Experimental Flavour Physics

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- Same physics, different environments
- The CKM mechanism: measuring the sides of the unitarity triangle
- CP violation: measuring the angles of the unitarity triangle
- Rare decays

Disclaimer and choices

- I do not want to present a ‘collection’ of measurements
- The phenomenological framework has been detailed by other speakers
- I have chosen
    - not to discuss kaon & charm physics (!)
    - not to discuss spectroscopy (including tetraquarks, pentaquarks)
    - I have made wild choices in b-physics
- My wish is that you go back home
    - having a feeling of some analyses
    - identifying the main differences between Belle-II and LHCb
    - being even more enthusiastic about flavour physics

Standard Model

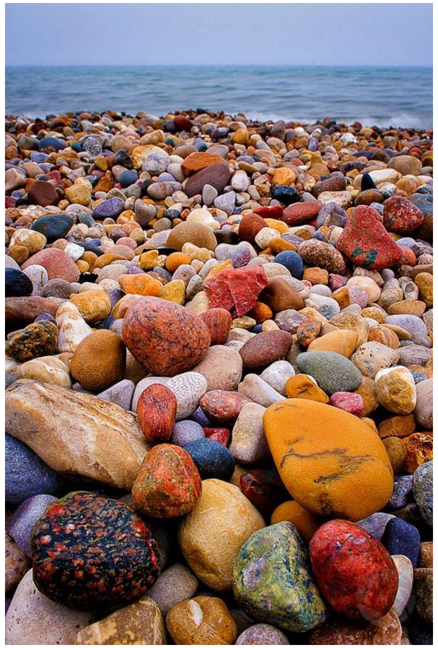
describes precisely a (very) large number of precise measurements

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 ?



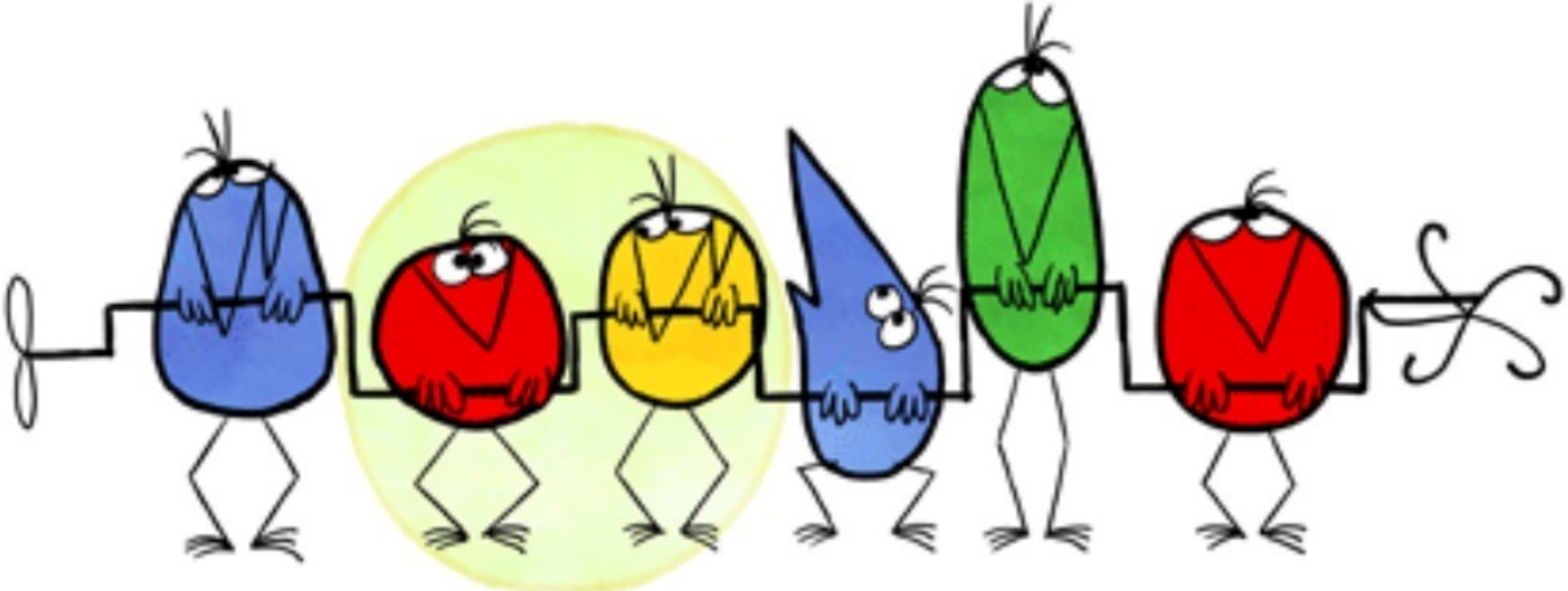
How to find cracks in the SM fortress ?

Heavy flavours physics

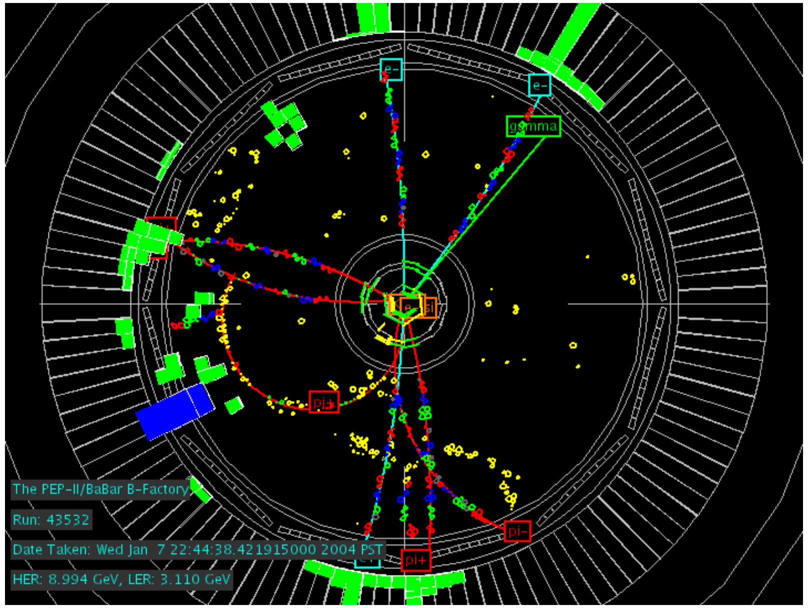
Direct evidence for new particles

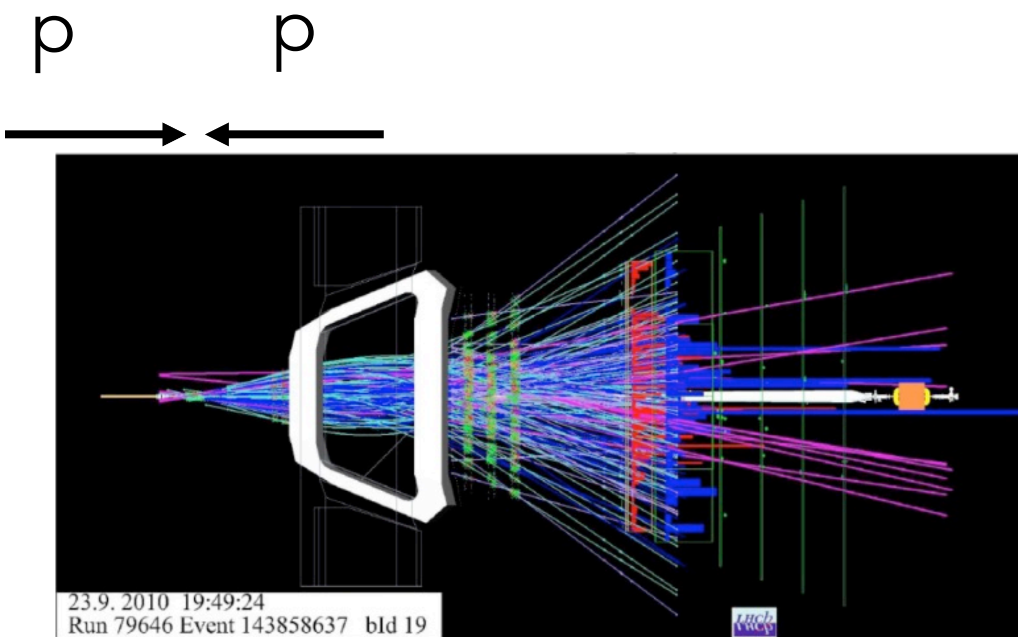
Indirect evidence through precision measurements sensitive to the presence of virtual states present in the decay of SM particles

Same physics
different environments

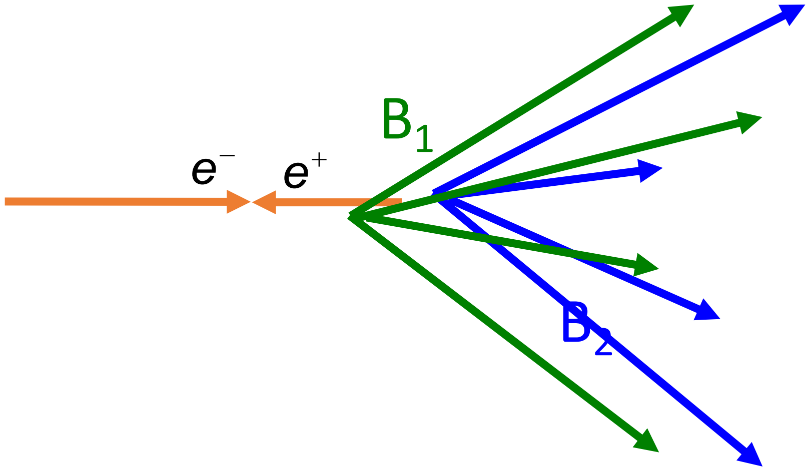


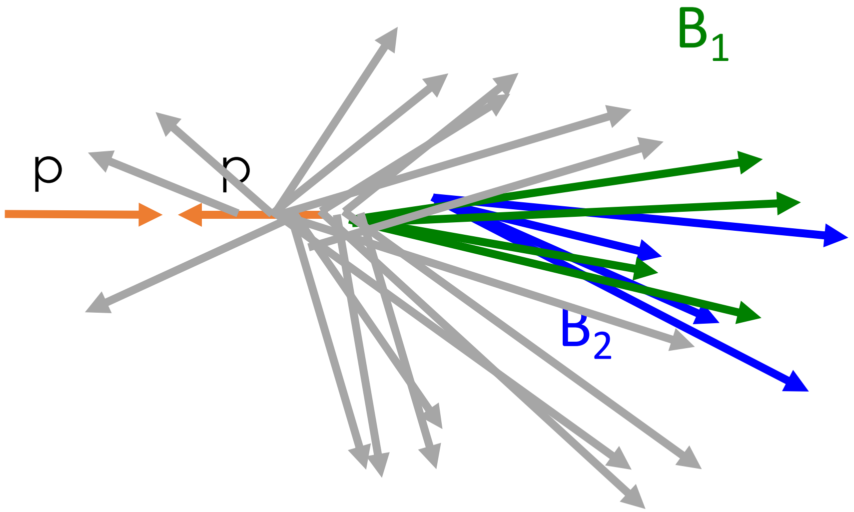
sketch of an event at B-factory and at LHCb



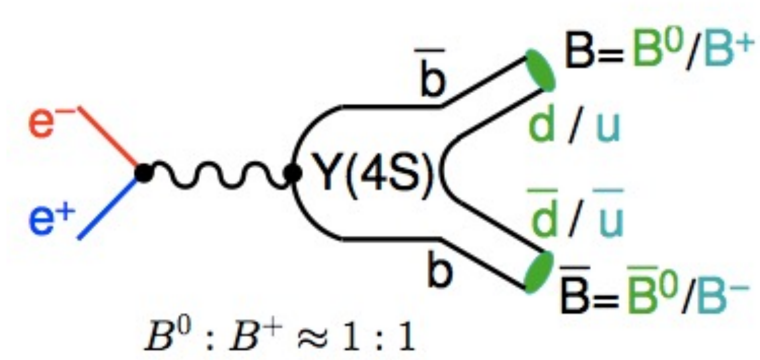


$\bullet\, e^-$ $e^+ \otimes$





B-Factories



M(Υ(4S))=10.58 GeV $J^{PC}= 1^{--}$

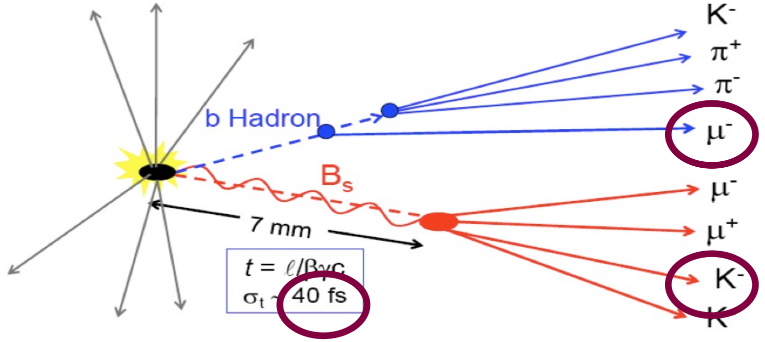
only (B^+, B^0) are produced (no fragmentation)

(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

Experiment	Integrated luminosity (*)	$b\bar{b}$ cross section	Hadronic background	Main b-hadron species species produced
BaBar	$433\,\text{fb}^{-1}$	1.1 nb	3.7 nb	$\overline{B}^0$ and B^-
Belle	$711\,\text{fb}^{-1}$	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	$9\,\text{fb}^{-1}$	140 μb (13 TeV)	60 mb	$\overline{B}^0$, B^-, $\overline{B}^0_s$, Λ_b and B_c^-

+cc

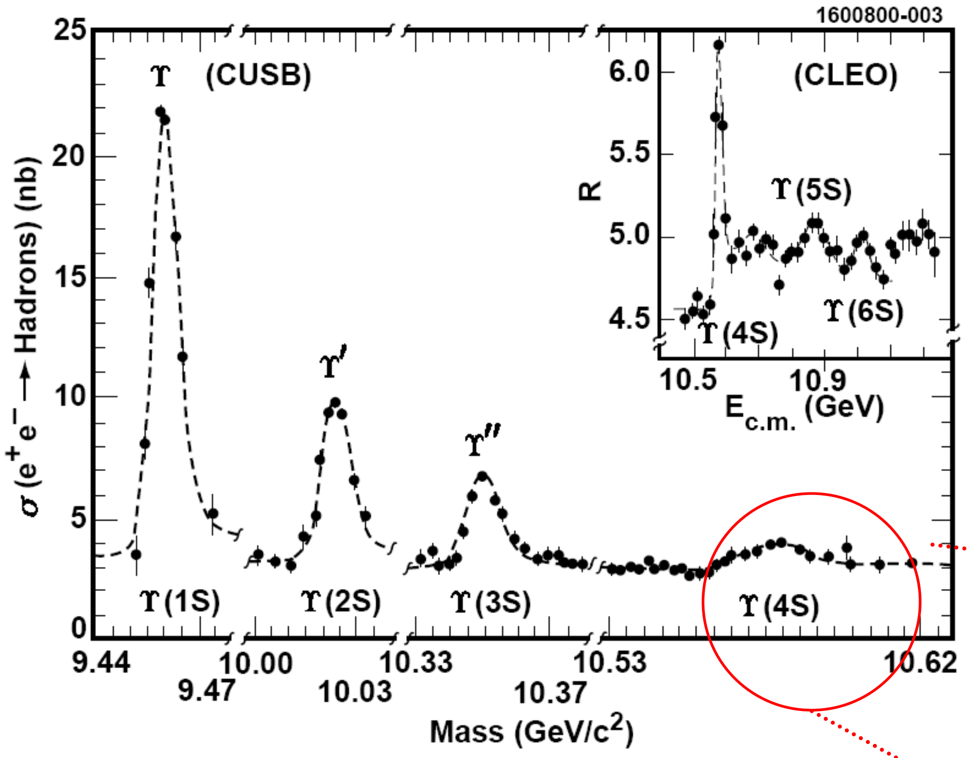
(*) at hand

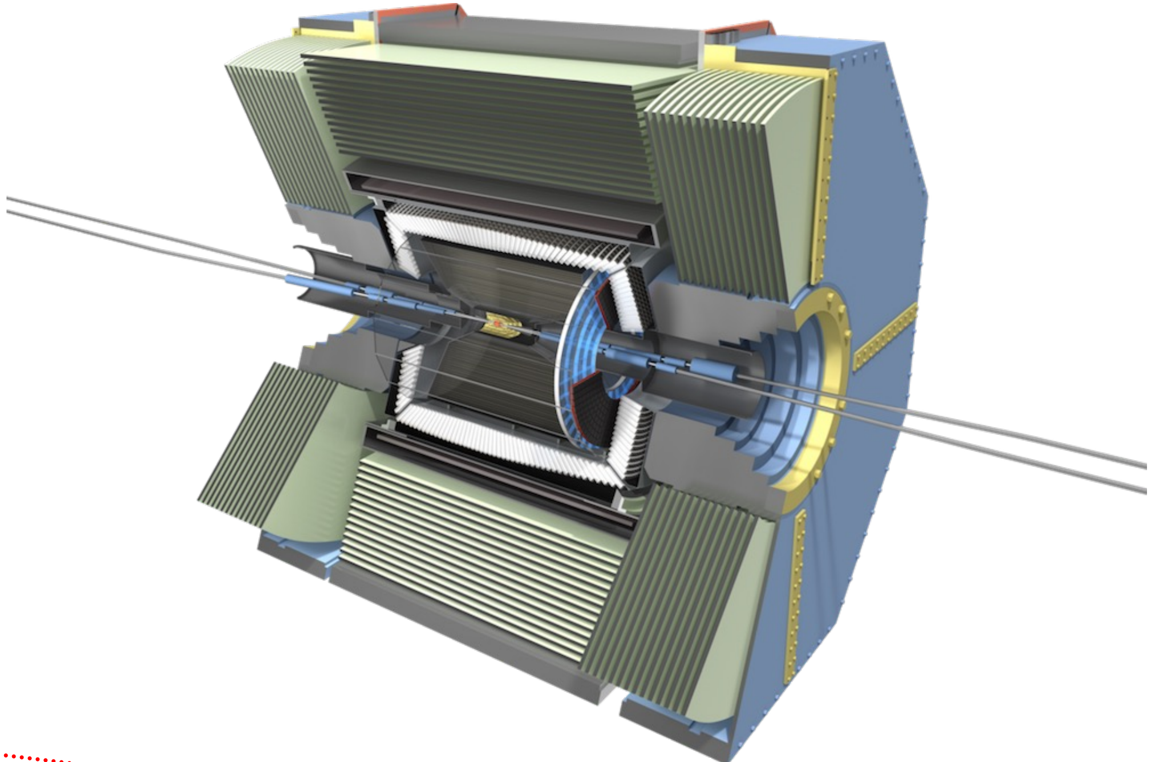
Very rough comparison:

