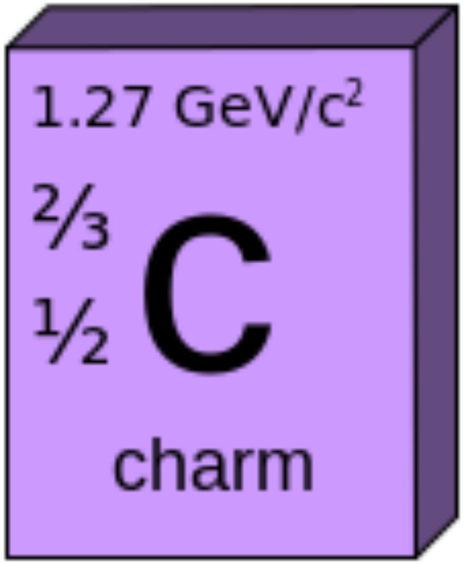
Charm physics

from an experimental point of view



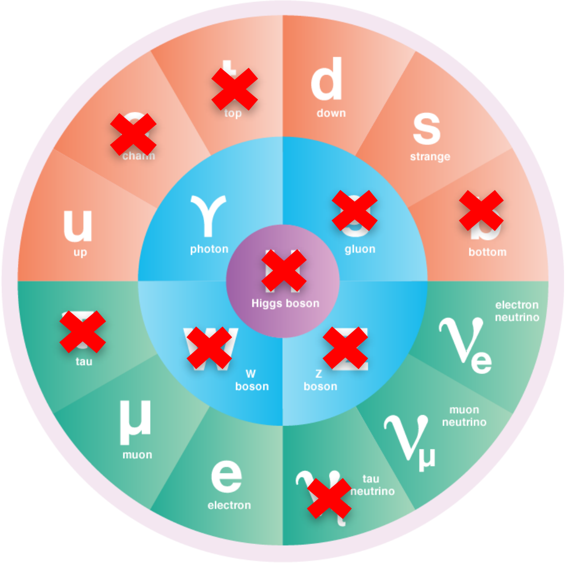
Angelo Carbone

University of Bologna

Discovery of charm quark

Before discovery: theory prediction

Known particles @ 1974



- The first speculations about ”charm”
  J.D. Bjorken and S.L. Glashow, Phys. Lett. 11 (1964) 255
- Massive lepton-pair production in h-h collisions S. D. Drell and T-M Yan, Phys. Rev. Lett. 25 (1970) 316
- Weak interactions with Lepton-Hadron symmetry
  S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D (1970) 1285 (GIM model)

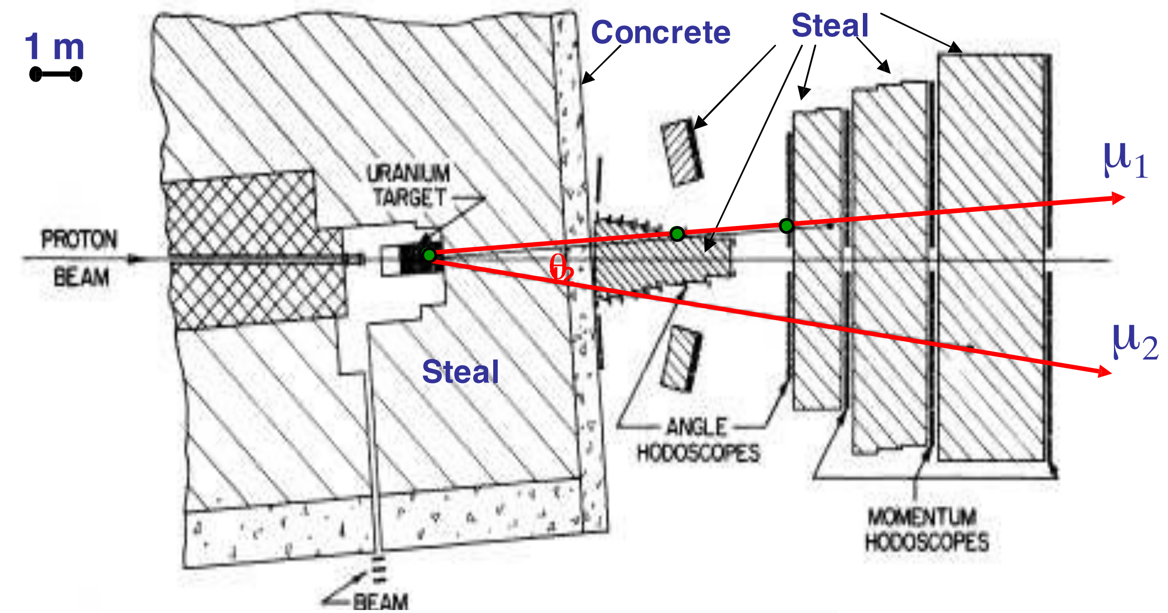
In April 1974 S.L. Glashow said:
”There are just three possibilities:
1 Charm is not found and I eat my hat
2 Charm is found by hadron spectroscopy, and we celebrate
3 Charm is found by outlanders, and you eat your hats.”

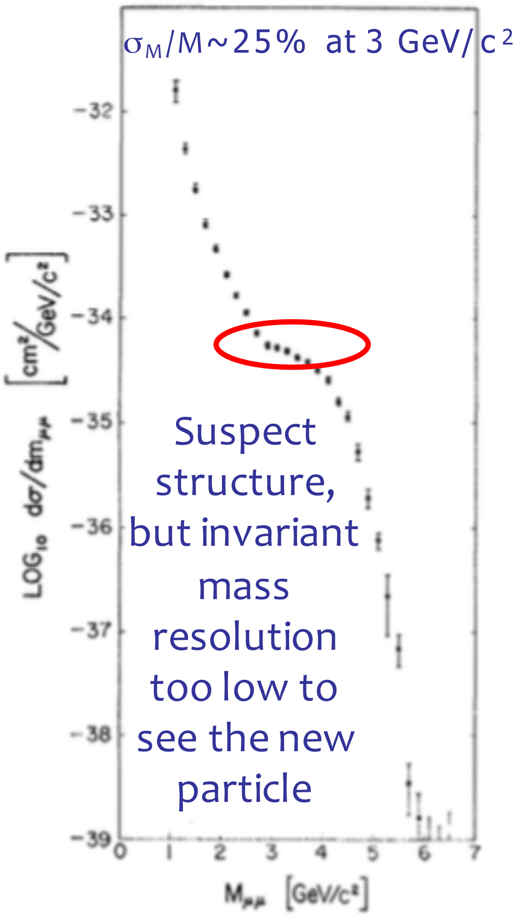
(International Conference on Experimental Meson Spectroscopy, 2-27 April 1974 Boston)
source: Fermilab-Conf97/432-E (story by John Yon for the E288 collaboration)

Dimuon measurements at AGS/BNL

Fixed target experiment (no B field!):
(J.H. Christenson et al. Phys. Rev. D8 (1973) 2016)

$p+U \rightarrow \mu^+\mu^- + X$
T_p = 22, 25, 28.5, 29.5 GeV



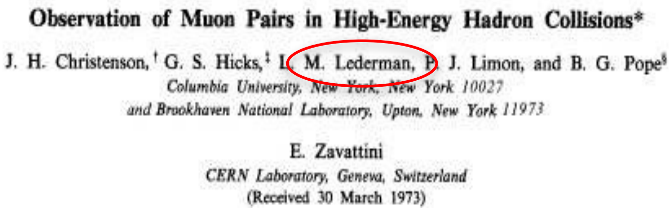


$\sigma_M/M \sim 25\%$ at 3 GeV/c^2

Suspect structure, but invariant mass resolution too low to see the new particle

Dimuon signal = difference between in-time and delayed coincidences!

$$M_{\mu\mu} = \sqrt{2\cdot p_1 p_2[1-\cos\theta_{12}]}$$

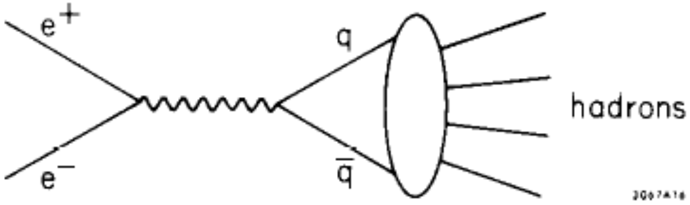


Observation of Muon Pairs in High-Energy Hadron Collisions*

J. H. Christenson,† G. S. Hicks,‡ L. M. Lederman, P. J. Limon, and B. G. Pope§
Columbia University, New York, New York 10027
and Brookhaven National Laboratory, Upton, New York 11973

E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 30 March 1973)

The R ratio



$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \cdot \sum_q Q_q$$

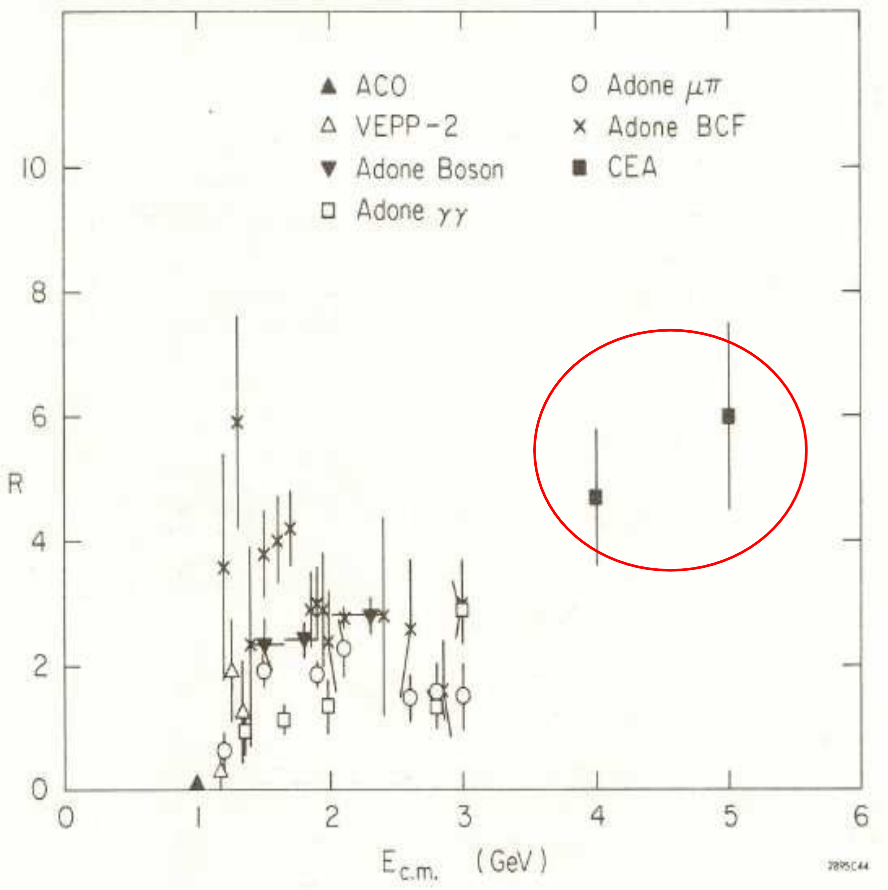
→ for u,d,s quarks R=2!

Measured R grows with energy!

- is quark model OK?
- a new quark?

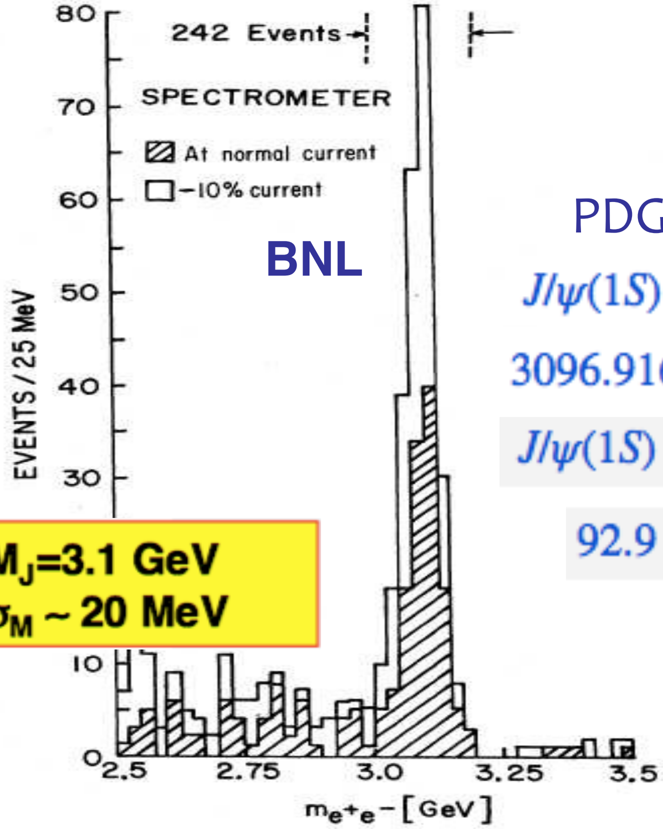
Direct motivation for B. Richter to measure the R ratio at SPEAR/SLAC

The R ratio (July 1974)



”November Revolution” - J/ψ discovery

J.J. Auber et al. PRL 33 (1974) 1404



BNL

M_J=3.1 GeV
σ_M ~ 20 MeV

$$p + Be \to \underbrace{e^+ + e^-}_{J} + X$$

PDG

$J/\psi(1S)$ MASS

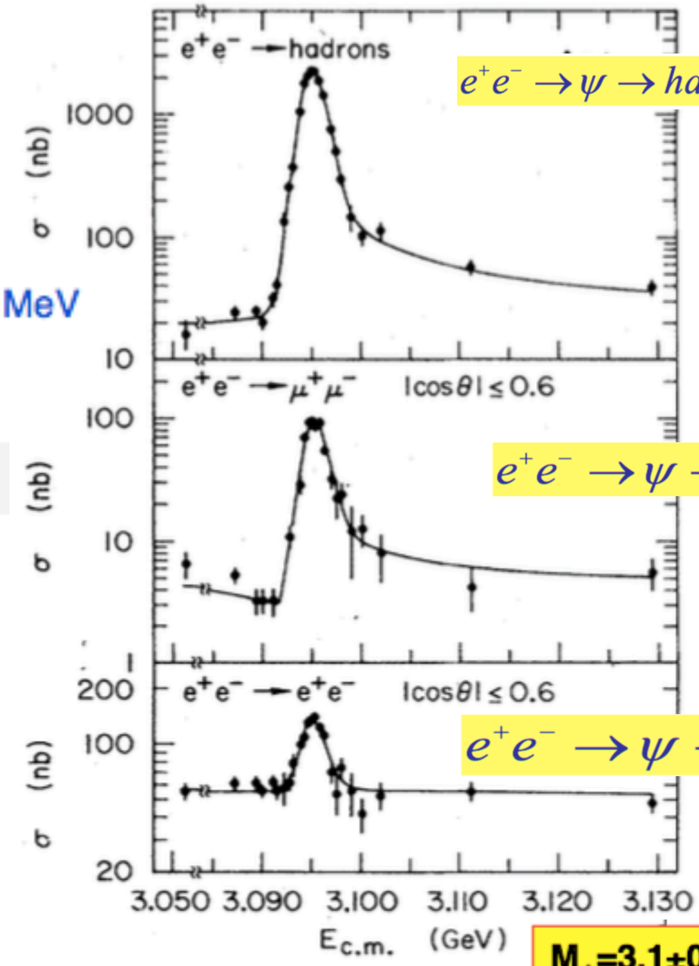
3096.916 ± 0.011 MeV

$J/\psi(1S)$ WIDTH

92.9 ± 2.8 keV

J.J. Augustin et al. PRL 33 (1974) 1406

SLAC



$e^+e^- \to \psi \to hadrons$

$e^+e^- \to \psi \to \mu^+\mu^-$

$e^+e^- \to \psi \to e^+e^-$

M_ψ=3.1±0.003 GeV
FWHM ≤ 1.3 MeV

Nobel prize

- Burton Richter and Samuel Ting were awarded the nobel prize of 1976

Burton Richter

Samuel Chao Chung Ting

Discovery of charmed neutral mesons at SPEAR/SLAC

G. Goldhaber et al., Phys. Rev. Lett. 37(1976) 265

$e^+e^- \rightarrow D^0\bar{D}^0 + X$

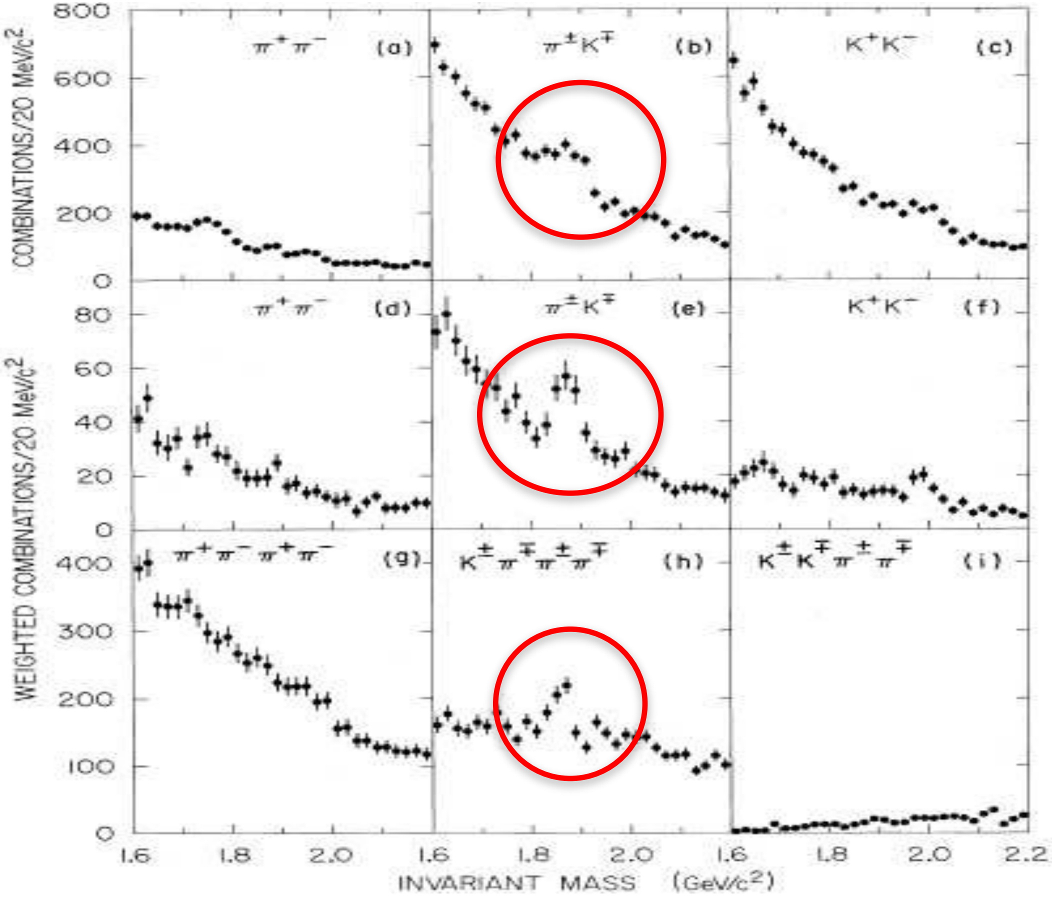
at $E_{c.m.}$= 3.9, 4.6 GeV

$m(D^0)$ =1865±15 MeV/c^2

PDG

D^0 MASS

1864.84 ± 0.05 MeV



Discovery of charmed D^{*+} mesons at SPEAR/SLAC

$$\boxed{e^+e^- \to D^- D^{*+} + X}$$

at $E_{c.m.} = 4.03$ GeV

D mesons decays:

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

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

At MARK I:

$$\boxed{\begin{array}{l} M = 2010 \pm 20 \text{ MeV} \\ \Gamma < 2 \text{ MeV} \end{array}}$$

PDG(2007):

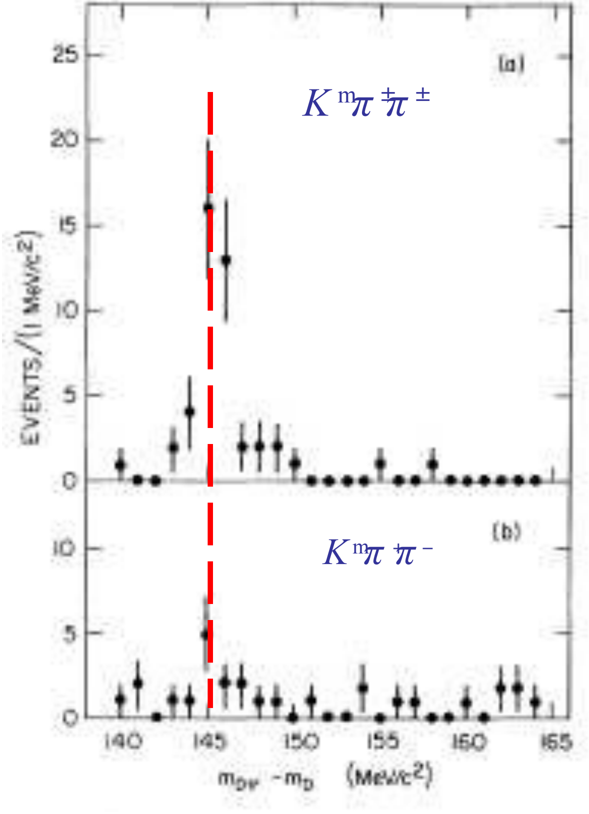
$D^{*+}(\quad\bar{\ }\quad), D^{*-}(\quad\bar{\ }\quad)$

$M = 2010 \pm 0.4$ MeV

$M_{D^*(2010)^+} - M_{D^+} = 140.64 \pm 0.10$ MeV

$M_{D^*(2010)^+} - M_{D^0} = 145.421 \pm 0.10$ MeV

G. J. Feldman et al., Phys. Rev. Lett. 37(1977)

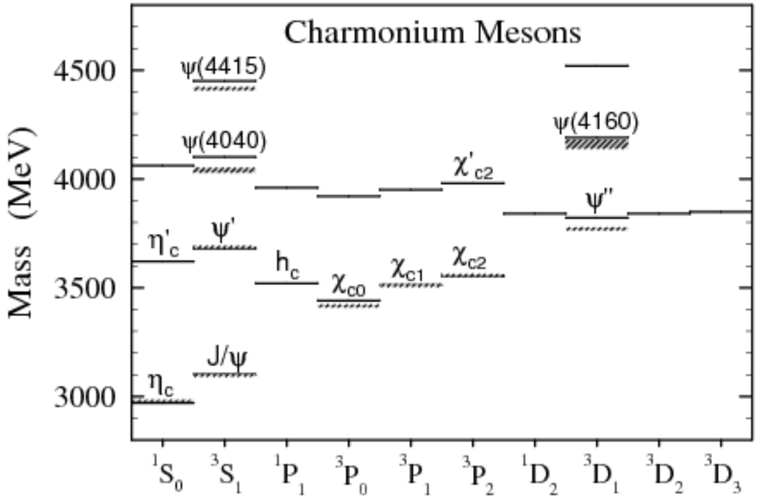


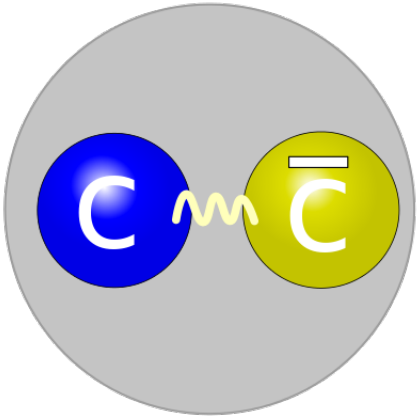
Experimental research with charm

Definitions

Charmonium

Particle with c-cbar quarks





Charmonium is a powerful tool for the understanding of the strong interaction.

