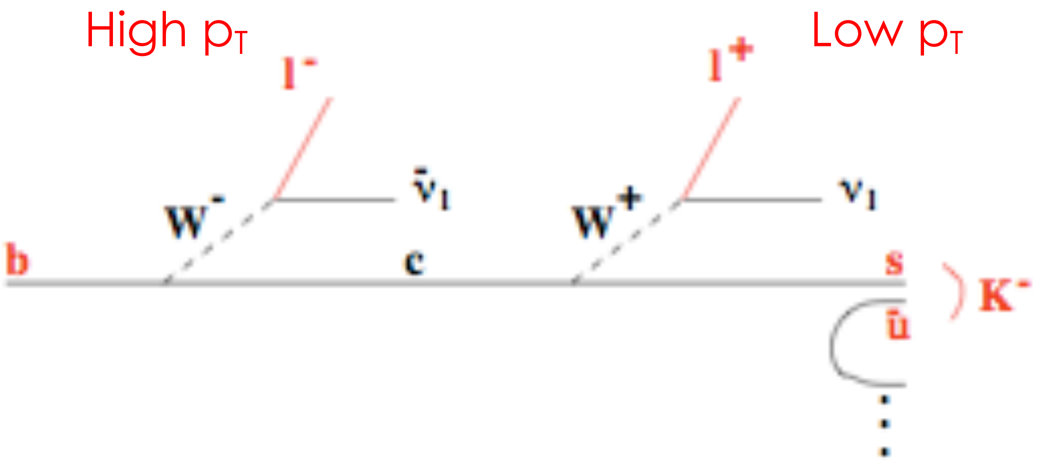
B flavour tagging : comparing B-factories and LHCb

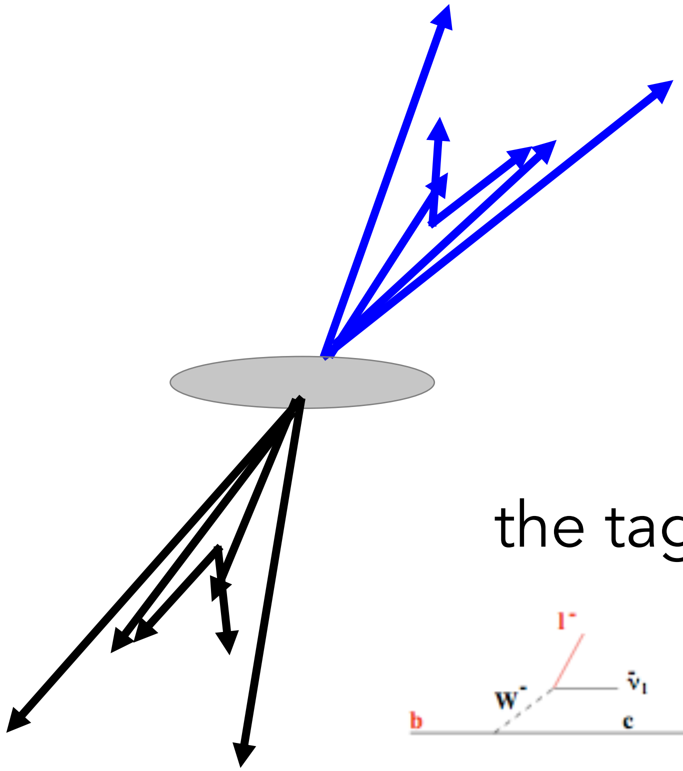
Tagging : determination of the flavour of the B (B or $\overline{B}$) at the production time



The charge of the lepton or of the K gives information on the b :

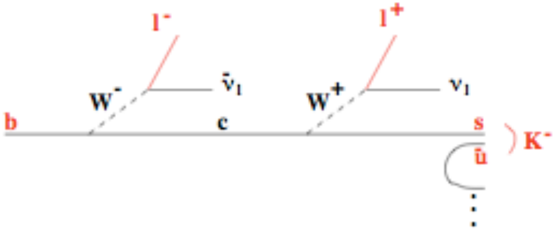
a high p_T ℓ^- or a K^- probably come from a $\overline{b}$ quark (and thus a B meson)

a high p_T ℓ^+ or a K+ probably come from a b quark (and thus a $\overline{B}$ meson)

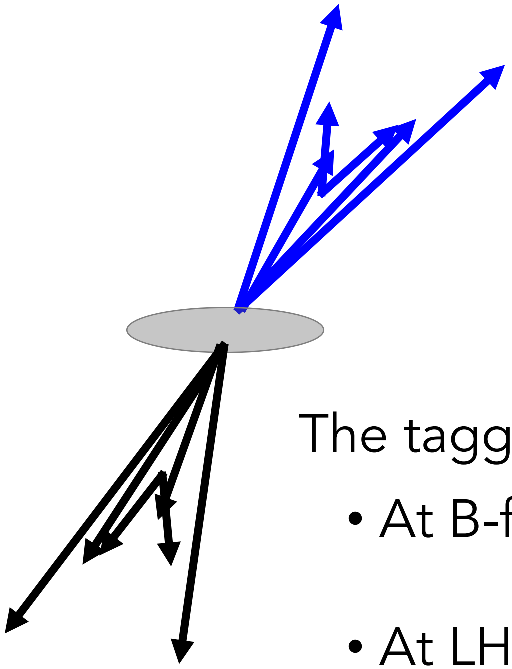


the fully reconstructed B meson
(*eg* $D^{*+}\pi$, $J/\boldsymbol{\Psi}$ Ks ....)

the tagging B



This is opposite side tagging.
It can be performed both at B-factories and LHC, but fundamental differences due to the production mechanism

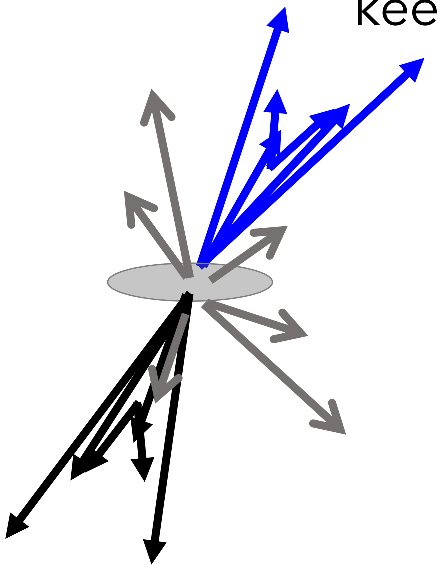


The B meson fully reconstructed
(*eg* $D^{*+}\pi$, J/Ψ Ks ….)

The tagging B

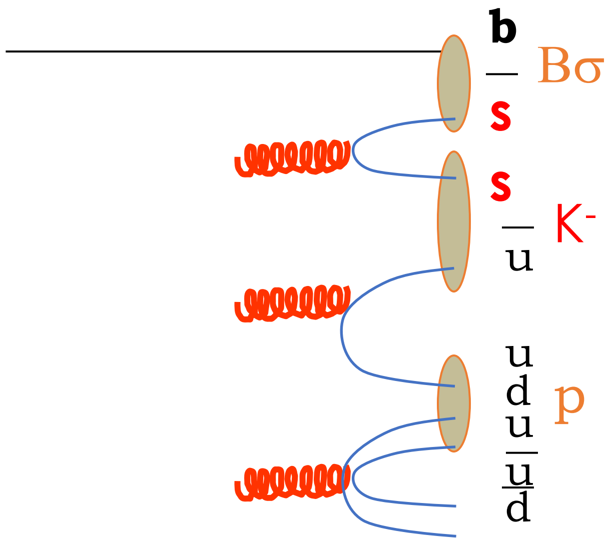
- At B-factories : coherent $B^0 \overline{B^0}$ production

- At LHC if a $\overline{B^0}$ is produced, at the same time one can have
at the same time a B_s, a B+ , a Λ_b ….
The B_s oscillates many time before decaying and does not
keep track of its flavour at the production time : information is lost



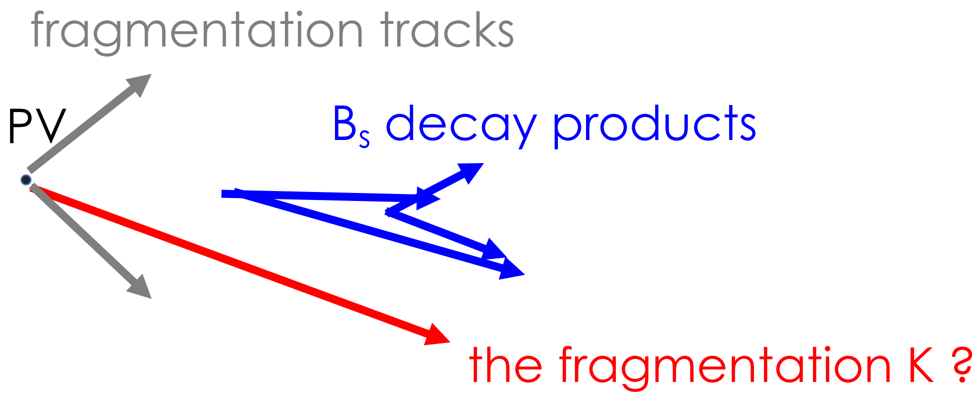
In addition at LHC they are all the fragmentation tracks and the tracks from the other interaction(s)

The fragmentation tracks can however helps the tagging : Same Side Tagging



Search for a track attached to the primary vertex (not to the B decay vertex), close to the B and not too slow

cannot be done at B-factories !



Tagging performances :

$$Q = \varepsilon(1-2\omega)^2 = \varepsilon D^2$$

tagging efficiency ε

mistag probability w ('wrong')

QxN : equivalent number of events perfectly tagged

B-Factories typical performance

Q ~ 30%

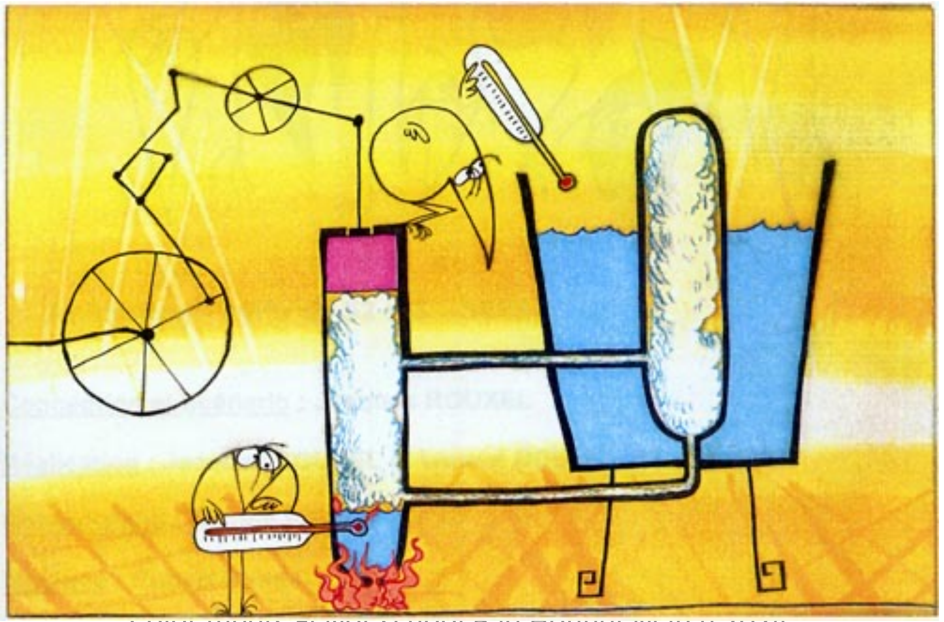
Hadron colliders

Q ~ 2% (Tevatron)

LHCb reaches 6%

1000 events reconstructed are equivalent to
- 300 perfectly tagged at B-Factories
- 60 perfectly tagged at LHCb

CP violation: measuring the angles of the unitarity triangle



Three types of CP violation

$$A : B \rightarrow f$$

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

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

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

CP violation in decay (« direct CP») :

$$B \xrightarrow{A} f$$

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

Only one existing for charged B

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

CP violation in mixing :

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

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

Not yet observed for B mesons.

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

CP violation in the interference between mixing and decay :

$$B^0 \rightarrow f$$

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

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

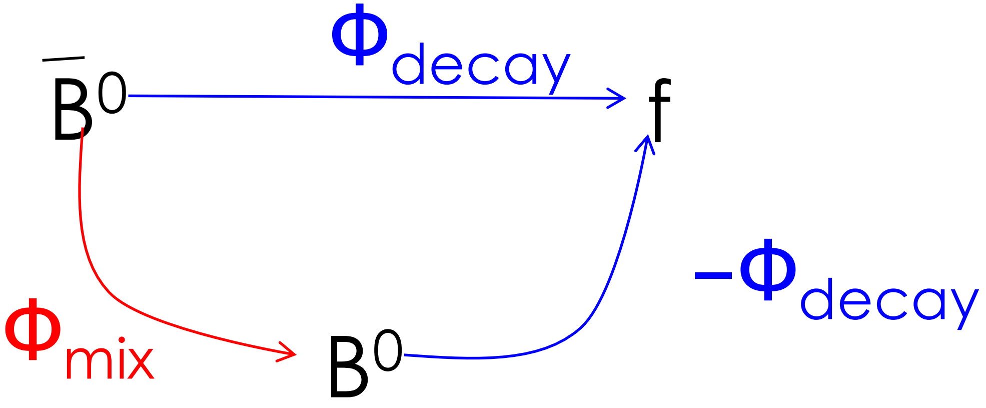
$$\bar{B}^0 \rightarrow B^0 \rightarrow f$$

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

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

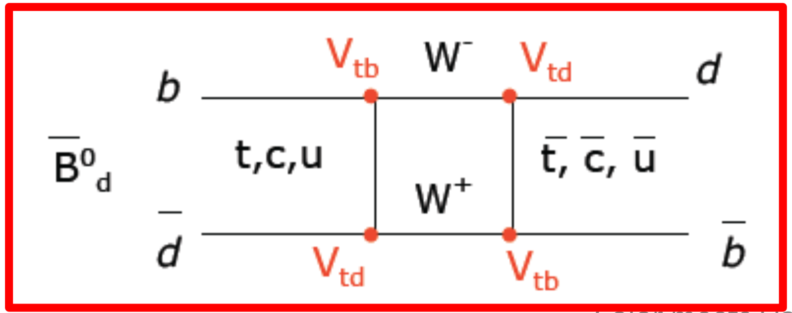
Discovery of CP violation in the B system : measurement of the β angle