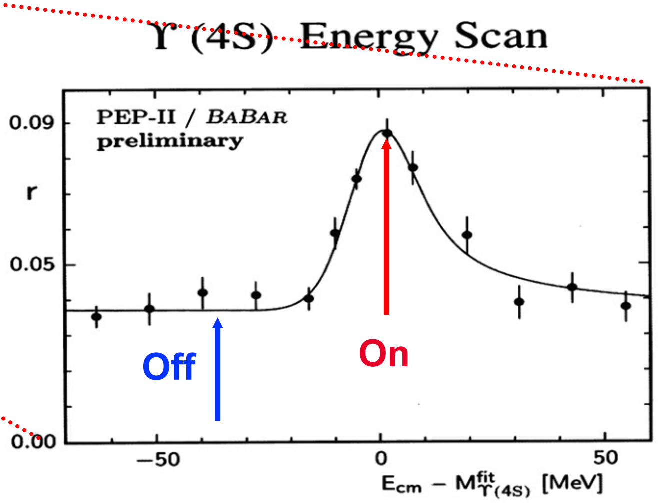
	B-Factories	LHCb
Average B-flight distance	200 µm *	1 cm
Typical bb rate	~10-100 Hz	~ 200 kHz
Event multiplicity	~10	~100
Number of channels	0,1 M	1,1 M

Belle-II (BFactories)

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



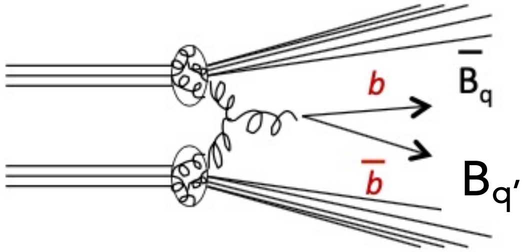


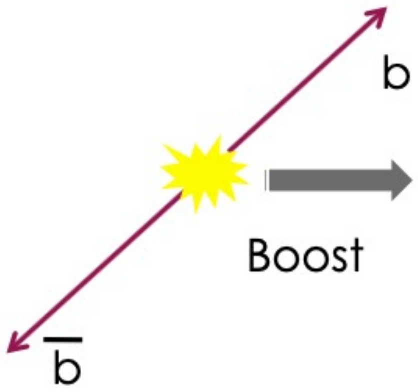


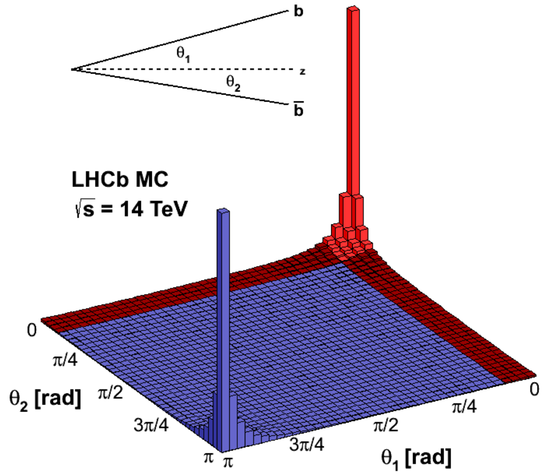
$\Upsilon(4S) \rightarrow B^+B^-, B^0B^0$
to approx. 50% each

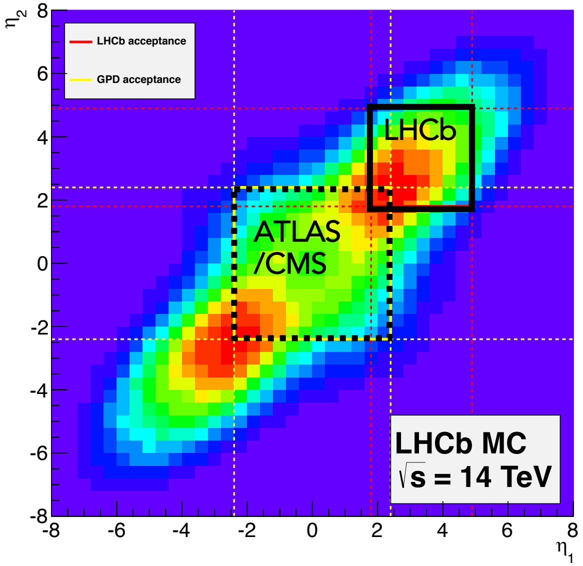
LHCb

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

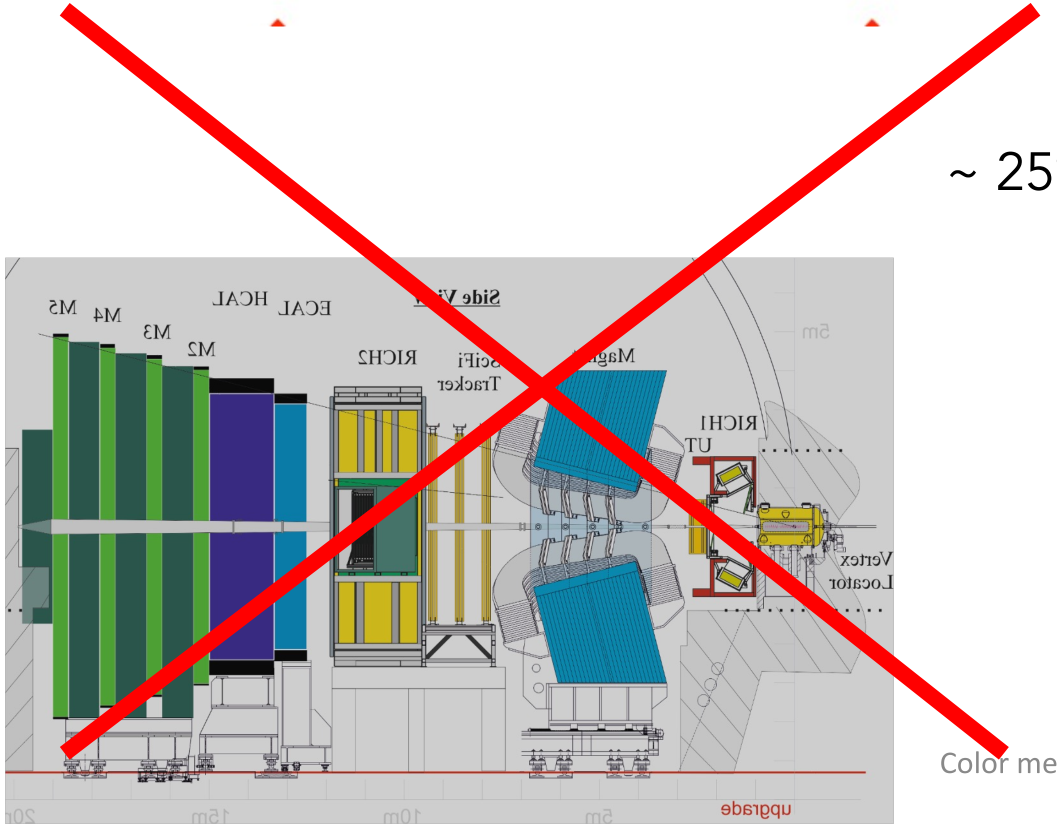


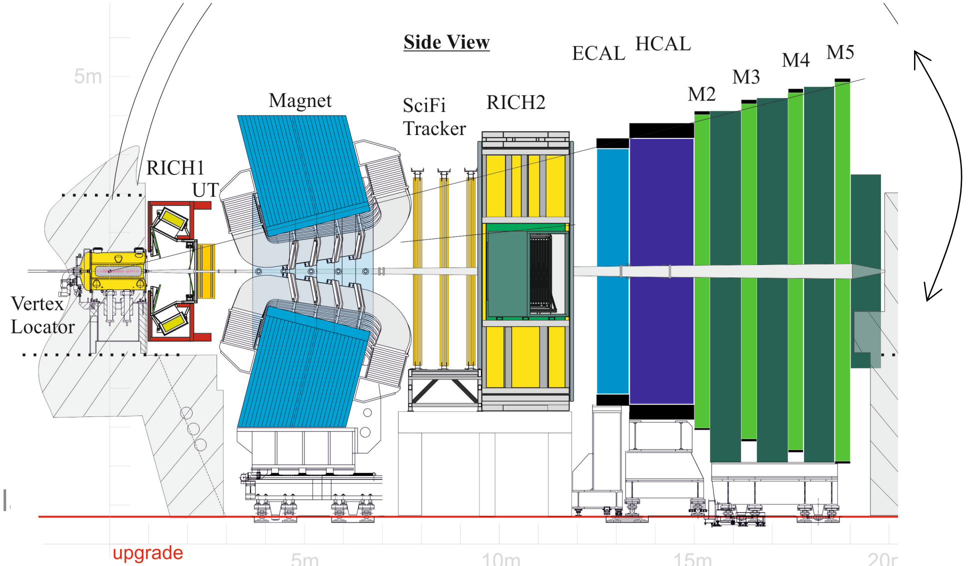






~ 25% of the $b\bar{b}$ production between 15 and 300 mrad





16 deg

A crucial difference between B-Factories and LHCb : trigger

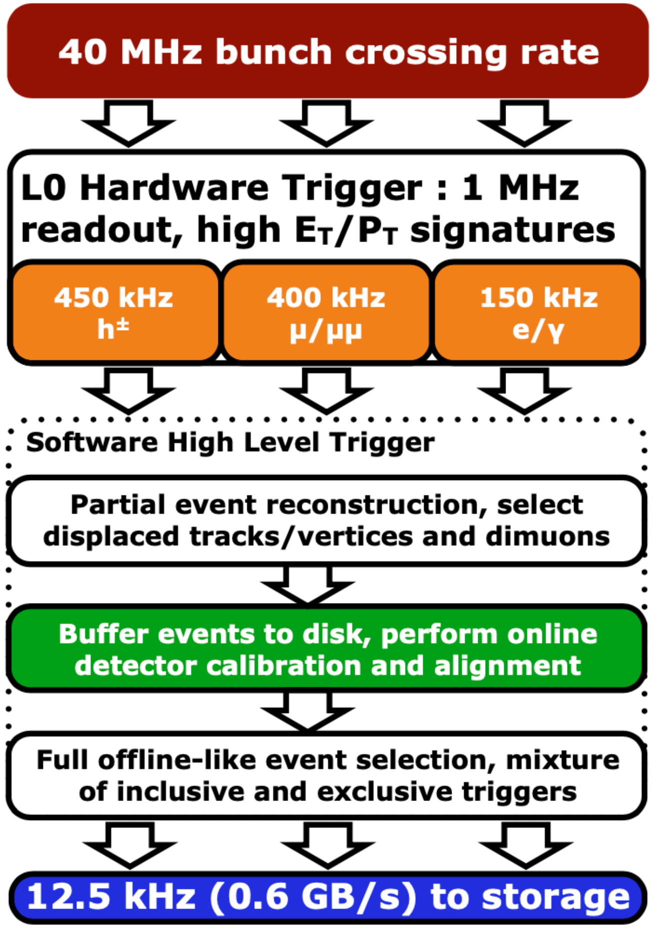
At B-Factories : recording of all $\Upsilon(4S)$ events possible

At LHCb bb production cross section is huge : 290 µb …. but the inelastic cross section is about 300 times larger

Should trigger on interesting events

At 13 TeV for Run3 (x5 higher peak lumi) :
Nominal Charm rate: 5 MHz
Nominal Beauty rate: 200 kHz

LHCb trigger diagram for the data recorded from 2015 to 2018



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

Software High Level Trigger

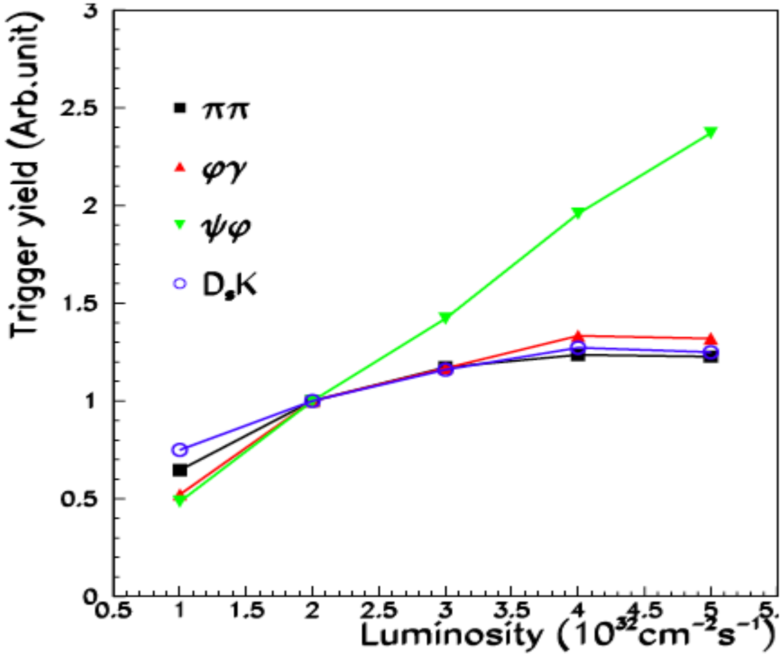
Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

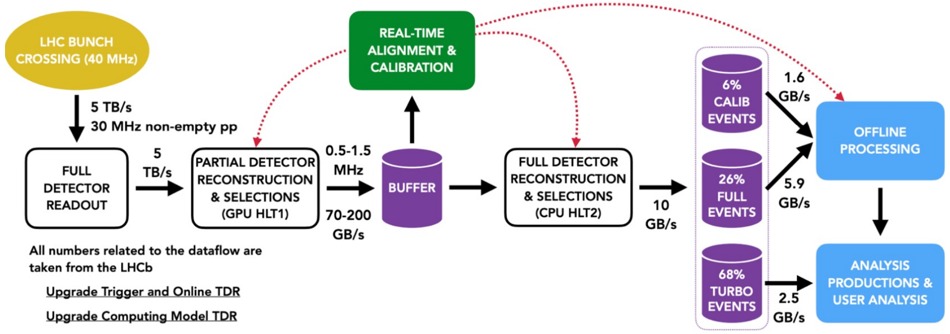
12.5 kHz (0.6 GB/s) to storage

Beauty: 40 kHz



LHCb trigger diagram for Run3 (from 2022)

Beauty: 200 kHz



LHC BUNCH CROSSING (40 MHz)

5 TB/s
30 MHz non-empty pp

FULL DETECTOR READOUT

5 TB/s

PARTIAL DETECTOR RECONSTRUCTION & SELECTIONS (GPU HLT1)

0.5-1.5 MHz
70-200 GB/s

BUFFER

REAL-TIME ALIGNMENT & CALIBRATION

FULL DETECTOR RECONSTRUCTION & SELECTIONS (CPU HLT2)

10 GB/s

6% CALIB EVENTS

26% FULL EVENTS

68% TURBO EVENTS

1.6 GB/s

5.9 GB/s

2.5 GB/s

OFFLINE PROCESSING

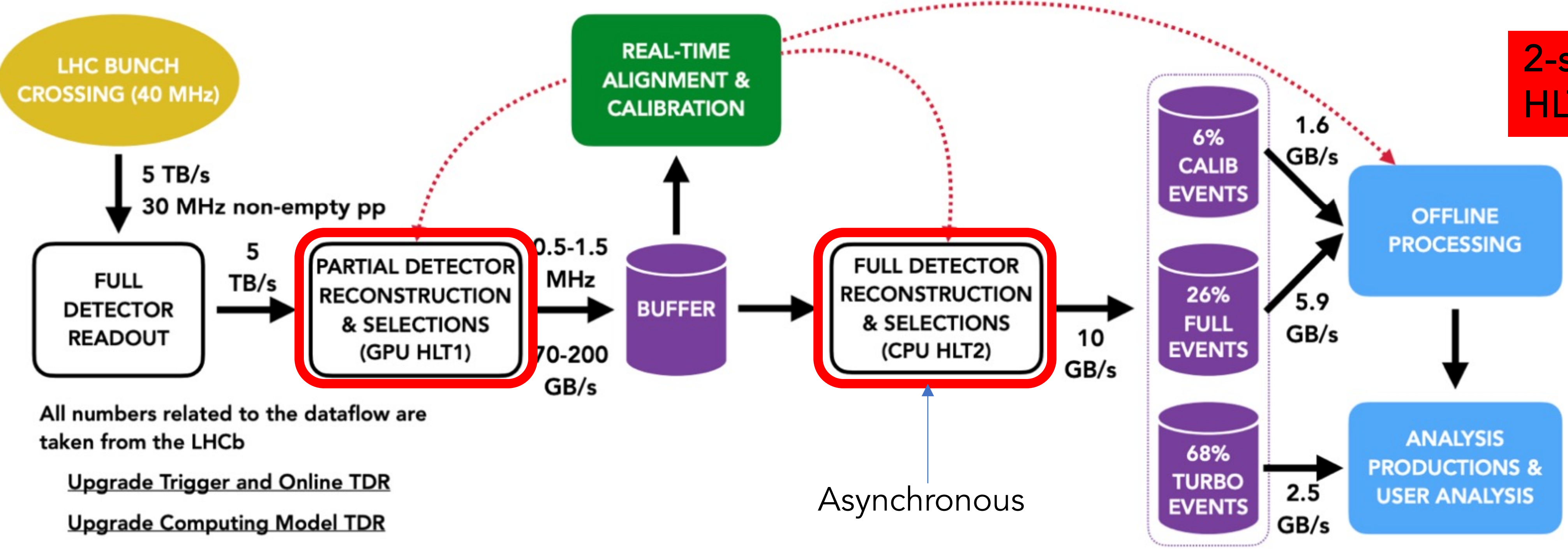
ANALYSIS PRODUCTIONS & USER ANALYSIS

All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

2-stage software trigger, HLT1 (GPU) & HLT2



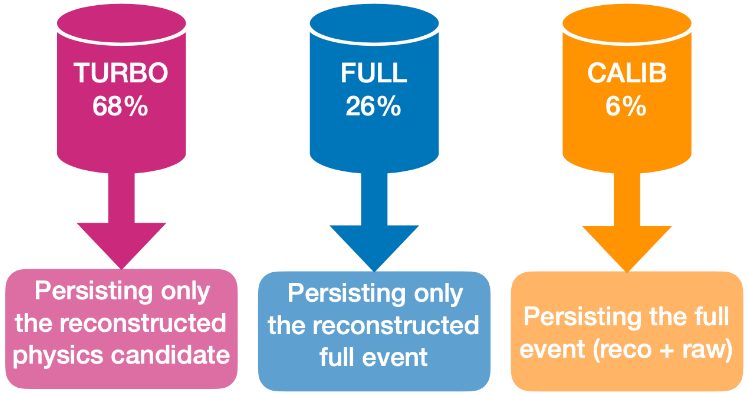
All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

