Flavor Physics

Cibrán Santamarina

Universidade de Santiago de Compostela

Bibliography

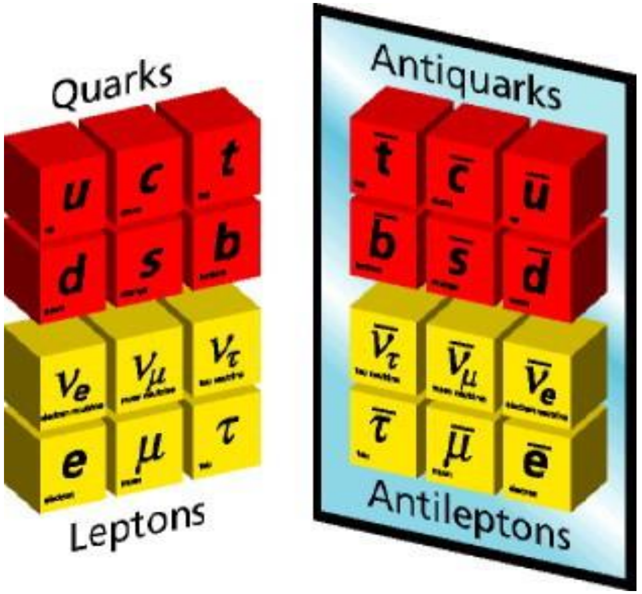
- For me the best reference (these slides reproduce a lot of them) are the notes:
- P. Kooijman & N. Tuning. Lectures on CP violation (or: The Physics of Anti-matter).
  - Available online: https://www.nikhef.nl/~h71/Lectures/2015/ppII-cpviolation-29012015.pdf
  - You can also find the slides by N. Tuning.
- Slides from three courses were also used:
  - M. Merk. CP Violation and the Standard Model. https://www.nikhef.nl/~i93/Presentations.html
  - O. Steinkamp. Flavour Physics. Chipp PhD Winter School 2013. http://www.physik.uzh.ch/~olafs/presentations/130121_CHIPP.pdf
  - F. Teubert. Indirect Searches of NP from Flavour Physics. TAE 2014.
- There are now several books that discuss CP violation with some detail. Two of them, that were also employed in the preparation of this material are:
  - M. Thomson. Modern Particle Physics. Cambridge University Press 2013.
  - A. Bettini. Introduction to Elementary Particle Physics. Cambridge University Press 2013.
- Finally, there is material on the latest Flavor Physics results. I have taken a lot of material from two recent presentations:
  - S. Blusk. New experimental results and prospects in flavor physics. DPF 2017, Fermilab.
  - J.J Saborido. CP Violation at LHCb. REFIS Benasque 2017.

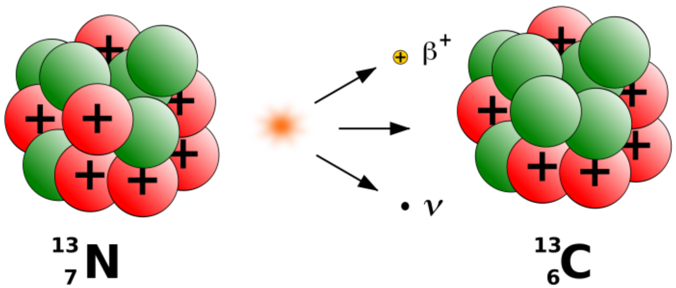
Roadmap

- First an introduction on discrete symmetries.
  - The weak interaction and flavor changes.
  - P violation.
  - CP violation and its relevance.
- Second a discussion of CPV in the Standard Model.
  - The Cabbibbo mechanism.
  - The CKM matrix and the SM.
  - Neutral mesons oscillation.
  - CPV classification.
- Third a discussion of relevant flavor physics results.
  - Experiments.
  - Measurements.

Flavour Physics

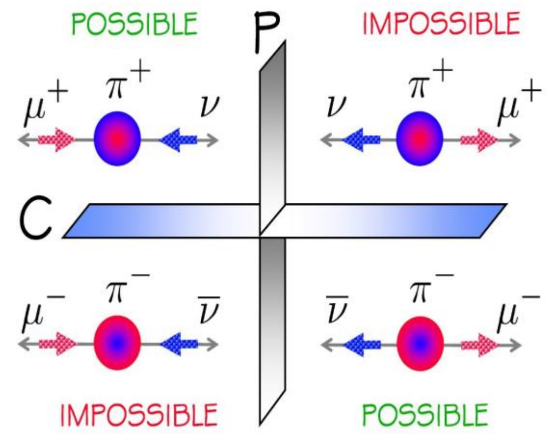
- In the Standard Model (SM) flavour physics is intimately related to the weak interaction.
  - It is the only SM interaction allowing transitions between different flavour families of either quarks and leptons.
  - Flavour is conserved in strong and electromagnetic interactions.
- Weak interaction is responsible for:
  - Beta decay
  - Muon decay
  - Kaon decays
  - Neutrino emission in nuclear reactions (solar neutrinos)
- There are three very important sectors in which flavour physics is involved:
  - **Quarks: measure mixing parameters, test SM predictions.**
  - Charged leptons: test lepton number conservation.
  - Neutrinos: measure neutrino masses and mixing parameters and determine their Majorana or Dirac nature.

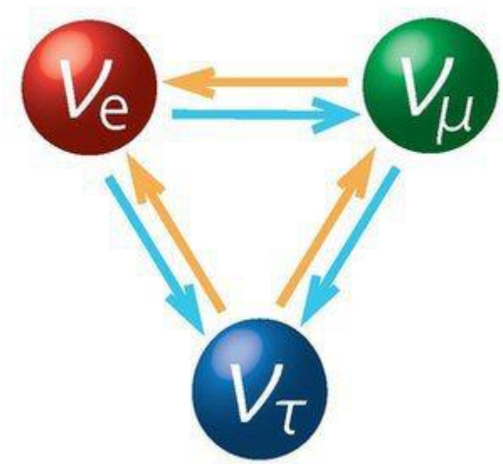




Weak Interaction and beyond

- Understanding the weak interaction implies
  - Analyzing the break-up of discrete simmetries, Parity (P), Charge Parity (CP) and Time Reversal (T)
- Study the properties of the fermion families and their interactions.
  - Masses, lifetimes, couplings, amplitudes, phases,…
- There is flavour physics in one of the evident examples of physics beyond the SM (BSM)
  - Neutrino masses, evident in oscillations
- And flavour physics could be involved into:
  - CP violating interactions BSM
  - Lepton and baryon number violation
  - Dark matter





Parity

- Parity: creates the mirror of a physical system.

$$\vec{r} \xrightarrow{P} -\vec{r} \qquad \vec{p} \xrightarrow{P} -\vec{p}$$

$$\vec{L} = \vec{r} \times \vec{p} \xrightarrow{P} \vec{L} = -\vec{r} \times -\vec{p}$$

Jim Morrison

- Until 1956, assumed that physical laws obey mirror symmetry:

$$[\mathbf{H},\ \mathcal{P}] = 0$$

- Parity is a unitary operator with eigenvalues either 1 or -1:

$$\psi'(\vec{r}) = P\psi(\vec{r}) = \psi(-\vec{r}) \quad \Rightarrow \quad P^2\psi(\vec{r}) = P\psi(-\vec{r}) = \psi(\vec{r})$$

- Eigenfunctions $\psi(r,\vartheta,\varphi) = \chi(r) Y_l^m(\vartheta,\varphi)$ have $(-1)^l$ parity.
- A nucleon (n or p) is an eigenstate of P.
  - No other object exists with the same charge, mass, etc.
  - The relative parity between states with different quantum numbers Q and B is arbitrary.
  - Due to conservation of baryon number and charge the eigenparity of electron, proton, and neutron can be fixed at +1.

Parity Violation

- **Parity violation**
  - Maximally violated in weak interactions.
  - Only left-handed components of particles participate in weak interactions.
  - Right-handed of antiparticles.
- Predicted by Lee and Yang (Nobel 1957), found by Wu in 1956 (Nobel 1978).

Chen Ning Yang
Prize share: 1/2

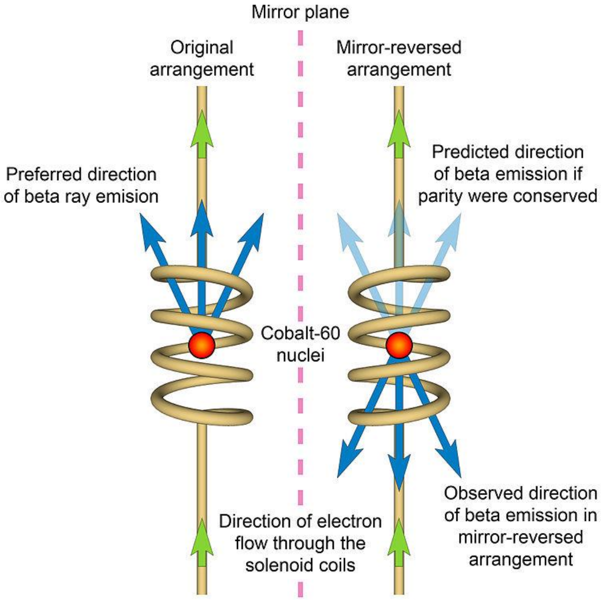
Tsung-Dao (T.D.) Lee
Prize share: 1/2

The Wu experiment

- Analyze the decays:

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni}^*(\rightarrow {}^{60}_{28}\text{Ni} + 2\gamma) + e^- + \bar{\nu}_e$$

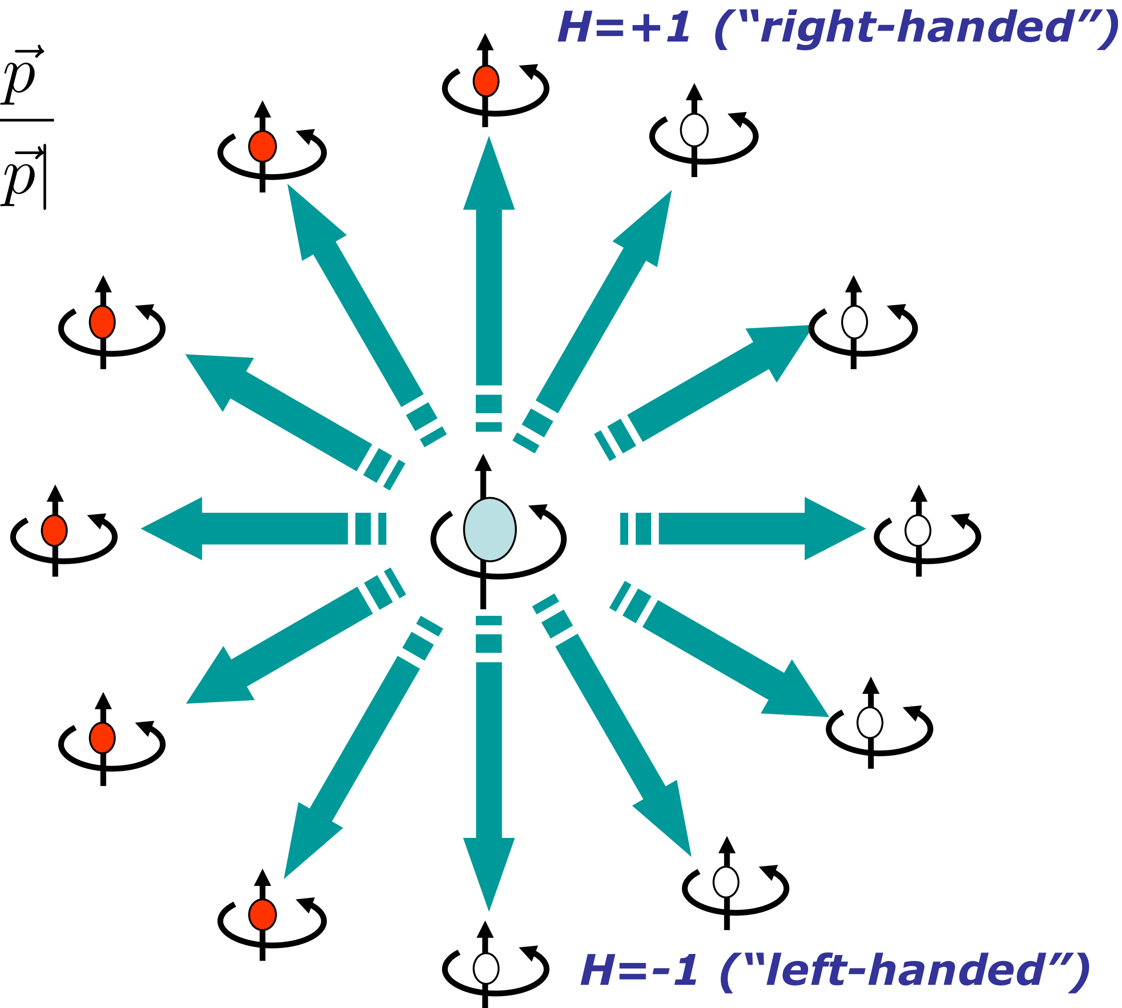
- **^{60}Co is spin-5 and ^{60}Ni is spin-4, both e^- and $\bar{\nu}_e$ are spin-½**
- γ-rays release from the ^{60}Ni in EM process.
  - EM respects P-conservation: distribution of γ-rays controls the polarization of emitted electrons and uniformity of ^{60}Co atoms.
  - The experiment compared the distribution of γ and e- emissions with the nuclear spins in opposite orientations.
    - **If e^- were always emitted in the same direction and proportion as the γ rays**: *P*-conservation would be true.
    - If the distribution of e^- did not follow the distribution of γ rays: *P*-violation would be established.



Spin and parity helicity

- Helicity = the projection of the spin on the direction of flight of a particle

$$H = \frac{\vec{S} \cdot \vec{p}}{|\vec{S} \cdot \vec{p}|}$$



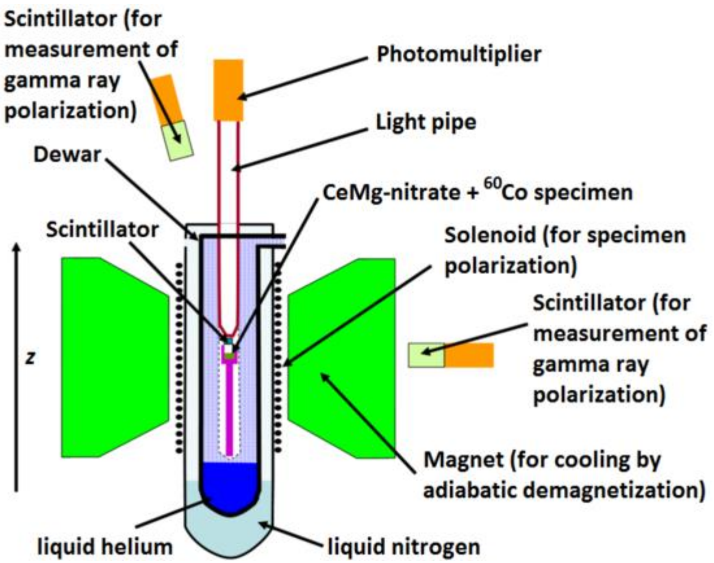
The Wu experiment

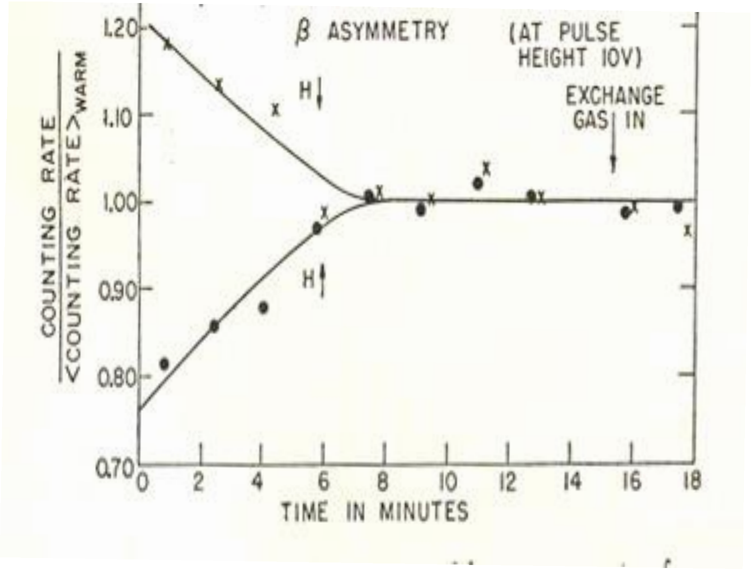
- Experimental challenge: obtain the highest polarization of ^{60}Co nuclei.
  - Due to the very small magnetic moments of nuclei high magnetic fields were required at extremely low temperatures.
  - Cryogenics in 1956 was not at the same stage as it is today.

- Radioactive cobalt was deposited on a crystal of cerium-magnesium nitrate and magnetized.

- A vertical solenoid was introduced to align the cobalt nuclei either upwards or downwards.

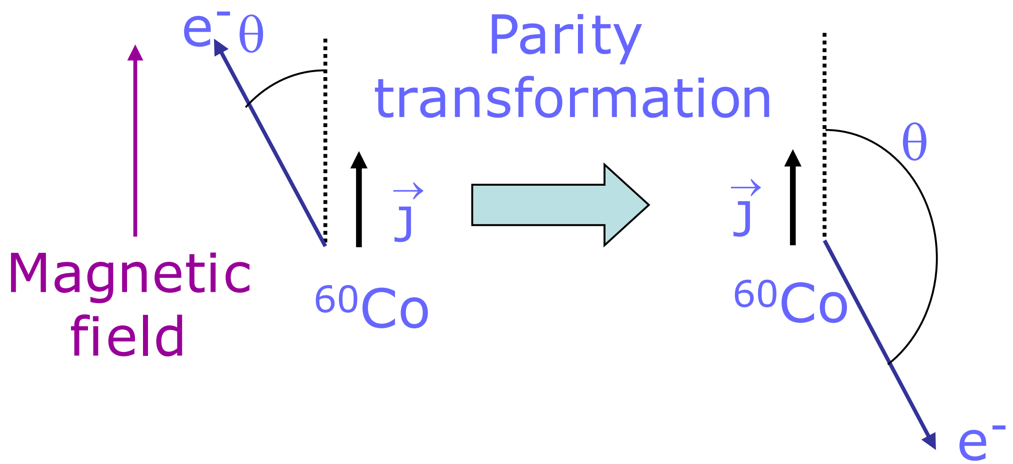
- The production of γ-rays was monitored using equatorial and polar counters as a measure of the polarization.
  - γ-ray polarization was continuously monitored over the next quarter-hour as the crystal warmed up and anisotropy was lost.
  - Likewise, beta-ray emissions were continuously monitored during this warming period.





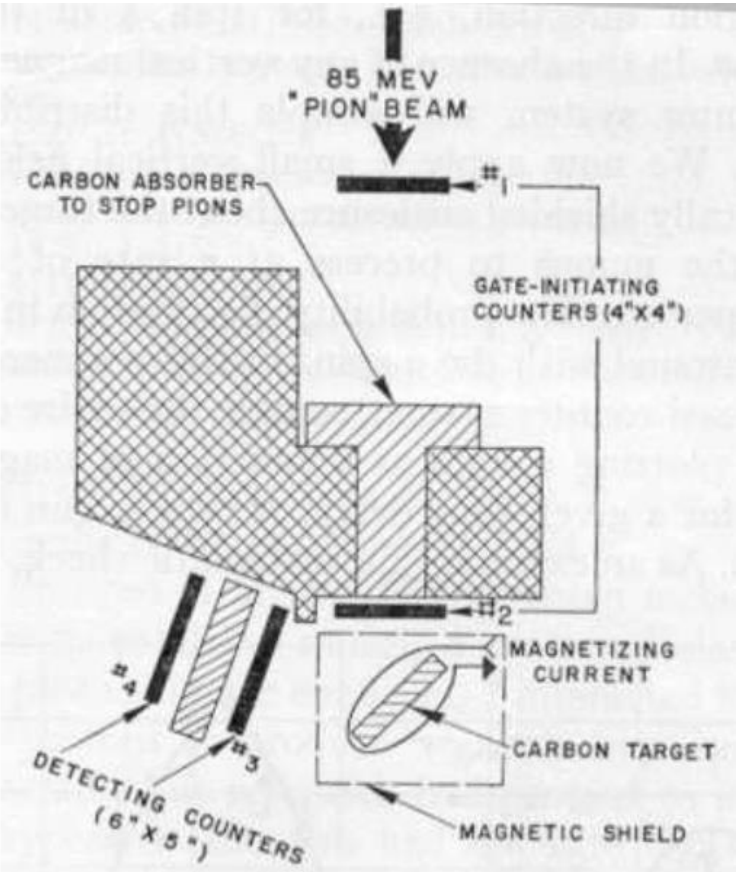
The Wu experiment

- **Electrons are preferentially emitted in direction opposite of ^{60}Co spin.**
  - Angular distribution of electrons: only pairs of left-handed (H=-1) electrons/right-handed anti-neutrinos are emitted.
  - Right-handed electrons are known to exist (H is not Lorentz-invariant) this means **no left-handed anti-neutrinos are produced in weak decay.**
- **Parity is 100% violated in weak processes.**
- How can you see that ^{60}Co violates parity symmetry?
  - If there is parity symmetry there should exist no measurement that can distinguish our universe from a parity-flipped universe, but we can!



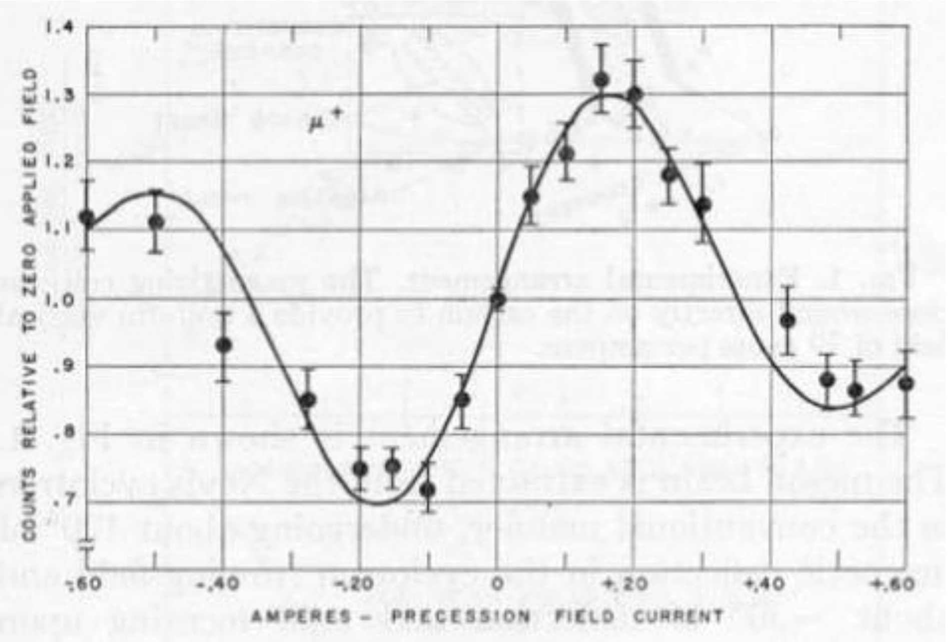
The Lederman experiment

- Charged pions of 85 MeV created in pp collisions and separated magnetically according to their charge.
- Subsequently decay
$$\pi^+ \to \mu^+ + \nu_\mu$$
- Muons stopped in carbon target with magnetic field perpendicular to their line of flight.
- Muons precess in magnetic field and decay.
  - Precession frequency $\omega_L = \frac{geB}{2m_\mu}$
  - g~2 (gyromagnetic ratio of the muon).



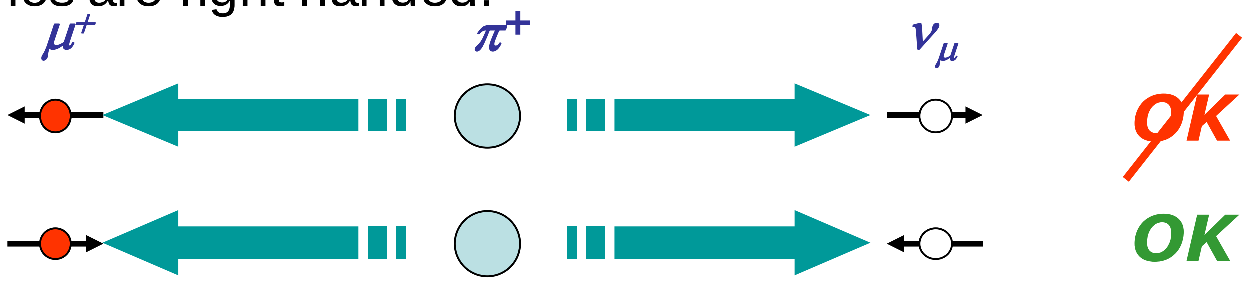
The Lederman experiment

- A counter placed at fixed angle is gated with a fixed delay after the entry of the muon into the target.
  - Detects e⁺ from $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ decays emitted with 1-1/3cosθ distribution.
- The experiment is repeated for several different settings of the magnetic field and precession frequency.
  - A clear oscillation is seen:
    - Muons are produced with non-zero polarization
    - Therefore, pion decay parity is not conserved.
- **The hypothesis of a single helicity for the neutrino can explain the result.**
- The wavelength of the oscillation allowed the first measurement of the gyromagnetic moment of the muon confirming its spin 1/2 nature.

