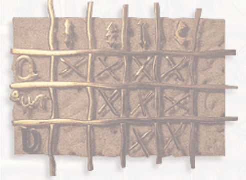
Flavours



Stéphane Monteil, monteil@in2p3.fr

Clermont University – IN2P3 / CNRS

Some authoritative literature about the lecture :

- BaBar physics book: http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html
- LHCb performance TDR: http://cdsweb.cern.ch/record/630827?ln=en
- A. Höcker and Z. Ligeti: CP Violation and the CKM Matrix. hep-ph/0605217
- The Belle II Physics TDR.

World Averages and Global Fits:

- Heavy Flavour Averaging Group: http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter: http://ckmfitter.in2p3.fr/
- UTFit: http://www.utfit.org/

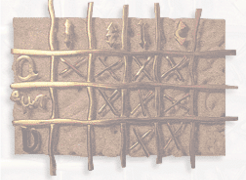
Motivations for a two-fold approach

- I will discuss Flavour Physics and *CP* violation in this lecture.

- Flavours are the tag (quantum number) that you put on elementary particles, *e.g.* the *b* quark has the beautiful flavour.

- Electromagnetism and strong interaction are flavour-blind. Charged weak interaction breaks flavour (up / down isospin). Up and Down particles, respectively, differ only by their mass. We'll focus on the heavy elements.

- Flavour Physics is a way to study the electroweak symmetry breaking, complementary to the Higgs boson decays and properties. I hence will spend a couple of slides with a reminder of the Standard Model (SM), by the prism of its free parameters **(introduction part of the lecture)**.



Motivations for a two-fold approach

• After electroweak spontaneous symmetry brought by the scalar isospin doublet field —> the mass matrix of the quarks is defined and the couplings of flavoured fermions are characterised by the Yukawa couplings.

• After the diagonalisation of the fermion mass matrix, **the mass mixing matrix** arises and shapes the couplings of the **weak charged currents.**

•*CP* symmetry breaking is at the heart of the understanding of this mass mixing matrix **(first part of the lecture)**.

• It does not saturate the interest of Flavour Physics. Several anomalies deserve comments **(second part of the lecture)**. In particular rare decays of heavy-flavoured particles might be a portal to Beyond SM.

Disclaimers

• This is an experimentalist point of view on a subject which is all about entanglements between experiment and theory.

• I won't discuss *CP* violation in the lepton sector nor light flavours decays and properties.

• I won't have time to discuss the main machines and experiments (having been) harvesting Flavour observables. Links are provided instead.

•Most of the materials concerning global tests of the CKM matrix SM are taken from the CKMfitter group results (assumed bias) and Heavy Flavour Averaging Group (and hence the experiments themselves). I borrowed materials in presentations from colleagues which I tried to cite correctly. There are much more materials than can be covered in an hour. I append in this lectures links to more complete lectures, in case you'd like to dig further the subjects.

Lecture’s Outline

- **Part 0:** the Standard Model (SM) of particle Physics in a glance (from its free parameters).

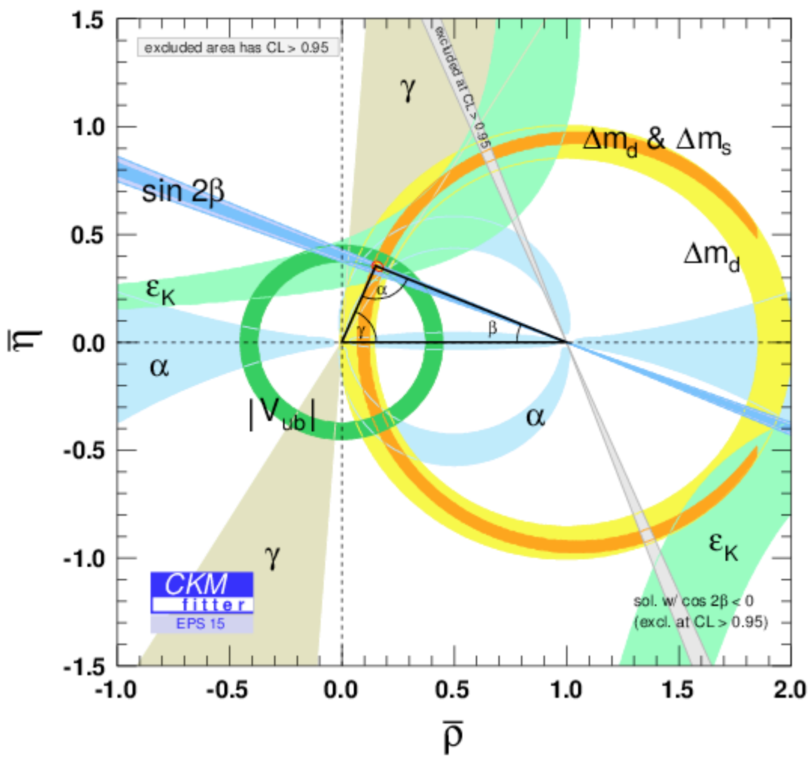
- **Part I:** *CP* violation and the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

- **Part II:** rare decays of heavy-flavoured particles.

- **Conclusion and Outlook:** the precision era of Flavour Physics starts.

Reorganisation:

- Among the 20 free parameters of the SM, one finds the (4) CKM matrix elements (decoupled from the rest of the theory). The consistency check of the SM hypothesis in that sector is a pillar of the SM:



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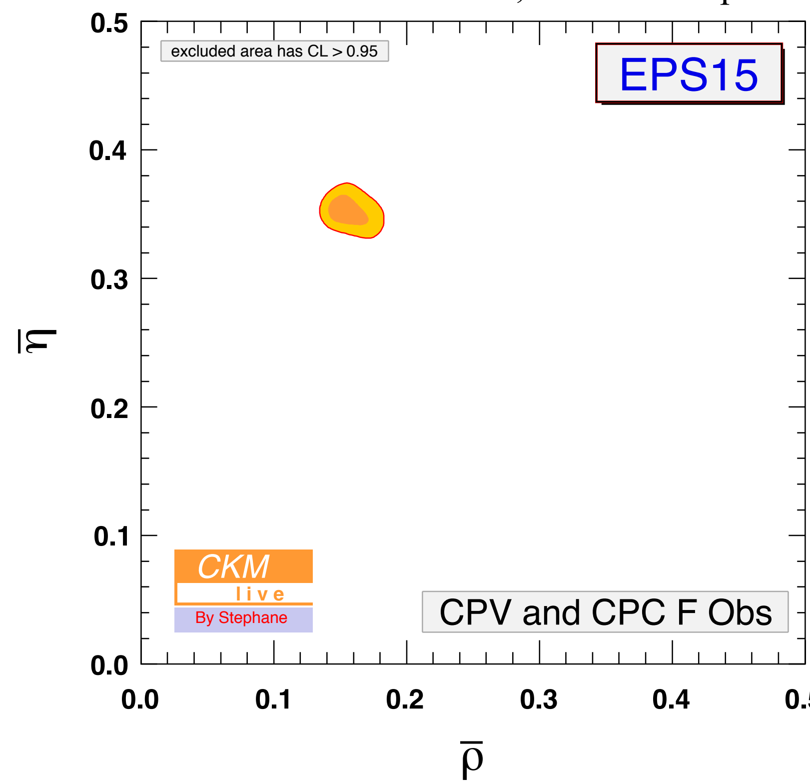
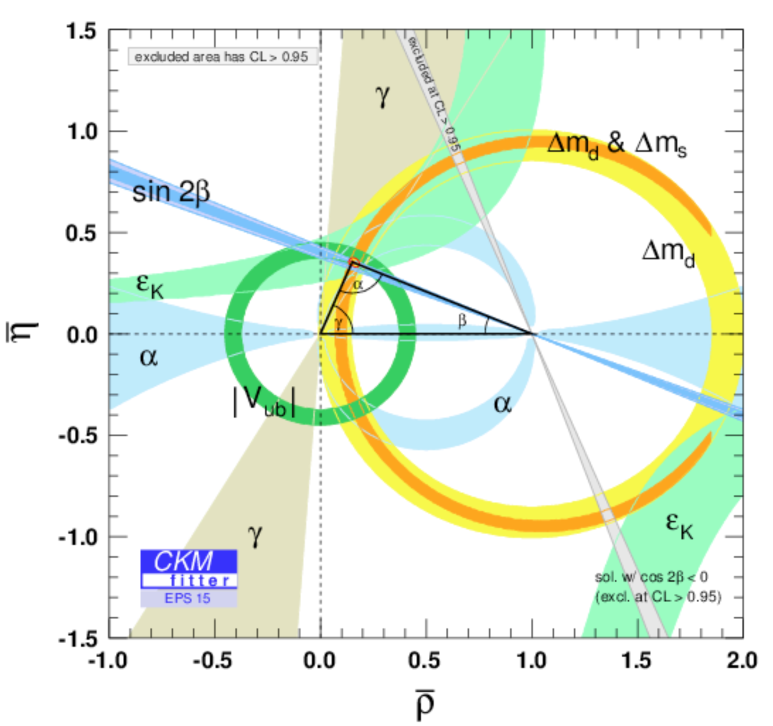
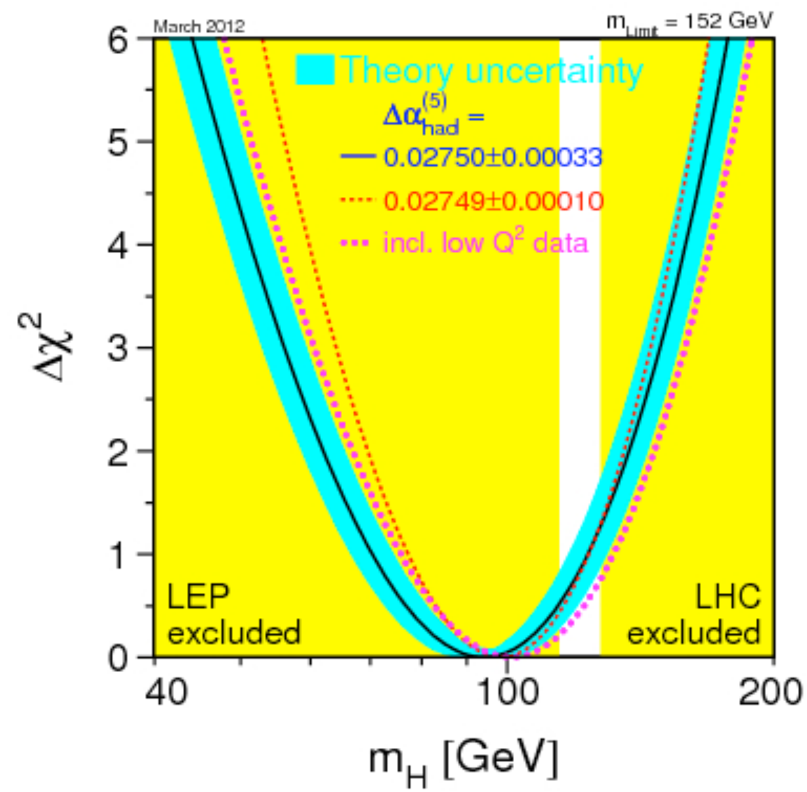


Introduction: SM became a theory

Recap:

- Two pillars: mass matrix and mass mixing matrix: EWPT and Flavours.





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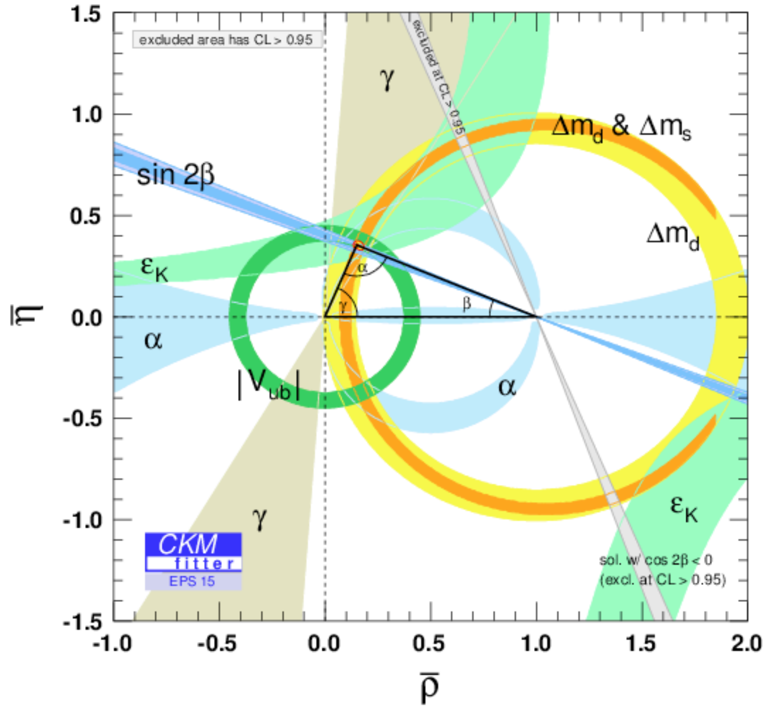

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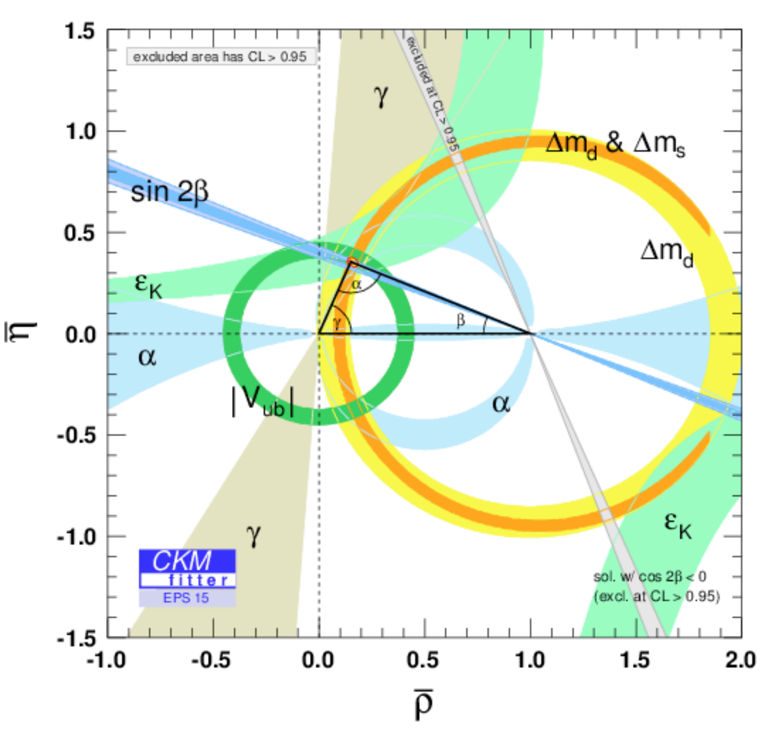

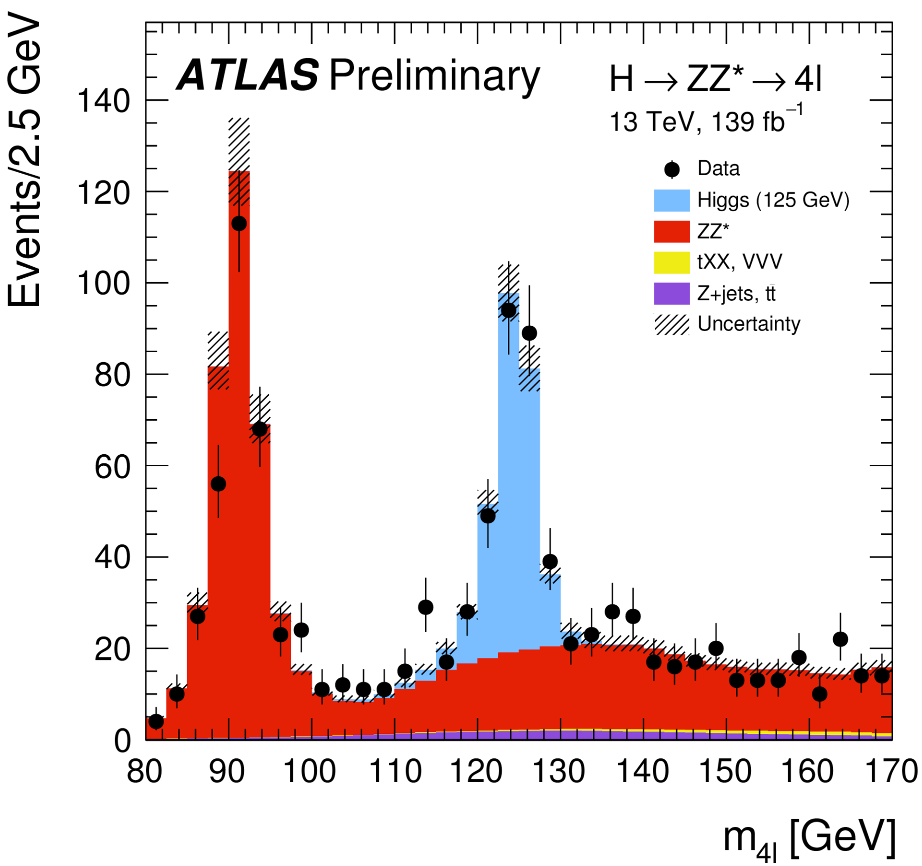

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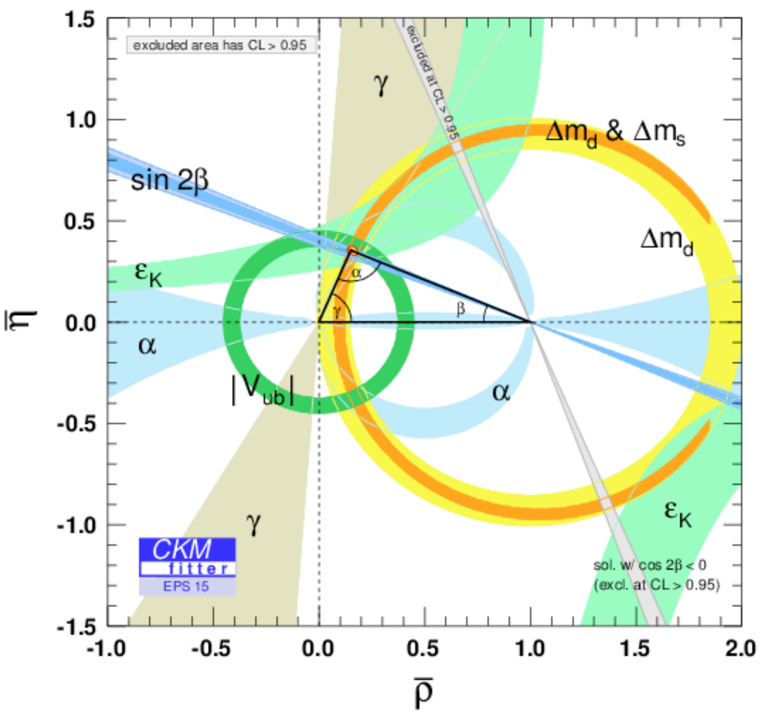
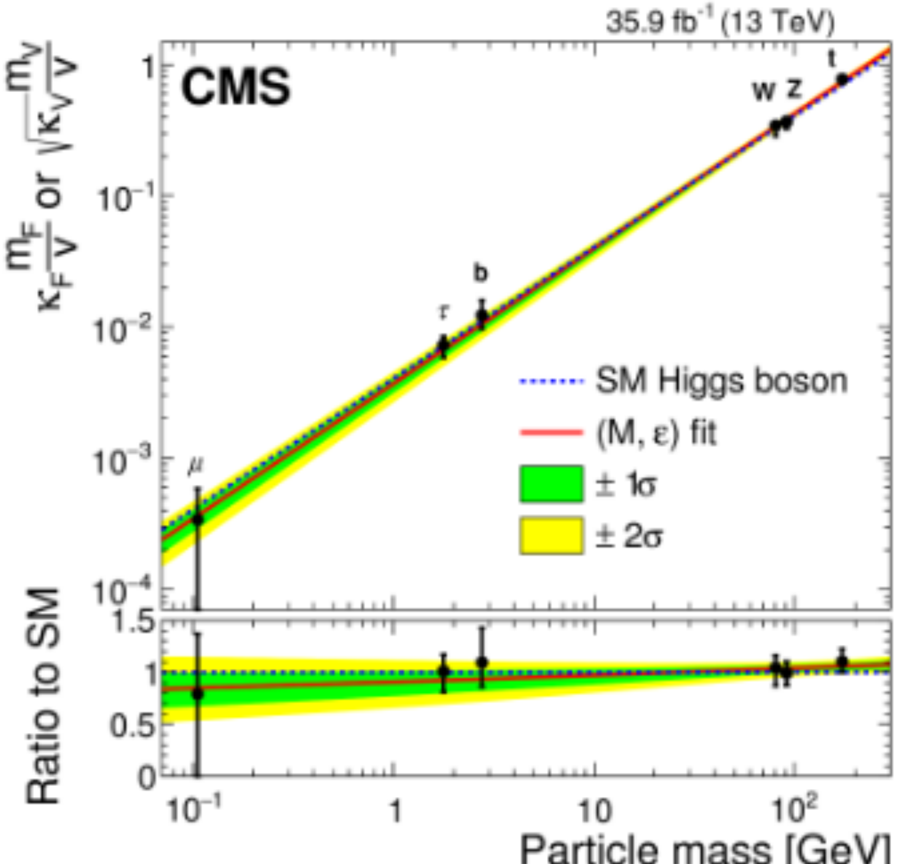


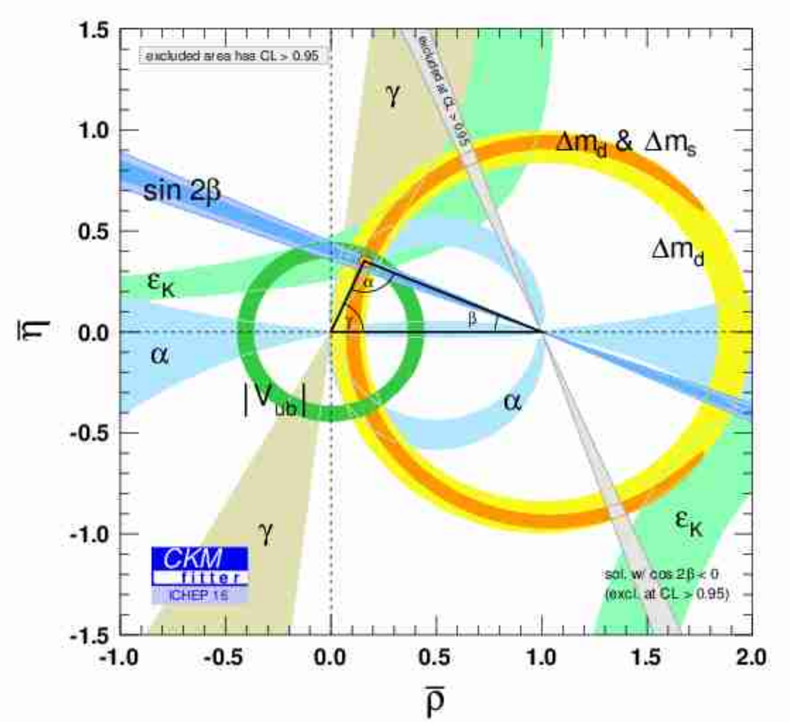
Mass mixing matrix



Mass matrix

Motivation

- In any HEP physics conference summary talk, you will find this plot, stating that (heavy) flavours and *CP* violation physics is a pillar of the Standard Model.



- One objective of this lecture is to undress this plot.

A more detailed outline

1. Foundations: setting the scene, the discovery of the *P* and *CP* violation.
2. Few elements about CKM. Machine and experiments. Main observables and measurements relevant to study *CP* violation.
3. The global fit of the SM: CKM profile.

Parity (space reflexion) symmetry breaking

Why *P* must be a good symmetry

If a variable describing a physical system is not an observable,

one can always find a mathematical transformation which lets the physical system invariant.

An observable is conserved.

Foundations: parity symmetry breaking

Why P must be a good symmetry

Non-observable	Mathematical transf.	Conserved quantity
Absolute spatial position	**Space translation**	**Momentum**
Absolute time	**Time translation**	**Energy**
Absolute space direction	**Rotation**	**Angular momentum**
Absolute right	**Space reflexion (mirror)**	**Parity**
Electric charge sign	**e→-e**	**Charge conjugation**
Absolute time sign	**t→-t**	**Time reversal**
Relative phase between electric charges	**Gauge transformation**	**The electric charge**

Evidence for *P* violation

- ✓ Before 1956 : all interactions were thought to be invariant under parity operation
- ✓ It was (quite comprehensively) tested for strong and electromagnetic interactions.
- ✓ Lee and Yang proposed an experiment to test it for weak interaction after the theta / tau puzzle.
- ✓ Designed and performed in 1956 by C.S. Wu and collaborators
- ✓ The Co^{60} experiment : Phys. Rev. 105, 1413-1414 (1957)

Foundations: parity symmetry breaking

Evidence for *P* violation

The magnetic field is directed to the right. The spins are aligned along to it.

$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

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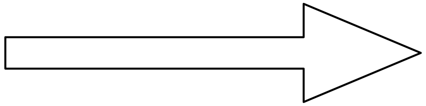

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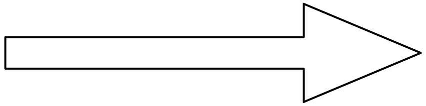

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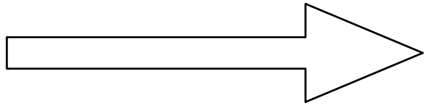

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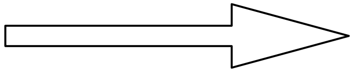

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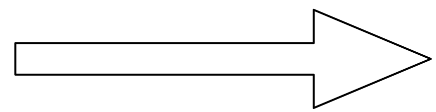
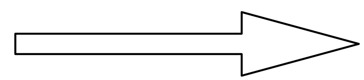
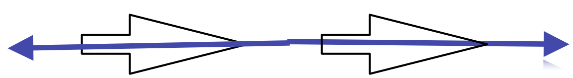
$^{60}\mathrm{Co}\ (J=5)$ 

$^{60}\mathrm{Ni}\ (J=4)$ 



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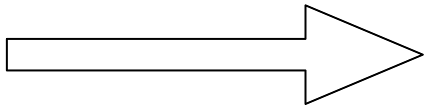

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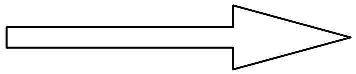

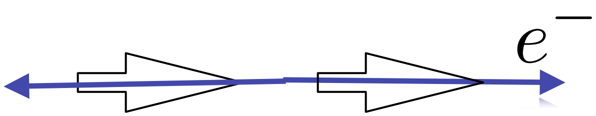

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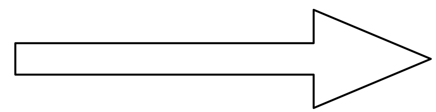

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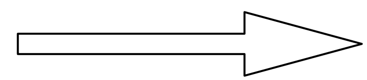

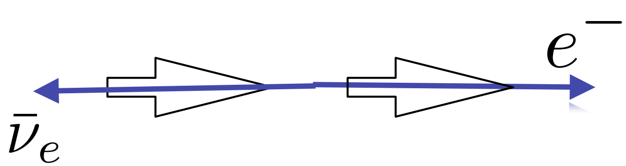

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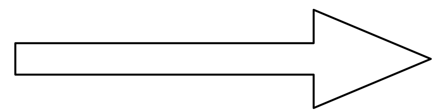

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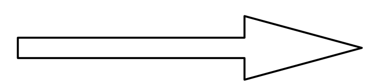

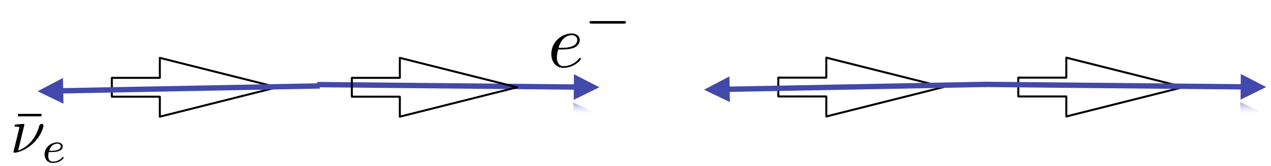

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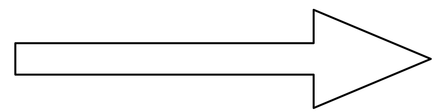

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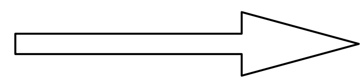

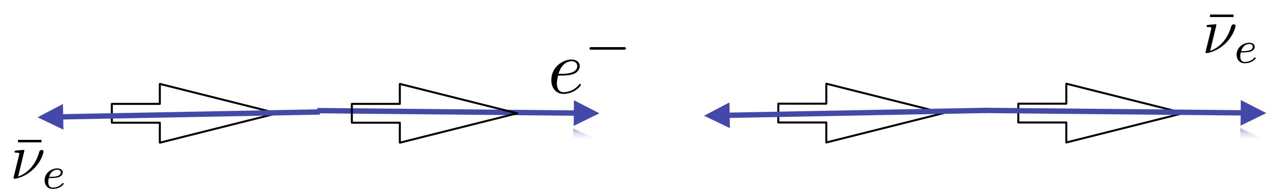

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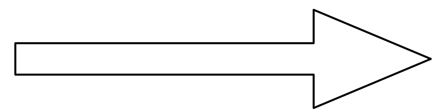
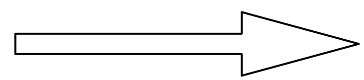
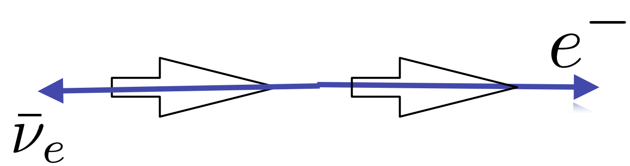
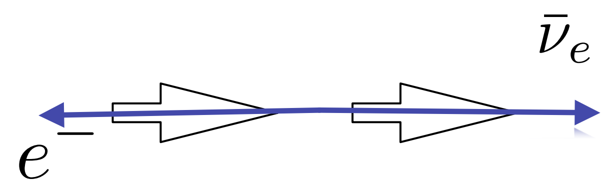
$^{60}\text{Co}\ (J = 5)$ 

$^{60}\text{Ni}\ (J = 4)$ 





Foundations: parity symmetry breaking

Evidence for *P* violation

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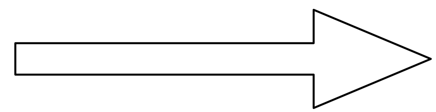

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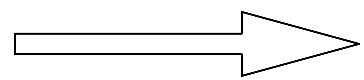

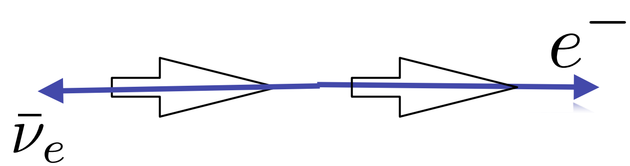

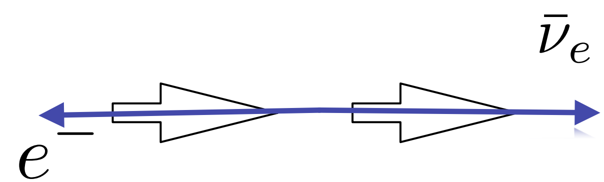

If the Nature can't distinguish left from right, then both decays are possible.

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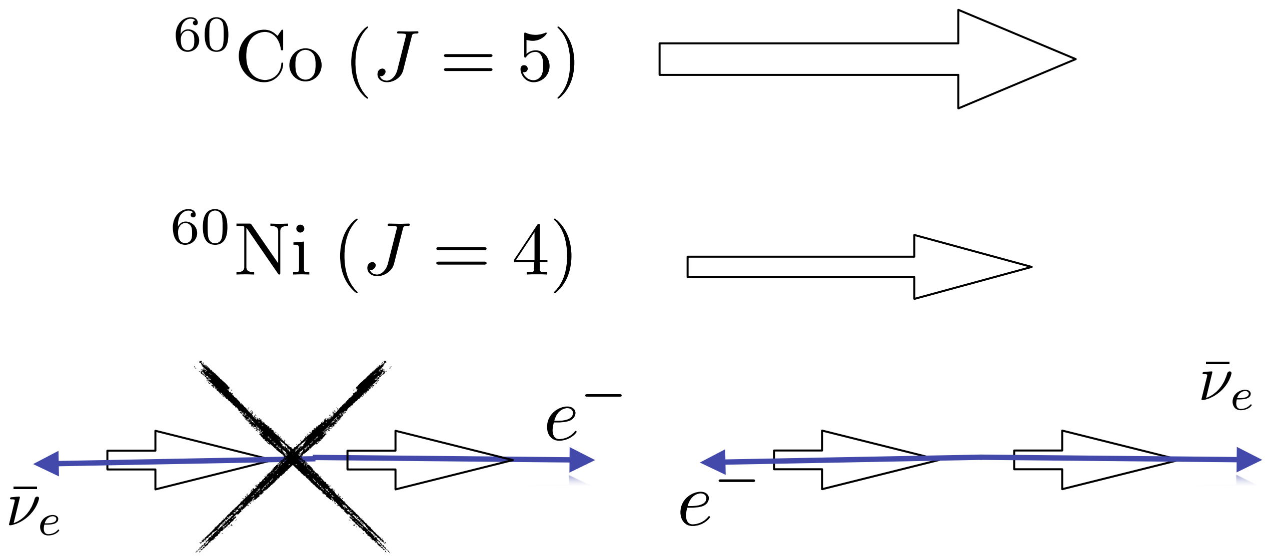
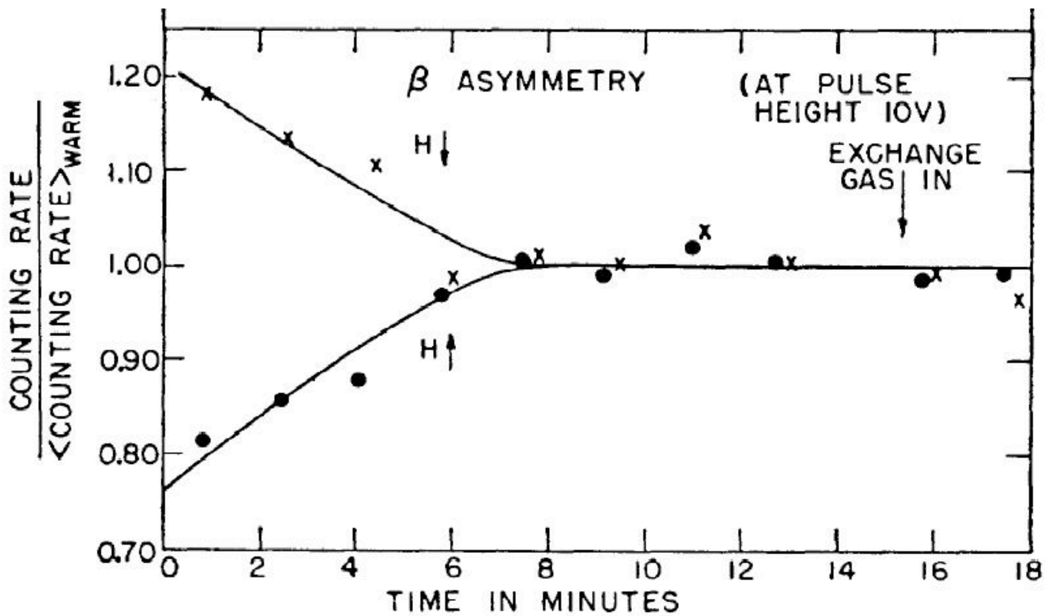


If the Nature can't distinguish left from right, then both decays are possible.

Evidence for *P* violation

- The magnetic field direction is changed and the rate for the electrons emission is measured in the two configurations. The asymmetry is reversed.



- The preferred chiral state is a right-handed anti-neutrino (left-handed electron).

Foundations: parity symmetry breaking

Evidence for *P* violation

- The experiment was conducted during Christmas holidays 1956.
- The paper is published rightafter (2.5 pages).
- Lee and Yang receives the Nobel Prize in 1957 (sounds like this evidence was not overlooked).
- Further experiments established that P and C are maximally violated in weak charged current. This brings $SU(2)_L$ the right symmetry of the weak interactions.

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

IN a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would
:essary evidence for parity conservation
:tion. In beta decay, one could measure
stribution of the electrons coming from
polarized nuclei. If an asymmetry in the
:tween θ and $180°-\theta$ (where θ is the angle
rientation of the parent nuclei and the
the electrons) is observed, it provides
oof that parity is not conserved in beta
/mmetry effect has been observed in the
d Co^{60}.
:nown for some time that Co^{60} nuclei can
›y the Rose-Gorter method in cerium
›balt) nitrate, and the degree of polari-
d by measuring the anisotropy of the
ıma rays.[2] To apply this technique to the
n, two major difficulties had to be over-

The Nobel Prize in Physics 1957

Chen Ning Yang
Prize share: 1/2

Tsung-Dao (T.D.) Lee
Prize share: 1/2

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee *"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"*

Foundations: parity symmetry breaking

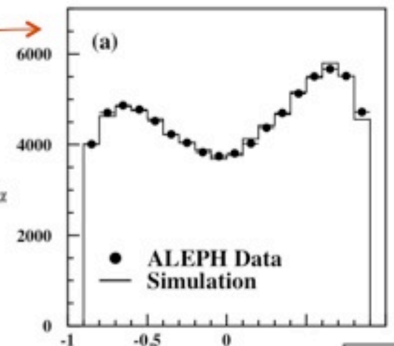
Modern parity violation experiments: LEP

The Standard Model Tests (Part II)

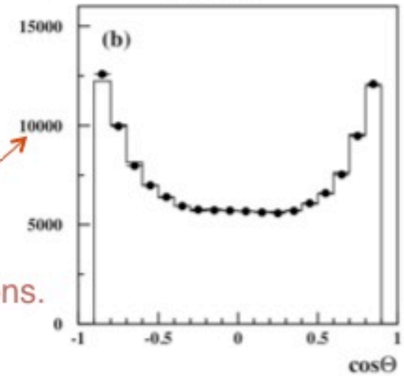
3.3 The Parity-Violating forward-backward asymmetries in e+e-.

- Then we fit the asymmetries to these data:

$$
\begin{aligned}
f_{ijkl} = & (F^{\rm rs}_{\ell,\rm b})_{ijkl} \int_l [1 + x^2 + \frac{8}{3} A^{\rm b}_{\rm FB}(1 - 2\overline{\chi}_{ijkl})\, x] {\rm d}x \\
+ & (F^{\rm ws}_{\ell,\rm b})_{ijkl} \int_l [1 + x^2 - \frac{8}{3} A^{\rm b}_{\rm FB}(1 - 2\overline{\chi}_{ijkl})\, x] {\rm d}x \\
+ & (F^{\rm asym}_{\rm bkg,b})_{ijkl} \int_l [1 + x^2 + \frac{8}{3} A^{\rm b}_{\rm FB}(1 - 2\overline{\chi}_{ijkl})(2\eta^{\rm b}_{ijk} - 1)\, x] {\rm d}x \\
+ & (F_{\ell,c})_{ijkl} \int_l (1 + x^2 - \frac{8}{3} A^{\rm c}_{\rm FB}\, x) {\rm d}x \\
+ & (F^{\rm asym}_{\rm c\to bkg})_{ijkl} \int_l [1 + x^2 - \frac{8}{3} A^{\rm c}_{\rm FB}(2\eta^{\rm c}_{ijk} - 1)\, x] {\rm d}x \\
+ & (F^{\rm asym}_{\rm s\to bkg})_{ijkl} \int_l [1 + x^2 + \frac{8}{3} A^{\rm s}_{\rm FB}(2\eta^{\rm s}_{ijk} - 1)\, x] {\rm d}x \\
+ & (F^{\rm asym}_{\rm d\to bkg})_{ijkl} \int_l [1 + x^2 + \frac{8}{3} A^{\rm d}_{\rm FB}(2\eta^{\rm d}_{ijk} - 1)\, x] {\rm d}x \\
+ & (F^{\rm asym}_{\rm u\to bkg})_{ijkl} \int_l [1 + x^2 - \frac{8}{3} A^{\rm u}_{\rm FB}(2\eta^{\rm u}_{ijk} - 1)\, x] {\rm d}x \\
+ & (F^{\rm sym}_{\rm bkg})_{ijkl} \int_l (1 + x^2) {\rm d}x,
\end{aligned}
$$



Parity violation even seen for charm.