Detector data received by O(500) FPGAs and built into events in the event building (EB) farm servers

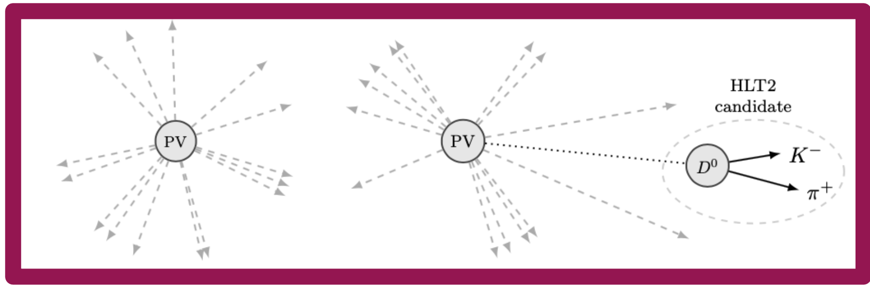
HLT2 output

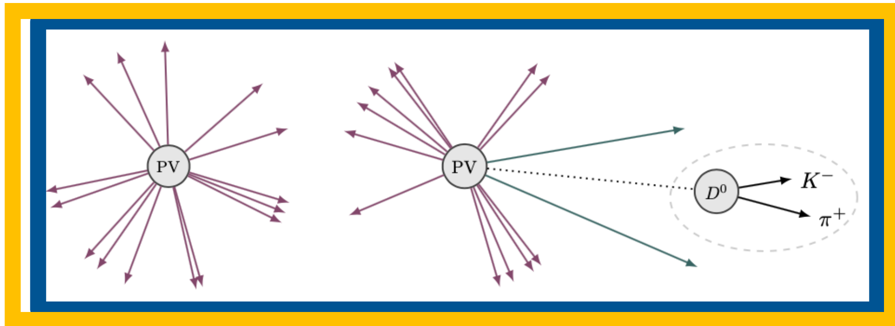


Persisting only the reconstructed physics candidate

Persisting only the reconstructed full event

Persisting the full event (reco + raw)

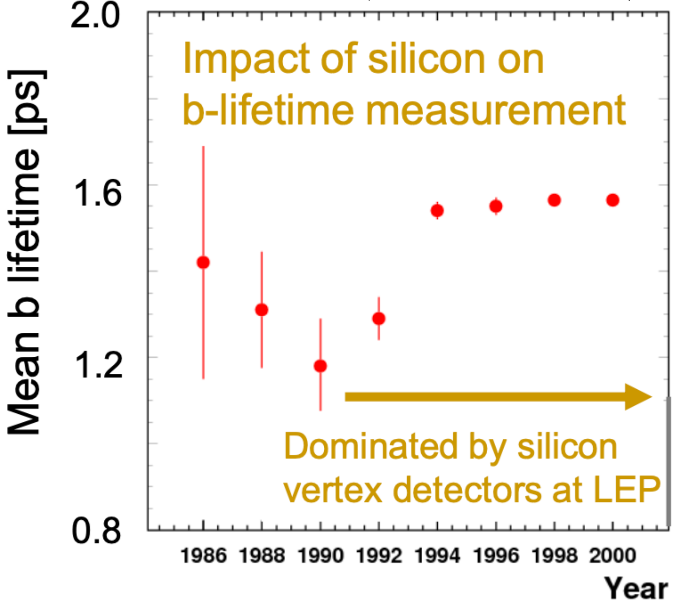




Key-aspects present in both experiments: vertex detectors

Silicon vertex detectors

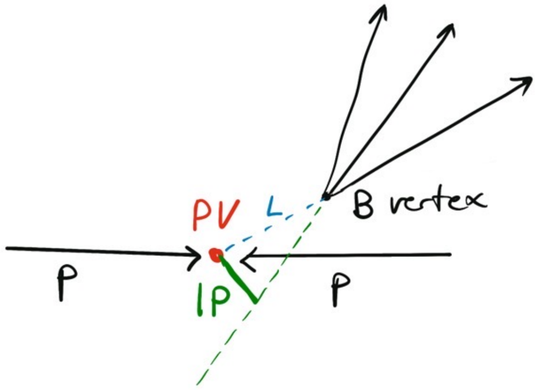
G. Wilkinson (CERN-FNAL 2019)



$$t = ml/p$$

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

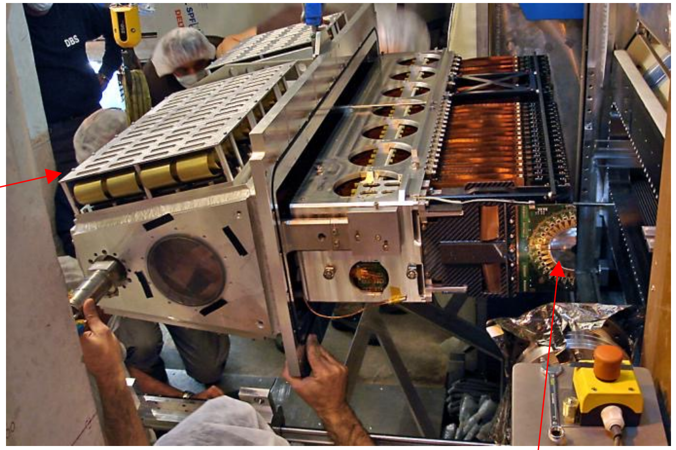
Aluminium foil separates VELO vacuum from LHC vacuum (+ shields it from high-frequency fields of the beams)

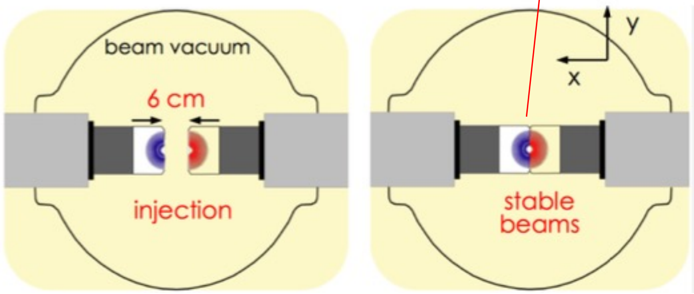


IP resolution <35 μm for p_T>1GeV/c

⇒ resolution on B_s decay time ~ 50 fs

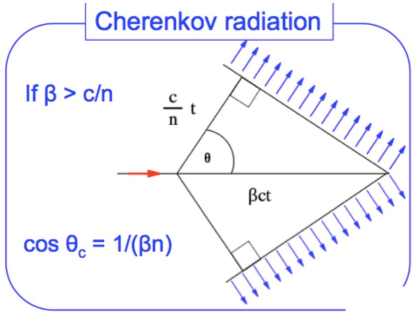
LHCb – VErtex LOcator





active area : ~8 mm from beam
New one even closer (~5 mm)

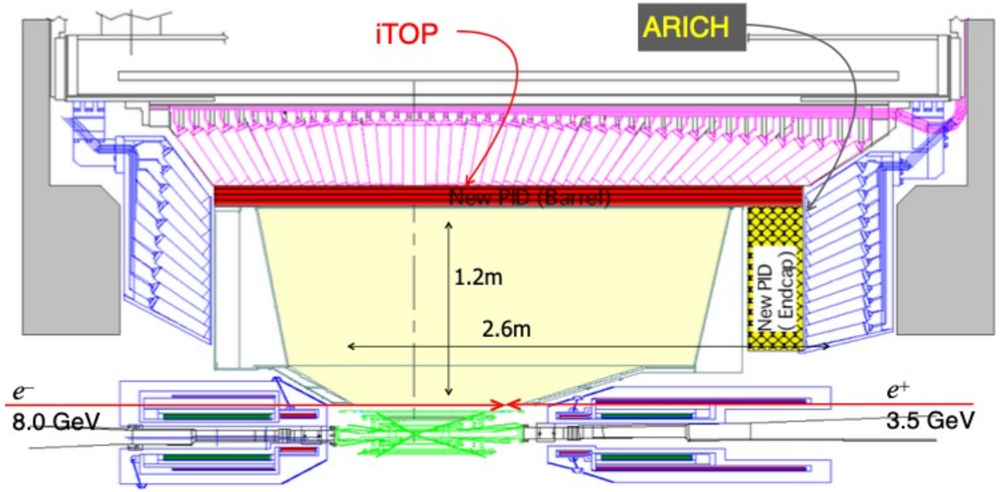
Key-aspects present in both experiments: hadron PID



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

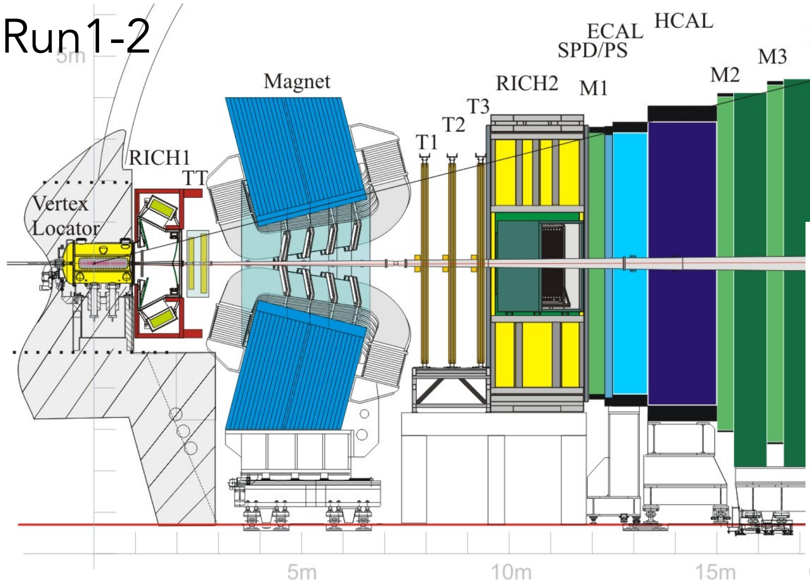
p being measured by the tracking, the particle is identified

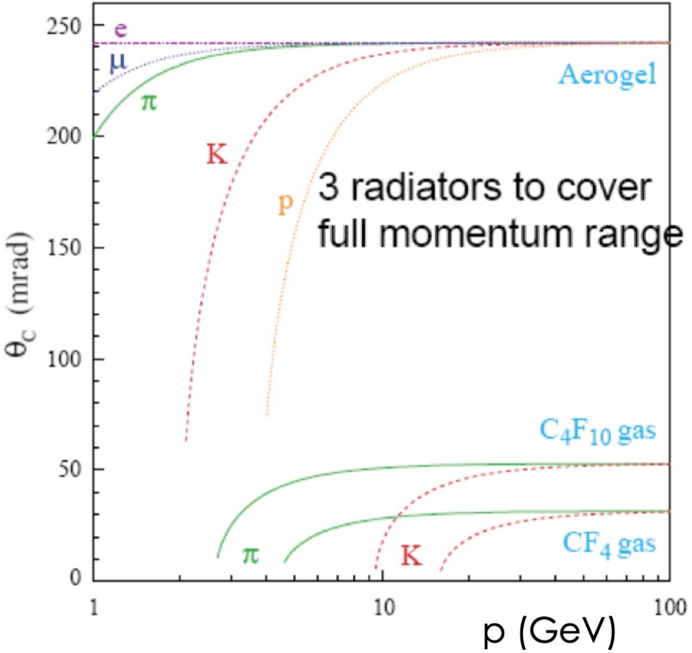
Belle-II: ToF and Cerenkov



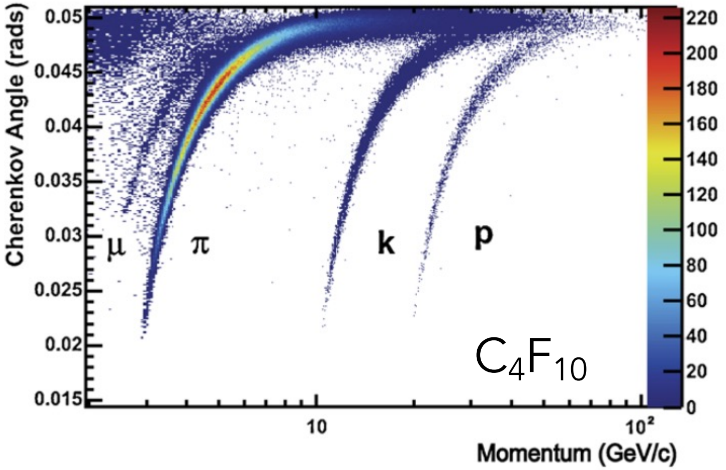
LHCb: Cerenkov

Run1-2





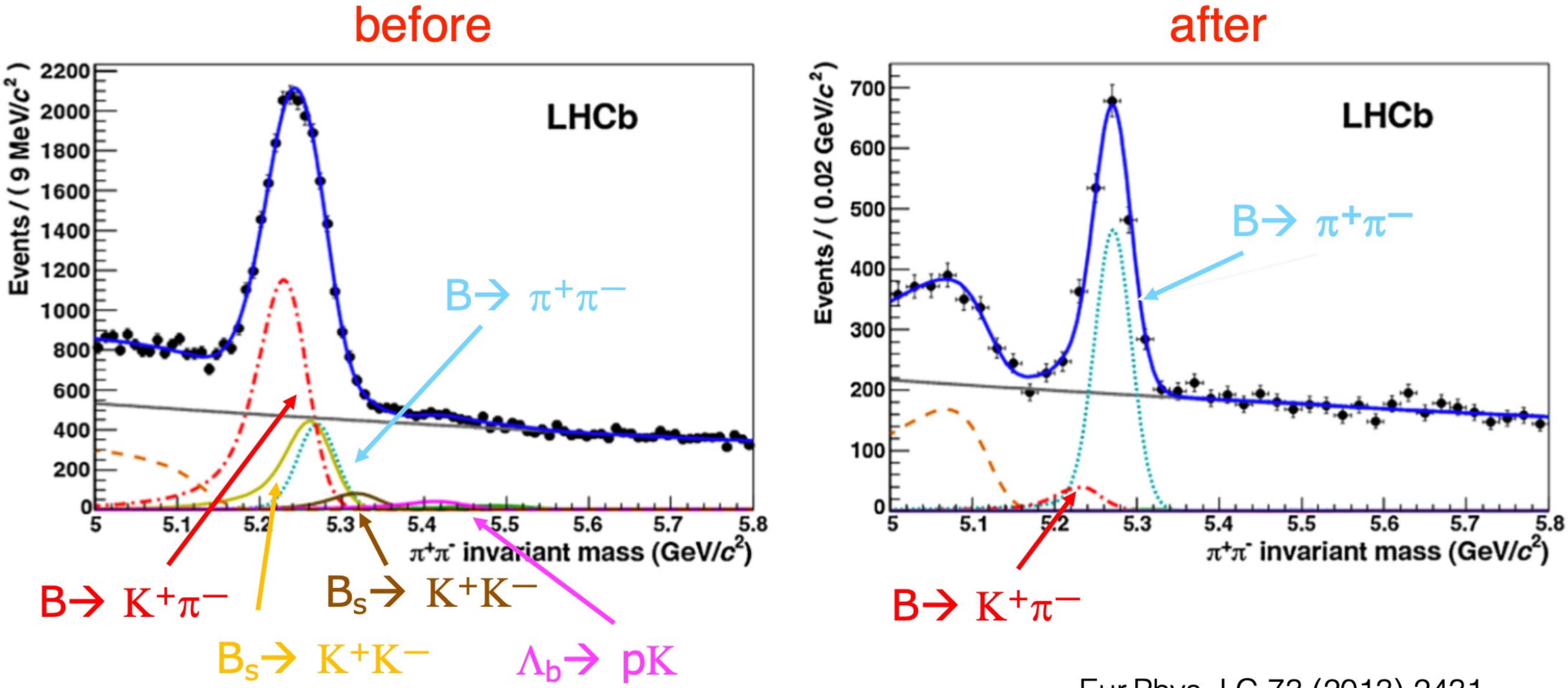
3 radiators to cover full momentum range