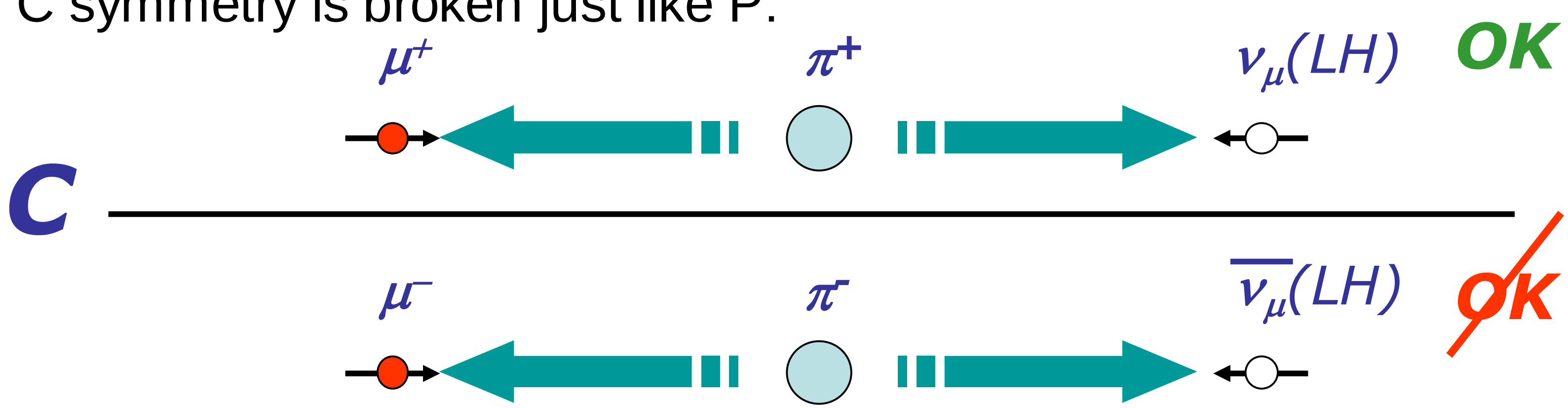


The Lederman experiment

- What Lederman experiment shows is that all neutrinos are left handed and all anti-neutrinos are right handed:

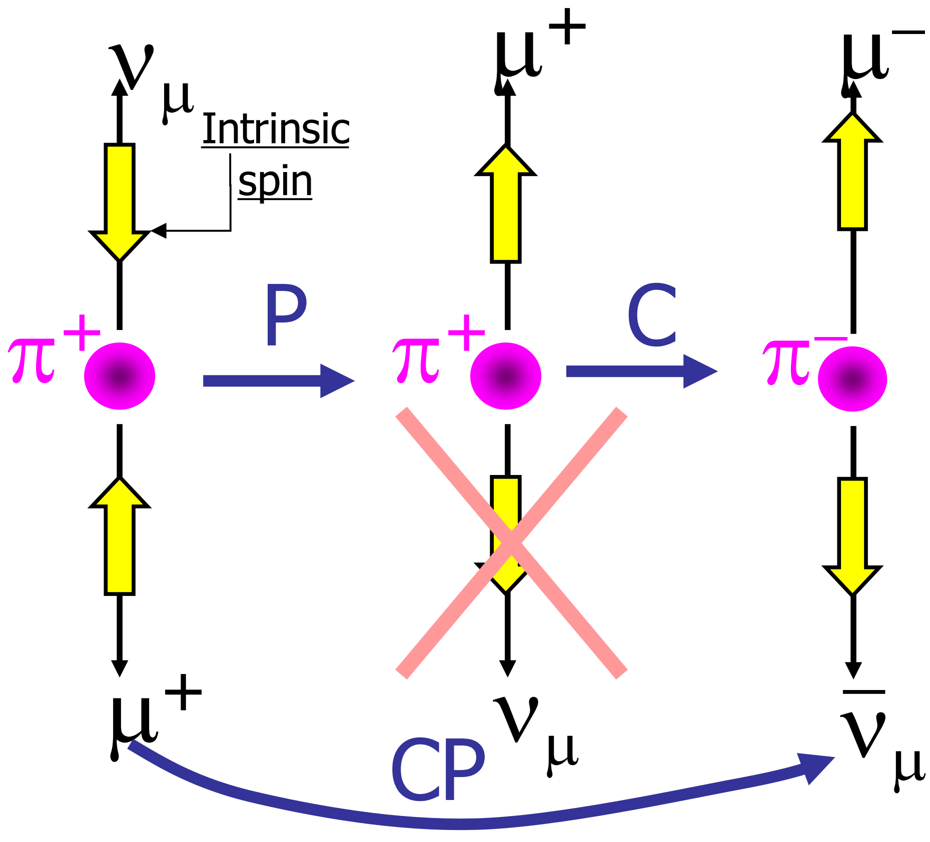


- Charge conjugation is the operation that exchanges particles into anti-particles.
- C symmetry is broken just like P:



The Lederman experiment

- An allowed reaction can be obtained if C and P transformations are combined:



CP was thought to be conserved in the weak interaction

The θ-τ puzzle

- 60 years ago physicists knew of two mesons, θ and τ, with the same mass and spin.
  - These names are now used for other particles.
- However, θ decayed into two pions, and τ decayed into three pions.

$$\Theta^+ \to \pi^+ + \pi^0 \qquad \tau^+ \to \pi^+ + \pi^+ + \pi^0$$

- Since the intrinsic parity of a pion is $P = -1$ the two final states have $P = +1$ and $P = -1$.
- The puzzle was resolved by the discovery of parity violation in weak interactions.
- Since the mesons decay through weak interactions parity is not conserved and both modes are decays of the same particle, the K^+.
- K^+ is not a CP eigenstate.

Neutral kaon mixing

- Strong interactions produce two different neutral *K* mesons of strangeness +1 ($K^0 = d\bar{s}$) and -1 ($\bar{K}^0 = \bar{d}s$).
- These two mesons are related by

$$\mathcal{CP}|K^0\rangle = |\bar{K}^0\rangle, \quad \mathcal{CP}|\bar{K}^0\rangle = |K^0\rangle$$

- And to the CP eigenstates:

$$\left|K_1^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\overline{K}^0\right\rangle\right) \quad CP = +1$$

$$\left|K_2^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle\right) \quad CP = -1.$$

Neutral kaon mixing

- Therefore $K_1^0 \to 2\pi,\ K_2^0 \not\to 2\pi;\ K_1^0 \not\to 3\pi,\ K_2^0 \to 3\pi.$
- K_1 and K_2 are not physical states.
  - They do not have definite mass and lifetime.
- **CP not conserved in the weak interaction!!**
- The physical states are K_S and K_L.
  - With lifetimes and widths

$$\tau_S = 89.54 \pm 0.04\,\text{ps} \qquad \tau_L = 51.16 \pm 0.21\,\text{ns}.$$

$$c\tau_S = 2.67\text{ cm}; \qquad c\tau_L = 15.5\text{ m}.$$

$$\Gamma_S = \frac{1}{\tau_S} = 7.4\,\mu\text{eV}; \quad \Gamma_L = \frac{1}{\tau_L} = 0.013\,\mu\text{eV}$$

  - And average and mass difference

$$m_{K^0} = 497.614 \pm 0.024\ \text{MeV} \qquad \Delta m \equiv m_L - m_S = 3.48 \pm 0.006\,\mu\text{eV}$$

What if CP was conserved in kaon mixing?

- In that case $K_S = K_1$ and $K_L = K_2$.

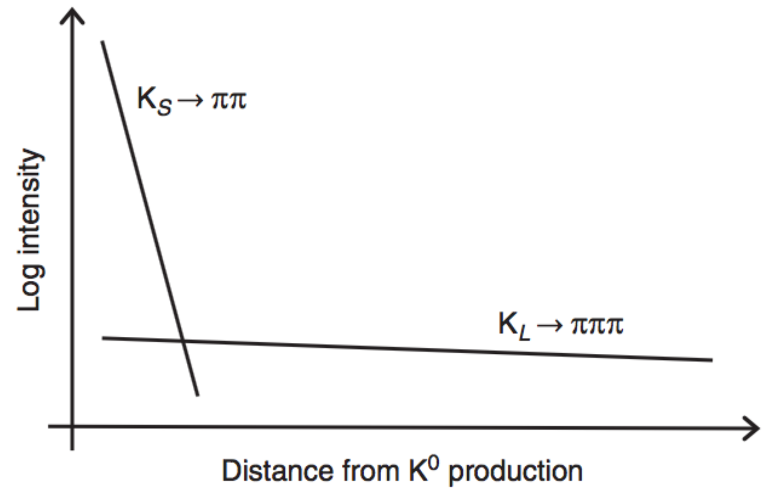
- Imagine we have an initial beam of K^0.

$$|K(0)\rangle = |K^0\rangle = \frac{1}{\sqrt{2}}[\,|K_1\rangle + |K_2\rangle] = \frac{1}{\sqrt{2}}[\,|K_S\rangle + |K_L\rangle].$$

- The time evolution (we shall see this in more detail) is given by:

$$|K_S(t)\rangle = |K_S\rangle \exp[-im_S t - \Gamma_S t/2],$$
$$|K_L(t)\rangle = |K_L\rangle \exp[-im_L t - \Gamma_L t/2],$$

- Since the lifetime of K_S is much smaller at a distance of ~15m we expect a pure beam of K_L.

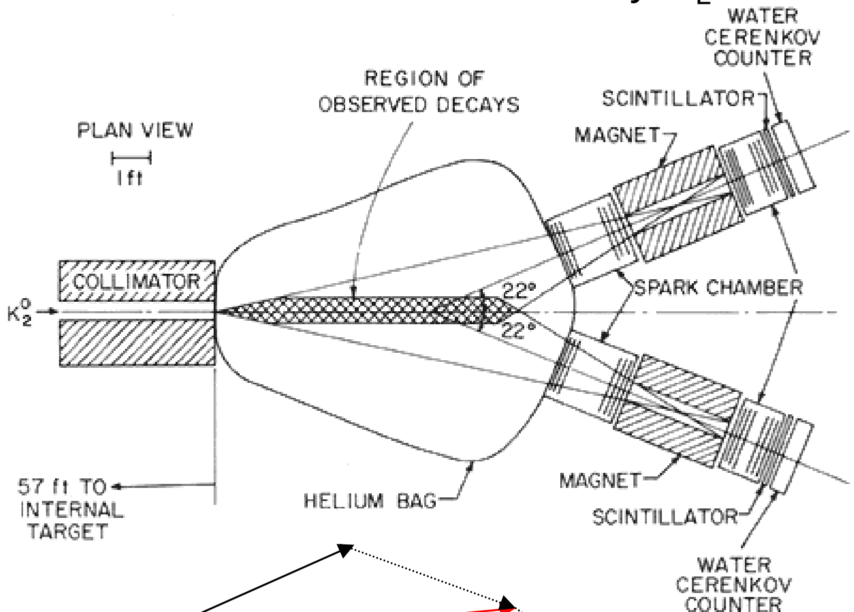


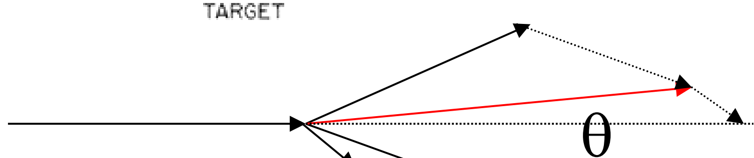
No decays into two pions are expected at this distance!!

Discovery of CP violation

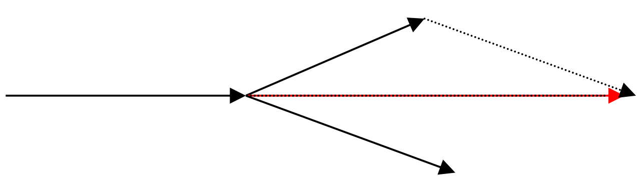
- Create a pure K_L (CP=-1) beam: (Cronin & Fitch BNL in 1964).
- Wait until the K_s component has decayed.
- If CP conserved, should *not* observe the decay $K_L \to 2$ pions.

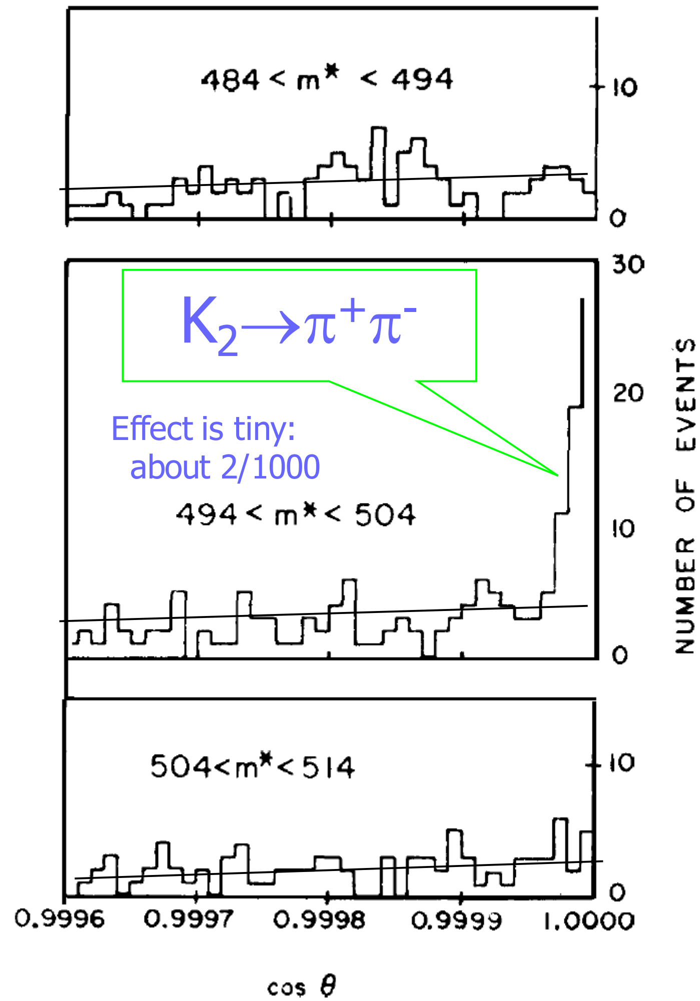
K_S: Short-lived CP even:
$K_1^0 \rightarrow \pi^+ \pi^-$
K_L: Long-lived CP odd:
$K_2^0 \rightarrow \pi^+ \pi^- \pi^0$





Main background: $K_L \to \pi^+ \pi^- \pi^0$





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Universidade de Santiago de Compostela

CP Violation in neutral kaons

There are two main ways of introducing CP violation into the neutral kaon system.

- CP violated in the $K^0 \leftrightarrow \bar{K}^0$ mixing process.
  - K_S and K_L do not correspond to the CP eigenstates, K_1 and K_2.
  - K_S and K_L can be related to CP eigenstates by the small (complex) parameter ε.

$$|K_S\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}(|K_1\rangle + \varepsilon|K_2\rangle) \qquad |K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}(|K_2\rangle + \varepsilon|K_1\rangle)$$

$|K_2\rangle \to \pi\pi\pi$, $\varepsilon|K_1\rangle \to \pi\pi$

This explains long distance two pion decays

- Second possibility: CP violated directly in the decay of a CP eigenstate.

$$|K_L\rangle = |K_2\rangle$$

$|K_2\rangle \to \pi\pi$, $|K_2\rangle \to \pi\pi\pi$

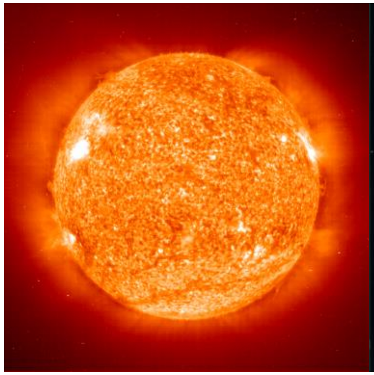
  - Relative strength of direct CPV parameterised by $\epsilon' = \frac{\Gamma(K_2 \to \pi\pi\pi)}{\Gamma(K_2 \to \pi\pi)}$
  - It is known that CP is violated in both mixing and directly in the decay.
  - NA48 (CERN) and KTeV (Fermilab) demonstrate direct CPV is relatively small.

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{\exp} = (16.6 \pm 2.3) \times 10^{-4}$$

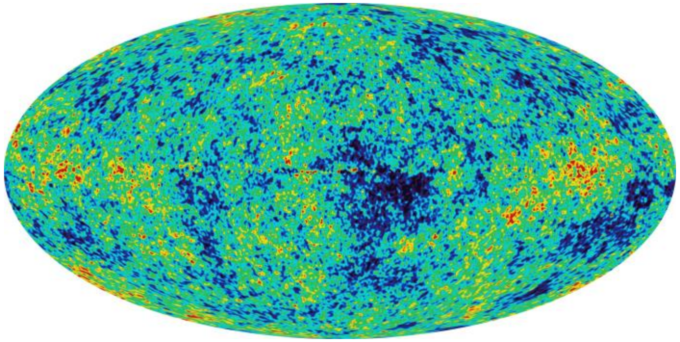
  - CPV **in mixing** is dominant in neutral kaon system.

Why CP violation matters?

- Visible Universe: matter rather than antimatter.
- Moon: lunar probes and astronauts would have vanished in a fireball.
- Sun and Milky Way: solar wind and cosmic rays do not destroy us.
- Local cluster of galaxies: radiation from annihilations at the boundaries.
- Microwave background: no disturbance by annihilation radiation. No large regions of antimatter within 10 billion light years (the whole visible universe?).
- Big Bang: equal amounts of matter and antimatter.
- Why so much of one and so little of the other? CP violation.







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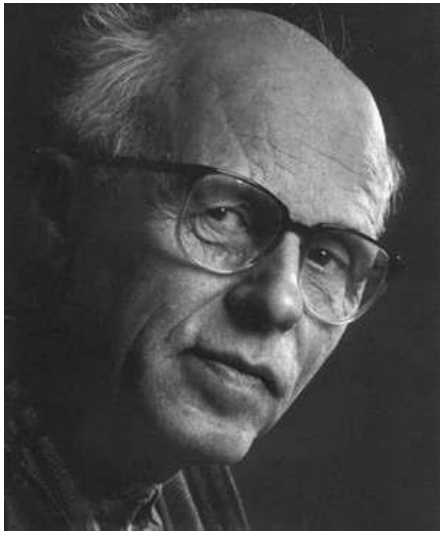
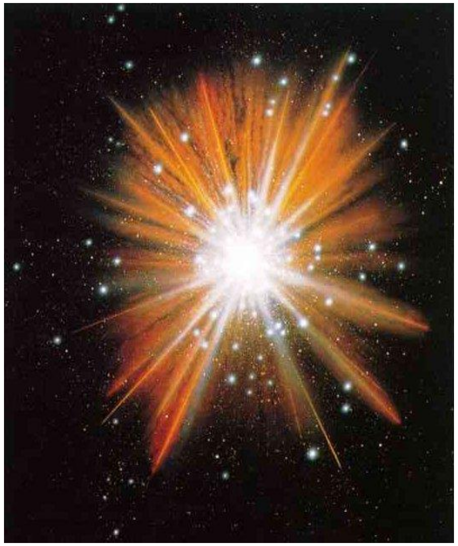
CP violation and matter-antimatter balance

- A. Sakharov's conditions (1967):
  - Unstable Proton: no baryon conservation.
  - Interactions violating C conjugation and CP symmetry: initial matterantimatter balance upset.
  - Universe: phase of extremely rapid expansion. Prevents restoration of balance due to CPT symmetry.
- Standard Model. Two ways to break CP:
  - QCD: unobserved.
  - Weak force: verified. Accounts for a small portion. Net mass ~ only a single galaxy ☹.
- Physics beyond SM?

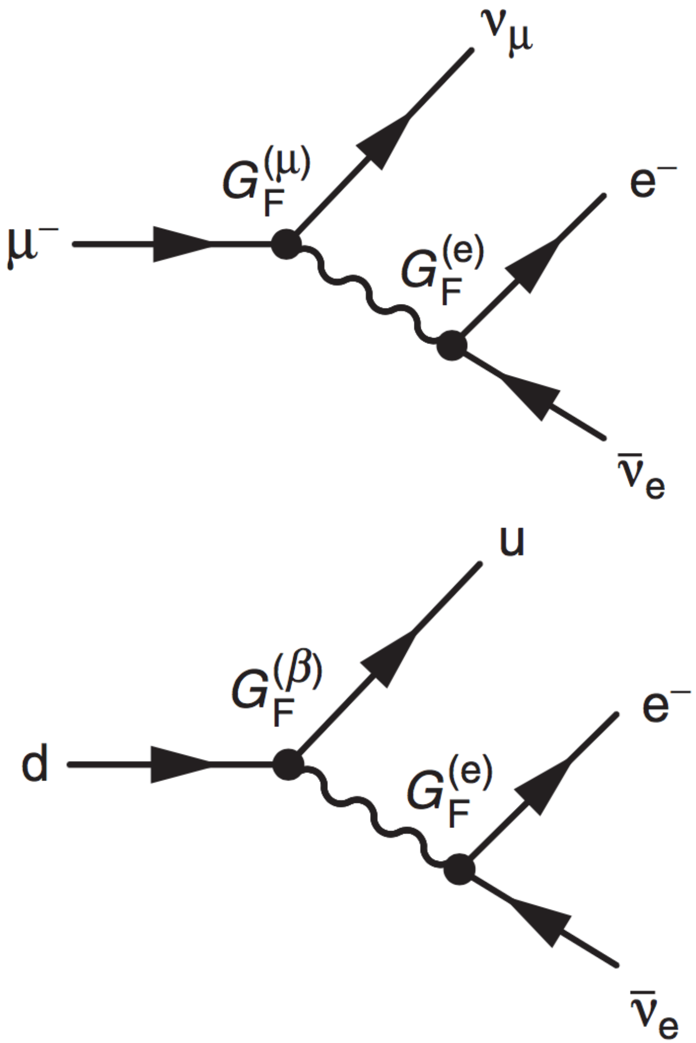




The Cabibbo mechanism

- In the SM the weak interaction to charged leptons and the corresponding neutrino is universal ($G^{(e)} = G^{(\mu)} = G^{(\tau)}$)

- The strength of the weak interaction for quarks can be determined from the study of nuclear β-decay.
  - The matrix element $|M|^2 \propto G^{(e)}G^{(\beta)}$
  - $G^{(\beta)}$ gives the coupling at the weak interaction vertex of the quarks.



The Cabibbo mechanism

- From β-decay rates for superallowed nuclear transitions the strength of the coupling at ud vertex is found 5% smaller than that at $\mu\nu_\mu$ vertex.

$$G_F^{(\mu)} = (1.166\,3787 \pm 0.000\,0006) \times 10^{-5}\,\mathrm{GeV}^{-2},$$
$$G_F^{(\beta)} = (1.1066 \pm 0.0011) \times 10^{-5}\,\mathrm{GeV}^{-2}.$$

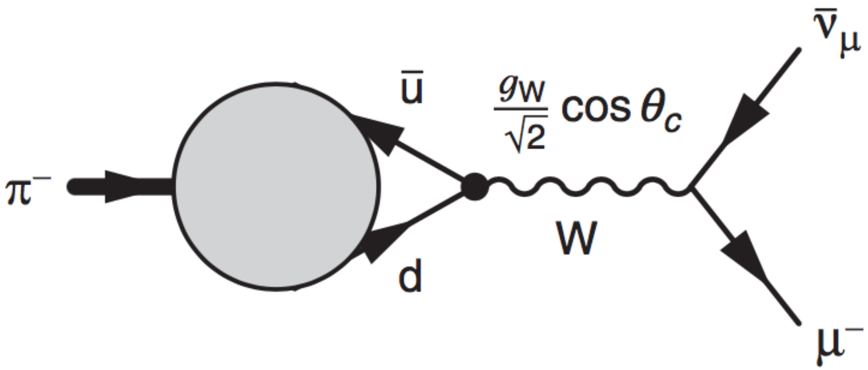
- Different coupling strengths are found for the ud and us weak charged-current vertices.
- These observations explained by the Cabibbo hypothesis.
  - Weak interactions of quarks have the same strength as the leptons.
  - Weak eigenstates of quarks (d′ and s′) differ from mass eigenstates (d and s).
  - They are related by the unitary matrix:

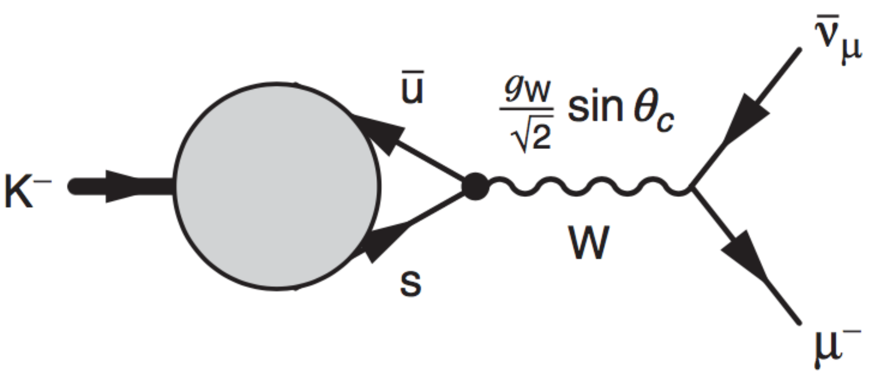
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

θ_c is the Cabibbo angle

The Cabibbo mechanism

- Nuclear β-decay involves the weak coupling between u and d quarks.
  - With the Cabibbo hypothesis: β-decay matrix elements proportional to $g_W \cos\theta_c$ and decay rates to $G_F \cos^2\theta_c$.
  - Matrix elements for $K^- \to \mu^- \nu_\mu$ and $\pi^- \to \mu^- \nu_\mu$ include factors of $\cos\theta_c$ and $\sin\theta_c$ and the K^- decay rate is suppressed by $\tan^2\theta_c$ relative to the π^- one.
  - Observed β-decay rates and measured ratio of $\Gamma(K^- \to \mu^- \nu_\mu)/\Gamma(\pi^- \to \mu^- \nu_\mu)$ can be explained if $\theta_c \simeq 13^\circ$.



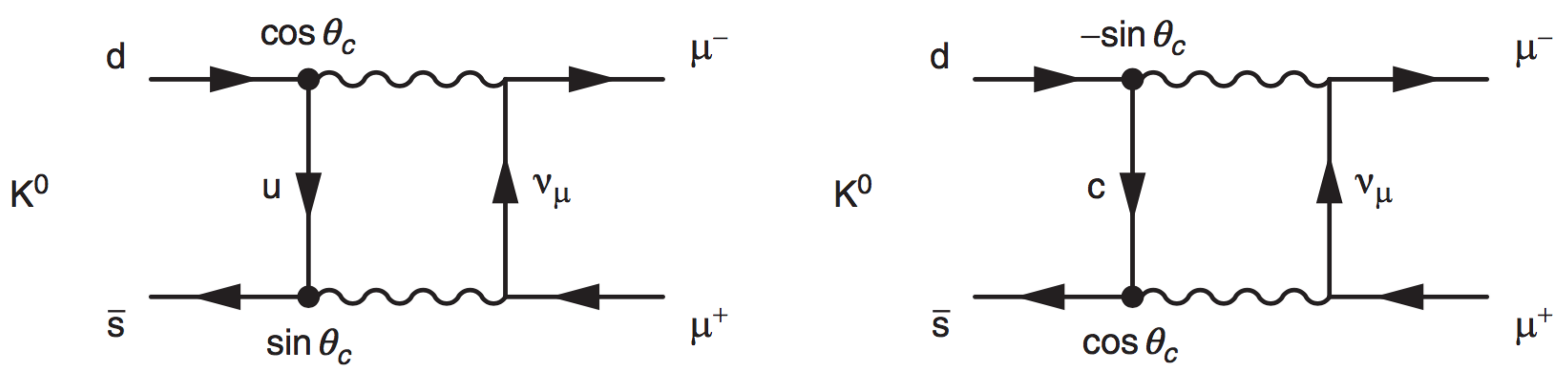


The Cabibbo mechanism

- When the Cabibbo mechanism was proposed the charm quark had not been discovered.
- Since it allows for ud and us couplings, the flavour changing neutral current (FCNC) decay $K_L \to \mu^+\mu^-$ can occur via the exchange of a virtual up-quark.
- Measured BR $(6.84 \pm 0.11) \times 10^{-9}$ much smaller than expected from this diagram alone.
- Explained by the Glashow, Iliopoulos and Maiani (GIM) mechanism (1970).
  - A postulated fourth (charm) quark coupled to the s′ weak eigenstate.
  - The two diagrams of the figure interfere with matrix elements:

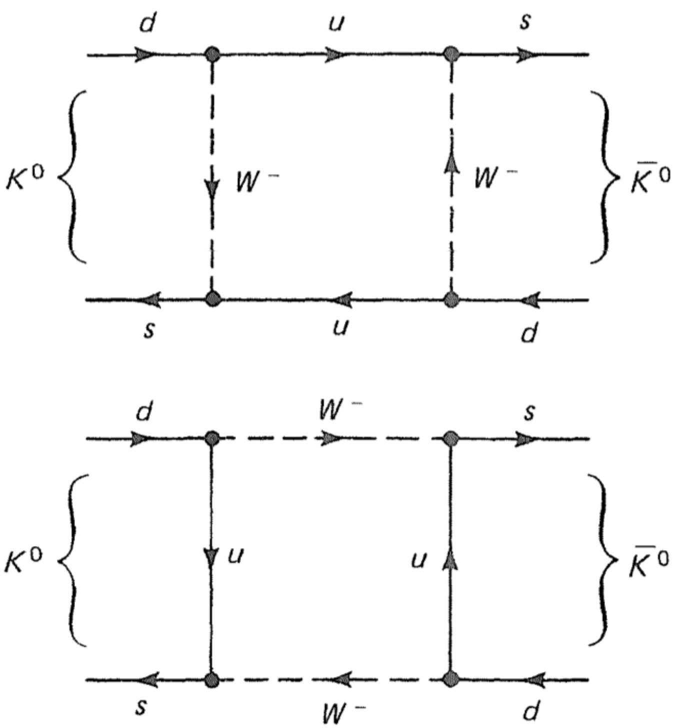
$$\mathcal{M}_\mathrm{u} + \mathcal{M}_\mathrm{c} \approx g_W^4 \cos\theta_\mathrm{c} \sin\theta_\mathrm{c} - g_W^4 \cos\theta_\mathrm{c} \sin\theta_\mathrm{c} = 0$$

  - Cancellation is not exact because of the different masses of the up and charm quarks.



