1 = |A_1|\, e^{i\theta 1}\, e^{i\delta 1}$

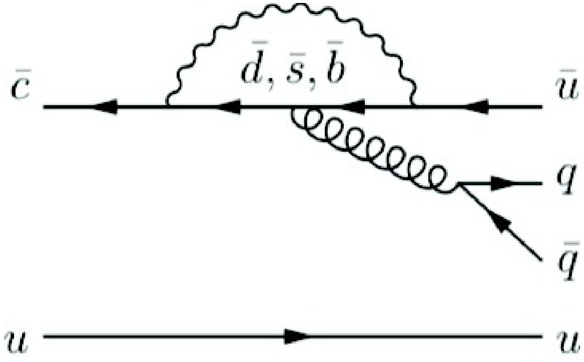


$A_2 = |A_2|\, e^{i\theta 2}\, e^{i\delta 2}$

CP

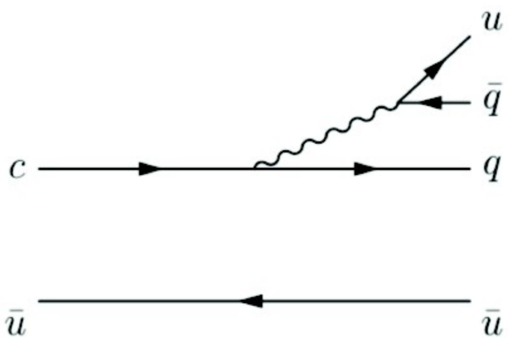


$\overline{A}_1 = |A_1|\, e^{i\theta 1}\, e^{-i\delta 1}$



$\overline{A}_2 = |A_2|\, e^{i\theta 2}\, e^{-i\delta 2}$

CP violation in decay



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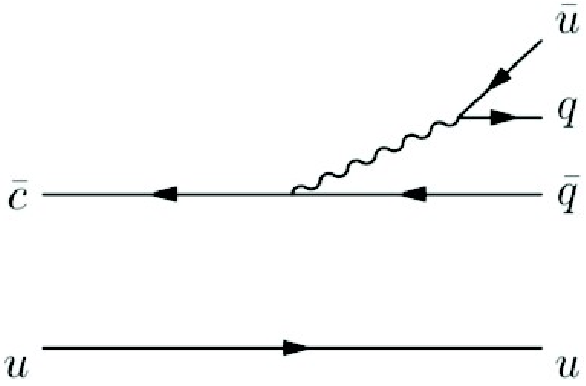
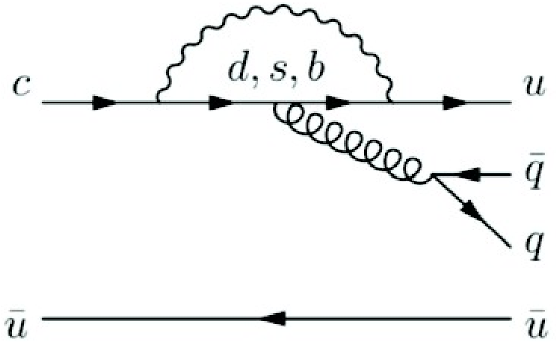
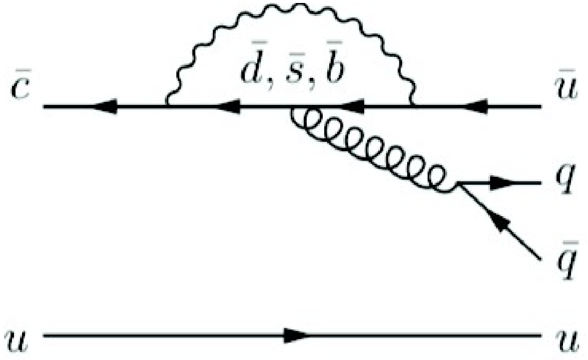
CP



$$\bar{A}_1 = |A_1|\, e^{i\theta 1}\, e^{-i\delta 1}$$



$$A_2 = |A_2|\, e^{i\theta 2}\, e^{i\delta 2}$$



$$\bar{A}_2 = |A_2|\, e^{i\theta 2}\, e^{-i\delta 2}$$

$$\boxed{|\bar{A}_1 + \bar{A}_2|^2 - |A_1 + A_2|^2 = 4\, |A_1|\, |A_2| \sin(\theta_1 - \theta_2)\ \sin(\delta_1 - \delta_2)}$$

CP violation in mixing

$$\Gamma(P^0 \rightarrow \bar{P}^0) \neq \Gamma(\bar{P}^0 \rightarrow P^0)$$

$$\Updownarrow$$

$$\boxed{|q/p| \neq 1}$$

CP violation in interference between mixing and decays

$$\Gamma(P^0 \rightarrow \bar{P}^0 \rightarrow f_{CP}) \neq$$
$$\Gamma(\bar{P}^0 \rightarrow P^0 \rightarrow f_{CP})$$

$$\Updownarrow$$

Relative phase $\delta \neq 0$

$$\lambda_f \equiv q/p\ \bar{A}_{\bar{f}}\ /A_f = |q/p\ \bar{A}_{\bar{f}}\ /A_f|\ e^{i\theta}\ e^{i\delta}$$

CP violation and its types

C – charge conjugation (particle → antiparticle) $\hat{C}|\vec{r}, t, q >= e^{i\alpha_1}|\vec{r}, t, -q >$

P – partity (spatial reflection) $\hat{P}|\vec{r}, t, q >= e^{i\alpha_2}|-\vec{r}, t, q >$

The CP discrete symmetry is broken if:

$$\boxed{\lambda_f \equiv q/p\ \bar{A}_{\bar{f}}\ /A_f \neq 1}$$

CP violation in decay

$$\Gamma(P^0 \rightarrow f) \neq \Gamma(\bar{P}^0 \rightarrow \bar{f})$$

$$|\bar{A}_{\bar{f}}\ /A_f| \neq 1$$

- Depends on decay mode

CP violation in mixing

$$\Gamma(P^0 \rightarrow \bar{P}^0) \neq \Gamma(\bar{P}^0 \rightarrow P^0)$$

$$|q/p| \neq 1$$

CP violation in interference between mixing and decay

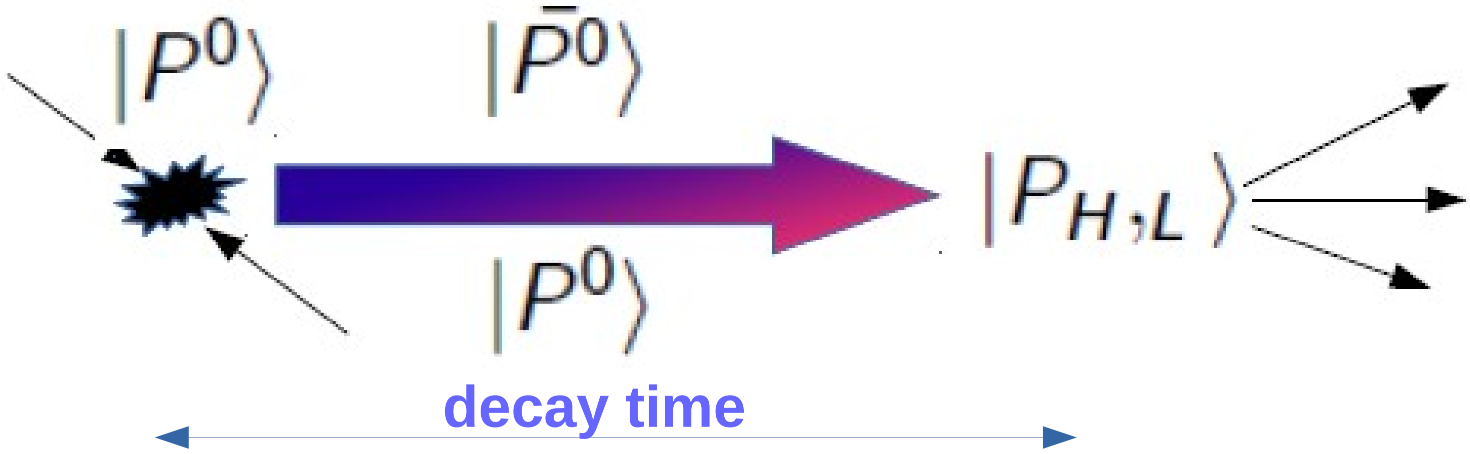
$$\Gamma(P^0 \rightarrow \bar{P}^0 \rightarrow f_{CP}) \neq \Gamma(\bar{P}^0 \rightarrow P^0 \rightarrow f_{CP})$$

$$\arg(q/p\ \bar{A}_{\bar{f}}\ /A_f) \neq 0$$

- Does not depend on decay mode
- only for neutral mesons

Mixing and CP symmetry searches in the charm sector

General experimental idea



1. determine flavour in the initial state
2. determine decay time
3. determine flavour in the final state
4. construct (time-dependent) asymmetry A(t)
5. reduce/control nuisance asymmetries by exploiting control channels
6. extract (mixing/CP/CPT) parameters from the fit

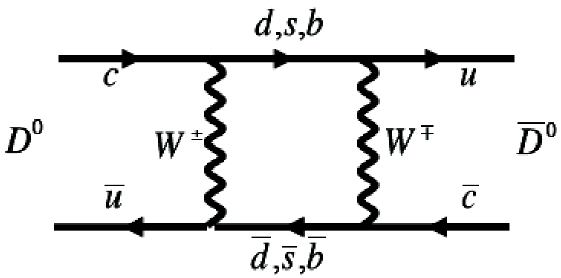
Mixing and CPV in charm

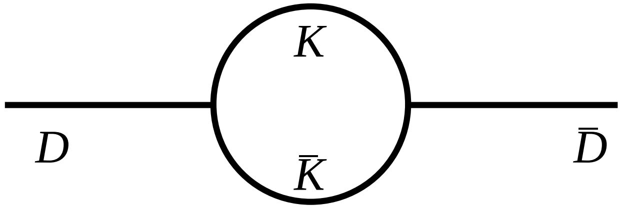
Standard Model predictions (PDG2016):

- **Predictions for mixing very imprecise**

  ***x, y:* O(10^{-2})- O(10^{-7})**

- Perturbative QCD valid for >> 1GeV
- Chiral perturbation theory valid: 0.1 to 1 GeV
- m(D^0) ≈ 1.864 GeV





long-range contributions dominates – hard to calculate

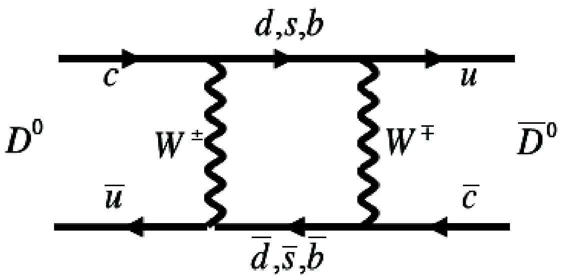
- **Almost no CPV effects expected ~ O(10^{-4})**