C_4F_{10}

h 2024

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



before

after

B→ $\pi^+\pi^-$

B→ $K^+\pi^-$

B_s→ K^+K^-

B_s→ K^+K^-

Λ_b→ pK

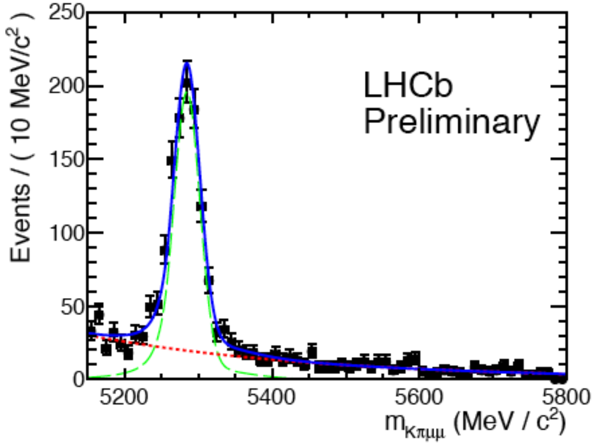
B→ $\pi^+\pi^-$

B→ $K^+\pi^-$

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

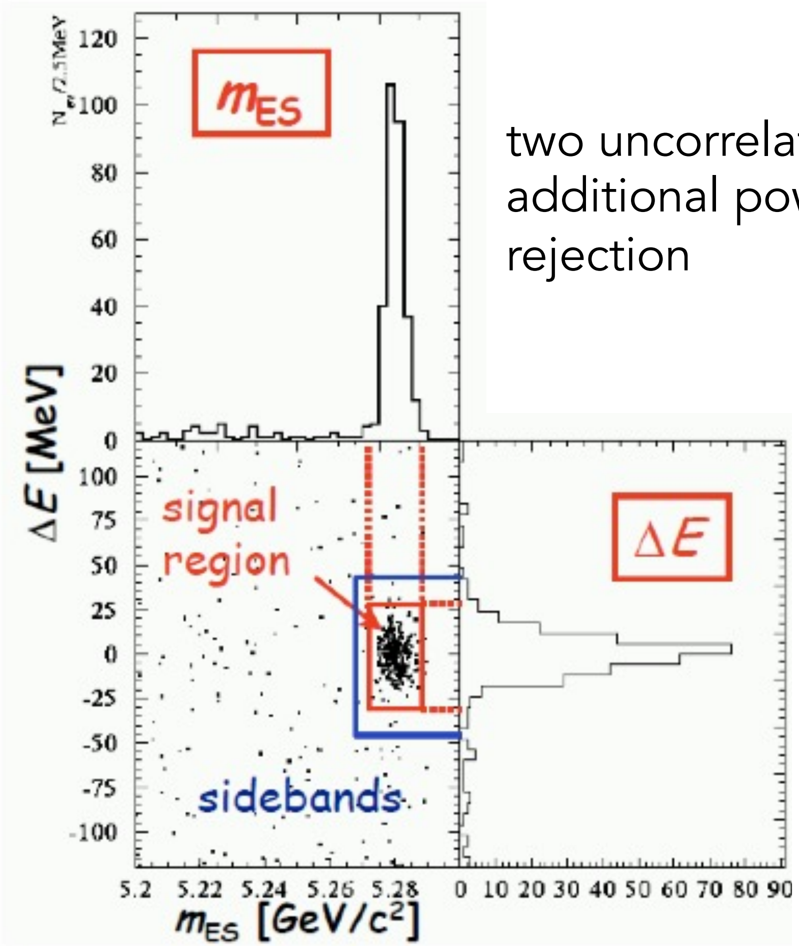
Signal selection

LHCb: ‘standard’ invariant mass plot



BFactories: 2 variables ΔE and m_{ES} or m_{BC}
From the lab frame boost all tracks back in the Υ(4S) rest frame

$$\sqrt{s} = 2E^{\star}_{\rm beam} \qquad \Delta E = E^{\star}_{B} - E^{\star}_{\rm beam}, \qquad m_{\rm bc} = \sqrt{E^{\star 2}_{\rm beam} - \boldsymbol{p}^{\star 2}_{B}},$$



two uncorrelated variables : additional power for background rejection

ΔE and m_{ES} or m_{BC}

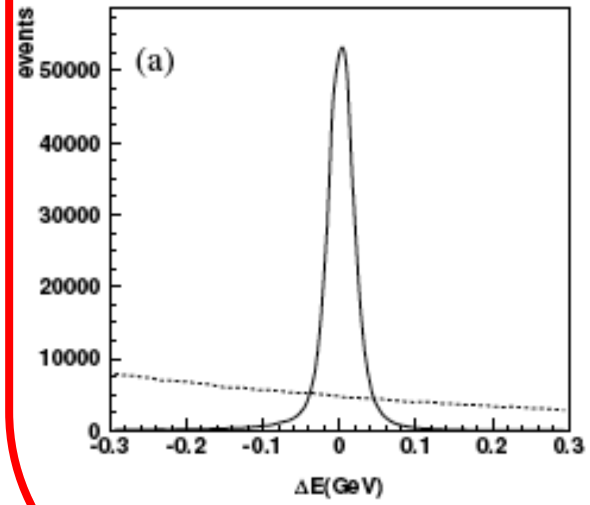
$$\Delta E = E_B^\star - E_{\rm beam}^\star,$$

$$\sigma^2_{\Delta E} = \sigma^2_{E_B^\star} + \sigma^2_{E_{\rm beam}^\star}$$

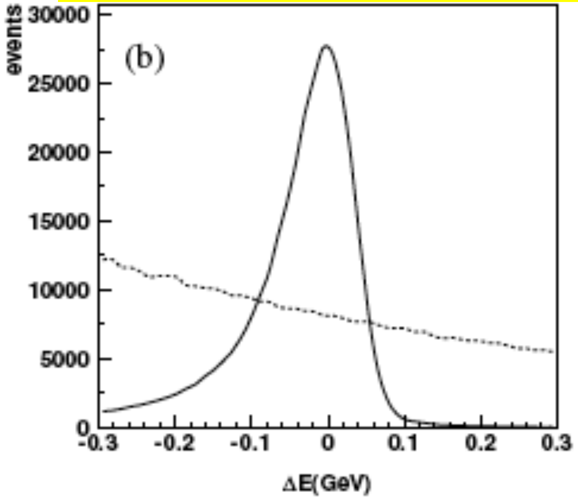
reconstruction (dominant)

beam energy spread

charged tracks only



charged tracks + neutral



$$m_{\rm bc} = \sqrt{E_{\rm beam}^{\star 2} - \boldsymbol{p}_B^{\star 2}},$$

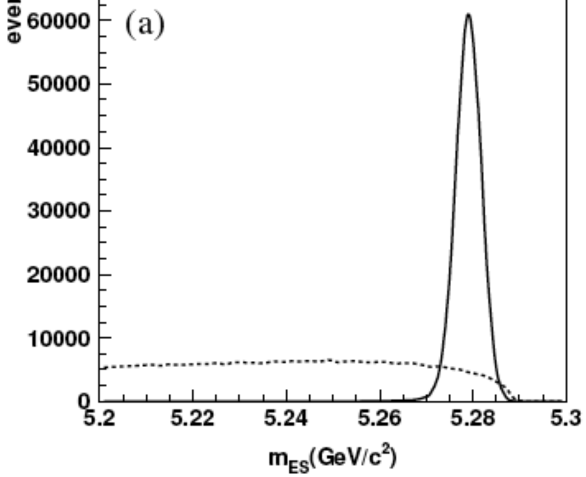
independent of the mass hypothesis of the particles

from detector measurement

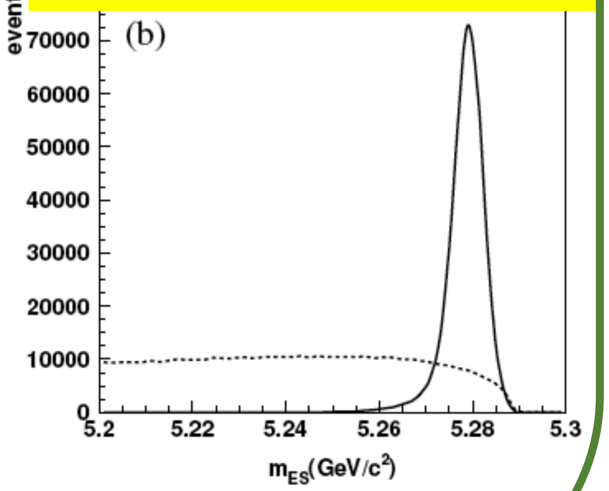
$$\sigma^2_{m_{\rm ES}} \approx \sigma^2_{E_B^\star} + \left(\frac{p_B^\star}{m_B}\right)^2 \sigma^2_{p_B^\star}$$

dominated by the beam energy knowledge

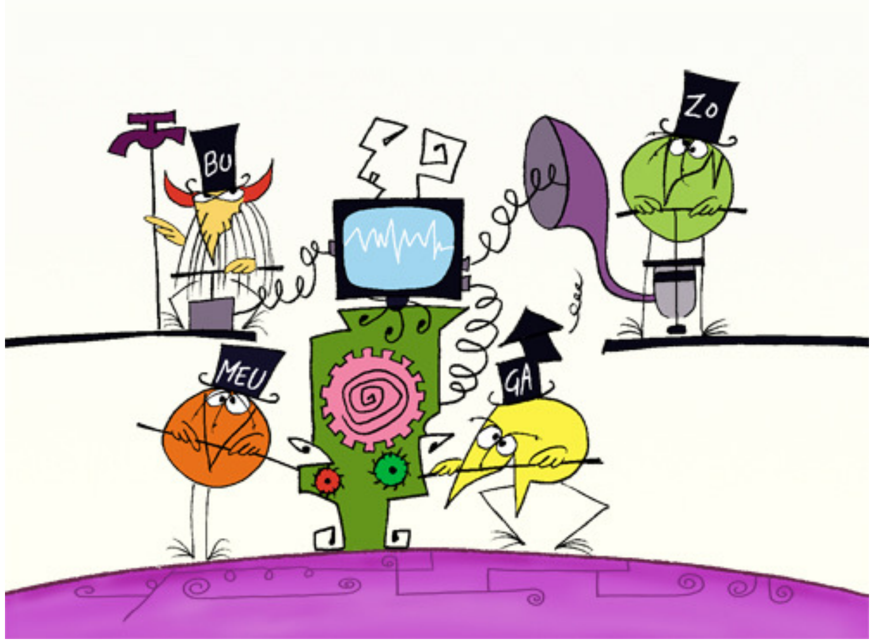
charged tracks only

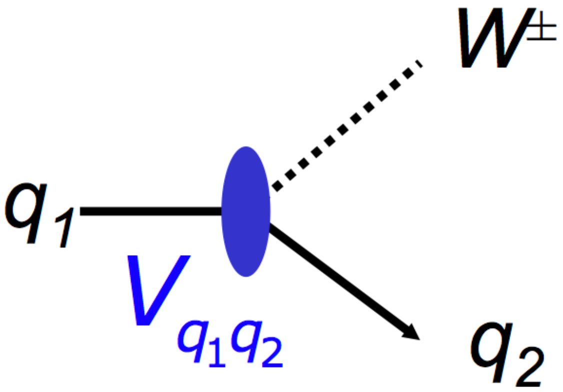


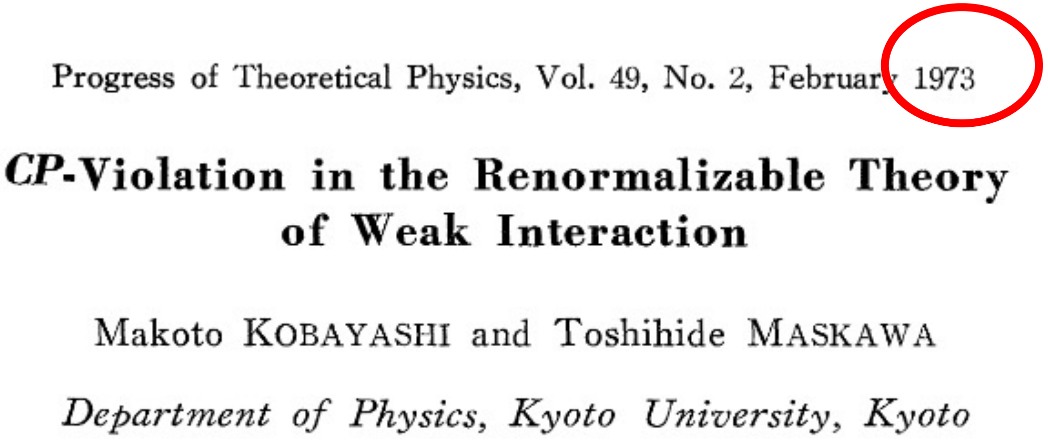
charged tracks + neutral



The CKM mechanism: measuring the sides of the unitarity triangle







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

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

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)

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

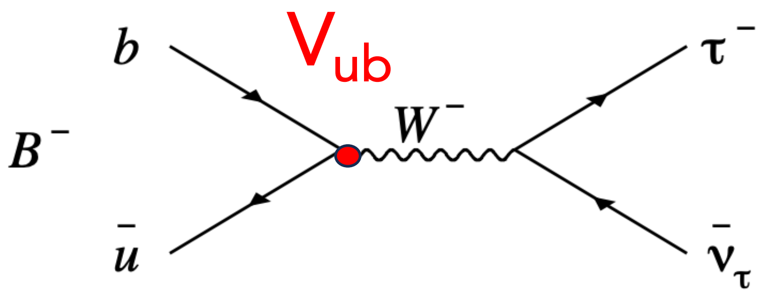
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

Measurements !

How to measure those numbers ?

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

Magnitudes are typically determined from branching ratios



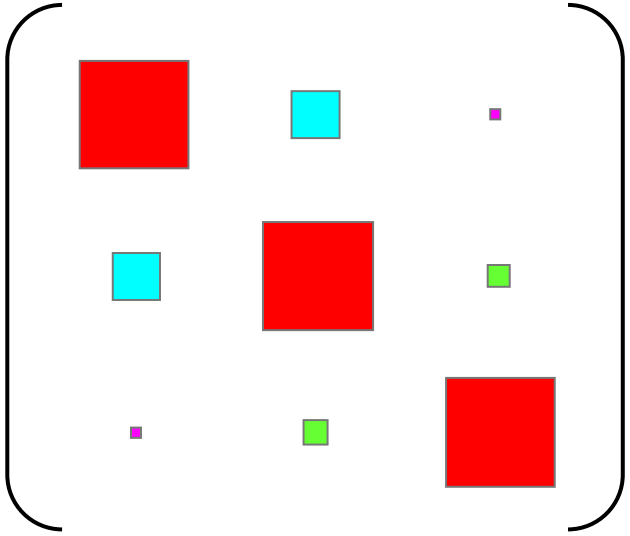
$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

TH input

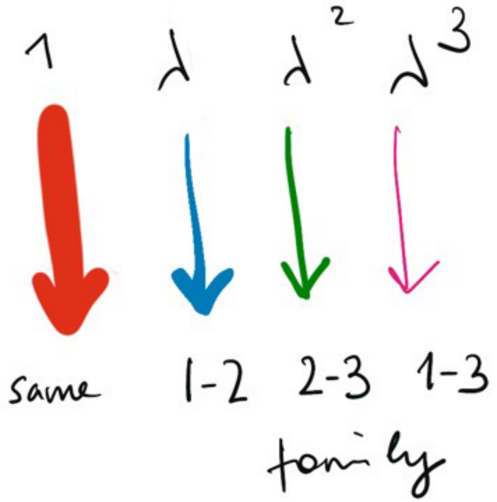
NB : only an example, other methods using other decays also exist !

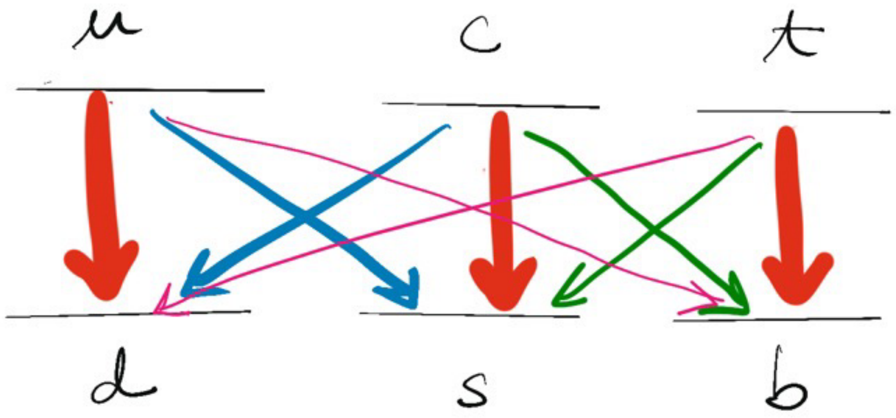
Phases : CP violation

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



Why this structure ?





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

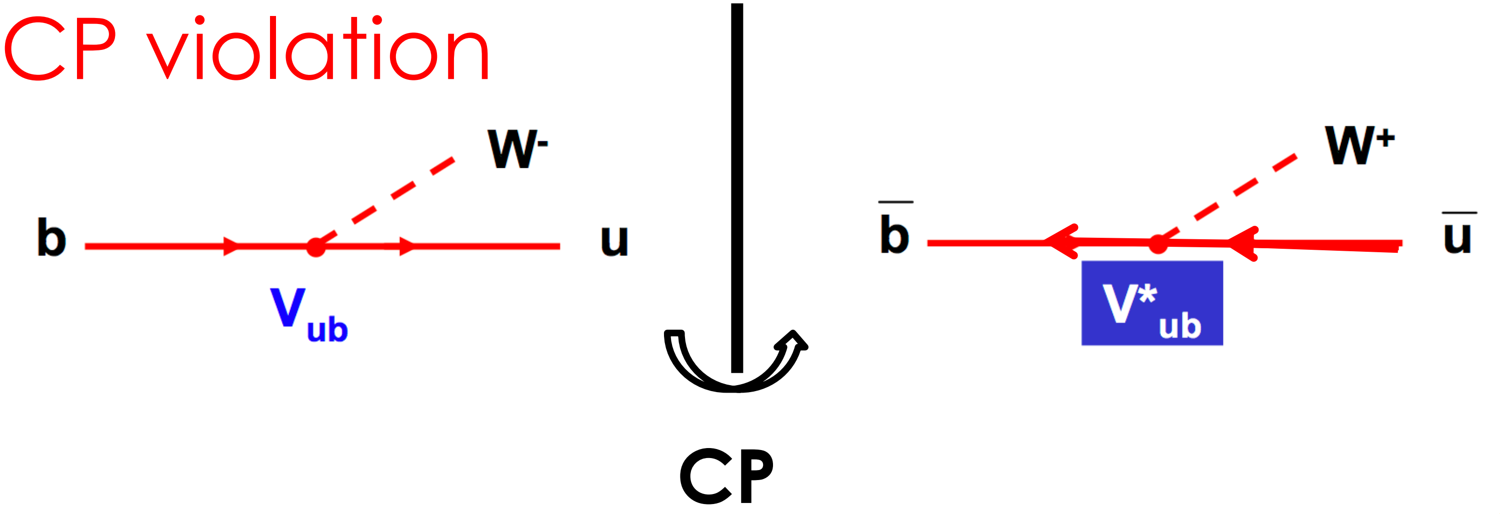
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{ub}

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

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

$V^*_{ub} \neq V_{ub}$ → CP violation

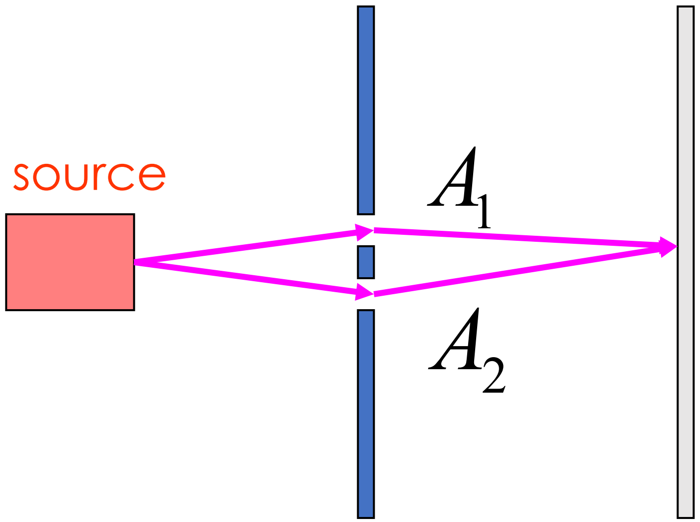


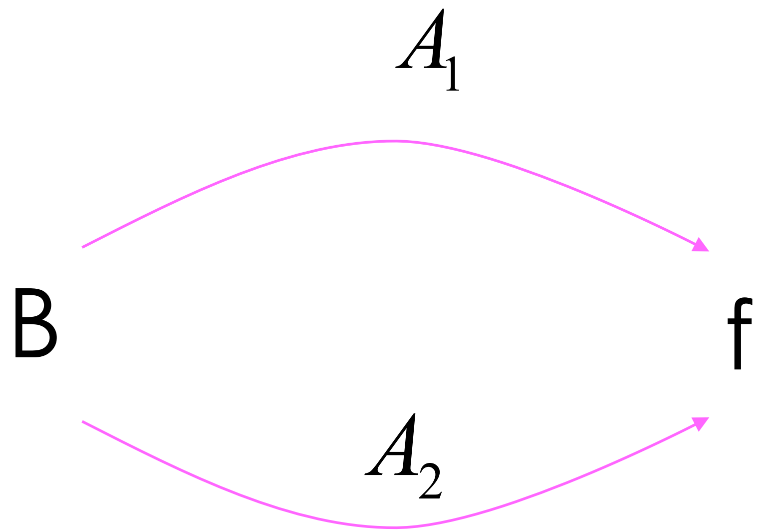
Large effects for particles with a b quark
Small effects for particles with a c or s quark

But CP violation has been discovered studying K^0 ($s\bar{d}$) mesons !