Includes QED and QCD effects.

Measuring simultaneously the mixing parameter w/ leptons.

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An intermediate conclusion

- ✓ Parity is violated in weak interaction.
- ✓ One gets from experimental results so far the following picture:

✓ Any theory of the weak interaction shall include these properties.

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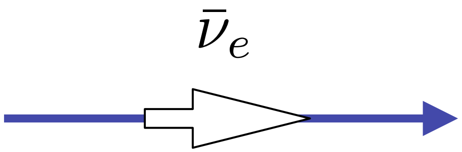

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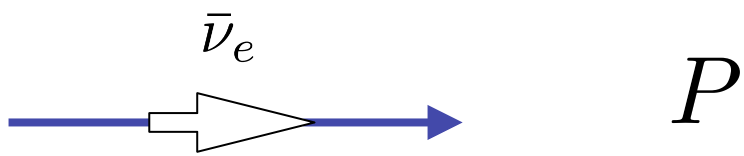

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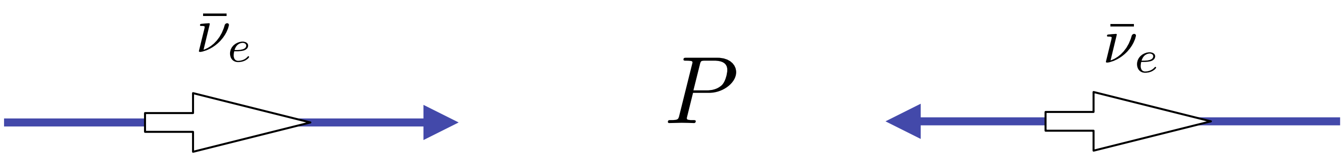

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Foundations: parity symmetry breaking

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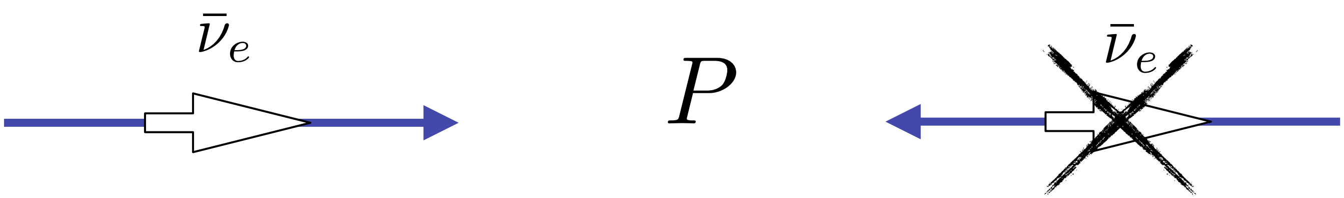

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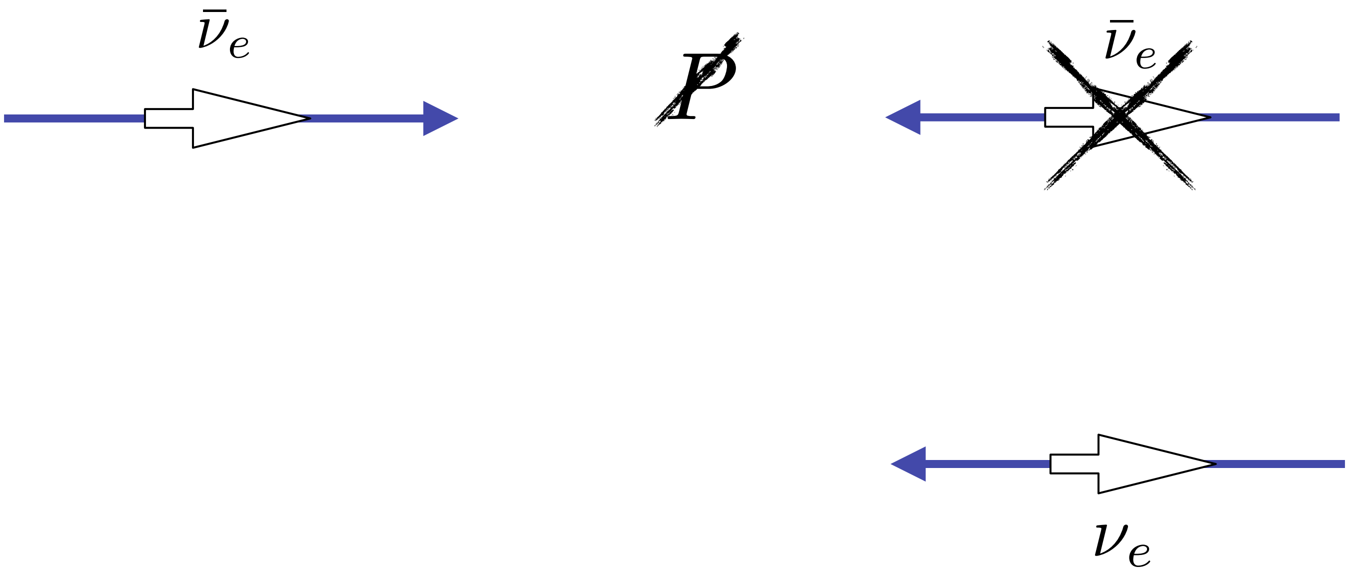

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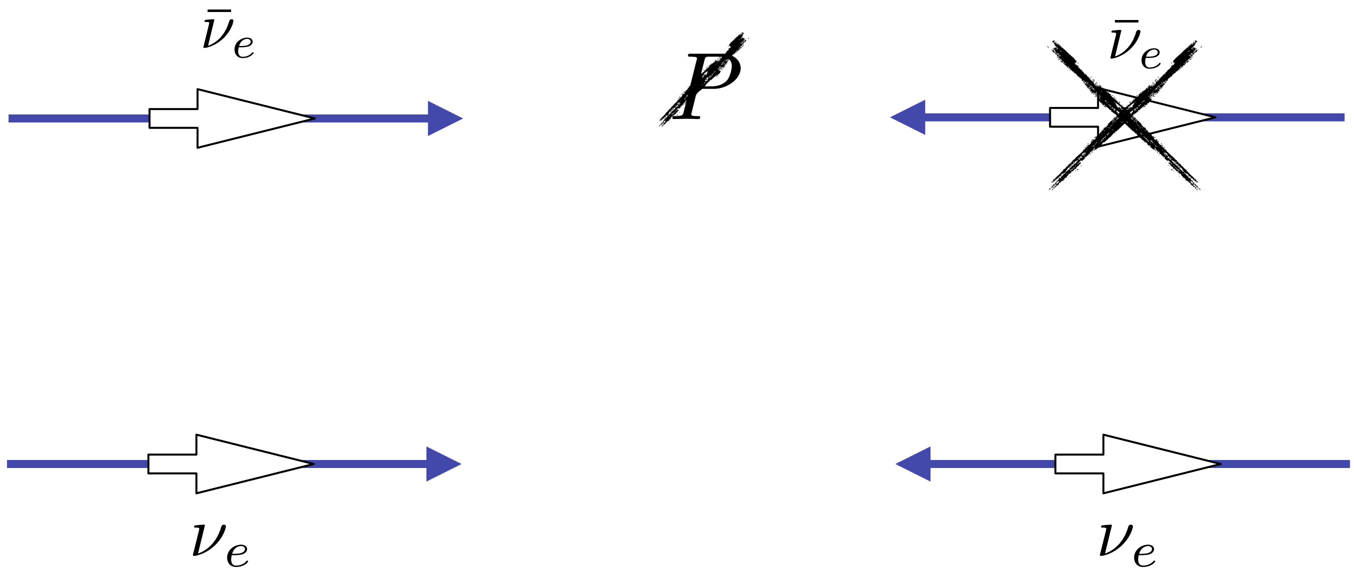

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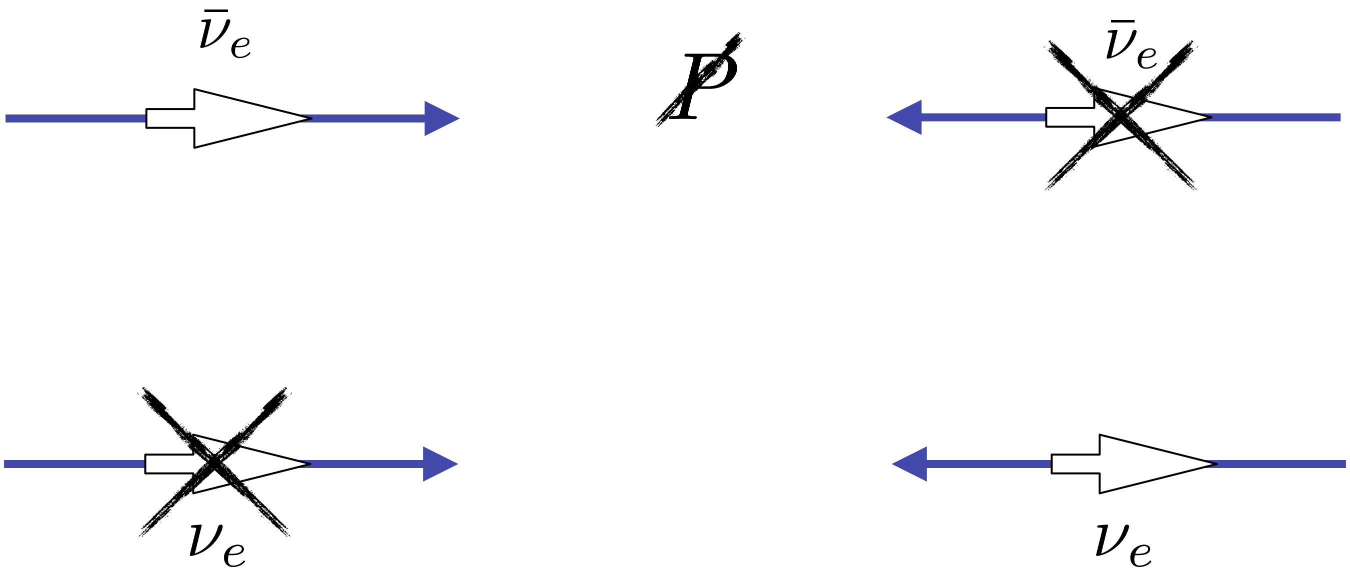

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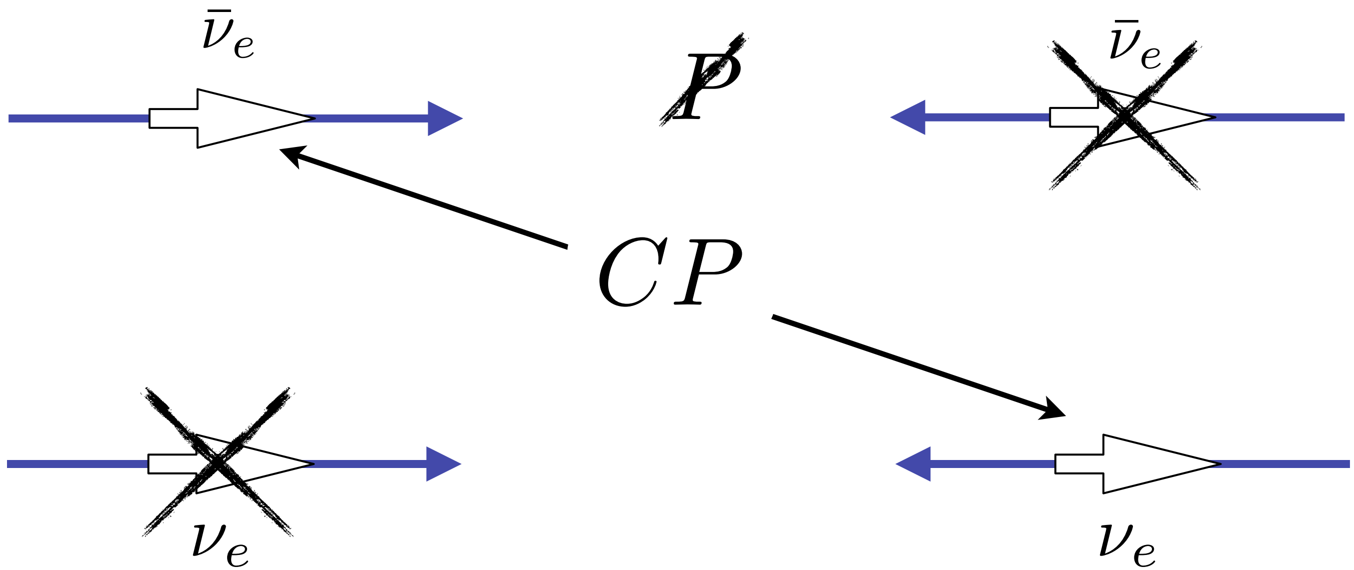
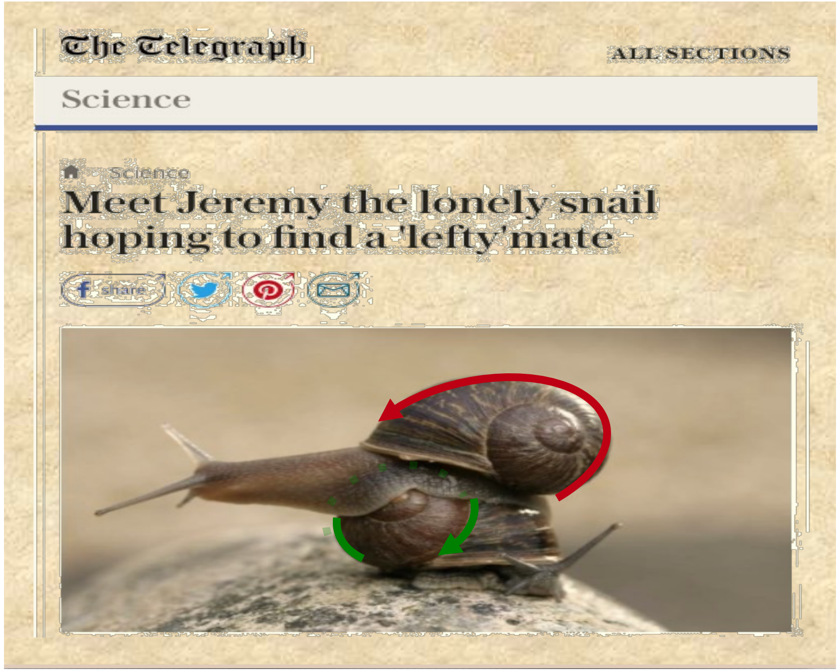


- ✓ Any theory of the weak interaction shall include these properties.

C and *P* breaking and *CP* symmetry

An intermediate conclusion

✓ Parity violation do occur elsewhere



✓But those are not of fundamental nature. The right-handed DNA molecule for instance can be synthesised.

CP symmetry

Question: OK, parity is violated in the weak interaction. But can't we restore the left-right symmetry by considering the product *C* x *P*? Seems a good symmetry at least in the pion decay.

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

Discovery of *CP* violation.

- With simple quantum mechanics, one can show that in absence of *CP* violation:

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

- Final states *CP* eigenvalues are +1 ($\pi\pi$) and -1 ($\pi\pi\pi$). If *CP* is a conserved quantity, one then should have:

$$
\begin{aligned}
K_1 &\rightarrow \pi\pi \\
K_2 &\rightarrow \pi\pi\pi .
\end{aligned}
$$

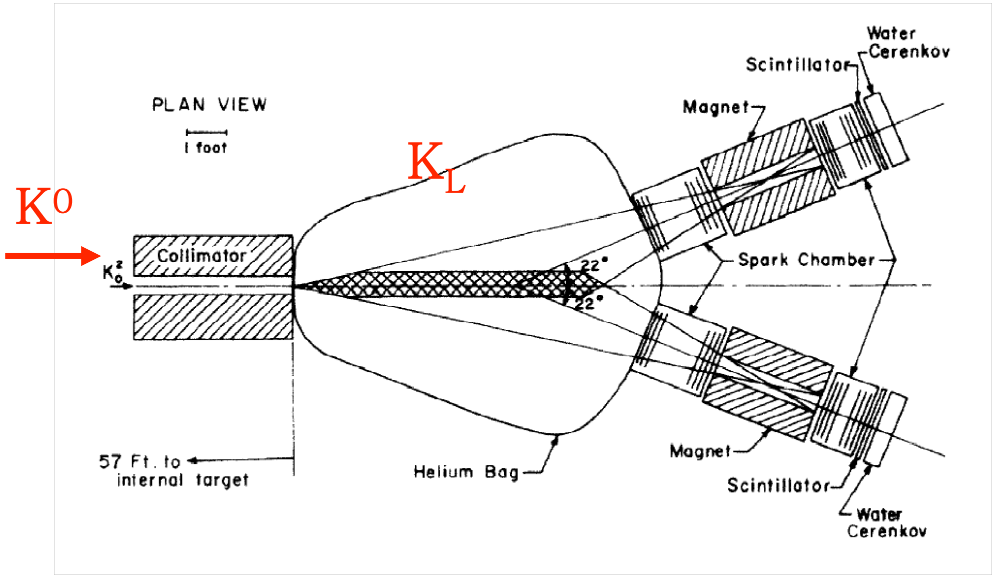
Which we'll identify as K^0_S and K^0_L respectively.

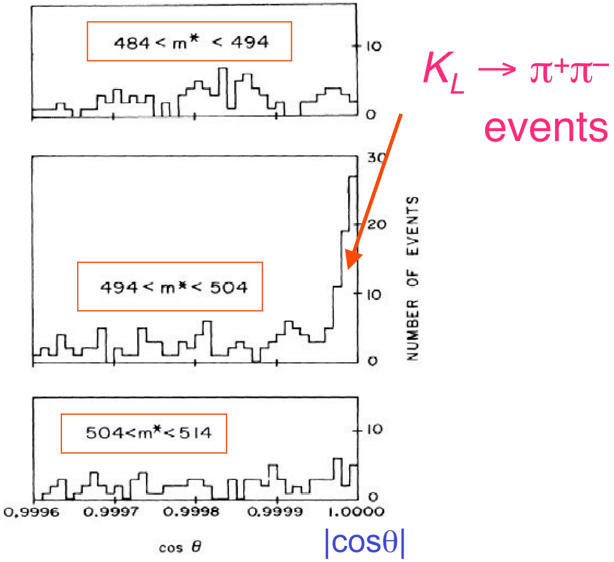
- measuring K^0_L decays into two pions ? Proof that *CP* symmetry is violated in weak interaction.

Discovery of *CP* violation.

- The CP violation in kaon system: Christenson, Cronin, Fitch , Turlay. Phys. Rev. Lett. 13 (1964) 138.

- Far after the target, only the long species of K^0 survive. They measured:





$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)} = (2.271 \pm 0.017)10^{-3}.$$

Discovery of *CP* violation.

Message Number 1:

The *CP* symmetry is violated in the mixing of neutral mesons, a pure electroweak phenomenon, *e.g.*

$$K^0 \longrightarrow \bar{K}^0 \neq \bar{K}^0 \longrightarrow K^0$$

1964, Brookhaven

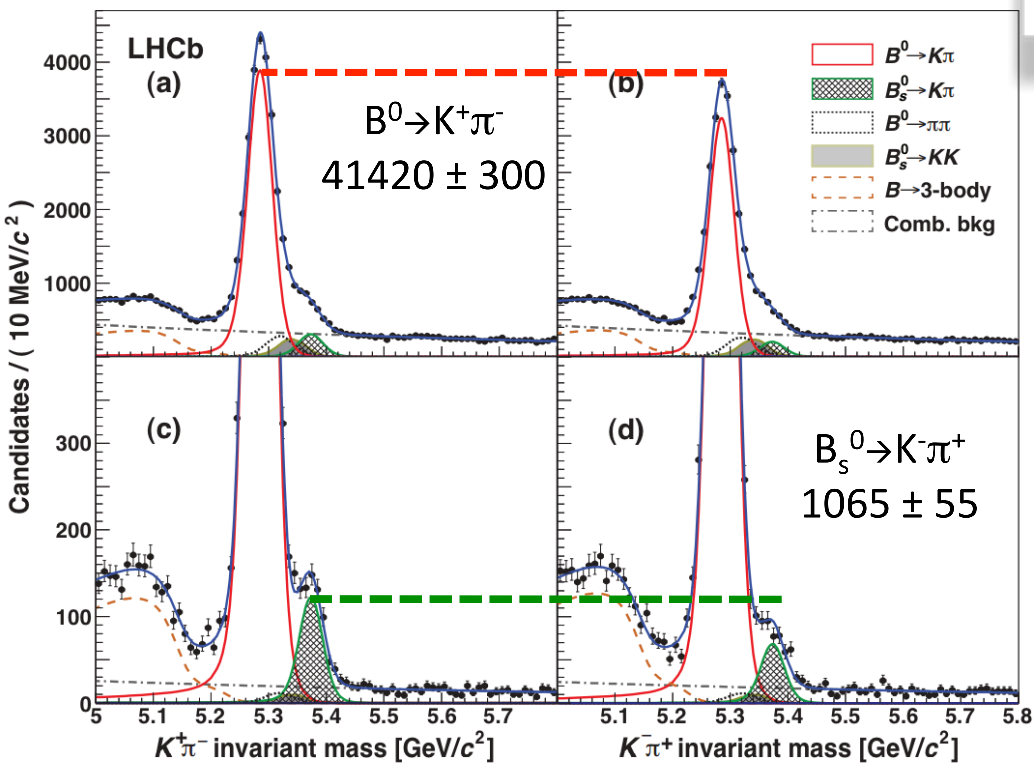
Foundations: *CP* symmetry breaking

Other discoveries of *CP* violation.

- Compare the decay rates of self-tagged modes $K\pi$

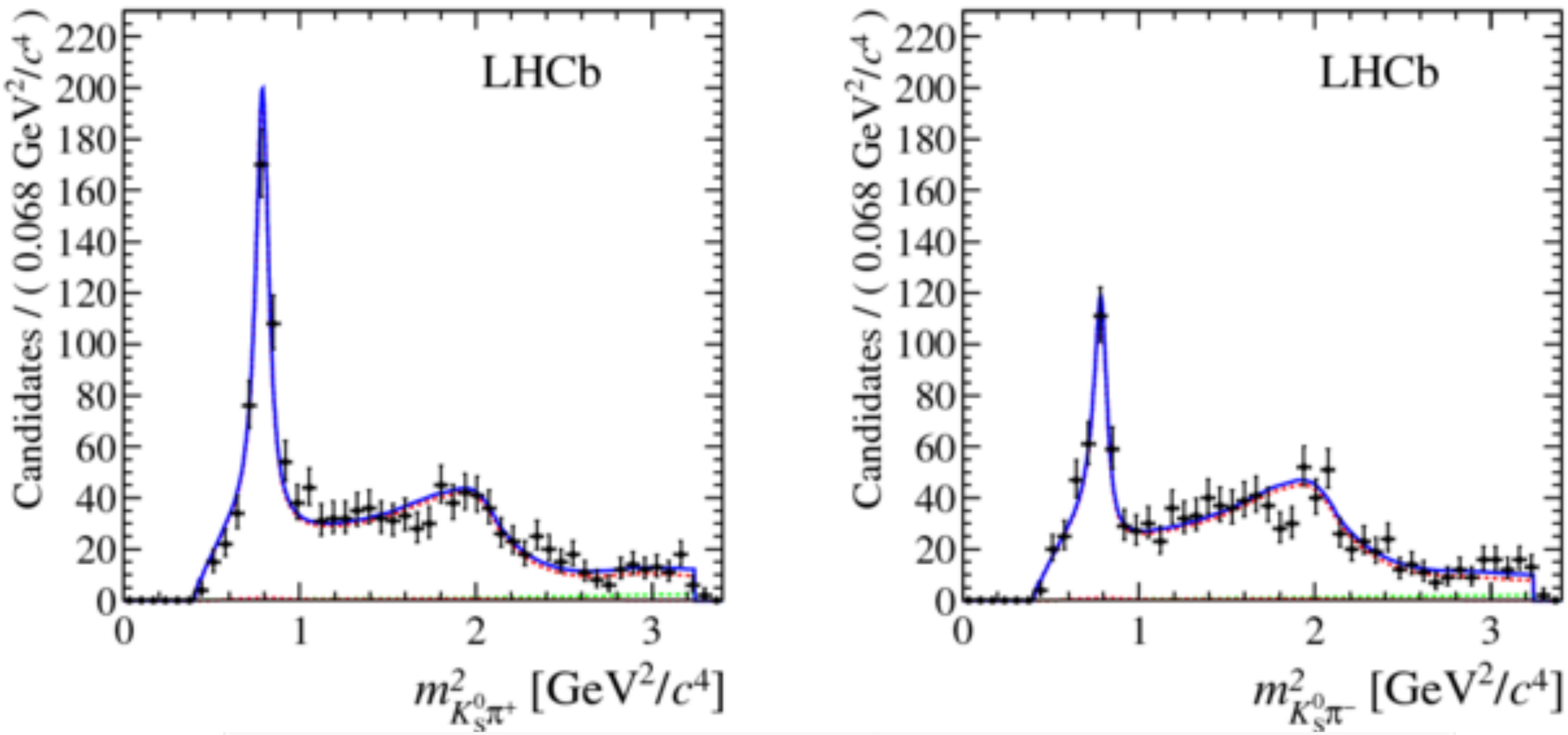
$\mathcal{L}$ = (1/fb @ √s = 7 TeV)

$$
\begin{aligned}
A_{\rm raw}(B^0 \to K^-\pi^+) &= -0.091 \pm 0.006, \\
A_{\rm raw}(B_s \to K^+\pi^-) &= 0.28 \pm 0.04,
\end{aligned}
$$



- Data-driven control of PID efficiencies thanks to the self-tagged mode $D^{*+} \to D^0 (K^-\pi^+)\pi^+$
- Raw asymmetries corrected from detection asymmetry (also D^{*+} control sample.
- *B* production asymmetry simultaneously measured from decay time distribution.

Other discoveries of *CP* violation.



Phys. Rev. Lett. 120, 261801 (2018)

$$A_{CP}(\overline{B}^0 \to K^*(892)^-\pi^+) = -0.30 \pm 0.06$$

Other discoveries of *CP* violation.

Message Number 2:

The *CP* symmetry is violated in the decay of beautiful particles, pure electroweak phenomenon, *e.g.*

$$B^0 \longrightarrow K^+\pi^- \neq \bar{B}^0 \longrightarrow K^-\pi^+$$

2004, B-factories

Other discoveries of *CP* violation.

Message Number 3:

The *CP* symmetry can be violated in the interplay (interference) of the two previous sources of *CP* violation, *e.g.*

$$B^0 \longrightarrow f_{CP} \quad \neq \quad \overline{B}^0 \longrightarrow f_{CP}$$

$$B^0 \searrow \overline{B}^0 \nearrow f_{CP} \qquad\qquad \overline{B}^0 \searrow B^0 \nearrow f_{CP}$$

2001, *B*-factories, will come back to that next

Concluding this introduction

- *C*, *P* and *CP* are (so far) conserved in electromagnetic and strong interactions.
- *C* and *P* symmetries are maximally violated by the charged weak interaction.
- *CP* symmetry is slightly violated in the electroweak interaction.

- There are three ways of *CP* violation to manifest in the Nature so far:

  1) In the mixing of neutral particles (observed solely in neutral kaon mixing - 1964).

  2) In the decay of the beautiful and strange mesons (K and $B_{d,s}$, 2001 and 2004,2013 resp.).

  3) In the interference between decay and mixing of the beautiful particles (2001, see next chapters) .

  And that's all.

A personal comment before going to SM

- We do not have yet a (satisfactory) dynamical mechanism to explain these discrete symmetry breakings. And to my knowledge, no mathematical Physics way to do so.

- Still, what comes next is elegant.

- We'll try to make sense of the *CP* symmetry breaking phenomena (within the SM).

The next Chapter of Part I starts at the next slide

The next Chapter of Part I starts at the next slide

A more detailed outline

1. Foundations: setting the scene, the discovery of the *P* and *CP* violation.
2. Few elements about CKM. Machine and experiments. Main observables and measurements relevant to study *CP* violation.
3. The global fit of the SM: CKM profile.

CKM: the unitarity triangle.

- We have touched that the Higgs field gives mass to bosons (EWSB) but also fermions (quarks and leptons), through the Yukawa couplings but this is not the end of the story:

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_{\mu}^{\dagger} [\sum_{ij} \bar{u}_i(q_2)\gamma^{\mu}(1-\gamma^5) V_{ij} d_j] + \text{h.c}$$

- After spontaneous symmetry breaking, and once the mass matrices are diagonalised, a paradigm determines also how the mass and weak eigenstates are related. This is governed by the CKM matrix. As for the (fermion) masses, nothing is predicted except the mass matrix must be unitary and c

$$\begin{pmatrix} u \\ s \\ b \end{pmatrix}_{EW} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} u \\ s \\ b \end{pmatrix}_{MASS}$$

CKM: the unitarity triangle.

- Weak eigenstates are therefore a mixture of mass eigenstates, controlled by the Cabibbo-Kobayashi-Maskawa elements V_{ij}: flavour changing charged currents between quark generations.

- This matrix is a 3X3, unitary, complex, and hence described by means of four parameters: 3 rotation angles and a phase. The latter makes possible the *CP* symmetry violation in the Standard Model.

- These four parameters are free parameters of the SM. As for electroweak gauge precision tests, they must be measured with some redundancy and the SM hypothesis is to be falsified by a consistency test. We will review in this lecture this overall test. But let's define first the parameters.

CKM: the unitarity triangle. Parameterisation.

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

Consider the Wolfenstein parametrization as in EPJ C41:1-131,2005 : unitary-exact at each order and phase- convention independent:

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}, \quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \quad \text{and} \quad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- λ is measured from $|V_{ud}|$ and $|V_{us}|$ in superallowed beta decays and semileptonic kaon decays, respectively.

- A is further determined from $|V_{cb}|$, measured from semileptonic charmed B decays.

- The last two parameters are to be determined from angles and sides measurements of the CKM unitarity triangle.

CKM: the unitarity triangle. Parameterisation.

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

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

CKM: the unitarity triangle. Representation.

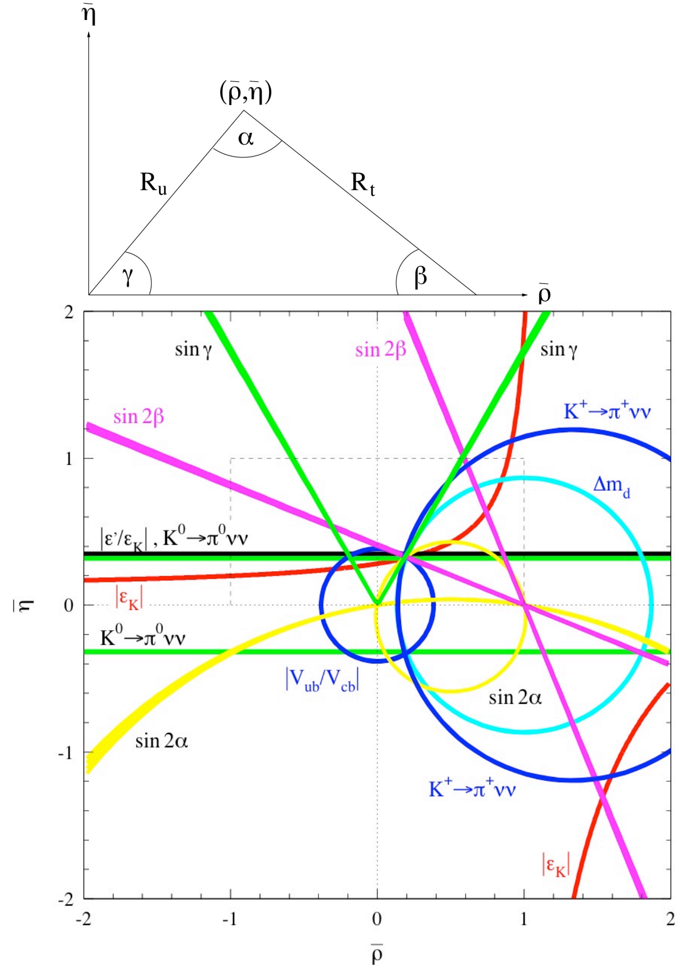
- An elegant way to represent the unitarity relations is to display them in the complex plane.

- $$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{cd}V_{cb}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0.$$

- The area of the triangle is half the Jarlskog invariant and measures the magnitude of the *CP* violation:

$$J \sum_{\sigma\gamma=1}^{3} \epsilon_{\mu\nu\sigma}\epsilon_{\alpha\beta\gamma} = \mathrm{Im}(V_{\mu\alpha}V_{\nu\beta}V_{\mu\beta}^*V_{\nu\alpha}^*) \,,$$

$$J = A^2\lambda^6\eta(1-\lambda^2/2) \simeq 10^{-5}$$



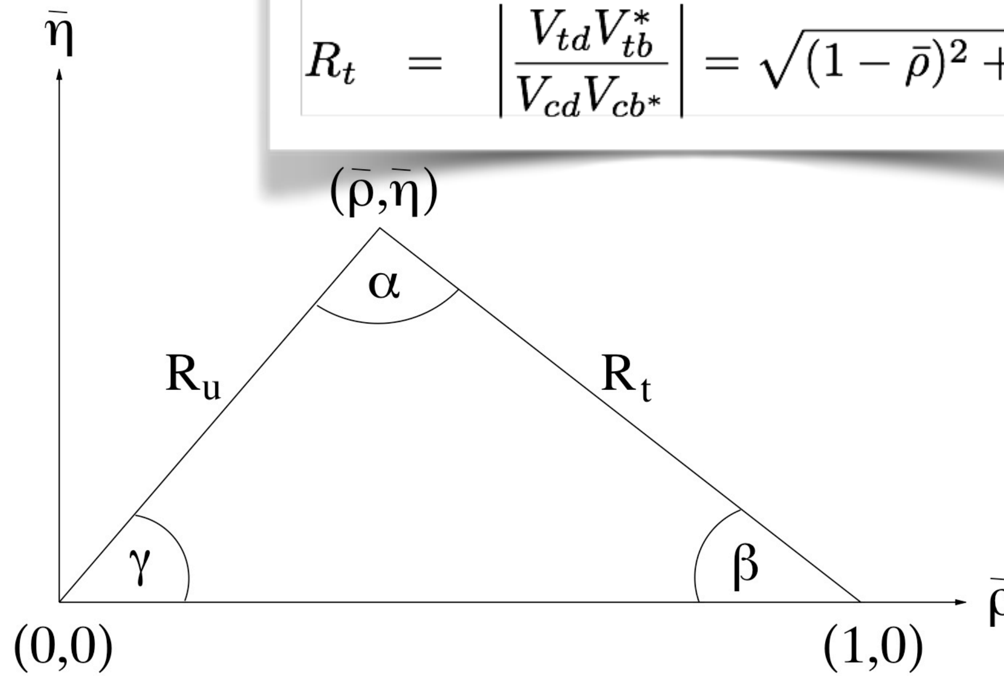
CKM: the unitarity triangle. Definitions.

- Sides and angles of the unitarity triangle.

- Normalization given by the matrix element $V_{cd}.V_{cb}{}^*$.

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{\bar\rho^2+\bar\eta^2}\,,$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar\rho)^2+\bar\eta^2}\,.$$



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$

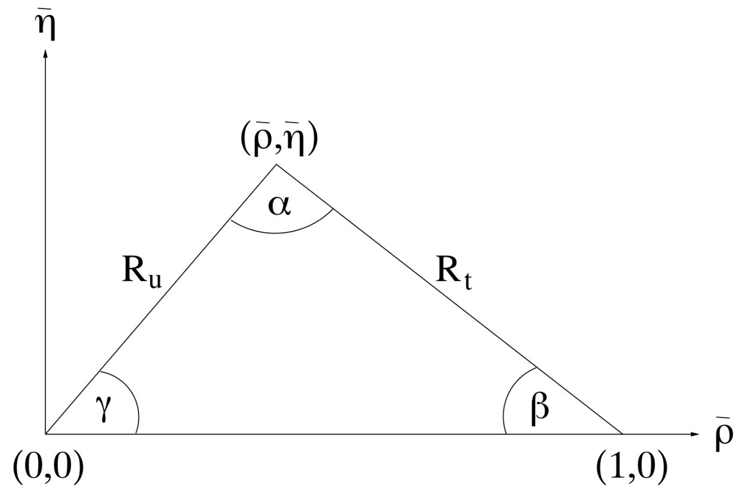
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

CKM: the unitarity triangle. Definitions.

- Sides of the unitarity triangle. Towards the experimental constraints:

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{\bar{\rho}^2 + \bar{\eta}^2}\,,$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}\,.$$



- R_u is measured by the matrix elements V_{ub} and V_{cb} determined from the semileptonic decays of *b*-hadrons.

- R_t implies the matrix element V_{td} and hence can be measured from the mixing of B^0 mesons.

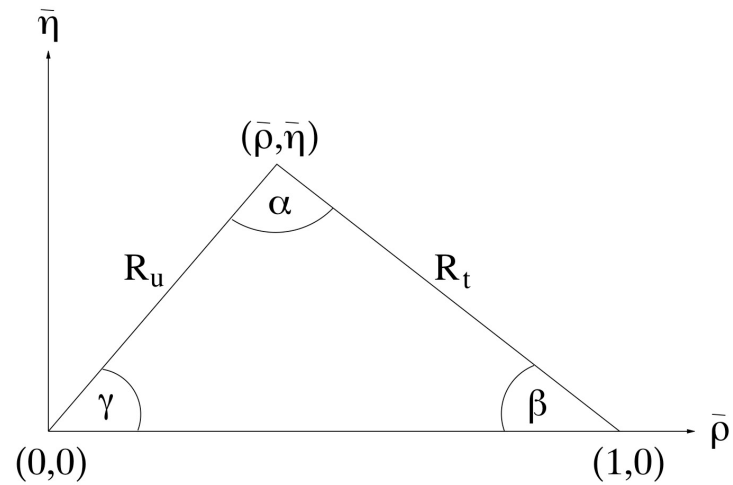
CKM: the unitarity triangle. Definitions.

• Angles of the unitarity triangle. Towards the experimental constraints:

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$

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



• The angle β is directly the weak mixing phase of the of B^0 mixing.

• The angle γ is the weak phase at work in the charmless *b*-hadrons decays.

• The angle α is nothing else than (π–β–γ) and can be exhibited in processes where both charmless decays and mixing are present.

Note: a phase is not an observable. Only phase differences can be measured.

CKM: the unitarity triangle. Experiments.

