Experimental heavy flavours

- Setting up the scene
- Heavy Flavours and the SM in a nutshell
- Experimental considerations
- Selected results
- Future

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European Research Council
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CHIARO SCURO

Interplay with lectures from
Diego Guadagnoli
Andreas Crivellin
Alberto Lusiani

Some useful links

- Heavy Flavour Averaging Group (HFLAV) https://hflav.web.cern.ch
- The Review of Particle Physics pdg.lbl.gov
- CKMfitter ckmfitter.in2p3.fr Utfit www.utfit.org/UTfit/
- Lectures notes : Y. Grossman & P. Tanedo, arXiv:1711.03624
- Recent results from ICHEP22 : https://agenda.infn.it/event/28874/timetable/#20220706

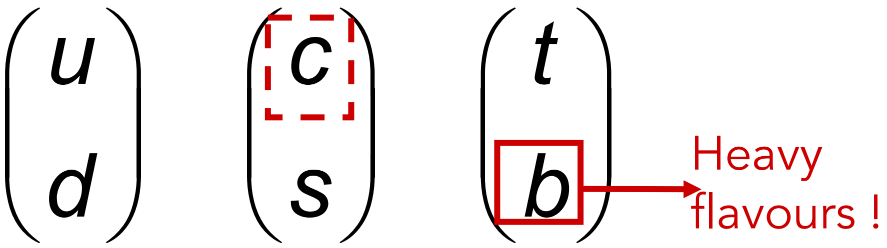
DISCLAIMER

No time to discuss

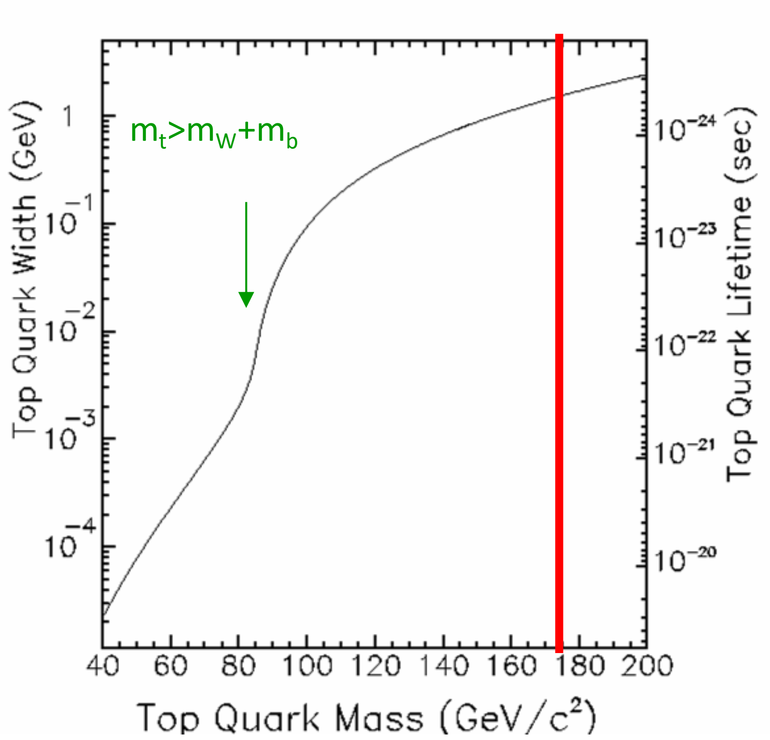
- Semileptonic decays (R(D*) !)
- Charm physics (discovery of CP violation in charm !)
- Kaon physics : in particular K $\rightarrow \pi \nu \bar{\nu}$
- The new zoo of particles (tetraquarks, pentaquarks)

Setting up the scene

Heavy flavours



Theoretical calculations easier in the case of hadrons composed of an heavy + light quarks



Phys. Lett. B 181 (157)

Why not the top quark ?

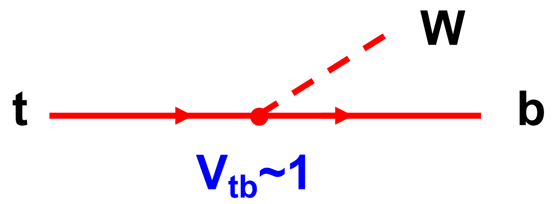
The decay $\propto m^5 \Rightarrow$ extremely short lifetime

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

$\Rightarrow$ no top hadrons

Study of top-quark is a field of research in its own (mostly ATLAS and CMS currently)

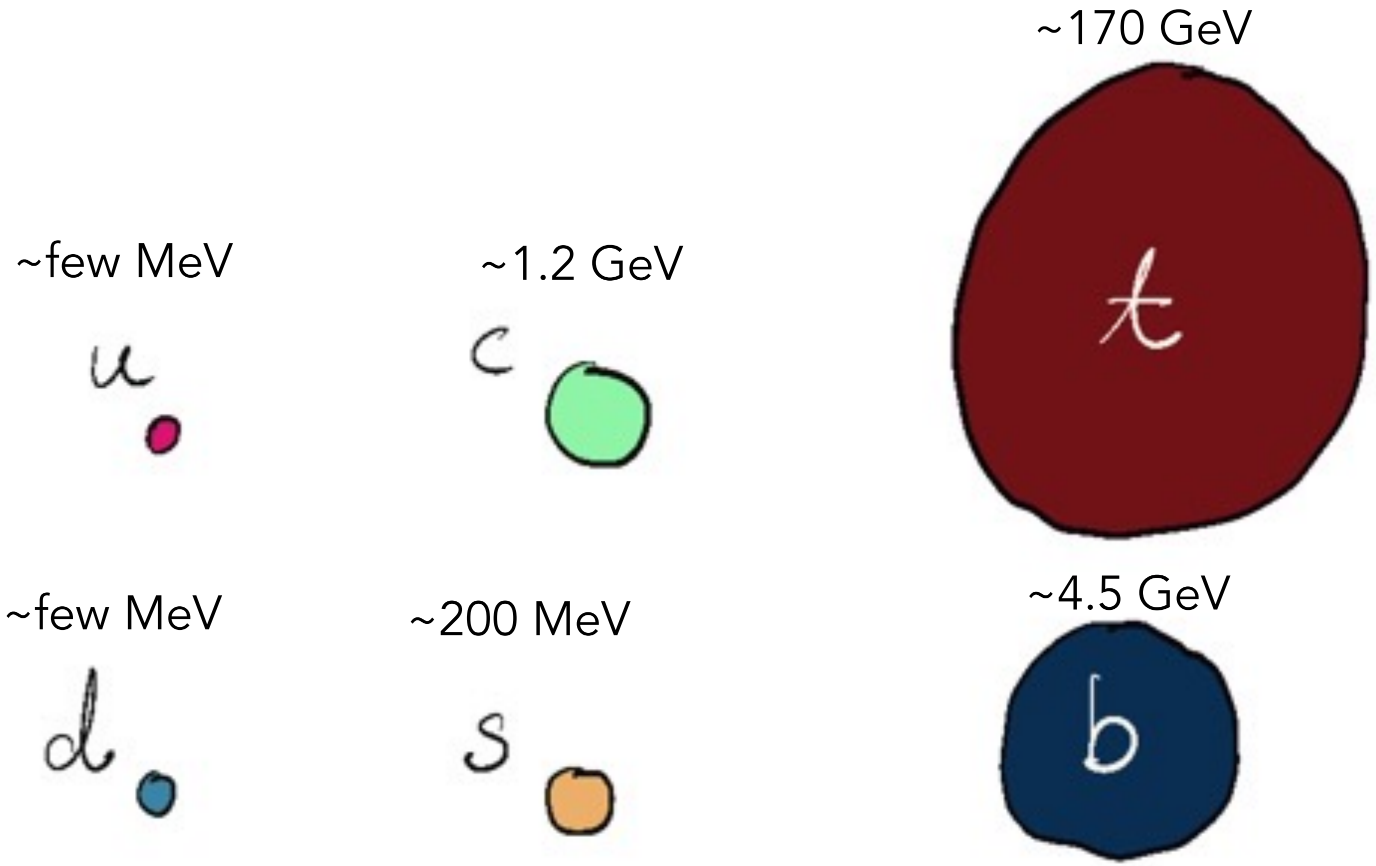
Importance of the top mass value in the electroweak gauge sector.



Tevatron + LHC (PDG) :
$|V_{tb}| = 1.014 \pm 0.029$

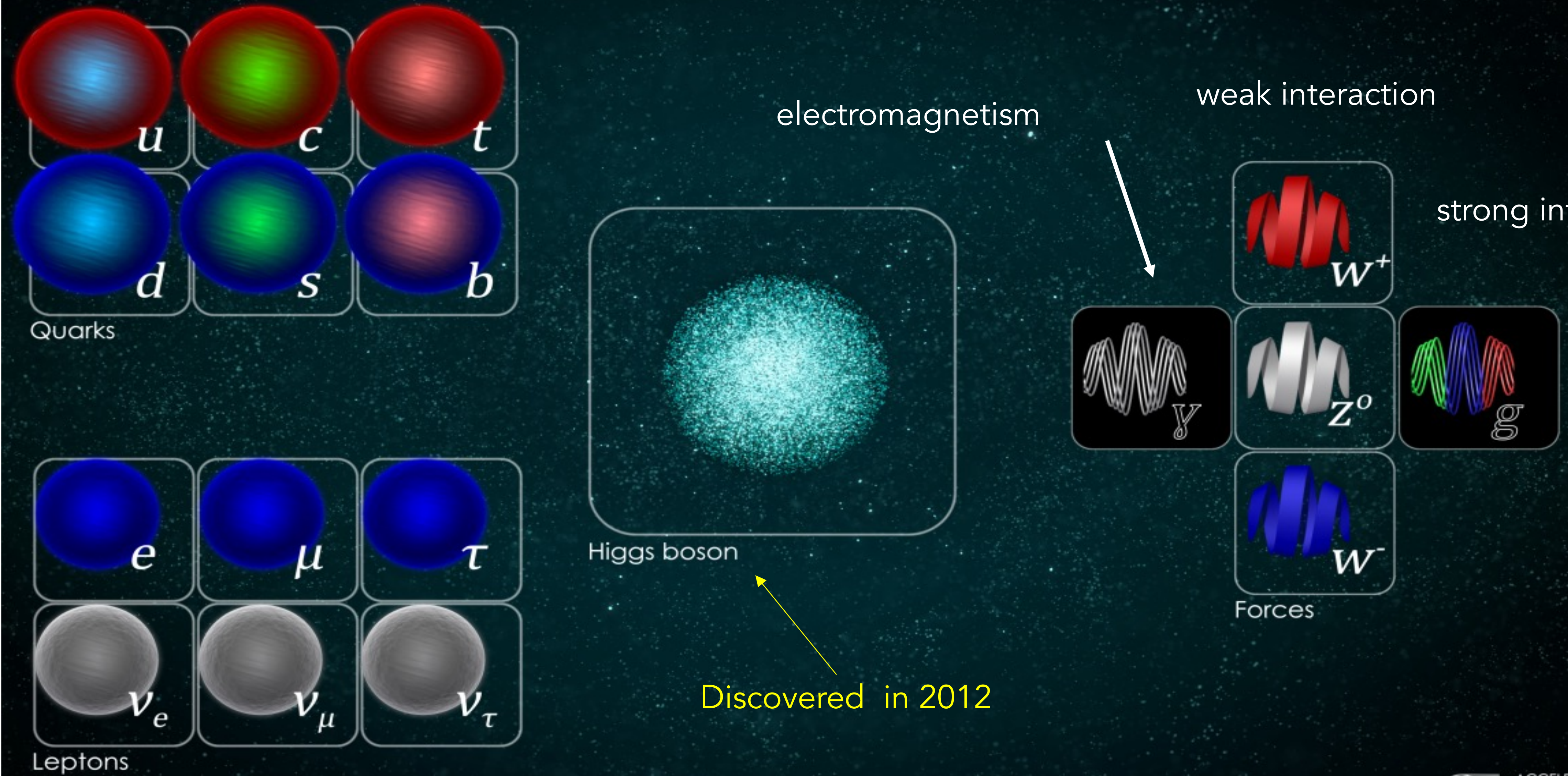
Flavour in the Standard Model

- different families
- 6 flavours of quarks in the SM: how do they couple to each other ?



approximate mass (MeV)

The Standard Model



electromagnetism

weak interaction

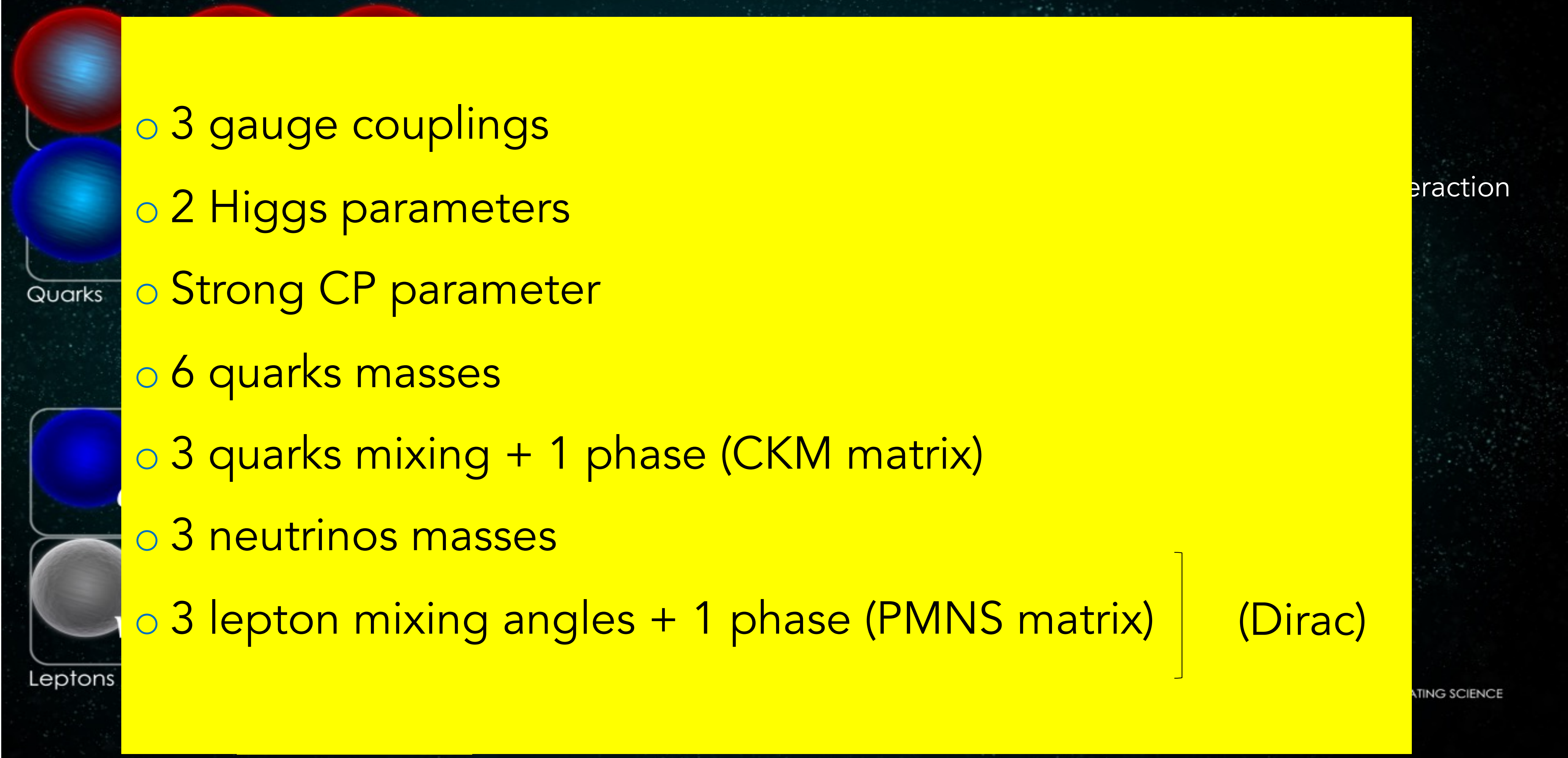
strong interaction

Discovered in 2012

+anti-matter

CERN ACCELERATING SCIENCE

The Standard Model



- 3 gauge couplings
- 2 Higgs parameters
- Strong CP parameter
- 6 quarks masses
- 3 quarks mixing + 1 phase (CKM matrix)
- 3 neutrinos masses
- 3 lepton mixing angles + 1 phase (PMNS matrix) (Dirac)

Standard Model

describes precisely a (very) large number of precise measurements

Does not explain various key-questions/observations :

- Dark matter candidate ?
- Large baryon asymmetry observed in the Universe
- Why 3 families ?
- Origin of the hierarchy of the W bosons couplings to the different quarks ?

~1980 - 2012: theory-guided
today: experimentally guided ?

How to find cracks in the SM fortress ?

Heavy flavours physics

Direct evidence for new particles

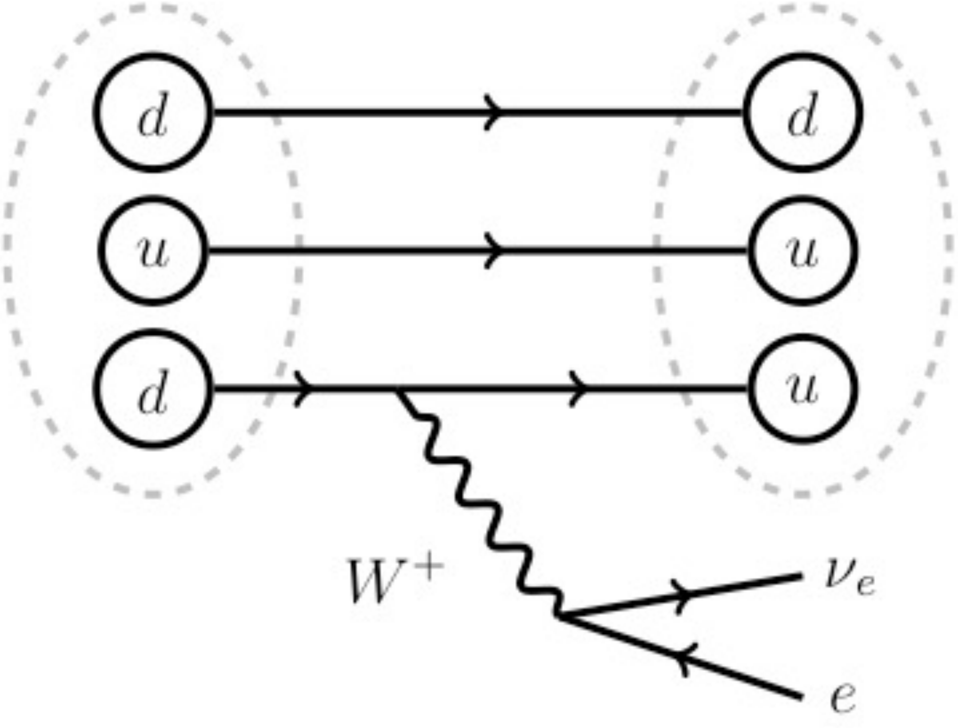
Indirect evidence through precision measurements sensitive to the presence of virtual states present in the decay of SM particles

Indirect searches

β decay of the neutron

Phenomena taking place at ~ 1 GeV reveals physics at the 100 GeV scale

M ~ 1 GeV

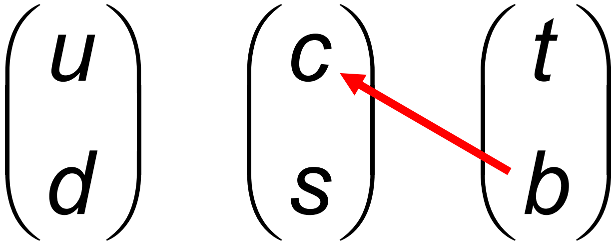


M ~ 1 GeV

The *b*-hadrons

1977

- The heaviest quark that forms bound states (mB ~ 5.3 GeV)
- Decays 'outside' its family



⇒ large lifetime ~ 1.5 ps : clear exp. signature (Si vertex detectors)

⇒ very large number of decays modes

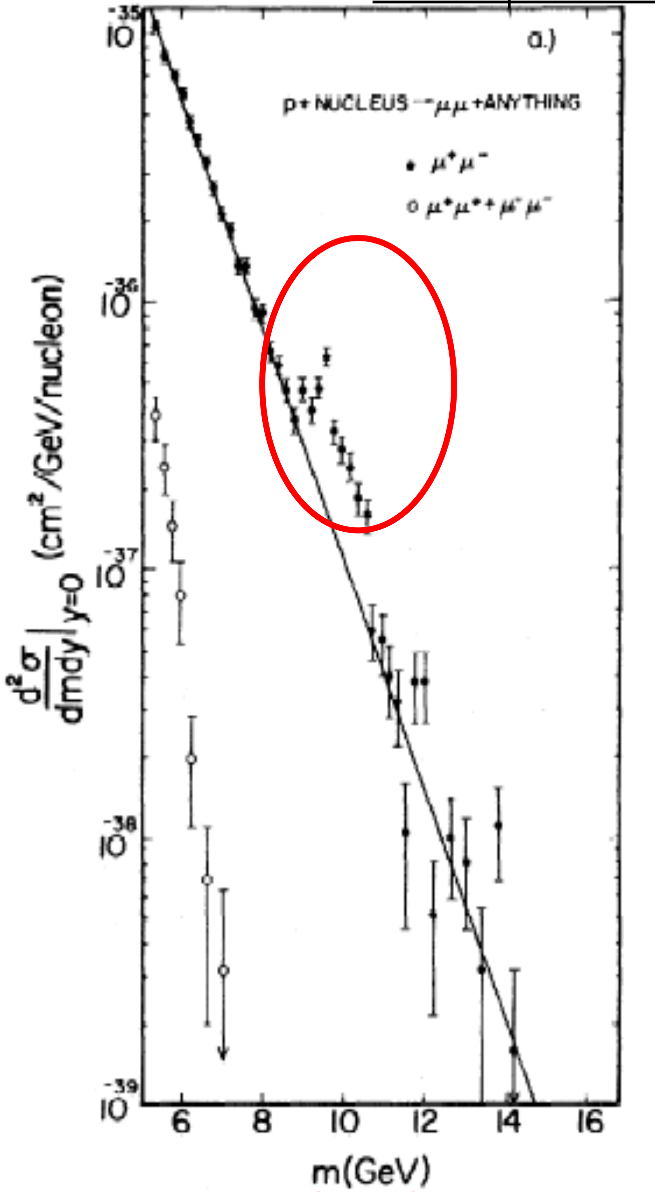
- CKM matrix

⇒ large CP violation effects

The ideal tool to search for signs of physics beyond SM

9.5-10.5 GeV : the series of ϒ

E288 experiment



Excess larger than the experimental resolution ⇒ > 1 resonance

The top quark at an e+ e- collider with √s=10 GeV in 1987 !

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

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

First hint of a *really large* m_{top}!

Argus Collaboration
Phys Lett B 192 p454

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

$$\approx 0.5\mathrm{ps}^{-1}$$

$\Rightarrow m_t > 50$ GeV

$B^0 \to D^{*-}\mu^+\nu$

$B^0 \to D^{*-}\mu^+\nu$

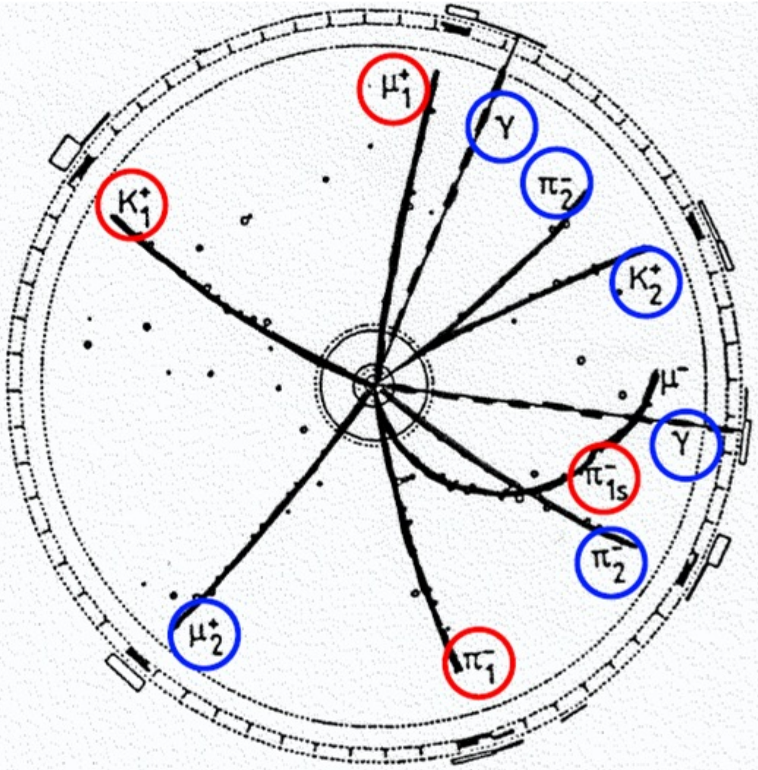
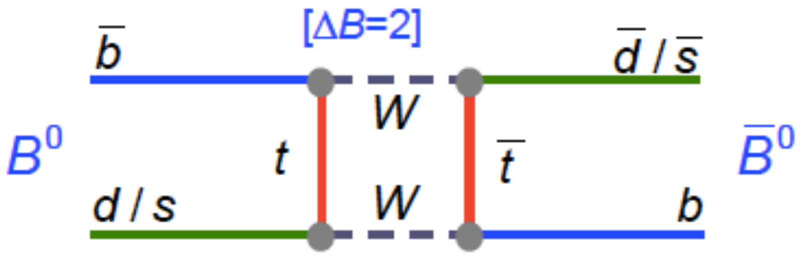


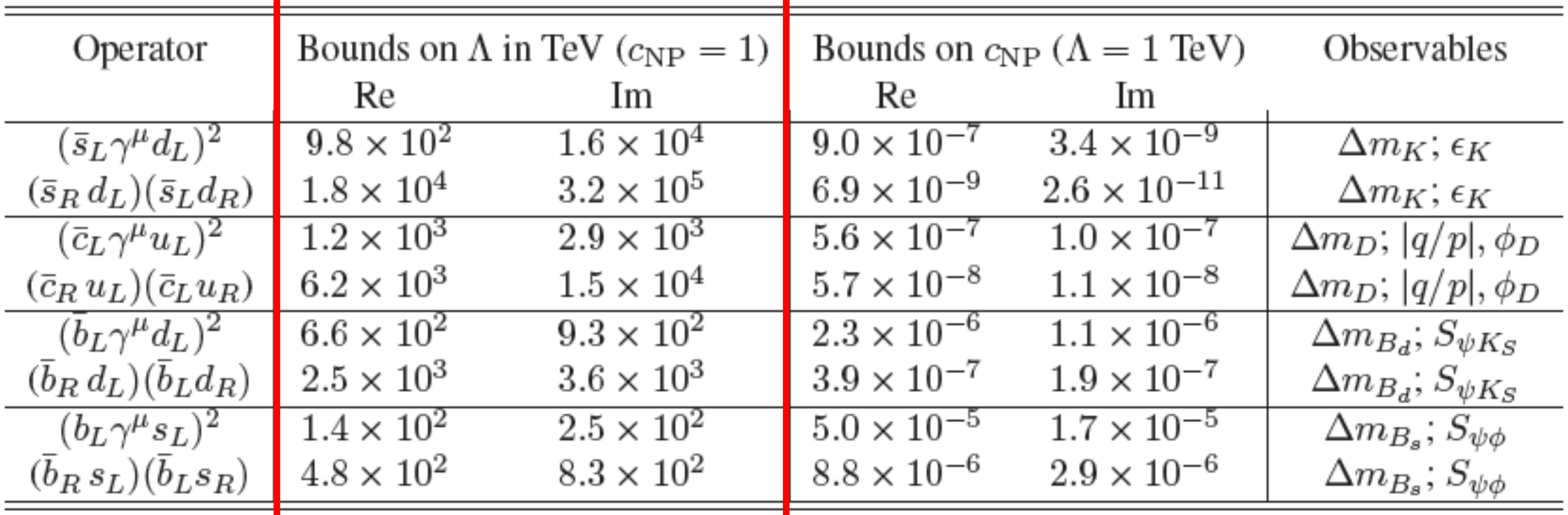
Fig. 11: The fully reconstructed ARGUS event [26] $e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0 \to B^0B^0$ as the first evidence for the occurance of $B^0\overline{B}^0$ oscillations.
$B^0 \to D_1^{*-}\mu_1^+\nu_1$,
$D_1^{*-} \to \pi_{1s}^-\overline{D}^0$, $\overline{D}^0 \to K_1^+\pi_1^-$.
$\overline{B}^0 \to B^0 \to D_2^{*-}\mu_2^+\nu$,
$D_2^{*-} \to \pi^0 D_2^-$,
$\pi^0 \to \gamma\gamma$, $D_2^- \to K_2^+\pi_2^-\pi_2^-$.



Flavour puzzle

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

NP scale and coupling



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

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

Large limits on the New Physics scale

why should NP follow the same flavour couplings (including same phase) as SM ?????

Heavy Flavours and the SM in a nutshell

Much more details in Diego's lectures

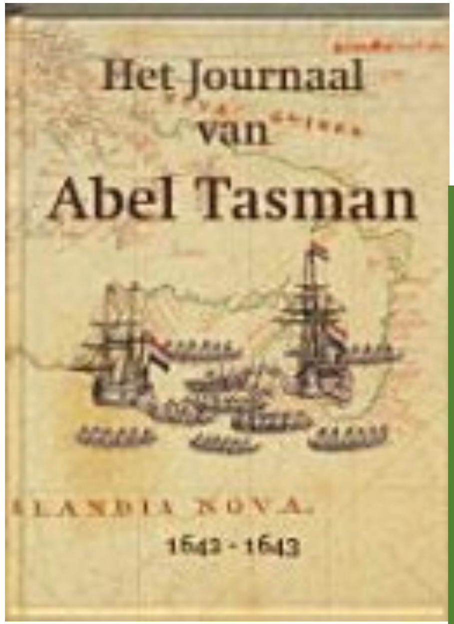
(

Symmetries are very important

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), ...



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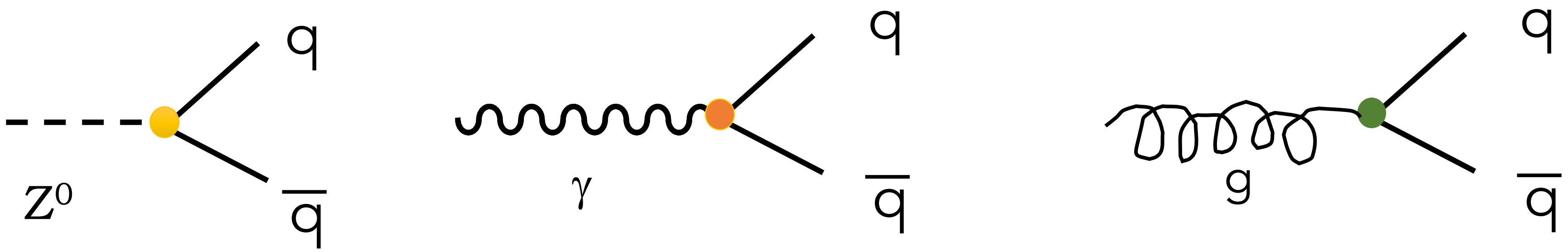
Abel Tasman 1603 –1659

Noether's theorem :
For any continuous symmetry for a given system corresponds a conservation law for this system.

Discrete symmetries

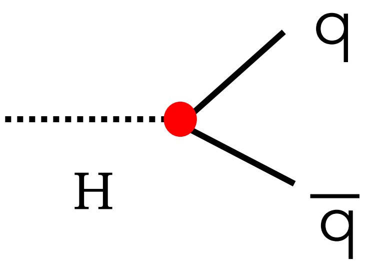
	P	C	T
Space vector x	-x	x	x
Momentum p	-p	p	-p
Spin s	s	s	-s

Quarks couplings in the SM

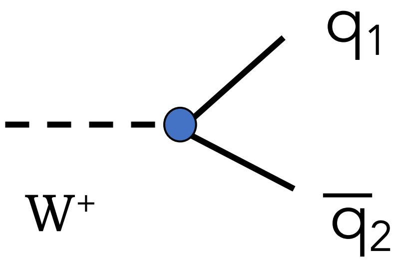


Photon, Z^0 and gluon : do not recognize the generations

Higgs couplings : flavour-diagonal and prop. to quark mass



Charged currents : flavour changing

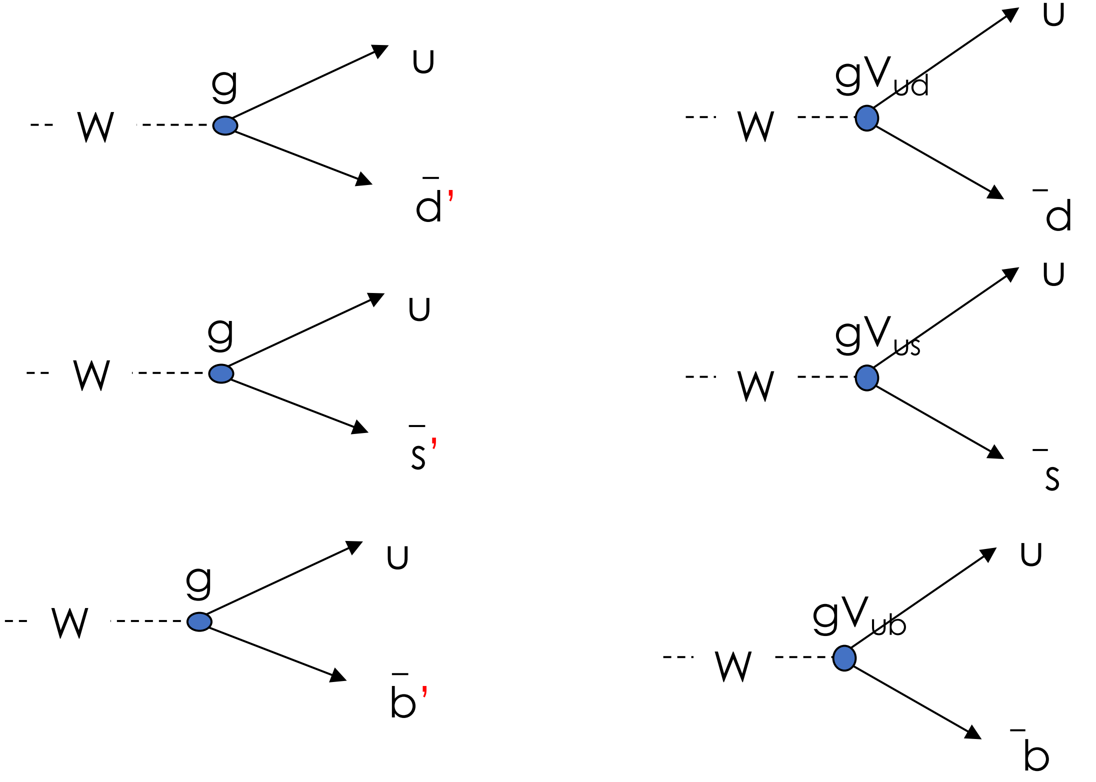


No Neutral Flavour Changing Current in the SM at tree level

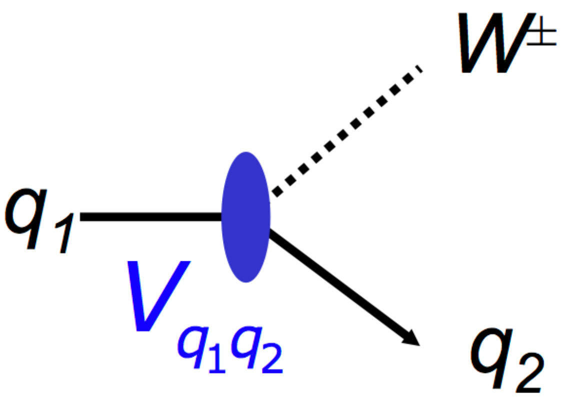
Weak interaction eigenstates ≠ Mass eigenstates (flavour or strong interaction eigenstates)

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

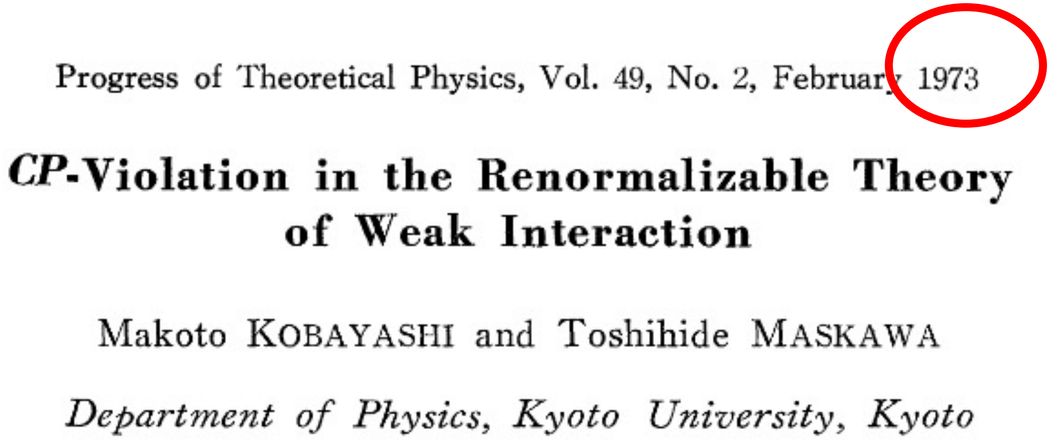
V_{CKM} Cabibbo-Kobayashi-Maskawa matrix



connected to the Higgs mechanism



$$V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = 1$$



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

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 4th quark

Prediction of the 3rd family

SM with 3 families: 3 angles (**θ_{ij}**) and one phase (**δ**)

V_{ub}

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

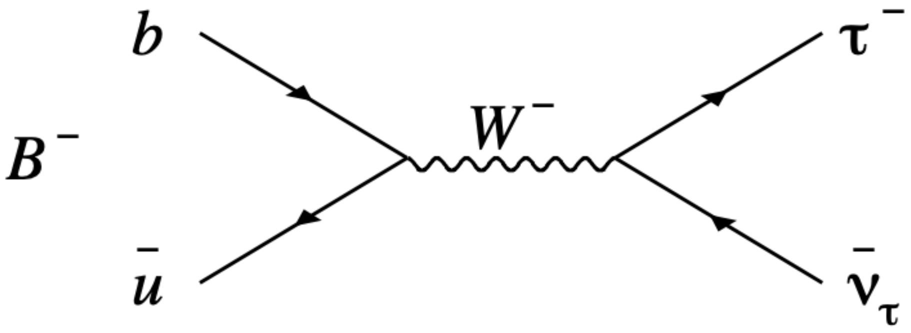
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

Measurements !

How to measure those numbers ?

Magnitudes are typically determined from branching ratios

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



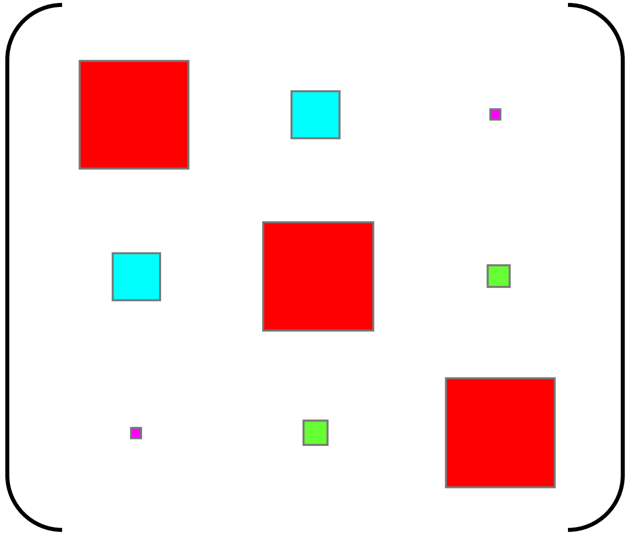
$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \underset{\uparrow}{f_B^2} |V_{ub}|^2 \tau_B$$

TH input

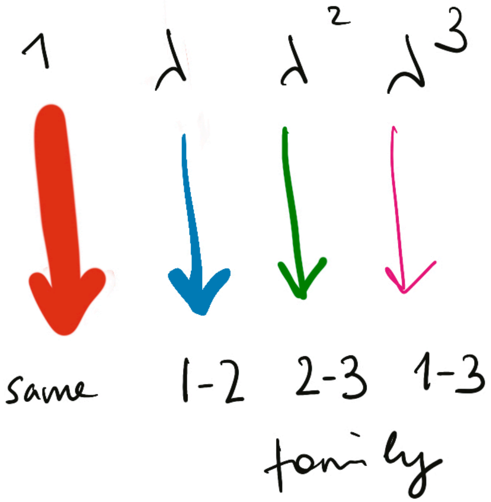
$$|V_{ub}| = (4.05 \pm 0.36) \times 10^{-3}$$

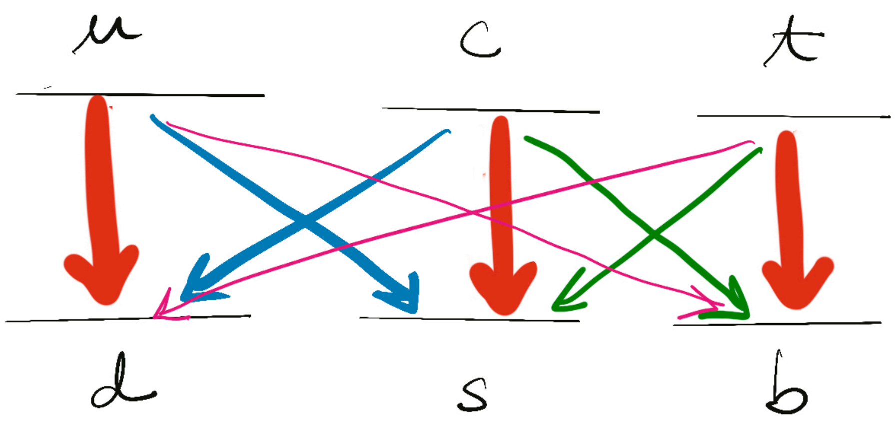
NB : only an example, other methods using other decays also exist !

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



Why this structure ?