Mixing and CPV in charm

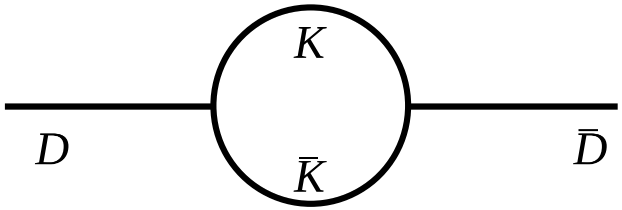
Standard Model predictions (PDG2016):

- Predictions for mixing very imprecise

  x, y: $O(10^{-2})$- $O(10^{-7})$



- Perturbative QCD valid for >> 1GeV
- Chiral perturbation theory valid: 0.1 to 1 GeV
- $m(D^0) \approx 1.864$ GeV



long-range contributions dominates – hard to calculate

- Almost no CPV effects expected ~ $O(10^{-4})$

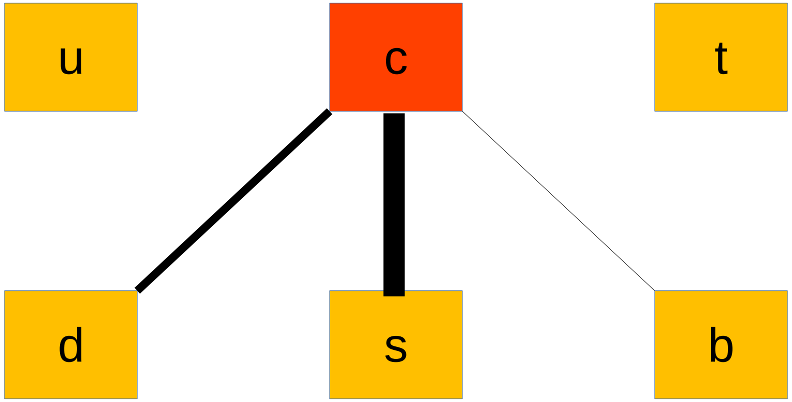
Experimental status:

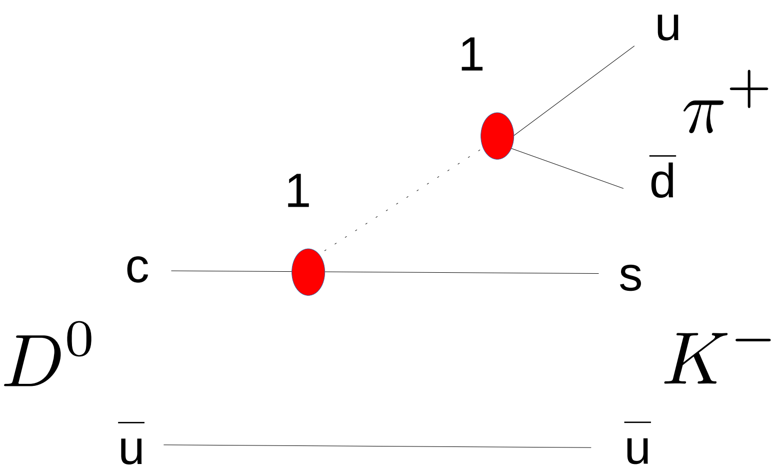
- **Mixing established (> 11 σ effect)**
  - First evidence Babar, Belle, CDF: PRL 98 (2007) 211802, PRL 98 (2007) 211803, PRL 100 (2008) 121802
  - Recent LHCb measurement: PRL 113 (2013) 231802, PRD 95 (2017) 052004 PRD 96 (2017) 099907, PRD97 (2018) 031101, Phys. Rev. Lett. 122 (2019) 211803, ...
- **CPV discovered in 2019 (5,3 σ effect)**

Charm in Standard Model

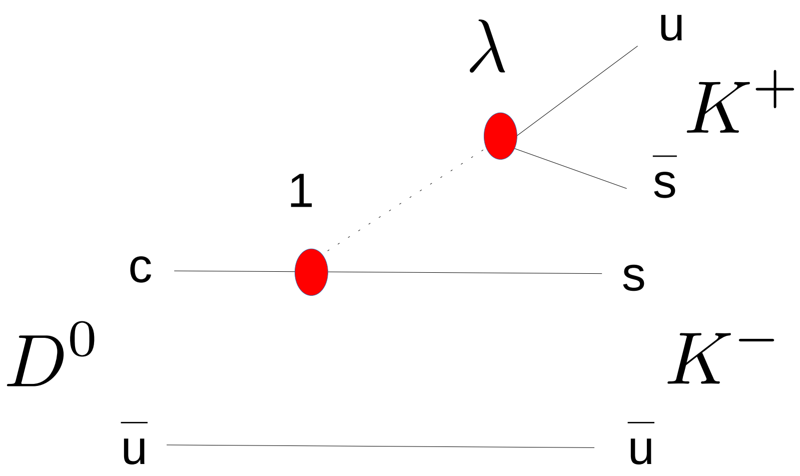
$$\lambda \approx 0.22$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{array}{cccc} & d & s & b \\ u & 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ c & -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ t & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array}$$

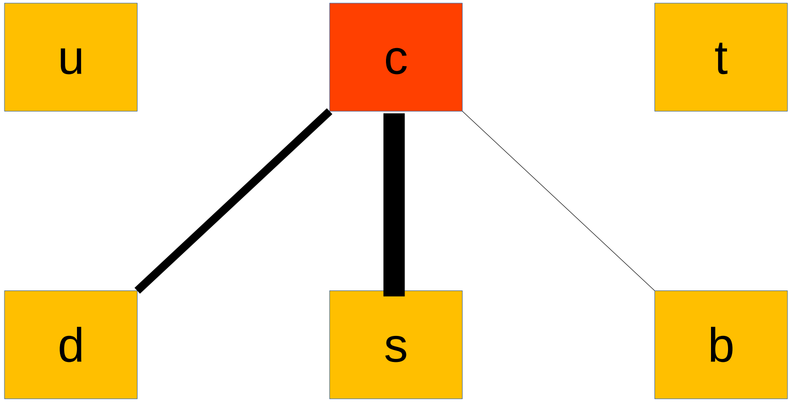




Cabbibo Favoured (CF)



Singly Cabbibo Suppresed (SCS)



Doubly Cabbibo Suppresed (DCS)

SCS are only processes in which CP in decays can be included in SM

CP violation

beauty

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \sim 23^\circ$$

$$\beta_s = \arg\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right) \sim 1^\circ$$

Precise tests of SM

---

charm

$$\beta_c = \arg\left(-\frac{V_{cd}V_{ud}^*}{V_{cs}V_{us}^*}\right) \sim 0.03^\circ$$

Search for New Physics effects

Experimental challenge:

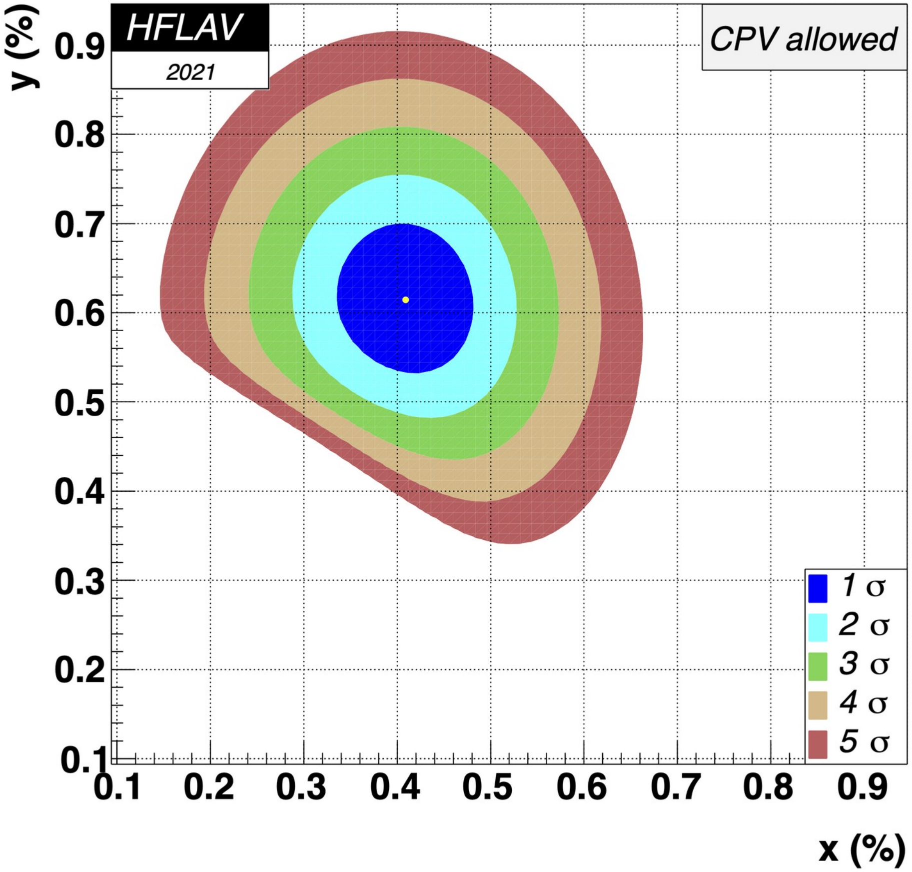
- High statistics
- Small systematics (<0.1%)

