

# Heavy Flavours

L1



L2

L3

- Heavy flavours ?
- Heavy flavours why ?
- Same physics, different environments
  
- Symmetries
- Standard Model: the CKM matrix
- Measuring a triangle
  
- What about QCD ?
- Searching for New Physics

Marie-Hélène Schune

LAL Orsay



# Heavy Flavours ?

	I	II	III	
mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	
charge	2/3	2/3	2/3	
spin	1/2	1/2	1/2	
	u	c	t	
	up	charm	top	
QUARKS				
mass	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	
charge	-1/3	-1/3	-1/3	
spin	1/2	1/2	1/2	
	d	s	b	
	down	strange	bottom	
LEPTONS				
mass	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	
charge	-1	-1	-1	
spin	1/2	1/2	1/2	
	e	$\mu$	$\tau$	
	electron	muon	tau	
GAUGE BOSONS				
mass	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	
charge	0	0	0	
spin	1/2	1/2	1/2	
	$\nu_e$	$\nu_\mu$	$\nu_\tau$	
	electron neutrino	muon neutrino	tau neutrino	
SCALAR BOSONS				
mass				$\approx 125.09 \text{ GeV}/c^2$
charge				0
spin				0
				1
				H
				Higgs
GAUGE BOSONS				
mass				$\approx 91.19 \text{ GeV}/c^2$
charge				0
spin				1
				Z
				Z boson
GAUGE BOSONS				
mass				$\approx 80.39 \text{ GeV}/c^2$
charge				$\pm 1$
spin				1
				W
				W boson

Fermionic domain of the Standard Model

and anti-matter

# The SM parameters for the fermionic sector

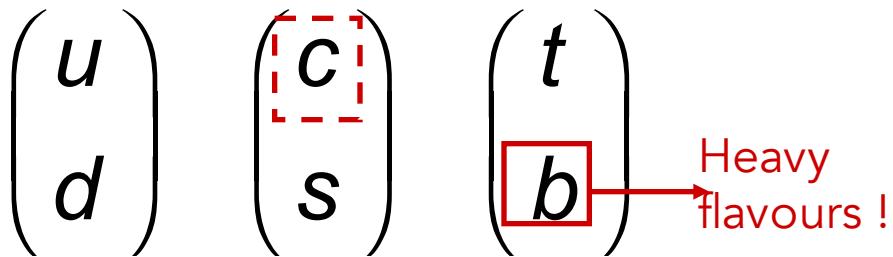
- 6 quark masses
- 3 quarks mixing angles and one phase
- 3 charged leptons masses
- 3 neutrinos masses
- 3 neutrinos mixing angles and one phase (if Dirac neutrinos)

## ... and many questions

- why so many fermions ?
- why 3 families ?
- why so different masses ?
- what breaks the symmetry between matter and anti-matter ?

Beyond the Standard Model Theories  
Jessie Shelton

# Reducing the scope of these lectures ...

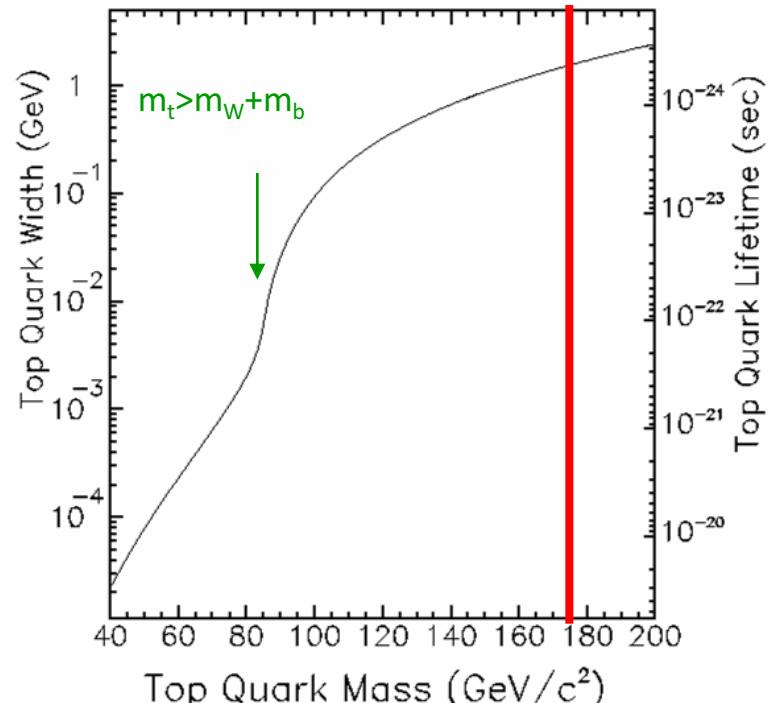


Why not the top quark ?

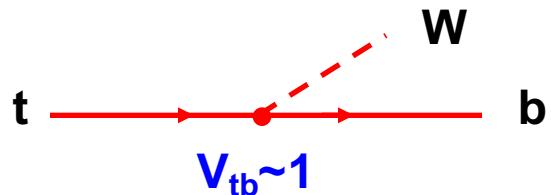
The decay  $\propto m^5 \Rightarrow$  extremely short lifetime

Hadronization time  $\sim 10^{-23} s$

$\Rightarrow$  no top hadrons



Phys. Lett. B 181 (157)



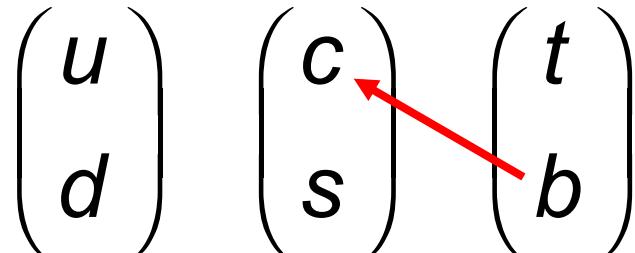
Tevatron + LHC :  
 $|V_{tb}| = 1.009 \pm 0.031$     [\[PDG\]](#)

Top in « Precision Measurements at Hadron Colliders » lectures  
Richard Hawking

# The b quark

9.5-10.5 GeV : the series of  $\Upsilon$

- The heaviest quark that forms bound states ( $m_B \sim 5.3$  GeV)
- Decays outside its family

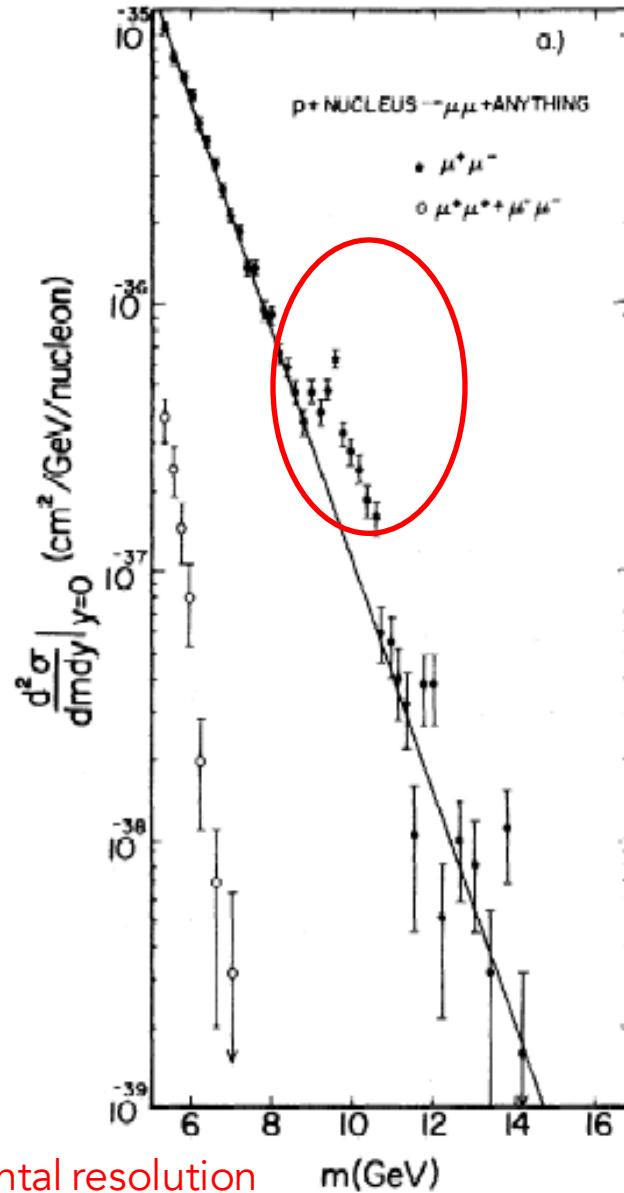


⇒ large lifetime  $\sim 1.5$  ps

⇒ very large number of decays modes

○ CKM matrix

⇒ large CP violation effects



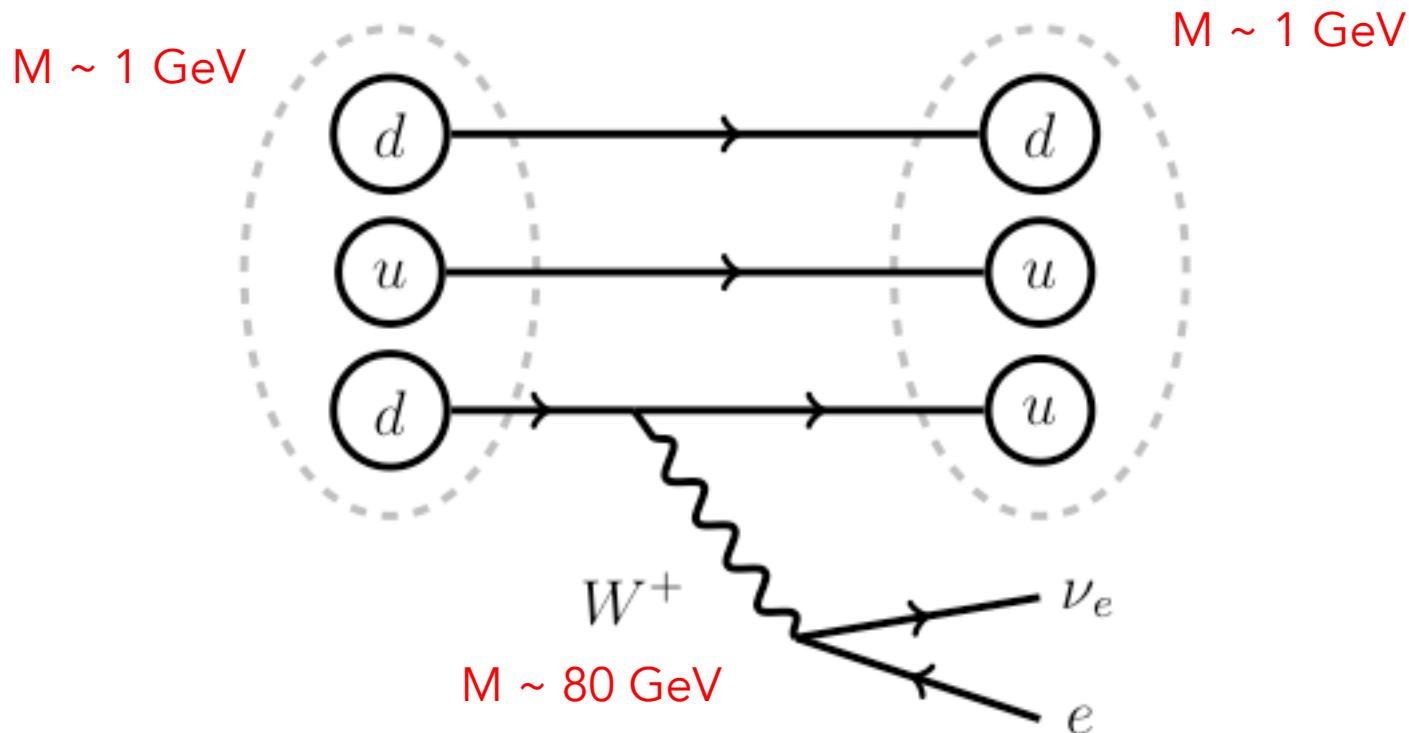
Excess larger than the experimental resolution

⇒ presence of more than one resonance

# Heavy Flavours why ?

$\beta$  decay of the neutron

Phenomena taking place at  $\sim 1$  GeV reveals physics at the 100 GeV scale



# The top quark at an e+ e- collider with $\sqrt{s}=10$ GeV in 1987 !

$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$  at  $\sqrt{s} = 10.58$  GeV

Argus Collaboration  
Phys Lett B 192 p454

Production of coherent  $B\bar{B}$  pairs

$B^0 \rightarrow D^* \mu^+ \nu$

$B^0 \rightarrow D^* \mu^+ \nu$

Fig. 11: The fully reconstructed ARGUS event [26]

$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow B^0 B^0$  as the first evidence for the occurrence of  $B^0 \bar{B}^0$  oscillations.

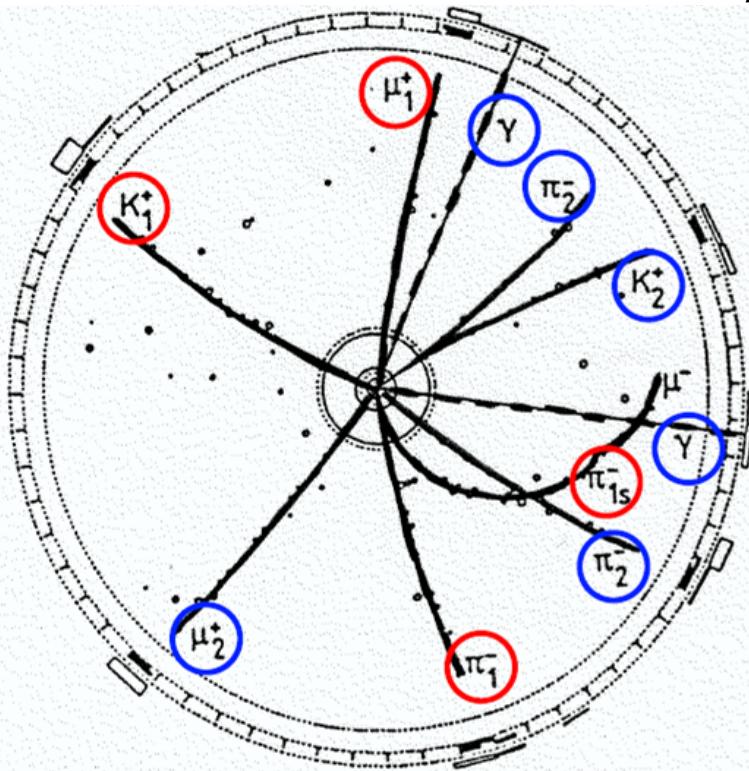
$B^0 \rightarrow D_1^* \mu_1^+ \nu$ ,  $\leftarrow$

$D_1^* \rightarrow \pi_1^-, \bar{D}^0$ ,  $\bar{D}^0 \rightarrow K_1^+ \pi_1^-$ .

$\bar{B}^0 \rightarrow B^0 \rightarrow D_2^* \mu_2^+ \nu$ ,  $\leftarrow$

$D_2^* \rightarrow \pi^0 \bar{D}_2^-$ ,

$\pi^0 \rightarrow \gamma \gamma$ ,  $\bar{D}_2^- \rightarrow K_2^+ \pi_2^- \pi_2^-$ .



$$\Delta m_B \approx 0.00002 \cdot \left( \frac{m_t}{\text{GeV}/c^2} \right)^2 \text{ ps}^{-1}$$
$$\approx 0.5 \text{ ps}^{-1}$$

$\Rightarrow m_t > 50 \text{ GeV}$

First hint of a  
really large  $m_{\text{top}}$ !

# Neutral mesons mixing

Pairs of self-conjugate mesons that can be transformed to each other via flavour changing weak interaction transitions are:

$$|K^0\rangle = |\bar{s}d\rangle \quad |D^0\rangle = |\bar{c}u\rangle \quad |B_d^0\rangle = |\bar{b}d\rangle \quad |B_s^0\rangle = |\bar{b}s\rangle$$

They are **flavour eigenstates** with definite quark content  $|M^0\rangle$   $|\bar{M}^0\rangle$

- useful to understand particle production and decay

Apart from the flavour eigenstates there are **mass eigenstates**:

- eigenstates of the Hamiltonian  $|M_L\rangle$   $|M_H\rangle$
- states of definite mass and lifetime
- They are propagating through space-time

$$|M_L\rangle = p|M^0\rangle + q|\bar{M}^0\rangle$$

$$|M_H\rangle = p|M^0\rangle - q|\bar{M}^0\rangle$$

Since flavour eigenstates are not mass eigenstates, the flavour eigenstates are mixed with one another as they propagate through space and time

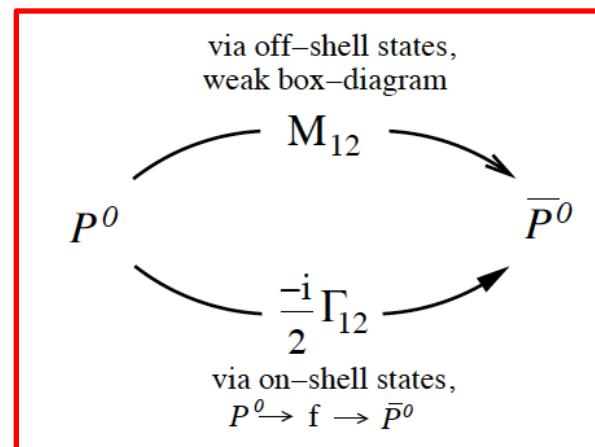
$|M^0(t)\rangle$  : the flavour state of a meson at time  $t$  which was produced as a  $M^0$  at  $t=0$

$|\bar{M}^0(t)\rangle$  : the flavour state of a meson at time  $t$  which was produced as a  $\bar{M}^0$  at  $t=0$

$$i \frac{d}{dt} \begin{pmatrix} |M^0(t)\rangle \\ |\bar{M}^0(t)\rangle \end{pmatrix} = \underbrace{\left( M - \frac{i}{2} \Gamma \right)}_{\equiv H \text{ (effective Hamiltonian)}} \begin{pmatrix} |M^0(t)\rangle \\ |\bar{M}^0(t)\rangle \end{pmatrix}$$

$$M - i/2 \Gamma = \begin{pmatrix} M - \frac{i}{2} \Gamma & M_{12} - \frac{i}{2} \Gamma_{12} \\ M_{12}^* - \frac{i}{2} \Gamma_{12}^* & M - \frac{i}{2} \Gamma \end{pmatrix}$$

assuming CPT  
(mass and total decay width of particle and anti-particle are the same)



$$H|M_L\rangle = \left( M_L - \frac{i}{2} \Gamma_L \right) |M_L\rangle$$

$$H|M_H\rangle = \left( M_H - \frac{i}{2} \Gamma_H \right) |M_H\rangle$$

Mass states are eigenvectors of  $H$

$$|M_{H,L}(t)\rangle = e^{-i(M_{H,L} - \frac{i}{2}\Gamma_{H,L})t} |M_{H,L}(t=0)\rangle \quad + \quad \begin{aligned} |M_L\rangle &= p|M^0\rangle + q|\bar{M}^0\rangle \\ |M_H\rangle &= p|M^0\rangle - q|\bar{M}^0\rangle \end{aligned}$$



Time evolution of a  $M^0(t=0)$  :  $|M^0(t)\rangle$  and of a  $\bar{M}^0(t=0)$  :  $|\bar{M}^0(t)\rangle$

$$\boxed{|M^0(t)\rangle = g_+(t) |M^0\rangle + \frac{q}{p} g_-(t) |\bar{M}^0\rangle \\ |\bar{M}^0(t)\rangle = \frac{p}{q} g_-(t) |M^0\rangle + g_+(t) |\bar{M}^0\rangle}$$

More general formulae

$$\begin{aligned} g_+(t) &= \frac{1}{2} e^{-iMt} \left( e^{-i\frac{1}{2}\Delta mt - \frac{1}{2}\Gamma_H t} + e^{+i\frac{1}{2}\Delta mt - \frac{1}{2}\Gamma_L t} \right) \\ g_-(t) &= \frac{1}{2} e^{-iMt} \left( e^{-i\frac{1}{2}\Delta mt - \frac{1}{2}\Gamma_H t} - e^{+i\frac{1}{2}\Delta mt - \frac{1}{2}\Gamma_L t} \right) \end{aligned}$$

$$M = (m_H + m_L)/2 \text{ and } \Delta m = m_H - m_L$$

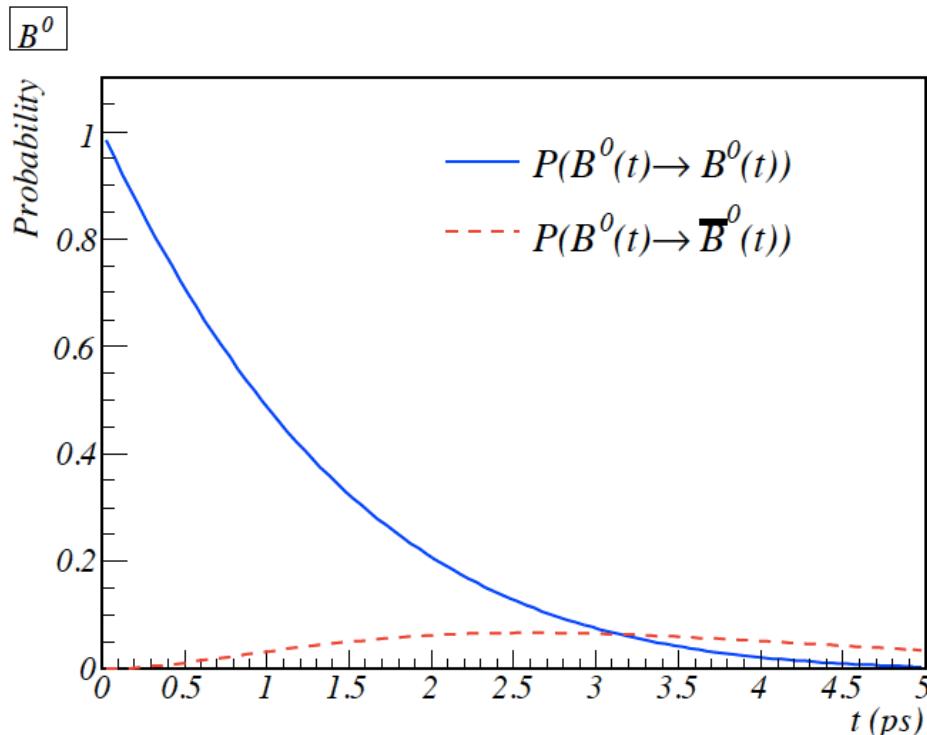
Starting from a  $B^0$  the probability to measure a  $B^0$  at time t is :

$$\left| \langle B^0 | H | B^0(t) \rangle \right|^2 = \frac{e^{-\Gamma t}}{2} (1 + \cos \Delta m t)$$

Starting from a  $B^0$  the probability to measure a  $\bar{B}^0$  at time t is :

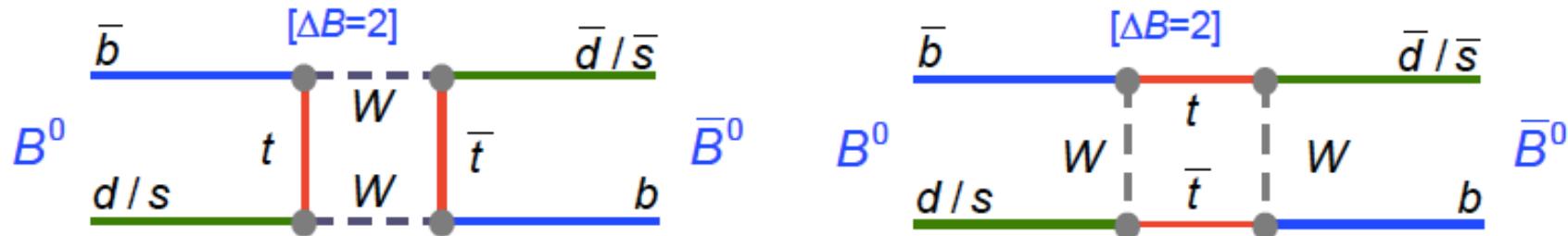
$$\left| \langle \bar{B}^0 | H | B^0(t) \rangle \right|^2 = \frac{e^{-\Gamma t}}{2} (1 - \cos \Delta m t)$$

For the  $B^0$  case where  $\Delta\Gamma \sim 0$  and assuming no CPV in the mixing ( $|q/p| = 1$ )



$\Delta m$  can be computed in the Standard Model

Effective FCNC Processes (CP conserving — top loop dominates in box diagram):



Perturbative QCD

$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2 \eta_B S(x_t) f_{B_q}^2 B_q |V_{tq} V_{tb}^*|^2$  (for  $q = d, s$ )

Loop integral (top loop dominates)

CKM Matrix Elements

Non-perturbative QCD : dominant theoretical uncertainty

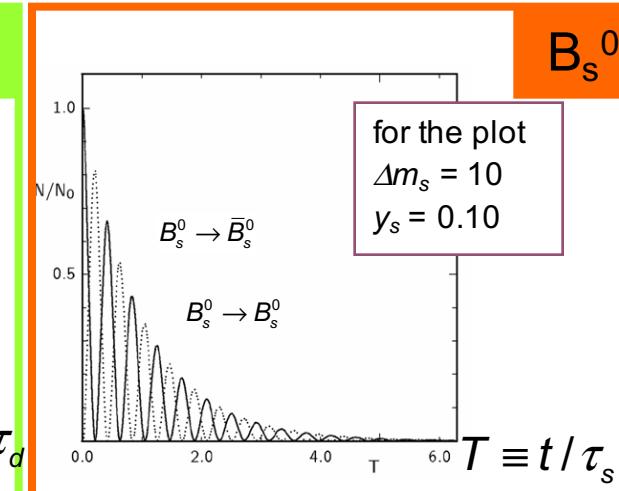
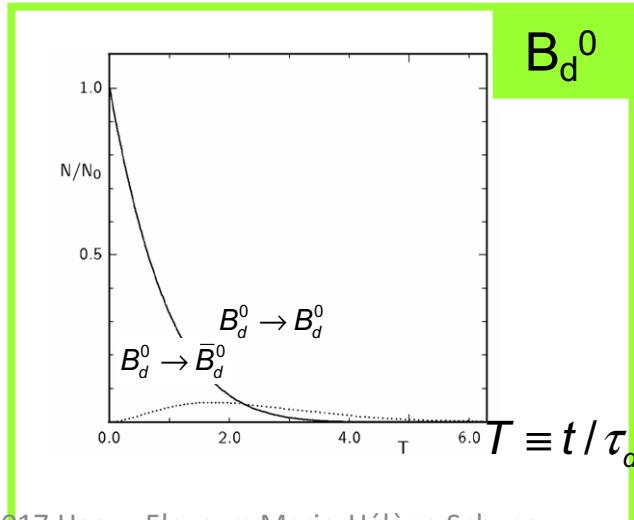
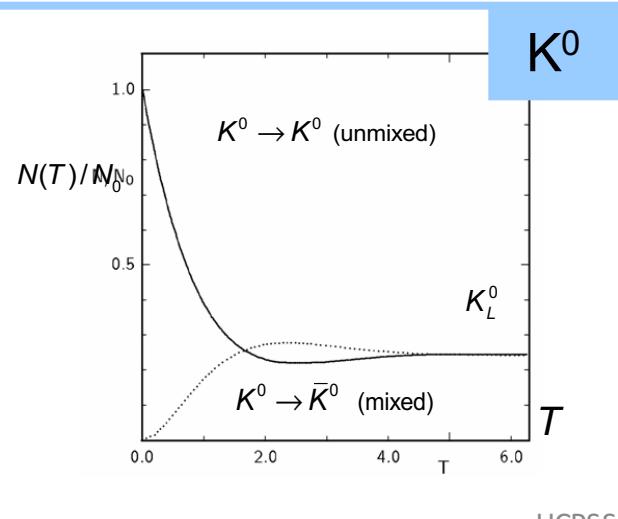
Diagram illustrating the computation of  $\Delta m_q$ . The equation shows the product of perturbative QCD factors ( $G_F^2/6\pi^2$ , quark masses,  $m_W$ ,  $\eta_B$ ,  $S(x_t)$ ,  $f_{B_q}^2$ ,  $B_q$ , CKM matrix elements  $|V_{tq} V_{tb}^*|^2$ ) and a loop integral factor (top loop dominance). The loop integral factor is influenced by Non-perturbative QCD, which is identified as the dominant theoretical uncertainty.

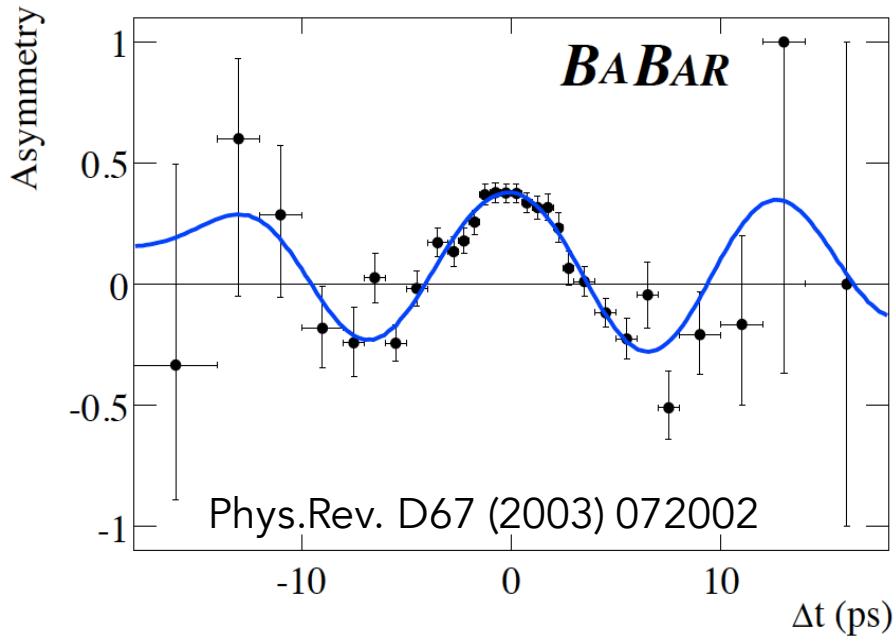
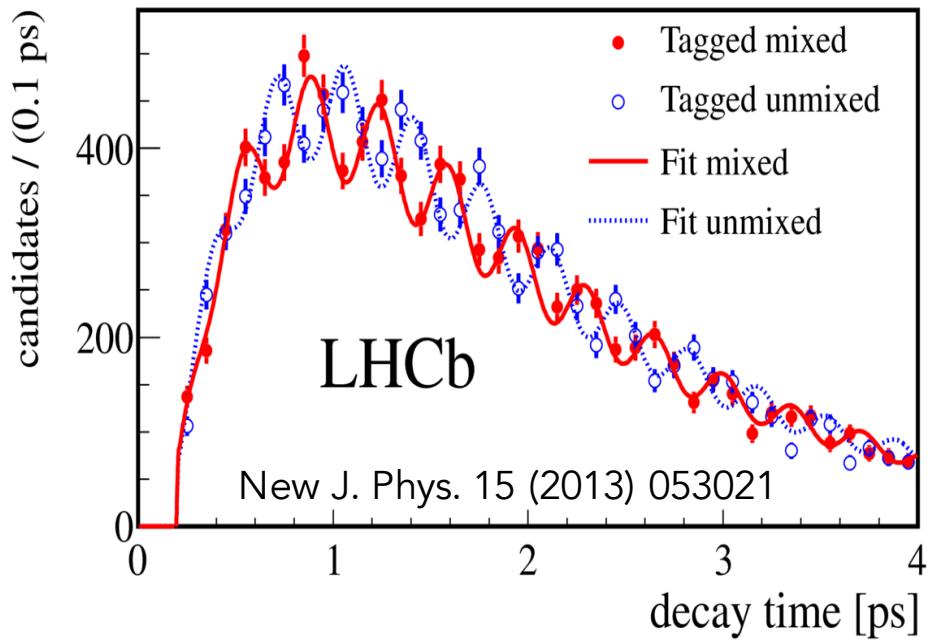
We define  $x \equiv \left( \frac{\Delta m}{\Gamma} \right)$     $y \equiv \left( \frac{\Delta \Gamma}{2\Gamma} \right)$   
 $x$  : the mixing frequency in unit of lifetime

$x >> 1$  rapid oscillation  
 $x << 1$  slow oscillation

Different behaviors for the different neutral mesons :

	$x = \Delta m / \Gamma$	$y = \Delta \Gamma / \Gamma$
$K^0$	$\sim 1$	$\sim 1$
$D^0$	$10^{-3}$ - $10^{-5}$	$10^{-3}$ - $10^{-5}$
$B_d^0$	$\sim 0.75$	$\sim$ few%
$B_s^0$	$\sim 25$	(10-15)%



$B_d^0$  $B_s^0$ HFLAV

LEP, Tevatron, B-Factories, LHCb

$$\Delta m_d = 0.5065 \pm 0.0019 \text{ ps}^{-1}$$

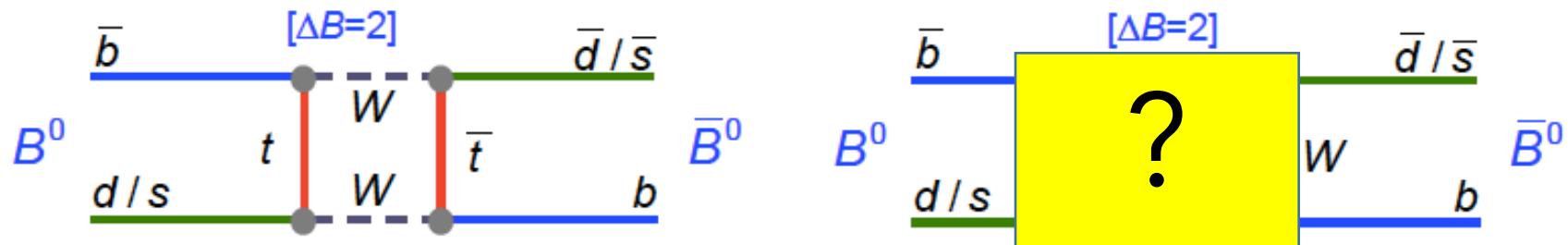
Precision :  $3.8 \cdot 10^{-3}$ HFLAV

CDF and LHCb

$$\Delta m_s = 17.757 \pm 0.021 \text{ ps}^{-1}$$

Precision :  $1.1 \cdot 10^{-3}$

Effective FCNC Processes ( $CP$  conserving — top loop dominates in box diagram):



Let's allow for NP in  $\Delta B=2$  transitions :

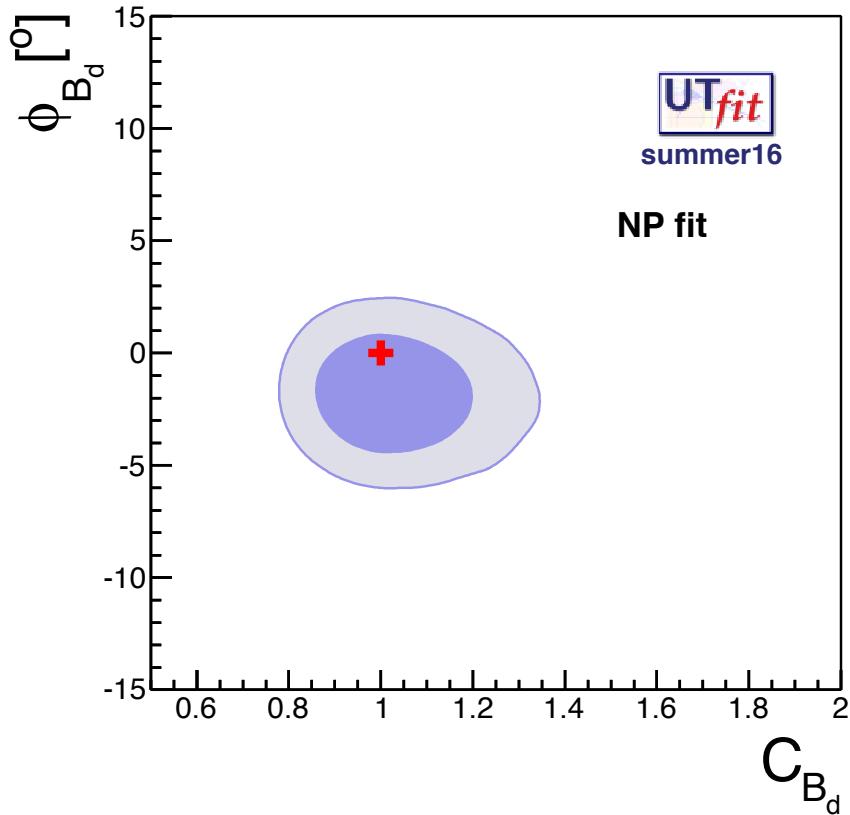
$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\text{eff}}^{\text{full}} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\text{eff}}^{\text{SM}} | \bar{B}_q^0 \rangle},$$



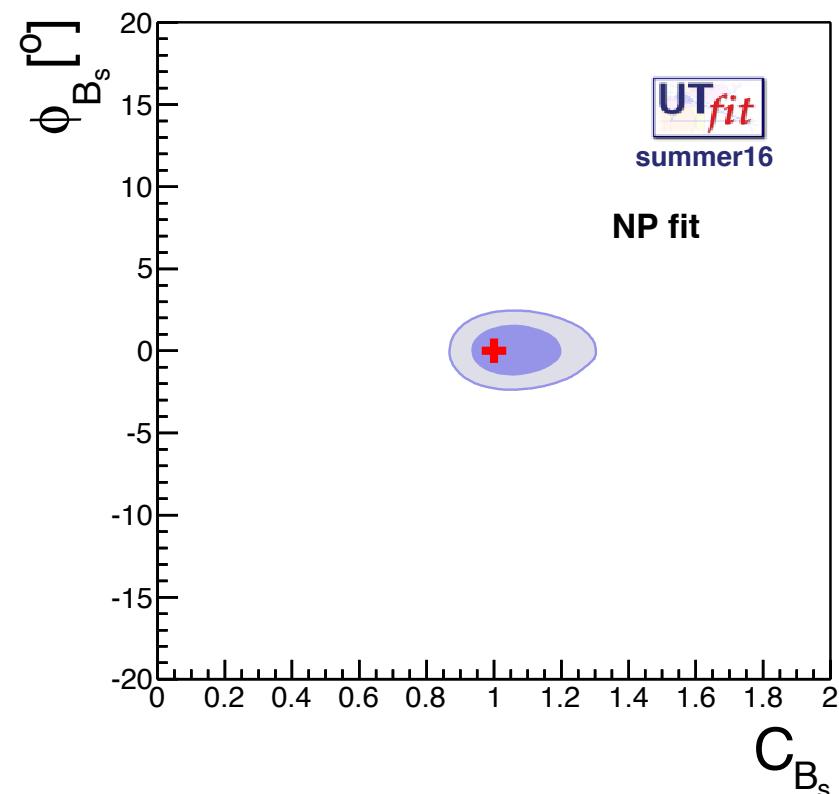
$$\begin{aligned} \Delta m_d^{\text{exp}} &= C_{B_d} \Delta m_d^{\text{SM}}, \\ \sin 2\beta^{\text{exp}} &= \sin(2\beta^{\text{SM}} + 2\phi_{B_d}), \\ \alpha^{\text{exp}} &= \alpha^{\text{SM}} - \phi_{B_d}, \\ \Delta m_s^{\text{exp}} &= C_{B_s} \Delta m_s^{\text{SM}}, \\ \phi_s^{\text{exp}} &= (\beta_s^{\text{SM}} - \phi_{B_s}), \end{aligned}$$

# A lot of inputs from B-Factories and LHCb

B<sub>d</sub> sector



B<sub>s</sub> sector



No sign of NP at the 10%-30% level ...

Flavour transitions probe **high mass scales** in quantum loops (eg FCNC)



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_{\text{NP}}}{\Lambda_{\text{NP}}^2} O_{ij}^{(6)}$$

New Physics **scale** and  
**coupling**

small      possible large  
contributions

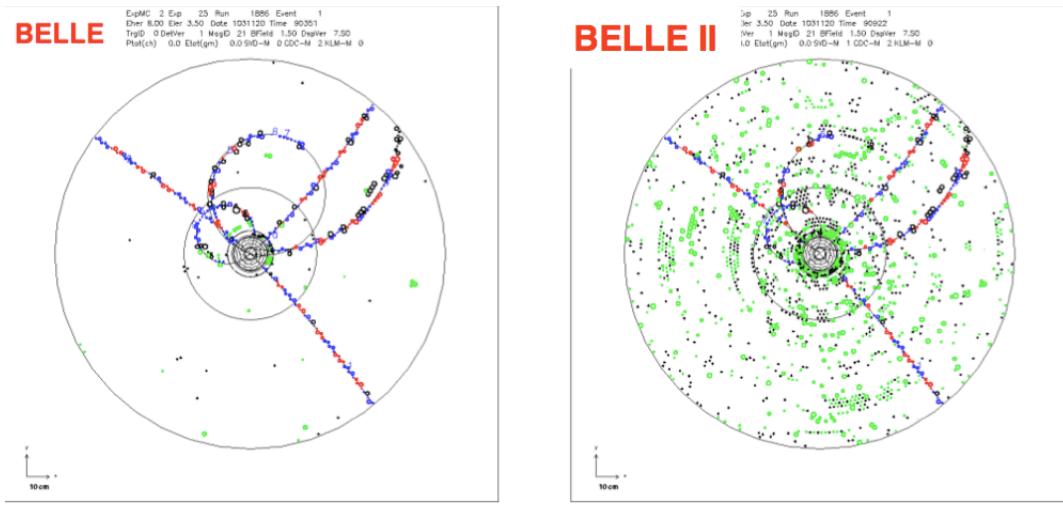
Ann. Rev. Nucl. Part. Sci. 60 (2010) 355, update from 2012

Operator	Bounds on $\Lambda$ in TeV ( $c_{\text{NP}} = 1$ )		Bounds on $c_{\text{NP}}$ ( $\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	$9.8 \times 10^2$	$1.6 \times 10^4$	$9.0 \times 10^{-7}$	$3.4 \times 10^{-9}$	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	$1.8 \times 10^4$	$3.2 \times 10^5$	$6.9 \times 10^{-9}$	$2.6 \times 10^{-11}$	$\Delta m_K; \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	$1.2 \times 10^3$	$2.9 \times 10^3$	$5.6 \times 10^{-7}$	$1.0 \times 10^{-7}$	$\Delta m_D;  q/p , \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	$6.2 \times 10^3$	$1.5 \times 10^4$	$5.7 \times 10^{-8}$	$1.1 \times 10^{-8}$	$\Delta m_D;  q/p , \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	$6.6 \times 10^2$	$9.3 \times 10^2$	$2.3 \times 10^{-6}$	$1.1 \times 10^{-6}$	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	$2.5 \times 10^3$	$3.6 \times 10^3$	$3.9 \times 10^{-7}$	$1.9 \times 10^{-7}$	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	$1.4 \times 10^2$	$2.5 \times 10^2$	$5.0 \times 10^{-5}$	$1.7 \times 10^{-5}$	$\Delta m_{B_s}; S_{\psi \phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	$4.8 \times 10^2$	$8.3 \times 10^2$	$8.8 \times 10^{-6}$	$2.9 \times 10^{-6}$	$\Delta m_{B_s}; S_{\psi \phi}$

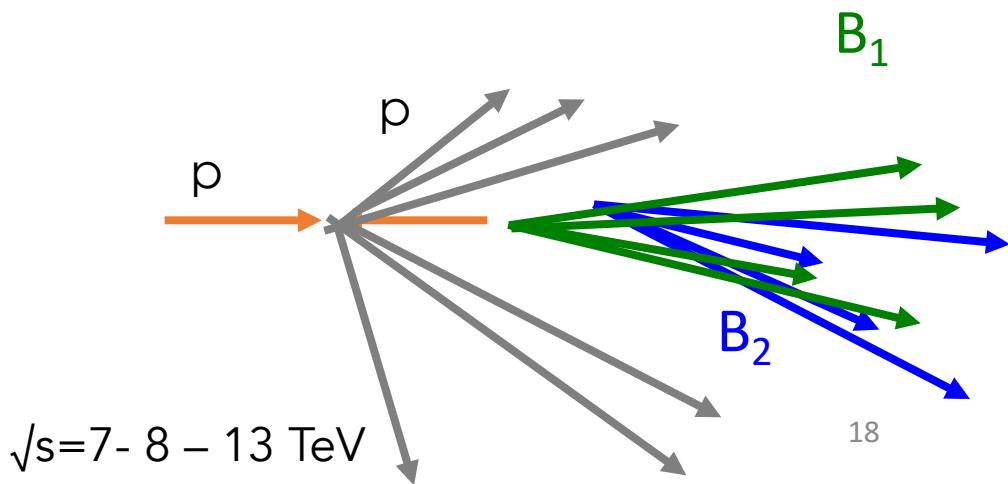
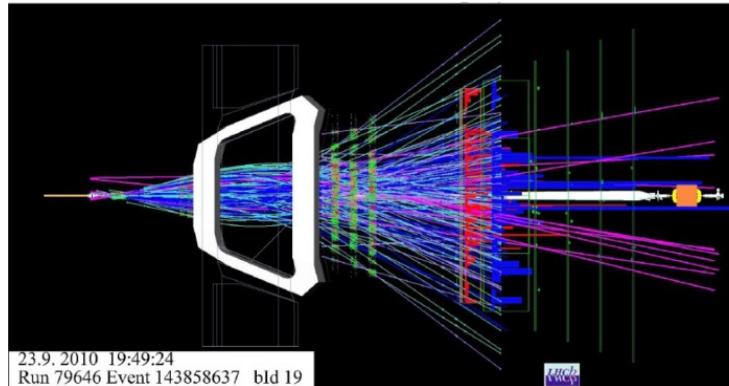
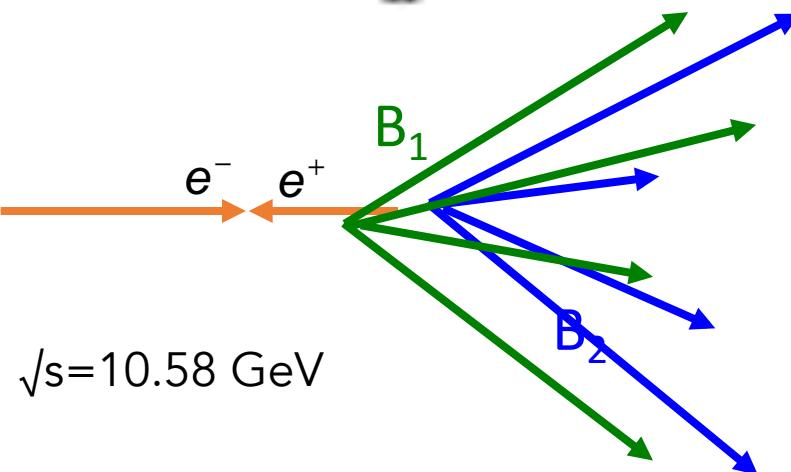
# Same physics, different environments

## B-Factories

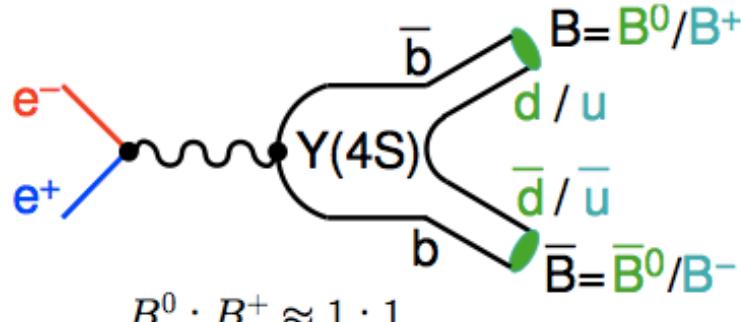
## LHCb



•  $e^-$   $e^+$   $\otimes$



## B-Factories



$$M(\Upsilon(4S)) = 10.58 \text{ GeV} \quad J^{PC} = 1^{--}$$

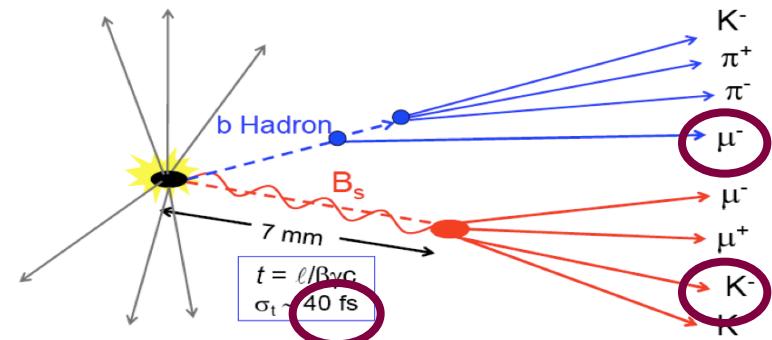
only  $(B^+, B^0)$  are produced (no fragmentation)

$(B^+, B^0)$  are produced nearly at rest in the  $\Upsilon(4S)$  cms

Two pseudoscalar bosons with  $L=1$ , antisymmetric wave function

If the two B could oscillate independently: they could become a state made up of two identical mesons (=bosons), this would be a symmetric state ...