Neutral meson oscillations

- We shall (soon) see that all neutral weak decaying mesons (K^0, D^0, B^0 and B_s^0) can oscillate into each other antiparticle.
  - We take a B^0 meson as an example.
  - The formalism is valid for any of the previously mentioned mesons.
- Consider $|B^0\rangle$ and $|\bar{B}^0\rangle$, strong and EM eigenstates with mass m and opposite flavor.
- An arbitrary superposition with time-dependent coefficients $a(t)$ and $b(t)$:



$$\psi(t) = a(t)\left|B^0\right\rangle + b(t)\left|\overline{B}^0\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

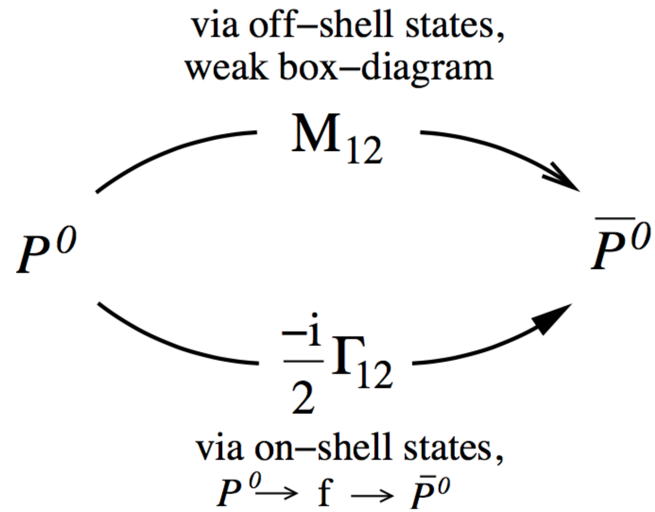
Neutral meson oscillations

- The time evolution is governed by

$$i\frac{\partial}{\partial t}\psi = H\psi$$

- Where

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



  - CPT invariance: $M = M_{11} = M_{22}$, $M_{21} = M_{12}^{*}$ and $\Gamma_{11} = \Gamma_{22}$, $\Gamma_{21} = \Gamma_{12}^{*}$
- The first matrix provides a *mass* term.
- Due to −i, Γ provides an exponential decay.
  - Because of this term H is not hermitian. The probability to observe either P^0 or $\bar{P}^0$ goes down with time:

$$\frac{d}{dt}\left(|a(t)|^2 + |b(t)|^2\right) = -\left(a(t)^{*} b(t)^{*}\right)\begin{pmatrix} \Gamma_{11} & 0 \\ 0 & \Gamma_{22} \end{pmatrix}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

Neutral meson oscillations

- There can be a relative phase between Γ_{12} (absorptive transition) and M_{12} (dispersive transition)

$$\phi = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

- This leads to

$$\begin{aligned}\Delta m &= 2|M_{12}| \\ \Delta\Gamma &= 2|\Gamma_{12}|\cos\phi\end{aligned}$$

- If T is conserved $\Gamma_{12}^* / \Gamma_{12} = M_{12}^* / M_{12}$ and adding a free phase Γ_{12} and M_{12} can be set real.
- Solving the time dependent matrix means finding the eigenstates and eigenvalues of H.
  - This will describe the masses and decay widths and the P^0, $\bar{P}^0$ combinations that correspond to the physical particles.

Neutral meson oscillations

- The eigenvalue equation is

$$\begin{vmatrix} M - \frac{i}{2}\Gamma - \lambda & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma - \lambda \end{vmatrix} = 0$$

- If we consider $F = \sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)}$ the resulting eigenvalues are $\lambda_\pm = M - \frac{i}{2}\Gamma \pm F$.

$$\lambda_+ = m_1 + \frac{i}{2}\Gamma_1 = M - \Re F - \frac{i}{2}(\Gamma - 2\Im F)$$

$$\lambda_- = m_2 + \frac{i}{2}\Gamma_2 = M + \Re F - \frac{i}{2}(\Gamma + 2\Im F)$$

- Where the mass and width of the two physical states are identified.
- Two standard definitions are:

$$\Delta m \equiv m_2 - m_1 = 2\Re\, F$$

$$\Delta\Gamma \equiv \Gamma_1 - \Gamma_2 = 4\Im\, F$$

Neutral meson oscillations

- Let us find the eigenstates.

$$
\begin{aligned}
|P_H\rangle &= p|P^0\rangle + q|\bar{P}^0\rangle \\
|P_L\rangle &= p|P^0\rangle - q|\bar{P}^0\rangle
\end{aligned}
$$

- Solving

$$
\left(\begin{array}{cc} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{array}\right)\left(\begin{array}{c} p \\ q \end{array}\right) = \lambda_{\pm}\left(\begin{array}{c} p \\ q \end{array}\right)
$$

- If P_H is the heavier state we have

$$
\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}
$$

- *q*/*p* can be related to the mixing phase as

$$
\frac{|\Gamma_{12}|}{|M_{12}|}\sin\phi = \frac{\Delta\Gamma}{\Delta m}\tan\phi = 2\Big(1 - \frac{|q|}{|p|}\Big)
$$

- This will be the size of a possible CP asymmetry for flavor-specific final states, a_{fs}.

Neutral meson oscillations

- The time evolution of the eigenstates is given by

$$
\begin{aligned}
|P_H(t)\rangle &= e^{-im_H t - \frac{1}{2}\Gamma_H t}|P_H(0)\rangle \\
|P_L(t)\rangle &= e^{-im_L t - \frac{1}{2}\Gamma_L t}|P_L(0)\rangle
\end{aligned}
$$

- Since the physical states are related to the eigenstates by

$$
\begin{aligned}
|P^0\rangle &= \frac{1}{2p}\left[|P_H\rangle + |P_L\rangle\right] \\
|\bar{P}^0\rangle &= \frac{1}{2q}\left[|P_H\rangle - |P_L\rangle\right]
\end{aligned}
$$

- The time evolution of a physical state is

$$
\begin{aligned}
|P^0(t)\rangle &= \frac{1}{2p}\left\{e^{-im_H t - \frac{1}{2}\Gamma_H t}|P_H(0)\rangle + e^{-im_L t - \frac{1}{2}\Gamma_L t}|P_L(0)\rangle\right\} \\
&= \frac{1}{2p}\left\{e^{-im_H t - \frac{1}{2}\Gamma_H t}(p|P^0\rangle + q|\bar{P}^0\rangle) + e^{-im_L t - \frac{1}{2}\Gamma_L t}(p|P^0\rangle - q|\bar{P}^0\rangle)\right\} \\
&= \frac{1}{2}\left(e^{-im_H t - \frac{1}{2}\Gamma_H t} + e^{-im_L t - \frac{1}{2}\Gamma_L t}\right)|P^0\rangle + \frac{q}{2p}\left(e^{-im_H t - \frac{1}{2}\Gamma_H t} - e^{-im_L t - \frac{1}{2}\Gamma_L t}\right)|\bar{P}^0\rangle \\
&= g_+(t)|P^0\rangle + \left(\frac{q}{p}\right)g_-(t)|\bar{P}^0\rangle
\end{aligned}
$$

Neutral meson oscillations

- The functions g_+ and g_- are defined as

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

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

- The corresponding antiparticle evolution being

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

- For an initial pure sample of P^0 the probability of finding a $\bar{P}^0$ at time t is

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

$$|g_\pm(t)|^2 = \frac{1}{4}\left(e^{-\Gamma_H t}+e^{-\Gamma_L t}\pm e^{-\Gamma t}(e^{-i\Delta mt}+e^{+i\Delta mt})\right) = \frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t \pm \cos\Delta mt\right)$$

Physical meaning of Γ as a decay length.

$\Gamma = (\Gamma_L+\Gamma_H)/2$ and $\Delta\Gamma = \Gamma_H - \Gamma_L$

CP violation in the SM

- The Cabibbo mixing matrix can be reduced to be real.
  - No CP violation involved.
- The extension to the three quark generations of the SM is described by the unitary Cabibbo–Kobayashi–Maskawa (CKM) matrix.
- The weak interaction eigenstates are related to the mass eigenstates by:

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

- And the weak charged vertices are given by:

$$-i\frac{g_{\mathrm{W}}}{\sqrt{2}}(\bar{\mathrm{u}},\ \bar{\mathrm{c}},\ \bar{\mathrm{t}})\gamma^{\mu}\tfrac{1}{2}(1-\gamma^{5})\begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}\begin{pmatrix} \mathrm{d} \\ \mathrm{s} \\ \mathrm{b} \end{pmatrix}$$

SYMMETRIES OF THE EW INTERACTION

-Symmetry: a powerful idea.
-Nature remains unaltered mixing-exchanging two particles.
-Eg.: strong sector, combine quarks (not loosing unitarity). SU(3). Isospin.
  - -This includes permutations.

-In the electroweak sector: combining left-handed fermions.
-Electroweak isospin.
-There are not left-handed neutrinos.
-Additionally there is a U(1) symmetry. Hypercharge: $Y_W = 2(Q - I_{W_z})$
-The EW sector (before symmetry break-up) is $SU(2)_L x U(1)_Y$ symmetric.
  - -Physicists discovered all these with experimental input(~1968)

$$\begin{pmatrix} I_{Wz} = +1/2 \\ I_{Wz} = -1/2 \end{pmatrix} = \begin{pmatrix} \nu_{eL} \\ e_L^- \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L^- \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L^- \end{pmatrix} \begin{pmatrix} \bar{d}'_R \\ \bar{u}_R \end{pmatrix}, \begin{pmatrix} \bar{s}'_R \\ \bar{c}_R \end{pmatrix}, \begin{pmatrix} \bar{b}'_R \\ \bar{t}_R \end{pmatrix}$$

$$\begin{pmatrix} e_R^+ \\ \bar{\nu}_{eR} \end{pmatrix}, \begin{pmatrix} \mu_R^+ \\ \bar{\nu}_{\mu R} \end{pmatrix}, \begin{pmatrix} \tau_R^+ \\ \bar{\nu}_{\tau R} \end{pmatrix} \begin{pmatrix} u_L \\ d'_L \end{pmatrix}, \begin{pmatrix} c_L \\ s'_L \end{pmatrix}, \begin{pmatrix} t_L \\ b'_L \end{pmatrix}$$

$$I_{W_z} = 0 = e_R^-, \quad \mu_R^-, \quad \tau_R^- \quad d_R, \quad u_R, \quad s_R, \quad c_R, \quad b_R, \quad t_R$$

$$e_L^+, \quad \mu_L^+, \quad \tau_L^+ \quad \bar{d}_L, \quad \bar{u}_L, \quad \bar{s}_L, \quad \bar{c}_L, \quad \bar{b}_L, \quad \bar{t}_L$$

CP Violation in the Weak Sector of the SM

Standard Model: unifies Strong and Electro-Weak interactions.
EW symmetry break-up: might describes mass generation.
Fermions: Yukawa couplings to the Higgs Boson (sandwich terms).

$$\mathcal{L}_Y = -\left(1+\frac{h(x)}{\nu}\right)\left((\bar{u}'_L, \bar{c}'_L, \bar{t}'_L)\mathbf{M}\begin{pmatrix} u'_R \\ c'_R \\ t'_R \end{pmatrix} + (\bar{d}'_L, \bar{s}'_L, \bar{b}'_L)\tilde{\mathbf{M}}\begin{pmatrix} d'_R \\ s'_R \\ b'_R \end{pmatrix} + h.c.\right)$$

$$q_{R,L} = \left(\frac{1\pm\gamma^5}{2}\right) q \qquad \bar{q} = q^\dagger\gamma^0$$

h(x): Higgs field *v:* vacuum expectation.
M's: complex mass matrixes depending on the Yukawa coefficients.
Simultaneously diagonalized define physical quarks:

$$\mathbf{M} = \mathbf{U_L^\dagger}\begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}\mathbf{U_R} \qquad \tilde{\mathbf{M}} = \mathbf{U_L^\dagger}\begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}\mathbf{U_R} \qquad \mathbf{q} = \mathbf{U}\mathbf{q}'$$

Mass part becomes:

$$\mathcal{L}_Y = -\left(1+\frac{h(x)}{\nu}\right)(m_u\bar{u}_L u_R + m_c\bar{c}_L c_R + m_t\bar{t}_L t_R + m_d\bar{d}_L d_R + m_s\bar{s}_L s_R + \bar{b}_L m_b b_R)$$

CP Violation in the Weak Sector of the SM (2)

How does this transformation change the rest of the Lagrangian?
Invariant except for one term:

$$\mathcal{L}_W = g(W_\mu^+ J_W^{\mu+} + W_\mu^- J_W^{\mu-})$$

Charged currents only term containing u-type and d-type quarks product:

$$J^{\mu+} = \frac{1}{\sqrt{2}}(\bar{u}'_L, \bar{c}'_L, \bar{t}'_L)\gamma^\mu \begin{pmatrix} d'_L \\ s'_L \\ b'_L \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu \mathbf{U}_u^{L\dagger}\mathbf{U}_d^L \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

Only term allowing flavor changes and breaking CP symmetry.
The product of the two U matrixes can be re-written as:

$$\mathbf{U}_u^{L\dagger}\mathbf{U}_d^L = \mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa matrix.

CP violation in the SM

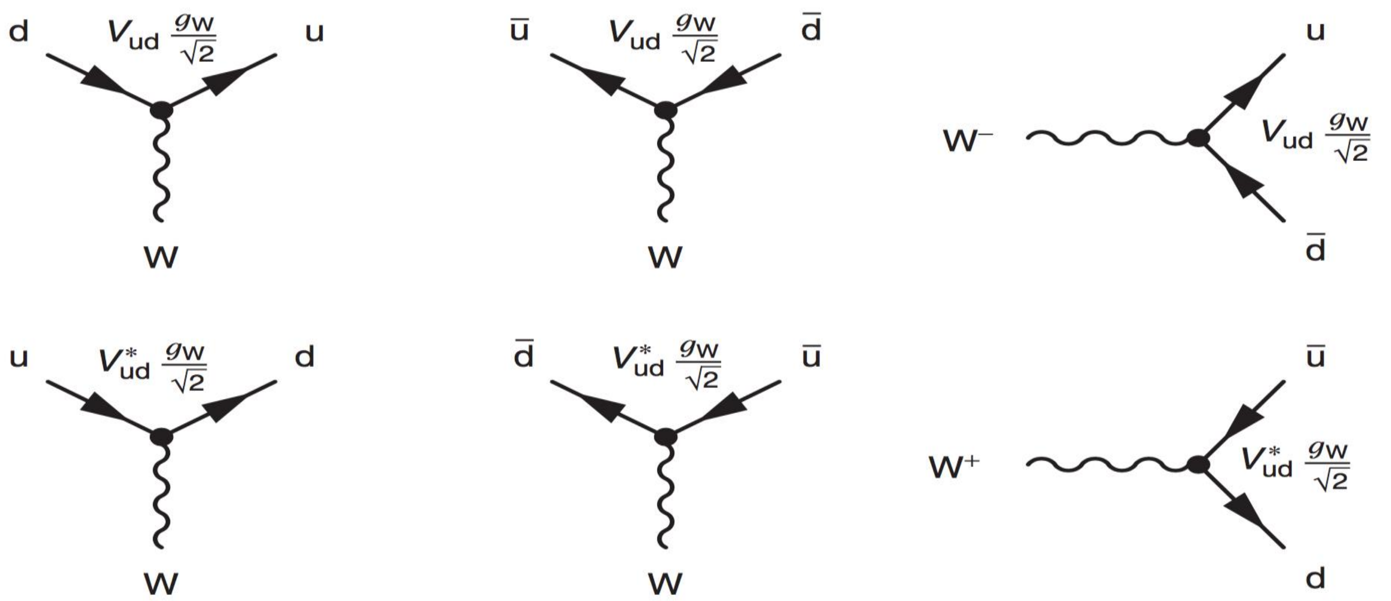
- The vertex factor for calculating Feynman diagrams involving flavour ud change in the weak interaction is

$$j^{\mu}_{\mathrm{du}} = -i\frac{g_W}{\sqrt{2}} V_{\mathrm{ud}}\, \bar{\mathrm{u}}\gamma^{\mu}\tfrac{1}{2}(1-\gamma^5)\mathrm{d}$$

- Whereas for du transitions we have

$$j^{\mu}_{\mathrm{ud}} = -i\frac{g_W}{\sqrt{2}} V^{*}_{\mathrm{ud}}\, \bar{\mathrm{d}}\gamma^{\mu}\tfrac{1}{2}(1-\gamma^5)\mathrm{u}$$

- In general



CKM

CKM matrix: unitary.
Minimum dimension to include a complex phase (CP violation): 3.
3x3 complex unitary matrix: three mixing angles and one phase.
1973 Makoto Kobayashi & Toshihide Maskawa: 3 quark families.
Extended Cabbibo 1963 idea of a unitary matrix of 2 quark families to explain weak interaction mixing.
2008 Nobel Prize of Physics.

KM predicted a 3rd family of quarks in 1973 to accommodate CP violation. At the time only 3 quarks were know (u,d,s).

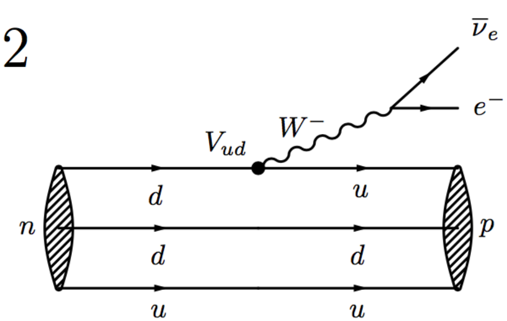
CP violation in the SM

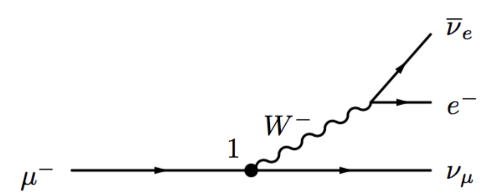
- A general nxn orthogonal matrix depends on n(n-1)/2 angles, describing the rotations among the n dimension. And (n-1)(n-2) phases.
- The CKM matrix is 3x3 and can be described by three rotation angles and a complex phase (s_{ij} = sin φ_{ij} and c_{ij} = cosφ_{ij}):

$$V_{\rm CKM} = \begin{pmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta'} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta'} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- The elements of the CKM matrix are measured from the flavour initial or final state eigenstates (mesons or baryons containing the corresponding quark).
- $V_{\rm ud}$ is determined from superallowed nuclear β-decays.

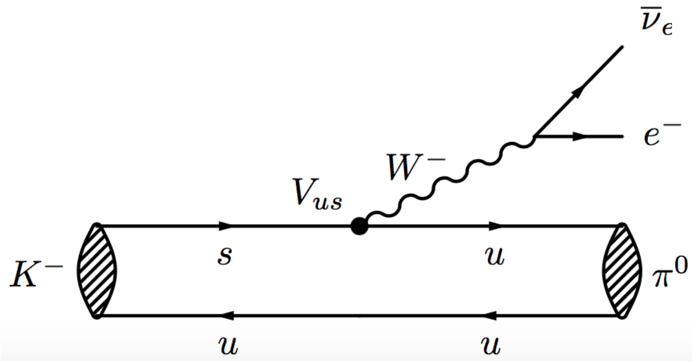
$$|V_{ud}| = 0.97425 \pm 0.00022$$



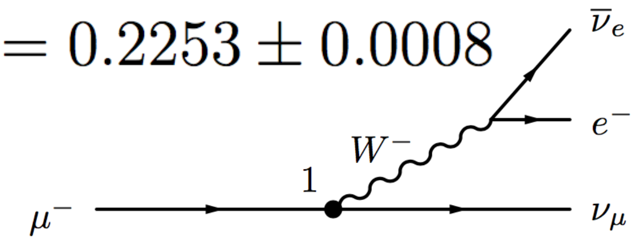


CP violation in the SM

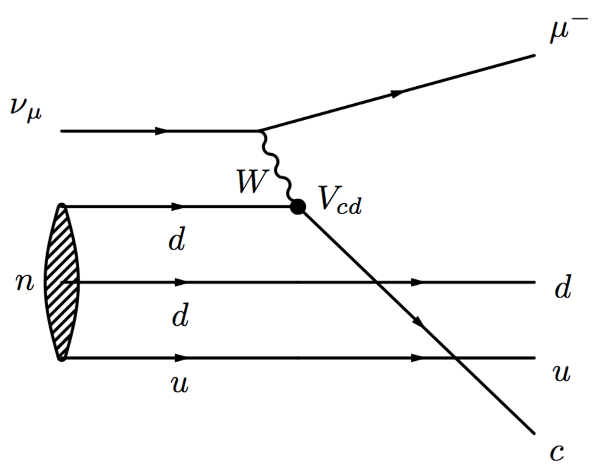
- $|V_{us}|$: is obtained analyzing semi-leptonic *K*-decays.



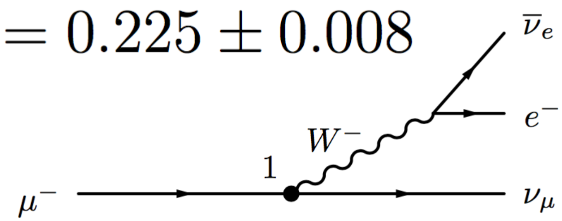
$$|V_{us}| = 0.2253 \pm 0.0008$$



- $|V_{cd}|$: Is obtained by the analysis of neutrino and anti-neutrino induced charm-particle production of the valence d-quark in a neutron (or proton) and on semileptonic charm decays.

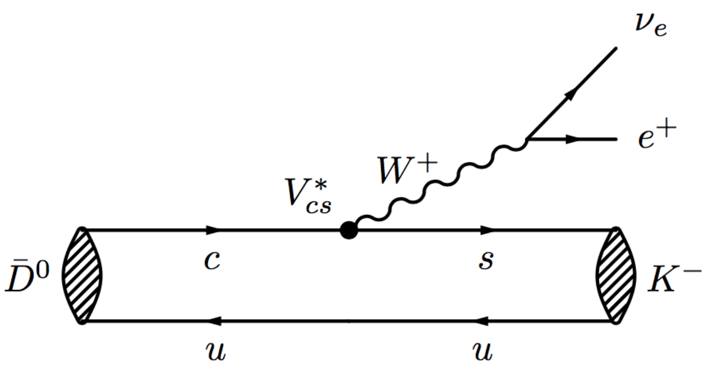


$$|V_{cd}| = 0.225 \pm 0.008$$

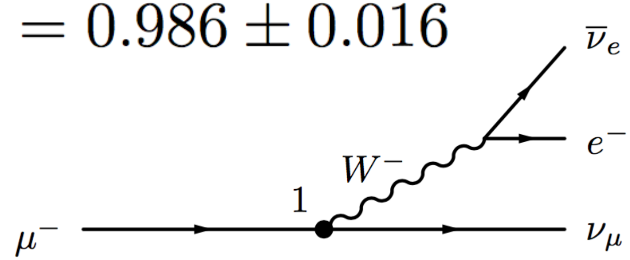


CP violation in the SM

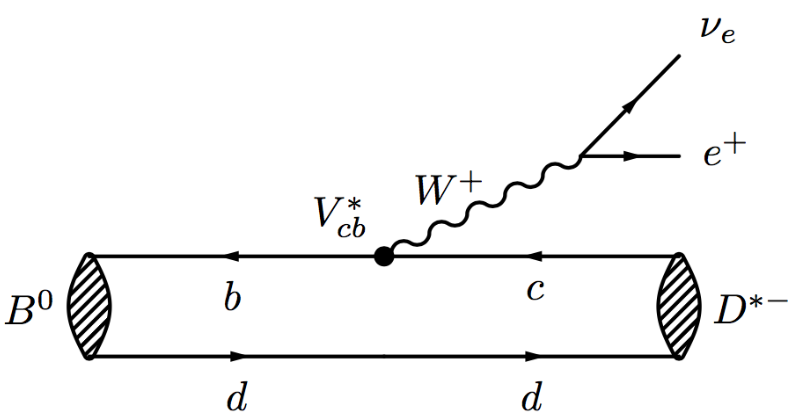
- $|V_{cs}|$: Main matrix element relevant for decay modes of the charm quark. Obtained analyzing semi-leptonic *D*-decays The major uncertainty is due to the form-factor of the D-meson.



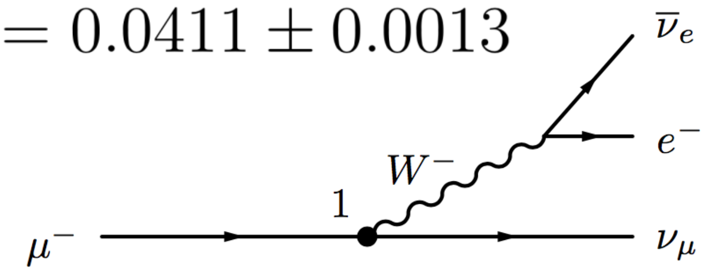
$$|V_{cs}| = 0.986 \pm 0.016$$



- $|V_{cb}|$: Determined from the $B \rightarrow \overline{D}^* l^+ \nu_l$ decay. A large amount of data is available on these decays from LEP and lower energy e^+e^- accelerators.



$$|V_{cb}| = 0.0411 \pm 0.0013$$



CP violation in the SM

- $|V_{td}|$ and $|V_{ts}|$:
  - Top quark elements cannot be measured from tree-level top-quark decays.
  - These elements are probed through loop diagrams

$$|V_{td}| = 0.0084 \pm 0.0006$$

$$|V_{ts}| = 0.0400 \pm 0.0027$$

  - The reason for the previous matrix elements to remain not accesible is that top decays into something different than Wb remains unobserved.
- CDF, D0, ATLAS and CMS measured the ratio of branching ratios Br(t→W b)/Br(t→Wq) finding the 95% CL:

$$|V_{tb}| = 1.021 \pm 0.032$$

CP violation in the SM

- In summary, our knowledge of the CKM matrix magnitudes is summarized in

$$V_{CKM} = \begin{pmatrix} 0.97427 & 0.22536 & 0.00355 \\ 0.22522 & 0.97343 & 0.0414 \\ 0.00886 & 0.0405 & 0.99914 \end{pmatrix} \pm \begin{pmatrix} 0.00014 & 0.00061 & 0.00015 \\ 0.00061 & 0.00015 & 0.0012 \\ 0.00032 & 0.0011 & 0.00005 \end{pmatrix}$$

- Remember the expresion for the CKM matrix as a function of the Euler angles (I did not give the multiplication result):

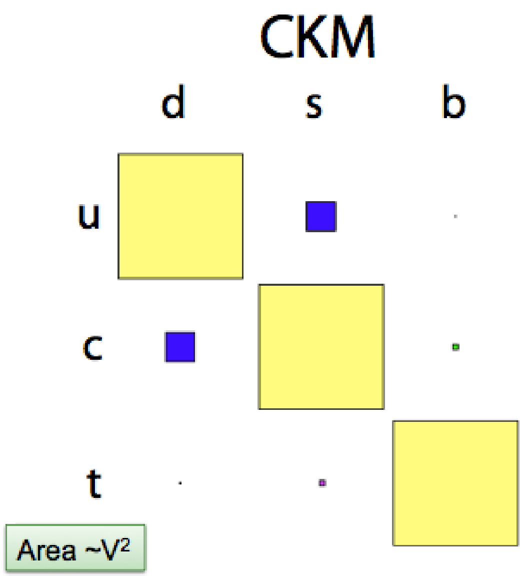
$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}}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

- Comparing the two expressions we see that s_{ij} are small and $s_{12} \gg s_{23} \gg s_{13}$. This motivated a parameterization of the CKM matrix proposed by Wolfenstein.