CP violation in the interference between mixing and decay

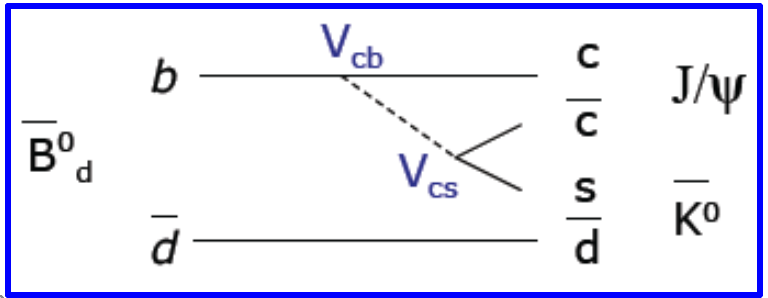


$$\Phi_d = \Phi_{mix} - 2\ \Phi_{decay}$$

Mixing



Decay



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

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

$B_d \Rightarrow \Delta\Gamma = 0$

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

direct CPV

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

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

CPV in the interference between mixing and decay

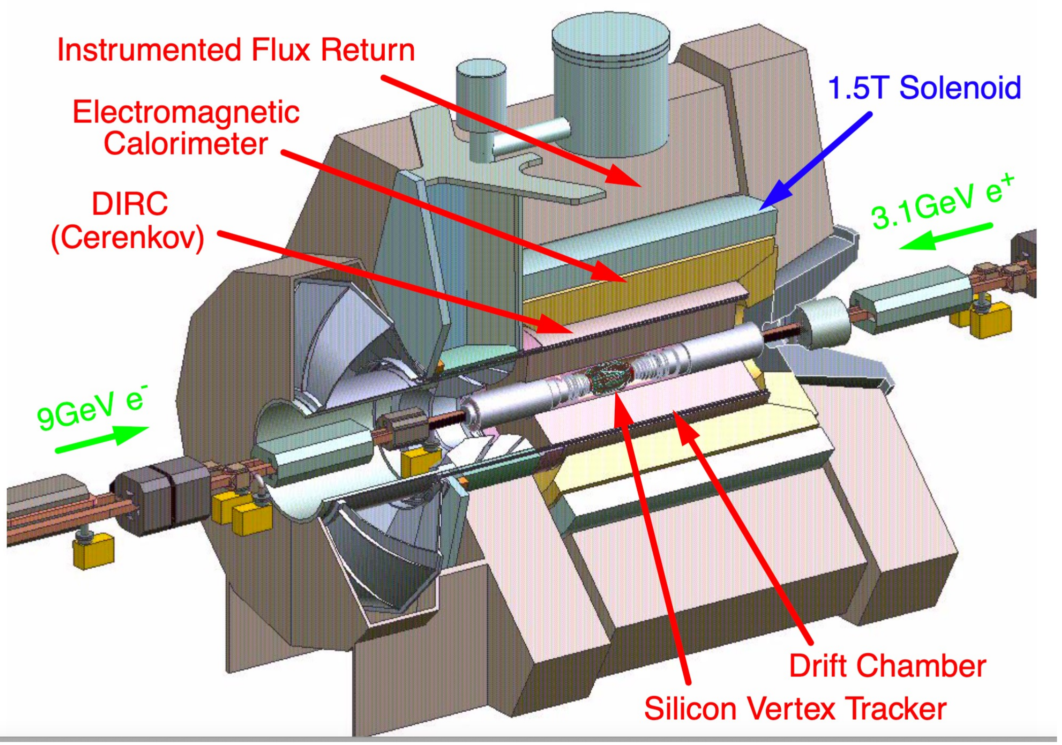
$B \to J/\psi\ K_s \quad \mathrm{Im}\,\lambda_{J/\psi K_S} = \sin 2\beta$

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

theoretically clean

Why are B-Factories detectors slightly asymmetric ?

BABAR Detector



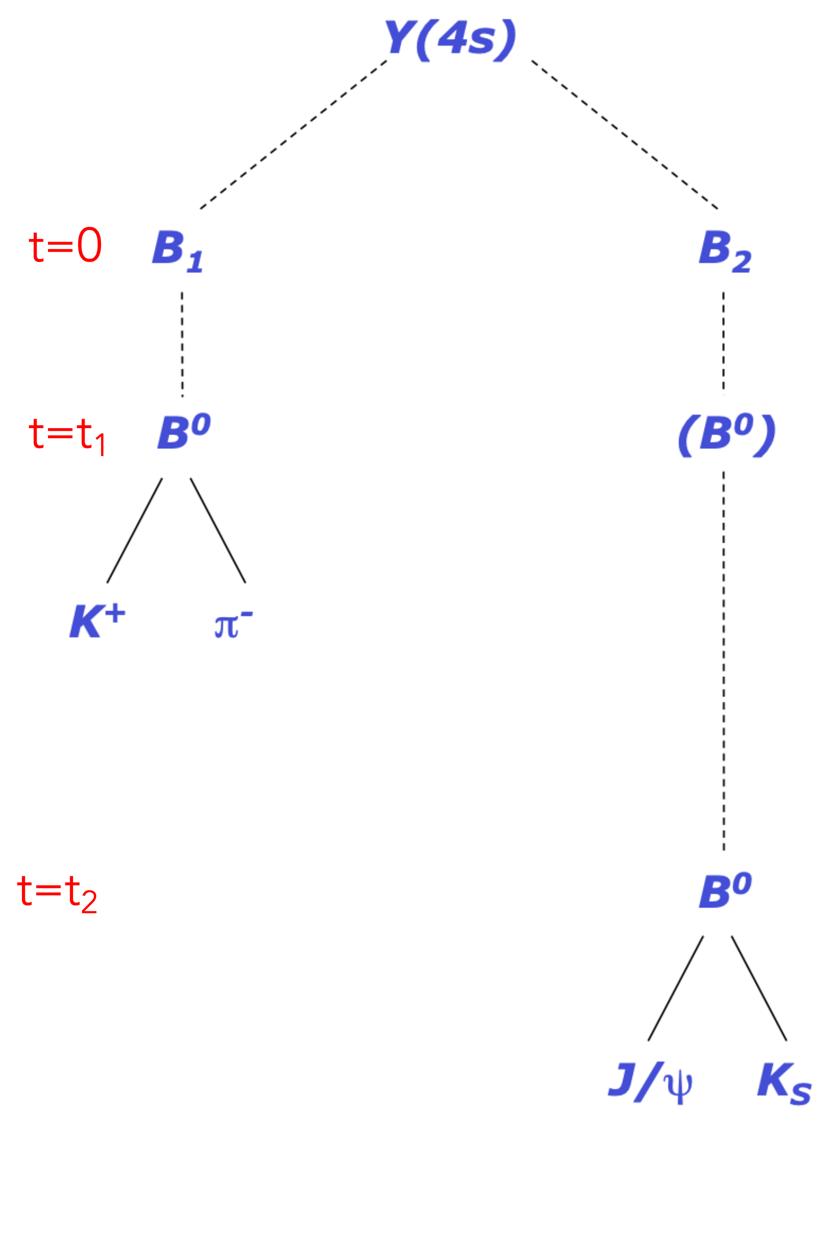
Time evolution of an Y(4S) decay

t=0 Y(4S) → B $\bar{B}$

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

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

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

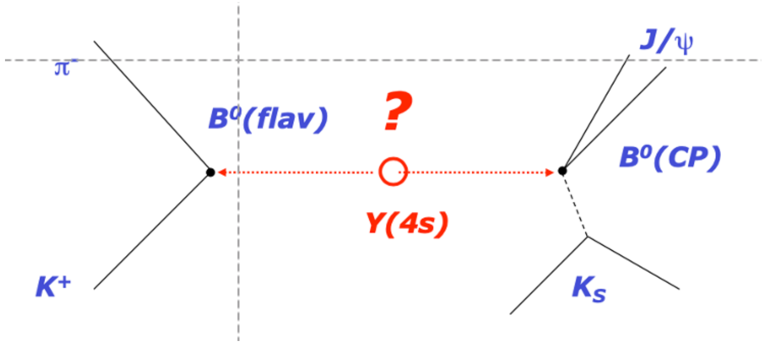


$t_2 > t_1$ or $t_2 < t_1$

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

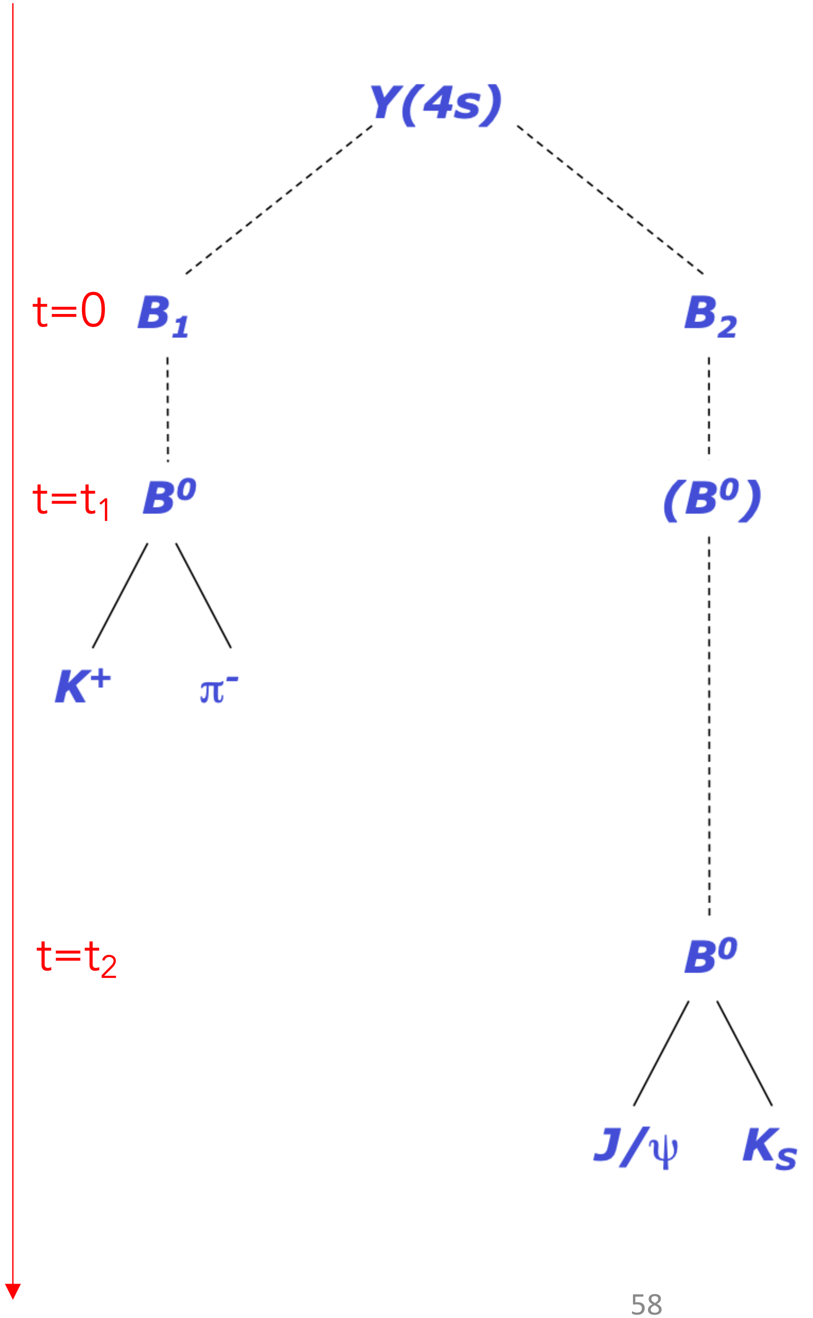
how to measure t_1 and t_2 ?

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



M(ϒ(4S) = 10.58 GeV

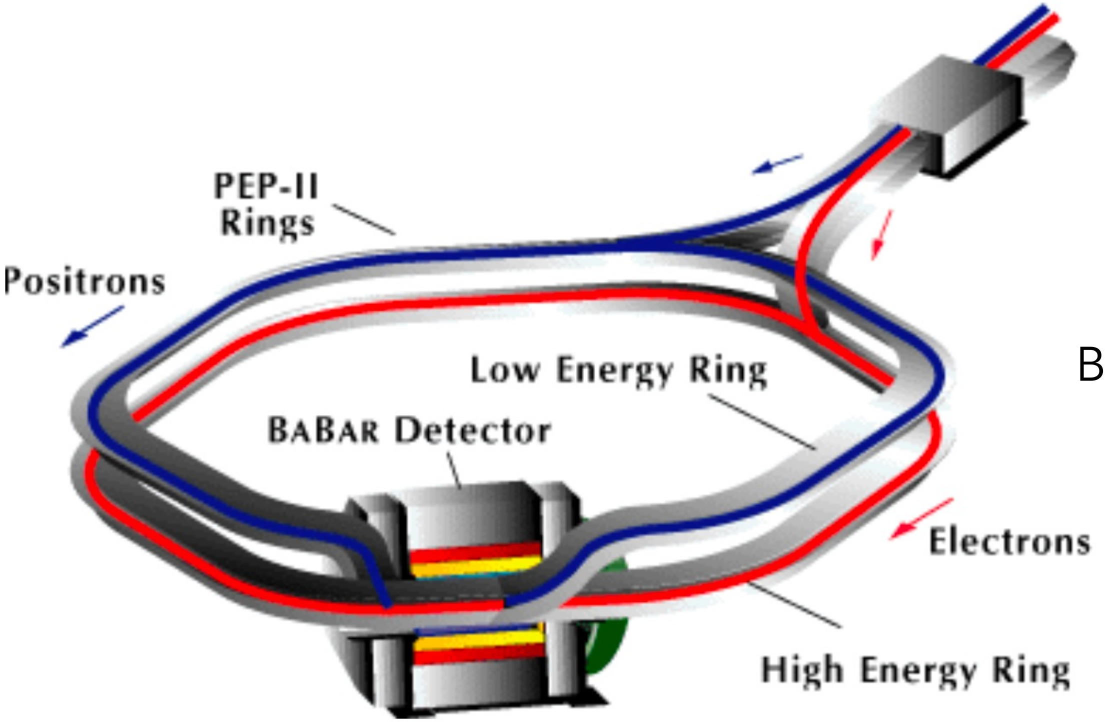
⇒ (B^+, B^0) are produced nearly at rest in the ϒ(4S) center of mass (p* ~ 340 MeV), ~ 30 μm between B_1 and B_2 decay vertices



Pier Oddone (LBL)

Make the Υ(4S) flies !

B Factory	e^- beam energy E_- (GeV)	e^+ beam energy E_+ (GeV)	Lorentz factor $\beta\gamma$	2 B separation
PEP-II	9.0	3.1	0.56	~ 250 μm
KEKB	8.0	3.5	0.425	~ 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 ?