## LHCb



Two independent b-hadrons produced

Time measured from primary vertex

All types of b-hadrons :  $B_s$  and  $\Lambda_b$  also

Fragmentation tracks

# Back of the enveloppe estimates

	$\sigma(b\bar{b})$	$\sigma(\text{inel})/\sigma(b\bar{b})$	$\int L dt$	Number of B produced in the detector acceptance
 	LHCb	$\sim 290 \mu b$	$\sim 300$	$1 fb^{-1} \text{ (2011)}$ + $2 fb^{-1} \text{ (2012)}$
	Run1			$450 10^9 b \bar{b}$ pairs
BaBar	$\sim 1 nb$	$\sim 4$	$425 fb^{-1} \text{ (BaBar)}$	$1.1 10^9 B \bar{B}$ pairs
BELLE			$700 fb^{-1} \text{ (BELLE)}$	

Super B factories :  
 $\sim 50 10^9 B \bar{B}$  pairs

	B-Factories	LHCb
Average B-flight distance	$200 \mu m *$	$1 cm$
Event multiplicity	$\sim 10$	$\sim 100$
Number of channels	$0,1 M$	$1,1 M$
Trigger efficiency	$> 99\%$	$\sim 90\% - 20\%$
Tagging quality factor	$\sim 30\%$	$5-6\%$

# Symmetries

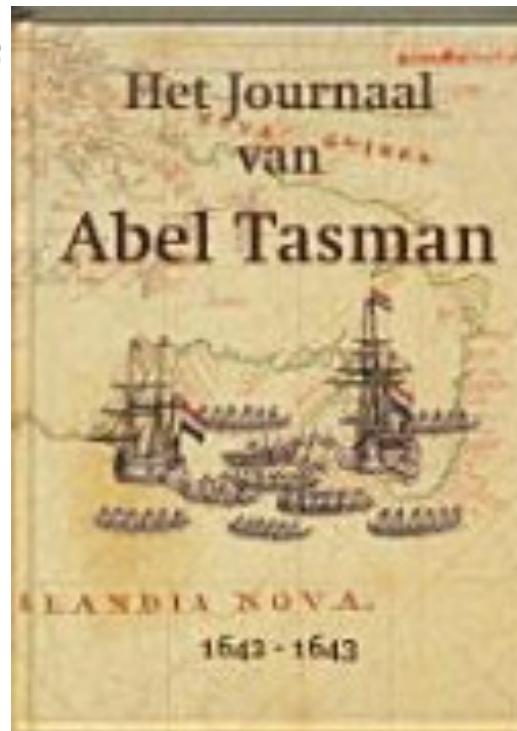
Instructions by the VOC (Dutch East India Company) in Aug 1642:

*“Since many rich mines and other treasures have been found in countries north of the equator between 15° and 40° latitude, there is no doubt that countries alike exist south of the equator. The provinces in Peru and Chili rich of gold and silver, all positioned south of the equator, are revealing proofs hereof.”*

Abel Tasman discovered Tasmania (Nov. 1642), New Zealand (Dec. 1642), Fiji (Jan 1643), ...



Abel Tasman 1603 –1659



# conservation laws and symmetries

In classical mechanics :

symmetry principle → non observable quantity → invariance



=> Noether's theorem :

For any continuous **symmetry** for a given system  
corresponds a **conservation law** for this system.



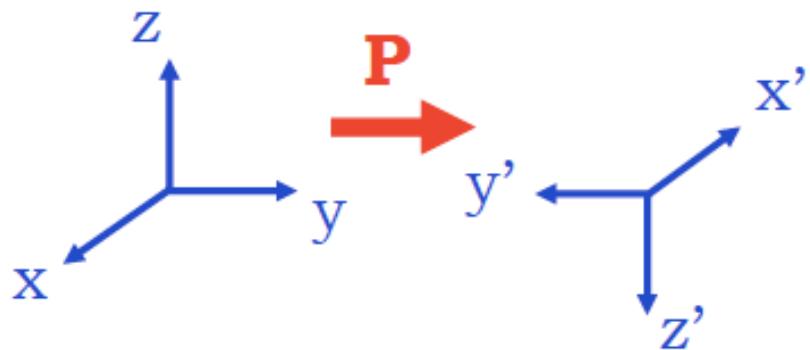
E. Noether



But also **discrete** symmetries

	P	C	T
Space vector x	-x	x	x
Momentum p	-p	p	-p
Spin s	s	s	-s

parity P:



Parity changes direction of momentum but  
NOT angular momentum or spin

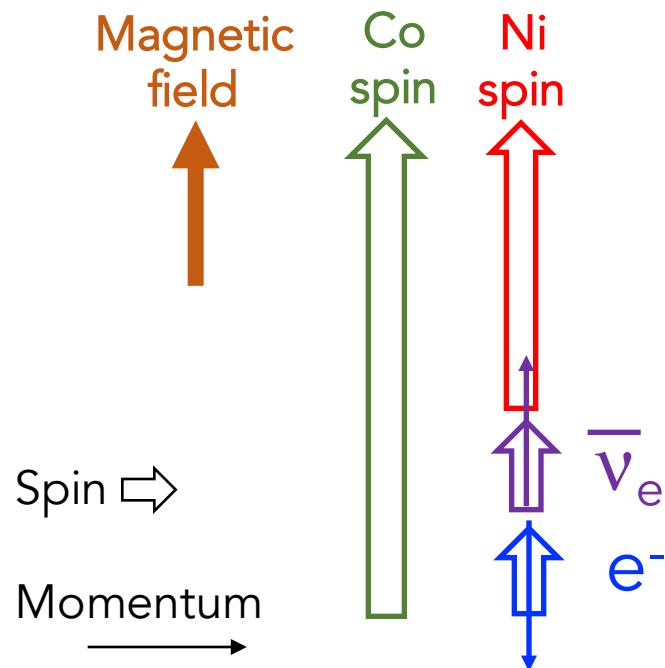
## The way to parity violation :

- Before 1956 : the physics laws should not change under Parity transformation (tested already for strong and electromagnetic interactions)
- in 1956 Lee and Yang proposed an experiment to test it for weak interaction
- Done in 1956 by C. S. Wu and collaborators : the  $^{60}\text{Co}$  experiment



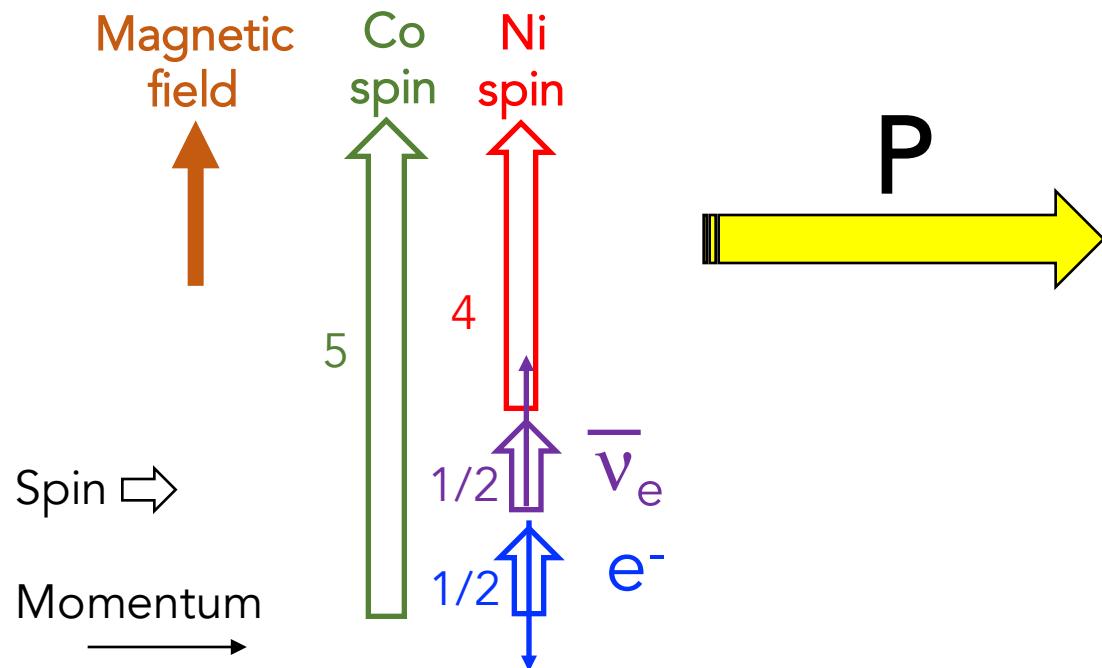
# Schematic overview of the Co<sup>60</sup> experiment

- $\beta$  decay : Co<sup>60</sup> ( $J=5$ )  $\rightarrow$  Ni<sup>60\*</sup> ( $J=4$ )  $e^- \bar{\nu}_e$  ( $n \rightarrow p e^- \bar{\nu}_e$ )
- Spin of the Co<sup>60</sup> aligned by a magnetic field
- record the direction of the emitted electrons



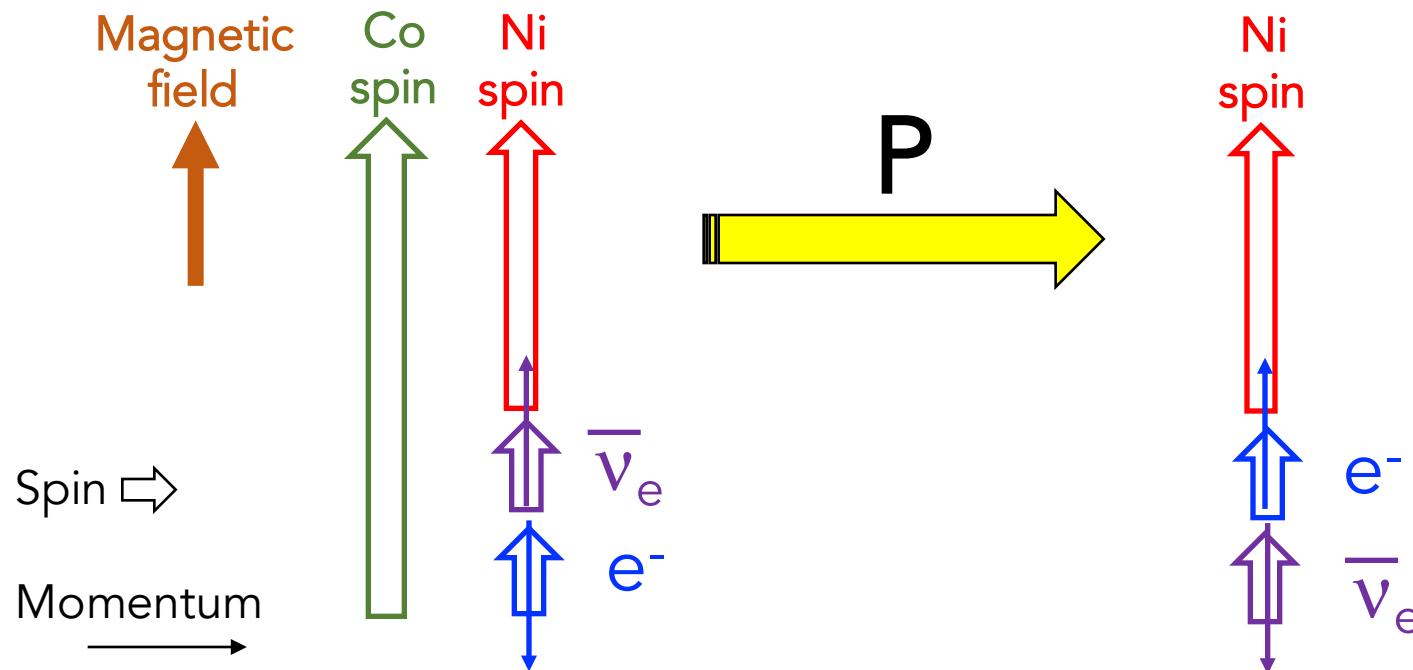
# Schematic overview of the Co<sup>60</sup> experiment

- $\beta$  decay : Co<sup>60</sup> ( $J=5$ )  $\rightarrow$  Ni<sup>60\*</sup> ( $J=4$ )  $e^- \bar{\nu}_e$   $(n \rightarrow p e^- \bar{\nu}_e)$
- Spin of the Co<sup>60</sup> aligned by a magnetic field
- record the direction of the emitted electrons



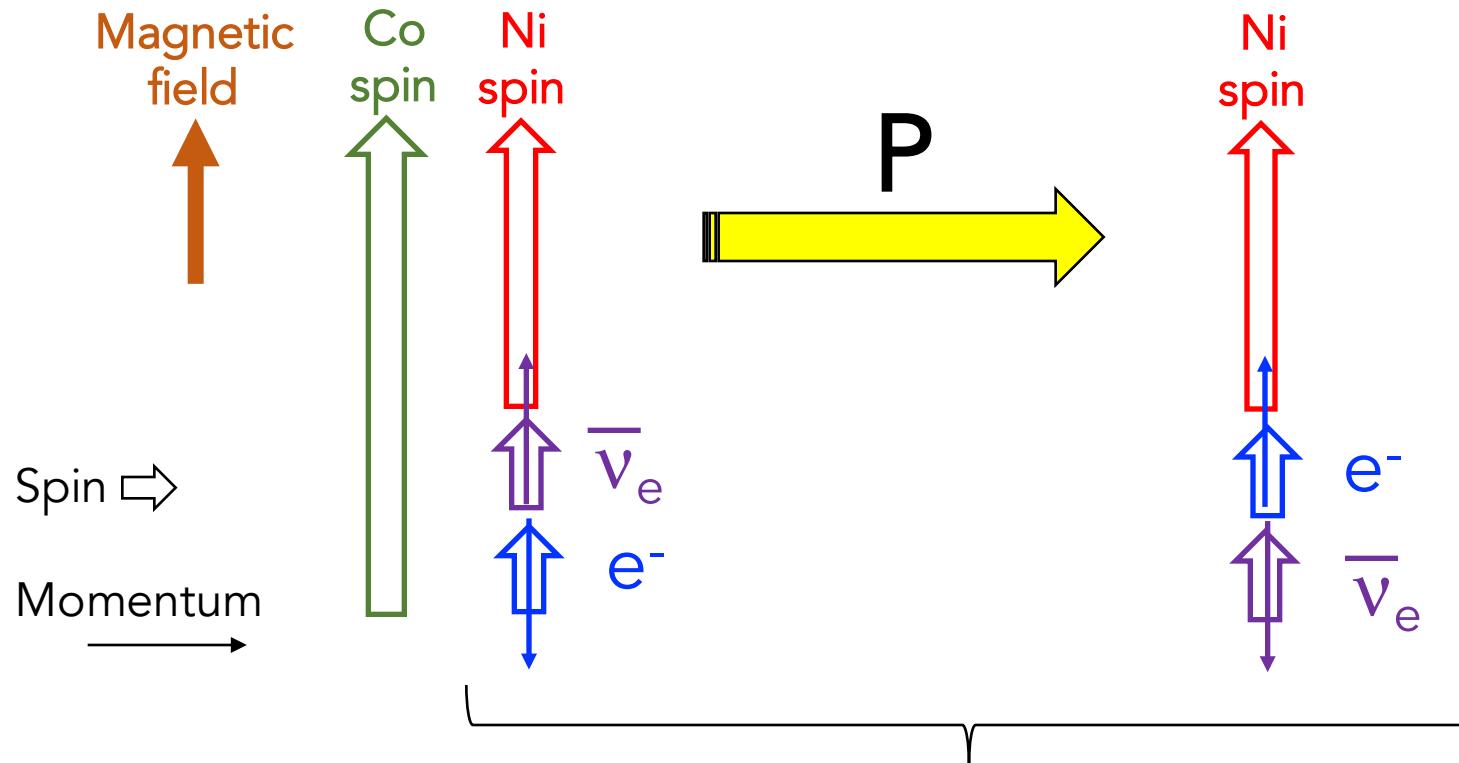
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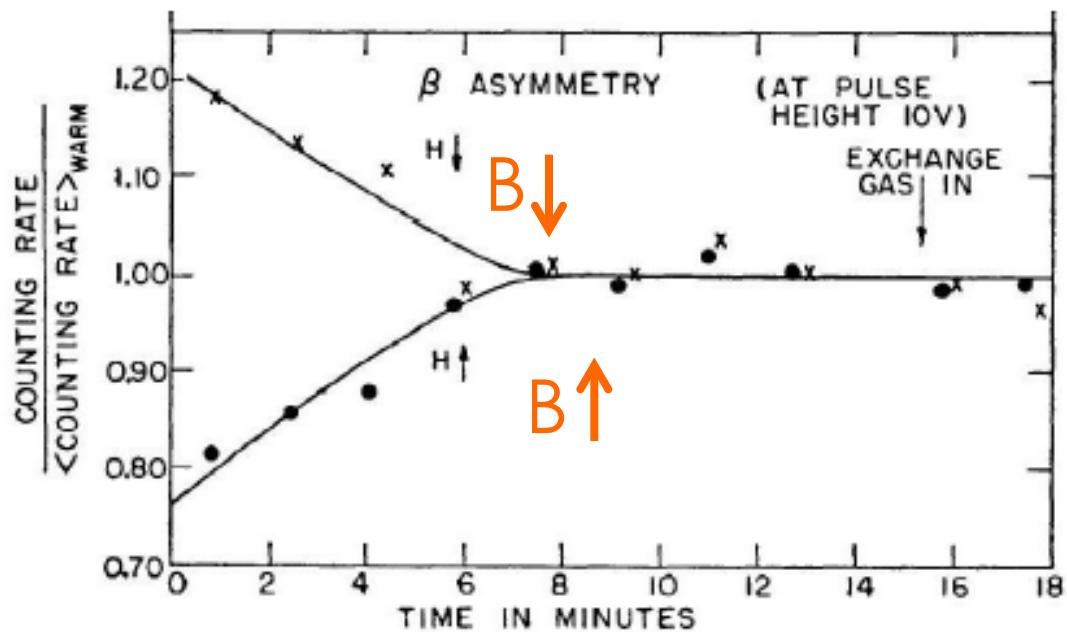


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- record the direction of the emitted electrons



If P is conserved these two configurations should have the same probability



Ni spin  
Ni spin

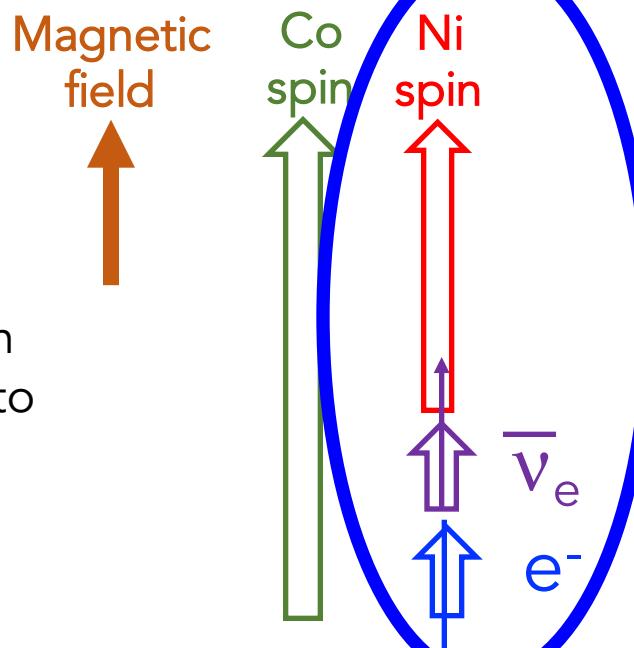


e-  
 $\bar{\nu}_e$

Ni spin  
Ni spin



e-  
 $\bar{\nu}_e$



The electrons are  
preferentially emitted in  
the direction **opposite** to  
the Co spin

# Charge conjugaison ( C ) :

Dirac 1928  
Anderson 1932

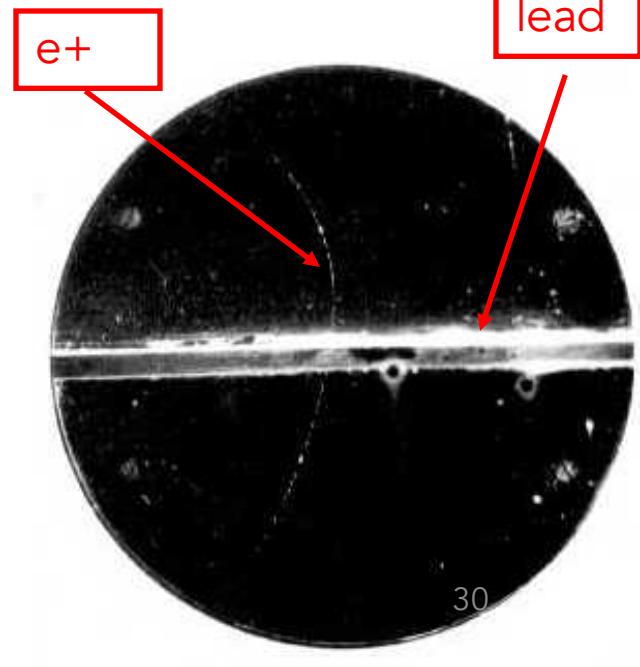
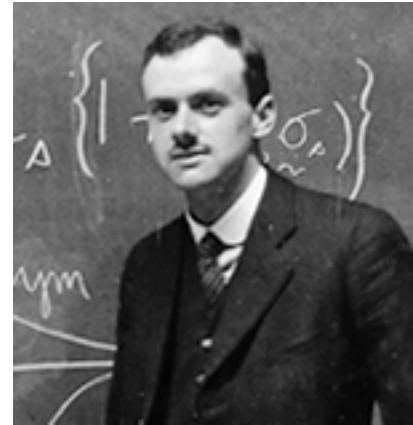
particle  $\longleftrightarrow$  antiparticle

$Q \longleftrightarrow -Q$

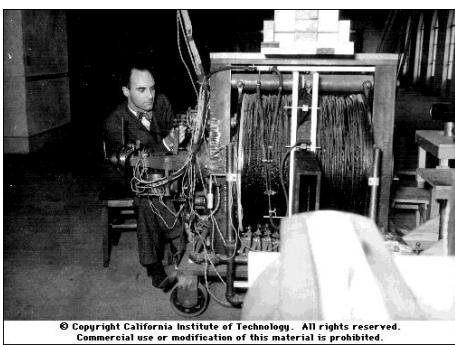
Leptonic number  $\longleftrightarrow -\text{Leptonic number}$

...  
true for all additive  
quantum numbers

Dirac



Anderson

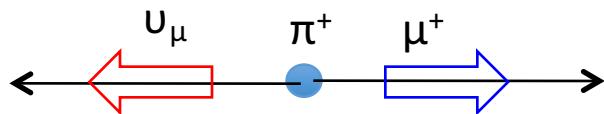
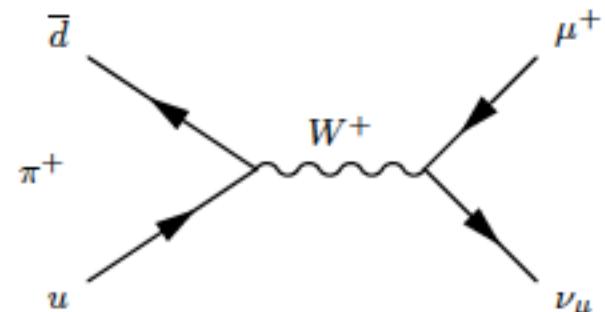


$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

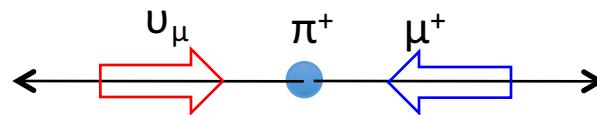
Spin of the pion : 0

Spin of the muon and neutrino :  $\frac{1}{2}$

$\xrightarrow{\hspace{1cm}}$  Momentum  
 spin



Right handed neutrino



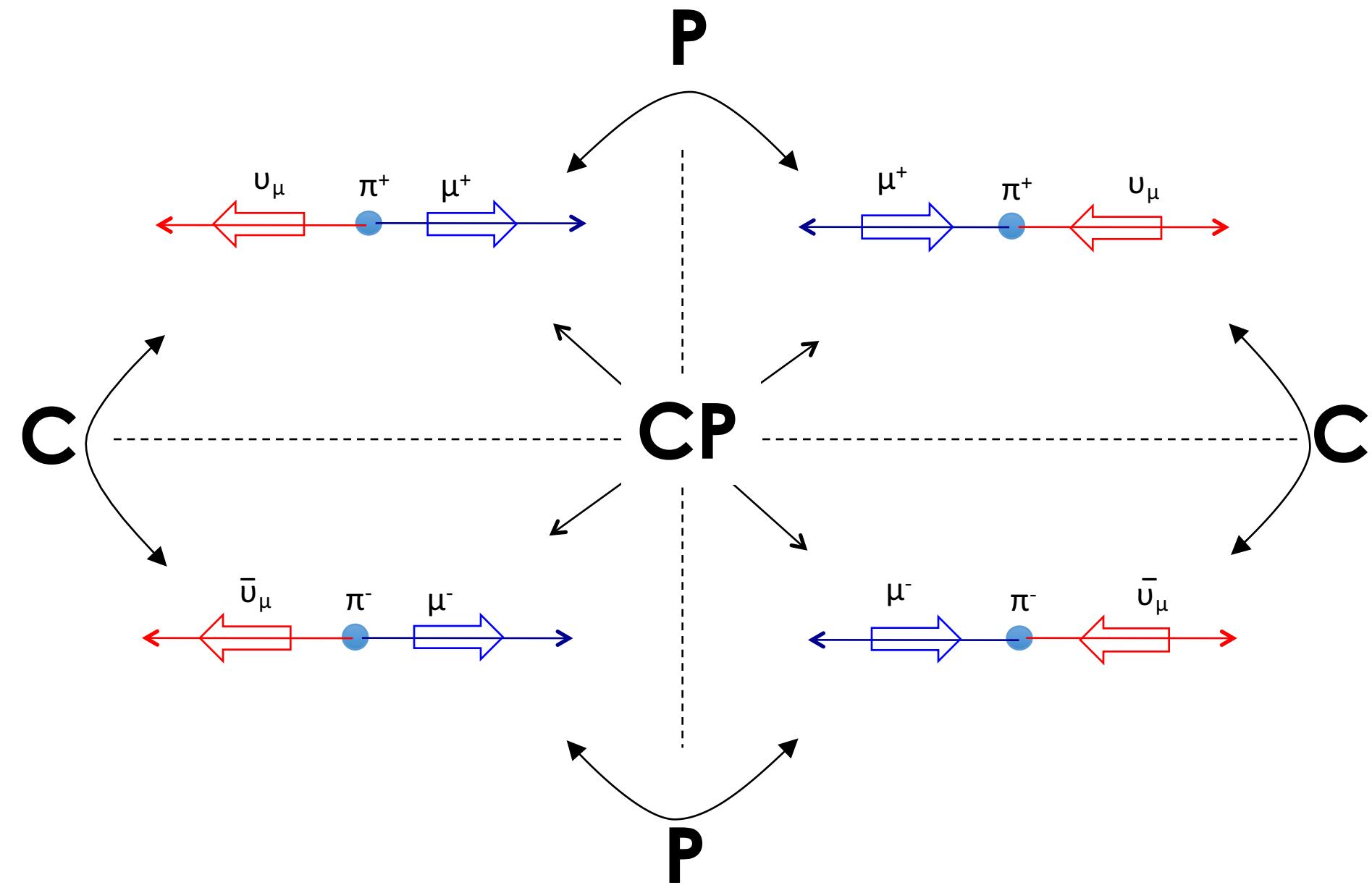
Left handed neutrino

→ Spin of the decay products : oppositely aligned

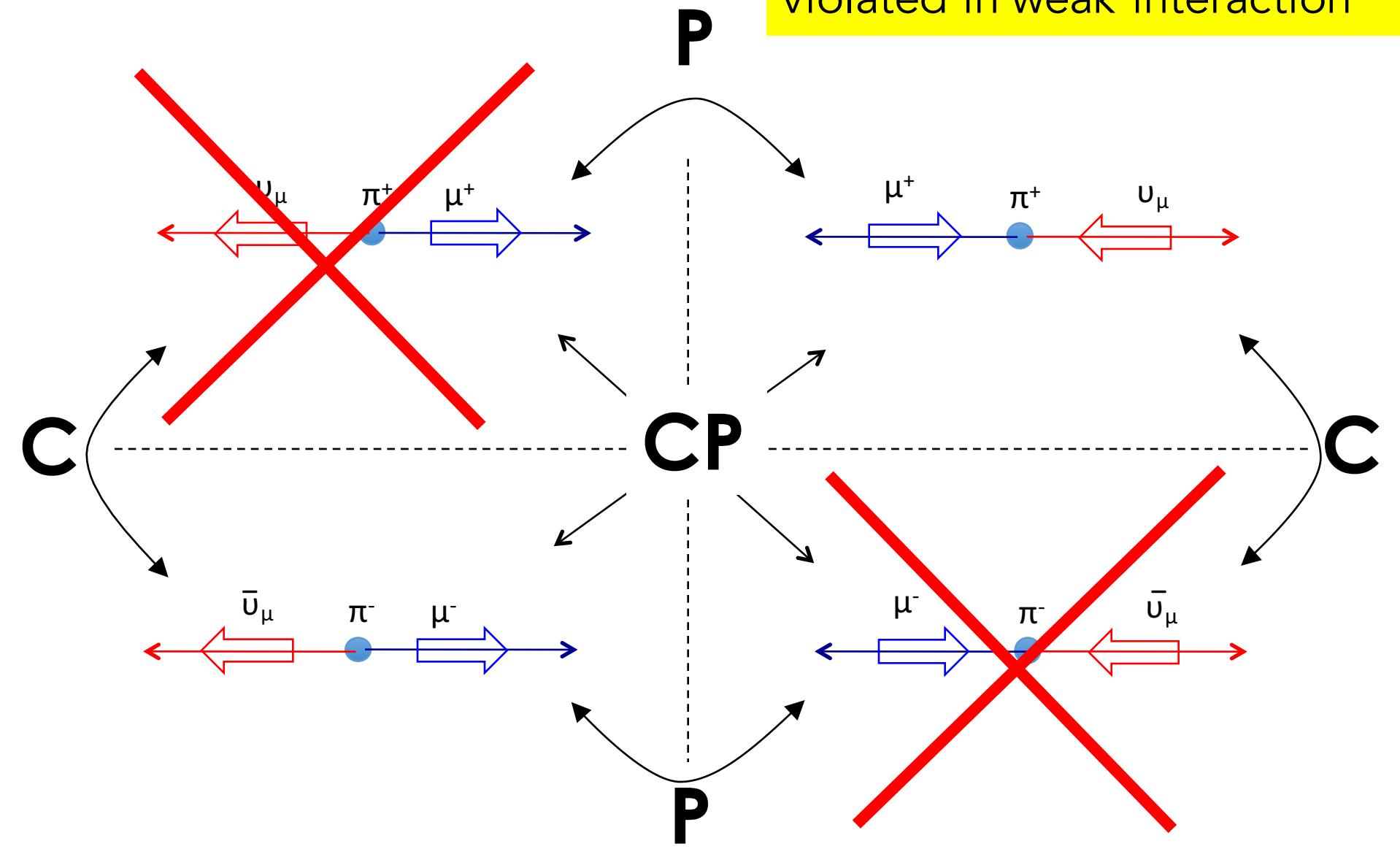
→ Helicity of the neutrino is the same as that of the muon



Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon\*  
 RICHARD L. GARWIN,<sup>†</sup> LEON M. LEDERMAN,<sup>‡</sup> AND MARCEL WEINRICH  
 Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York  
 (Received January 15, 1958)

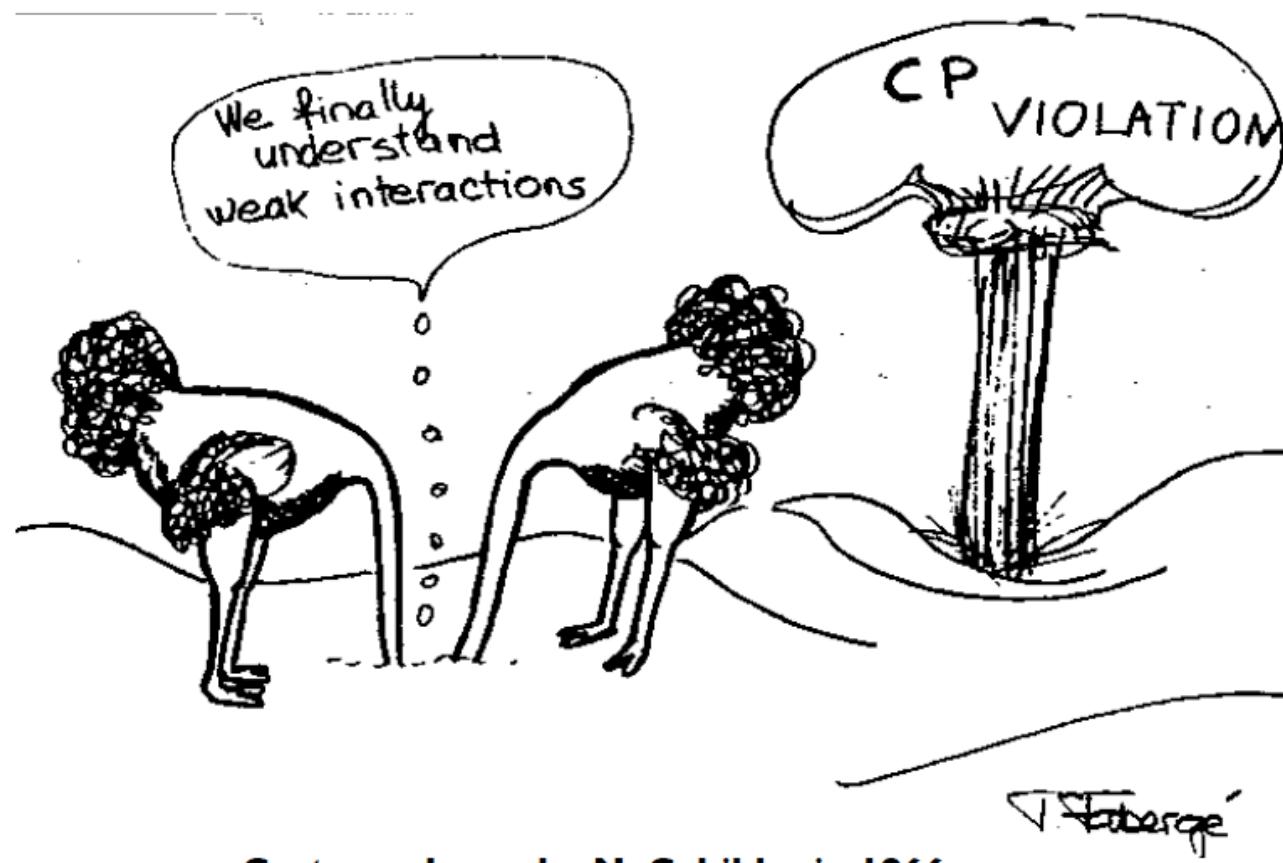


P and C are maximally violated in weak interaction



The  $\nu$  is left handed (the anti-neutrino is right handed)

$$\Gamma(\pi^+ \rightarrow \ell^+ \nu_\ell) = \Gamma(\pi^- \rightarrow \ell^- \bar{\nu}_\ell)$$



# The $K^0$ - $\bar{K}^0$ system

## Observation of Long-Lived Neutral $V$ Particles\*

K. LANDE, E. T. BOOTH, J. IMPEDUGLIA, AND L. M. LEDERMAN,  
*Columbia University, New York, New York*

AND

W. CHINOWSKY, *Brookhaven National Laboratory,  
Upton, New York*  
(Received July 30, 1956)

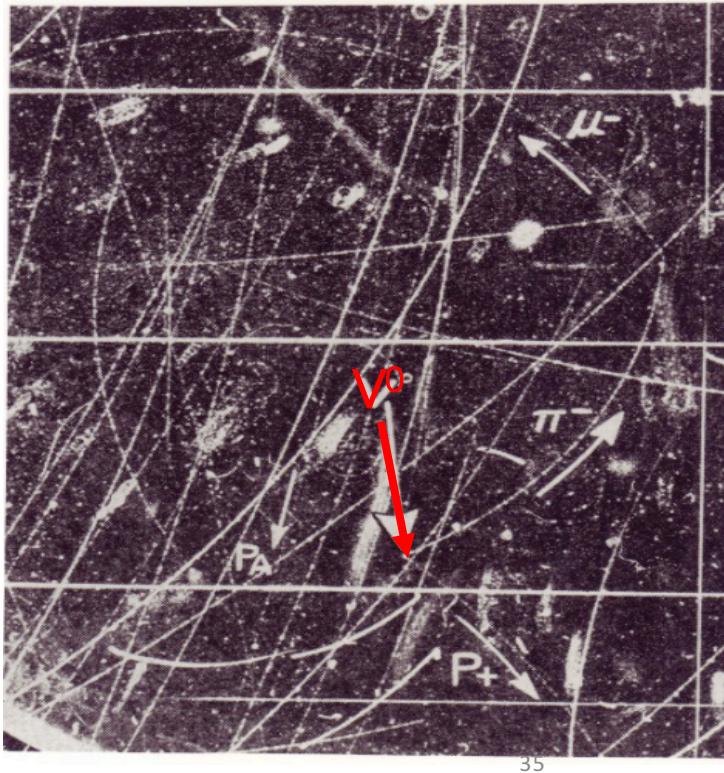
→ Two states :

$$|K_1\rangle \rightarrow \pi\pi$$

$$|K_2\rangle \rightarrow \pi\pi\pi$$

Same mass ( $\sim 500$  MeV)

Very different lifetimes



Brookhaven, 1956

$M(\pi) \sim 140$  MeV  
 $M(K) \sim 500$  MeV

$K_2$  lifetime  $\sim 10000$   $K_1$  lifetime due to phase space

# CP violation in the $K^0$ system

NB :  $K_1 = K_S$  and  $K_2 = K_L$

$$\left|K^0\right\rangle = \left|\bar{s}d\right\rangle \quad \text{CP} \left|K^0\right\rangle = \left|\bar{K}^0\right\rangle \quad \Rightarrow \quad \left|K^0\right\rangle \quad \left|\bar{K}^0\right\rangle \quad \left.\right]_{\text{not CP eigenstates}}$$
$$\left|\bar{K}^0\right\rangle = \left|\bar{d}s\right\rangle$$

One can build :

$$\left|K_1\right\rangle = \frac{1}{\sqrt{2}} \left( \left|K^0\right\rangle + \left|\bar{K}^0\right\rangle \right) \quad \left.\right]_{\text{CP eigenstates}}$$
$$\left|K_2\right\rangle = \frac{1}{\sqrt{2}} \left( \left|K^0\right\rangle - \left|\bar{K}^0\right\rangle \right)$$

$$\left|K_1\right\rangle \rightarrow \pi\pi$$

$$\left|K_2\right\rangle \rightarrow \pi\pi\pi$$

$\text{CP}(\pi\pi) = +1$  and  $\text{CP}(\pi\pi\pi) = -1$

if CP is a good symmetry for the weak interaction :

~~$$\left|K_1\right\rangle \rightarrow \pi\pi$$~~

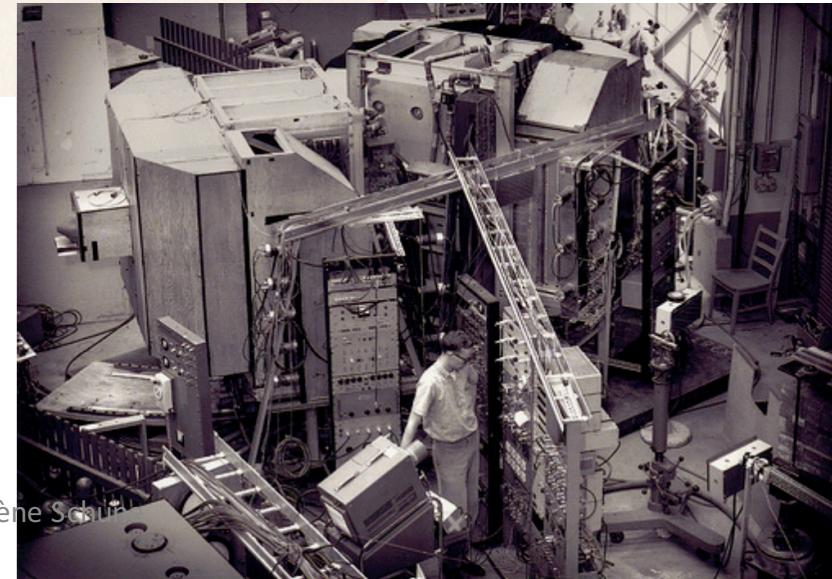
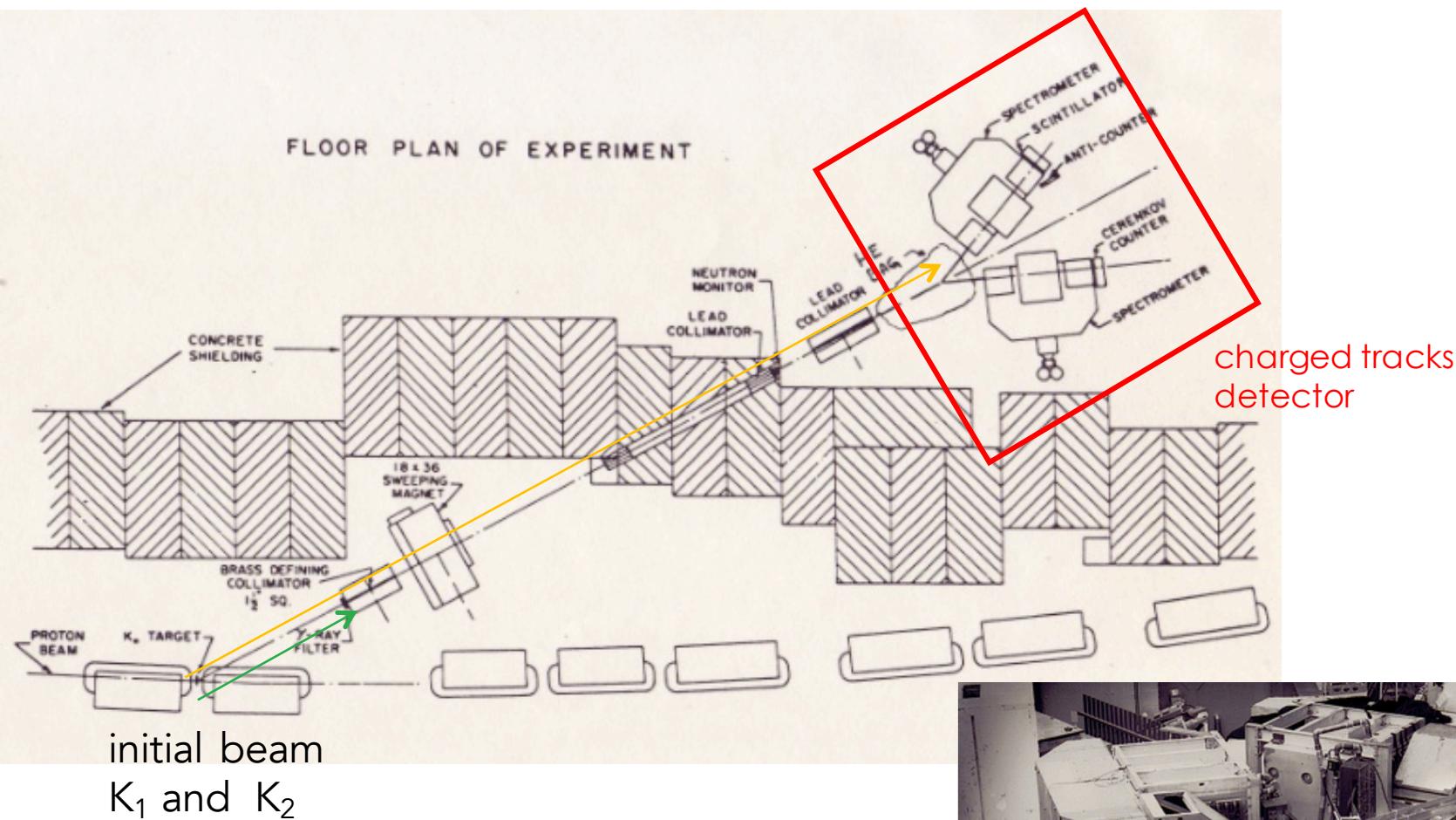
$$|K_1\rangle \rightarrow \pi\pi$$



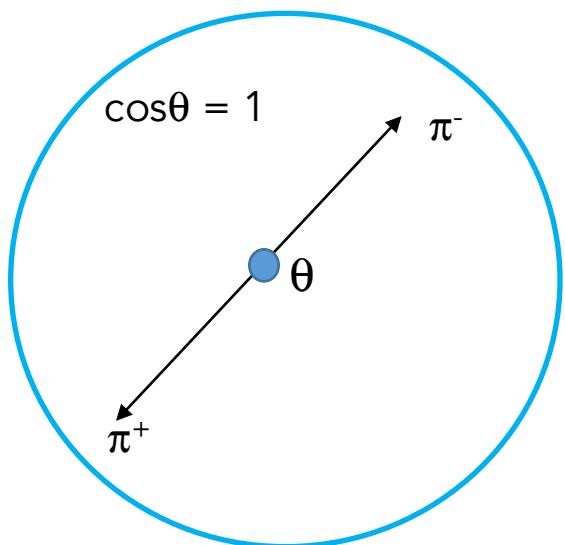
Search for the signal of the decay  $|K_2\rangle \rightarrow \pi\pi$  far (20 meters)  
from the production point of the  $K_1$  and  $K_2$

?