Wolfstein parametrization of the CKM matrix

- Defining

$$s_{13} = \lambda$$
$$s_{23} = A\lambda^2$$
$$s_{13}e^{-i\delta_{13}} = A\lambda^3(\rho - i\eta)$$



- Being A, ρ and η of order unity.
- With this parametrization

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

- Which is accurate up to order of λ^3.

The unitarity of the CKM matrix

- The unitarity condition for the CKM matrix imposes constraints on its elements.

$$V^\dagger V = V V^\dagger = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Three of them express the weak universality.

$$\begin{aligned} V_{ud}V_{ud}^* + V_{us}V_{us}^* + V_{ub}V_{ub}^* &= 1 \\ V_{cd}V_{cd}^* + V_{cs}V_{cs}^* + V_{cb}V_{cb}^* &= 1 \\ V_{td}V_{td}^* + V_{ts}V_{ts}^* + V_{tb}V_{tb}^* &= 1 \end{aligned}$$

  - The squared sum of the coupling strengths of the u-quark to the d, s and b-quarks is equal to the overall charged coupling of the c and t-quarks.

- Furthermore, the sums add up to 1, eliminating the possibility to couple to a 4th down-type quark.
  - This relation deserves continuous experimental scrutiny.

The unitarity of the CKM matrix

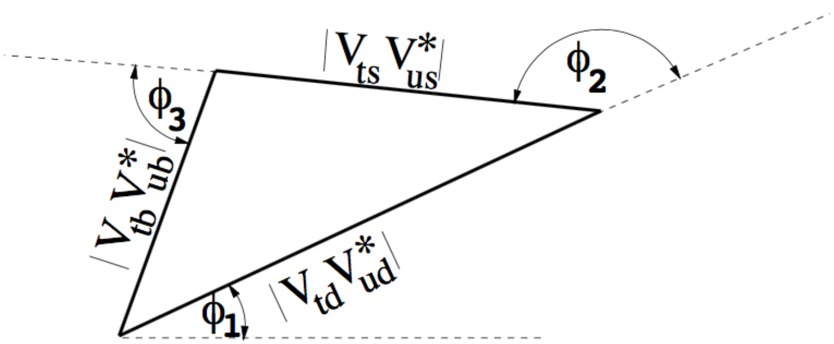
- There are three other independent relations

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$$
$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$$

- From the previous new relations, also obtained from $V^\dagger V = \mathbb{1}$, can be derived: $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

- Each of the above can be interpreted as the sum of three complex numbers (2d vectors) forming a triangle.



The unitarity of the CKM matrix

- The Wolfstein parametrization reveals that all unitarity triangles contain terms of different order in λ except two.

$$\begin{array}{ccccccc} V_{ud}V_{ub}^* & + & V_{cd}V_{cb}^* & + & V_{td}V_{tb}^* & = 0 \\ V_{td}V_{ud}^* & + & V_{ts}V_{us}^* & + & V_{tb}V_{ub}^* & = 0 \\ \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & \end{array}$$

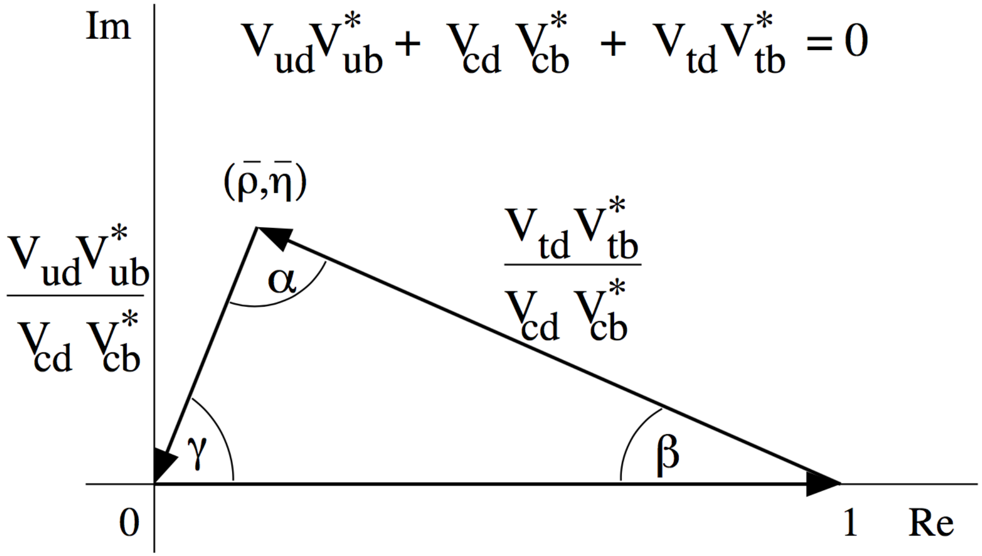
- This means that all the triangles except these two are very squeezed and less sensitive to CP violation.
- The first relation can be rewritten, in terms of the Wolfstein parameters, as:

$$\overline{\rho} + i\overline{\eta} \equiv \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- Where $\overline{\rho} = \rho(1 - \frac{1}{2}\lambda^2) + \mathcal{O}(\lambda^4)$ $\overline{\eta} = \eta(1 - \frac{1}{2}\lambda^2) + \mathcal{O}(\lambda^4)$

The unitarity of the CKM matrix

- This is the celebrated unitarity triangle

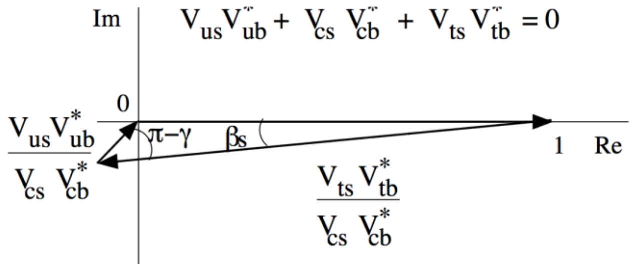


- That motivates the angle definitions

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \qquad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

The unitarity of the CKM matrix

- The other triangle is at the origin of the β_s angle



$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

- The Wolfstein parametrization adopts a phase convention such that

$$V_{CKM,\text{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

- Since CP violation requires that $V_{ij} \neq V_{ij}^*$ turns out that the surface of the unitary triangle is different from zero.
- In fact all triangles have the same, surface which is half the Jarlskog invariant

$$J = \Im(V_{11}V_{22}V_{12}^*V_{21}^*) = \Im(V_{22}V_{33}V_{23}^*V_{32}^*) = \ldots.$$

- That in our known parametrizations can be expressed as

$$J = A^2\lambda^6\eta = c_{12}c_{13}^2c_{23}s_{12}s_{13}s_{23}\sin\delta_{13}$$

Classification of CPV effects

- Let us consider a meson, its CP conjugated, a final state and its CP conjugated. This results in four decay amplitudes:

$$A(f) = \langle f|T|P^0\rangle \qquad \bar{A}(f) = \langle f|T|\bar{P}^0\rangle$$
$$A(\bar{f}) = \langle \bar{f}|T|P^0\rangle \qquad \bar{A}(\bar{f}) = \langle \bar{f}|T|\bar{P}^0\rangle$$

- If we define the parameters

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}, \qquad \bar{\lambda}_f = \frac{1}{\lambda_f}, \qquad \lambda_{\bar{f}} = \frac{q}{p}\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}, \qquad \bar{\lambda}_{\bar{f}} = \frac{1}{\lambda_{\bar{f}}}$$

- And consider the time evolution

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

- We can see that the time dependent decay rates, defined as

$$\Gamma_{P^0\to f}(t) = |\langle f|T|P^0(t)\rangle|^2$$

Classification of CPV effects

- Are given by:

$$\begin{aligned}
\Gamma_{P^0\to f}(t) &= |A_f|^2 \left(|g_+(t)|^2 + |\lambda_f|^2|g_-(t)|^2 + 2\Re[\lambda_f g_+^*(t) g_-(t)]\right) \\
\Gamma_{P^0\to \bar f}(t) &= |\bar A_{\bar f}|^2 \left|\frac{q}{p}\right|^2 \left(|g_-(t)|^2 + |\bar\lambda_{\bar f}|^2|g_+(t)|^2 + 2\Re[\bar\lambda_{\bar f} g_+(t) g_-^*(t)]\right) \\
\Gamma_{\bar P^0\to f}(t) &= |A_f|^2 \left|\frac{p}{q}\right|^2 \left(|g_-(t)|^2 + |\lambda_f|^2|g_+(t)|^2 + 2\Re[\lambda_f g_+(t) g_-^*(t)]\right) \\
\Gamma_{\bar P^0\to \bar f}(t) &= |\bar A_{\bar f}|^2 \left(|g_+(t)|^2 + |\bar\lambda_{\bar f}|^2|g_-(t)|^2 + 2\Re[\bar\lambda_{\bar f} g_+^*(t) g_-(t)]\right)
\end{aligned}$$

- Where

$$\begin{aligned}
|g_\pm(t)|^2 &= \frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t \pm \cos\Delta m t\right) \\
g_+^*(t) g_-(t) &= \frac{e^{-\Gamma t}}{2}\left(\sinh\frac{1}{2}\Delta\Gamma t + i\sin\Delta m t\right) \\
g_+(t) g_-^*(t) &= \frac{e^{-\Gamma t}}{2}\left(\sinh\frac{1}{2}\Delta\Gamma t - i\sin\Delta m t\right)
\end{aligned}$$

- In the decay rates the terms proportional $|A|^2$ are associated with decays without oscillation, the terms proportional to $|A|^2(q/p)^2$ or $|A|^2(p/q)^2$ are associated with decays following a net oscillation. The terms proportional to Re(g^*g) are associated to the interference between the two cases.

Classification of CPV effects

- The previous expressions can be combined to give the so-called **master equations**:

$$\Gamma_{P^0\to f}(t) = |A_f|^2 \frac{e^{-\Gamma t}}{2}\left((1+|\lambda_f|^2)\cosh\frac{1}{2}\Delta\Gamma t + 2\Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t + (1-|\lambda_f|^2)\cos\Delta m t - 2\Im\lambda_f\sin\Delta m t\right)$$

$$\Gamma_{\bar{P}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 \frac{e^{-\Gamma t}}{2}\left((1+|\lambda_f|^2)\cosh\frac{1}{2}\Delta\Gamma t + 2\Re\lambda_f \sinh\frac{1}{2}\Delta\Gamma t + (1-|\lambda_f|^2)\cos\Delta m t + 2\Im\lambda_f\sin\Delta m t\right)$$

- Where the sinh and sin terms are associated to the interference between the decays with and without oscillation.
- The master equations are often expressed as

$$\Gamma_{P^0\to f}(t) = |A_f|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f\sinh\frac{1}{2}\Delta\Gamma t + C_f\cos\Delta m t - S_f\sin\Delta m t\right)$$

$$\Gamma_{\bar{P}^0\to f}(t) = |A_f|^2 \left|\frac{p}{q}\right|^2 (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f\sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta m t + S_f\sin\Delta m t\right)$$

- After defining $D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2}$ $\quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$ $\quad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}$

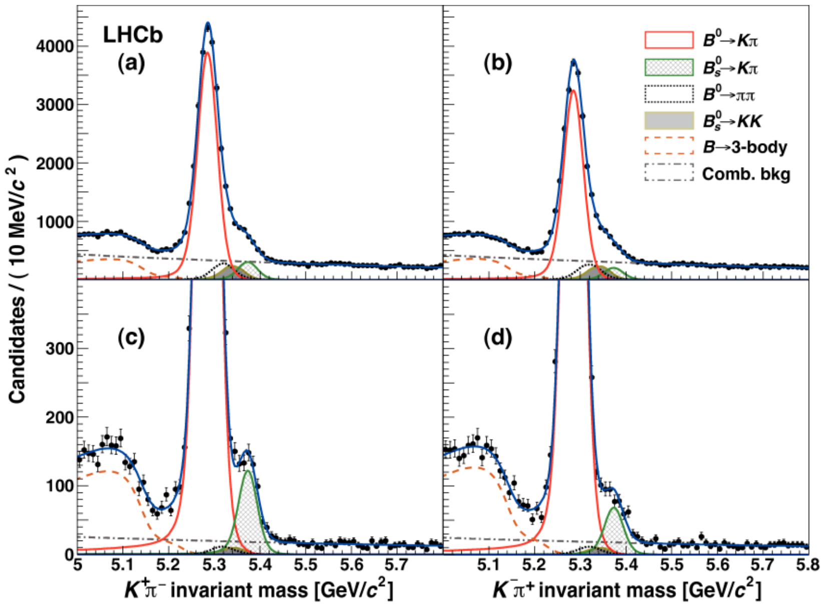
- For a given final state f we only have to find λ_f to fully describe the decay of the oscillating mesons.

CPV in decay

- When the decay rate of a B to a final state f differs from the decay rate of an anti-B to the CP-conjugated final state.

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

- This happens if $\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$



- The canonical example of such a case are the $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays.
- A CP asymmetry is observed for such decays of

$$A_{CP} = \frac{\Gamma_{B^0 \to K^+\pi^-} - \Gamma_{B^0 \to K^-\pi^+}}{\Gamma_{B^0 \to K^+\pi^-} + \Gamma_{B^0 \to K^-\pi^+}} = -0.082 \pm 0.006 \qquad A_{CP} = \frac{\Gamma_{B_s^0 \to K^-\pi^+} - \Gamma_{B_s^0 \to K^+\pi^-}}{\Gamma_{B_s^0 \to K^-\pi^+} + \Gamma_{B_s^0 \to K^+\pi^-}} = 0.26 \pm 0.04$$

- Since charged mesons do not oscillate this is the only type of asymmetry they present.

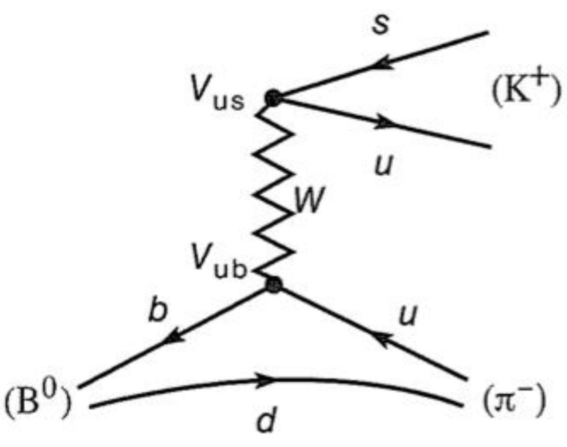
CPV in decay in a nutshel

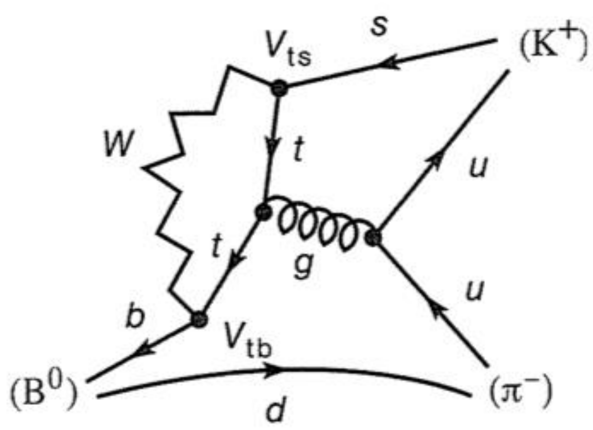
Decays with Tree and Penguin contributions: interfere ⇒ CPV

-$\phi_{1,2}$ weak phases. -$\theta_{1,2}$ strong phases.

$$A_1 = |A_1| e^{i\phi_1} e^{i\theta_1}$$
$$\overline{A}_1 = |A_1| e^{-i\phi_1} e^{i\theta_1}$$

$$A_2 = |A_2| e^{i\phi_2} e^{i\theta_2}$$
$$\overline{A}_2 = |A_2| e^{-i\phi_2} e^{i\theta_2}$$



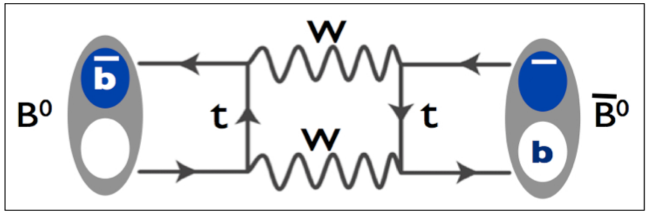


$$\left|\frac{\overline{A}}{A}\right|^2 = \left|\frac{\overline{A_1} + \overline{A_2}}{A_1 + A_2}\right|^2 \neq 1 \Leftrightarrow \phi_1 \neq \phi_2 \;\&\&\; \theta_1 \neq \theta_2$$

CPV in mixing

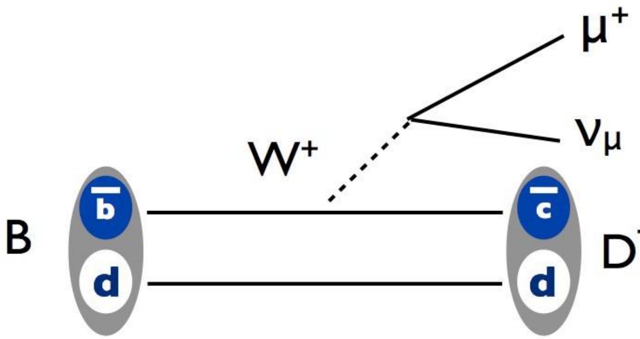
- This occurs if the oscillation from meson to anti-meson is different from the oscillation from anti-meson to meson:

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



- There us CPV if $|q/p| \neq 1$.
- To measure that decay rates in which the $\bar{b}$-quark in the B^0-meson decays weakly to a positively charged lepton are compared to rates of the *b*-quark in the $\bar{B}^0$ meson into a negatively lepton..
  - An event with two leptons with equal charge in the final state means that one of the two *B*-mesons oscillated.
  - The asymmetry in the number of two positive and two negative leptons allows to compare the oscillation rates.
  - Examples are $B^0_{(s)} \to D^-_{(s)}\mu^+\nu_\mu X$ modes

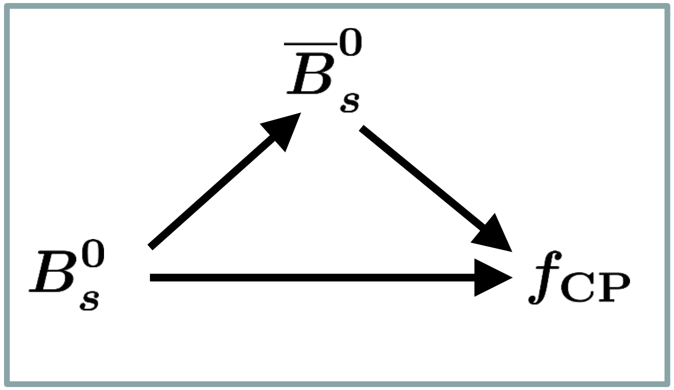
$$a_{sl}^d = (-4.7 \pm 0.6) \times 10^{-4}$$
$$a_{sl}^s = (2.22 \pm 0.27) \times 10^{-5}$$



Artuso, Borissov, Lenz [arXiv:1511.09466]

CPV in interference between a decay with and without mixing

- Also referred to as CPV involving oscillations.
- It is measured in decays to a final state that is common for the B^0 and $\bar{B}^0$ meson.
- CP is violated if $\Gamma(P^0{}_{(\rightsquigarrow \bar{P}^0)} \to f)(t) \neq \Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)} \to f)(t)$
- In particular CP-eigenstates verify that two amplitudes contribute to the transition.



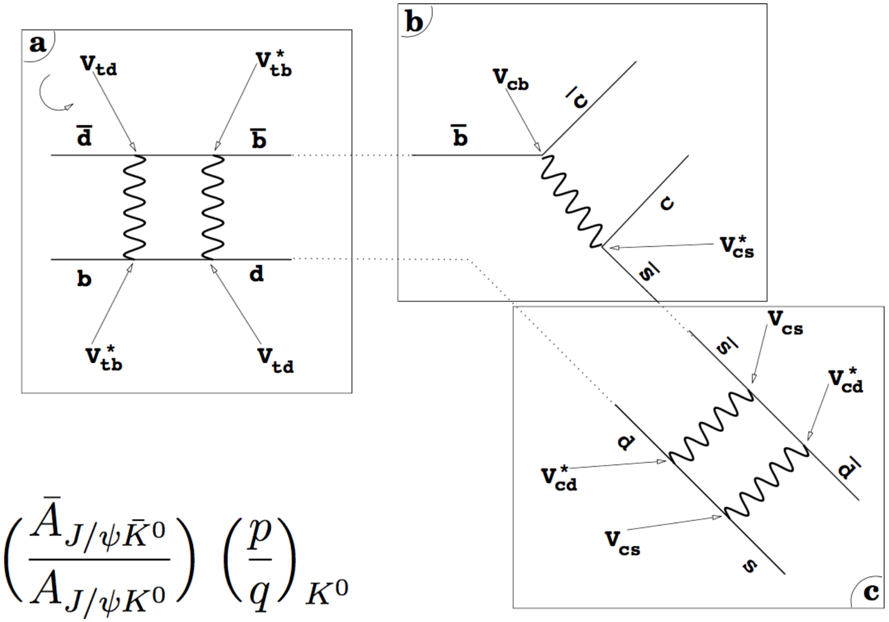
- If there is not CPV in mixing, $\left|\frac{q}{p}\right| = 1$, the time dependent CP asymmetry is given by:

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f \cos \Delta m t - 2S_f \sin \Delta m t}{2\cosh \frac{1}{2}\Delta\Gamma t + 2D_f \sinh \frac{1}{2}\Delta\Gamma t}$$

CPV in interference between a decay with and without mixing

- The canonical example is the $B^0 \to J/\psi K_S^0$ decay.
- If we had considered the $B^0 \to J/\psi K^0$ mode we would have a different state for B^0 and $\bar{B}^0$, since $\bar{B}^0 \to J/\psi \bar{K}^0$.
- For the meson and anti-meson to have a common final state the mass eigenstates are considered: $|K_S^0\rangle = p|K^0\rangle + q|\bar{K}^0\rangle$
- The considered diagrams are b+c and a+b+c and the corresponding CP conjugated.
- In this case the CP asymmetry simplifies because of the common final state and $\Delta\Gamma \approx 0$. In this case

$$A_{CP}(t) = \frac{\Gamma_{B^0(t)\to f} - \Gamma_{\bar{B}^0(t)\to f}}{\Gamma_{B^0(t)\to f} + \Gamma_{\bar{B}^0(t)\to f}} \approx -\Im\lambda_f \sin(\Delta m t)$$



- For this decay λ has three parts

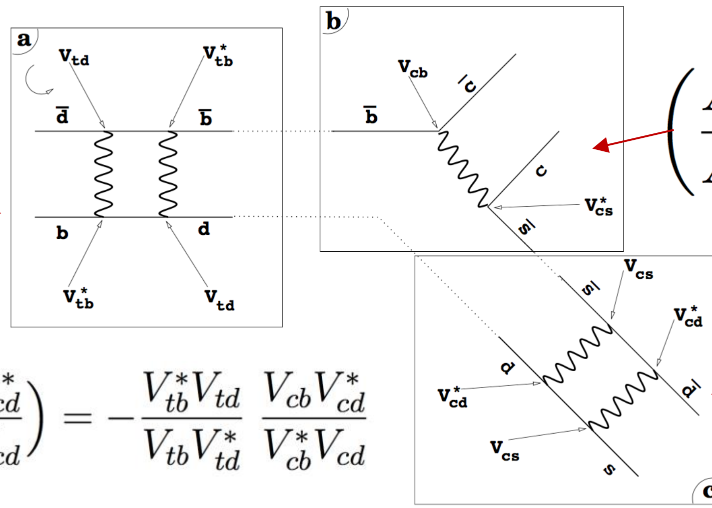
$$\lambda_{J/\psi K_S^0} = \left(\frac{q}{p}\right)_{B^0} \left(\eta_{J/\psi K_S^0} \frac{\bar{A}_{J/\psi K_S^0}}{A_{J/\psi K_S^0}}\right) = -\left(\frac{q}{p}\right)_{B^0} \left(\frac{\bar{A}_{J/\psi \bar{K}^0}}{A_{J/\psi K^0}}\right) \left(\frac{p}{q}\right)_{K^0}$$

CPV in interference between a decay with and without mixing

- Let us analyze these three parts

$$\lambda_{J/\psi K^0_S} = \left(\frac{q}{p}\right)_{B^0} \left(\eta_{J/\psi K^0_S} \frac{\bar{A}_{J/\psi K^0_S}}{A_{J/\psi K^0_S}}\right) = -\left(\frac{q}{p}\right)_{B^0} \left(\frac{\bar{A}_{J/\psi \bar{K}^0}}{A_{J/\psi K^0}}\right) \left(\frac{p}{q}\right)_{K^0}$$

$$\left(\frac{q}{p}\right)_{B^0} = \sqrt{\frac{M_{12}^*}{M_{12}}} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$



$$\left(\frac{\bar{A}}{A}\right) = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}$$

$$\left(\frac{p}{q}\right)_{K} = \sqrt{\frac{M_{12}}{M_{12}^*}} = \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}$$

- Therefore

$$\lambda_{J/\psi K^0_S} = -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right) \left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right) \left(\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right) = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}$$

- And $\Im \lambda_{J/\psi K^0_S} = -\sin\left\{\arg\left(\frac{V_{tb}^* V_{td} V_{cb} V_{cd}^*}{V_{tb} V_{td}^* V_{cb}^* V_{cd}}\right)\right\} = -\sin\left\{2\arg\left(\frac{V_{cb} V_{cd}^*}{V_{tb} V_{td}^*}\right)\right\} \equiv \sin 2\beta$
- In summary, a time-dependent analysis of this channel provides a measurement of the beta angle

$$A_{\mathrm{CP},\, B^0 \to J/\psi K^0_S}(t) = -\sin 2\beta \sin(\Delta m t)$$

How is this done?

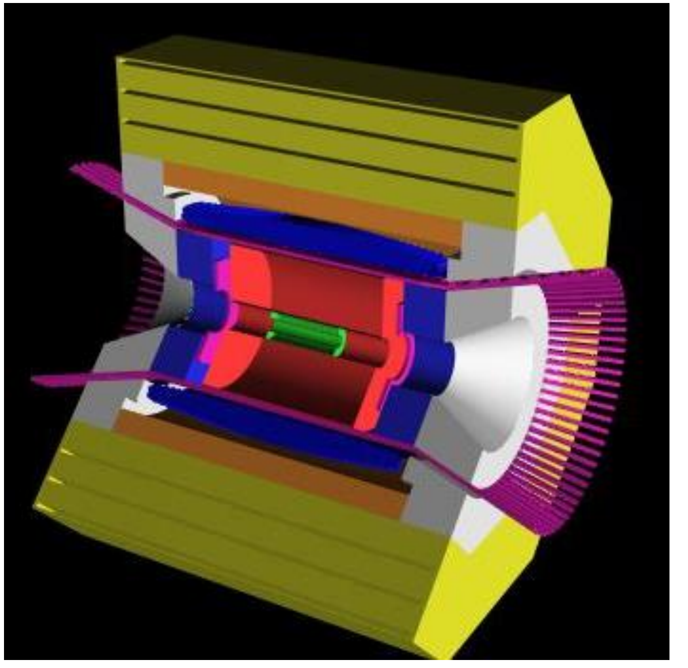
- We have seen so far the formalism to access relevant magnitudes involving B meson decays.
- Which are the key experiments to perform such measurements and their characteristics are the topic of the following slides.
- We will cover also relevant measurements that have not been treated in the canonical examples.
- And will cover how to search for physics BSM.

CLEO

- A wise way of producing B-mesons is in e^+e^- colliders.
- The CMS energy is tuned to the Y(4s) resonance (the 4-th lowest mass bb meson) that almost exclusively decays into B^0-B^0 and B+-B- (50% each) pairs.

$$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\bar{B}^0$$

- This resonance was discovered at CLEO and CUSB experiments at Cornell
- CLEO was the main experiment in this lab dedicated to the study of B-mesons.
- The e^+e^- beams were symmetric.