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

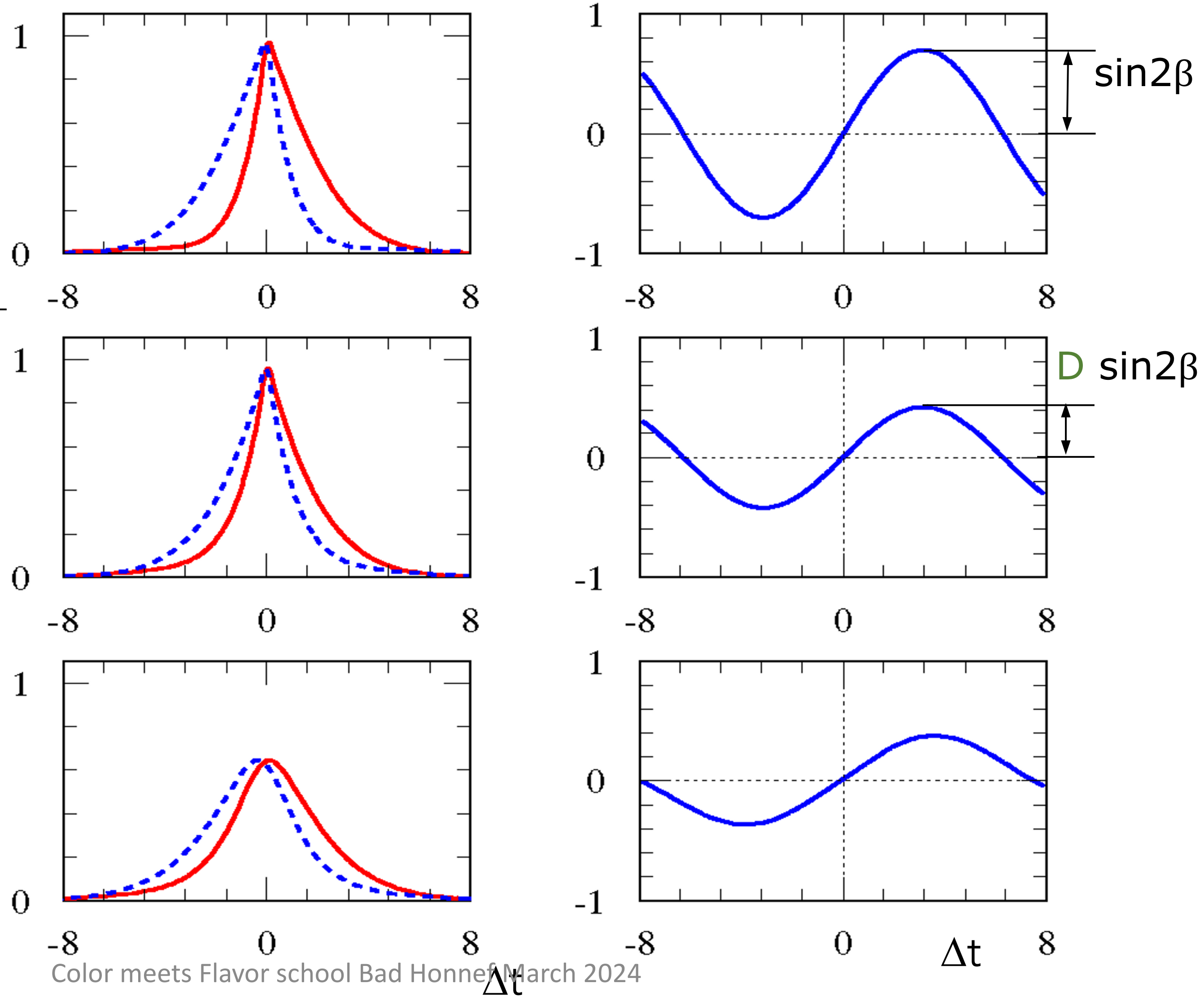
$F(\Delta t)$ $\overline{F}(\Delta t)$ $A_{cp}(\Delta t)$

B^0 or $\overline{B}^0$ produced ?

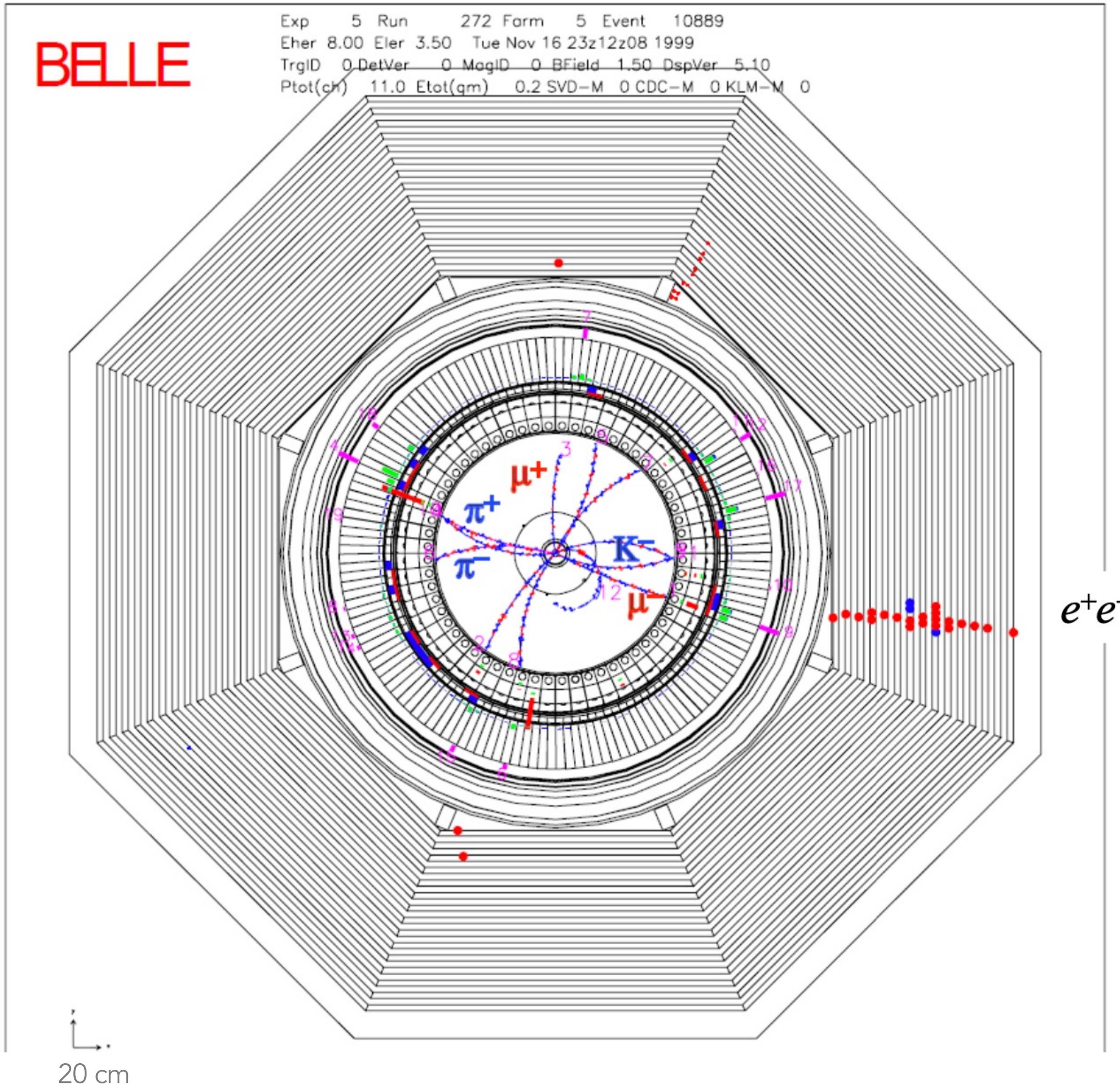
Everything perfect

Add tag mistakes
Dilution: D=1-2w

Add imperfect
Δt resolution



Early tagged $B \to J/\psi K_S$ event (Nov 1999)