Open charm

Charmed hadrons

Charmed hardons decays are a powerful tool for the understanding of the week interaction

Definitions

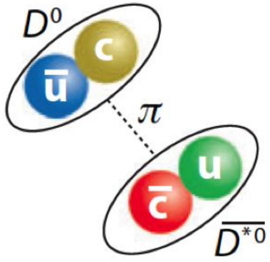
Exotic hadraons

Exotic hadrons do not have a structure of the q-qbar pairs or three-quark combinations

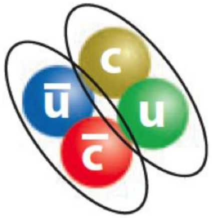
They are tetraquarks, bound states of four quarks, or pentaquarks, i.e. five quarks bound together

Their properties are under study

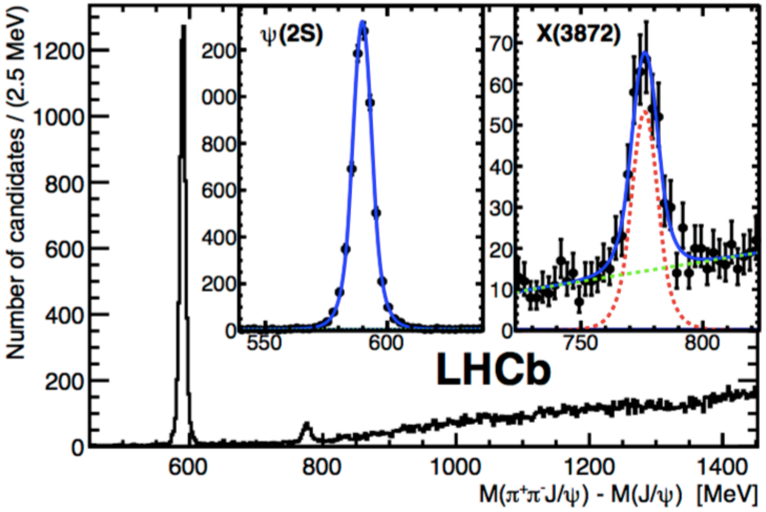
X(3872)



D^0–$\overline{D^{*0}}$ "molecule"



Diquark–diantiquark



Definitions

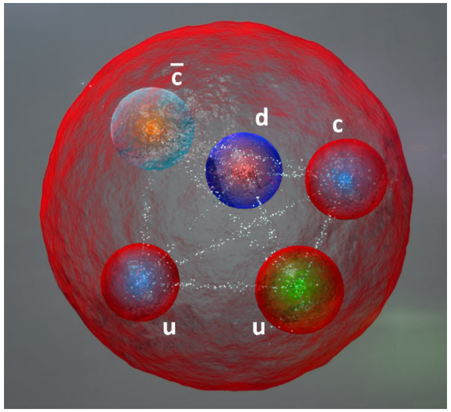
Exotic hadraons

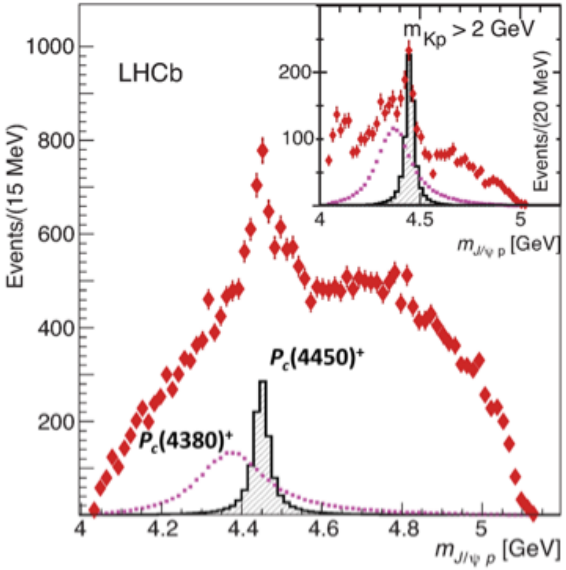
Exotic hadrons do not have a structure of the q–qbar pairs or three–quark combinations

They are tetraquarks, bound states of four quarks, or pentaquarks, i.e. five quarks bound together

Their properties are under study

$P_c(4450)$+ and $P_c(4380)$+

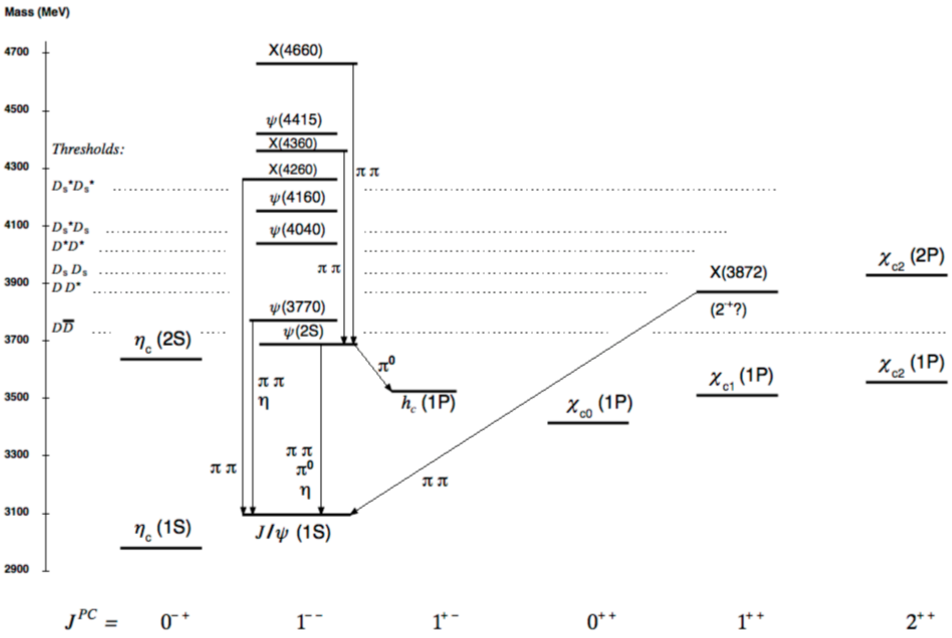


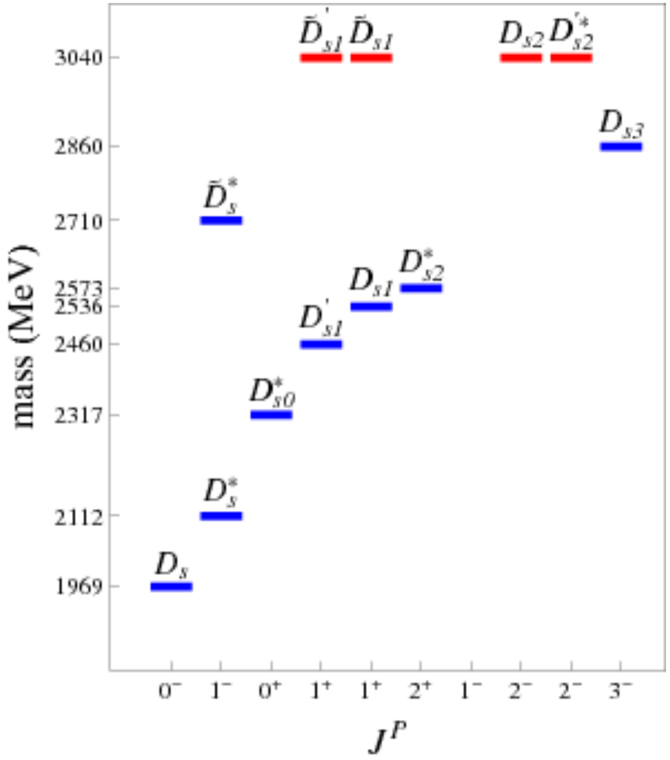


Definitions

Charmonium spectroscopy

Open charm spectroscopy





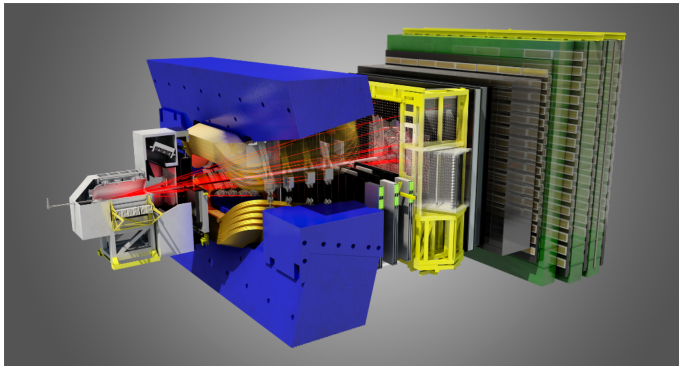
What charm physics ?

- Charmonium, exotics and open charm production
- Charmonium and Exotics spettroscopy
- CP violation and mixing with charm mesons decays
- Pure leptonic, semi-leptomic and rare charm decays
- Today we will concentrate on CP violation and mixing with charm mesons decays @ LHCb

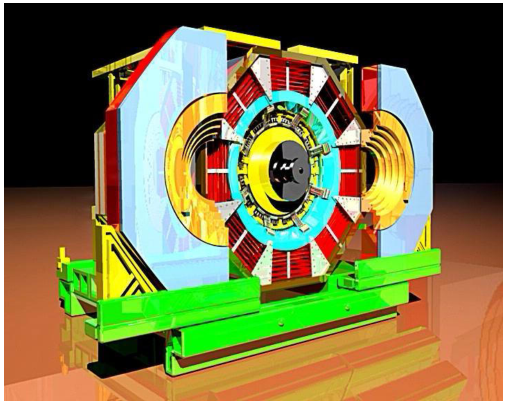
Where?

Main results from

LHCb @ LHC (pp collider)



BESIII@ BEPCII e^+e^- collider



Results also from

ATLAS CMS ALICE BaBar Belle CDF

Future

LHCb-upgrade @ LHC(pp collider)

BESIII upgrade @ BEPCII(e^+e^- collider)

PANDA @ FAIR (anti-proton fixed target)

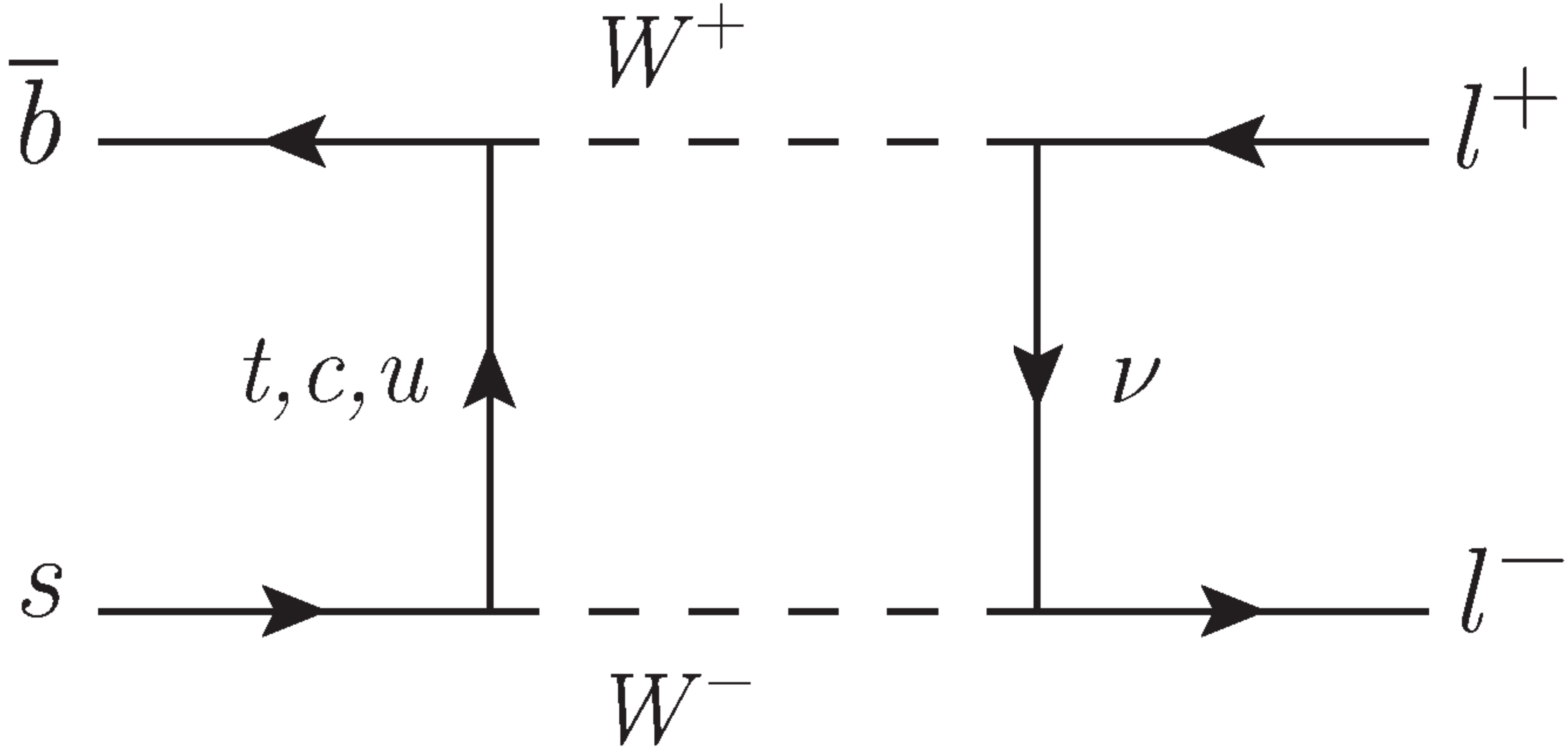
Belle-II @ KEK (e^+e^- collider)

The indirect search of New Physics

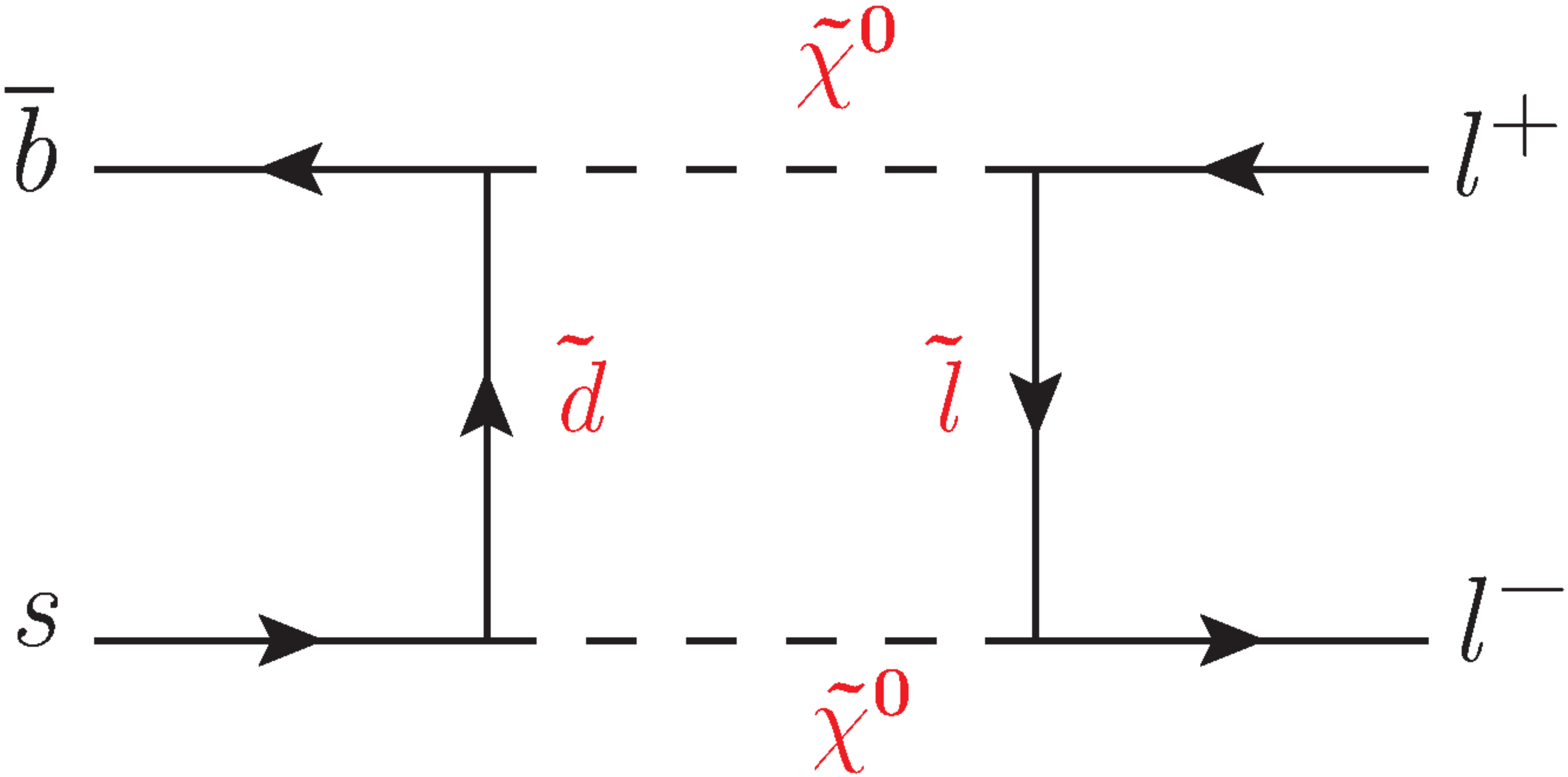
Observed deviations from values expected according to the Standard Model will indirectly hint to the existence of New Physics

Why?