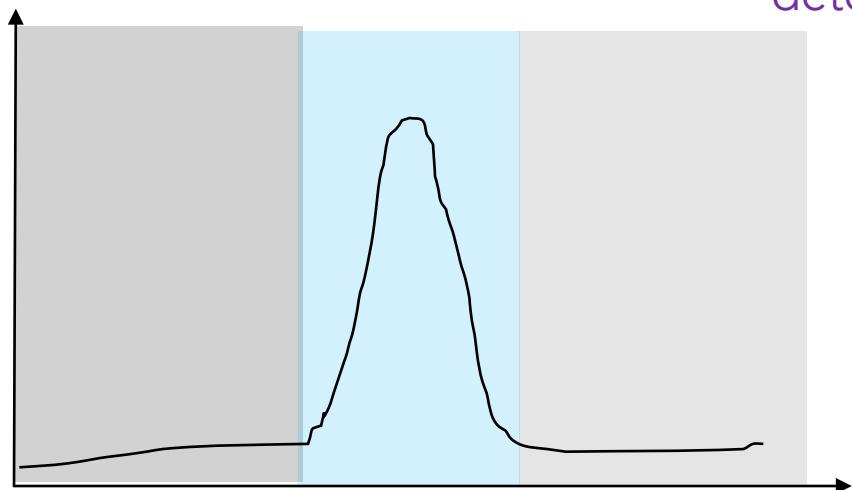
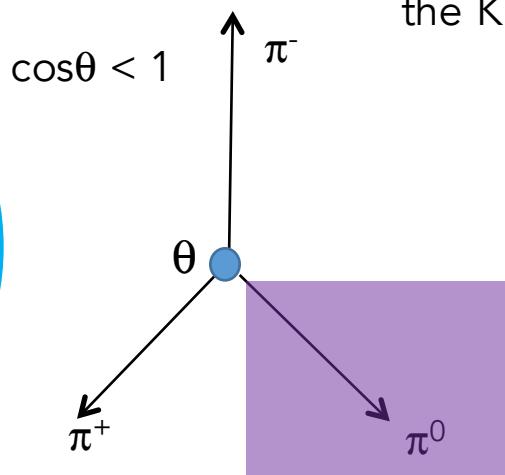
# Cronin & Fitch experiment 1964



signal



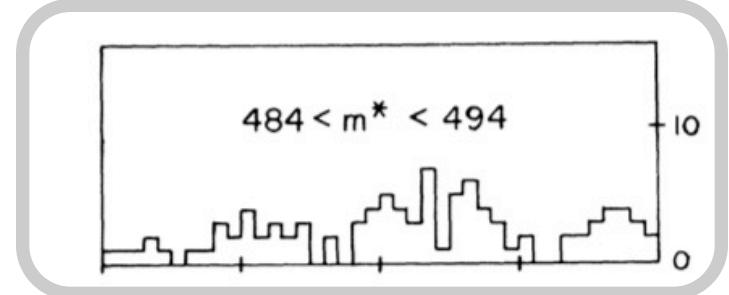
background



Two informations :

- The  $\pi^+\pi^-$  invariant mass ( $m^*$ )
- The opening angle between the two pions in the K center of mass frame

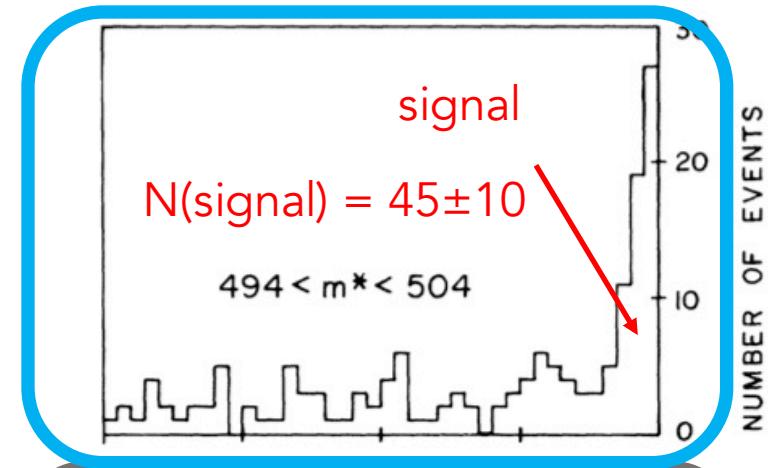
$484 < m^* < 494$



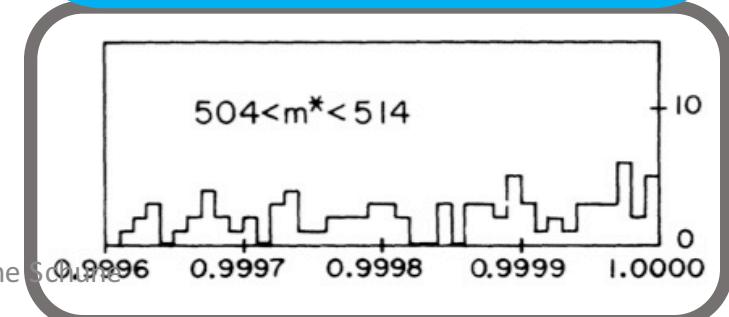
signal

$N(\text{signal}) = 45 \pm 10$

$494 < m^* < 504$



$504 < m^* < 514$



1964

EVIDENCE FOR THE  $2\pi$  DECAY OF THE  $K_2^0$  MESON\*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§  
 Princeton University, Princeton, New Jersey  
 (Received 10 July 1964)

We would conclude therefore that  $K_2^0$  decays to two pions with a branching ratio  $R = (K_2 \rightarrow \pi^+ + \pi^-) / (K_2^0 \rightarrow \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$  where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the  $K_2^0$ . The presence of a two-pion decay mode implies that the  $K_2^0$  meson is not a pure eigenstate of  $CP$ . Expressed as

## The Nobel Prize in Physics 1980



James Watson  
Cronin  
Prize share: 1/2



Val Logsdon Fitch  
Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

R. Turlay was a PhD student  
 J Christenson was a graduate student

« The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments. » (From Nobel prize)

Today : 
$$\frac{A(|K_2\rangle \rightarrow \pi\pi)}{A(|K_1\rangle \rightarrow \pi\pi)} = (2.271 \pm 0.017) 10^{-3}$$
      0.7 % precision !

# One word on precision and the search for NP

VOLUME 6, NUMBER 10

PHYSICAL REVIEW LETTERS

MAY 15, 1961

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## DECAY PROPERTIES OF $K_2^0$ MESONS\*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov

Joint Institute of Nuclear Research, Moscow, U.S.S.R.

(Received April 20, 1961)

1961

Combining our data with those obtained in reference 7, we set an upper limit of 0.3% for the relative probability of the decay  $K_2^0 \rightarrow \pi^- + \pi^+$ . Our results on the charge ratio and the degree of the  $2\pi$ -decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in  $K^0$  decay.

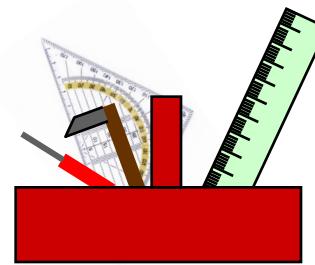
Stopped by funding agency

Discovery : 1964 ...

Precision is the key word, not only for K physics  
Large statistics

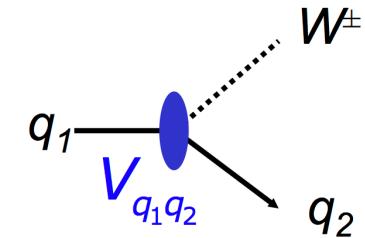
# Standard Model: the CKM matrix

...our toolbox

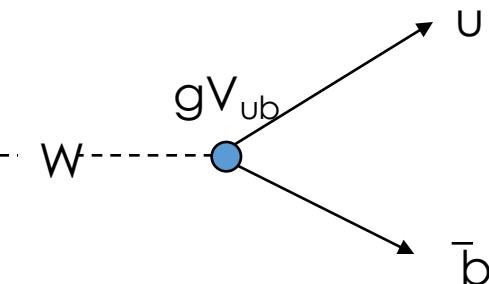
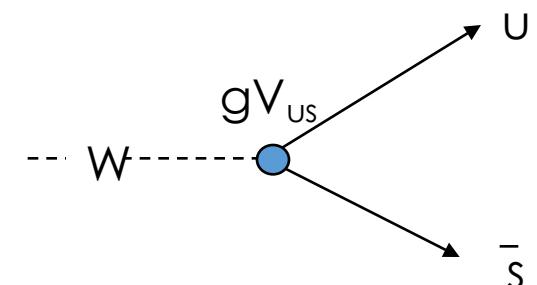
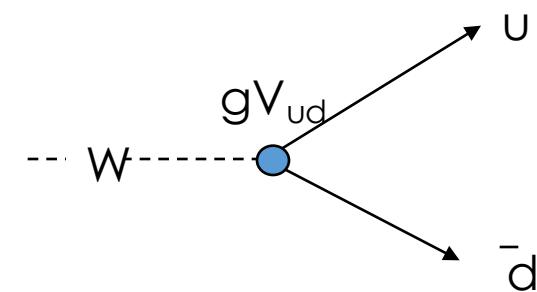


# $V_{CKM}$ Cabibbo-Kobayashi-Maskawa matrix

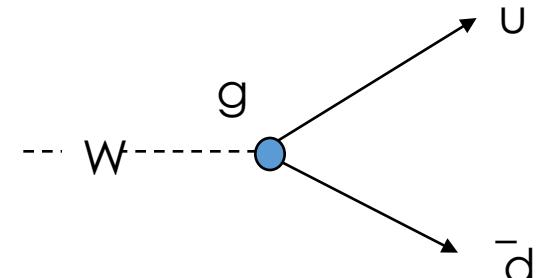
Two different way of seeing the charged interactions among quarks



In the basis dealing with mass eigenstates :



In the basis where :  
charged interactions are just  
between members of the same family  
and « CKM » is diagonal



Weak interaction eigenstates

$\neq$

Mass eigenstates (flavour or strong interaction eigenstates)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

# **CP-Violation in the Renormalizable Theory of Weak Interaction**

Makoto KOBAYASHI and Toshihide MASKAWA

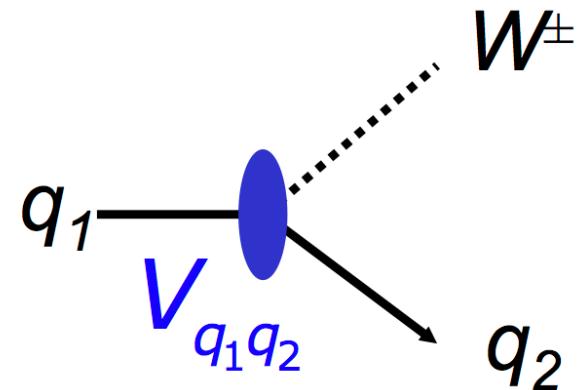
*Department of Physics, Kyoto University, Kyoto*

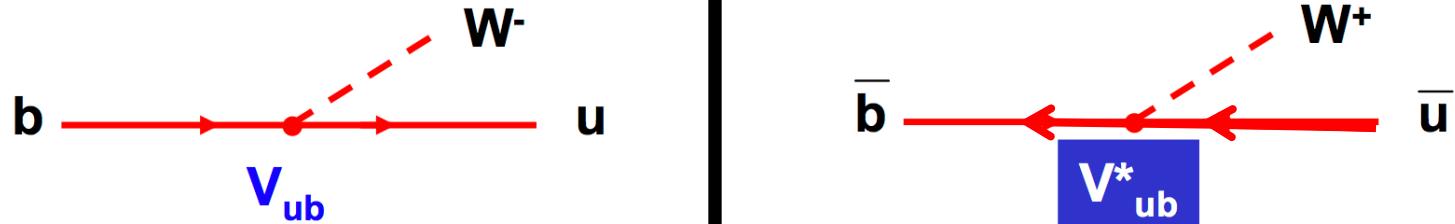
1973

Before the discovery  
of the 4<sup>th</sup> quarkPrediction of the 3<sup>rd</sup>  
family

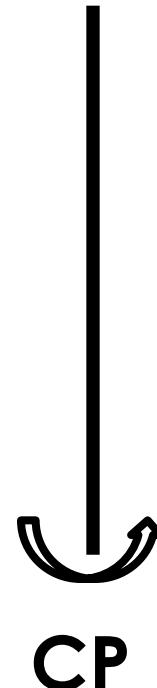
# families	# angles	# reducible phases	# irreducible phases
n	n(n-1)/2	2n-1	n(n+1)/2 -(2n-1)=(n-1)(n-2)/2
2	1		0
3	3		1
4	6		3

$$(u \quad c \quad t) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

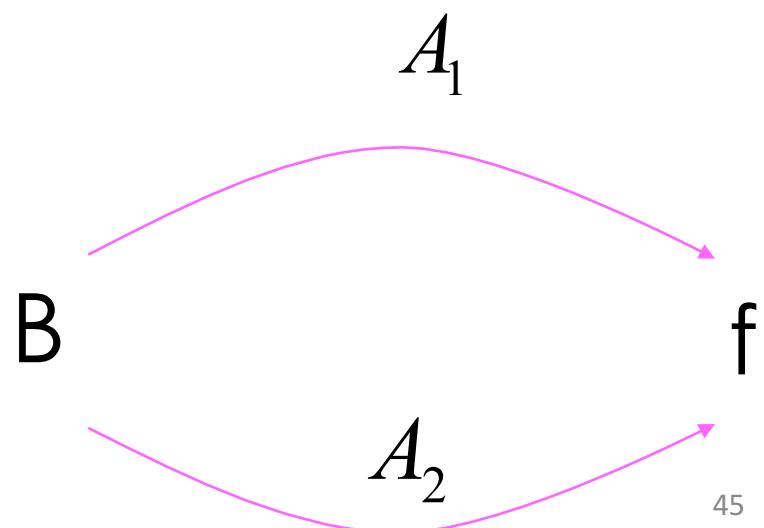
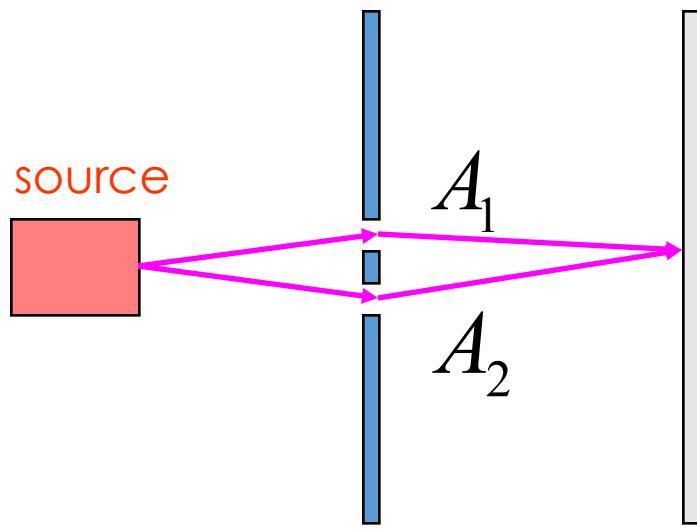




$V_{ub}^* \neq V_{ub} \rightarrow \text{CP violation}$



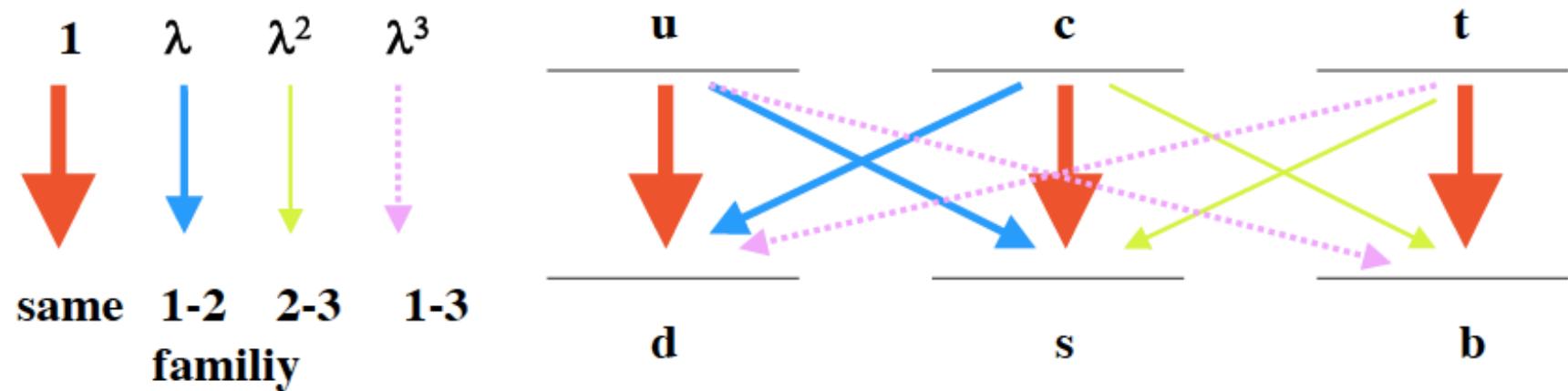
One amplitude : no sensitivity on phase ( $|V_{ij}|^2 = |V_{ij}^*|^2$ )



No prediction on the  $V_{ij}$  → they need to be measured

### → Experimental observations:

$$\left( \begin{array}{ccc} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{array} \right) = \left( \begin{array}{ccccc} \text{Red} & & & & \\ & \text{Cyan} & & & \\ & & \text{Purple} & & \\ & \text{Cyan} & & \text{Red} & \\ & & & & \text{Green} \\ \text{Purple} & & & \text{Green} & \\ & & & & \text{Red} \end{array} \right)$$



3 families 3 angles ( $\theta_{ij}$ ) and one phase ( $\delta$ )

$$V_{\text{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$V_{ub}$

$c_{ij} = \cos \theta_{ij}$   
 $s_{ij} = \sin \theta_{ij}$

→ Wolfenstein parametrization in power of  $\lambda$  ( $= \sin \theta_C$ ) =  $s_{12} = |V_{us}| \sim 0.22$

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \frac{1}{2}\lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

# Measuring triangles

*Stay within the 3 families*

$$(u \quad c \quad t) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity of  $V_{CKM}$      $VV^\dagger = V^\dagger V = 1$

→ 9 relations     $\sum_{k=1}^n V_{ik} V_{jk}^* = \delta_{ij},$

The non-diagonal elements of the matrix products correspond to 6 triangle equations

(a)

$$V_{td} V_{ts}^*$$

$$V_{ud} V_{us}^*$$

$$V_{cd} V_{cs}^*$$

(b)  $V_{ud} V_{us}^* \triangle V_{td} V_{tb}^*$   
 $V_{cd} V_{cb}^*$

$$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0 \quad \lambda \lambda \lambda^5$$

$$\boxed{V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0} \quad \boxed{\lambda \lambda \lambda^3}$$

$$\boxed{V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0} \quad \boxed{\lambda \lambda \lambda^2}$$

$$\boxed{V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0} \quad \boxed{\lambda \lambda \lambda^3}$$

$$V_{td}^* V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0 \quad \lambda \lambda \lambda^4$$

$$\boxed{V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0} \quad \boxed{\lambda \lambda \lambda^5}$$

(c)  $V_{us} V_{ub}^* \frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*}$

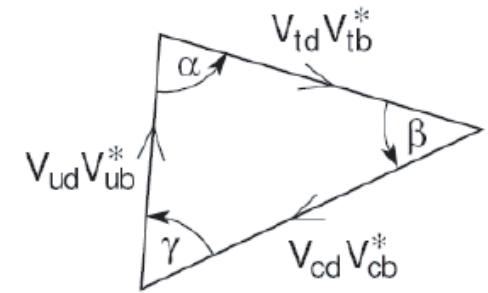
They all have the same area, proportionnal to the amount of CP violation in the SM

"the" unitarity triangle :  $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

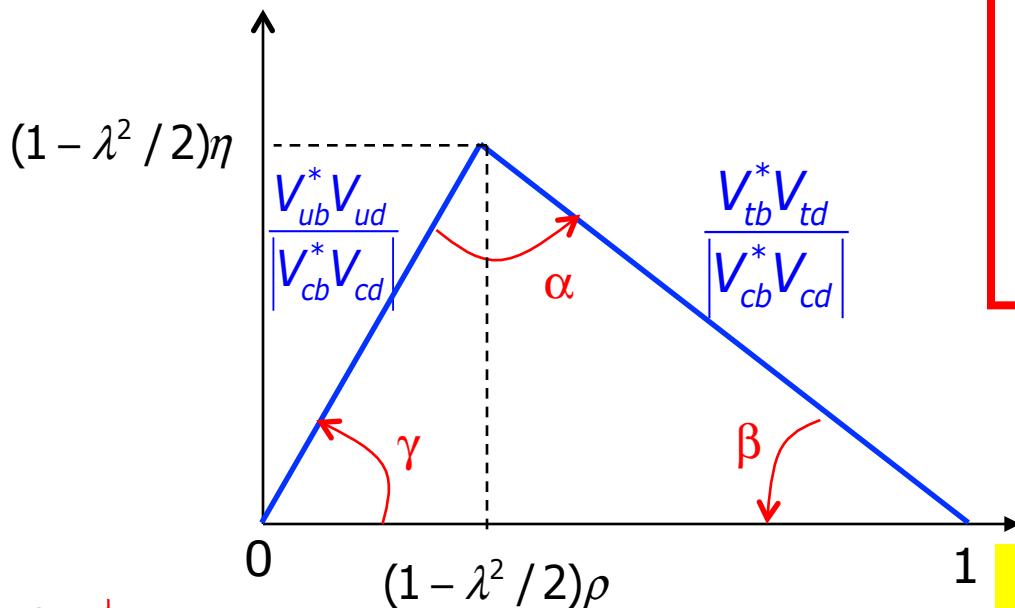
$$V_{td} V_{tb}^* = A\lambda^3(1 - \rho - i\eta) + A\lambda^5(\rho + i\eta)$$

$$V_{ud} V_{ub}^* = A\lambda^3(\rho + i\eta) \times (1 - \frac{\lambda^2}{2}) \quad \text{at order } \lambda^5$$

$$V_{cd} V_{cb}^* = -A\lambda^3$$



Basis of the triangle aligned on the real axis, normalized to 1



$$\begin{aligned}\alpha &= \phi_2 \\ \beta &= \phi_1 \\ \gamma &= \phi_3\end{aligned}$$

$$\beta = \arg\left(\frac{V_{td} V_{tb}^*}{|V_{cd} V_{cb}^*|}\right) = \text{atan}\left(\frac{(1 - \lambda^2 / 2)\eta}{1 - (1 - \lambda^2 / 2)\rho}\right)$$

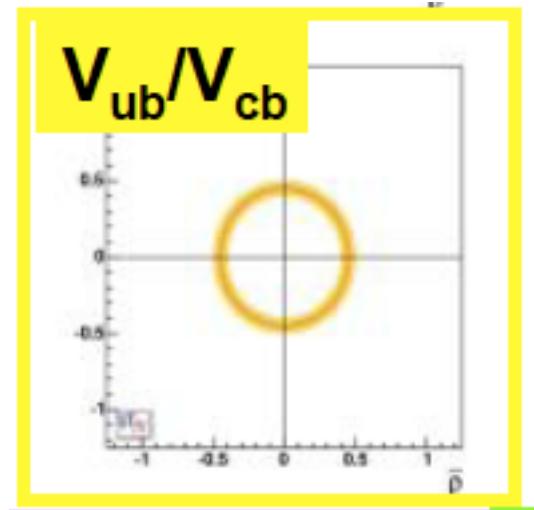
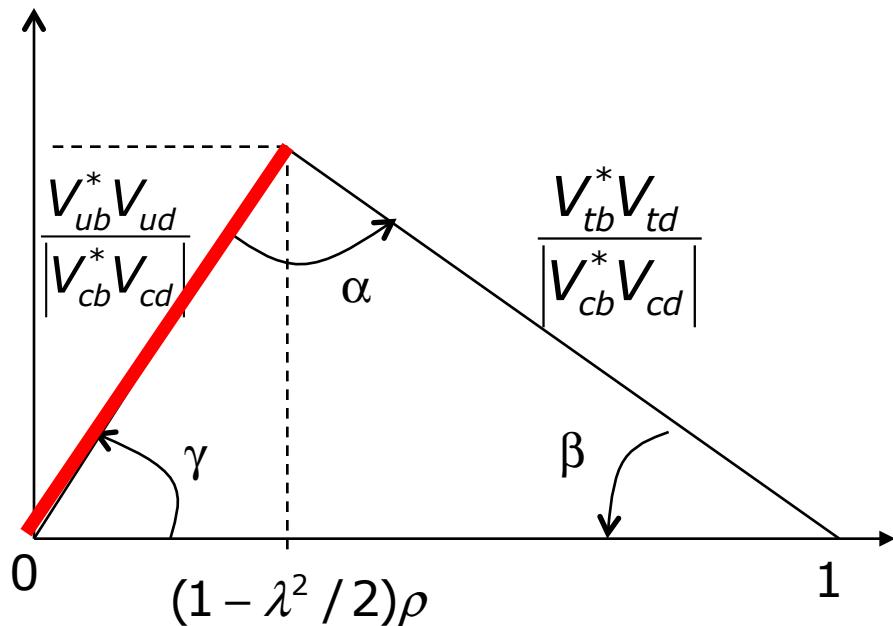
$$\gamma = \arg\left(\frac{V_{ud} V_{ub}^*}{|V_{cd} V_{cb}^*|}\right) = \text{atan}\left(\frac{\eta}{\rho}\right)$$

$$\alpha + \beta + \gamma = \pi$$

2 sides ; 3 angles  
 ⇒ aim : to overconstrain this **unitarity triangle**  
 precision test of the Standard Model

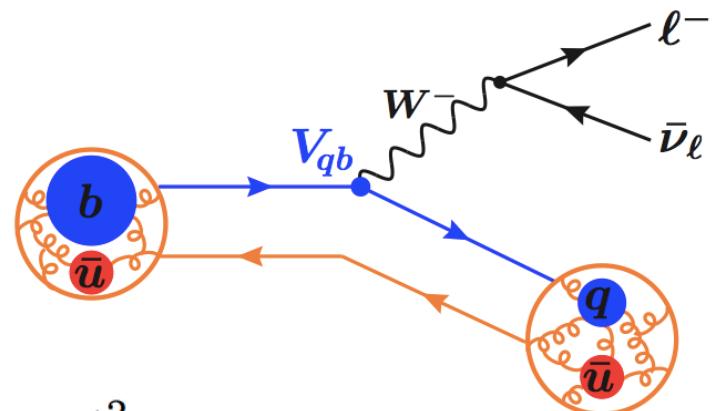


$$(1 - \lambda^2 / 2)\eta$$



- The CKM magnitudes  $|V_{ub}|$  and  $|V_{cb}|$  are determined from semileptonic B meson decays

$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q} \gamma_\mu P_L b | B \rangle \right|^2$$



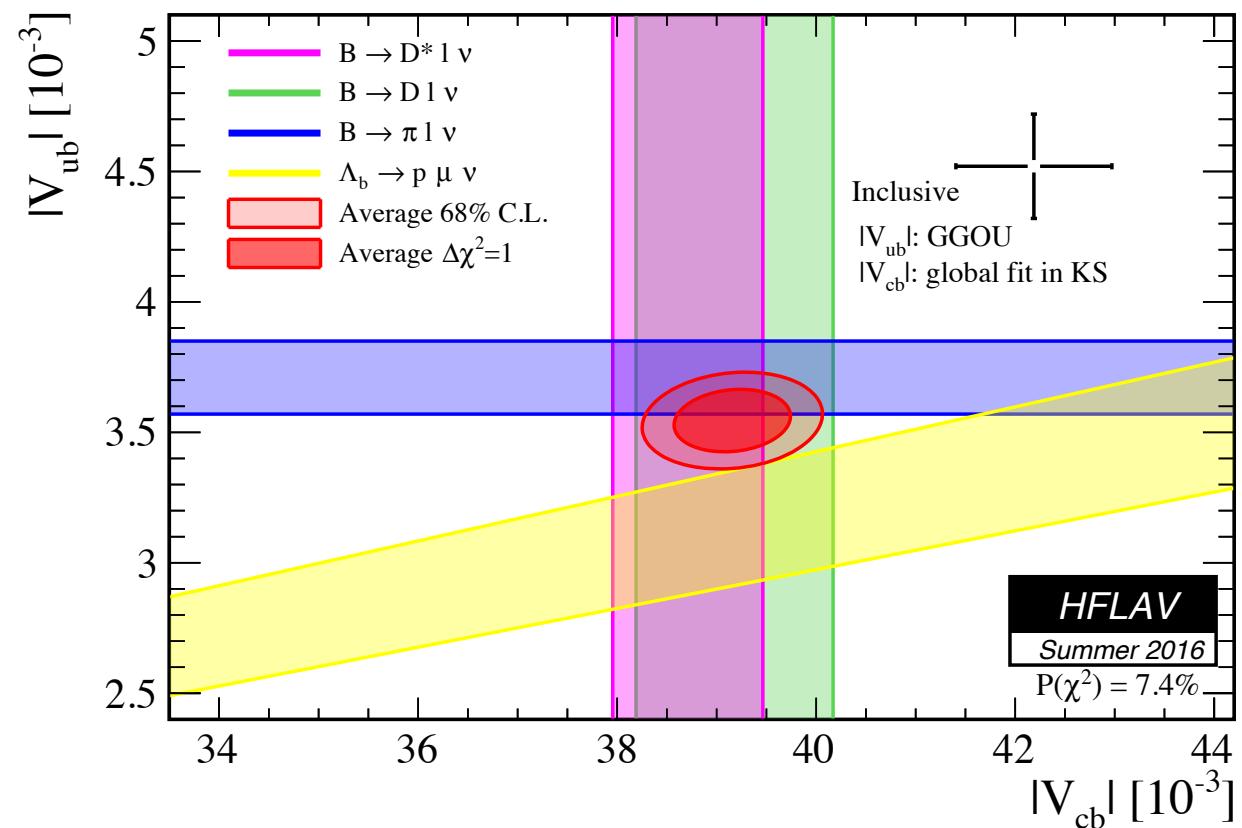
# Inclusive vs exclusive

	Experiment	Theory
Exclusive $ V_{cb} ,  V_{ub} $	$B \rightarrow D l\nu, D^* l\nu, \pi l\nu$ (low backgrounds)	Lattice QCD, light cone sum rules
Inclusive $ V_{cb} ,  V_{ub} $	$B \rightarrow X_c l\nu, X_u l\nu$ (higher background)	Operator product expansion

Several theory models to deal with the FF in  $B \rightarrow D^* l\nu$

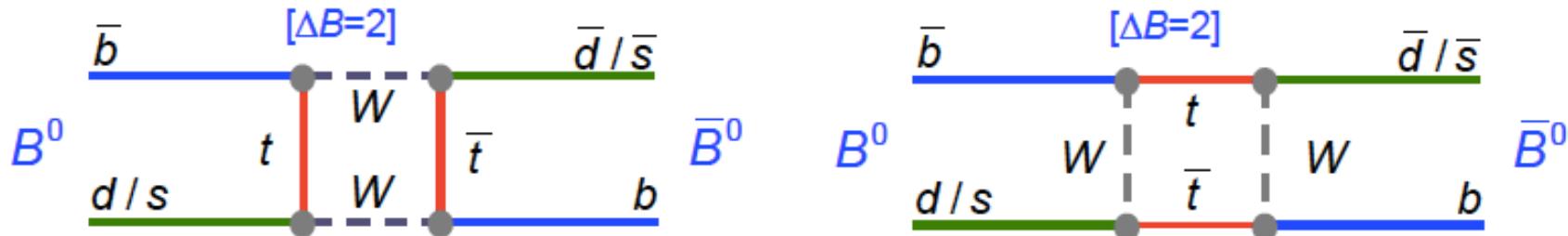
Same data , variation of  $V_{cb}$  by +6 to +9 %

arXiv 1703.06124 and  
Phys.Lett. B771 (2017) 359-364



# $B^0$ - $\bar{B}^0$ oscillations

Effective FCNC Processes ( $CP$  conserving — top loop dominates in box diagram):



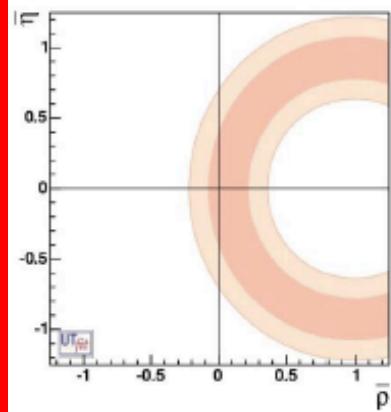
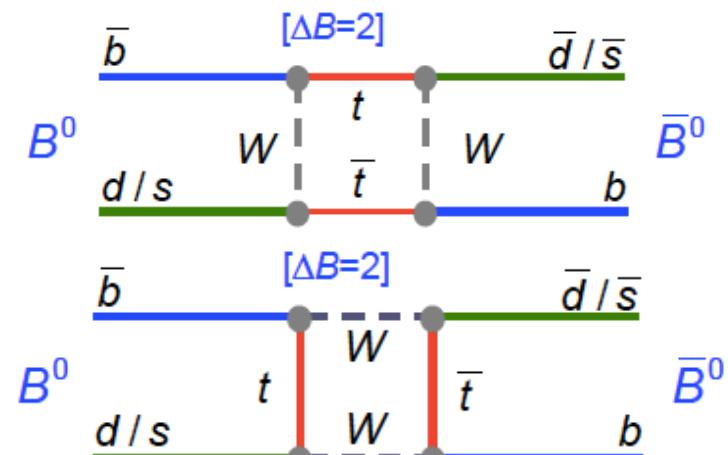
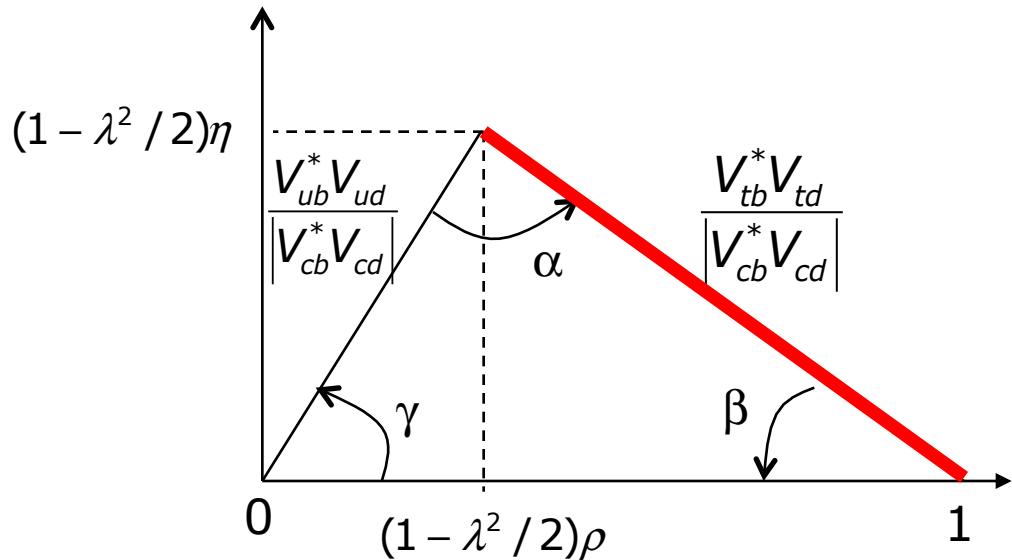
Perturbative QCD

$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2 \eta_B S(x_t) f_{B_q}^2 B_q |V_{tq} V_{tb}^*|^2 \quad (\text{for } q = d, s)$$

CKM Matrix Elements

Loop integral  
(top loop dominates)

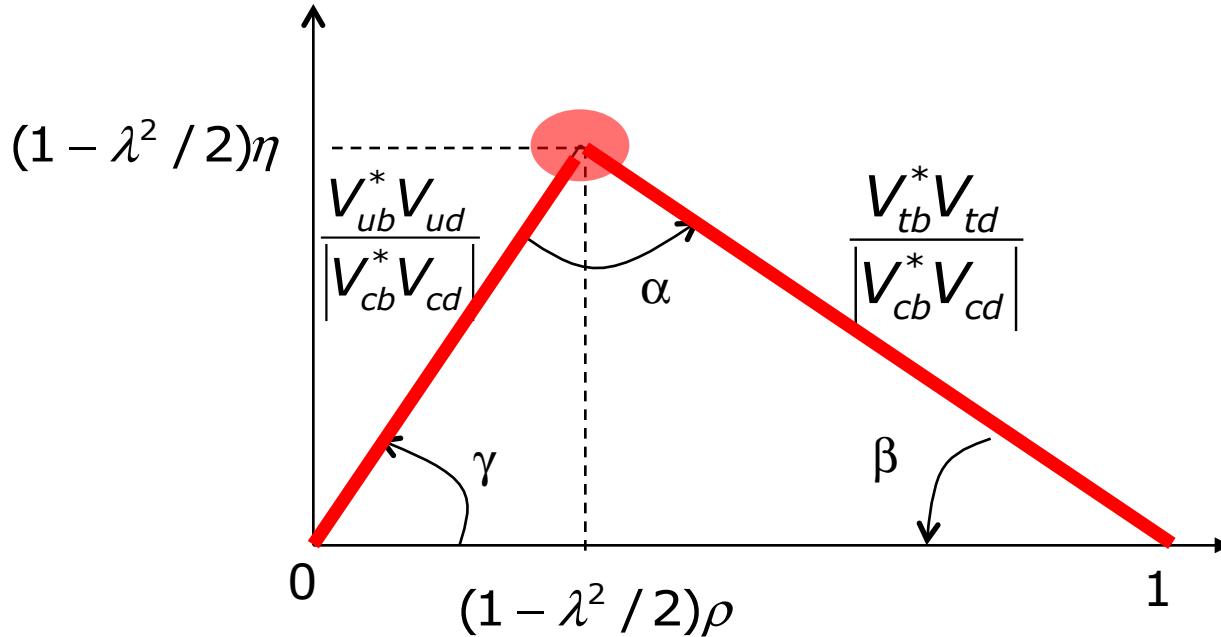
Non-perturbative QCD :  
dominant theoretical  
uncertainty



Oscillation frequency of  $B_d \sim |V_{td}|^2$

$$\overline{AB} = \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} = \sqrt{(1 - \rho)^2 + \eta^2} = \frac{1}{\lambda} \left| \frac{V_{td}}{V_{cb}} \right| \sim \frac{1}{\lambda} \left| \frac{V_{td}}{V_{ts}} \right|$$

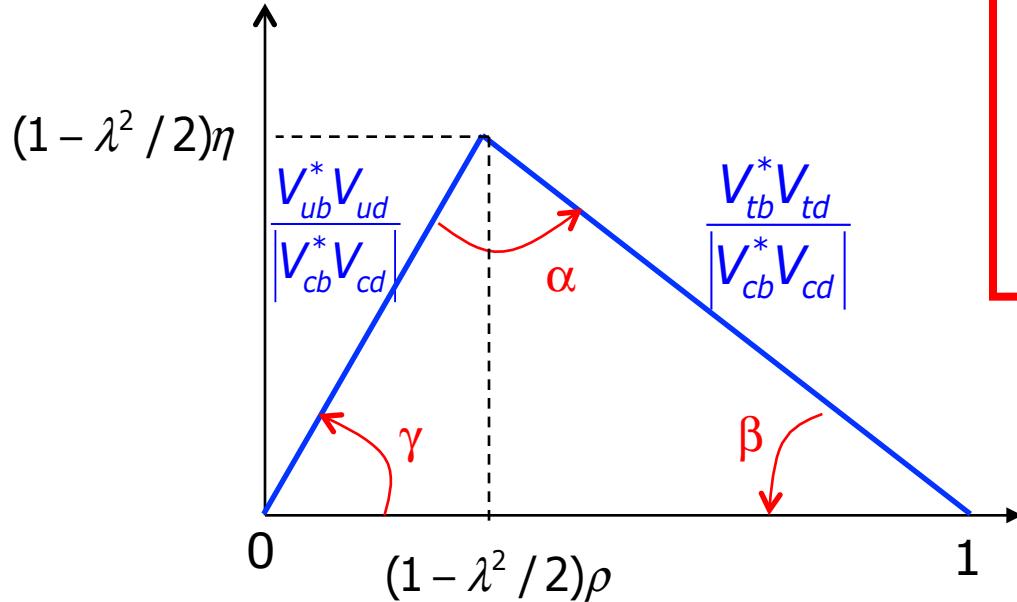
Circle around (1,0) in the  $\bar{\rho}-\bar{\eta}$  plane



The apex of the triangle can be determined  
 → The area is known

What about the angles ?