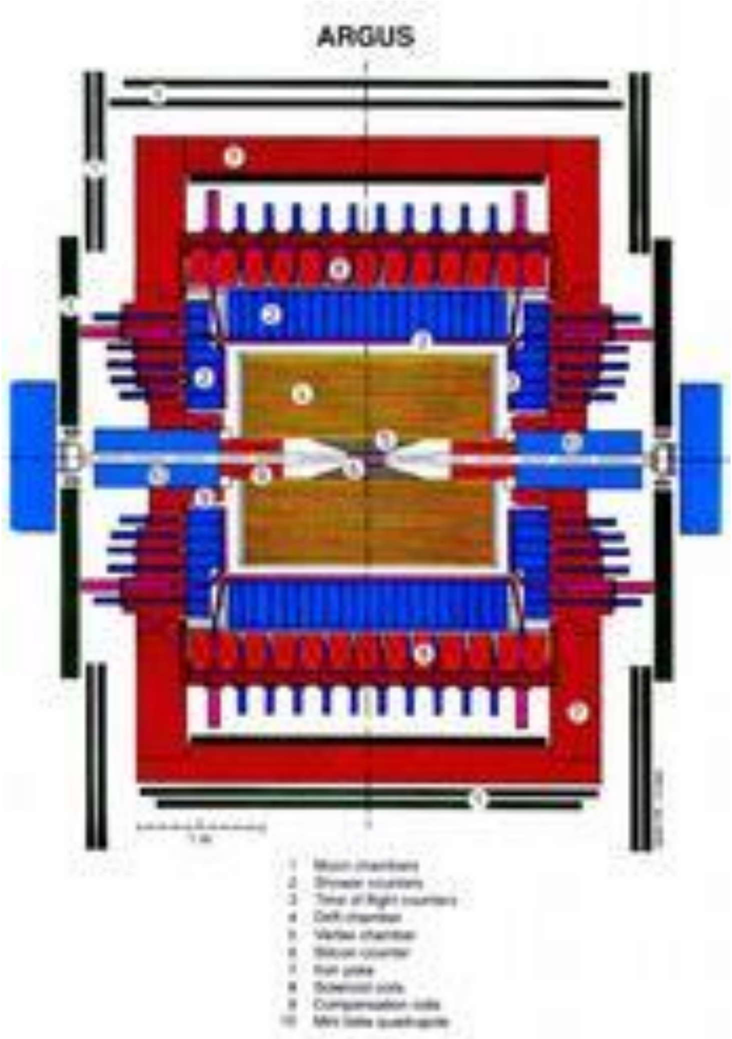


ARGUS

- The European competitor of CLEO was ARGUS.
- The ARGUS **A R**ussian-**G**erman-**U**nited States-**S**wedish Collaboration) experiment performed such measurements using the electron-positon pairs of *DORIS II* at DESY.
  - Construction started in 1979
  - Operation 1982-1992
- The problem with symmetric e^+e^- beams is

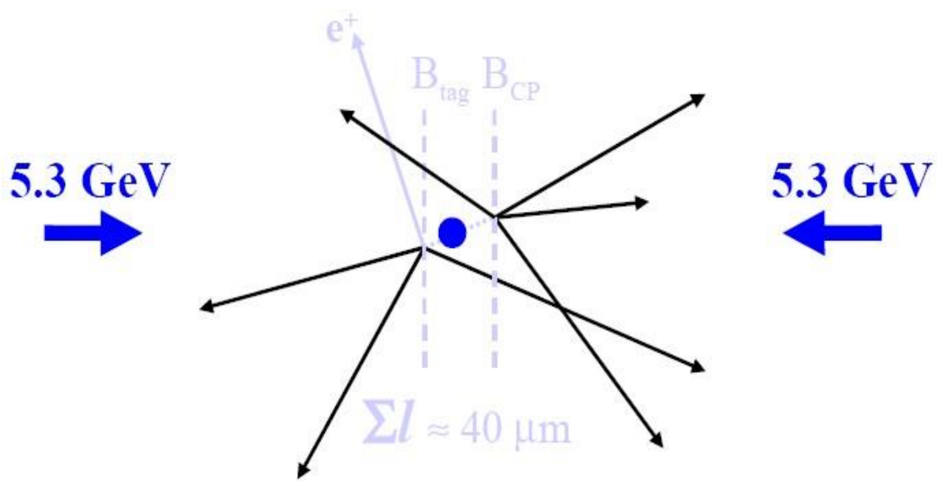
$m_{\Upsilon(4s)}$ = 10.58 GeV → p_B= 340 MeV → $\beta\gamma$ = 0.064

- Therefore the mean B decay length $c\tau\beta\gamma$ ~ 30 μm.
  - This is too close to be resolved by tracking detectors.



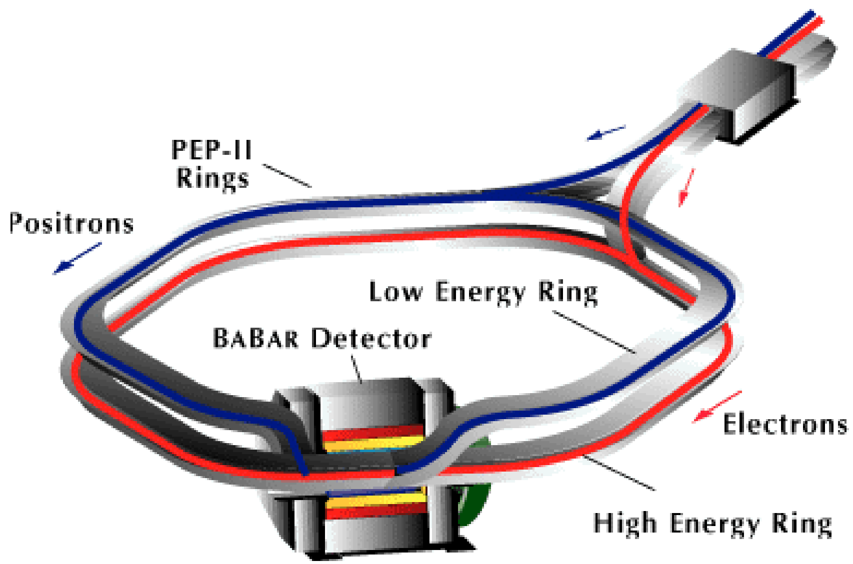
Coherent B-B pairs

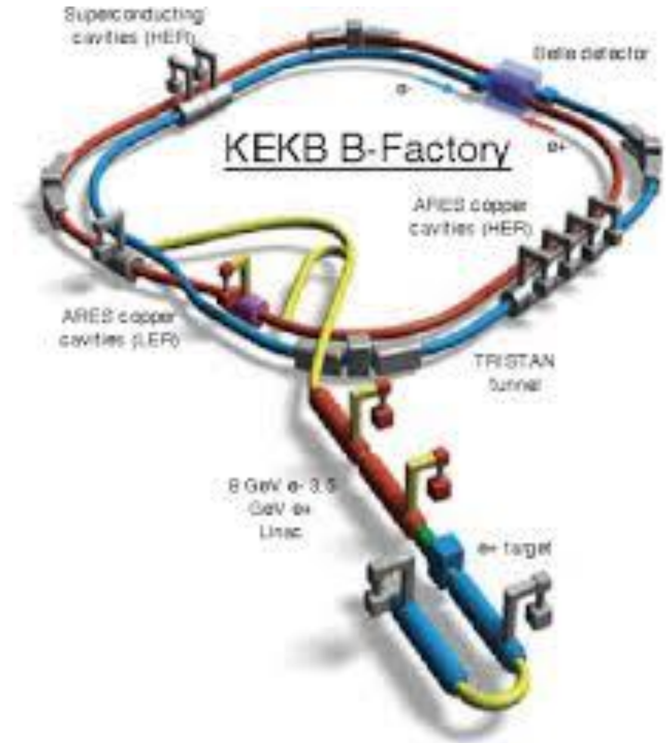
- The advantage of producing meson-antimeson pairs in colliders is that the pair is produced in a coherent quantum state.
- Both mesons oscillate in phase until one decays.
- Simply counting the asymmetry in charged leptons CPV in mixing can be detected.
- However, to observe the oscillation pattern the difference of decay times needs to be measured.
- How can this be achieved?



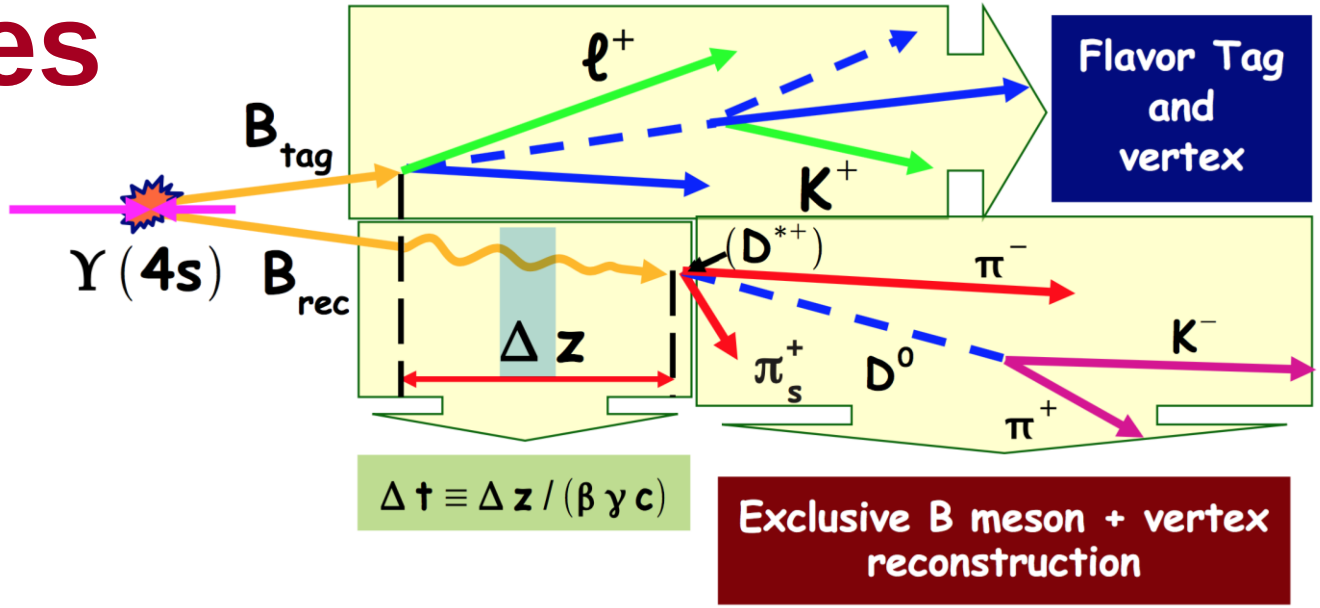
B-factories

- With the use of asymmetric e^+e^- beams.
- The $\Upsilon(4s)$ will not be produced at rest in the laboratory.
  - The two B mesons will have significant momentum with respect each other to produce measurable distances.
  - For example, the PEP-II collider at SLAC collides beams of 9 GeV e^- with beams of 3.1 GeV e^+.
    - With that $\beta\gamma \sim 0{,}56$ and $c\tau\beta\gamma \sim 260\ \mu m$.
  - KEKB collided 7GeV e^- with 2.6 e^+.
    - $\beta\gamma$ Calculate and $c\tau\beta\gamma \sim$ Calculate μm.





B-factories

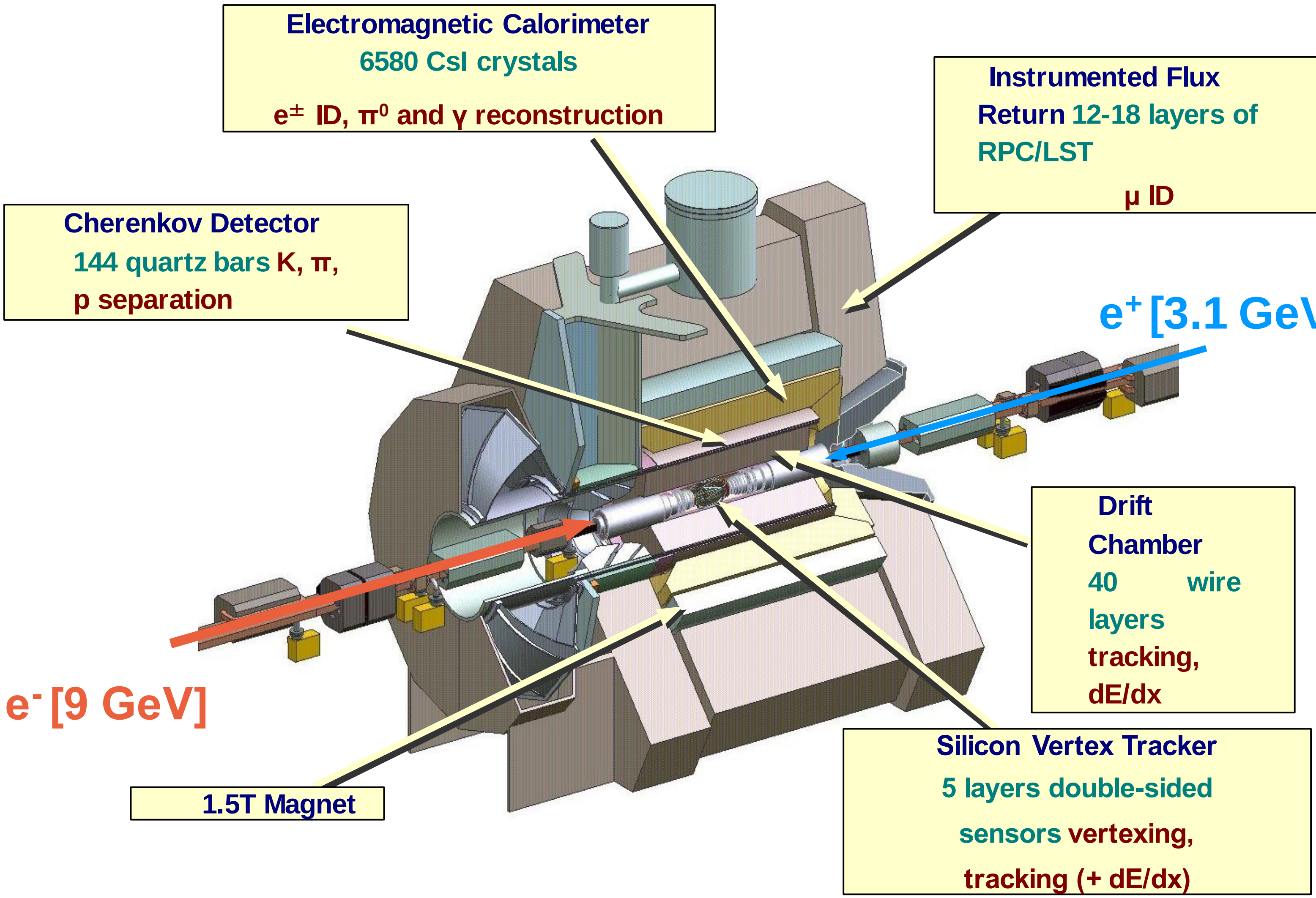


- The B factories strategy for mixing analysis consisted of:

1. Reconstruct B_{rec} fully → B_{rec} decay vertex, momentum and flavor at decay assign remaining final-state particles to B_{tag} decay (not necessarily full reconstruction).
2. Reconstruct B_{tag} decay vertex → fixes t=0 for oscillation measurement infer flavor of B_{tag} at its decay → fixes flavor of B_{rec} at t=0.
3. B_{rec} oscillated (not oscillated) if opposite (same) flavor at t=0 and decay.
4. Calculate oscillation time from B_{rec} momentum and Δz of decay vertices.

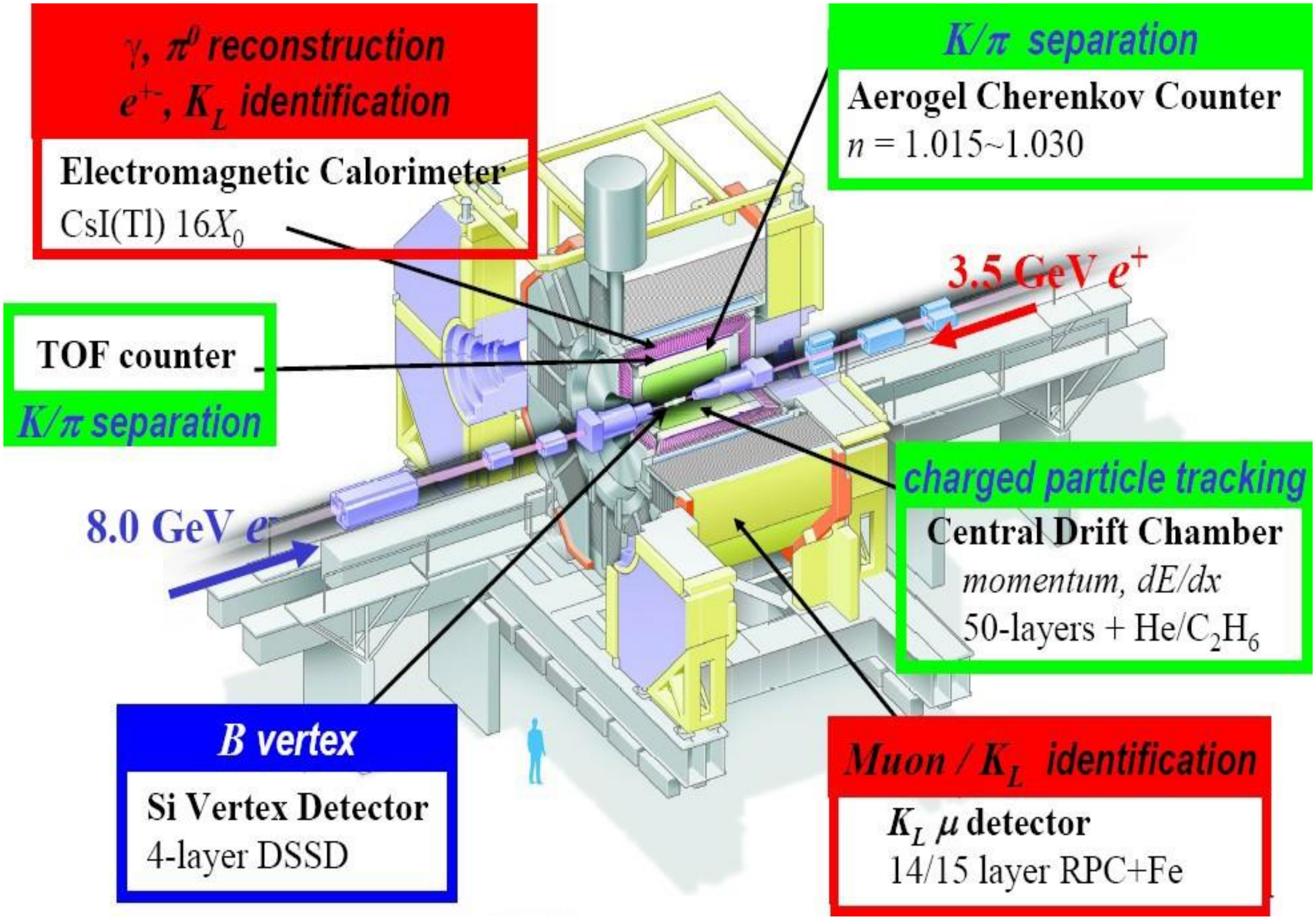
The BaBar spectrometer

[NIM A479 (2002) 1]



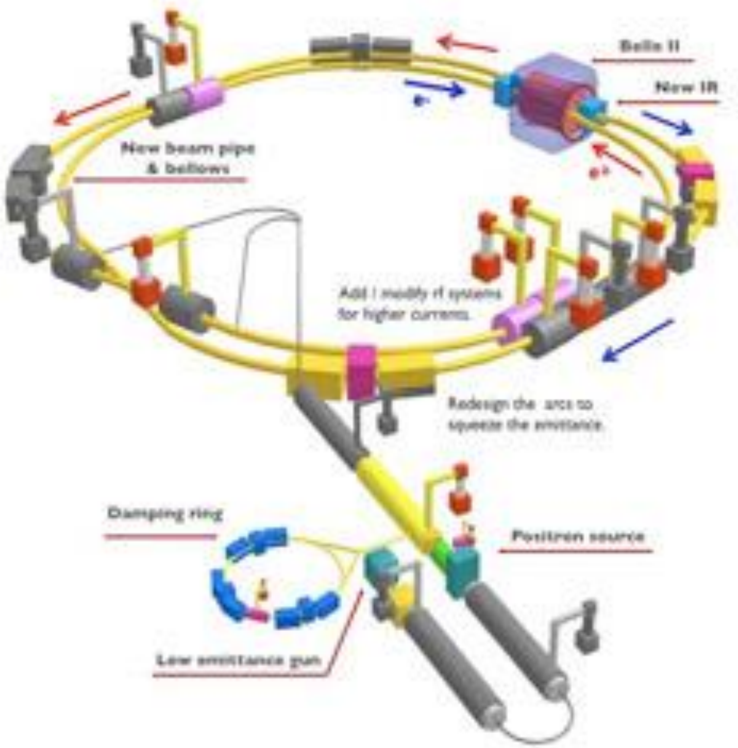
The Belle spectrometer

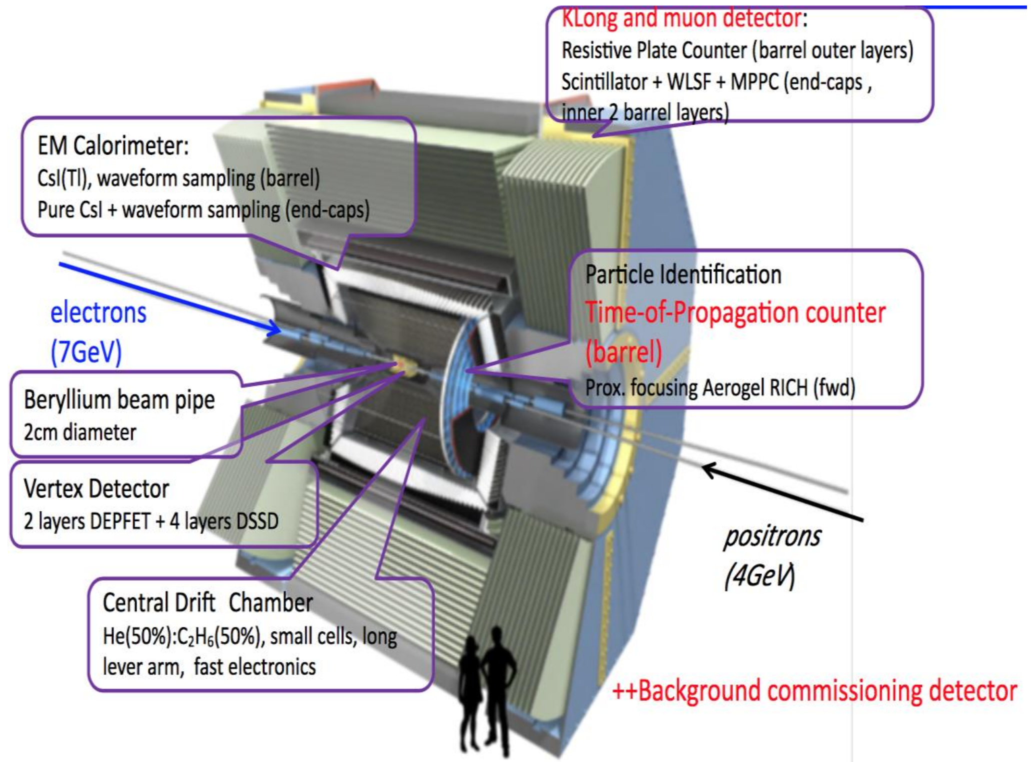
[NIM A479 (2002) 117]



Belle II

- An upgraded version of both the KEKB and Belle spectrometers is ongoing.
- BaBar stopped taking data in 2008.
- Aims at a luminosity of $8x10^{35}$ $cm^{-2}s^{-1}$ thus 10^{10} BB pairs per year.
- First physics runs in fall 2018.





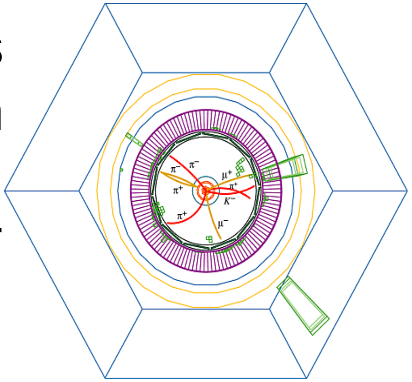
Cibrán Santamarina
Universidade de Santiago de Compostela

Hadron colliders

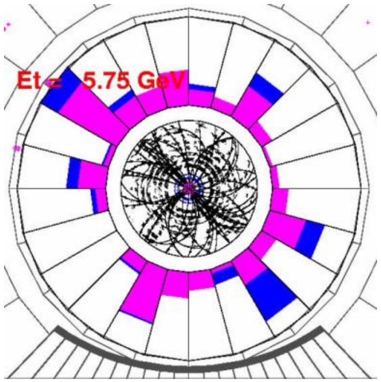
- The other way of producing b hadrons is in hadron colliders.
- Hadron collider advantages:
  - All species of b hadrons produced: $B^{\pm}$, B^0_s, B^0, B^+_c, Λ_b.
  - σ_{bb} much higher than at B factories.
- Hadron collider disadvantages:
  - σ_{bb}/σ_{tot} much smaller than at B factories.
  - Large number of additional particles from underlying hadronic interaction.
- The way to overcome these difficulties is to rely in the high transverse momentum originated in the heavy mass of the b-particles and the large impact parameter originated in the long lifetime of b-particles in the lab system.