Distinctive flavour sector of Standard Model not necessarily replicated in extended theories

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

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

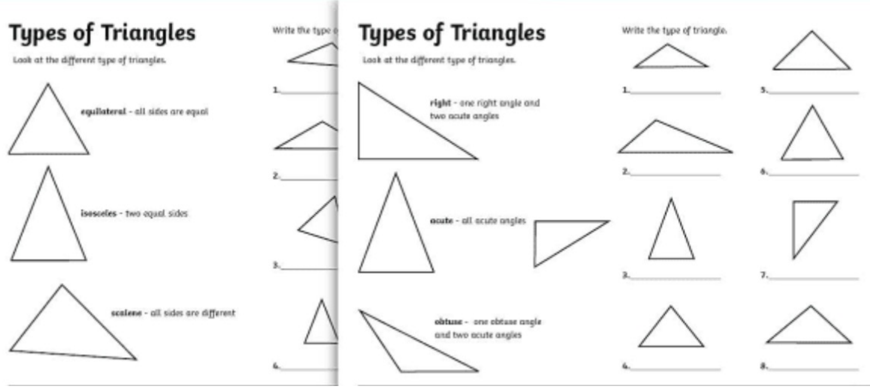
$$\bar{A}_{\bar{f}} = A(\bar{B} \to \bar{f}) = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

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

Write the type

1.

2.

3.

4.

Types of Triangles

Look at the different type of triangles.

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.

1.

2.

3.

4.

5.

6.

7.

8.

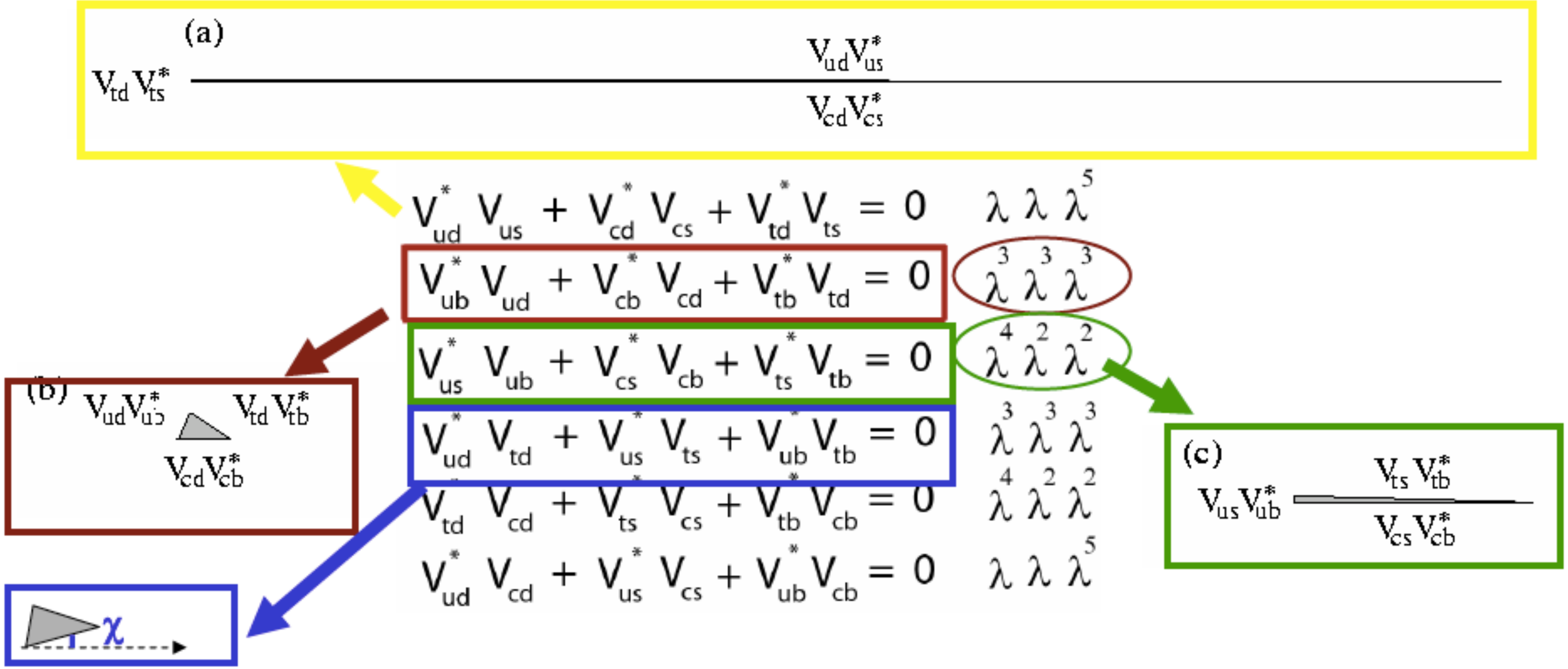
Stay within the 3 families

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

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

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

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



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

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

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

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

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

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

They all have the same area *J*/2

$$J = c_{12}c_{13}^2c_{23}s_{12}s_{13}s_{23}\sin\delta \approx 3\times10^{-5}$$

Jarlskog invariant

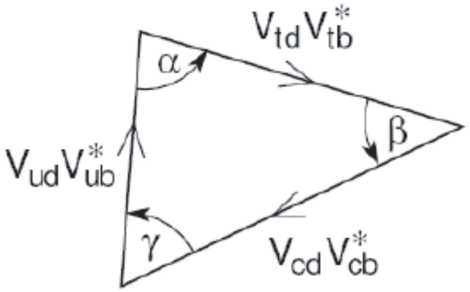
“the” unitarity triangle : $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

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

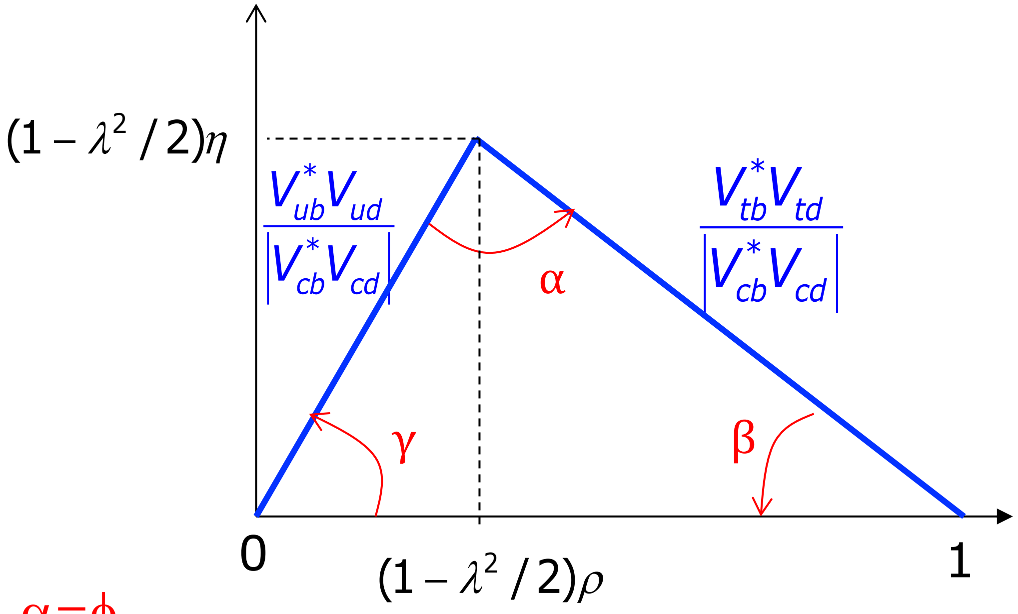
$$V_{ud}\, V_{ub}^* = A\lambda^3(\rho+i\eta)\times(1-\frac{\lambda^2}{2})$$

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

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



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



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

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

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

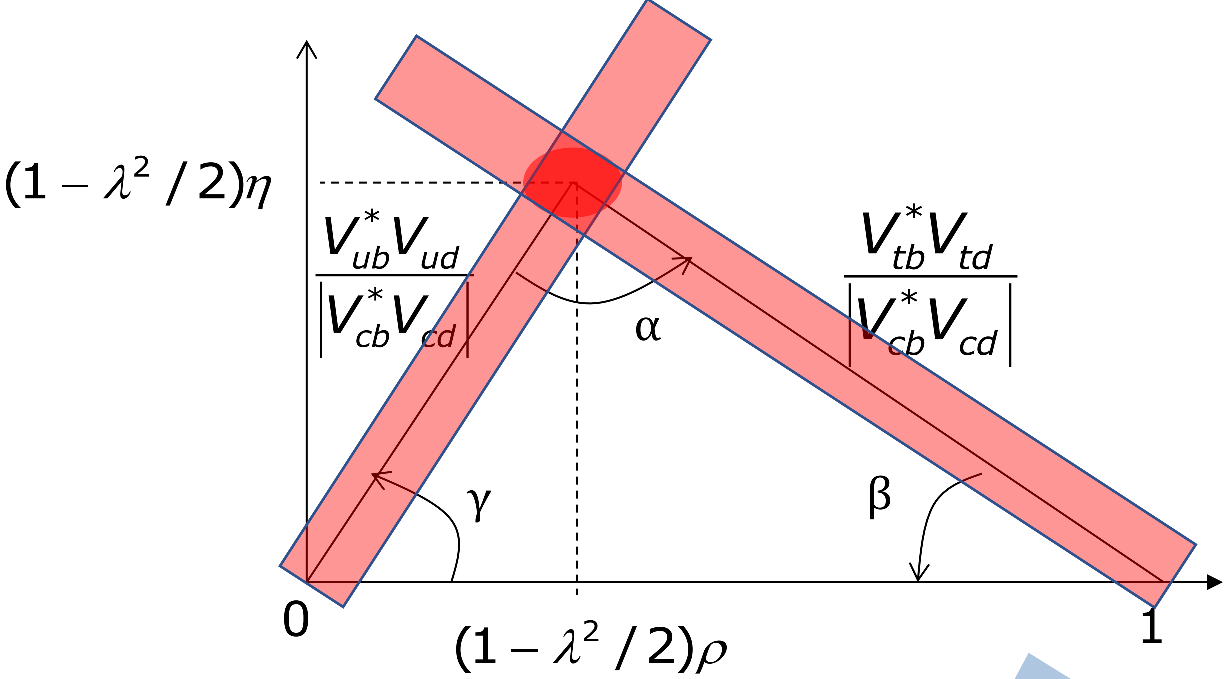
2 sides ; 3 angles

⇒ aim : to overconstrain this unitarity triangle

precision test of the Standard !

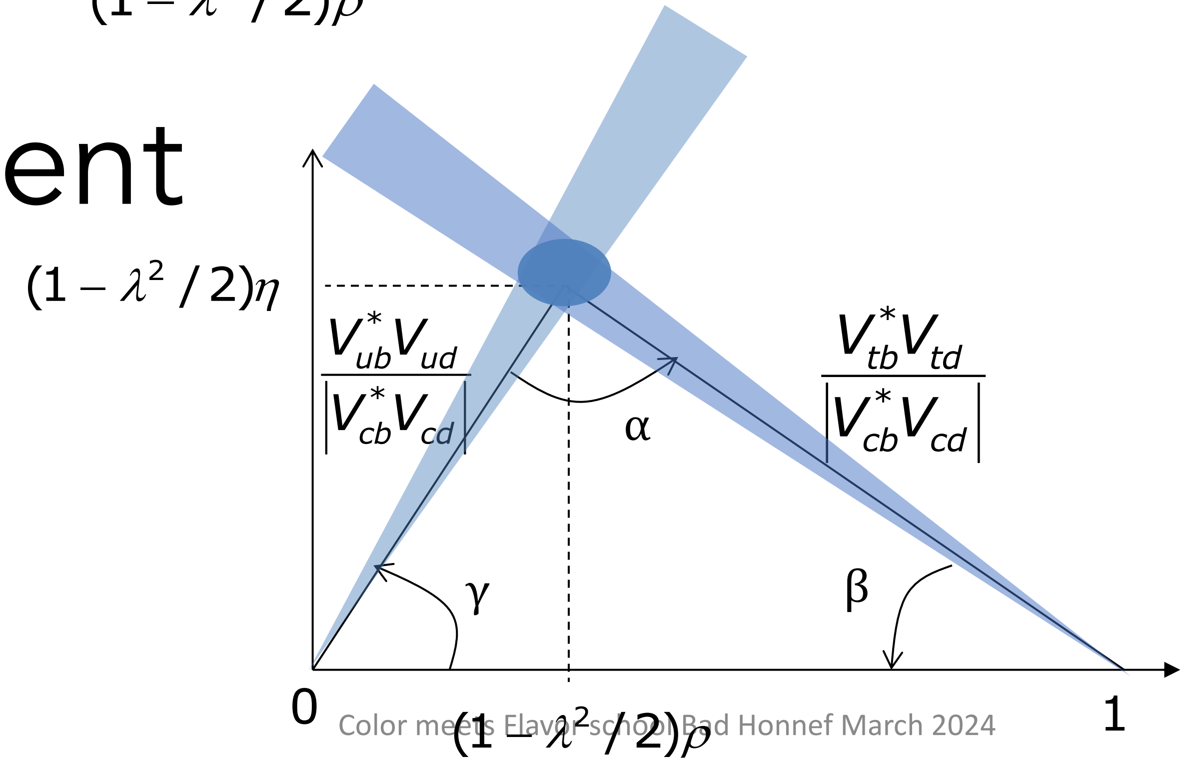
$\alpha=\phi_2$
$\beta=\phi_1$
$\gamma=\phi_3$

Is



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

in agreement with

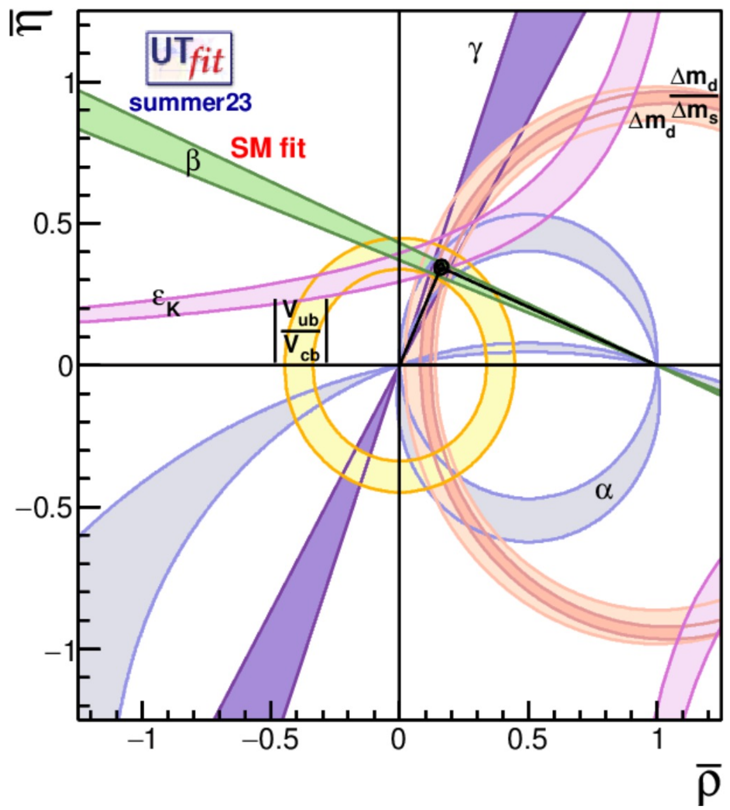


?