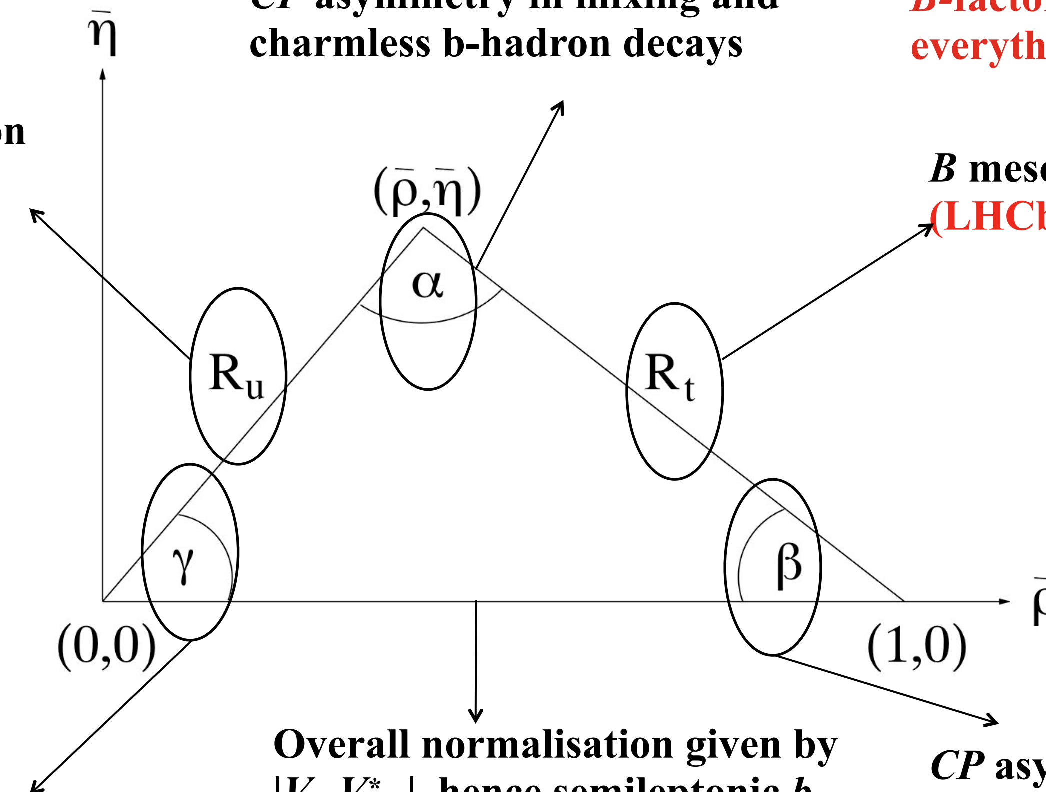
- Summary:

***CP* asymmetry in mixing and charmless b-hadron decays**

***B*-factories measure everything**

Semileptonic b-hadron decays (LHCb in)

***B* meson mixing (LHCb in)**



***CP* asymmetry in $b \rightarrow u$ *b*-hadron decays (LHCb in)**

Overall normalisation given by $|V_{cd}V^*_{cb}|$, hence semileptonic *b* decays

***CP* asymmetry in mixing processes (LHCb in)**

CKM: the unitarity triangle. Machine and Experiments.

There are many machines and experiments which are interested in the Flavour Physics and *CP* violation. As for their pioneering role, we'll mention ARGUS (DESY, Ge), CLEO (Cornell, US) and LEP (CERN, EU) experiments. The kaon sector is not in the scope of this lecture. Major results came from NA48 (CERN, EU) and KTeV (FNAL, US) though. Japan and Cern projects for kaon physics should bring extremely valuable results. Tevatron used to provide as well world class measurements in heavy flavours physics.

But the *B*-factories (now Belle II) and the LHCb experiment at LHC definitely dominate the landscape.

A complete review of the observables is given here: (just click).

The next Chapter of Part I starts at the next slide

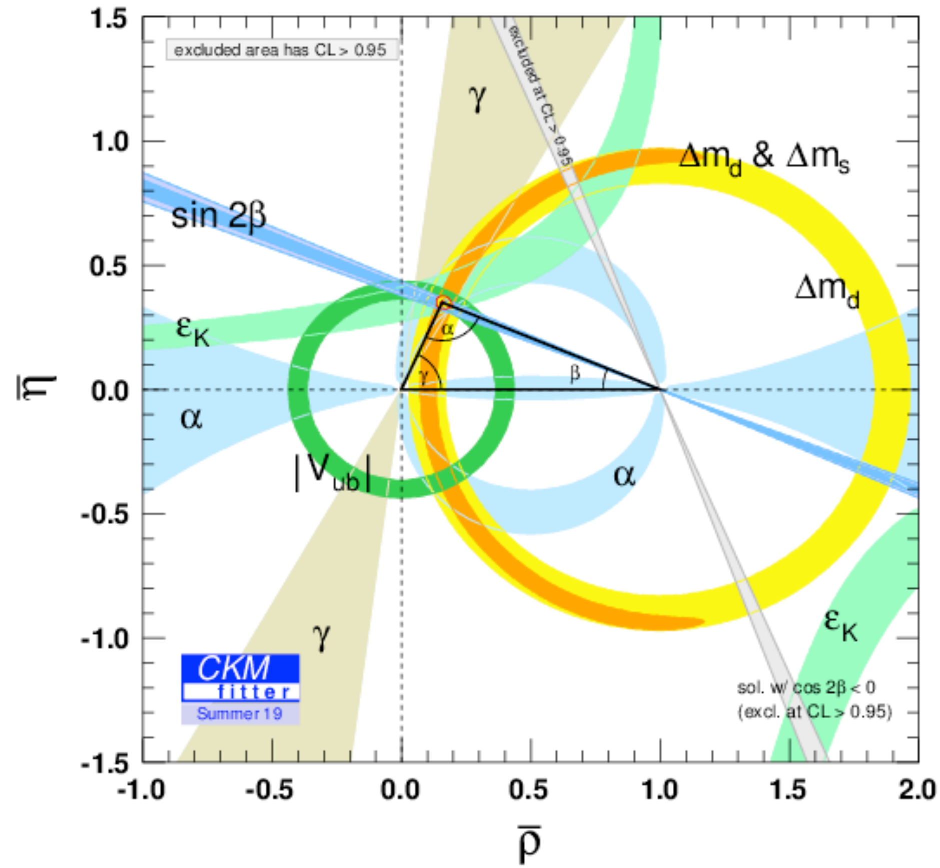
CKM: the global fit. The observables and parameters.

- List of the inputs: in the details.
- The ones discussed in the previous link
- α, γ
- Lattice parameters. And ratios.
- The tauonic *B* decay.

Parameter	Value ± Error(s)	Reference	Errors GS	Errors TH
$\|V_{ud}\|$ (nuclei)	0.97425 ± 0.00022	[1]	⋆	-
$\|V_{us}\|$ $(K_{\ell 3})$	0.2254 ± 0.0013	[2]	⋆	-
$\|V_{ub}\|$	$(3.92 \pm 0.09 \pm 0.45) \times 10^{-3}$	[3, 4]	⋆	⋆
$\|V_{cb}\|$	$(40.89 \pm 0.38 \pm 0.59) \times 10^{-3}$	[3]	⋆	⋆
$\|\varepsilon_K\|$	$(2.229 \pm 0.010) \times 10^{-3}$	[5]	⋆	-
Δm_d	(0.507 ± 0.005) ps^{-1}	[3]	⋆	-
Δm_s	(17.77 ± 0.12) ps^{-1}	[6]	⋆	-
$\sin(2\beta)_{[c\bar{c}]}$	0.673 ± 0.023	[3]	⋆	-
$S^{+-}_{\pi\pi}$, $C^{+-}_{\pi\pi}$, $C^{00}_{\pi\pi}$	Inputs to isospin analysis	[3]	⋆	-
$\mathcal{B}_{\pi\pi}$ all charges	Inputs to isospin analysis	[3]	⋆	-
$S^{+-}_{\rho\rho,L}$, $C^{+-}_{\rho\rho,L}$, $S^{00}_{\rho\rho}$, $C^{00}_{\rho\rho}$	Inputs to isospin analysis	[3]	⋆	-
$\mathcal{B}_{\rho\rho,L}$ all charges	Inputs to isospin analysis	[3]	⋆	-
$B^0 \to (\rho\pi)^0 \to 3\pi$	Time-dependent Dalitz analysis	[7, 8]	⋆	-
$B^- \to D^{(*)}K^{(*)-}$	Inputs to GLW analysis	[3]	⋆	-
$B^- \to D^{(*)}K^{(*)-}$	Inputs to ADS analysis	[3]	⋆	-
$B^- \to D^{(*)}K^{(*)-}$	GGSZ Dalitz analysis	[3]	⋆	-
$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)$	$(1.68 \pm 0.31) \times 10^{-4}$	[9]	⋆	-
$\overline{m}_c(m_c)$	$(1.286 \pm 0.013 \pm 0.040)$ GeV	[12]	⋆	⋆
$\overline{m}_t(m_t)$	$(165.02 \pm 1.16 \pm 0.11)$ GeV	[10]	⋆	⋆
B_K	$0.723 \pm 0.004 \pm 0.067$	[16]	⋆	⋆
$\alpha_s(m_Z^2)$	0.1176 ± 0.0020	[5]	-	⋆
η_{cc}	Calculated from $\overline{m}_c(m_c)$ and α_s	[17]	-	⋆
η_{ct}	0.47 ± 0.04	[18]	-	⋆
η_{tt}	0.5765 ± 0.0065	[17, 18]	-	⋆
$\eta_B(\overline{\mathrm{MS}})$	0.551 ± 0.007	[19]	-	⋆
f_{B_s}	$(228 \pm 3 \pm 17)$ MeV	[16]	⋆	⋆
B_s	$1.28 \pm 0.02 \pm 0.03$	[16]	⋆	⋆
f_{B_s}/f_{B_d}	$1.199 \pm 0.008 \pm 0.023$	[16]	⋆	⋆
B_s/B_d	$1.05 \pm 0.01 \pm 0.03$	[16]	⋆	⋆

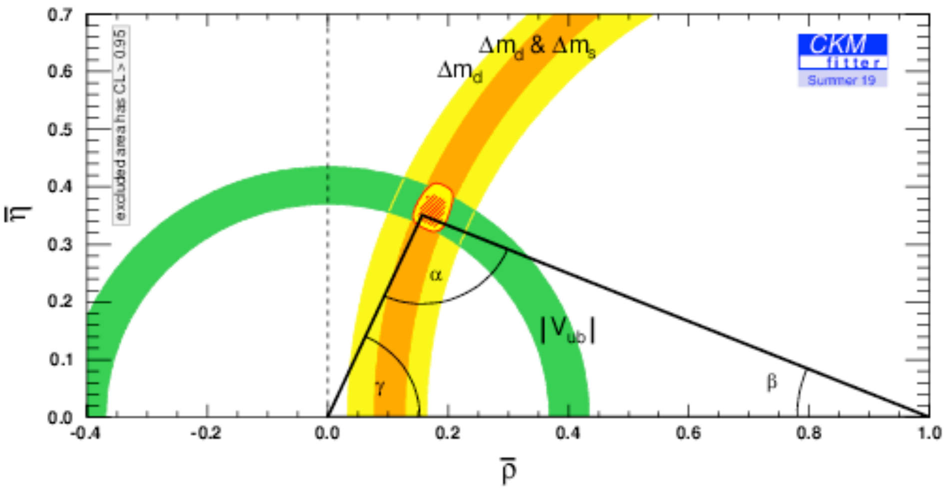
the CKM profile

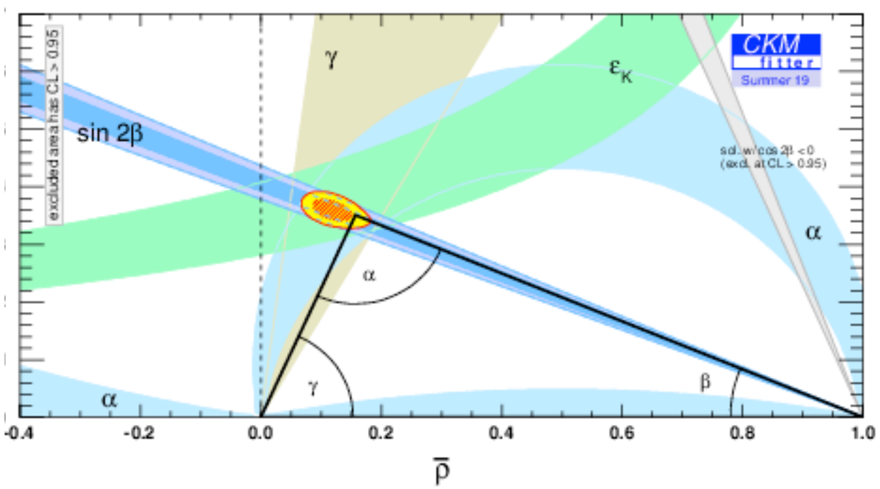
- The global picture:
- Notice to read the picture: regions outside the coloured area are excluded at 95 % Confidence Level.
- There is one and only one region of Wolfenstein parameter space which is common to all the constraints.
- In other terms, there is a remarkable consistency between all of the observables.
- The superimposed triangle is the best fit result.



the CKM profile

- The global picture: comparison of observables constraints.
- *CP*-conserving against *CP*-violating.

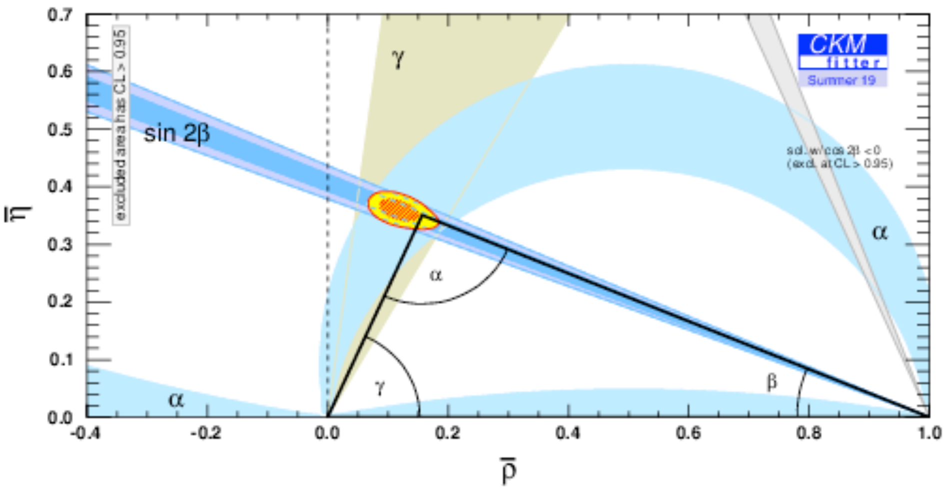


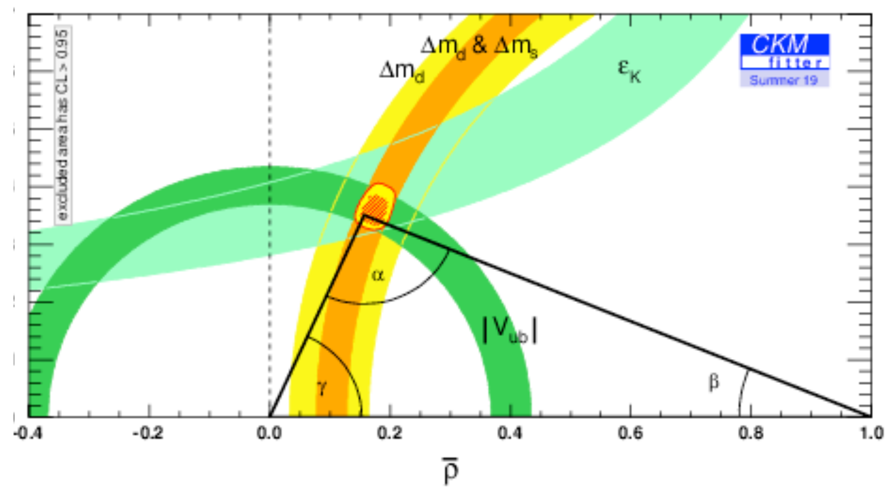


- Correct agreement. *CP*-conserving observables can quantify *CP* violation.

the CKM profile

- The global picture: comparison of observables constraints.
- Angles (No theory) against No angles (Hadronic uncert.).

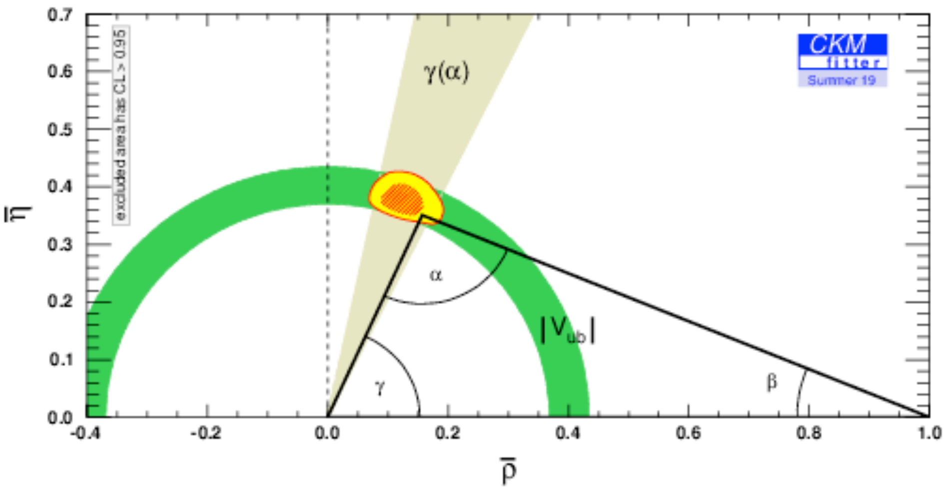


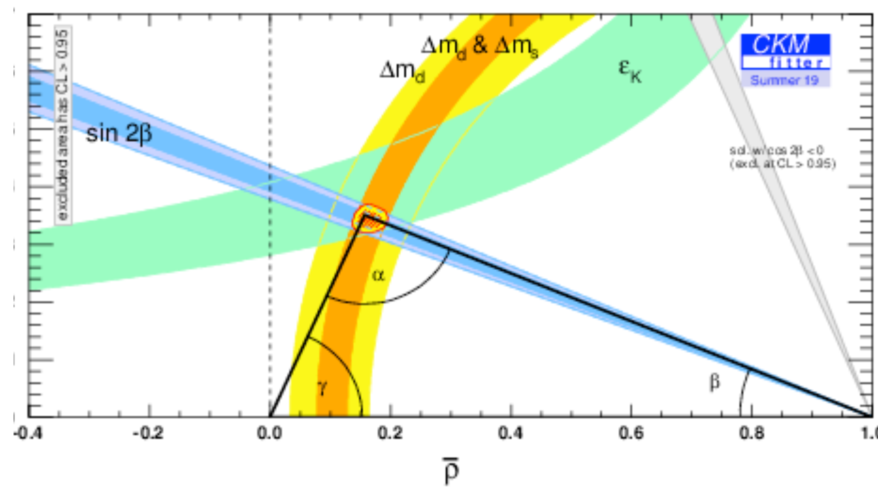


- Correct agreement. Remember that only observables with a good theoretical control are considered in the global fit.

the CKM profile

- The global picture: comparison of observables constraints.
- Trees against Loops.





- Trees are thought to be pure SM. Loops could exhibit New Physics. Fair agreement.

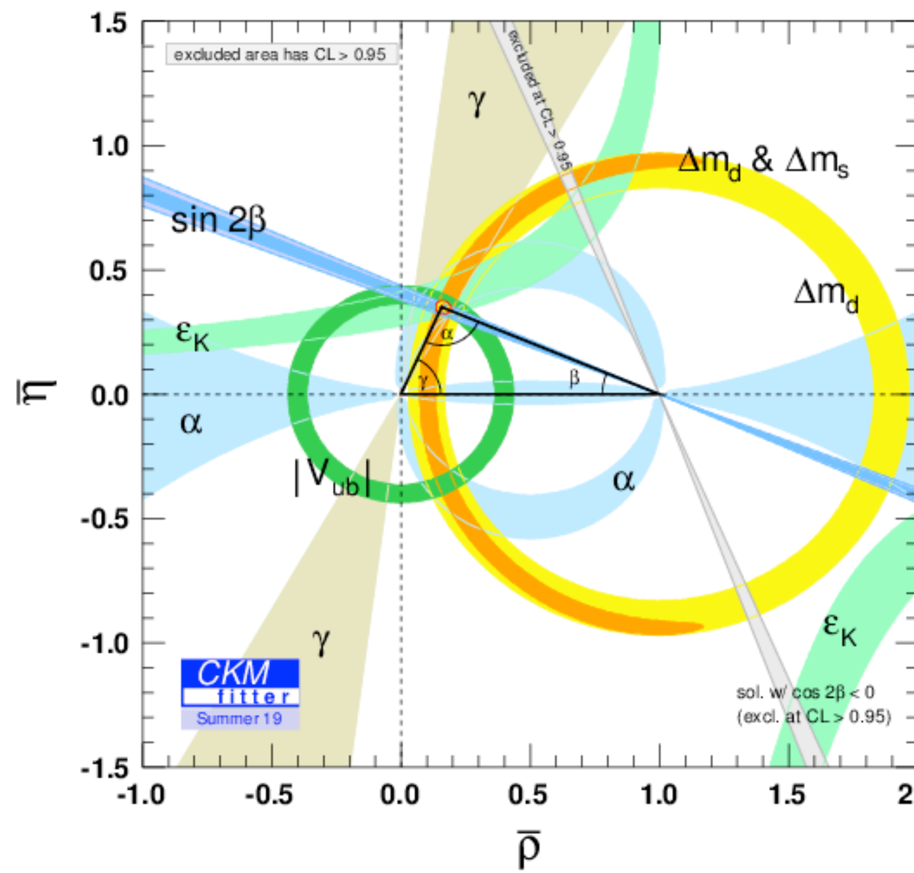
the CKM profile

- The global picture:

- This is a tremendous success of the Standard Model and especially the Kobayashi-Maskawa mechanism. This is simultaneously an outstanding experimental achievement by the *B* factories.

- CKM is at work in weak charged current.

- The KM phase IS the dominant source of *CP* violation in *K* and *B* system.



the CKM profile: Back to the future

- Recreational Homework. Find the break through measurements along the past two decades.

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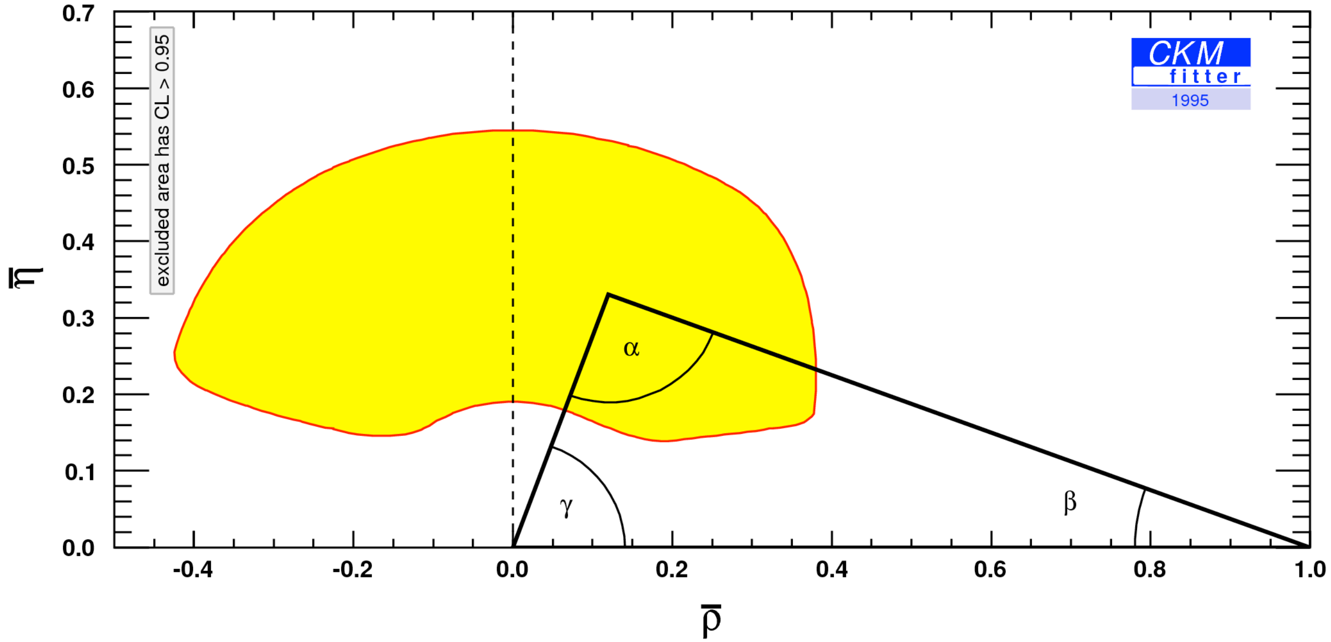

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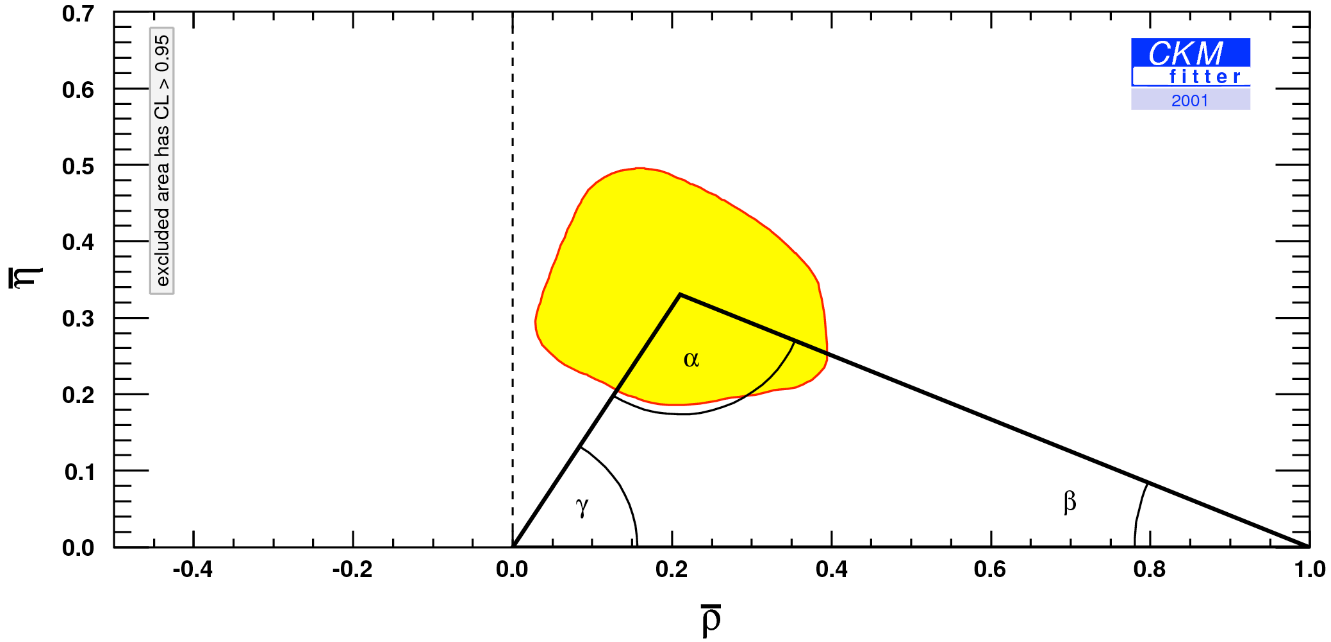

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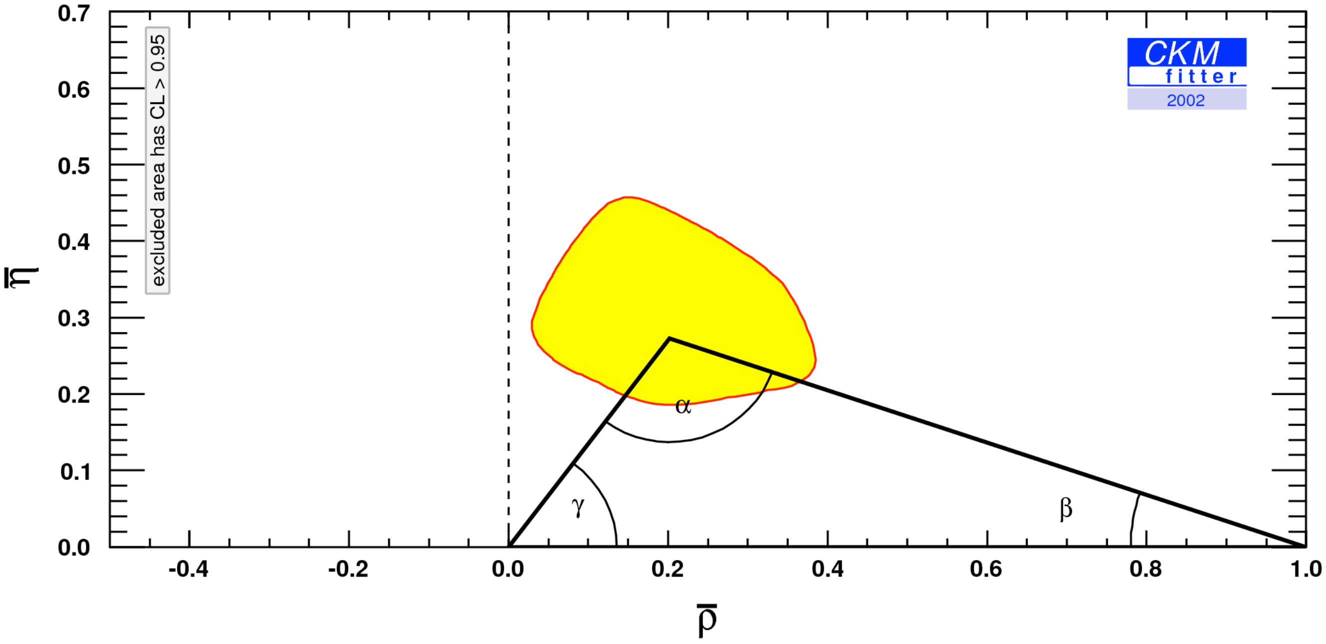

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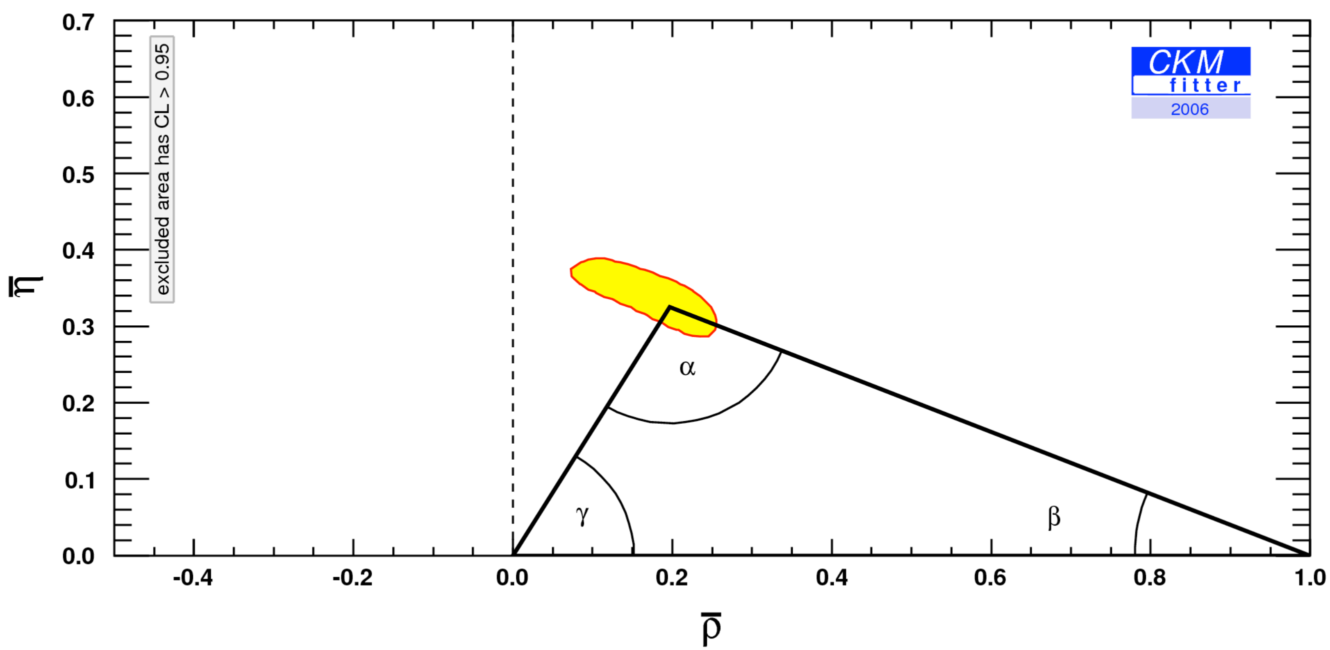

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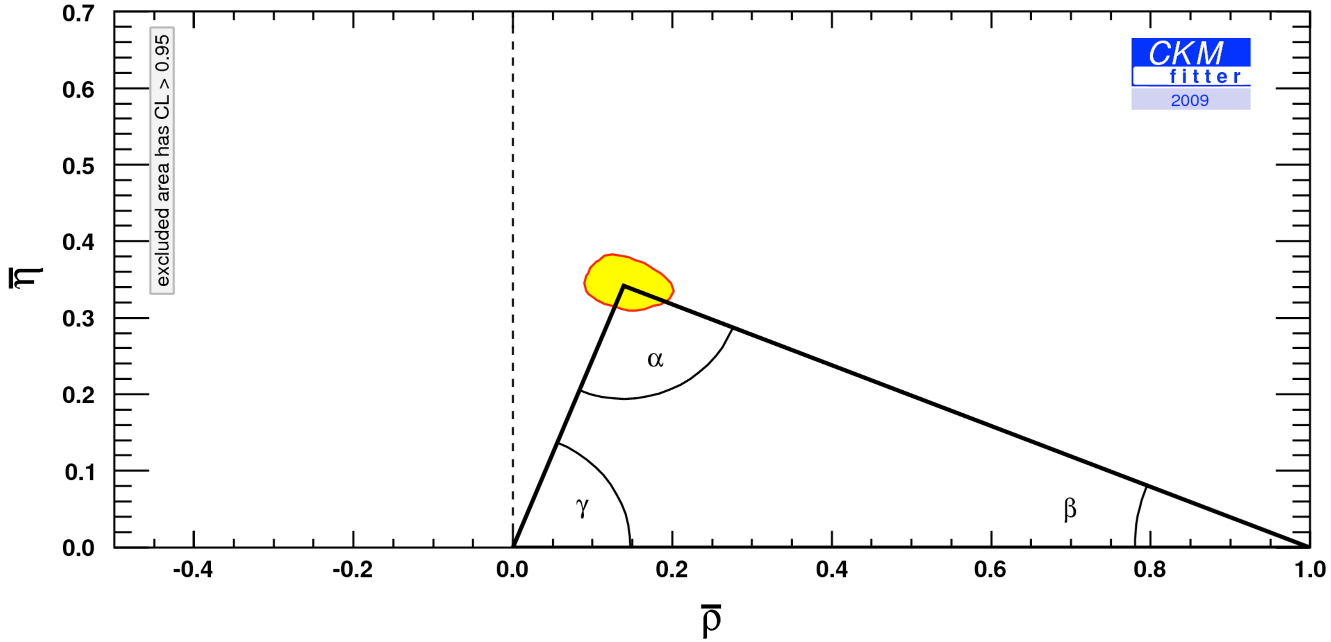