$e^+e^- \to BB$

$\to K^- X$

$\to J/\psi K_S$

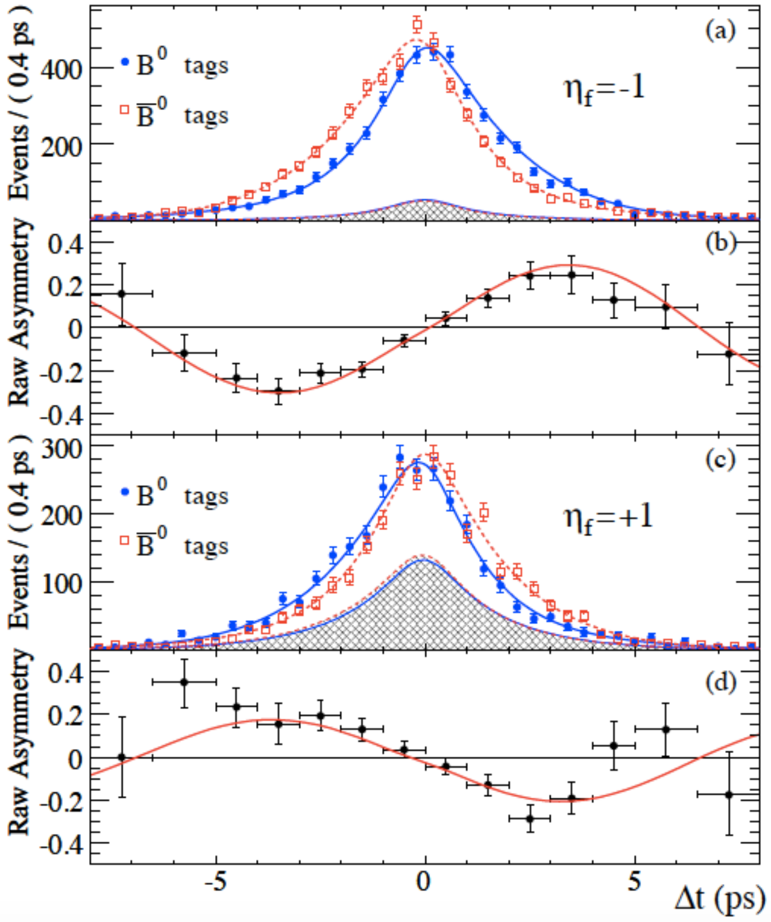
$\to \pi^+\pi^-$

$\to \mu^+\mu^-$

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

B-factories

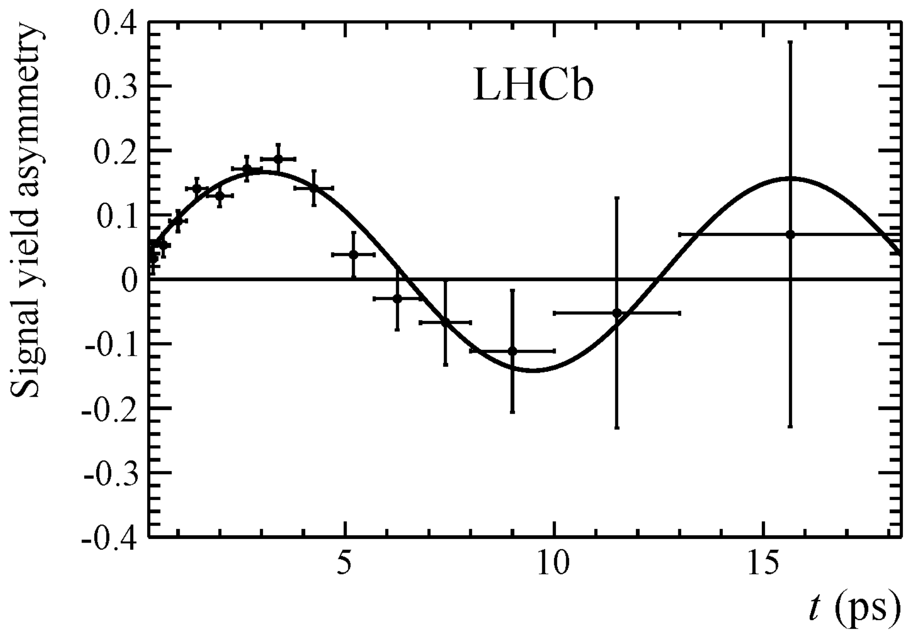
Δt



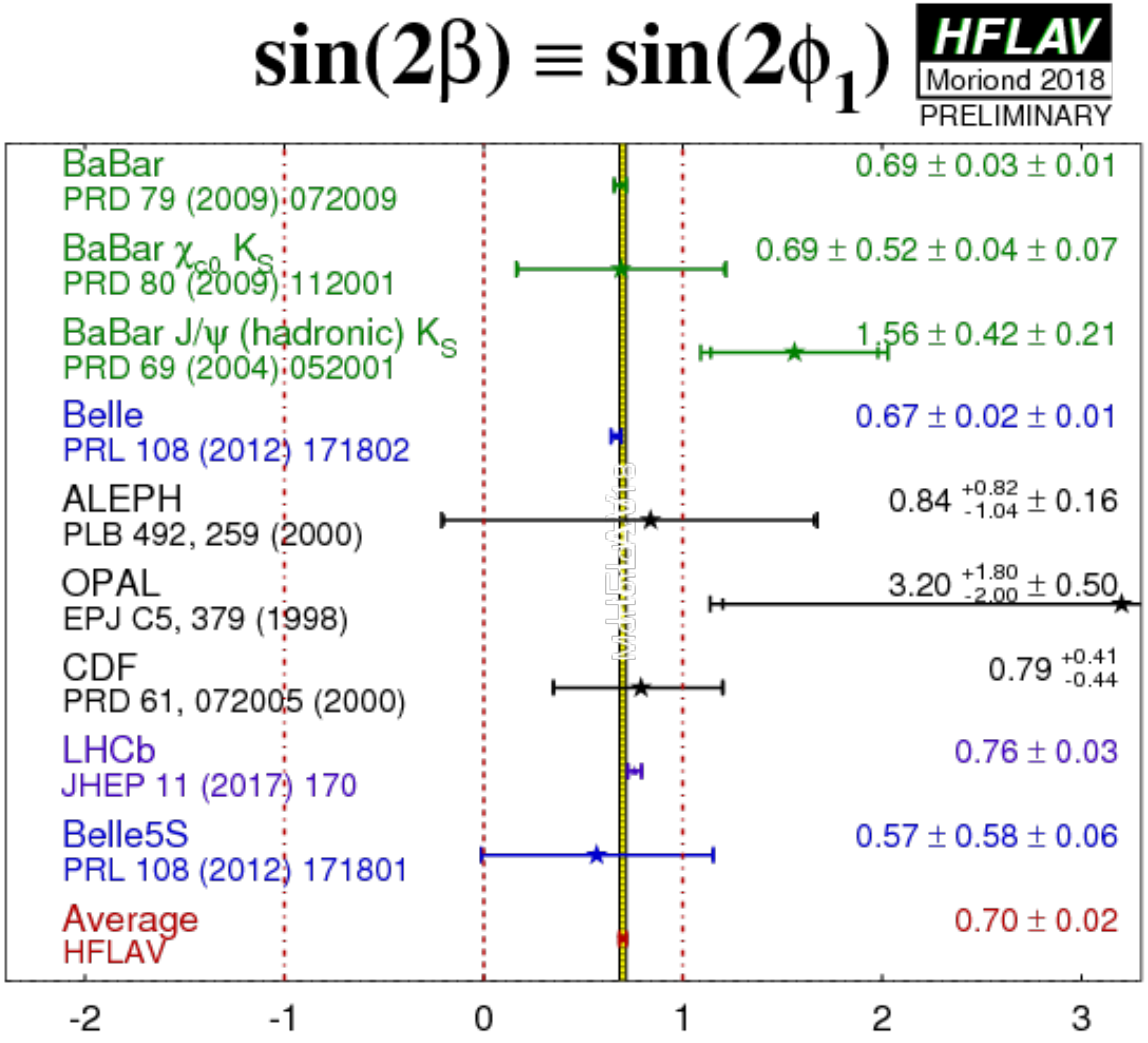
sin2β = 0.687 ±0.028 ±0.012

BaBar Phys.Rev.D79:072009,2009

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

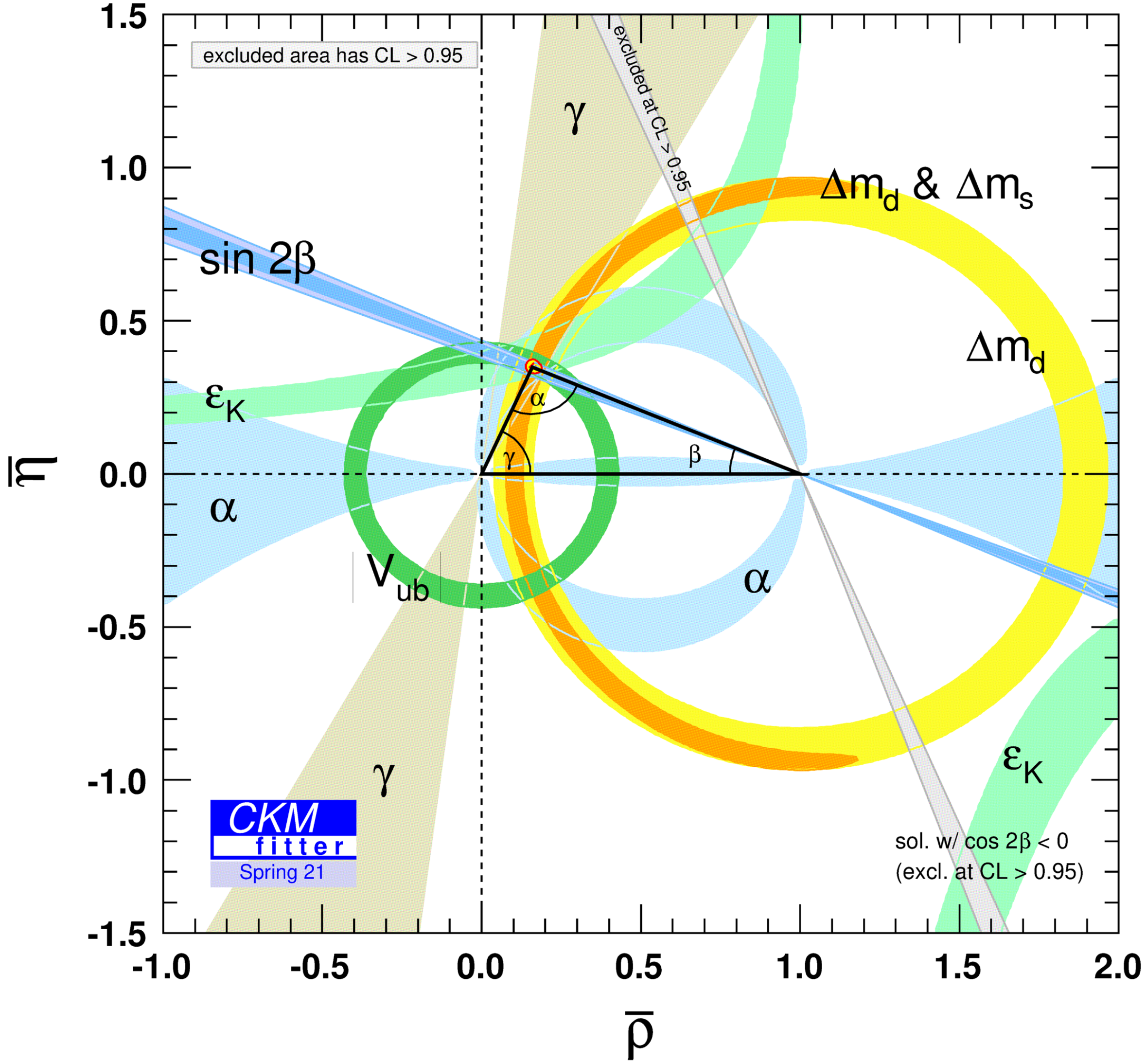


t



sin(2β) ≡ sin(2φ1)
HFLAV
Moriond 2018
PRELIMINARY
BaBar
PRD 79 (2009) 072009
0.69 ± 0.03 ± 0.01
BaBar χc0 KS
PRD 80 (2009) 112001
0.69 ± 0.52 ± 0.04 ± 0.07
BaBar J/ψ (hadronic) KS
PRD 69 (2004) 052001
1.56 ± 0.42 ± 0.21
Belle
PRL 108 (2012) 171802
0.67 ± 0.02 ± 0.01
ALEPH
PLB 492, 259 (2000)
0.84 +0.82 -1.04 ± 0.16
OPAL
EPJ C5, 379 (1998)
3.20 +1.80 -2.00 ± 0.50
CDF
PRD 61, 072005 (2000)
0.79 +0.41 -0.44
LHCb
JHEP 11 (2017) 170
0.76 ± 0.03
Belle5S
PRL 108 (2012) 171801
0.57 ± 0.58 ± 0.06
Average
HFLAV
0.70 ± 0.02
-2
-1
0
1
2
3

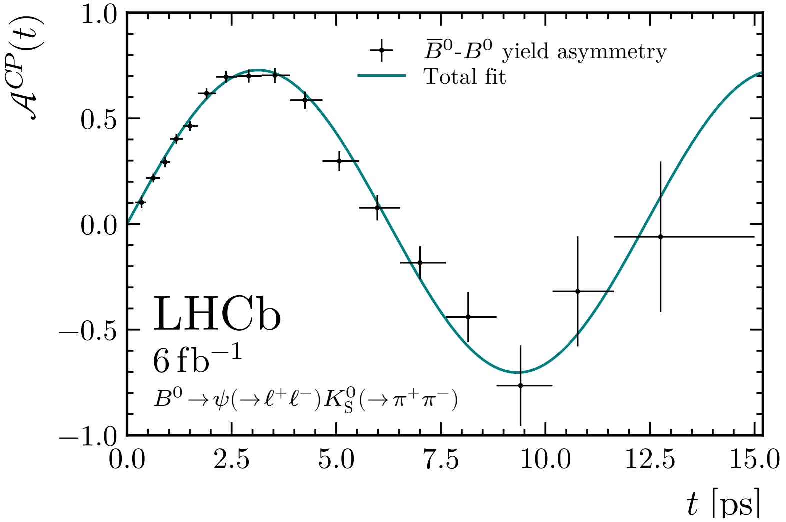
3 % precision !

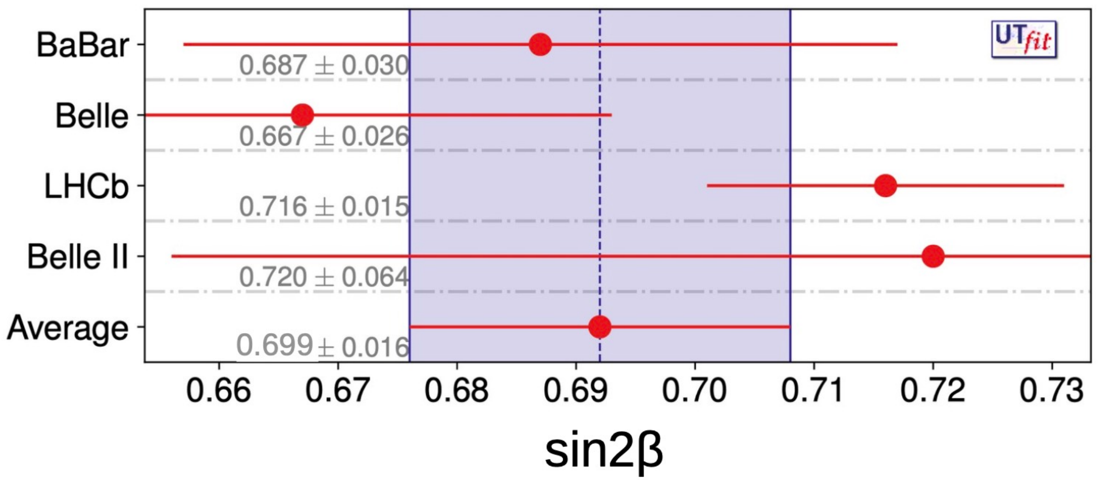


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δmd & Δms
sin 2β
Δmd
εK
α
Vub
CKM fitter
Spring 21
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

We are now entering into a new precision era

LHCb-PAPER-2023-013

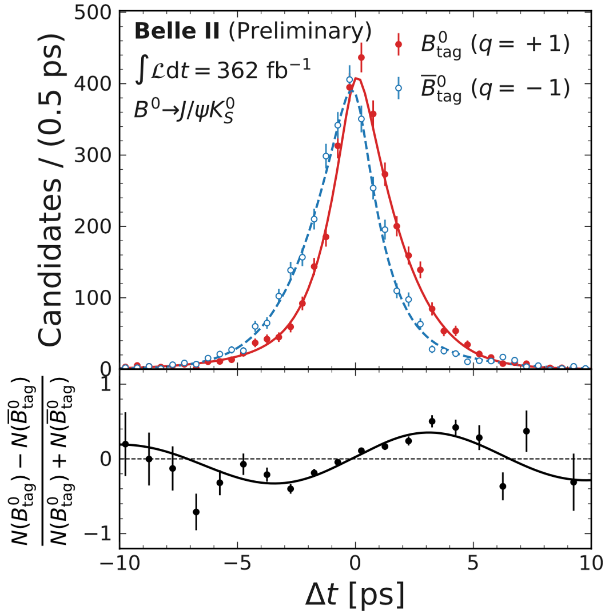




$$S_{\psi K^0_S} = 0.717 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$

2.1% precision

2402.17260

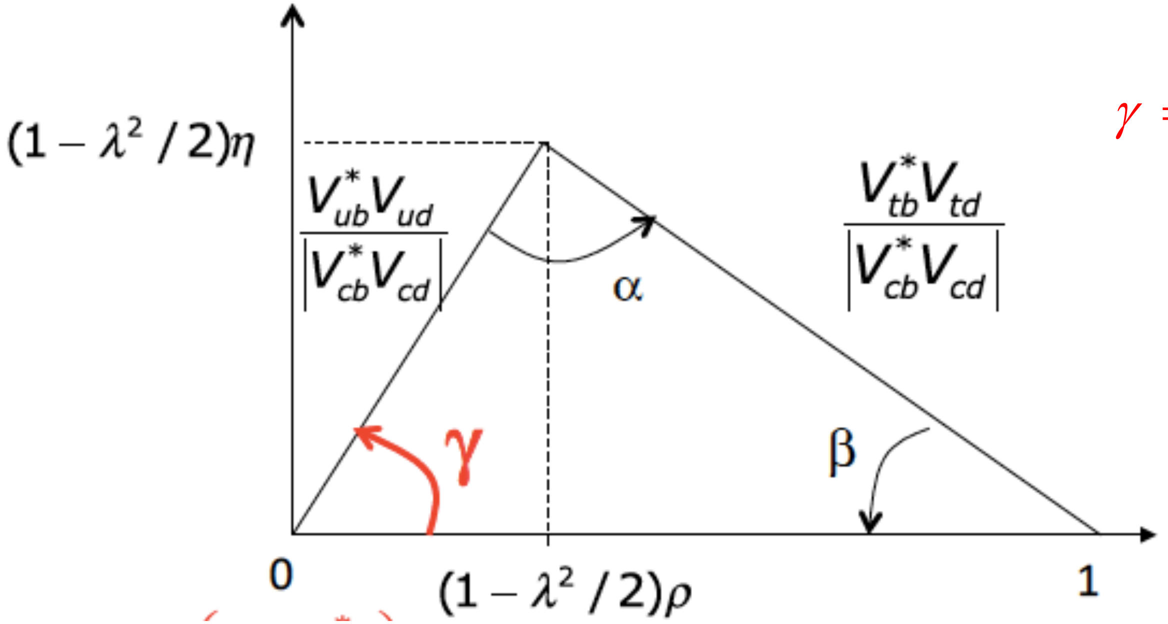


$$\varepsilon_{\text{tag}} = (37.40 \pm 0.43 \pm 0.36)\%$$

$$S = \quad 0.724 \pm 0.035 \pm 0.014,$$

5.2% precision

Measurement of the γ angle: direct CP violation

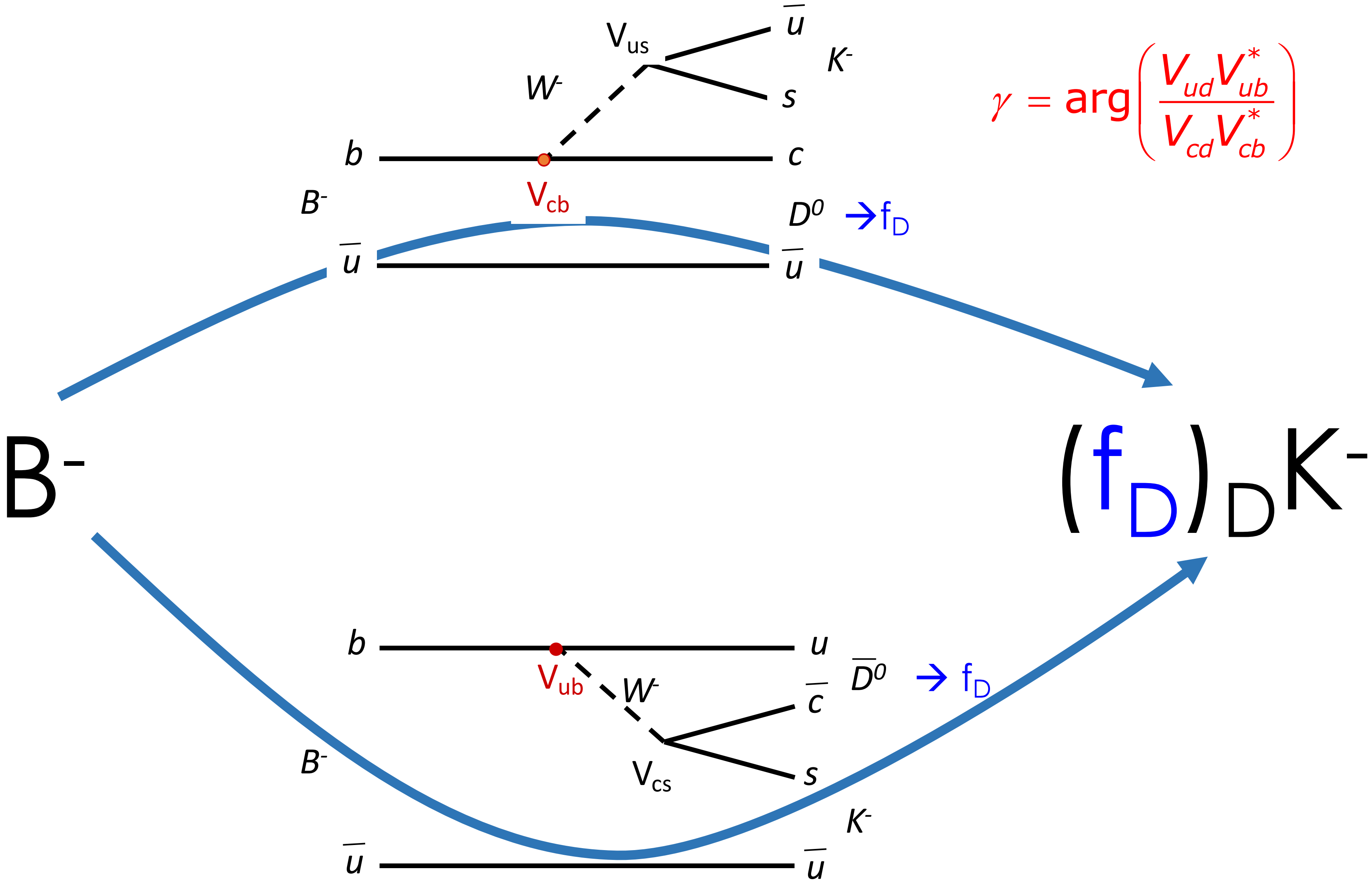


$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Value precisely predicted in the SM context from other triangle parameters

$\Rightarrow$ 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 $K\pi$, $K_s\,\pi\pi$, …