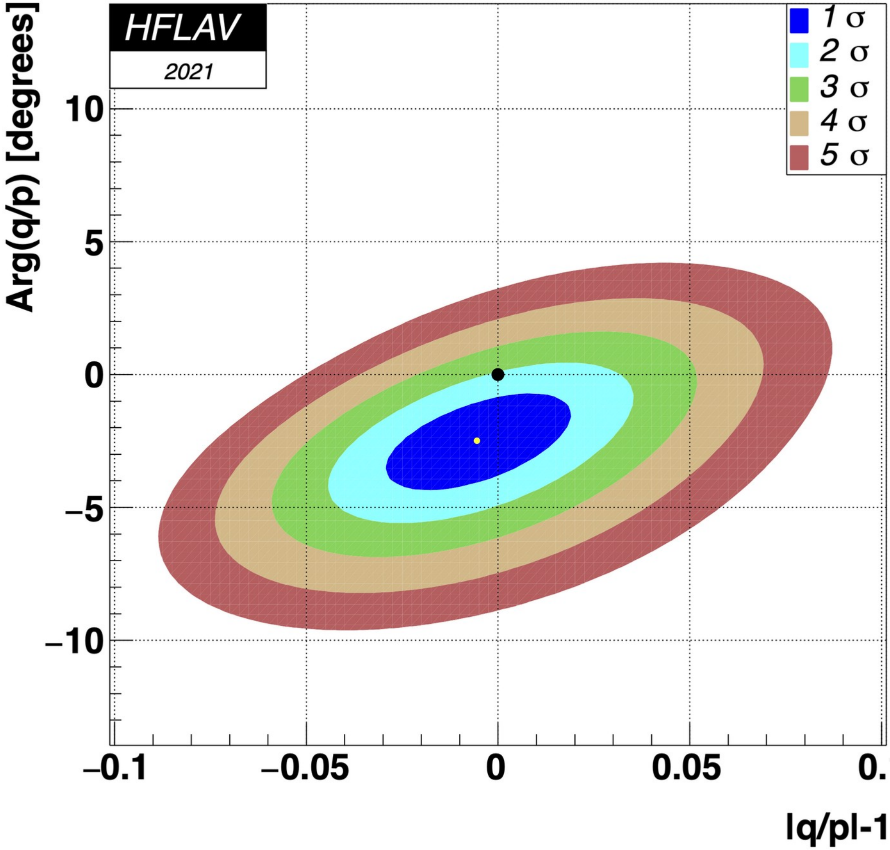
Mixing and CPV in charm

$x = \frac{\Delta m}{\Gamma}$

$y = \frac{\Delta\Gamma}{2\Gamma}$

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



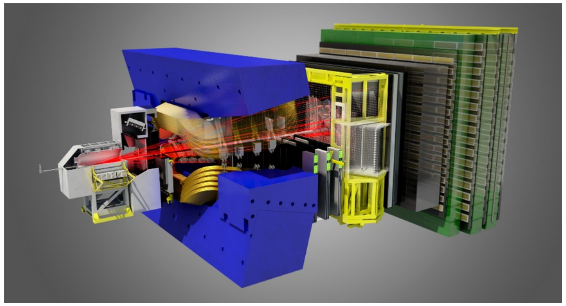


x or y ≠ 0 → mixing

|q/p|≠ 1 → CPV in mixing

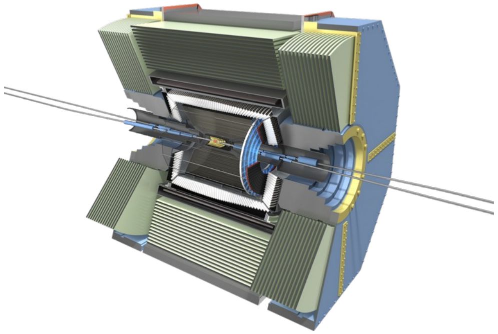
Charming players

LHCb



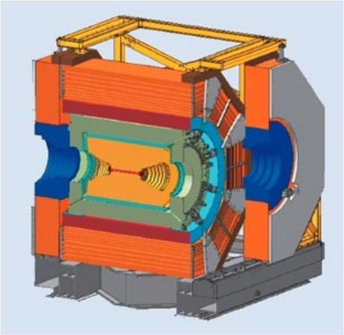
- **High cross-sections:**
  - Decays in charged final states **yield of 9 fb^{-1} @LHCb compares with 50 ab^{-1}**@Belle-2
  - baryon production (e.g. Λ_c)
- **Good decay-time resolution (~45 fs ~ 0.1 τ(D^0))**
- **Busy environment**
  - non-trivial triggers
  - non-trivial efficiency corrections

Belle-2



- **Good reconstruction for neutral particles**
- **Known initial state:**
  - Better separation between prompt and secondaries production (in B decays)
- **Clean environment:**
  - Milder efficiency variation
  - Easier control of systematics
  - Absolute asymmetry measurement possible

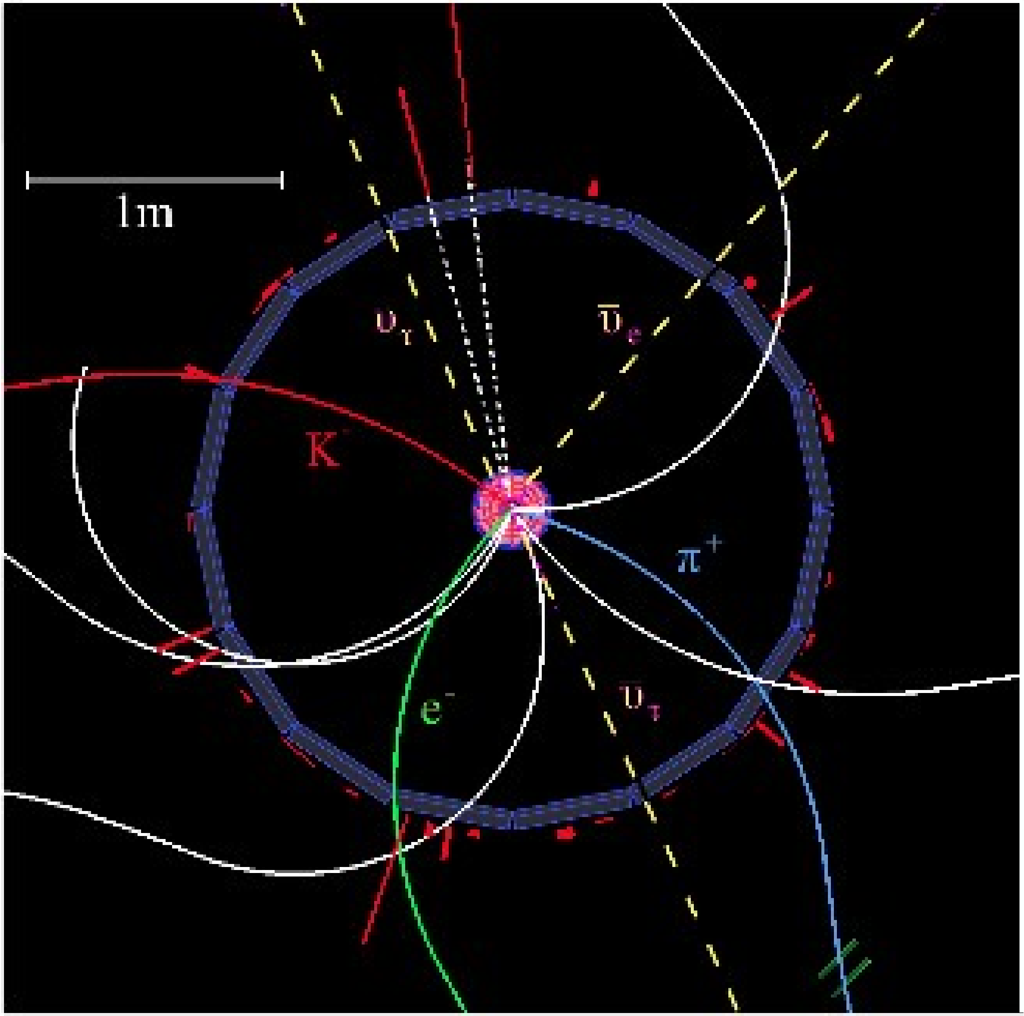
BES-III



- **Background-free charm**
- **No time measurement since charm not boosted**
- **Quantum entangled pairs Ψ(3370)→ $D\bar{D}$**
- Complementary measurements to LHCb and Belle-2 e.g. measurement of strong phases