Facility	$\sqrt{s}$	σ_{bb} [nb]	σ_{bb}/σ_{tot}
e^+e^- @ Y(4s) □(4s)	10.58 GeV	1	0.25
HERA-B pA	42 GeV	~ 30	10^{-6}
Tevatron pp	1.96 TeV	5×10^3	10^{-3}
LHC pp	7 TeV	3×10^5	10^{-2}
LHC pp	14 TeV	6×10^5	10^{-2}

$$B^0 \to J\psi K^0_S$$



event in BaBar

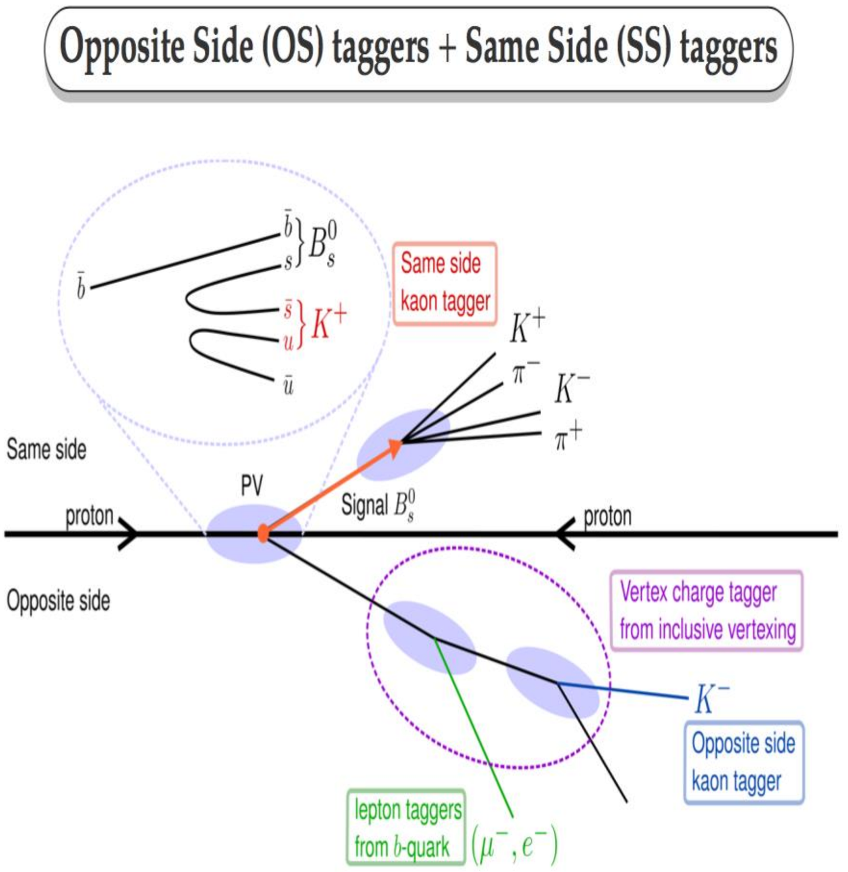


event in CDF

Cibrán Santamarina
Universidade de Santiago de Compostela

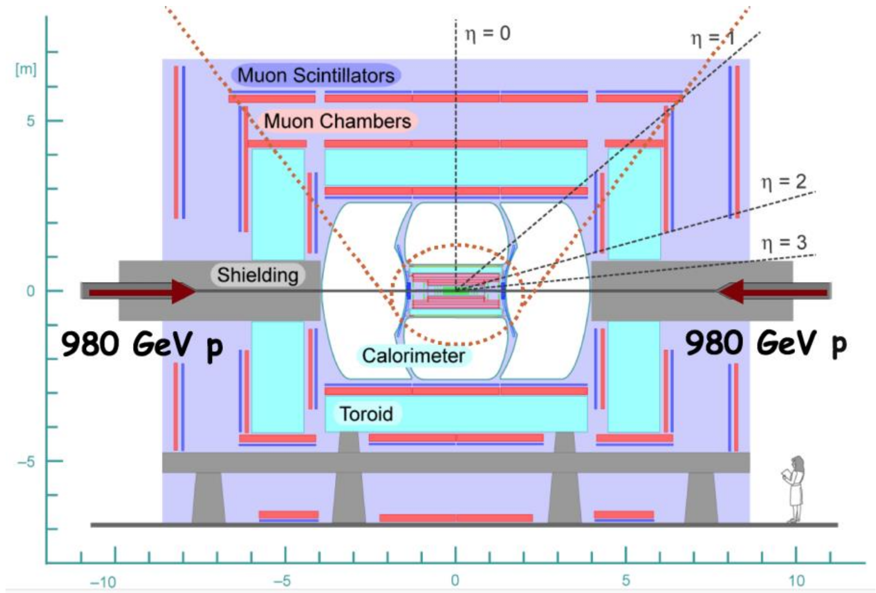
Production of bb in hadron colliders

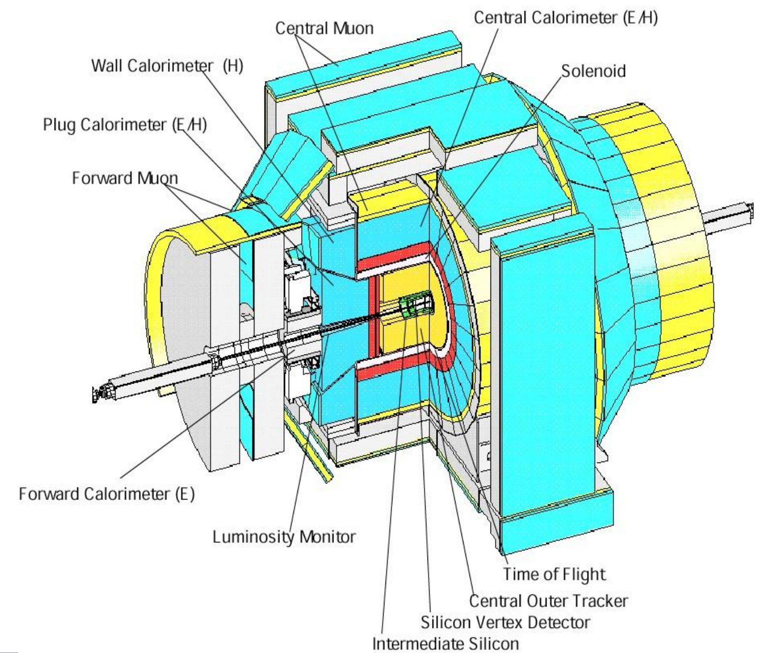
- **<u>The bb pair is not created in a coherent quantum state</u>**
  - The oscillation measurement is made with respect to the primary vertex.
    - B flavor needs to be known at production.
  - Primary vertex reconstruction: excellent precision due to large number of charged tracks from underlying event.
- The flavor tagging is performed in messier environment. Tagging power of ~ 5%.
  - "Opposite side tagging" as in B factories (lepton, kaon, vertex charge).
  - "Same side tagging": charge of a lepton or a kaon from b decay.



The Tevatron GDPs

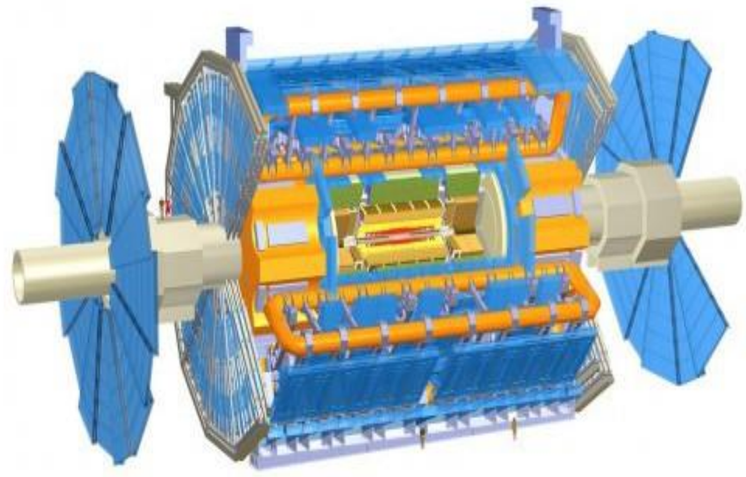
- At the p-pbar collider in Fermilab two General Purpose Detectors were installed: CDF and D0.
- Their main target was to discover the top quark and eventually the Higgs boson.
- However they also had an ambitious B-physics program.
  - Their main challenge was the trigger and the π/K identification.
  - The achieved very good results for example in the analysis of the $B_s^0 \to J/\psi\phi$ decay (B^0_s was not usually produced in the B factories although Belle had dedicated runs)

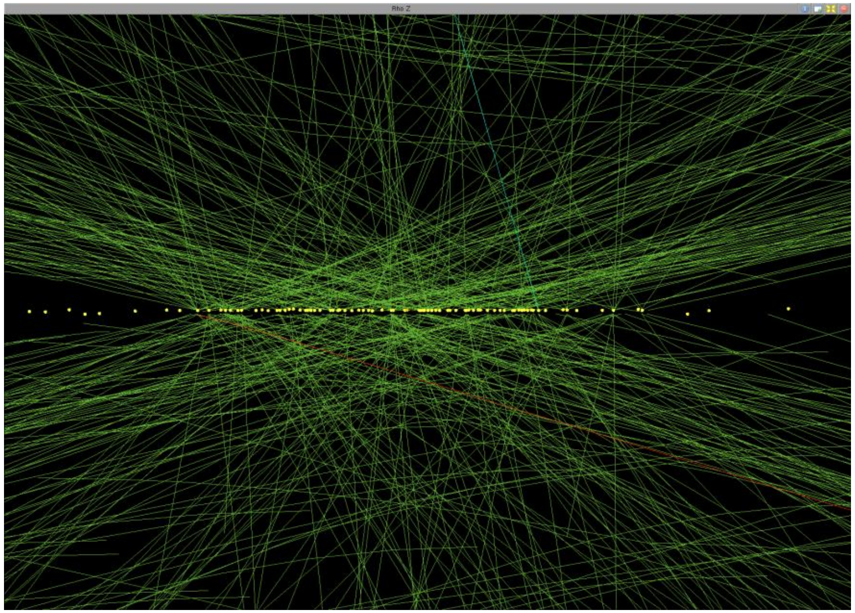


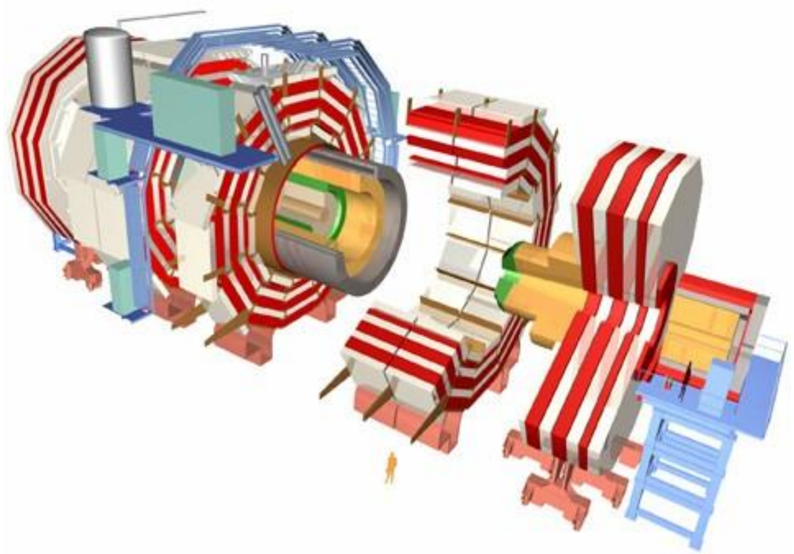


The LHC GDPs

- As for the Tevatron the LHC GDPs, ATLAS and CMS also have a B-physics program.
  - It has produced excellent results.
- The challenge is to trigger and select b-hadron decays in the midst of the pile up environment.

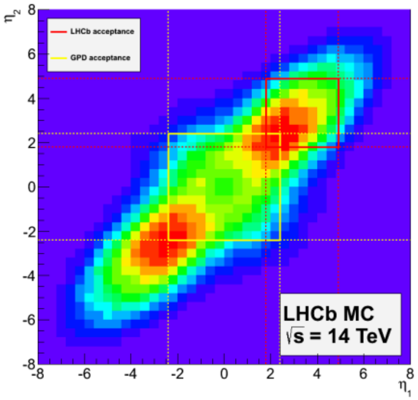


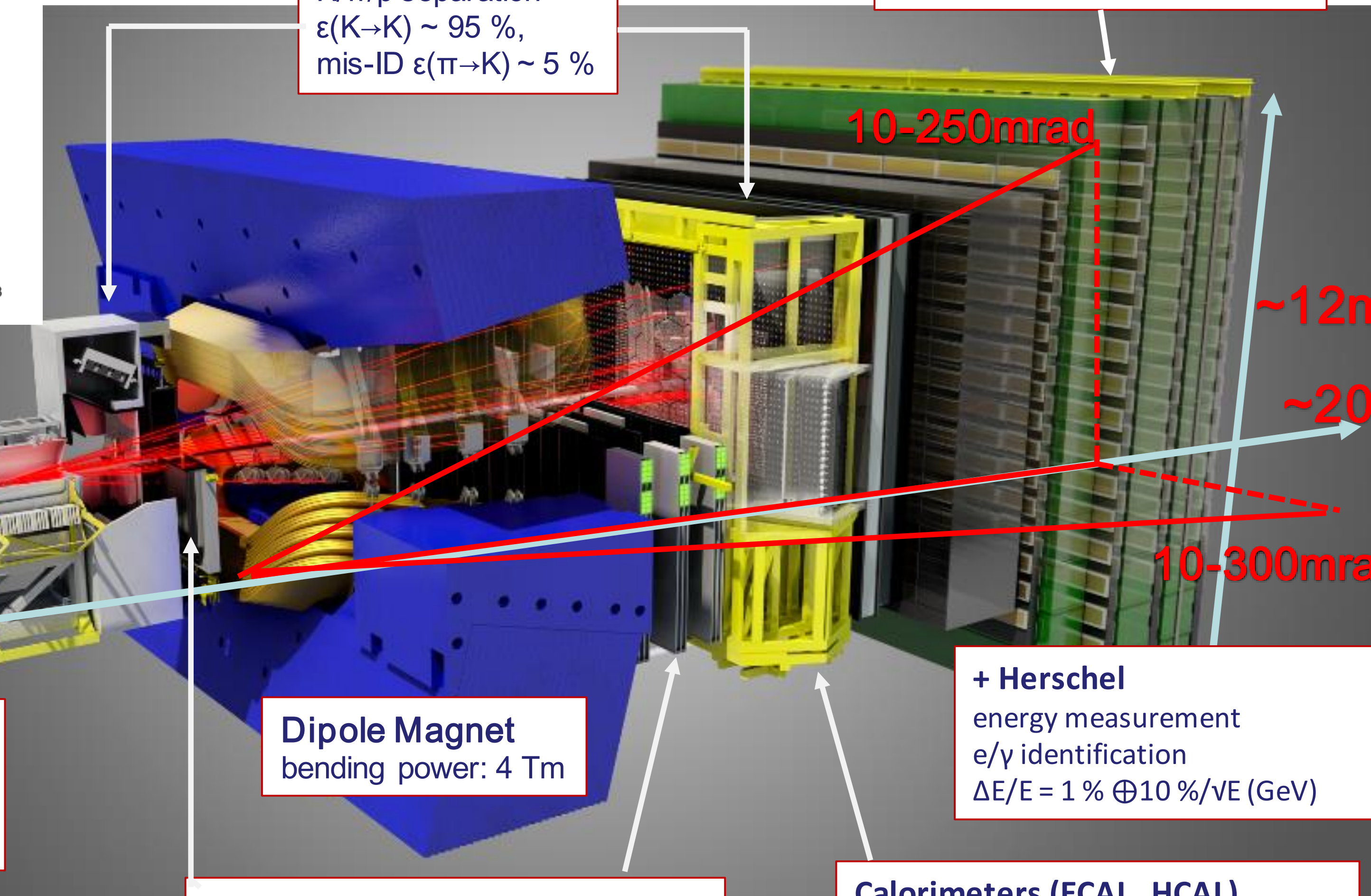




JINST 3 (2008) S08005

$b\bar{b}$ acceptance





RICH detectors
K/π/p separation
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %

Muon system
μ identification ε(μ→μ) ~ 97 %,
mis-ID ε(π→μ) ~ 1-3 %

Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm

Dipole Magnet
bending power: 4 Tm

Tracking system: IT, TT and OT
momentum resolution
$\Delta p/p = 0.4\%–0.8\%$
(5 GeV/c – 100 GeV/c)

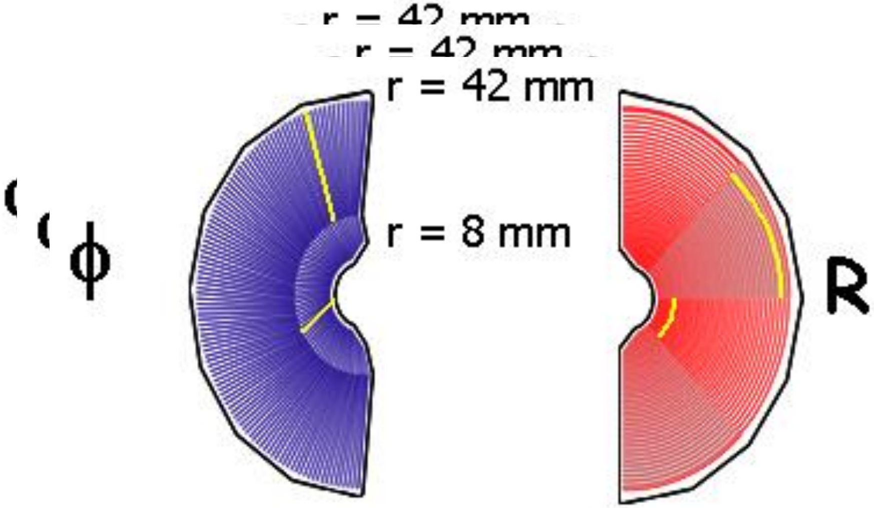
+ Herschel
energy measurement
e/γ identification
$\Delta E/E = 1\,\% \oplus 10\,\%/\sqrt{E}$ (GeV)

Calorimeters (ECAL, HCAL)
energy measurement
e/γ identification
$\Delta E/E = 1\,\% \oplus 10\,\%/\sqrt{E}$ (GeV)

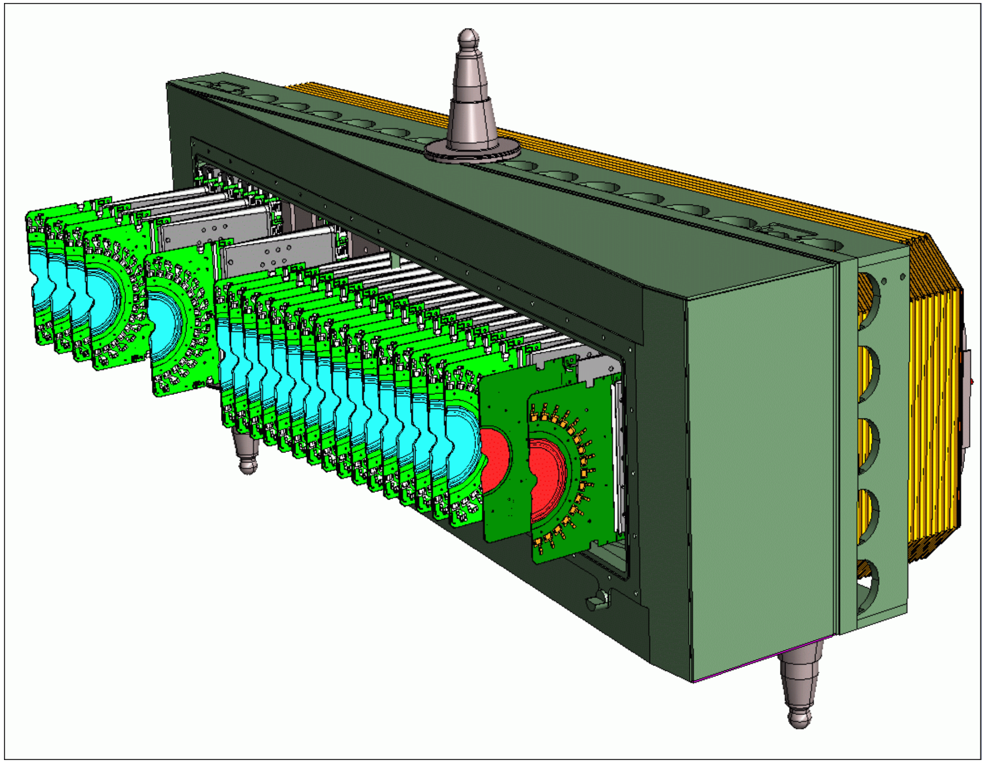
LHCb

LHCb Velo

- One of the mains characteristics of LHCb is its capability of resolving secondary vertices.
- This is possible



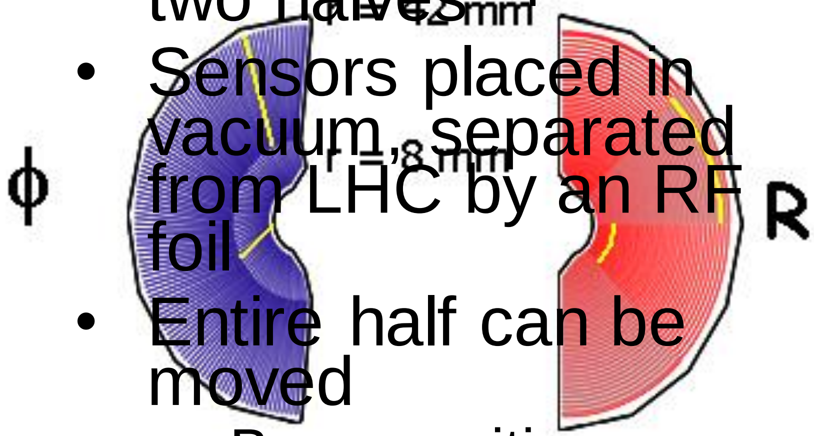
  - 2048 channels
  - 300 μm thick

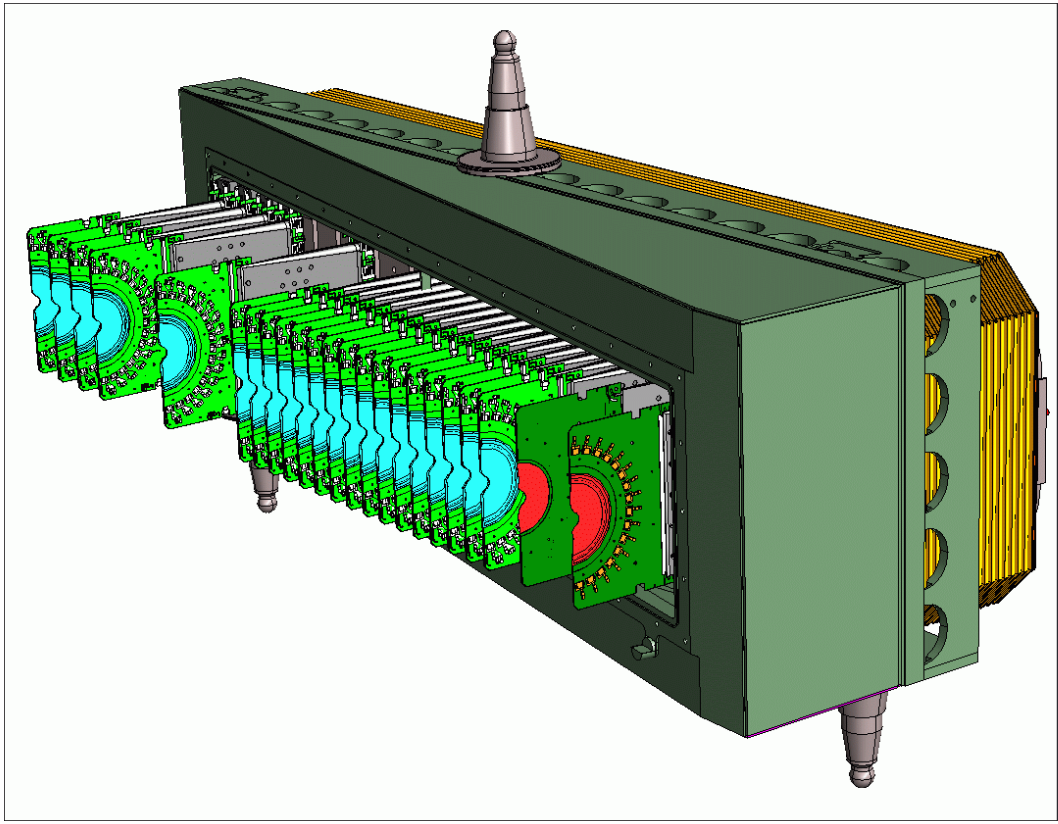


LHCb Velo

- One of the mains characteristics of LHCb is its capability of resolving secondary vertices
- Detector divided in two halves
- Sensors placed in vacuum, separated from LHC by an RF foil
- Entire half can be moved
  – Beam position unknown
  – Beam halo during injection

- 21 modules per half + 2 Pile Up sensors
- Per module, one R and one Φ sensor
  - □ Silicon strip sensors
  - □ 2048 channels
  - □ 300 μm thick

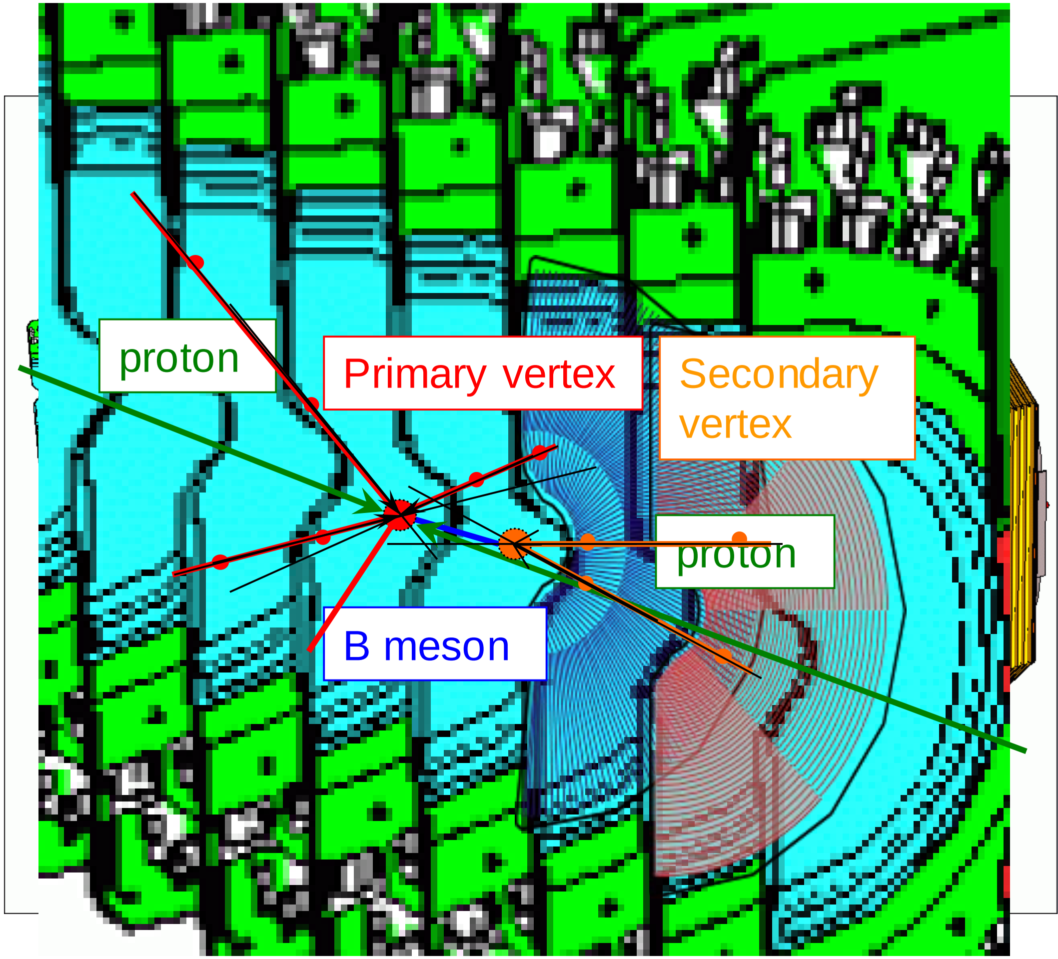




LHCb Velo

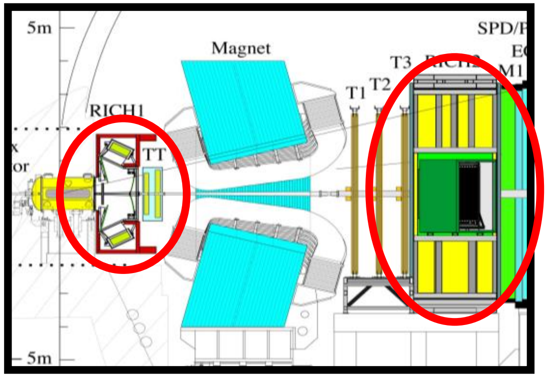
Slide from Ivan Mous

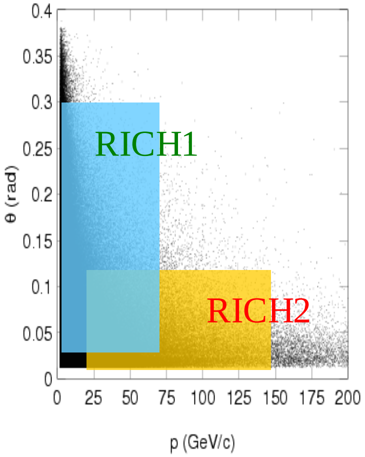
- Proton beams collide inside VELO
- B mesons and other particles produced in p-p interaction
- B mesons decay, produce new particles
- Decay products pass through sensors
- Primary and secondary Vertex can be reconstructed
- Vertices displaced (≈1cm)
  - Identify B mesons
  - Determine B meson lifetime

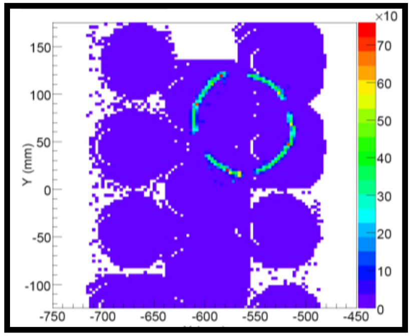


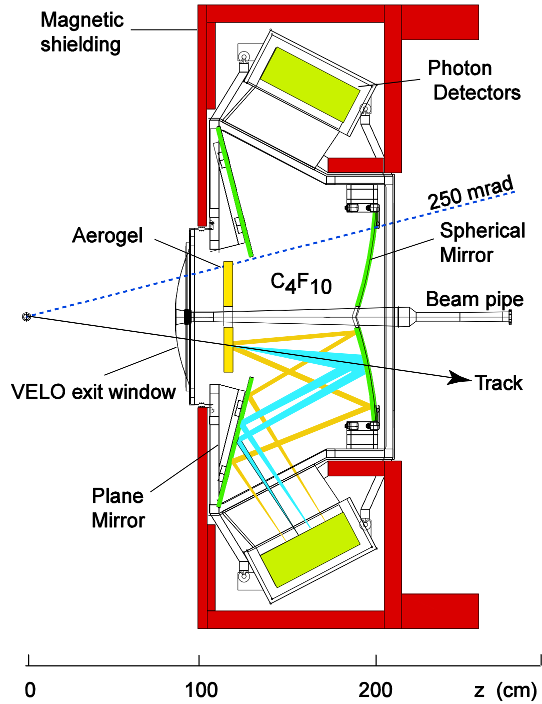
LHCb RICH

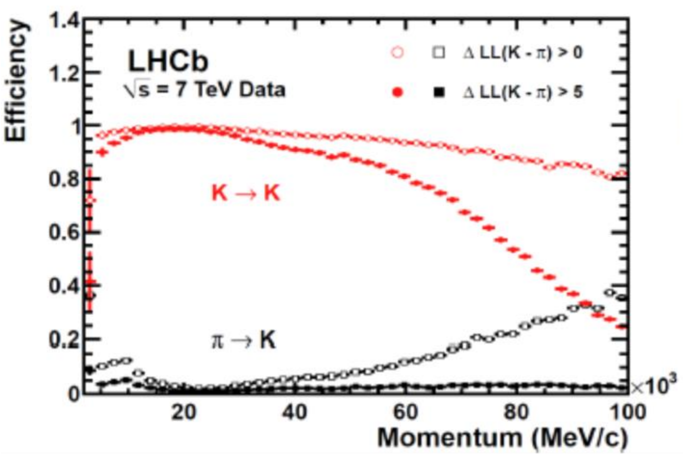
- Particle ID: p~2-100 GeV provided by two RICH detectors.
- Cherenkov light produced in a radiator gas is focused with mirrors, to produce ring images in a fly eye array of PMs.
- The ring pattern permits identification of hadron species.