→Wolfenstein parametrization in power of λ (=sinϑ_c) = s_{12} = $|V_{us}|$ ~ 0.22

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

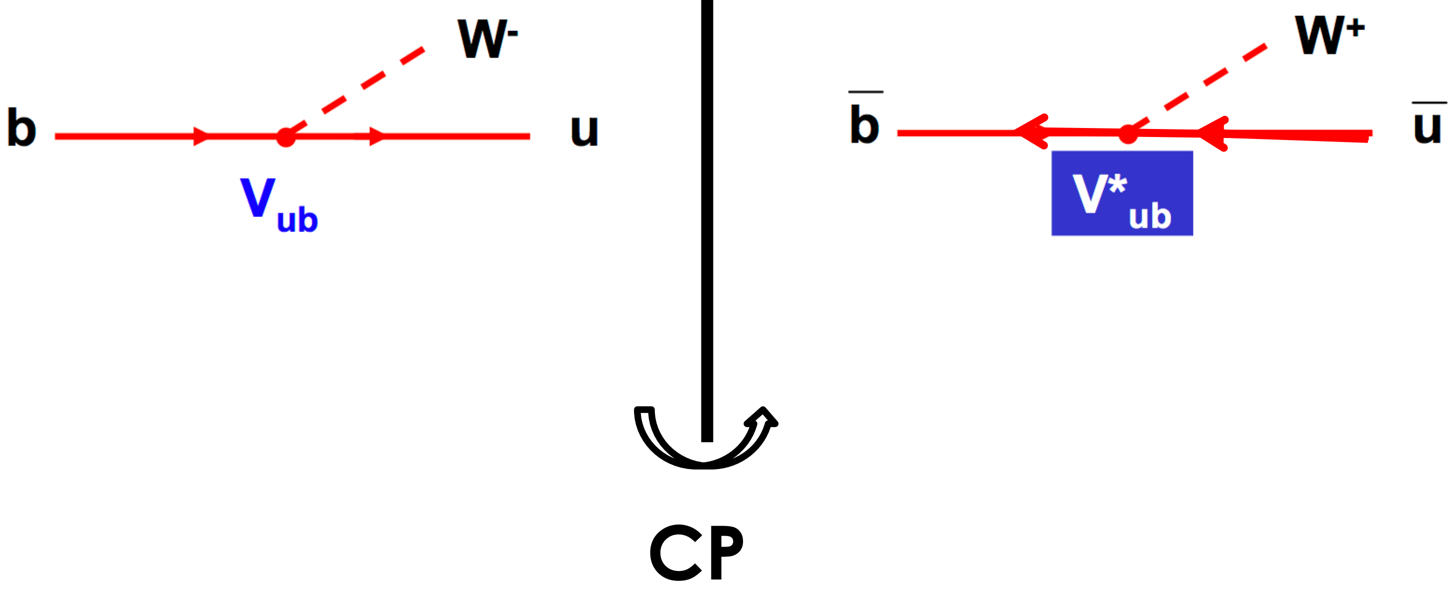
V_{ub}

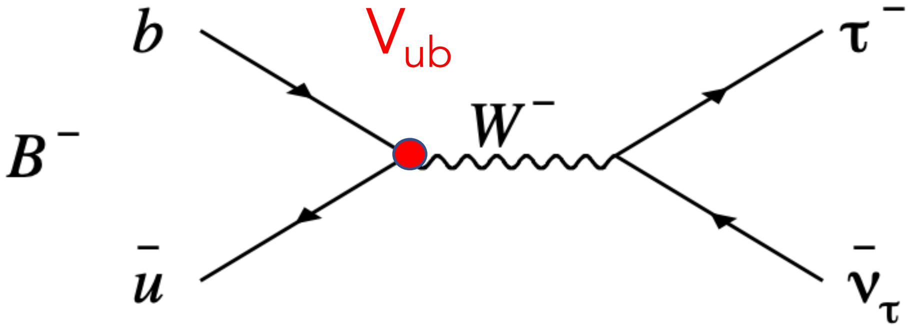
$$= \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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

V_{ub}

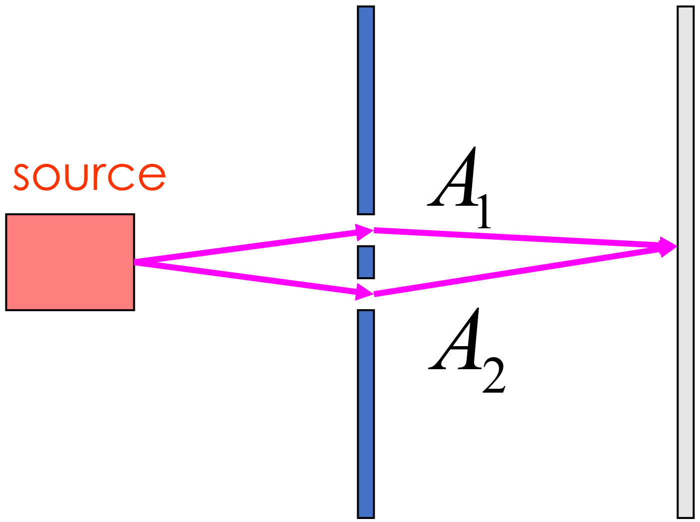
$V^*_{ub} \neq V_{ub}$ → CP violation

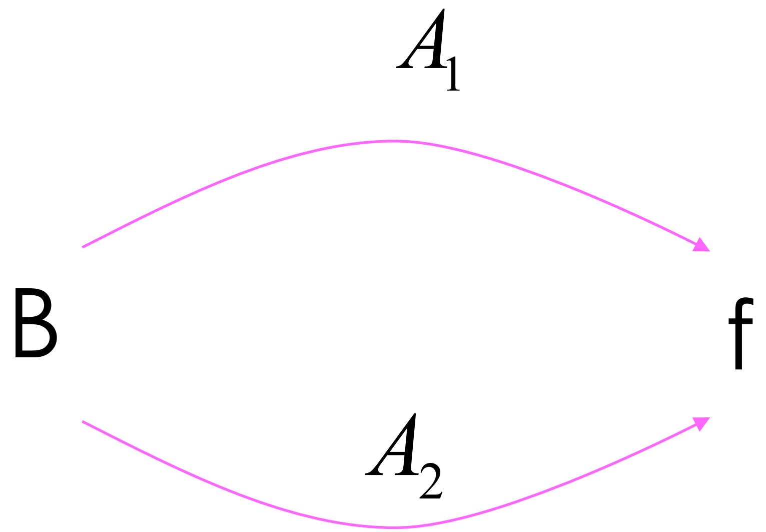




Could we use this decay mode to observe CP violation in the SM ?

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





Sensitivity to the phase difference

δ_i strong phase

ϕ_i weak phase

CP

$$A_f = A(B \to f) = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)}$$

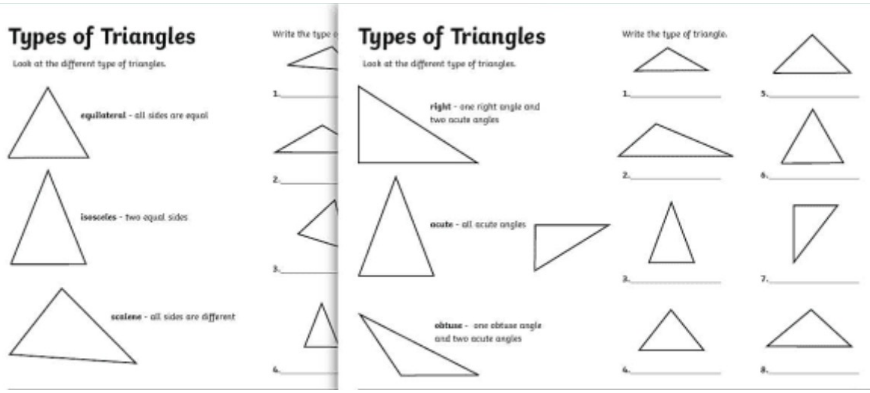
$$\bar{A}_{\bar{f}} = A(\bar{B} \to \bar{f}) = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

to observe CPV :

$\delta_1 \neq \delta_2$

$a_2 \neq 0$

Triangle(s)



Types of Triangles

Look at the different type of triangles.

equilateral - all sides are equal

isosceles - two equal sides

scalene - all sides are different

right - one right angle and two acute angles

acute - all acute angles

obtuse - one obtuse angle and two acute angles

Write the type of triangle.

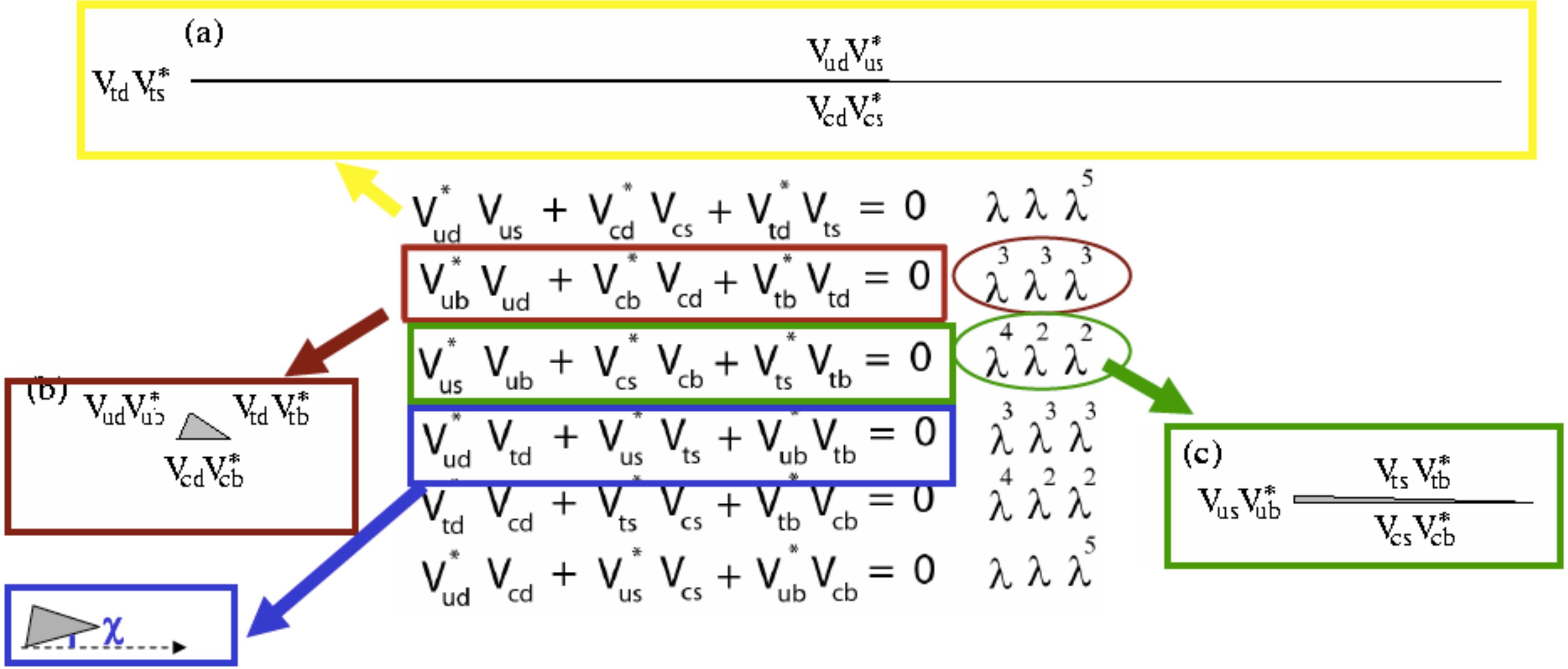
Stay within the 3 families

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

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 → 6 triangle equations



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

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

$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0 \qquad \lambda^4\ \lambda^2\ \lambda^2$$

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

$$V_{td} V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0 \qquad \lambda^4\ \lambda^2\ \lambda^2$$

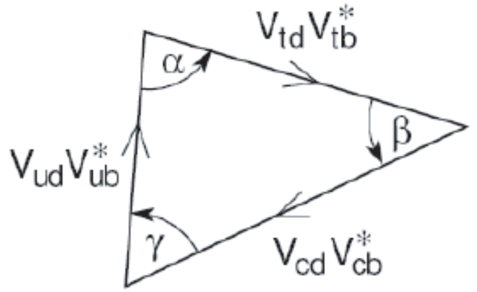
$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0 \qquad \lambda\ \lambda\ \lambda^5$$

They all have the same area *J*/2

$$J = c_{12}c_{13}^2 c_{23}s_{12}s_{13}s_{23}\sin\delta \approx 3 \times 10^{-5}$$

Jarlskog invariant

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



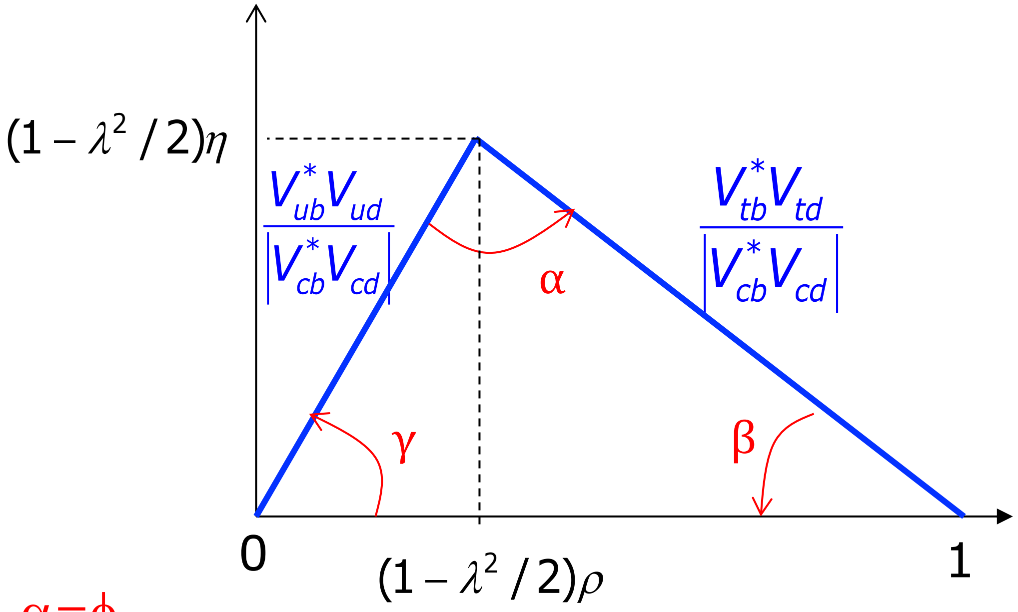
$$V_{td}\,V_{tb}^{*} = A\lambda^{3}(1-\rho-i\eta) + A\lambda^{5}(\rho+i\eta)$$

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

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

at order $\boldsymbol{\lambda}^{5}$

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



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

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

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

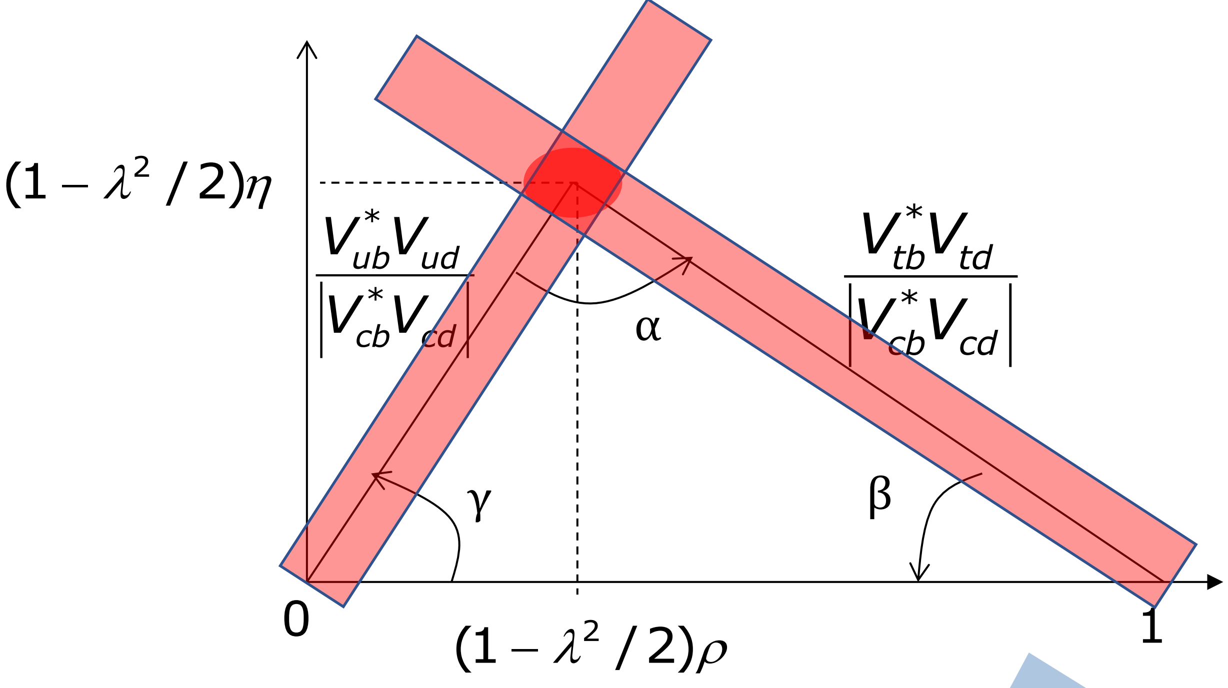
2 sides ; 3 angles

⇒ aim : to overconstrain this unitarity triangle

precision test of the Standard !

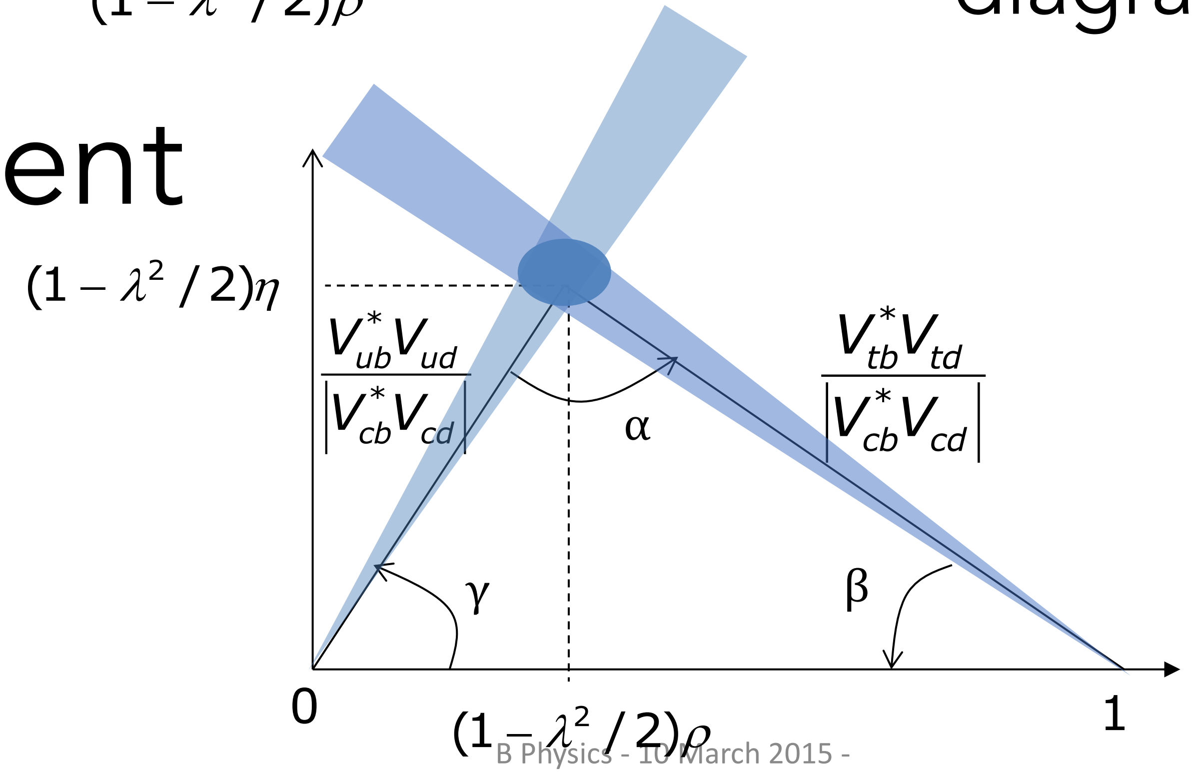
$\alpha=\phi_2$
$\beta=\phi_1$
$\gamma=\phi_3$

Is



Are the measurements involving only tree diagrams in agreement with measurements involving loop and box diagrams ?

in agreement with



?

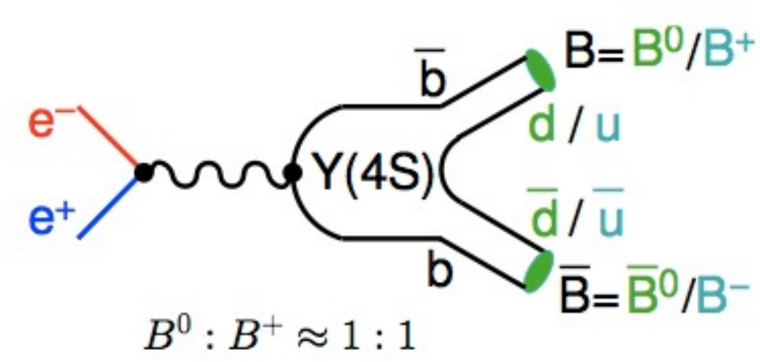
I am not going to describe all the measurements !

- Neutral meson mixing
- CP violation
- Rare decays ($b \to s\ell\ell$)

Highly selected results on these (selected !) topics but before …

Experimental considerations

B-Factories



M(Υ(4S))=10.58 GeV $J^{PC}= 1^{--}$

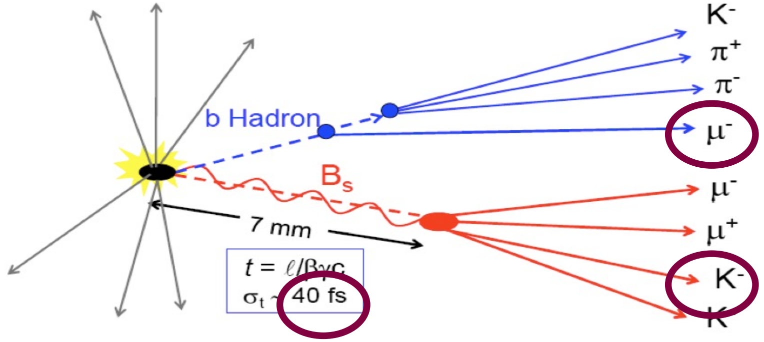
only (B^+, B^0) are produced (no fragmentation)

(B^+, B^0) are produced nearly at rest in the Υ(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

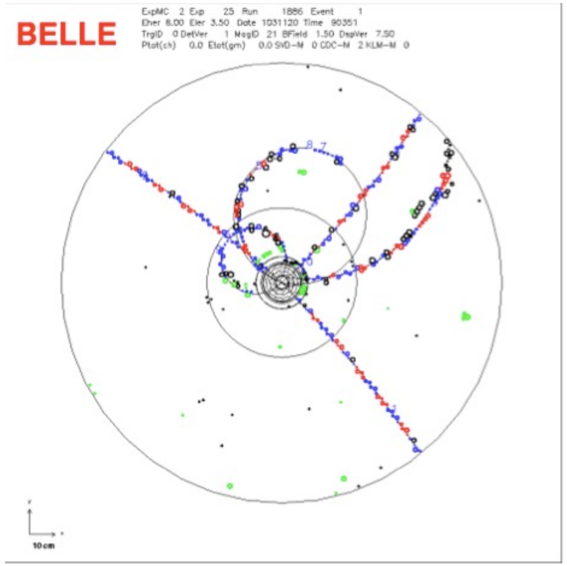
Time measured from primary vertex

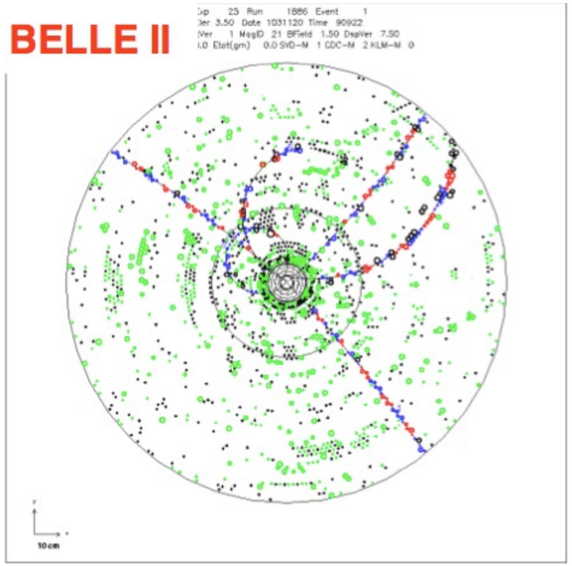
All types of b-hadrons : B_s and Λ_b also

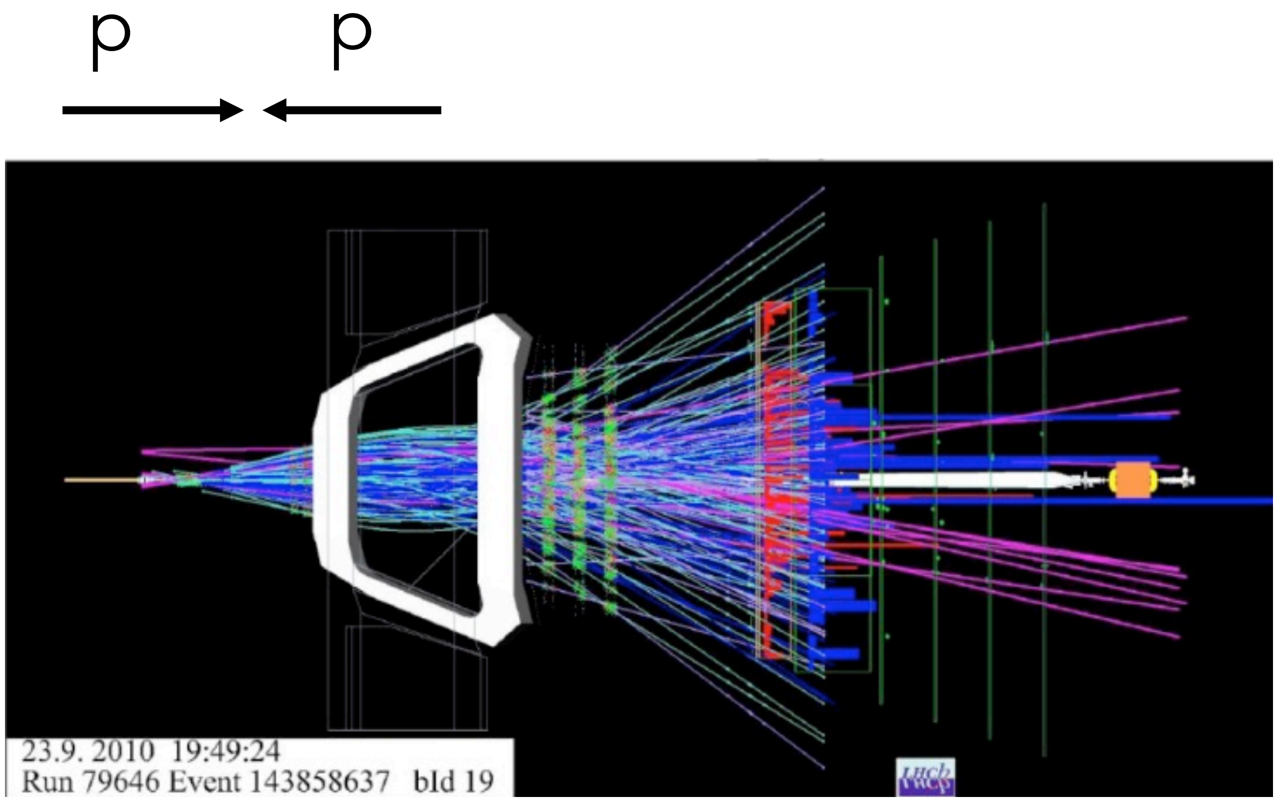
Fragmentation tracks

B-Factories

LHCb







• e^- e^+ ⊗

Experiment	**Integrated luminosity**	**$b\bar{b}$ cross section**	**Hadronic background**	**Main b-hadron species species produced**
BaBar	$433\,\mathrm{fb}^{-1}$	1.1 nb	3.7 nb	$\overline{B}^0$ and B^-
Belle	$711\,\mathrm{fb}^{-1}$	1.1 nb	3.7 nb	$\overline{B}^0$ and B^-
Belle II	400 fb^{-1}	1.1 nb	3.7 nb	$\overline{B}^0$ and B^-
LHCb	$9\,\mathrm{fb}^{-1}$	140 μb	60 mb	$\overline{B}^0$, B^-, $\overline{B}^0_s$, Λ_b and B_c^-

(13 TeV)

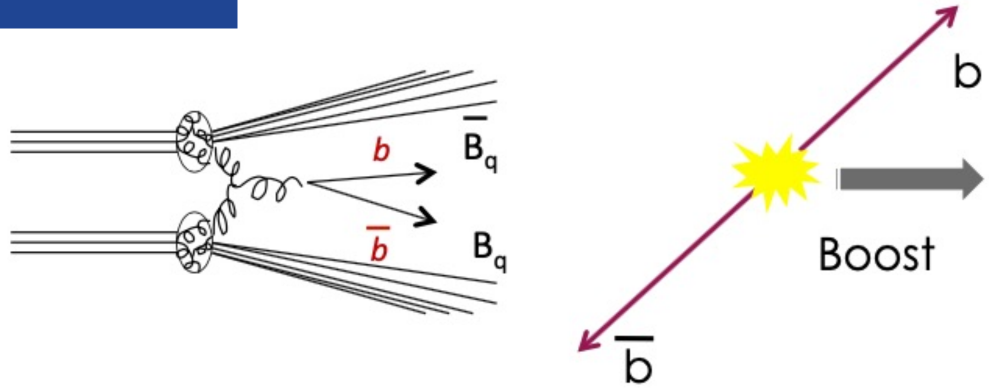
Very rough comparison:

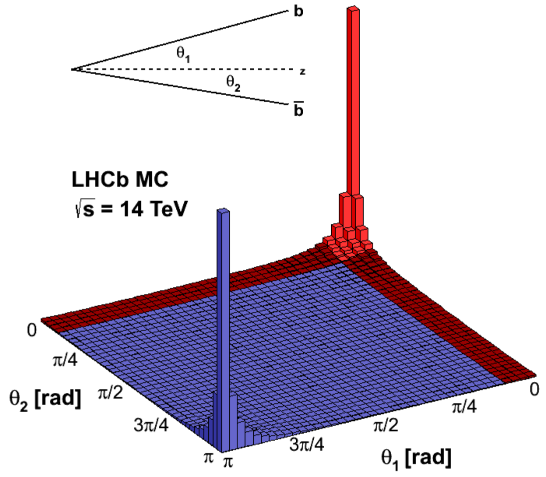
	B-Factories	LHCb
Average B-flight distance	200 µm *	1 cm
# b-hadrons in acceptance	~2 10^6 b decays/fb	~10^{11} b decays/fb
Typical bb rate	~10-100 Hz	~ 500 kHz
Event multiplicity	~10	~100
Number of channels	0,1 M	1,1 M
Trigger efficiency	> 99%	~90% - 20%
Tagging quality factor	~30%	5-6%

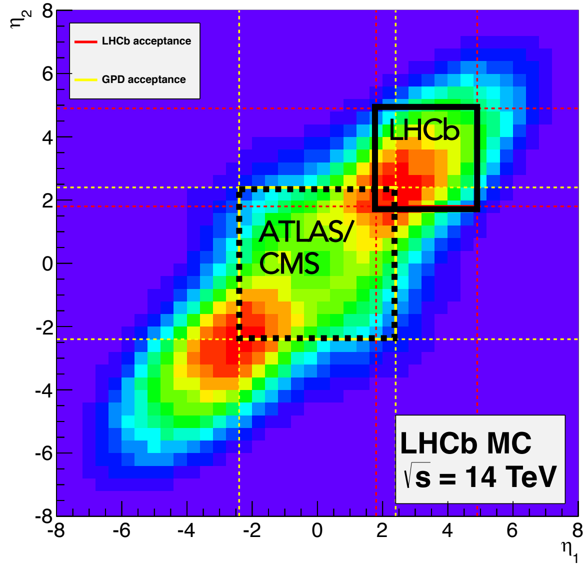
$\varepsilon(1-2\omega)^2$

LHCb

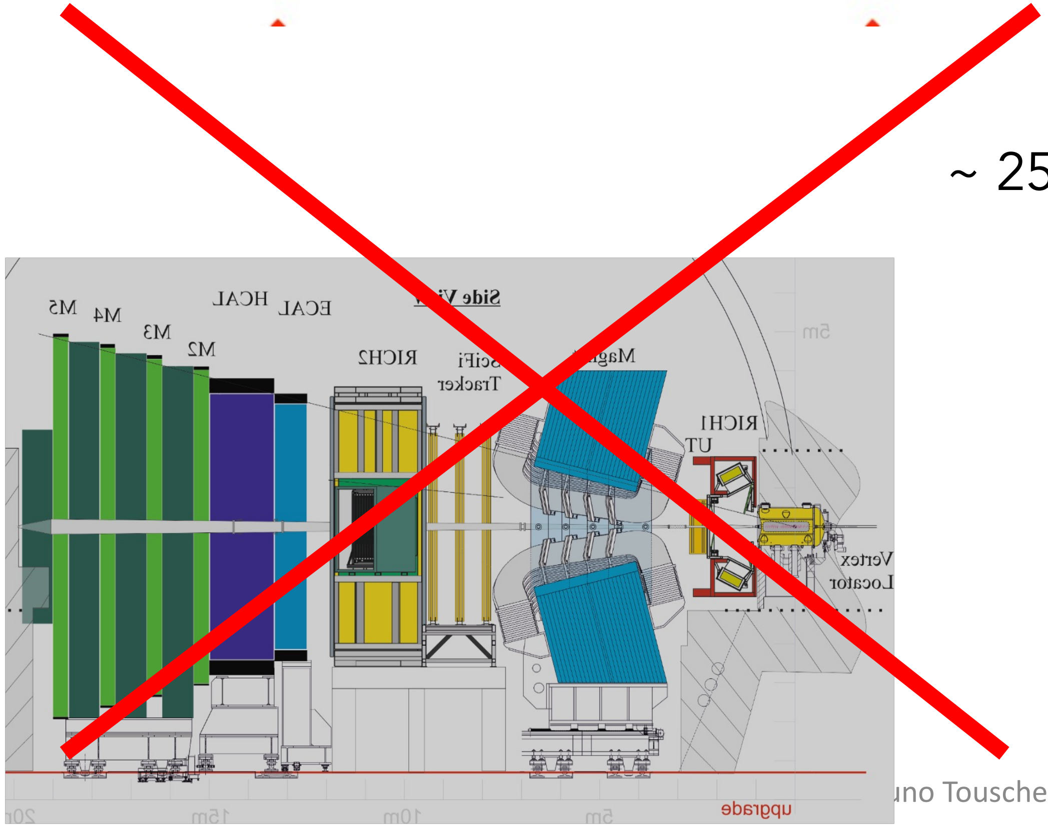
The 2 b-quarks are produced in the same direction along the beam axis

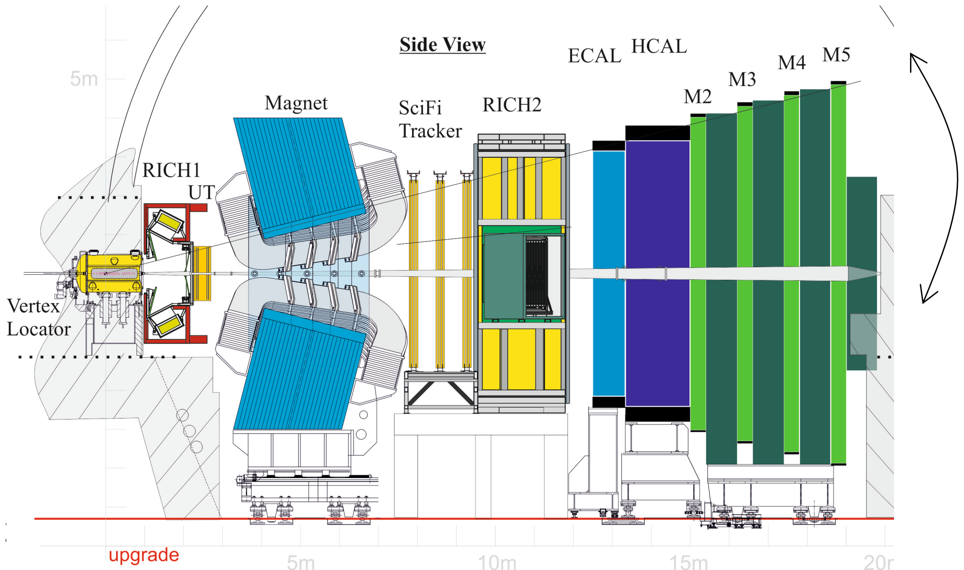






~ 25% of the $b\bar{b}$ production between 15 and 300 mrad

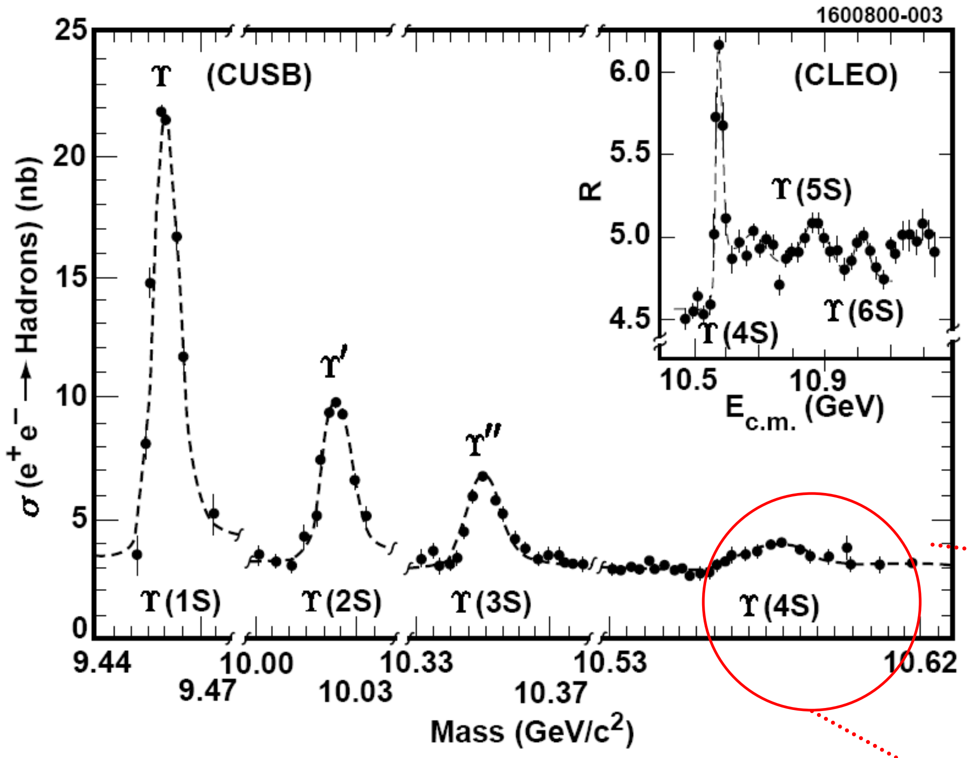


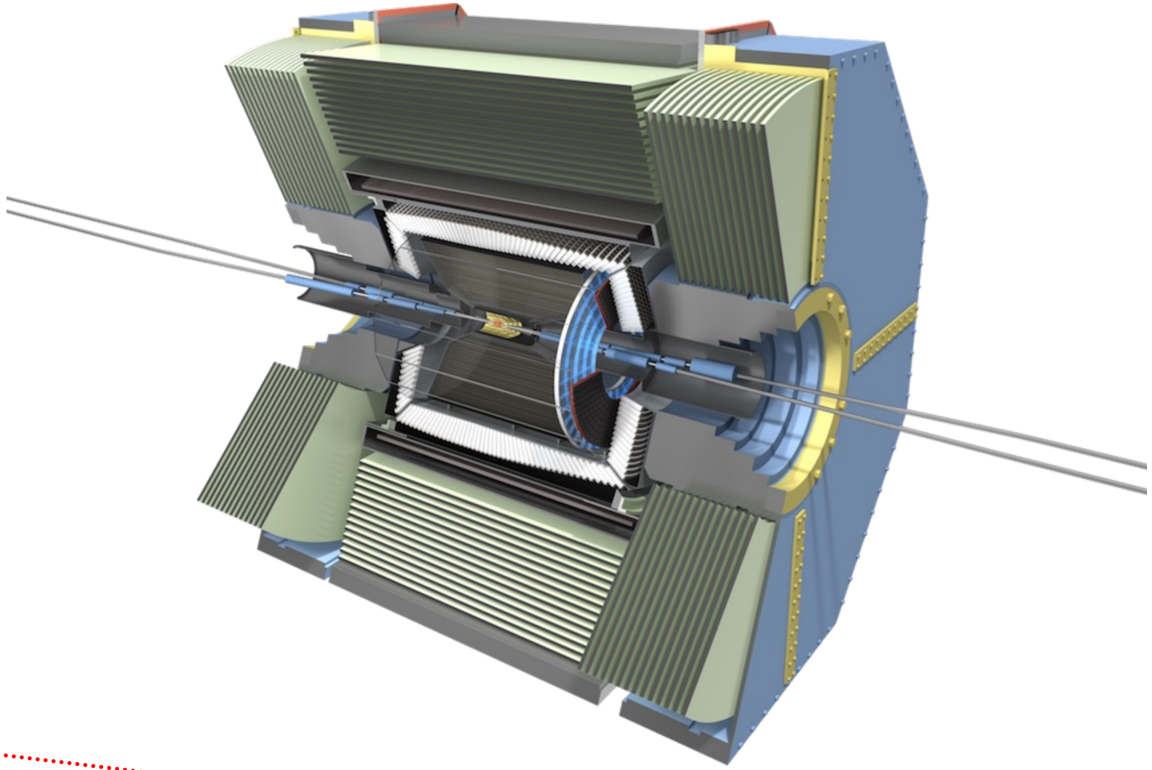


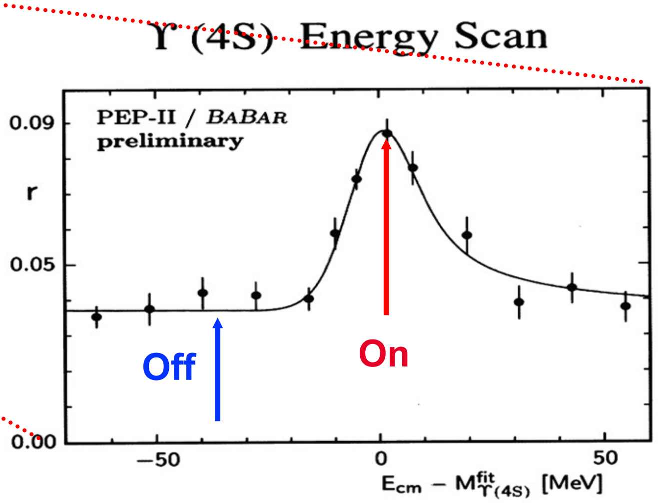
16 deg

Belle-II (BFactories)

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





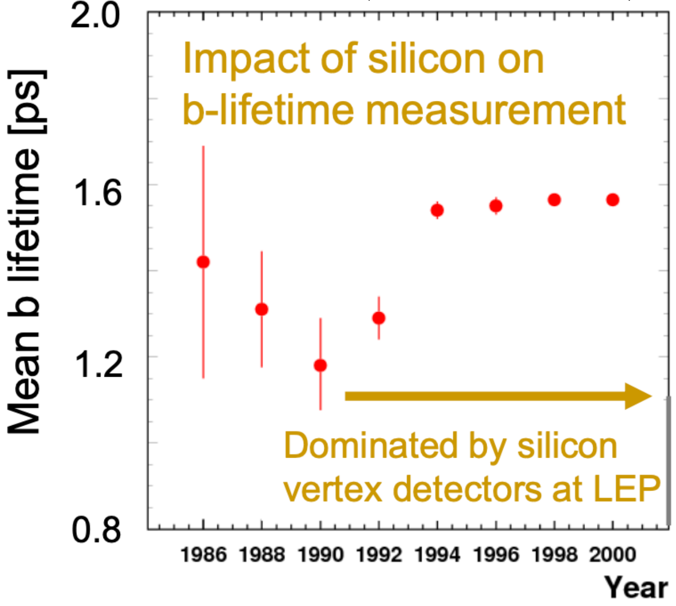


ϒ(4S) → B^+B^-, B^0B^0
to approx. 50% each

Key-aspects present in both experiments: vertex detectors

Silicon vertex detectors

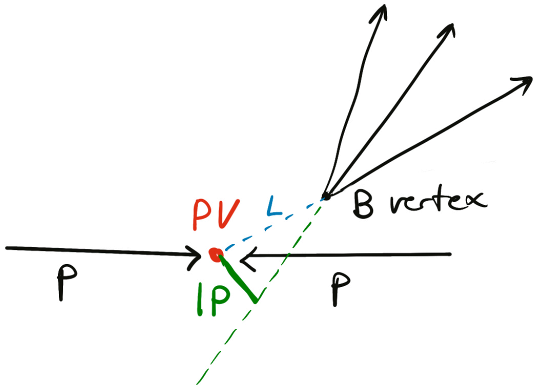
G. Wilkinson (CERN-FNAL 2019)



$$t = ml/p$$

$$\sigma_t = \left(\frac{m}{p}\right)^2 \sigma_l^2 + \left(\frac{t}{p}\right)^2 \sigma_p^2$$