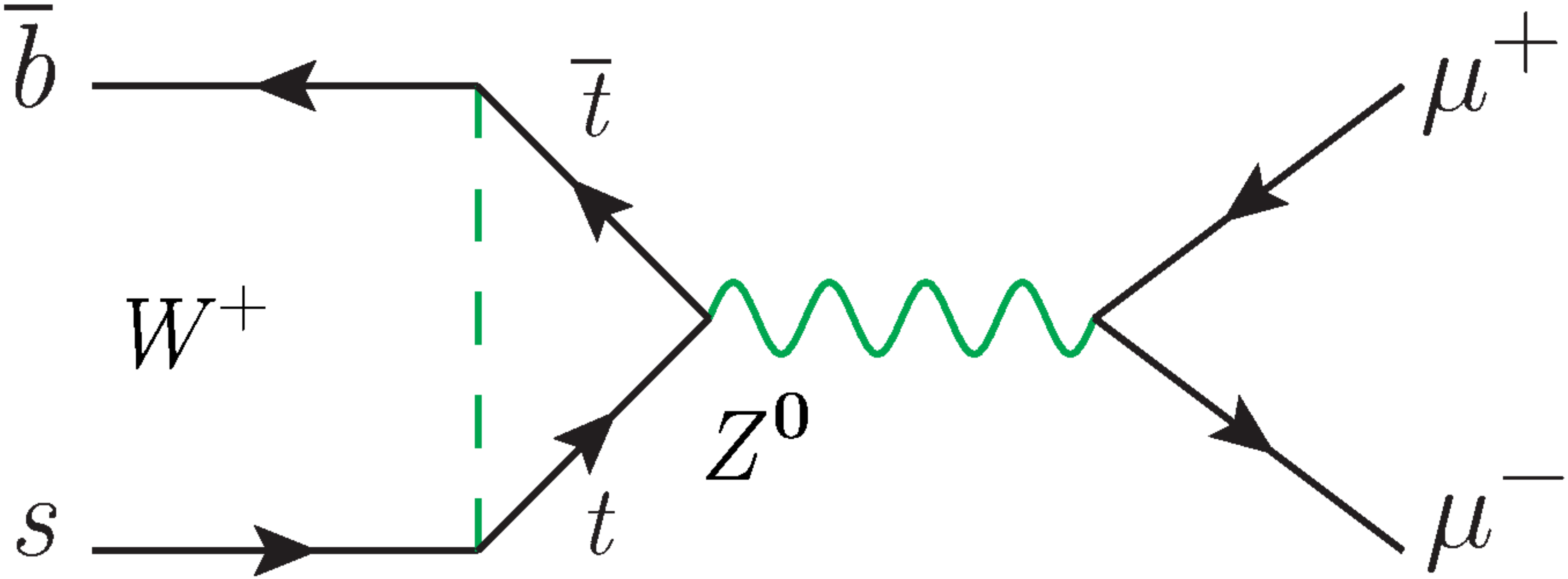
Standard Model



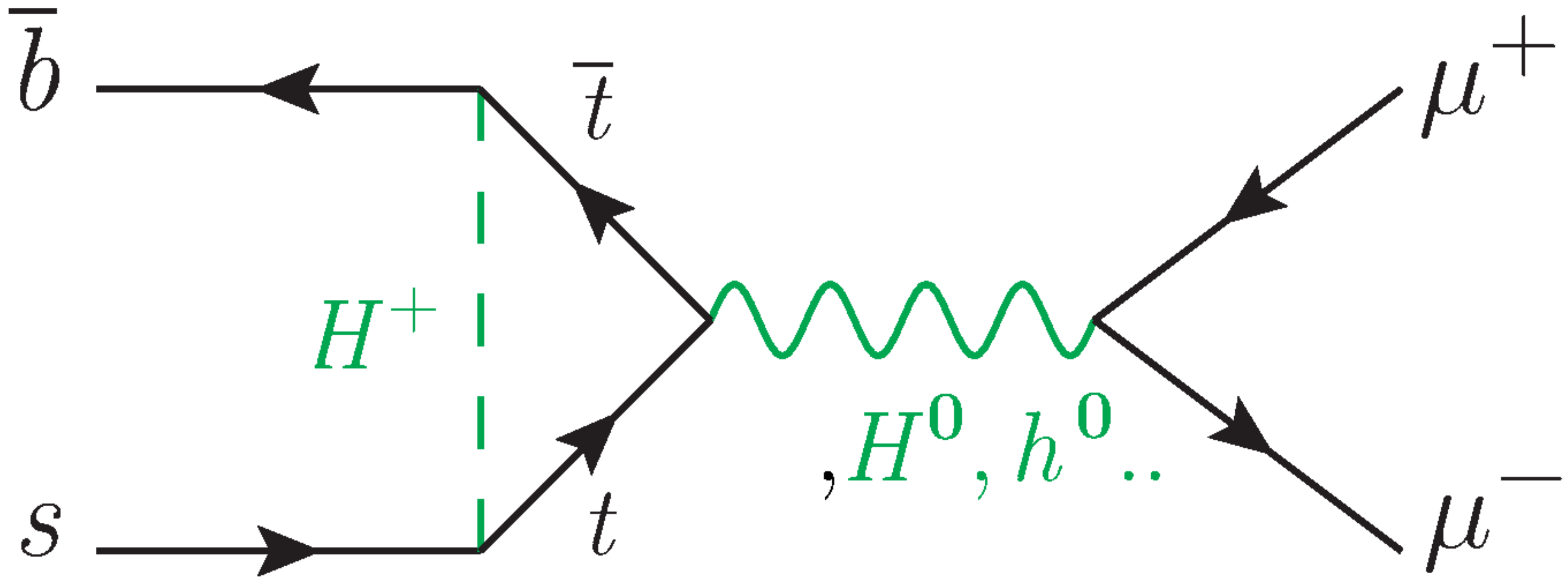
Beyond Standard Model



Standard Model

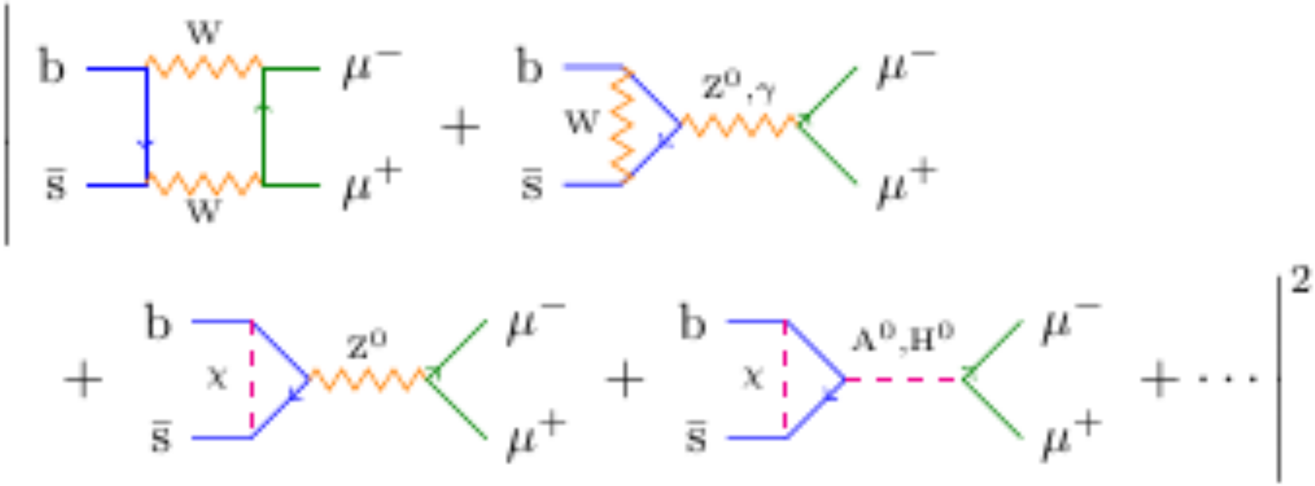


Beyond Standard Model

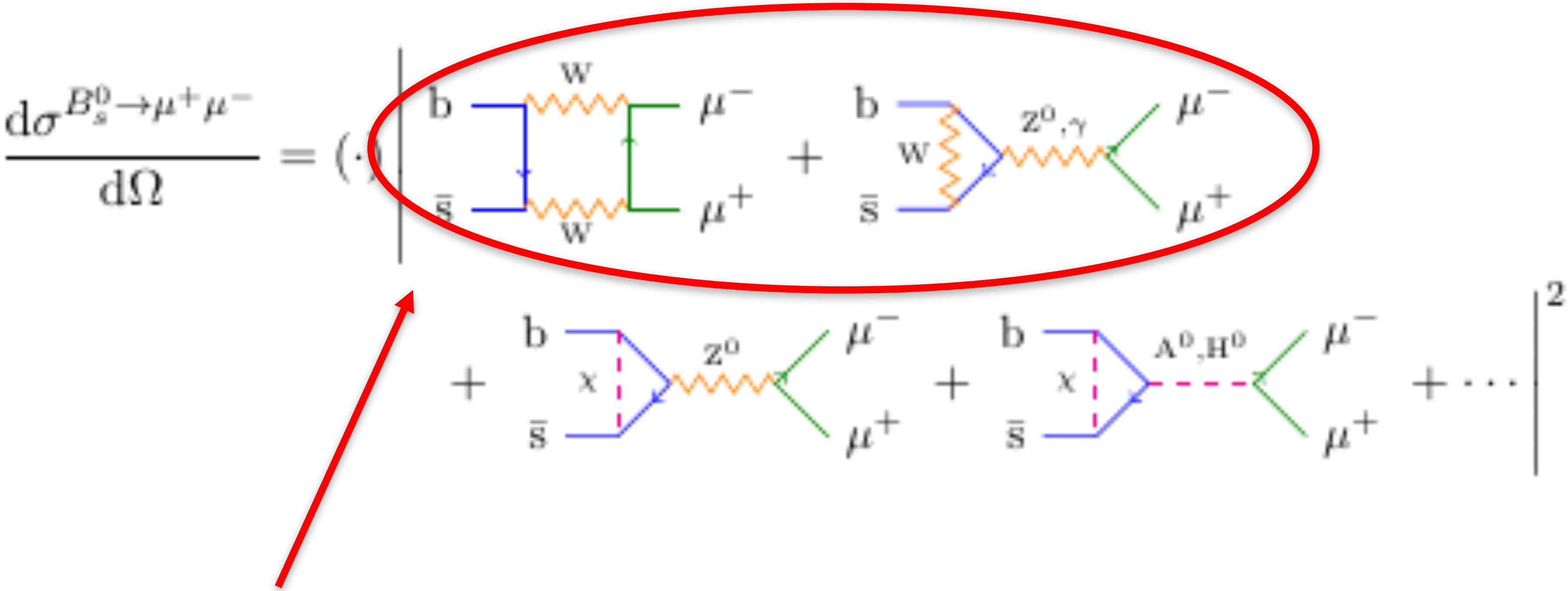


If this the nature…

$$\frac{d\sigma^{B_s^0\to\mu^+\mu^-}}{d\Omega} = (\cdot)\left| \quad + \quad + \quad + \quad + \cdots \right|^2$$

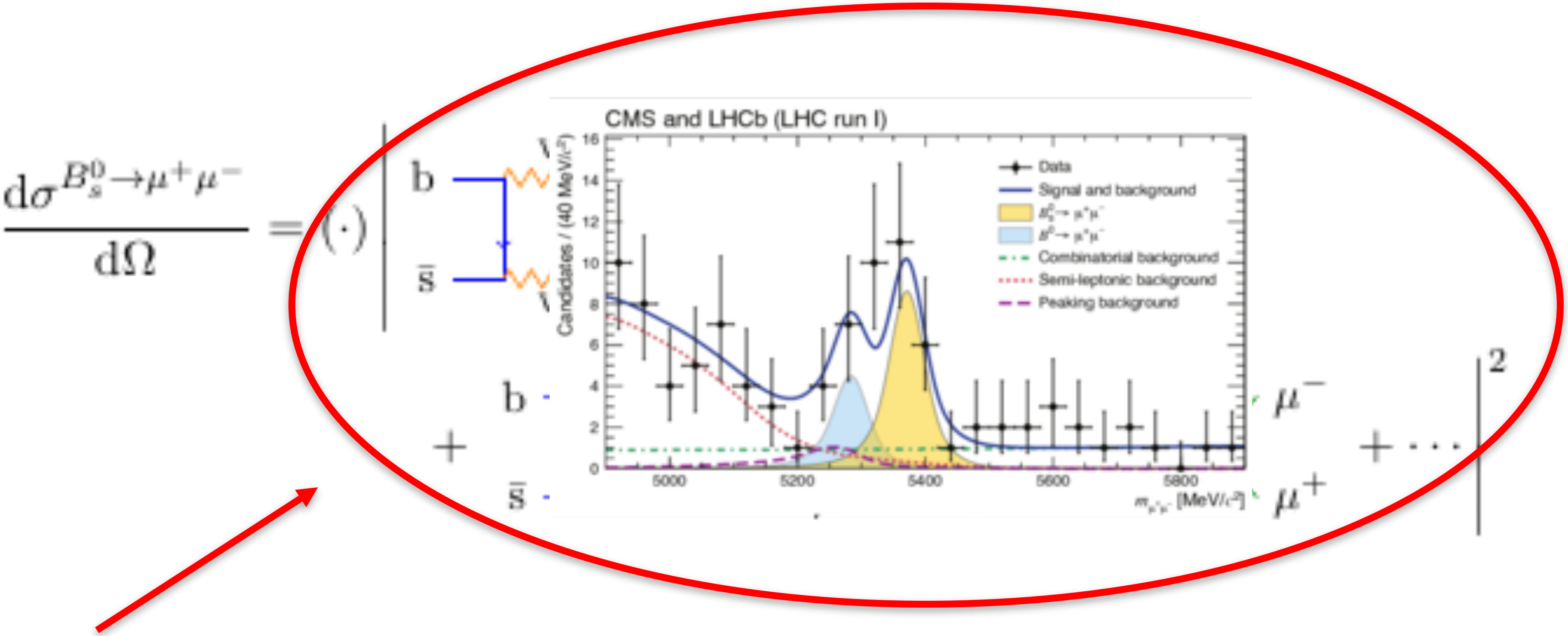


… and



SM predicts this

…

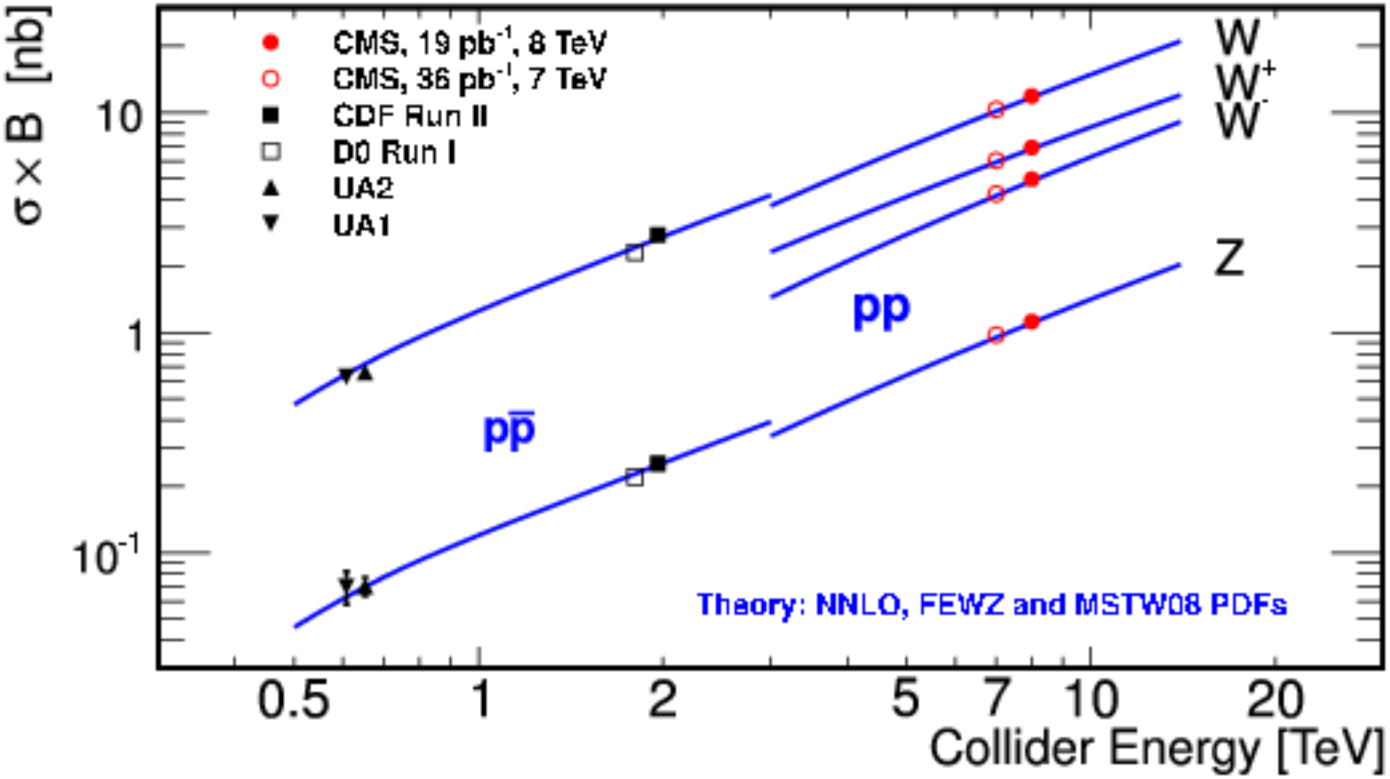


…and you measure a value significantly different from SM (which is not the case so far)

You win the Nobel prize…

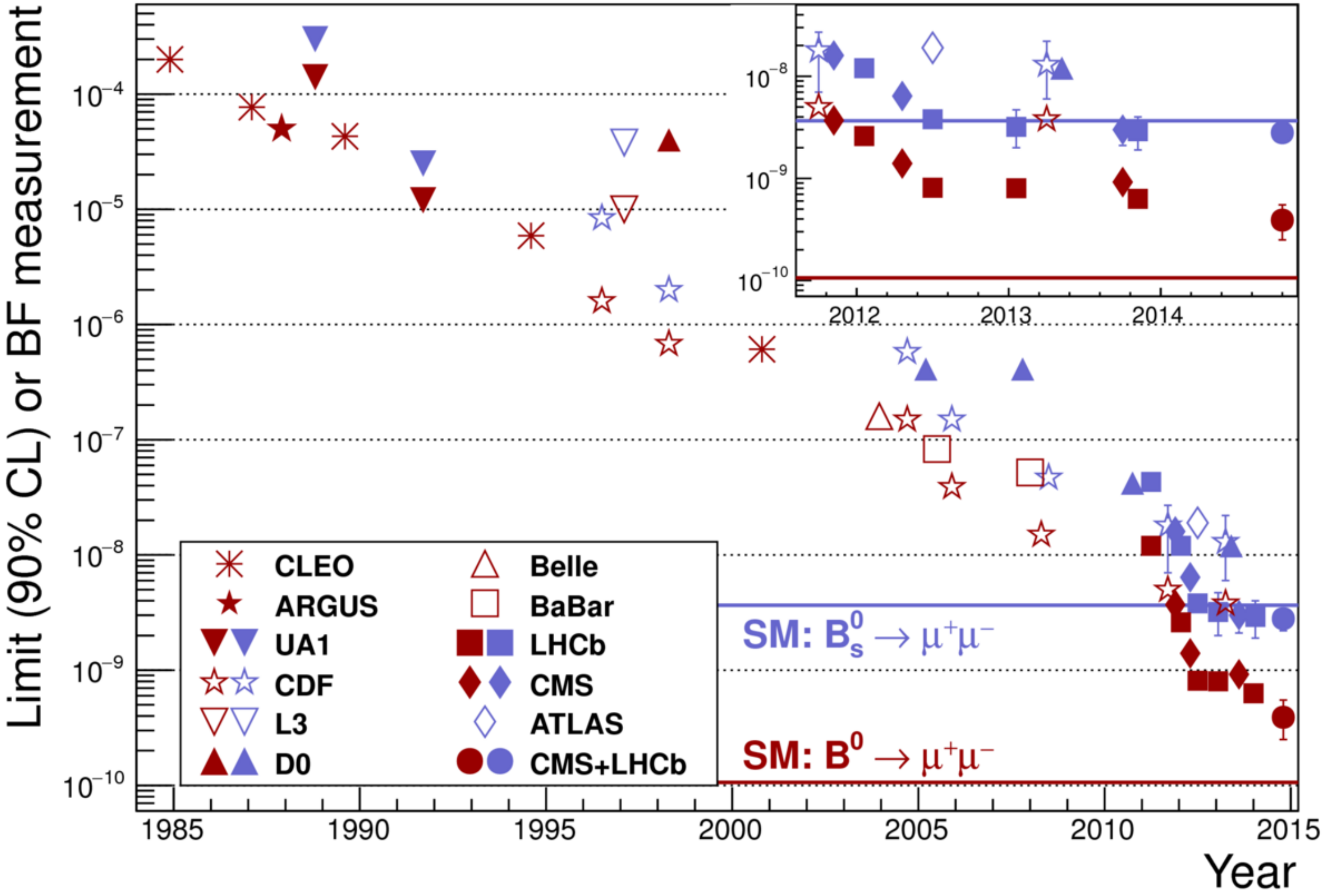
Direct search of new particle

- Main ingredient: ENERGY in C.M.
  - Now at LHC 13 TeV



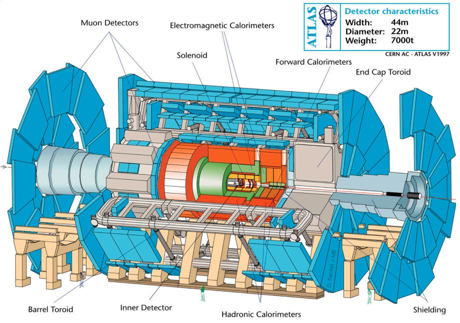
Indirect search for New Physics

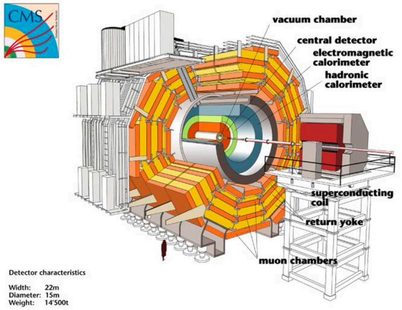
- Main ingredient: Statistics



LHCb is the right place to search for NP

- LHC experiments aim to discover New Physics beyond the Standard Model
- Direct searches of new particles produced at the LHC energy are performed by general purpose detectors: Atlas and CMS