# Measurements of the angles



$$\beta = \arg\left(\frac{V_{td} V_{tb}^*}{|V_{cd} V_{cb}^*|}\right) = \text{atan}\left(\frac{(1 - \lambda^2 / 2)\eta}{1 - (1 - \lambda^2 / 2)\rho}\right)$$

$$\gamma = \arg\left(\frac{V_{ud} V_{ub}^*}{|V_{cd} V_{cb}^*|}\right) = \text{atan}\left(\frac{\eta}{\rho}\right)$$

$$\alpha + \beta + \gamma = \pi$$

CP violation !

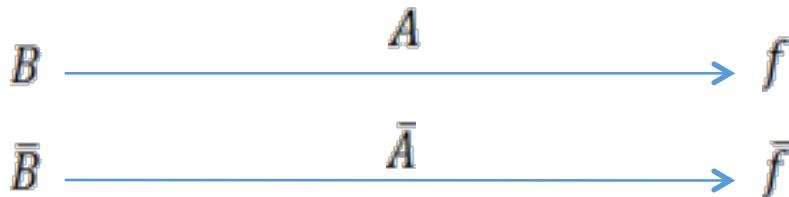
# Three types of CP violation

CP


$$A : B \rightarrow f$$
$$\bar{A} : \bar{B} \rightarrow \bar{f}$$

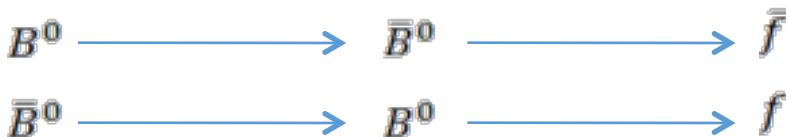
CP violation if  $|A|^2 \neq |\bar{A}|^2$

CP violation in decay (« direct CP ») :



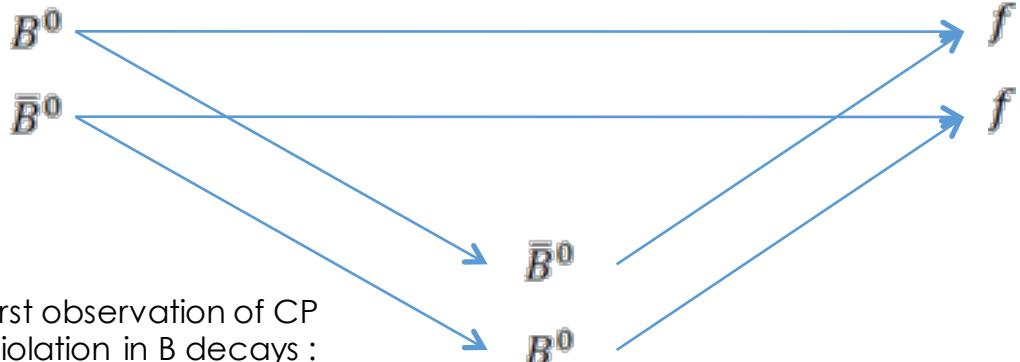
Only one existing for charged B

CP violation in mixing :



Not yet observed for B mesons.

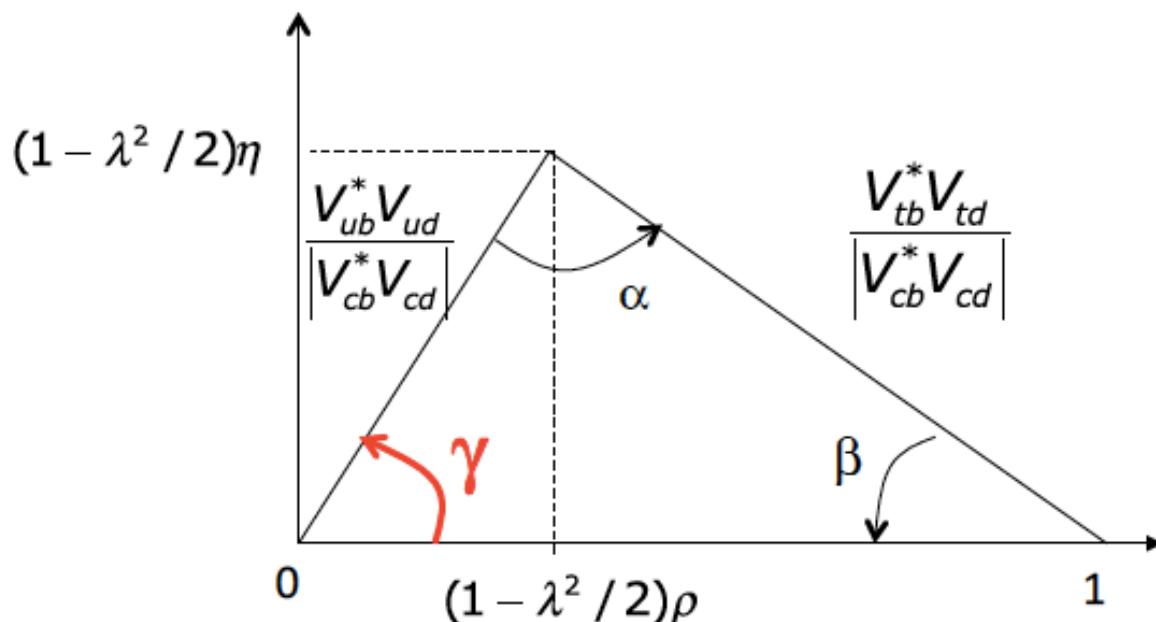
CP violation in the interference between mixing and decay :



First observation of CP violation in B decays :  
 $\sin(2\beta)$  measurement.

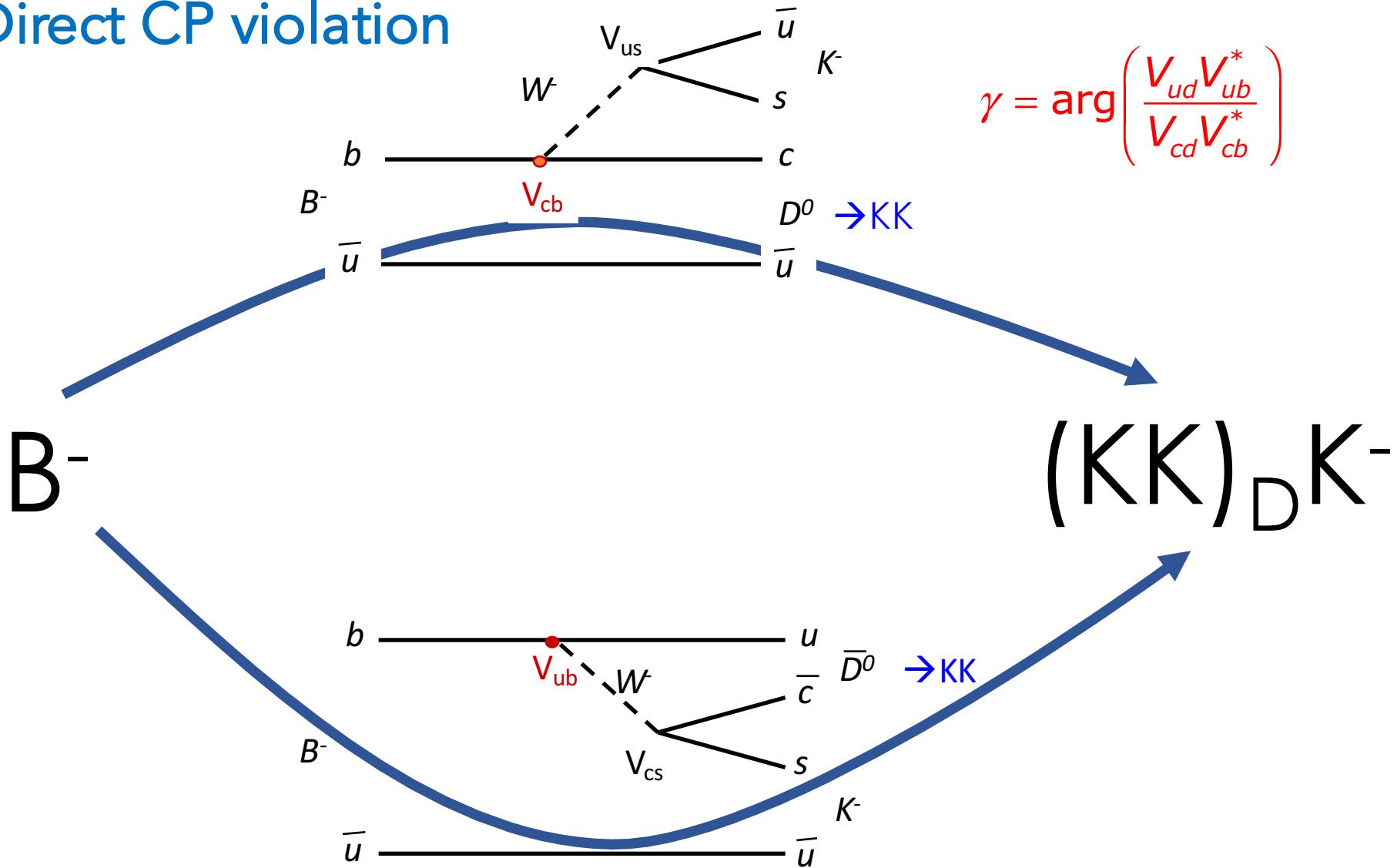
# an example of direct CP : γ measurement with DK

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



$$\gamma = \arg \left( \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$$

# Direct CP violation



Theory :

- tree diagrams

Experiment :

- a lot of modes
- enough information to extract all th. parameters from data



$$A(B^- \rightarrow D^0 \left( \rightarrow f_{CP} \right) K^-) = A_c$$

$$A(B^+ \rightarrow D^0 \left( \rightarrow f_{CP} \right) K^+) = A_c$$

$$A(B^- \rightarrow \bar{D}^0 \left( \rightarrow f_{CP} \right) K^-) = A_u e^{i(\delta_B - \gamma)}$$

$$A(B^+ \rightarrow D^0 \left( \rightarrow f_{CP} \right) K^+) = A_u e^{i(\delta_B + \gamma)}$$

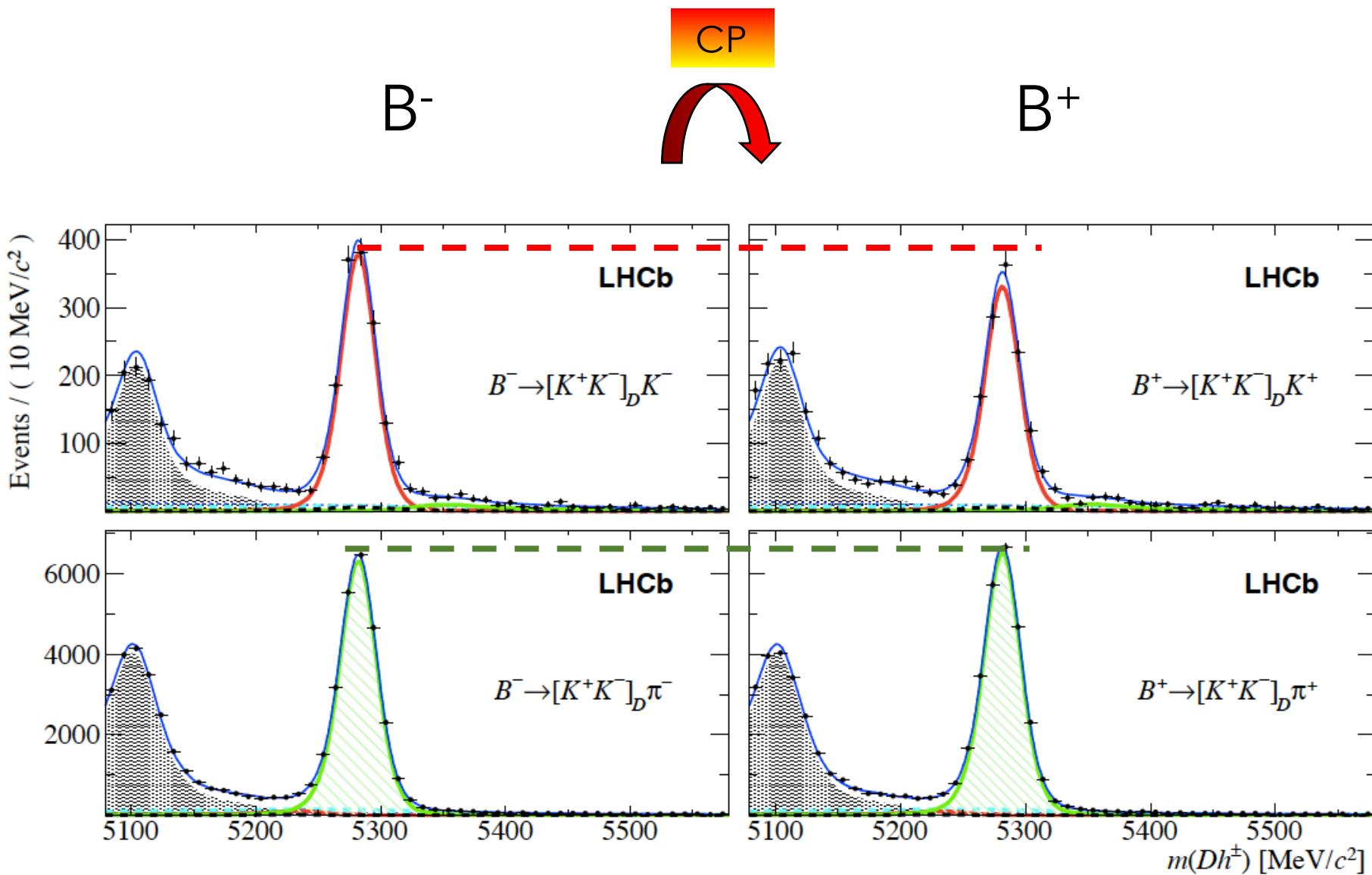
$\gamma$  : weak phase alters sign under CP

$\delta_B$  : strong phase : CP invariant

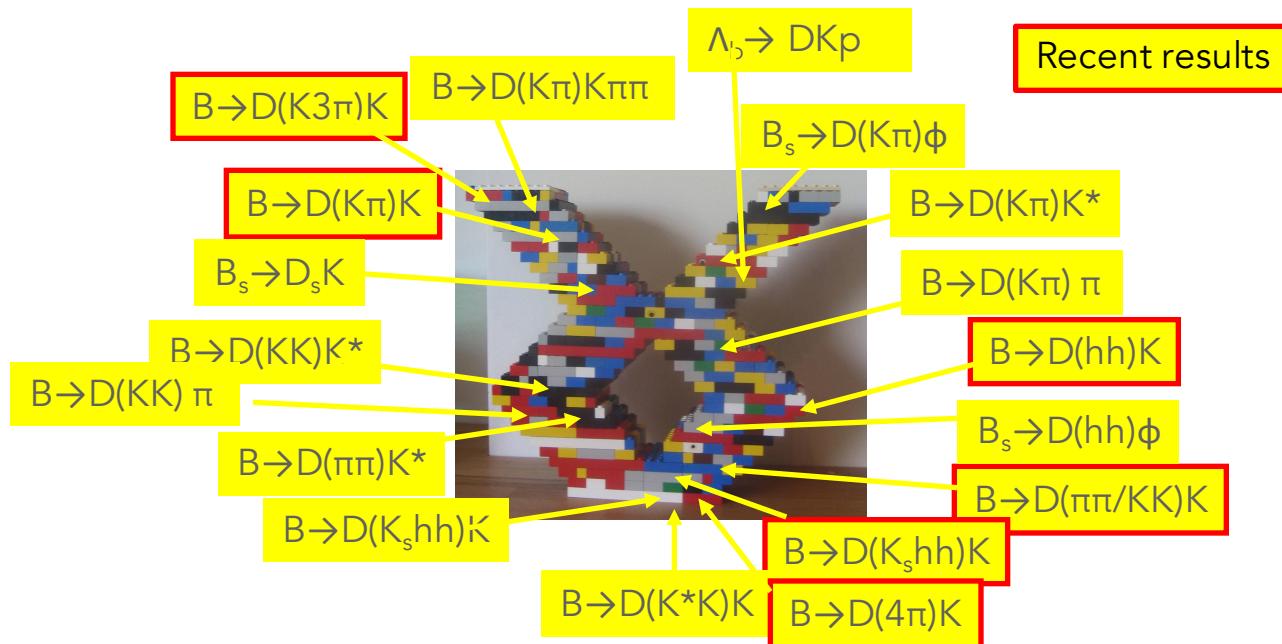
$$r_B = \frac{A_u}{A_c}$$

$$\Gamma(B^- \rightarrow f_{CP} K^-) = \left| A_c + A_u e^{i(\delta_B - \gamma)} \right|^2 = A_c^2 \times (1 + r_B^2 + 2r_B \cos(\delta_B - \gamma))$$

$$\Gamma(B^+ \rightarrow f_{CP} K^+) = \left| A_c + A_u e^{i(\delta_B + \gamma)} \right|^2 = A_c^2 \times (1 + r_B^2 + 2r_B \cos(\delta_B + \gamma))$$



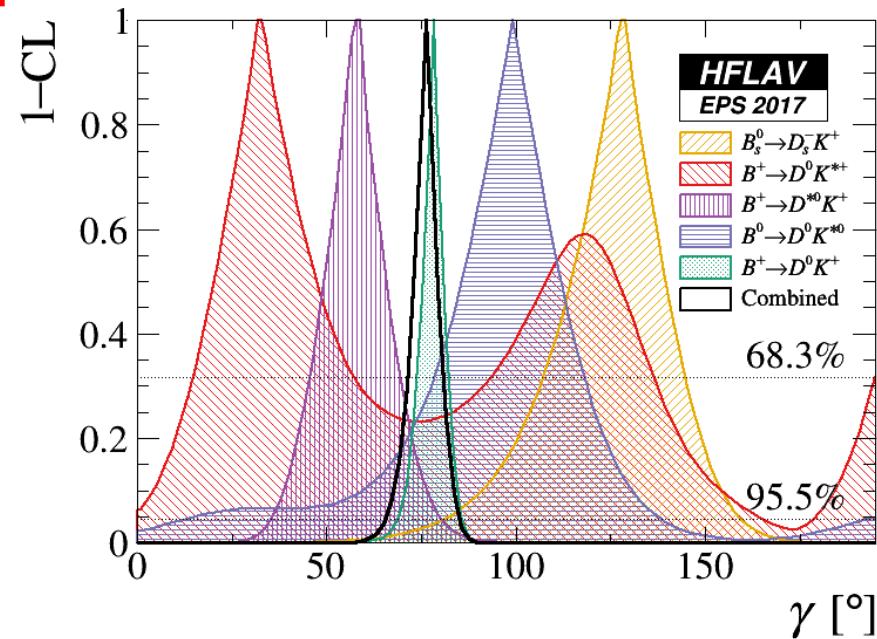
Many modes are used to obtain the best sensitivity on the  $\gamma$  angle



HFLAV

$$\gamma = (76.2^{+4.7}_{-5.0})^\circ$$

Dominated by LHCb



# CP violation in the mixing

Mass eigenstates

$$|M_L\rangle = p|M\rangle + q|\bar{M}\rangle$$

Flavour eigenstates

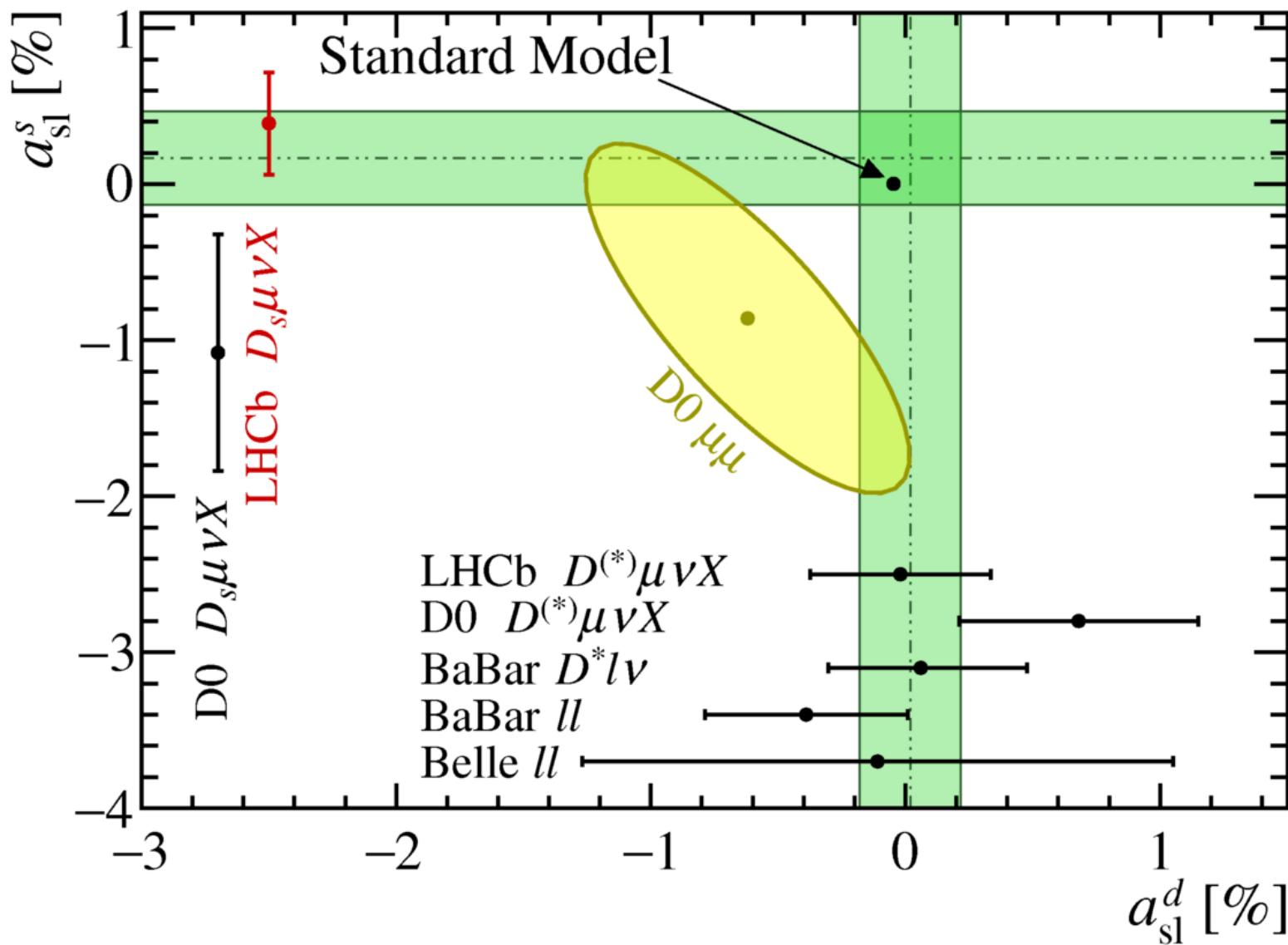
$$|M_H\rangle = p|M\rangle - q|\bar{M}\rangle$$

$$\left|\frac{q}{p}\right| \neq 1 \quad P(B \rightarrow \bar{B}) \neq P(\bar{B} \rightarrow B)$$

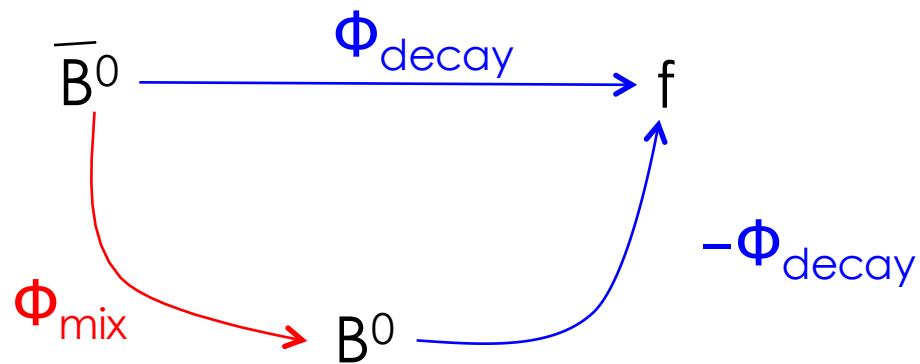
$$a_{sl}^q = \frac{P(\overline{B}_q \rightarrow B_q) - P(B_q \rightarrow \overline{B}_q)}{P(\overline{B}_q \rightarrow B_q) + P(B_q \rightarrow \overline{B}_q)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx \frac{\Delta\Gamma_q}{\Delta m_q} \tan\phi_q^{12}$$

So far only observed in the K system

Expected to be small in the SM ;  $\sim -5 \cdot 10^{-4}$  ( $B_d$ ) and  $2 \cdot 10^{-5}$  ( $B_s$ )

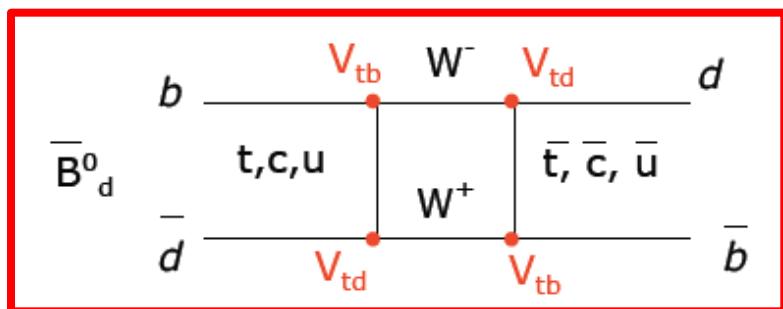


# CP violation in the interference between mixing and decay

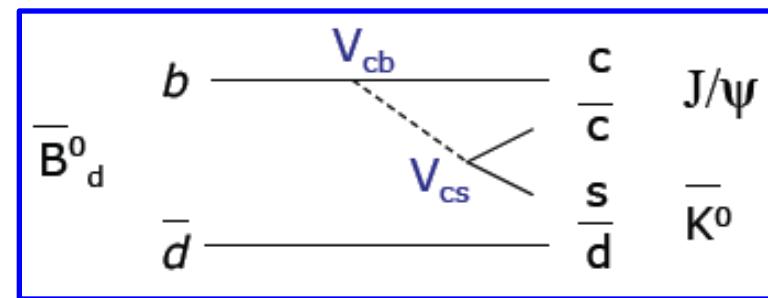


$$\Phi_d = \Phi_{\text{mix}} - 2 \Phi_{\text{decay}}$$

Mixing

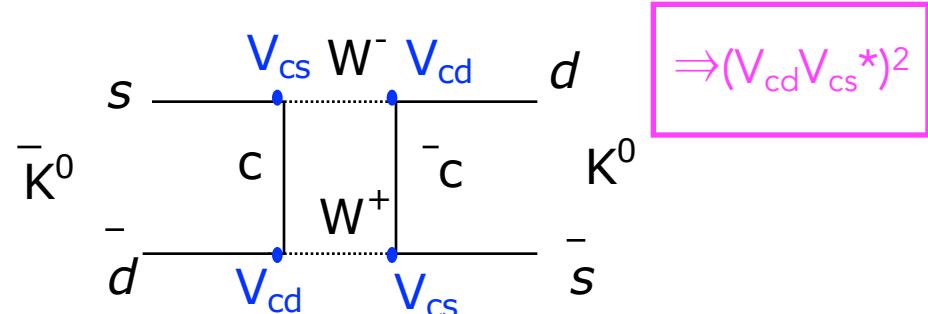
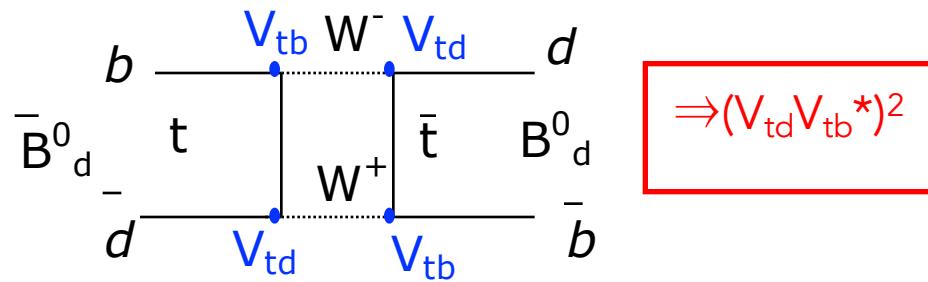
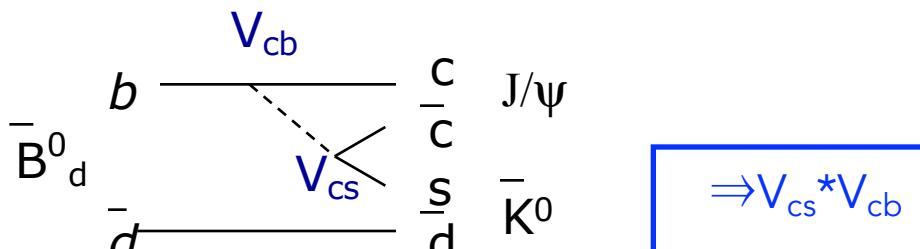


Decay



# Measurement of $\sin(2\beta)$ with $B^0 \rightarrow J/\Psi K^0$

CP violation : difference between  $B^0$  and  $\bar{B}^0$



$$\beta = \text{Arg} \left( \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)$$

$$\left( \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} \right);$$

$$\left( \frac{V_{cd}^* V_{cb}}{V_{td}^* V_{tb}} \frac{V_{tb}^* V_{td}}{V_{cd} V_{cb}^*} \frac{V_{cs}^* V_{cs}}{V_{cs} V_{cs}^*} \right)$$

$$\text{Im} \left( z \times \frac{1}{z^*} \right) = \sin(2\text{Arg}(z))$$

Experimentally clean (tree diagram, second order diagram (penguin) has the same phase at first order in  $\lambda$ )

What do we expect to see ?

$$P(B^0 \rightarrow f_{CP}, \Delta t) \propto (1 - \sin 2\beta \sin \Delta t)$$

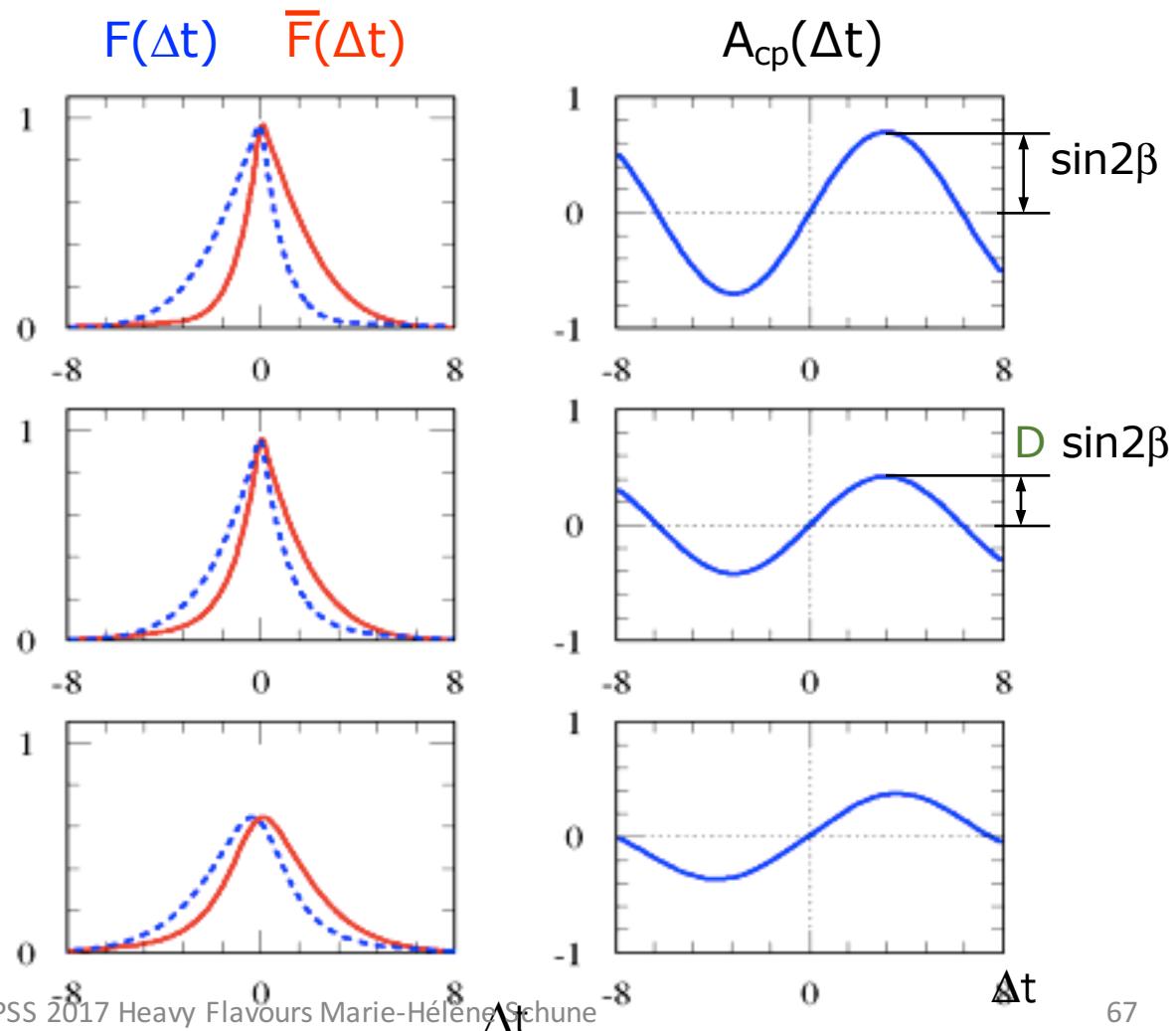
$$P(\overline{B^0} \rightarrow f_{CP}, \Delta t) \propto (1 + \sin 2\beta \sin \Delta t)$$

$$A_{CP}(\Delta t) = \frac{P(\overline{B^0} \rightarrow f_{CP}, \Delta t) - P(B^0 \rightarrow f_{CP}, \Delta t)}{P(\overline{B^0} \rightarrow f_{CP}, \Delta t) + P(B^0 \rightarrow f_{CP}, \Delta t)} = \sin 2\beta \sin \Delta t$$

Everything perfect

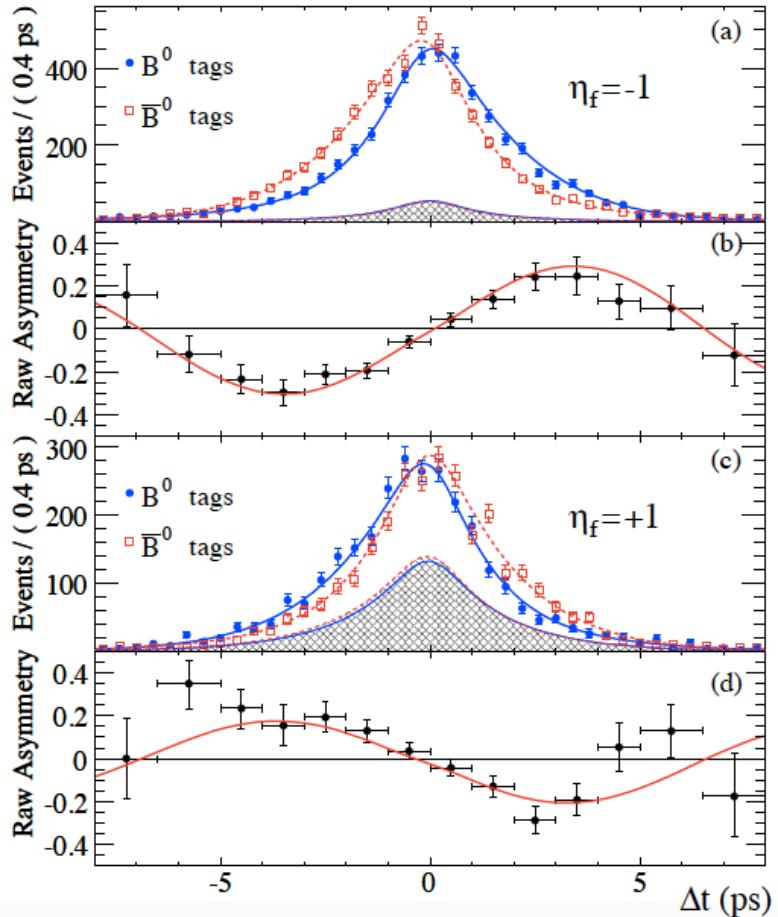
Add tag mistakes  
*Dilution:*  $D=1-2w$

Add imperfect  
 $\Delta t$  resolution



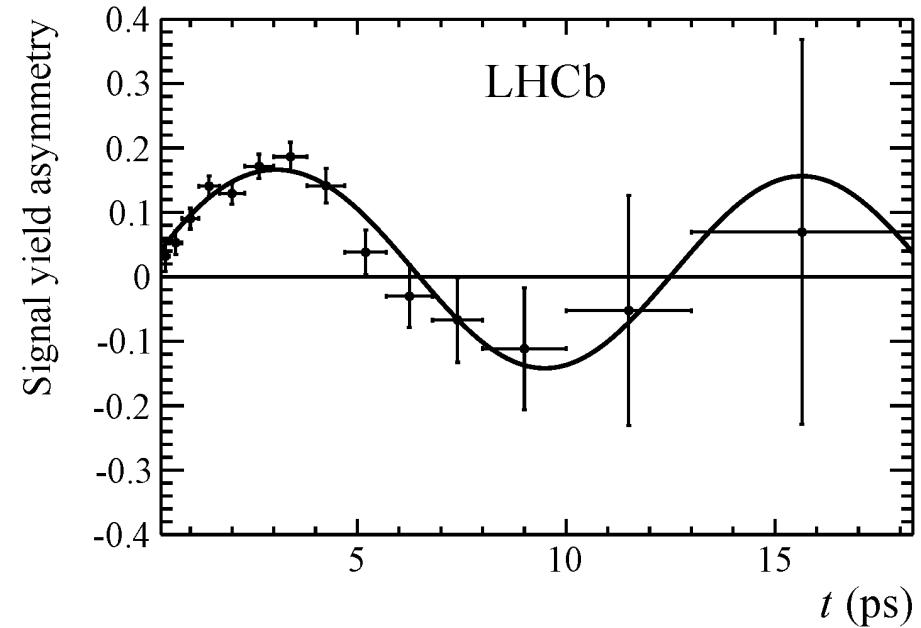
$$a_{f_{CP}}(t) = \frac{\text{Prob}(B^0(t) \rightarrow f_{CP}) - \text{Prob}(\overline{B^0}(t) \rightarrow f_{CP})}{\text{Prob}(B^0(t) \rightarrow f_{CP}) + \text{Prob}(\overline{B^0}(t) \rightarrow f_{CP})} = \sin(2\beta) \sin(\Delta mt)$$

B-factories



$$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$$

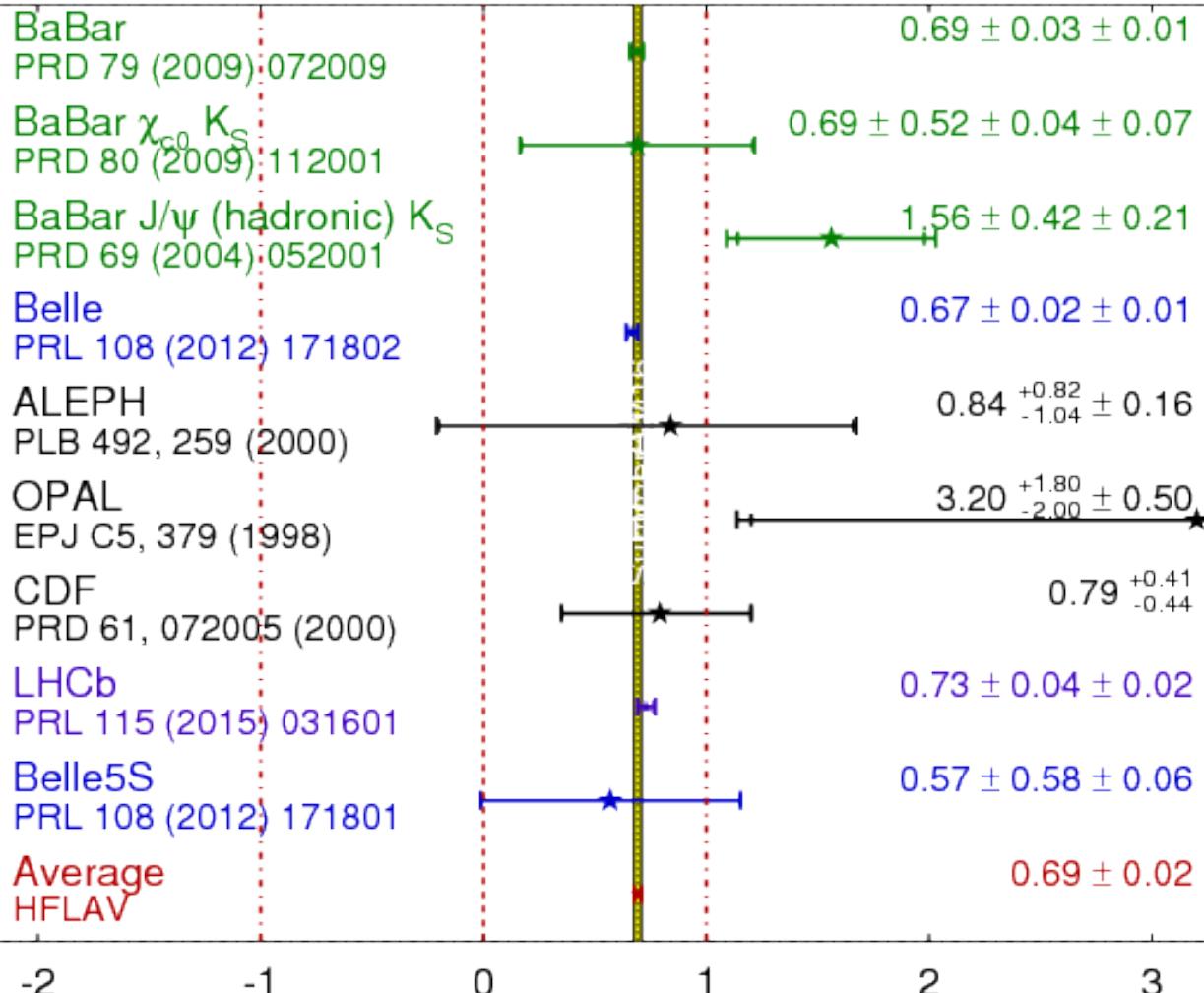
[Phys. Rev. Lett. 115, 031601 \(2015\)](#)



BaBar Phys.Rev.D79:072009,2009

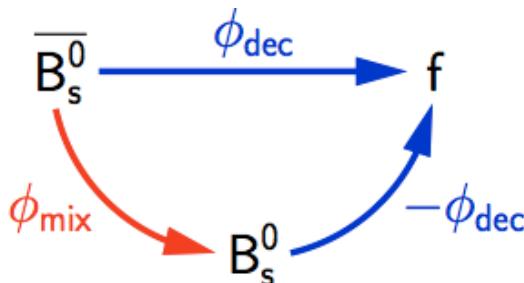
# $\sin(2\beta) \equiv \sin(2\phi_1)$

**HFLAV**  
Summer 2016



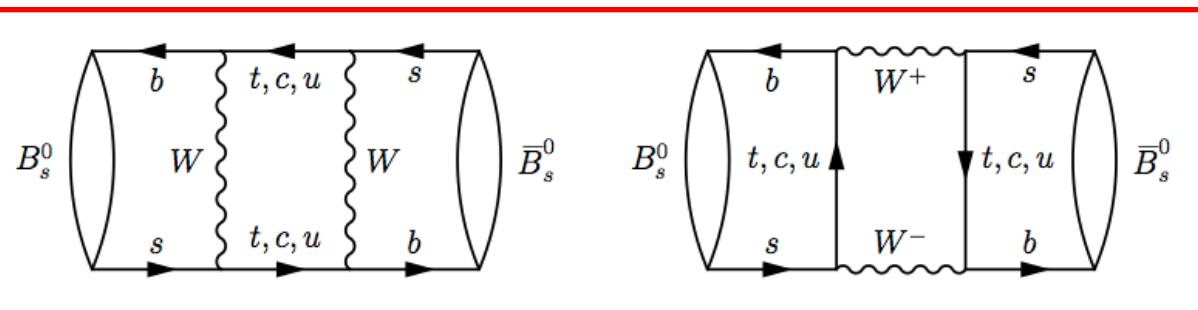
3 % precision !