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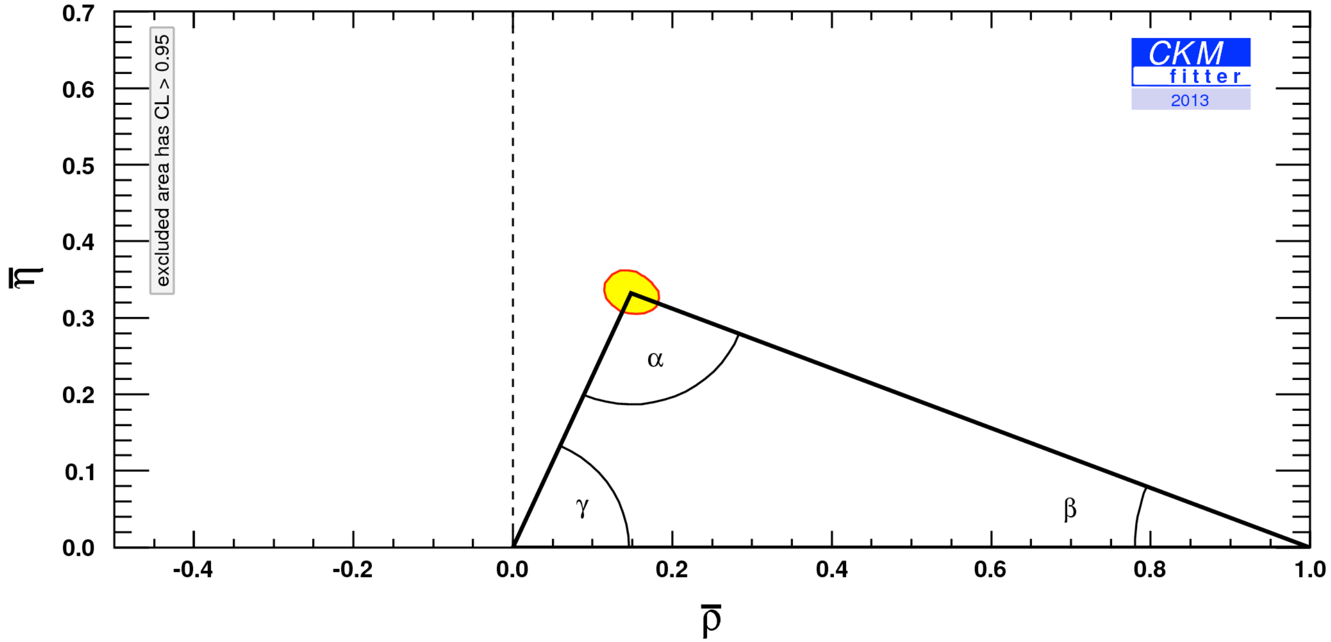

the CKM profile: Back to the future

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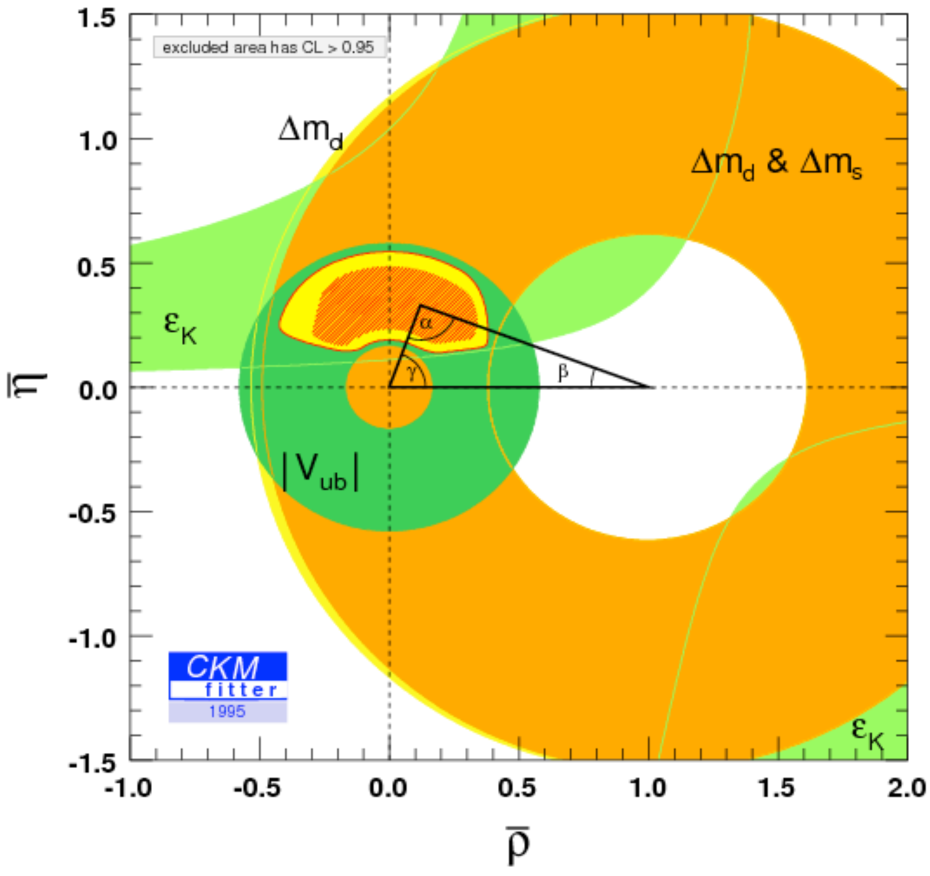
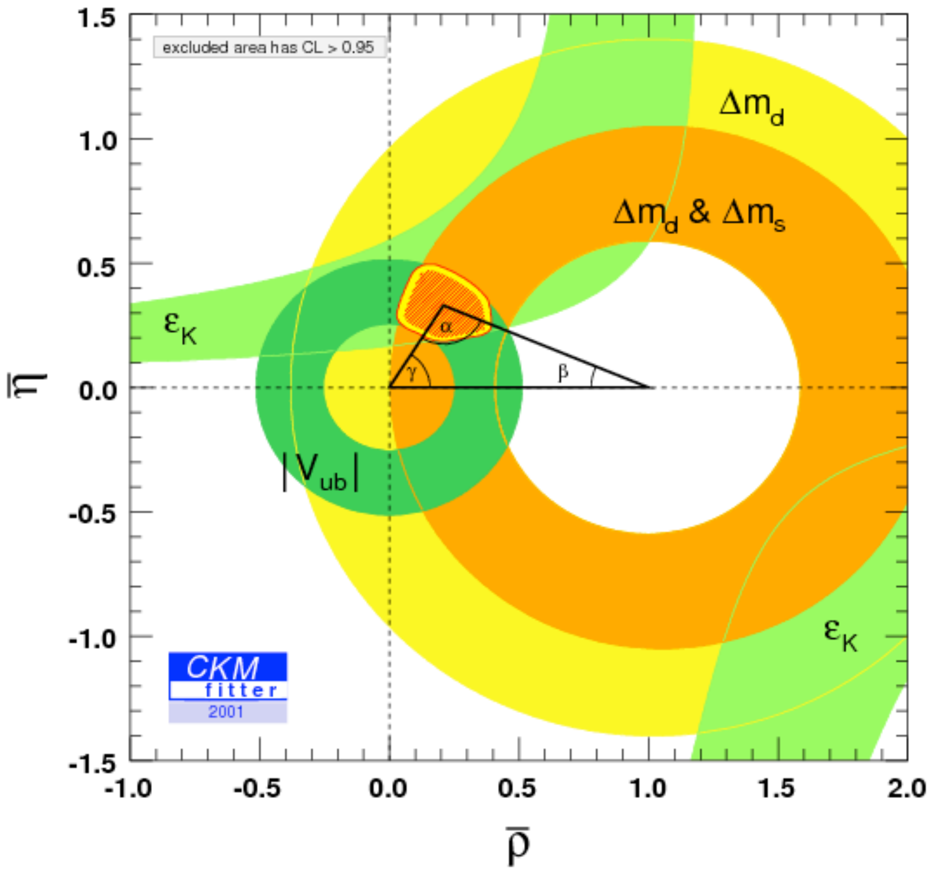
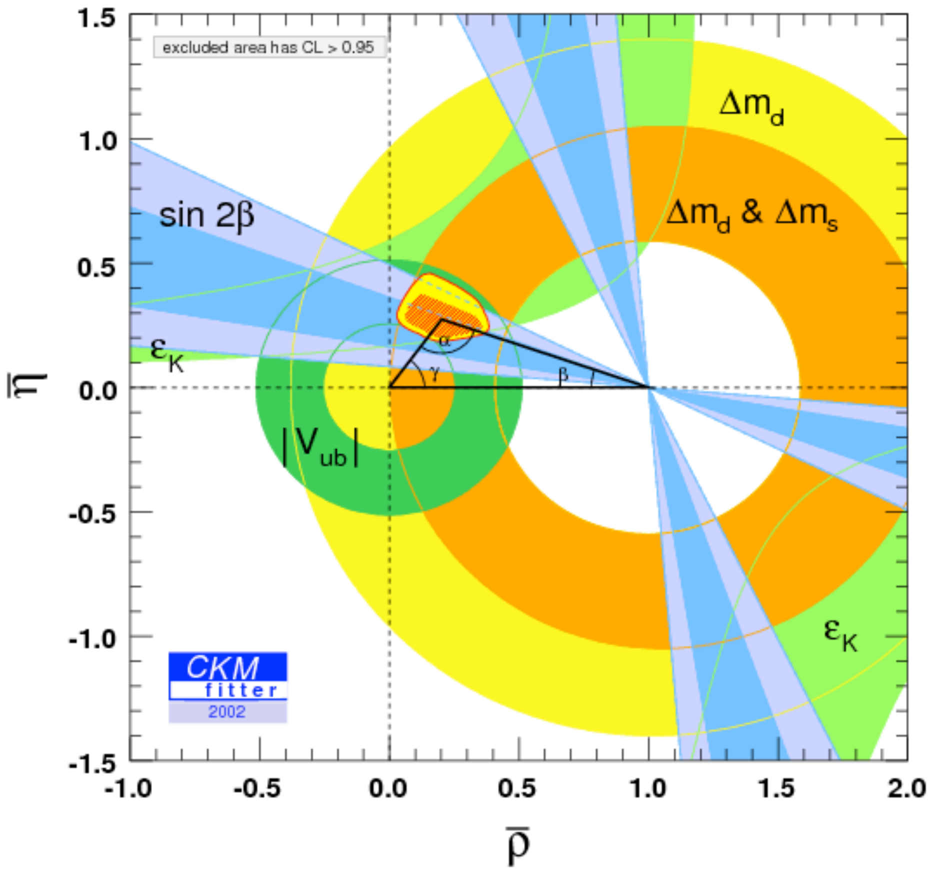


the CKM profile: Back to the future



the CKM profile: Back to the future



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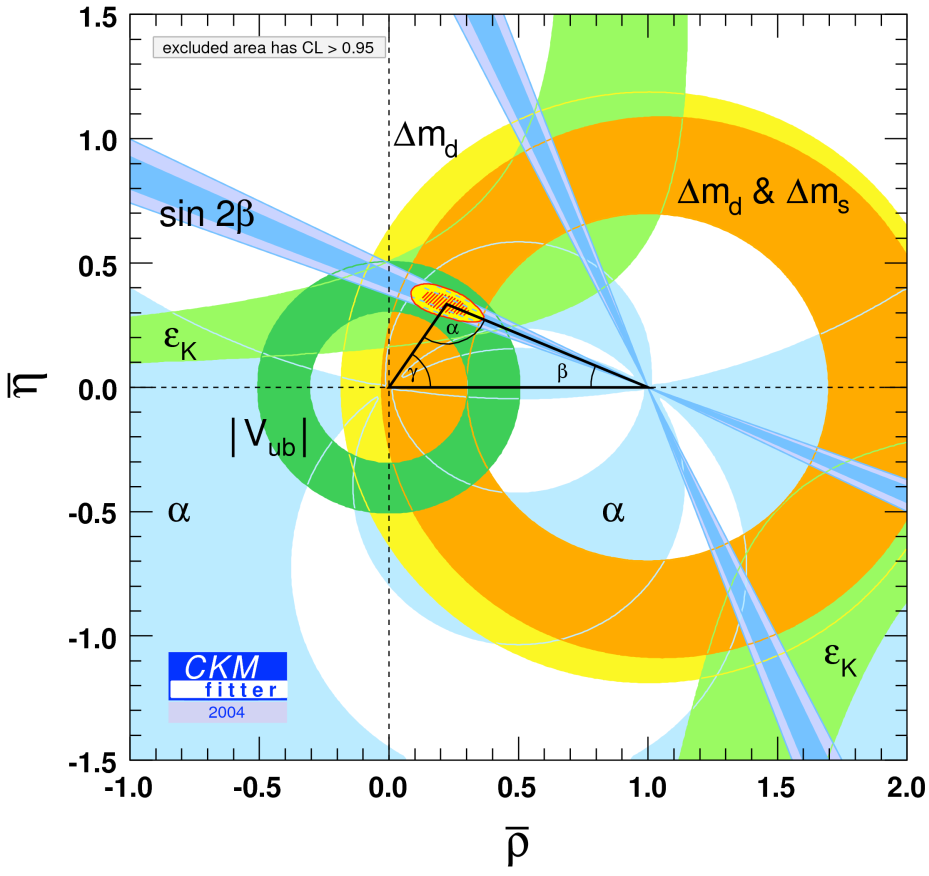

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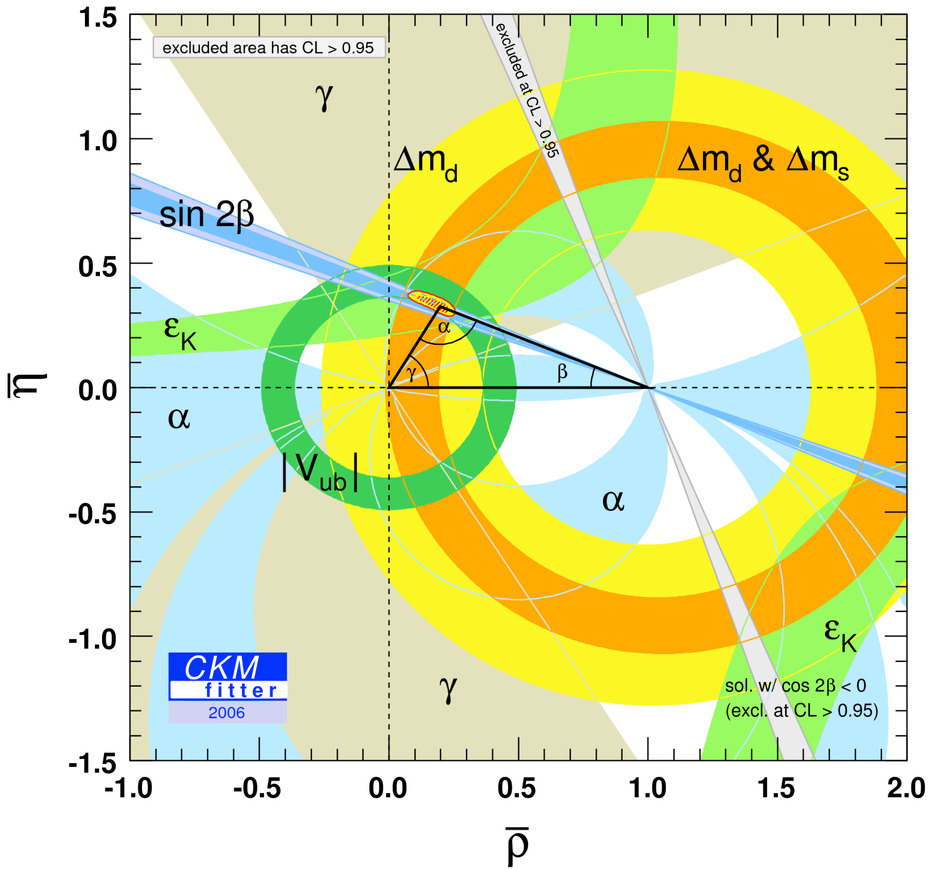

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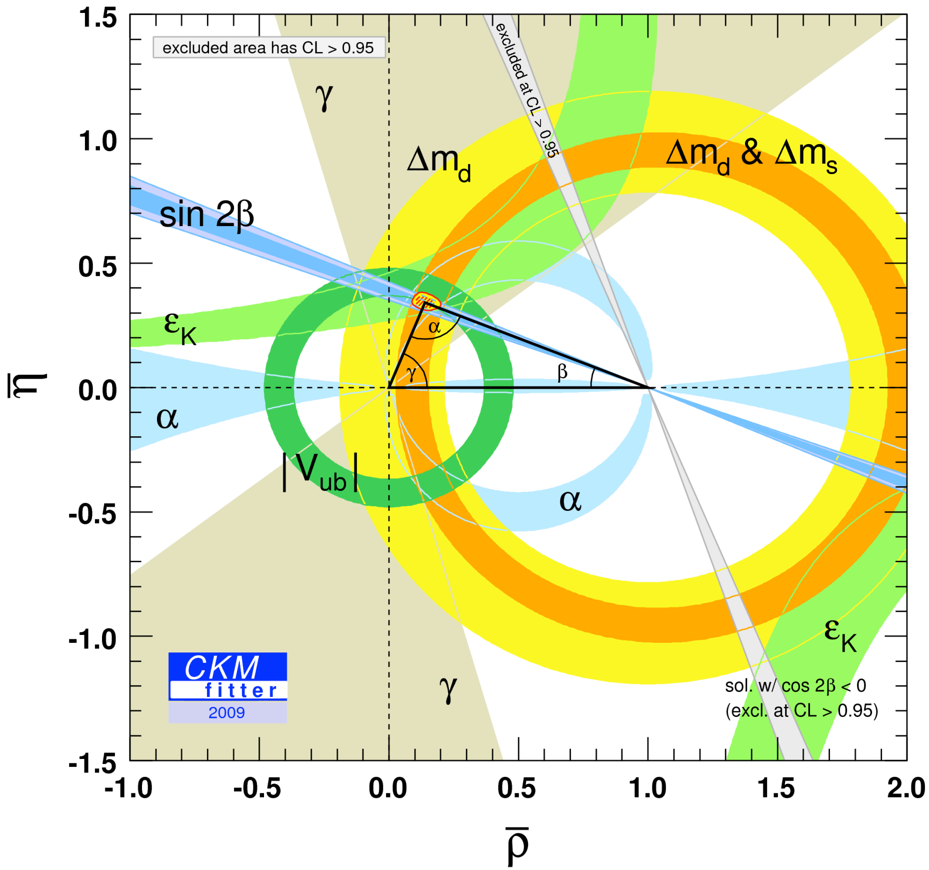

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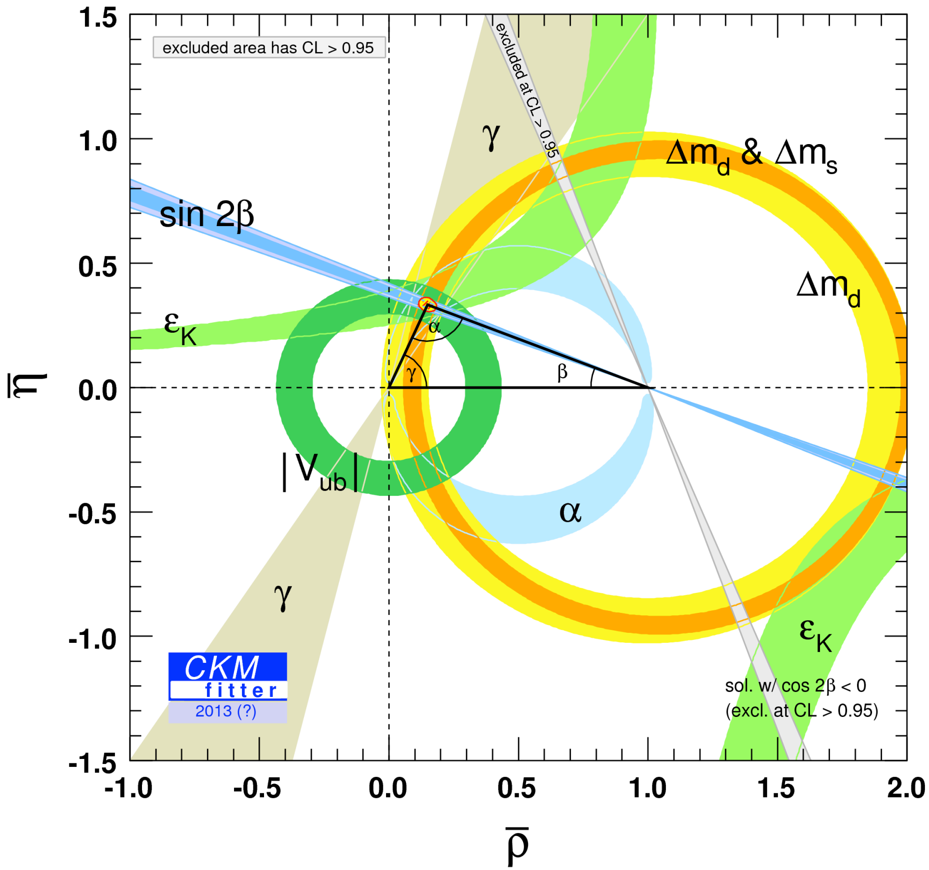

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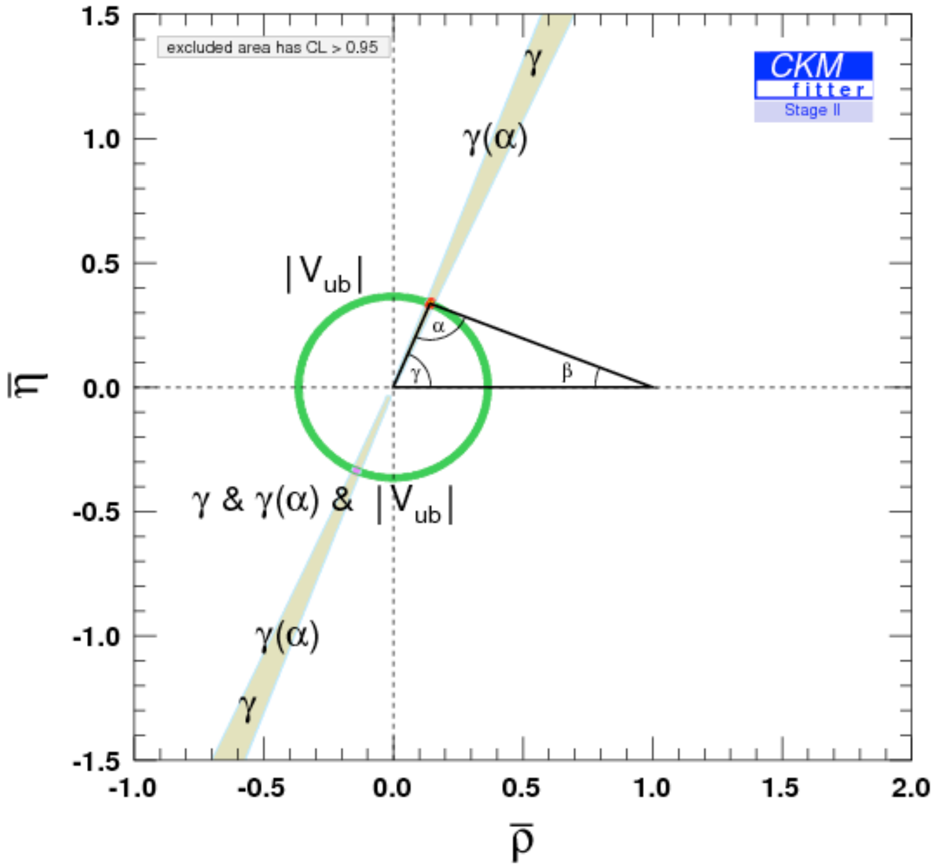


the CKM profile: Back to the future

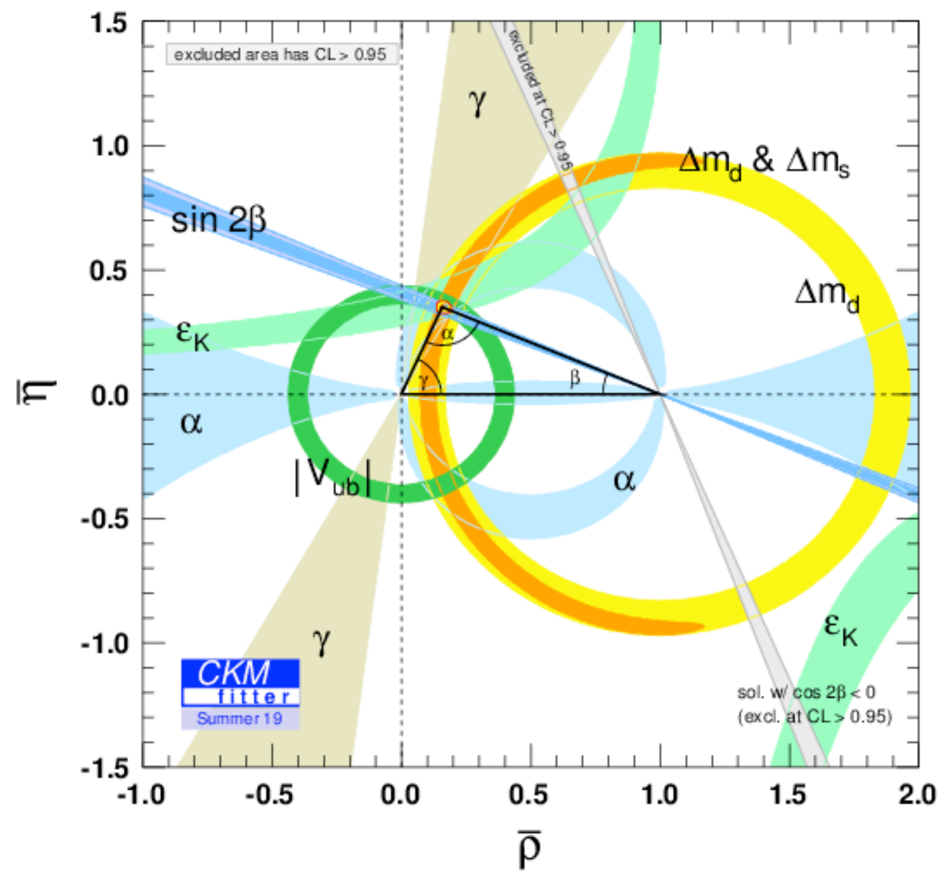
- 1995: starting point given by the top quark mass measurement. *K* and *B* mixings can be predicted.
- 2001: pre-*B*-factories era. LEP/CLEO based UT. Comparison with kaon mixing gives a consistency check.
- 2002: *CP* violation in the interference between decay and mixing is observed. This is the first true consistency test of the Standard Model.
- 2004: alpha angle is constrained.
- 2006: Δm_s (and first gamma angle constraint).
- 2013: LHCb dominating the gamma measurement.
- 2028: Super Flavour Factory (SuperKEKB) and LHCb (upgrade): additionally LQCD improvement. A New Physics perspective.

Standard Model predictions

- Now that the Standard Model hypothesis is validated [Validated does not mean that the SM is THE theory: it means that it passed the statistical test !!!] it's relevant to make the metrology of the CKM parameters.

- Additionally, perform consistency checks. Exclude the meas. of the observable you want to predict from the global fit and … compare !

- Please pick your favourite around here: http://ckmfitter.in2p3.fr.



Part I — *CP* symmetry breaking and CKM matrix

Standard Model predictions

- Predictions can be made on single observables not present in the global fit but depending on the CKM parameters.

- Here is an example of such predictions Phys.Rev. D84 (2011) 033005

- LHCb and Belle II can measure some of these observables: null test of the SM hypothesis.

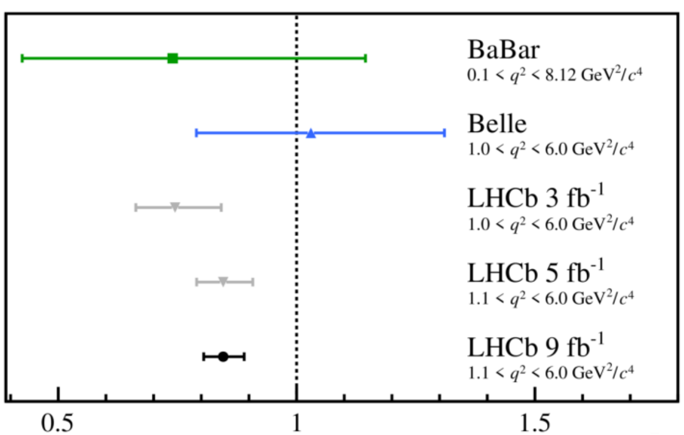
- To date, all measurements are aligned with the predictions. I will critically examine this statement in a minute.

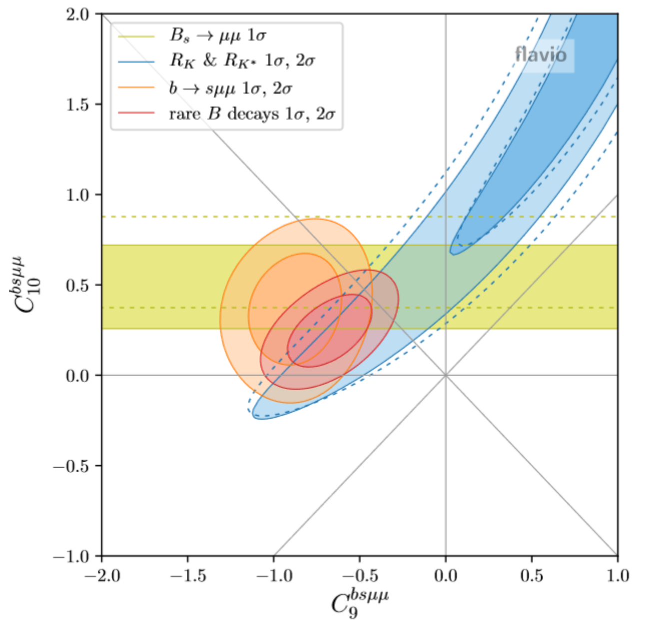
Charged Leptonic Decays				
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	$(16.8 \pm 3.1)\cdot 10^{-5}$	[4]	$(7.57\ ^{+0.98}_{-0.61})\cdot 10^{-5}$	2.8
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	$< 10^{-6}$	[10]	$(3.74\ ^{+0.44}_{-0.38})\cdot 10^{-7}$	-
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$	$(5.29 \pm 0.28)\cdot 10^{-2}$	[10]	$(5.44\ ^{+0.05}_{-0.17})\cdot 10^{-2}$	0.5
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$	$(5.90 \pm 0.33)\cdot 10^{-3}$	[10]	$(5.39\ ^{+0.21}_{-0.22})\cdot 10^{-3}$	1.3
$\mathcal{B}(D^+ \to \mu^+\nu_\mu)$	$(3.82 \pm 0.32 \pm 0.09)\cdot 10^{-4}$	[9]	$(4.18\ ^{+0.13}_{-0.20})\cdot 10^{-4}$	0.6
Neutral Leptonic B decays				
$\mathcal{B}(B_s^0 \to \tau^+\tau^-)$	-		$(7.73\ ^{+0.37}_{[illegible]})\cdot 10^{-7}$	-
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$< 32\cdot 10^{-9}$	[10]	$(3.64\ ^{+0.17}_{-0.31})\cdot 10^{-9}$	-
$\mathcal{B}(B_s^0 \to e^+e^-)$	$< 2.8\cdot 10^{[illegible]}$	[10]	$(8.54\ ^{[illegible]}_{-0.72})\cdot 10^{-14}$	-
$\mathcal{B}(B_d^0 \to \tau^+\tau^-)$	$< 4.1\cdot 10^{-3}$	[10]	$(2.36\ ^{+0.12}_{-0.21})\cdot 10^{-8}$	-
$\mathcal{B}(B_d^0 \to \mu^+\mu^-)$	$< 6\cdot 10^{-9}$	[10]	$(1.13\ ^{+0.06}_{-0.11})\cdot 10^{-10}$	-
$\mathcal{B}(B_d^0 \to e^+e^-)$	$< 8.3\cdot 10^{-9}$	[10]	$(2.64\ ^{+0.13}_{-0.24})\cdot 10^{-15}$	-
$B_q - \bar{B}_q$ mixing observables				
$\Delta\Gamma_s/\Gamma_s$	$0.092^{+0.051}_{-0.054}$	[10]	$0.179\ ^{+0.067}_{-0.071}$	0.[illegible]
$a^d_{\rm SL}$	$(-47 \pm 46)\cdot 10^{-4}$	[10]	$(-6.5\ ^{+1.9}_{-1.7})\cdot 10^{-4}$	0.8
$a^s_{\rm SL}$	$(-17 \pm 91^{+12}_{-23})\cdot 10^{-4}$	[26]	$(0.29\ ^{+0.09}_{-0.08})\cdot 10^{-4}$	0.2
$a^s_{\rm SL} - a^d_{\rm SL}$	-		$(6.8\ ^{+1.9}_{-1.7})\cdot 10^{-4}$	-
$\sin(2\beta)$	0.678 ± 0.020	[10]	$0.832\ ^{[illegible]}_{-0.033}$	2.7
$2\beta_s$	$[0.04; 1.04] \cup [2.16; 3.10]$	[27]	$0.0363\ ^{+0.0016}_{-0.0015}$	-
	$0.76\ ^{+0.36}_{-0.38} \pm 0.02$	[28]		
Radiative B decays				
$\mathcal{B}(B_d \to K^*(892)\gamma)$	$(43.3 \pm 1.8)\cdot 10^{-6}$	[10]	$(64\ ^{+22}_{-21})\cdot 10^{-6}$	1.2
$\mathcal{B}(B^- \to K^{*-}(892)\gamma)$	$(42.1 \pm 1.5)\cdot 10^{-6}$	[10]	$(66\ ^{+21}_{-20})\cdot 10^{-6}$	1.1
$\mathcal{B}(B_s \to \phi\gamma)$	$(57^{+21}_{-18})\cdot 10^{-6}$	[10]	$(65\ ^{+31}_{-24})\cdot 10^{-6}$	0.1
$\mathcal{B}(B \to X_s\gamma)/\ \mathcal{B}(B \to X_c\ell\nu)$	$(3.346 \pm 0.247)\cdot 10^{-3}$	[10]	$(3.03\ ^{+0.34}_{-0.32})\cdot 10^{-3}$	0.2
Rare K decays				
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.75^{+1.15}_{-1.05})\cdot 10^{-10}$	[29]	$(0.854\ ^{+0.116}_{-0.098})\cdot 10^{-10}$	0.8

The Part II starts at the next slide

Motivation

- In any recent HEP physics conference summary talk, you would have found these kinds of plot, stating that we are #CautiouslyExcited



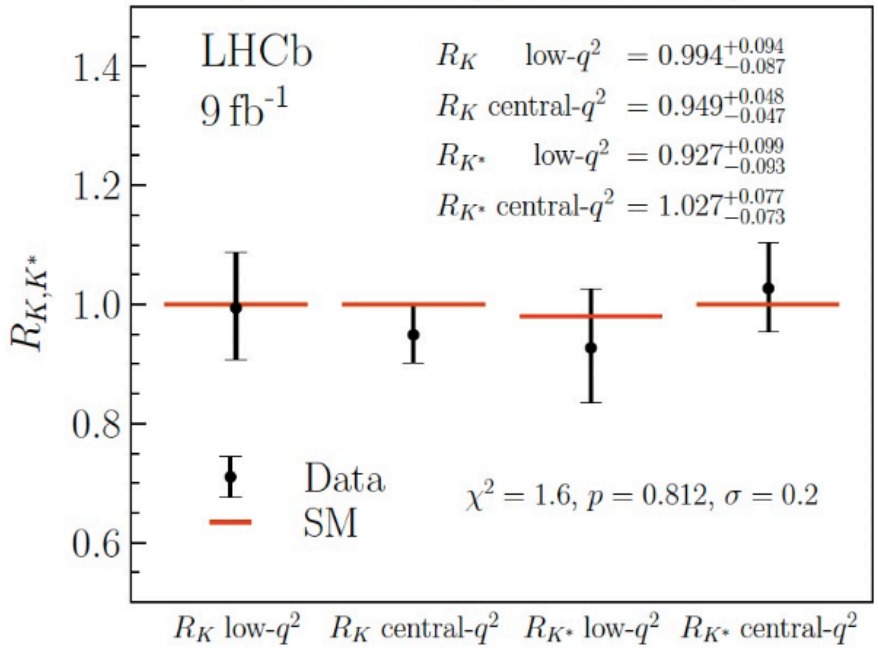


- The second objective of this lecture is to undress those plots and give the state-of-the-art of the scrutiny.

Motivation

- Actually, one is finding nowadays this very plot:

[arXiv:2212.09152] [arXiv:2212.09153]



- SM stroke back. Yet, fundamental interest of these searches remains!

Why are rare decays interesting?

- Rare decays correspond to loop-level weak processes, usually at rates lower than $O(10^{-6})$

- They do not happen at tree-level in the SM.

- They are as such strongly suppressed:

  - the mass of the virtual mediating particles.

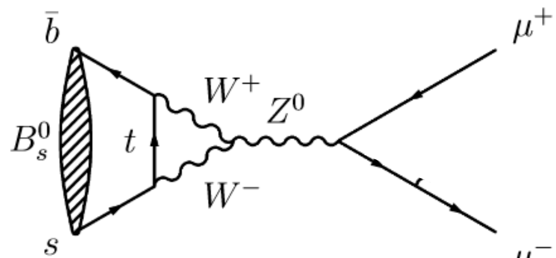
  - the factoring CKM elements.

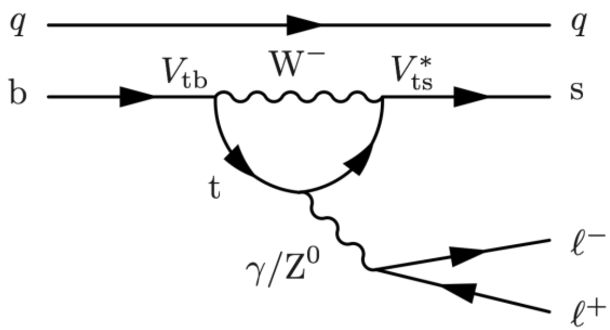
- Beyond the SM, new (well, unraveled yet) particles can contribute, by contrast, at tree-level. We think they are much heavier than the known mediating particles but could bring significant contributions. Ideal laboratory to search indirectly for those !

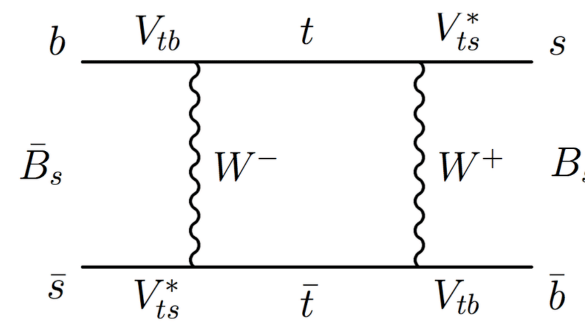
Why are rare decays interesting?

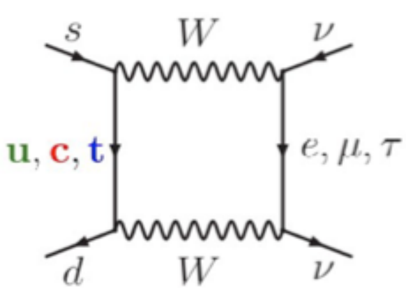
- A personal selection of historical break-throughs related to rare decays:
  - The *CP* violation discovery we just studied.
  - The Flavour-Changing Neutral Current $K^0 \to \mu\mu$ absence [well, $O(10^{-9})$] yielded the prediction of the *c* quark.
  - The oscillation frequency B^0—anti-B^0 suggested the existence of the *t* quark (with a mass > 50 GeV).
  - The transition $b \to s\gamma$ suggests a high-mass H^+, should a potential charged Higgs in two-Higgs doublet model exist in the Nature.
- When a discovery (or closure) path is relevant, it’s worth pursue it!

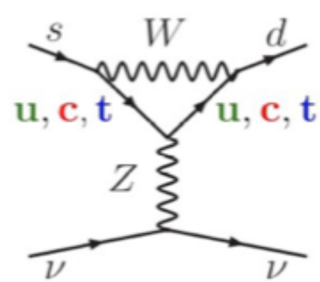
Let’s write some diagrams in the SM

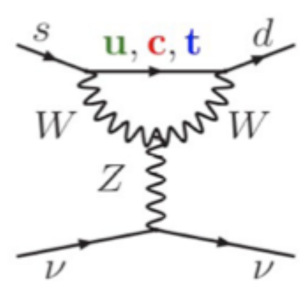












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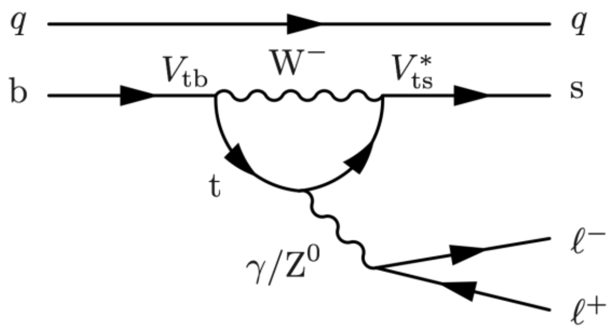
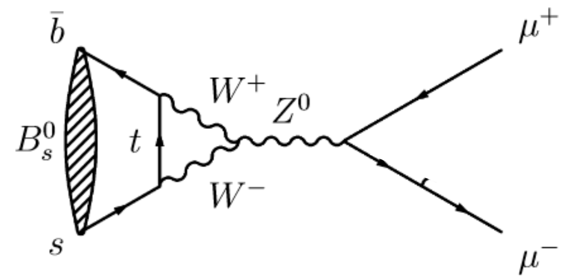
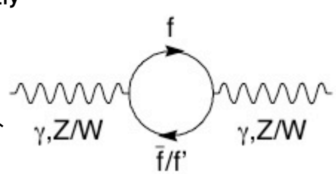
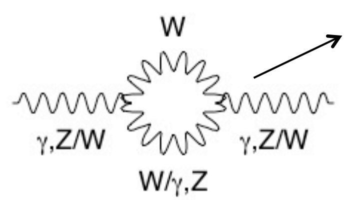




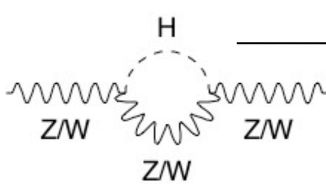
Rendez-vous this Friday: same Physics to probe at HE

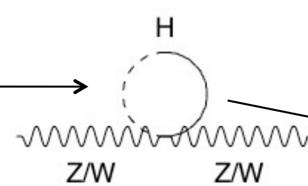
Top dominates. Mostly sensitive to m^2_t





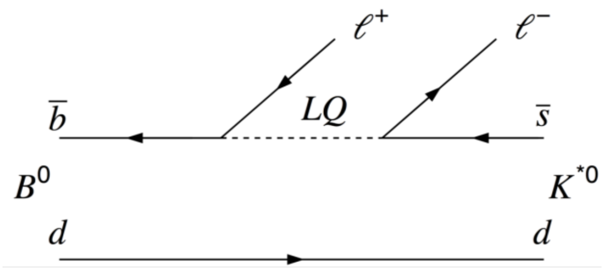
Non abelian structure of the EW theory. TGC.