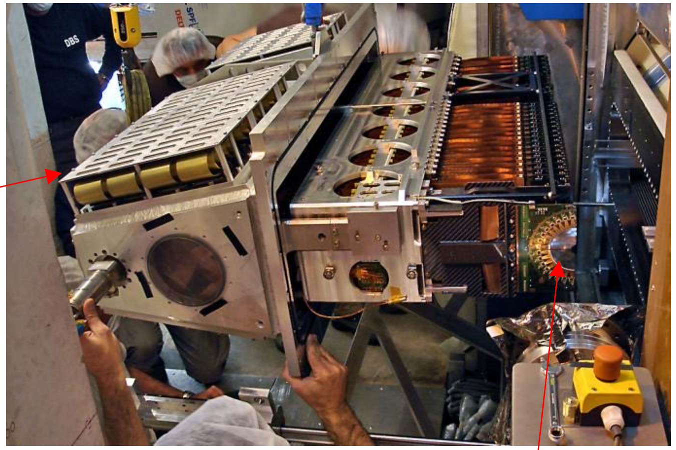
Aluminium foil separates VELO vacuum from LHC vacuum (+ shields it from high-frequency fields of the beams)

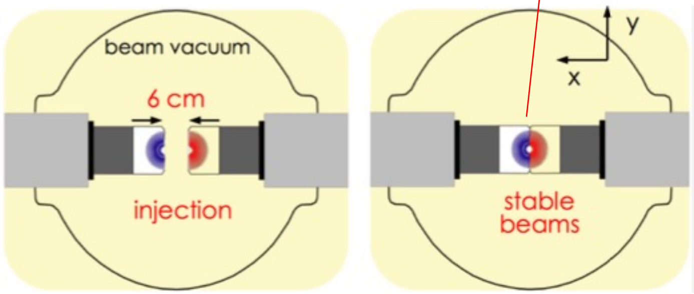


IP resolution <35 μm for p_T>1GeV/c

⇒ resolution on B_s decay time ~ 50 fs

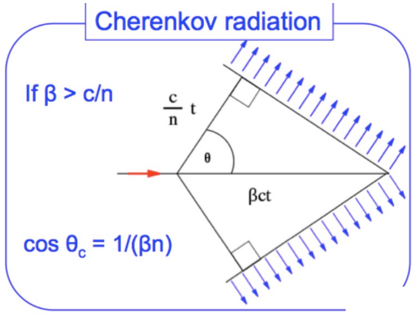
LHCb – VErtex LOcator





active area : 8.2 mm from beam

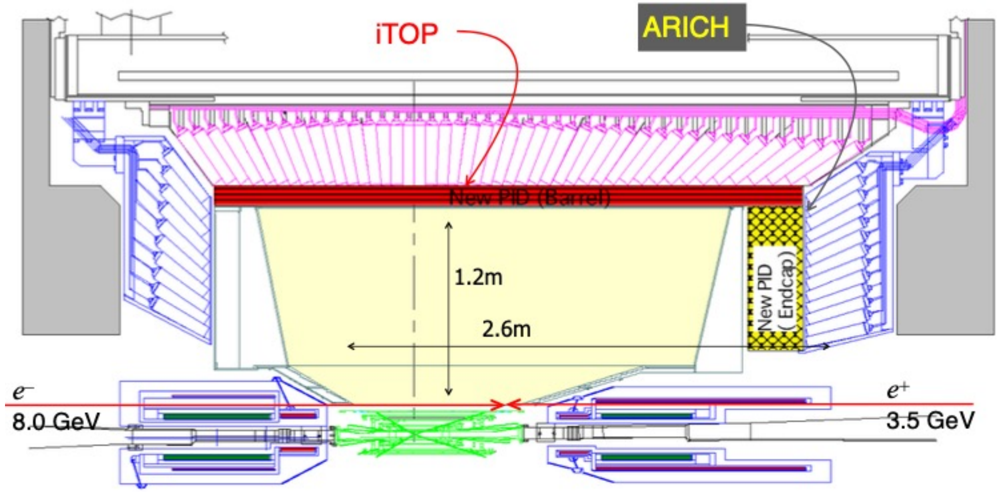
Key-aspects present in both experiments: hadron PID



$$\cos\left(\theta_C\right) = \frac{1}{n}\sqrt{1+\left(\frac{m}{p}\right)^2}$$

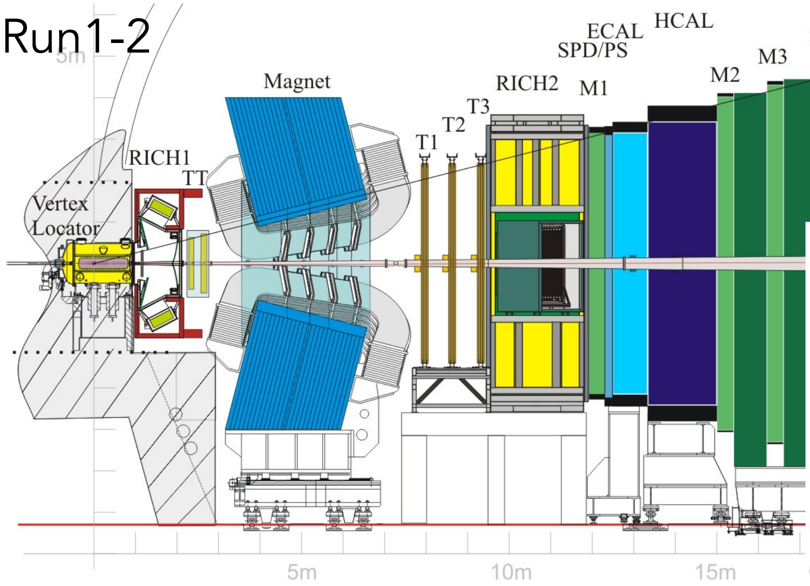
p being measured by the tracking, the particle is identified

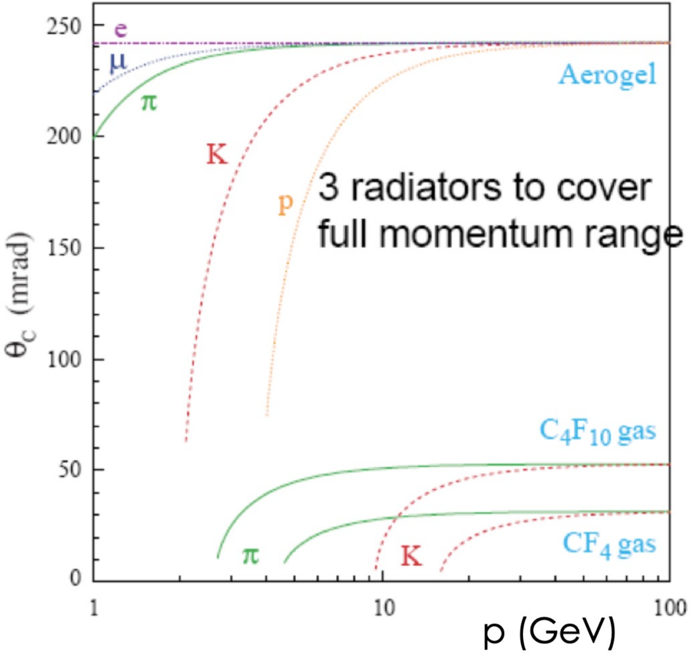
Belle-II: ToF and Cerenkov



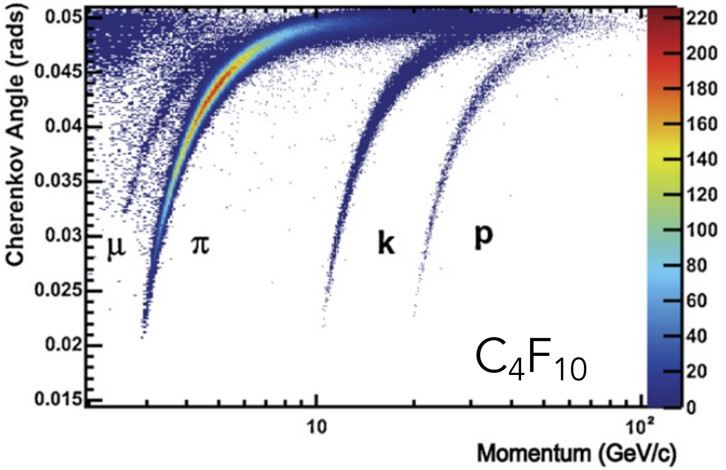
LHCb: Cerenkov

Run1-2

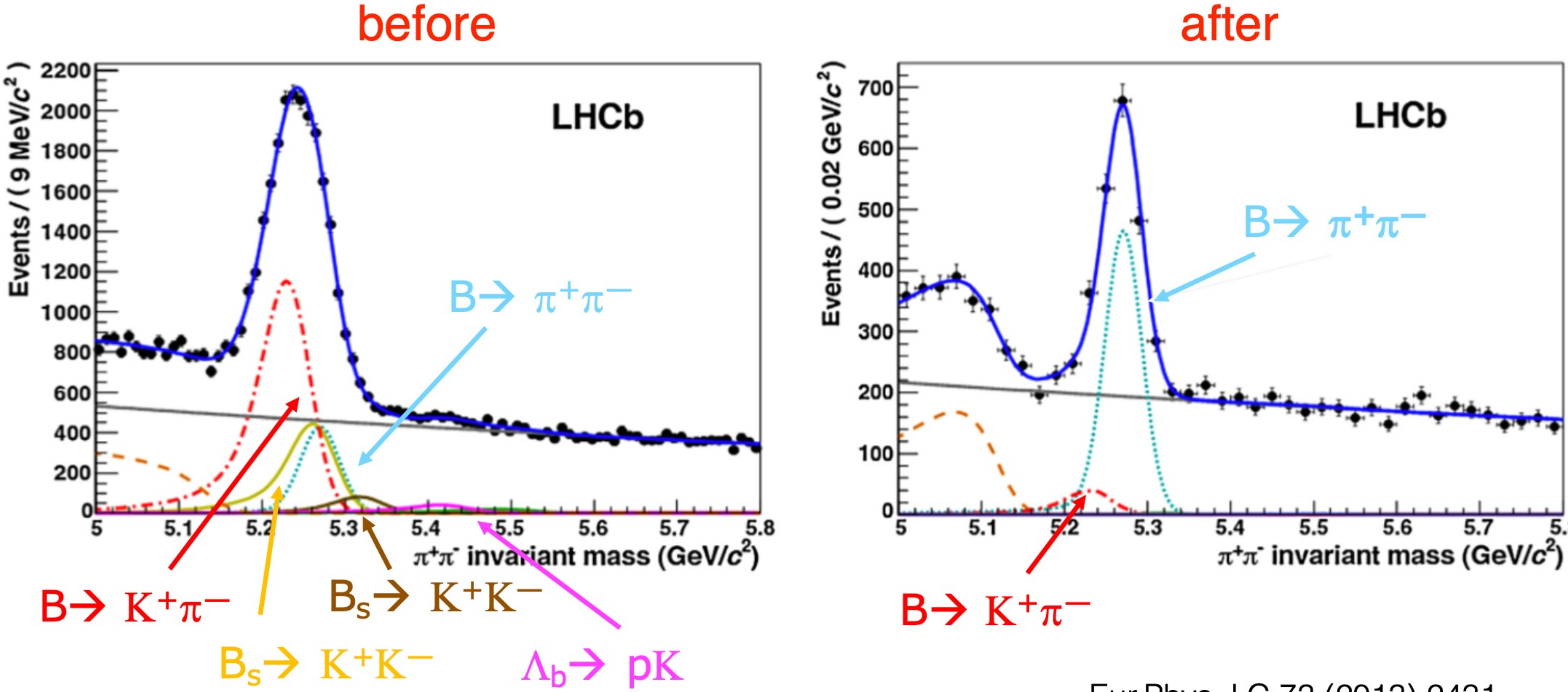




3 radiators to cover full momentum range



Impact of the RICH on $B^0 \rightarrow \pi\pi$ observation in LHCb



Eur.Phys.J.C 73 (2013) 2431

Selected results

- Neutral meson mixing

- CP violation

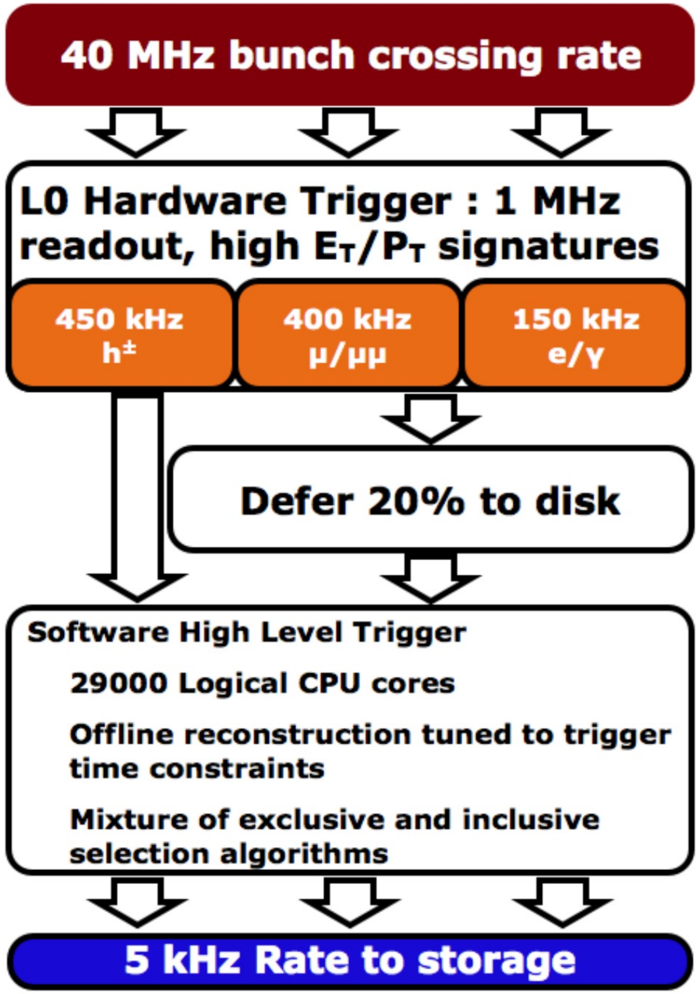
- Rare decays ($b \to s\ell\ell$)

(

But before, few words on triggering at LHCb

Extremely large bb and cc cross section at 13 TeV
→ 45 kHz of bb in acceptance and 1 MHz cc in LHCb acceptance

Run1 & Run2 : no full readout of the detector possible at 40 MHz (LHC collision rate)



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz **$h^\pm$**	**400 kHz** **$\mu/\mu\mu$**	**150 kHz** **e/γ**

Defer 20% to disk

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

p_T cuts driven by bandwdith splitting

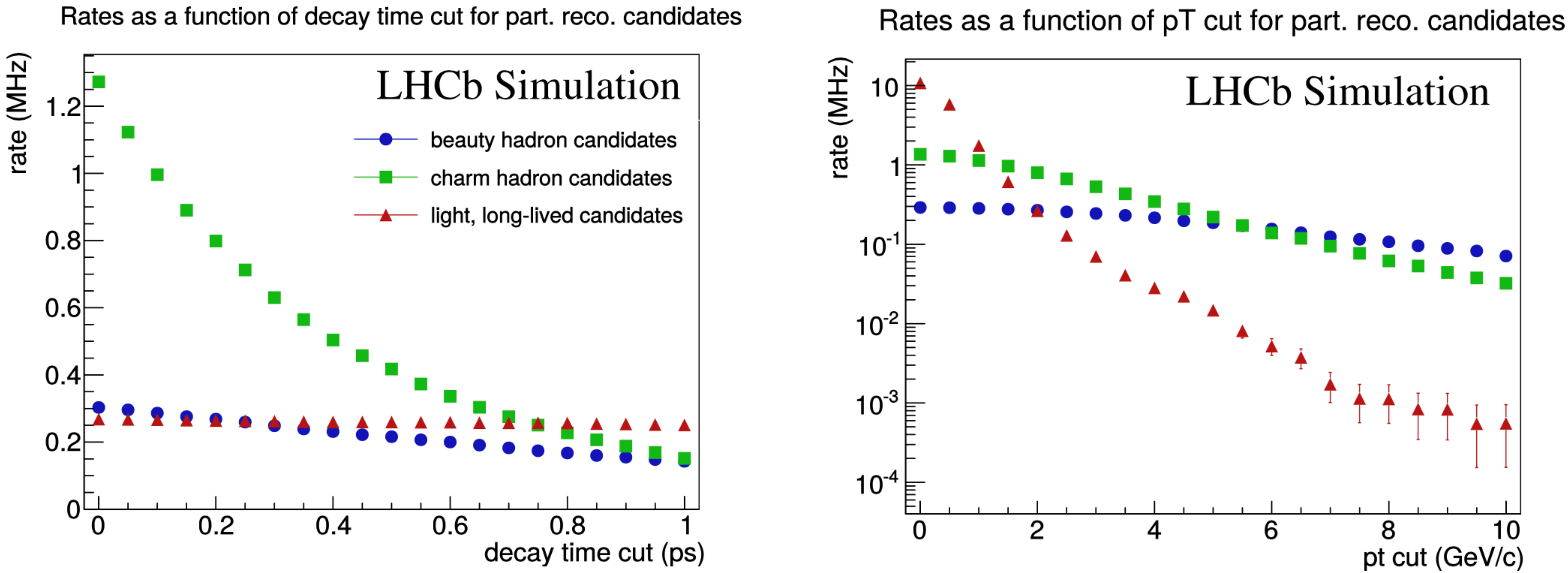
PDG :
BR(b → K^+ X) ~ 74 %
even more charged pions !

Electrons and muons are different : electrons can also come from photons conversions (pi0 create a lot of photons)

Calorimeter : busy !

this is Run1 ; in Run2 we reached 12 kHz (two-stage HLT trigger)

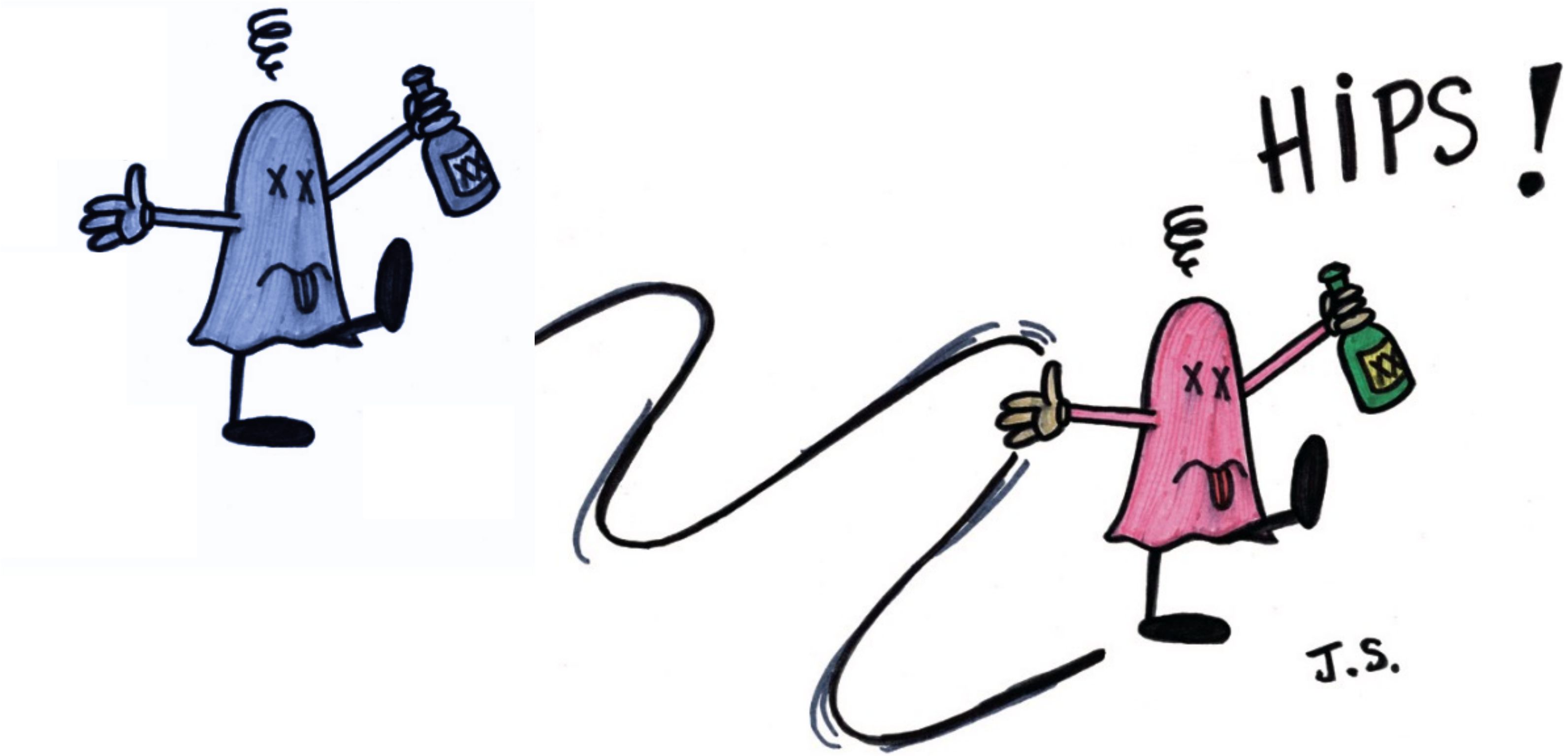
In Run3 (which is starting now)



Full reconstruction and wise choices to be made ….

)

Neutral meson mixing



Adapted from © Elementaire

Neutral mesons mixing

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

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

They are flavour eigenstates with definite quark content

- useful to understand particle production and decay

$$|M^0\rangle \; |\bar{M}^0\rangle$$

Apart from the flavour eigenstates there are mass eigenstates:

- eigenstates of the Hamiltonian
- states of definite mass and lifetime
- They are propagating through space-time

$$|M_L\rangle \; |M_H\rangle \qquad \tau_H \quad \tau_L$$

$$m_H \quad m_L$$

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

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

q, p are complex

$|p|^2 + |q|^2 = 1$

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

$$i\frac{d}{dt}\begin{pmatrix}|M^0(t)\rangle\\|\bar{M}^0(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|M^0(t)\rangle\\|\bar{M}^0(t)\rangle\end{pmatrix}$$

Time evolution:

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

More general formulae

No CP violation in mixing: |q/p| =1

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

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

$|M^0(t)\rangle$: 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

$$i\frac{d}{dt}\begin{pmatrix}|M^0(t)\rangle\\|\bar{M}^0(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|M^0(t)\rangle\\|\bar{M}^0(t)\rangle\end{pmatrix}$$

$\Delta m = m_H - m_L$

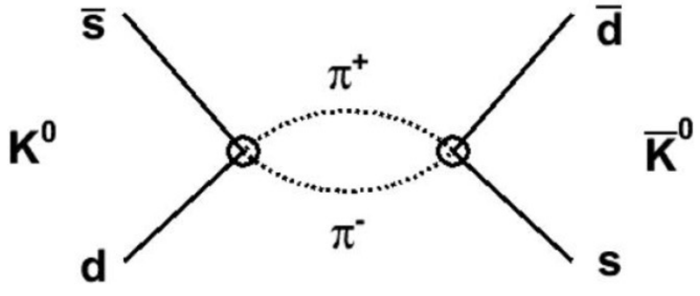
$\Delta\Gamma = \Gamma_L - \Gamma_H$

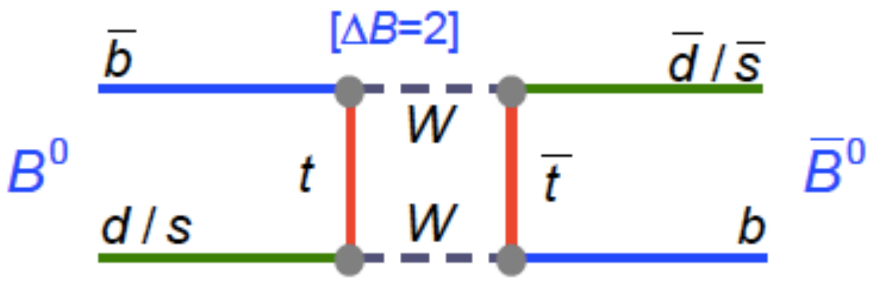
time evolution :
$$\propto e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right)-\cos\left(\Delta m t\right)\right]$$

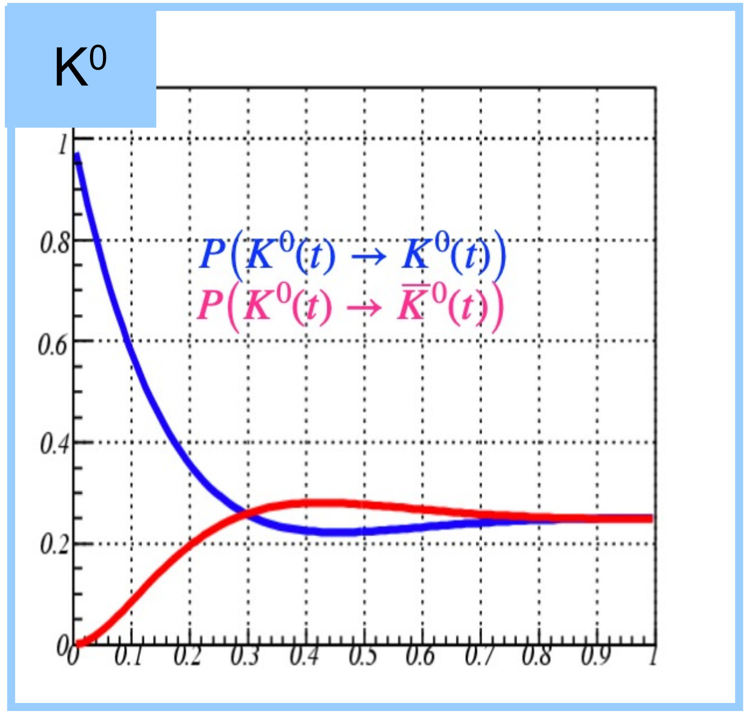
Physical origin:

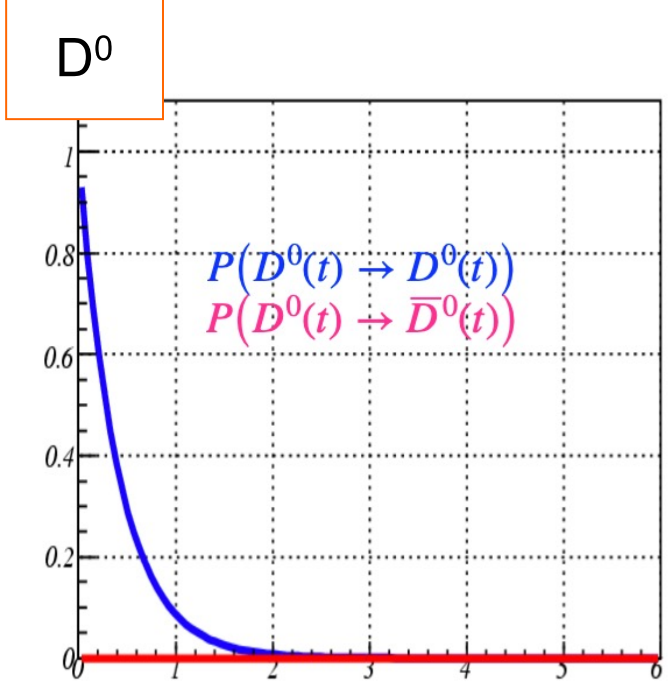
long range (common final states)

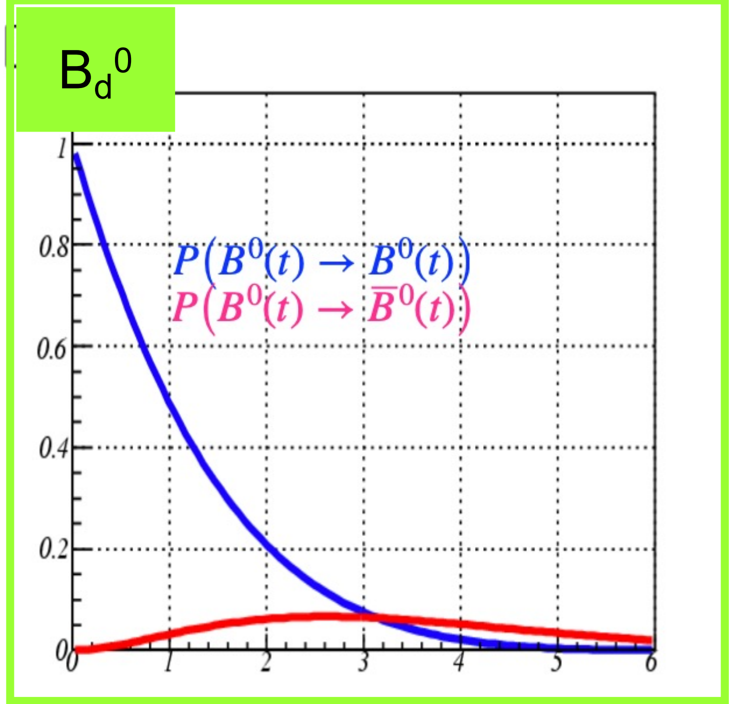
short range (box diagrams)

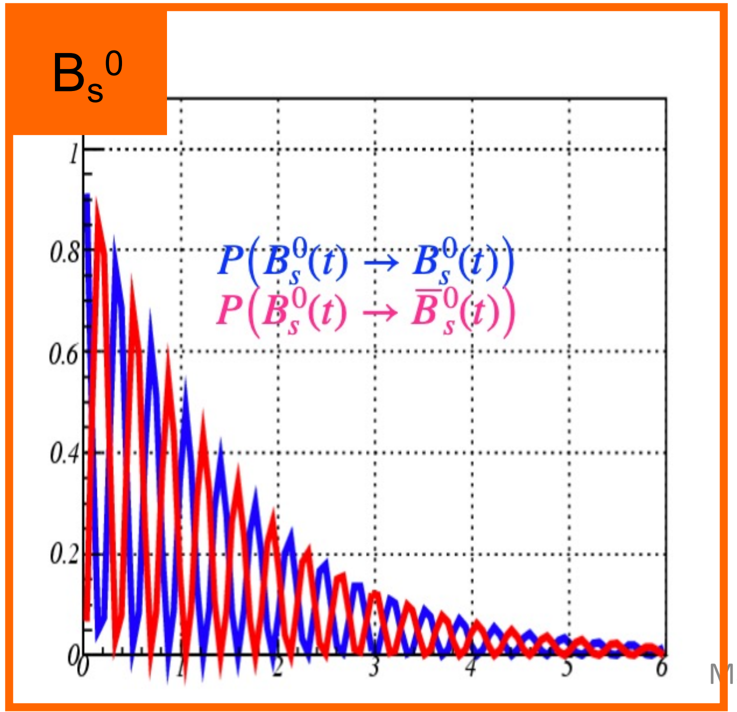










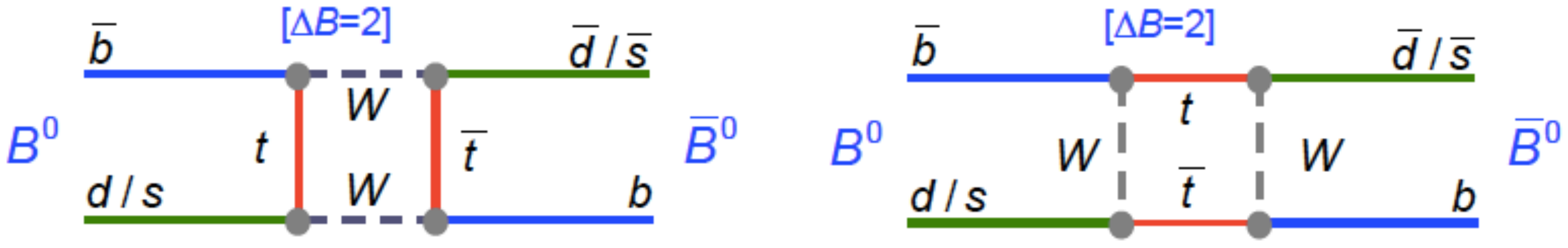


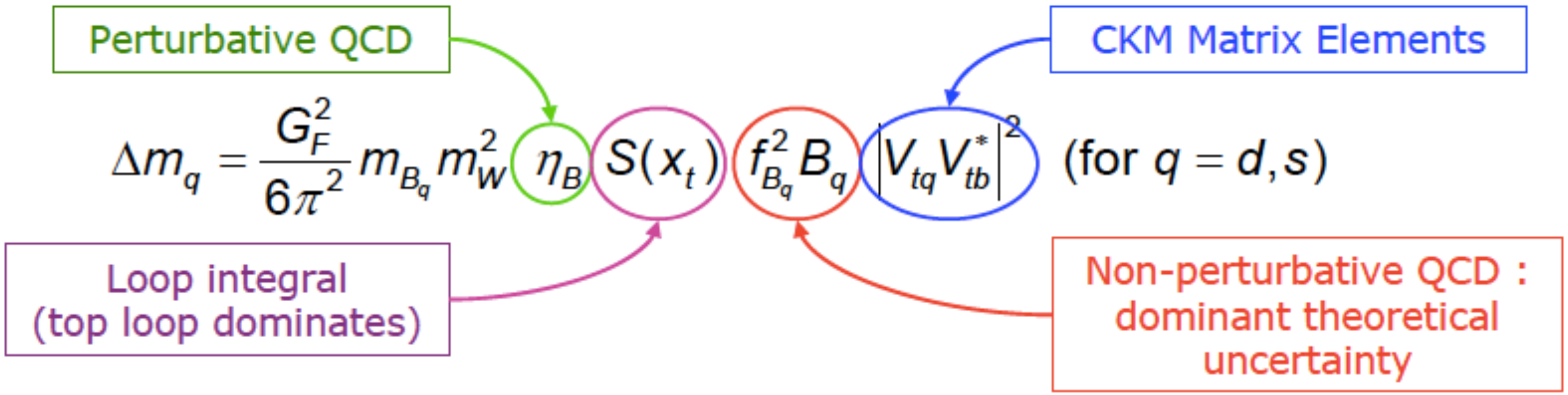
	$x=\Delta m/\Gamma$	$y=\Delta\Gamma/2\Gamma$
K^0	~500	~1
D^0	10^{-3}-10^{-5}	~ 710^{-3}
B_d^0	~0.77	~2 10^{-3}
B_s^0	~27	~6 10^{-2}

A lot of experimental consequences

Δm can be computed in the Standard Model

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





Perturbative QCD

CKM Matrix Elements

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

Loop integral
(top loop dominates)

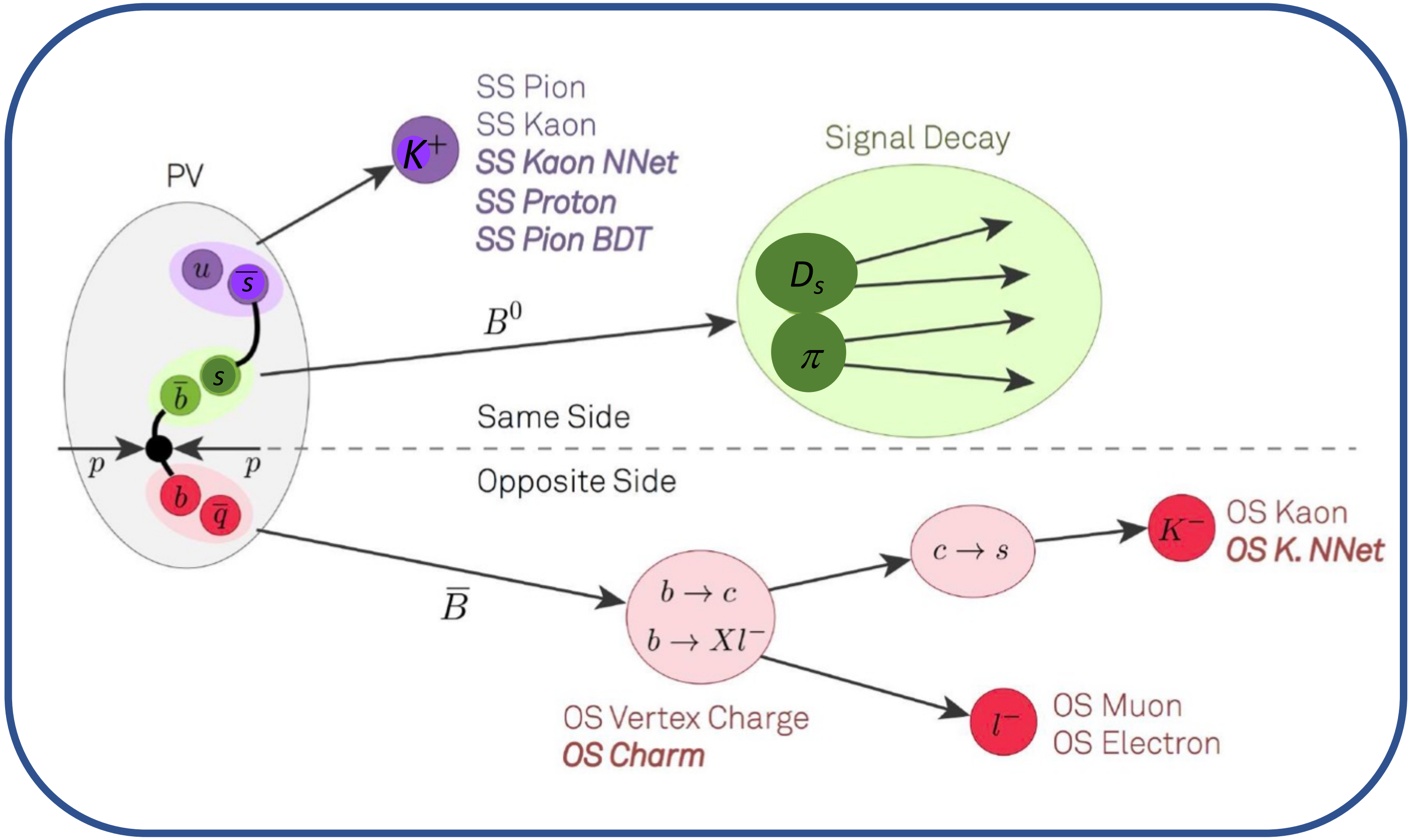
Non-perturbative QCD :
dominant theoretical
uncertainty

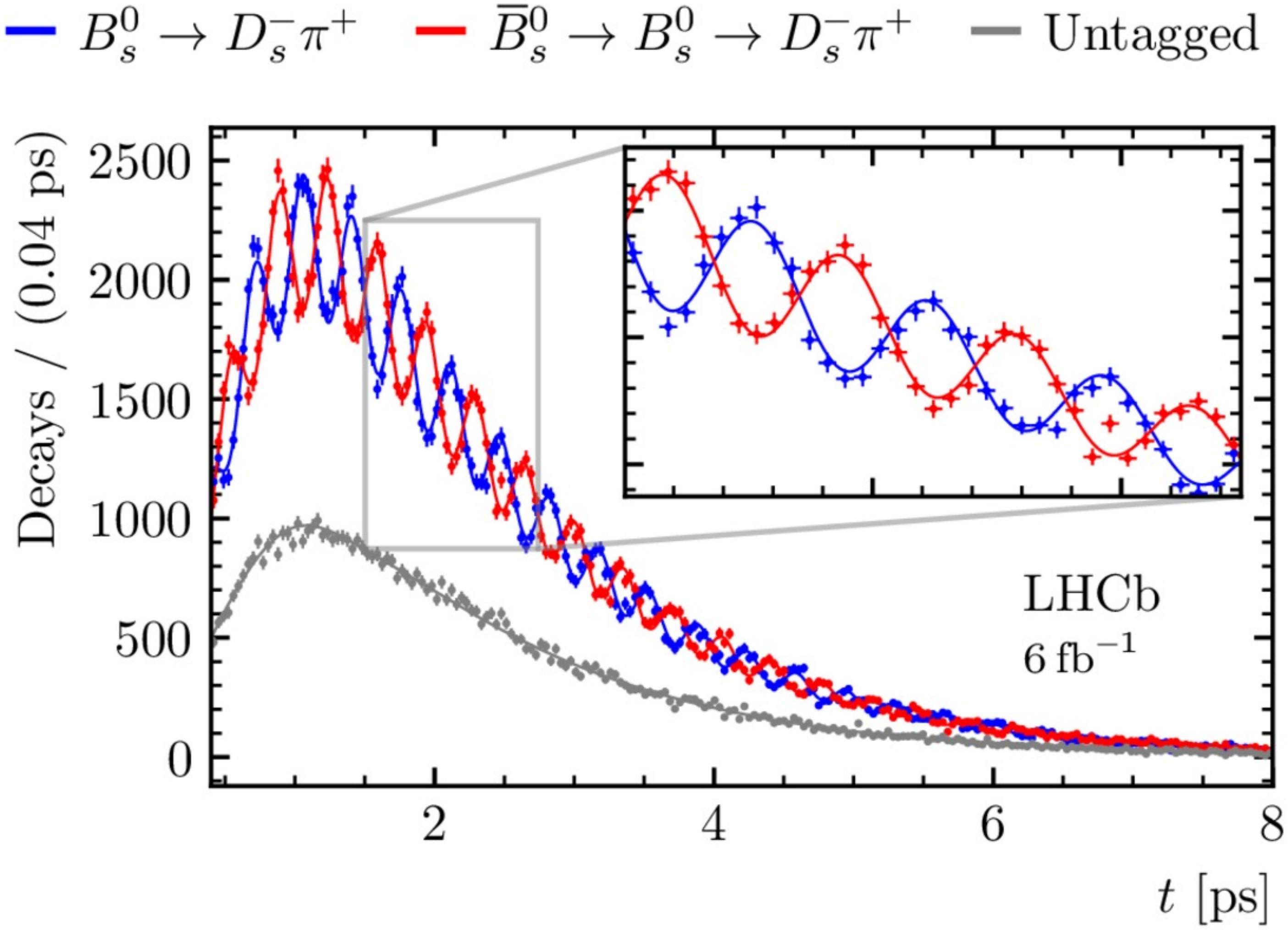
Measurement of the oscillation frequency of the B$_s$ meson in a nutshell

- Select a flavour specific final state : $B_s^0 \to D_s^- \pi^+ \quad \overline{B_s^0} \to D_s^+ \pi^+$
- Tag the flavour at production time
- Measure the time:

$$t = ml/p$$

$$\sigma_t = \left(\frac{m}{p}\right)^2 \sigma_l^2 + \left(\frac{t}{p}\right)^2 \sigma_p^2$$



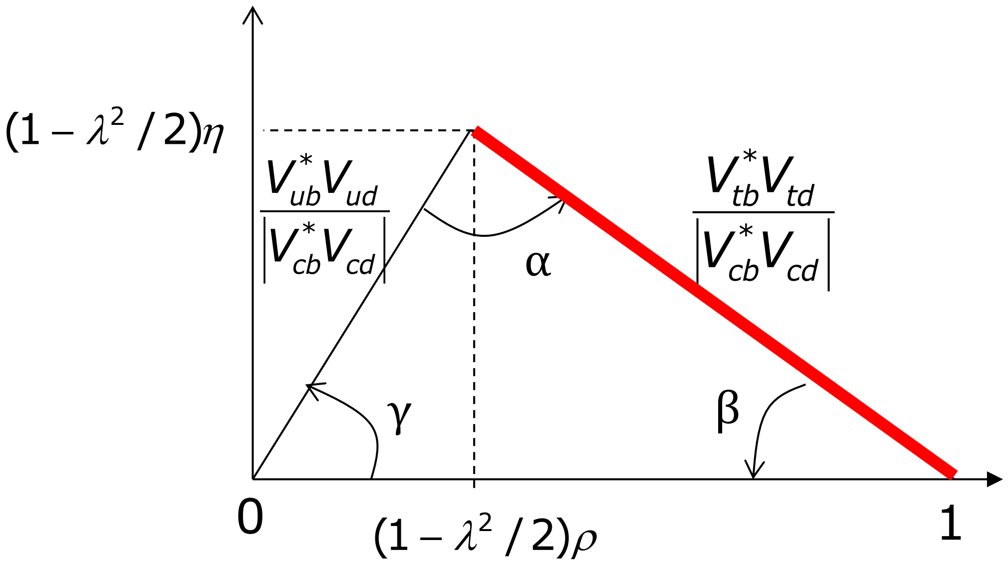


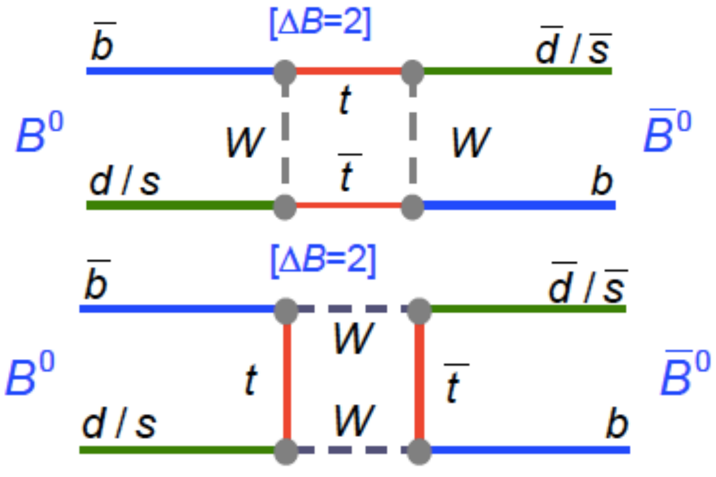
- Different flavour at decay and production
- Same flavour at decay and production