Example: B decay

BELLE

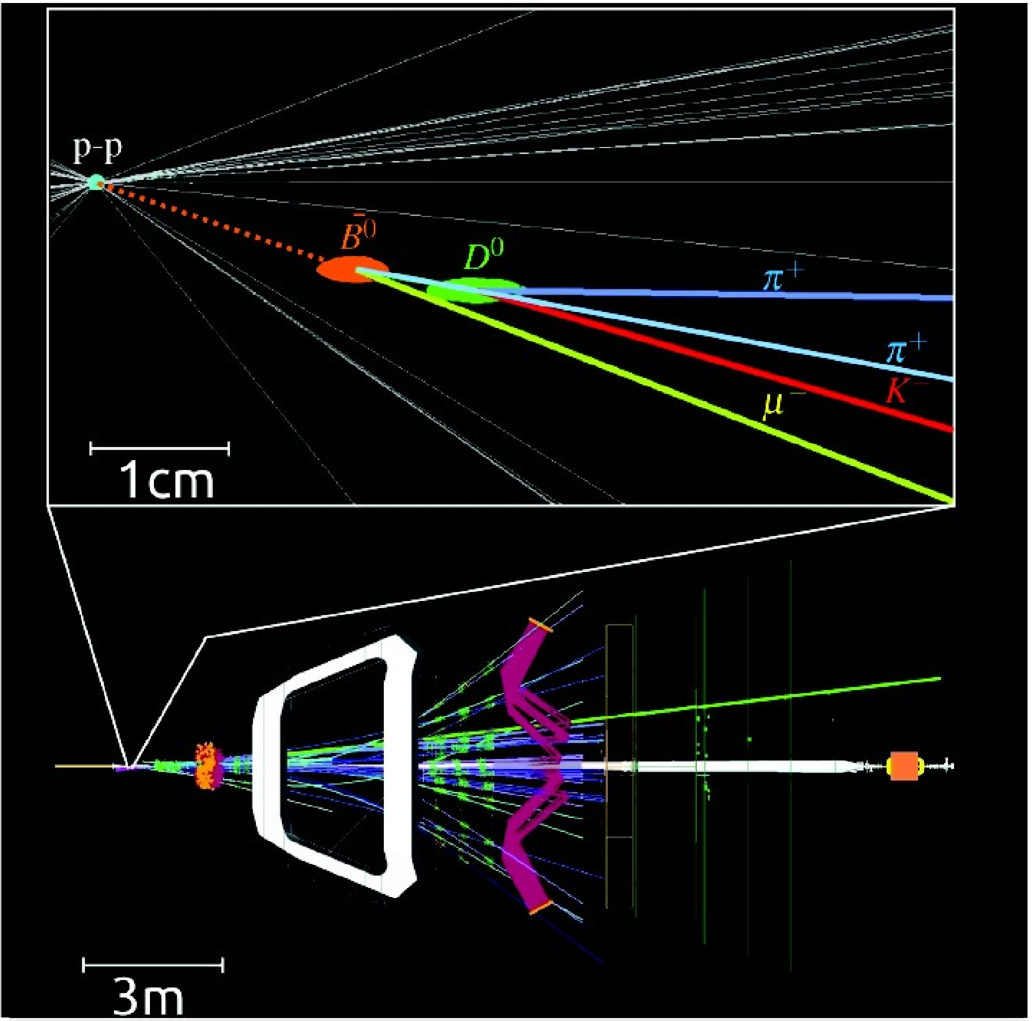


$Y(4S) \rightarrow B^+ \ B^-$

$B^- \rightarrow D^0 \ \tau^- \ \nu_\tau$

$D^0 \rightarrow K^- \ \pi^+$ $\tau^- \rightarrow e^- \ \nu_e \ \nu_\tau$

LHCb



$B^0 \rightarrow D^{*+} \ \tau^- \ \nu_\tau$

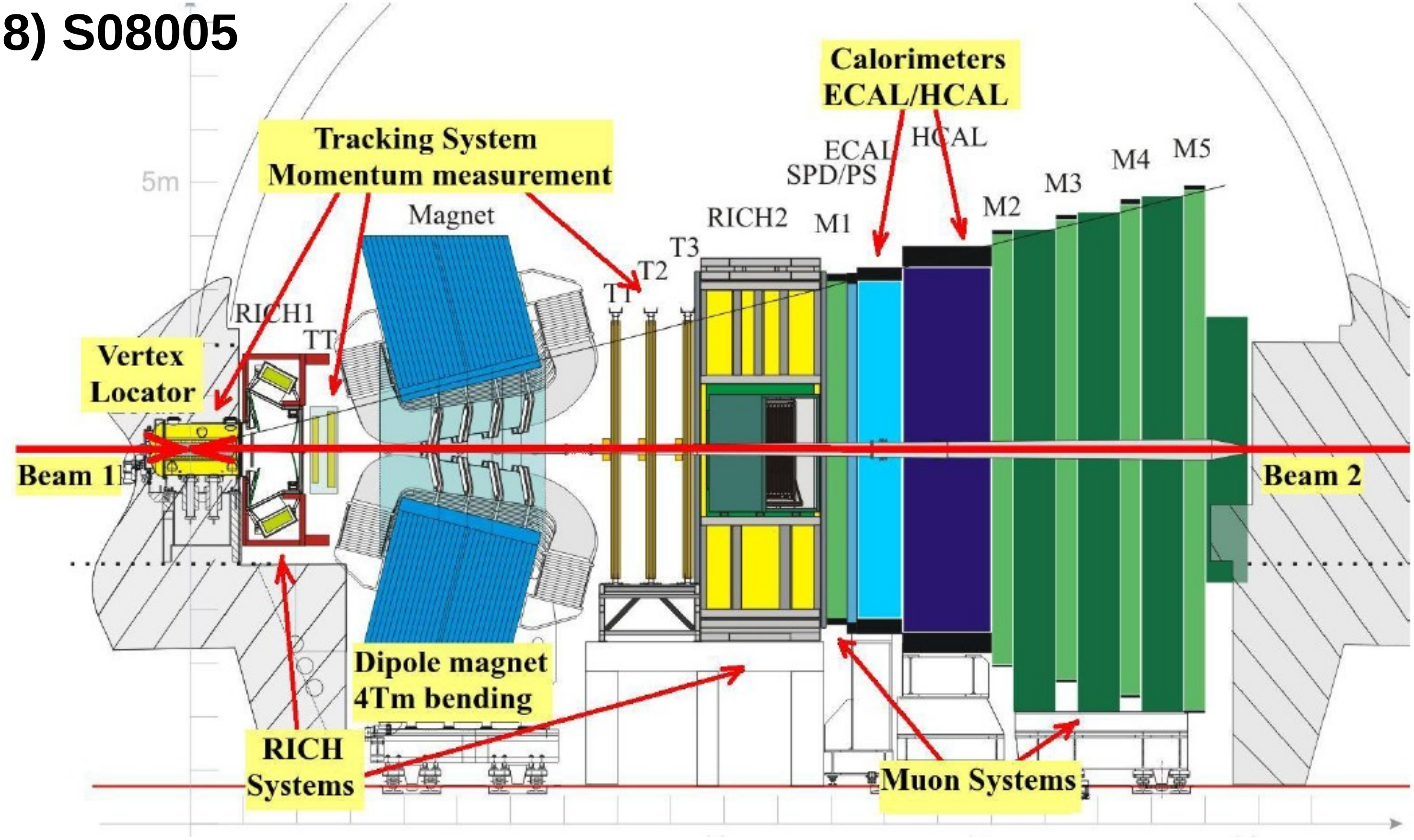
$D^{*+} \rightarrow D^0 \ \pi^+$

$D^0 \rightarrow K^- \ \pi^+$ $\tau^- \rightarrow \mu^- \ \nu_\mu \ \nu_\tau$

G.Ciezarek et al.,
Nature 546(2017)227

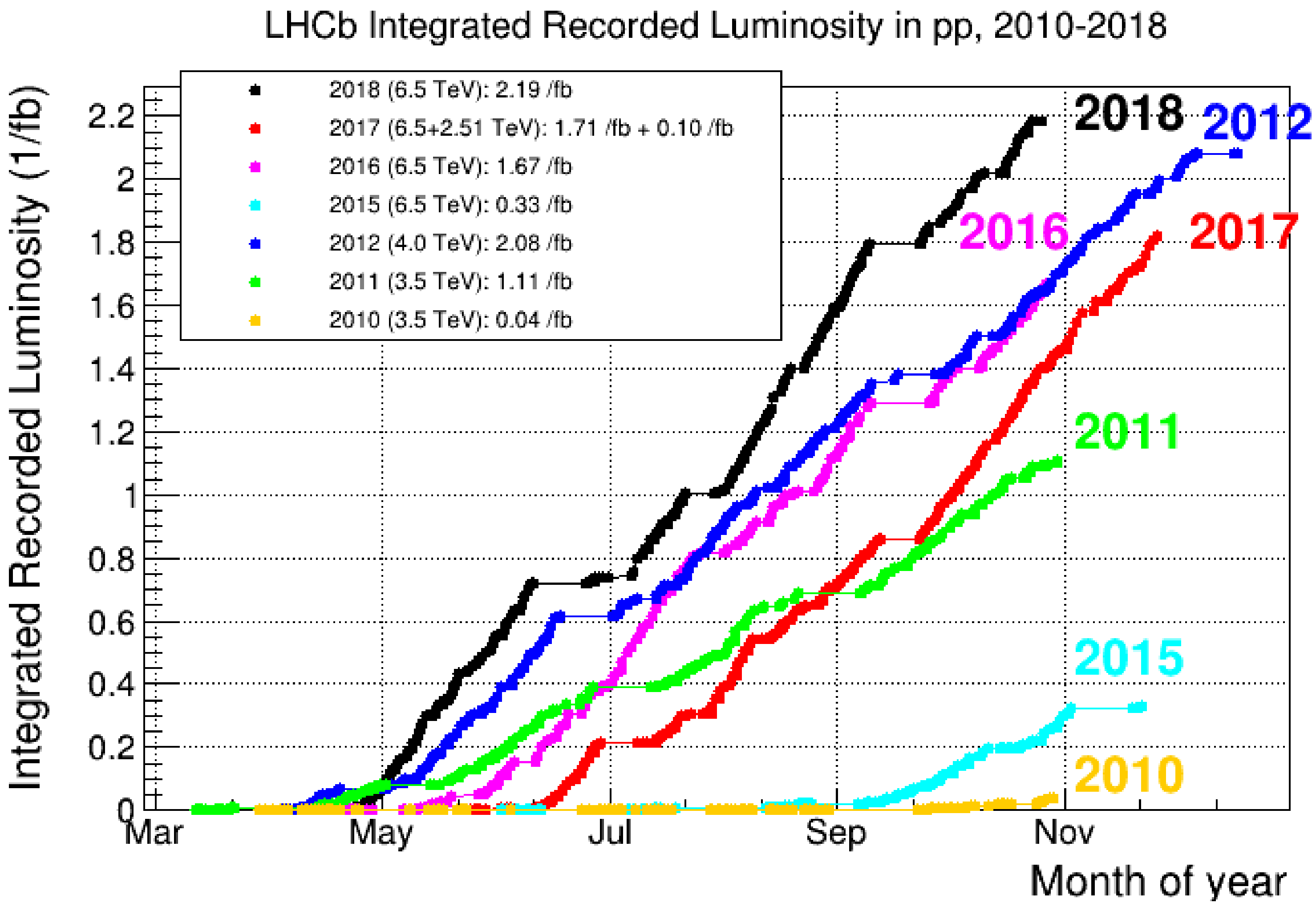
Large Hadron Collider beauty detector

JINST 3 (2008) S08005



- Single-arm forward spectrometer covering range $2 < \eta < 5$ ($10 < \theta < 300$ mrad)
- Momentum resolution $\Delta p/p = 0.4$ -0.6 % @ 5 GeV/c to @ 100 GeV/c

  (**~8 MeV/c^2 mass resolution** for two-body charm decay)
- Impact parameter resolution: 20 μm from high p_T tracks (**decay lifetime ~45 fs ~ 0.1 $\tau(D^0)$**)



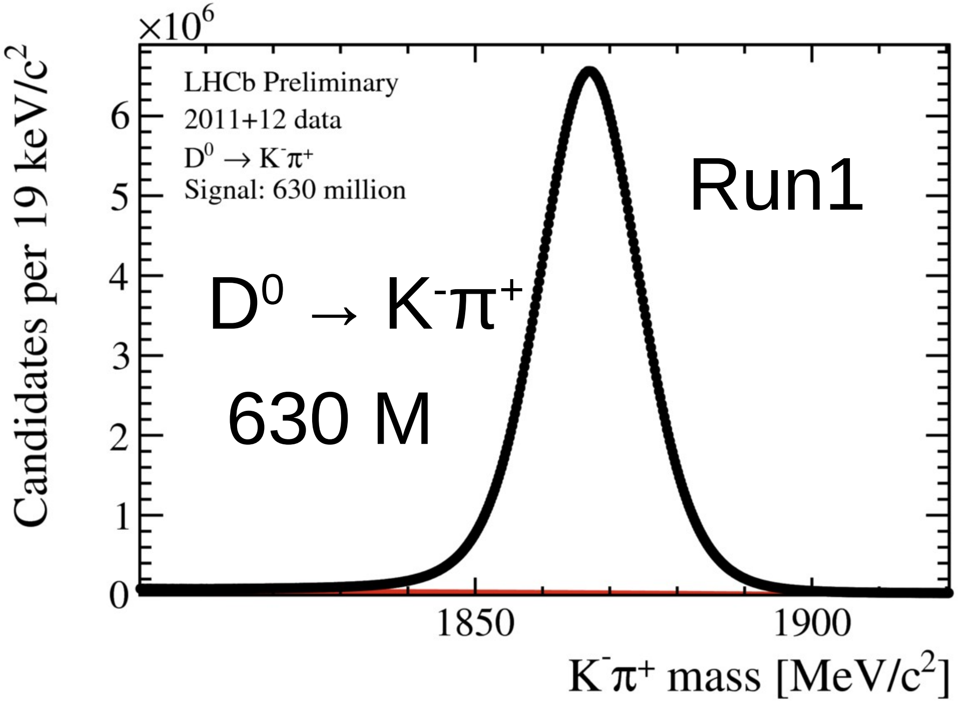
Run I (2011-2012): 3 fb^{-1} @7 and @8 TeV