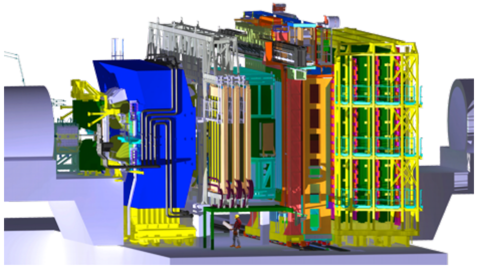




LHCb is designed for indirect searches

- Look for discrepancies in the Standard Model predictions due to the presence of new heavy particles in loop diagrams

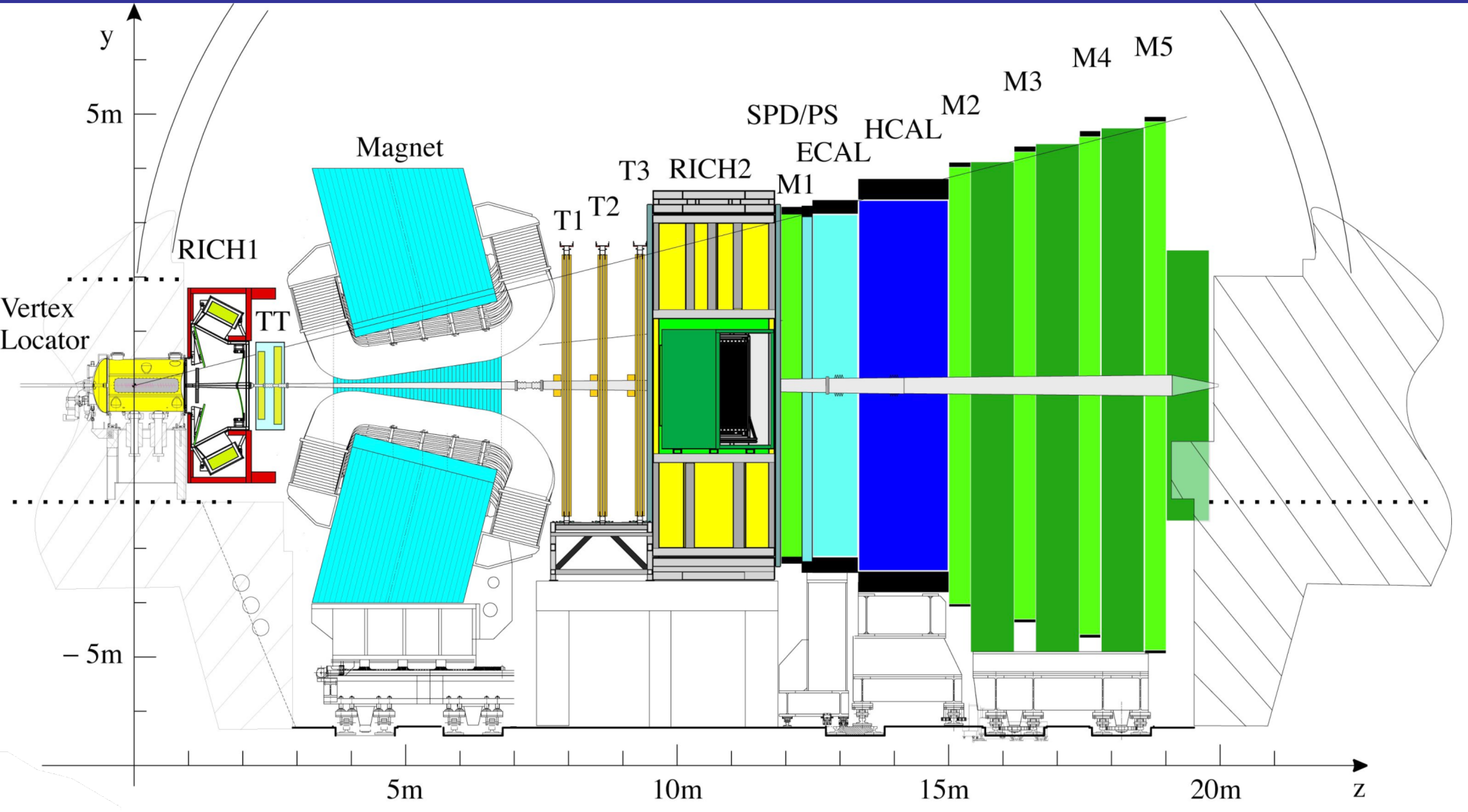
- Perform precision measurements of CP violation and rare decays of heavy hadrons
- Beauty and Charm decays are an ideal place to search for such effects



Charm and New Physics

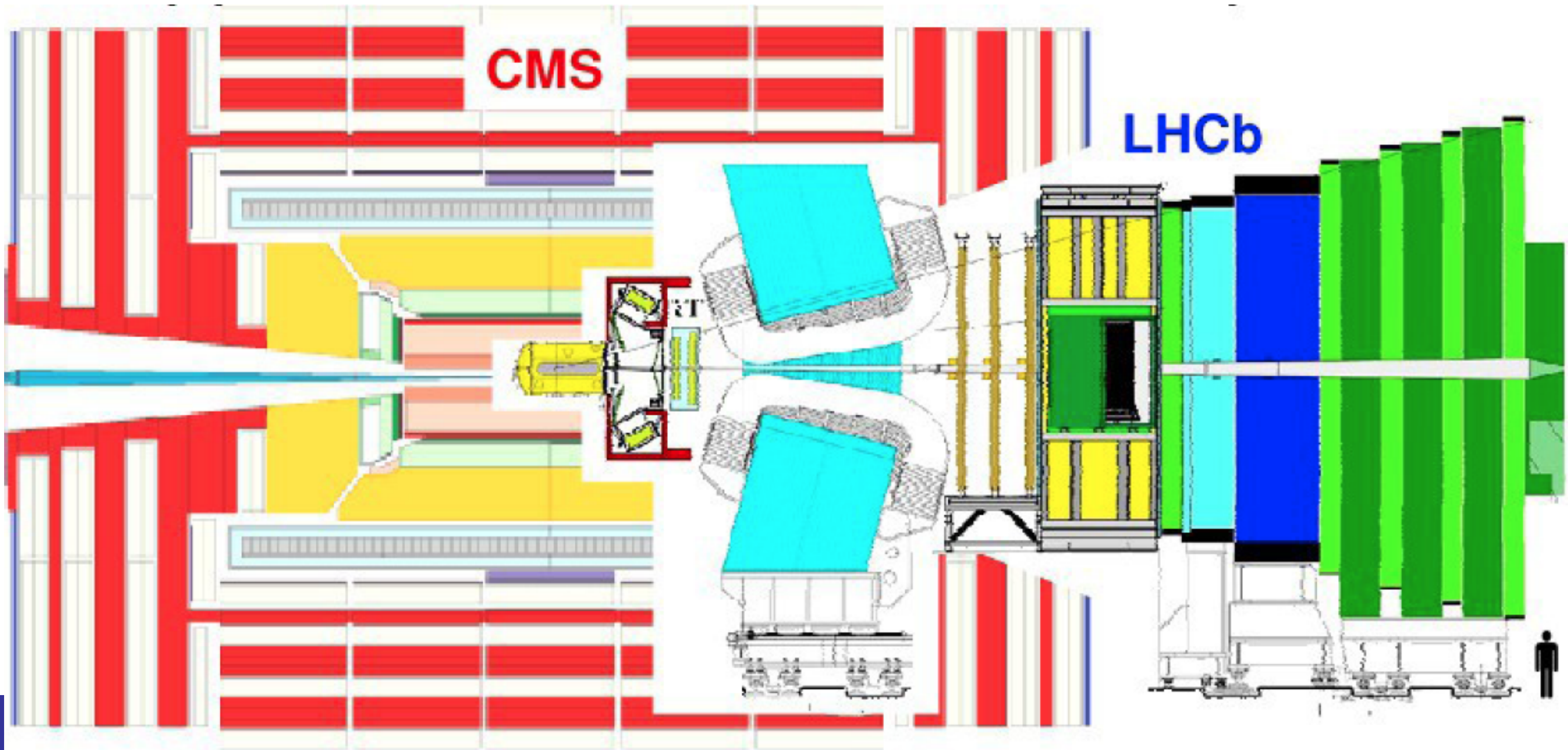
- In indirect searches for new physics, charm furnish a unique probe of flavour physics in the up-quark sector
  - complementary to strange and bottom physics
- Indirect searches for NP with charm gives complementary constraints to direct searches at the Energy Frontier
- Precision measurements in charm are necessary as inputs for B physics ($B \rightarrow DK$, $B \rightarrow D\pi$) and the measurement of the CKM angle γ
- Many "null-tests" available, one of them is the search for CP violation, which is expected to be small in SM (but not zero)
  - ... but SM predictions are difficult to be calculated

The LHCb Detector

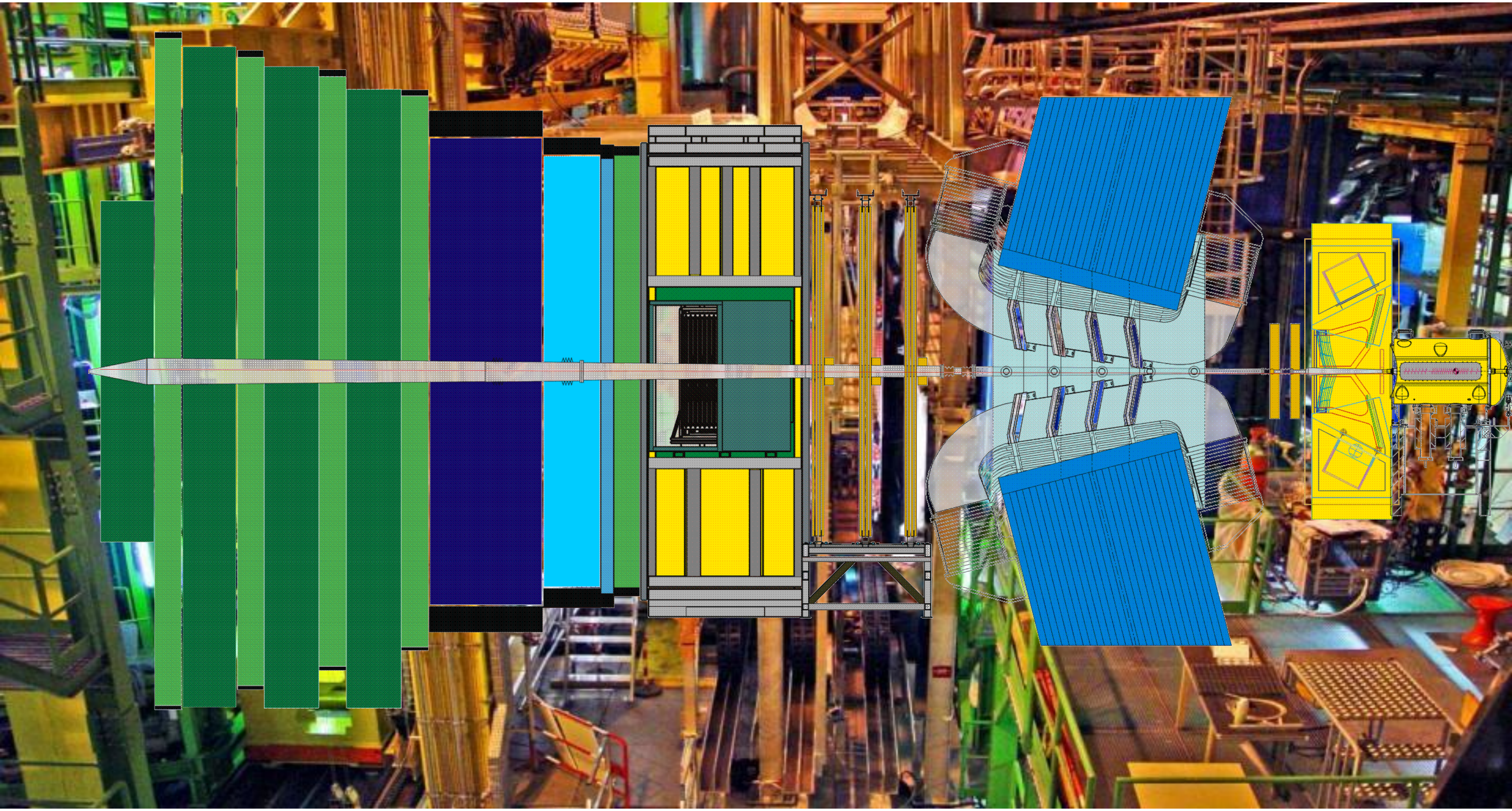


Detector Geometry

- Complementary to ATLAS & CMS
- Much less expensive



LHCb detector



Charm and D^0 production at LHC

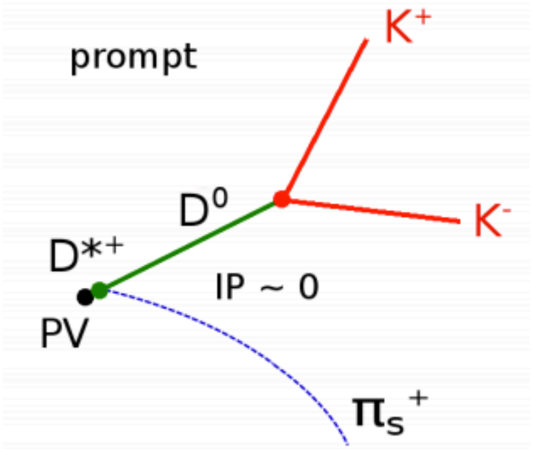
LHCb is designed for beauty physics, but it offers a great opportunity to perform charm physics as well

$$\sigma(pp \to c\bar{c}) = \begin{array}{llll} (1419 \pm 134)\mu b & @ & 7\mathrm{TeV} & \mathrm{Nucl.Phys.B871(2013)1} \\ (2940 \pm 240)\mu b & @ & 13\mathrm{TeV} & \mathrm{JHEP03(2016)159} \end{array}$$

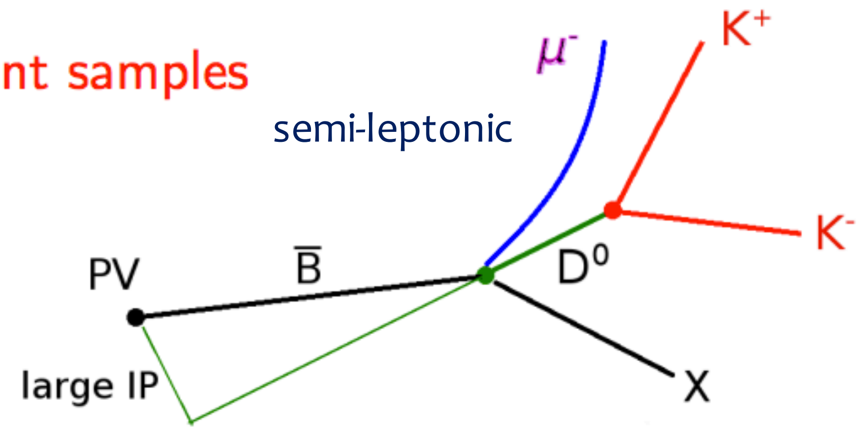
About 20 times more $b\bar{b}$

$p_T < 8$ GeV/c, $2.0 < y < 4.5$

Two mechanisms of D^0 production



Independent samples



Charm and D⁰ production at LHC

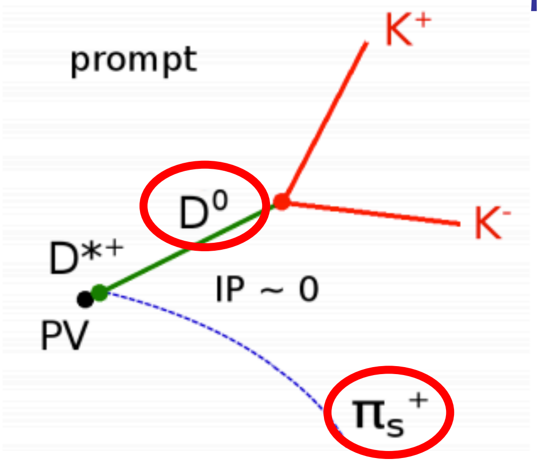
LHCb is designed for beauty physics, but it offers a great opportunity to perform charm physics as well

$$\sigma(pp \rightarrow c\bar{c}) = \begin{array}{llll} (1419 \pm 134)\mu b & @ & 7\mathrm{TeV} & \mathrm{Nucl.Phys.B871(2013)1} \\ (2940 \pm 240)\mu b & @ & 13\mathrm{TeV} & \mathrm{JHEP03(2016)159} \end{array}$$

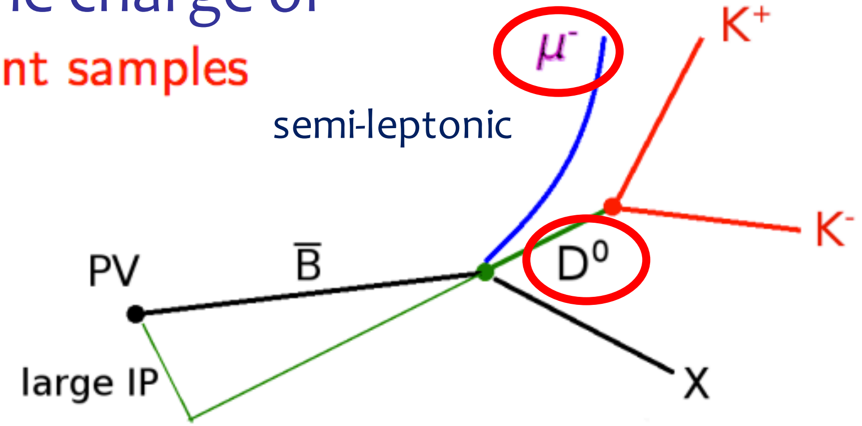
About 20 times more $b\bar{b}$

$p_T < 8$ GeV/c, $2.0 < y < 4.5$

Experimentally we can tag D⁰ flavour at production by means of the charge of



Independent samples



Charm and D⁰ production at LHC

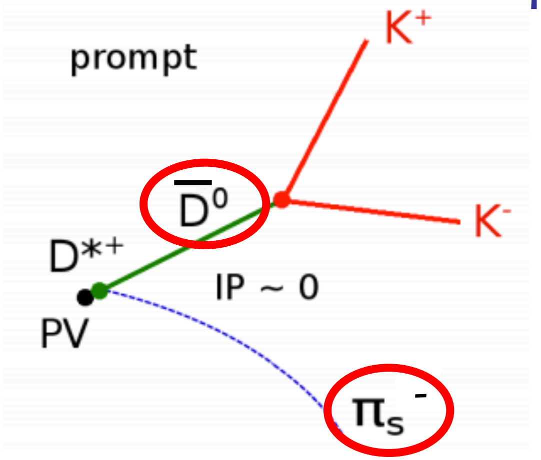
LHCb is designed for beauty physics, but it offers a great opportunity to perform charm physics as well

$$\sigma(pp \to c\bar{c}) = \begin{array}{lll} (1419 \pm 134)\mu b & @ \;\; 7\text{TeV} & \text{Nucl.Phys.B871(2013)1} \\ (2940 \pm 240)\mu b & @ \; 13\text{TeV} & \text{JHEP03(2016)159} \end{array}$$