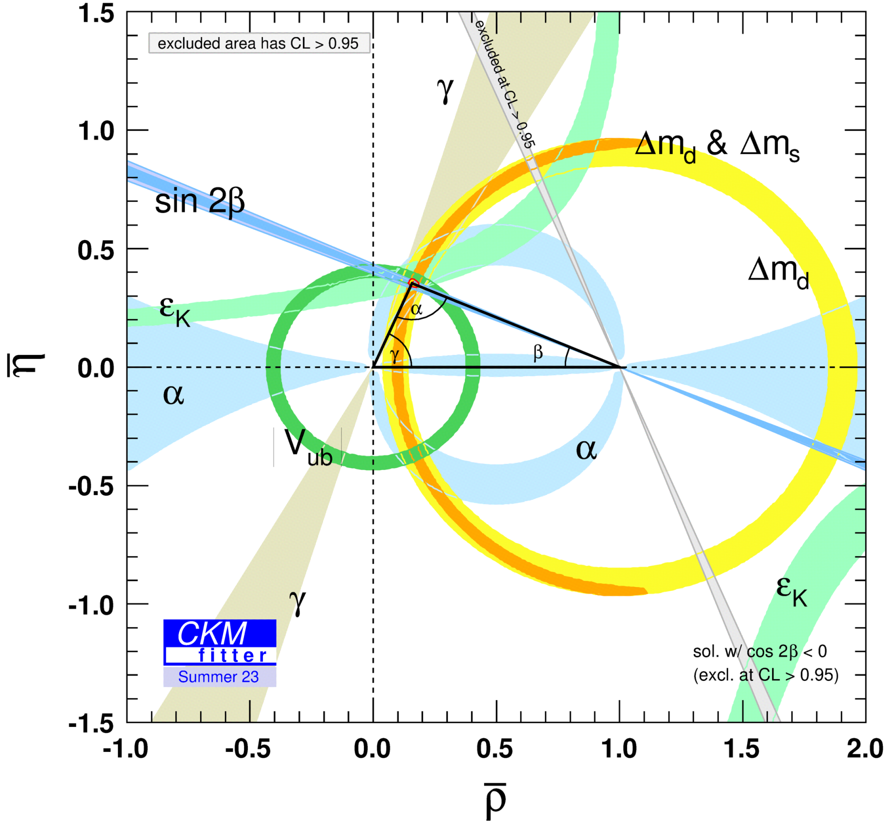
Two main collaborations for CKM fits:

Different statistical treatments (bayesian or frequentist)
Different choices of TH inputs
Mostly similar exp results

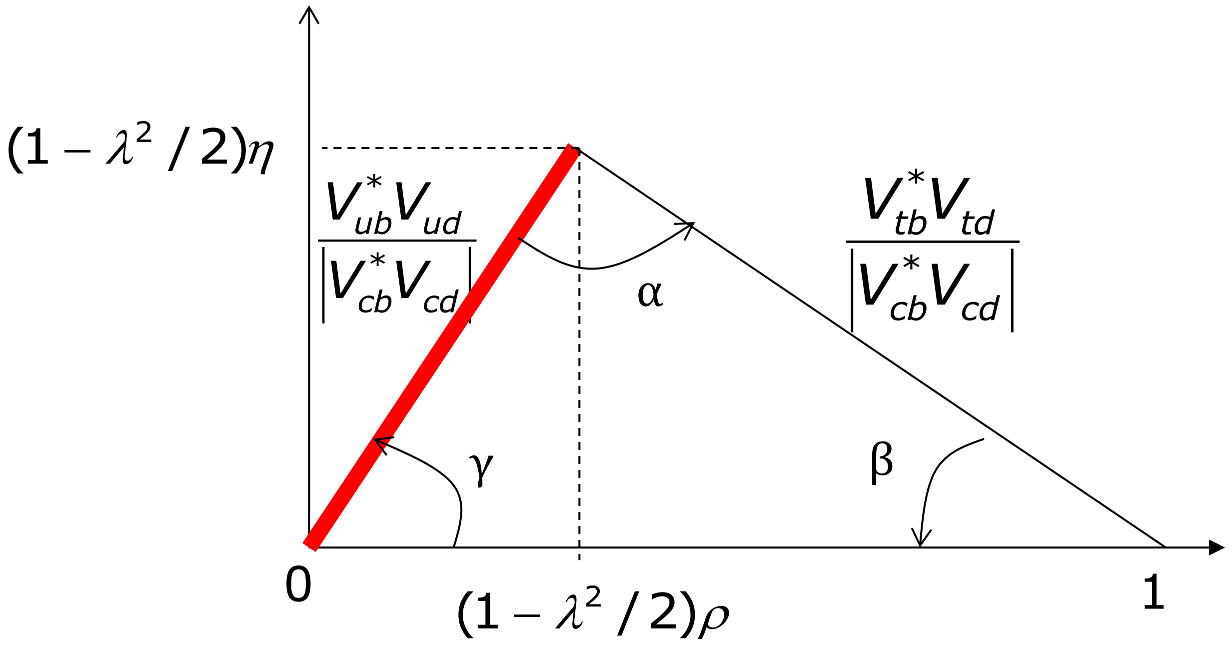
UTfit

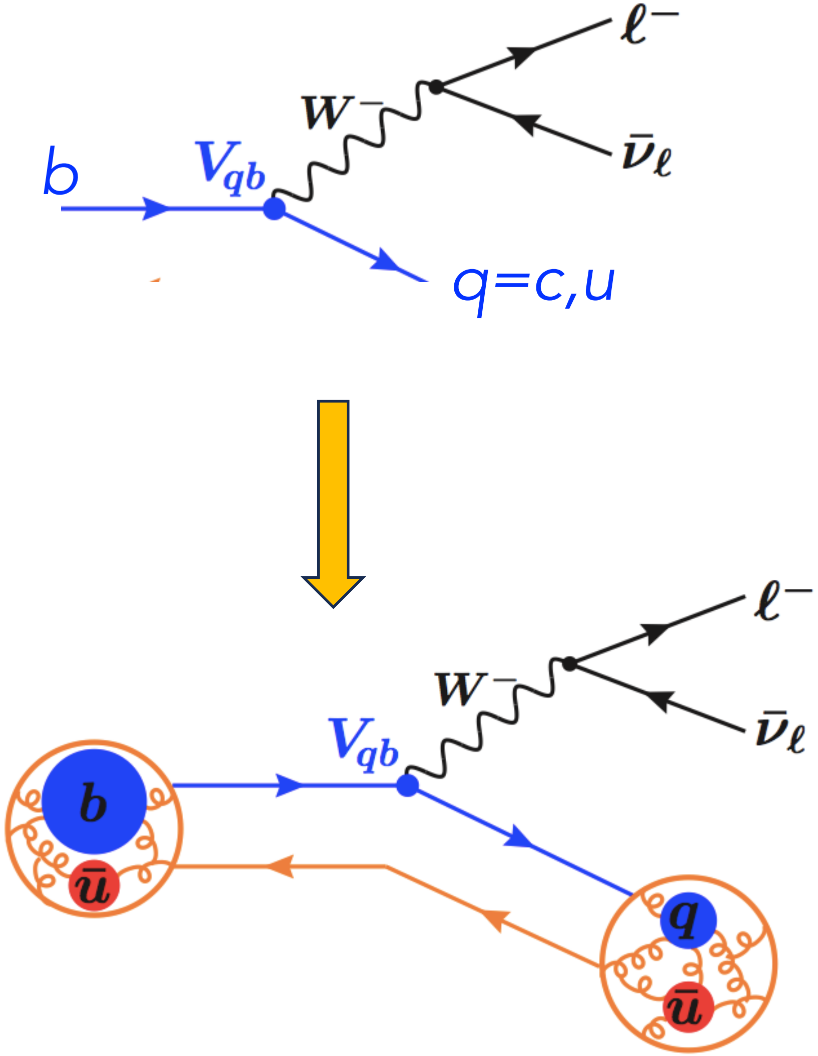


CKMfitter



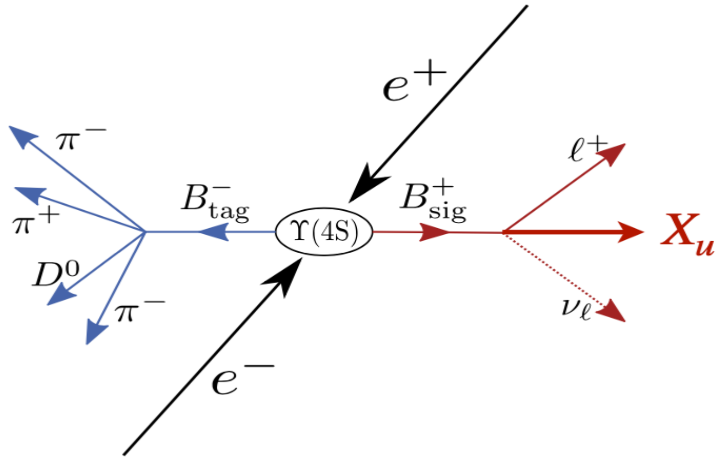
The CKM magnitudes $|V_{ub}|$ and $|V_{cb}|$ are determined from semileptonic B meson decays





- $|V_{cb}|$ is entering everywhere
- Dealing with hadrons not quarks

BFactories (Belle-II)

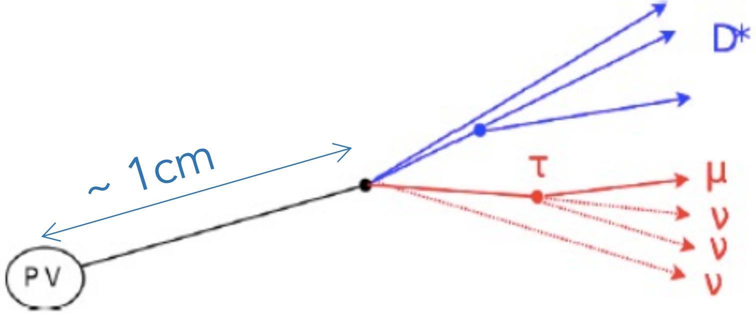


Beam energy const. + tag-side
→kinematical constraints

Inclusive decays

Access to absolute BR

LHCb



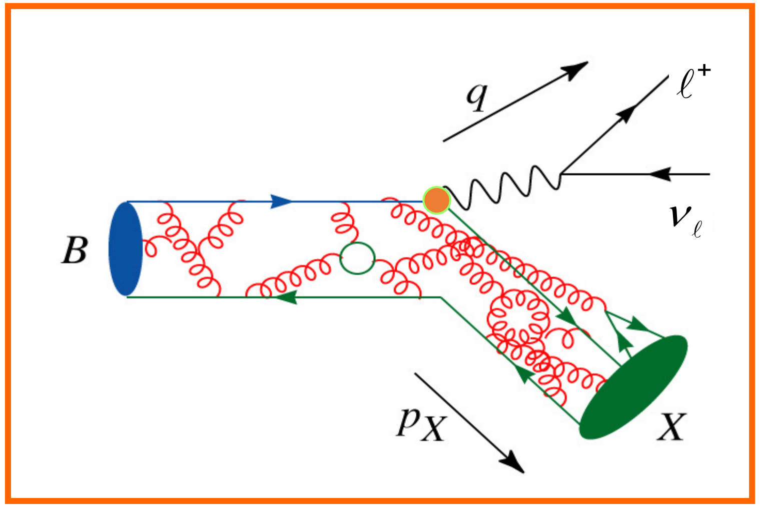
Very large boost→ flight distance reconstruction
→kinematical constraints

All b-hadrons species

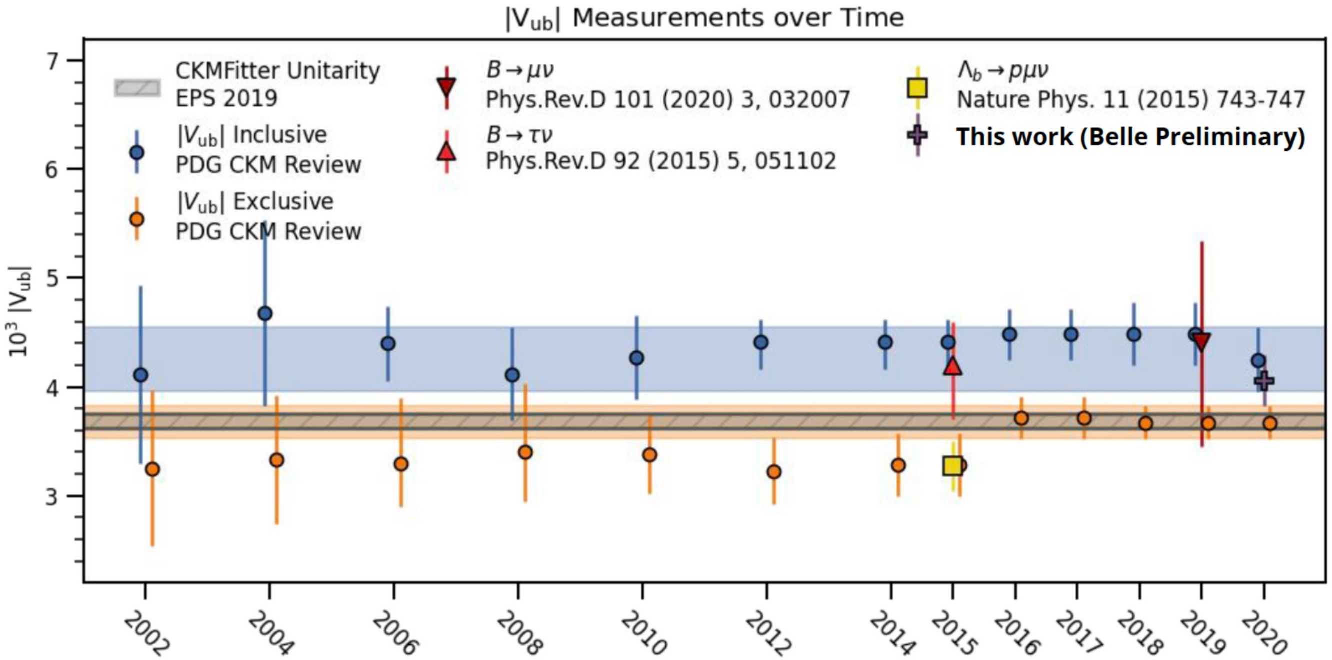
No access to absolute BR

Exclusive or inclusive measurements ?

exclusive	inclusive
$B \to \pi\, \ell\nu$	$B \to X_u\, \ell\nu$
$B \to D^*\, \ell\nu$	$B \to X_c\, \ell\nu$
QCD form factors	Heavy Quark symmetry+ OPE

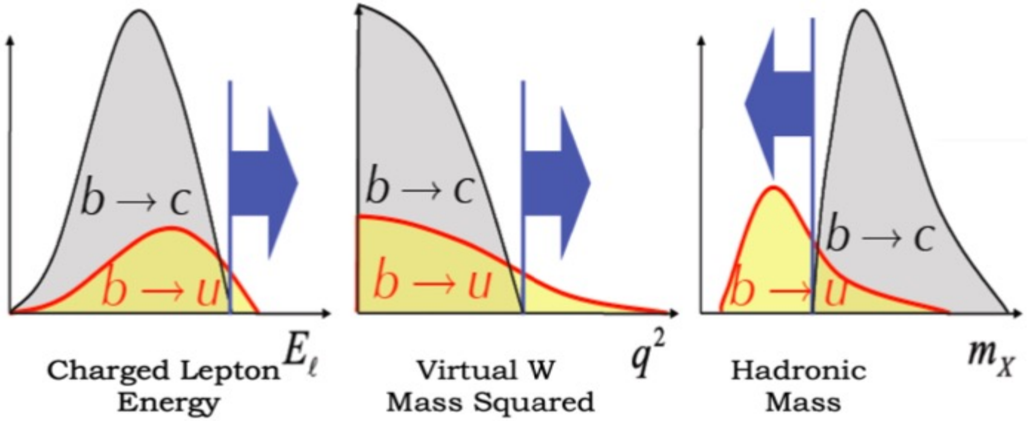


Should not matter … but with increasing precision tensions appeared



SnowMass 2021

$|V_{ub}|$: inclusive determinations



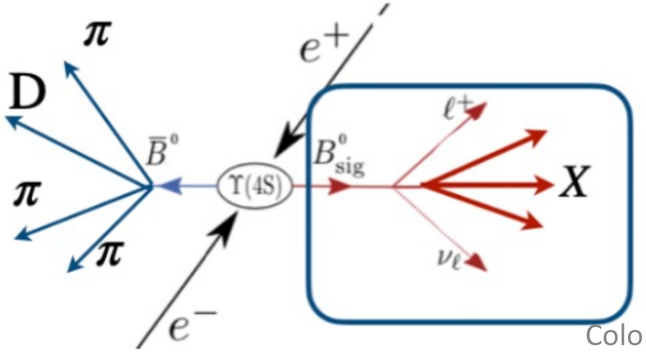
$$\frac{\Gamma(b \to u \ell \nu)}{\Gamma(b \to c \ell \nu)} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} = |\lambda(\rho - i\eta)|^2 \approx \frac{1}{150}$$

Even with modern technics, the reduction of the huge b->c background has significant consequences on the systematics uncertainties

HQET breaks down due to experimental cuts

More information, higher purity reconstructing the other B.

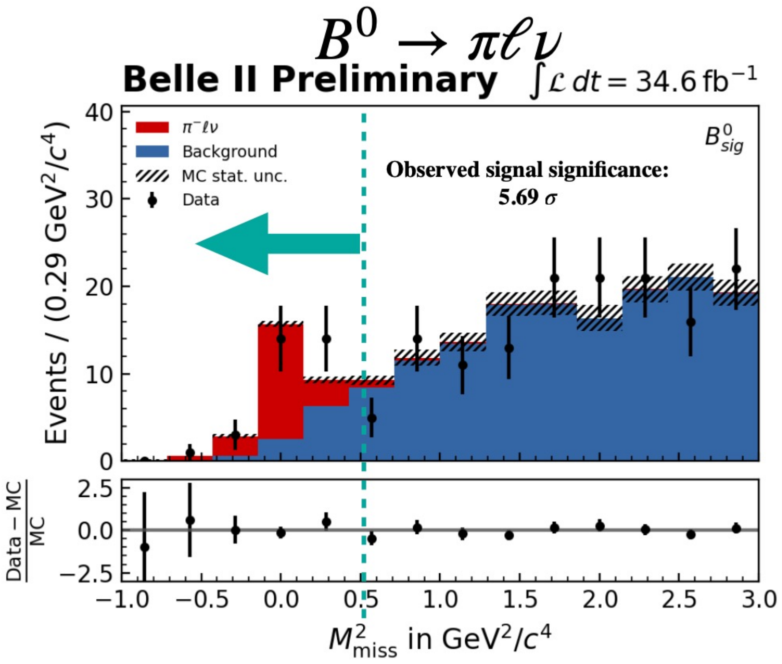
→ Future

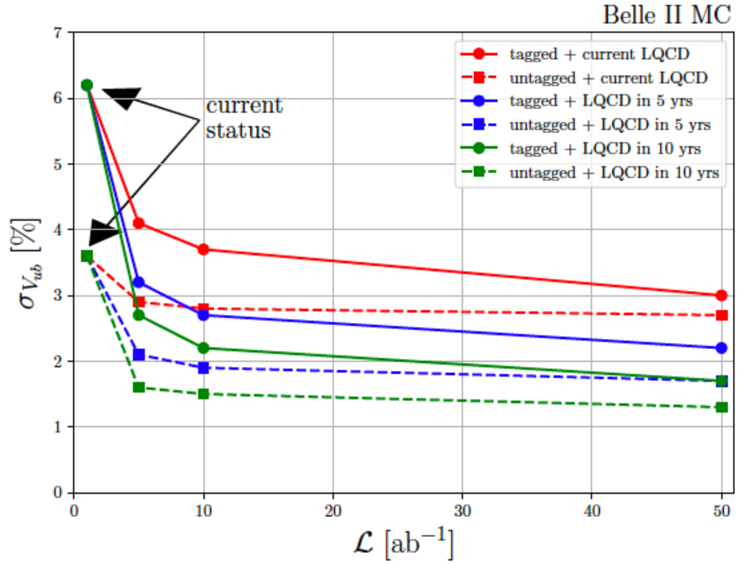


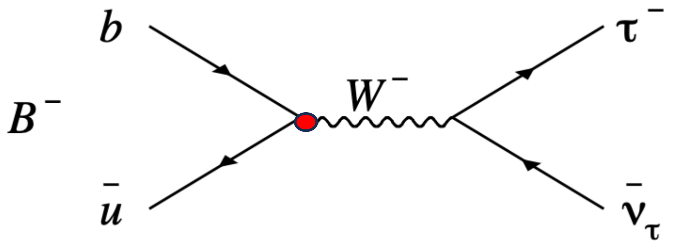
Use very effective ML techniques (Adversarial Networks or Aspiration Networks with which one can explicitly avoid to shape a variable of interest)