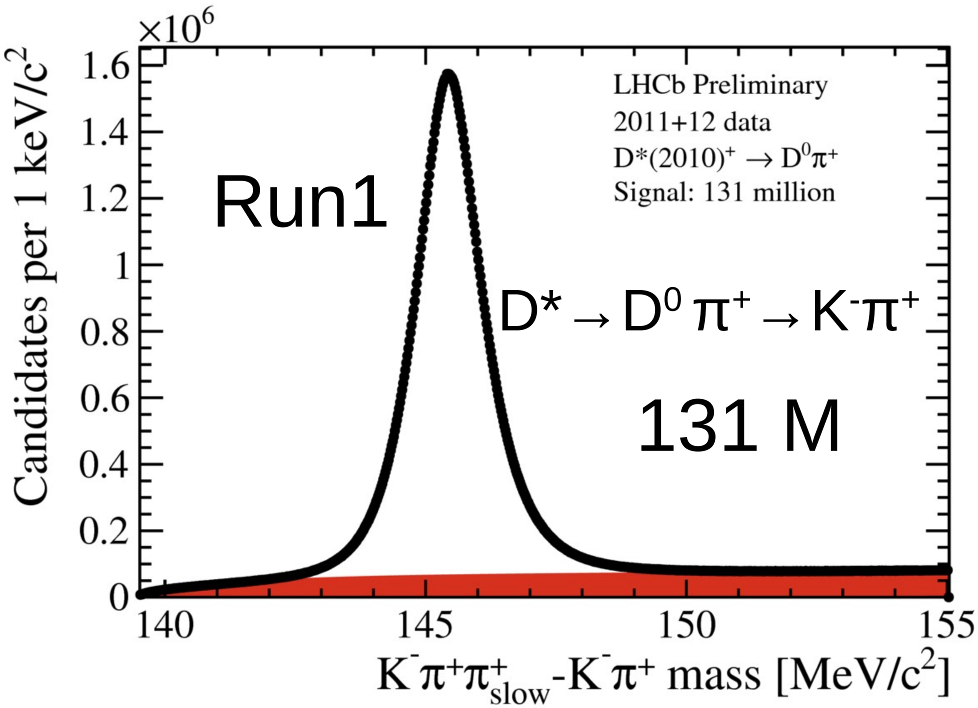
Run II (2015-2018): 6 fb^{-1} @13 TeV

Total sample collected: 9 fb^{-1}

LHCb is also charming...

LHCb-CONF-2016-005





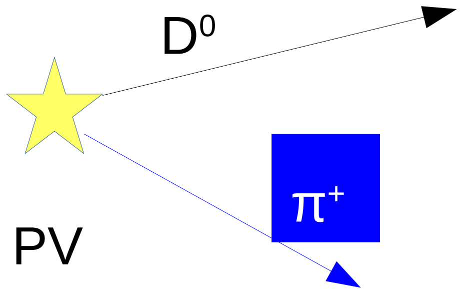
Charm produced copiously in pp collisions:

- $\sigma(pp \rightarrow c\bar{c}) \sim 1419\ \mu b$ @ 7 TeV **Nucl.Phys.B871(2016) 1**
- $\sigma(pp \rightarrow c\bar{c}) \sim 2840\ \mu b$ @ 13 TeV **JHEP03(2017) 74**

Few billions of $D^0 \rightarrow K^-\pi^+$ events reconstructed from the collected sample.

Tagging of initial flavour

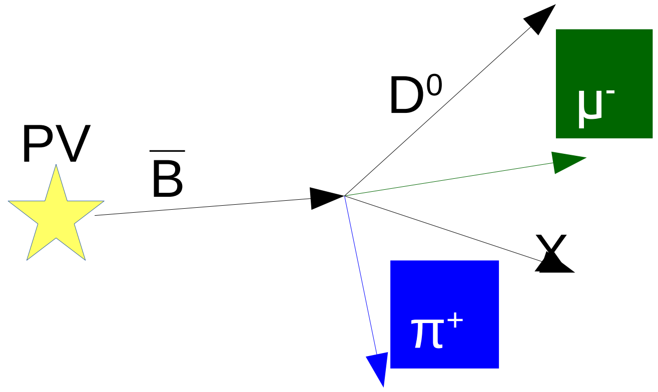
Prompt charm



$D^{*+} \rightarrow D^0\pi^+$

Decay time acceptance limits

(Double-tagged) secondary charm



$\overline{B} \rightarrow D^{*+}\mu^- X$

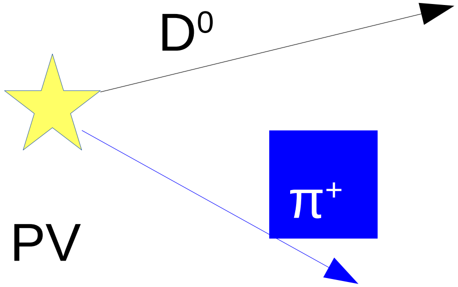
$D^{*+} \rightarrow D^0\pi^+$

All decay time available

- $D^{*+} \rightarrow D^0\pi^+$ (largest yield, high purity, $\sigma(t) \approx 0.1\,\tau$)
- $\overline{B} \rightarrow D^{*+}\mu^- X$ (1/6 * yield, lower purity, $\sigma(t) \approx 0.3\,\tau$)
- $\overline{B} \rightarrow D^{*+}\mu^- X$ $D^{*+} \rightarrow D^0\pi^+$ (1/40 * yield, highest purity $\sigma(t) \approx 0.3\,\tau$)

Tagging of initial flavour

Prompt charm

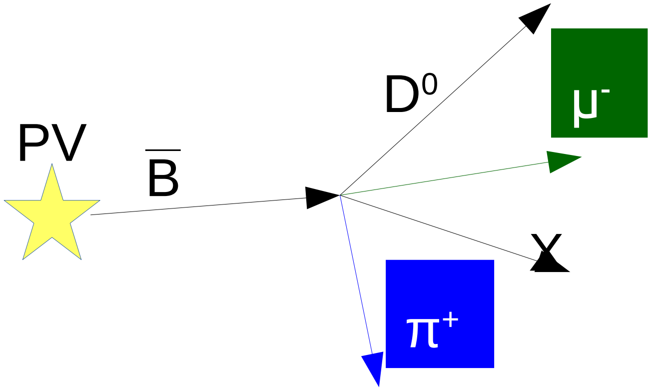


$\mathbf{pp \rightarrow D^{*+}}$

$\mathbf{D^{*+} \rightarrow D^0}\color{blue}{\boldsymbol{\pi^+}}$

- Large cross-section
- Decay time acceptance limits

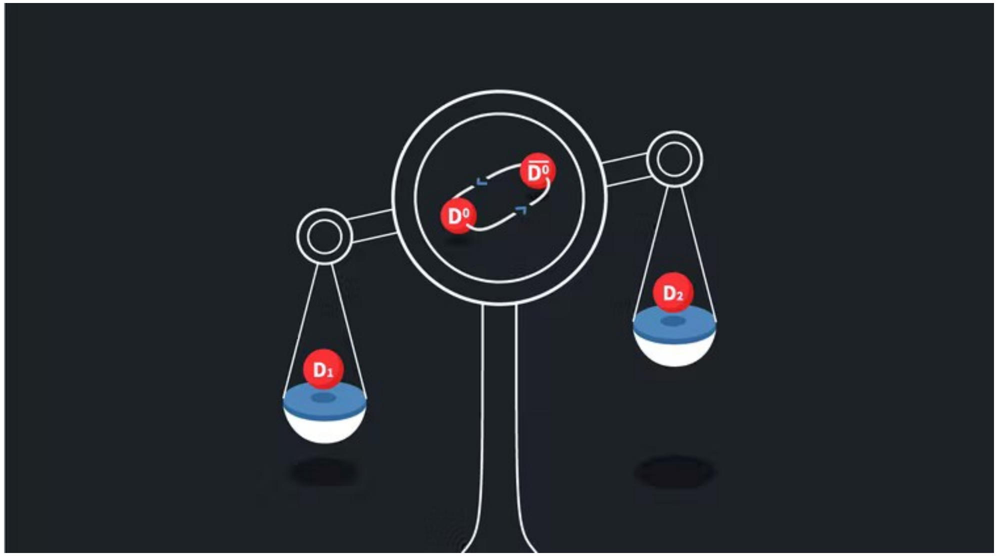
(Double-tagged) secondary charm



$\mathbf{pp \rightarrow \overline{B} \rightarrow D^{*+}}\color{green}{\boldsymbol{\mu^-}}\,\mathbf{X}$