$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\,\mathrm{ps}^{-1}$$

LHCb-PAPER-2021-005

Impact on the unitarity triangle determination



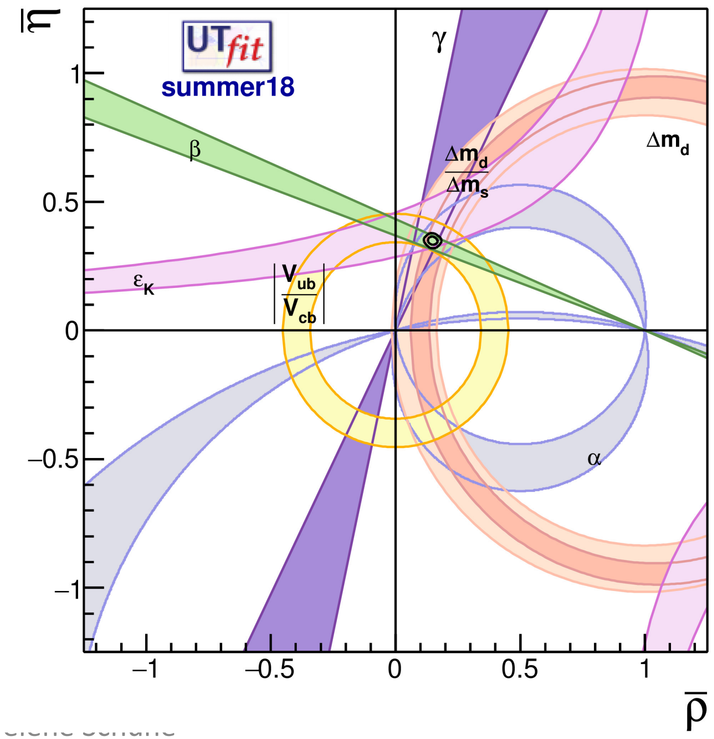


$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} m_W^2 \;\; \eta_B \;\; S(x_t) \;\; f_{B_d}^2 B_d \;\; \left|V_{td}V_{tb}^*\right|^2$$

$$\Delta m_s = \frac{G_F^2}{6\pi^2} m_{B_s} m_W^2 \;\; \eta_B \;\; S(x_t) \;\; f_{B_s}^2 B_s \;\; \left|V_{ts}V_{tb}^*\right|^2$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \cdot \boxed{\frac{f_{B_d}^2 B_d}{f_{B_s}^2 B_s}} \cdot \lambda^2 \left(\left(1-\bar{\rho}\right)^2 + \bar{\eta}^2\right)$$

smaller theoretical uncertainty



CP violation

Due to lack of time I have put in the back-up slides the nice story of the discovery of CP violation in the Kaon system

I strongly encourage you to look at them

Bruno Touschek drawing (on P violation)

Three types of CP violation

$$A : B \rightarrow f$$

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

$$\lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

CP violation in decay (« direct CP») :

$$B \xrightarrow{A} f$$

$$\bar{B} \xrightarrow{\bar{A}} \bar{f}$$

Only one existing for charged B

$$|\frac{\overline{A}}{A}| \neq 1$$

CP violation in mixing :

$$B^0 \longrightarrow \bar{B}^0 \longrightarrow \bar{f}$$

$$\bar{B}^0 \longrightarrow B^0 \longrightarrow f$$

Not yet observed for B mesons.

$$|\frac{q}{p}| \neq 1$$

CP violation in the interference between mixing and decay :

$$\begin{tikzcd}
B^0 \arrow[rr] \arrow[ddr] & & f \\
\bar{B}^0 \arrow[rr] \arrow[dddr] & & f \\
& \bar{B}^0 \arrow[uur] & \\
& B^0 \arrow[uur] &
\end{tikzcd}$$

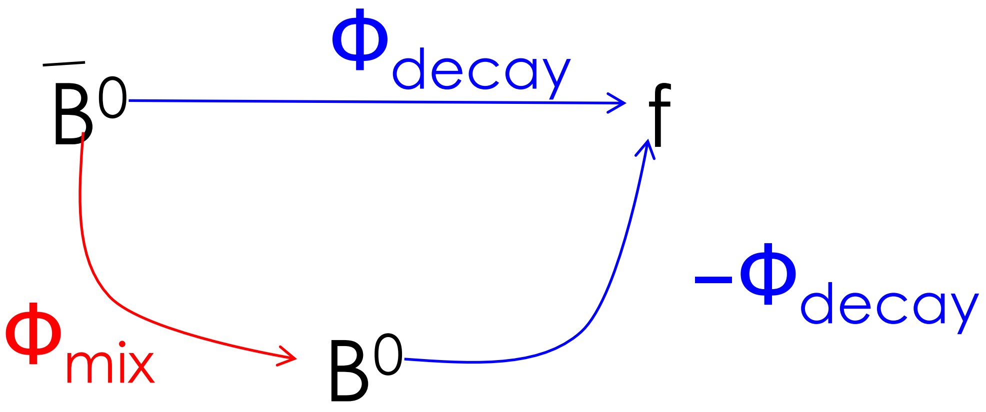
First observation of CP violation in B decays : sin(2β) measurement.

$$\Im\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0$$

In all cases:
two amplitudes ($A = A_1 + A_2$) are needed for the observation

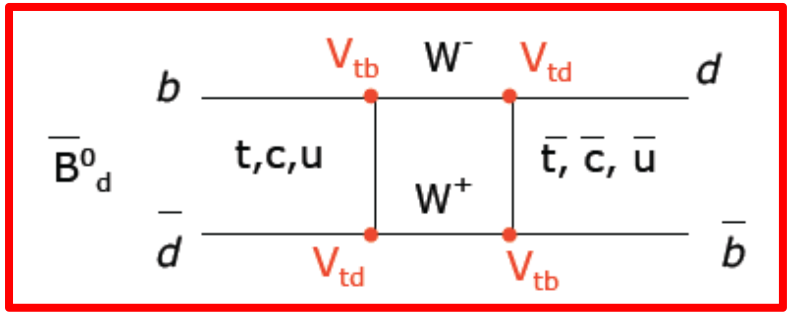
Discovery of CP violation in the B system : measurement of the β angle

CP violation in the interference between mixing and decay

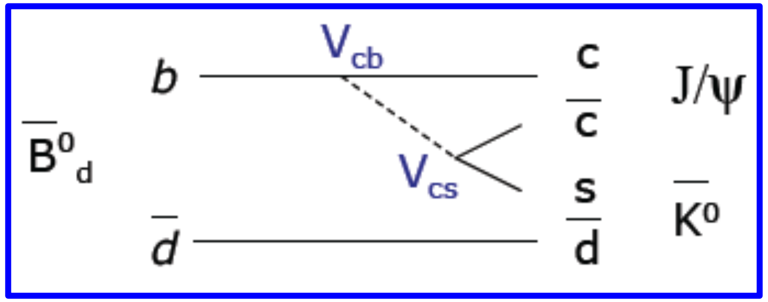


$$\Phi_d = \Phi_{mix} - 2\,\Phi_{decay}$$

Mixing



Decay



$$\mathrm{P}(B^0 \to f_{CP}, \Delta t) \propto e^{-\Gamma t}\left(1 - \left(S_f \sin \Delta t \; - C_f \cos \Delta t\right)\right)$$
$$\mathrm{P}\left(\overline{B^0} \to f_{CP}, \Delta t\right) \propto e^{-\Gamma t}\left(1 + \left(S_f \sin \Delta t \; - C_f \cos \Delta t\right)\right)$$

$\mathrm{B_d} \Rightarrow \Delta\Gamma = 0$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

direct CPV

$$\lambda_f = \frac{q}{p}\frac{<f\,|\,H\,|\,\overline{B}^0>}{<f\,|\,H\,|\,B^0>} \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$$S_f = \frac{2\mathrm{Im}[\lambda_f]}{1+|\lambda_f|^2}$$

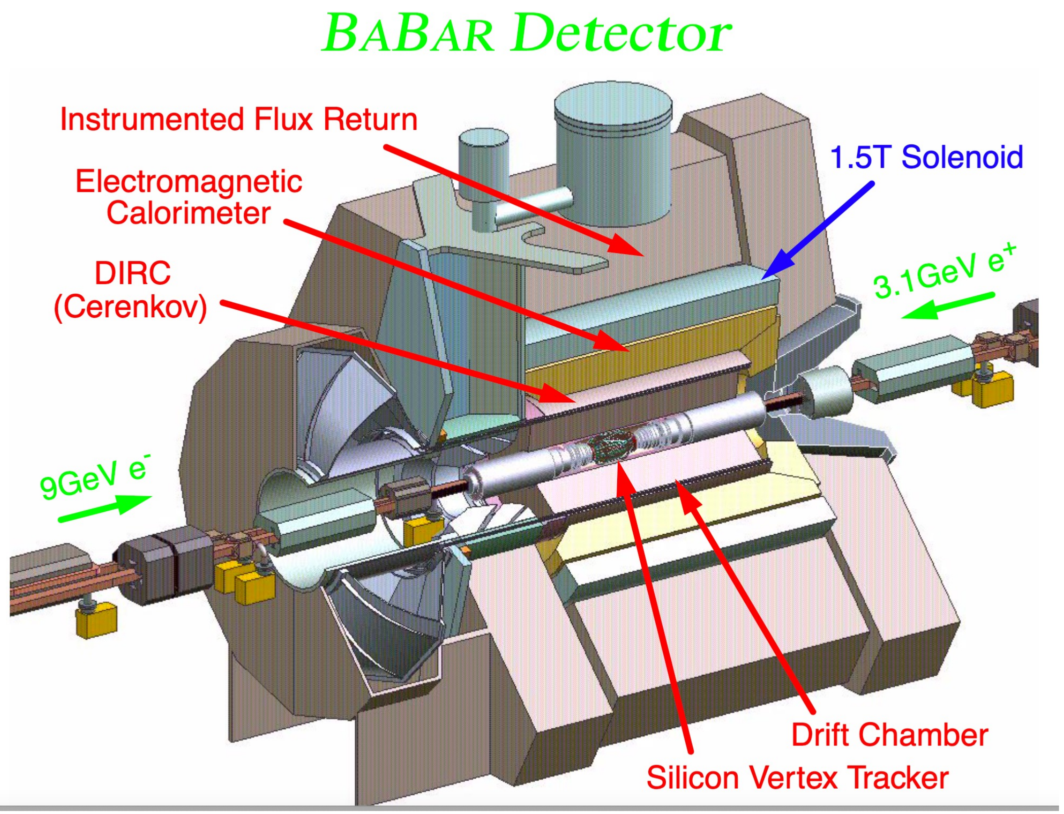
CPV in the interference
between mixing and decay

B→J/ψ K$_s$ $\quad \mathrm{Im}\,\lambda_{J/\psi K_S} = \sin 2\beta$

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

theoretically clean

Why are B-Factories detectors slightly asymmetric ?



Time evolution of an Y(4S) decay

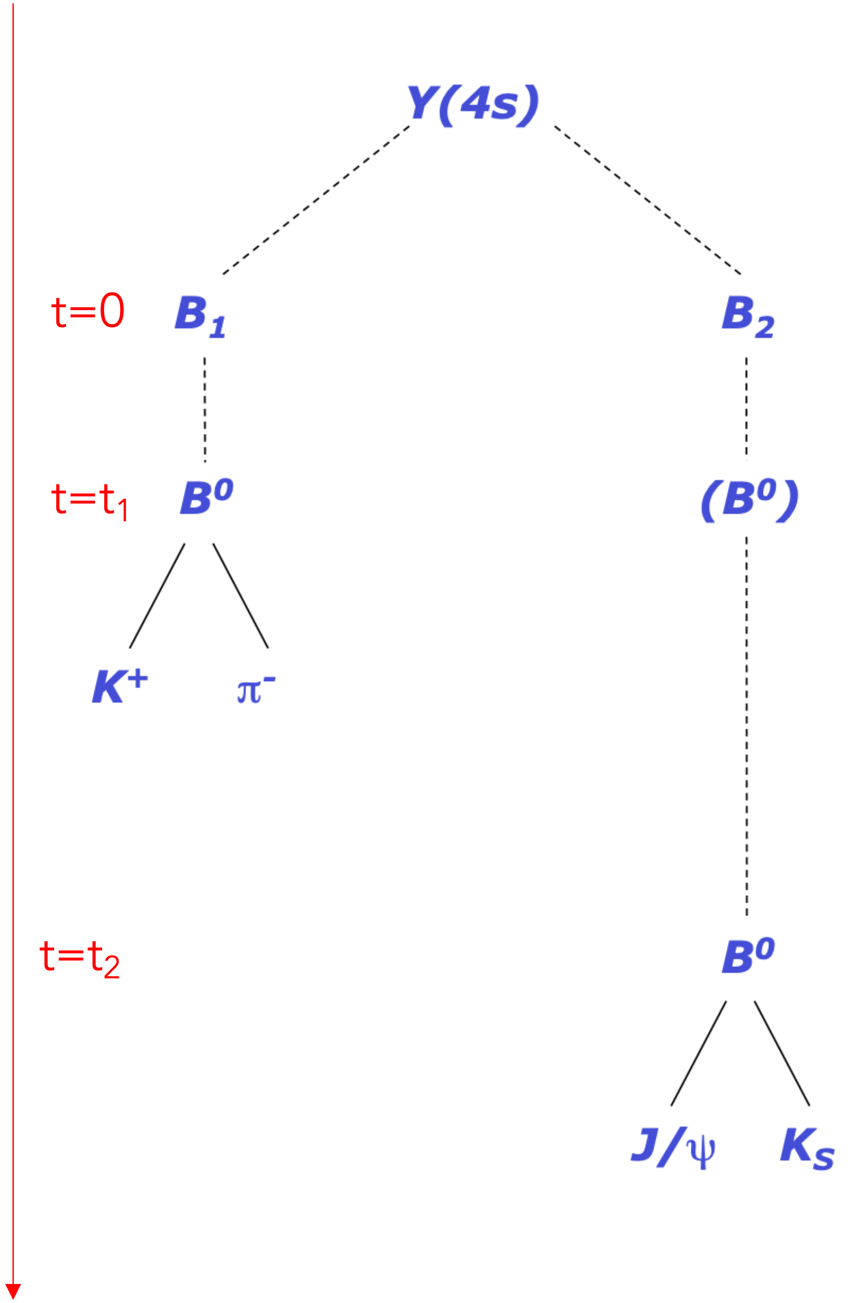
t=0 Y(4S) → $B\ \overline{B}$

Neither B is a specific eigenstate but they evolve coherently (ie B and $\overline{B}$)

$t=t_1$ one of the two mesons (B_1) decays
if B_1 is a flavor eigenstate, B_2 also

$t=t_2$ the other meson (B_2) decays
it can decay as a B^0 or a B^0 (mixing can take place) or a CP eigenstate

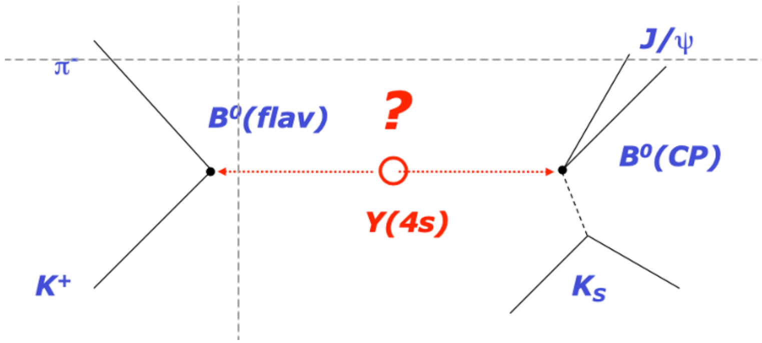
$t_2>t_1$ or $t_2<t_1$



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

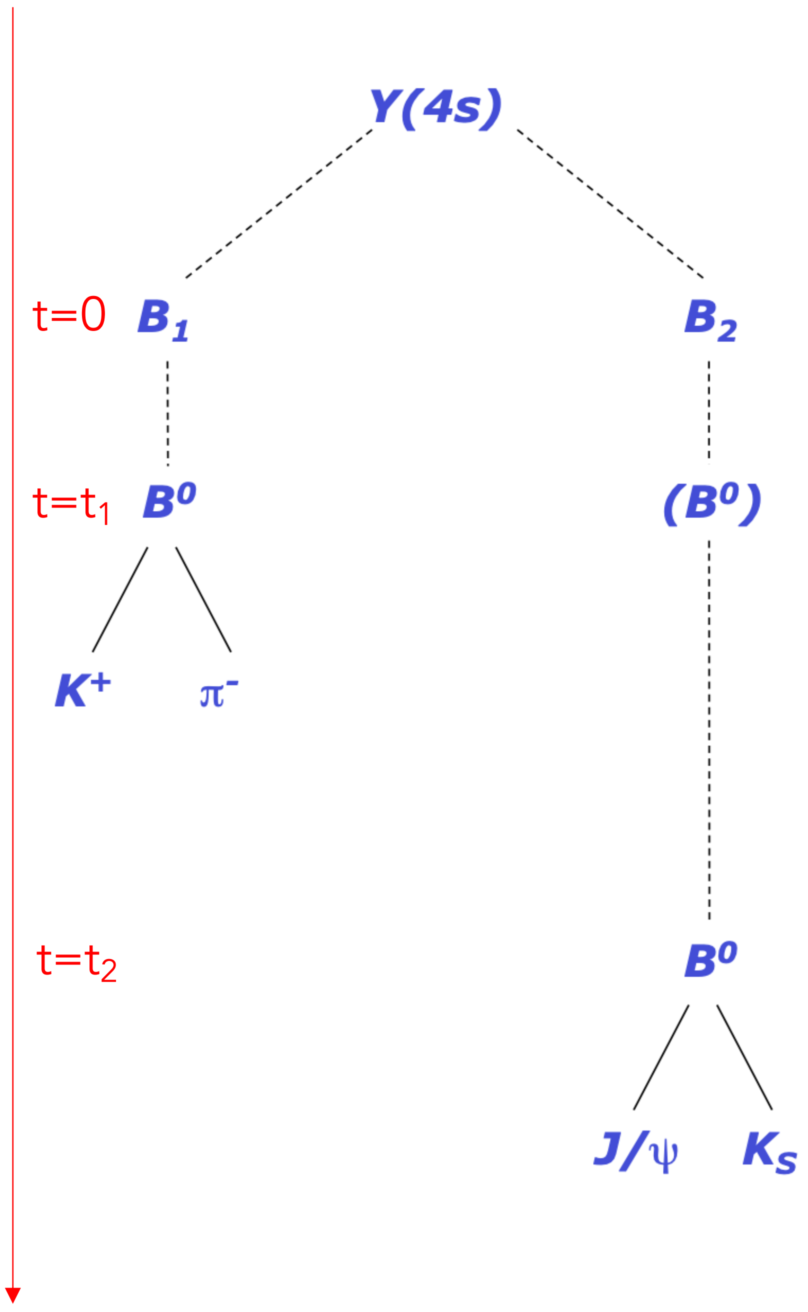
how to measure t_1 and t_2 ?

We do not know where the ϒ(4S) has decayed



M(ϒ(4S) = 10.58 GeV

⇒ (B^+, B^0) are produced nearly at rest in the ϒ(4S) center of mass (p* ~ 340 MeV), ~ 30 μm between B_1 and B_2 decay vertices



Pier Oddone (LBL)

Make the Υ(4S) flies !

BaBar

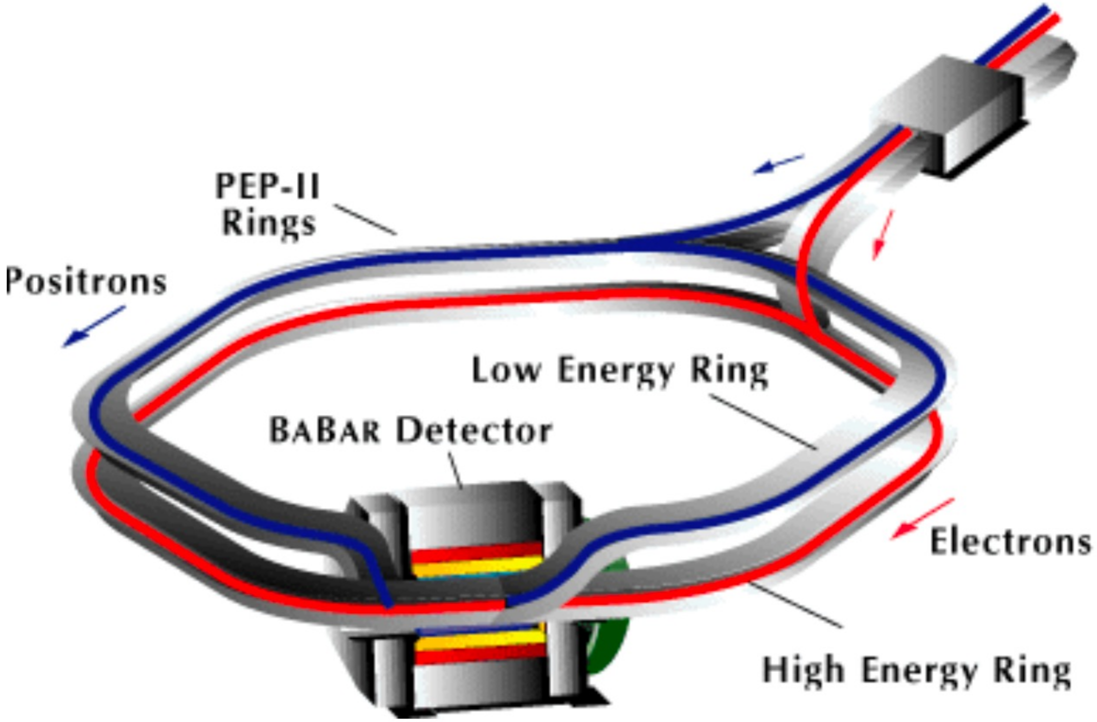
e+ beam : 3.1 GeV
e- beam : 9 GeV

βγ= .56 → 2 B separaration ~ 250 μm

Belle

e+ beam : 3.5 GeV
e- beam : 8 GeV

βγ= .43 → 2 B separaration ~ 200 μm



Belle-II lower boost 4 (e+) GeV vs 7 (e-) GeV

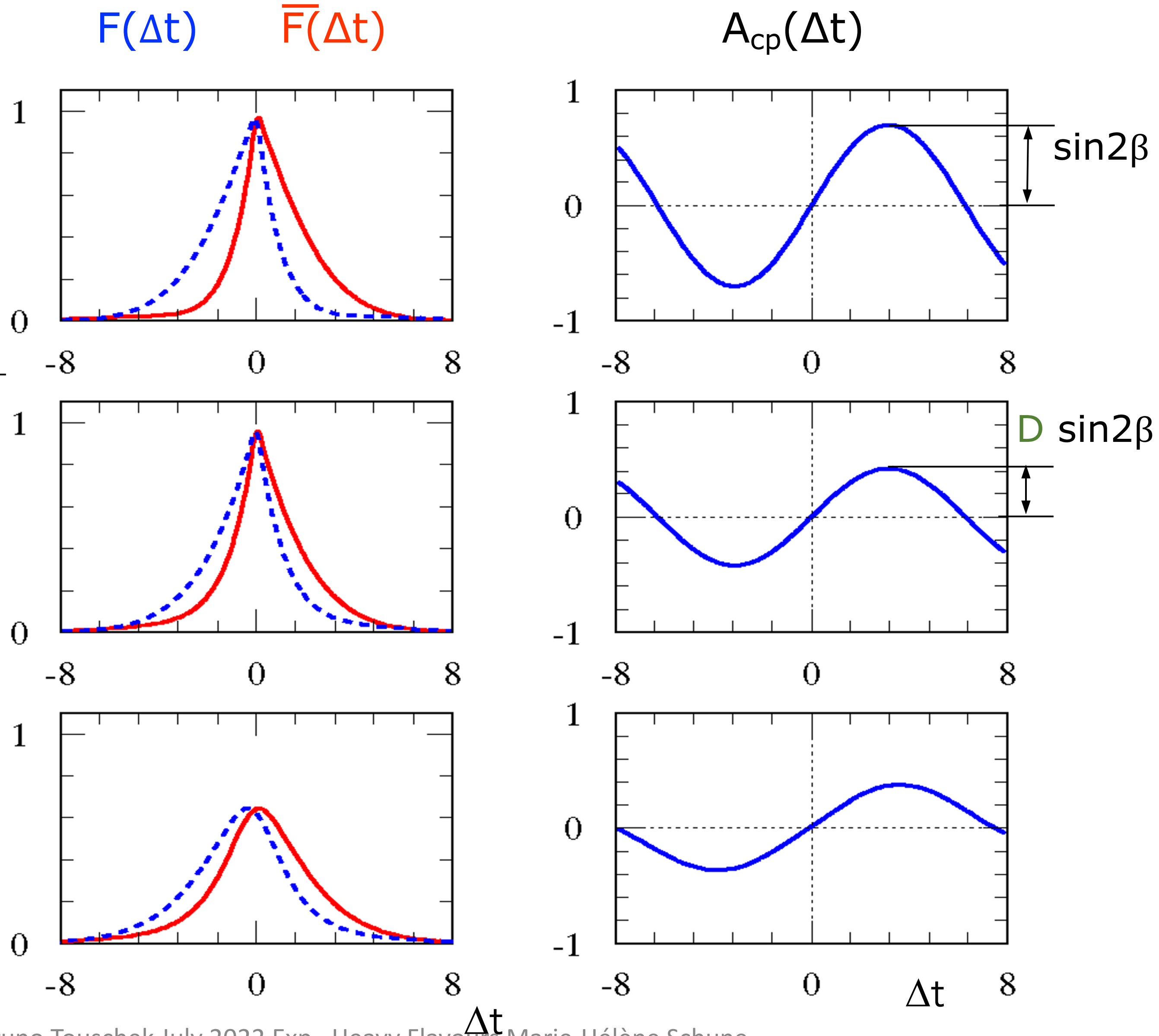
Why are B-Factories detectors slightly asymmetric ?

because we want to measure Δt
otherwise no sensitivity to β angle

$$\int_{-\infty}^{+\infty} \sin 2\beta \sin \Delta m\Delta t \; d\Delta t = 0$$

What do we expect to see ?

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



Everything perfect

Add tag mistakes

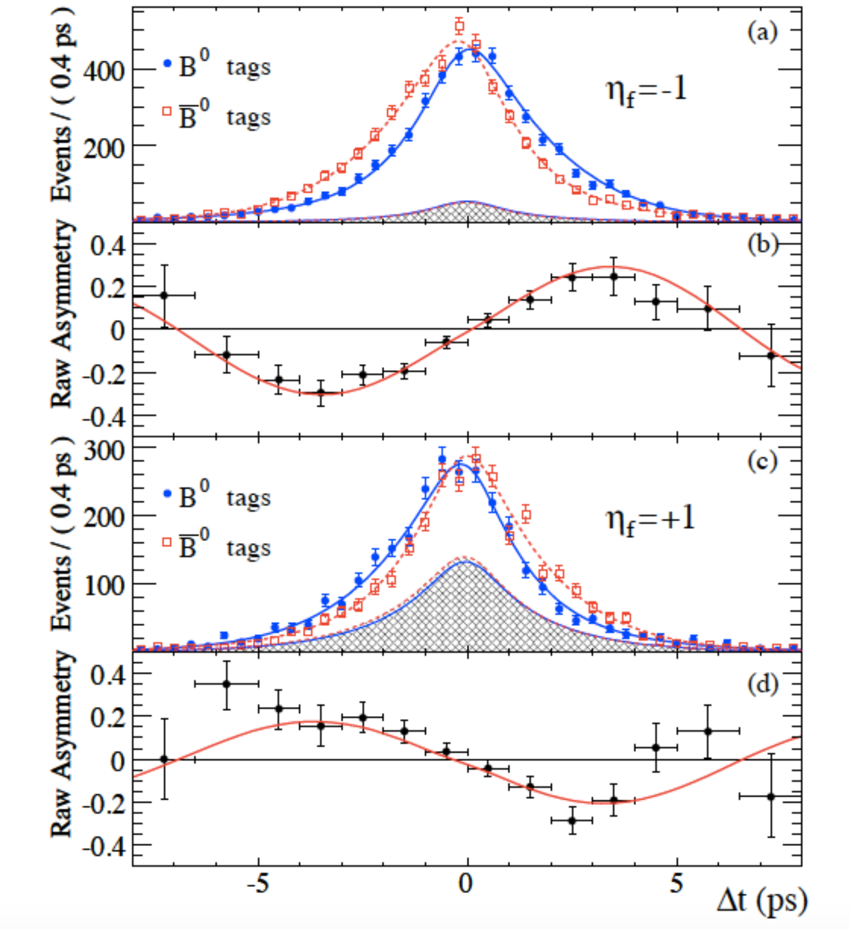
Dilution: D=1-2w

Add imperfect

Δt resolution

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

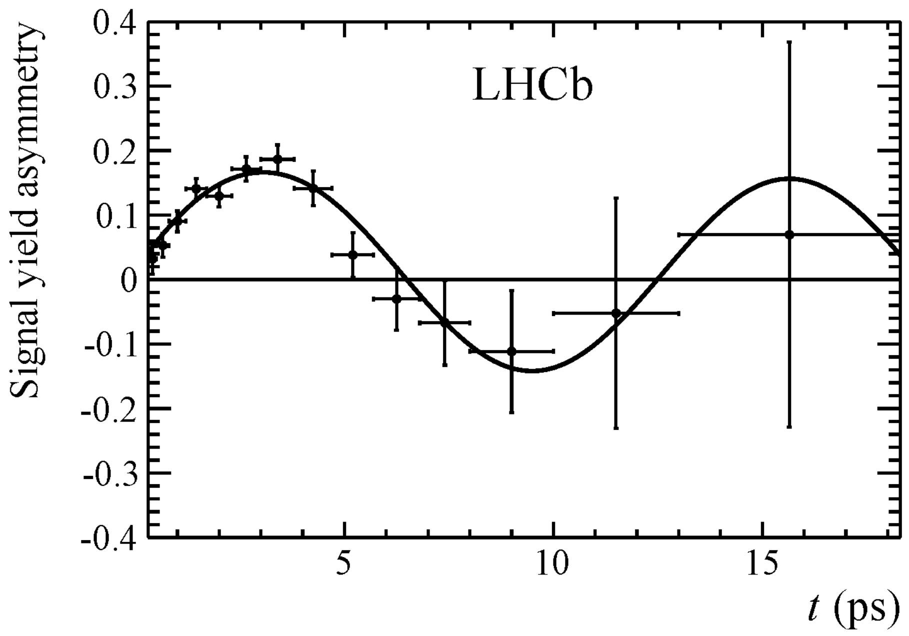
B-factories

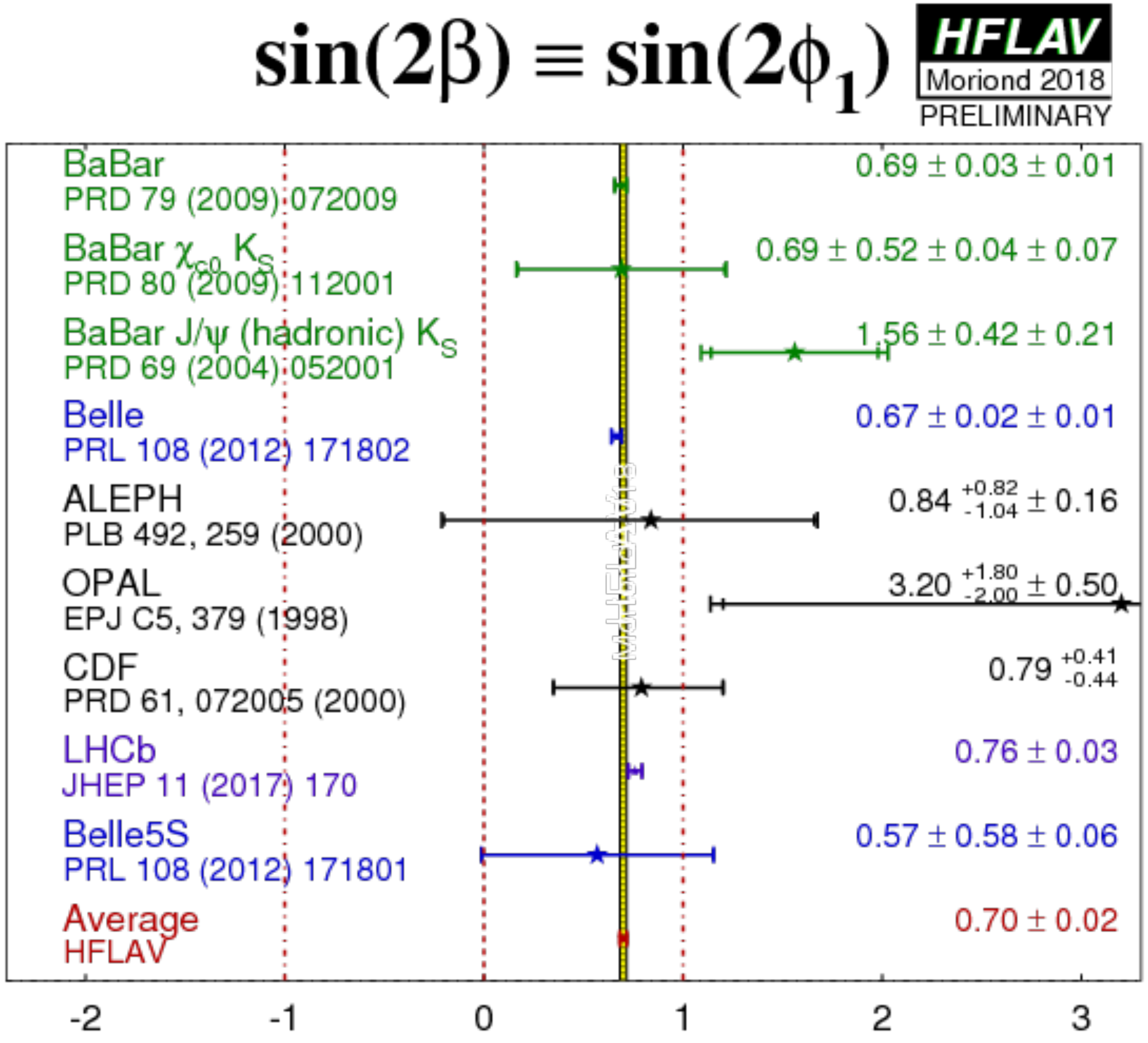


sin2β = 0.687 ±0.028 ±0.012

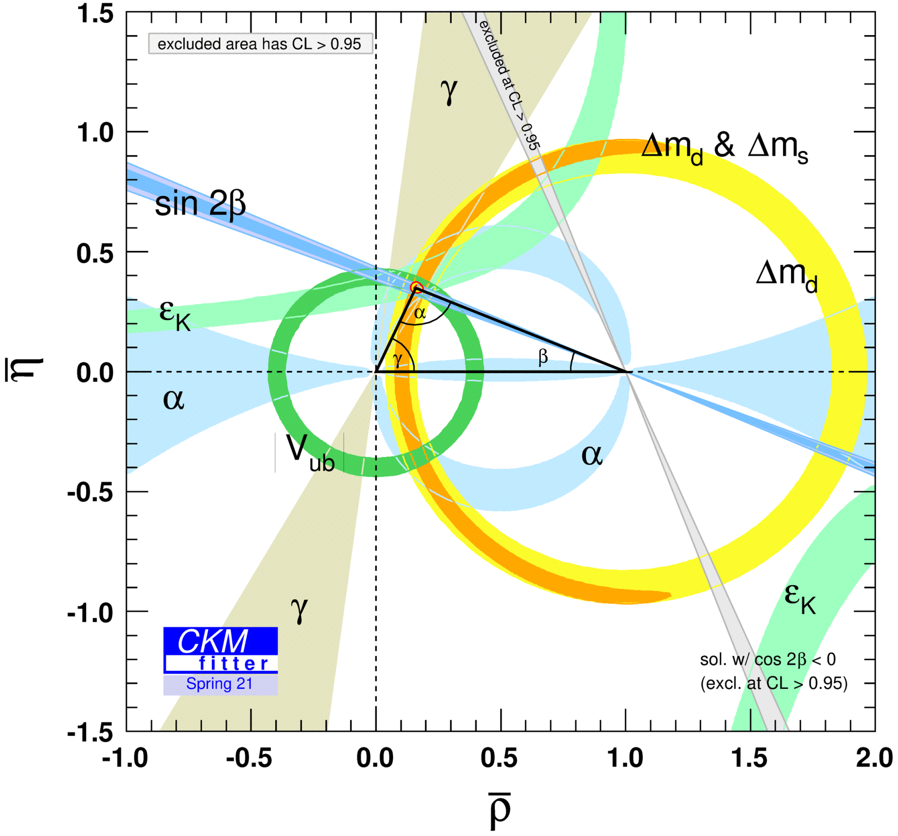
BaBar Phys.Rev.D79:072009,2009

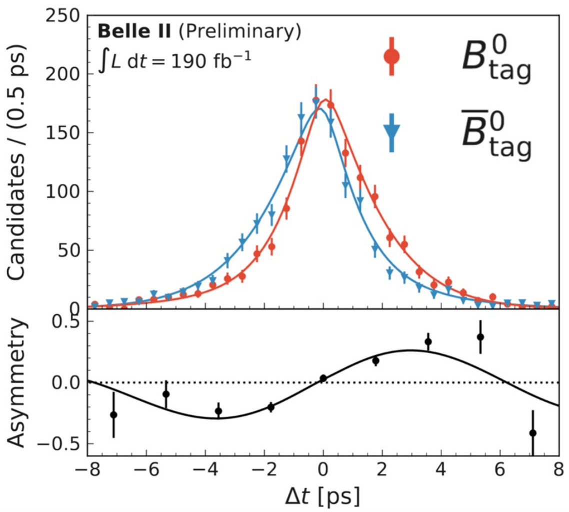
Phys. Rev. Lett. 115, 031601 (2015)





3 % precision !

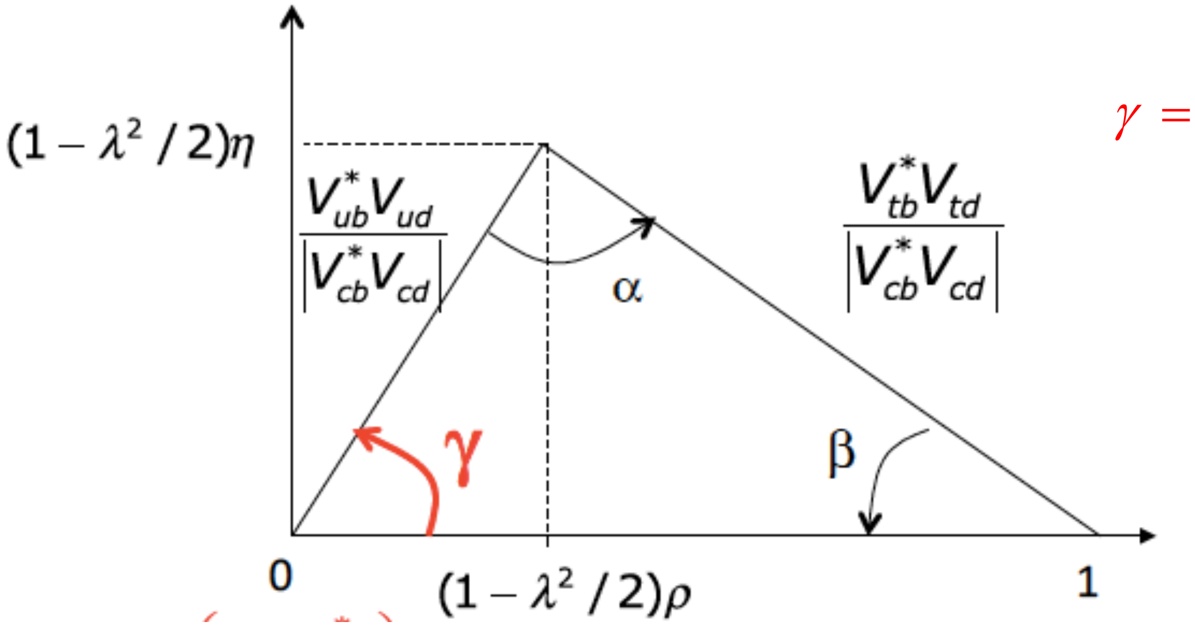




Chiara La Licata @ICHEP2022

0.720 ± 0.062 (stat.) ± 0.016 (syst.)