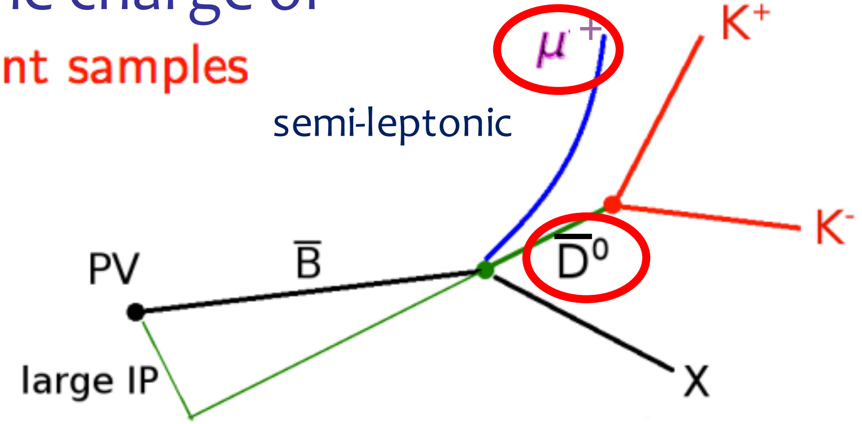
About 20 times more $b\bar{b}$

$p_T < 8$ GeV/c, $2.0 < y < 4.5$

Experimentally we can tag D⁰ flavour at production by means of the charge of



Independent samples



D^0 Mixing

The D^0 and $\overline{D}^0$ mesons are produced as flavor eigenstate
They propagate and decay according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

D^0 Mixing

The D^0 and $\overline{D}^0$ mesons are produced as flavor eigenstate
They propagate and decay according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Mixing occurs because D^0 and $\overline{D}^0$ are linear combinations of mass eigenstate

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

D⁰ Mixing

The D⁰ and $\overline{D}$⁰ mesons are produced as flavor eigenstate
They propagate and decay according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Mixing occurs because D⁰ and $\overline{D}$⁰ are linear combinations of mass eigenstate

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

The mass eigenstate develop in time as follow

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$

$$e_{1,2}(t) \equiv \exp\left[-i\left(M_{1,2} - \frac{i}{2}\Gamma_{1,2}\right)t\right]$$

D^0 Mixing

The D^0 and $\overline{D}^0$ mesons are produced as flavor eigenstate
They propagate and decay according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Mixing occurs because D^0 and $\overline{D}^0$ are linear combinations of mass eigenstate

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

The mass eigenstate develop in time as follow

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$

$$e_{1,2}(t) \equiv \exp\left[-i\left(M_{1,2} - \frac{i}{2}\Gamma_{1,2}\right)t\right]$$

Two parameters characterize the D^0 and D^0 mixing

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

D^0 Mixing

The D^0 and $\overline{D}^0$ mesons are produced as flavor eigenstate

They propagate and decay according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Mixing occurs because D^0 and $\overline{D}^0$ are linear combinations of mass eigenstate

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

The mass eigenstate develop in time as follow

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$

$$e_{1,2}(t) \equiv \exp\left[-i\left(M_{1,2} - \frac{i}{2}\Gamma_{1,2}\right)t\right]$$

Two parameters characterize the D^0 and D^0 mixing

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

If both x and y are different from zero, mixing occurs

$$|\langle\overline{D}^0|D^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

$$|\langle D^0|\overline{D}^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

D^0 Mixing

The D^0 and $\overline{D}^0$ mesons are produced as flavor eigenstate
They propagate and decay according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

Mixing occurs because D^0 and $\overline{D}^0$

The mass eigenstate develop in time

Mixing is well established

Charm mixing parameters are small < 10^{-2}

Two parameters characterizes the D^0 and D^0 mixing

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

If both x and y are different from zero, mixing occurs

$$|\langle \overline{D}^0 | D^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

$$|\langle D^0 | \overline{D}^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

CP Violation in Charm

3 modes of observing CP violation

CP Violation in Charm

3 modes of observing CP violation

in decay: amplitudes for a process and its conjugate differ

direct CPV

CP Violation in Charm

3 modes of observing CP violation

in decay: amplitudes for a process and its conjugate differ

direct CPV

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

in interference between mixing and decay diagrams

indirect CPV

CP Violation in Charm

3 modes of observing CP violation

in decay: amplitudes for a process and its conjugate differ

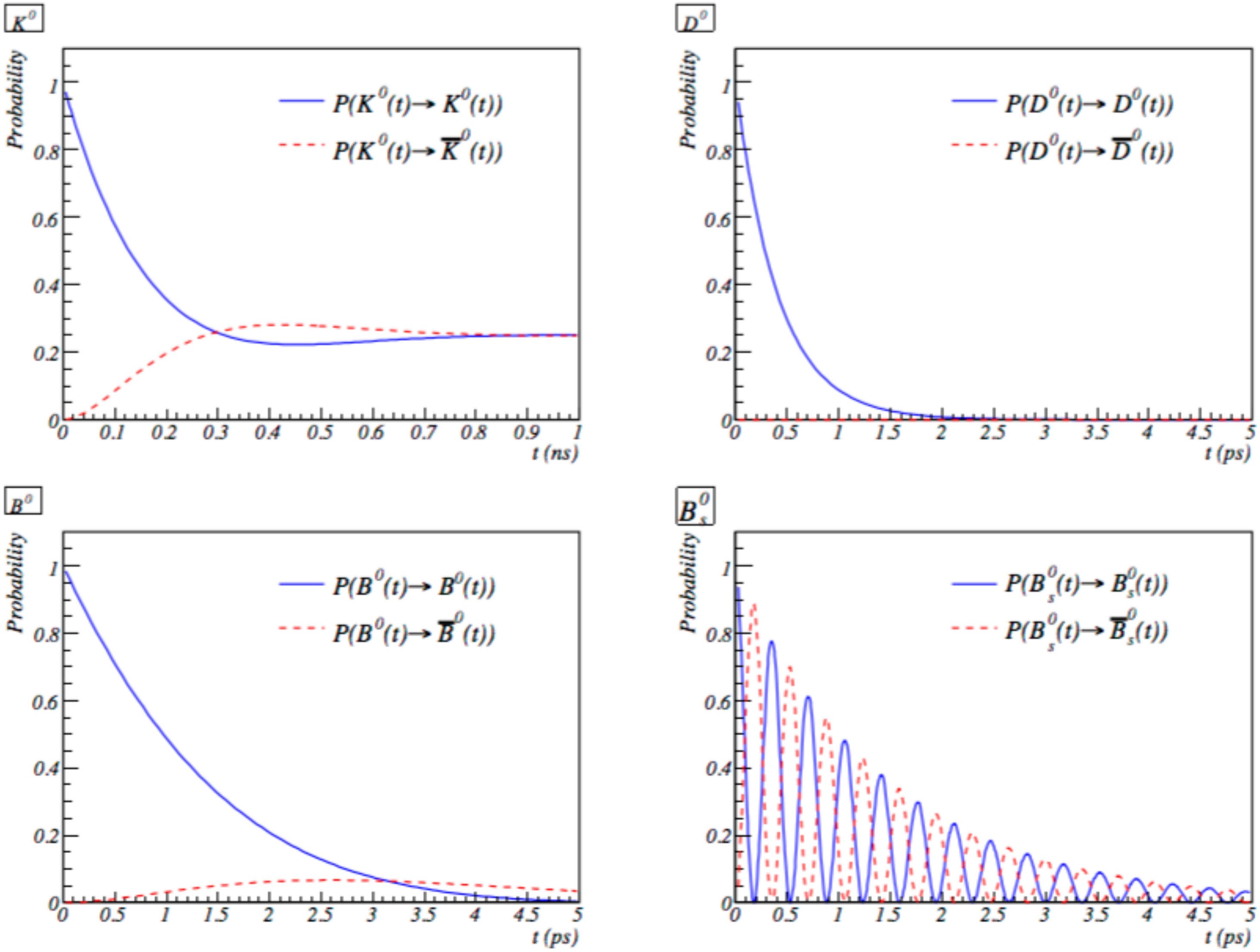
direct CPV

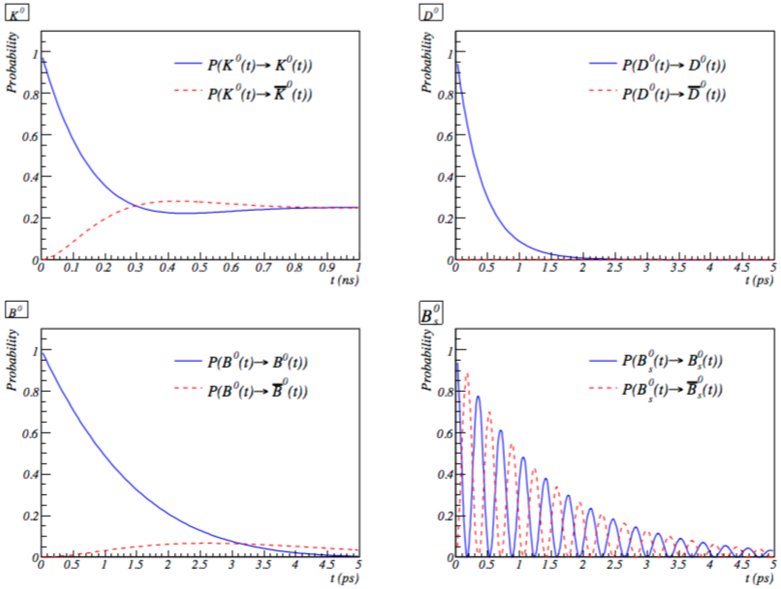
CP violation is not yet observed

in interference between mixing and decay diagrams

indirect CPV

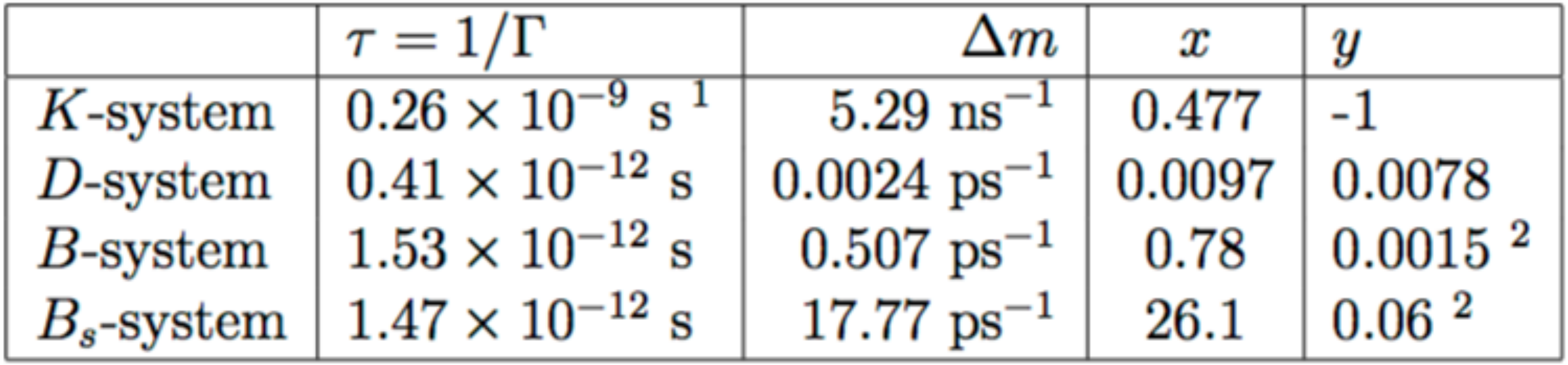
Neutral meson oscillation


K^0
Probability
$P(K^0(t) \rightarrow K^0(t))$
$P(K^0(t) \rightarrow \overline{K}^0(t))$
0, 0.2, 0.4, 0.6, 0.8, 1
0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1
t (ns)
D^0
Probability
$P(D^0(t) \rightarrow D^0(t))$
$P(D^0(t) \rightarrow \overline{D}^0(t))$
0, 0.2, 0.4, 0.6, 0.8, 1
0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5
t (ps)
B^0
Probability
$P(B^0(t) \rightarrow B^0(t))$
$P(B^0(t) \rightarrow \overline{B}^0(t))$
0, 0.2, 0.4, 0.6, 0.8, 1
0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5
t (ps)
B_s^0
Probability
$P(B_s^0(t) \rightarrow B_s^0(t))$
$P(B_s^0(t) \rightarrow \overline{B}_s^0(t))$
0, 0.2, 0.4, 0.6, 0.8, 1
0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5
t (ps)



$$x = \frac{\Delta m}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

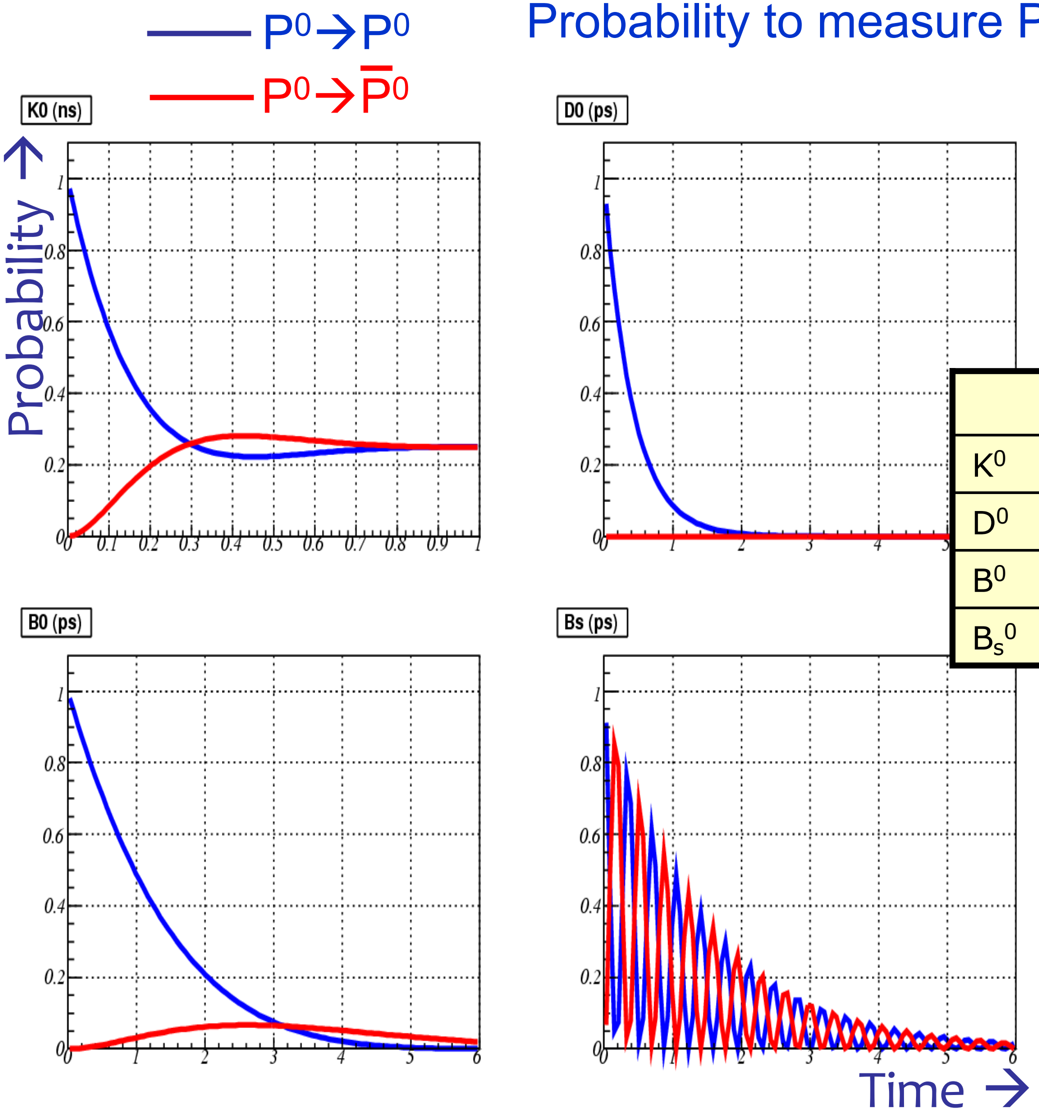
	$\tau = 1/\Gamma$	Δm	x	y
K-system	0.26×10^{-9} s [1]	5.29 ns^{-1}	0.477	-1
D-system	0.41×10^{-12} s	0.0024 ps^{-1}	0.0097	0.0078
B-system	1.53×10^{-12} s	0.507 ps^{-1}	0.78	0.0015 [2]
B_s-system	1.47×10^{-12} s	17.77 ps^{-1}	26.1	0.06 [2]



	$\tau = 1/\Gamma$	Δm	x	y
K-system	0.26×10^{-9} s [1]	5.29 ns^{-1}	0.477	-1
D-system	0.41×10^{-12} s	0.0024 ps^{-1}	0.0097	0.0078
B-system	1.53×10^{-12} s	0.507 ps^{-1}	0.78	0.0015 [2]
B_s-system	1.47×10^{-12} s	17.77 ps^{-1}	26.1	0.06 [2]

Compare the mesons:

Probability to measure P or $\overline{P}$, when we start with 100% P



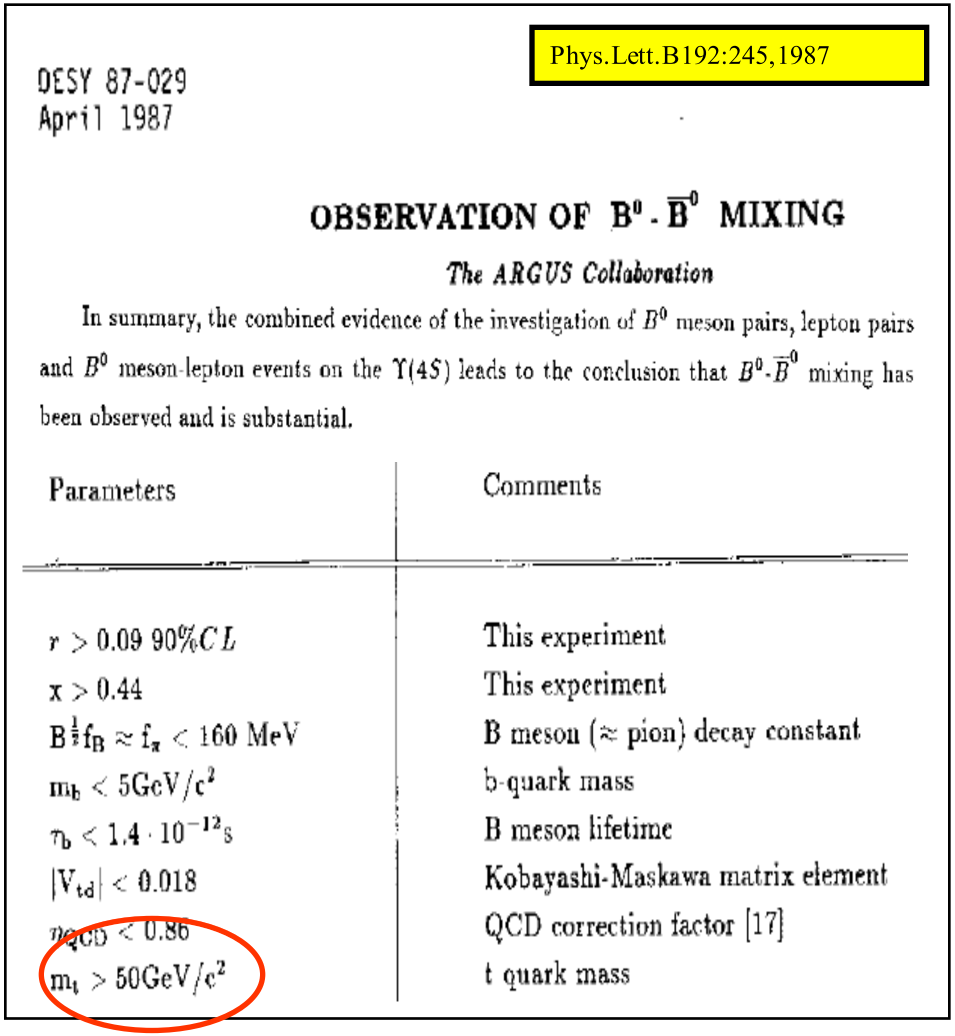
	$<\tau>$	ΔM	$x=\Delta M/\Gamma$	$y=\Delta\Gamma/2\Gamma$
K^0	$2.6\ 10^{-8}$ s	5.29 ns^{-1}	$\Delta M/\Gamma_S=0.49$	~ 1
D^0	$0.41\ 10^{-12}$ s	0.001 fs^{-1}	10^{-2}	10^{-2}
B^0	$1.53\ 10^{-12}$ s	0.507 ps^{-1}	0.78	~0
B_s^0	$1.47\ 10^{-12}$ s	17.8 ps^{-1}	12.1	~0.05

$x=\Delta M/\Gamma$: avg nr of oscillations before decay

B^0 mixing: 1987 Argus

- B^0 oscillations:
  - First evidence of heavy top
  - m_{top}>50 GeV

NB: loops can reveal heavy (new) particles!