- 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

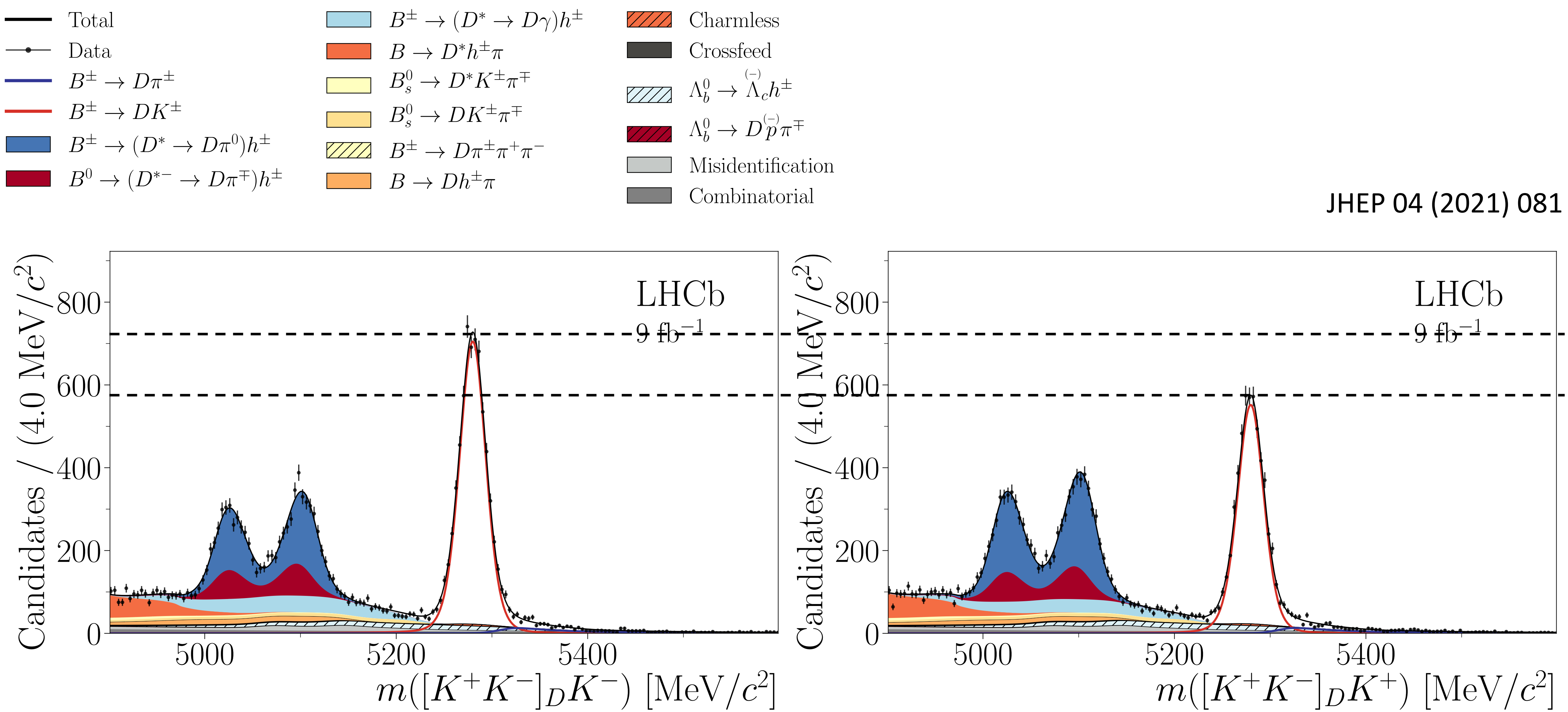
δ_B : strong phase : CP invariant

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

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

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

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



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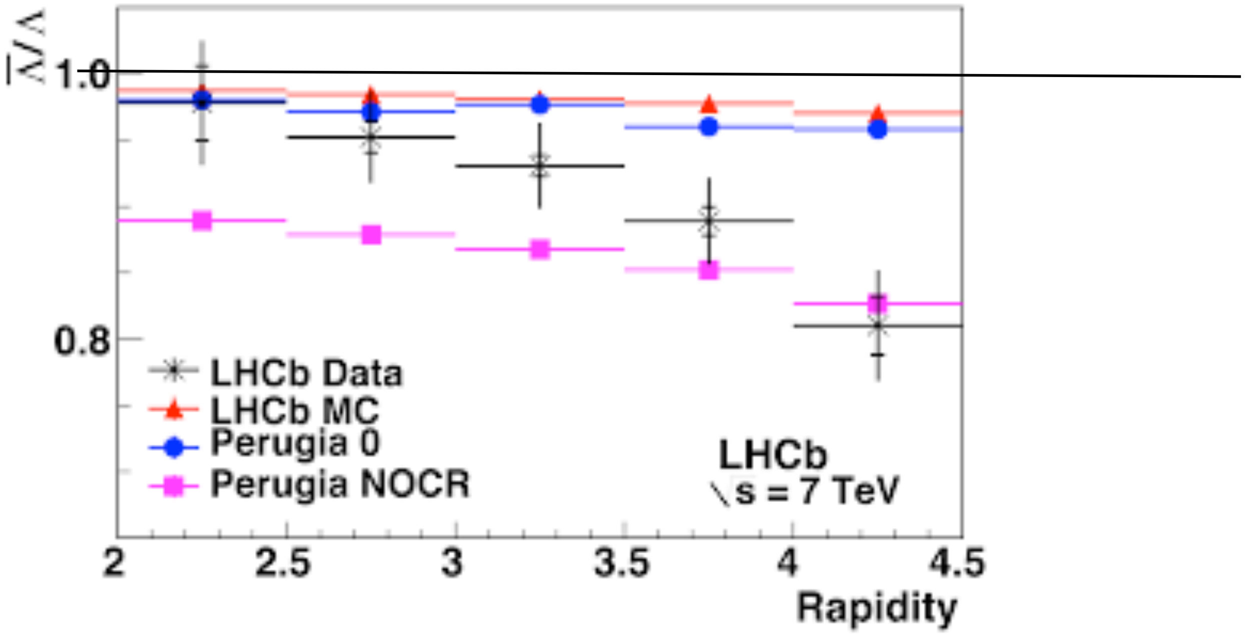
$$A_K^{CP} = \quad 0.136 \quad \pm 0.009 \quad \pm 0.001$$

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

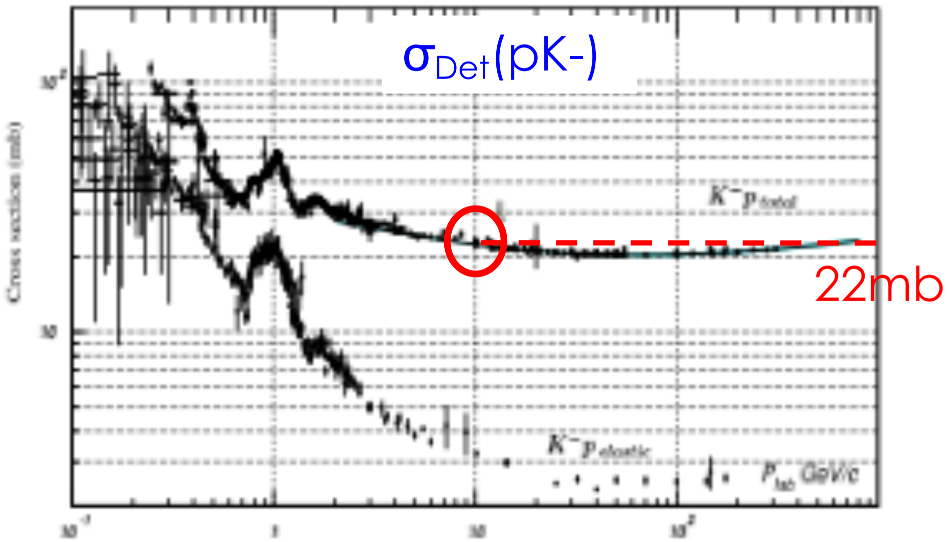
2 protons in the initial state
⇒ higher probability to pick up a diquark than an anti-diquark

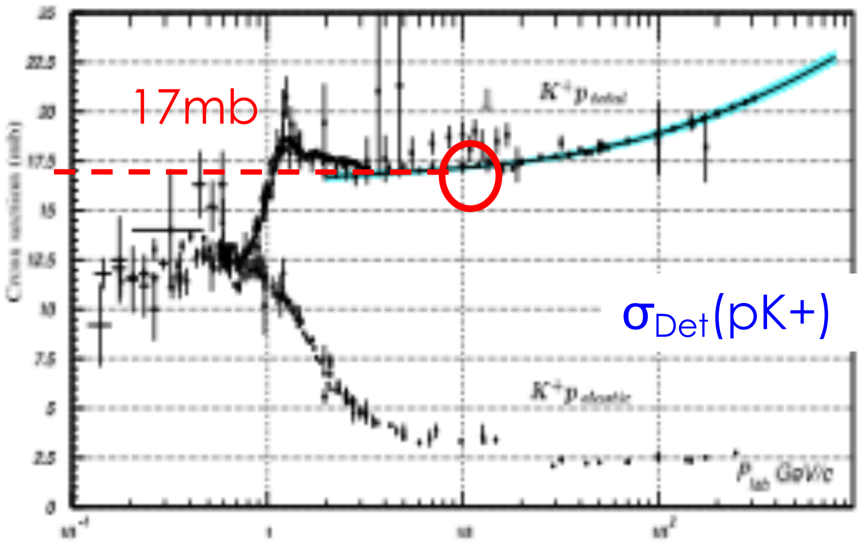


⇒ more b-baryons than anti-b-baryons
but same probability to have a b-quark than anti-b-quark ⇒ less B^-(b anti-u) than B^+ (anti-b u)

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

$\sigma_{Det}(pK-) > \sigma_{Det}(pK+)$ but $\sigma_{Det}(pPi-) \sim \sigma_{Det}(pPi+)$





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

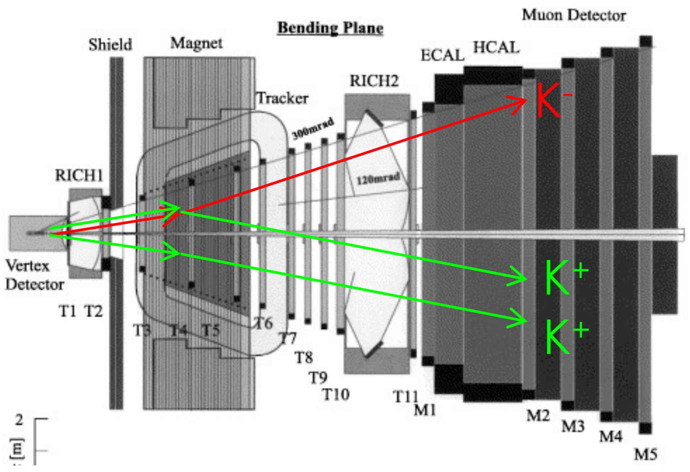
Both Pi- p and Pi+ p have annihilation

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

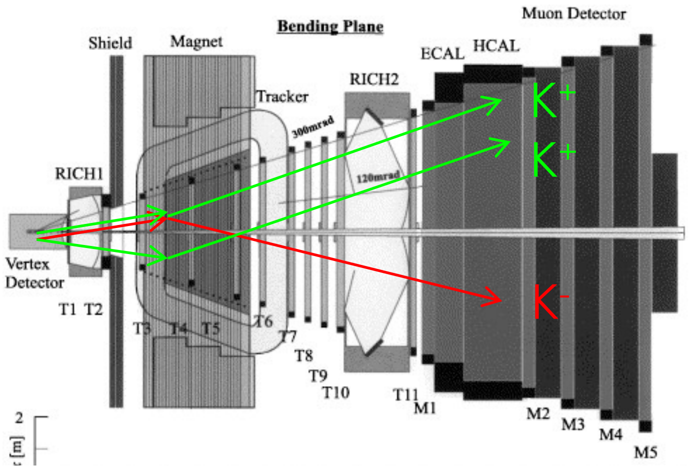
detection asymmetries 2/2

- 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 :

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

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

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

....

More involved analyses :

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

1) Use a CP mode for the D^0

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

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

(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)
$$\begin{cases} D^0 \to K^-\pi^+ \\ D^0 \to K^-\pi^+\pi^0 \\ D^0 \to K^-\pi^+\pi^-\pi^+ \end{cases}$$

(Very) small Branching Ratios

Strong phase between the D^0 decays

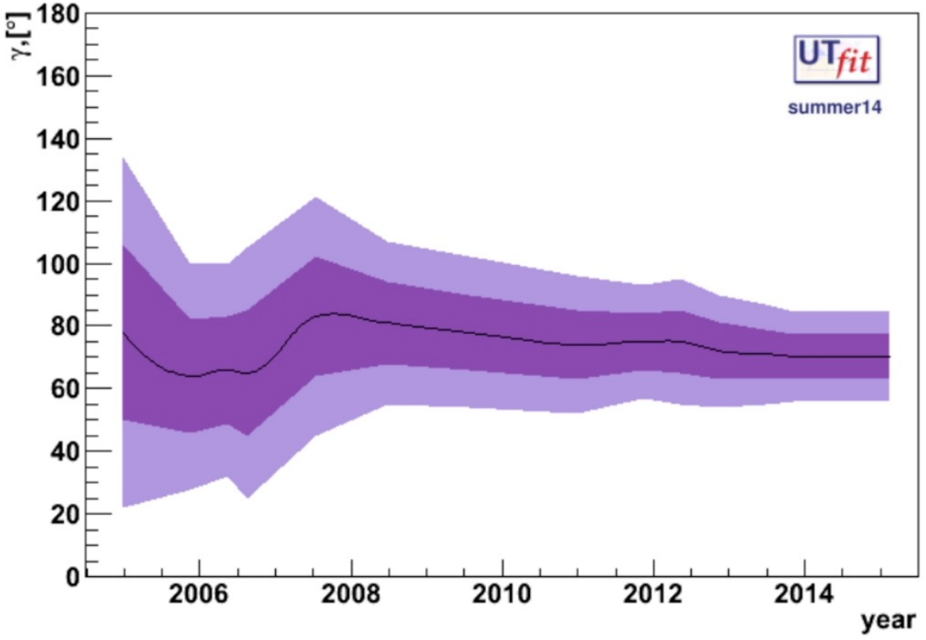
3) Use the $D^0 \to K_S \pi \pi$ decay

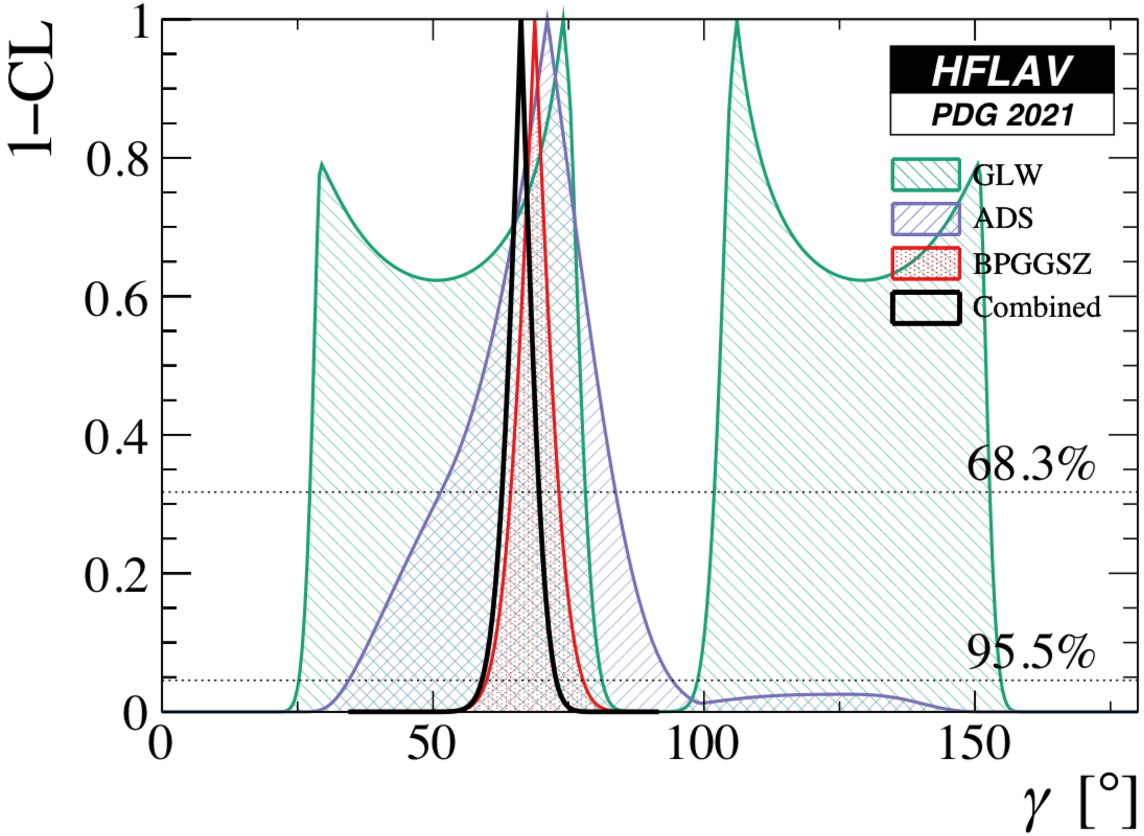
Dalitz BPGGSZ (Bondar, Poluetkov, Giri, Grossman, Soffer, Zupan)