At LHC the equivalent of  $B^0 \rightarrow J/\psi K^0$  is  $B_s \rightarrow J/\psi \phi$

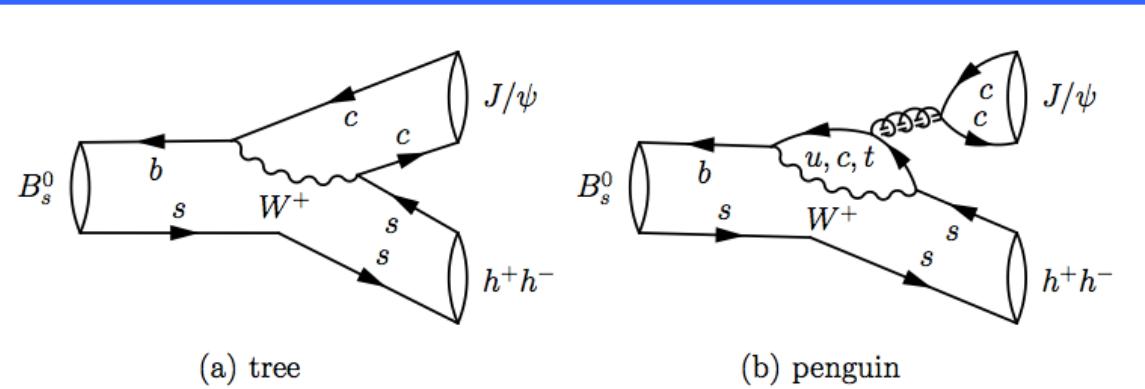


$$\phi_s = \phi_{\text{mix}} - 2 \phi_{\text{dec}}$$

$\Phi_s$  is the equivalent to  $2\beta$



Mixing



Decay

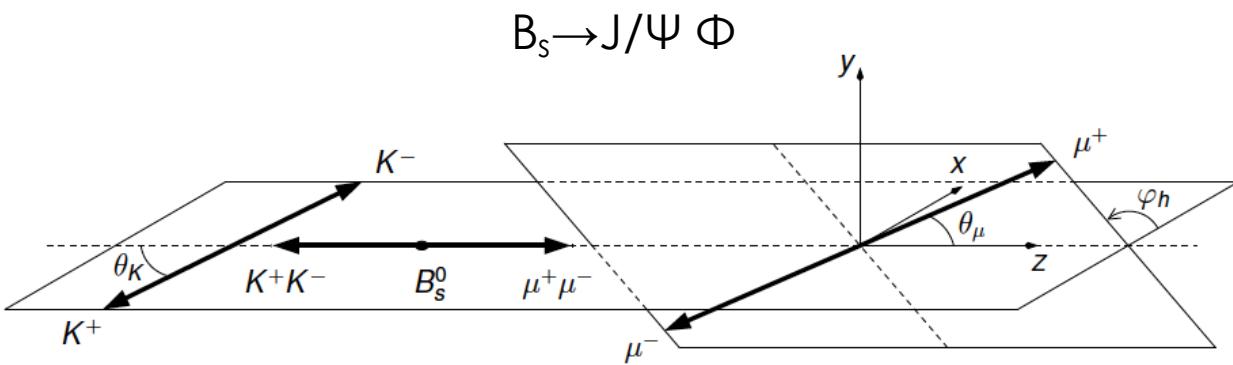
$$\Phi_s = -2 \beta_s$$

$$\beta_s = \arg(-V_{ts} V_{tb}^*) / (V_{cs} V_{cb}^*)$$

$\text{PS} \rightarrow \text{VV}$ , admixture of **CP-odd** and **CP-even** states, measure also  $\Delta\Gamma_s$ .

$\Rightarrow$  3 “P-wave” amplitudes of KK system ( $A_0, A_{\text{perp}}, A_{\text{para}}$ )

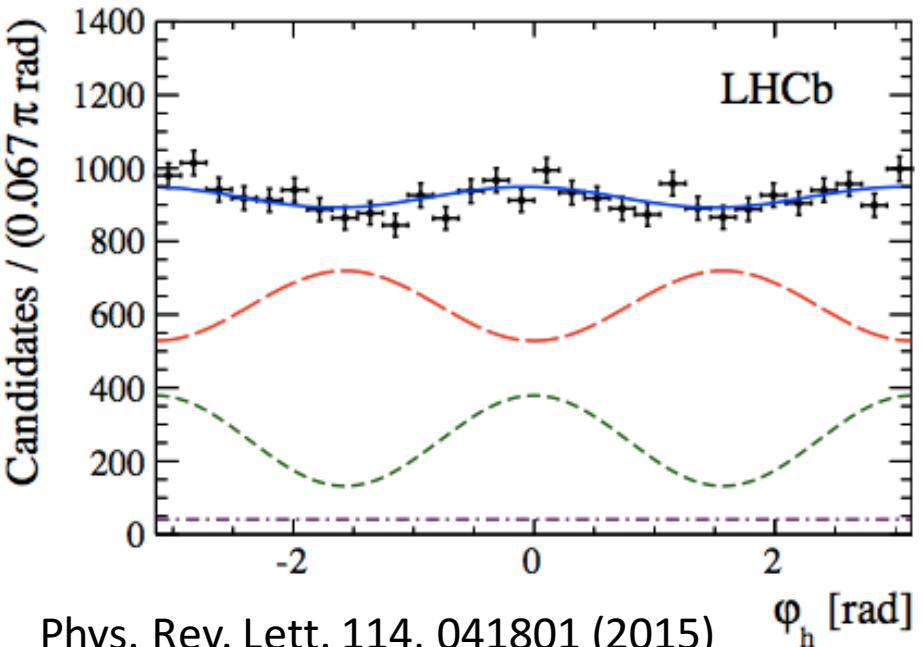
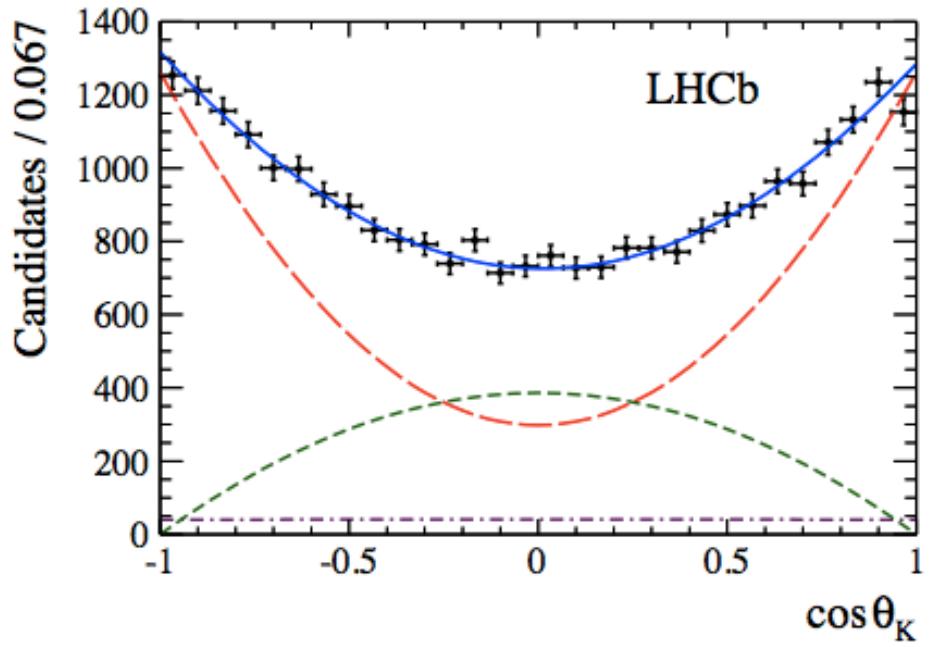
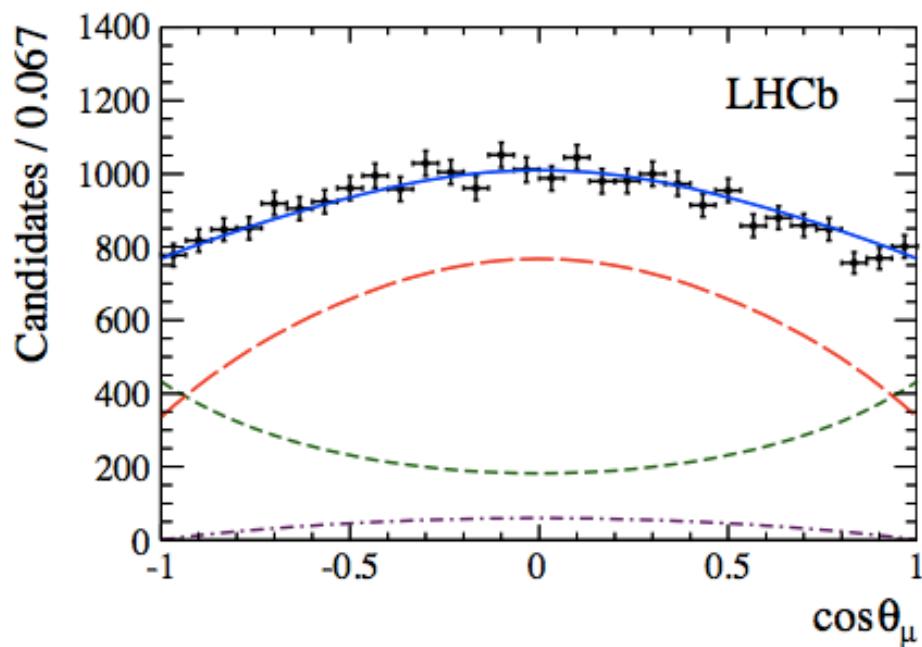
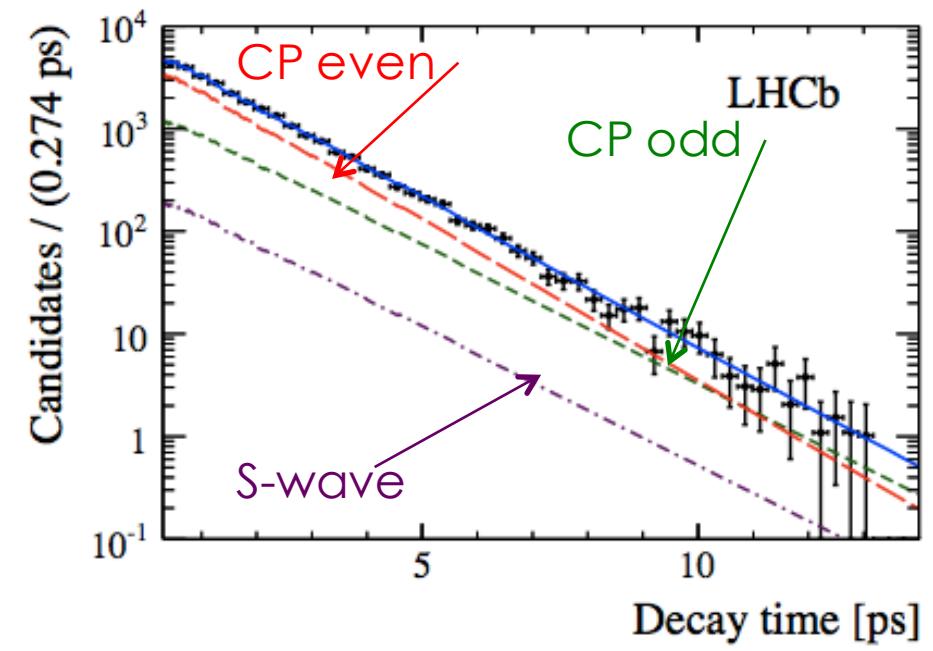
- o 1 “S-wave” amplitude ( $A_s$ )
- o 10 terms with all the interferences
- o  $\varphi_s, \Delta\Gamma_s, \Gamma_s$



+  $B_s \rightarrow J/\Psi f_0(\pi\pi)$  simpler analysis ( $\text{PS} \rightarrow \text{V PS}$ )

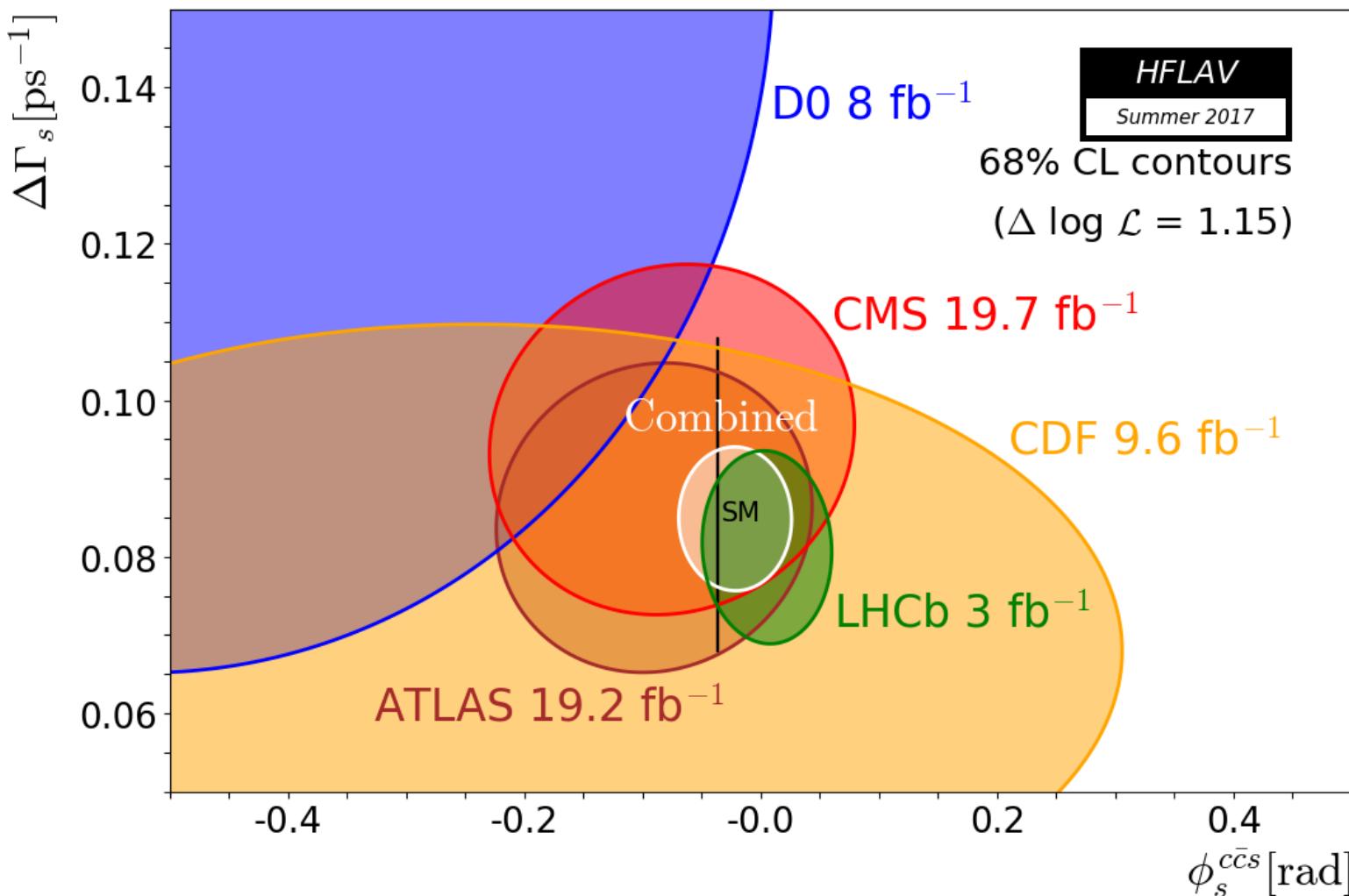
Experimentally :

- o Relatively large branching ratio.
- o Easy to trigger on muons from  $J/\Psi \rightarrow \mu^+\mu^-$ .



HFLAV

SM :  $\Phi_s = -0.0370 \pm 0.0006$  rad  
(prediction from a fit using other measurements)

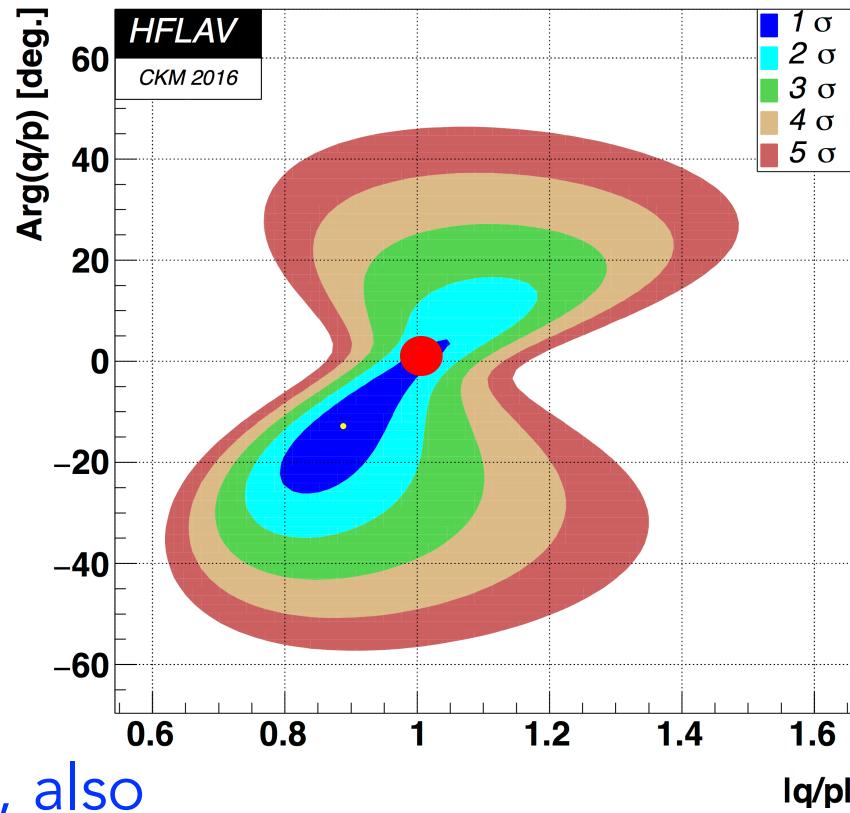


CP violation has been observed for K mesons and B hadrons

What about charm ?

Not yet observed :

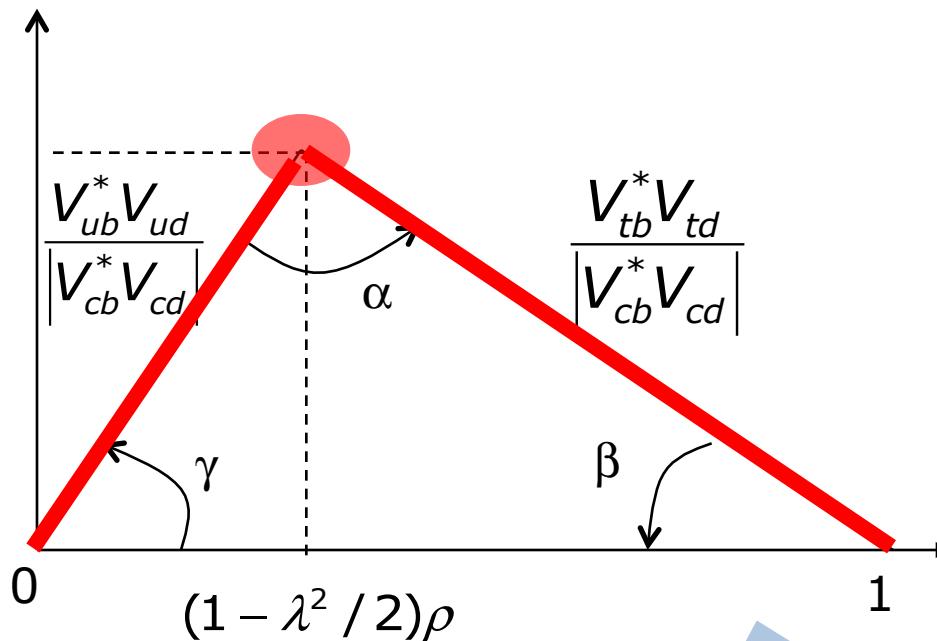
measurements  
consistent with the  
point (1,0) ●



NB : expected to be tiny in SM, also  
a good place to search for NP

|S

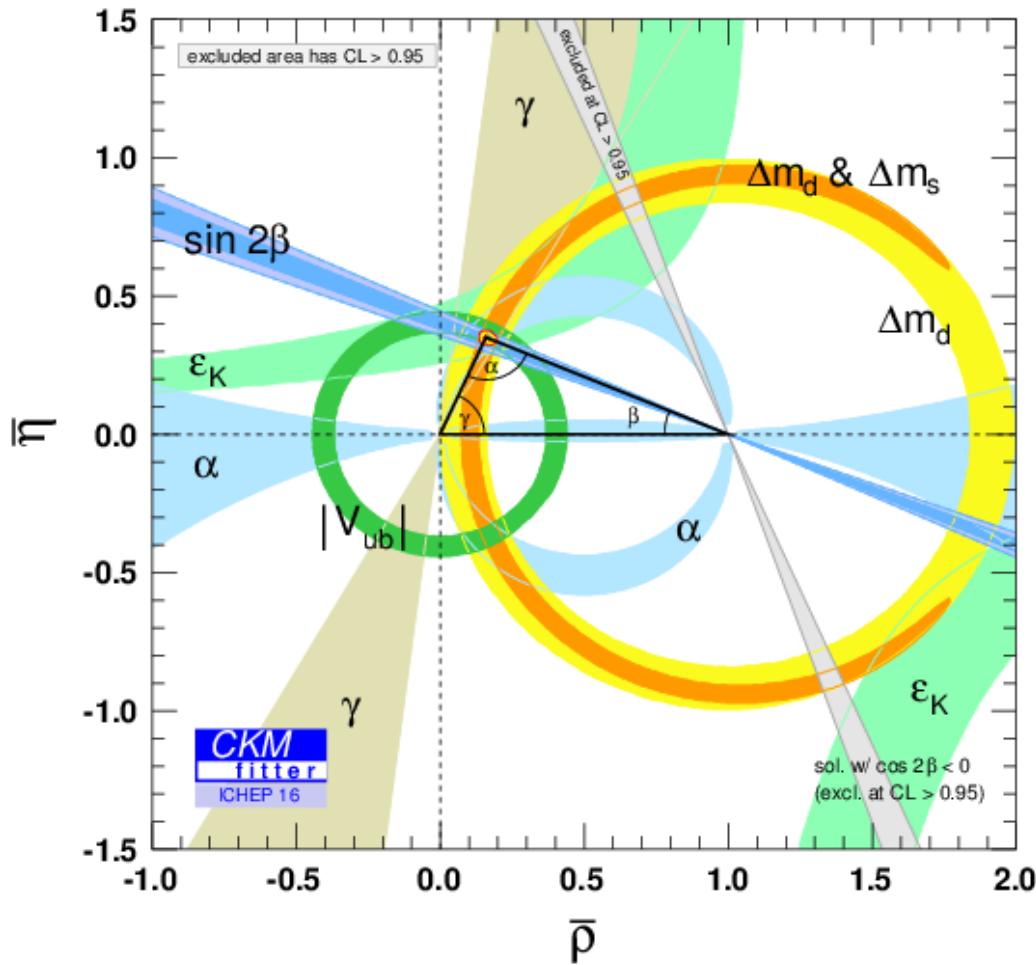
$$(1 - \lambda^2 / 2)\eta$$



in  
agreement  
with

$$(1 - \lambda^2 / 2)\eta$$

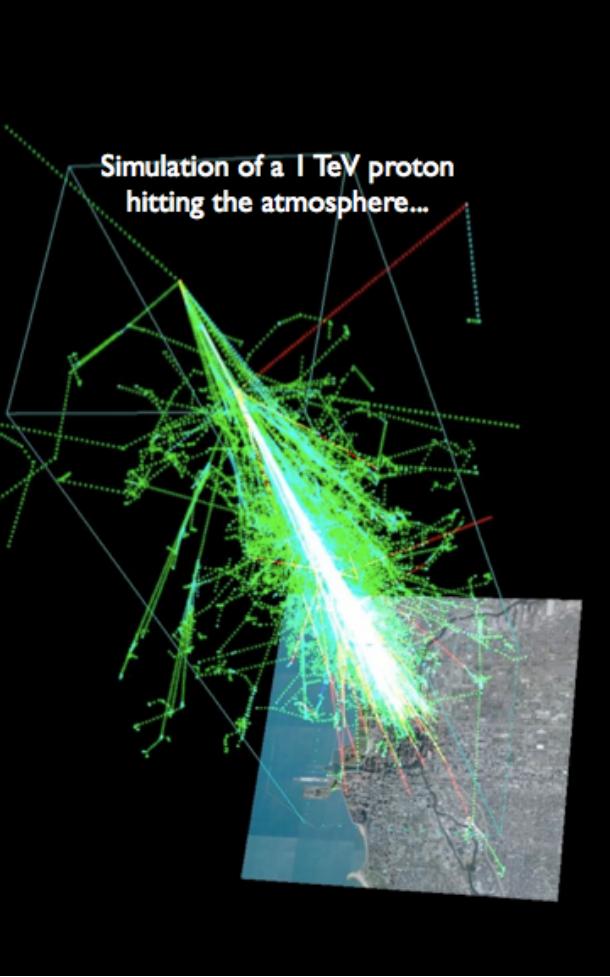
?



<http://ckmfitter.in2p3.fr/>

See also  
<http://www.utfit.org/UTfit/>

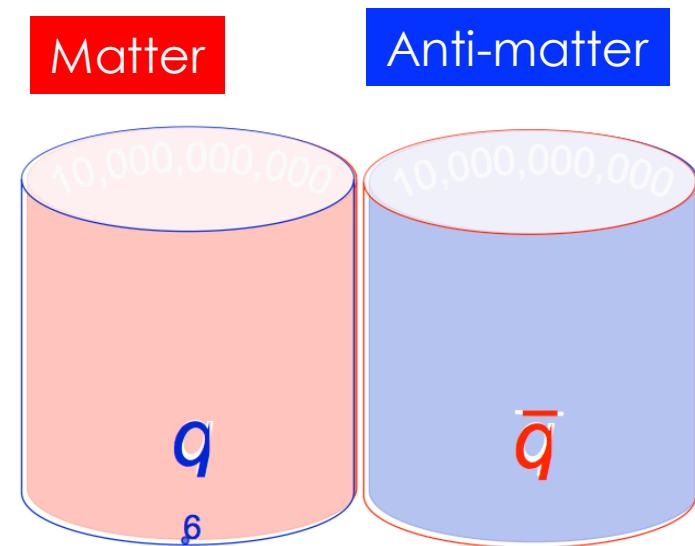
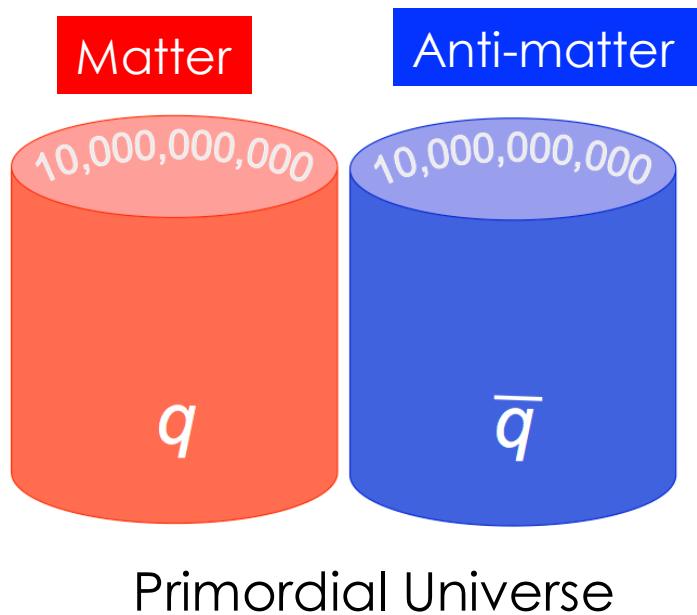
- The CKM matrix has a clear (and not explained !) hierarchy
- With the current precision, CP violation well described by the CKM mechanism



- Anti-matter in cosmic rays
- No sign of light emission (anti-galaxy ...)
- No sign of anti-nuclei (anti-He<sup>4</sup> ... )  
Searches on-going



# Anti-matter in the Universe and Big Bang

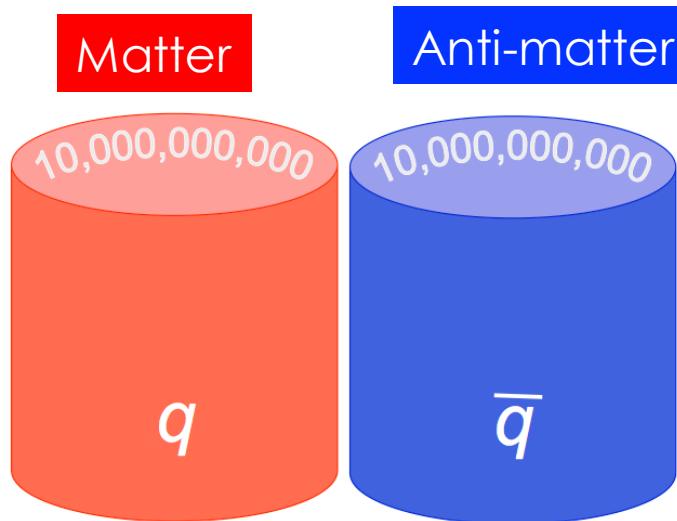


$$\frac{n(\text{baryon}) - n(\text{antibaryon})}{n_\gamma} \sim 6 \cdot 10^{-10}$$

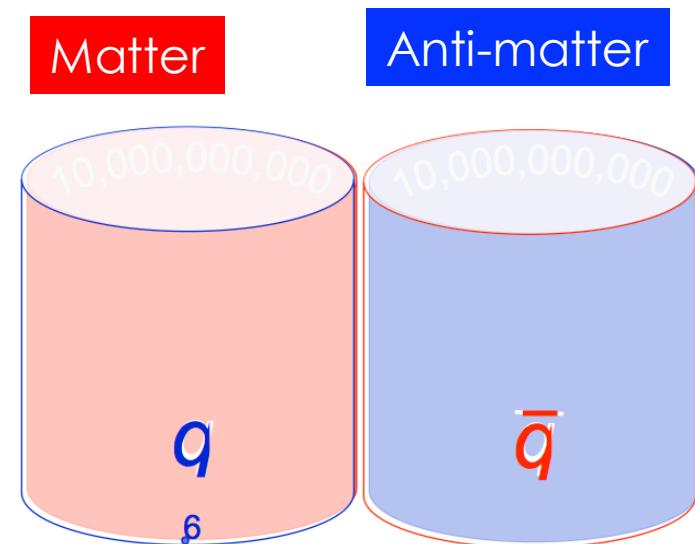
The 3 Sakharov conditions(1967)

1. Baryonic number violation:  $X \rightarrow p e^-$
2. C and CP symmetries violation:  $\Gamma(X \rightarrow p e^-) \neq \Gamma(\bar{X} \rightarrow \bar{p} e^+)$
3. To be out of equilibrium:  $\Gamma(X \rightarrow p e^-) \neq \Gamma(p e^- \rightarrow X)$

# Anti-matter in the Universe and Big Bang



Primordial Universe



Today

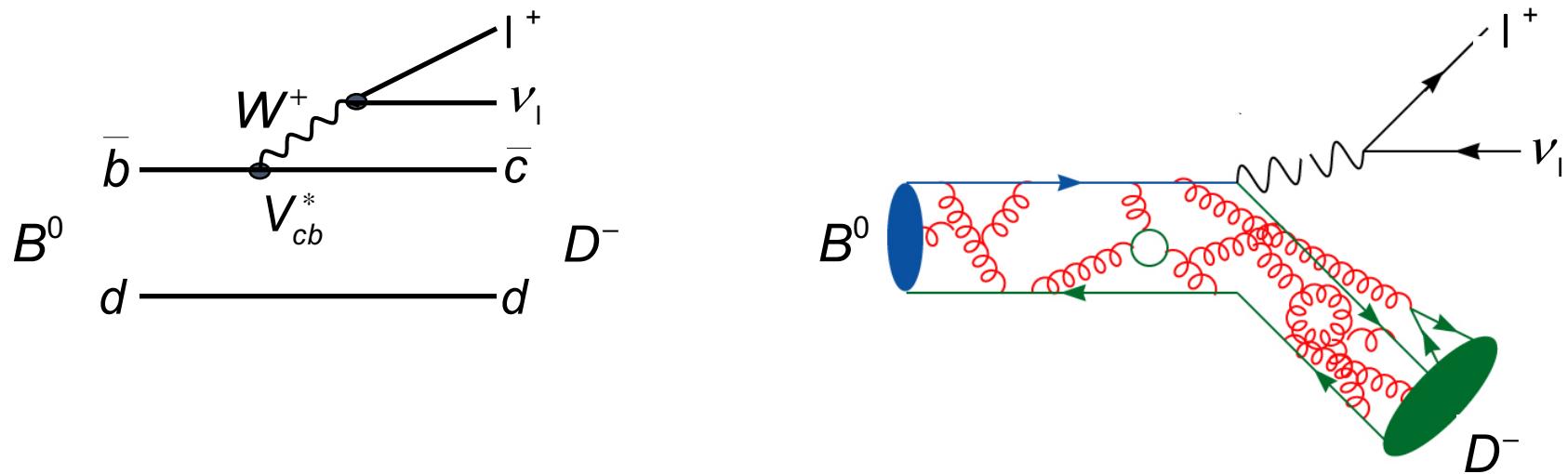
$$\frac{n(\text{baryon}) - n(\text{antibaryon})}{n_\gamma} \sim 6 \cdot 10^{-10}$$

## The 3 Sakharov conditions(1967)

1. Baryonic number non-conservation
2. C and CP violation
3. To be out of equilibrium. (Temperature)

But the CP violation phase of the SM is orders of magnitude too small

# What about QCD ?

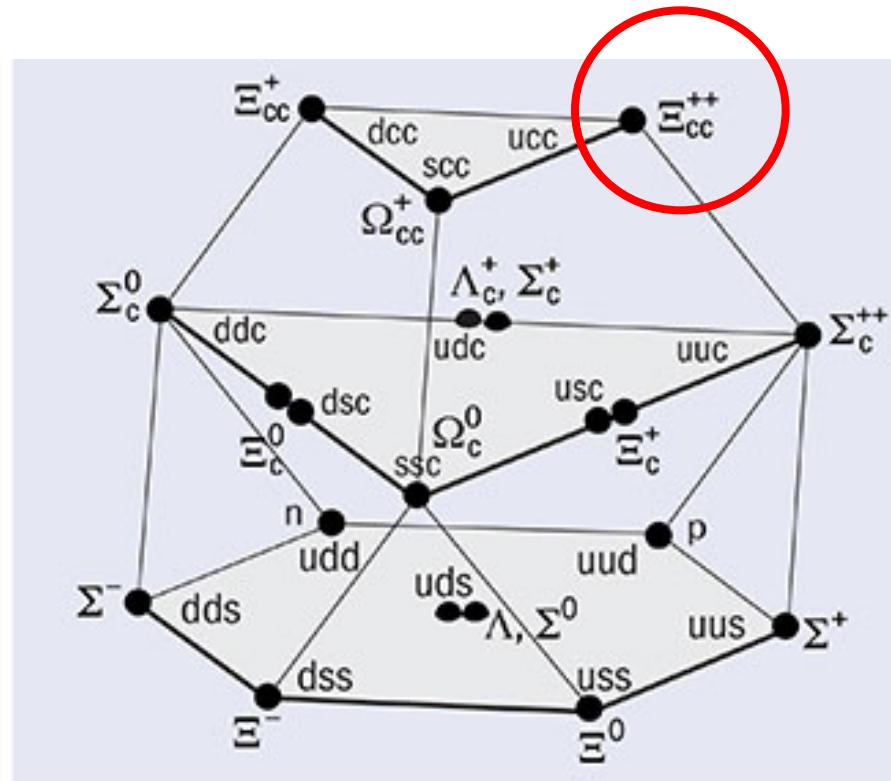
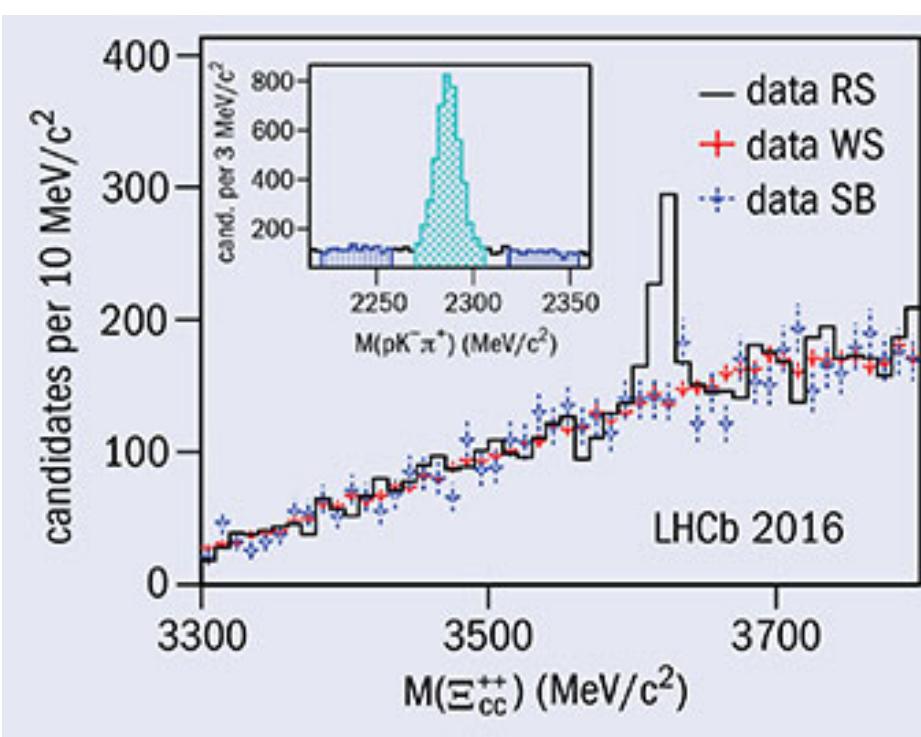


We need to better understand QCD for a fully efficient extraction of CKM parameters  
... and/or to find experimental workarounds to avoid these related theoretical uncertainties

But b-hadrons studies are also a tool to study QCD

# Observation of new baryons

$$\Xi^{++}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \quad (\text{ccu}) \text{ baryon}$$



First baryon containing two heavy (c or b) quarks  
⇒ very interesting tool for testing QCD

# The quarks model Gell-Man and Zweig (1964)

Volume 8, number 3

PHYSICS LETTERS

1 February 1964

AN  $SU_3$  MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING



## A SCHEMATIC MODEL OF BARYONS AND MESONS \*

M. GELL-MANN

*California Institute of Technology, Pasadena, California*

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber  $n_t - n_{\bar{t}}$  would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin  $\frac{1}{2}$  and  $z = -1$ , so that the four particles  $d^-$ ,  $s^-$ ,  $u^0$  and  $b^0$  exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon  $b$  if we assign to the triplet  $t$  the following properties: spin  $\frac{1}{2}$ ,  $z = -\frac{1}{3}$ , and baryon number  $\frac{1}{3}$ . We then refer to the members  $u^{\frac{2}{3}}$ ,  $d^{-\frac{1}{3}}$ , and  $s^{-\frac{1}{3}}$  of the triplet as "quarks" 6)  $q$  and the members of the anti-triplet as anti-quarks  $\bar{q}$ . Baryons can now be constructed from quarks by using the combinations  $(q q q)$ ,  $(q q \bar{q} \bar{q})$ , etc., while mesons are made out of  $(q \bar{q})$ ,  $(q q \bar{q} \bar{q})$ , etc. It is assuming that the lowest baryon configuration  $(q q q)$  gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration  $(q \bar{q})$  similarly gives just 1 and 8.