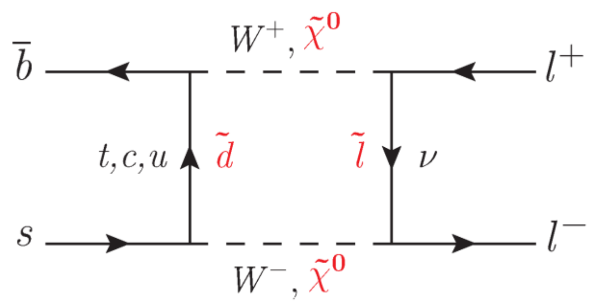


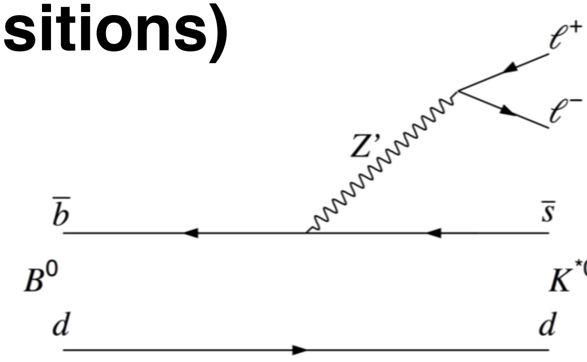


Scalar sector. Contains Higgs mass info.

Let's write some diagrams BSM (the outermost were never tested … in quark transitions)





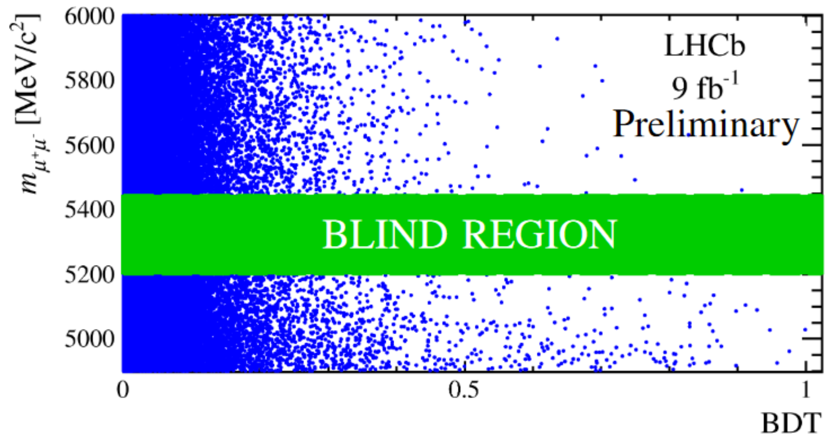


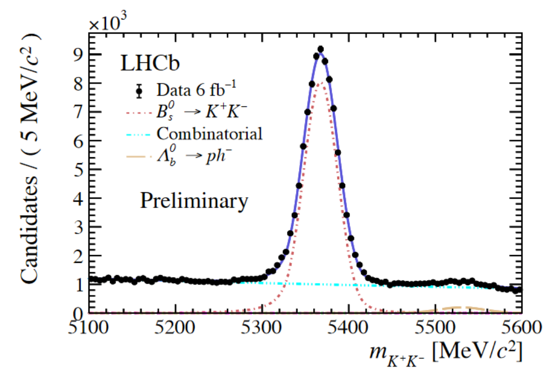
The menu of observables comes next

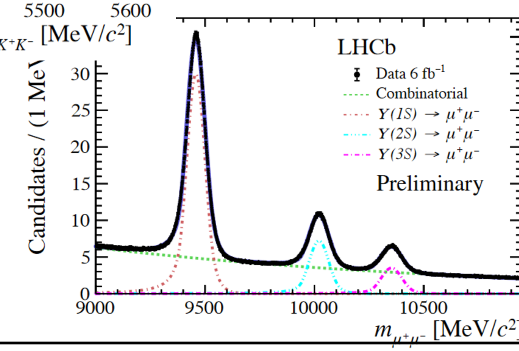
- The search for Flavour-Changing Neutral Current $B_s^0 \to \mu\mu$
- The Flavour-Changing Neutral Currents $b \to s\ell\ell$
  - Lepton universality observables
  - Angular observables
  - Branching fractions
- A glance at $b \to c\tau\nu$ decay rates

Part II — $B_s \to \mu\mu$ (ex. of LHCb-PAPER-2021-007)

- Strategy
  - Use full Run 1 + Run 2 data
  - Muon pairs with invariant-mass $m \in [4.9, 6.0]$ GeV
  - Use the topological properties of the decay / good displaced vertex
  - Suppress misidentification of particles with tight PID and muon detector requirements
  - Calibrate mass and width of signals
  - Signal region blind until analysis is finalised



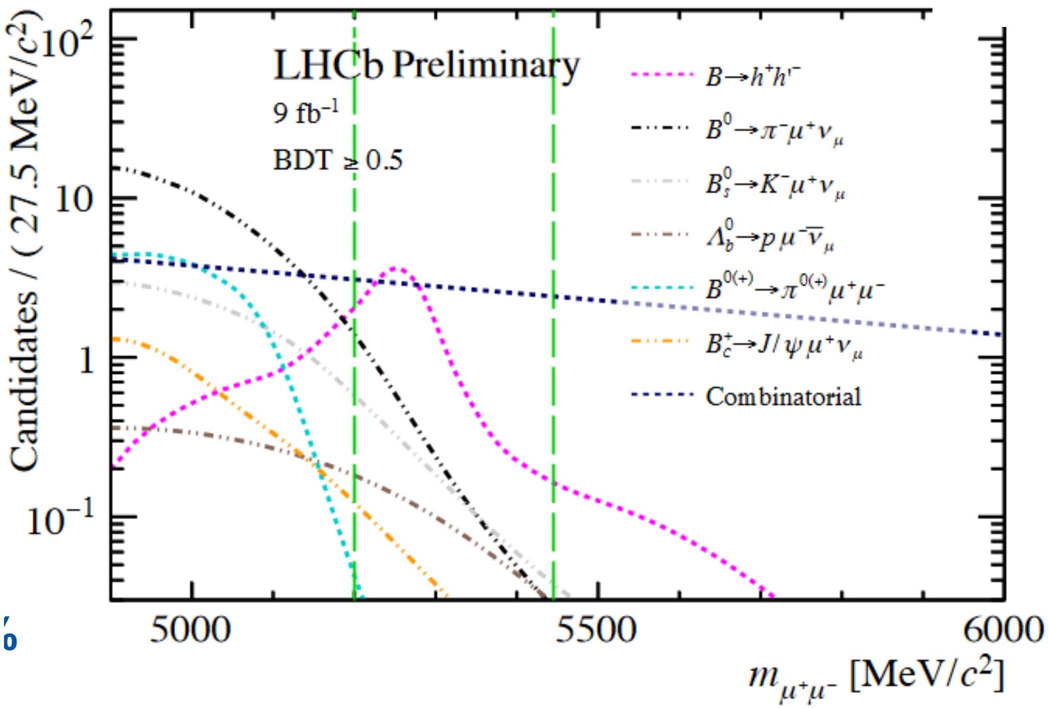


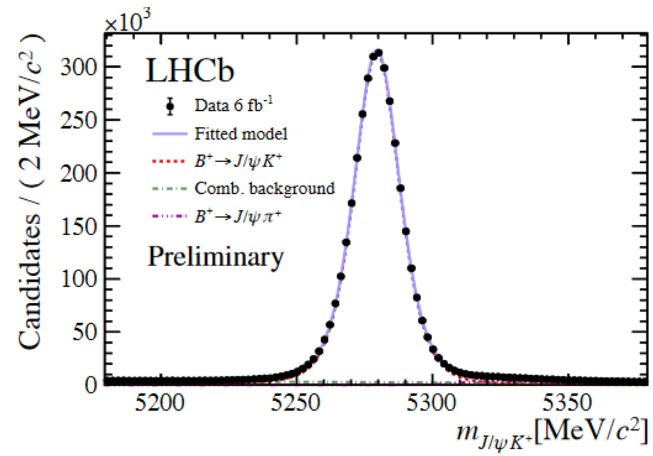


Part II — $B_s\to\mu\mu$ (ex. of LHCb-PAPER-2021-007)

- Strategy:
  - Normalise the yields to known branching fractions
  - Analysis of backgrounds

$$\mathcal{B}(B^0_{d,s}\to\mu^+\mu^-) = \overbrace{\underbrace{\frac{\mathcal{B}_{norm}}{N_{norm}}\times\frac{\epsilon_{norm}}{\epsilon_{sig}}}_{\alpha_d}\times\frac{f_{norm}}{f_{d,s}}}^{\alpha_s}\times N_{B^0_{d,s}\to\mu^+\mu^-}$$





Part II — $B_s \to \mu\mu$ (ex. of LHCb-PAPER-2021-007)

- Results:

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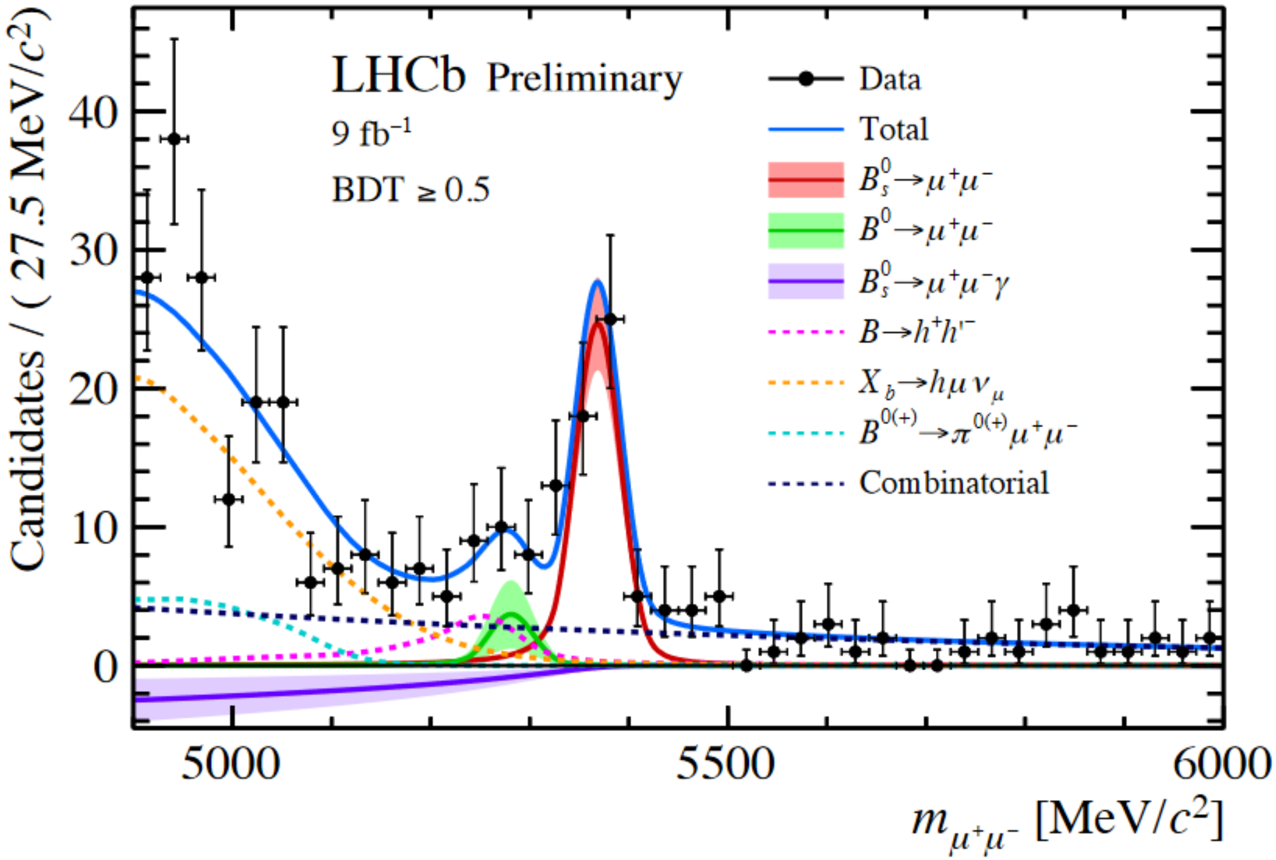
- Results:



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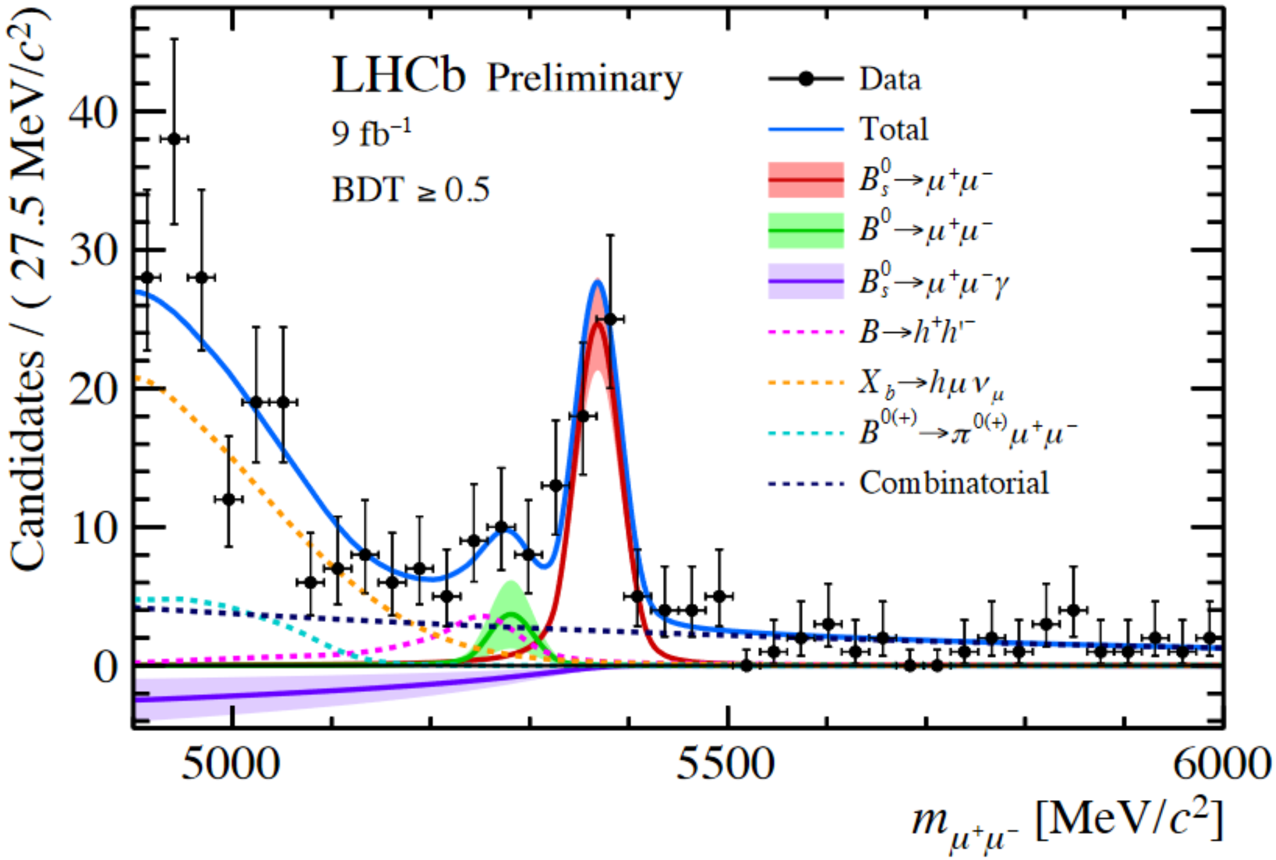
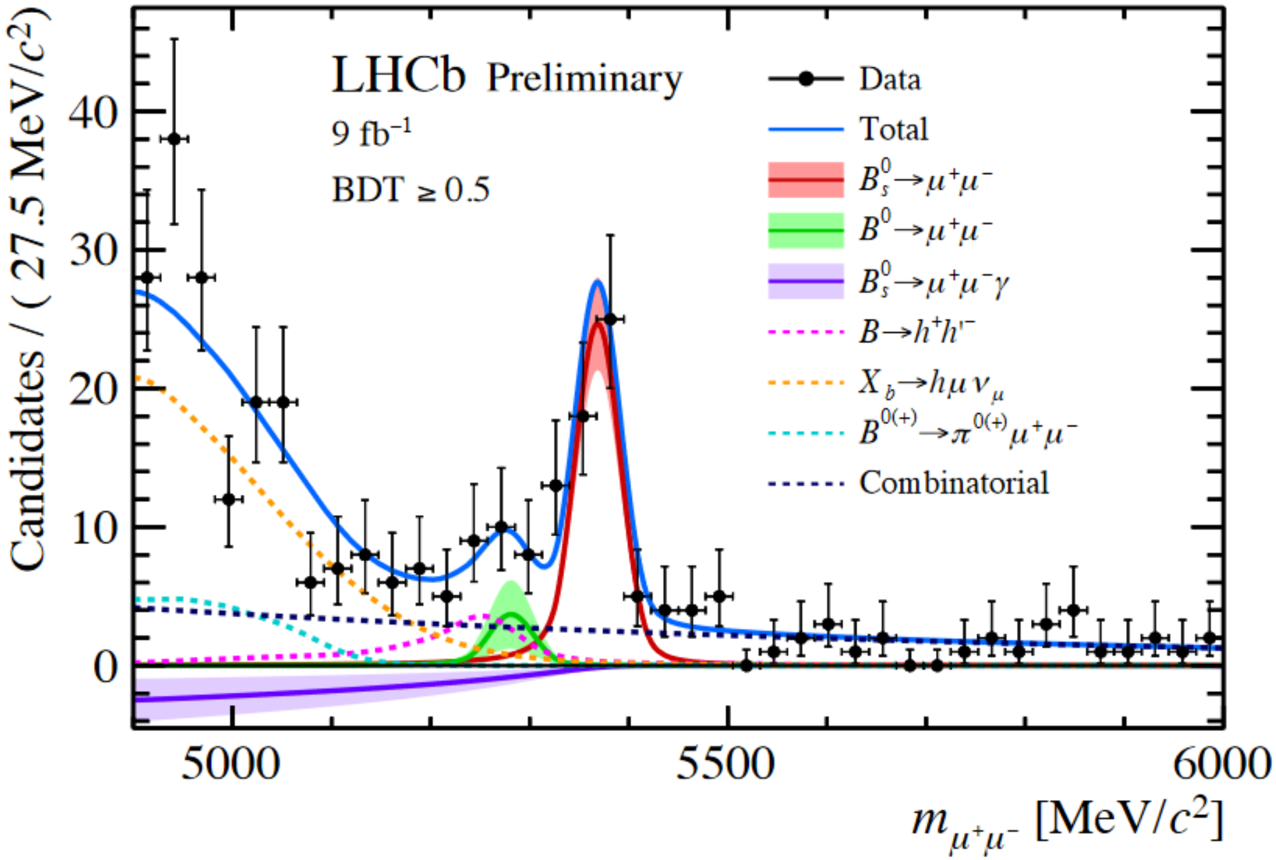
- Results:



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

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \times 10^9 = 3.27\, ^{+0.12}_{-0.16}.$$

- Results:



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

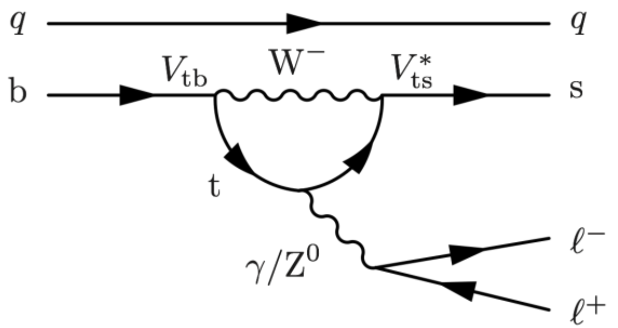
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \times 10^9 = 3.27 \,^{+0.12}_{-0.16}. \quad \text{SM.}$$

Part II — $b \to s\mu\mu$ and $b \to see$

- Not an annihilation, two quarks left in the final state

- This defines an ensemble of possible decays to study: since LHCb is the place to look at and that charged particles are preferred, one has

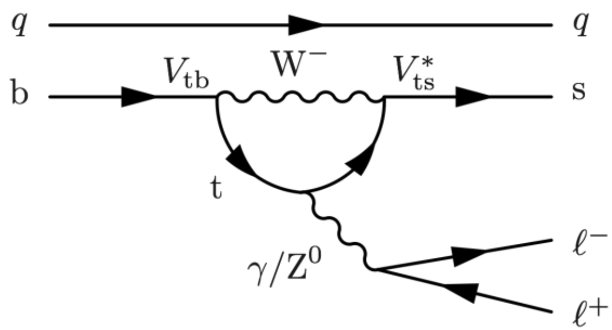
  - $B^+ \to K^+ \ell\ell$, $B^+ \to K^{*+} \ell\ell$ ($K^{*+} \to K_S \pi^+$)
  - $B^0 \to K^{*0} \ell\ell$
  - $B_s \to \phi\ell\ell$
  - $\Lambda_b \to \Lambda^* \ell\ell$ ($\Lambda^* \to pK^-$)



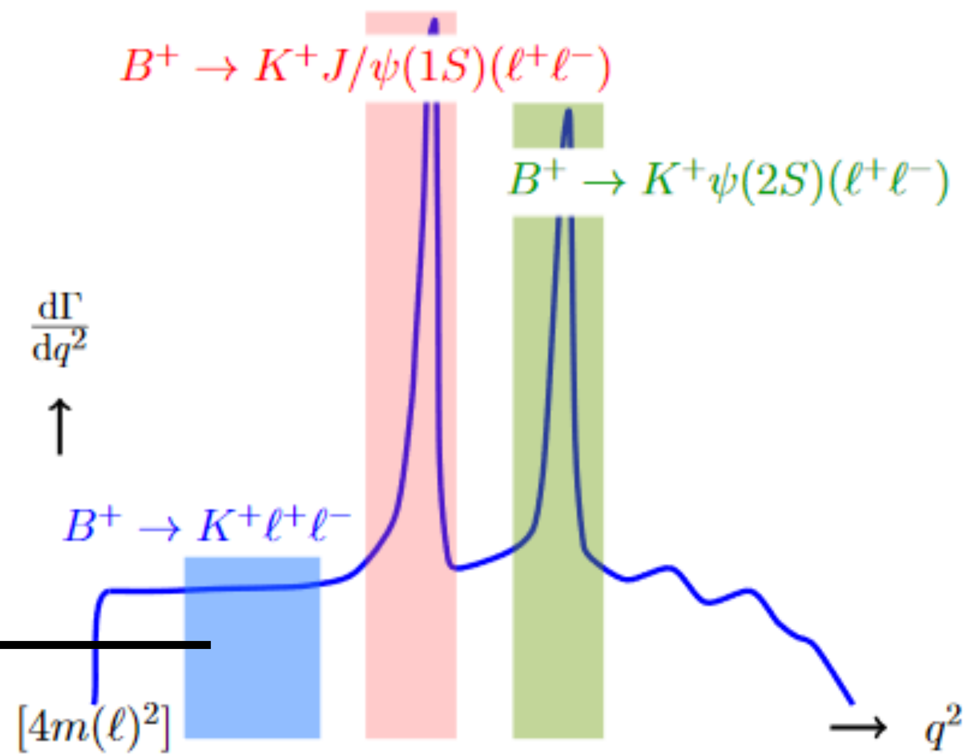
- One can:
  - Compare rates into electrons with muons (Test of the Lepton Flavour Universality LFU — theoretically clean)
  - Analyse the angular distributions of the decays with muons (we have ways to factor out some QCD from-factors).
  - Measure the branching fractions (there, it is not theoretically clean).

Part II — $b \rightarrow s\mu\mu$ and $b \rightarrow see$

The key physics quantity to study the decay is the invariant-mass of the dilepton pair, so-called q^2 :



REGION OF INTEREST



Part II — $b\to s\mu\mu$ and $b\to see$ — LFU tests

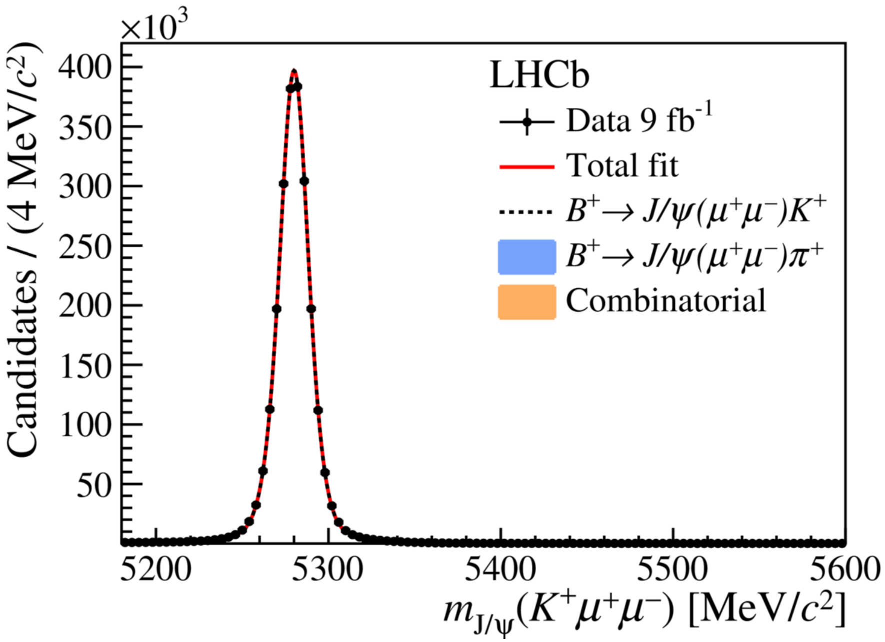
- It consists in comparing the rates of the decays into electrons and muons.
- Theoretical prediction is safe and straightforward (close to unity, mild dependence as function of q^2), *e.g.* this one
- Experimental measurements (at least at LHCb) is challenging: electrons and muons are not selected with the same triggers, the reconstruction of the electrons suffer from bremhstrahlung photons etc …
- Yet, one can measure double ratios ! *e.g.* :

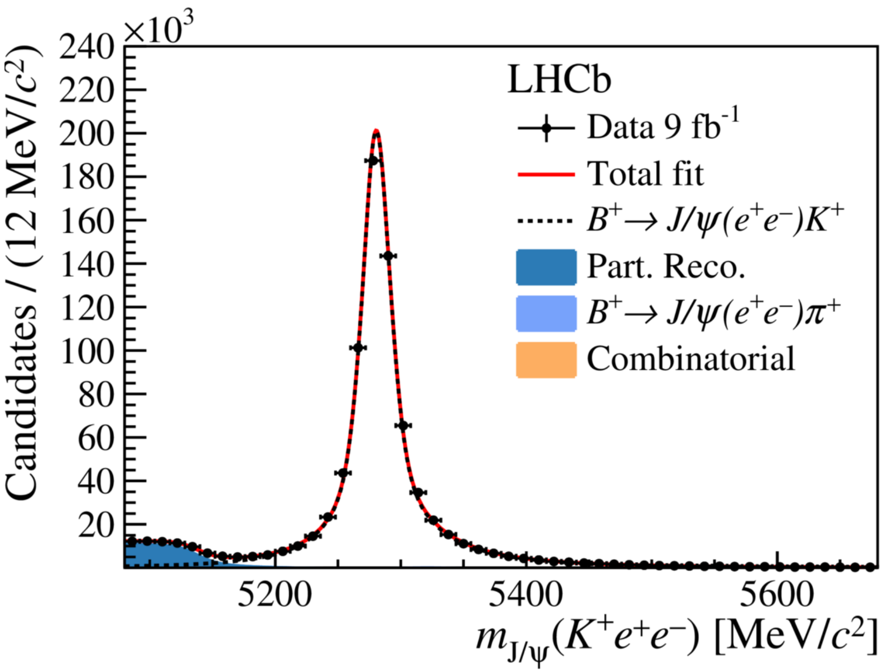
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

- Factors out efficiency systematics. Residual mis-modellings calibrated with data control samples. J/Psi does not decay weakly.

back

- Calibration modes:

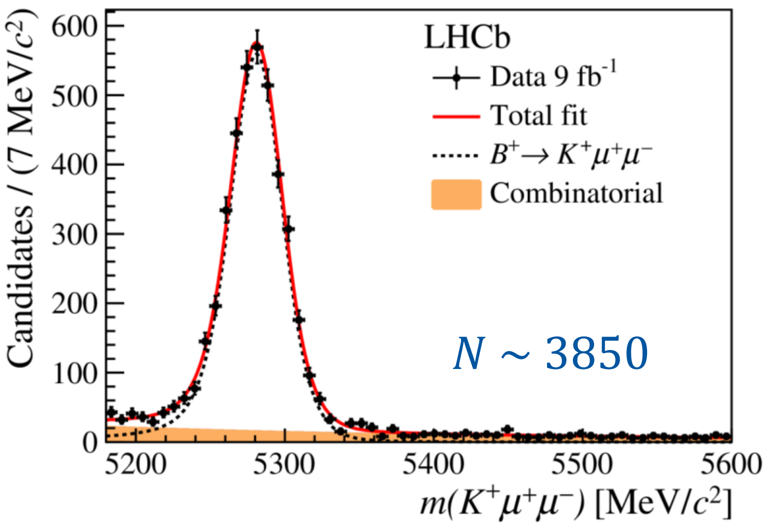


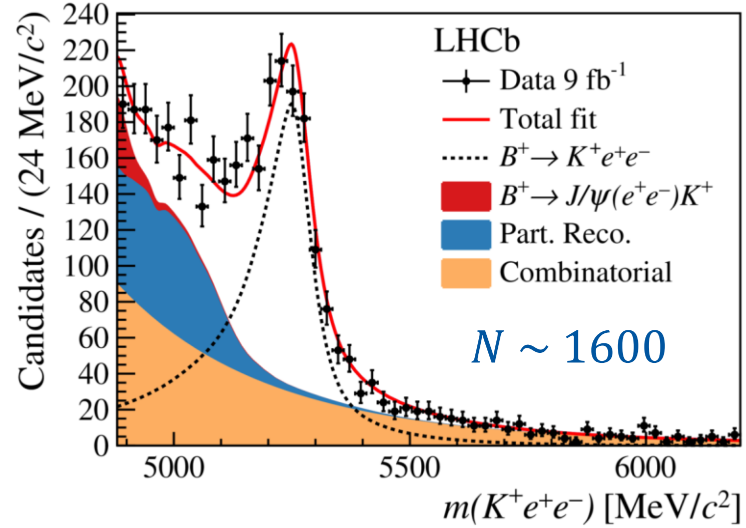


The ratio of the two must be unity. $r_{J/\psi} = 0.981 \pm 0.020\ (\mathrm{stat} + \mathrm{syst})$

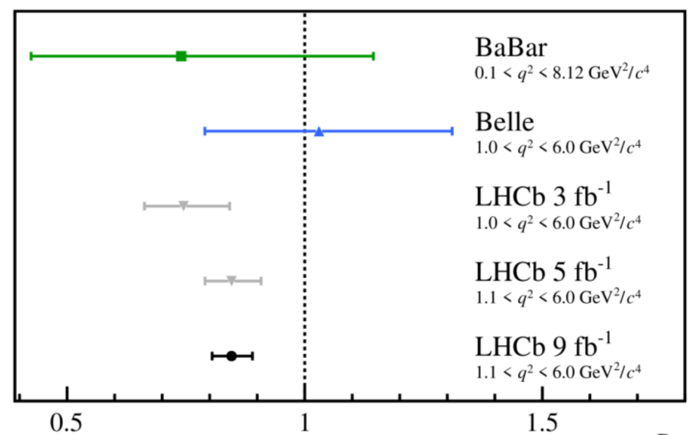
Double ratio with Psi(2S) can be determined $R_{\psi(2S)} = 0.997 \pm 0.011\ (\mathrm{stat} + \mathrm{syst})$

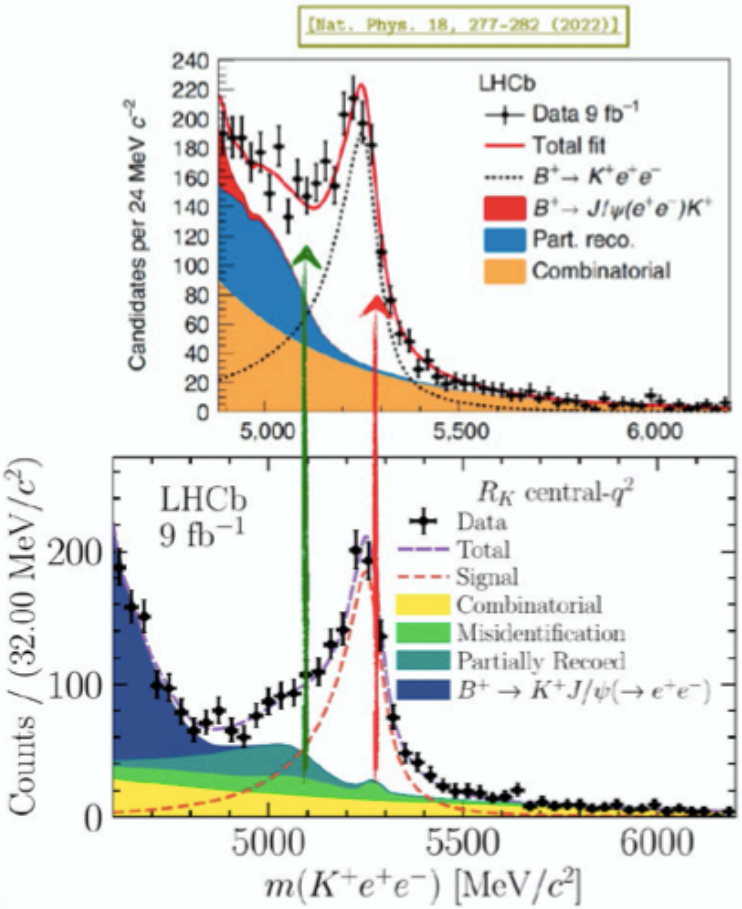
- Results:





$$R_K = 0.846 \,{}^{+0.042}_{-0.039}\,{}^{+0.013}_{-0.012}$$





- Different PID cut used ➡ Allowed σ_{stat} : ± 0.033
- Mis-ID rate from $D^{*-} \to D^0(K\pi)\pi$
- With new(previous) analysis requirements

	Sample	$\pi \to e$	$K \to e$
(11+12)	RUN 1	1.78 (1.70) %	0.69 (1.24) %
(15+16)	RUN 2P1	0.83 (1.51) %	0.18 (1.25) %
(17+18)	RUN 2P2	0.80 (1.50) %	0.16 (1.23) %

single-misID	× **1 (Run1)** × **2 (Run2)**	× **2 (Run1)** × **7 (Run2)**
double-misID	× **1² (Run1)** × **2² (Run2)**	× **2² (Run1)** × **7² (Run2)**

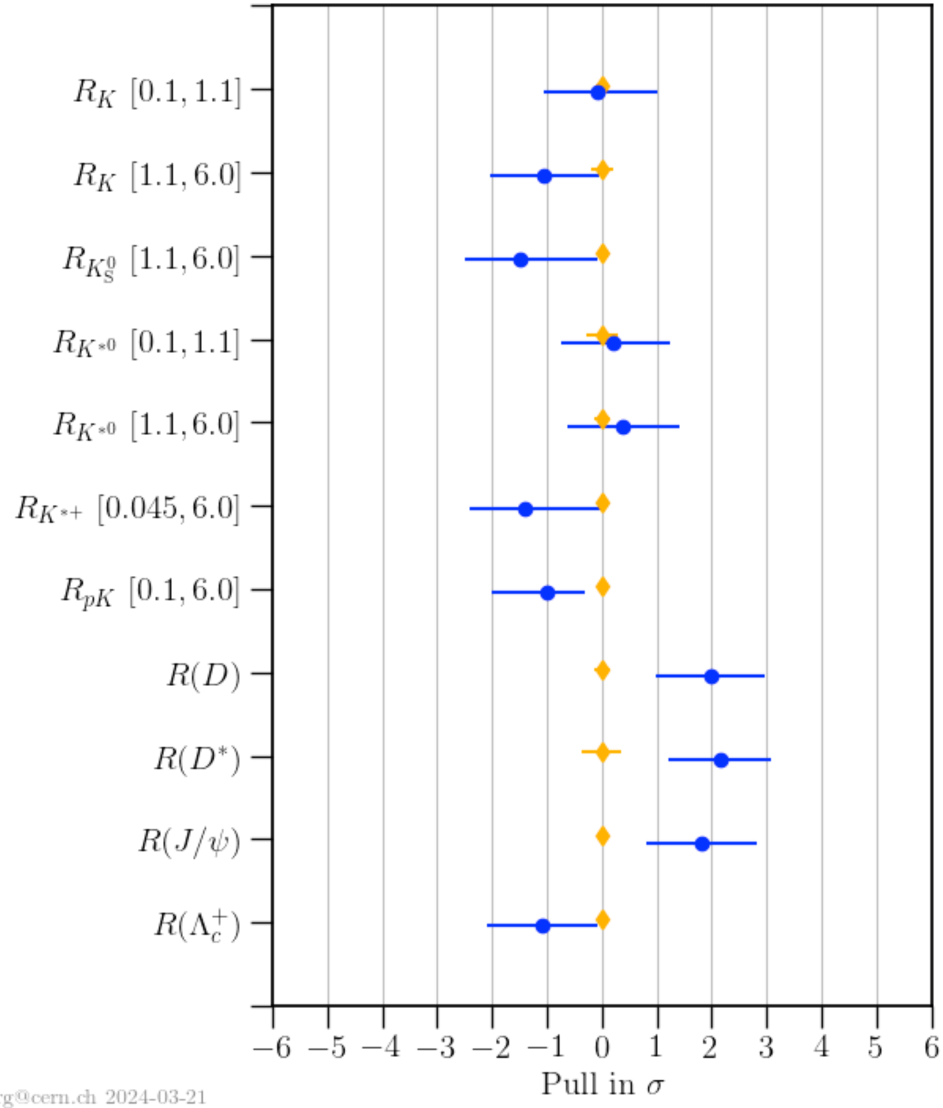
- Shift due to contamination at looser working point : $+\mathbf{0.064}$
- Shift due to not inclusion of background in mass fit: $+\mathbf{0.038}$

Adds linearly

Part II — LFU tests (bigger picture)

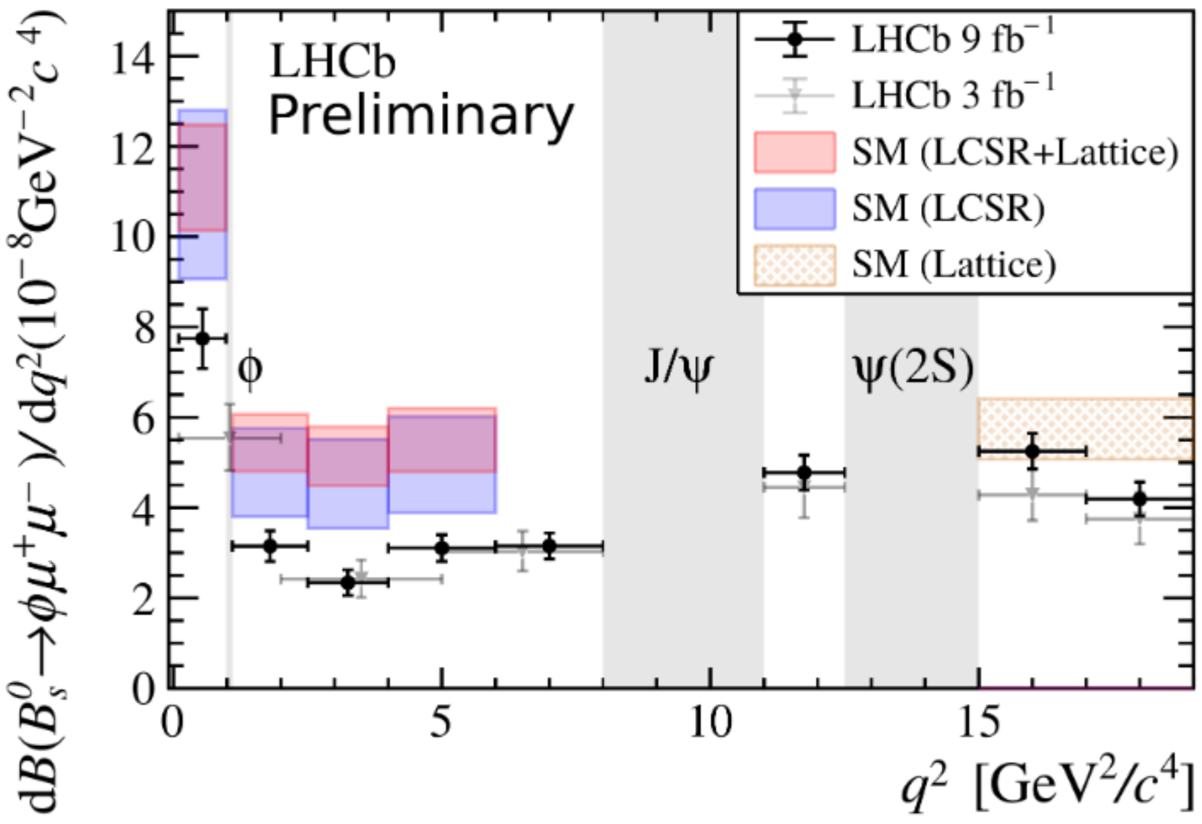
- Results: same pattern observed previously in R_{K^*} (and R_{pK})

- My sentence two years ago: “It comes on existing anomalous terrain. Demands a further scrutiny. LHCb updates are expected soon. Belle II will enter the game in the next years”



Part II — Branching fractions

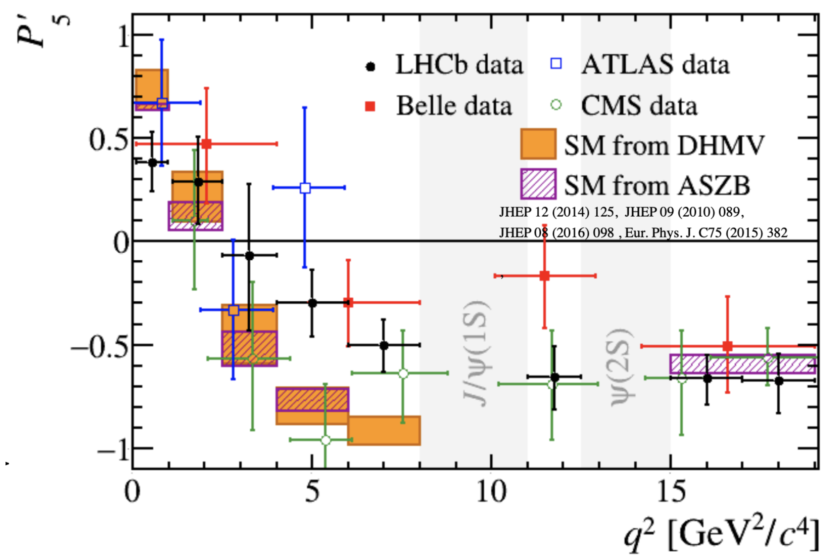
- Comment: absolute branching fraction prediction precisions are plagued by hadronic parameters uncertainties.
- Results: yet, a consistent pattern is observed here as well. The muon rate is systematically lower than the prediction. A spring result as example.