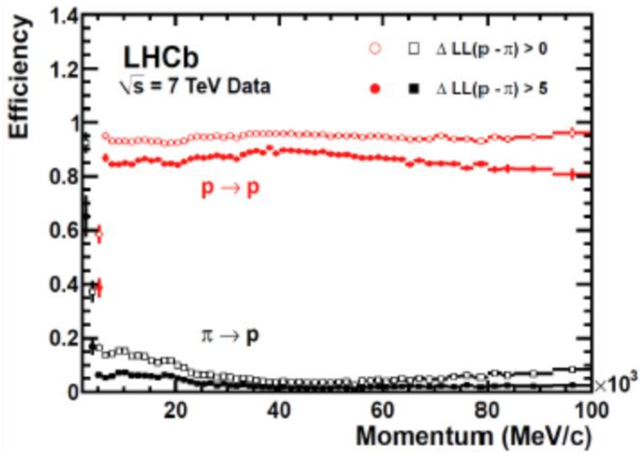






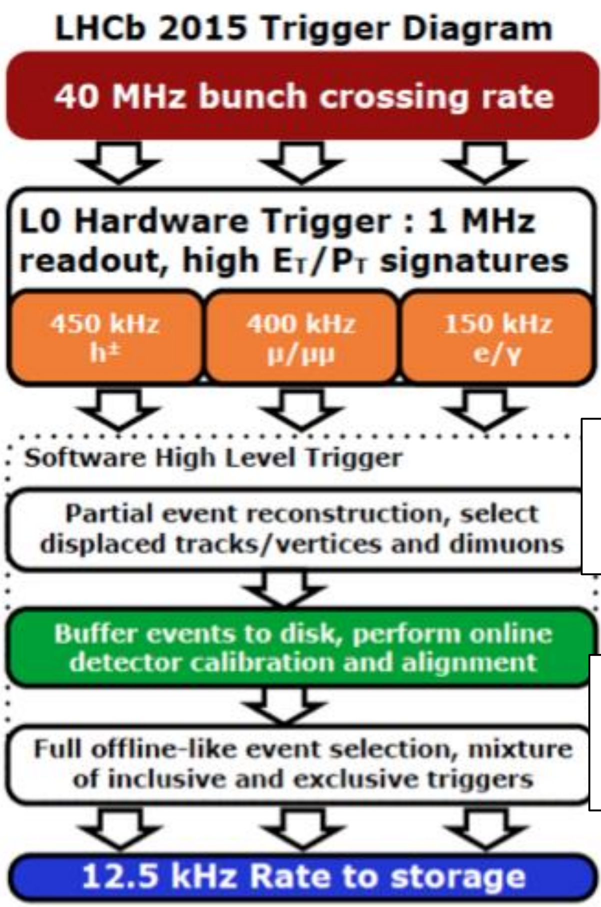






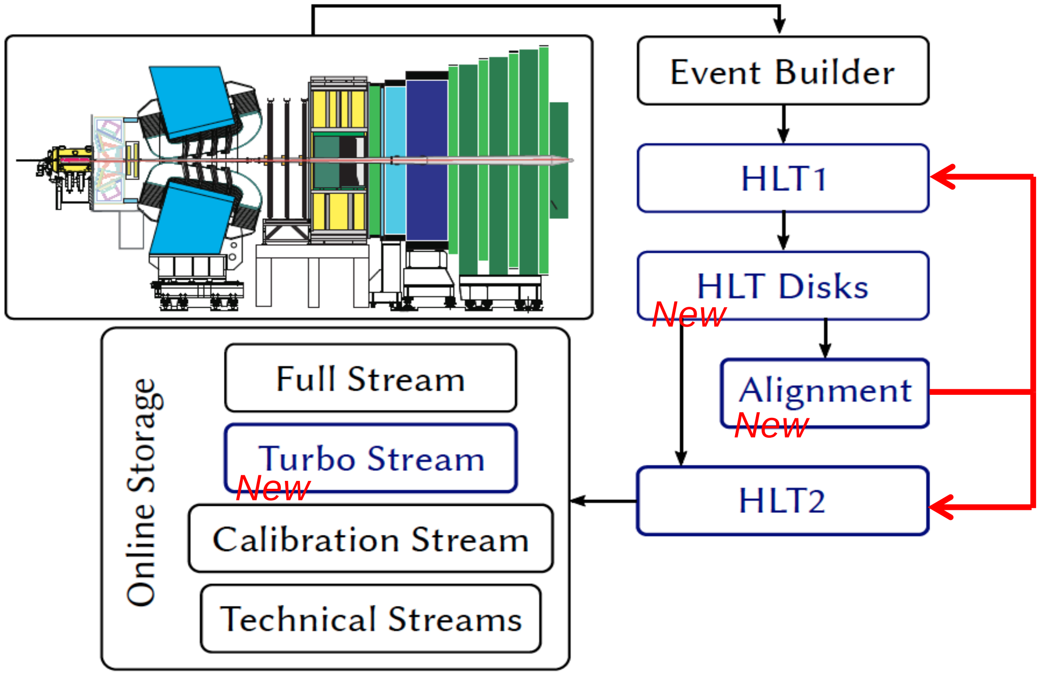
LHCb new trigger

New trigger system



~50k logical cores

~5PB disk space



Same online and offline reconstruction and PID!

- prompt alignment and calibration
- completely automatic and in real-time

Physics out of the trigger with Turbo Stream

- Raw info discarded, candidates direclty available 24h after being recorded

Flavor Physics highlights

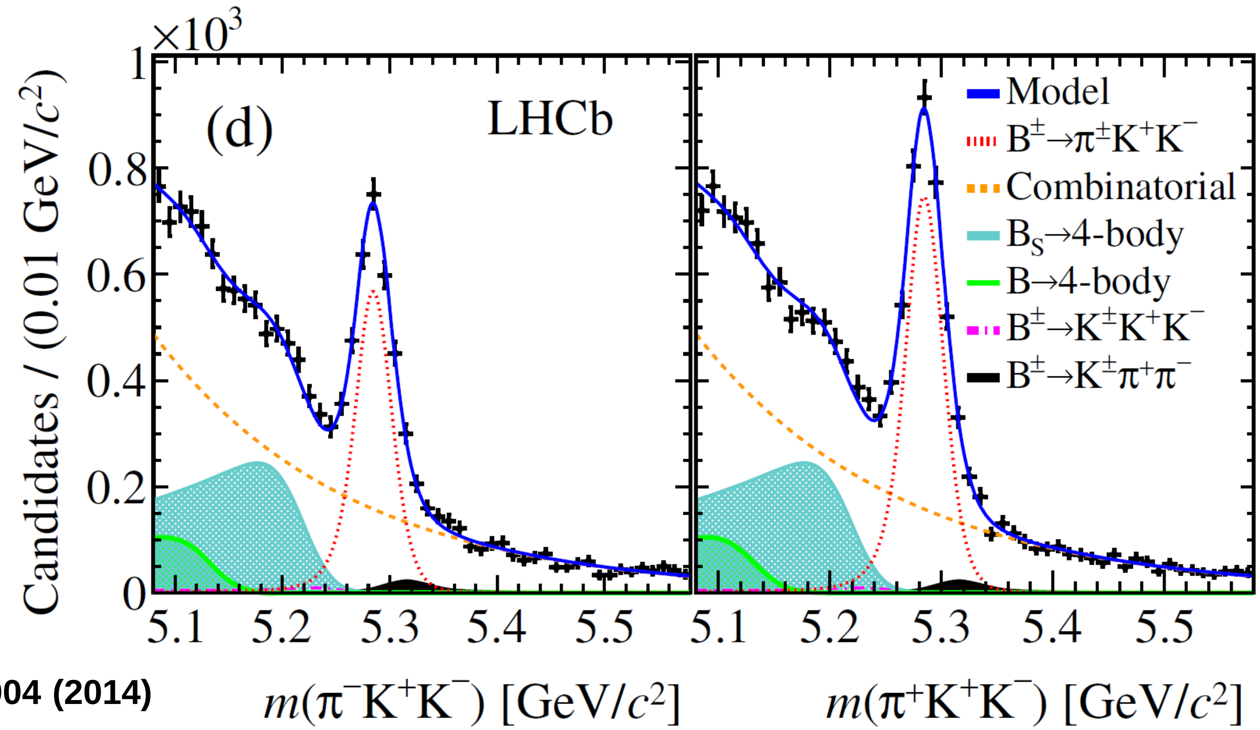
Direct CPV

Slide from J Saborido

- Not only the already shown canonical $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$.
- Also charmless three body decays.
- These modes can show huge assymetries in regions of the Dalitz-plot.

$$A_{CP}(B^\pm \to \pi^\pm K^+ K^-) = -0.123 \pm 0.022$$

$B^- \to \pi^- K^+ K^-$ $\qquad$ $B^+ \to \pi^+ K^+ K^-$



PRD 90, 112004 (2014)

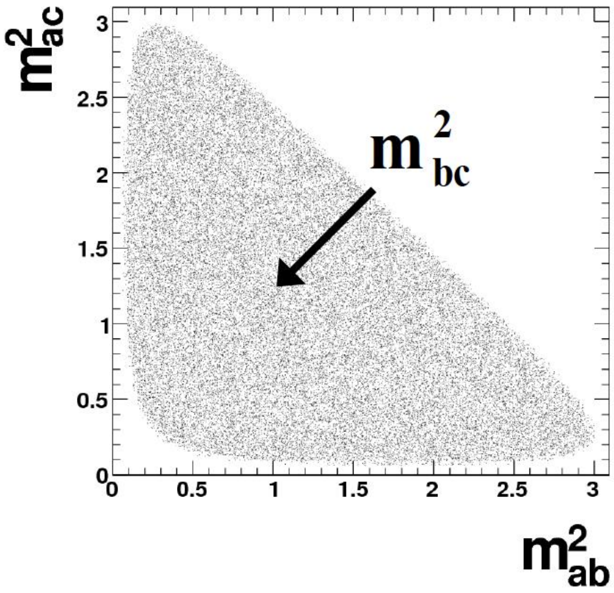
Dalitz plot

- A Dalitz plot is a useful technique for the analysis of three body decays.
- Two invariant relativistic variables are constructed in a $P \to a + b + c$ decay:

$$m_{ab} = (p_a + p_b)^{\mu}(p_a + p_b)_{\mu}$$
$$m_{ac} = (p_a + p_c)^{\mu}(p_a + p_c)_{\mu}$$

- The third combination, m_{bc} depends on these two (the choice is arbitrary).
  - It can be shown (exercise) that:

$$m_P^2 + m_a^2 + m_b^2 + m_c^2 = m_{ab}^2 + m_{ac}^2 + m_{bc}^2$$

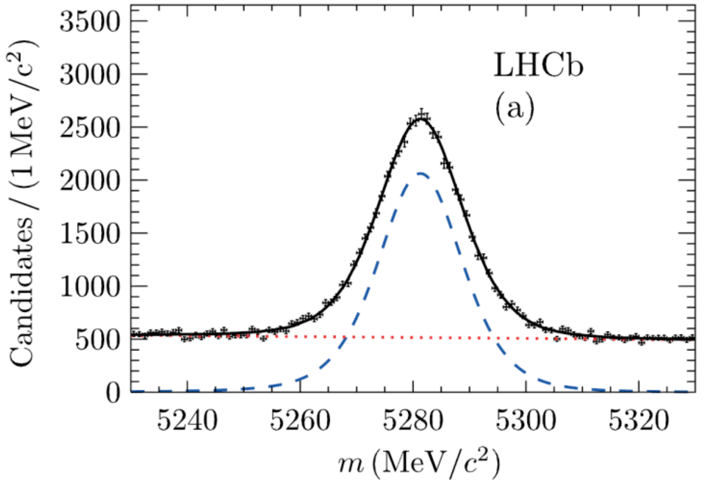


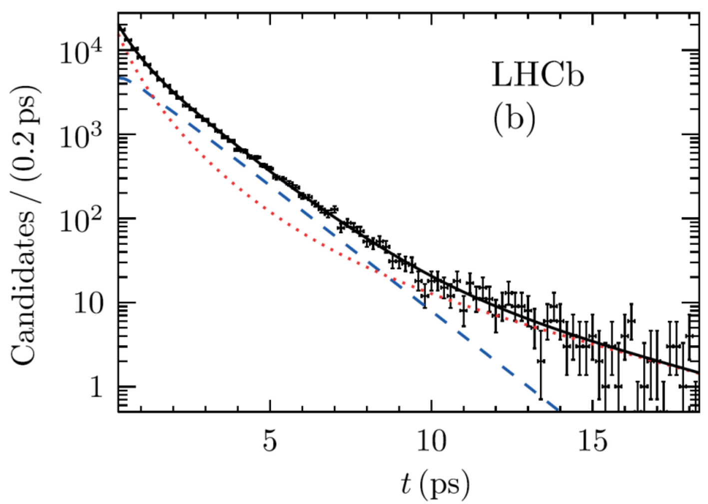
Slide from J Saborido

sin(2β)

Effective tagging efficiency: (3.02 ± 0.05) %
Typical time resolution: 45 fs

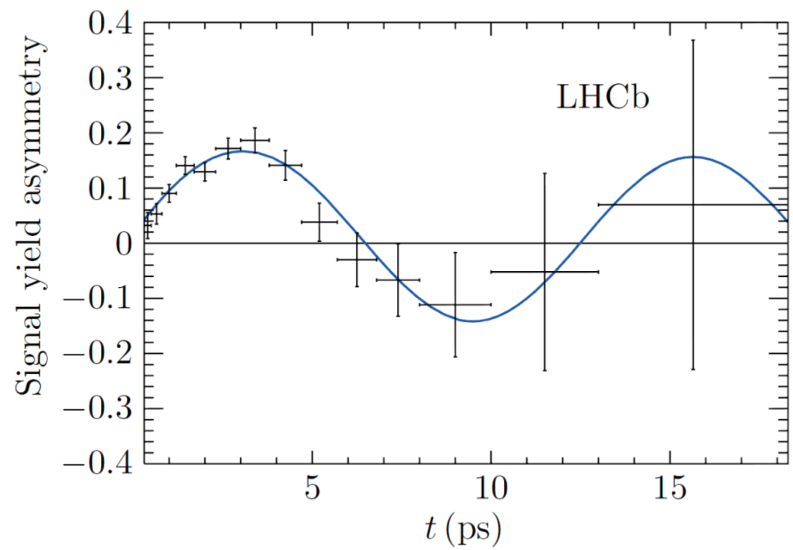
LHCb has become competitive with B-factory measurements.





41560 ± 270 tagged
$B^0 \to J/\psi\, K_S$ decays

$$\mathcal{A}(t) = S\sin(\Delta m t) - C\cos(\Delta m t)$$

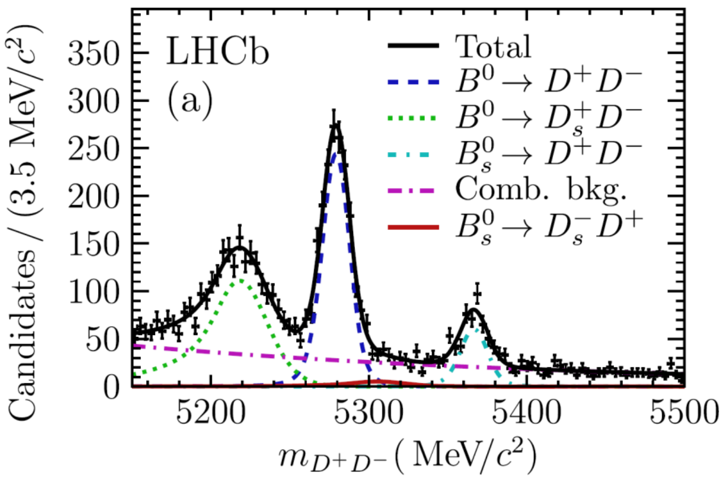


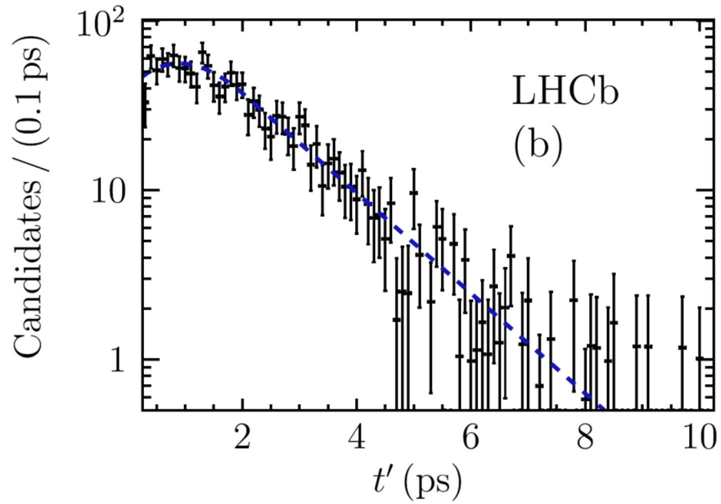
$$S = +0.731 \pm 0.035 \pm 0.020$$
$$C = -0.038 \pm 0.032 \pm 0.005$$

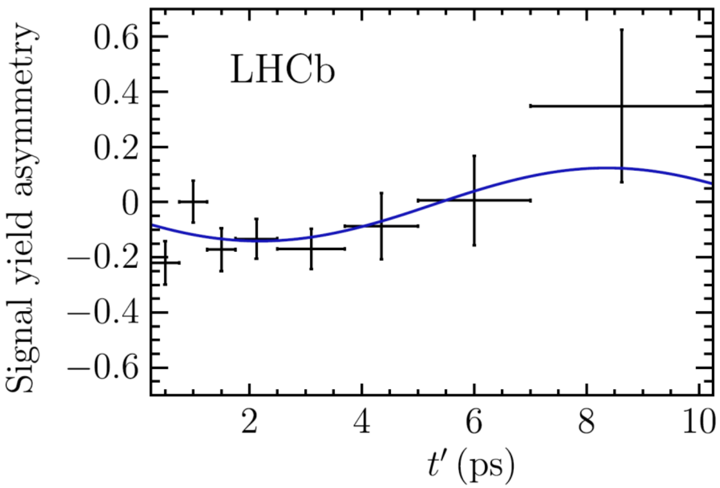
Slide from J Saborido

Time-dependent CPV in $B^0 \to D^+D^-$ decays

PRL 117, 261801 (2016)







$$\frac{d\Gamma(t,d)}{dt} = \propto e^{-t/\tau}[1 - d\, S \sin(\Delta m t) + d\, C \cos(\Delta m t)]$$

(d is the B^0 flavour at production time)

$$\frac{S}{\sqrt{1-C^2}} = -\sin(\phi_d + \Delta\phi) \qquad \phi_d = 2\beta$$

$S = -0.54^{+0.17}_{-0.16} \pm 0.05$

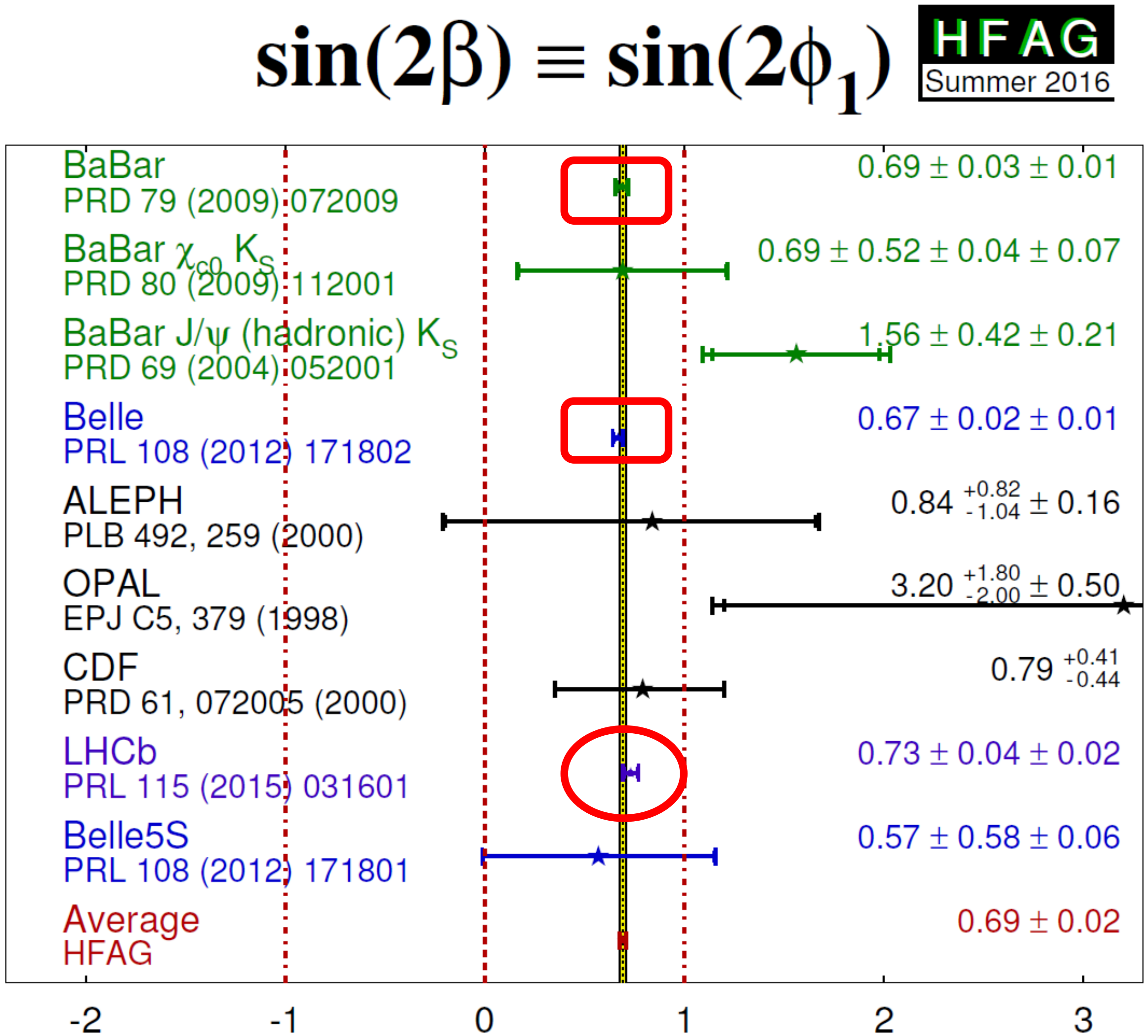
$C = +0.26^{+0.18}_{-0.17} \pm 0.05$

$\Delta\phi = -0.16^{+0.19}_{-0.21}$

Observed CPV at a level of $4.0\,\sigma$

sin(2β)

Slide from J Saborido



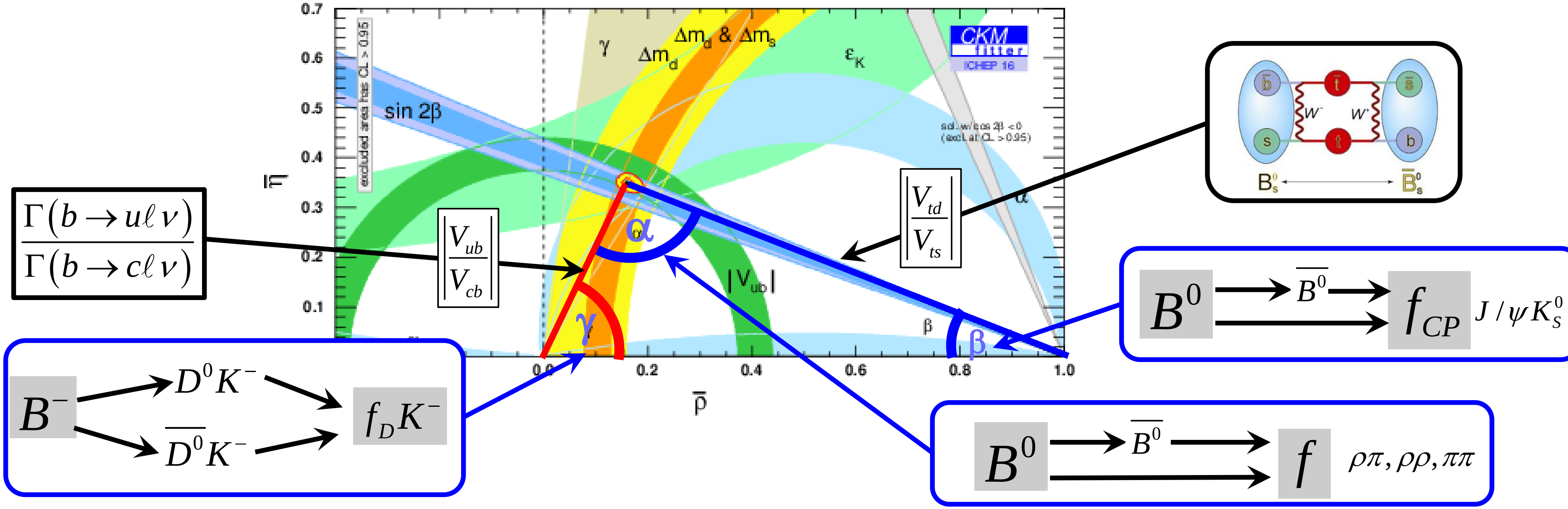
World average $\sin 2\beta = 0.69 \pm 0.02$

Slide from S Blusk

Probing CKM: Unitarity triangle

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

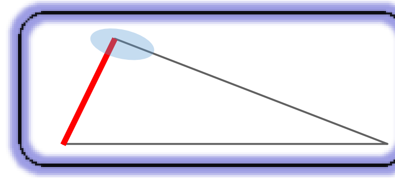
❖ Unitarity of **V** → **Triangles in complex plane** (5 others, incl. one for B_s decays)



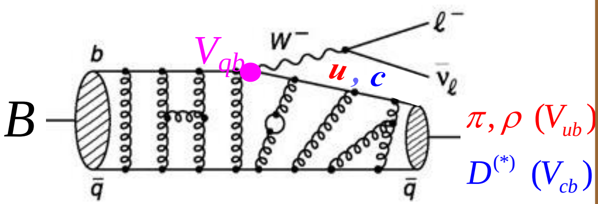
❑ Worldwide amalgamation of many results in B decays (and kaons, for ε_K)

- ❑ **$|V_{ub}/V_{cb}|$ & γ (tree level)** ---- **β, α, V_{td}, V_{ts} (loop level)** could contain NP in $B_{(s)}$ mixing.
- ❑ If SM CKM is correct, all measurements must agree on the apex of this triangle.