$\mathbf{D^{*+} \rightarrow D^0}\color{blue}{\boldsymbol{\pi^+}}$

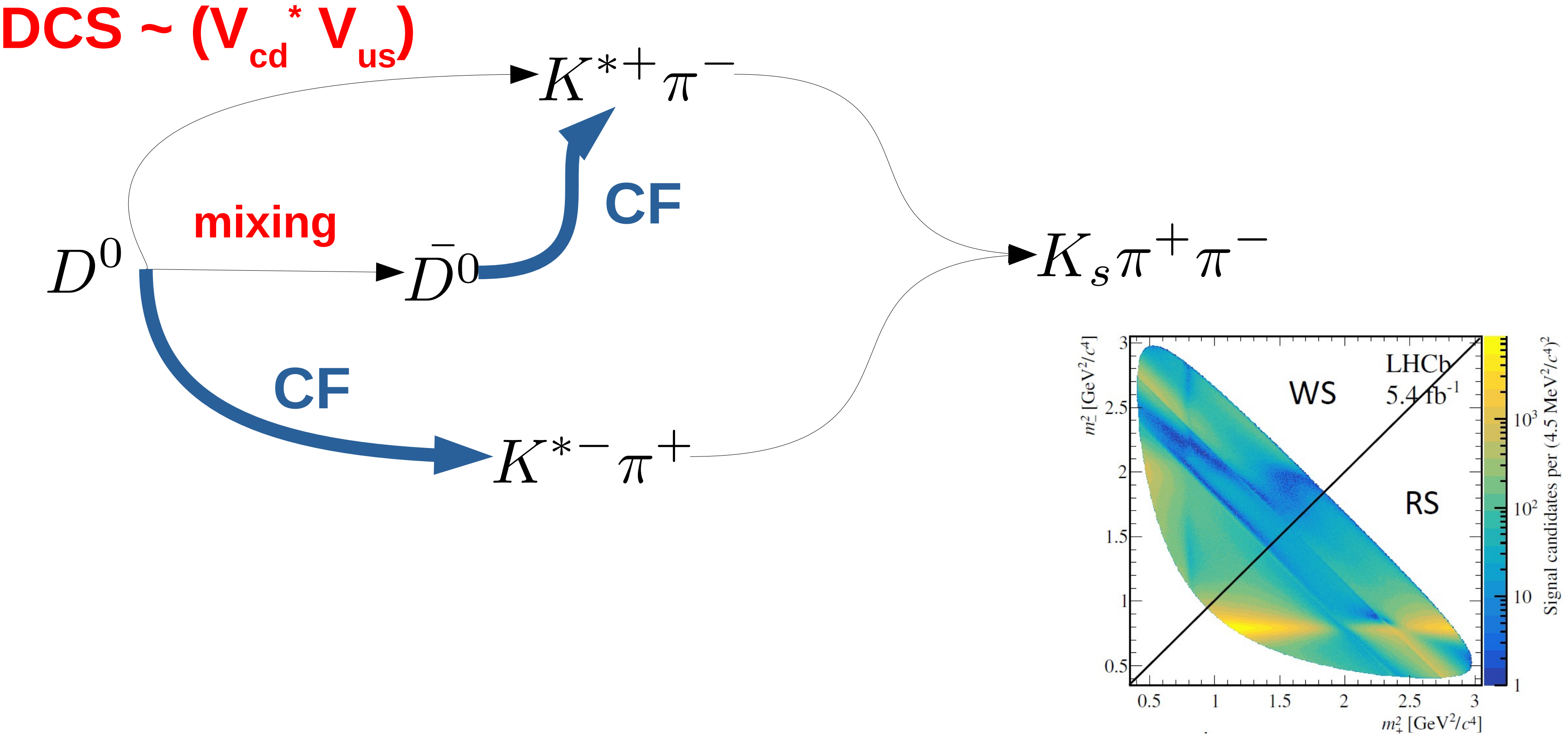
- Smaller cross-section
- All decay time available



Mass difference between Neutral charm-meson eigenstates

Phys. Rev. Lett. 127 (2021) 111801

Golden channel: $D^0 \to (K_s \pi^+ \pi^-)$ (Run II 5.4 fb^{-1})



DCS ~ ($V_{cd}^* V_{us}$)

$K^{*+}\pi^-$

mixing

CF

D^0

$\bar{D}^0$

$K_s\pi^+\pi^-$

CF

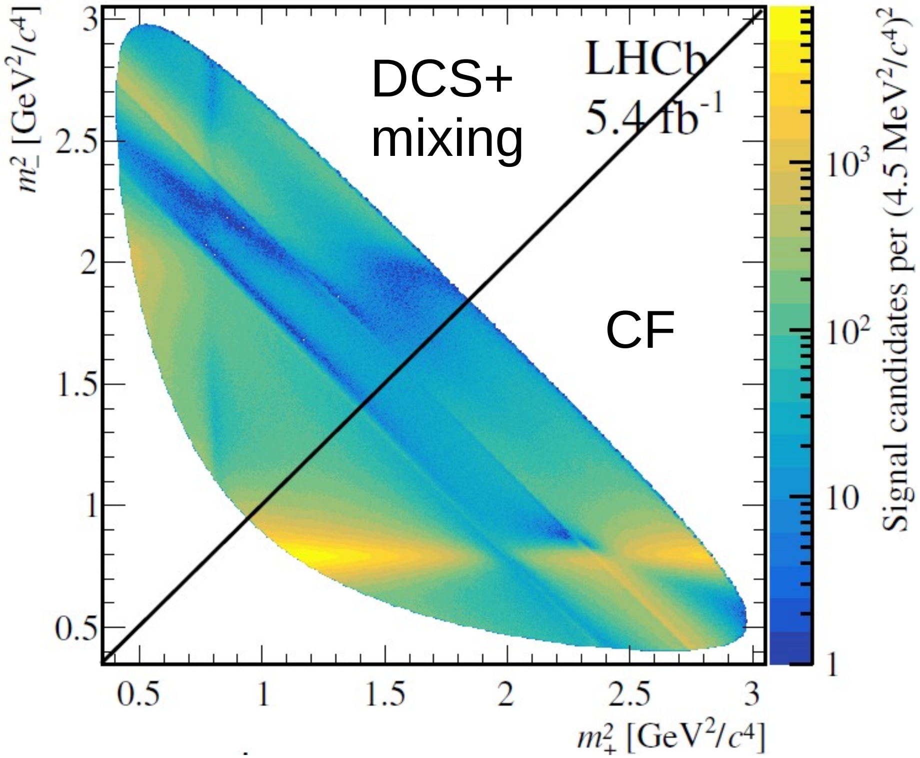
$K^{*-}\pi^+$

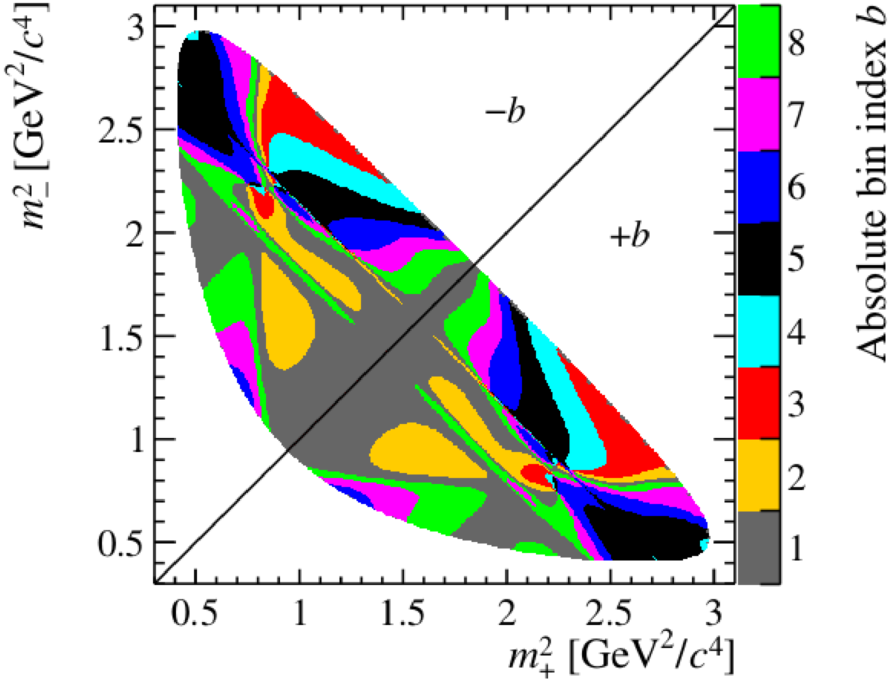
- For CF and DCS modes CP symmetry violation strongly suppressed
- 3-body decay can be described by 2 parameters (Dalitz plot analysis)

Phys. Rev. Lett. 127 (2021) 111801

‘Bin-flip’ method for searches of CPV with multi-body charm decays:

Phys. Rev. D 97, 031101 (2018)