$|V_{ub}|$: exclusive determinations

B →$\pi\ell\nu$ differential BF





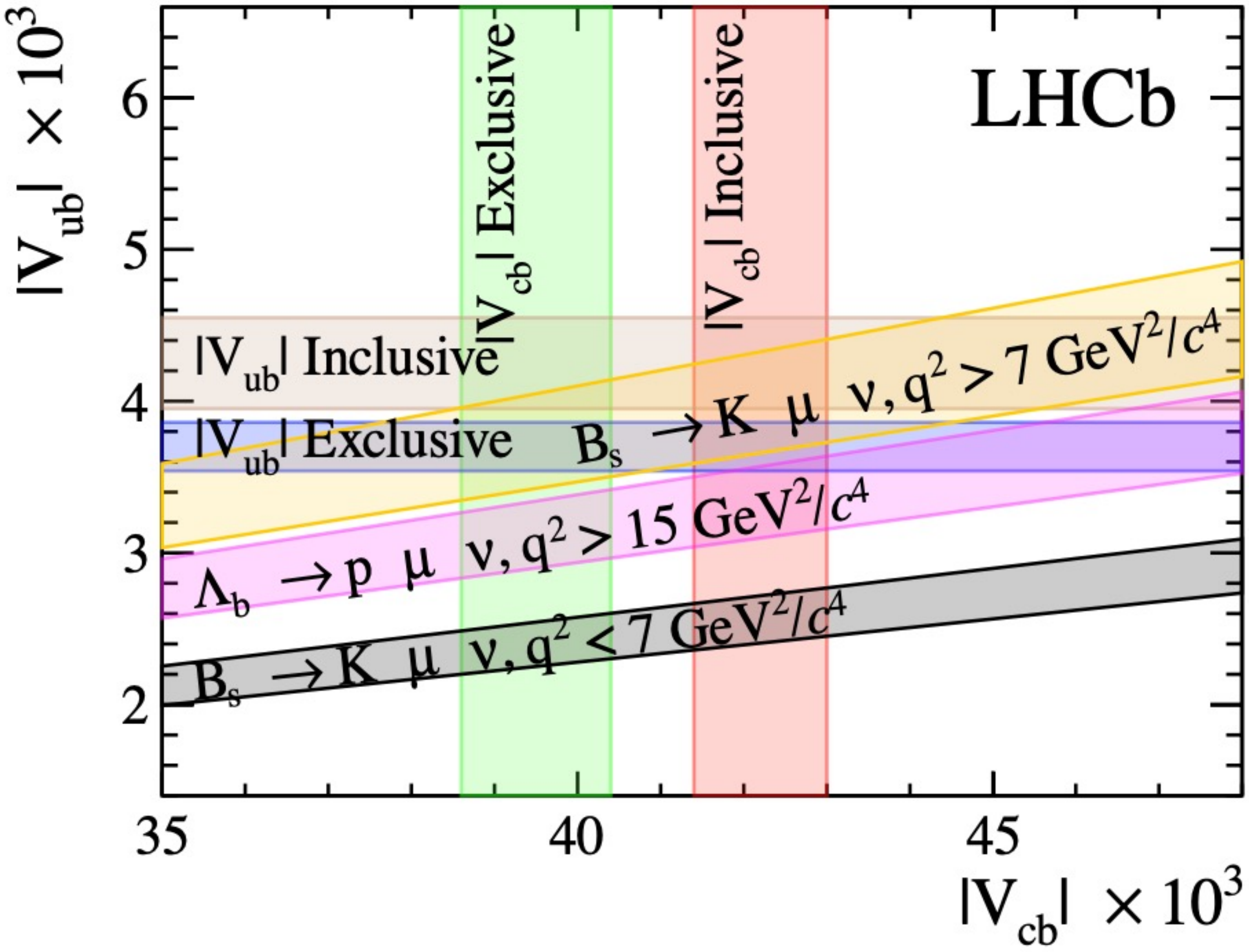


$$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2 f_B^2|V_{ub}|^2\tau_B$$

LHCb is also bringing information (but Λ_c BF knowledge is an issue)

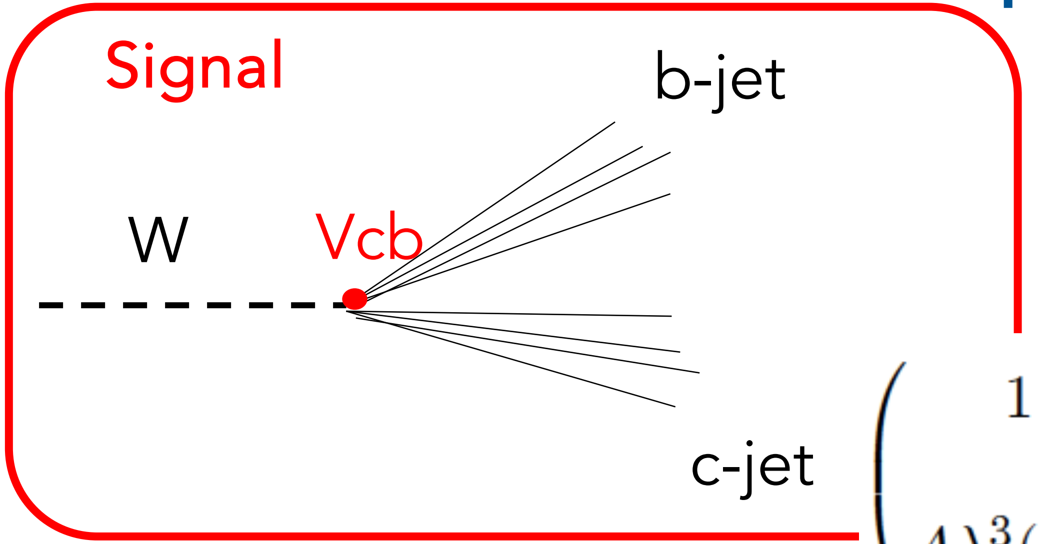
$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}}$$

$$\boxed{\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004}$$



Taken from Basem Khanji@ Implications workshop 2020

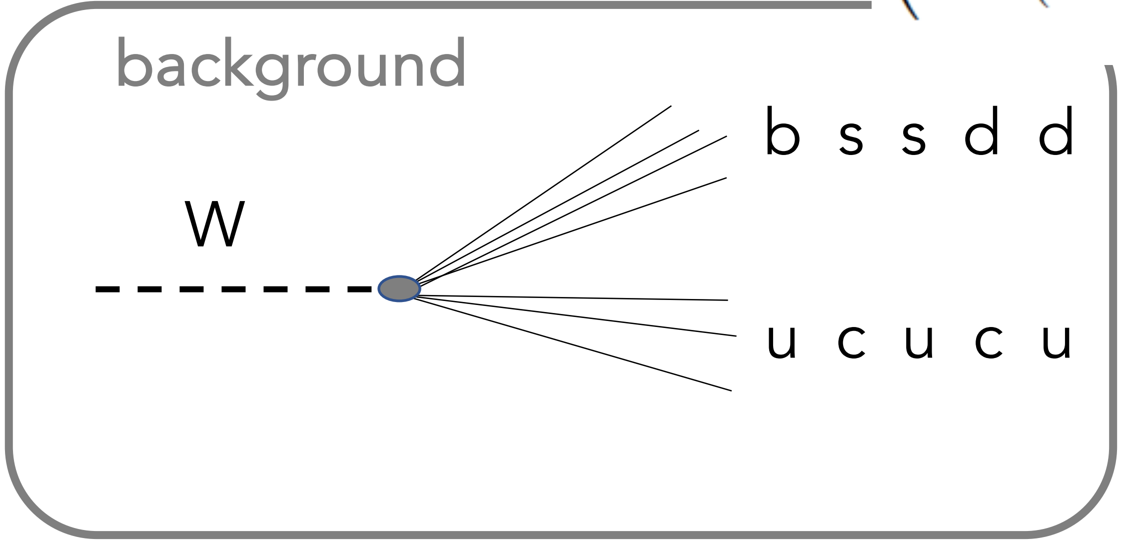
New colliders = new opportunities $|V_{cb}|$ from W decays



BR(W→ q_1 $\underline{q}_2$) = 67%

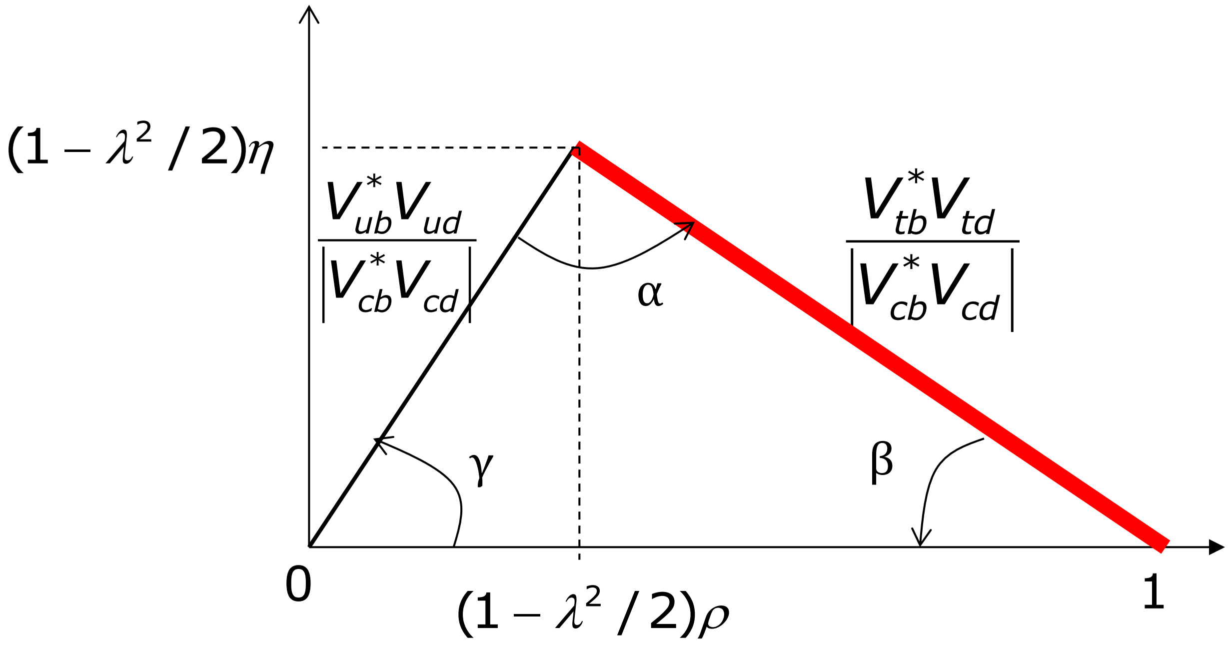
Signal 220k W→ (bc) for 10^8 WW

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



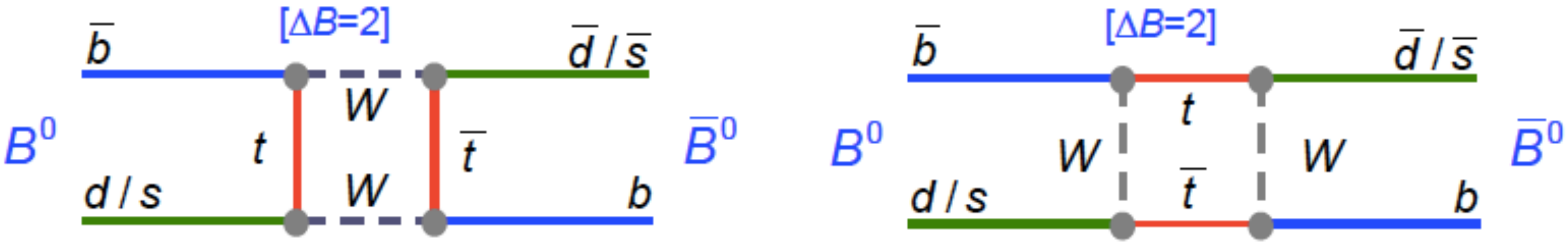
depends crucially on: b-jet, c-jet, light jet flavour tagging

V_{cb} precision down to 0.4% (or less ?!) ?


$(1-\lambda^2/2)\eta$
$\frac{V_{ub}^* V_{ud}}{|V_{cb}^* V_{cd}|}$
α
$\frac{V_{tb}^* V_{td}}{|V_{cb}^* V_{cd}|}$
γ
β
0
$(1-\lambda^2/2)\rho$
1

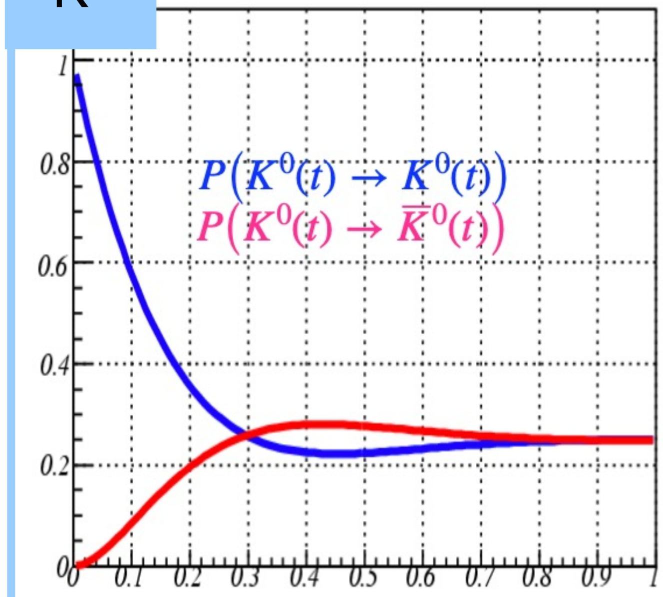
Neutral meson mixing

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

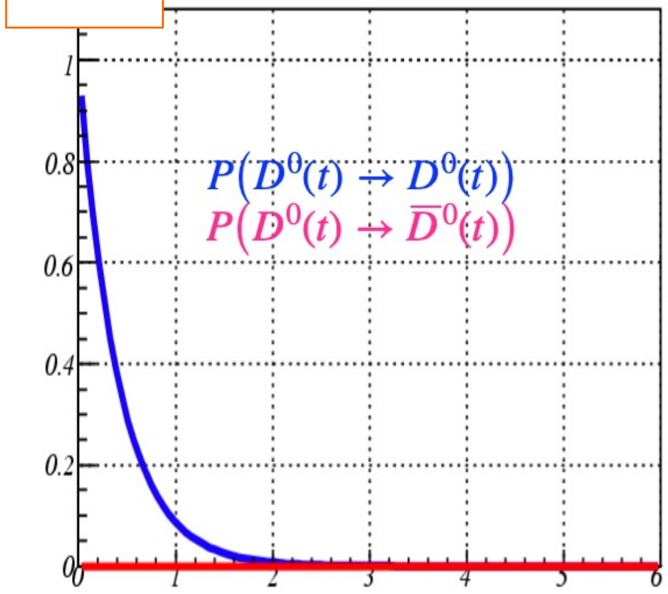


$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2 \overbrace{\eta_B}^{\text{Perturbative QCD}} \underbrace{S(x_t)}_{\substack{\text{Loop integral}\\ \text{(top loop dominates)}}} \underbrace{f_{B_q}^2 B_q}_{\substack{\text{Non-perturbative QCD :}\\ \text{dominant theoretical}\\ \text{uncertainty}}} \overbrace{\left|V_{tq}V_{tb}^*\right|^2}^{\text{CKM Matrix Elements}} \quad (\text{for } q = d, s)$$

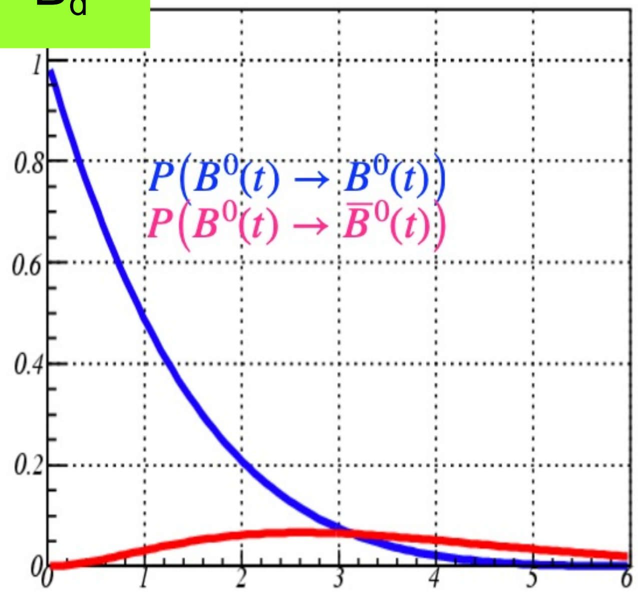
K^0



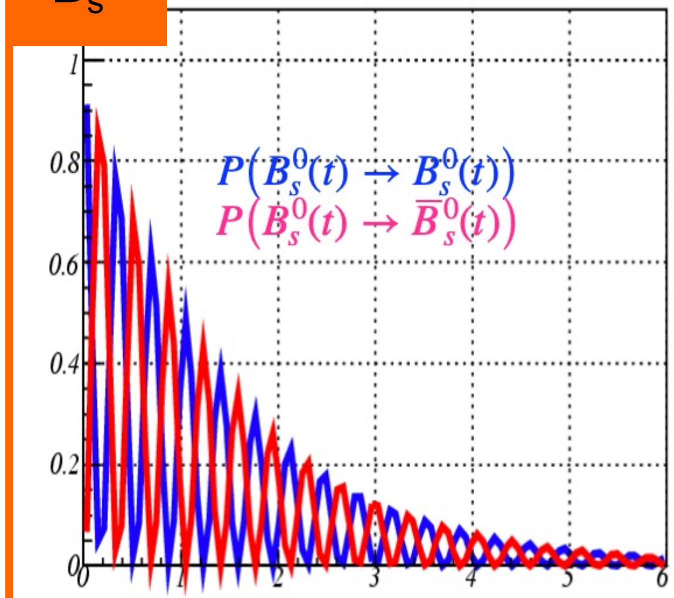
D^0



B_d^0



B_s^0



	$x=\Delta m/\Gamma$	$y=\Delta\Gamma/2\Gamma$
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