Measurement of the γ angle: direct CP violation

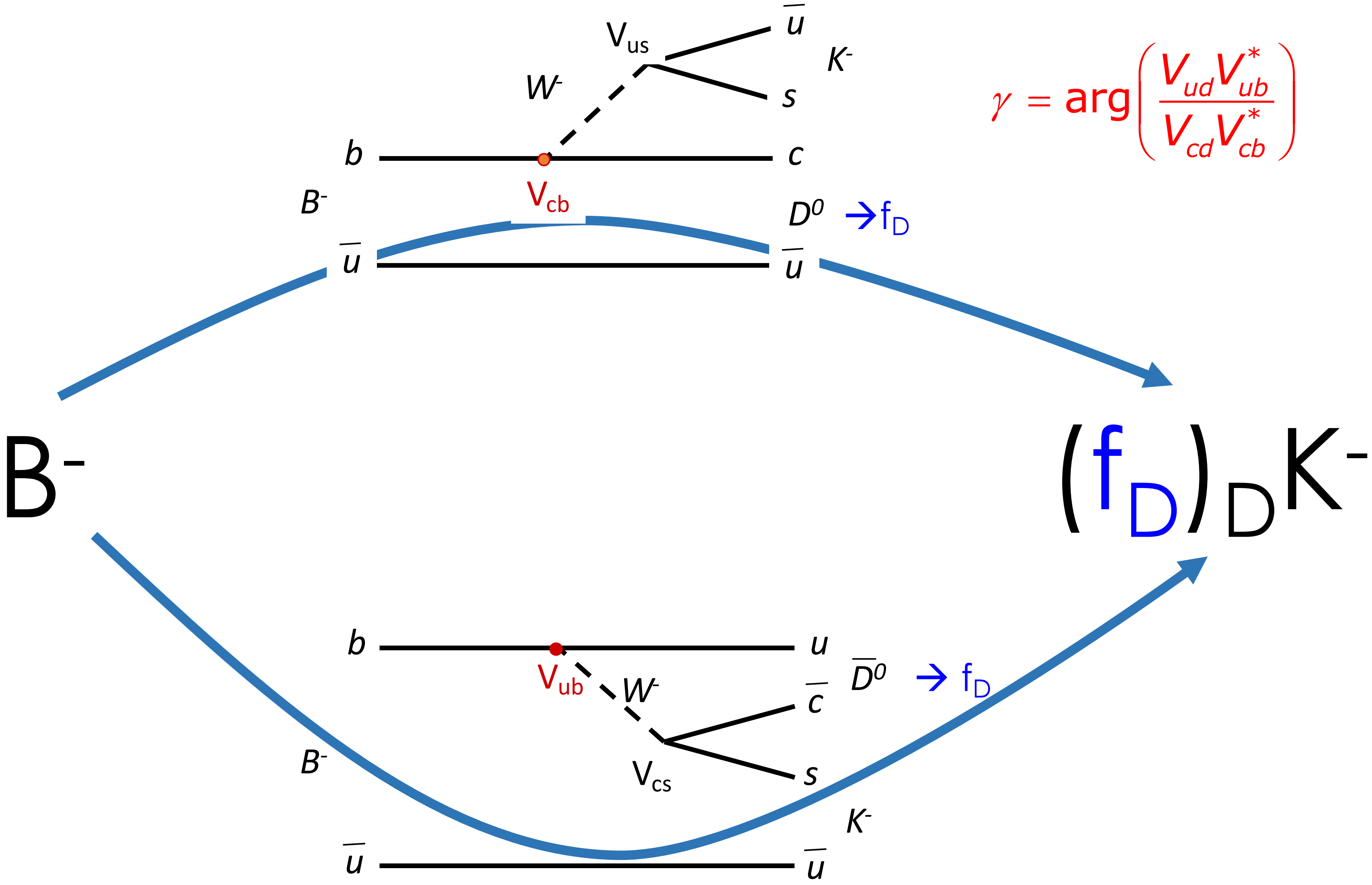


$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Value precisely predicted in the SM context from other triangle parameters

⇒ it is important to measure it precisely

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



f_D = KK, $\pi\pi$

but also Kπ, K_s $\pi\pi$, …

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

CP

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

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

γ : weak phase alters sign under CP

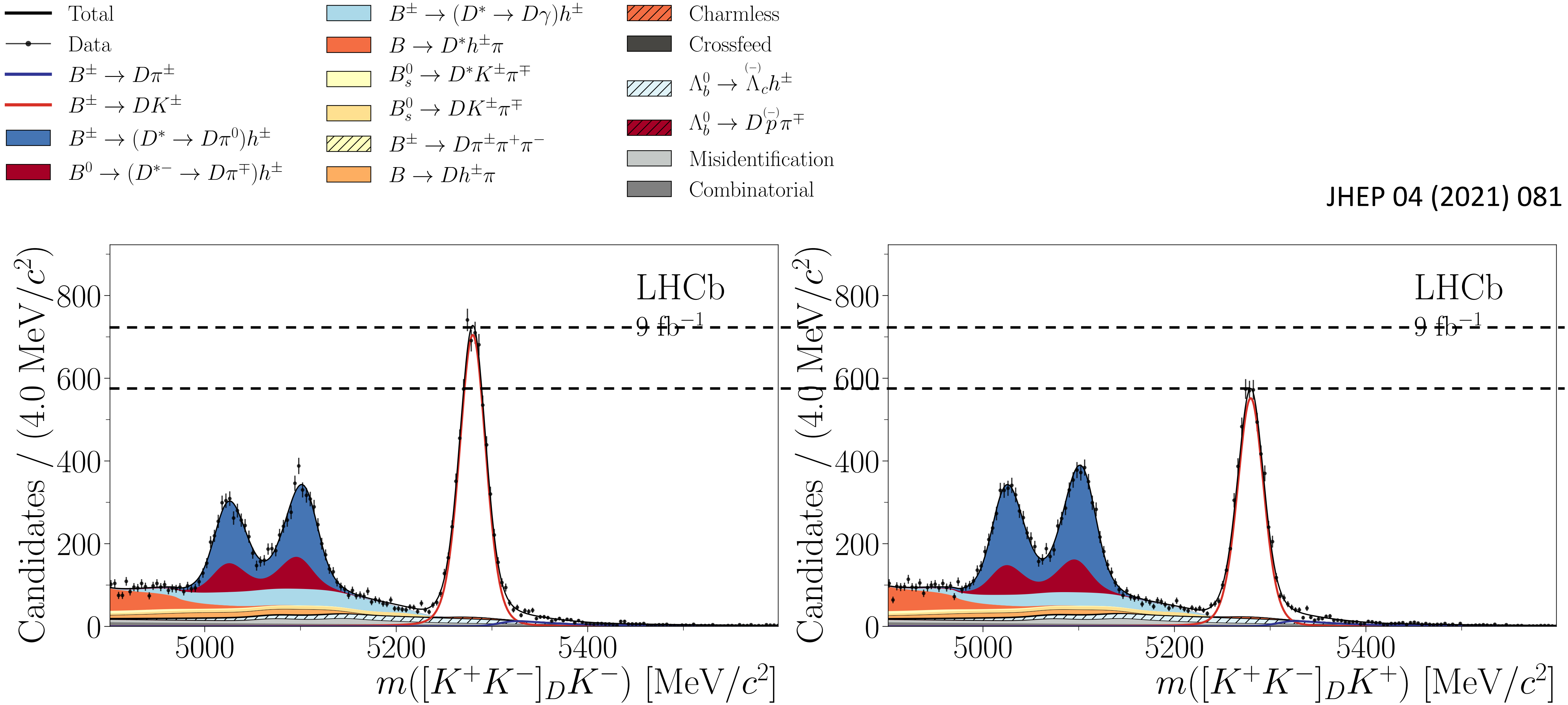
δ_B : strong phase : CP invariant

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

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

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

3 unknows : r_B δ_B and γ ⇒ additional information needed : other decay modes (KK, ππ, Kπ, …)



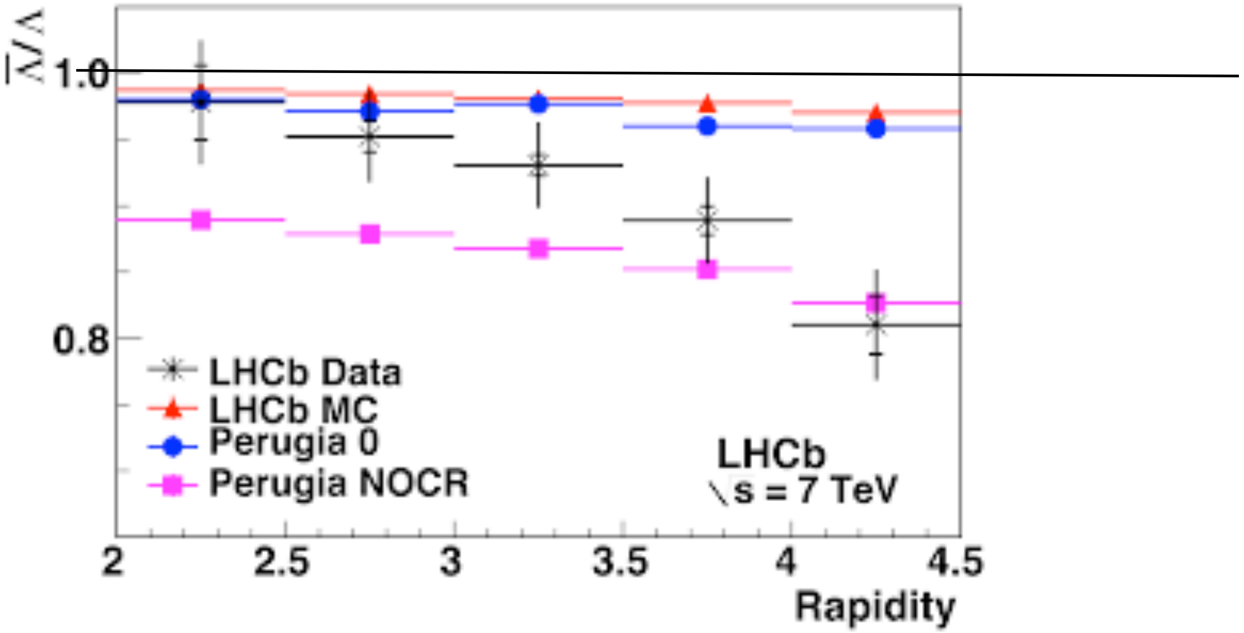
JHEP 04 (2021) 081

$$\boxed{A_K^{CP} = \quad 0.136 \quad \pm 0.009 \quad \pm 0.001}$$

But there are other sources of asymmetries :

- different numbers of B^+ and B^- produced : pp initial state ⇒ slightly less B^- than B^+ : (-0.8 ± 0.7)% due to the hadronization asymmetry

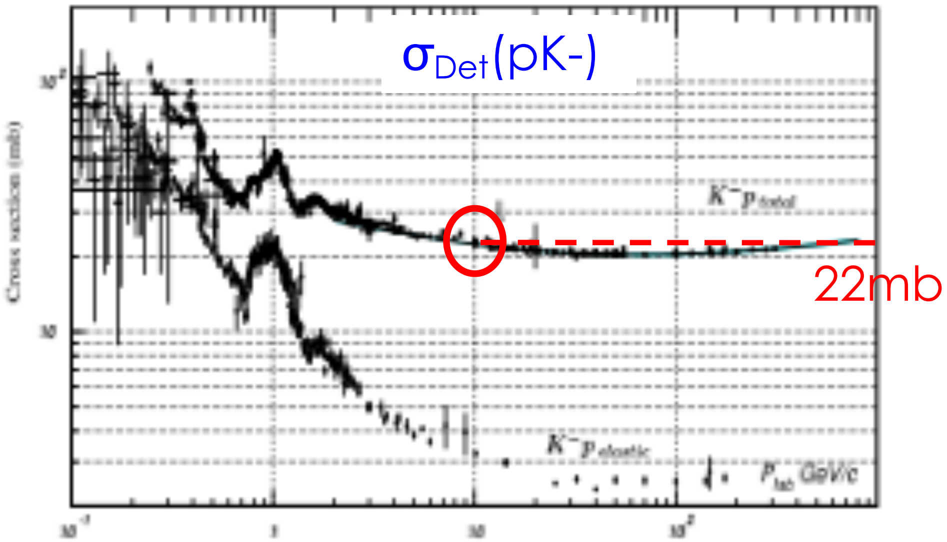
2 protons in the initial state
⇒ higher probability to pick up a diquark than an anti-diquark

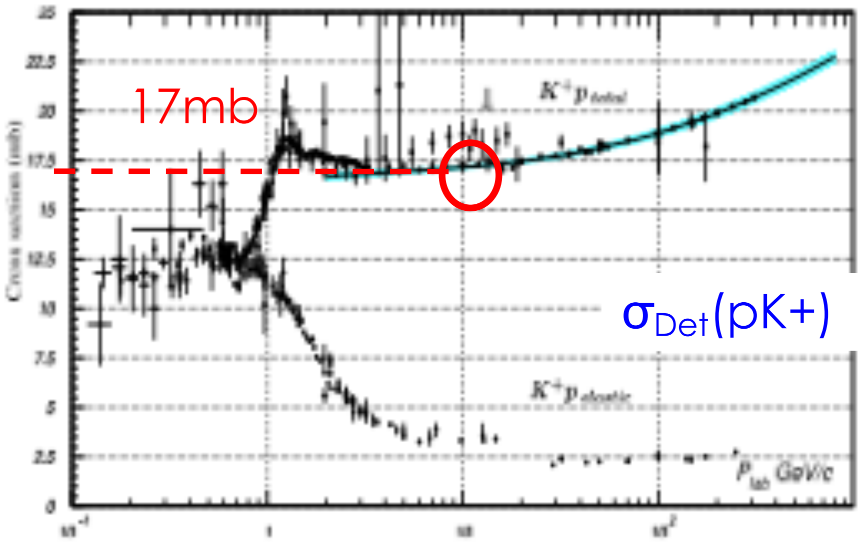


⇒ more b-baryons than anti-b-baryons
since one has the same probability to have a b-quark than anti-b-quark
⇒ less B^-(b anti-u) than B^+ (anti-b u)

- detection asymmetries 1/2
  - K^- and K^+ have different interaction length (negligible for pions)

σ_{Det}(pK-)>σ_{Det}(pK+) but σ_{Det}(pPi-)~σ_{Det}(pPi+)





K- p can have q qbar annihilation (but not K+)

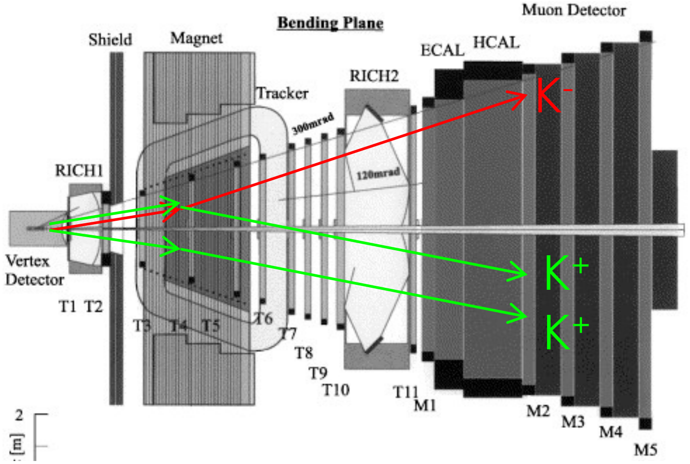
Both Pi- p and Pi+ p have annihilation

$$
\overset{\text{p}}{\begin{pmatrix} u \\ u \\ d \end{pmatrix}} \qquad \overset{\text{K+}}{\begin{pmatrix} u \\ \bar{s} \end{pmatrix}} \qquad \overset{\text{K-}}{\begin{pmatrix} \bar{u} \\ s \end{pmatrix}}
$$

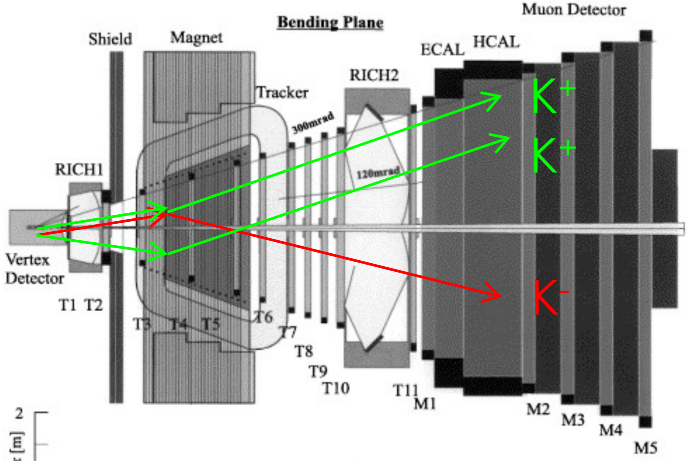
• detection asymmetries 2/2

- a part of the detector can have a lower efficiency : effect reduced by a flip in magnet polarity

Polarity Up



Polarity Down



Use together signal and control channels :

$$A_{meas}\left(\left(K\pi\right)_D\pi\right) = \overset{=0}{\cancel{A_{CP}\left(\left(K\pi\right)_D\pi\right)}} + A_{\text{Prod}} + A_{K\ \text{Det}}$$

$$A_{meas}\left(\left(K\pi\right)_D K\right) = A_{CP}\left(\left(K\pi\right)_D K\right) + A_{\text{Prod}} + 2\times A_{K\ \text{Det}}$$

$$A_{meas}\left(\left(KK\right)_D K\right) = A_{CP}\left(\left(KK\right)_D K\right) + A_{\text{Prod}} + A_{K\ \text{Det}}$$

....

More involved analyses :

+ inputs from charm factories (CLEO-c, BES-III)

1) Use a CP mode for the D⁰

GLW (Gronau, London, Wyler)
CP+ and CP- modes

$(K^+K^-, \pi^+\pi^-) \leftarrow$ $\rightarrow (K_S\pi^0, \phi K_S, \eta K_S, \rho K_S, \omega K_S)$

(Very) small Branching Ratios

CP- mostly for Belle-II

2) Use CA($K^-\pi^+$) mode for the V_{ub} decay and DCS($K^-\pi^+$) for the V_{cb} decay

ADS (Atwood, Dunietz, Soni) $\left\{ \begin{array}{l} D^0 \rightarrow K^-\pi^+ \\ D^0 \rightarrow K^-\pi^+\pi^0 \\ D^0 \rightarrow K^-\pi^+\pi^-\pi^+ \end{array} \right.$

(Very) small Branching Ratios

Strong phase between the D⁰ decays

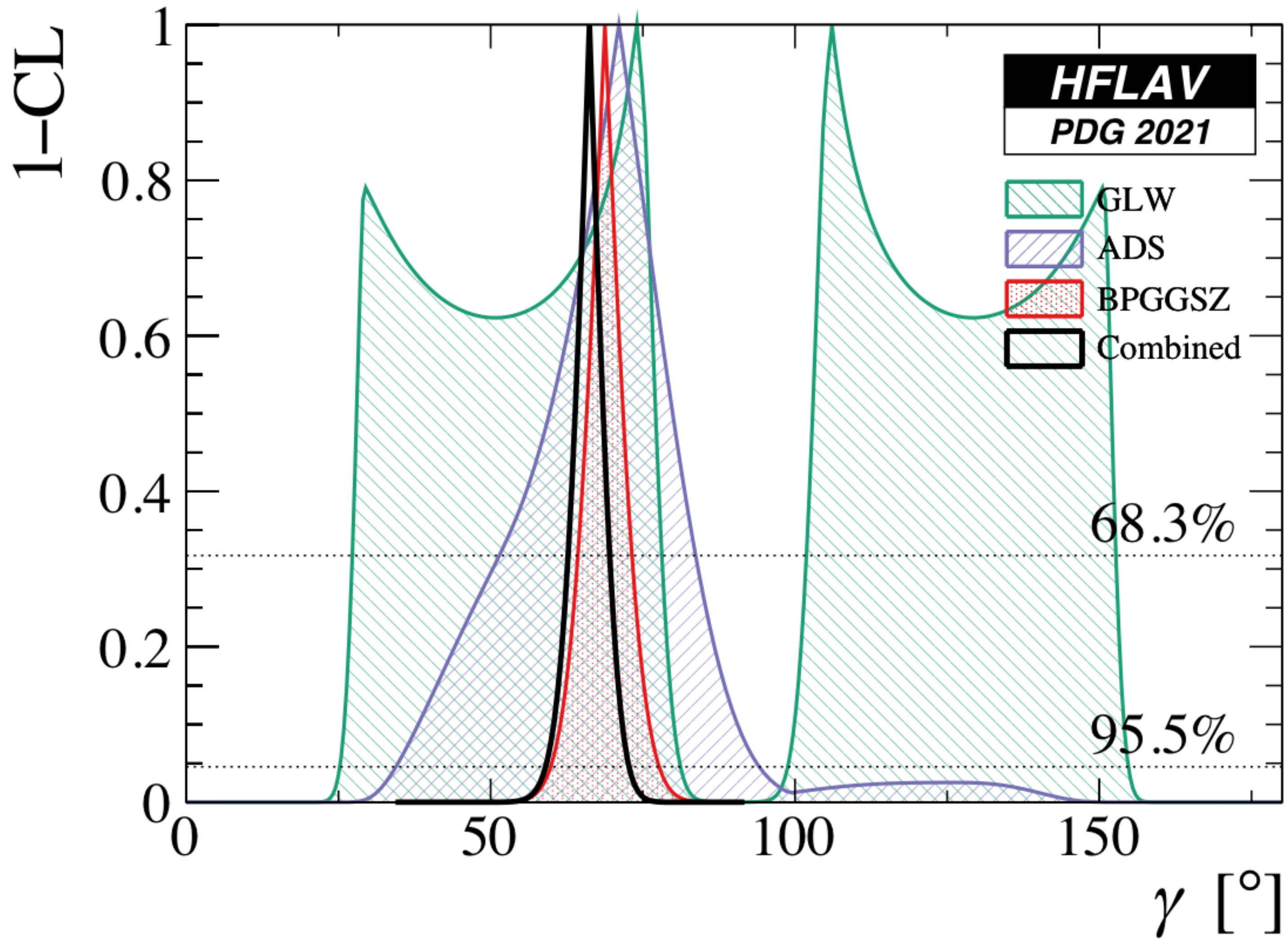
3) Use the $D^0 \rightarrow K_S \pi \pi$ decay

Dalitz BPGGSZ (Bondar, Poluetkov, Giri, Grossman, Soffer, Zupan)

3 body decay : 2D plane (Dalitz plot) analysis

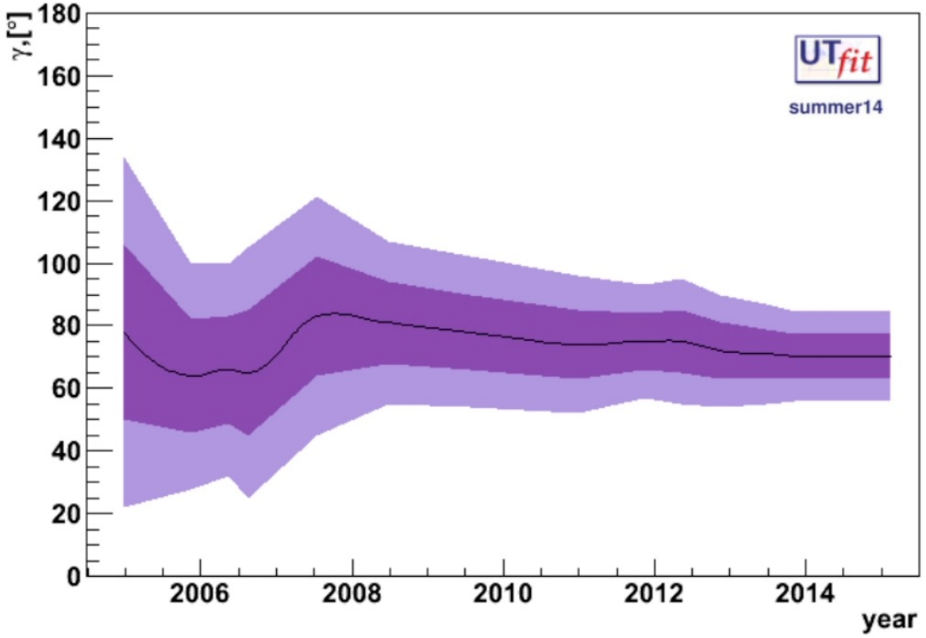
Dalitz plot description

More precise way to measure γ

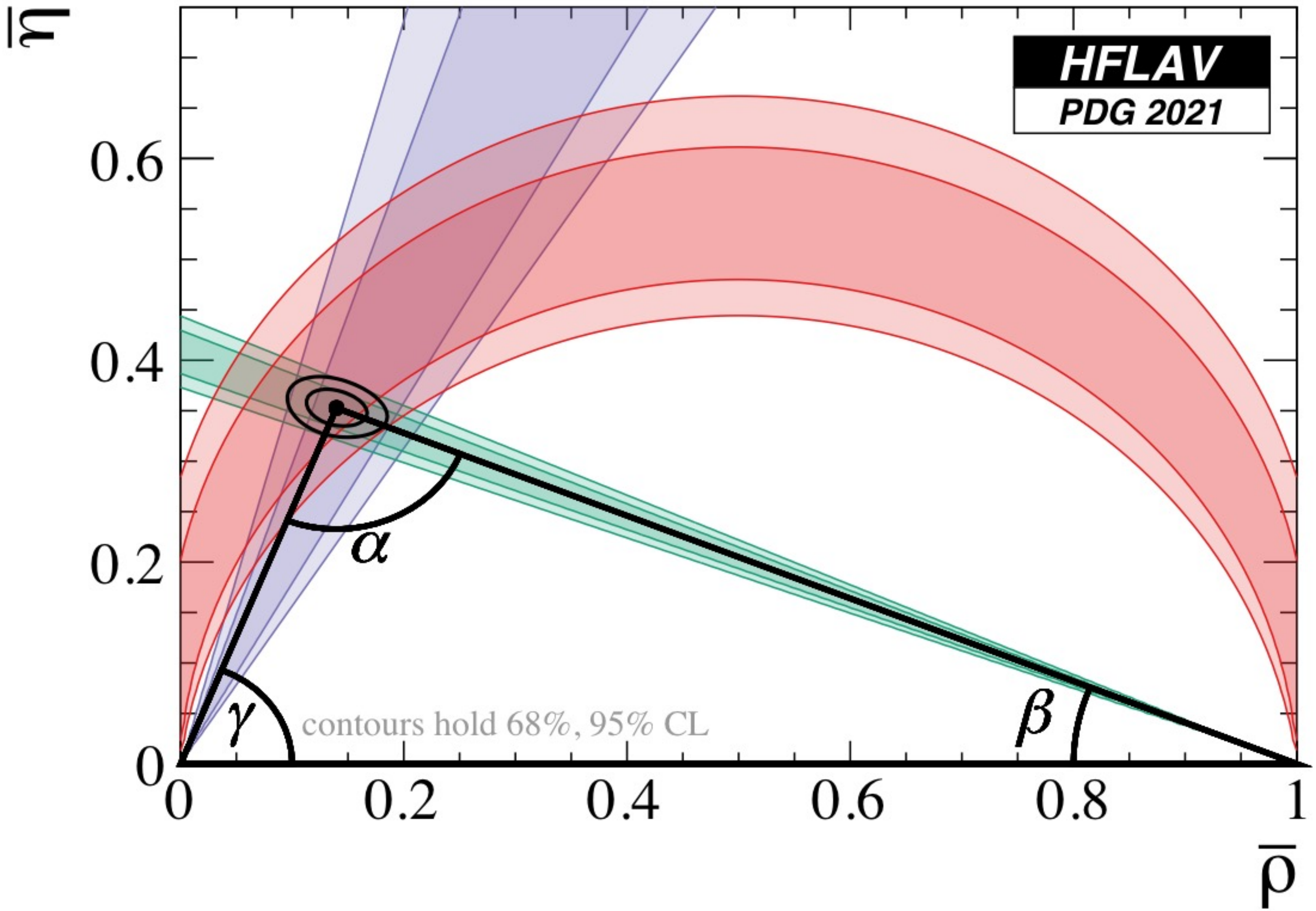


Dominated by LHCb

$$\gamma = (66.2\ ^{+3.4}_{-3.6})^{\circ}$$

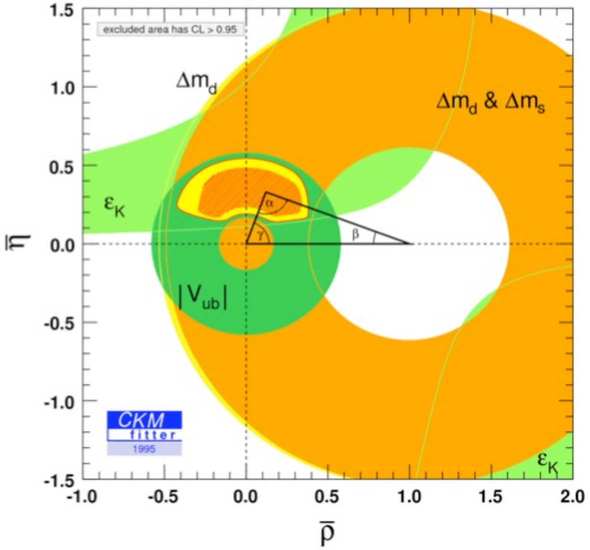


a factor 2 improvement since 2015

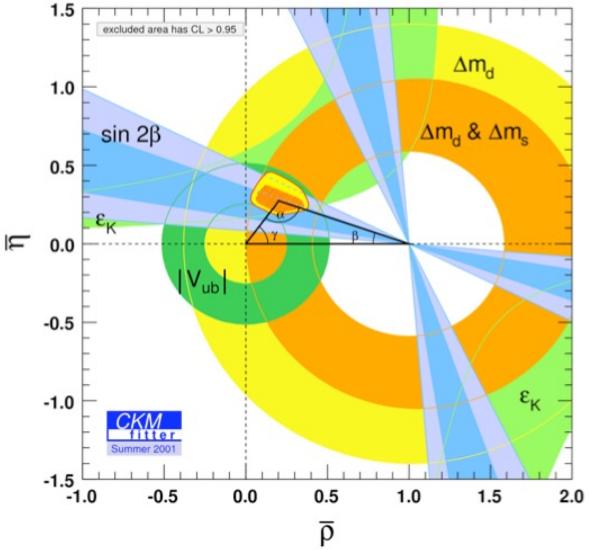

HFLAV
PDG 2021
$\bar{\eta}$
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
$\bar{\rho}$
α
β
γ
contours hold 68%, 95% CL

impressive improvement

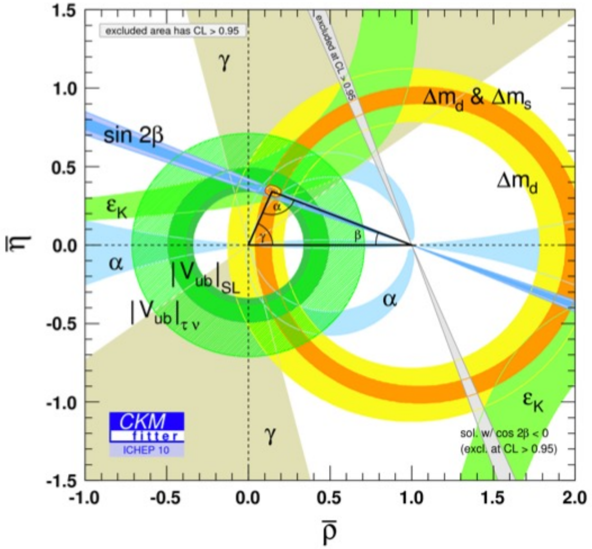
1995



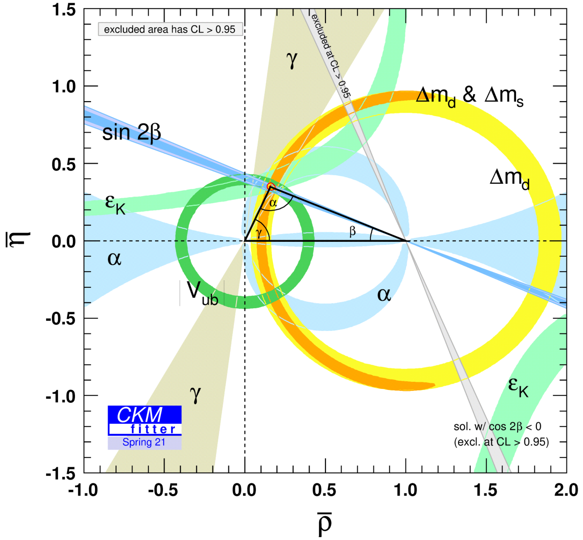
2001



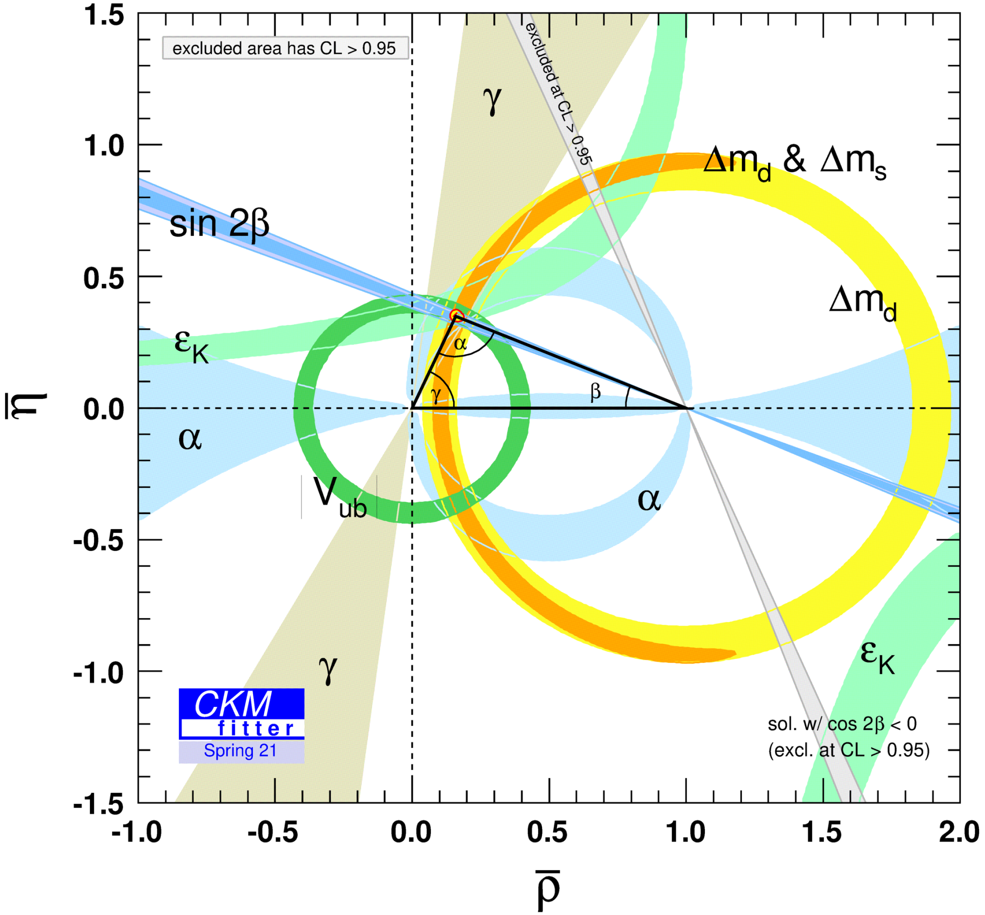
2010

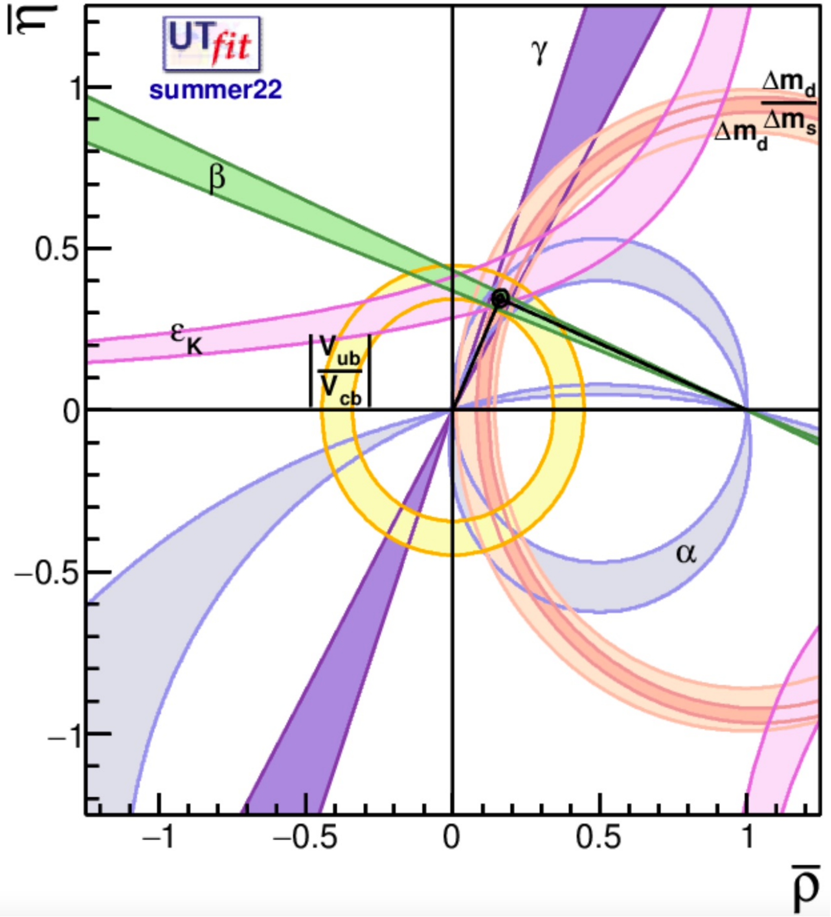


2021



http://ckmfitter.in2p3.fr/





http://www.utfit.org/UTfit/

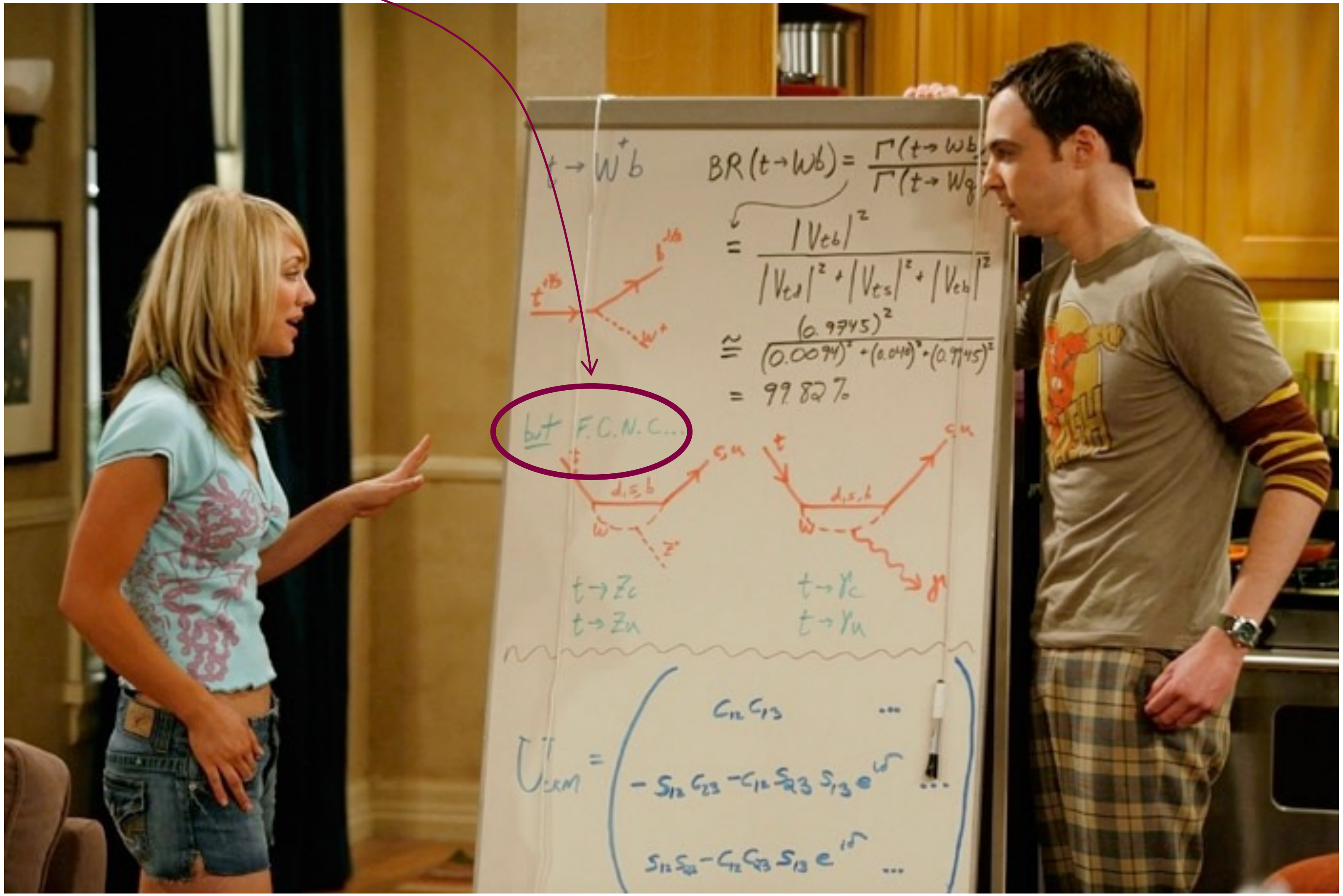
M Bona @ICHEP2022

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

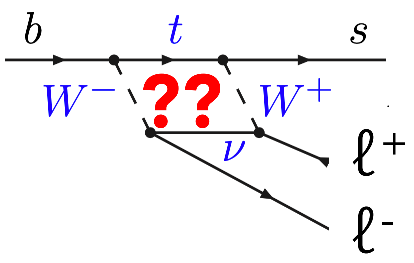
More precision is mandatory (NP currently at 10-20%)

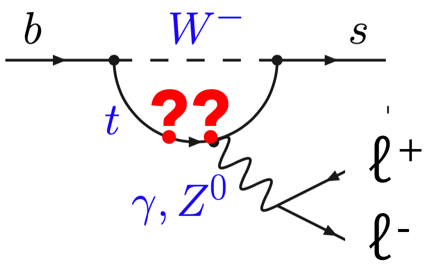
Rare decays ($b\longrightarrow s\ell\ell$)

FCNC



Flavour Changing $b \to s\,\ell\ell$ Neutral Current





Forbidden at tree-level in SM → BR of 10^{-6} – 10^{-10}
New physics contribution can be same order as SM

$$C_i = C_i^{SM} + C_i^{NP}$$

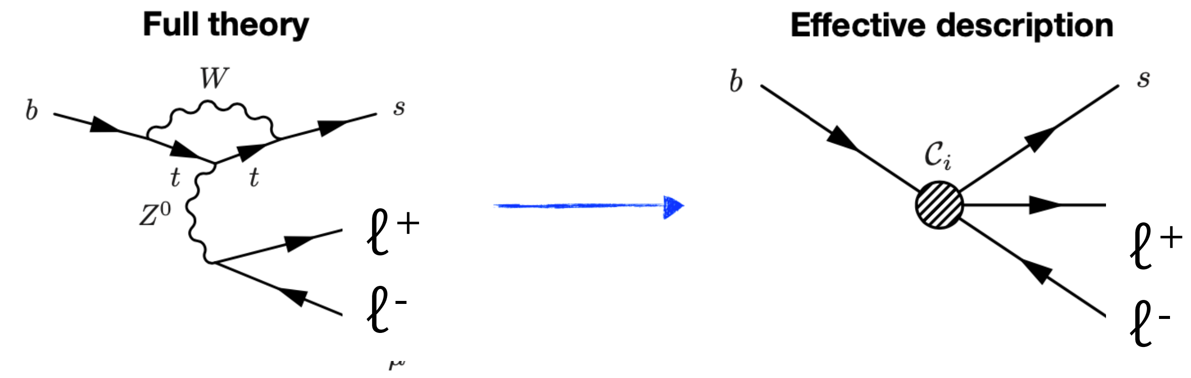
Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+\ell^-)$

Effective-Hamiltonian approach

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{\mathrm{e}^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i C_i O_i + \mathrm{h.c.}$$

NP enters here
$C_i = C_i^{\rm SM} + C_i^{\rm NP}$

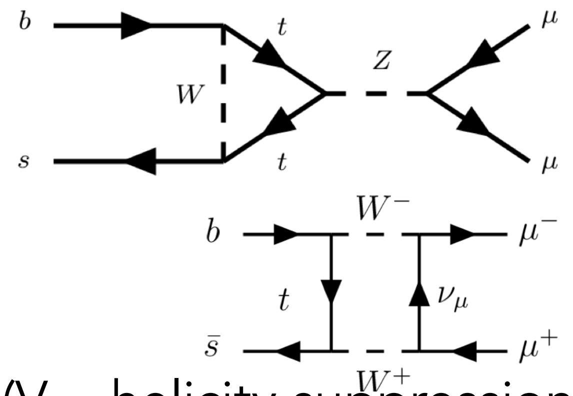
Operator encoding
Lorentz structure

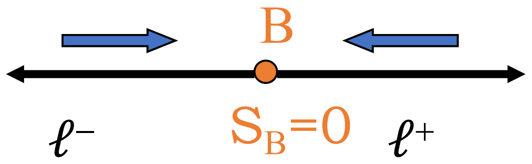


~ Fermi's description of the neutron decay

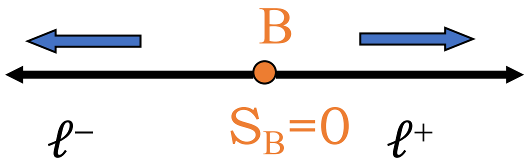
Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X