## Baryons, mesons... and more ?

G. Zweig \*)  
CERN - Geneva

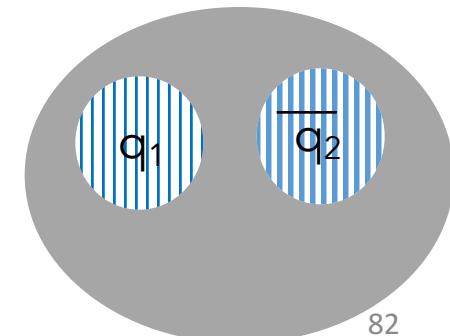
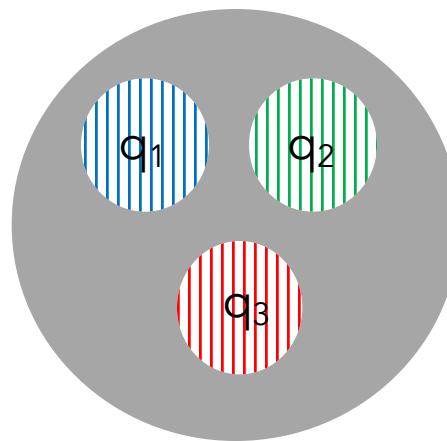
## ABSTRACT

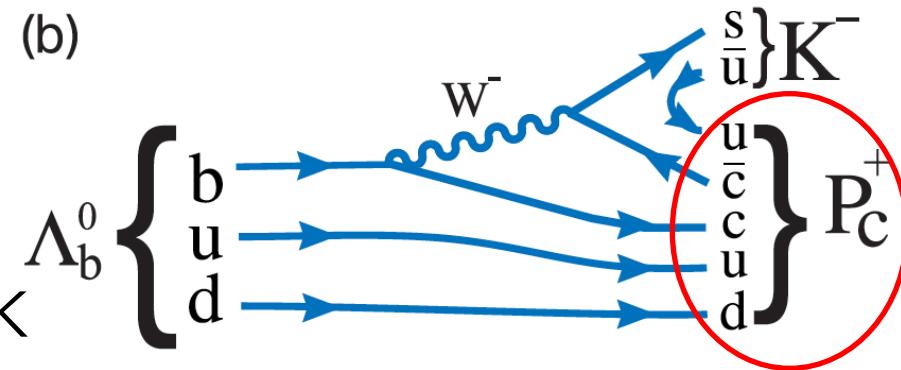
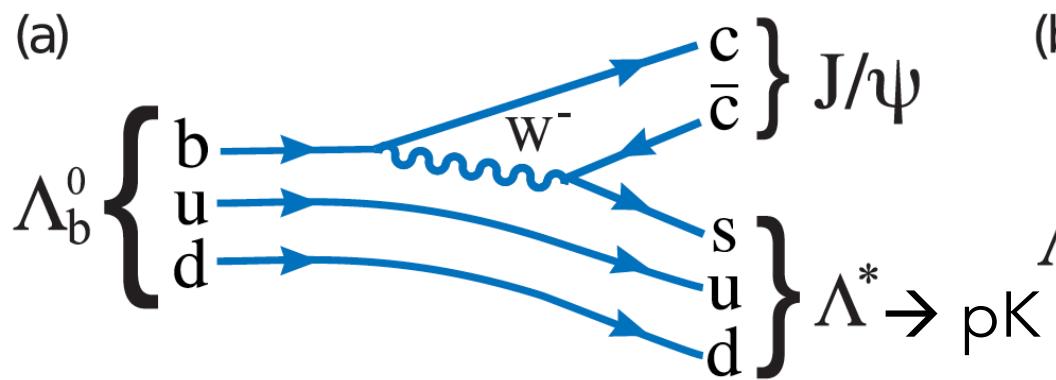
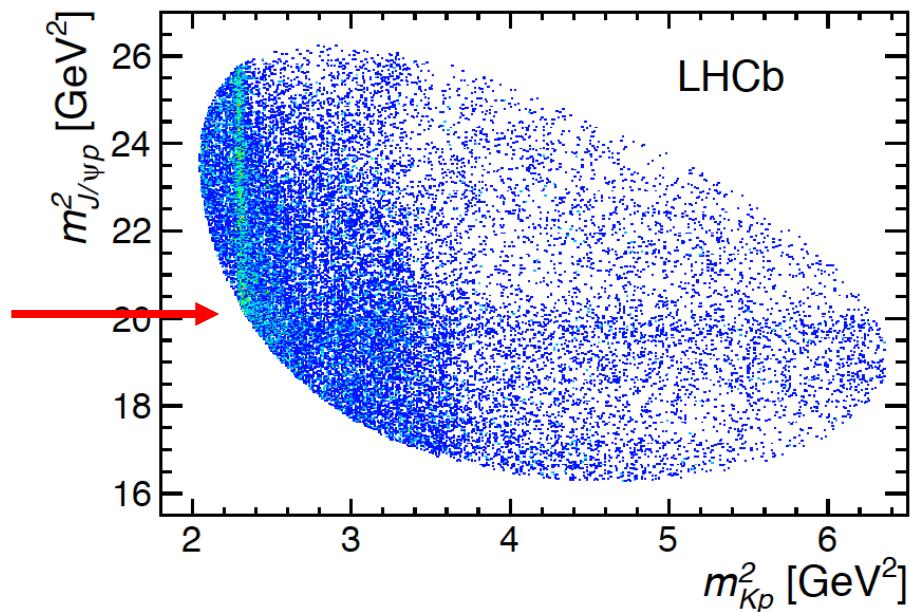
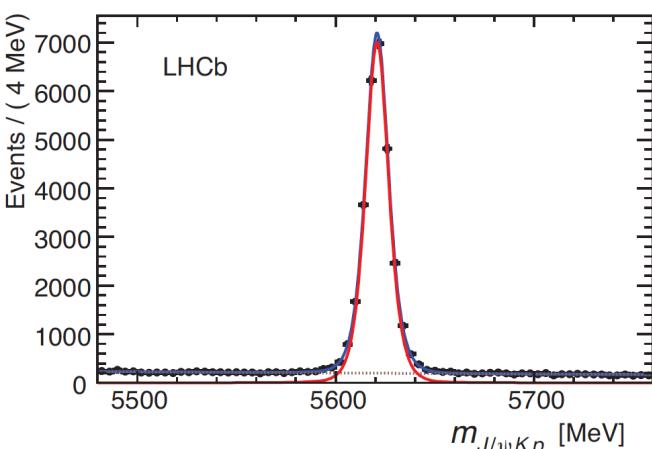


Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number  $\frac{1}{3}$  and is consequently fractionally charged.  $SU_3$  (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The break-

baryons :  $qqqq\bar{q}$

mesons :  $q\bar{q} q\bar{q}$



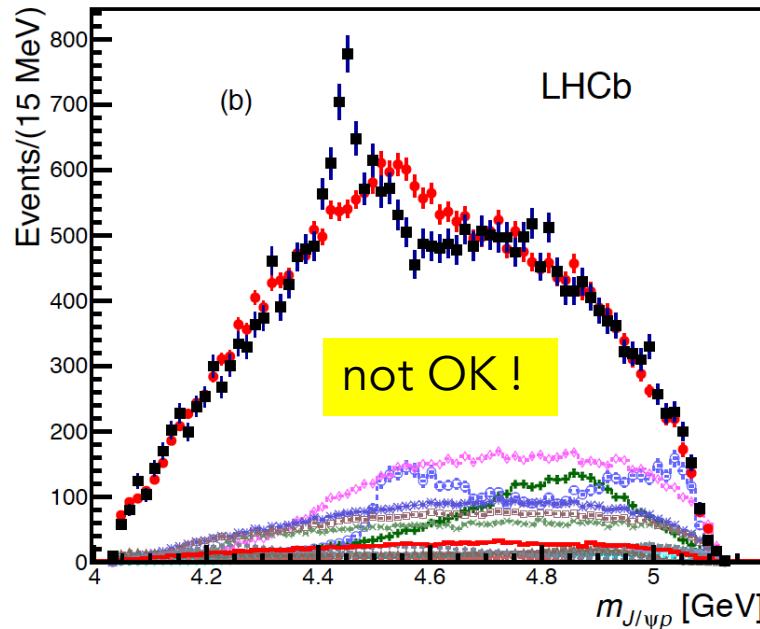
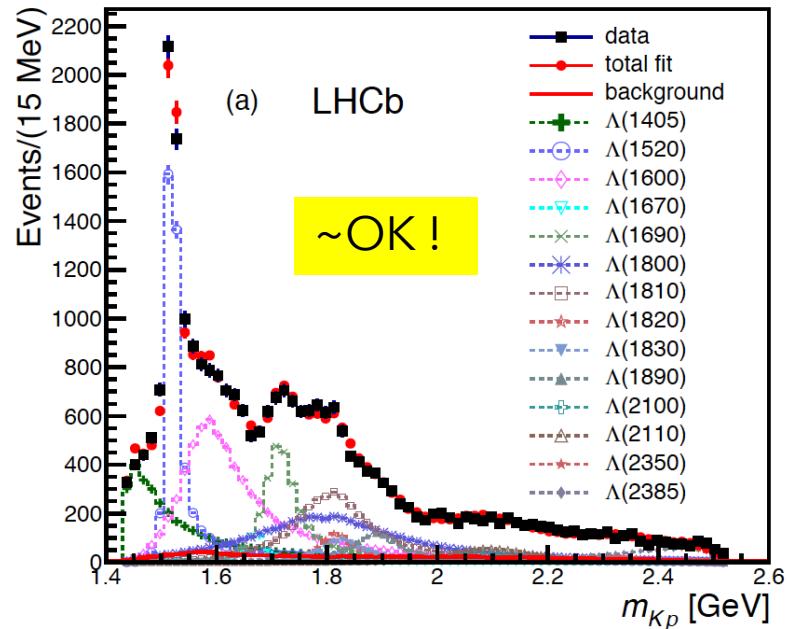
$\Lambda_b \rightarrow J/\psi p K$  decays

A pentaquark ?

short-lived  $\sim 10^{-23}$  s resonances :  
mass peaks  
angular distributions (unique  $J^P$  quantum numbers)

Analysis with all what is known :

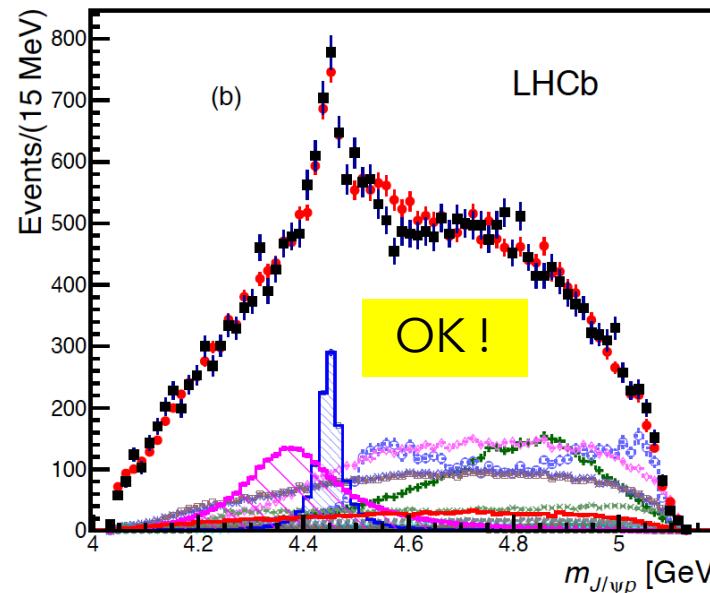
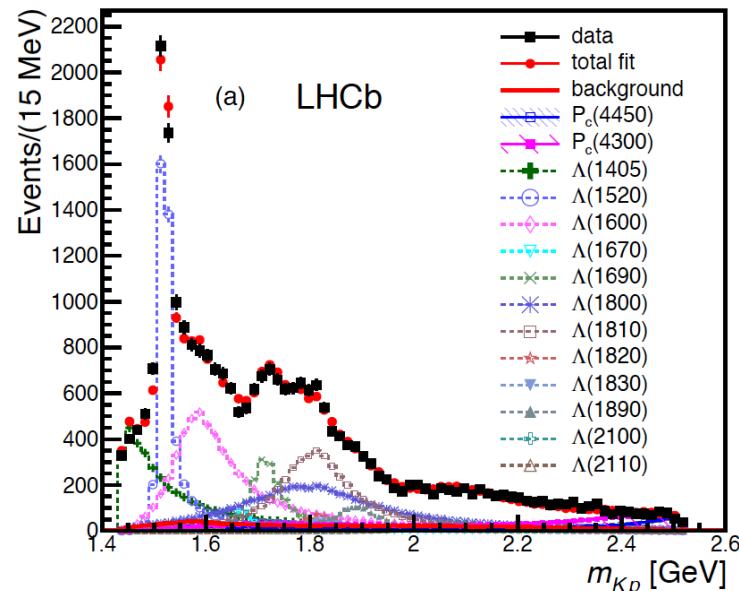
[Phys. Rev. Lett. 115, 072001 \(2015\)](#)



Data  
Fit

Adding 2  $P_c$  states:

[Phys. Rev. Lett. 115, 072001 \(2015\)](#)

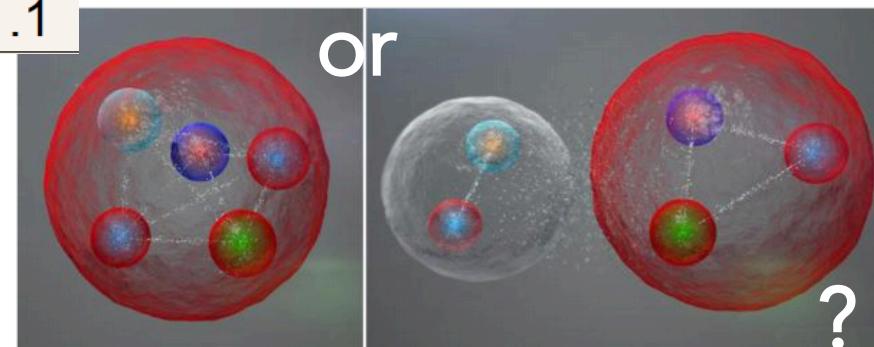


Data  
Fit

85

Mass (MeV)	Width (MeV)	Fit fraction (%)
$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$

$J^P = (3/2^-, 5/2^+)$

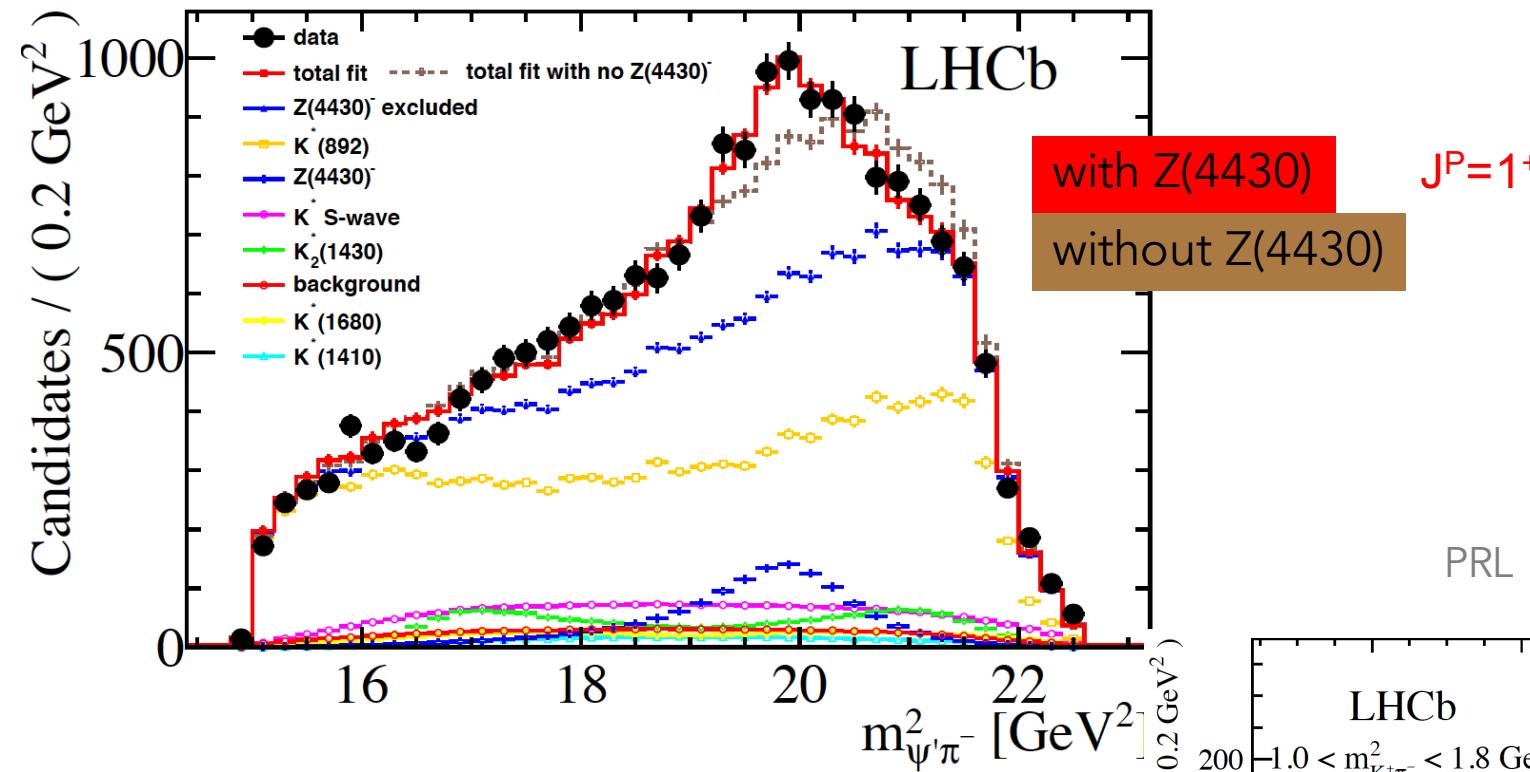


Possible layout of the quarks in a pentaquark particle. The five quarks might be tightly bound (left). They might also be assembled into a meson (one quark and one antiquark) and a baryon (three quarks), weakly bound together (Image: Daniel Dominguez)

But also a tetraquark !

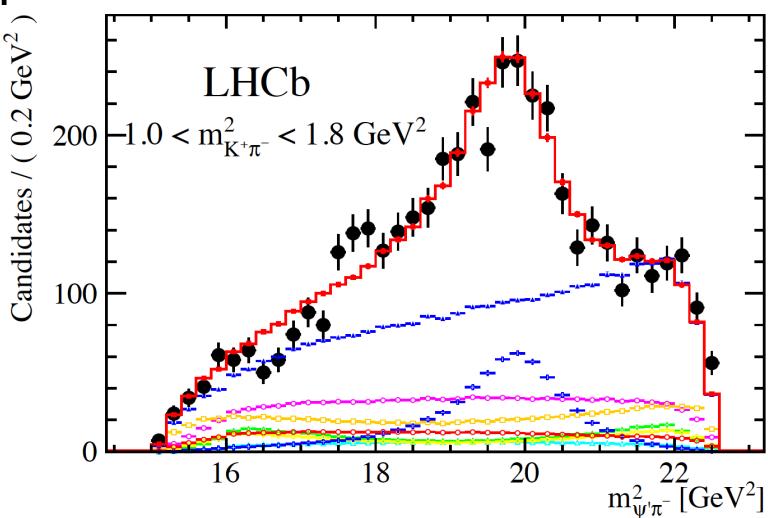
Belle, BaBar, LHCb

$B^0 \rightarrow \psi' \pi^- K^+$ , peak in  $m(\psi' \pi^-)$ , charged charmonium state must be exotic, not  $q\bar{q}$



PRL 112 (2014) 222002

First observed by Belle in 2008  
LHCb ruled out other possibilities in 2014



# Searching for New Physics : rare decays

Operator Product Expansion allows to separate

- the low energy effects (non-perturbative QCD, difficult to calculate), form factors, decay constants ... ( $O_i$ )
- the high-energy effects (perturbative QCD + weak interaction+ potential New Physics) ( $C_i$ )

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left( \sum_{i=1 \dots 10, S, P} (C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu)) \right)$$



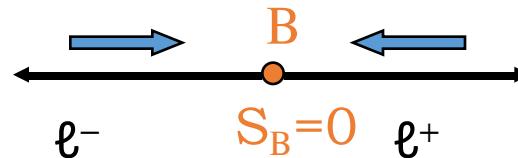
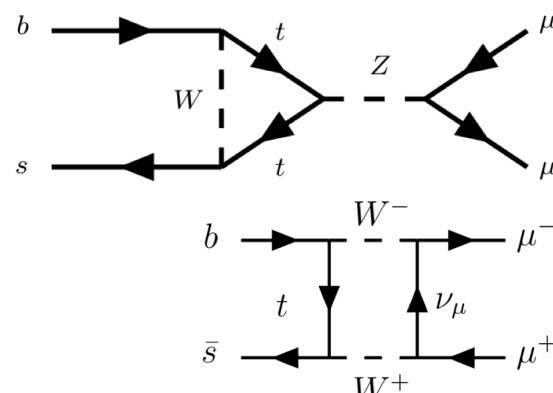
i=7 : photon  
i=9 : vector current  
i=10 : axial-vector current  
i=S,P : scalar, pseudo scalar operators

$\mu$  is the limit between the two regimes (few GeV)

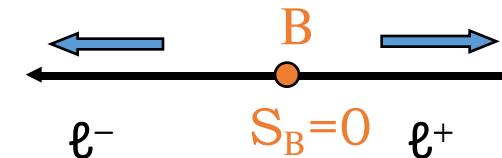
NP :

- Modified Wilson coefficients:  $C_i = C_i^{SM} + C_i^{NP}$
- Additional New Physics operators:  $\sum_j C_j^{NP} O_j^{NP}$

# $B_{d,s} \rightarrow \mu\mu$



left-handed particle  
left-handed anti-particle



right-handed particle  
right-handed anti-particle

SM : very rare ( $V_{tq}$ , helicity suppression)

In the SM, in the massless limit: left-handed anti-particle & right-handed particle are forbidden

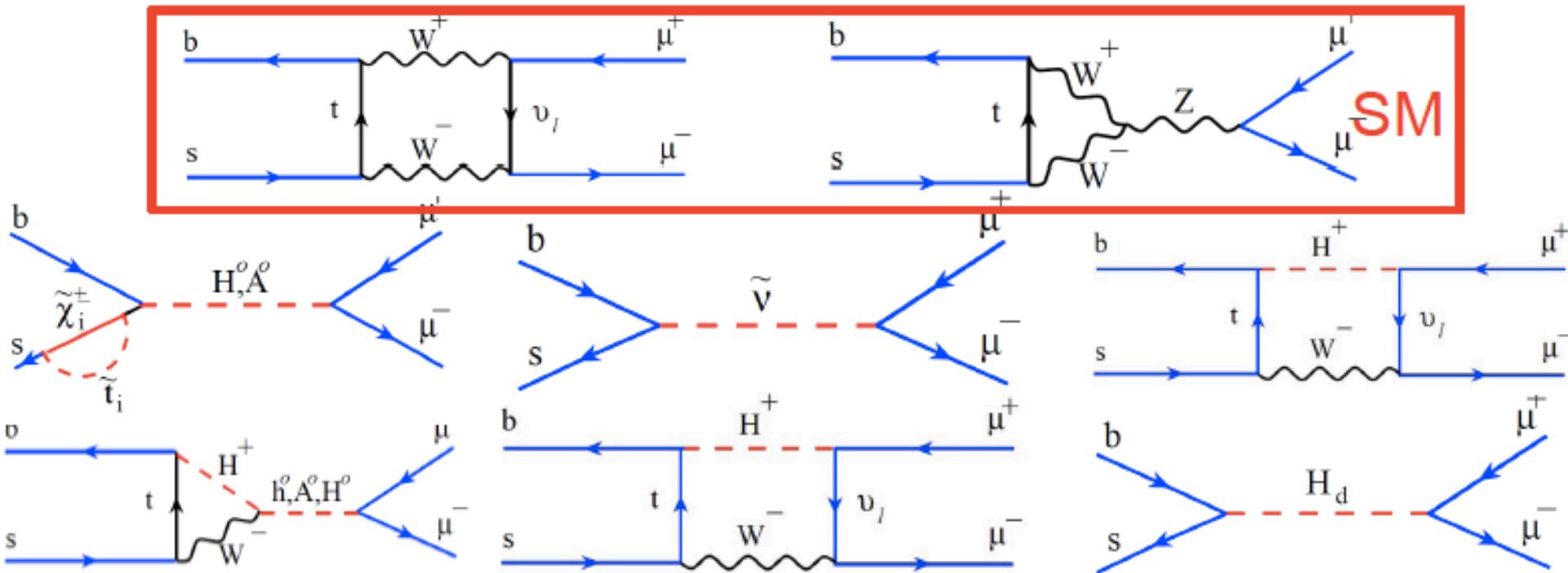
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

SM prediction

Due to CKM, the  $B_d$  modes are further suppressed by a factor 1/30  
 Search for  $B_d$  and  $B_s$ : the branching fractions could be modified differently by New Physics

## Sensitive to the scalar sector of flavour couplings

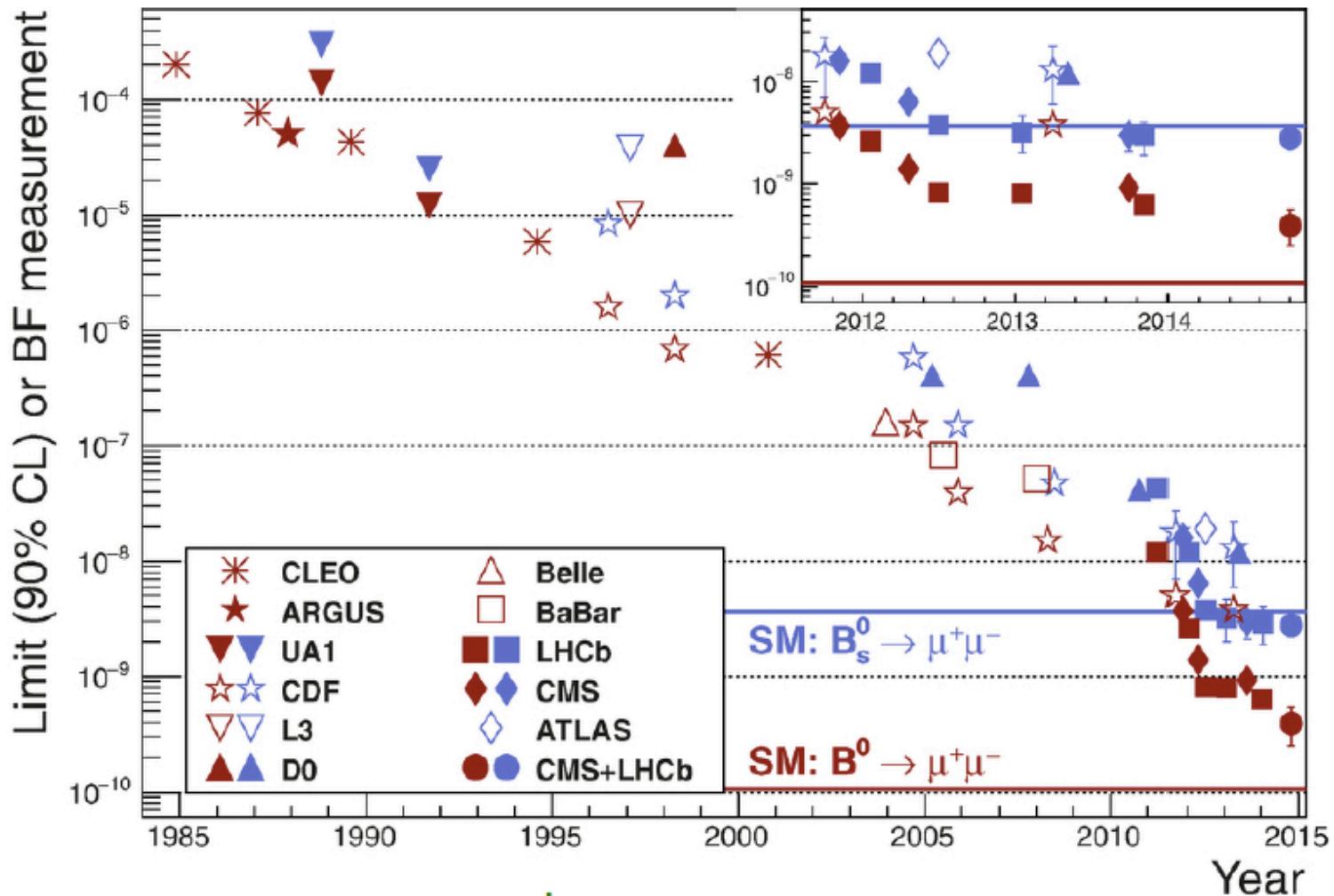


In New Physics models with an extended Higgs sector the BR can be largely enhanced

$$\text{BR}^{\text{MSSM}} \propto \tan^6 \beta / M_A^4$$

! here,  $\tan\beta =$  ratio of the vevs of the two Higgs doublets

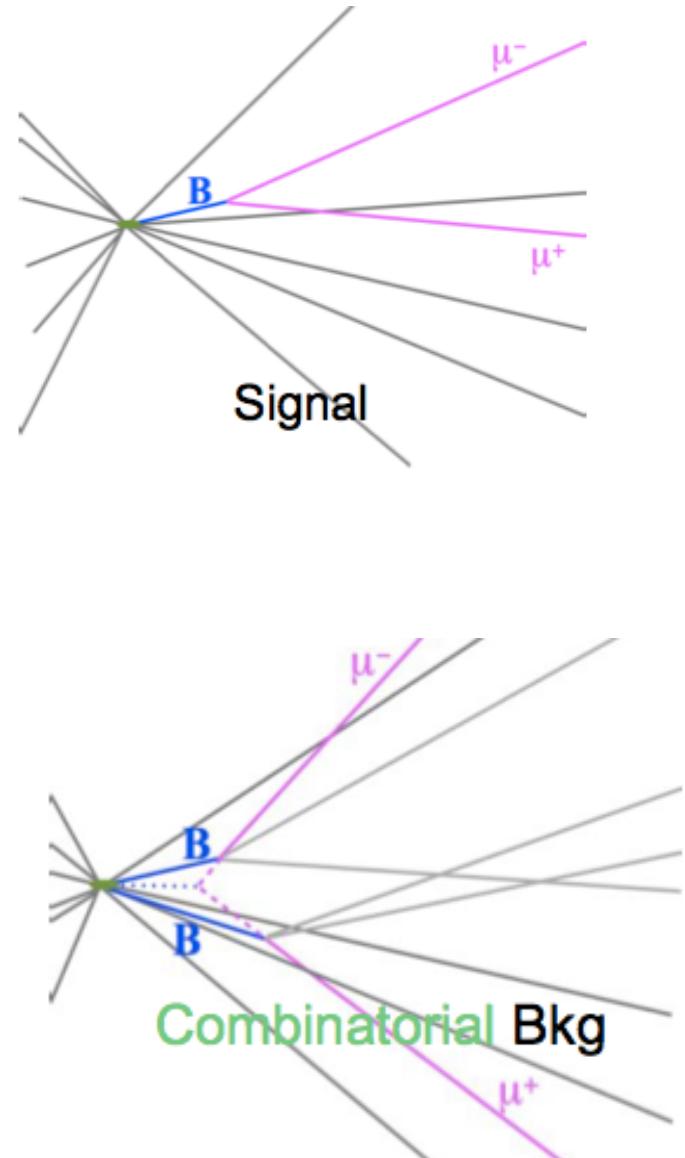
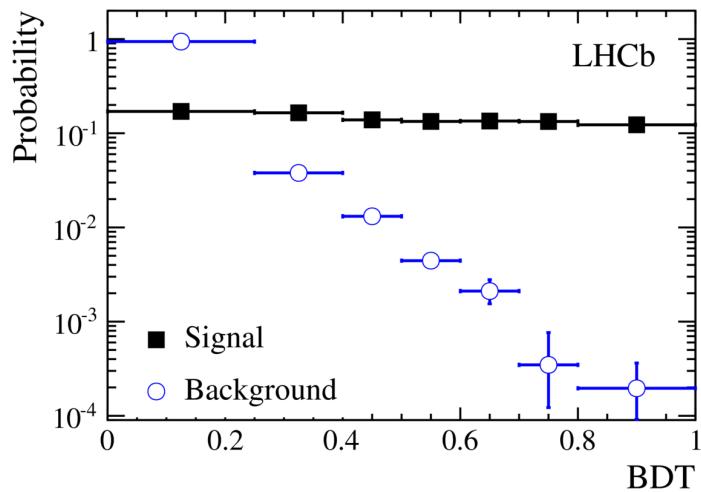
$$B_{(s)}^0 \rightarrow \mu^+ \mu^-$$

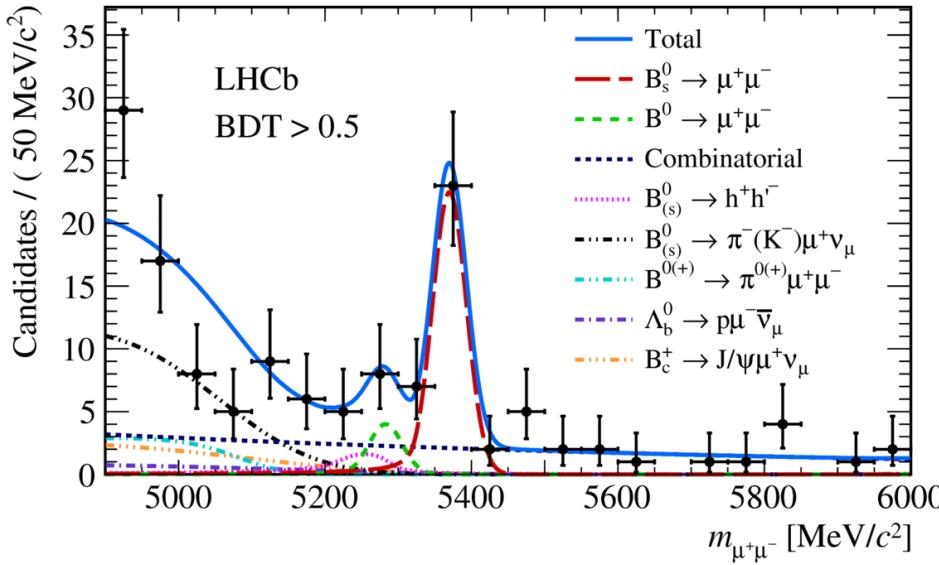


Clean experimental signature (TeVatron, ATLAS and CMS)

# Main ingredients

- Huge sample of B mesons
- Efficient trigger
- Powerful selection
  - Vertex resolution
  - Mass resolution
  - Muon ID
- BDT algorithm

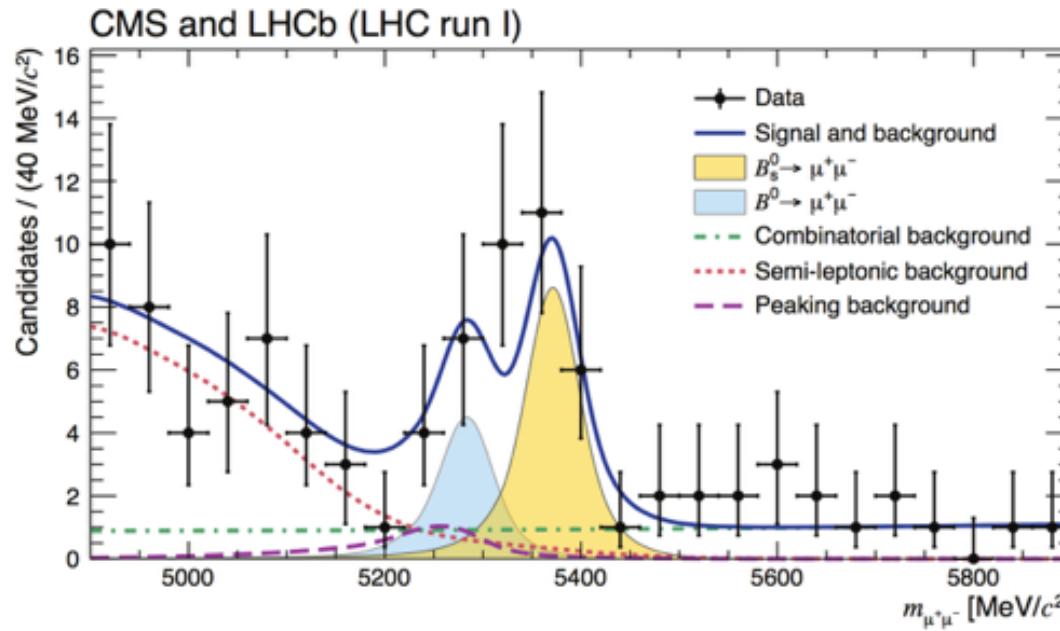




$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-10}$$

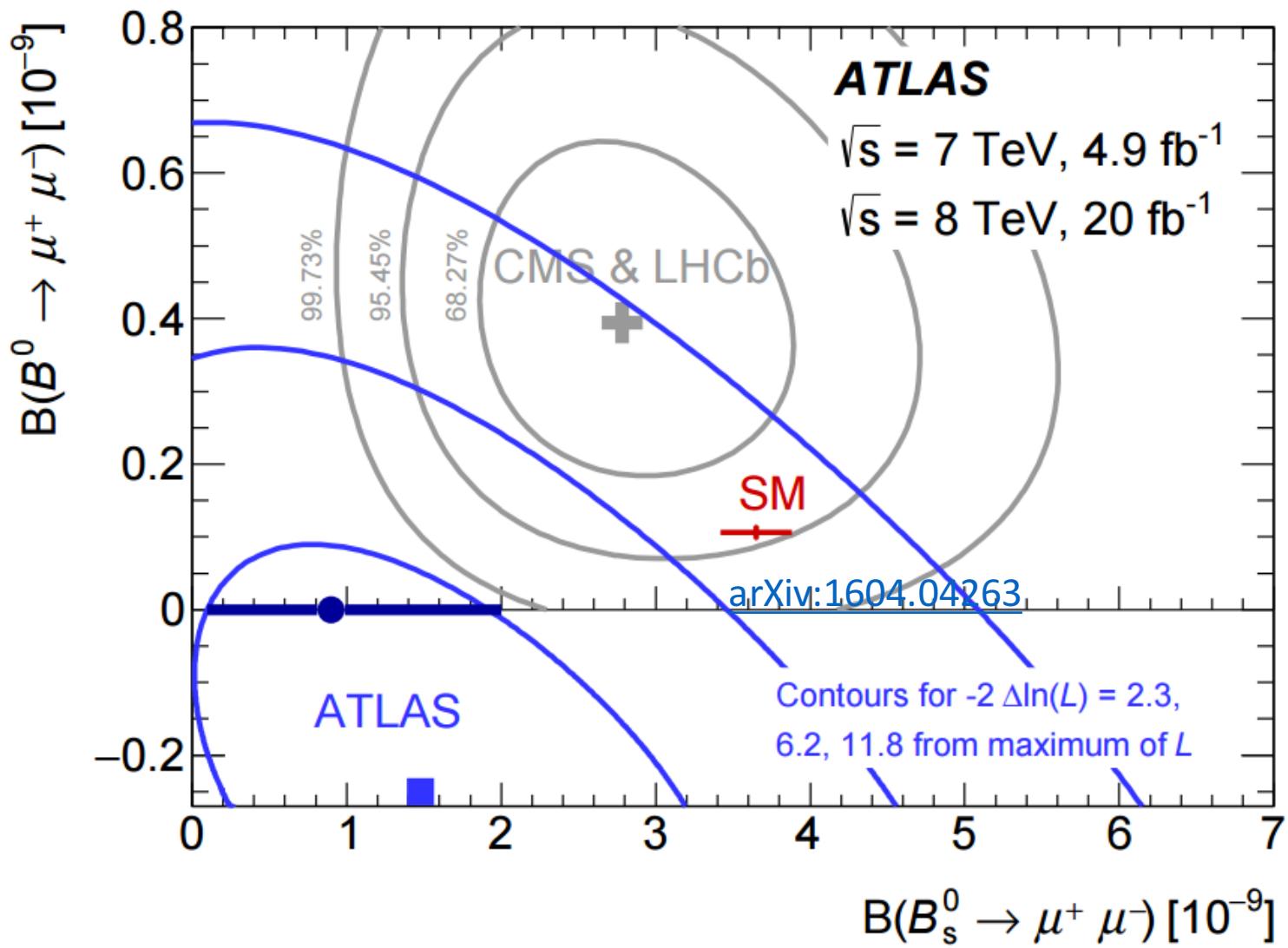
[Phys. Rev. Lett. 118, 191801 \(2017\)](#)



$$\mathcal{B}(B_s^0 \rightarrow \mu^-\mu^+) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^-\mu^+) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

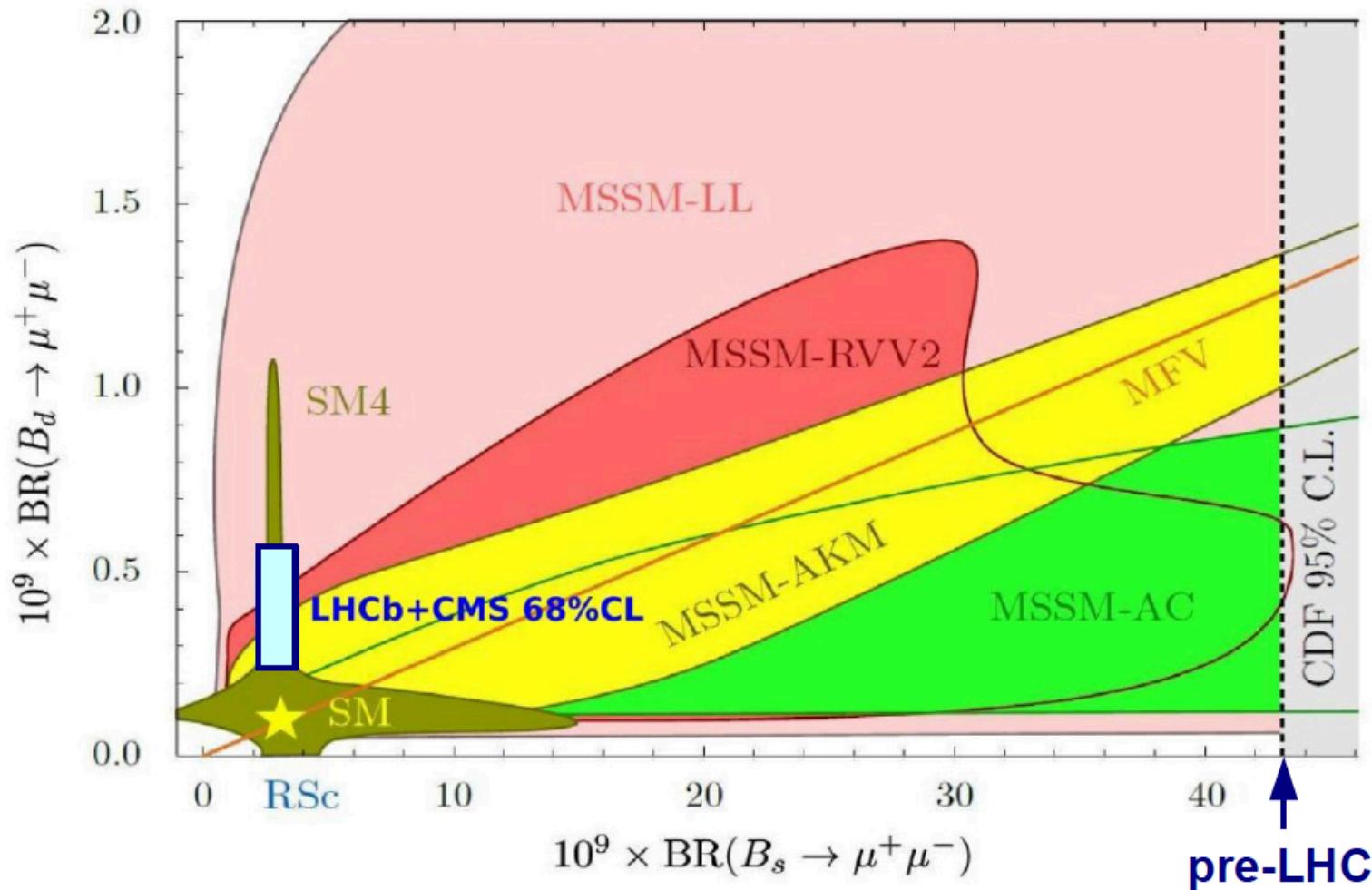
[Nature 522, 68-72 \(04 June 2015\)](#)



Eur. Phys. J. C76 (2016) 513

# Constraints on New Physics models

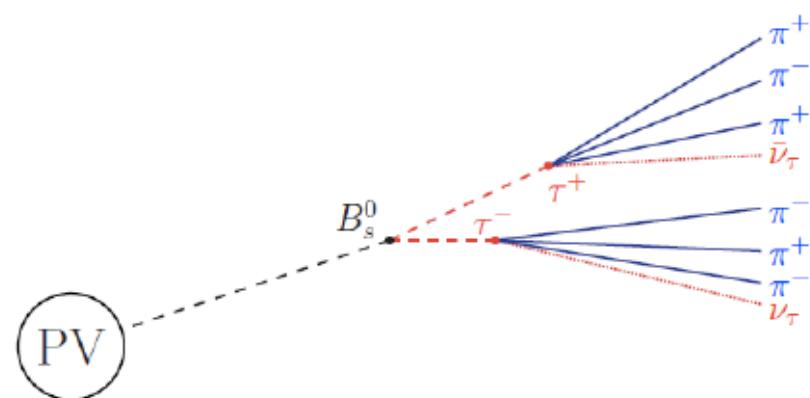
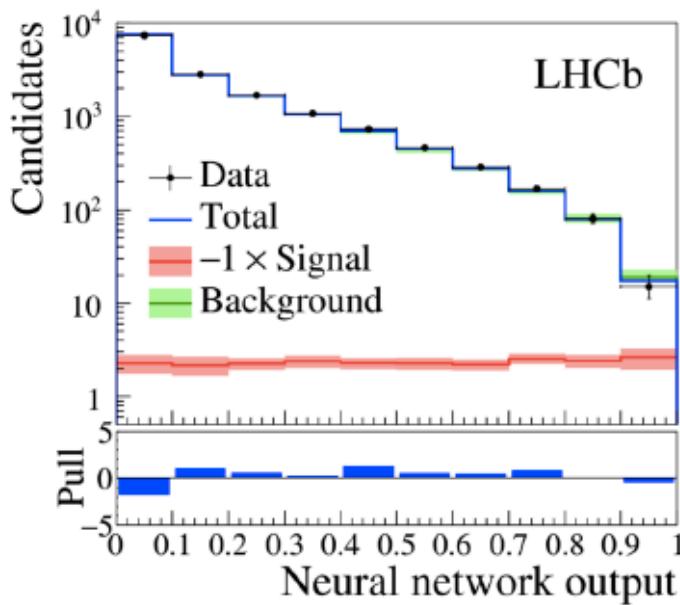
In favourable cases (large  $\tan \beta$ )



modified from [NC C035N1 (2012) 249]

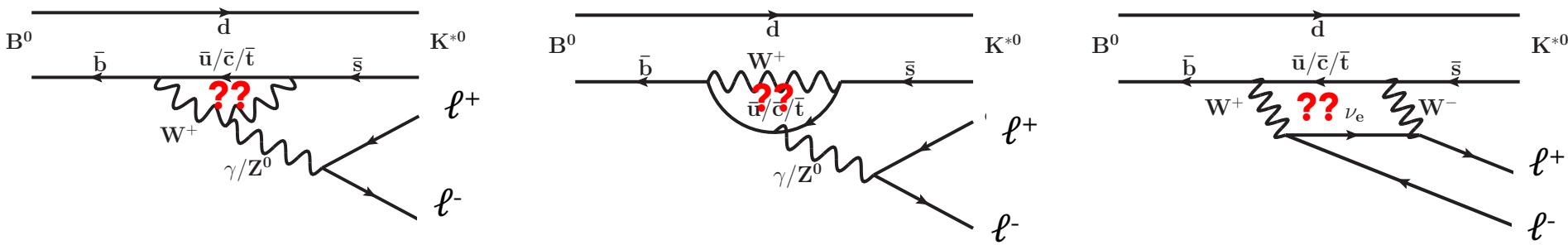
# $B_{(s)} \rightarrow \tau^+ \tau^-$

- Experimentally very challenging due to final state neutrinos
- LHCb uses  $\tau \rightarrow \pi^- \pi^+ \pi^- \nu$  decay
- Fit the output of a NN using Run1 data



- First experimental result on the  $B_s$   
 $BR(B_s^0 \rightarrow \tau^+ \tau^-) < 6.8 \times 10^{-3}$  (95%CL)
- Best limit on  $B^0$   
 $BR(B^0 \rightarrow \tau^+ \tau^-) < 2.1 \times 10^{-3}$  (95%CL)
- Still orders of magnitude above SM but proof of concept that rare decays into taus can be done at hadron collider

# $b \rightarrow s \ell \ell$ transitions



Relative importance of the different diagrams varies with  $q^2 = M^2(\ell^+ \ell^-)$