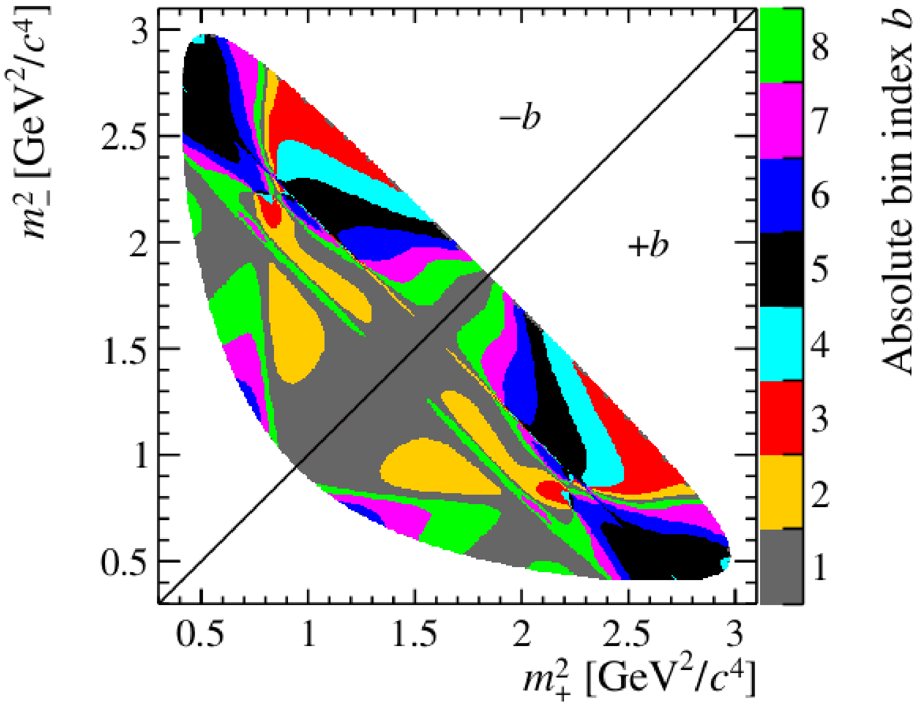


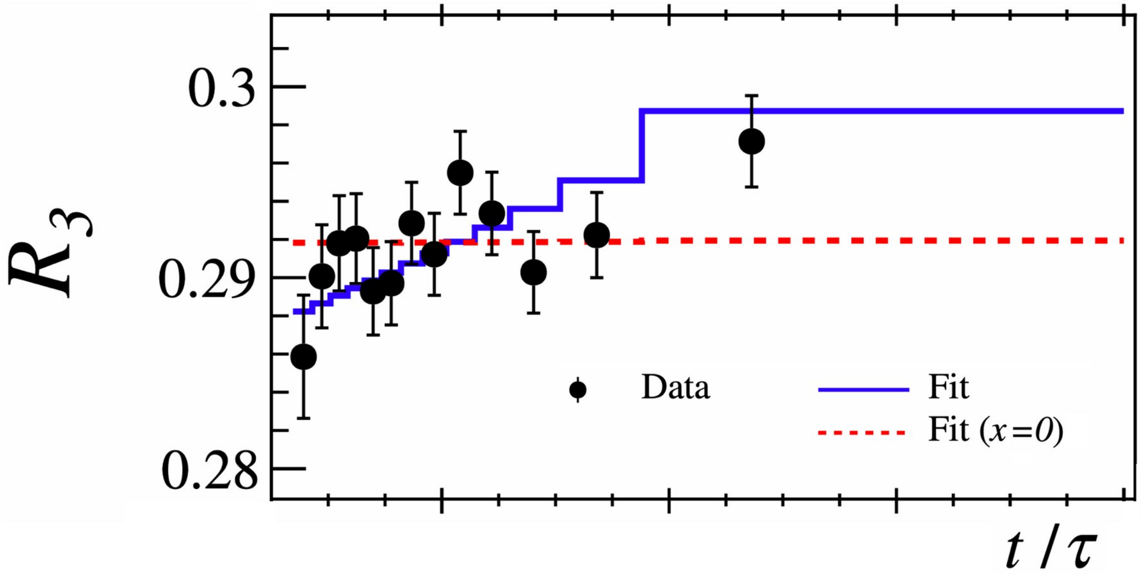


- ~31 M event candidates
- Charm tagged with the soft pion charge

$$m_\pm^2 \equiv \begin{cases} m^2(K_S^0\pi^\pm) & \text{for } D^0 \to K_S^0\pi^+\pi^- \\ m^2(K_S^0\pi^\mp) & \text{for } \overline{D}^0 \to K_S^0\pi^+\pi^- \end{cases}$$

Phys. Rev. Lett. 127 (2021) 111801





Strong phases taken from CLEO and BES-III measurements

- Measure yield ratio R_{bj} between b and -b in bins j of decay time
- R_{bj} are functions of x_{CP}, y_{CP}, Δx, Δy candidates
- Resolutions: decay-time~ 60 fs, mass squared ~0.006 GeV^2

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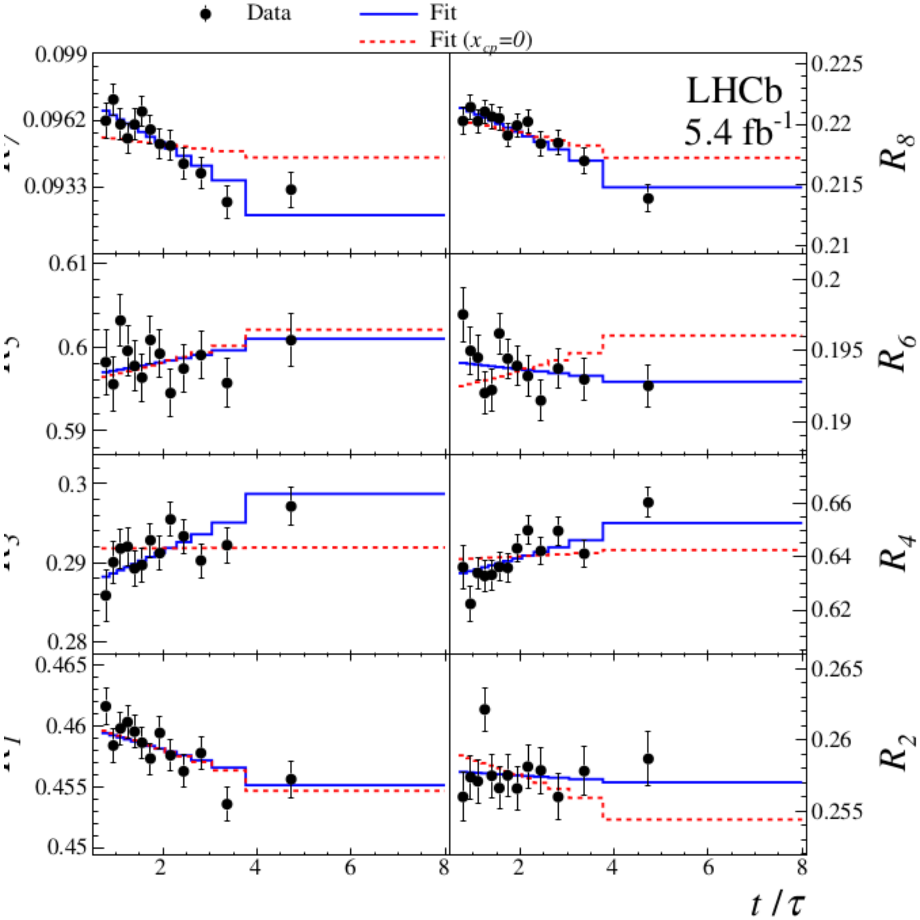

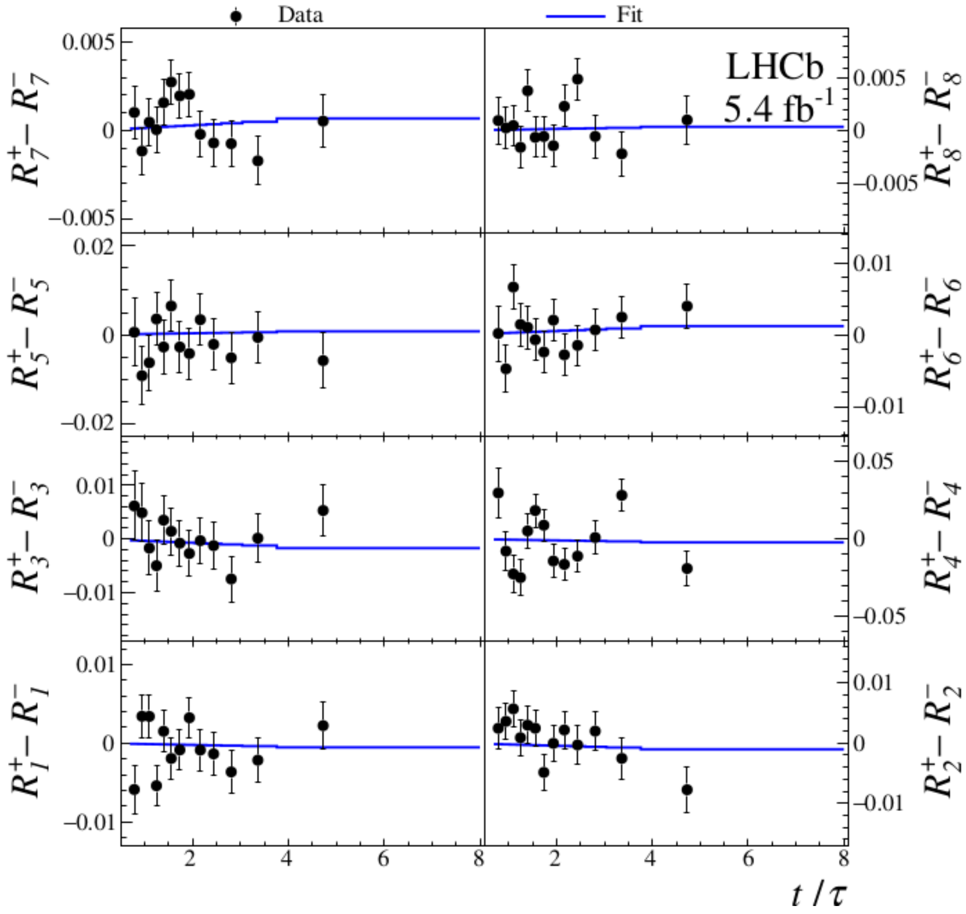

$$z_{CP} \pm \Delta z = -(q/p)^{\pm 1}(y \pm ix)$$

$$x_{CP} = -\mathrm{Im}(z_{CP}),\, y_{CP} = -\mathrm{Re}(z_{CP})$$

$$\Delta x = -\mathrm{Im}(\Delta z),\, \Delta y = -\mathrm{Re}(\Delta z)$$

$$x_{CP} = x,\, y_{CP} = y$$

$$\Delta x = \Delta y = 0$$

if CP conserved

Δy is more often referred to as A_Γ

- R_{bj} are functions of x_{CP}, y_{CP}, Δx, Δy candidates
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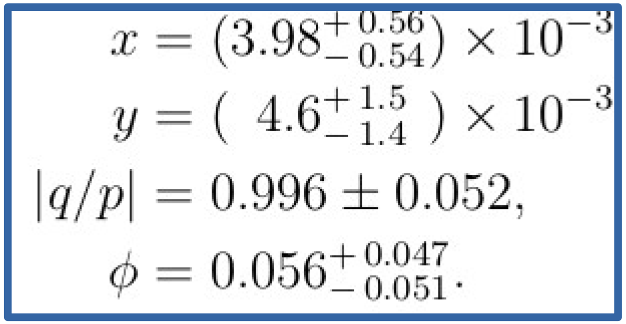

$$
\begin{aligned}
x &= (3.98^{+0.56}_{-0.54}) \times 10^{-3} \\
y &= (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3} \\
|q/p| &= 0.996 \pm 0.052, \\
\phi &= 0.056^{+0.047}_{-0.051}.
\end{aligned}
$$

$$x = \frac{\Delta m}{\Gamma}$$

$$y = \frac{\Delta\Gamma}{2\Gamma}$$

- Consistent with CP symmetry conservation
- Result statistically limited
- Mixing phenomena confirmed

The first evidence of charm eigenstates mass difference

(more than 7 σ effect)

Oscillation period ~630 ps (compared 0.4 ps of D0 lifetime)

m_1-m_2 = 6.4×10^{-6} eV ~ (1×10^{-38} g)