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





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

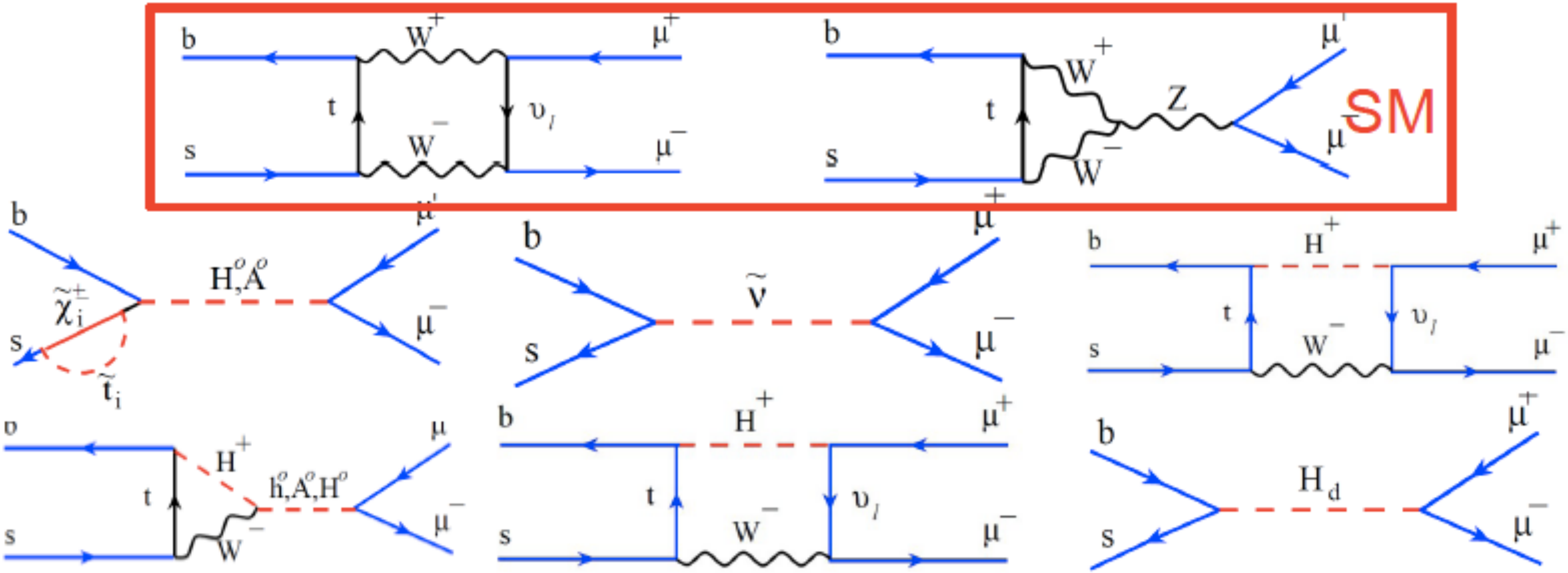
JHEP10 (2019) 232

$$\boxed{\begin{aligned} \mathcal{B}(B_s^0 \to \mu^+\mu^-) &= (3.66 \pm 0.14) \times 10^{-9} \\ \mathcal{B}(B^0 \to \mu^+\mu^-) &= (1.03 \pm 0.05) \times 10^{-10} \end{aligned}}$$

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

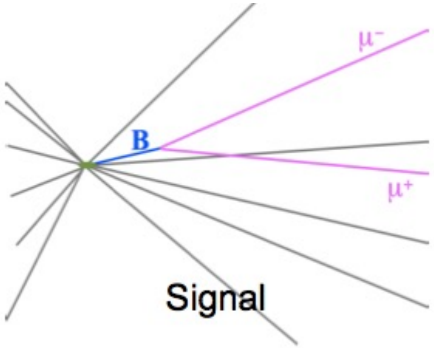


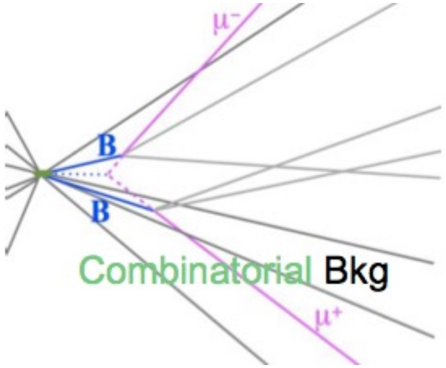
In New Physics models with an extended Higgs sector the BR can be largely enhanced

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

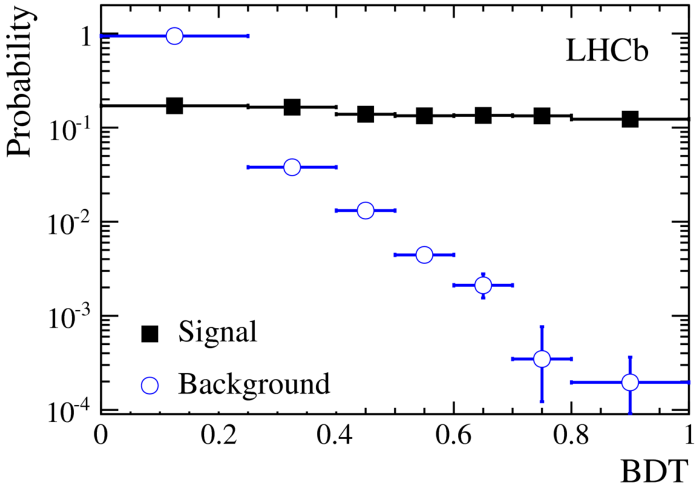
tanβ = ratio of the vevs of
the two Higgs doublets

Analysis in a nutshell

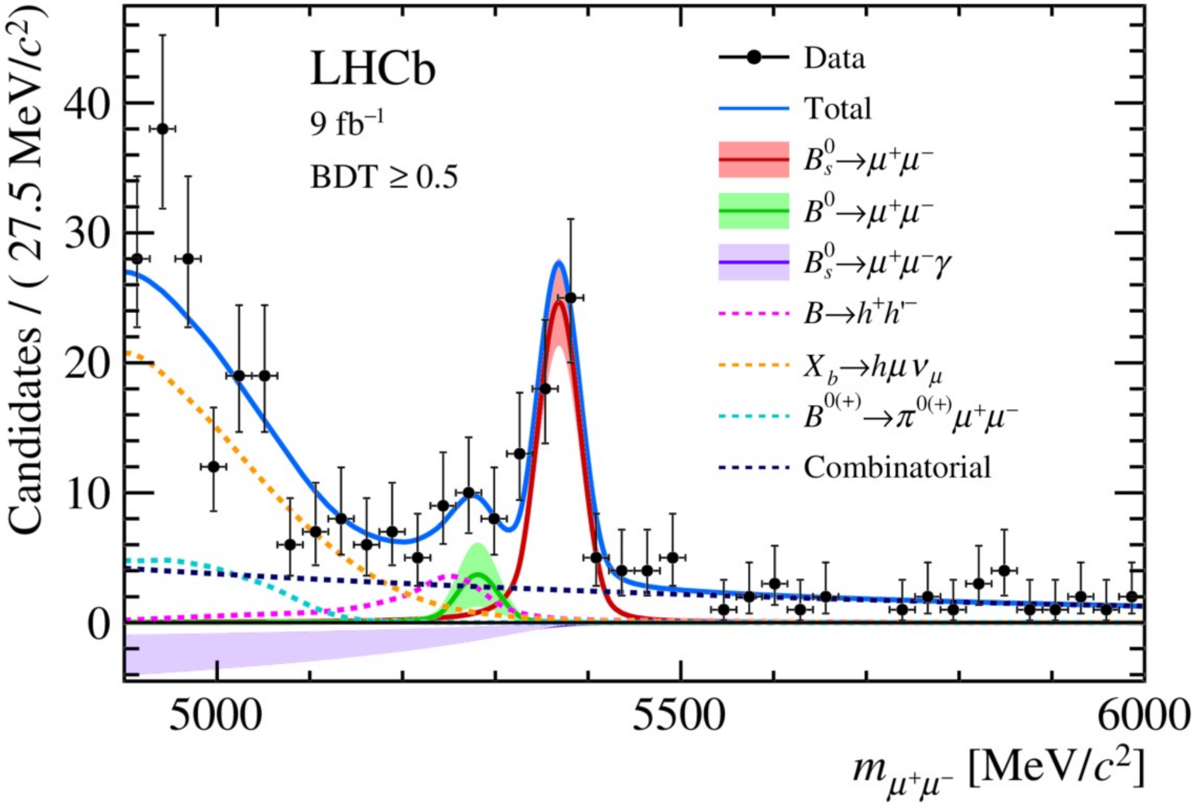


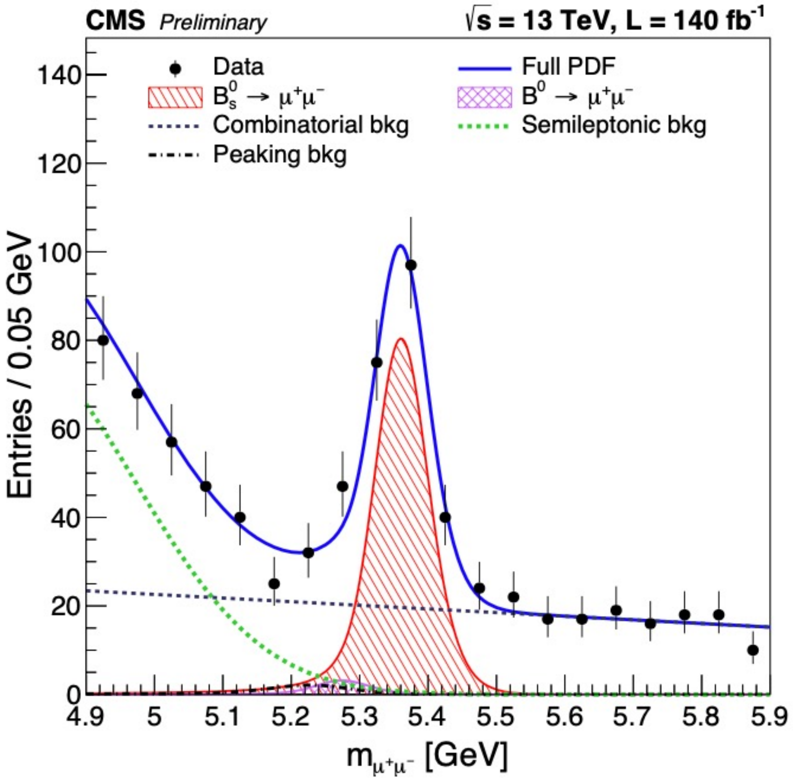


- Huge sample of B mesons
- Efficient trigger
- Powerful selection
  - Vertex resolution
  - Mass resolution
  - Muon ID
- BDT algorithm



- Extract the yields
- Compute the BR normalizing to $B^+ \to J/\psi K^+$ or $B^0 \to K^+\pi^-$





$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\mathrm{stat})\ ^{+0.19}_{-0.16}\,(\mathrm{syst})\ ^{+0.14}_{-0.13}\,(f_\mathrm{s}\,/\,f_\mathrm{u})\right] \times 10^{-9}$$

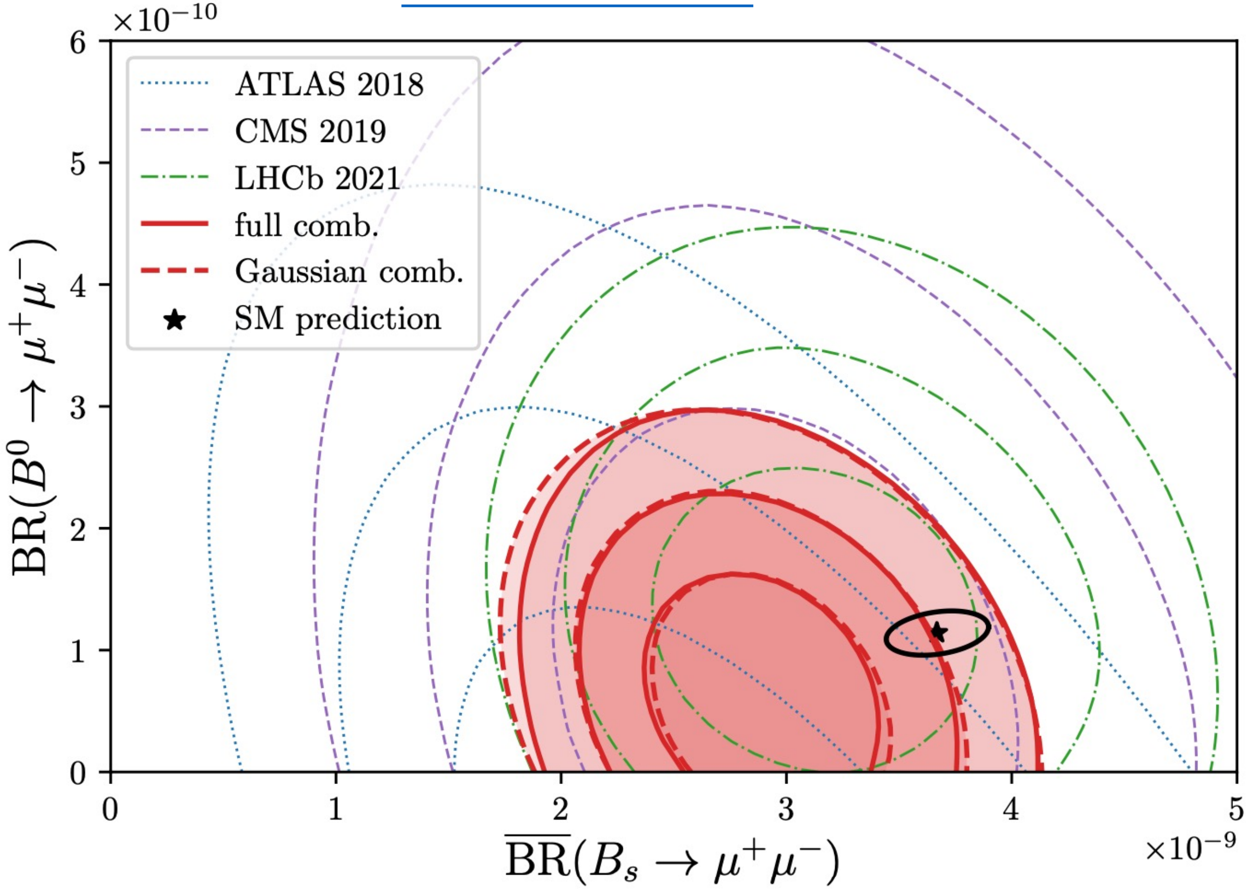
LHCb-PAPER-2021-007

D.Kovalskyi @ICHEP2022

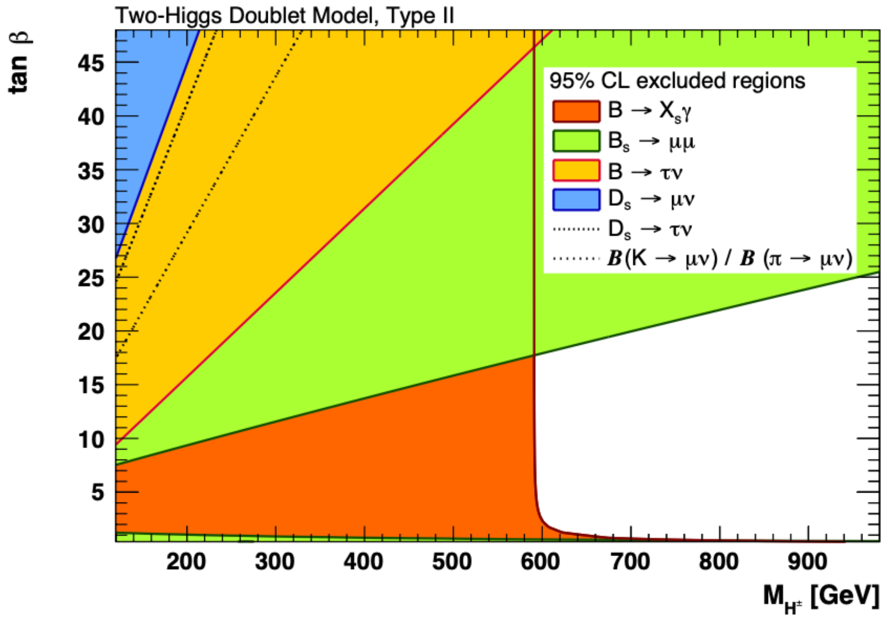
$$\boxed{\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+\,0.46\,+\,0.15}_{-\,0.43\,-\,0.11}) \times 10^{-9}}$$

$$\boxed{\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}}$$ @ 95 % CL

arXiv:2103.13370



Important input for models buidling

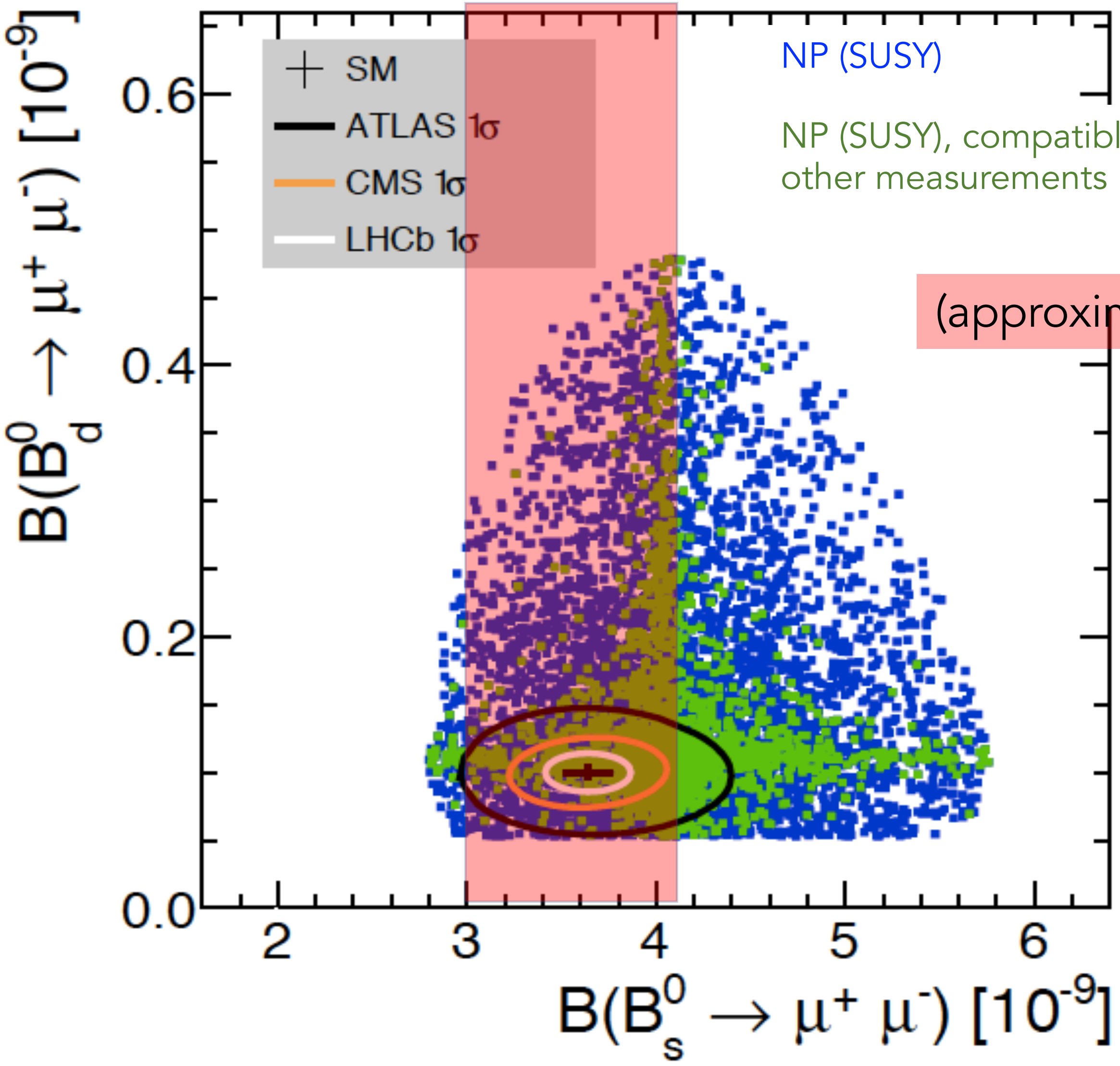


Eur. Phys. J. C78, 675 (2018)

Important to check B_d vs B_s : if there is New Physics does it couples as SM ?

Other variables : $B_s \to \mu\mu$ effective lifetime

Expected sensitivities at HL-LHC



NP (SUSY)

NP (SUSY), compatible with other measurements

(approximate) current 1σ combination

arXiv:1812.07638

Experimental sensitivity:

- dominated by systematics (f_s/f_d)
- close to the SM uncertainty (CKM matrix elements, B_s decay constant)

Additional observables:

- effective lifetime (precision for LHCb : 8% for 23 fb^{-1} and 2 % with 300 fb^{-1})
- time dependent CP asymmetry (sensitive to NP phase) . Accessible only with 300 fb^{-1}

Why don't you look at $B_s \rightarrow ee$?

SM prediction

more helicity suppression !

$$\mathcal{B}(B_s^0 \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$$

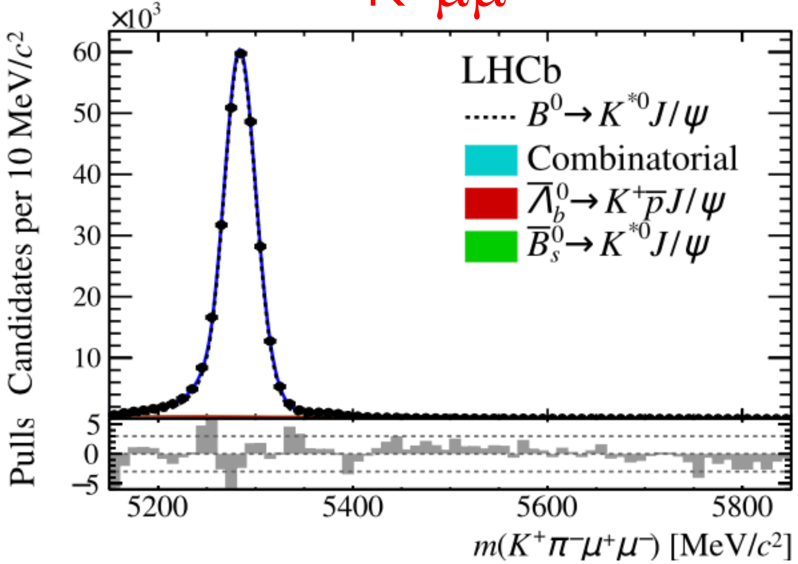
$$\mathcal{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

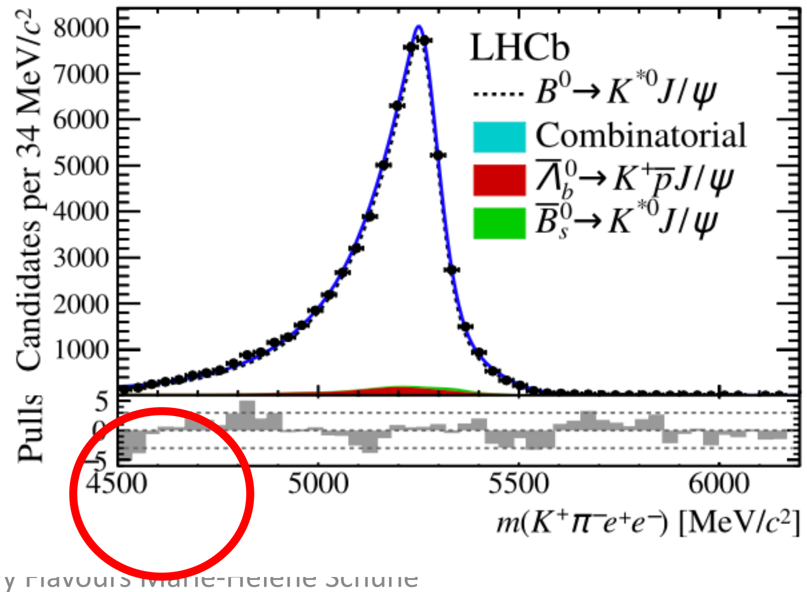
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

But electrons emit Bremsstrahlung photons ….

K*μμ

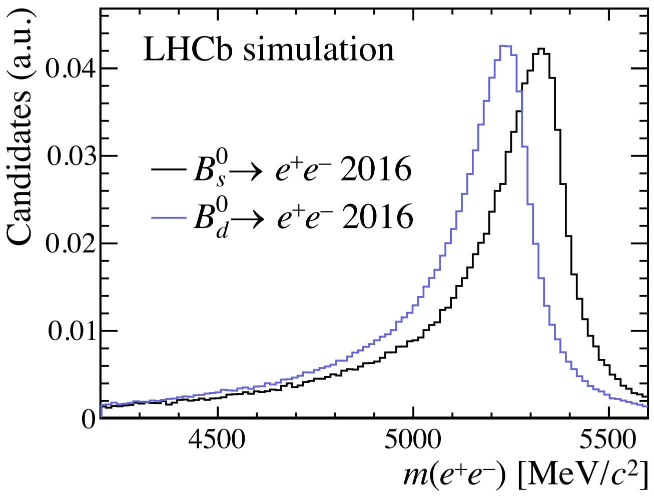


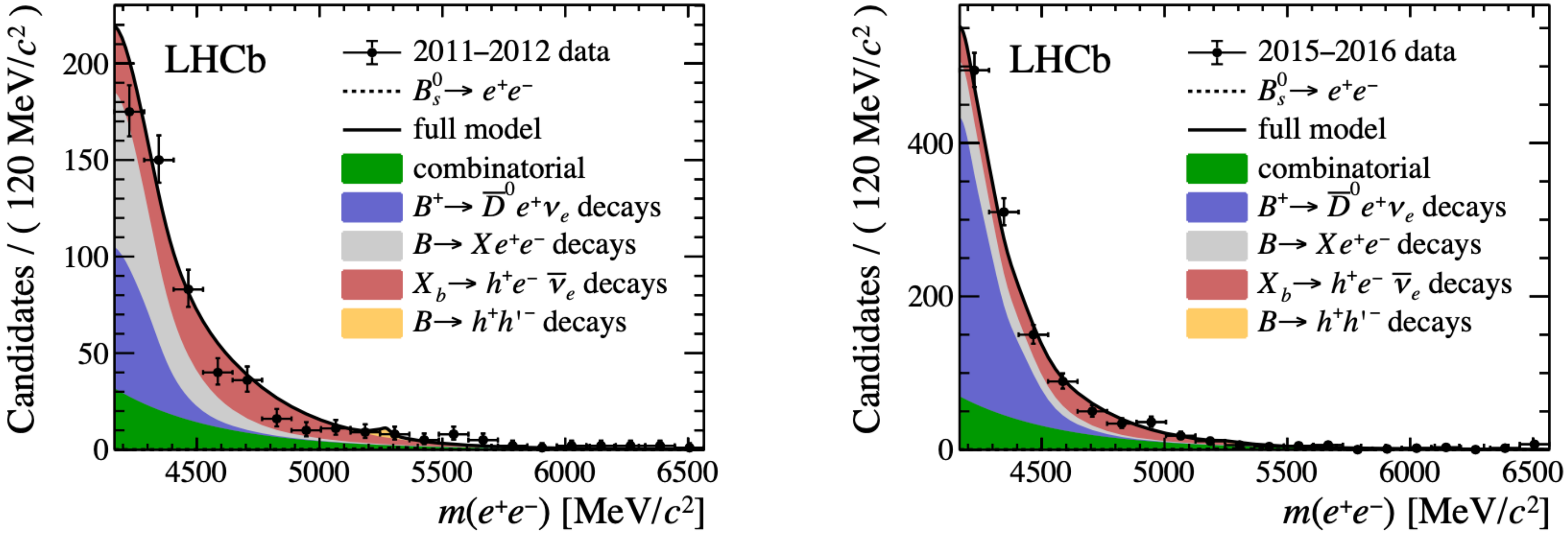
K*ee



LHCb-PAPER-2020-001

Not enough mass resolution to separate B_d from B_s



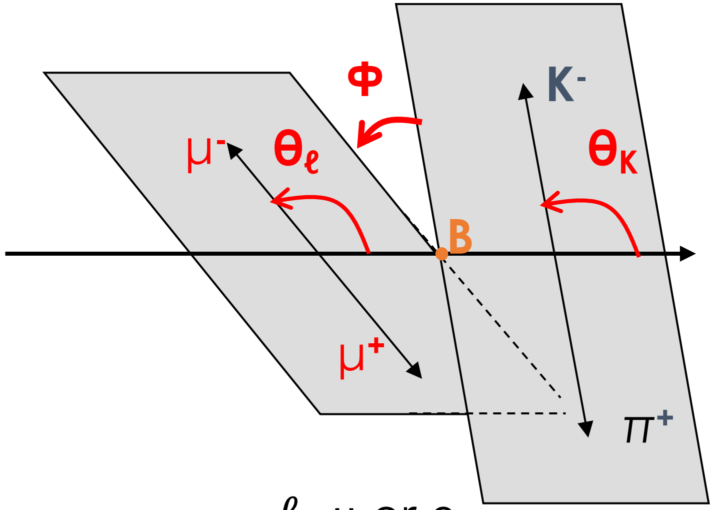


$$\mathcal{B}(B_s^0 \to e^+e^-) < 9.4\,(11.2) \times 10^{-9} \text{ at } 90\,(95)\,\% \text{ confidence level}$$ (5 fb^{-1})

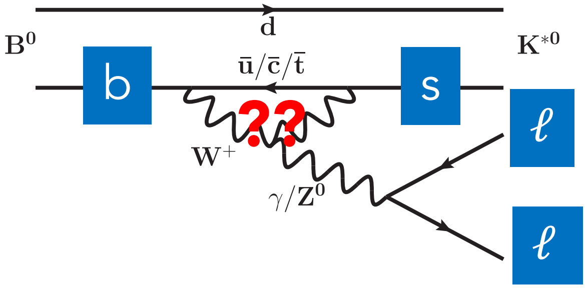
b→sℓℓ transitions : B→K*ℓℓ

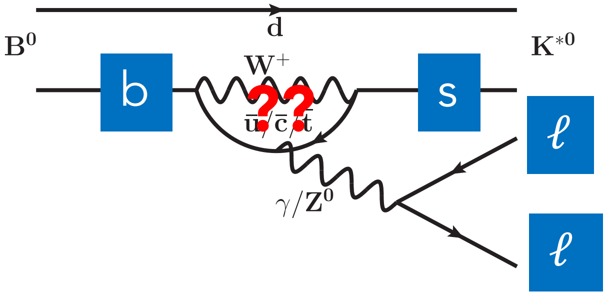
4 particles final state
System described by:

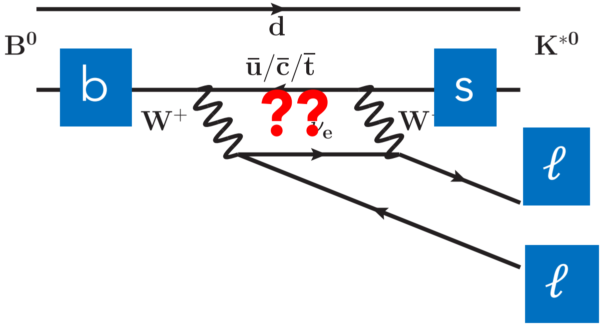
- $q^2 = M^2(\ell\ell)$
- 3 angles



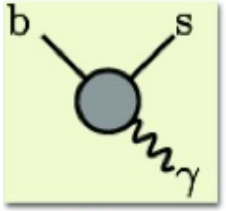
ℓ=μ or e



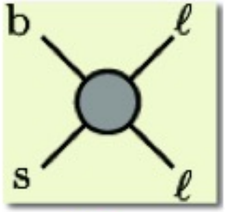




Interferences between



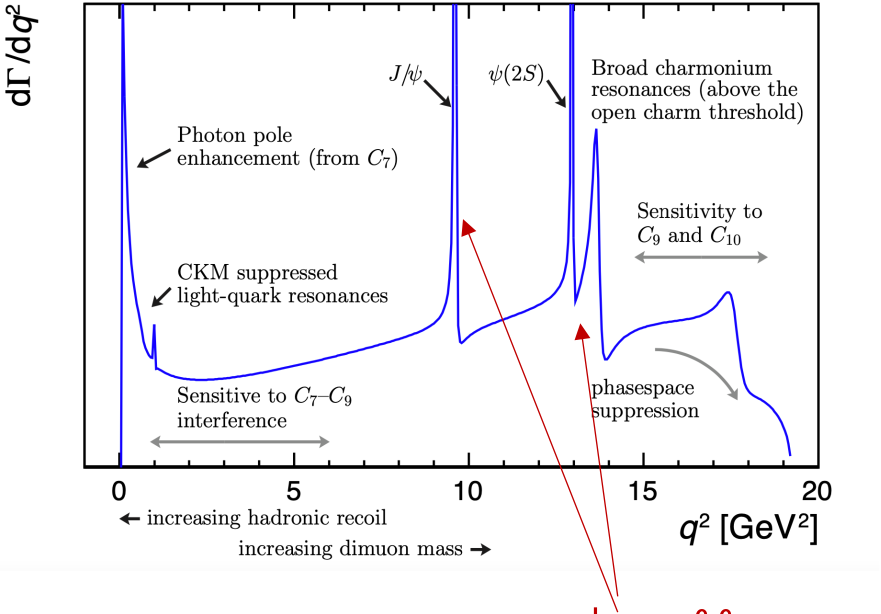
$O_{7\gamma}$



$O_{9,10}$

and their right-counter parts

Prog.Part.Nucl.Phys.02(2017)50



$b \to s\ell\ell$

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

$$\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$$

I_i (i=1,9) are encoding the matrix elements of the decay

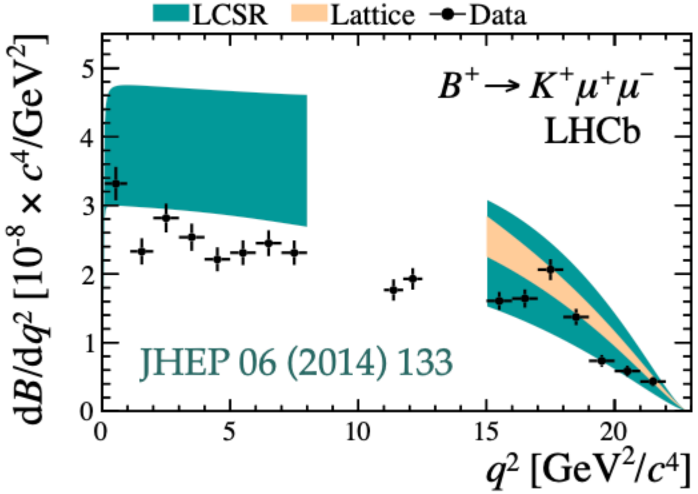
Relative importance of the different diagrams varies with $q^2 = M^2(\ell^+\ell^-)$

Many observables :

- BF (but large theoretical uncertainties due to non-perturbative QCD)
- Angular observables (ratios of I_i to remove Form Factors and be more sensitive to the Wilson coefficients)
- Ratios of BF (test of Lepton Flavour Universality : ℓ = e or μ)

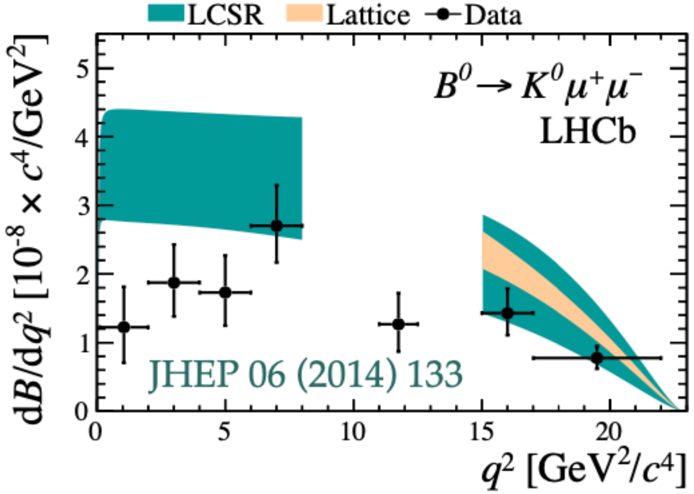
theoretical cleanness

$B^+ \to K^+\mu^+\mu^-$



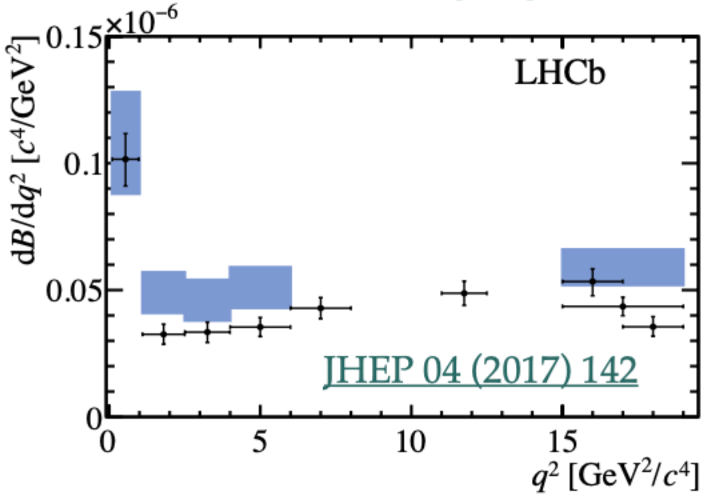
JHEP 06 (2014) 133

$B^0 \to K^0\mu^+\mu^-$



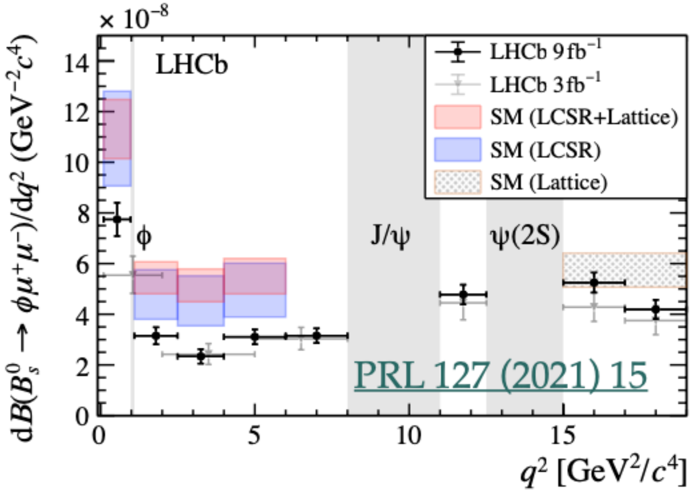
JHEP 06 (2014) 133

$B^0 \to K^{*0}\mu^+\mu^-$



JHEP 04 (2017) 142

$B_s \to \phi\mu^+\mu^-$



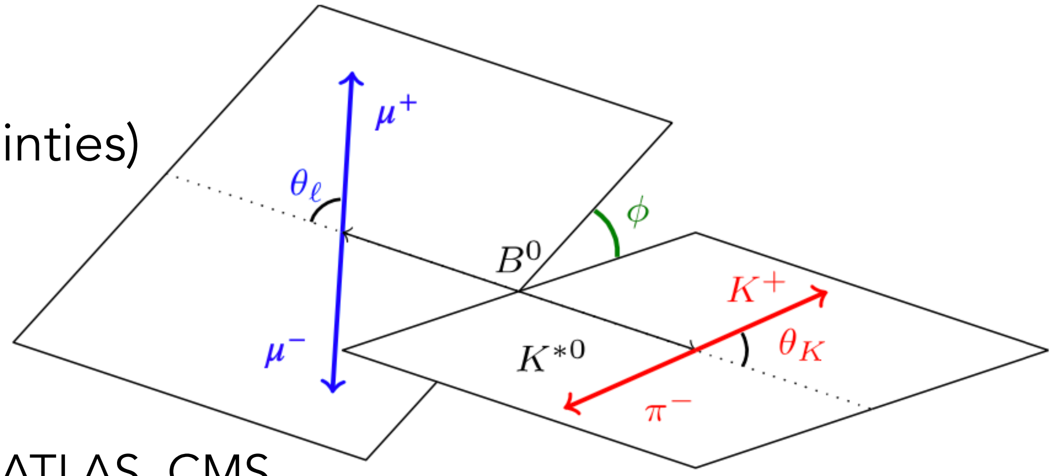
PRL 127 (2021) 15

- Low values for the BR with respect to predictions

- but large (and correlated !) theoretical uncertainties

Angular analyses

(with optimized variables to reduce the Form factors uncertainties)

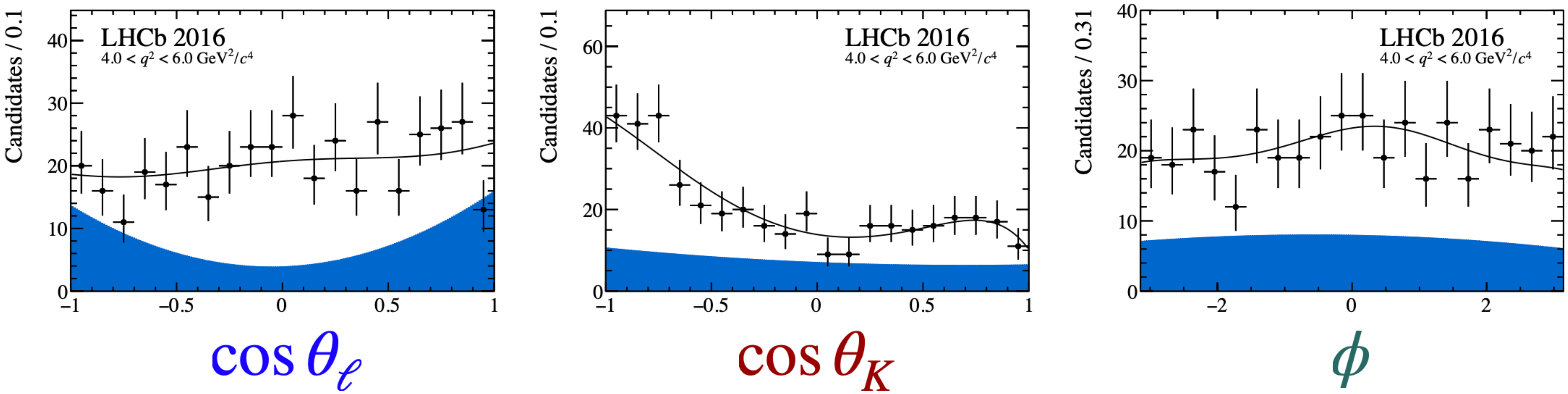


B→Vℓℓ, V = K*, ϕ are particularly interesting

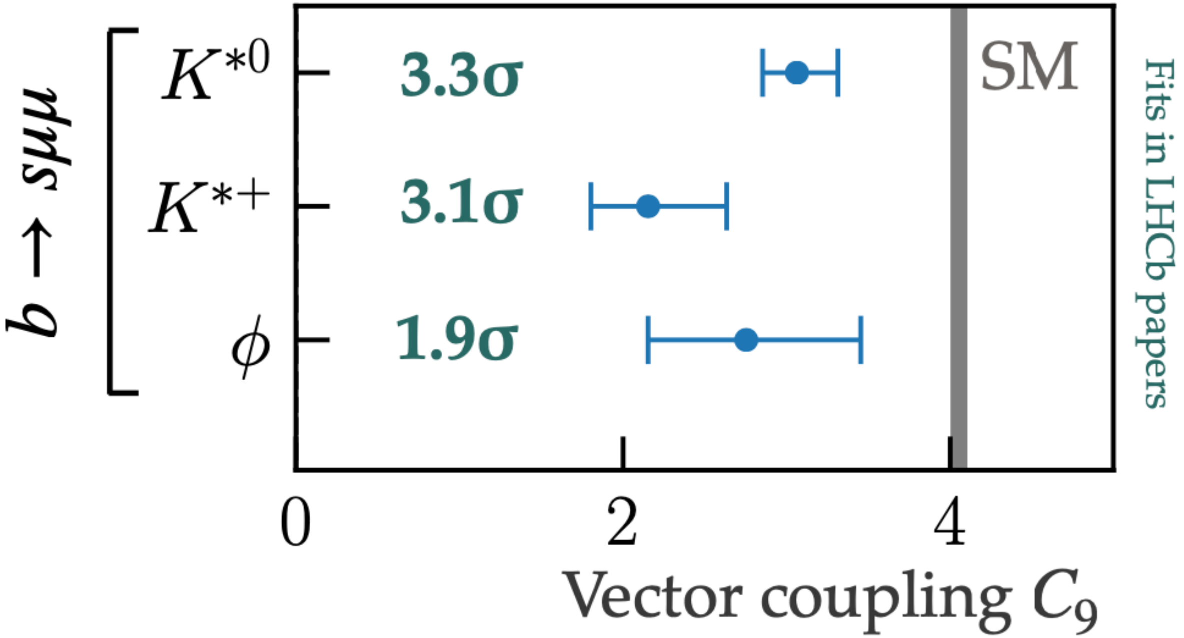
Results dominated by LHCb, but also inputs from B-factories and ATLAS, CMS

$B^0 \to K^*\mu^+\mu^-$ in $4.0 < q^2 < 6.0$ GeV^2

LHCb-PAPER-2020-002

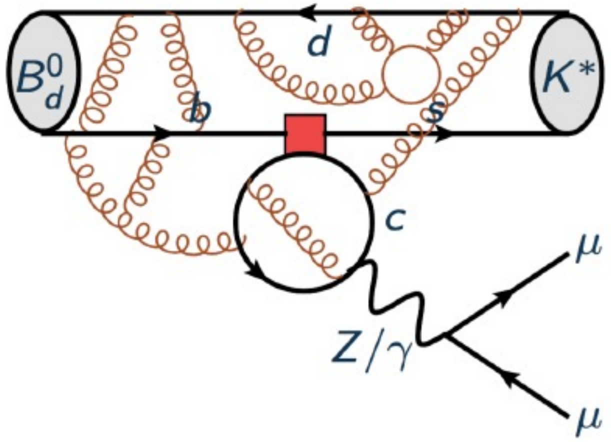


Some (coherent) tensions with respect to SM predictions on angular observables (eg P'_5 but not only)



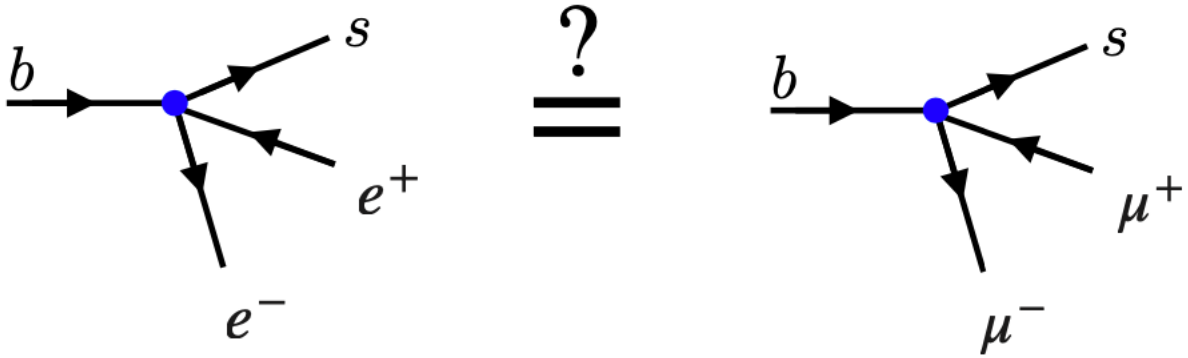
From Martino Borsato (SUSY2022)

but :



difficult to compute : to be constrained by measurements (on-going efforts)

⇒Lepton Flavour Universality tests

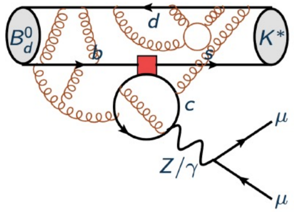


theoretically very clean (1%. uncertainty)

Experimental challenges vary (a lot !)