Phys.Lett.B192:245,1987

DESY 87-029
April 1987

OBSERVATION OF B^0 - $\bar{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ $90\% CL$	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5 \mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50 \mathrm{GeV}/c^2$	t quark mass

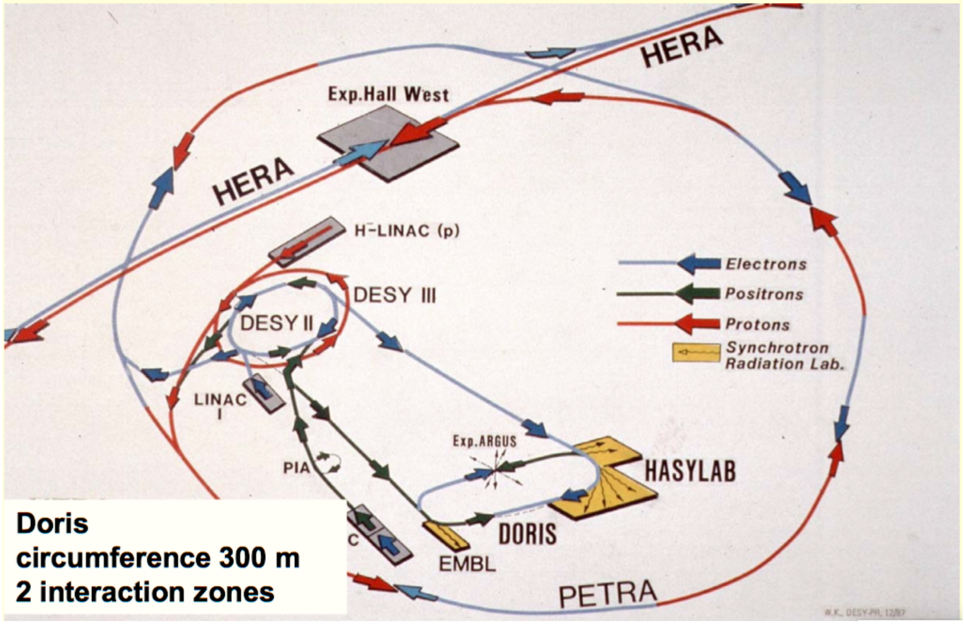
B⁰ mixing: 1987 Argus

$$r = \frac{x^2}{x^2+2} \qquad\qquad x = 0.73 \pm 0.28$$

$$x = \frac{\Delta M}{\Gamma} = 32\pi \frac{B f_B^2 m_t^2 m_b}{m_\mu^5} \frac{\tau_b}{\tau_\mu} \mid V_{td} \mid^2 \eta_{QCD}$$

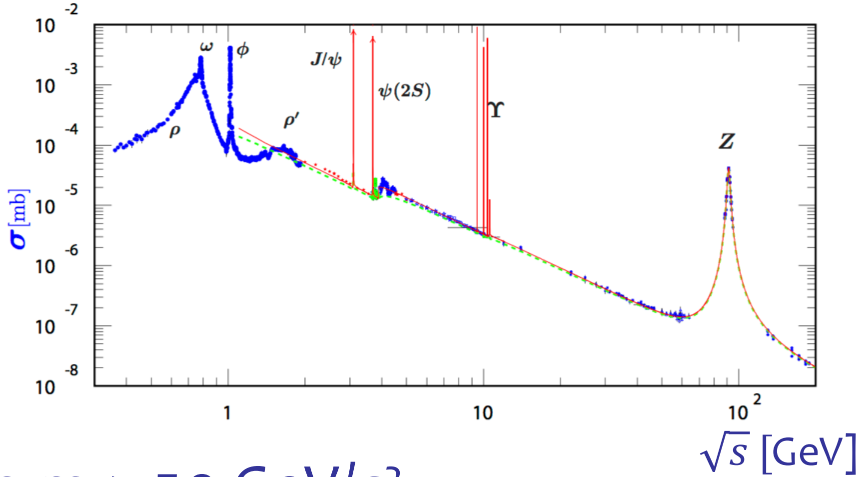
The observed value of r provides a strong constraint on parameters of the standard model. It can still be accommodated by the standard model within the present knowledge of its parameters provided the top quark is existing and heavy ($m_t > 50 GeV/c^2$).

Potential of indirect research



Doris
circumference 300 m
2 interaction zones

DORIS II (1982 – 1993)
$e^+ e^-$ collider with a center of mass energy of 11.2 GeV



The ARGUS experiment establish $m_t > 50$ GeV/c²

Today: $m_t = 173 \pm 0.51 \pm 0.71\ \mathrm{GeV}/c^2$

Indirect CP violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

How A_Γ is measured

- The time-dependent CP asymmetry for D^0 decay decaying into a final state CP eingenstate (i.e. K^-K^+ or $\pi^-\pi^+$) is defined as

$$A_{CP}(t) \equiv \frac{\Gamma(D^0 \to f;t) - \Gamma(\overline{D}^0 \to f;t)}{\Gamma(D^0 \to f;t) + \Gamma(\overline{D}^0 \to f;t)} \qquad A_{CP}(t) \approx A_{CP}^{\mathrm{dir}} - A_\Gamma \frac{t}{\tau}$$

where $A_\Gamma \equiv \dfrac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\overline{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\overline{D}^0}}$, $\hat{\Gamma}$ is the effective D^0 lifetime.

A_Γ can be approximated in terms of D^0 mixing parameter x, y, ϕ,

$$A_\Gamma \approx \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right] \qquad \phi = \arg\left[\frac{q\overline{A}_f}{pA_f}\right]$$

How A_Γ is measured

What we measure is

$$A_{raw}\left(f,[t_i,t_j]\right)=\frac{N(B\to D^0\mu^- X)-N(B\to \overline{D}^0\mu^+ X)}{N(B\to D^0\mu^- X)+N(B\to \overline{D}^0\mu^+ X)}$$

Then we fit the time evolution of the asymmetries to extract A_Γ

$$A_{RAW}^{CP}\left(t\right)\approx A_0-A_\Gamma\frac{t}{\tau}$$

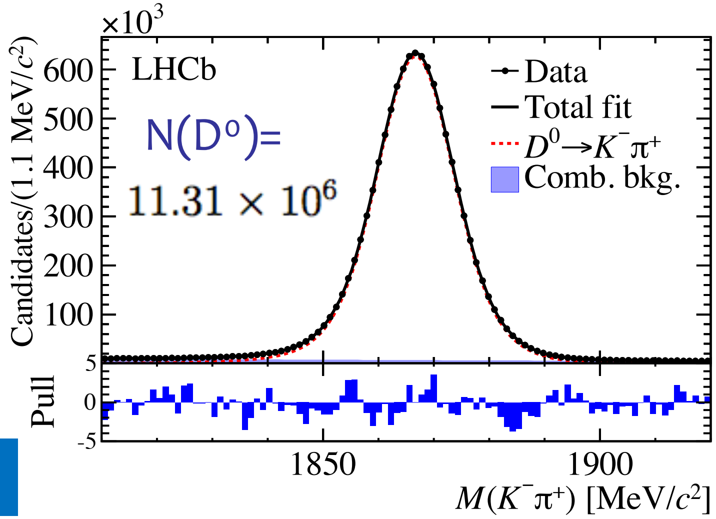
in 50 bins of D^0 decay time.

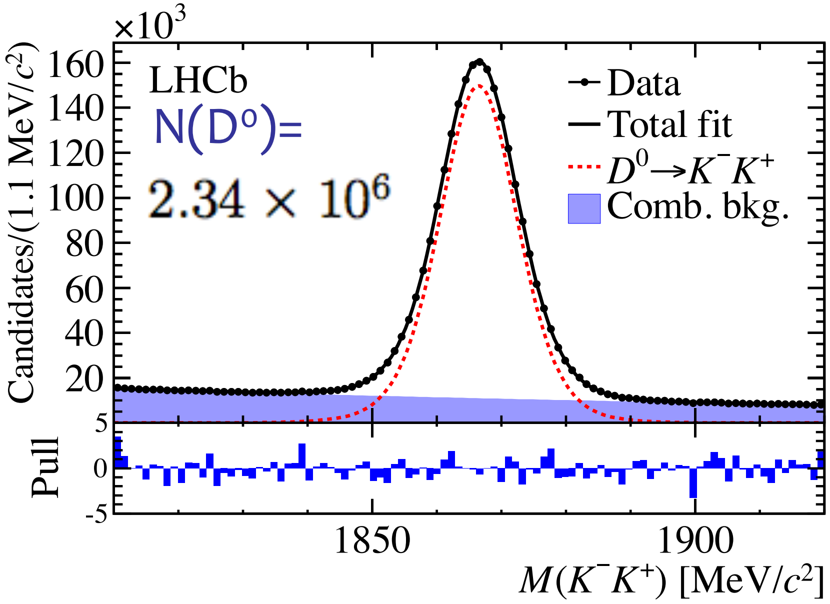
The A_{raw} is affected by muon detection asymmetry and D^0 production asymmetry, which introduces a bias on A_{CP}^{dir} but not on A_Γ.

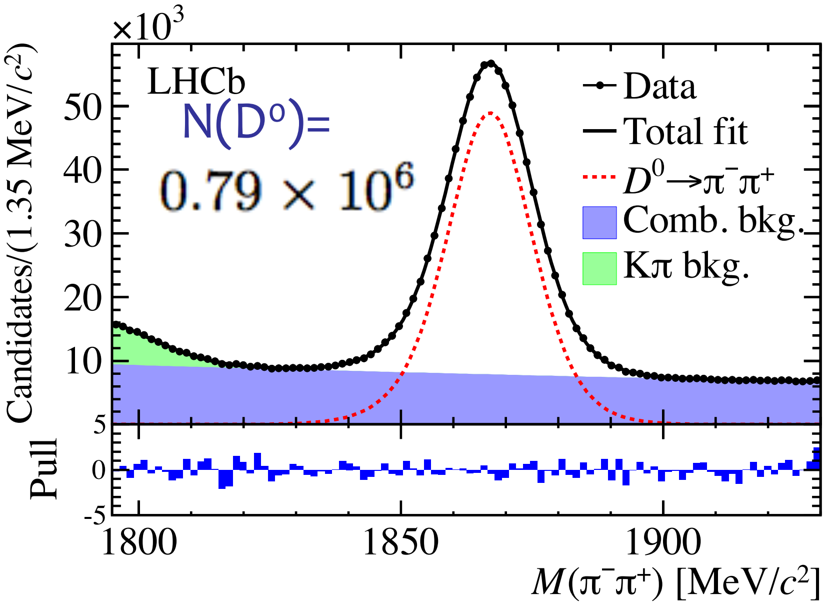
Yields with L = 3fb^{-1} (RUN-1)

- Latest LHCb measurement using D^0 from semi-leptonic B decays
- Full Run-1 dataset, L=3 fb^{-1}
- $D^0 \rightarrow K^-\pi^+$ used as control channel

[arXiv:1501.06777, JHEP 04 (2015) 043]

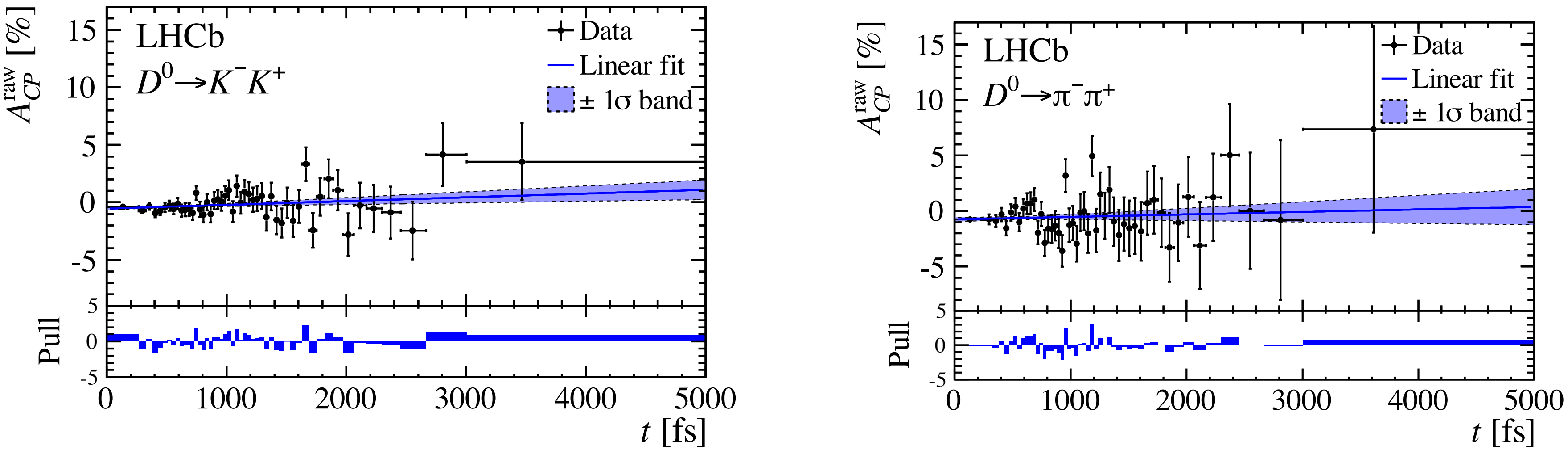

N(D^0)= 11.31×10^6


N(D^0)= 2.34×10^6


N(D^0)= 0.79×10^6

Results

[arXiv:1501.06777, JHEP 04 (2015) 043]



Fits to the time evolution of the asymmetries give

$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077\,^{+0.026}_{-0.034})\%$$

$$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145\,^{+0.025}_{-0.033})\%$$

Statistically dominated uncertainty
Largest systematic contribution coming from the mistag asymmetry

In agreement with previous LHCb measurements using prompt D⁰ (1fb⁻¹)

$$A_\Gamma(KK) = (-0.035 \pm 0.062 \pm 0.012)\%$$

$$A_\Gamma(\pi\pi) = (0.033 \pm 0.106 \pm 0.014)\%$$

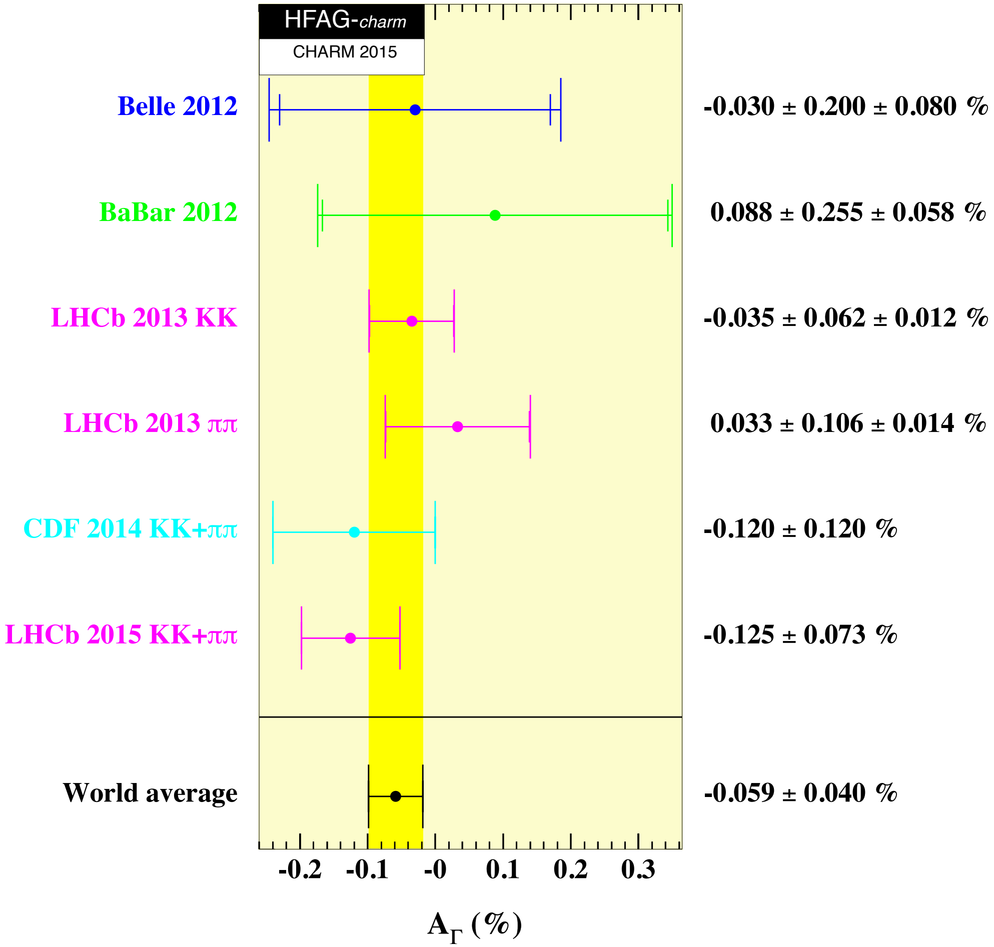
[PRL 112 (2014) 041801]

A_Γ average

[arXiv:1501.06777, JHEP 04 (2015) 043]

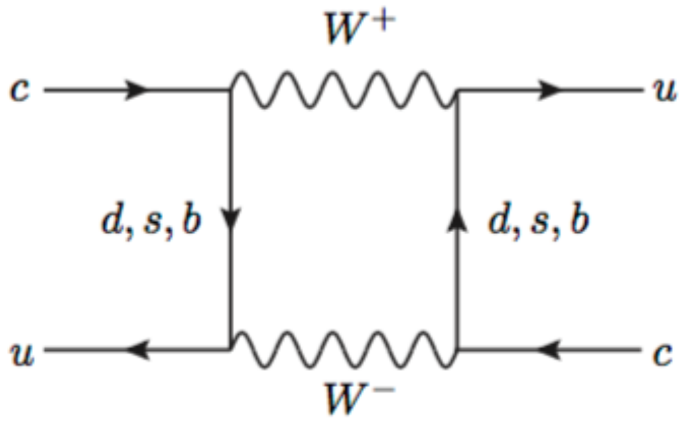
Assuming indirect CP violation to be independent from the D^0 final state, the overall LHCb average, including pion-tagged measurement is

$$A_\Gamma = (-0.056 \pm 0.044)\%$$

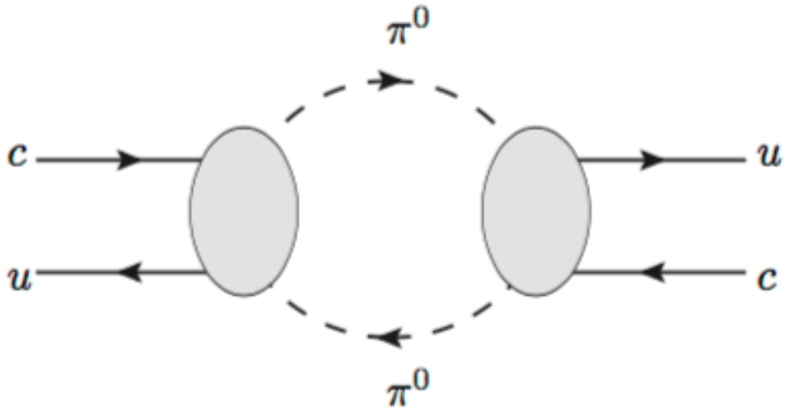


Update of the most precise measurement (pion-tagged) with 3/fb (Run-1) is ongoing

D^0 mixing with $D^0 \rightarrow K^+\pi^-$ decay



"Short distance"



"Long distance"

Short distance contribution is CKM + GIM suppressed. NP might manifest in the loop

Long distance contribution is dominant but hard to predict

CKM suppression: b quark
GIM suppression: d,s quark

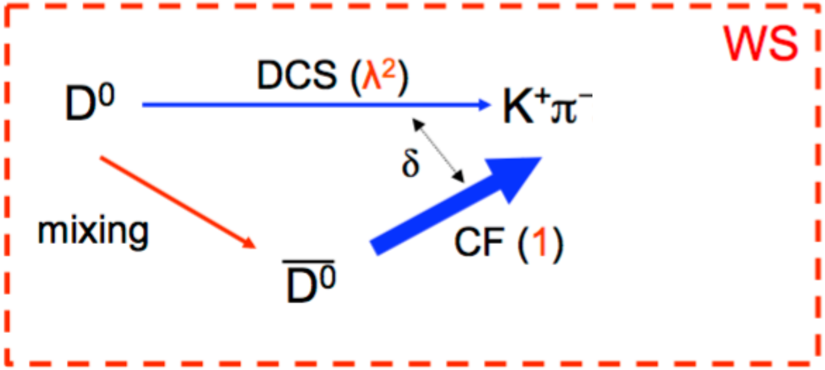
How the D^0 oscillation is observed

- The D^0 flavor at the production is tagged by $D^{*+} \rightarrow D^0\pi^+_s$
- Measure the time dependent ratio of Wrong-Sign $D^{*+} \rightarrow [K^+\pi^-]\,\pi^+_s$ and Right-Sign (RS) $D^{*+} \rightarrow [K^-\pi^+]\,\pi^+_s$