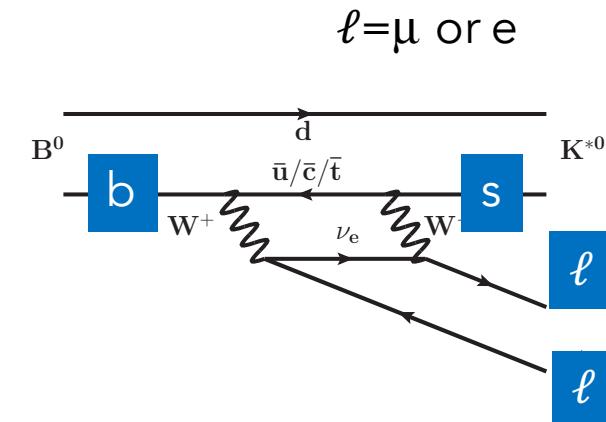
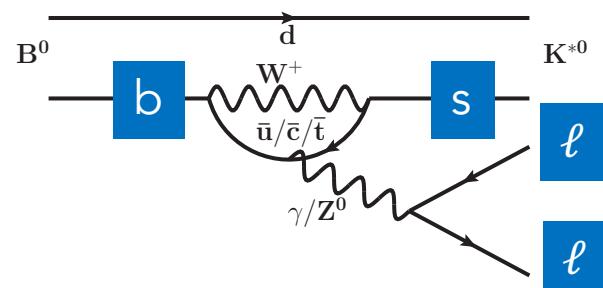
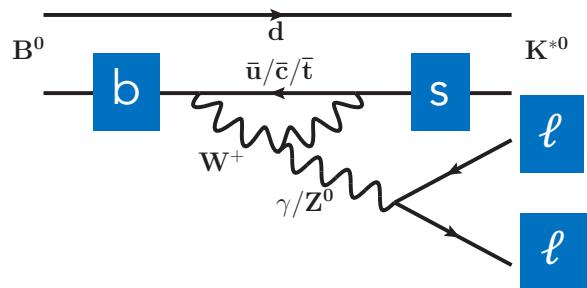
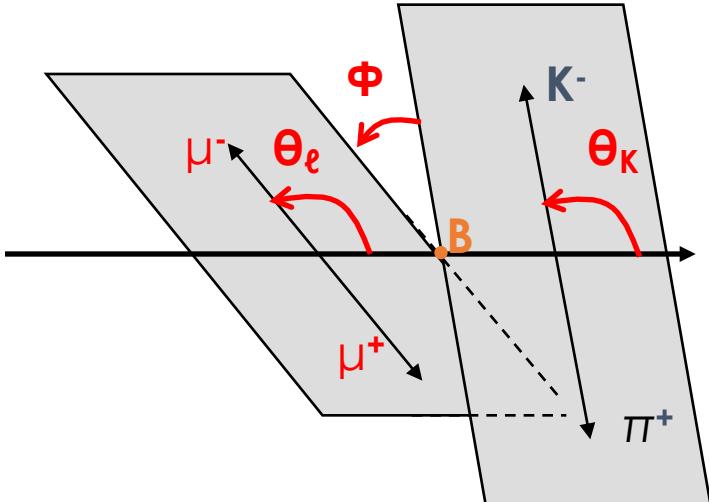
Many observables :

- BF (but large theoretical uncertainties due to non-perturbative QCD)
- Ratios of BF (test of LFU)
- Angular observables

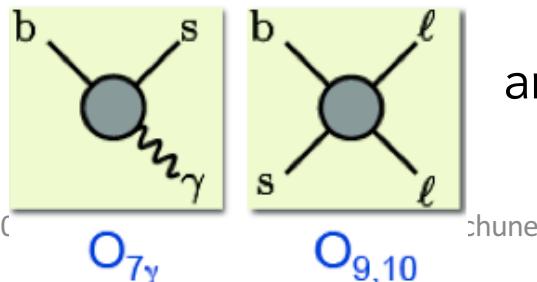
# Study of $B^0 \rightarrow K^{*0} \mu\mu$

4 particles final state  
System described by:

- $q^2 = M^2(\ell\ell)$
- 3 angles



Interferences between



and their right-counter parts

$$B^0 \rightarrow K^{*0} \mu\mu$$

Matrix element of the decay depends on the  $K^{*0}$  polarization

... → Amplitudes

an example :

$$A_{\perp}^{L,R} = N\sqrt{2}\lambda^{1/2} \left[ \left\{ (\mathcal{C}_9^{(\text{eff})} + \mathcal{C}'_9^{(\text{eff})}) \mp (\mathcal{C}_{10}^{(\text{eff})} + \mathcal{C}'_{10}^{(\text{eff})}) \right\} \frac{V(q^2)}{m_B + m_{K^*}} + \right. \\ \left. + \frac{2m_b}{q^2} (\mathcal{C}_7^{(\text{eff})} + \mathcal{C}'_7^{(\text{eff})}) T_1(q^2) \right],$$

Effective coupling for a potentially higher energy scale : **Wilson coefficients**  
 $\mathcal{C}_{7,9,10}$

Hadronic (non perturbative ) effects : Form factors V and T . Models or lattice QCD

The amplitudes depend on  $q^2$

$$\frac{d^4\Gamma}{dq^2 d \cos \theta_\ell d \cos \theta_K d\phi} = \frac{9}{32\pi} \left[ I_1^s \sin^2 \theta_K + I_1^c \cos^2 \theta_K \right. \\ \left. + I_2^s \sin^2 \theta_K \cos 2\theta_\ell + I_2^c \cos^2 \theta_K \cos 2\theta_\ell \right. \\ \left. + I_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \right. \\ \left. + I_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + I_6 \sin^2 \theta_K \cos \theta_\ell \right. \\ \left. + I_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi \right. \\ \left. + I_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right],$$

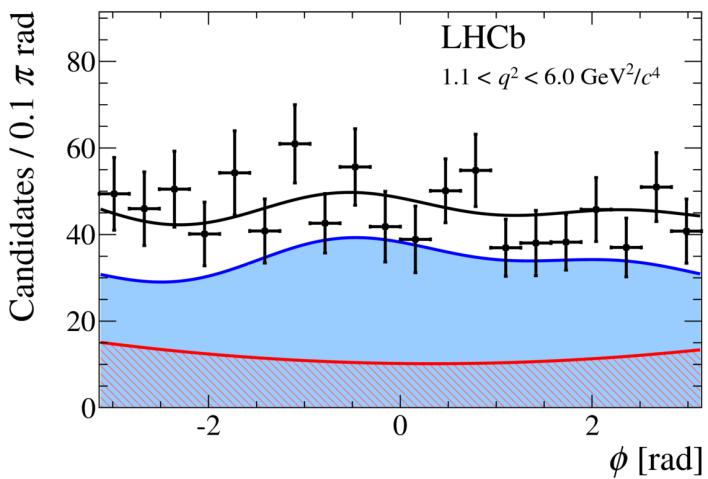
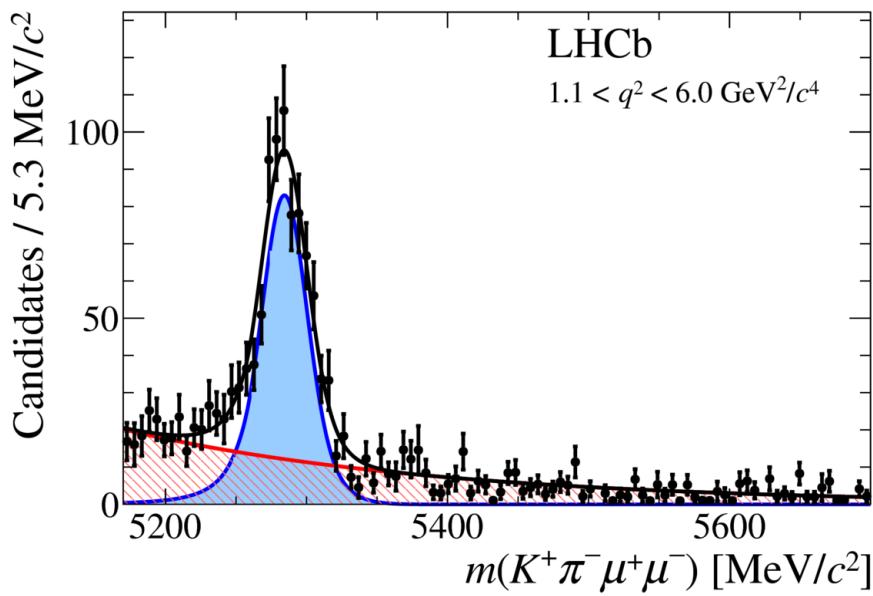
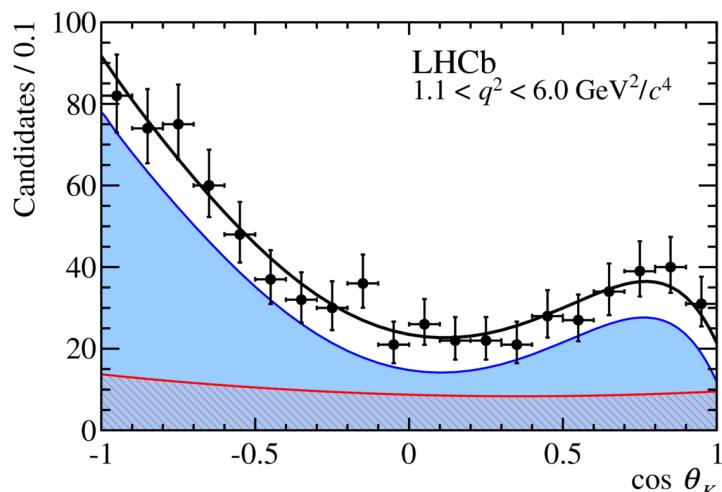
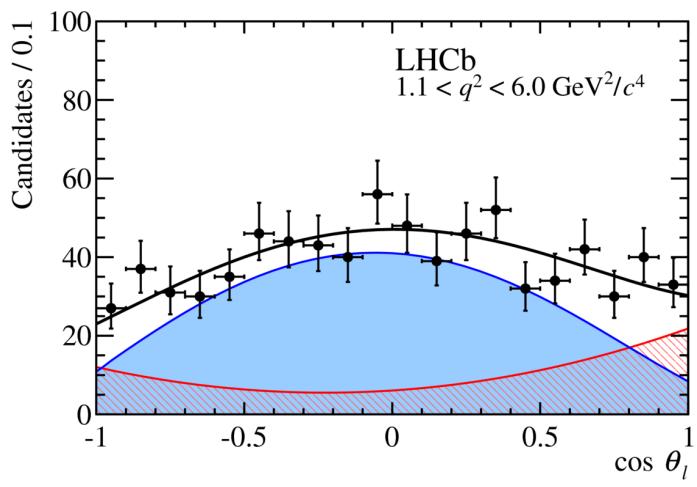
The  $C^{(i)}_{7..10}$  are encoded in the  $I_{i=1..9}$

Ratios of  $I_i$  can be built to remove FF dependence

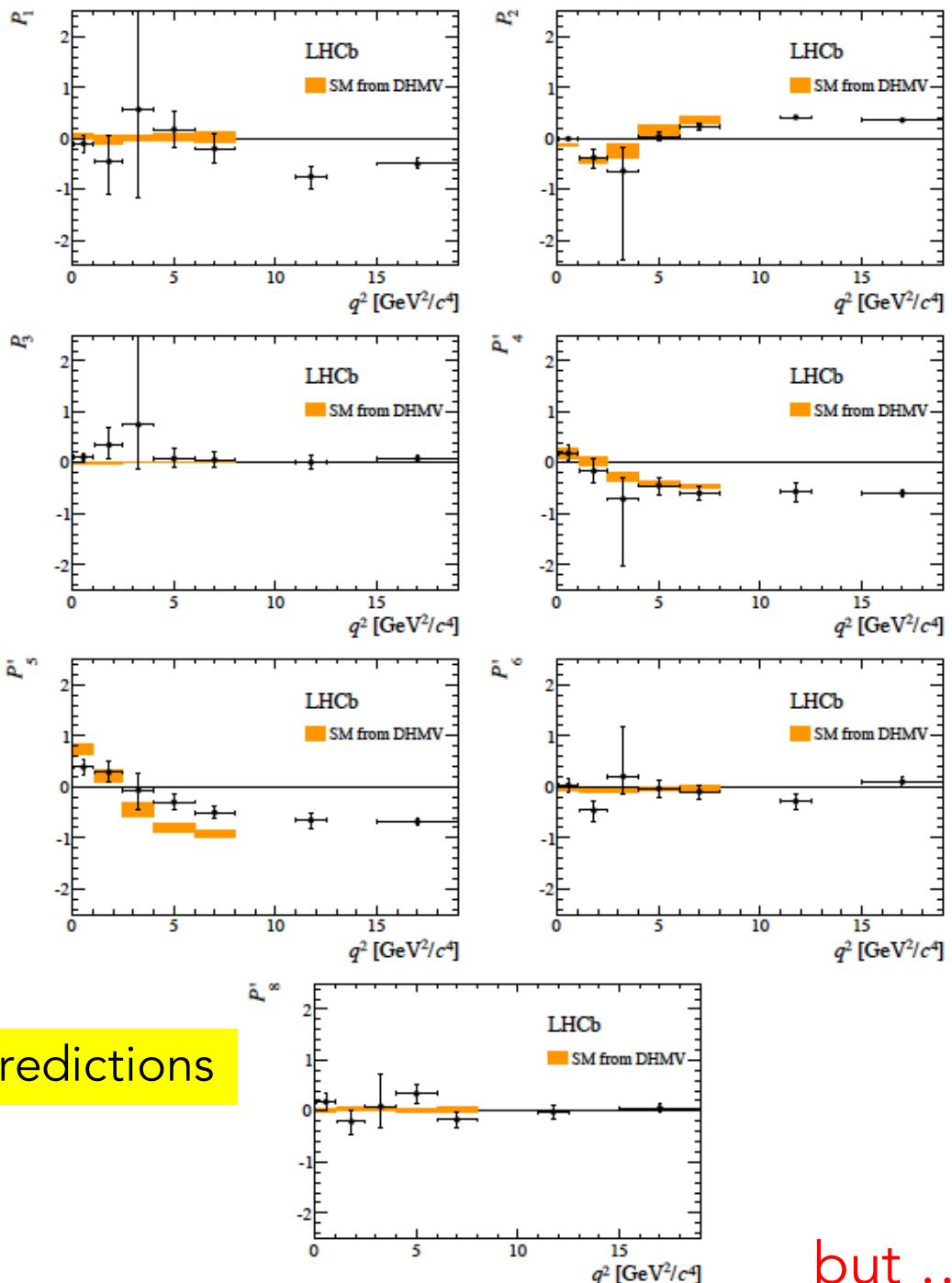
# → Angular analysis in bins of $q^2$

[JHEP 02 \(2016\) 104](#)

an example :



Mainly parameters values  
extracted in each  $q^2$  bin :

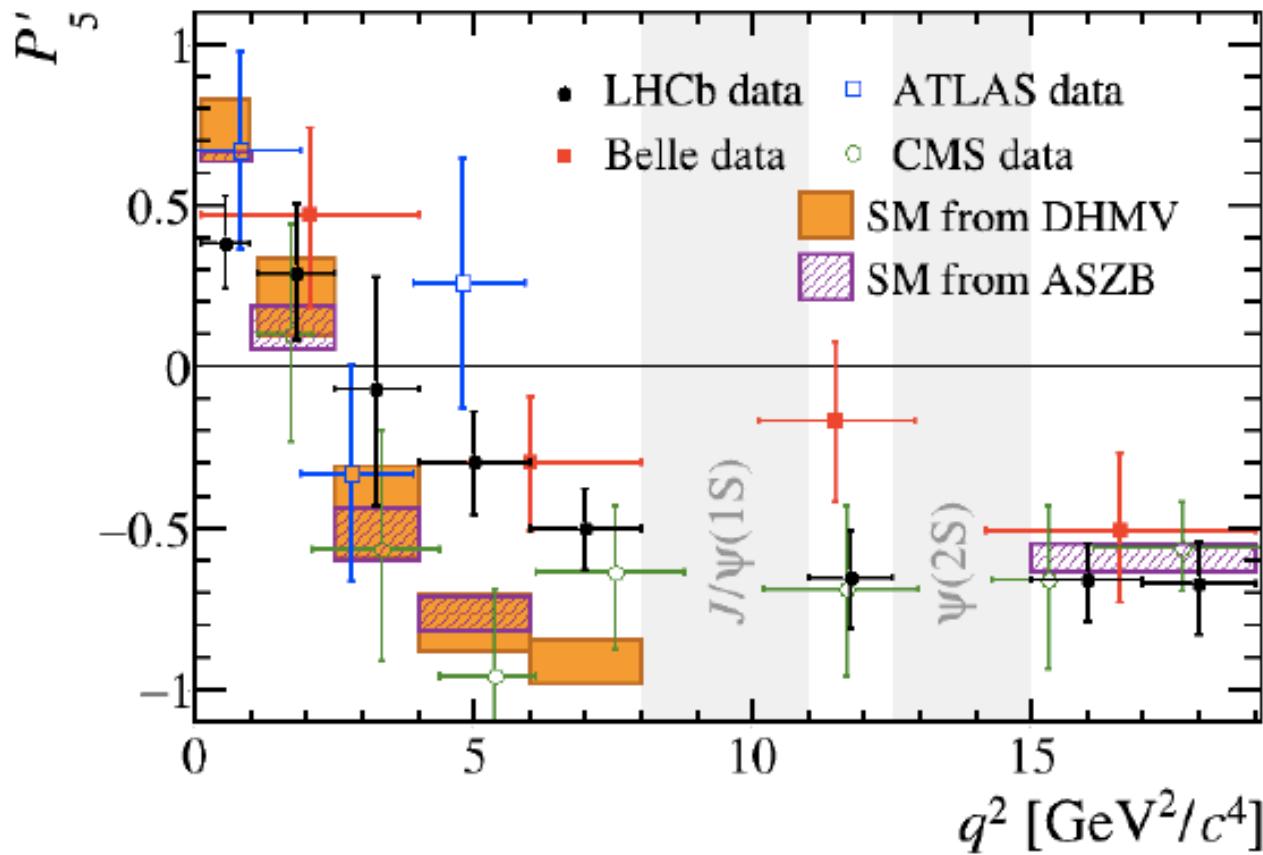


Mostly in agreement with SM predictions

but ...

Not all of them

$$P'_5 = \sqrt{2} \frac{\operatorname{Re}(A_0^L A_{\perp}^{L*} - A_0^R A_{\perp}^{R*})}{\sqrt{(|A_0^L|^2 + |A_0^R|^2) (|A_{\parallel}^L|^2 + |A_{\parallel}^R|^2 + |A_{\perp}^L|^2 + |A_{\perp}^R|^2)}}$$



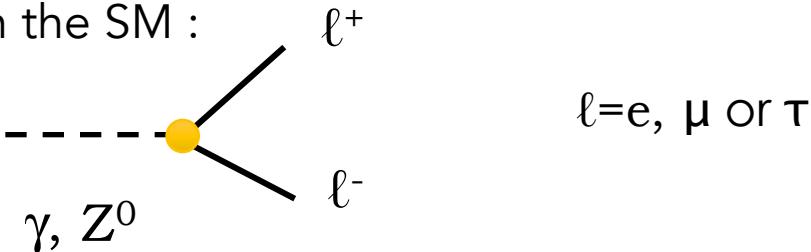
LHCb JHEP 02(2016) 104

Belle PRL118, 111801 (2017)

ATLAS, preliminary Moriond EW 2017

CMS, preliminary Moriond EW 2017<sup>102</sup>

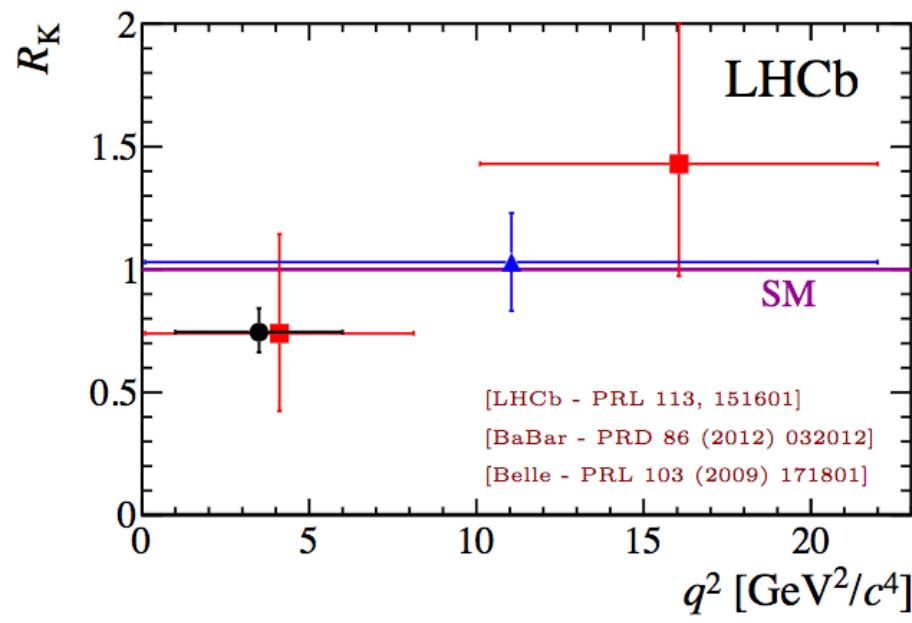
In the SM :



The only difference is kinematics  
(lepton masses)

$$R_K = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma[B^+ \rightarrow K^+ e^+ e^-]}{dq^2} dq^2} R_{K^*}$$

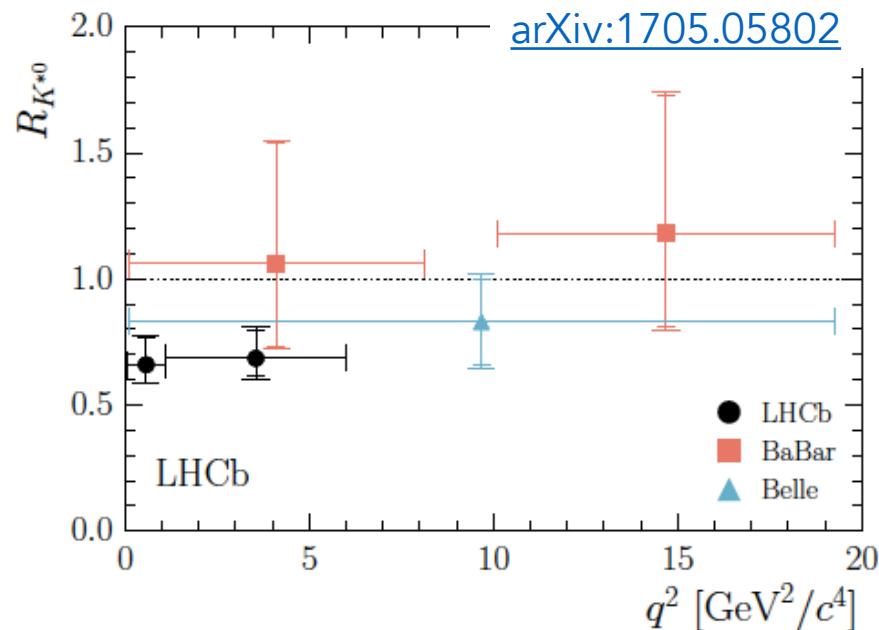
● LHCb ■ BaBar ▲ Belle



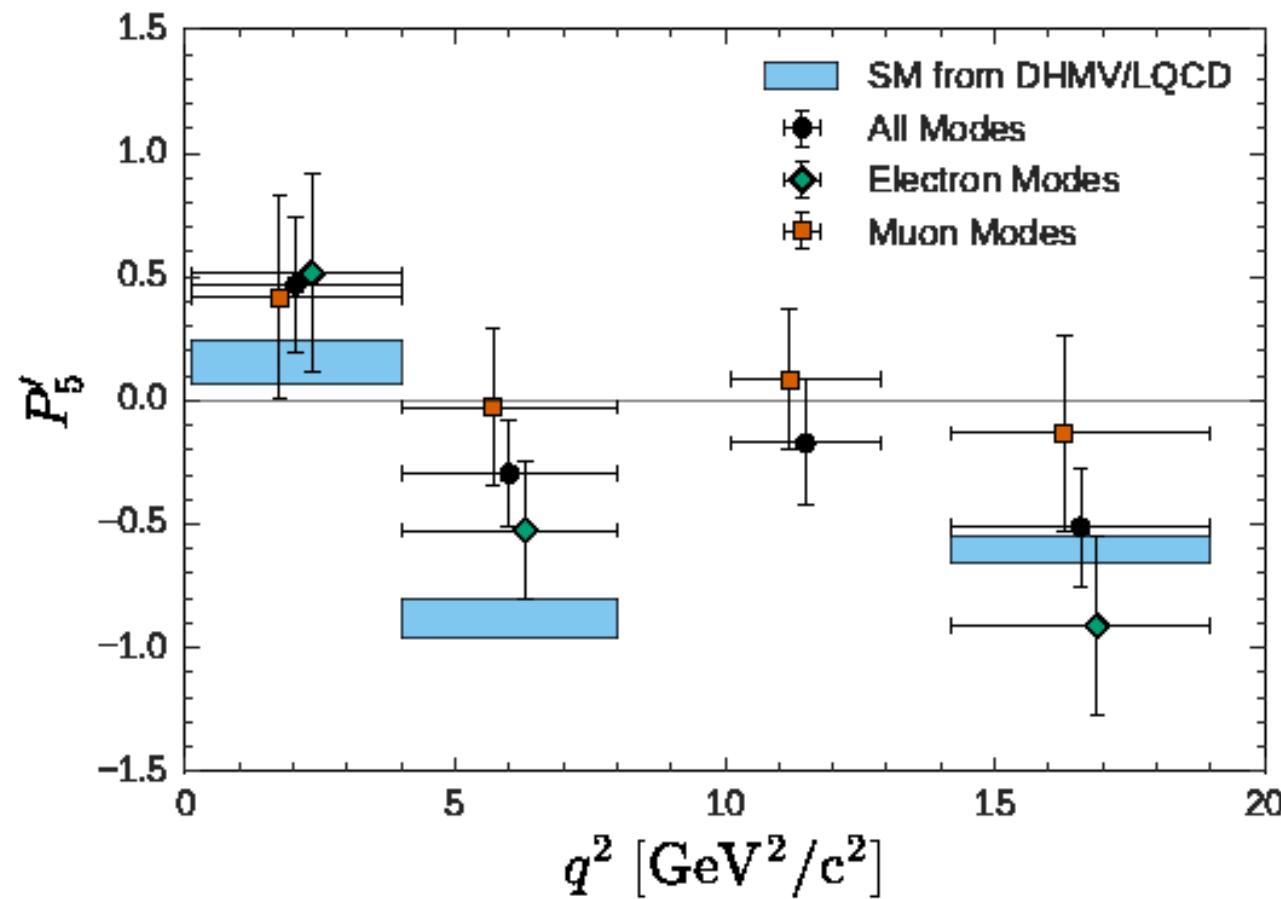
2 – 3  $\sigma$  effects

From a detector point of view  
leptons are very different

- [PRD 86 \(2012\) 032012](#)
- [PRL 103 \(2009\) 171801](#)

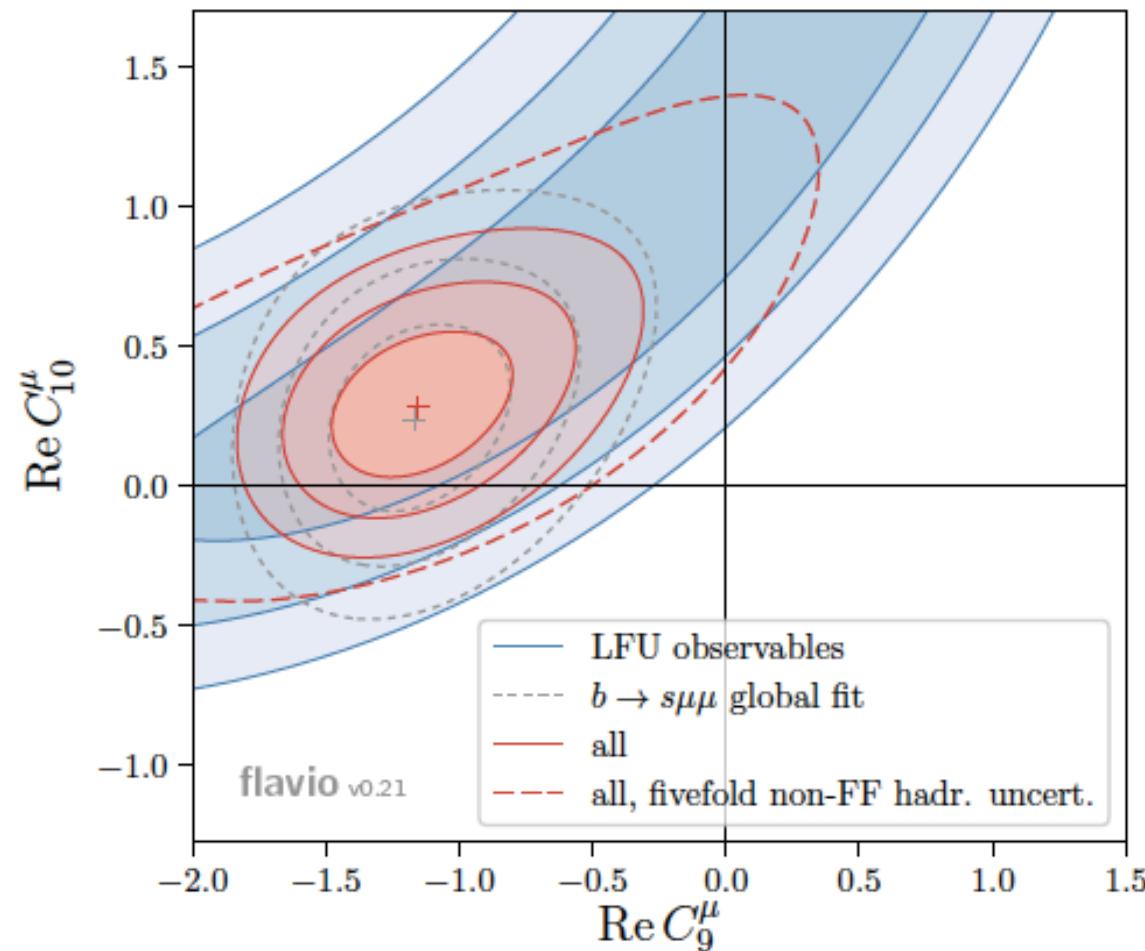


## Test of lepton universality in angular observables : BELLE



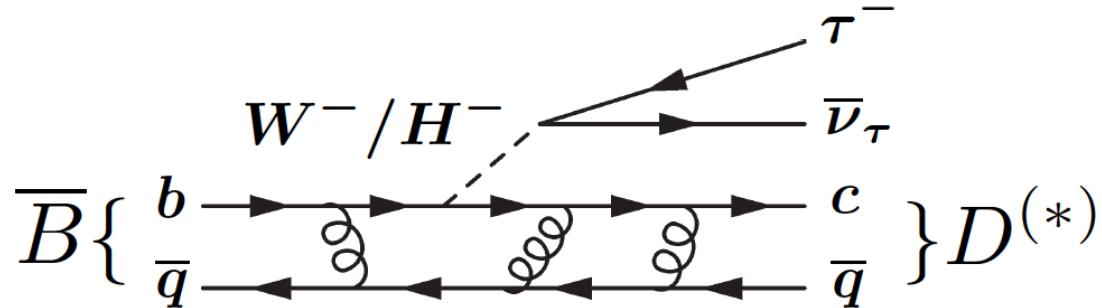
$2 - 3 \sigma$  effects ... statistically very limited but a consistent pattern

A lot of theoretical activity



[arXiv:1704.05435](https://arxiv.org/abs/1704.05435)

# Another tension in LFU tests: $B \rightarrow D^{(*)} \tau \nu$



$$R_{D^{(*)}} = \frac{BR(B \rightarrow D^{(*)} \tau \nu_\tau)}{BR(B \rightarrow D^{(*)} \mu \nu_\mu)}$$

In the SM the only difference is the lepton mass  
→ precisely predicted

Sensitive to charged Higgs, leptoquarks...

Challenging channel :

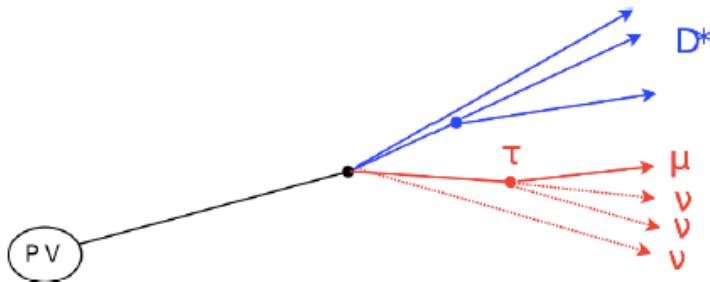
- 2 to 3 neutrinos ( $\tau$  hadronic decay or muonic decay)
- Backgrounds (partially reconstructed ( $D^{**}$ ), combinatorial ...)

$\tau \rightarrow \mu \nu \nu$

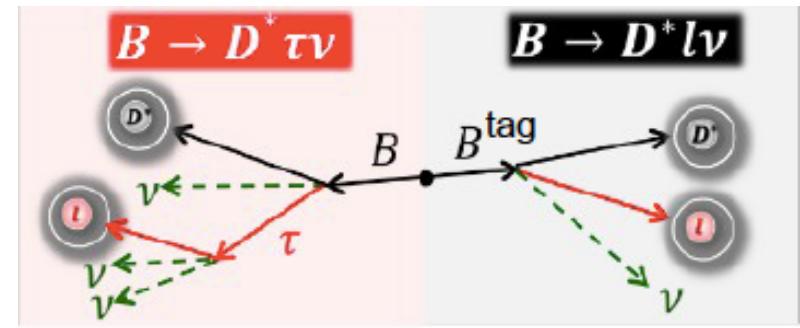
$\tau \rightarrow \pi \pi \pi \nu$

Aim is to reconstruct the kinematics of the decay  
... despite the missing neutrinos

LHCb



B-factories

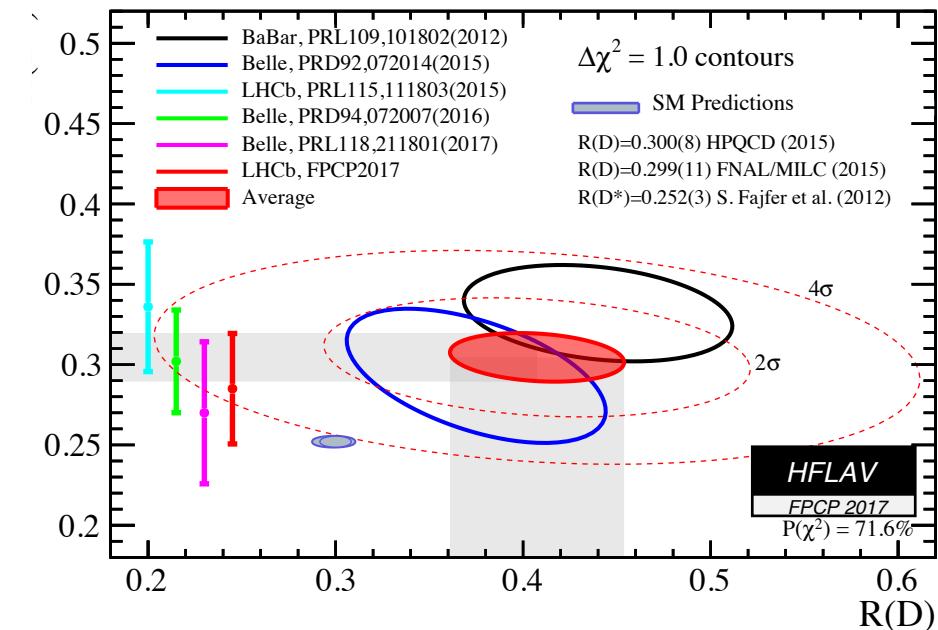
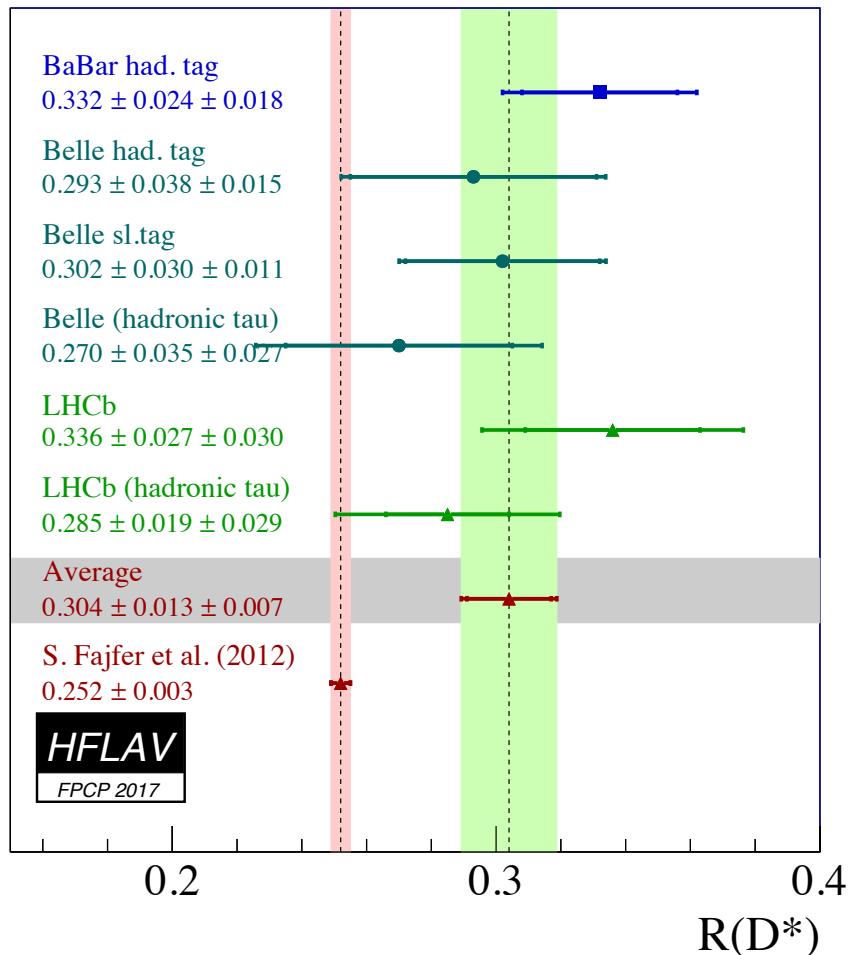


Takes advantage of the large boost

- flight direction to measure the transverse component of the missing momentum
- Boost  $\gg$  energy release in the decay  
⇒ reasonable approximation of the rest frame kinematics

Reconstruction of the other  $B$  (no other particles) : hadronic or semi-leptonic (less constraints)

- little activity in the calorimeter
- Use the total cm energy



Results  $4\sigma$  away from the SM

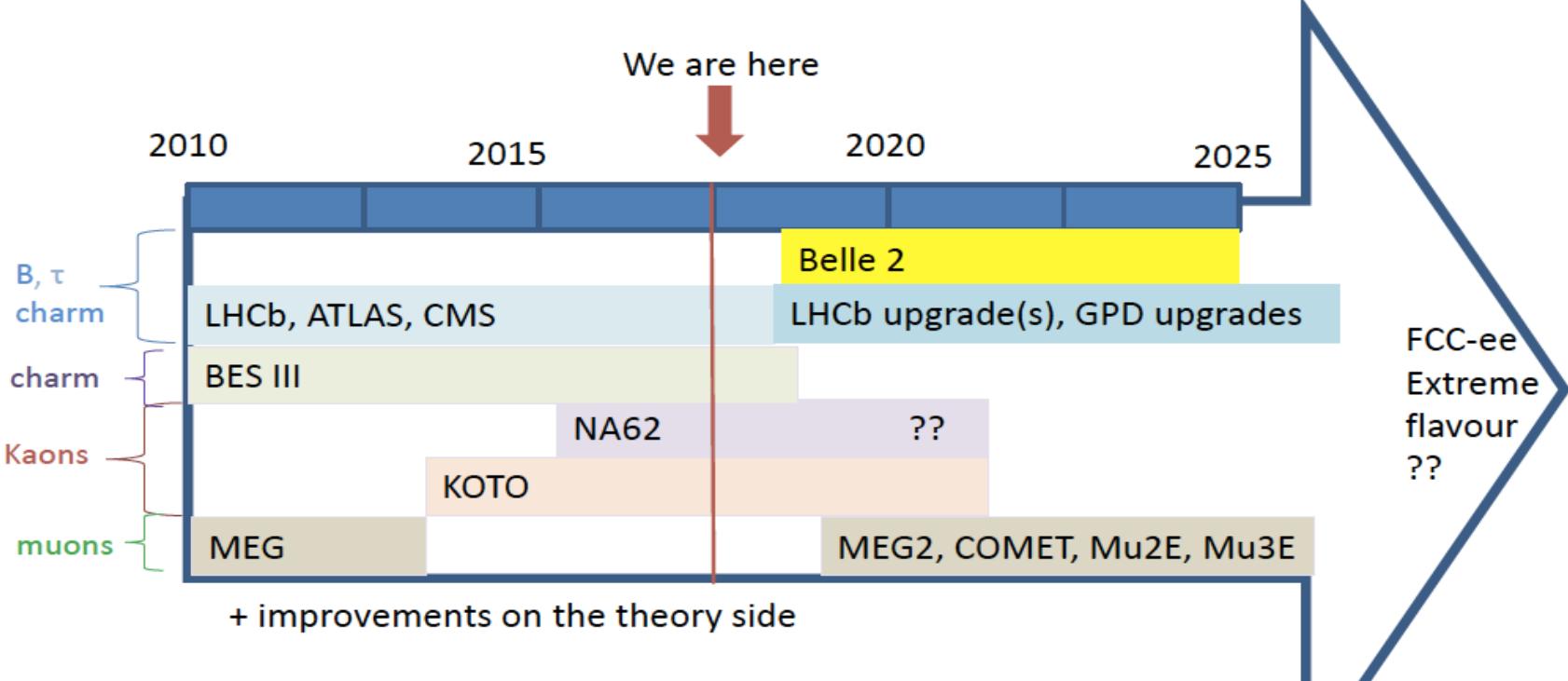
# Accumulations of tensions wrt SM

- In some cases :
  - negligible theoretical uncertainties
  - but experimentally challenging
- A common pattern ?
- but no single effect  $> 5 \sigma$  (yet)



At the electroweak scale, the CKM mechanism dominates CP violation

More data !  
Run-2  
Belle-2  
Upgrades (LHCb)



In 1964 the discovery of CP violation came as a surprise

HF physics is intrinsically linked with matter-antimatter asymmetry but SM does not provide the proper amount of asymmetry

HF physics offers a unique opportunity to access NP at very high scales

Some interesting hints, but more data is needed to conclude

HF is much more than what I had time to touch on ...

# Thank you for your attention

Based on lectures given with Achille Stocchi

and also on slides from Tim Gershon, Gerhard Raven, Niels Tuning

and EPS2017 results

Heavy Flavour Averaging Group <http://www.slac.stanford.edu/xorg/hfag/>  
Reviews of the PDG : [http://pdg.lbl.gov/2017/reviews/contents\\_sports.html](http://pdg.lbl.gov/2017/reviews/contents_sports.html)

The Physics of the B factories arXiv:1406.6311

CKM fits : <http://ckmfitter.in2p3.fr/> & <http://www.utfit.org/>

# Backup slides



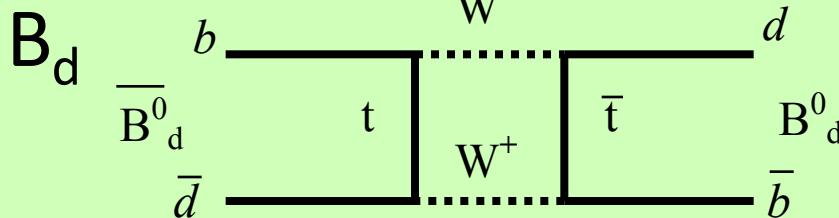
## Dirac's Nobel prize lecture (1933 !)

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.