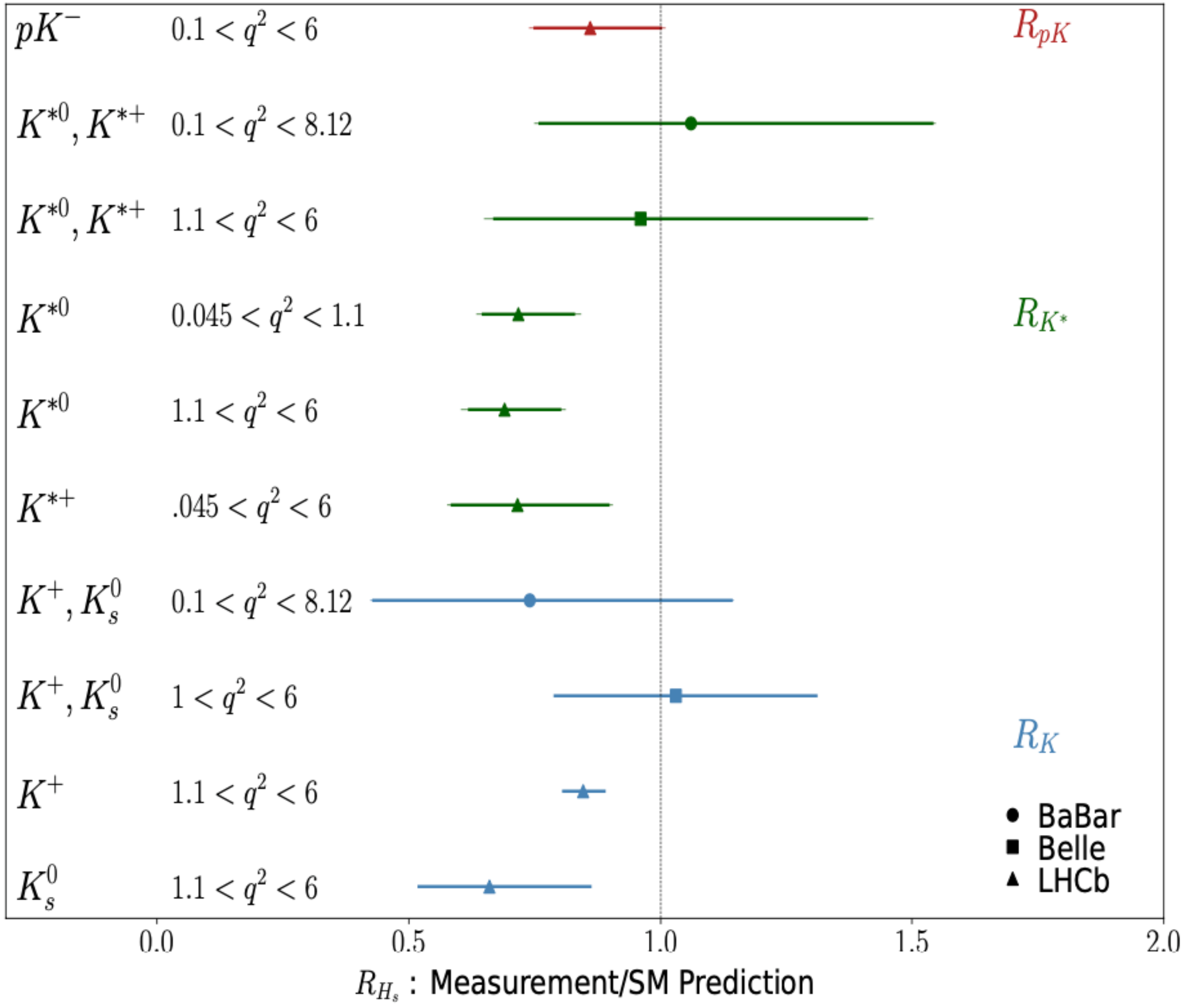
$$R_{H_s} = \frac{\mathrm{BR}\left(H_b \to H_s \mu^+ \mu^-\right)}{\mathrm{BR}\left(H_b \to H_s e^+ e^-\right)} \overset{\text{SM}}{=} 1.00 \pm 0.01$$

ratios of angular observables



is flavor universal

$$R_{H_s} = \frac{\mathrm{BR}\left(H_b \to H_s\mu^+\mu^-\right)}{\mathrm{BR}\left(H_b \to H_s e^+e^-\right)}$$

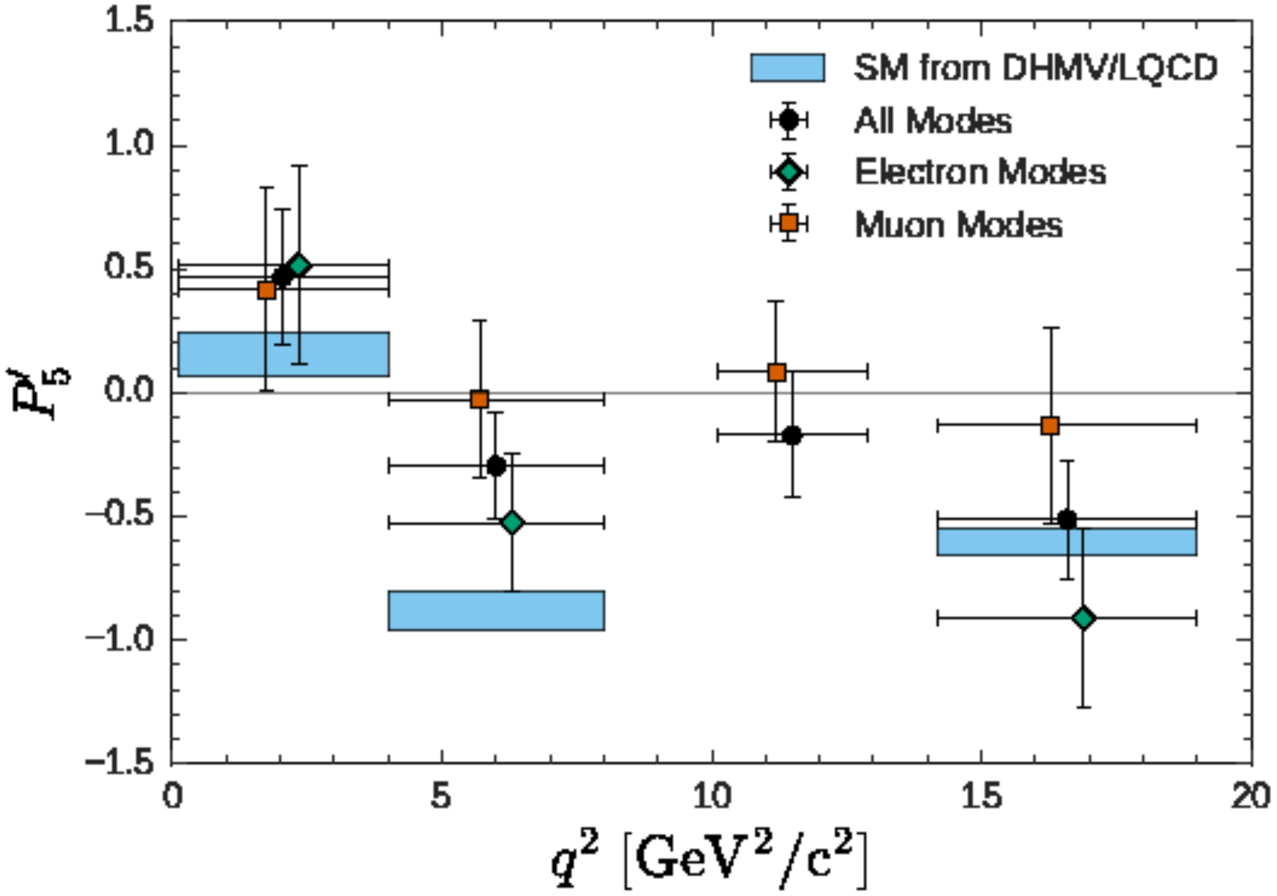


More precise results from various experimental contexts is a must !

One measurement > 3 σ

PRL 118 (2017) 111801

Test of lepton universality in angular observables : BELLE



B-factories @Y(4S)

☺
- Low energy : moderate bremsstrahlung
- beam energy constraint ⇒ B mass resolution only depends on the beam energy knowledge
- no triggering issue
- $N(b \to see) \sim N(b \to s\,\mu\mu)$

☹
- Statistical challenges (cross section x BR)

LHCb

☹
- Significant bremsstrahlung
- triggering issue
- challenging LHC environment
- $N(b \to see) \sim 1/4 * N(b \to s\,\mu\mu)$

☺
- Large samples

but without the events produced you do nothing … independently of how clever you are !

New Physics

Better understanding of the SM (QCD…)

We are here

© J-Trenchand-Photos 2013

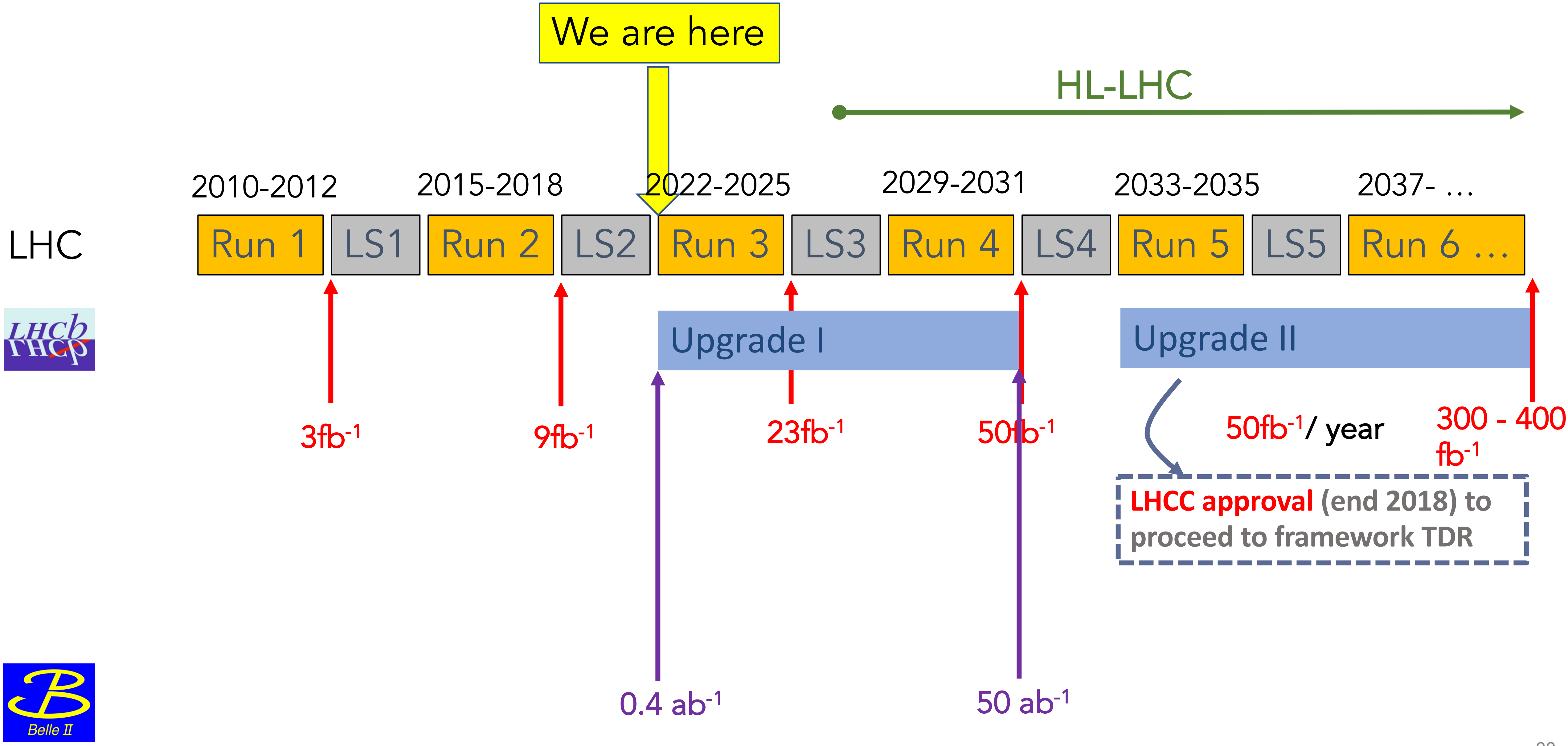
(not too far) Future

(very fast overview due to lack of time)

We *know* there are important phenomena still to be observed (*e.g.* mixing-induced CPV)

Many (theoretically clean) measurements cannot still be made or are statistically limited (eg b→dℓℓ)

Where are we going ?



We are here

HL-LHC

2010-2012 2015-2018 2022-2025 2029-2031 2033-2035 2037- …

LHC

Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6 …

Upgrade I

Upgrade II

$3fb^{-1}$

$9fb^{-1}$

$23fb^{-1}$

$50fb^{-1}$

$50fb^{-1}$/ year

300 - 400 fb^{-1}

LHCC approval (end 2018) to proceed to framework TDR

$0.4\ ab^{-1}$

$50\ ab^{-1}$

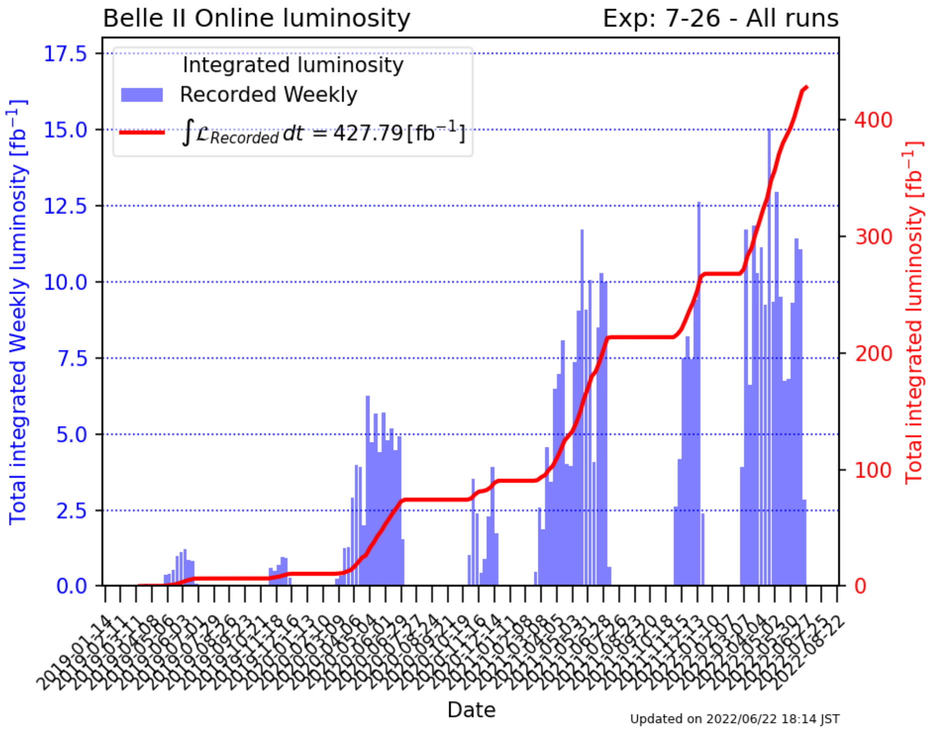
Belle-II

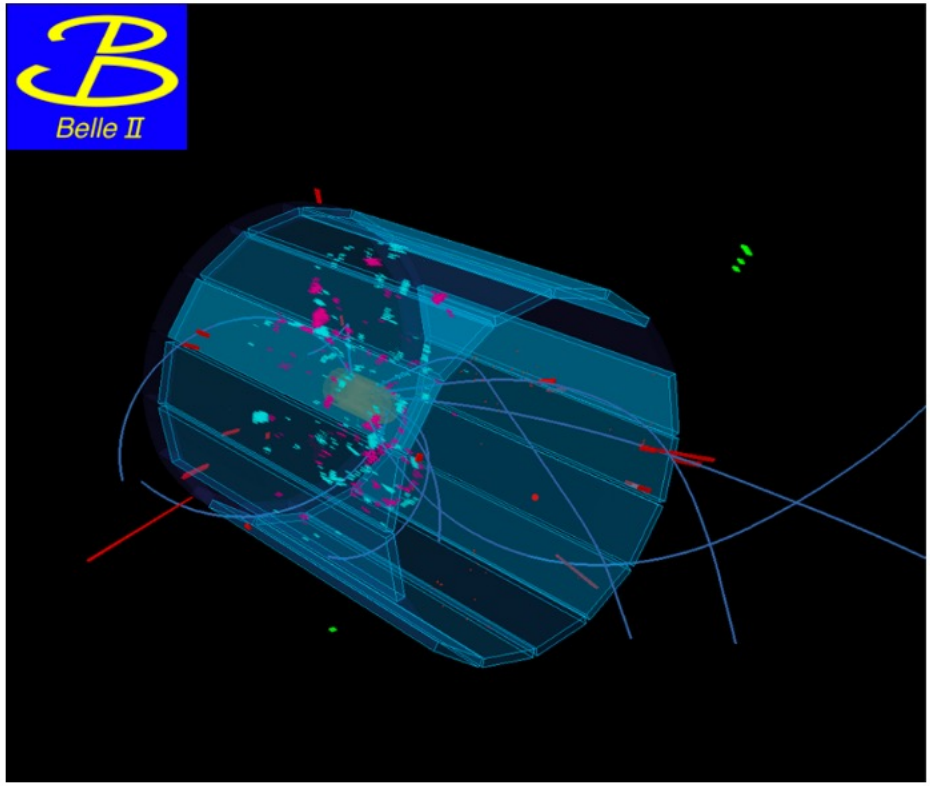
All components upgraded from Belle except crystal elm calorimeter muon / KL)

Belle-II has recorded ~ BaBar sample

Detector performances > B-Factories ones

Improved performances in analyses techniques

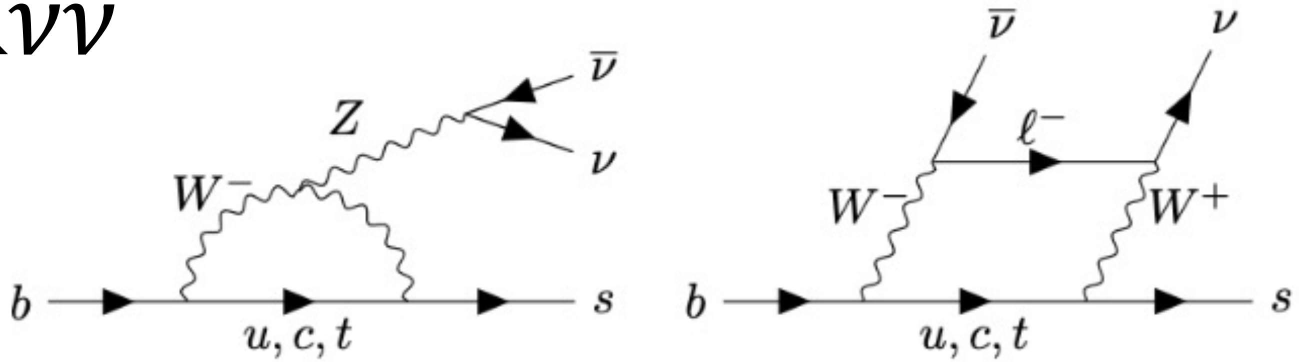




400 fb^{-1} at hand
LS1 has just started. Duration ~ 18 months
expect to collect ~ 50ab^{-1} by 2030

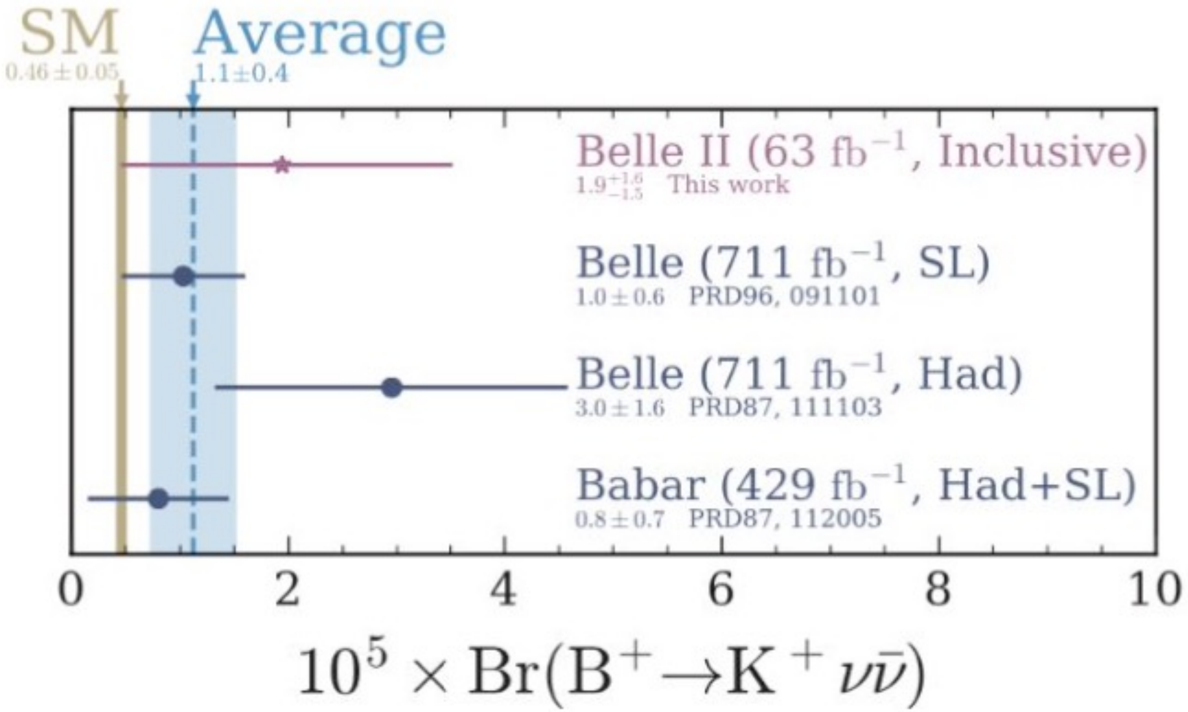
B→K$\nu\bar{\nu}$

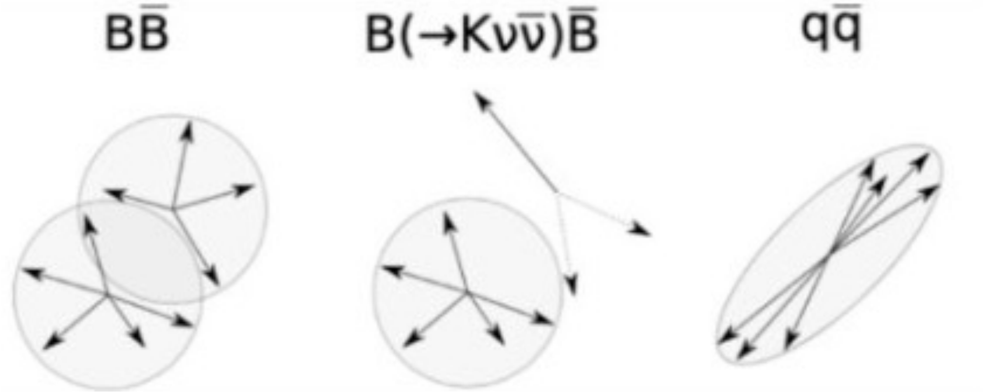
Just an example !



$$\mathscr{B}(\mathbf{B}^+ \to \mathbf{K}^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$$

(not yet observed)



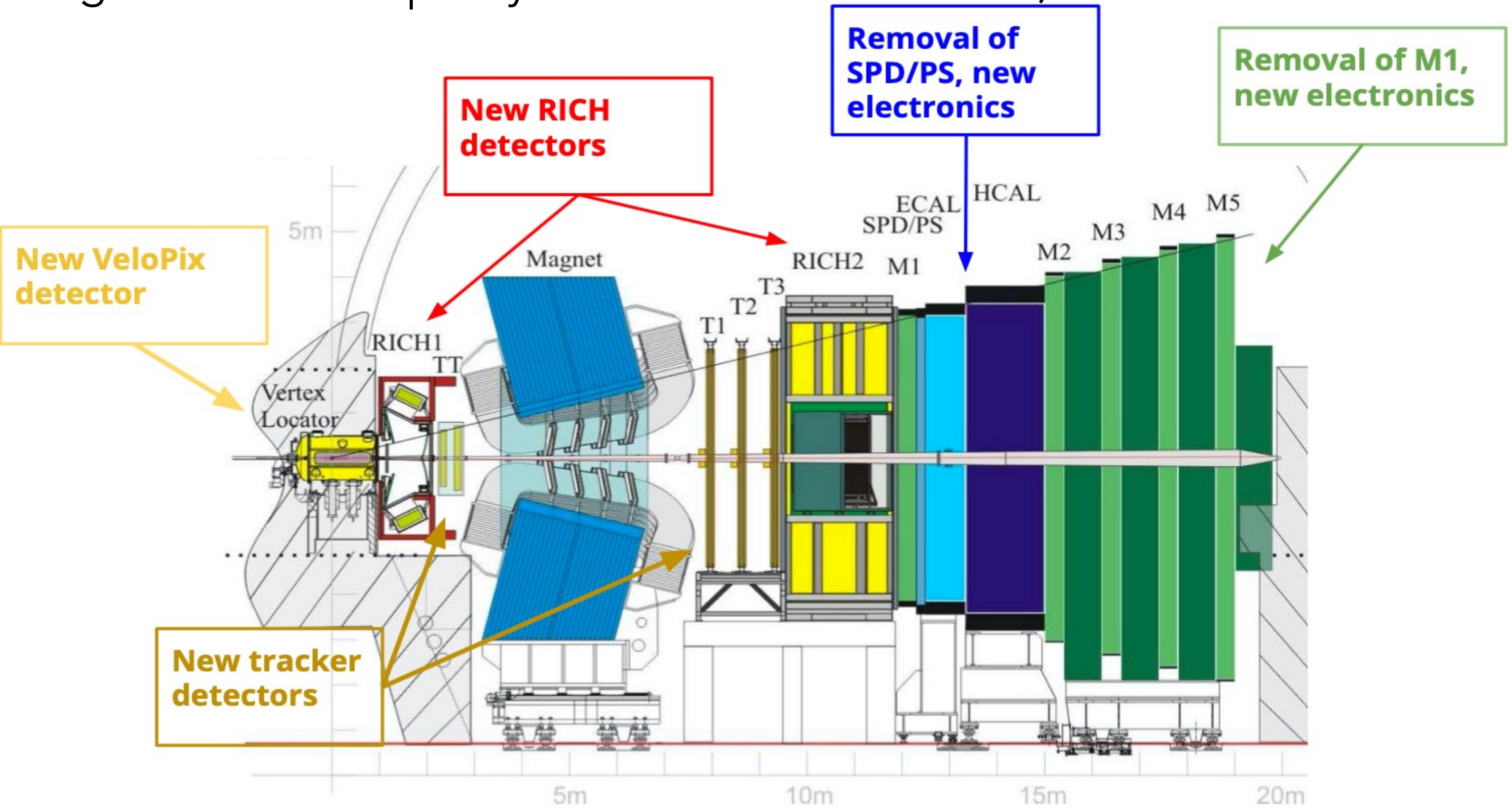


Rely on the B tag reconstruction
Unique to Belle-II

LHCb –Upgrade

→ all detector read-out at 40 MHz (30 MHz collisions to be handled by the event filter farm)

luminosity x5 wrt Run2
5.5 visible interactions/crossing
Higher track multiplicity from ~<70> to ~<180>)



New VeloPix detector

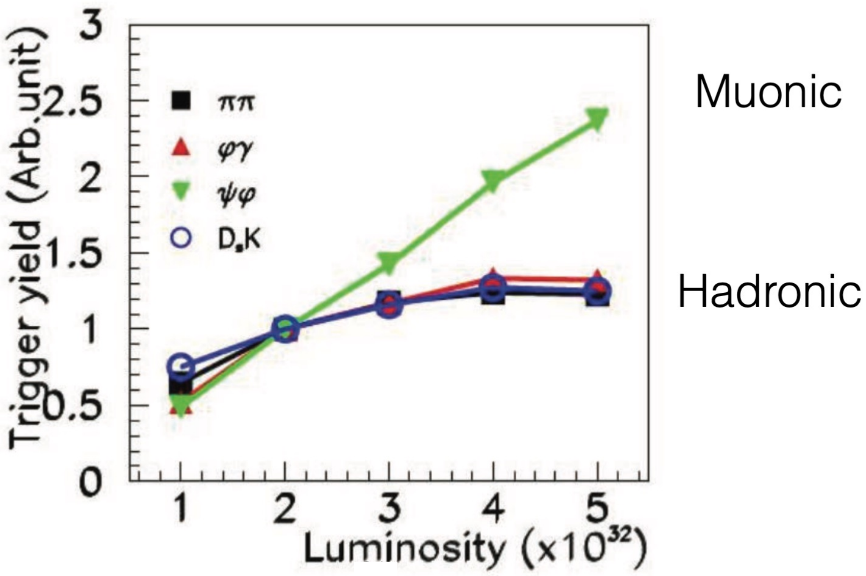
New RICH detectors

Removal of SPD/PS, new electronics

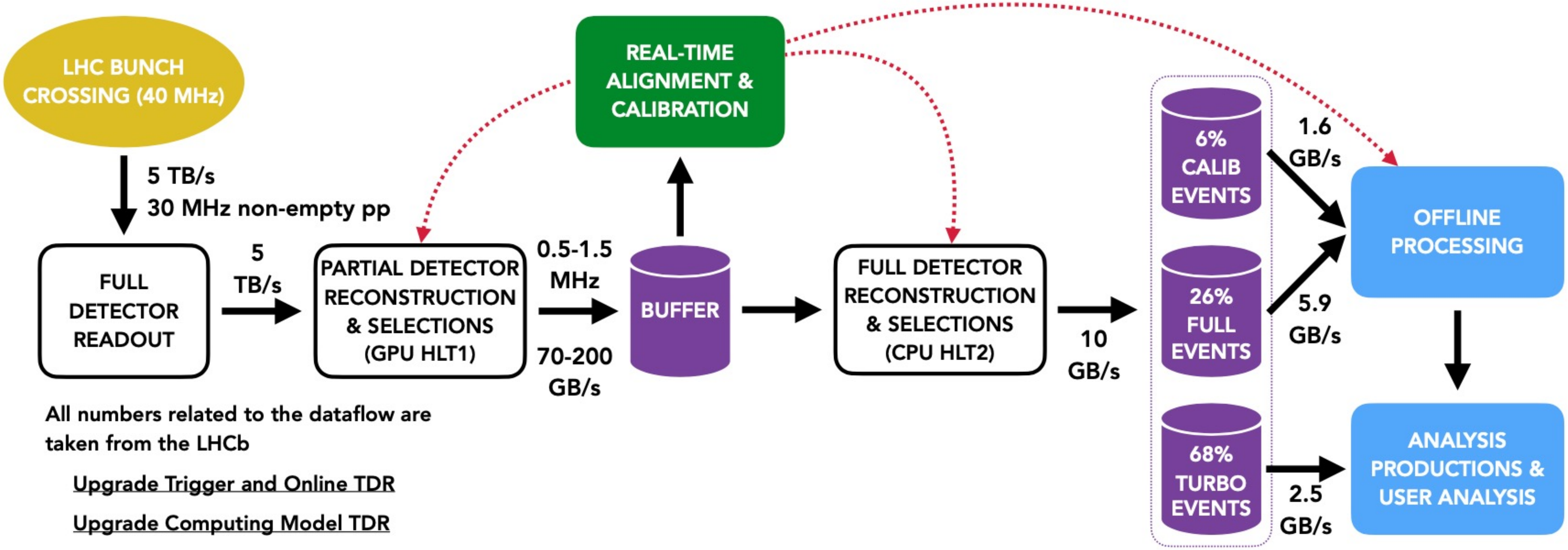
Removal of M1, new electronics

New tracker detectors

L0 bottleneck



now taking data !



All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

M. Alexander, LHCC March 2021

~2% of the events will contain a reconstructible *b*-hadron

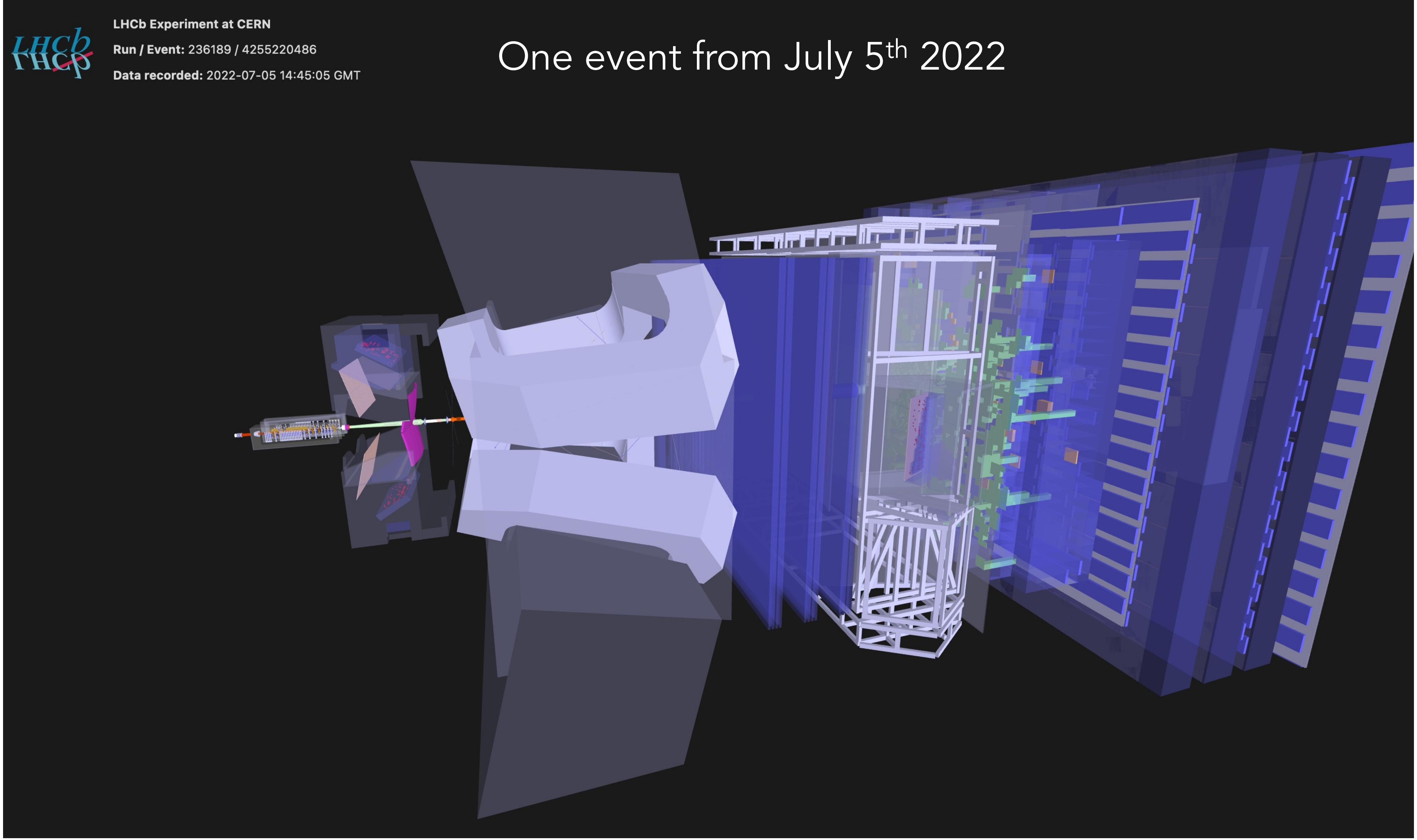
Particle type	Run I (kHz)	Upgrade (kHz)
b-hadrons	17.3	270
c-hadrons	66.9	800
Light long-lived hadrons	22.8	264

includes expected trigger and reconstruction efficiencies.

Comput. Phys. Commun. 208 (2016) 35-42

System will mostly categorize signal !

One event from July 5th 2022



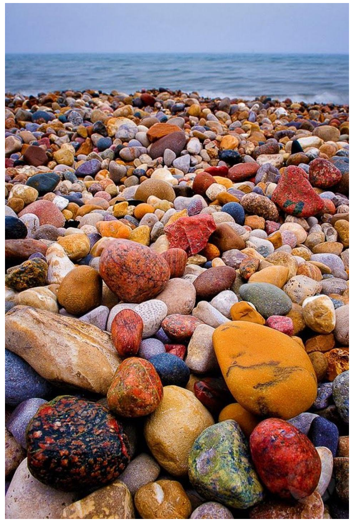
In summary, and ….

CKM (including mixing & CP violation)

Mostly launched by B-factories (BaBar & Belle)

Nowadays playground of LHCb and Belle-II : complementarity (fully reconstructed vs ν neutrals, B_s and Λ_b, …)

At the electroweak scale, the CKM mechanism dominates CP violation



FCNC b→ sll

A bunch of tensions with respect to SM predictions

Joint phenomenological and experimental efforts to constraint hadronic nuisances

Belle-II results will be of prime importance, but full data sample needed

LHCb Upgrade has the statistical power but experimentally challenging for the electron modes

A lot of new data will come
Exciting times ahead !

…. a last word !

- In 1964 the discovery of CP violation came as a surprise
- Heavy Flavour physics is intrinsically linked with matter-antimatter asymmetry but SM does not provide the proper amount of asymmetry
- Heavy Flavour physics offers a unique opportunity to access NP at very high scales
- Some tensions in decays involving $b \to s\ell\ell$ transitions more data is needed to pin-point the origin.
- Heavy Flavour physics is much more that what I had time to touch upon

Thank you for your attention

Backup slides

The nice story of CP violation discovery in the Kaon system

CP violation in the K^0 system

1

What was experimentally known: two states , same mass and very different lifetimes

K_2 lifetime ~ 10000 K_1 lifetime

$\left|K_1\right\rangle \to \pi\pi$ $\quad$ $\left|K_2\right\rangle \to \pi\pi\pi$

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

2

$\left|K^0\right\rangle = \left|s\bar{d}\right\rangle$ $\quad$ $\left|\bar{K}^0\right\rangle = \left|\bar{d}s\right\rangle$

$CP\left|K^0\right\rangle = \left|\bar{K}^0\right\rangle$

$\Rightarrow$ not CP eigenstates

$\Downarrow$

One can build :

$$\left.\begin{aligned}\left|K_1\right\rangle &= \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right)\\ \left|K_2\right\rangle &= \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right)\end{aligned}\right]$$

CP eigenstates

$CP\,|K_1\rangle = |K_1\rangle$

$CP\,|K_2\rangle = -\,|K_2\rangle$

$|K_1\rangle \to \pi\pi$ $|K_2\rangle \to \pi\pi\pi$ CP(ππ) = +1 and CP(πππ) = -1

if CP is a good symmetry for the weak interaction : $\cancel{|K_2\rangle \to \pi\pi}$

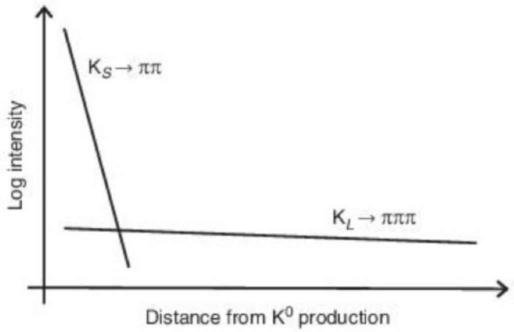
Test it

After some time, pure K_2 beam

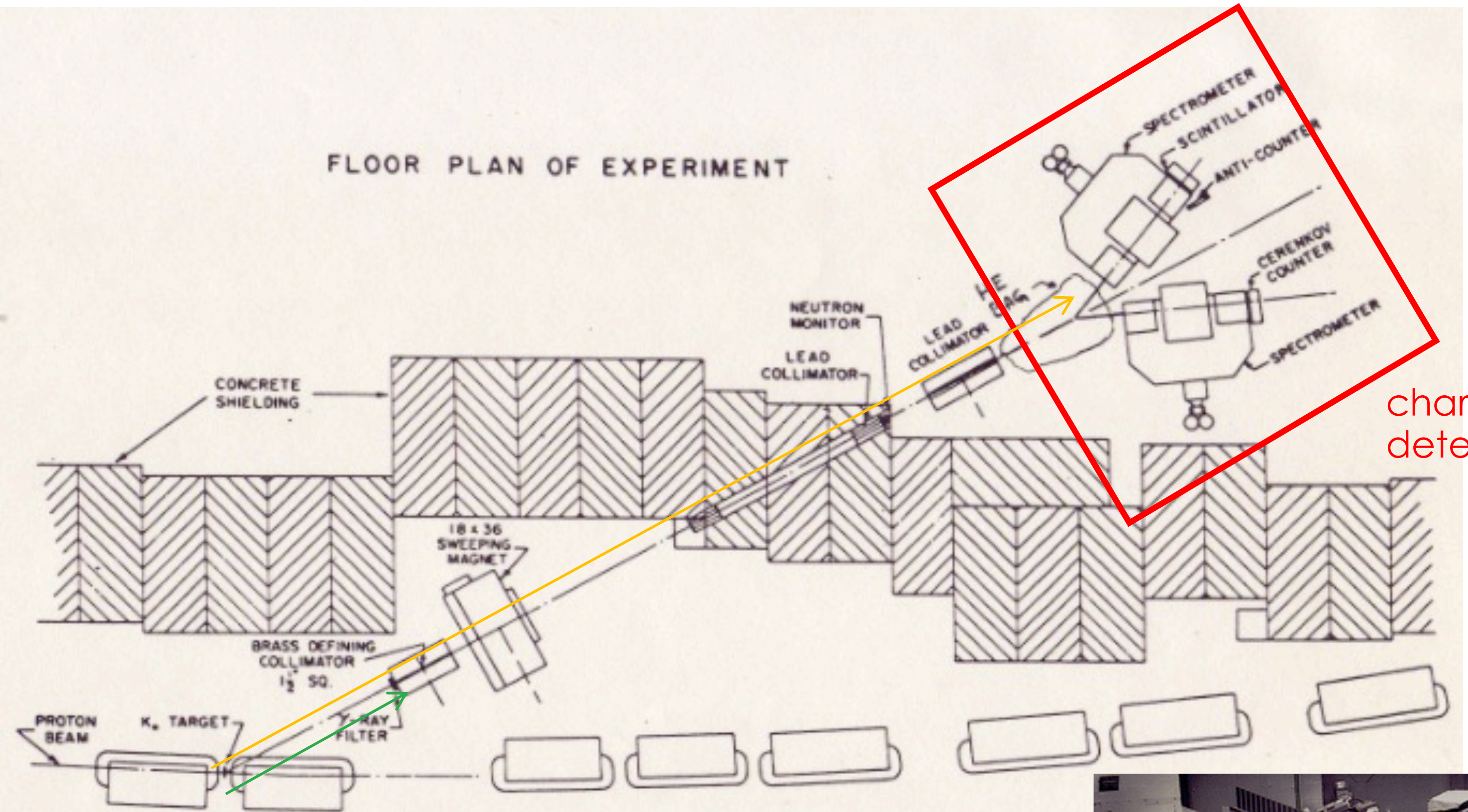
initial beam
K_1 and K_2

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

?