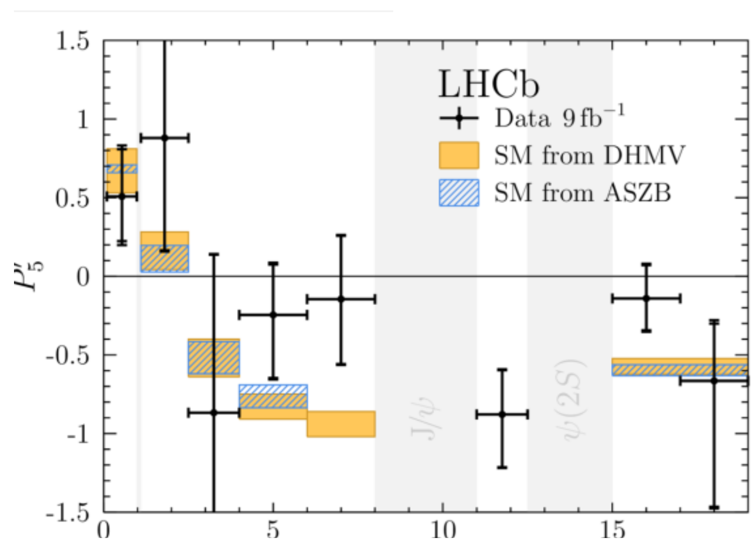


Part II — Angular analyses

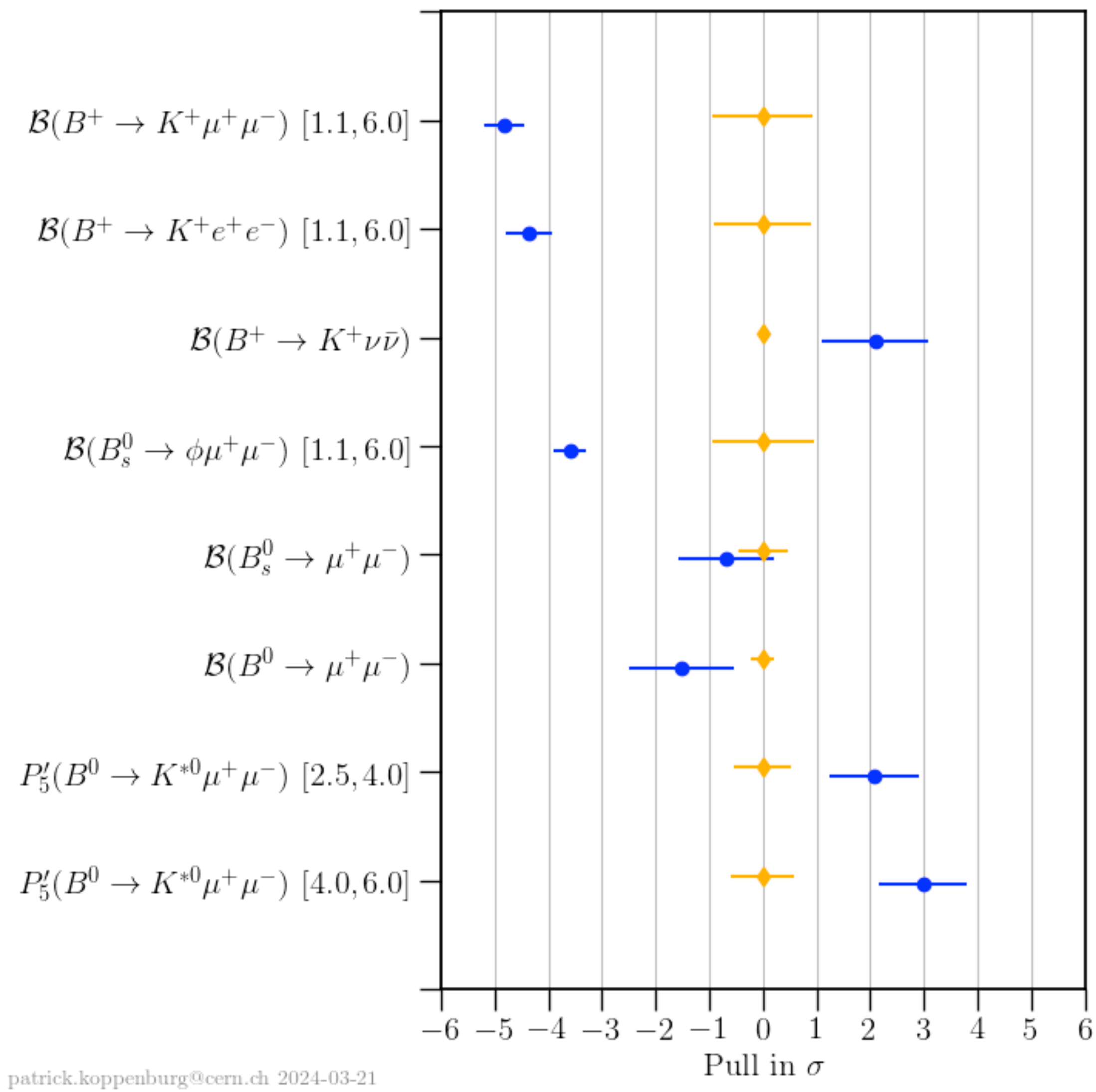
- Comment: again significant QCD uncertainties in the prediction. Immense efforts were spent to factor most of them out though.

- Results: another place where tensions with the SM arise.





Part II — BF and angular analyses (bigger picture)



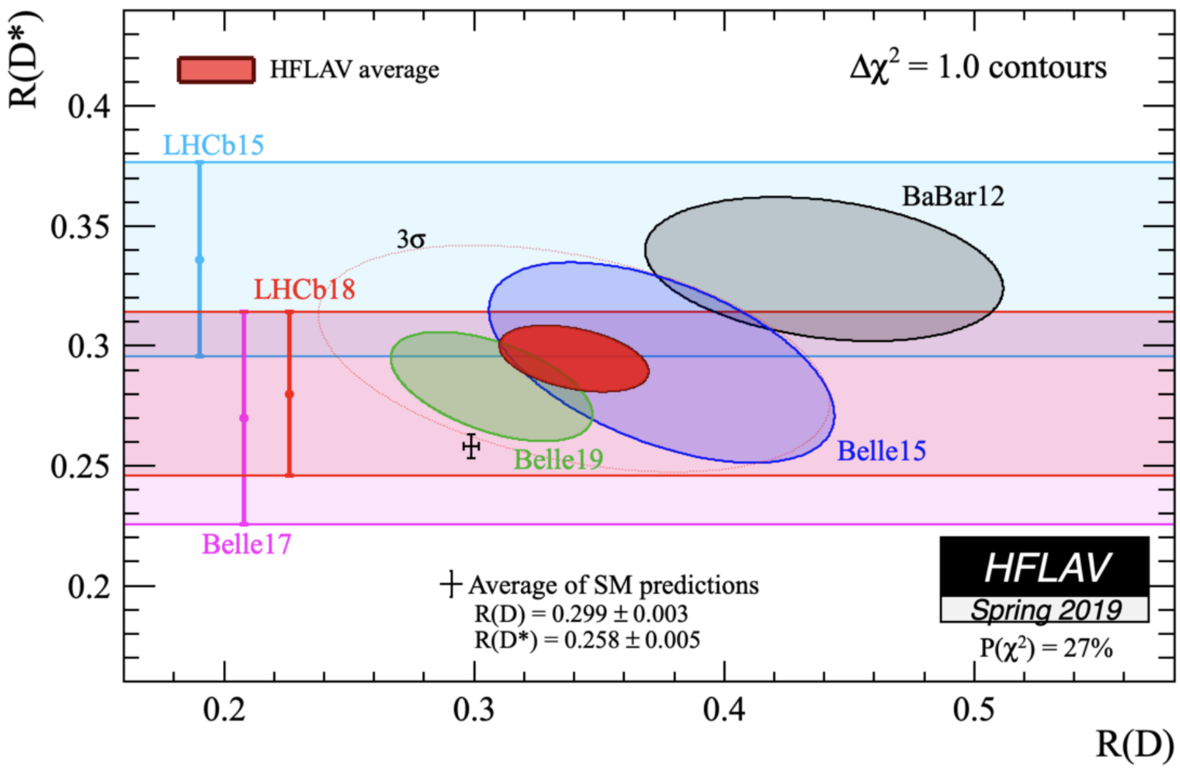
Part II — $b\to c\tau\nu$ decay rates

- Definition:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

- Results:

$$R_D(\text{th}) = 0.299 \pm 0.003\,;\, R_D(\text{exp}) = 0.340 \pm 0.030,$$
$$R_{D^*}(\text{th}) = 0.258 \pm 0.005\,;\, R_{D^*}(\text{exp}) = 0.295 \pm 0.014.$$



- Interpretation: if true, BSM Physics coupled preferentially to tau.

Part II — Rare decays anomalies interpretation

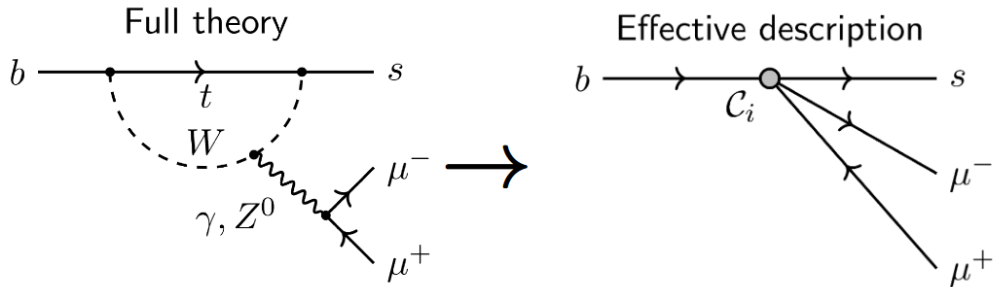
- There are anomalies in $b \to c\tau\nu$ and $b \to s\mu\mu$ transitions.

- The level of these anomalies is about three standard deviations departures from the SM predictions.

- Each anomaly can receive a more or less appealing phenomenological interpretation.

- Instead, can we aim at qualifying the departure in a model-independent way ? For instance, asking the question: are these anomalies consistent?

- The answer is YES ! By means of Effective Field Theory. It consists of the SM Lagrangian + non-renormalisable operators (actually dimension 6 operators at first). This approach is valid as far as one can integrate out the heavy fields.



- The relavant operators are:

$$\mathcal{O}_7^{ij} = \frac{e\, m_{d_j}}{(4\pi)^2} (\bar{d}_i\, \sigma_{\mu\nu}\, P_R\, d_j)\, F^{\mu\nu}\,, \qquad \mathcal{O}_9^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{d}_i\, \gamma^\mu\, P_L\, d_j)(\bar{\ell}\, \gamma_\mu\, \ell')\,,$$

$$\mathcal{O}_{10}^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{d}_i\, \gamma^\mu\, P_L d_j)(\bar{\ell}\, \gamma_\mu\, \gamma_5\, \ell')\,, \qquad \mathcal{O}_S^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{d}_i\, P_R\, d_j)(\bar{\ell}\, \ell')\,,$$

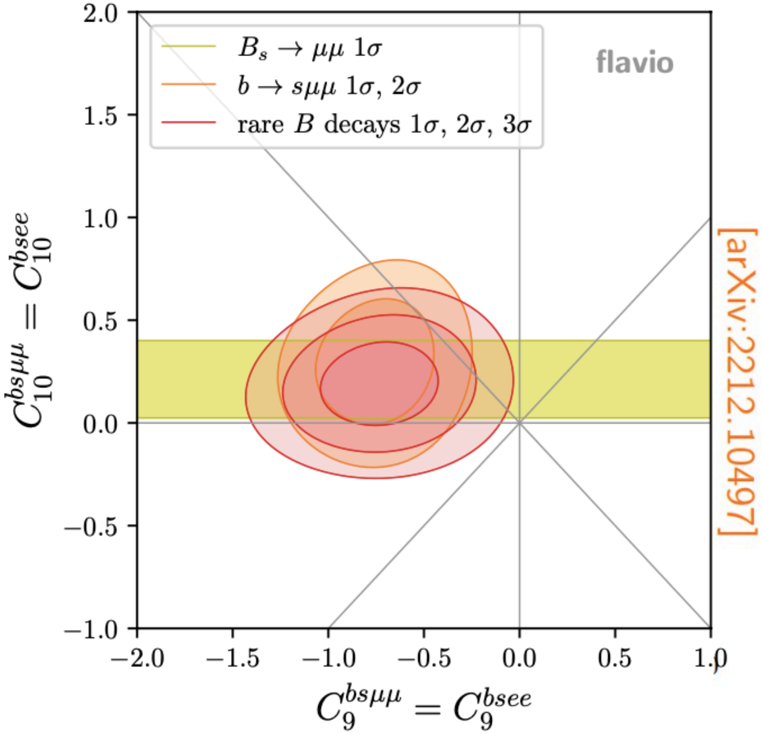
$$\mathcal{O}_P^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{d}_i\, P_R\, d_j)(\bar{\ell}\, \gamma_5\, \ell')\,, \qquad \mathcal{O}_T^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{d}_i \sigma_{\mu\nu}\, d_j)(\bar{\ell} \sigma^{\mu\nu}\, \ell')\,,$$

$$\mathcal{O}_{T5}^{ij;\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{d}_i \sigma_{\mu\nu}\, d_j)(\bar{\ell} \sigma^{\mu\nu}\, \gamma_5\, \ell')$$

- The effective operator are coming with effective coupling constants, denoted the Wilson coefficients (fully calculable for their SM component, careful at the running with the scale mu)

$$\mathcal{L}_{\text{eff}} \propto \frac{4G_F}{\sqrt{2}} \sum_k C_k(\mu)\mathcal{O}_k(\mu).$$

Part II — Rare decays anomalies interpretation



- Multiple global fits in the literature (I picked here 2012.13241 and arXiv:2103.13370, many others around). Significance of the departure with SM flirts with 5 standard deviations.

- They all tell the same: the anomalies provide a consistent pattern and require a modification of the SM C_9.

Part III — Conclusion and outlook

- The observation of *P* and *CP* violation has shaped our understanding of the elementary interactions.

- All the CP-conserving and CP-violating observables are accounted for in the Kobayashi-Maskawa paradigm, embodied in the SM. This makes a pillar of the SM.

- A single *CP*-violating phase allows to comprehend the meson decays and mixing asymmetries phenomena. The advent of Belle II and the continuation of LHCb will allow to enter the precision era and test further the paradigm (and hopefully shake it).

- Meanwhile, rare decays of heavy-flavoured particles have been analysed meticulously. Anomalies are reported and find an appealing (common) explanation. Here again, the advent of Belle II and the continuation of LHCb shall unravel BSM Physics if the anomalies stand.

Part III — Conclusion and outlook

- It was thought by numbers of the HEP community that the supersymmetry would appear at the turn-on of the LHC. This did not happen. A “light” narrow scalar was indeed discovered but it looks *to date* like the Brout-Englert-Higgs boson of the Standard Model.

- The experimentalists among you have entered the field at exciting times. Orphan of the no-lose theorem, the path towards the answers to fundamental questions will be again shaped by experimental breakthroughs (hopefully).

- Flavour Physics (and precision physics) is a key player in this scrutiny, with the emerging anomalies we have discussed.

Back-ups / Les renforts
(The complete introduction about
***P* and *CP* symmetries follows)**

A more detailed outline

1. Introduction: setting the scene. History and recent past of the parity violation experiments. The discovery of the *CP* violation.
2. Few elements about CKM. Machine and experiments. Main observables and measurements relevant to study *CP* violation.
3. The global fit of the SM: CKM profile.
4. New Physics exploration with current data: two examples.

Parity symmetry breaking

Some authoritative literature about the lecture :

- ✓ Lee, T.D. and Yang, C.N. (1956) *Question of parity conservation in weak interactions*, Phys. Rev. 104(1): 254-258 (1956).
- ✓ The ^{60}Co experiment: Phys. Rev. 105, 1413-1414 (1957)
- ✓ The ^{152}Eu experiment: Phys. Rev. 109, 1015 (1958).

The foundations

1. Antimatter discovery – C. Anderson.

2. The parity violation measurement – C.S. Wu.

3. The parity violation measurement – Goldhaber et al.

4. The emergence of the V-A theory. Premises of $SU(2)_L$.

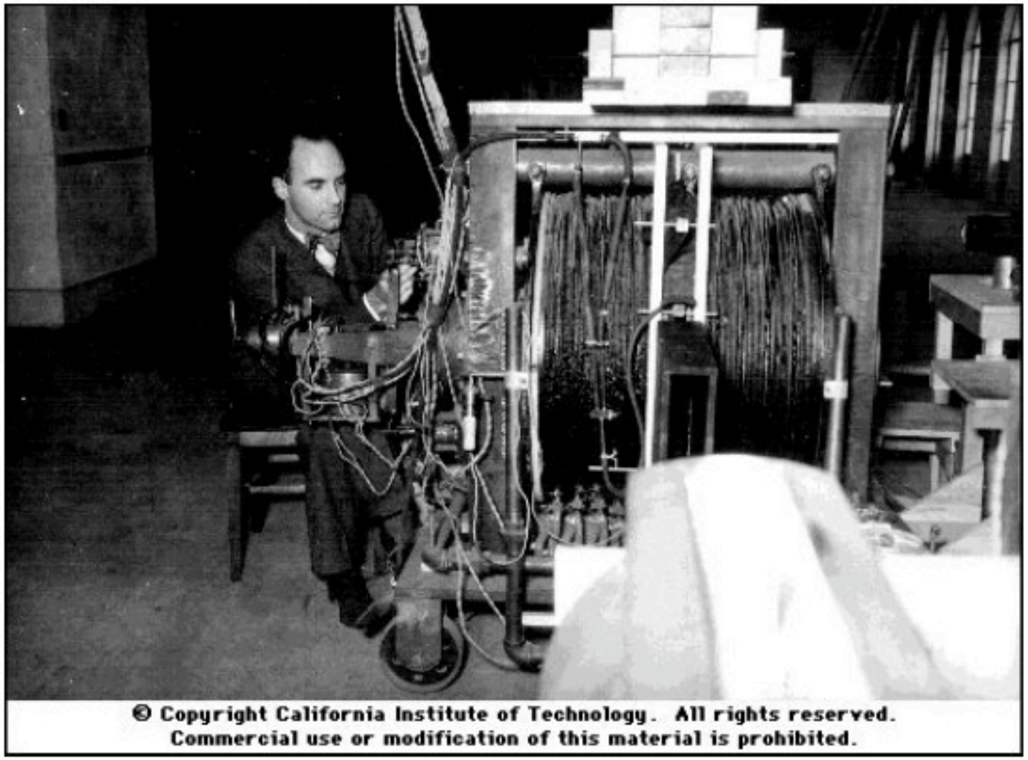
5. Recent parity violation measurements at LEP/SLD.

6. Selection of *CP* violation phenomena.

Antimatter exists.

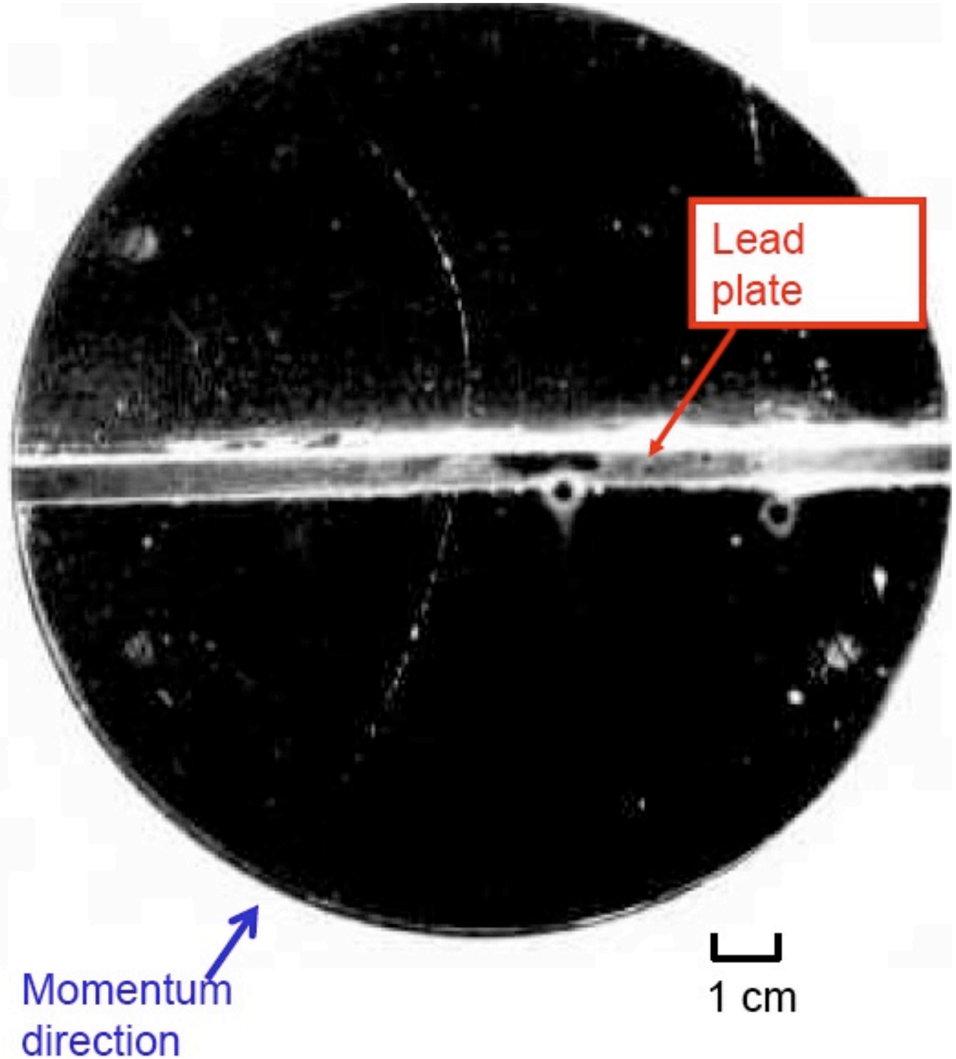
In 1929, P.A.M. Dirac solves the free motion of a relativistic spin 1/2 particle (electron or proton). It happened that there should exist a solution of negative energy, which he interpreted as an antiparticle.

Dirac spin 1/2 : $(i\gamma^\mu \partial_\mu - m)\psi = 0$



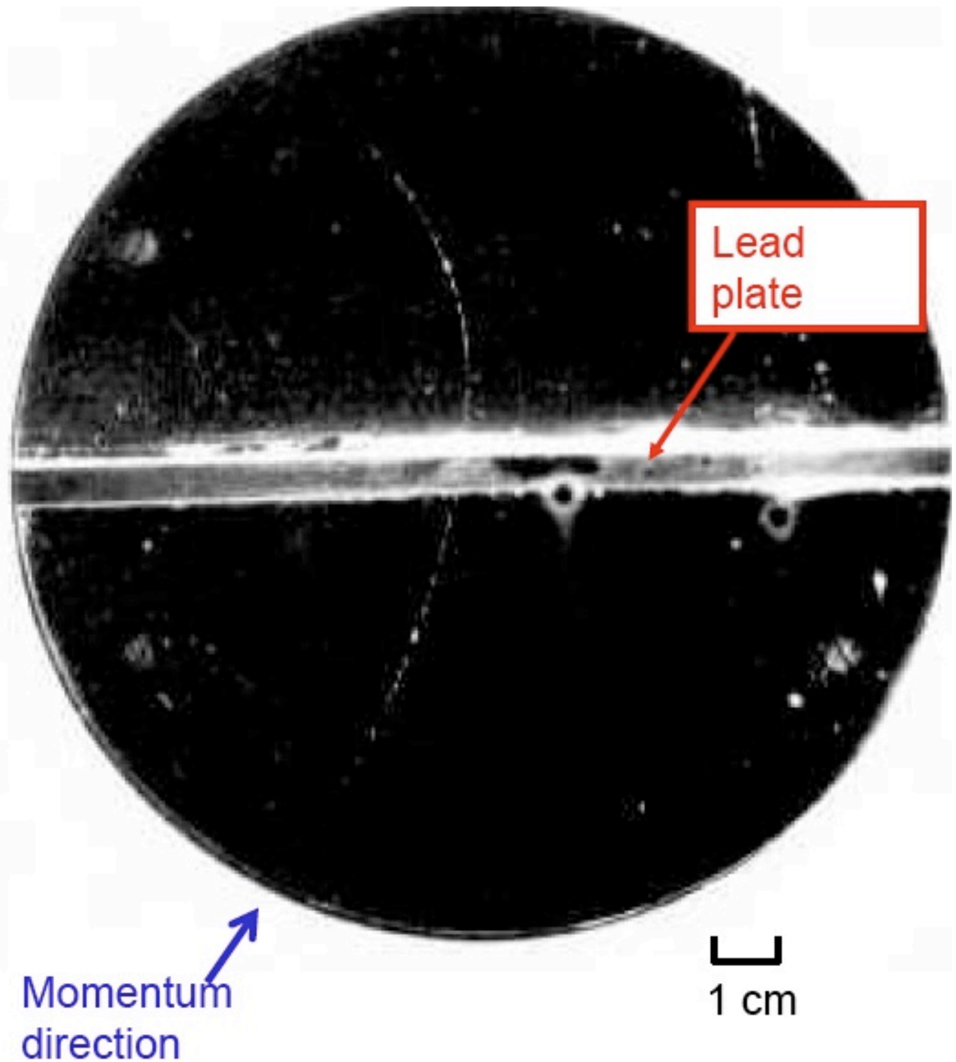
Anderson at work: discovery of the positron in 1932.

Parity symmetry breaking



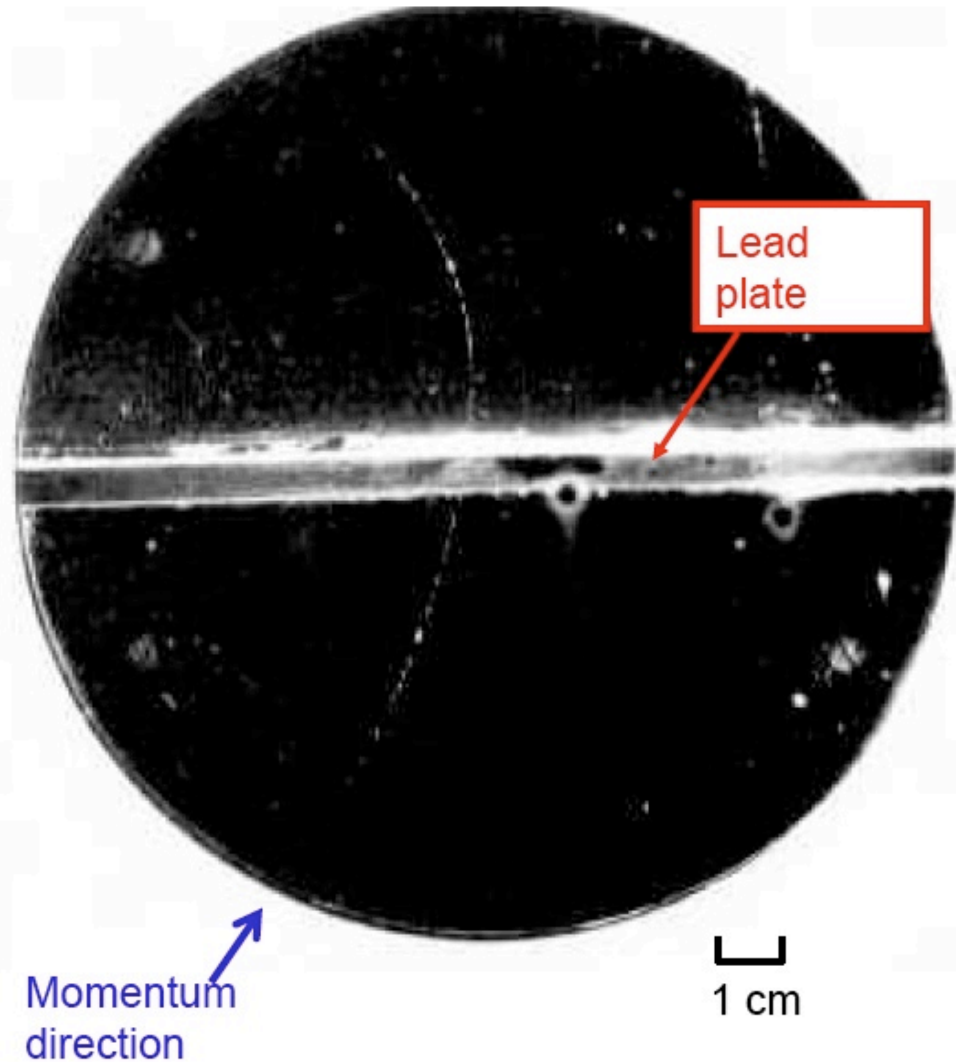
Parity symmetry breaking

- The radius of curvature is smaller above the plate. The particle is slowed down in the lead → the particle is incoming from the bottom.



Parity symmetry breaking

- The radius of curvature is smaller above the plate. The particle is slowed down in the lead → the particle is incoming from the bottom.
- The magnetic field direction is known:
  → positive charge



Parity symmetry breaking

- The radius of curvature is smaller above the plate. The particle is slowed down in the lead → the particle is incoming from the bottom.
- The magnetic field direction is known:
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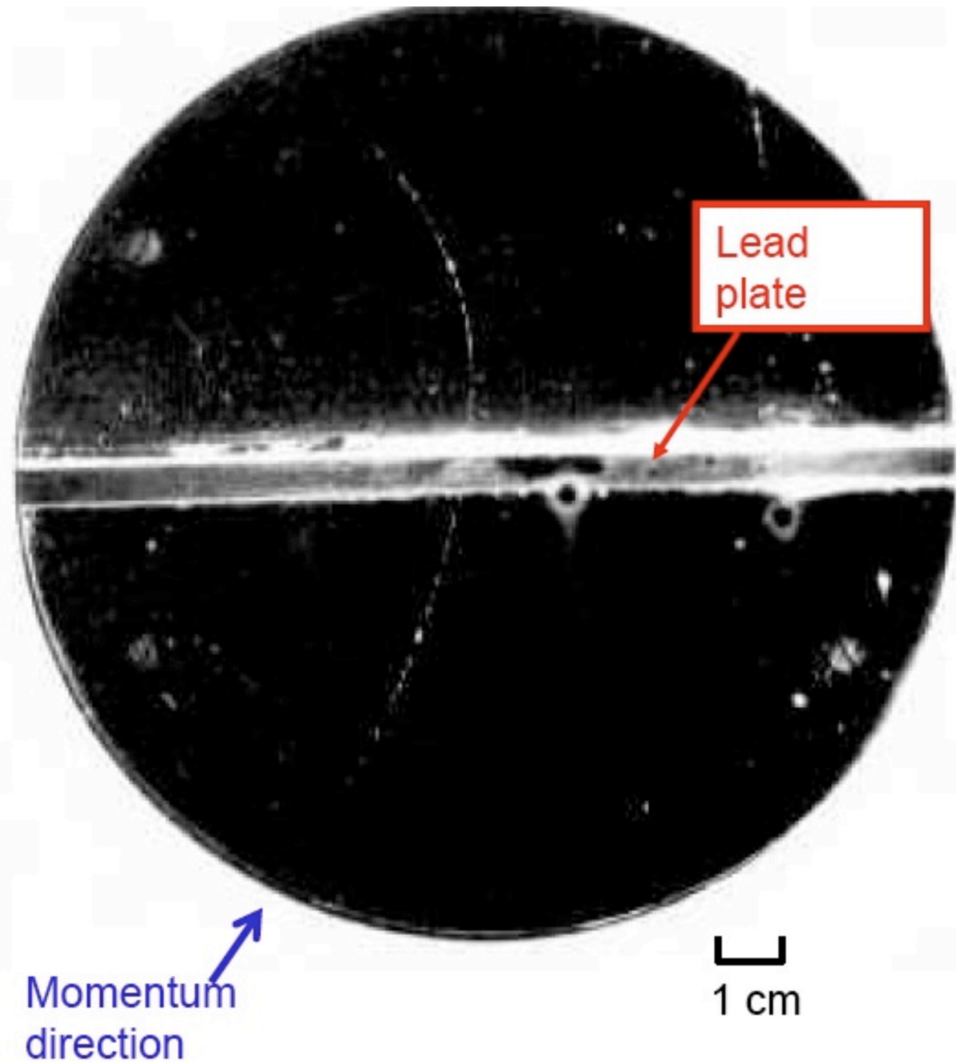
- From the density of the drops one can measure the ionizing power of the particle→ minimum ionizing particle.



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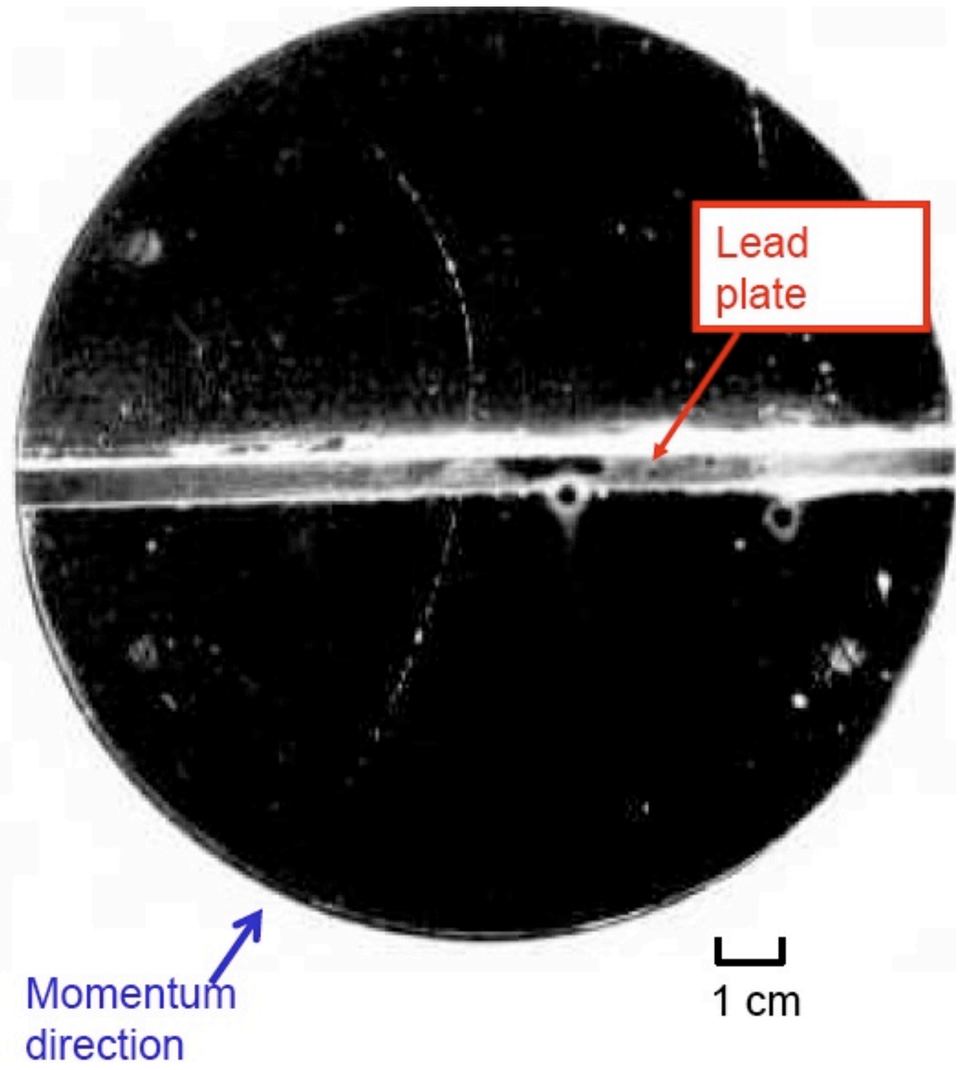

Parity symmetry breaking

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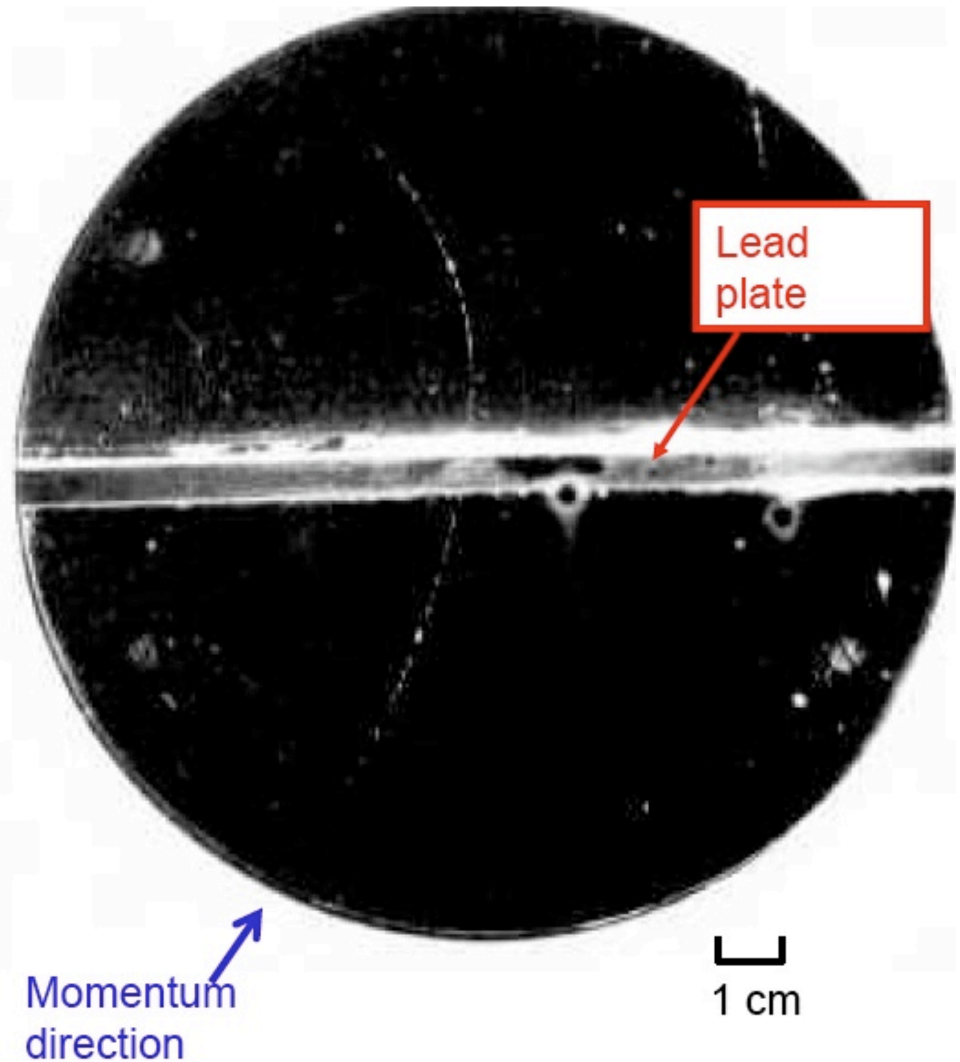
- From the density of the drops one can measure the ionizing power of the particle→ minimum ionizing particle.
- Similar ionizing power before and after the plate → same particle on the 2 sides.
- Curvature measurement after the lead: particle of ~23MeV → it is not a non-relativistic proton because it would have lost all its energy after ~5mm (a track of ~5 cm is observed).