Different values for  $x$ :

$\Delta m$

$\Gamma$



$$f(m_t)[V_{td}^* V_{tb}]^2 \sim m_t^2 \lambda^6$$

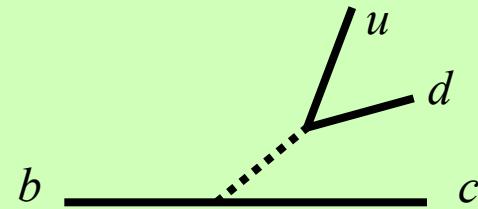
$$f(m_c)[V_{cd}^* V_{cb}]^2 \sim m_c^2 \lambda^6 \text{ totally negligible}$$

Slow oscillations

$$\Delta m_d \sim 0.50 \text{ ps}^{-1}$$

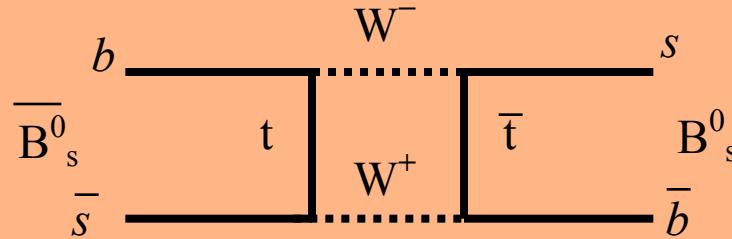
$$1/\Gamma_d \sim 1.50 \text{ ps}$$

$$x = \Delta m_d / \Gamma_d \sim 0.75$$



$$[V_{ud}^* V_{cb}]^2 \sim \lambda^4$$

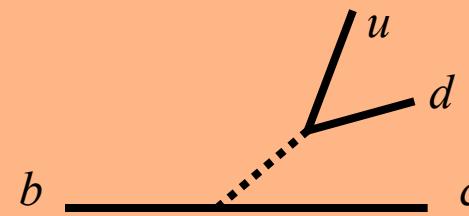
$B_s$



$$f(m_t)[V_{ts}^* V_{tb}]^2 \sim f(m_t) \lambda^4$$

$$x_s = \Delta m_s / \Gamma_s \sim m_t^2$$

$\sim$  very large  $x_s >> 1$



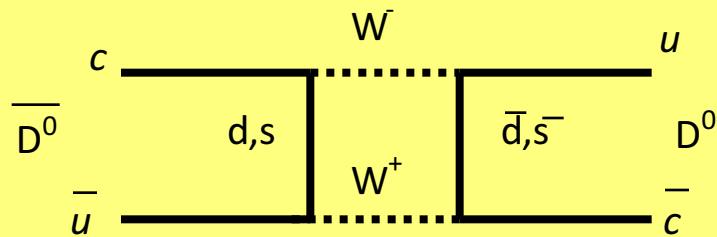
$$[V_{ud}^* V_{cb}]^2 \sim \lambda^4$$

$$\Delta m_s \sim 17 \text{ ps}^{-1}$$

$$1/\Gamma_s \sim 1.50 \text{ ps}$$

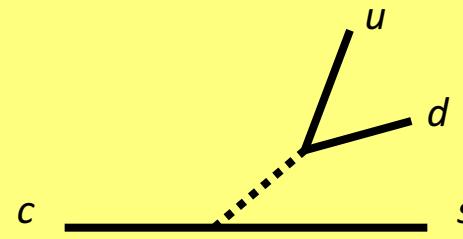
Rapid oscillations

$$x = \Delta m_s / \Gamma_s \sim 25$$

$\Delta m$  $\Gamma$  $D^0$ 

$$f(m_s)[V_{cs}^*V_{us}]^2 \sim f(m_s)\lambda^2$$

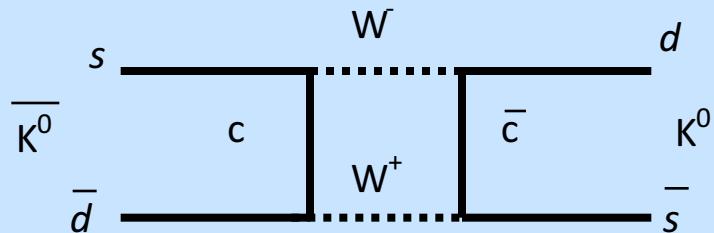
$$f(m_d)[V_{cd}^*V_{ud}]^2 \sim f(m_d)\lambda^2$$



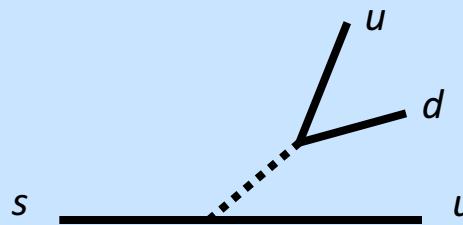
$$x \ll 1$$

$$[V_{ud}^*V_{cs}]^2 \sim 1$$

$$x \sim 10^{-3} - 10^{-5}$$

 $K^0$ 

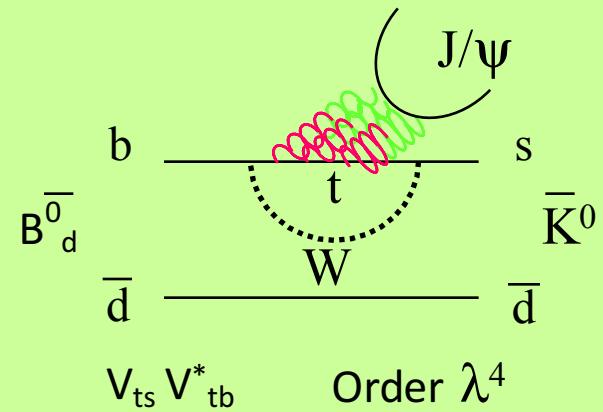
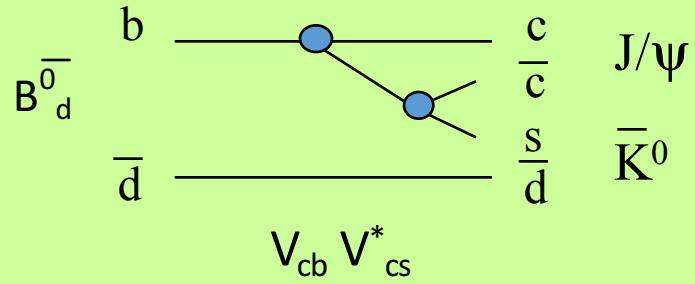
$$f(m_c)[V_{cd}^*V_{cs}]^2 \sim f(m_c)\lambda^2$$



$$x \sim 1$$

$$[V_{ud}^*V_{us}]^2 \sim \lambda^2$$

Extraction of  $\sin 2\beta$  from  $J/\psi K^0$  theoretically clean at % level



1. The diagram at tree level is dominant
2. The second diagram (Penguin) has the same phase at order  $\lambda^2$  since  $V_{ts}$  is complex and differs from  $V_{cb}$  at order  $\lambda^4$

Probability to observe in the state  $f$  a  $B^0$  produced at time  $t=0$ :

$$P(B^0(0) \rightarrow f) = |\langle f | H | B^0(t) \rangle|^2$$

$$P(B^0(0) \rightarrow f) = \frac{e^{-\Gamma t}}{2} \left\{ (1 + \cos \Delta m t) |\langle f | H | B^0 \rangle|^2 + (1 - \cos \Delta m t) \left| \frac{q}{p} \right|^2 |\langle f | H | \bar{B}^0 \rangle|^2 \right. \\ \left. - 2 \sin \Delta m t \times \text{Im} \left( \frac{q}{p} \langle f | H | \bar{B}^0 \rangle \langle f | H | B^0 \rangle^* \right) \right\}$$

Probability to observe in the state  $f$  a  $\bar{B}^0$  produced at time  $t=0$ :

$$P(\bar{B}^0(0) \rightarrow f) = |\langle f | H | \bar{B}^0(t) \rangle|^2$$

$$P(\bar{B}^0(0) \rightarrow f) = \frac{e^{-\Gamma t}}{2} \left\{ (1 + \cos \Delta m t) |\langle f | H | \bar{B}^0 \rangle|^2 + (1 - \cos \Delta m t) \left| \frac{p}{q} \right|^2 |\langle f | H | B^0 \rangle|^2 \right. \\ \left. - 2 \sin \Delta m t \times \text{Im} \left( \frac{p}{q} \times \langle f | H | B^0 \rangle \langle f | H | \bar{B}^0 \rangle^* \right) \right\}$$

( $\Delta\Gamma$  is neglected )

If one starts for example by a pure sample of  $B^0$  particles (produced by strong interaction) the probability to measure a  $\bar{B}^0$  at time  $t$  is :

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\bar{B}^0\rangle \quad |g_-(t)|^2 \left|\frac{p}{q}\right|^2$$

$$|\bar{B}^0(t)\rangle = \frac{p}{q}g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle$$

$$\begin{aligned} |g_{\pm}(t)|^2 &= \frac{1}{4} (e^{-\Gamma_H t} + e^{-\Gamma_L t} \pm e^{-\Gamma t} (e^{-i\Delta m t} + e^{+i\Delta m t})) \\ &= \frac{1}{4} (e^{-\Gamma_H t} + e^{-\Gamma_L t} \pm 2e^{-\Gamma t} \cos \Delta m t) \\ &= \frac{e^{-\Gamma t}}{2} \left( \cosh \frac{1}{2} \Delta \Gamma t \pm \cos \Delta m t \right) \quad \Gamma = (\Gamma_L + \Gamma_H)/2 \text{ and } \Delta \Gamma = \Gamma_H - \Gamma_L \end{aligned}$$

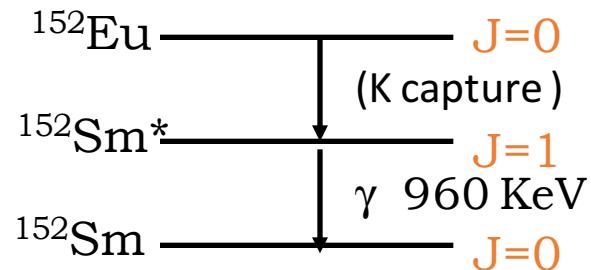
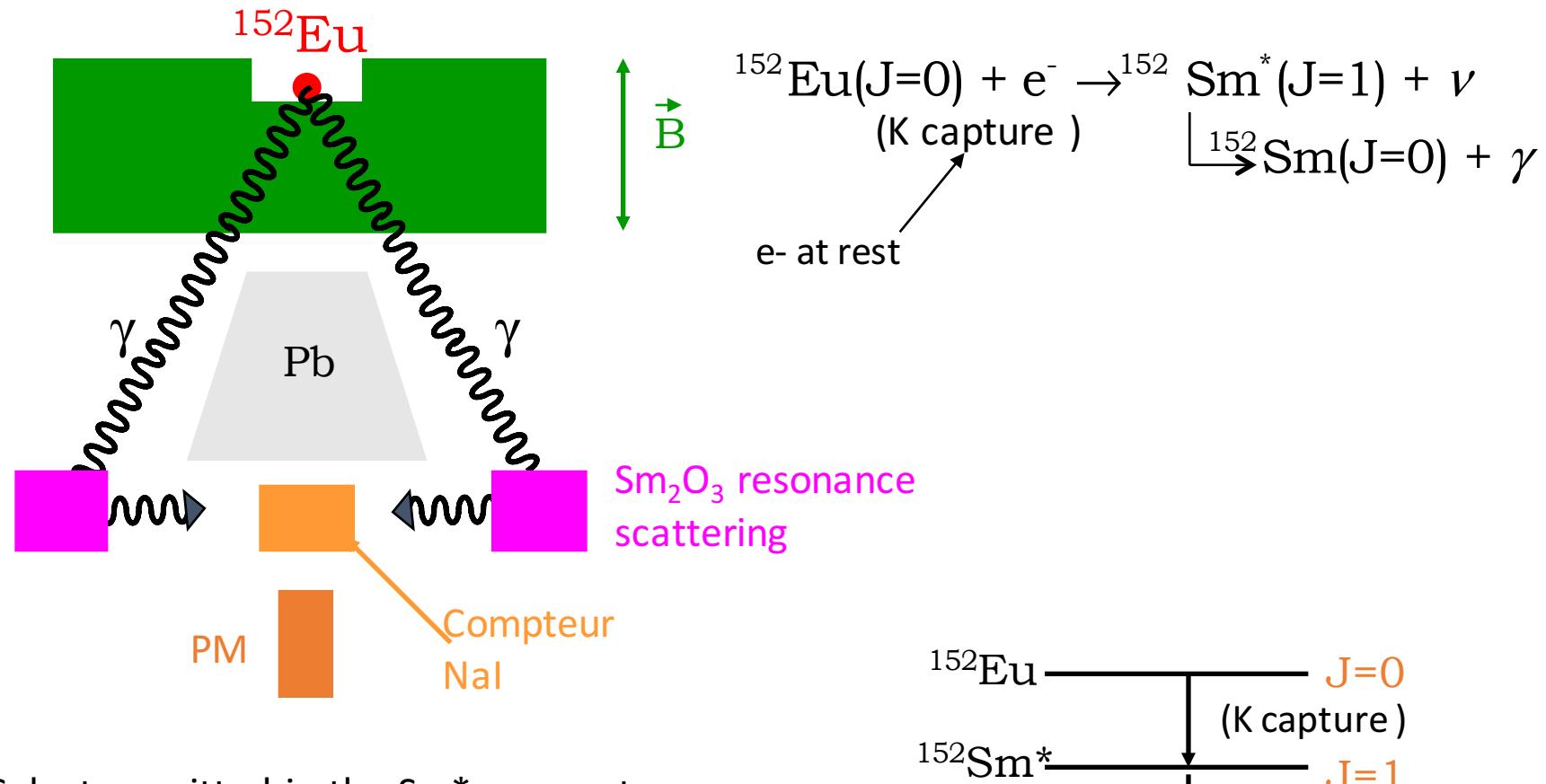
For the  $B^0$  case where  $\Delta \Gamma \sim 0$  and assuming no CPV in the mixing



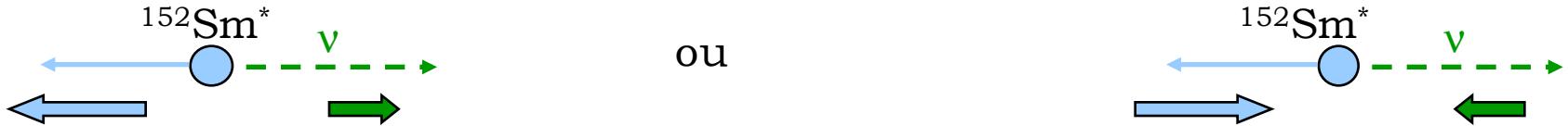
# Goldhaber experiment

Helicity : projection of the spin on the momentum direction

(Phys. Rev. 109:1015-1017, 1958)



- reaction :  $^{152}\text{Eu}(\text{J}=0) + e^- \rightarrow ^{152}\text{Sm}^*(\text{J}=1) + \nu$   
 $J_i = \frac{1}{2} \Rightarrow J_f = \frac{1}{2} \Rightarrow$  opposite spin projections for the  $\text{Sm}^*$  and the  $\nu \Rightarrow$  same helicities



- reaction:  $^{152}\text{Sm}^*(\text{J}=1) \rightarrow ^{152}\text{Sm}(\text{J}=0) + \gamma$  (forbidden  $J_z(\text{Sm}^*) = 0$ )  
The  $\gamma$  is emitted forward in the  $^{152}\text{Sm}^*$  direction  
The 3 final state particles ( $\text{Sm}$ ,  $\gamma$  et  $\nu$ ) are colinear .

- Final state particles helicity :  $S(\nu)=\pm 1/2$ ,  $S(\gamma)= \pm 1$ ,  $S(e)= \pm 1/2$

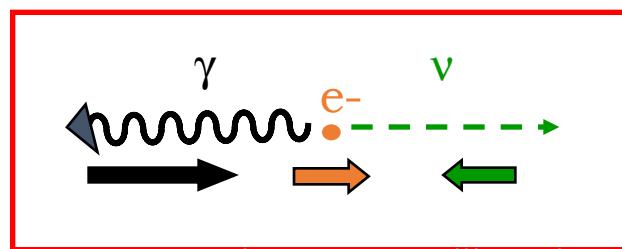
Two possible configurations :



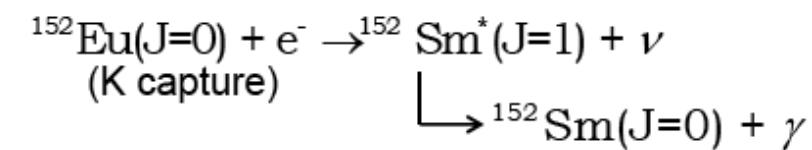
⇒ the helicities of the  $\gamma$  and  $\nu$  are the same.

- The  $\gamma$  polarisation is measured to measure the neutrinos helicity

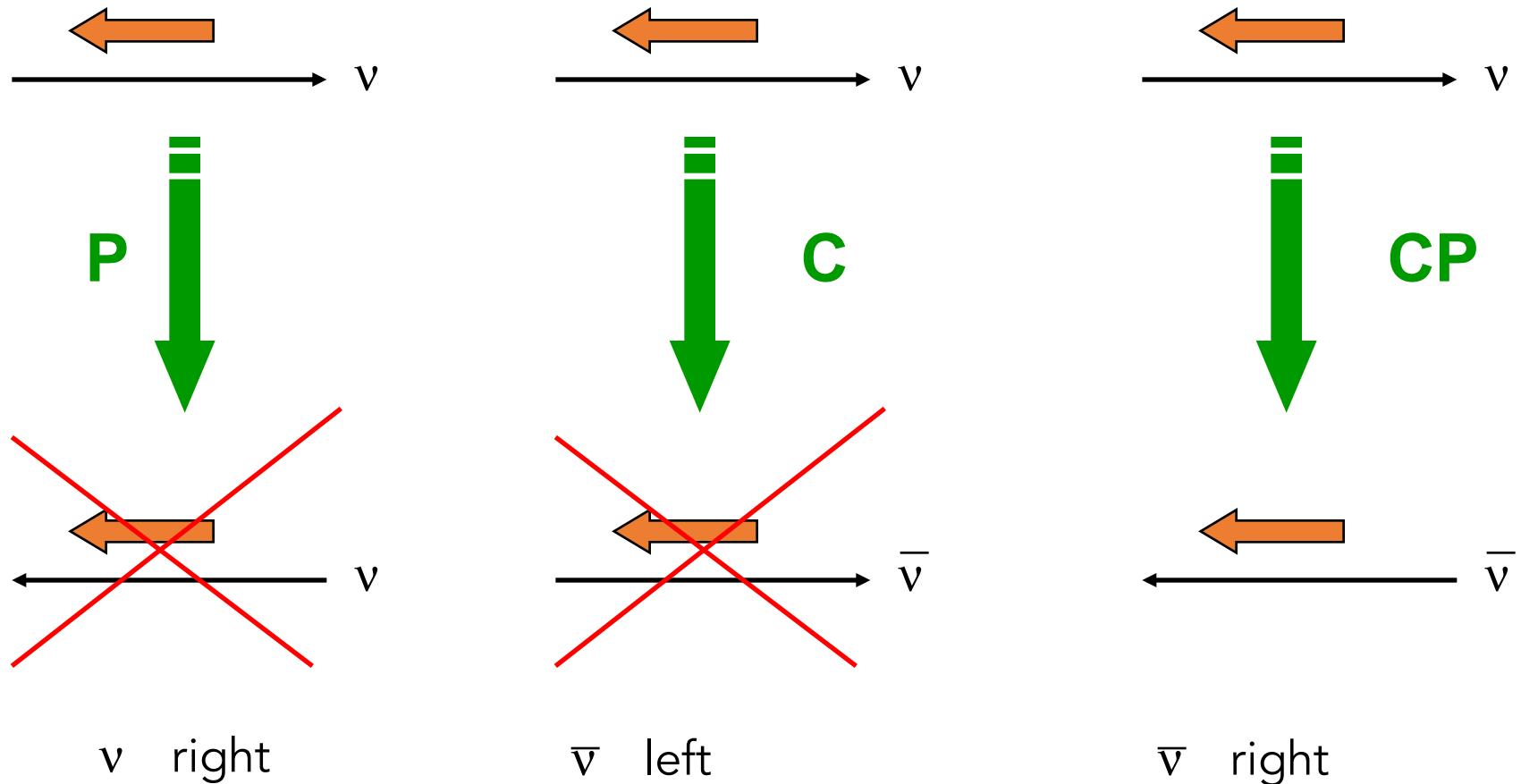
Only left handed neutrinos are seen



$\gamma$  polarisation is measured using spin flip in magnetic field

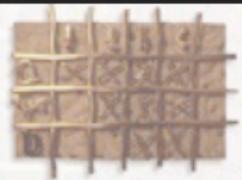


C et P are automatically violated in weak decays involving neutrinos :



One sees that the anti-particles helicity is the opposite of the particles helicity.

The v is left handed (the anti-neutrino is right handed)



# Parity symmetry breaking

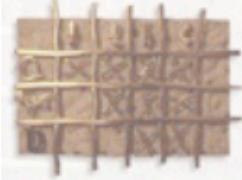
Aparté: what is the helicity? What is the chirality?

Let's have a look first to the solutions ( $E > 0$ ) of Dirac equation written in the Pauli-Dirac basis:

$$\gamma^0 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix} \quad \gamma^k = \begin{pmatrix} 0 & \sigma_k \\ -\sigma_k & 0 \end{pmatrix} \quad \gamma^5 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

For the sake of the simplicity of the notation, I consider the momentum along the z coordinate only.

$$u_1 = \sqrt{E + m} \begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix} \quad u_2 = \sqrt{E + m} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -\frac{p}{E+m} \end{pmatrix}$$



# Parity symmetry breaking

Aparté: what is the helicity? What is the chirality?

$$\hat{h} = \frac{1}{2} \vec{p} \cdot \vec{\sigma} = \frac{1}{2} p \cdot \begin{pmatrix} \sigma_3 & 0 \\ 0 & \sigma_3 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\hat{h} = \frac{p}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad u_1 = \sqrt{E+m} \begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix}$$
$$u_2 = \sqrt{E+m} \begin{pmatrix} 0 \\ 1 \\ 0 \\ -\frac{p}{E+m} \end{pmatrix}$$

$$\hat{h} \cdot u_1 = \frac{1}{2} u_1 ,$$

$$\hat{h} \cdot u_2 = -\frac{1}{2} u_2 .$$

*u<sub>1</sub>* and *u<sub>2</sub>* are helicity eigenstates



# Parity symmetry breaking

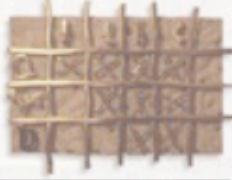
Aparté: what is the helicity? What is the chirality?

Let's project those states with the chirality projectors:

$$P_L = \frac{1}{2}(1 - \gamma^5) = \begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix} \quad P_R = \frac{1}{2}(1 + \gamma^5) = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix} \quad u_1 = \sqrt{E+m} \begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix}$$

$$P_L u_1 = \frac{1}{2} \sqrt{E+m} \begin{pmatrix} 1 - \frac{p}{E+m} \\ 0 \\ -1 + \frac{p}{E+m} \\ 0 \end{pmatrix} \quad P_R u_1 = \frac{1}{2} \sqrt{E+m} \begin{pmatrix} 1 + \frac{p}{E+m} \\ 0 \\ 1 + \frac{p}{E+m} \\ 0 \end{pmatrix}$$

$$u_1 = P_L u_1 + P_R u_1 = \frac{1}{2} \left(1 - \frac{p}{E+m}\right) \sqrt{E+m} \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} + \frac{1}{2} \left(1 + \frac{p}{E+m}\right) \sqrt{E+m} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$



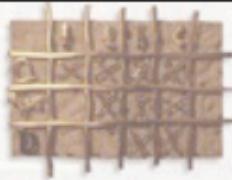
# Parity symmetry breaking

Aparté: what is the helicity? What is the chirality?

$$u_L = \sqrt{E + m} \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} \quad u_R = \sqrt{E + m} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

$$u_1 = P_L u_1 + P_R u_1 = \frac{1}{2} \left(1 - \frac{p}{E + m}\right) \sqrt{E + m} \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix} + \frac{1}{2} \left(1 + \frac{p}{E + m}\right) \sqrt{E + m} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

$$u_1 = P_L u_1 + P_R u_1 = \frac{1}{2} \left(1 - \frac{p}{E + m}\right) u_L + \frac{1}{2} \left(1 + \frac{p}{E + m}\right) u_R$$



# Parity symmetry breaking

Aparté: what is the helicity? What is the chirality?

$$u_1 = P_L u_1 + P_R u_1 = \frac{1}{2} \left(1 - \frac{p}{E+m}\right) u_L + \frac{1}{2} \left(1 + \frac{p}{E+m}\right) u_R$$

- For a massless particle, helicity IS chirality.
- For ultra-relativistic particles ( $E \gg m$ ), helicity IS chirality.
- The heavier is a particle, the larger is the mixing of chiral states for a given helicity.

# $CP$ violation and time dependence

Starting once again from the time evolution of the  $B^0$  and  $\bar{B}^0$  mesons  
 time-dependent rates of an initially pure flavor state :

$$\left| \langle f | H | B^0(t) \rangle \right|^2 = |A_f|^2 \cdot |g_+(t) + \lambda_f g_-(t)|^2 \text{ and } \left| \langle f | H | \bar{B}^0(t) \rangle \right|^2 = \left| \frac{p}{q} \right|^2 \cdot |A_f|^2 \cdot |g_-(t) + \lambda_f g_+(t)|^2$$

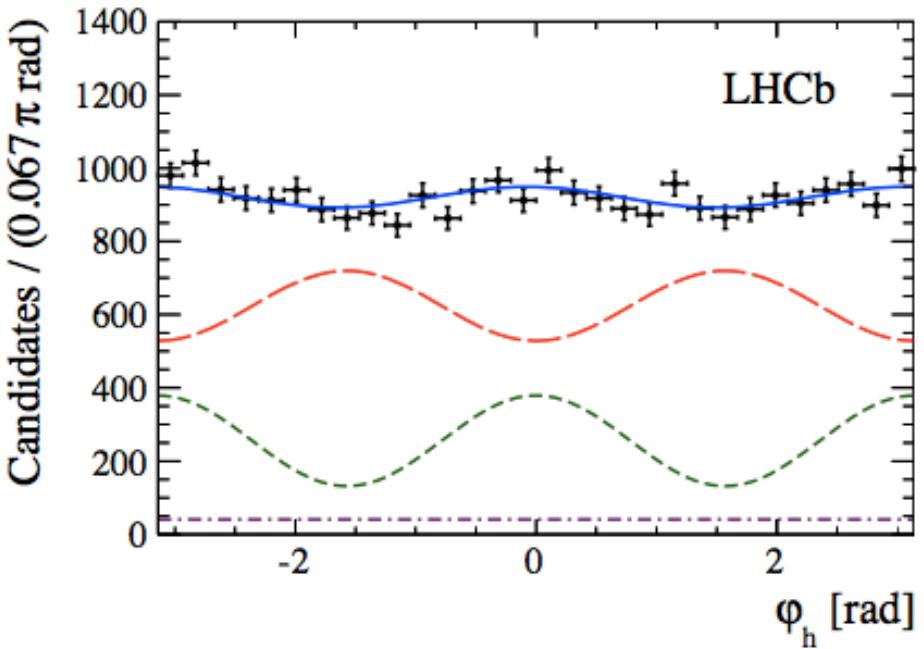
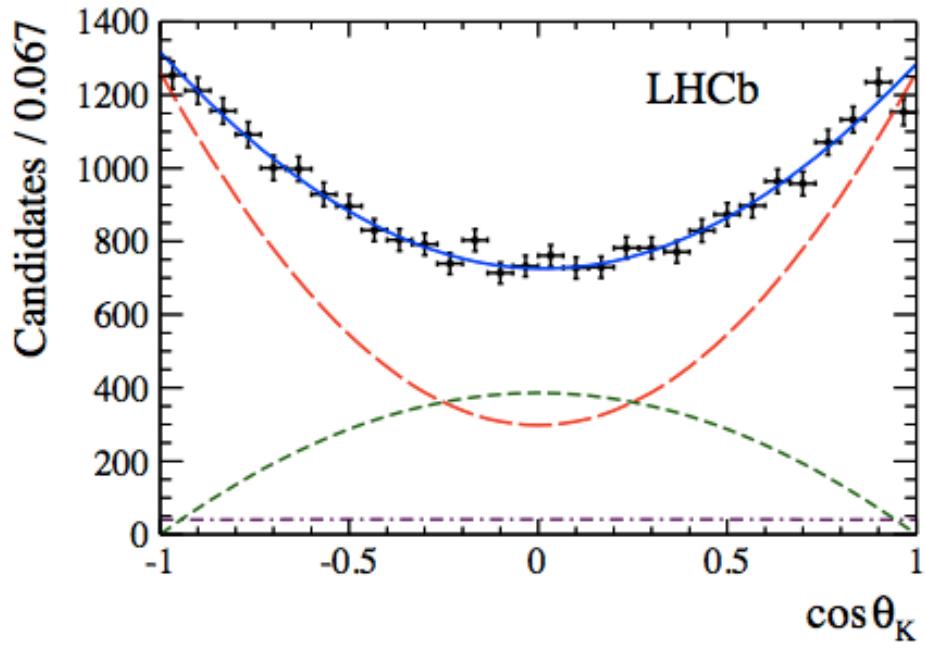
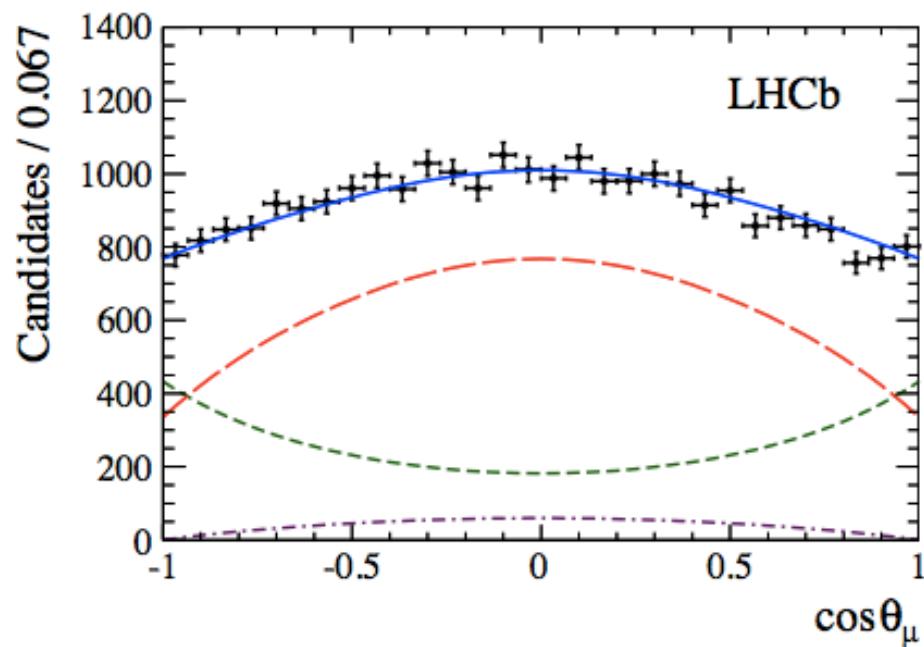
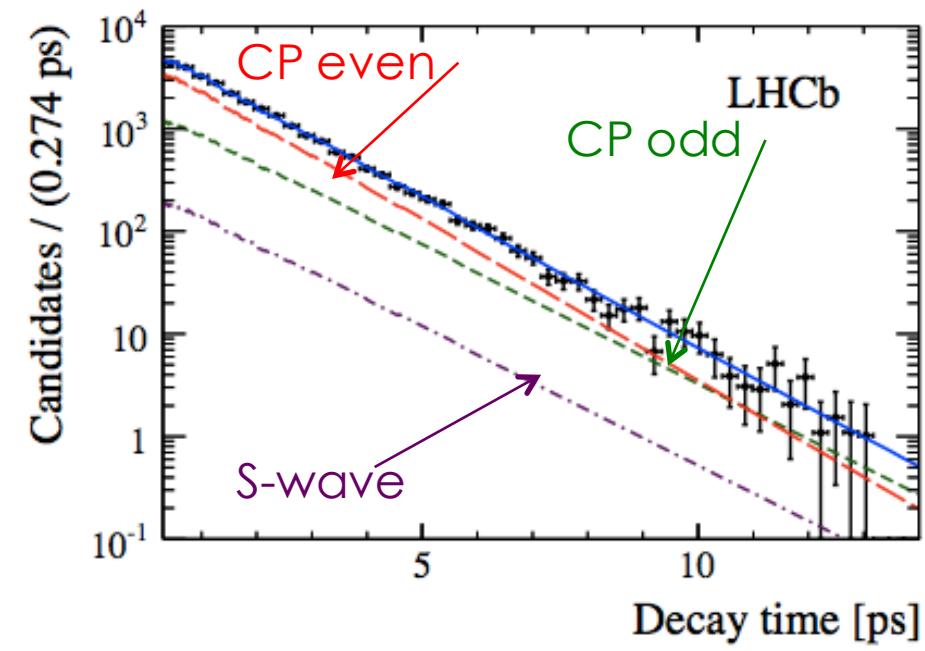
$$\lambda_f = \frac{q}{p} \frac{\langle f | H | \bar{B}^0 \rangle}{\langle f | H | B^0 \rangle} \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f}$$

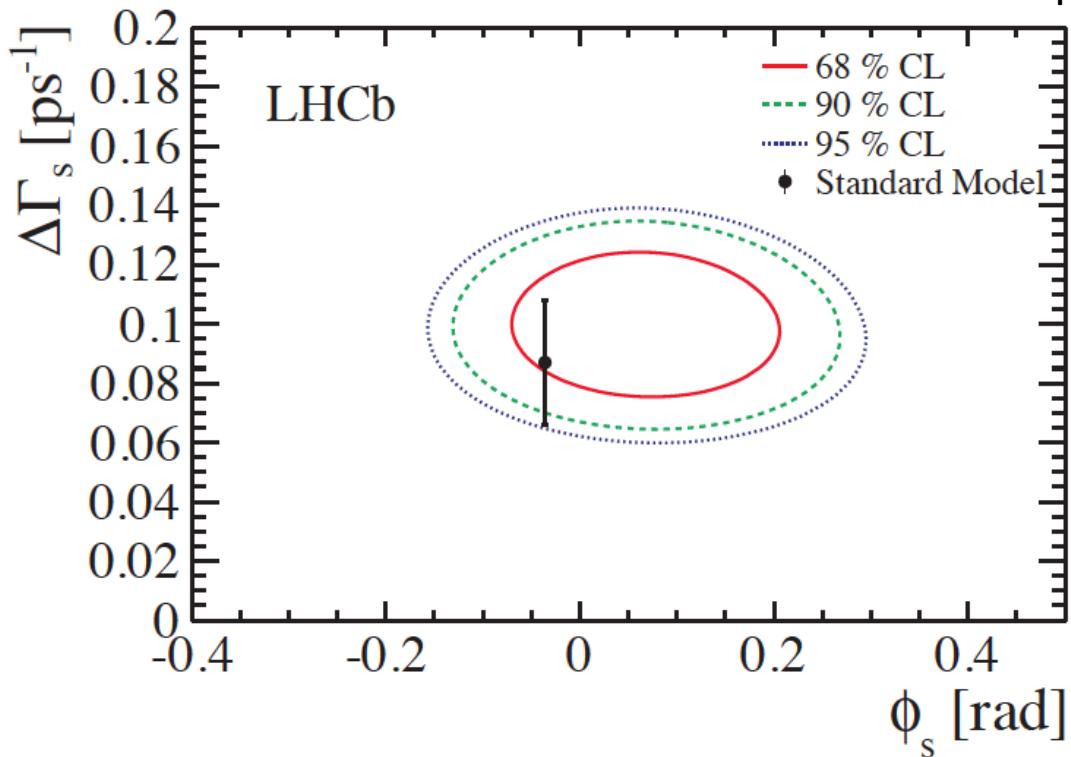
after some trigonometry and assuming no CPV in mixing ( $|q/p| = 1$ ) (exp. checked)

$$\begin{aligned} \left| \langle f | H | B^0(t) \rangle \right|^2 &= e^{-t/\tau_B} \cdot |A_f|^2 \frac{1+|\lambda_f|^2}{2} [1 + C_f \cos(\Delta m_d t) - S_f \sin(\Delta m_d t)] & C_f &= \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \\ \left| \langle f | H | \bar{B}^0(t) \rangle \right|^2 &= e^{-t/\tau_B} \cdot |A_f|^2 \frac{1+|\lambda_f|^2}{2} [1 - C_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t)] & S_f &= \frac{2 \operatorname{Im}[\lambda_f]}{1+|\lambda_f|^2} \end{aligned}$$

$|\lambda_f|^2$  : direct CPV

$\operatorname{Im}[\lambda_f]$  : CPV in the interference between mixing and decay





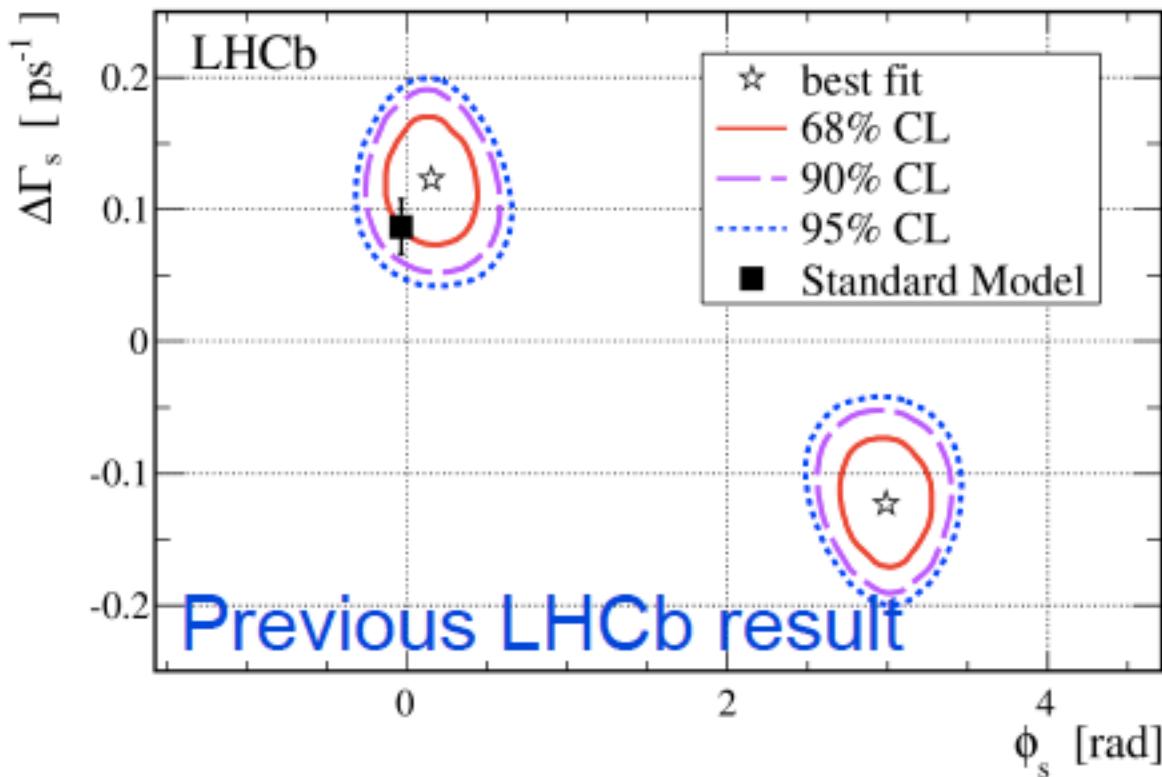
Combined LHCb result with  $B_s^0 \rightarrow J/\psi \varphi$ ,  $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

$$\phi_s = 0.01 \pm 0.07(\text{stat}) \pm 0.01(\text{syst}) \text{ rad},$$

$$\Gamma_s = 0.661 \pm 0.004(\text{stat}) \pm 0.006(\text{syst}) \text{ ps}^{-1},$$

$$\Delta\Gamma_s = 0.106 \pm 0.011(\text{stat}) \pm 0.007(\text{syst}) \text{ ps}^{-1}.$$

Until recently there was a two-fold ambiguity in the measurement of the CP-violating phase



How did the other (non-SM) option go away?

$K^+K^-$  P-wave :

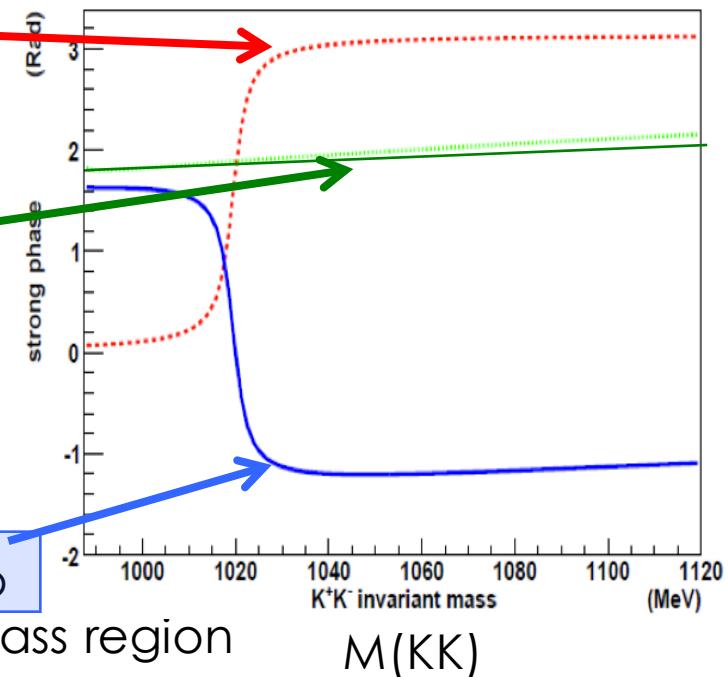
Phase of Breit-Wigner amplitude increases rapidly across  $\phi(1020)$  mass region

$K^+K^-$  S-wave:

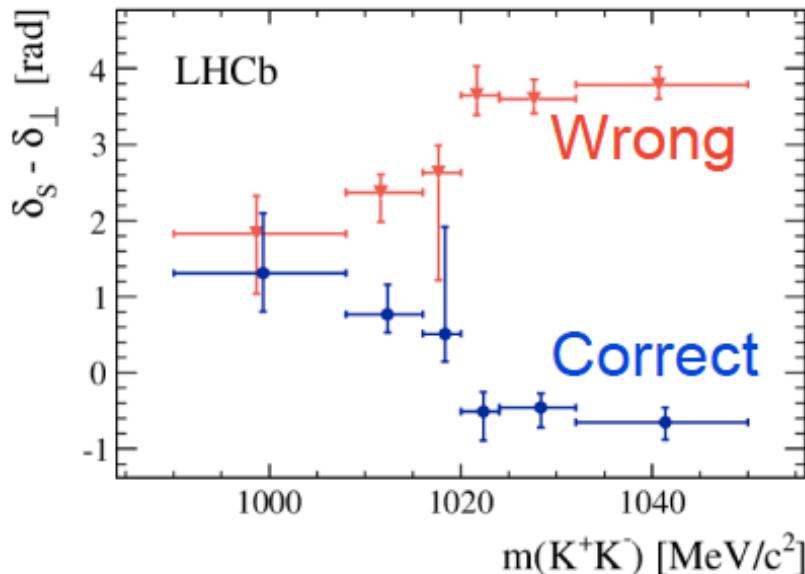
Phase of Flatté amplitude for  $f_0(980)$  relatively flat (similar for non-resonance)

Phase difference between S- and P-wave amp

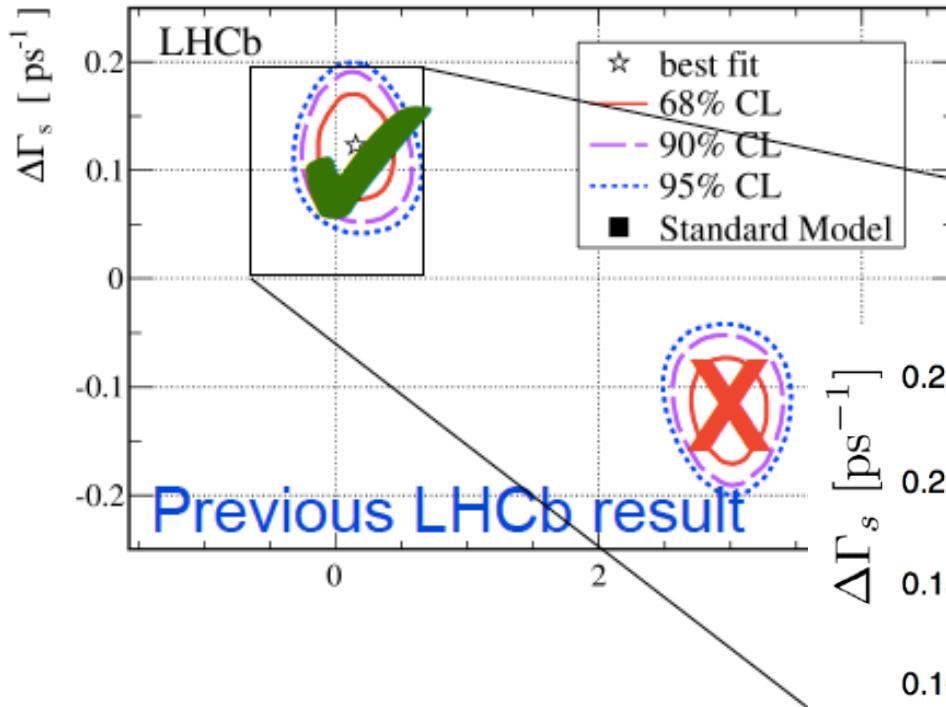
$\delta_{S\perp} = \delta_S - \delta_\perp$  decreases rapidly across  $\phi(1020)$  mass region



Get the sign of phase shift wrong if picking wrong  $(\phi_s, \Delta\Gamma_s)$  solution



# The unique solution can now be identified



Previous LHCb result