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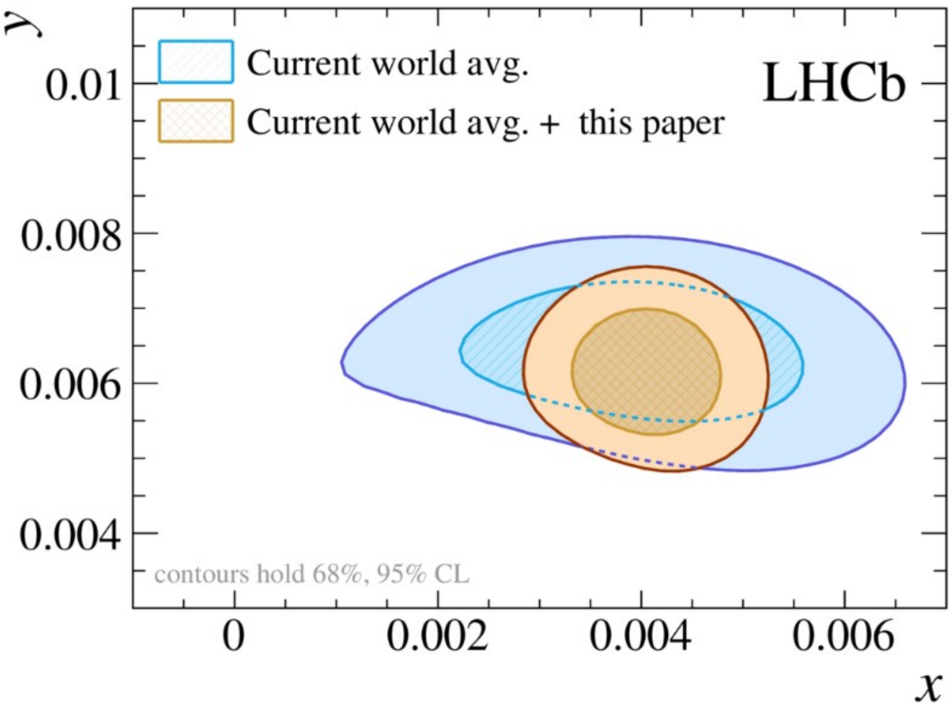
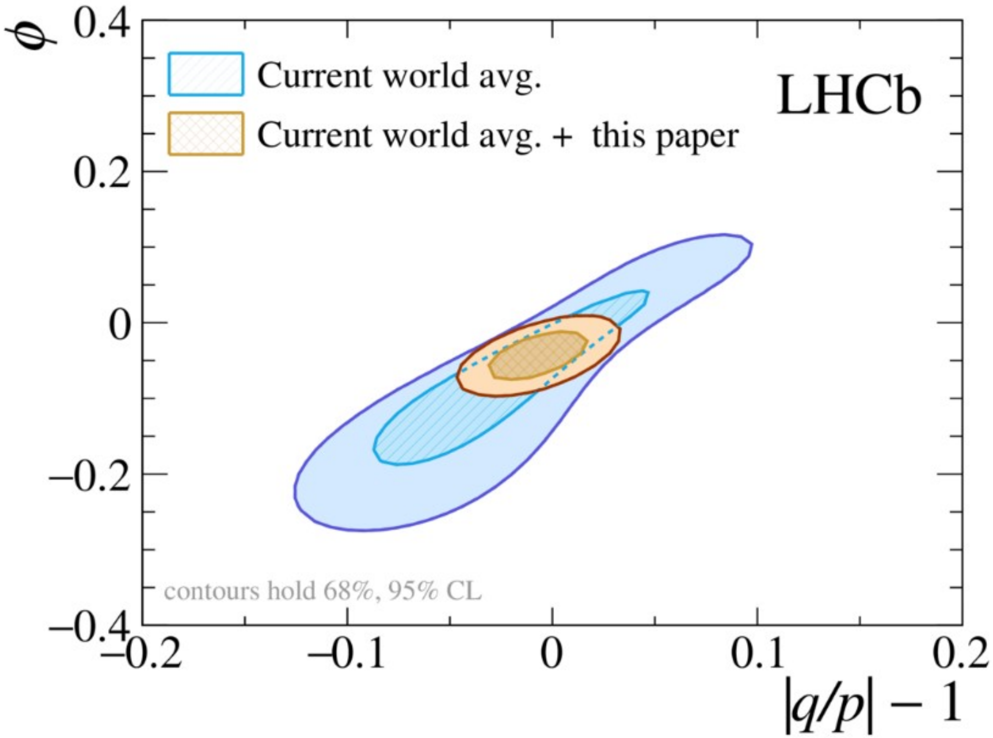
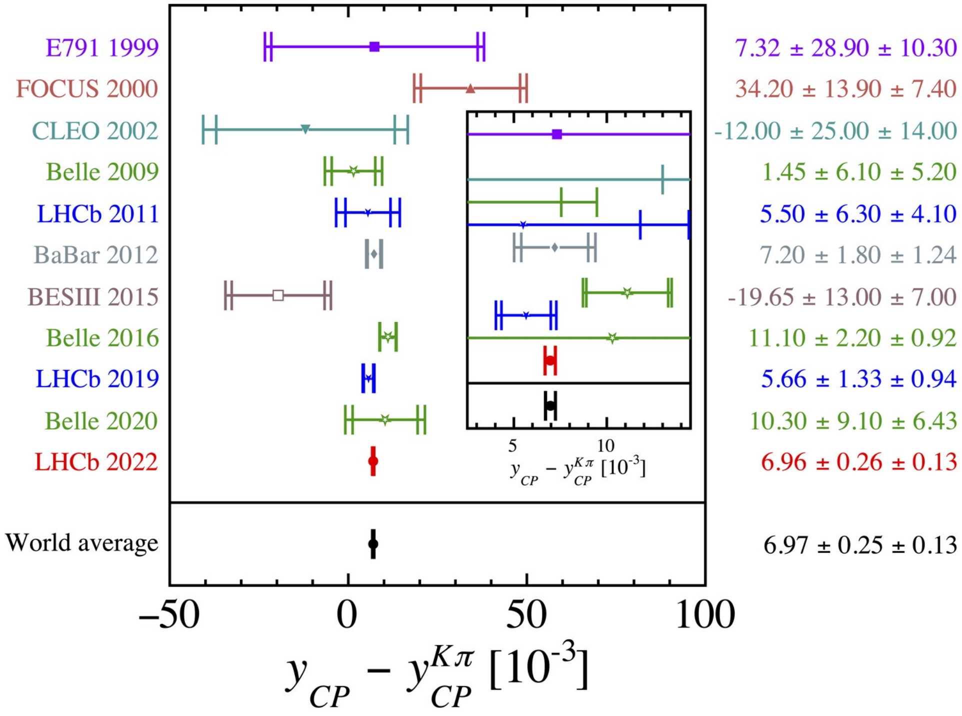


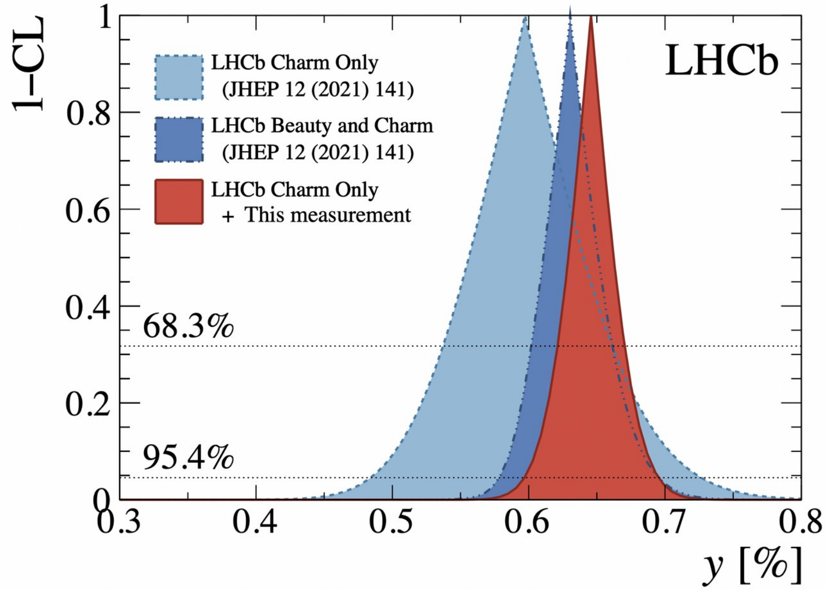


https://arxiv.org/abs/2202.09106

Also y dominated by recent LHCb result of y_{CP} using two-body D0 decays

$$y = \frac{\Delta\Gamma}{2\Gamma}$$





Discovery of CP violation (in decays) in charm

Phys. Rev. Lett. 122 (2019) 211803

Observation of CP violation in charm decays

- $D^0 \rightarrow \pi^+\pi^-$ (K^+K^-)
- Run II, L = 6 fb^{-1} @13 TeV
- Initial charm tagged with π (μ) charge

$$A_{\mathrm{raw}}(f) = \frac{N(D^0 \rightarrow f) - N(\overline{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\overline{D}^0 \rightarrow f)}$$

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$$A_{\text{raw}}(f) = \boxed{A_{CP}(f)} + \cancel{A_D(f)} + \boxed{A_D(\pi_s^+)} + \boxed{A_P(D^{*+})}$$

Symmetric final state

Should be the same for $\pi^+\pi^-$ and K^+K^- if the kinematics are the same

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$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

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Combined Run I and Run II (9 fb^{-1})

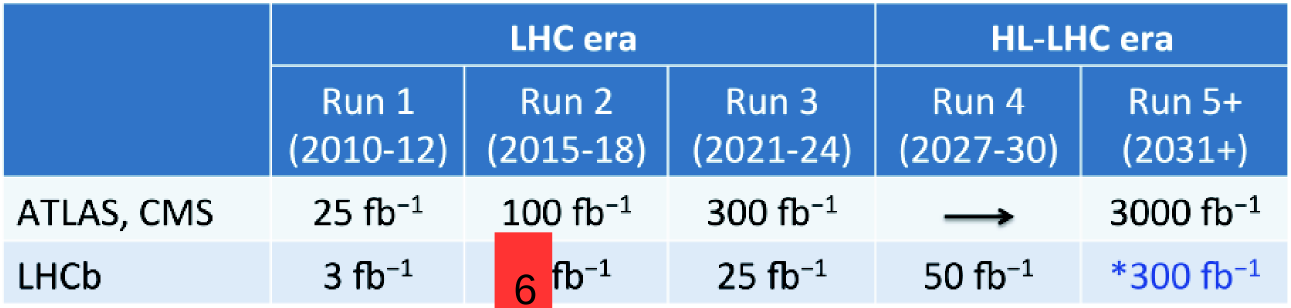
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

Effect 5.3 σ from zero

First observation of CP violation in the decays of charm mesons

Summary

- Mixing and discrete symmetry violation studies as tests of SM and probes of NP effects,
- Charm sector attractive due to the suppressed CP effects from SM
- In some of the channels LHCb has reached the sensitivity of SM expectation O(10^{-4})
- CP violation and mixing in the charm confirmed
- **For the first time the mass difference of the charm eigenstates was measured**
- Results are limited statistically:
  - Many analysis ongoing
  - LHC Run 3 has started and Belle-2 is taking data



	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	6 fb^{-1}	25 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2 × 10^{34} cm^{-2}

Thank you for your attention