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

Dalitz plot description

More precise way to measure γ



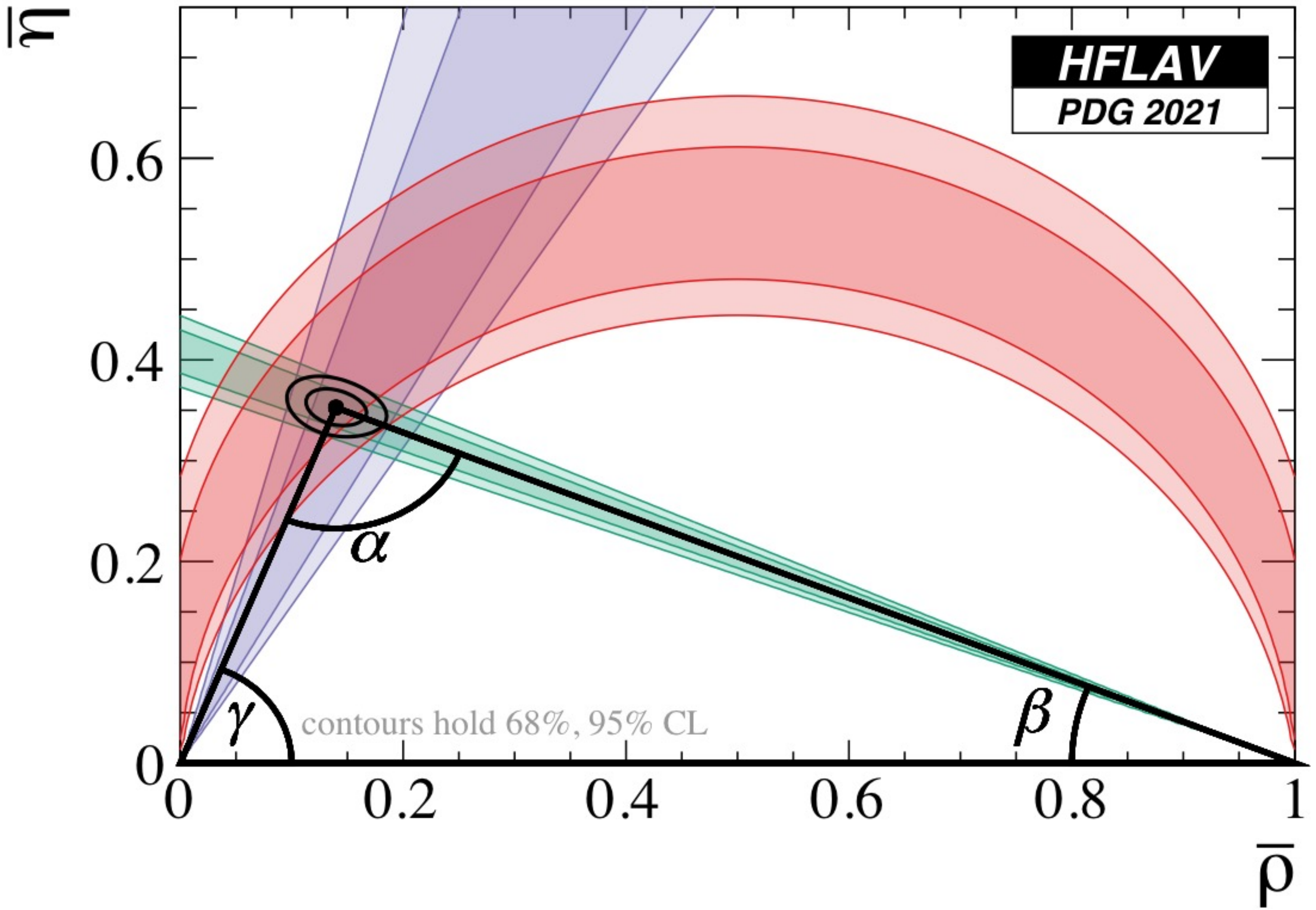


a factor 2 improvement since 2015

Dominated by LHCb

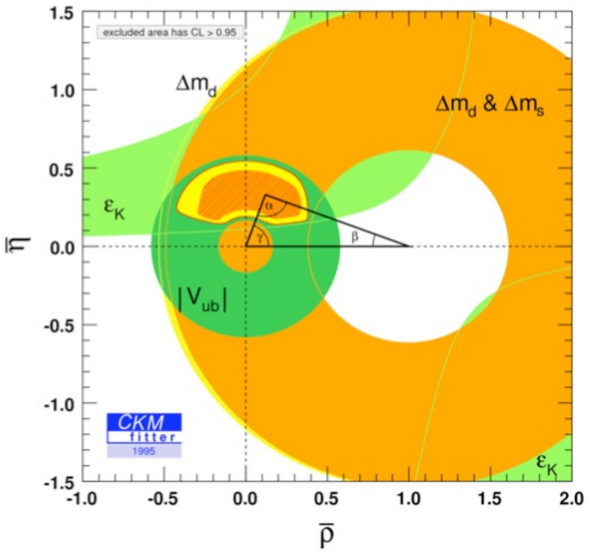
$\gamma = (66.2\,^{+3.4}_{-3.6})^{\circ}$

D mixing to be taken into account

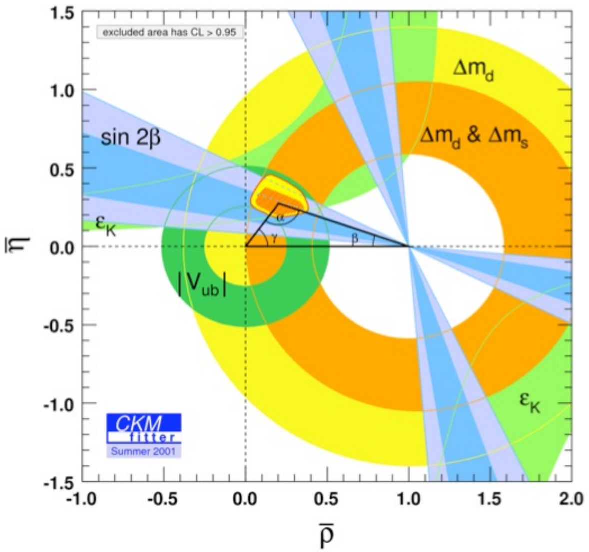

HFLAV
PDG 2021
contours hold 68%, 95% CL
α
β
γ
$\bar{\eta}$
$\bar{\rho}$
0
0.2
0.4
0.6
0.8
1

impressive improvement…

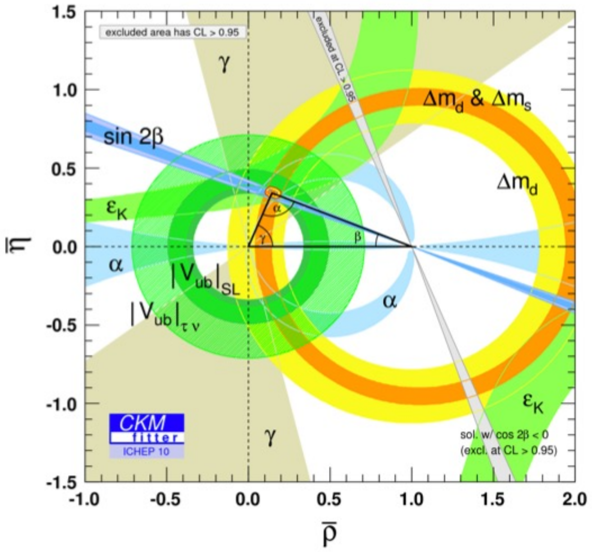
1995



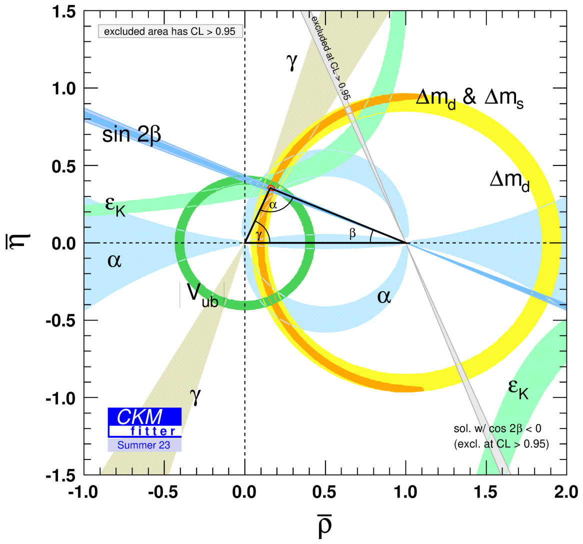
2001



2010

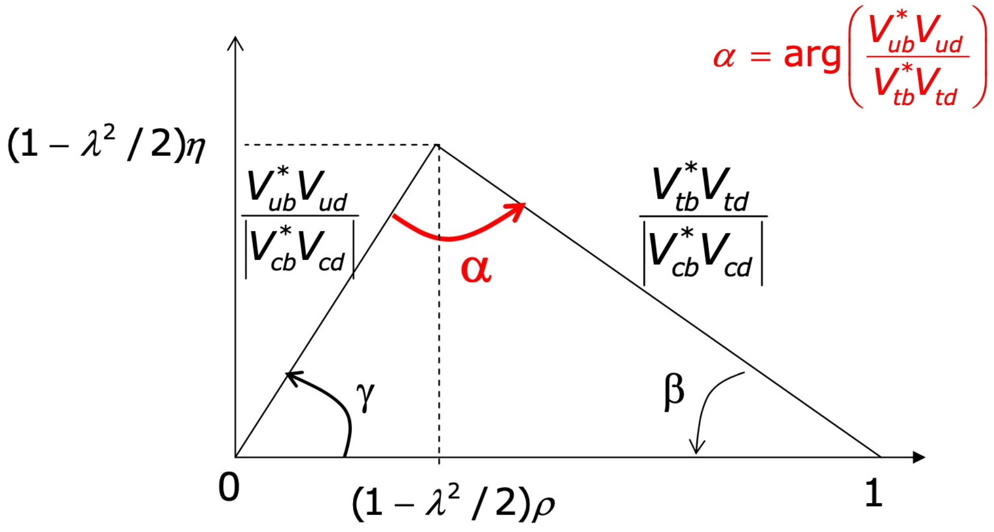


2023



…due to experiments and theoretical progresses.

and what about α ?



In terms of ρ and η:

$$\sin 2\alpha = \frac{2\overline{\eta}[\overline{\eta}^2 + \overline{\rho}(\overline{\rho}-1)]}{[\overline{\eta}^2 + (1-\overline{\rho})^2][\overline{\eta}^2+\overline{\rho}^2]}$$

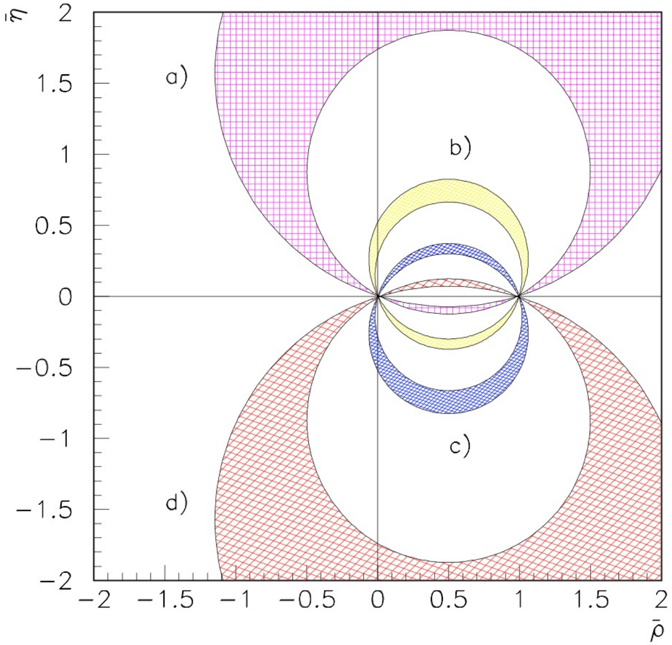
Since α is extracted from $\sin 2\alpha$, we are faced with a four-fold ambiguity: $\alpha,\ \frac{1}{2}\pi-\alpha,\ \alpha+\pi$, and $\frac{3}{2}\pi-\alpha$. The ambiguity yields four distinct circles:

because for each value of a there is a circle centred at

$$(x_\alpha, y_\alpha) = (\frac{1}{2}, \frac{\cot\alpha}{2}),$$

and of radius

$$r_\alpha = \frac{1}{2}\frac{1}{\sin\alpha}.$$



See BaBar physics book for more details ;)

Extra slide

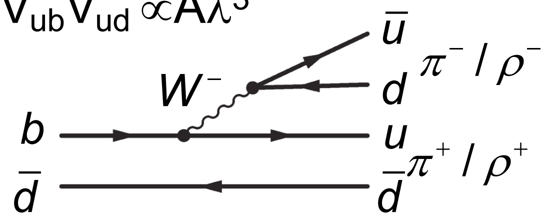
But are we measuring really α ?