$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$

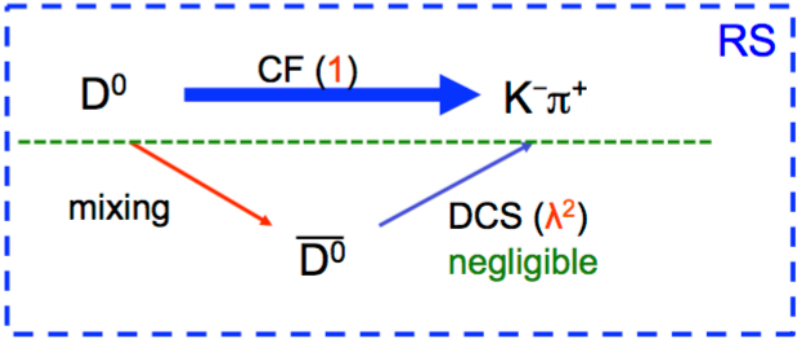
For WS two processes interfere:

- Mixing then Cabibbo-Favoured decay
- Doubly-Cabibbo-Suppressed decay



For RS only one process dominates:

- Cabibbo-Favoured decay



D⁰ WS/RS as function time

Considering negligible CP violation and in the limit of x,y<<1, to second order in t/τ, the time-dependence of the phase-space integrated decay rate ratio R(t) is approximated by:

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

τ is the average D_0 lifetime

R_D is the ratio of suppressed-to- favored decay rates

δ is the strong-phase difference between the suppressed and favored amplitudes

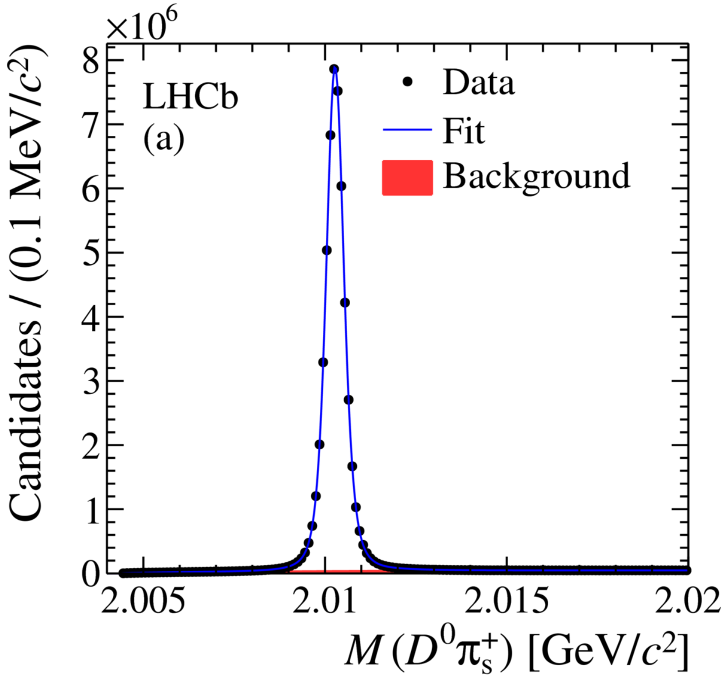
$$x' \equiv x \cos\delta + y \sin\delta$$

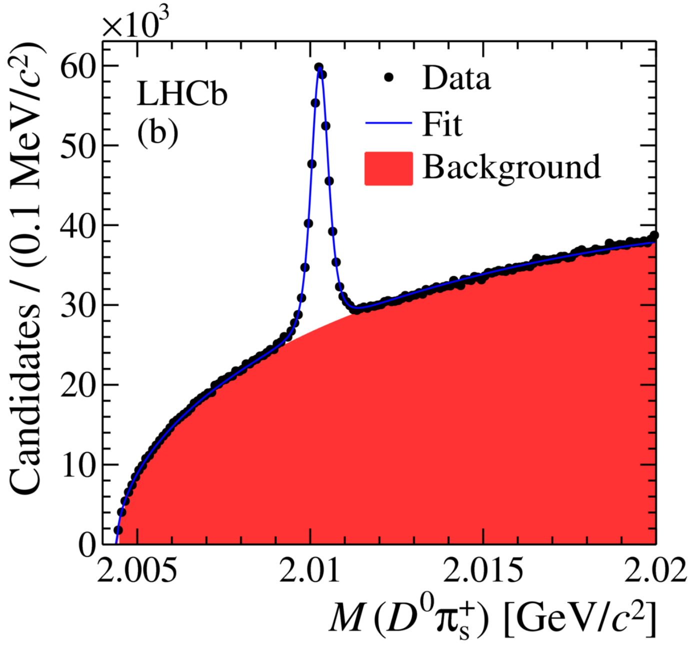
$$y' \equiv y \cos\delta - x \sin\delta$$

$$\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\overline{D}^0 \to K^+\pi^-) = -\sqrt{R_D} e^{-i\delta}$$

D⁰ signal yields

RUN-1: L = 3/fb [arXiv:1602.07224, submitted to PRL]



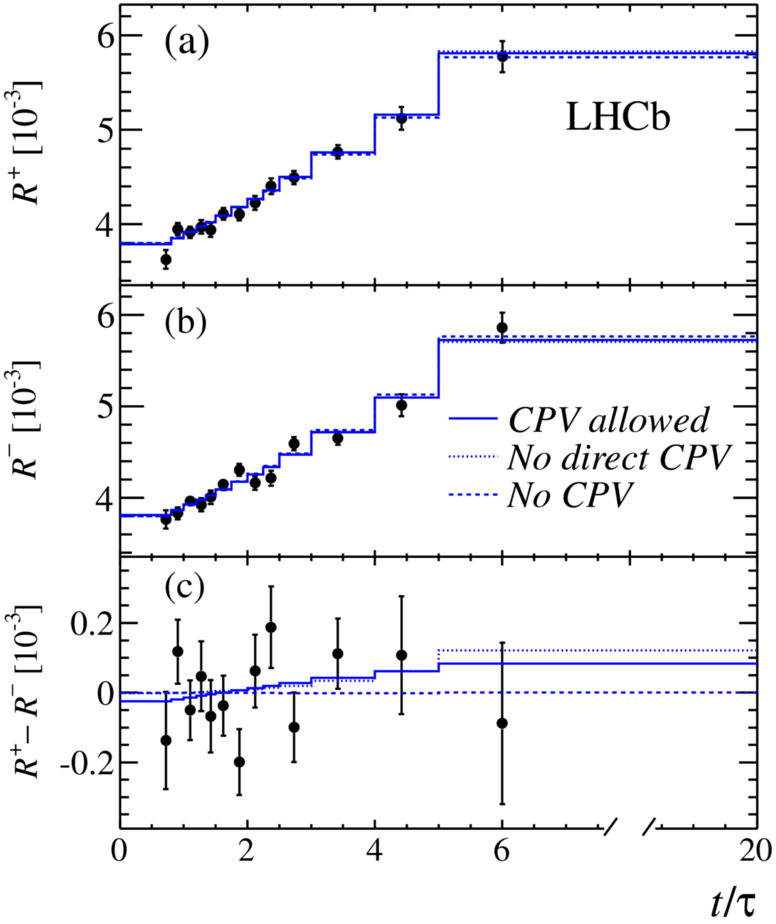


To study the time dependence, the WS/RS ratio is calculated in 13 bins of D⁰ decay time

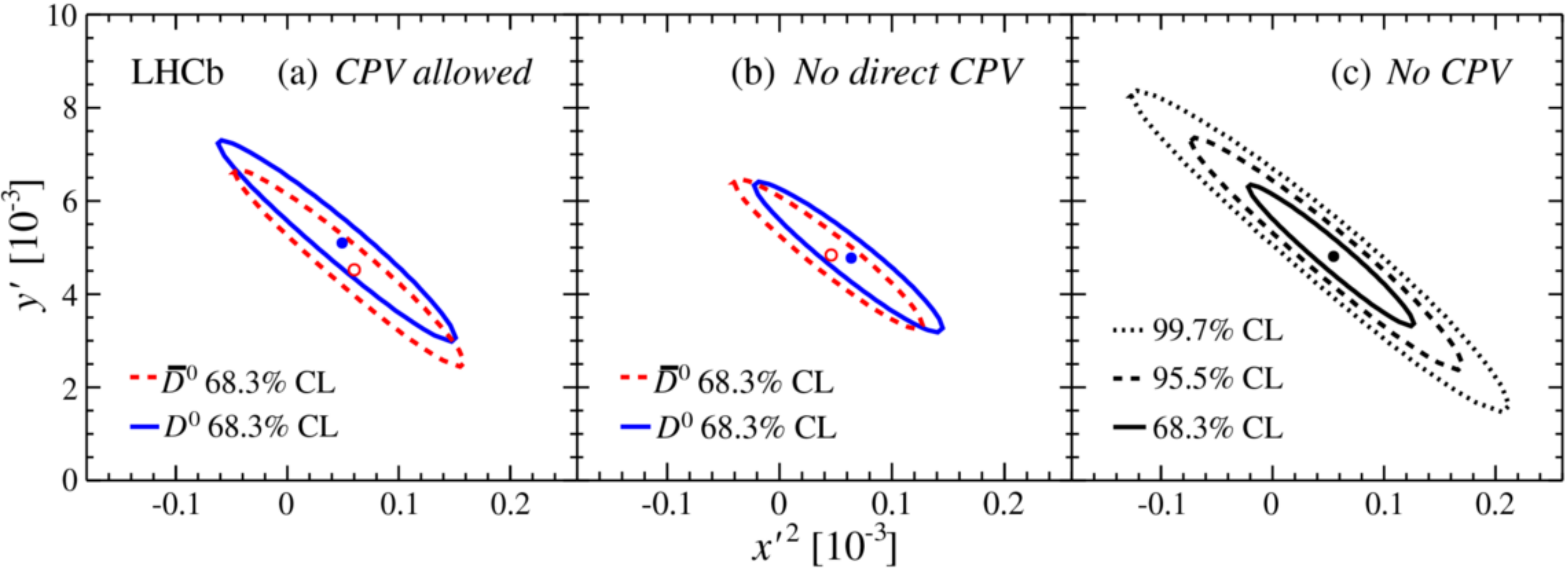
Result on search for CP violation in mixing

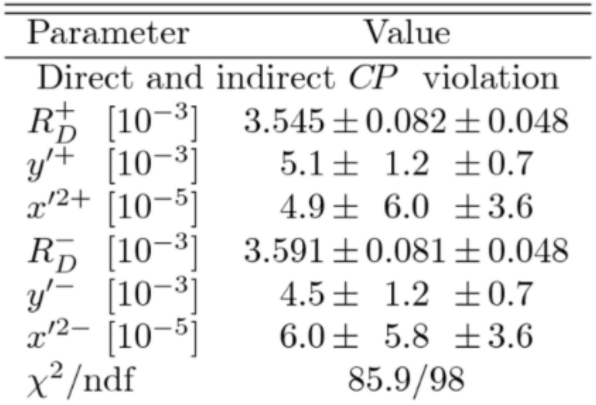
Allowing for CP violation, the WS rates $R_+(t)$ and $R_-(t)$ of initially produced D^0 and $\bar{D}^0$ mesons are functions of independent sets of mixing parameters

$$(R_D^{\pm},\, x'^{2\pm},\, y'^{\pm})$$



Result on search for CP violation in mixing





Parameter	Value
Direct and indirect CP violation	
R_D^+ [10^{-3}]	$3.545 \pm 0.082 \pm 0.048$
y'^+ [10^{-3}]	$5.1 \pm 1.2 \pm 0.7$
x'^{2+} [10^{-5}]	$4.9 \pm 6.0 \pm 3.6$
R_D^- [10^{-3}]	$3.591 \pm 0.081 \pm 0.048$
y'^- [10^{-3}]	$4.5 \pm 1.2 \pm 0.7$
x'^{2-} [10^{-5}]	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf	85.9/98

$0.75 < |q/p| < 1.24$ at the 68.3% confidence level

Current experimental status on D^0 mixing

Search for direct CP violation with $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$

Time-integrated CP asymmetry

CP asymmetry is defined as

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

with $f=K^-K^+$ and $f=\pi^-\pi^+$

The flavour of the initial state (D^0 or $\overline{D}^0$) is tagged by the charge of the slow pion from, $D^{*\pm} \to D^0\pi^\pm$

The raw asymmetry for tagged D^0 decays to a final state f is given by

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

where N refers to the number of reconstructed events of decay after background subtraction

Production and detection asymmetries

What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

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

CP asymmetry

Any charge-dependent asymmetry in slow pion reconstruction

$D^{*\pm}$ production asymmetry

- No detection asymmetry for D^0 decays to K^-K^+ or $\pi^-\pi^+$
- … if we take the raw asymmetry difference

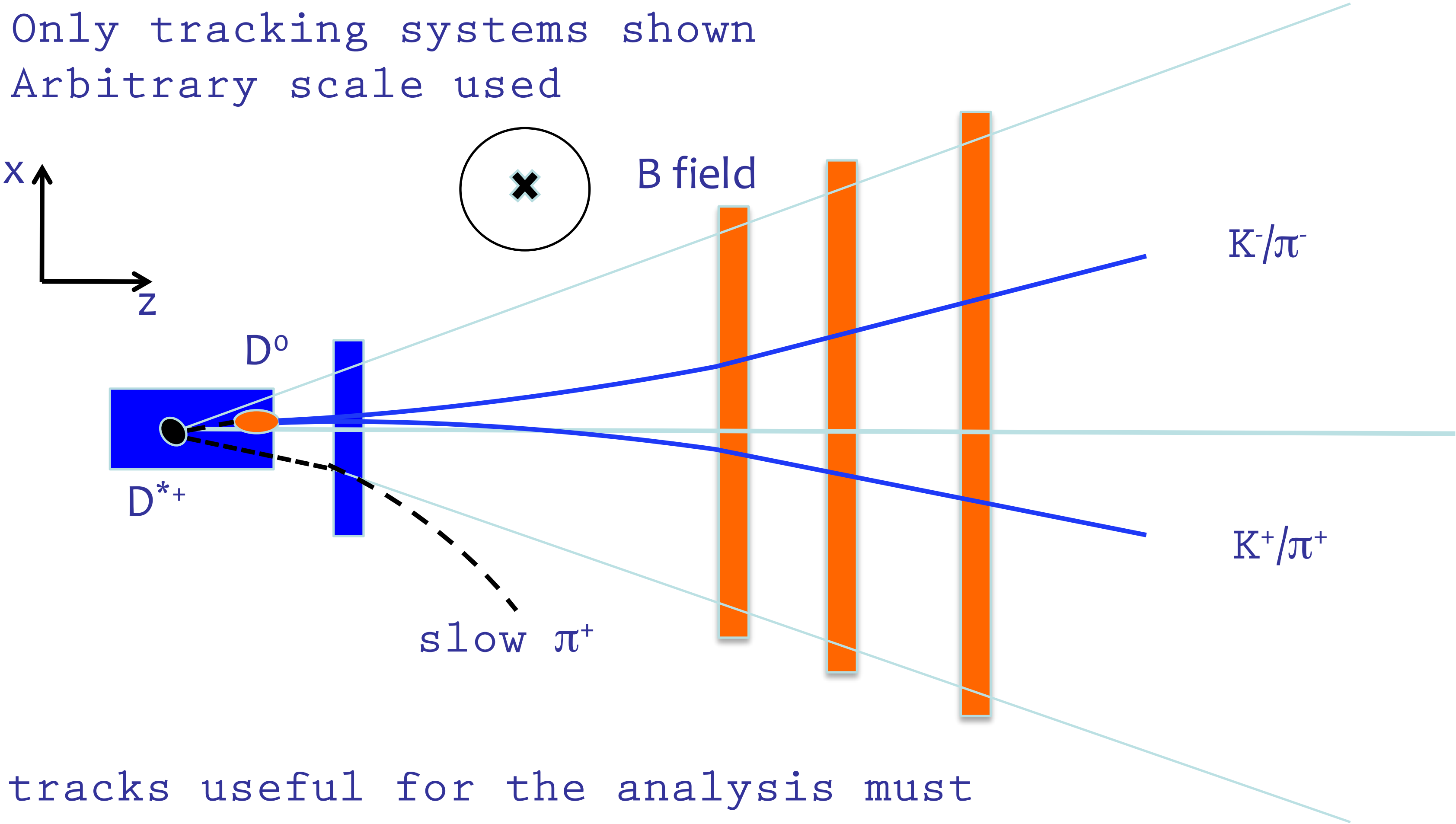
$$\boxed{\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)}$$

- the D^{*+} production and the slow pion detection asymmetries will cancel

() complication in the analysis

D^{*+}/D^{*-} reconstruction efficiency

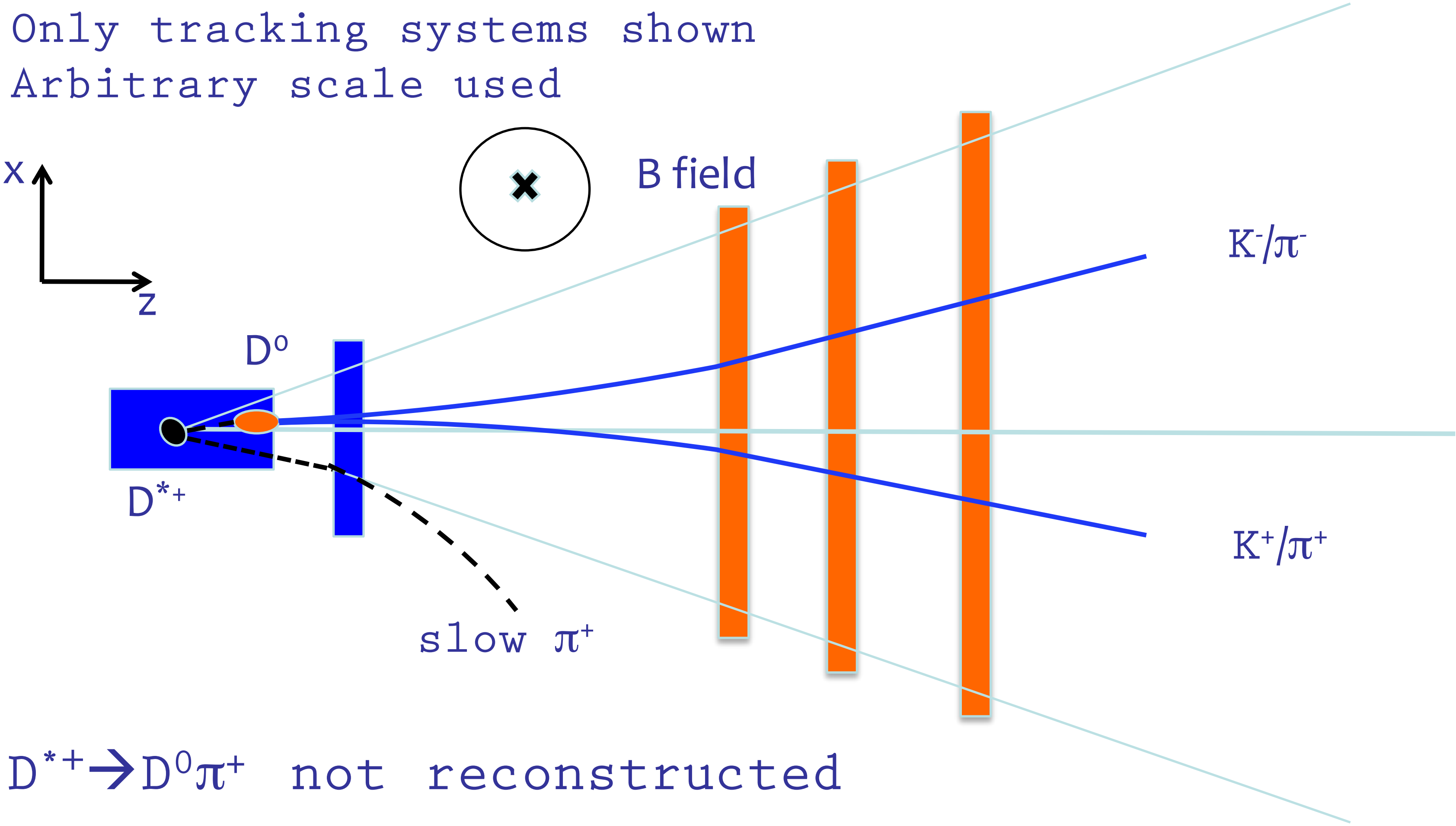
LHCb simplified bending plane view
Only tracking systems shown
Arbitrary scale used