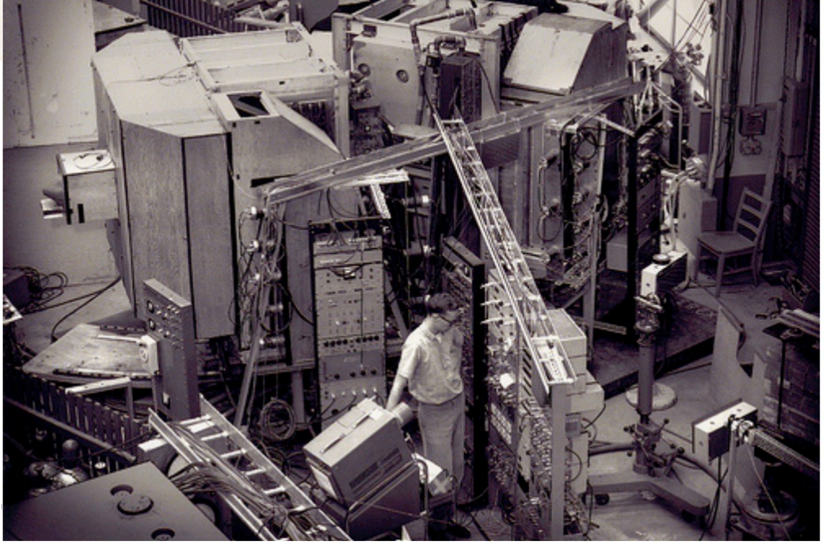


Cronin& Fitch experiment 1964



charged tracks detector

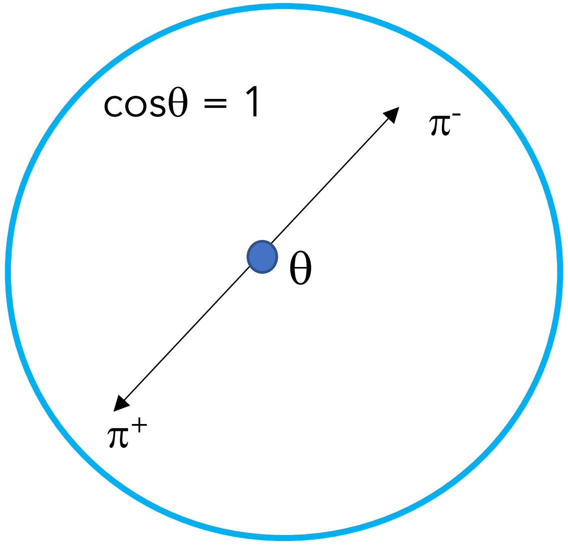
initial beam
K_1 and K_2



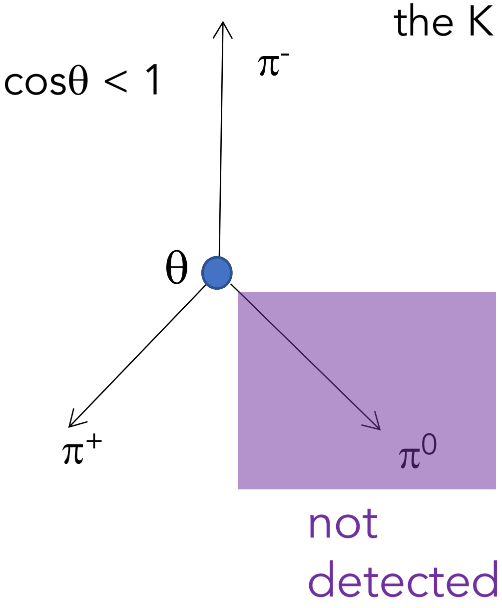
Two informations :

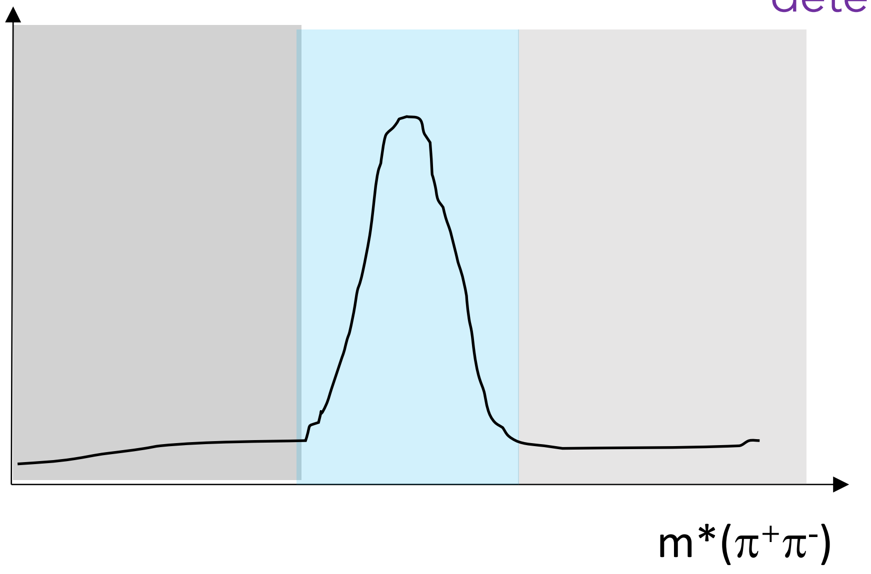
- The $\pi^+ \pi^-$ invariant mass (m*)
- The opening angle between the two pions in the K center of mass frame

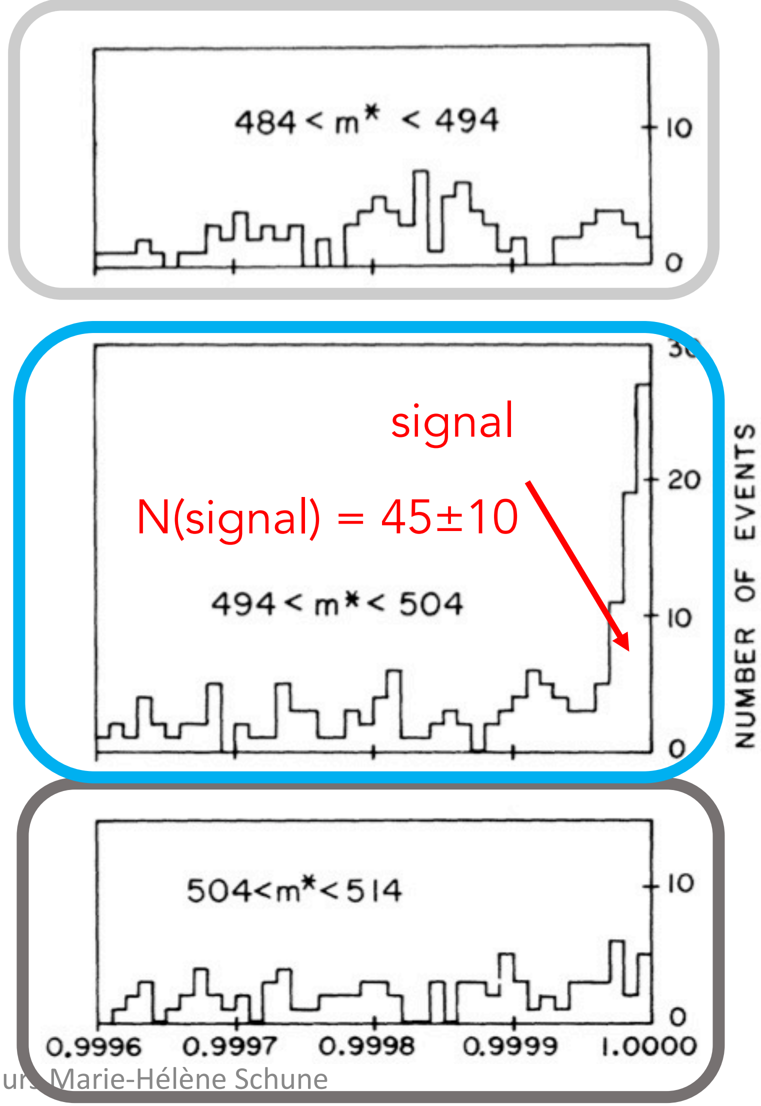
signal



background







signal

N(signal) = 45±10

$|K_1\rangle \to \pi\pi$ $|K_2\rangle \to \pi\pi\pi$ CP(ππ) = +1 and CP(πππ) = -1

if CP is a good symmetry for the weak interaction : $\xcancel{|K_2\rangle \to \pi\pi}$

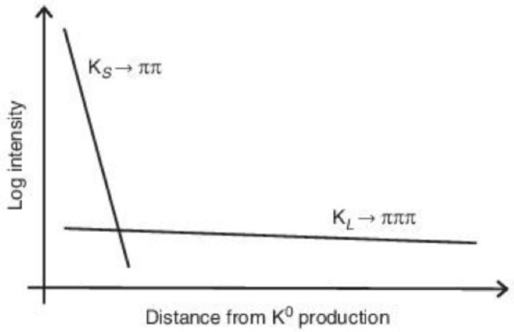
Test it

After some time, pure K_2 beam

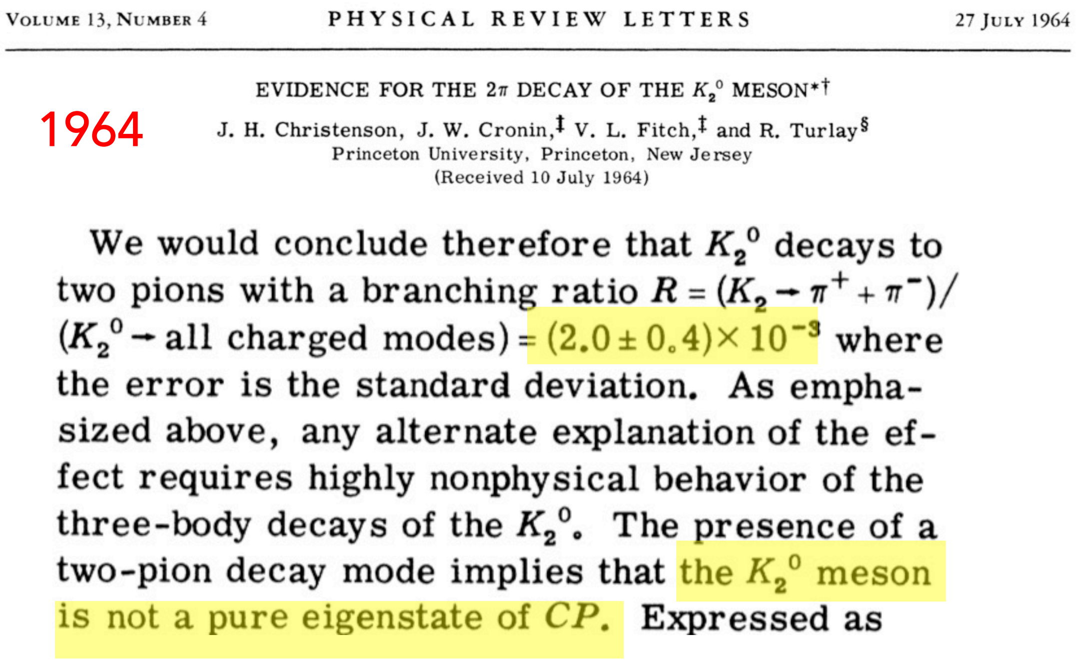
initial beam
K_1 and K_2

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

?



1964


VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

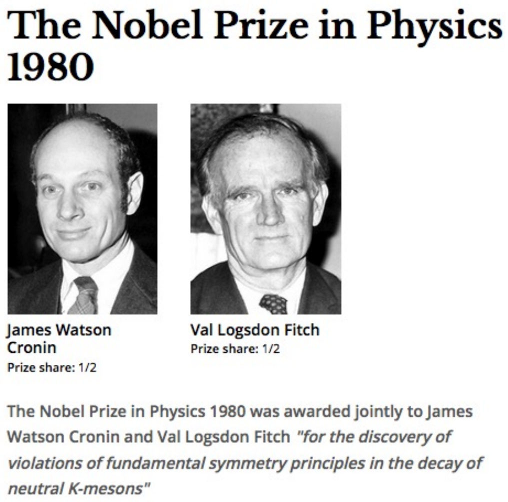
J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ 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

today 0.7 % precision !

$$|K_L> = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(\left|K_2\right\rangle + \epsilon\left|K_1\right\rangle\right) \sim \left|K_2\right\rangle$$

$$|K_S> = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(\left|K_1\right\rangle + \epsilon\left|K_2\right\rangle\right) \sim \left|K_1\right\rangle$$


The Nobel Prize in Physics 1980

James Watson Cronin
Prize share: 1/2

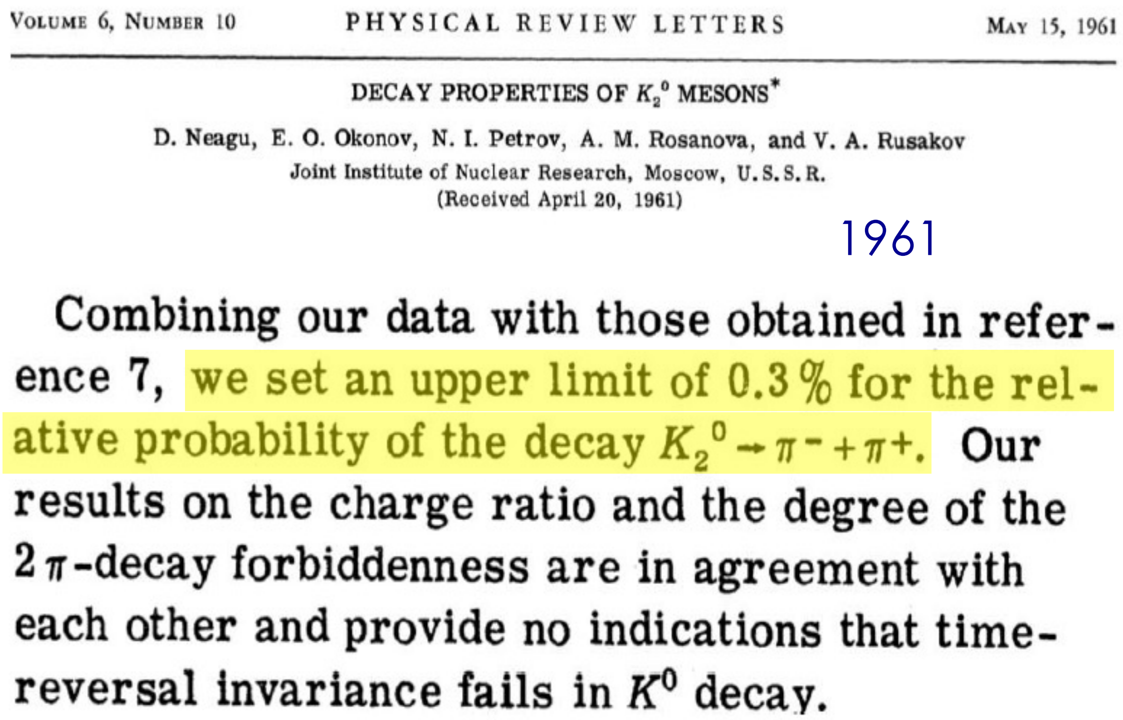
Val Logsdon Fitch
Prize share: 1/2

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"*

« 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)

3 families !

One word on precision and the search for NP



VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1961

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)

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

1961

Stopped by funding agency

Discovery : 1964 …

Precision is the key word, not only for K physics

)

$B_s \to \mu\mu$ effective lifetime

PRL 109 (2012) 04180

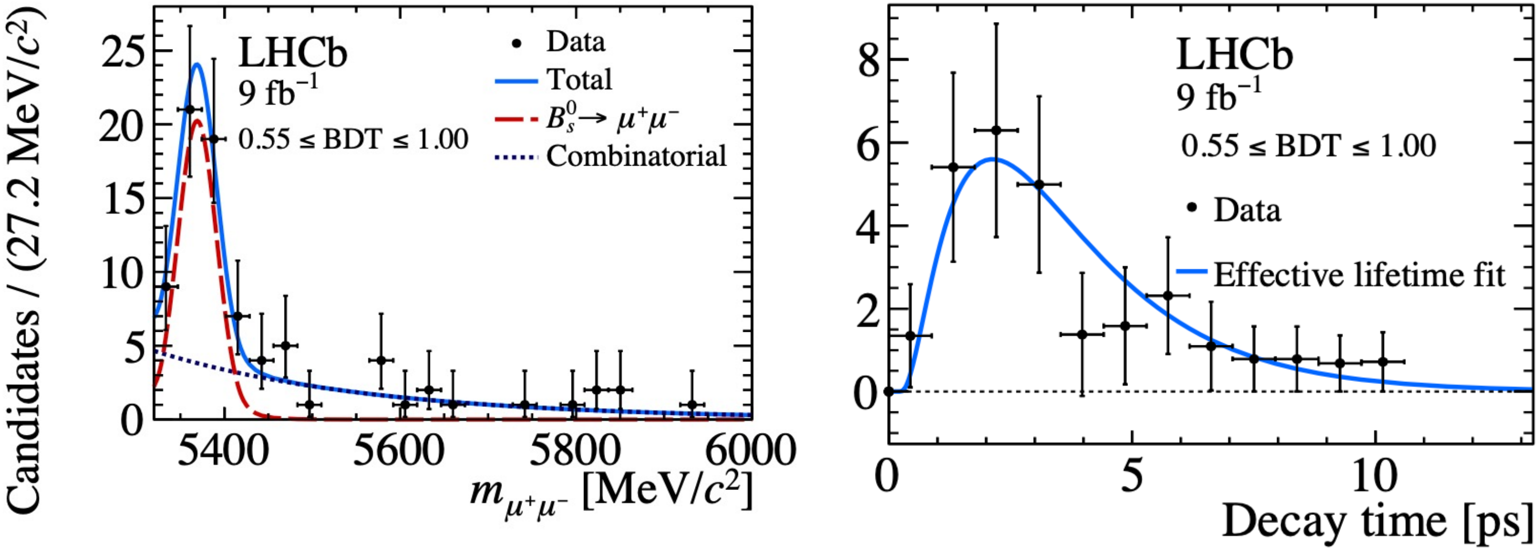
$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2}\left(\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right)$$

$$y_s \equiv \tau_{B_s}\Delta\Gamma_s/2$$

$\Delta\Gamma_s$: lifetime different between the 2 mass eigenstates

$\boxed{A_{\Delta\Gamma}^{\mu^+\mu^-}}$ =+ 1 in the SM
can take any value between -1 and +1 in New Physics models

⇒ additional information with respect to the BR measurement



$$\boxed{\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03\ ps}$$

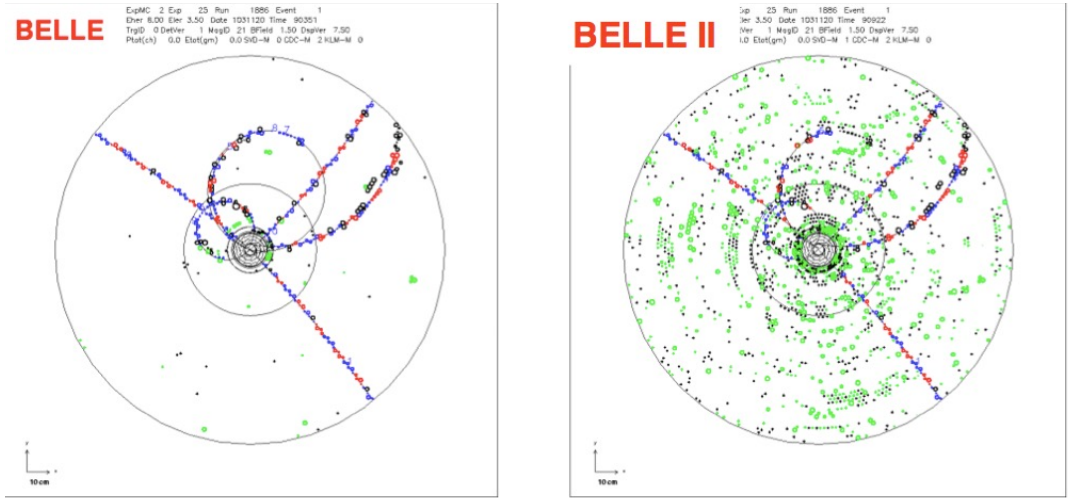
consistent with +1 at 1.5 σ

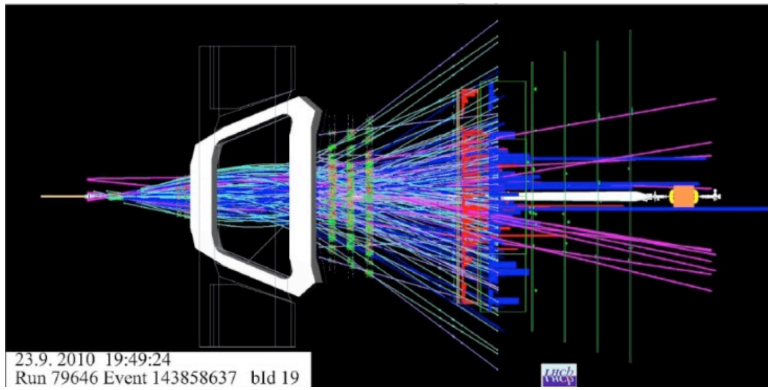
(not yet precise enough)

arXiv:2103.13370

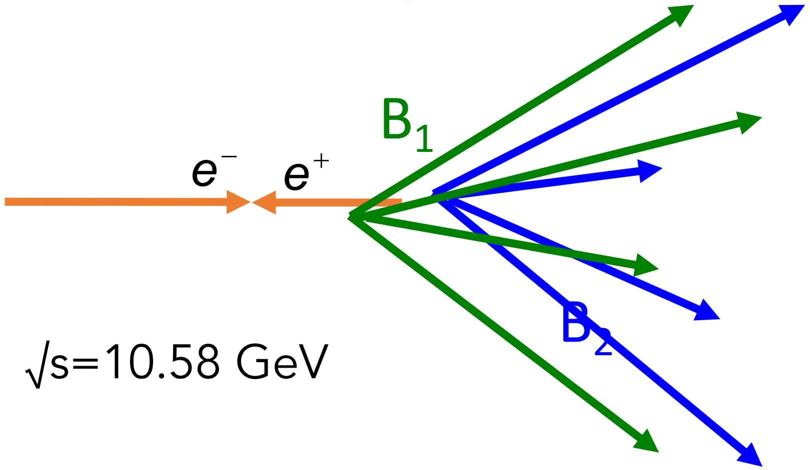
B-Factories

LHCb

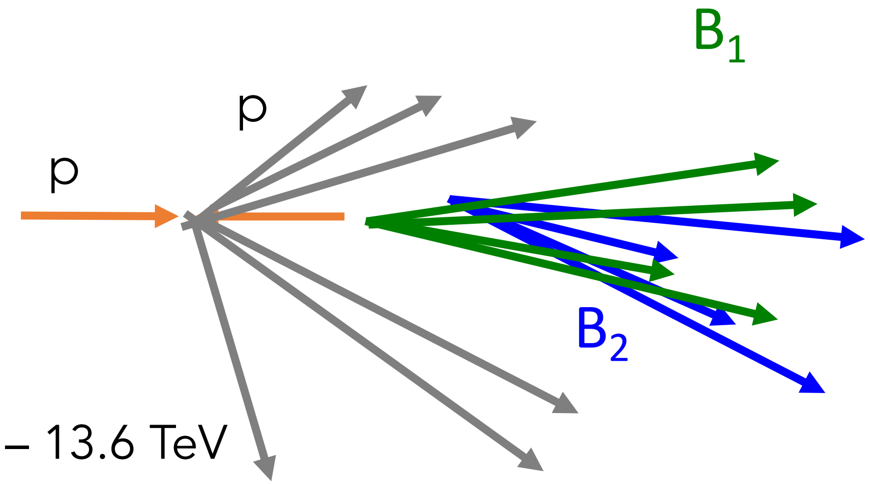




• e^- e^+ ⊗

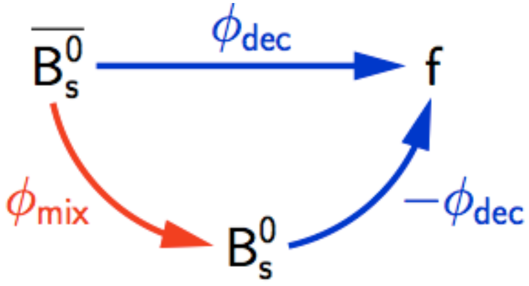


$\sqrt{s}$=10.58 GeV



$\sqrt{s}$=7- 8 – 13.6 TeV

$B_s \rightarrow J/\Psi\ \phi$ analog of the previous case ($B_d \rightarrow J/\Psi\ K_s$)

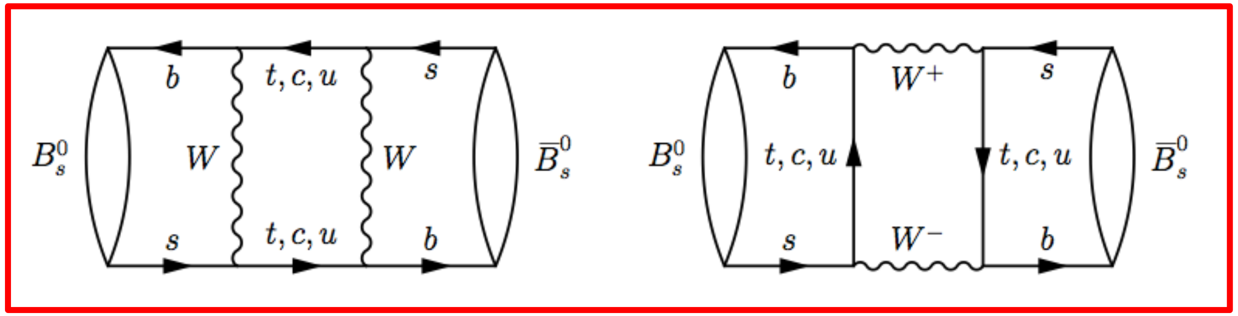


$$\phi_s = \phi_{mix} - 2\,\phi_{dec}$$

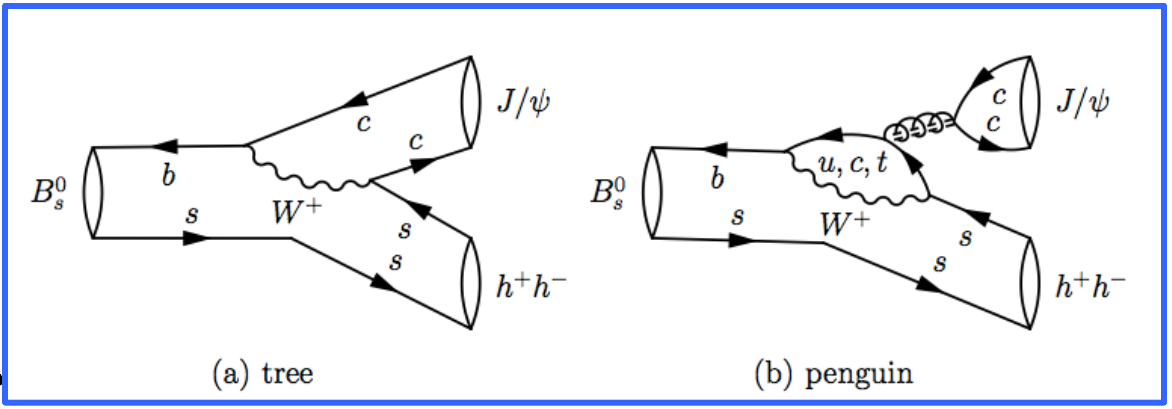
PS → VV, admixture of CP-odd and CP-even states, measure also $\Delta\Gamma_s$.

$\Rightarrow$ 3 “P-wave” amplitudes of KK system

- 1 “S-wave” amplitude (A_S)
- 10 terms with all the interferences
- φ_S , $\Delta\Gamma_{S,}$, Γ_S



Mixing



(a) tree

(b) penguin

Decay

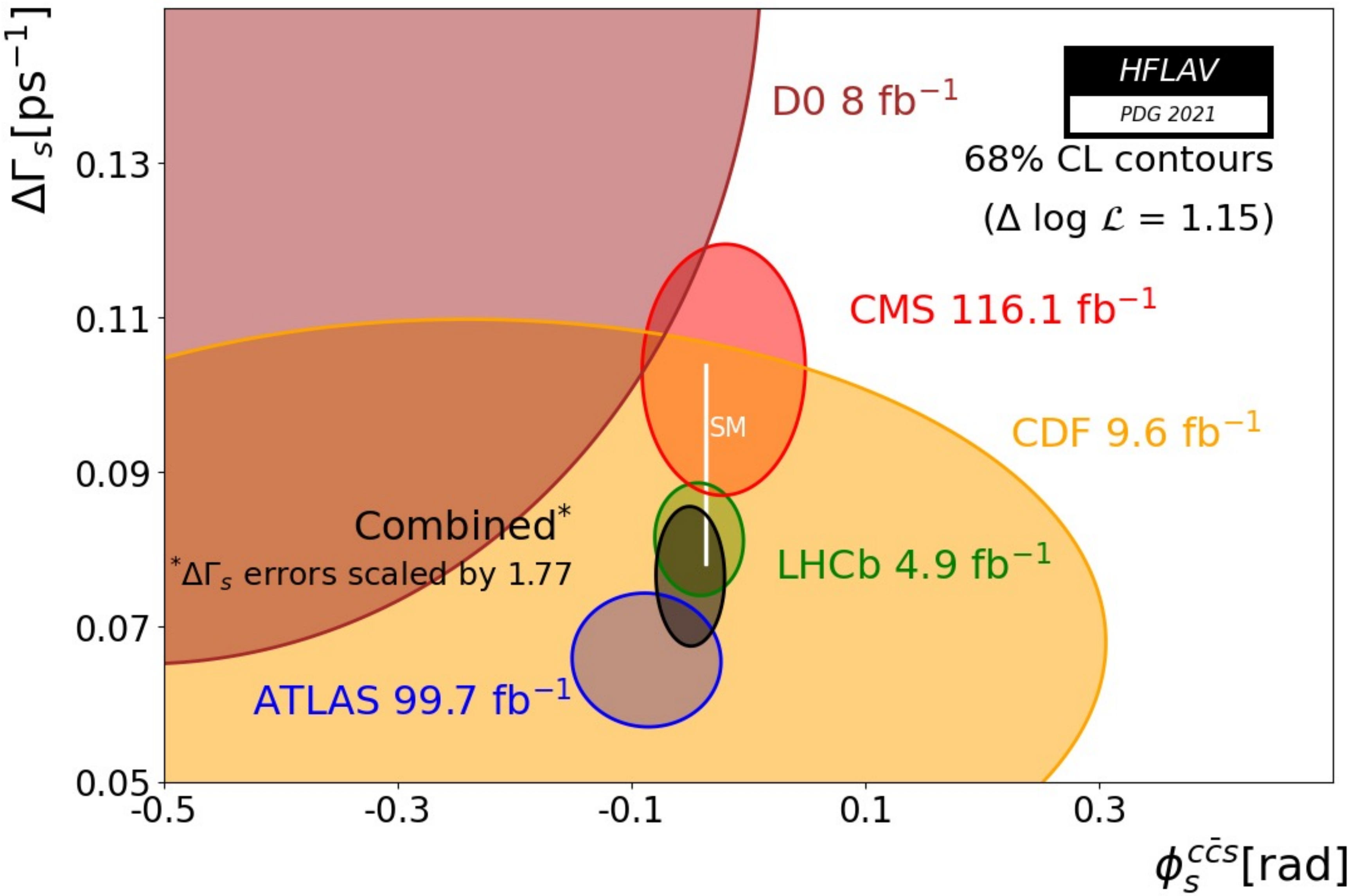
Probing CKM matrix elements complex at higher order

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

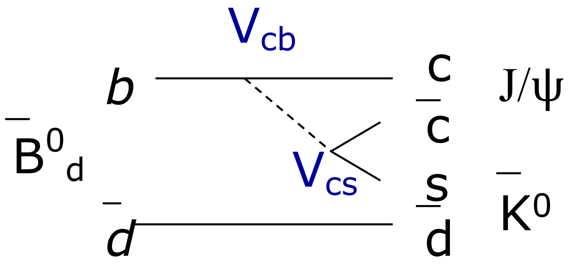
$$\Rightarrow \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{A^2\lambda^5}{2}(1-2\rho)-i\,A^2\lambda^5\eta & 1-\lambda^2/2-\lambda^4(\frac{1}{8}+\frac{A^2}{2}) & A\lambda^2 \\ A\lambda^3(1-(1-\lambda^2/2)(\rho+i\eta)) & -A\lambda^2(1-\lambda^2/2)(1+\lambda^2(\rho+i\eta)) & 1-\frac{A^2\lambda^4}{2} \end{pmatrix} +\mathcal{O}(\lambda^6)$$

HFLAV

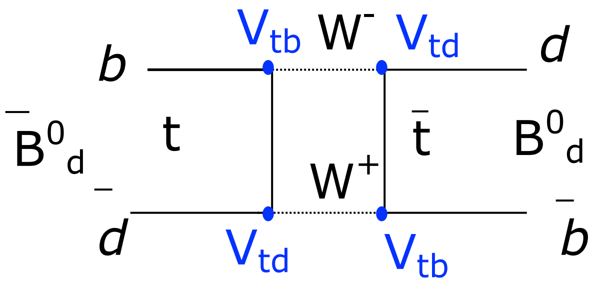
SM : Φ_s=-0.0370 ±0.0008 rad
(prediction from a fit using other measurements)



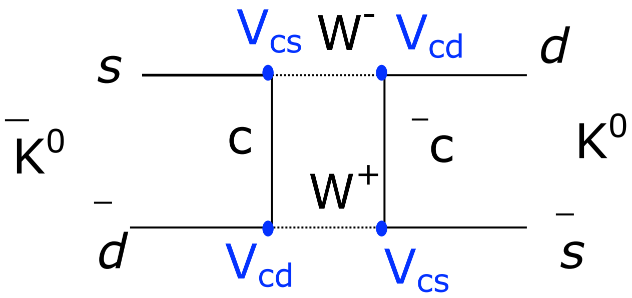
Measurement of sin(2β) with B⁰→J/Ψ K⁰



decay



B⁰ mixing



K⁰ mixing

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

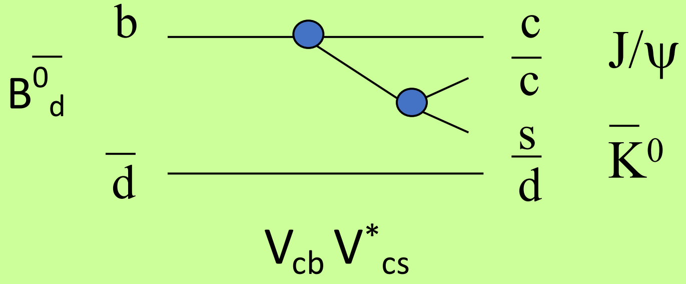
$$\beta = Arg\left(\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

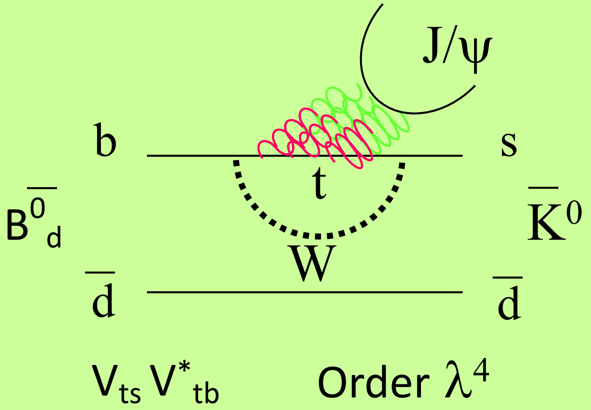
$$\left(\frac{V_{cd}^*V_{cb}}{V_{td}^*V_{tb}}\frac{V_{tb}^*V_{td}}{V_{cd}V_{cb}^*}\cancel{\frac{V_{cs}^*}{V_{cs}}}\cancel{\frac{V_{cs}}{V_{cs}^*}}\right)$$

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

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

Extraction of sin2β from J/ψ 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 λ^2 since V_{ts} is complex and differs from V_{cb} at order λ^4

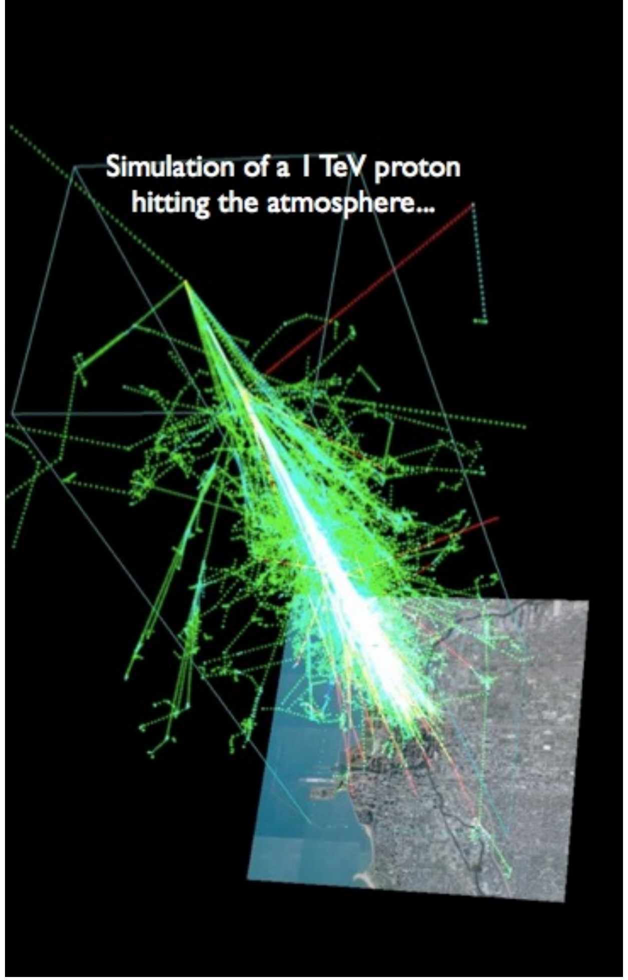
Coupling c	r=20% today	r=10% tomorrow	r=1% after tomorrow
Order 1	Λ_{NP} ~ 20 TeV	Λ_{NP} ~ 30 TeV	Λ_{NP} ~ 100 TeV
MFV	Λ_{NP} ~ 180 GeV	Λ_{NP} ~ 250 GeV	Λ_{NP} ~ 800 GeV

MFV ≡ no new sources of flavour and CP violation
NP contributions governed by SM Yukawa couplings.

an ad-hoc way to solve the 'Flavour problem', it has not been proven to be correct : … experimental tests !

Λ_{NP} ~ 1 TeV
+ flavour-mixing protected by additional symmetries (as MFV)

Couplings can be still large if
Λ_{NP} > 1..10..TeV

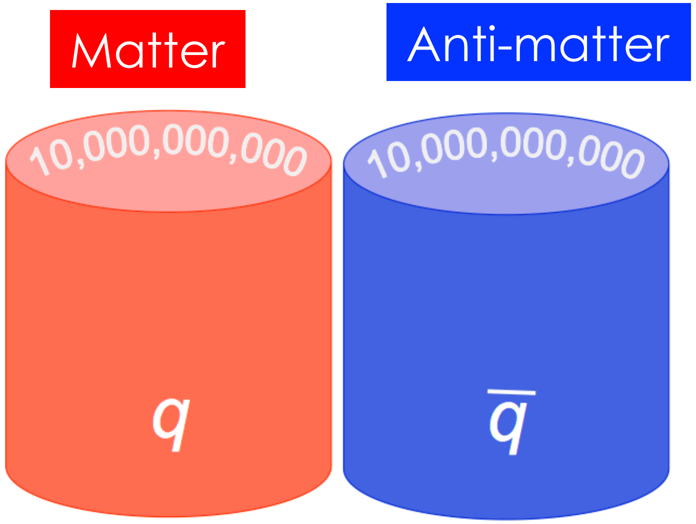


- Anti-matter in cosmic rays

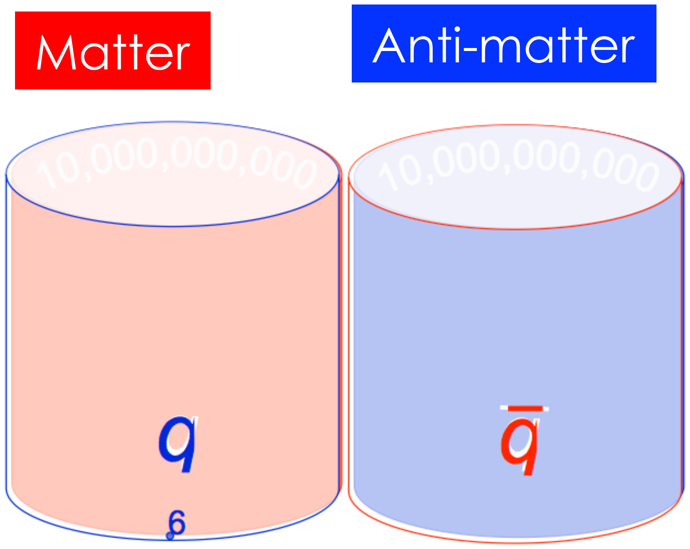
- No sign of light emission (anti-galaxy …)

•No sign of anti-nuclei (anti-He^4 …)
Searches on-going

Anti-matter in the Universe and Big Bang



Primordial Universe



Today

$$\frac{n(baryon) - n(antibaryon)}{n} \sim 6\ 10^{-10}$$

The 3 Sakharov conditions(1967)

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

Using CPV from SM ~ 10^{-19}
Neutrino sector
Discrepancies from CKM
New Physics