Interference between mixing and decay

$B^0 \rightarrow \pi^+\pi^- / \rho^+\rho^-$

Assuming pure tree diagram:

$\propto V_{ub}V_{ud} \propto A\lambda^3$



$$P(\overset{(-)}{B^0}(t)) = e^{-t/\tau_B} \cdot |A|^2 \frac{1+|\lambda|^2}{2}\left[1 \overset{(-)}{+} C\cos(\Delta m_d t) \overset{(+)}{-} S\sin(\Delta m_d t)\right]$$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad S = \frac{2\Im m(\lambda)}{1+|\lambda|^2}$$

$$\lambda = \frac{q}{p}\cdot\frac{\bar{A}}{A} = e^{-2i\beta}\cdot e^{-2i\gamma} = e^{2i\alpha}$$

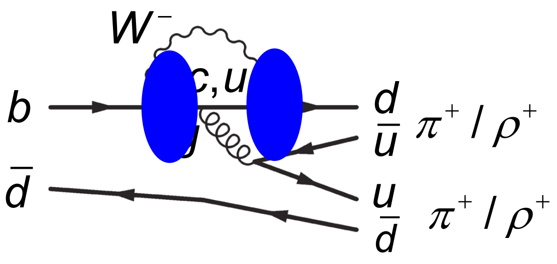
C=0

S=sin(2α)

But penguins may be of the same order of magnitude as trees:

$\propto V_{tb}V_{td} \propto A\lambda^3$

!!



$$\lambda = e^{i2\alpha}\frac{T + P e^{+i\gamma}e^{i\delta}}{T + P e^{-i\gamma}e^{i\delta}}$$

δ relative strong phase between T and P

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2} \neq 0$$

$$S = \sqrt{1-C^2}\,\sin(2\alpha_{eff})$$

what is measured is NOT exactly α

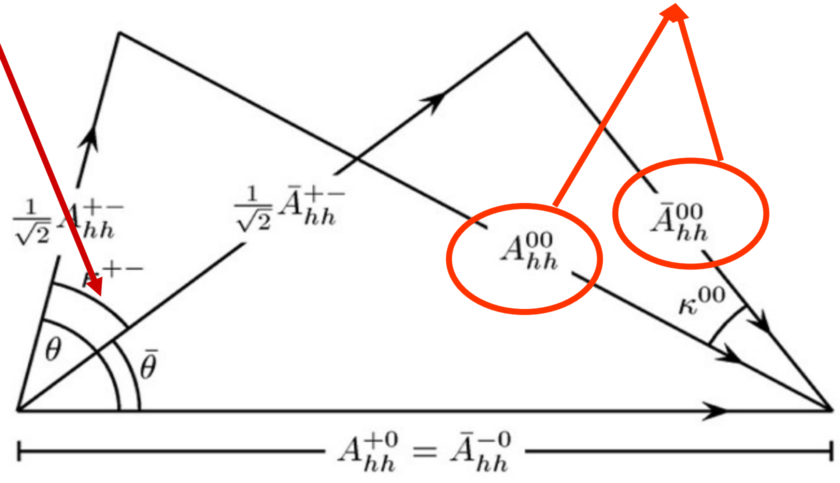
Extra slide

To extract α from α_{eff} : use SU(2)-isospin

Isospin triangles :

$\kappa^{+-} = 2(\alpha_{eff} - \alpha)$

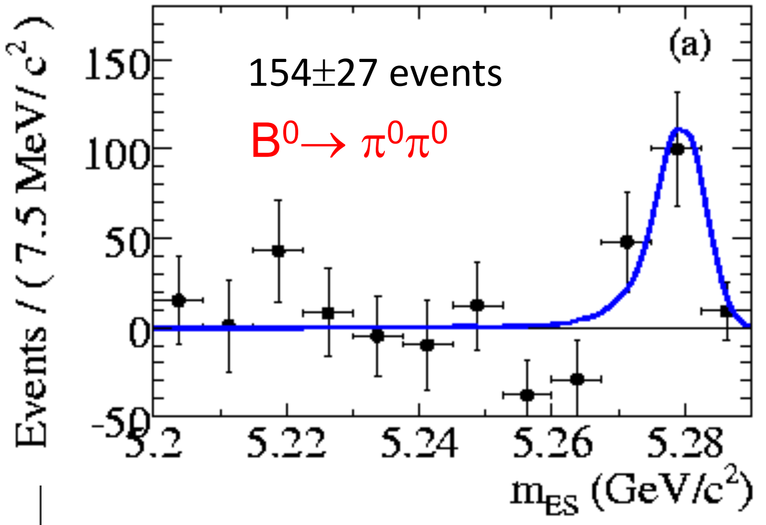
$B^0 \rightarrow \pi^0\pi^0$



In order to bound $|\alpha-\alpha_{eff}|$ needs $\pi^{\pm}\pi^0$ and $\pi^0\pi^0$ ...

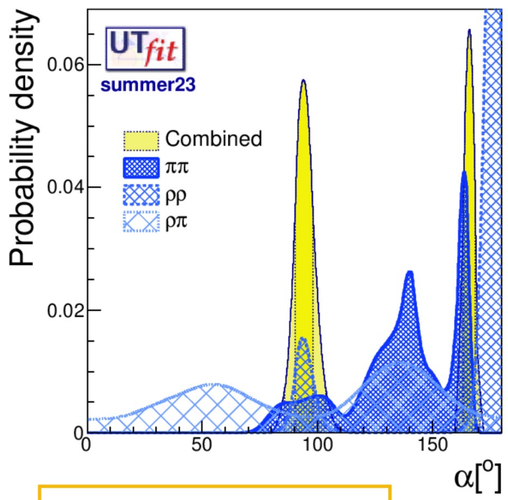
The $\pi^0\pi^0$ final state is pure penguin

BABAR, background subtracted



$\pi^0\pi^0$ is too small for a isospin analysis and too large to set a useful $|\alpha-\alpha_{eff}|$ limit…

$\Rightarrow$ Use the $B^0 \rightarrow \rho^+\rho^-$ mode which, by chance (!) has a small value for $BR(B^0 \rightarrow \rho^0\rho^0)$



$\alpha = (93.8 \pm 4.5)^o$

UTfit

What could we say about NP ?

Extra slide

Let's allow for NP in ΔF=2 transitions (UTFit style) :

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

UTFit

CKMFitter

$$M_{12} = (M_{12})_{SM} \times (1 + h e^{2i\sigma}),$$

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$

$$A_{CP}^{B_d \to J/\psi K_S} = \sin 2(\beta + \phi_{B_d})$$

$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right)$$

$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

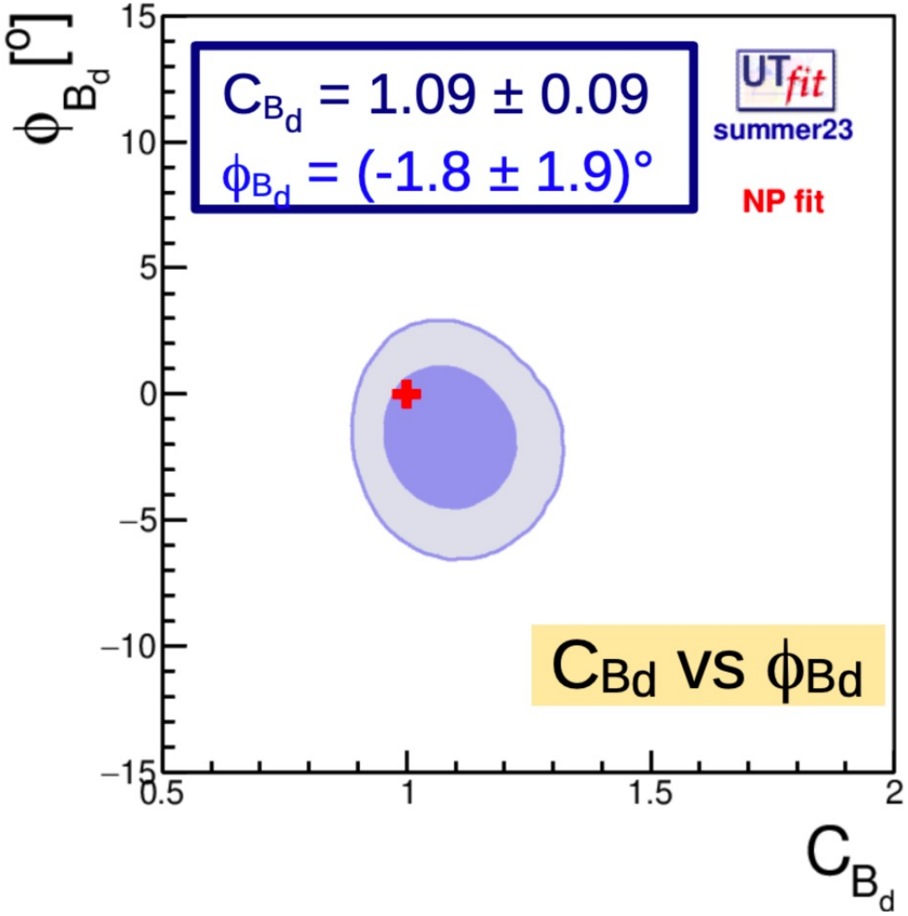
$$A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$

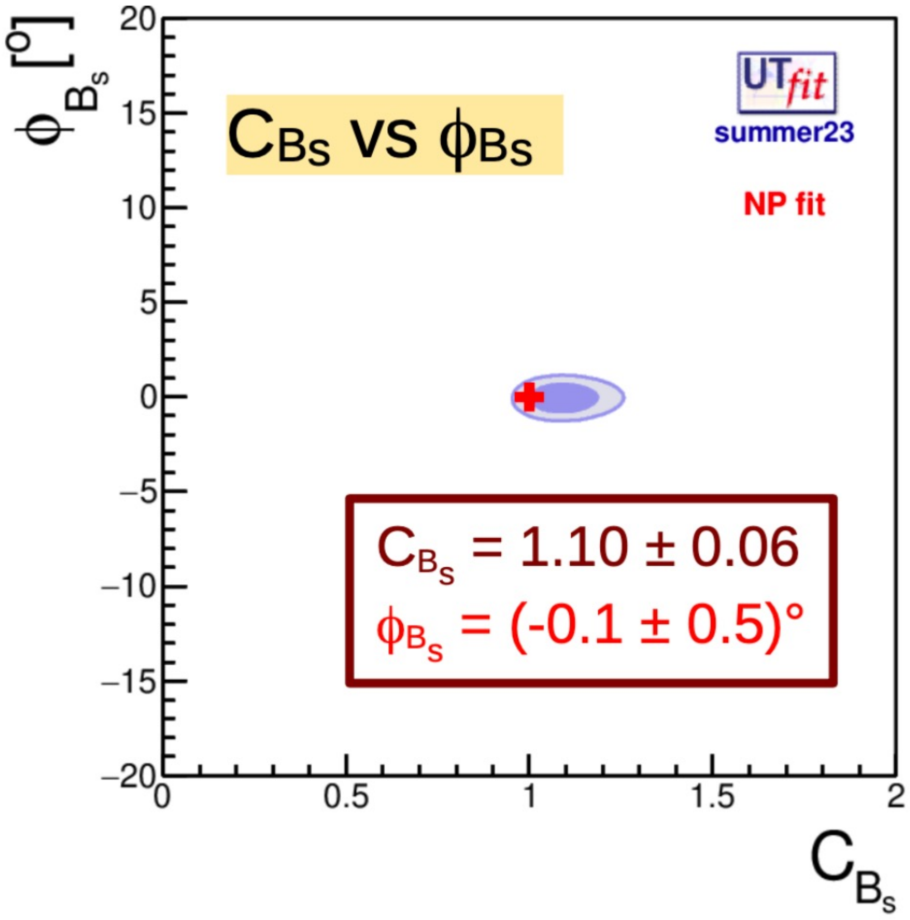
$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

→ add some parameters to your CKM fit

There is enough experimental redundant information so that the CKM parameters are extracted with ~ the same precision

Extra slide





+ SM

dark: 68%
light: 95%

From UTFit collaboration at EPS 2023 (Maurizio Pierrini)

Extra slide

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

The ratio of NP/SM amplitudes is:

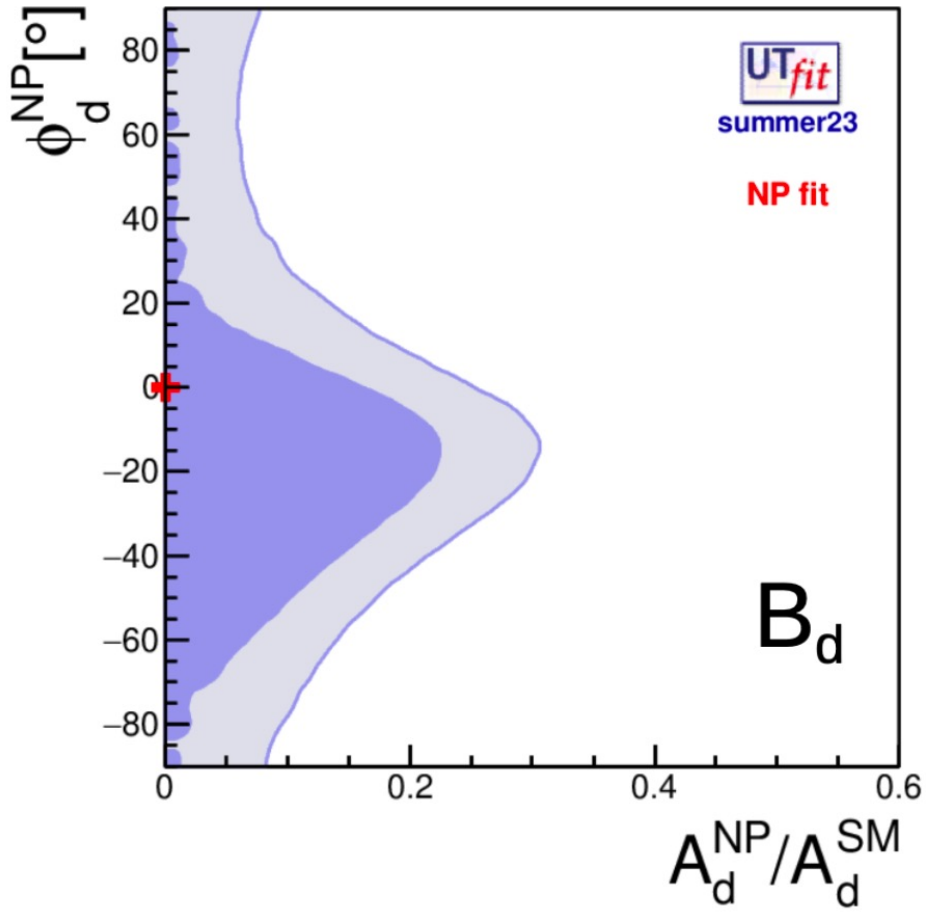
< 25% @68% prob. (35% @95%) in B_d mixing

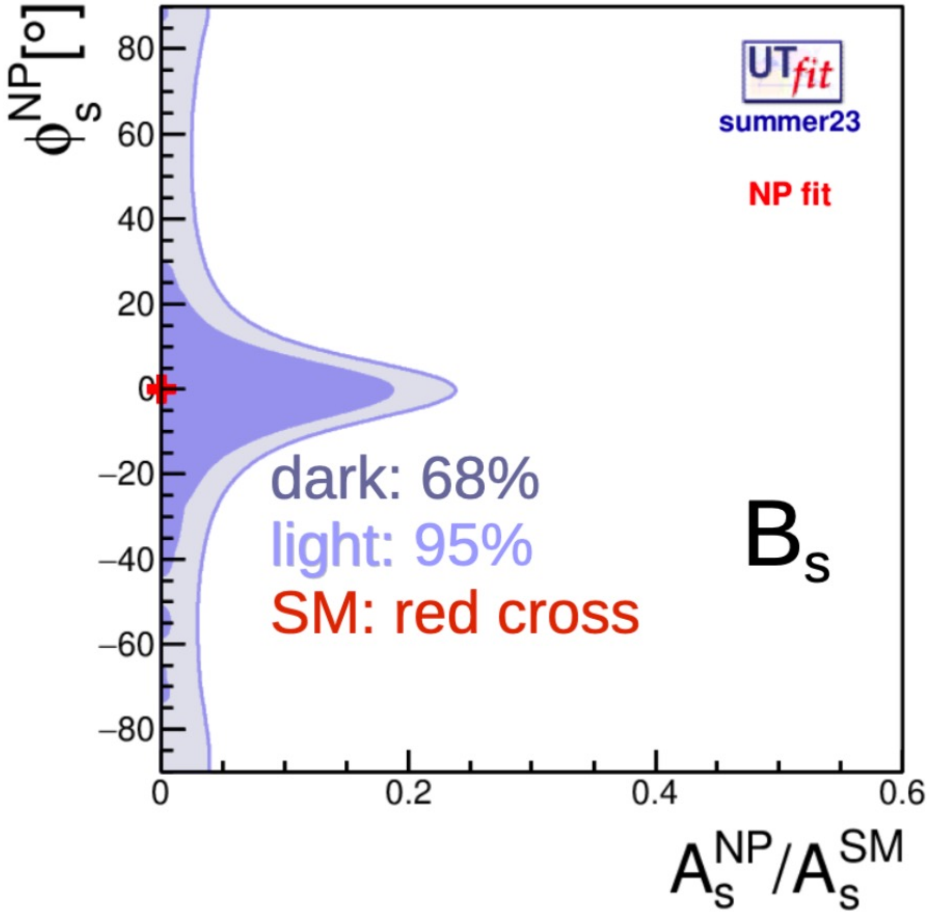
< 25% @68% prob. (30% @95%) in B_s mixing

dark: 68%

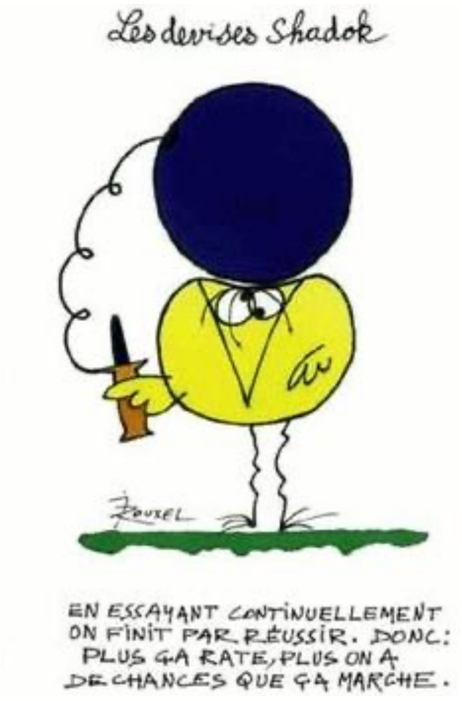
light: 95%

SM: red cross





Rare decays


Les devises Shadok
EN ESSAYANT CONTINUELLEMENT
ON FINIT PAR RÉUSSIR. DONC:
PLUS ÇA RATE, PLUS ON A
DE CHANCES QUE ÇA MARCHE.