Parity symmetry breaking

Why *P* must be a good symmetry

A variable describing a physical system is not an observable.

One can always find a mathematical transformation which lets the physical system invariant.

An observable is conserved.

Parity symmetry breaking

Why *P* must be a good symmetry

Non-observable	Mathematical transf.	Conserved quantity
Absolute spatial position	Space translation	Momentum
Absolute time	Time translation	Energy
Absolute space direction	Rotation	Angular momentum
Absolute right	Space reflexion (mirror)	Parity
Electric charge sign	$e \rightarrow -e$	Charge conjugation
Absolute time sign	$t \rightarrow -t$	Time reversal
Relative phase between electric charges	Gauge transformation	The electric charge

Evidence for *P* violation

- ✓ Before 1956 : all interactions were thought to be invariant under parity operation
- ✓ It was (quite comprehensively) tested for strong and electromagnetic interactions.
- ✓ Lee and Yang proposed an experiment to test it for weak interaction after the theta / tau puzzle.
- ✓ Designed and performed in 1956 by C.S. Wu and collaborators
- ✓ The Co^{60} experiment : Phys. Rev. 105, 1413-1414 (1957)

Evidence for *P* violation

The magnetic field is directed to the right. The spins are aligned along to it.

$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

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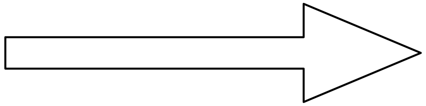

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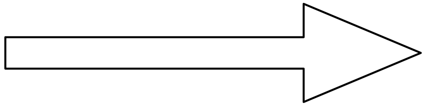

$$^{60}\mathrm{Ni}\ (J = 4)$$

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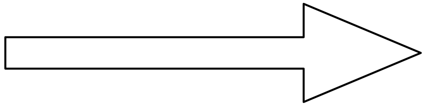
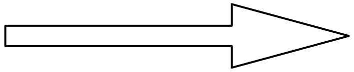


$$^{60}\mathrm{Ni}\ (J = 4)$$



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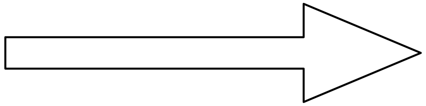
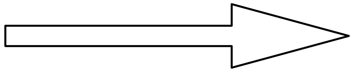
The magnetic field is directed to the right. The spins are aligned along to it.

$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

$^{60}\mathrm{Co}\ (J = 5)$ 

$^{60}\mathrm{Ni}\ (J = 4)$ 

Evidence for *P* violation

The magnetic field is directed to the right. The spins are aligned along to it.

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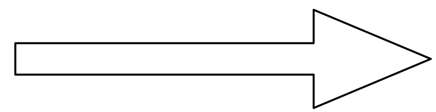
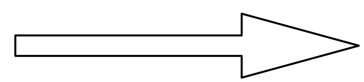
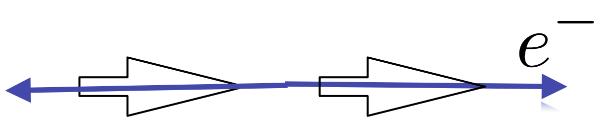
$^{60}\mathrm{Co}\ (J = 5)$



$^{60}\mathrm{Ni}\ (J = 4)$





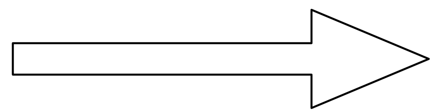
Parity symmetry breaking

Evidence for *P* violation

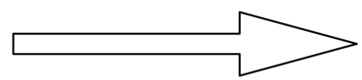
The magnetic field is directed to the right. The spins are aligned along to it.

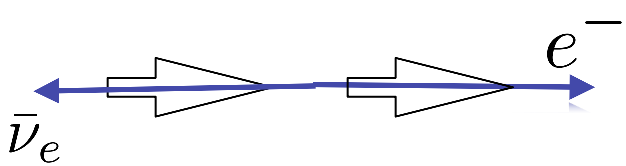
$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

$$^{60}\mathrm{Co}\ (J = 5)$$



$$^{60}\mathrm{Ni}\ (J = 4)$$





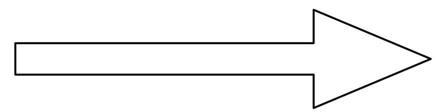
Parity symmetry breaking

Evidence for *P* violation

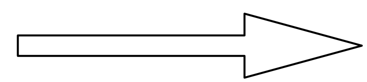
The magnetic field is directed to the right. The spins are aligned along to it.

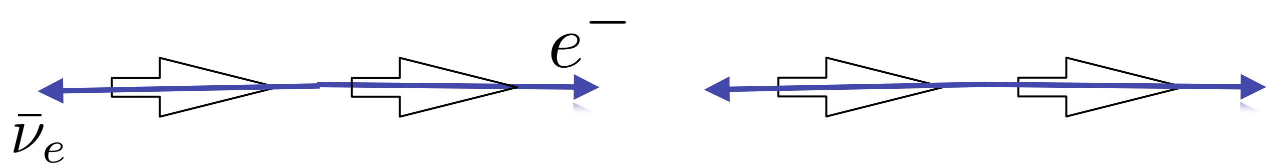
$$^{60}\text{Co} \to {}^{60}\text{Ni} + e^- + \bar{\nu}_e$$

$$^{60}\text{Co}\ (J = 5)$$



$$^{60}\text{Ni}\ (J = 4)$$





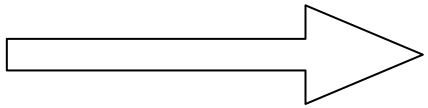
Parity symmetry breaking

Evidence for *P* violation

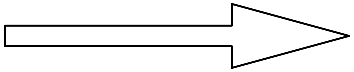
The magnetic field is directed to the right. The spins are aligned along to it.

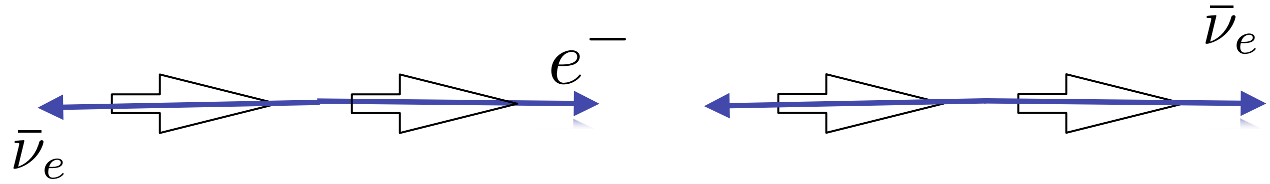
$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

$$^{60}\mathrm{Co}\ (J=5)$$



$$^{60}\mathrm{Ni}\ (J=4)$$





Parity symmetry breaking

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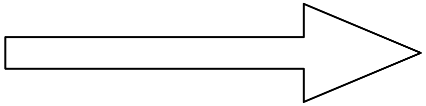
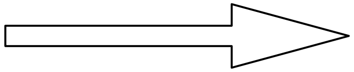
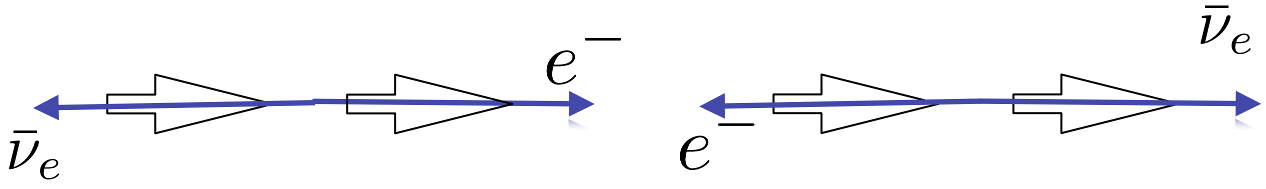


$$^{60}\mathrm{Ni}\ (J = 4)$$





Parity symmetry breaking

Evidence for *P* violation

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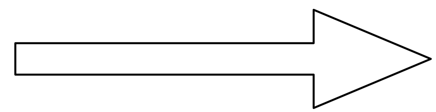
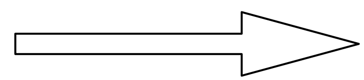
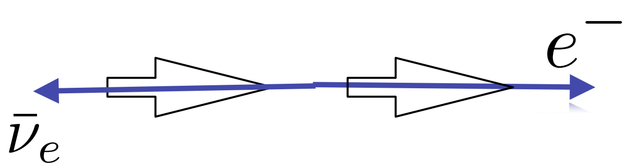
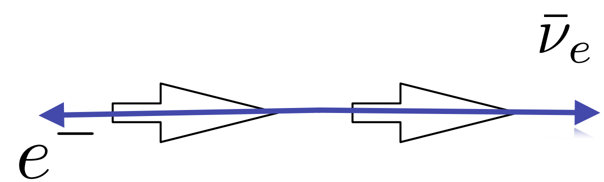


$^{60}\mathrm{Ni}\ (J = 4)$







If the Nature can't distinguish left from right, then both decays are possible.

Evidence for *P* violation

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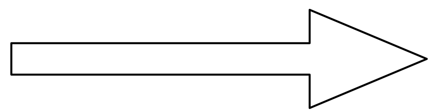

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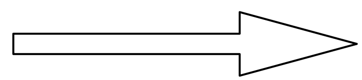
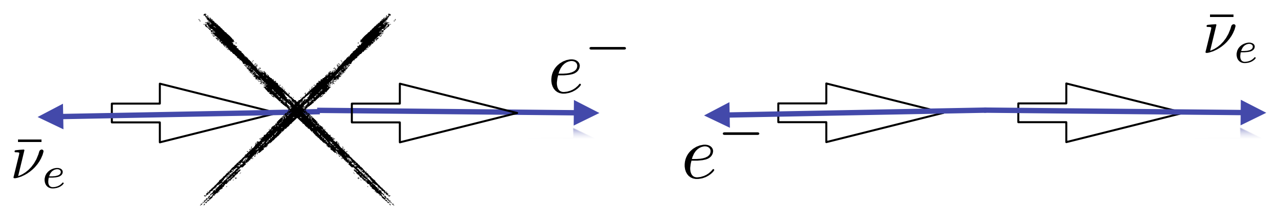
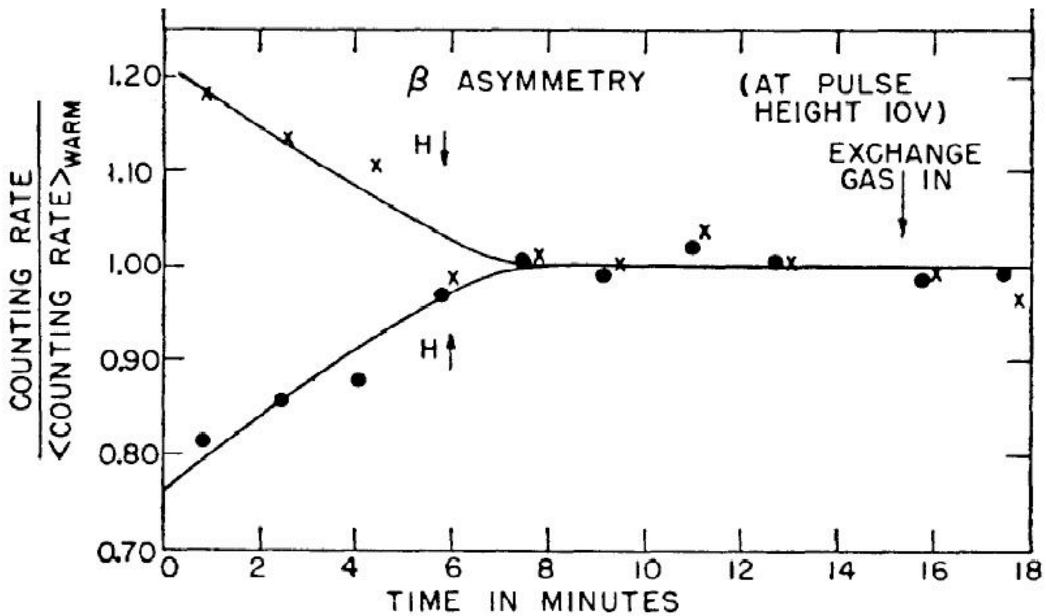




If the Nature can't distinguish left from right, then both decays are possible.

Evidence for *P* violation

- The magnetic field direction is changed and the rate for the electrons emission is measured in the two configurations. The asymmetry is reversed.



- The preferred chiral state is a right-handed anti-neutrino (left-handed electron).

Evidence for *P* violation

- The experiment was conducted during Christmas holidays 1956.
- The paper is published rightafter (2.5 pages).
- Lee and Yang receives the Nobel Prize in 1957 (sounds like this evidence was not overlooked).

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would
cessary evidence for parity conservation
tion. In beta decay, one could measure
stribution of the electrons coming from
polarized nuclei. If an asymmetry in the
tween θ and $180°-\theta$ (where θ is the angle
rientation of the parent nuclei and the
the electrons) is observed, it provides
oof that parity is not conserved in beta
mmetry effect has been observed in the
l Co^{60}.
nown for some time that Co^{60} nuclei can
y the Rose-Gorter method in cerium
balt) nitrate, and the degree of polari-
d by measuring the anisotropy of the
ma rays.[2] To apply this technique to the
n, two major difficulties had to be over-

The Nobel Prize in Physics 1957

Chen Ning Yang
Prize share: 1/2

Tsung-Dao (T.D.) Lee
Prize share: 1/2

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee *"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"*

Parity symmetry breaking

Neutrinos are left-handed

The Goldhaber experiment:

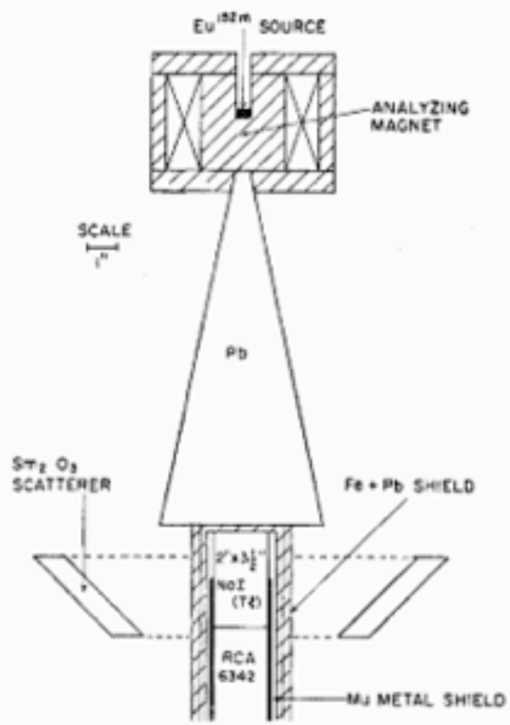
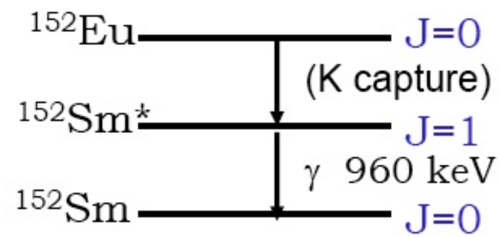


FIG. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm_2O_3 scatterer: 1850 grams.

$$^{152}\mathrm{Eu}(J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu$$

(K capture)

$$\hookrightarrow {}^{152}\mathrm{Sm}(J=0) + \gamma$$



The spins of all final states particles are constrained. The gammas aligned with the ^{152}Sm are selected and their polarization is measured.

Parity symmetry breaking

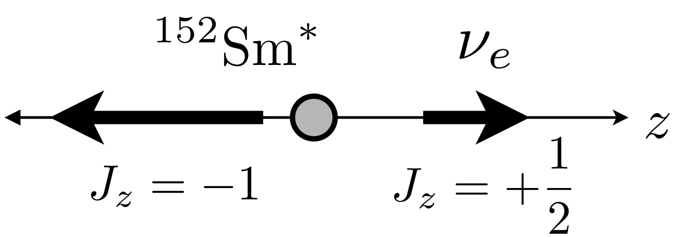
Neutrinos are left-handed

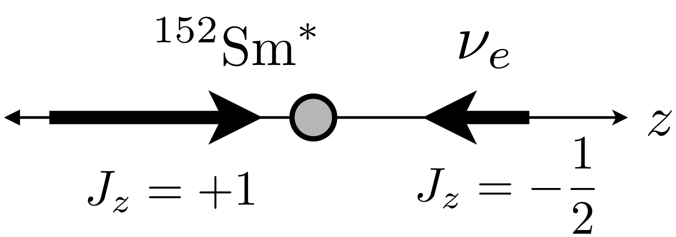
The Goldhaber experiment:

We write down the spin constraints: the spin of the electron defines the initial and the final states. We shall end up with a one-half spin projection.

$$^{152}\mathrm{Eu}(J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu_e$$

Two configurations are possible:





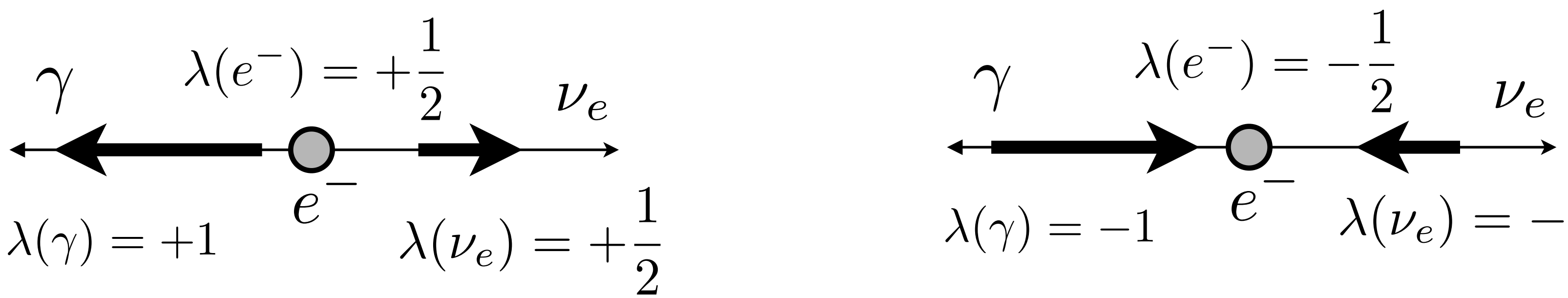
Neutrinos are left-handed

The Goldhaber experiment: $^{152}\mathrm{Eu}(J=0) + e^- \to {}^{152}\mathrm{Sm}^*(J=1) + \nu_e$

The above *K*-capture is followed by the excited Samarium decay:

$$^{152}\mathrm{Sm}^*(J=1) \to {}^{152}\mathrm{Sm}(J=0) + \gamma$$

The gamma (as a massless vector boson) has two possible polarisations, which manifest in the two and only two possible configurations of helicities:



From the gamma polarization measurement, Goldhaber et al. show that only left-handed neutrinos are found (i.e, the second configuration) in β decays. Goldhaber, Grodzins, Sunyar, Phys. Rev. 109, 1015 (1958).

Neutrinos are left-handed

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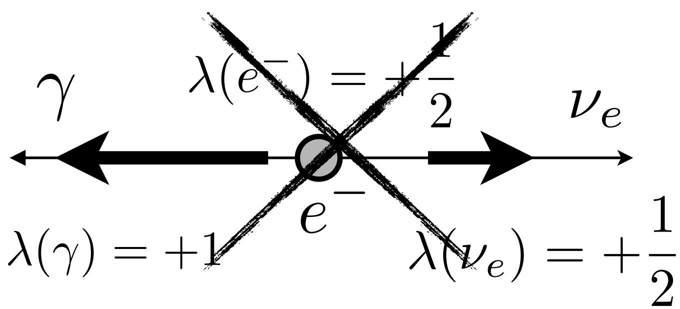

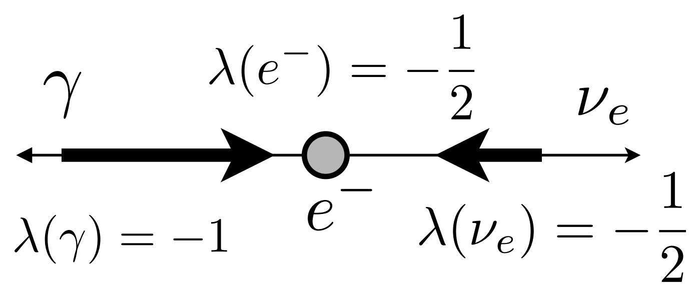

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Aparté: what is helicity? What is chirality?

(

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

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

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

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

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

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

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

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

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

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

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

u_1 and u_2 are helicity eigenstates

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

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

Let's project those states with the chirality projectors:

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

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

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

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

Parity symmetry breaking

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

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

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

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

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

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

- For a massless particle, helicity IS chirality.

- For ultra-relativistic particles (*E*>>*m*), helicity IS chirality.

- The heavier is a particle, the larger is the mixing of chiral states for a given helicity.

Parity symmetry breaking

Aparté: what is helicity? What is chirality?

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓Quantum Field Theory: requirement of Lorentz Invariance (LI) of the matrix elements strongly constrains the form of the interaction vertices. We learnt QED and QCD to have vector currents. In general, 5 and only 5 combinations of 2 spinors and γ-matrices complies with Lorentz Invariance. They are called covariant bilinears:

Type	Expression	Components	Mediating Boson
Scalar	$\bar{\Psi}\Phi$	1	Spin 0
PseudoScalar	$\bar{\Psi}\gamma^5\Phi$	1	Spin 0
Vector	$\bar{\Psi}\gamma^\mu\Phi$	4	Spin 1
Axial Vector	$\bar{\Psi}\gamma^\mu\gamma^5\Phi$	4	Spin 1
Tensor	$\bar{\Psi}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\Phi$	6	Spin 2

Parity symmetry breaking

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓WE, have to find which form or combination of forms would fit the experimental observation that parity symmetry is maximally violated in weak interaction and that left-handed helicity (=chirality) neutrinos seem to be the only authorized state in that scope.

✓ First a reminder on chirality states. Let's consider a half-spin particle:

$$(i\gamma^\mu \partial_\mu - m)\Psi = 0.$$

$$\Psi = \Psi_L + \Psi_R, \Psi_L = P_L\Psi, \Psi_R = P_R\Psi,$$

$$P_{L,R} = \frac{(1 \pm \gamma^5)}{2},$$

$$\gamma^5 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}.$$

Parity symmetry breaking

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

✓There are two vertex interaction forms complient with our objectives: these are the Vector-AxialVector interaction:

$$\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi = \bar{\Psi}(P_L+P_R)\gamma^{\mu}(1-\gamma^{5})(P_L+P_R)\Psi$$
$$\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi = 2\bar{\Psi}(P_L+P_R)\gamma^{\mu}(P_L^2+P_LP_R)\Psi$$
$$\bar{\Psi}\gamma^{\mu}(1-\gamma^{5})\Psi = 2\bar{\Psi}_L\gamma^{\mu}\Psi_L$$

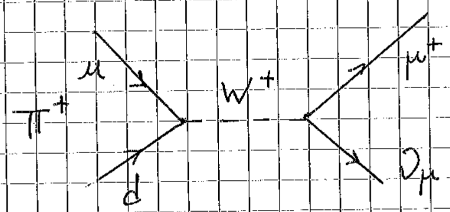
✓Selection of chirality states. Only LL couplings allowed for particles. Maximal violation of the parity symmetry. A natural candidate for the weak interaction.

✓*Homework 1: show that vectorial interactions selects democratically LL and RR interaction vertices. Show as well that [V+A] does the same as [V-A].*

Parity symmetry breaking

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

π Decay - Decay width and related matter.
Hands out.



$$d\Gamma = \frac{1}{2E}\,\frac{1}{(2s_{\pi^+}+1)}\sum_{spins}|\mathcal{M}|^2\,dQ.$$

(1) HADRONIC MATRIX ELEMENT $j^\mu_q = \bar{u}(u)\gamma^\mu(1-\gamma^5)v(\bar{d})$

Since quarks, cannot be calculated perturbatively for the strong interaction $\longrightarrow j^\mu_q = f_\pi p^\mu$. p = momentum of π.

(2) LEPTONIC MATRIX ELEMENT AND $\mathcal{M}$.

$j_{\ell\mu} = \bar{u}(\mu^+)\gamma_\mu(1-\gamma^5)u(\nu_\mu)$ and $\mathcal{M} = \frac{G_F}{\sqrt{2}}[j^\mu_q][j_{\ell\mu}]$.

$\longrightarrow \mathcal{M} = \frac{G_F}{\sqrt{2}} f_\pi m_\mu [\bar{u}(\mu^+)(1-\gamma^5)u(\nu_\mu)]$

Neutrinos are left-handed. Implications: the decay of the pion as an illustration

③ SUM OVER FINAL STATES SPINS

$$|\overline{\mathcal{M}}|^2 = \sum_{spins} \mathcal{M}\mathcal{M}^* = 4\, G_F^2 f_\pi^2 m_\mu^2\, P(\mu)\cdot P(\nu_\mu)$$

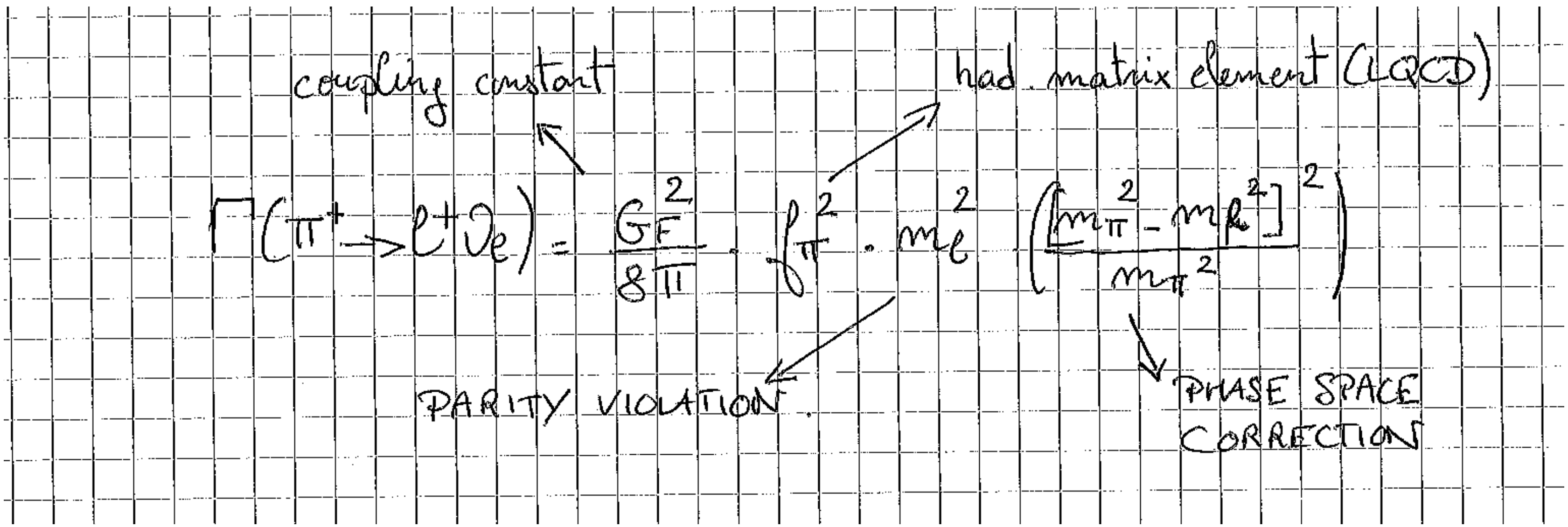
④ PHASE SPACE INTEGRATION

$$dQ = \frac{d^3 p(\mu)}{(2\pi)^3 \cdot 2E(\mu)} \cdot \frac{d^3 p(\nu_\mu)}{(2\pi)^3 \cdot 2E(\nu_\mu)} (2\pi)^4 \delta^{(4)}\left(P - p(\mu) - p(\nu_\mu)\right)$$

⑤ BOTTOMLINE

$$\Gamma = \frac{G_F^2}{8\pi} f_\pi^2 \cdot \frac{m_\mu^2}{m_\pi^2}\left(m_\pi^2 - m_\mu^2\right)^2$$

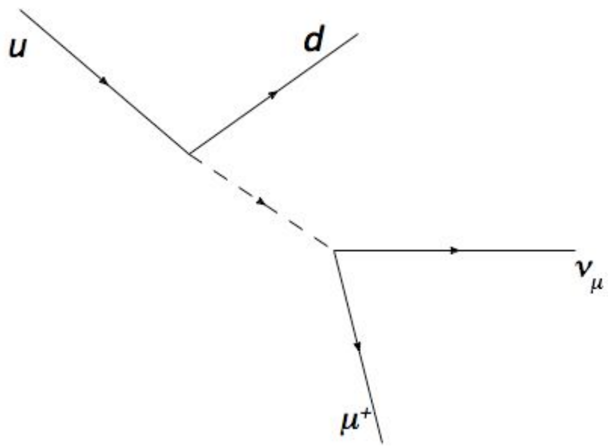
Neutrinos are left-handed. Implications: the decay of the pion as an illustration



✓Interpretation: you force the antilepton to be in its wrong helicity state (chirality is definitely right-handed). Electrons must hate you more than muons do (at least in the ratio of the squared masses).

Parity symmetry breaking

Neutrinos are left-handed. Implications: the decay of the pion as an illustration



To remove the QCD part of the decay width which is badly determined, it is relevant to consider a ratio of decay widths in leptons.

Again, we can compare the predictions with the different allowed Lorentz Invariant structures of the interaction to the measurement.

$$\frac{\Gamma(\pi^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to e^+ \nu_e)} = (0.813 \pm 0.004).10^4,$$

$$\frac{\Gamma(\pi^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to e^+ \nu_e)} = 0.2 \quad (\text{S or P prediction}),$$

$$\frac{\Gamma(\pi^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to e^+ \nu_e)} = 0.78\ 10^4 \quad (\text{V} - \text{A prediction}).$$

Neutrinos are left-handed. Implications:
the decay of the pion as an illustration

✓Final notes on the subject:

- If the electron and muon decay widths differ a lot, lepton and antilepton decay widths are the same within experimental uncertainties, making *CP* a good symmetry of the weak interaction.
- In the actual calculation (which I strongly encourage you to perform), you will observe a slight tension between the prediction and the measurement. Anticipating a bit the following elements of this lecture, this disagreement is related to the probability of the $d \to u$ transition which is not amounting to unity.

Modern parity violation experiments:LEP/SLD

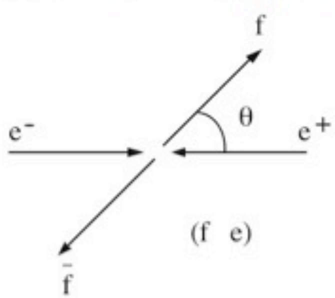
The Standard Model Tests (Part II)

3.3 The Parity-Violating forward-backward asymmetries in e+e-.

- Parity is maximally violated in weak interactions. This induces the fermion particle in the final state to be produced preferentially in the direction of the initial electron.

$$\frac{d\sigma^f}{d\cos\theta} = \sigma^f_{\rm tot} \cdot [\frac{3}{8}(1+\cos^2\theta) + A^{f\bar{f}}_{\rm FB}\cos\theta]$$

- The experimentalist's job is to identify the nature of the fermion and count how many times it is find forward (i.e in the electron direction)



$$A^{f\bar{f}}_{\rm FB} = \frac{N_F - N_B}{N_F + N_B} \text{ with } N_F = \int_0^1 \frac{d\sigma_{f\bar{f}}}{d\cos\theta} \cdot d\cos\theta$$

$$A^{f\bar{f}}_{\rm FB} \propto A_e \cdot A_f \propto \frac{g^e_V g^e_A}{(g^e_V)^2 + (g^e_A)^2} \cdot \frac{g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$$

Hence depends primarily to $\sin^2\theta_{\rm eff}$

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Modern parity violation experiments: SLD

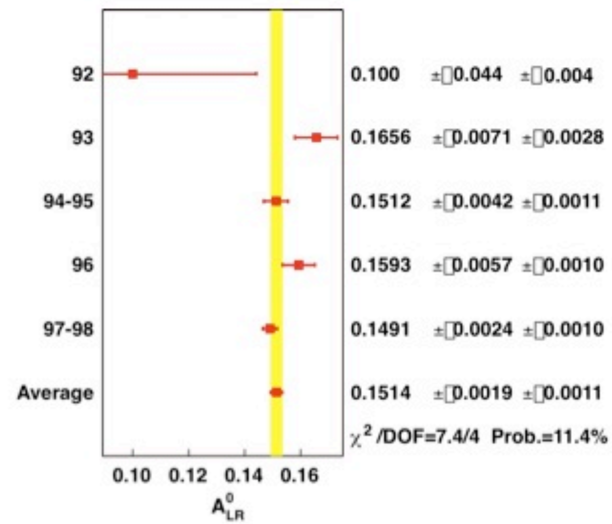
The Standard Model Tests (Part II)

3.4 The Parity-Violating Left-Right asymmetry from SLD

- We have seen in 3.3 that A_e was an excellent laboratory.
- SLC machine polarized the electron beam.
- Hence, knowing the polarization and just measuring the LL and RR production of Z boson yields A_e :

$$A_{\mathrm{LR}} = \frac{N_L - N_R}{N_L + N_R} \cdot \frac{1}{\langle P_e \rangle}$$

$$\langle P_e \rangle_{1998} = 0.7292 \pm 0.0038$$



$$A^0_{\mathrm{LR}} = 0.1514 \pm 0.0022$$
$$\sin^2\theta_{\mathrm{eff}} = 0.23097 \pm 0.00027.$$

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Parity symmetry breaking

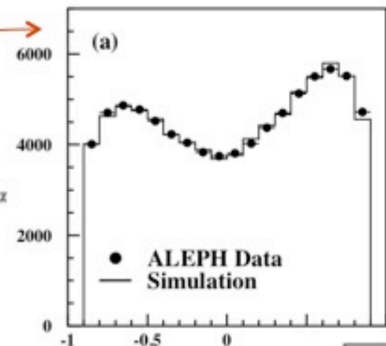
Modern parity violation experiments: LEP

The Standard Model Tests (Part II)

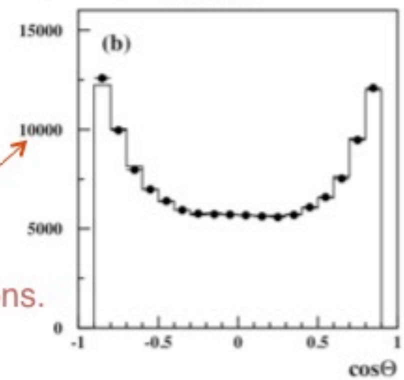
3.3 The Parity-Violating forward-backward asymmetries in e+e-.

- Then we fit the asymmetries to these data:

$$
\begin{aligned}
f_{ijkl} = {} & (F^{\mathrm{rs}}_{\ell,\mathrm{b}})_{ijkl}\int_l [1+x^2+\frac{8}{3}A^{\mathrm{b}}_{\mathrm{FB}}(1-2\overline{\chi}_{ijkl})\,x]\mathrm{d}x \\
& + (F^{\mathrm{ws}}_{\ell,\mathrm{b}})_{ijkl}\int_l [1+x^2-\frac{8}{3}A^{\mathrm{b}}_{\mathrm{FB}}(1-2\overline{\chi}_{ijkl})\,x]\mathrm{d}x \\
& + (F^{\mathrm{asym}}_{\mathrm{bkg,b}})_{ijkl}\int_l [1+x^2+\frac{8}{3}A^{\mathrm{b}}_{\mathrm{FB}}(1-2\overline{\chi}_{ijkl})(2\eta^{\mathrm{b}}_{ijk}-1)\,x]\mathrm{d}x \\
& + (F_{\ell,c})_{ijkl}\int_l (1+x^2-\frac{8}{3}A^{\mathrm{c}}_{\mathrm{FB}}\,x)\mathrm{d}x \\
& + (F^{\mathrm{asym}}_{\mathrm{c}\to\mathrm{bkg}})_{ijkl}\int_l [1+x^2-\frac{8}{3}A^{\mathrm{c}}_{\mathrm{FB}}(2\eta^{\mathrm{c}}_{ijk}-1)\,x]\mathrm{d}x \\
& + (F^{\mathrm{asym}}_{\mathrm{s}\to\mathrm{bkg}})_{ijkl}\int_l [1+x^2+\frac{8}{3}A^{\mathrm{s}}_{\mathrm{FB}}(2\eta^{\mathrm{s}}_{ijk}-1)\,x]\mathrm{d}x \\
& + (F^{\mathrm{asym}}_{\mathrm{d}\to\mathrm{bkg}})_{ijkl}\int_l [1+x^2+\frac{8}{3}A^{\mathrm{d}}_{\mathrm{FB}}(2\eta^{\mathrm{d}}_{ijk}-1)\,x]\mathrm{d}x \\
& + (F^{\mathrm{asym}}_{\mathrm{u}\to\mathrm{bkg}})_{ijkl}\int_l [1+x^2-\frac{8}{3}A^{\mathrm{u}}_{\mathrm{FB}}(2\eta^{\mathrm{u}}_{ijk}-1)\,x]\mathrm{d}x \\
& + (F^{\mathrm{sym}}_{\mathrm{bkg}})_{ijkl}\int_l (1+x^2)\mathrm{d}x,
\end{aligned}
$$



Parity violation even seen for charm.