Measurement of the oscillation frequency of the B_s meson in a nutshell

- Select a flavour specific final state : $B_s^0 \rightarrow D_s^- \pi^+ \quad \overline{B_s^0} \rightarrow D_s^+ \pi^-$
- Tag the flavour at production time (will come back to it later)
- Measure the time:

$$t = ml/p$$

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

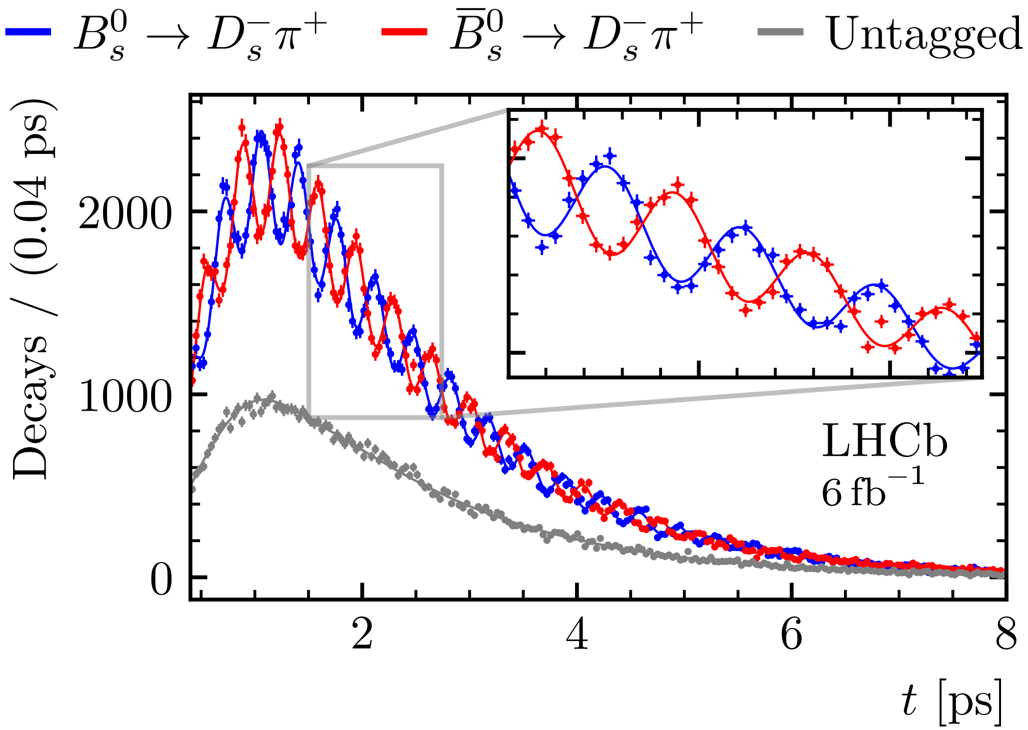
~50 fs resolution

LHCb Δm_s measurement

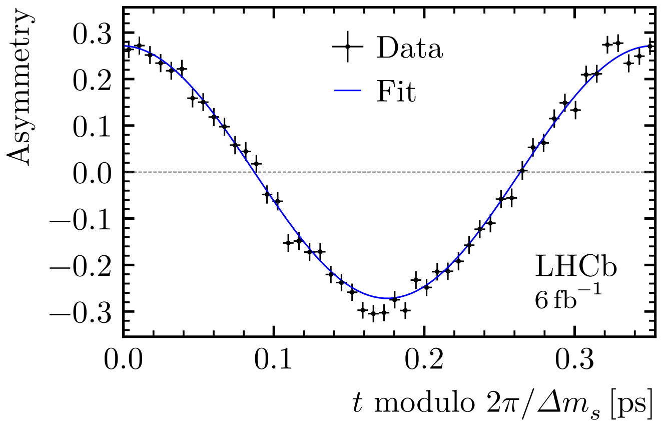
$B_s \rightarrow D_s\, \pi$

different flavour at decay and production

same flavour at decay and production



LHCb-PAPER-2021-005



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

3 10^{-4} precision

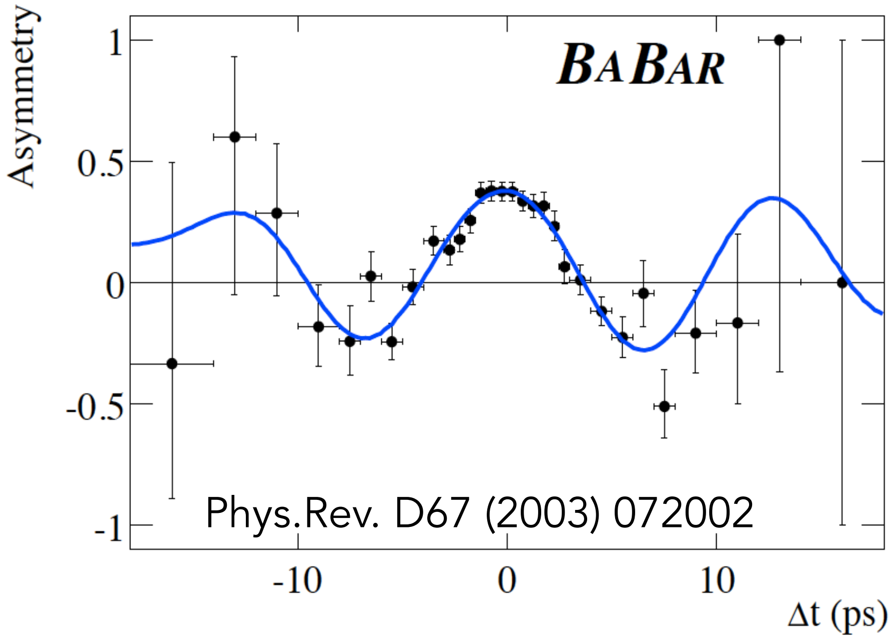
tagging power ~ 6%

(factor 2 improvement wrt first publication (New J. Phys. 15 (2013) 053021))

Δm_d is also measured (even before)

Extra slide

(by many experiments)   HFLAV

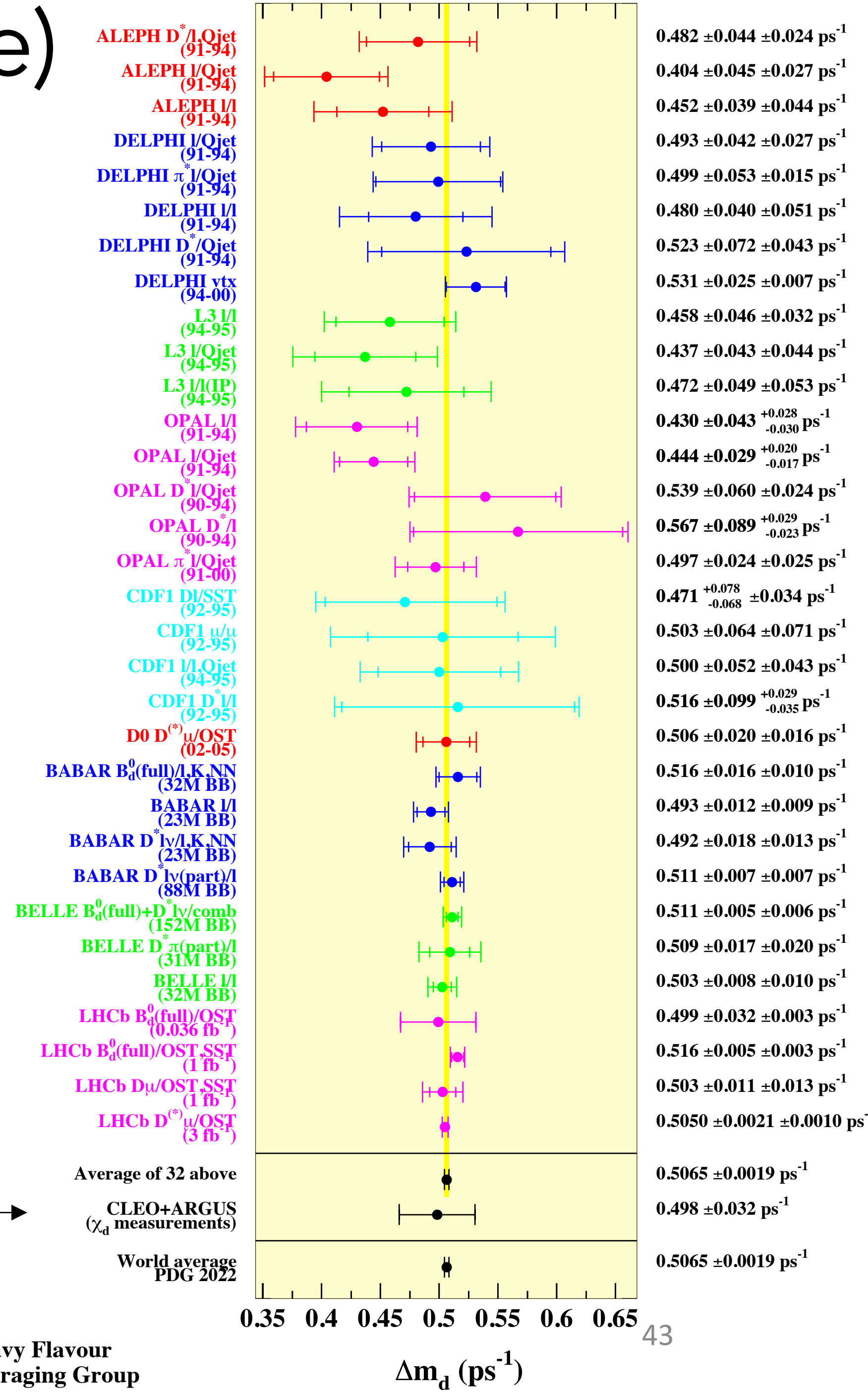


Phys.Rev. D67 (2003) 072002

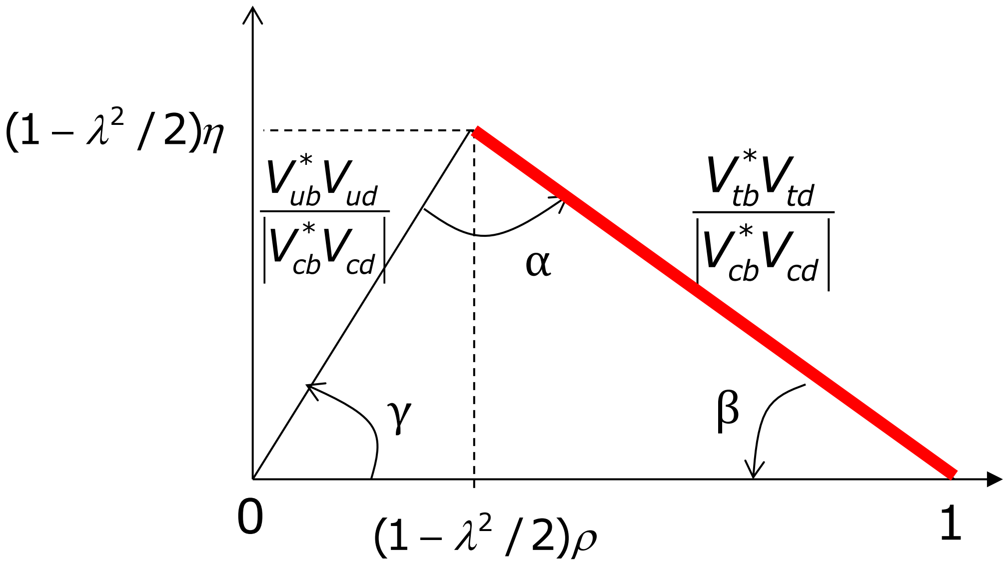
Δm_d=0.5065 ± 0.0019 ps^{-1}

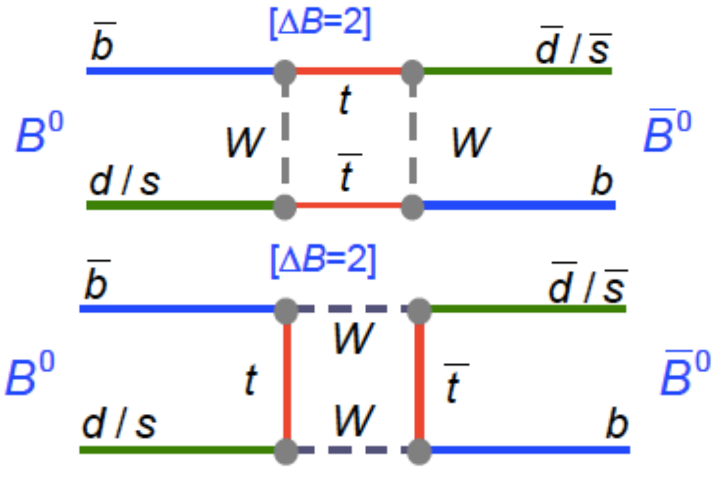
Precision : 3.8 10^{-3}

time integrated measurements →



Impact on the unitarity triangle determination



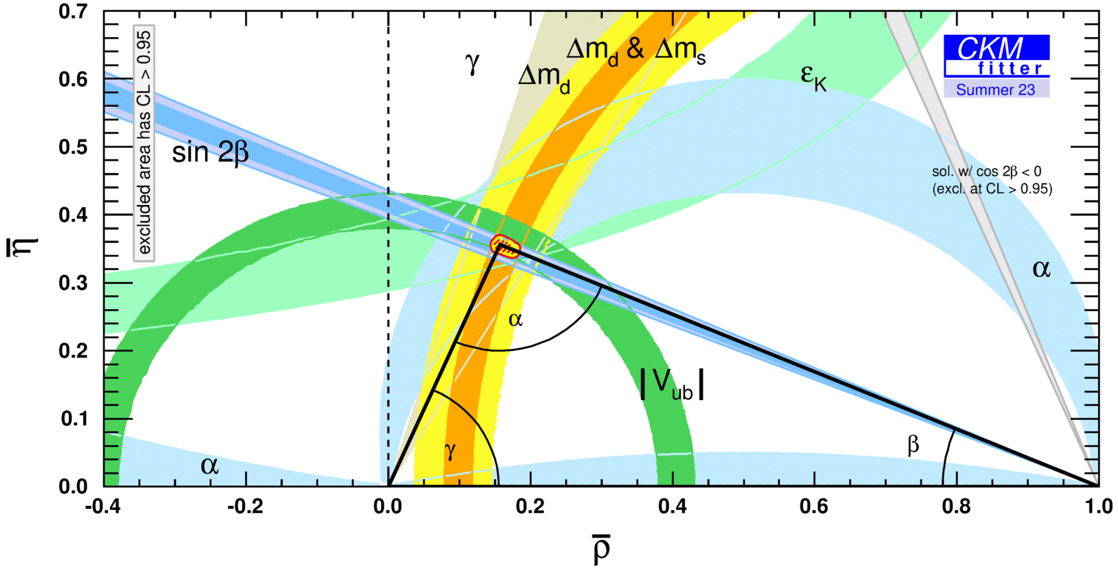


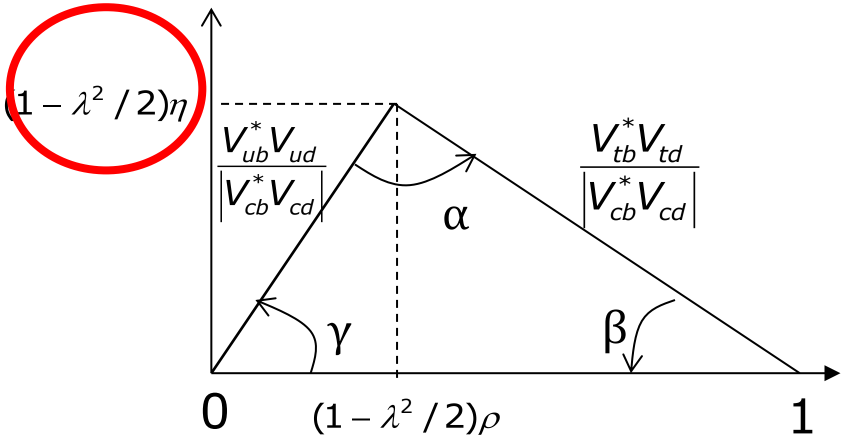
$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} m_W^2 \;\; \eta_B \;\; S(x_t) \;\; f_{B_d}^2 B_d \;\; \left|V_{td}V_{tb}^*\right|^2$$

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

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

smaller theoretical uncertainty



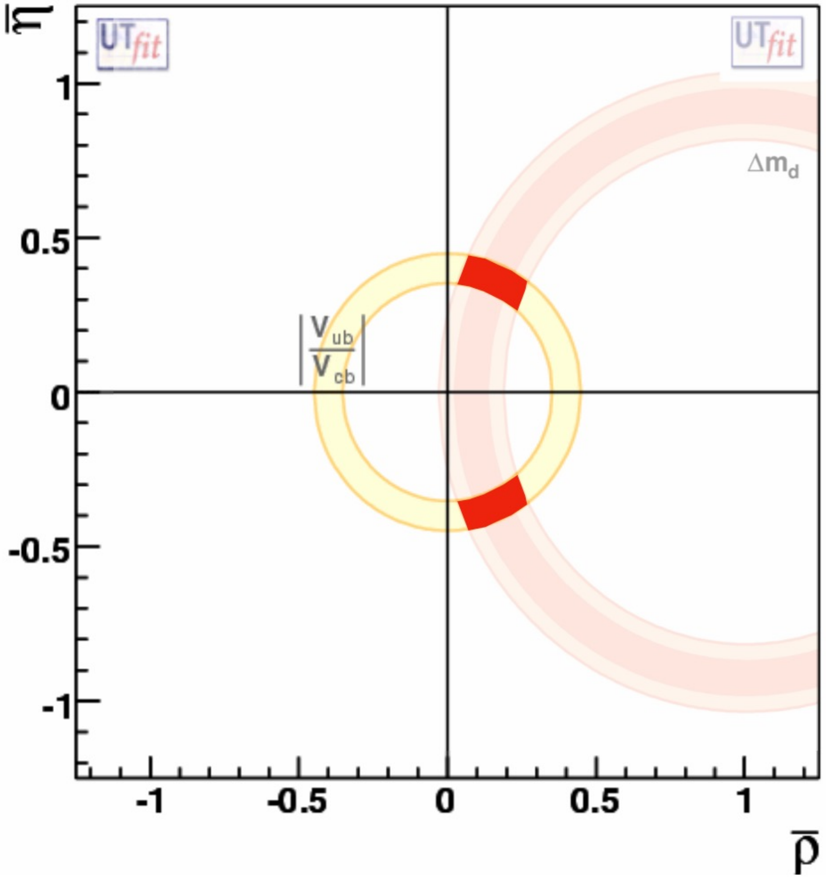


$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Measurements not involving CP violation:

- $|V_{ub}/V_{cb}|$
- B_d and B_s mixing

$\eta \neq 0$



We would know that CP is violated even if we would not have directly observed it