Which experiments ?

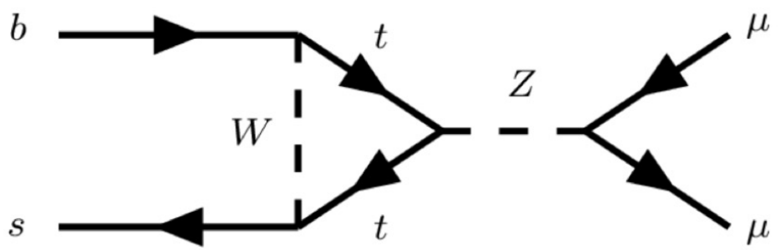
- Branching fractions of the order of 10^{-7} ($B^0 \to K^* \ell \ell$) to 10^{-10} ($B_d \to \mu\, \mu$)
- B-Factories : 100% efficiency
- LHCb few % efficiency (yields extrapolated from published values)

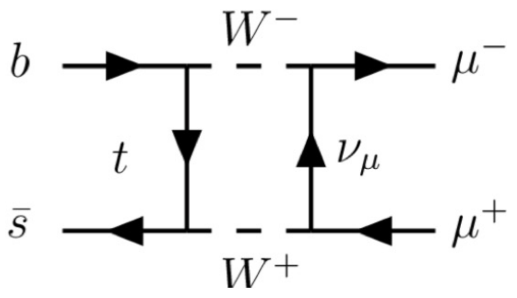
Experiment	$B^0 \to K^* \ell \ell$	$B_s \to \mu\, \mu$	$B_d \to \mu\, \mu$
B-Factories 1 ab^{-1}	200	-	0
B-Factories 50 ab^{-1}	10000	-	10
LHCb 9 fb^{-1}	5000	150	15
LHCb 50 fb^{-1} / 300 fb^{-1}	30000/180000	800	80

but at B-Factories : $B \to K\, \nu\, \nu$

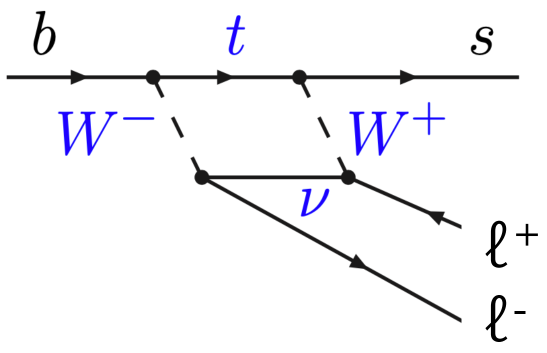
(very) rare decays: $b \rightarrow s\ \ell^+\ell^-$ transitions

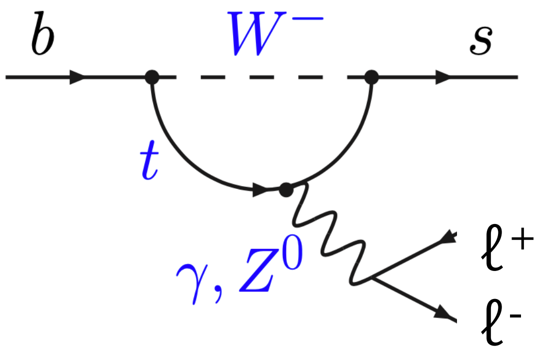
$B_s \rightarrow \ell^+\ell^-$





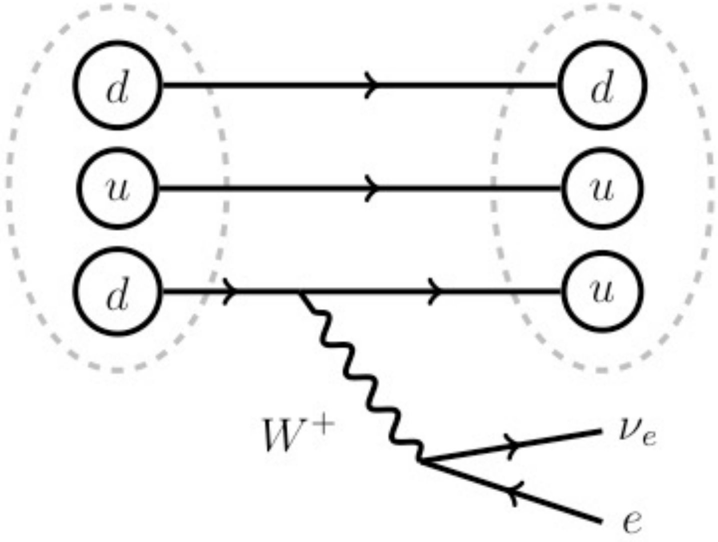
$H_b \rightarrow H_s\ \ell^+\ell^-$



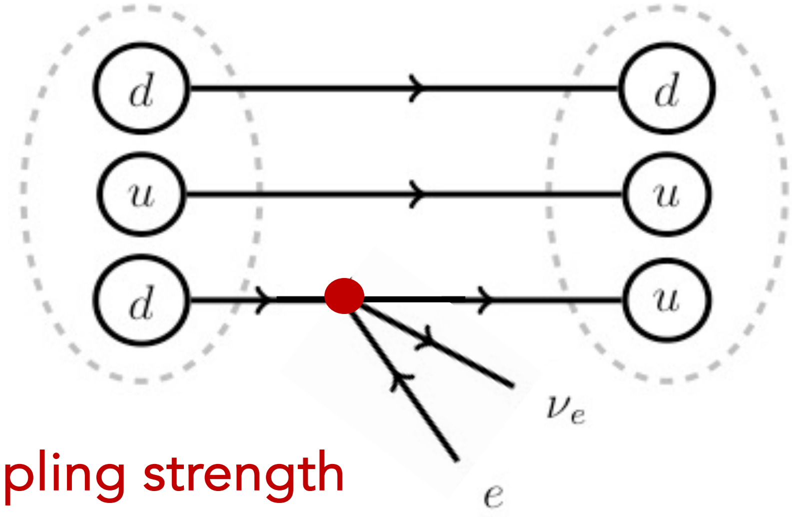


EFT for Heavy Flavours in a nutshell

neutron β decay



Expansion in q^2/M_W^2:



coupling strength

$$i\mathcal{A} = \left(\frac{ie}{\sqrt{2}\sin\theta_W}\right)^2 V_{ud}^*(\bar{\nu}_l\gamma_\nu P_L\ell)\frac{ig_{\mu\nu}}{q^2 - M_W^2 + i\epsilon}(\bar{d}\gamma_\mu P_L u)$$

$$i\mathcal{A} = i\frac{4G_F}{\sqrt{2}}V_{ud}^*(\bar{\nu}_l\gamma^\mu P_L\ell)(\bar{d}\gamma_\mu P_L u) + \mathcal{O}\left(\frac{q^2}{M_W^2}\right)$$

$$G_F \equiv \sqrt{2}\frac{e^2}{8\sin^2\theta_W M_W^2} \equiv \sqrt{2}\frac{g}{8M_W^2}$$

Measurement of the effective coupling ⇒ constraints on g/M_W^2

$$\mathcal{H}_{NP} \propto \frac{c_{\mathrm{NP}}}{\Lambda_{\mathrm{NP}}^2}$$

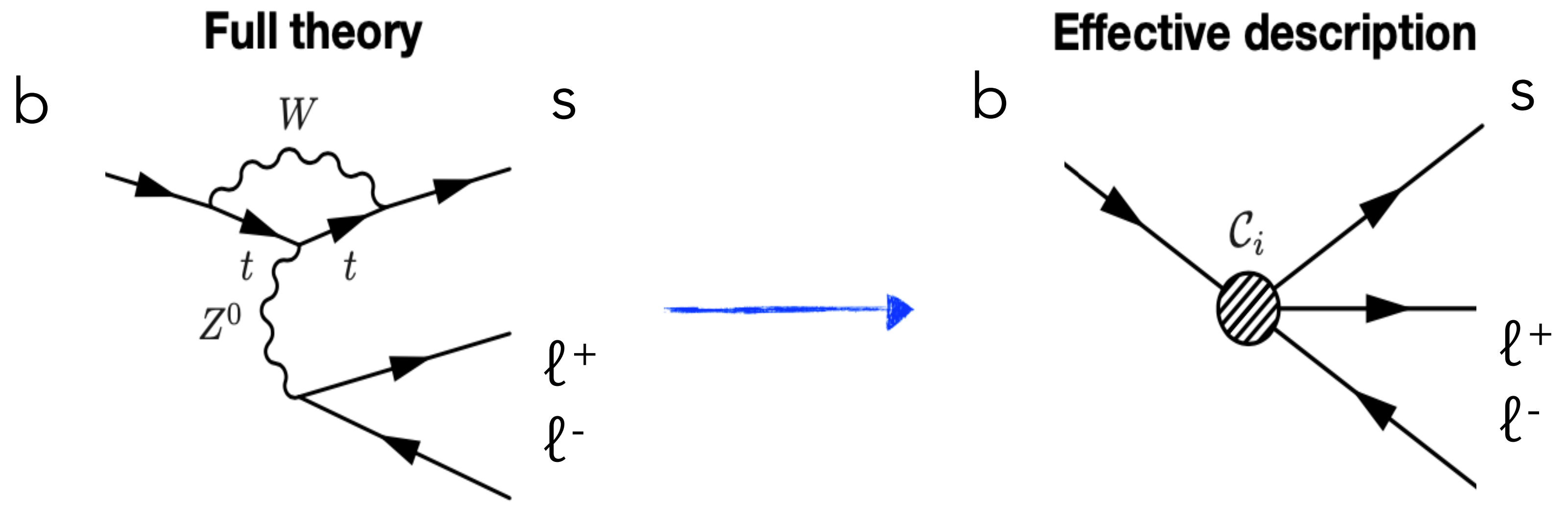
Assuming a coupling value one can say something on the scale of the heavy particle involved without detailed knowledge of them …

$$i\,\mathcal{A} = \frac{i\,g}{2M_W^2} V_{ud}^* (\bar{\nu}_l \gamma^\mu P_L \ell)(\bar{d}\gamma_\mu P_L u)$$

Effective coupling:
Wilson coefficient

low energy interaction
non-perturbative QCD etc …

Weak Effective Theory



W, Z, top, …
integrated out

~ Fermi's description of neutron β decay

$$\mathcal{L}_{\text{eff}} \propto G_F V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

$C_i^{(\prime)} = C_i^{SM\,(\prime)} + C_i^{NP\,(\prime)}$ — perturbative, contains the short distance physics. q^2 independent. Heavy NP

$O_i^{(\prime)}$ — non-perturbative, Lorentz structure, long distance physics.. q^2 dependent.

Which operators and Wilson coefficients ?

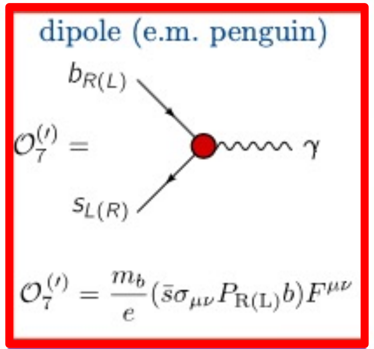
$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$

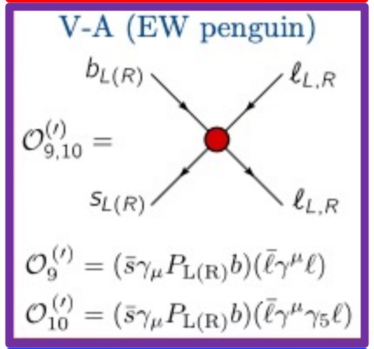
$O_9^{(\prime)} \propto (\bar{s}\gamma_{\mu}P_{L(R)}b)(\bar{l}\gamma_{\mu}l)$

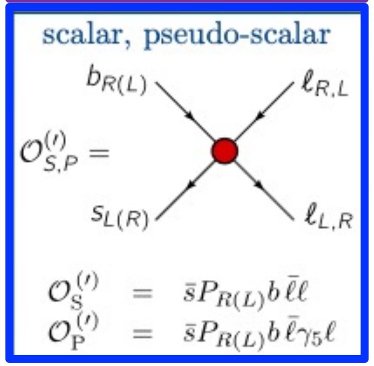
$O_{10}^{(\prime)} \propto (\bar{s}\gamma_{\mu}P_{L(R)}b)(\bar{l}\gamma_{\mu}\gamma_5 l)$

$O_S^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{l}\,l)$

$O_P^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{l}\gamma_5 l)$







Coupling	$b \to s\gamma$	$b \to s\ell\ell$	$B \to \ell\ell$
$C_7^{(\prime)}$			
$C_9^{(\prime)}$			
$C_{10}^{(\prime)}$			
$C_S^{(\prime)}$ & $C_P^{(\prime)}$			

A priori different
for ℓ = e and $\ell = \mu$

Primed operators and Wilson Coefficients:
$P_L \to P_R$ and $m_b \to m_s$

In the SM

$\mathcal{O}_{7,9,10}$ (and $\mathcal{O}'_7$)

$$\mathcal{C}_7^{\rm SM}(\mu_b) = -0.29, \quad \mathcal{C}_9^{\rm eff\,SM}(\mu_b) = 4.1, \quad \mathcal{C}_{10}^{\rm SM}(\mu_b) = -4.3$$

$\mu_b = \mathcal{O}(m_b)$

$\mathcal{C}_{7'}^{\rm SM}(\mu_b) \simeq -0.006$

m_s/m_b suppression

if there is New Physics :

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

real

can be imaginary

- No need to specific a precise model (Leptoquark, Z ' , …)
- Approach working for heavy New Physics (> M_W)