Includes QED and QCD effects.

Measuring simultaneously the mixing parameter w/ leptons.

S.Monteil TESchool of High Energy Physics

An intermediate conclusion

- ✓ Parity is violated in weak interaction.
- ✓ One gets from experimental results so far the following picture:

- ✓ Any theory of the weak interaction shall include these properties.

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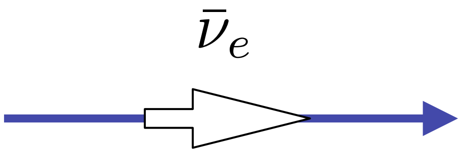

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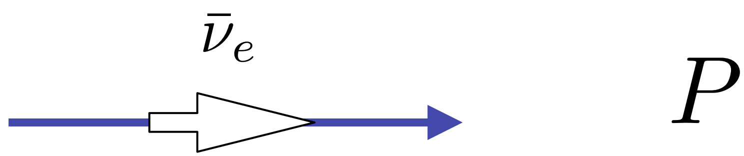

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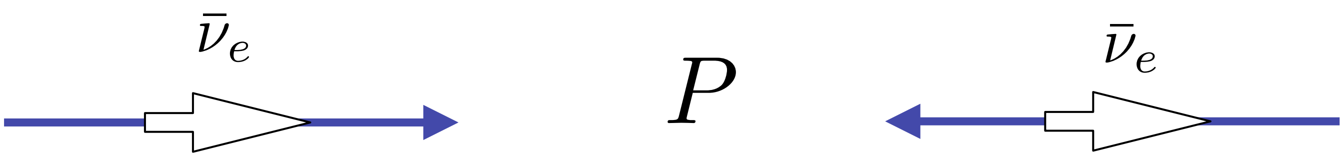

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C and *P* breaking and *CP* symmetry

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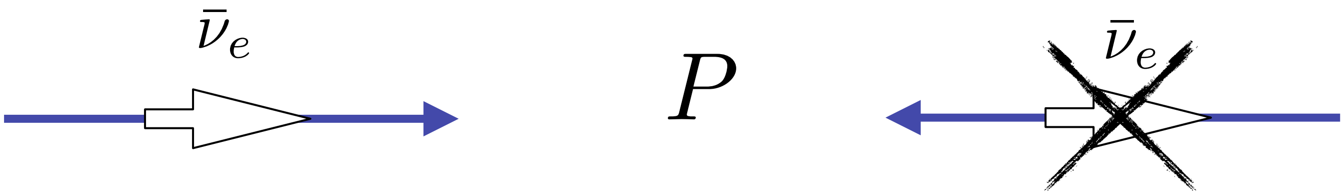

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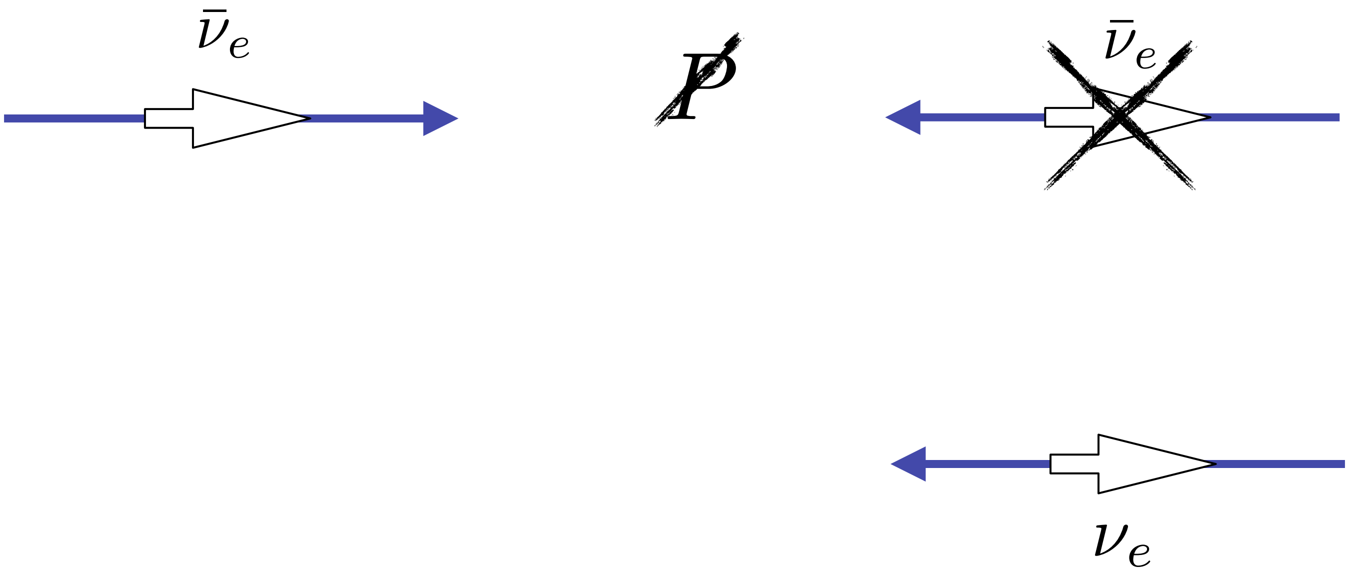

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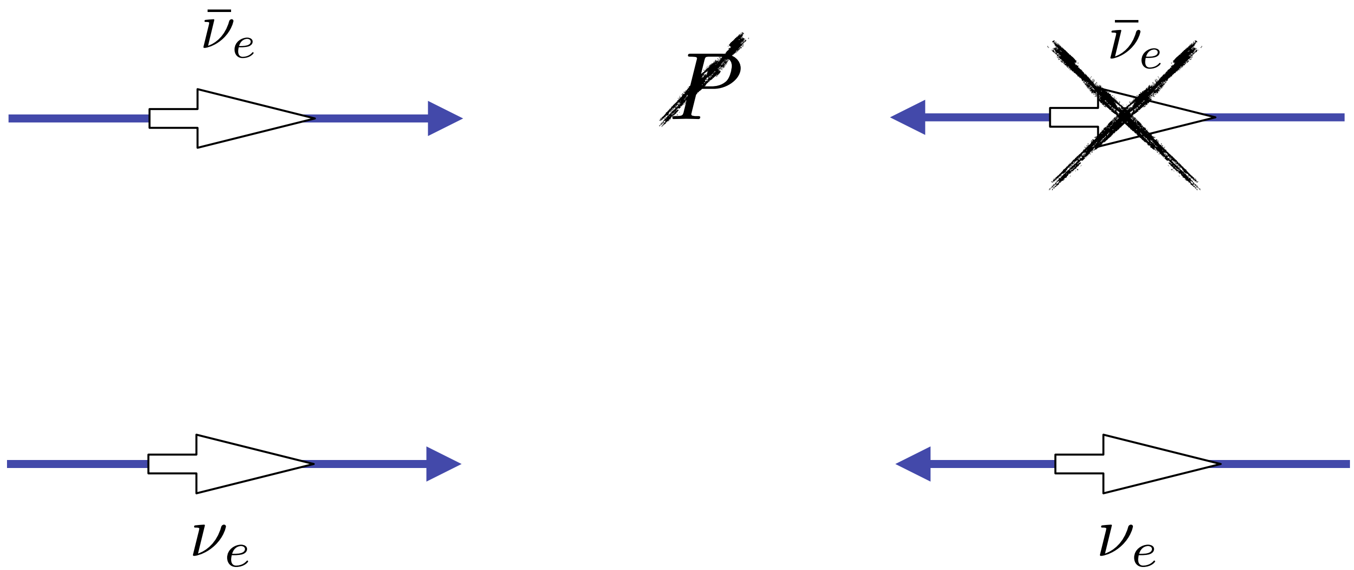

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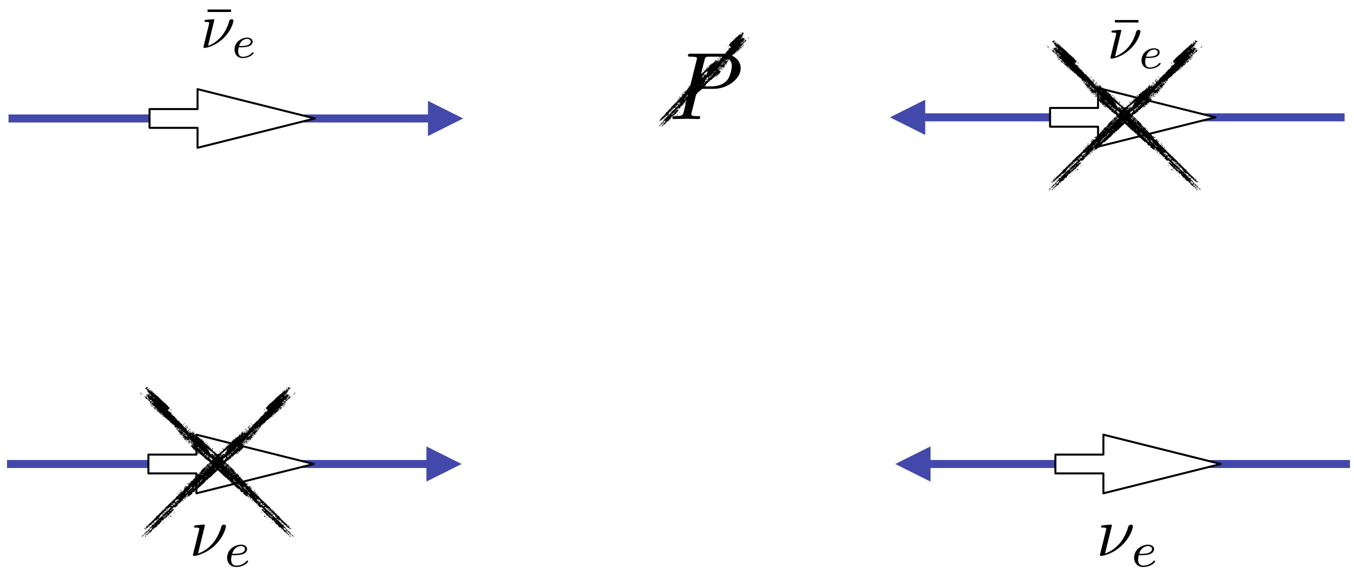

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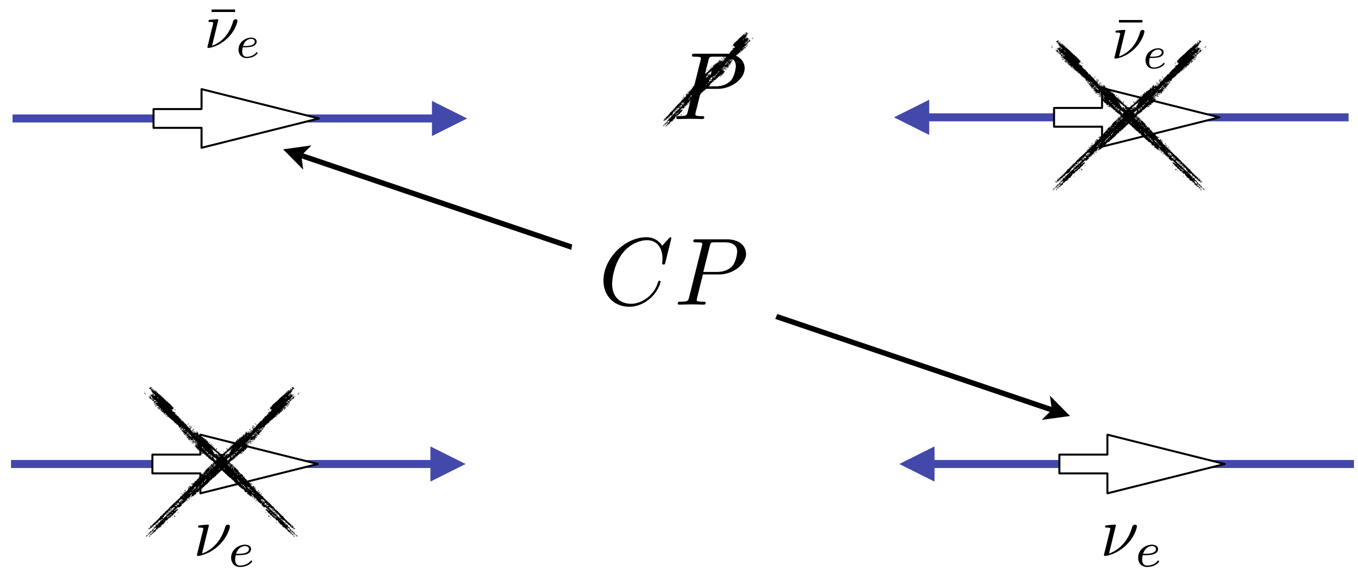
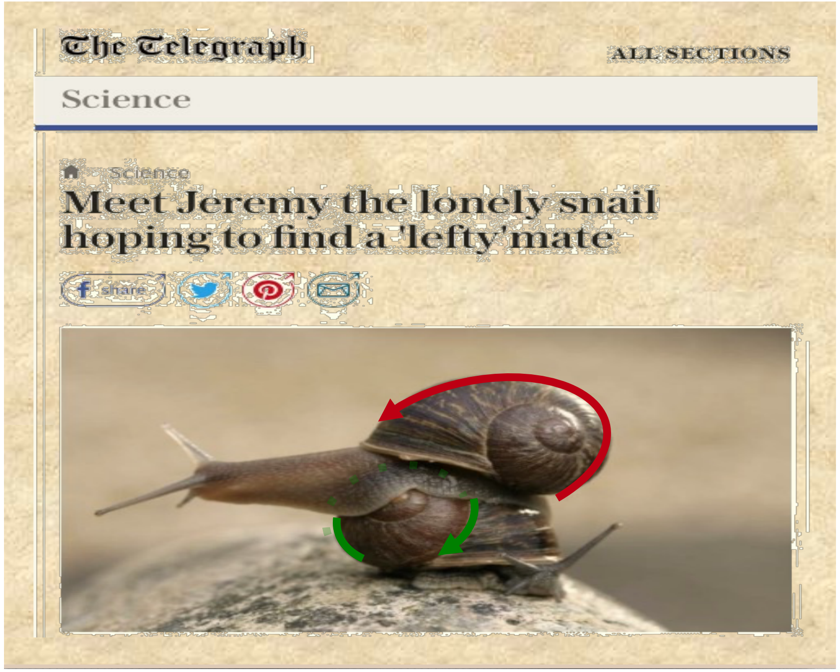


- ✓ Any theory of the weak interaction shall include these properties.

An intermediate conclusion

✓ Parity violation do occur elsewhere



The Telegraph ALL SECTIONS

Science

Science

Meet Jeremy the lonely snail hoping to find a 'lefty' mate

share

✓But those are not of fundamental nature. The DNA molecule for instance can be synthesised.

CP symmetry

Question: OK, parity is violated in the weak interaction. But can't we restore the left-right symmetry by considering the product *C* x *P*? Seems a good symmetry at least in the pion decay.

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

Discovery of *CP* violation.

- With simple quantum mechanics, one can show that in absence of *CP* violation:

$$CP|K_1\rangle = \frac{1}{\sqrt{2}}(CP|K^0\rangle + CP|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) = +|K_1\rangle$$
$$CP|K_2\rangle = \frac{1}{\sqrt{2}}(CP|K^0\rangle - CP|\bar{K}^0\rangle) = \frac{1}{\sqrt{2}}(|\bar{K}^0\rangle - |K^0\rangle) = -|K_2\rangle$$

- Final states *CP* eigenvalues are +1 ($\pi\pi$) and -1 ($\pi\pi\pi$). If *CP* is a conserved quantity, one then should have:

$$K_1 \rightarrow \pi\pi$$
$$K_2 \rightarrow \pi\pi\pi.$$

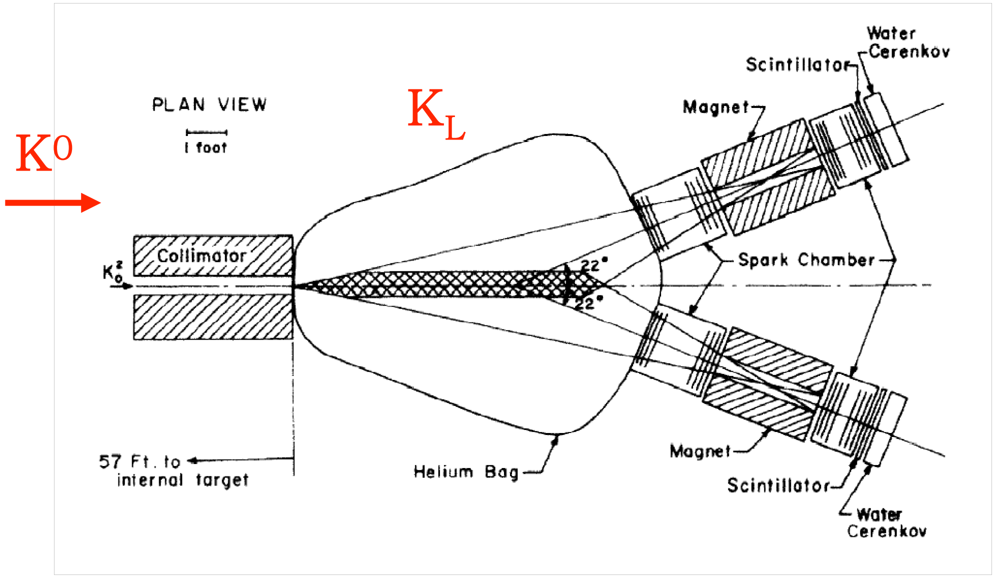
Which we'll identify as K^0_S and K^0_L respectively.

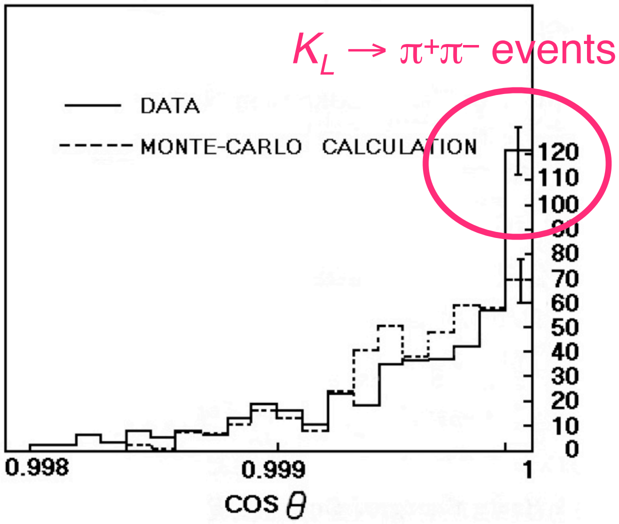
- measuring K^0_L decays into two pions ? Proof that *CP* symmetry is violated in weak interaction.

Discovery of *CP* violation.

- The CP violation in kaon system: Christenson, Cronin, Fitch , Turlay. Phys. Rev. Lett. 13 (1964) 138.

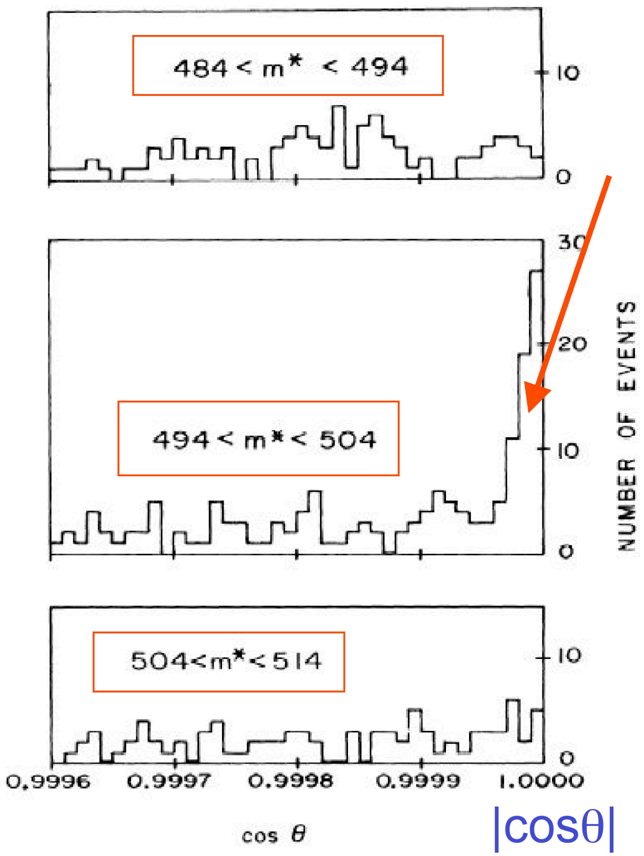
- Far after the target, only the long species of K^0 survive. They measured:





$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)}$$

Discovery of *CP* violation.



- Two-body decay : in the K^0 center of mass system the two π are back to back : |cosθ|=1.

- Today's more precise measurement for the ratio of amplitudes:

$$|\eta_{+-}| = \frac{A(K^0_L \to \pi\pi)}{A(K^0_S \to \pi\pi)} = (2.271 \pm 0.017)10^{-3}.$$

Discovery of *CP* violation.

Message Number 1:

The *CP* symmetry is violated in the mixing of neutral mesons, a pure electroweak phenomenon, *e.g.*

$$K^0 \longrightarrow \bar{K}^0 \neq \bar{K}^0 \longrightarrow K^0$$

Discoveries of *CP* violation

• At LHC, compare the decay rates of $B^0_{d,s}$ and *anti*$B^0_{d,s}$ into self-tagged final states $K\pi$

$$A_{CP}(B^0 \to K\pi) = \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

$$A_{CP}(B^0_s \to \pi K) = \frac{\Gamma(\bar{B}^0_s \to \pi^- K^+) - \Gamma(B^0_s \to \pi^+ K^-)}{\Gamma(\bar{B}^0_s \to \pi^- K^+) + \Gamma(B^0_s \to \pi^+ K^-)}.$$

• These raw asymmetries must be corrected from detection asymmetry and *B* production asymmetry:

$$A_\Delta(B^0_{(s)} \to K\pi) = \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)} \to K\pi)$$

• Ingredients: these analyses are heavily relying on Particle Identification performance. It is also necessary to master the *B* production asymmetry and the differences of charged particle detection efficiencies (data-driven estimates).

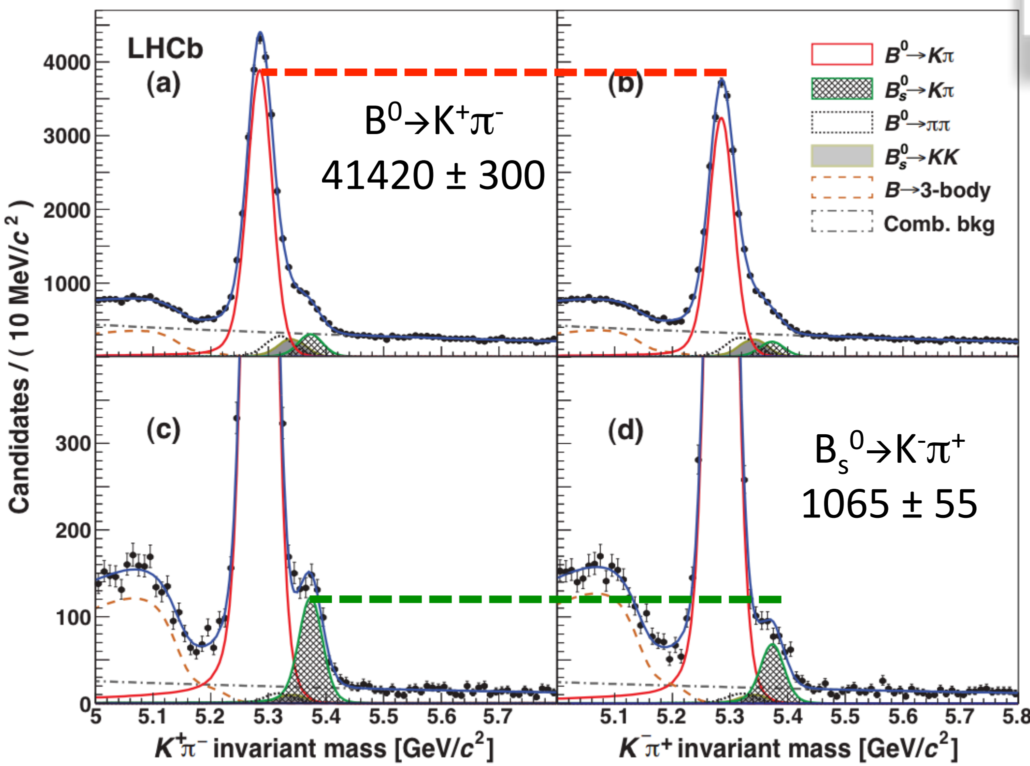
CP symmetry breaking

Other discoveries of *CP* violation.

- Compare the decay rates of self-tagged modes $K\pi$

$$A_{\rm raw}(B^0 \to K^-\pi^+) = -0.091 \pm 0.006,$$
$$A_{\rm raw}(B_s \to K^+\pi^-) = 0.28 \pm 0.04,$$

$\mathcal{L}$ = (1/fb @ √s = 7 TeV)



- Data-driven control of PID efficiencies thanks to the self-tagged mode $D^{*+} \to D^0\,(K^-\pi^+)\,\pi^+$
- Raw asymmetries corrected from detection asymmetry (also D^{*+} control sample.
- *B* production asymmetry simultaneously measured from decay time distribution.

Other discoveries of *CP* violation.

$$A_{\rm CP}(B^0 \to K^-\pi^+) = -0.080 \pm 0.007\,(\text{stat.}) \pm 0.003\,(\text{syst.}),$$
$$A_{\rm CP}(B_s \to K^+\pi^-) = 0.27 \pm 0.04\,(\text{stat.}) \pm 0.01\,(\text{syst.}).$$

- World best measurement for the B^0

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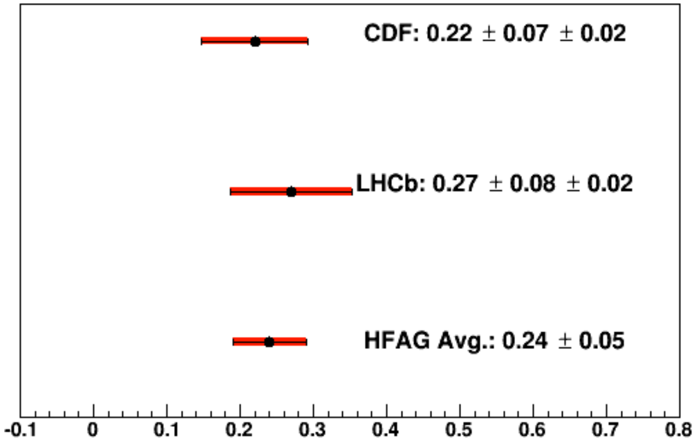
- Former results for B_s

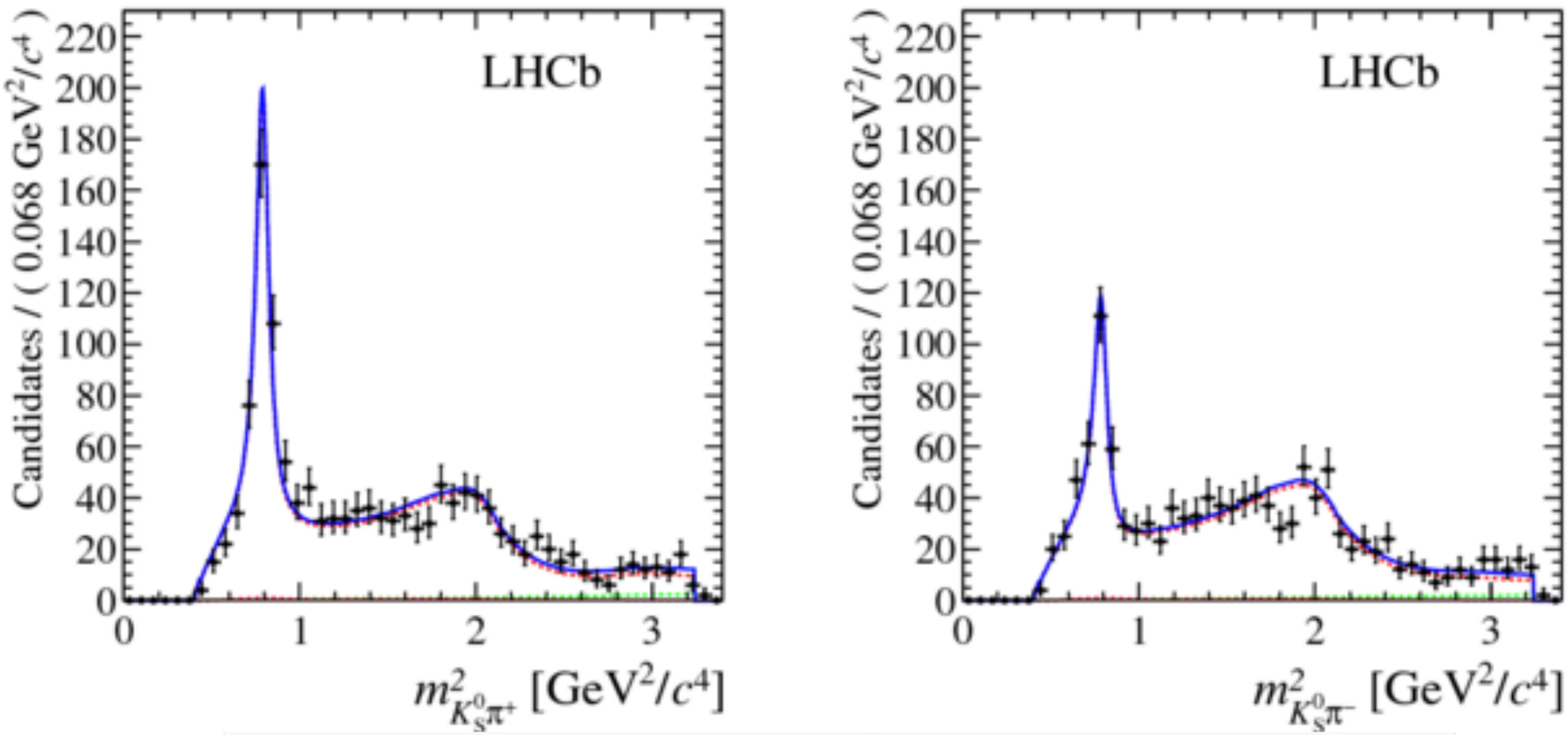


CDF-PUBLIC-10726

Phys. Rev. Lett. 108 (2012)

- **First observation of *CPV* in the B_s system.**

Other discoveries of *CP* violation.



Phys. Rev. Lett. 120, 261801 (2018)

$$A_{CP}(\overline{B}^0 \to K^*(892)^-\pi^+) = -0.30 \pm 0.06$$

Other discoveries of *CP* violation.

Message Number 2:

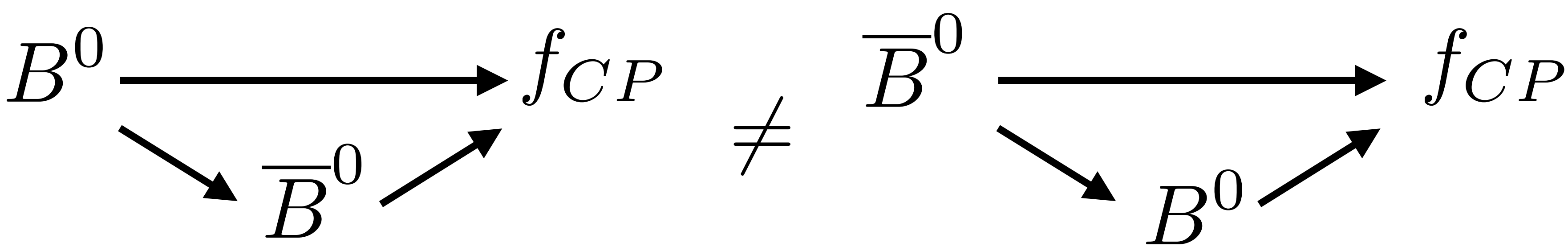
The *CP* symmetry is violated in the decay of beautiful particles, pure electroweak phenomenon, *e.g.*

$$B^0 \longrightarrow K^+\pi^- \neq \bar{B}^0 \longrightarrow K^-\pi^+$$

Other discoveries of *CP* violation.

Message Number 3:

The *CP* symmetry can be violated in the interplay (interference) of the two previous sources of *CP* violation, *e.g.*



Concluding this introduction

- *C*, *P* and *CP* are (so far) conserved in electromagnetic and strong interactions.
- *C* and *P* symmetries are maximally violated by the weak interaction.
- *CP* symmetry is slightly violated in the electroweak interaction.

- There are three ways of *CP* violation to manifest in the Nature so far:

  1) In the mixing of neutral particles (observed solely in neutral kaon mixing - 1964).

  2) In the decay of the beautiful and strange mesons (*K* and $B_{d,s}$, 2001 and 2004,2013 resp.).

  3) In the interference between decay and mixing of the beautiful particles (2001, see next chapters) .

  And that's all.

A personal comment before going to Chapter II

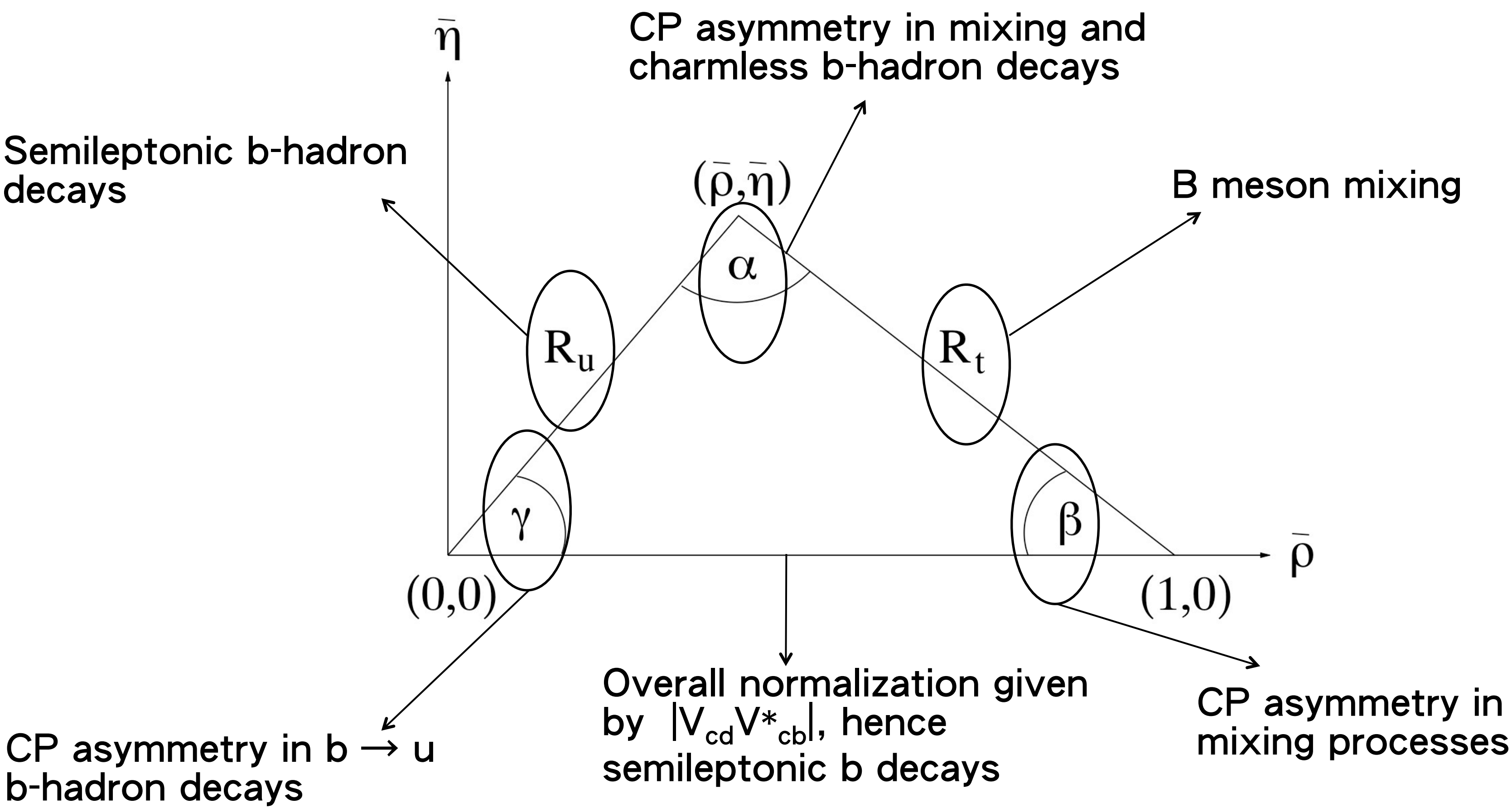
- We do not have yet a (satisfactory) dynamical mechanism to explain these discrete symmetry breakings. And to my knowledge, no mathematical Physics way to do so.

- Still, what comes next is elegant.

- We'll try to make sense of the *CP* symmetry breaking phenomena.

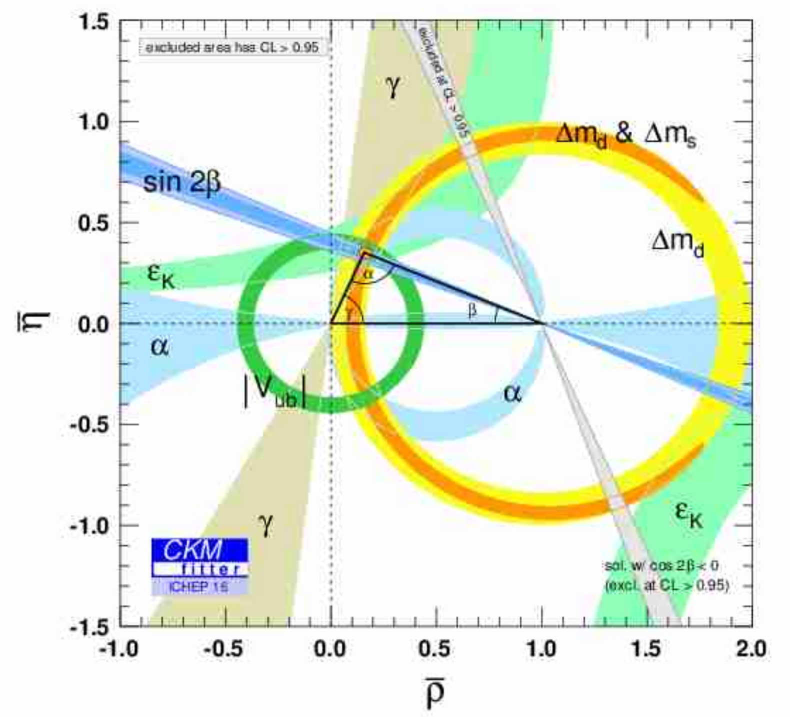
2.4 Introduction: which measurements and where?

- B factories: all ! As far as UT is concerned.



Motivation

• In any HEP physics conference summary talk, you will find this plot, stating that (heavy) flavours and *CP* violation physics is a pillar of the Standard Model.



• One objective of this lecture is to undress this plot.