tracks useful for the analysis must
cross all the tracking station

D^{*+}/D^{*-} reconstruction efficiency

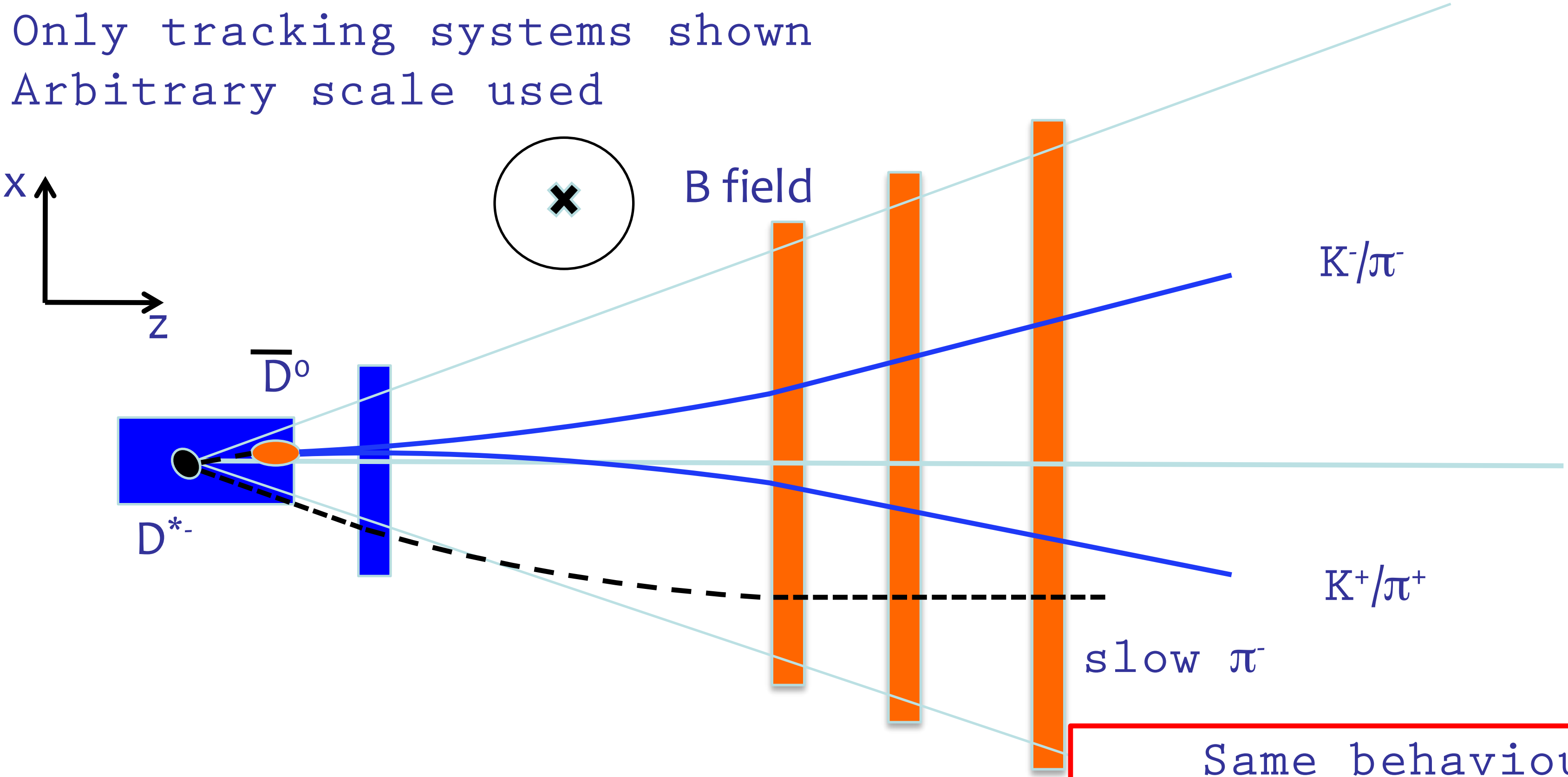
LHCb simplified bending plane view
Only tracking systems shown
Arbitrary scale used



$D^{*+} \rightarrow D^0\pi^+$ not reconstructed

D^{*+}/D^{*-} reconstruction efficiency

LHCb simplified bending plane view
Only tracking systems shown
Arbitrary scale used



$D^{*+} \rightarrow D^0\pi^+$ not reconstructed
$D^{*-} \rightarrow D^0\pi^-$ reconstructed

Same behaviour observed also for tracks which cross the beam-pipe, (i.e. small $|P_y/P_z|$ of slow

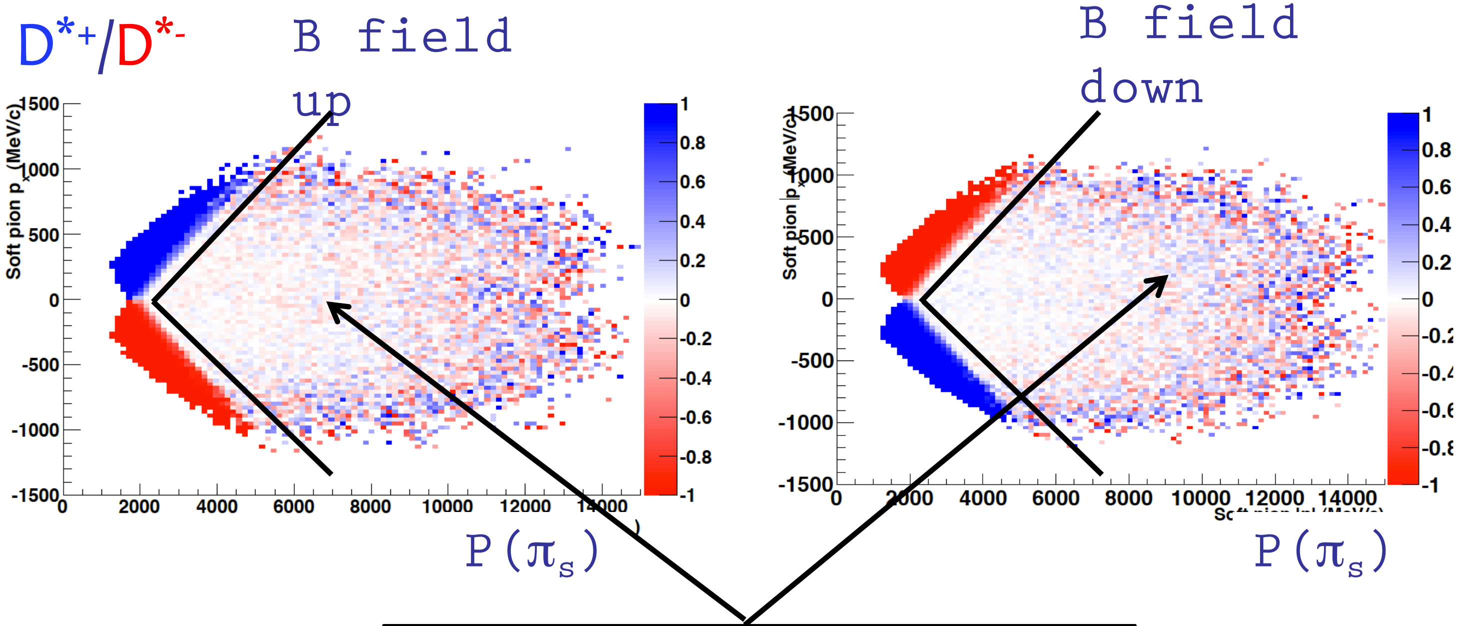
Fiducial cuts

- There are regions of phase space where only D^{*+} or only D^{*-} is kinematically possible.
  - this causes large value of A_{CP}^{Raw} up to 100% in the edges regions where only D^{*+} or D^{*-} is reconstructed
- This asymmetry is independent of the D^0 decay modes but it breaks the assumption that the raw asymmetries are small
- and it carries a risk of second-order systematic effects if the ratio of efficiencies of $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ varies in the affected region.

Fiducial cuts

- The edge regions are therefore excluded with cuts in the slow pion(P_x,P) plane.

Raw asymmetry of $D^{*+} \rightarrow D^0(KK)\pi^+$ and cc in the (P_x, P) plane of slow pion



Accepted region
reject 25% of events

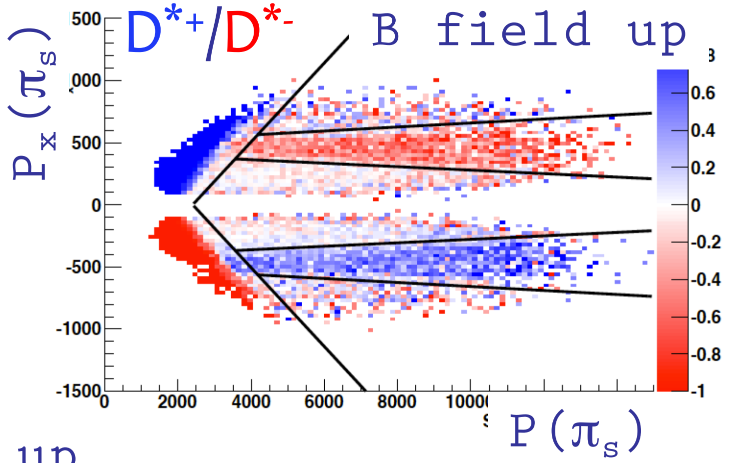
Fiducial cuts

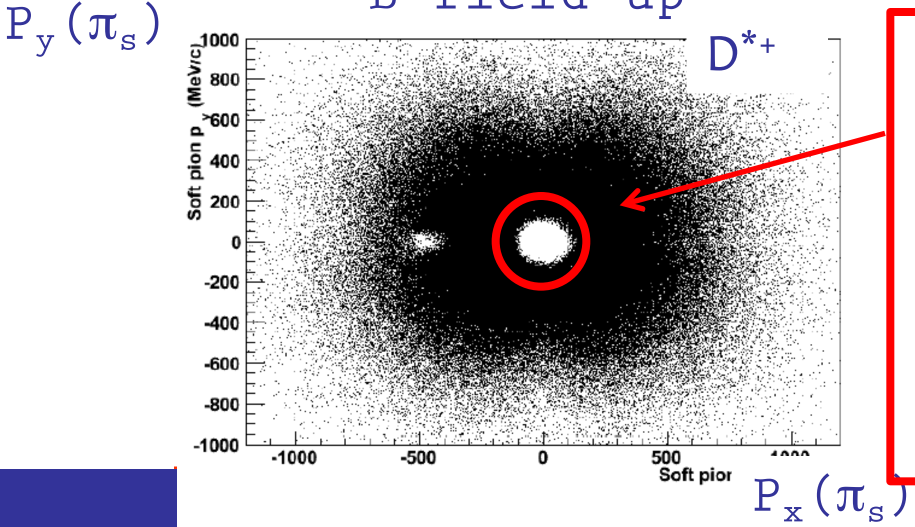
- The edge regions are therefore excluded with cuts in the slow pion(P_x,P) plane.

Raw asymmetry of $D^{*+} \rightarrow D^0(KK)\pi^+$ + cc in the (P_x,P) plane of slow pion

$|P_y/P_z|$(slow π)<0.2

beam pipe region





Soft pions go directly into the beam pipe
(low P_x and P_y)
These events are lost No charge dependents

Fiducial cuts

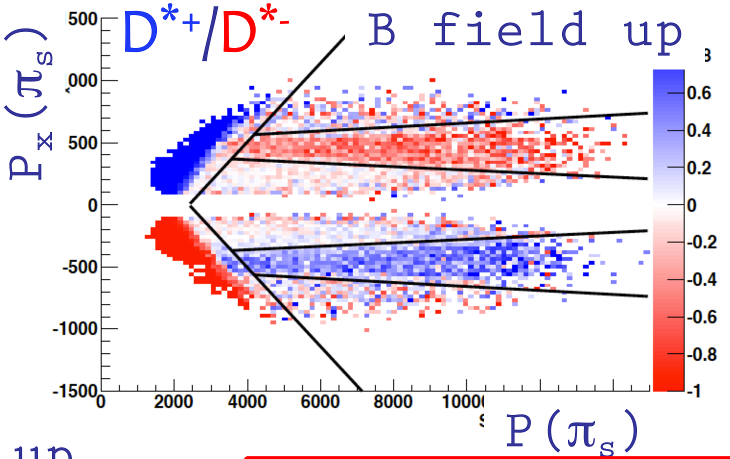
- The edge regions are therefore excluded with cuts in the slow pion(P_x,P) plane.

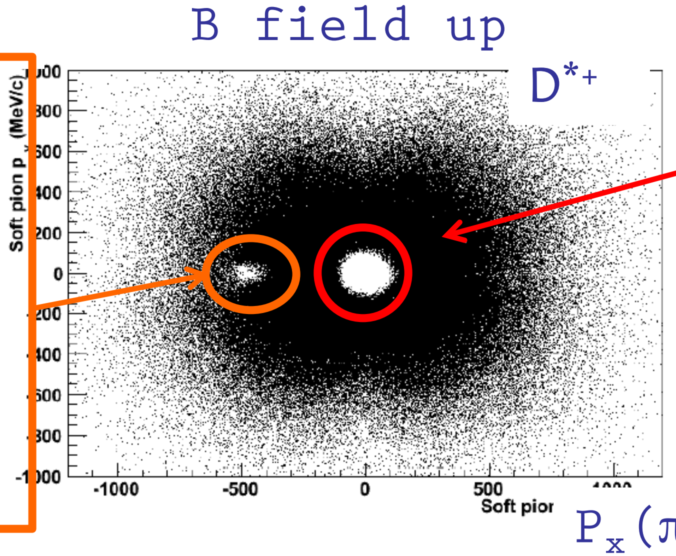
Further 5% events rejected

Raw asymmetry of $D^{*+} \rightarrow D^0(KK)\pi^+$ + cc in the (P_x,P) plane of slow pion

$|P_y/P_z|$(slow π)<0.2

beam pipe region





Soft pions swept through the beam pipe where there is no tracking station These events are lost Charged dependent

Soft pions go directly into the beam pipe (low P_x and P_y) These events are lost No charge dependents

Fiducial cuts

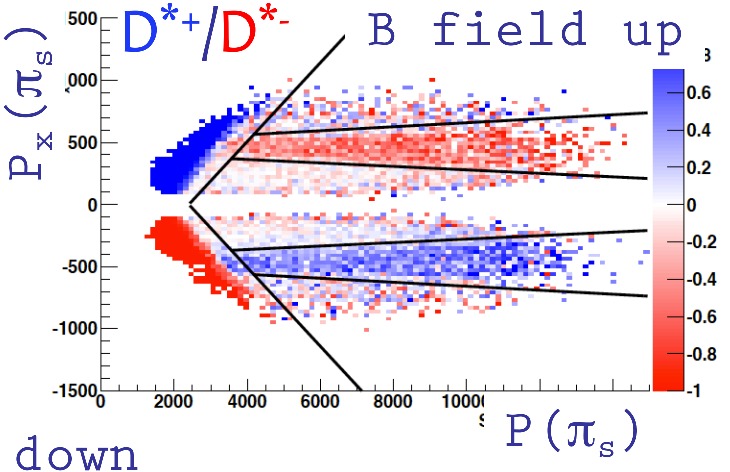
- The edge regions are therefore excluded with cuts in the slow pion(P_x,P) plane.

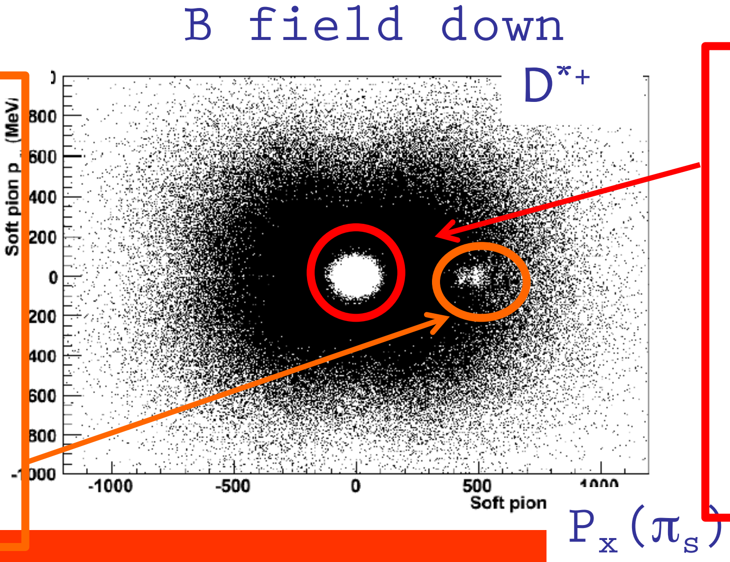
Further 5% events rejected

Raw asymmetry of $D^{*+} \rightarrow D^0(KK)\pi^+$ + cc in the (P_x,P) plane of slow pion

$|P_y/P_z|$(slow π)<0.2

beam pipe region





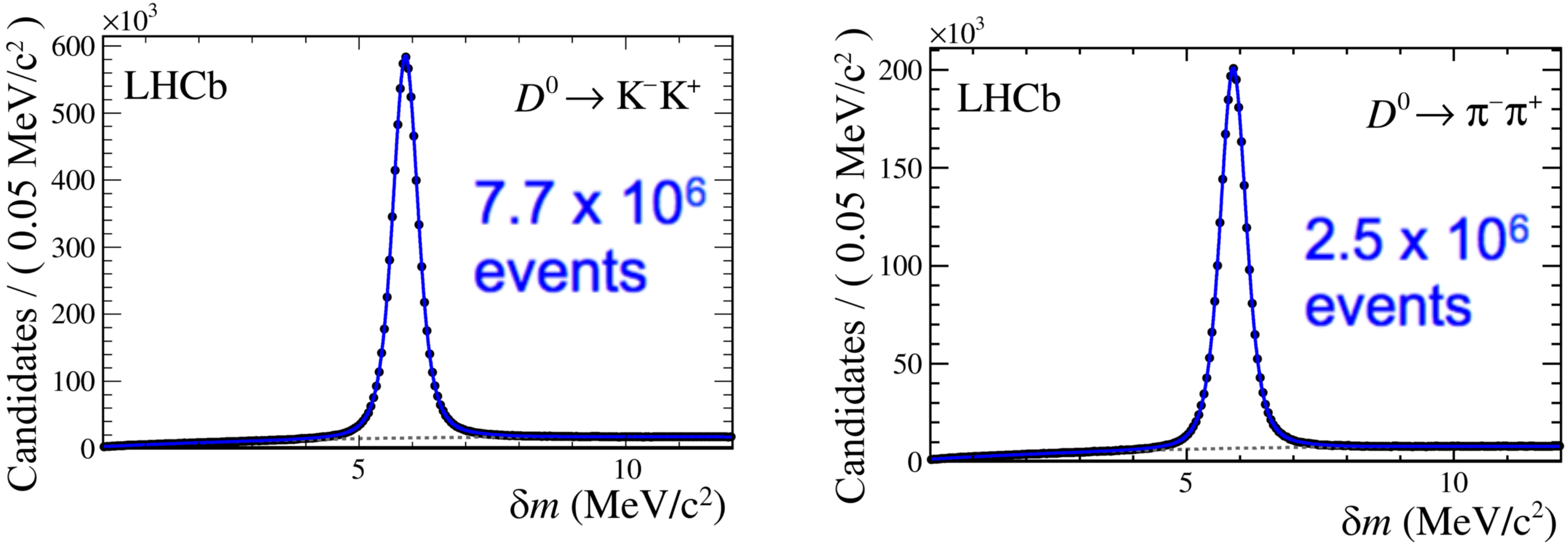
Soft pions swept through the beam pipe where there is no tracking station These events are lost Charged dependent

Soft pions go directly into the beam pipe (low P_x and P_y) These events are lost No charge dependents

Signal yields

[arXiv:1602.03160, PRL 116 (2016) 191601]

RUN-1: L = 3/fb



$$\delta m \equiv m(h^+h^-\pi_s^+) - m(h^+h^-) - m(\pi^+)$$

Signal yields and $A_{raw}(KK)$ and $A_{raw}(\pi\pi)$ are obtained from minimum χ^2 fits to the binned δm distributions of the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ samples

Results

[arXiv:1602.03160, PRL 116 (2016) 191601]

$$\Delta A_{CP} = (-0.10 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst}))\ \%$$

This is the most precise measurement of a time-integrated CP asymmetry in the charm sector from a single experiment.

In agreement with the LHCb muon-tagged measurement: Run-1 3/fb

$$\Delta A_{CP} = 0.14 \pm 0.16^{\text{stat}} \pm 0.08^{\text{syst}}\ \%$$ JHEP07(2014)041

Results

[arXiv:1602.03160, PRL 116 (2016) 191601]

The observable ΔA_{CP} is mostly sensitive to direct CP asymmetry, Δa^{dir}_{CP}, but with a small contribution also to indirect CP asymmetry, a^{indir}_{CP}

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &\approx \Delta a^{\rm dir}_{CP}\left(1 + \frac{\overline{\langle t\rangle}}{\tau}\, y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau}\, a^{\rm ind}_{CP}\end{aligned}$$

$\sim 0.12 \times 10^{-2}$

$\sim 2 \times 10^{-4}$

$$a^{\rm ind}_{CP} = (0.058 \pm 0.044)\%$$

$$\Delta a^{\rm dir}_{CP} = (-0.061 \pm 0.076)\%$$