Clean SM measurements -- $|V_{ub}/V_{cb}|$



Exclusive decays

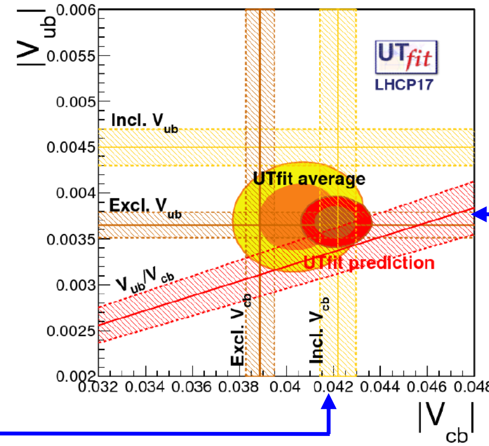


$$\frac{d\Gamma}{dq^2} = |V_{qb}|^2 \; |FF(q^2)|^2 \times \left(\begin{array}{c}\text{known} \\ \text{factors}\end{array}\right)$$

Need FF($q^2 = 0$) from LQCD

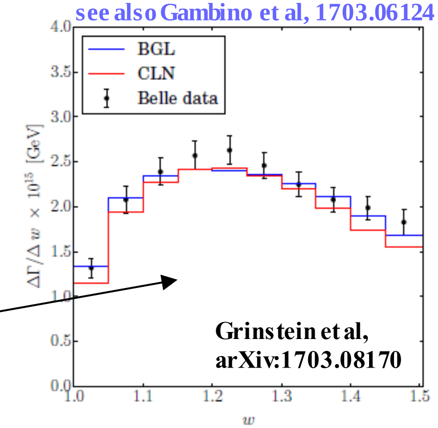
Inclusive decays: $b \to X\ell\nu$

- Inclusive properties e.g., p_ℓ
- **Theory** input to **extrapolate** to full phase space, esp for X_u.



- Longstanding tension in V_{ub} and V_{cb}.
- Global fit "prefers" $|V_{cb}|_{incl}$ and $|V_{ub}|_{excl}$.

see also Gambino et al, 1703.06124



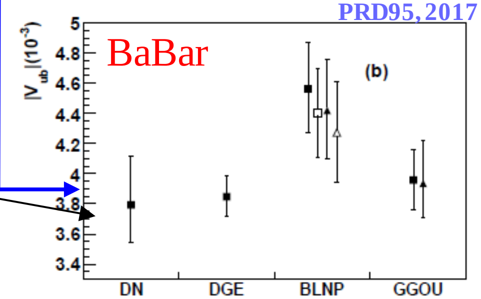
- Grinstein *et al*, suggest alternate FF fit (BGL) to recent Belle $B \to D^* \ell\nu$ data.

$$|V_{cb}|_{excl} = (37.4 \pm 1.3) \times 10^{-3} \quad [\text{ CLN }]$$

$$|V_{cb}|_{excl} = (41.9^{+2.0}_{-1.9}) \times 10^{-3} \quad [\text{ BGL }]$$

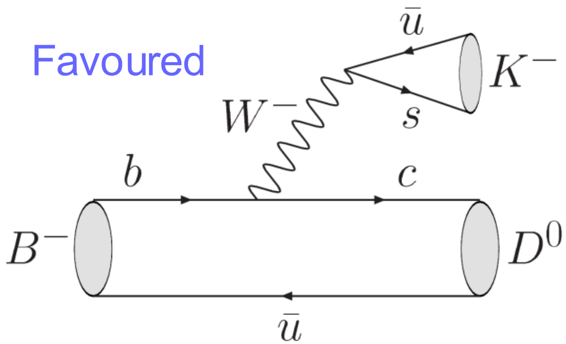
- New BaBar analysis of $|V_{ub}|_{incl}$ with different HQE extrapolation schemes (closer to $|V_{ub}|_{excl}$)
- Inclusive & exclusive m'ments converging ? **More data needed!**

PRD95, 2017

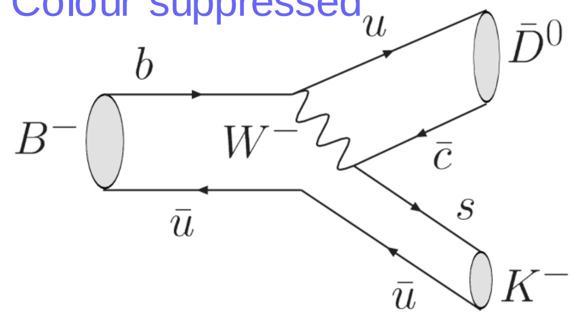


The CKM unitarity angle γ

Favoured

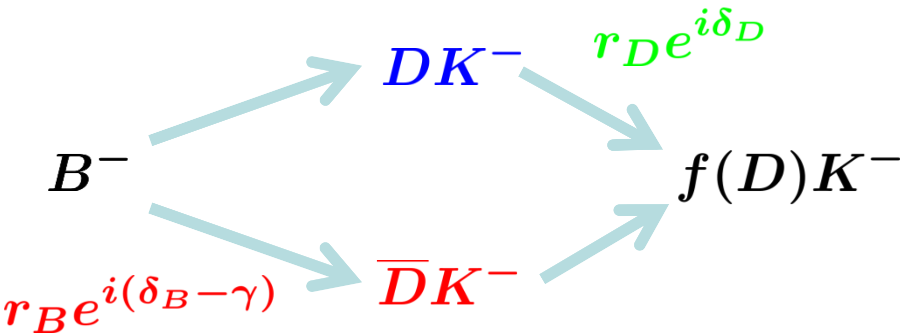


Colour suppressed



coherence factor

$$\Gamma(B^\pm \to [f]_D K^\pm) = r_D^2 + r_B^2 + 2\kappa r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$ (example of decay rate)



weak phase

$$\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \gamma)}$$

CP conserving phases

$$\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} = r_D e^{i\delta_D}$$

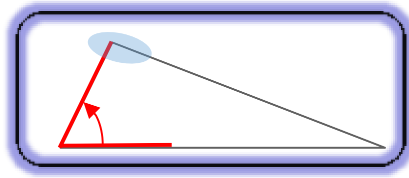
Three main methods depending on the D final state:

GLW, $D \to$ CP-eigenstate $(\pi\pi, KK)$

ADS, $D \to$ quasi-flavour-specific state $(K\pi, K\pi\pi\pi)$

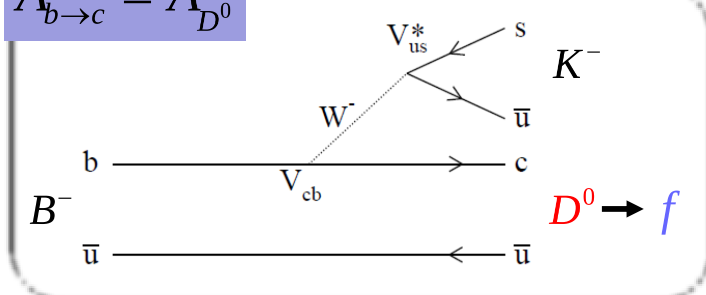
GGSZ, $D \to$ self-conjugated multibody final state $(K_S\pi\pi, K_SKK)$

CKM: Clean SM measurements -- γ



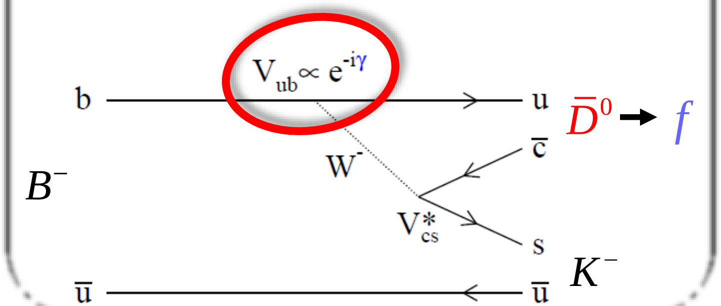
- Arises from **interference** between $b\rightarrow c$ and $b\rightarrow u$ transitions, when using final states, ***f***, accessible to both D^0 and $\overline{D}^0$.

$$A_{b\to c} = A_{D^0}$$



$f = K_S^0\pi^-\pi^+ (GGSZ)$
$K^+K^-, \pi^+\pi^- (GLW)$
$K^+\pi^- (ADS)$
+...other

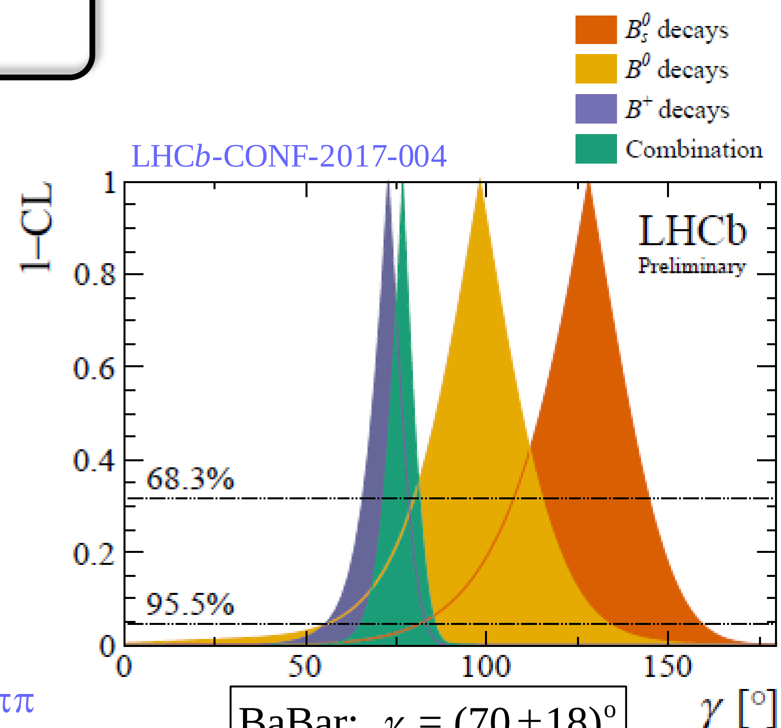
$$A_{b\to u} = r_B e^{i\delta_B} e^{-i\gamma} A_{\overline{D}^0}$$



Many "variants"

- $B\rightarrow D^*K$, DK^*, $DK\pi\pi$
- $B_s\rightarrow D_sK$, ..
- $\Lambda_b\rightarrow DpK^-$

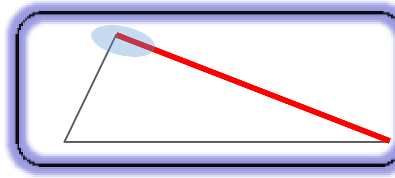
LHCb-CONF-2017-004



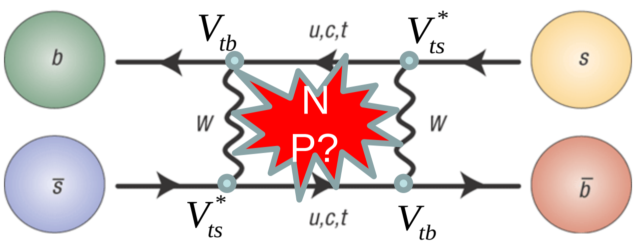
BaBar: $\gamma = (70\pm18)^o$
Belle: $\gamma = (73^{+13}_{-15})^o$
LHCb: $\gamma = (76.8^{+5.1}_{-5.7})^o$

Slide from S Blusk

CKM - $|V_{td} / V_{ts}|$: could contain NP contributions



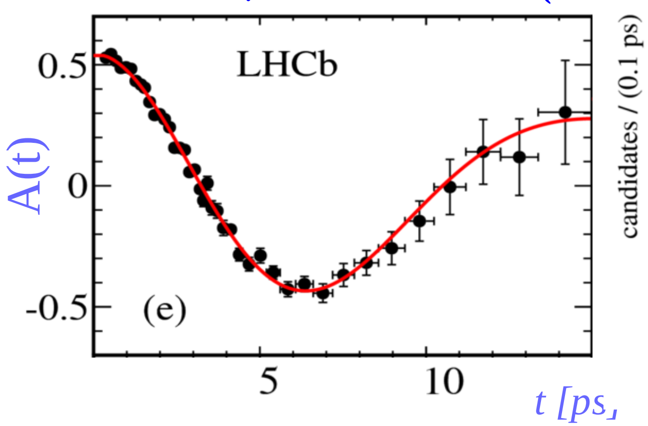
- Currently, best precision from $B_{(s)}$ mixing



$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B^0}}\left(\frac{f_{B_s}}{f_{B^0}}\right)^2 \frac{B_{B_s}}{B_{B^0}}\left|\frac{V_{ts}}{V_{td}}\right|^2$$

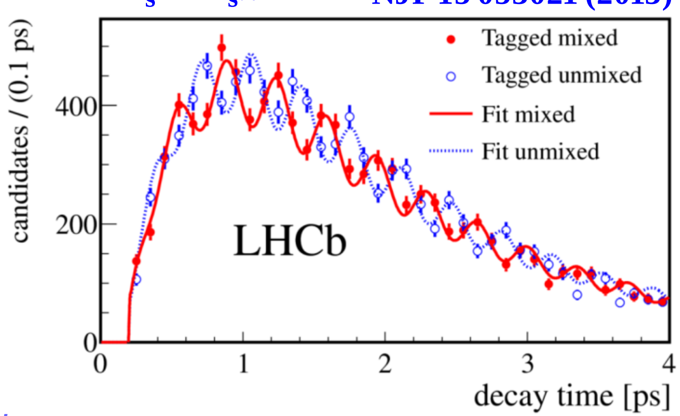
❑ **NP in box diagram could modify mixing rate (Δm)**

$B^0 \to D^* \mu\nu$ **EPJC 76 (2016)**



$\Delta m_d = 0.5051 \pm 0.0021 \pm 0.0010\ \mathrm{ps}^{-1}$

$B_s \to D_s\pi$ **NJP 15 053021 (2013)**



$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \mathrm{ps}^{-1}$

HFlav, arXiv:1612.07233 (**if** no NP)

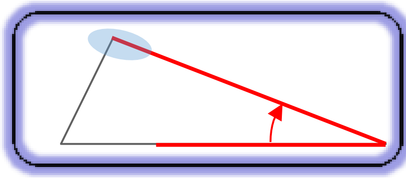
$$\left|\frac{V_{td}}{V_{ts}}\right| = (20.53 \pm 0.04 \pm 0.32) \times 10^{-2}$$

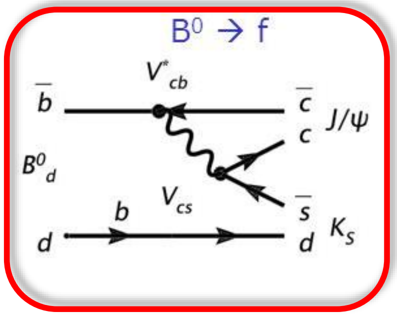
↑ Exp ↑ Theory

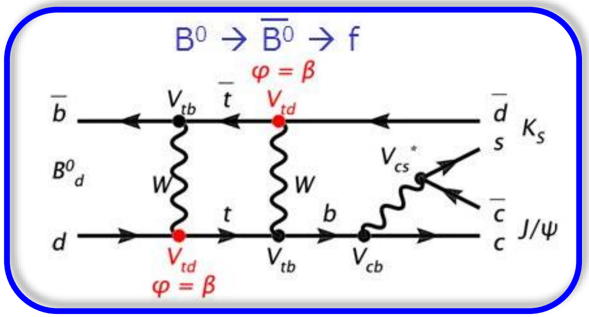
Slide from S Blusk

sin(2β): could contain NP contributions

- **Phase associated with B^0 mixing** (V_{td})
- Interference between **direct decay** & **mixing+decay**.



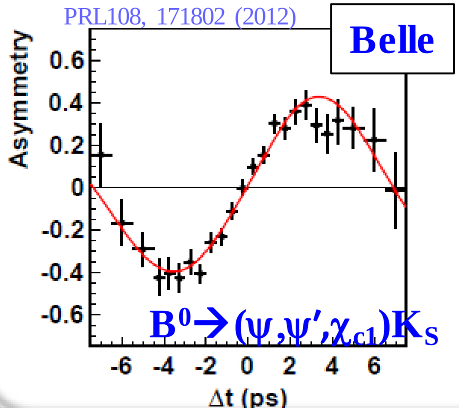


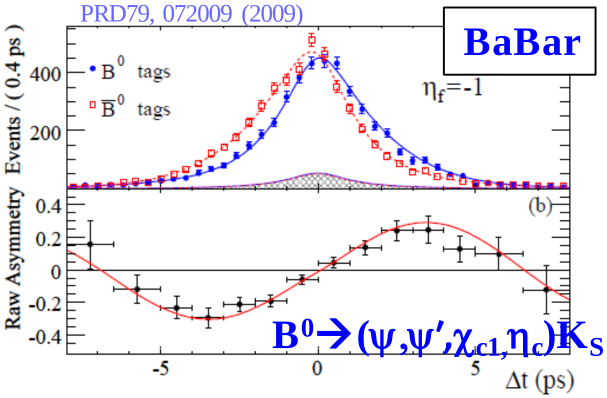


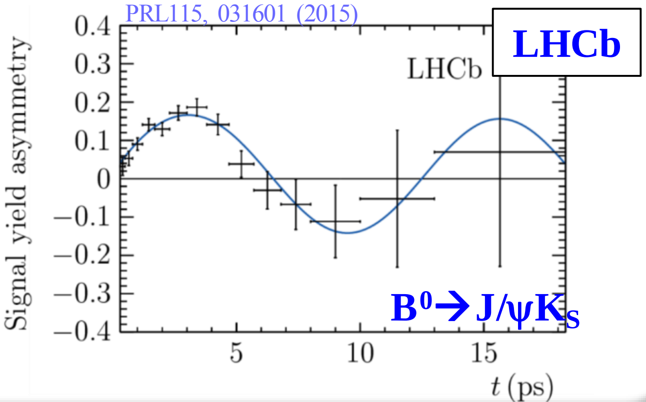
$$A(t)=\frac{N_{\bar{B}^0\to f}-N_{B^0\to f}}{N_{\bar{B}^0\to f}+N_{B^0\to f}}=\sin(2\beta)\sin(\Delta m\cdot t)$$

$$\langle\sin 2\beta\rangle_{WA}=0.691\pm0.017$$

HFlav, arXiv:1612.07233 Stat. error > syst. err



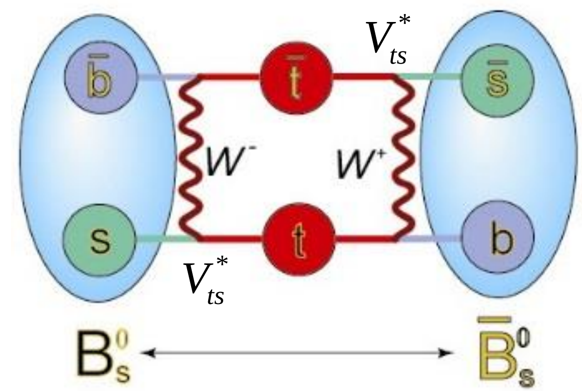




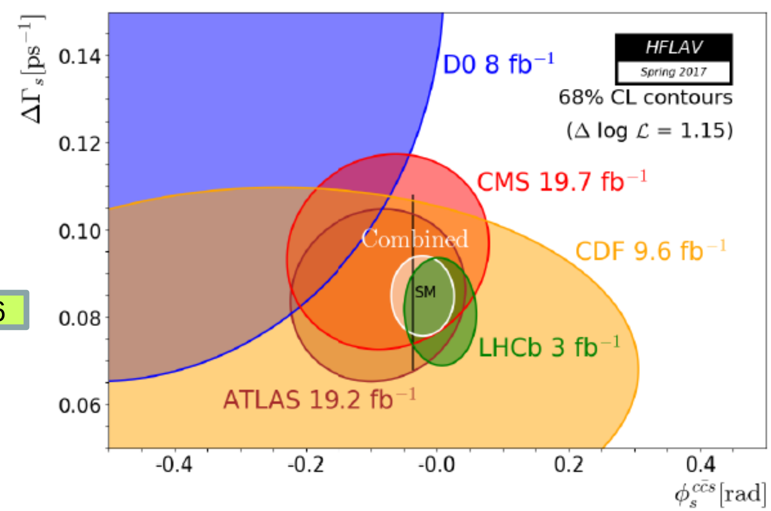
$2\beta_s$

Slide from S Blusk

- **Phase of B_s mixing** [V_{ts}] (analog of sin(2β) for B^0)
- Small & precisely known in SM (-37.6 ± 0.08 mrad)
  - NP in "box" diagram could introduce new phases.
- Currently consistent w/ SM.
  - LHCb Upgrade(s) needed to push uncertainty below 0.01 rad.



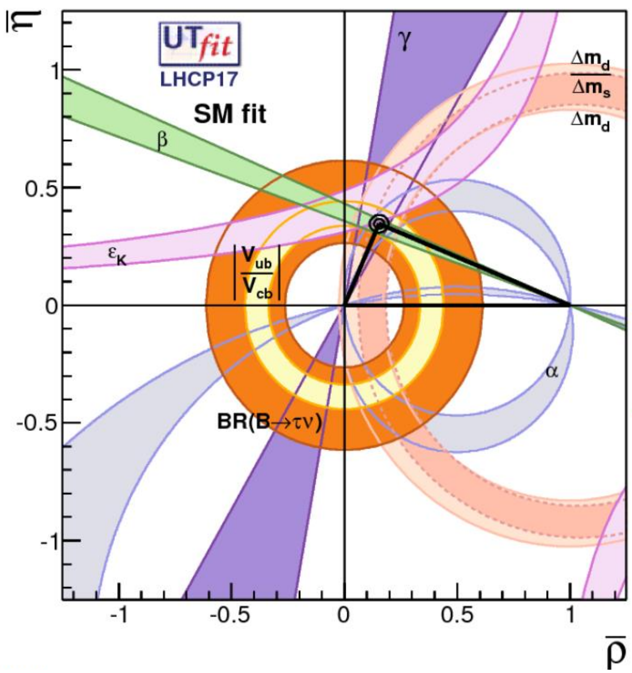
Exp.	Mode	Lumi	ϕ_s [rad]	
LHCb	$J/\psi KK$	$3\,fb^{-1}$	$-0.058 \pm 0.049 \pm 0.006$	[PRL 114, 041801 (2015)]
	$J/\psi KK$ HM	$3\,fb^{-1}$	$+0.119 \pm 0.107 \pm 0.034$	[arXiv:1704.08217] 2017
	$J/\psi \pi\pi$	$3\,fb^{-1}$	$-0.070 \pm 0.068 \pm 0.008$	[PLB 736 (2014) 186]
	$\psi(2S)\phi$	$3\,fb^{-1}$	$+0.23^{+0.29}_{-0.28} \pm 0.02$	[PLB 762 (2016) 253]
	$D_s^+ D_s^-$	$3\,fb^{-1}$	$+0.02 \pm 0.17 \pm 0.02$	[PRL 113, 211801 (2014)]
ATLAS	$J/\psi \phi$	$19.2\,fb^{-1}$	$-0.098 \pm 0.084 \pm 0.040$	[JHEP 1608 (2016) 147] 2016
CMS	$J/\psi \phi$	$19.7\,fb^{-1}$	$-0.075 \pm 0.097 \pm 0.031$	[PLB 757 (2016) 97] 2016
Average	-	-	-0.021 ± 0.031	[HFLAV]
Theory	-	-	-0.0376 ± 0.0008	[CKMFitter]



Constraints on NP in B decays

Slide from S Blusk

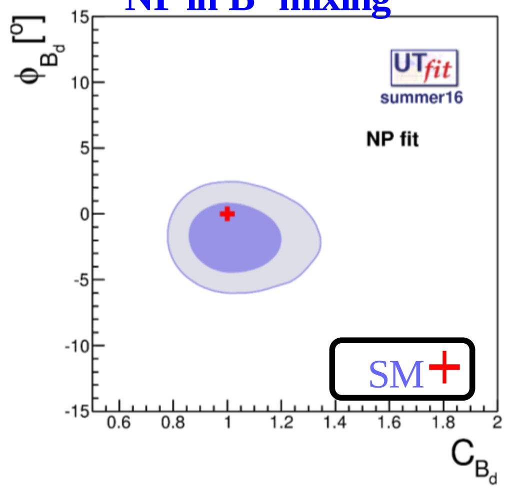
❑ Does $(\rho,\eta)_{tree} = (\rho,\eta)_{loop}$?



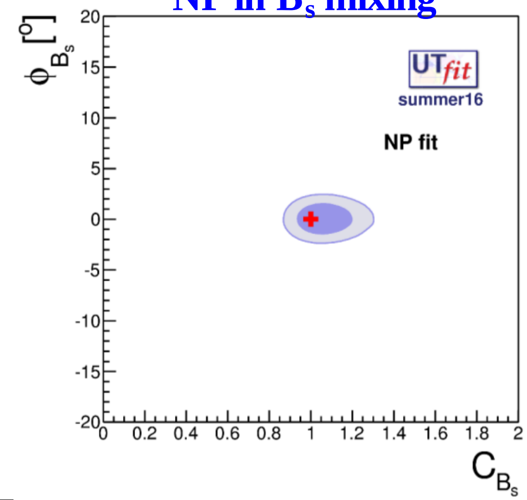
Model Independent constraints on NP in $B_{(s)}$ mixing

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

NP in B^0 mixing



NP in B_s mixing

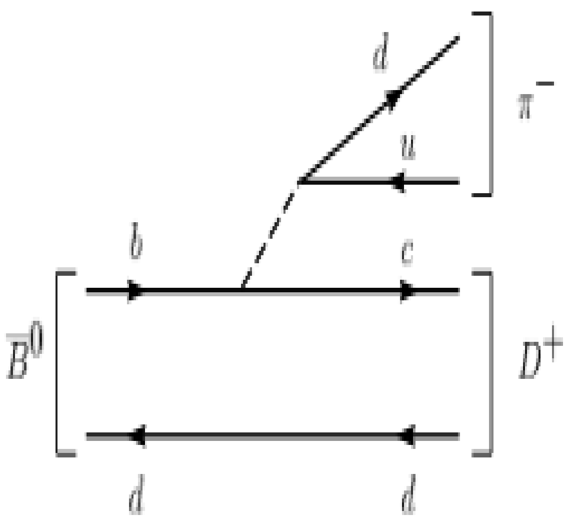


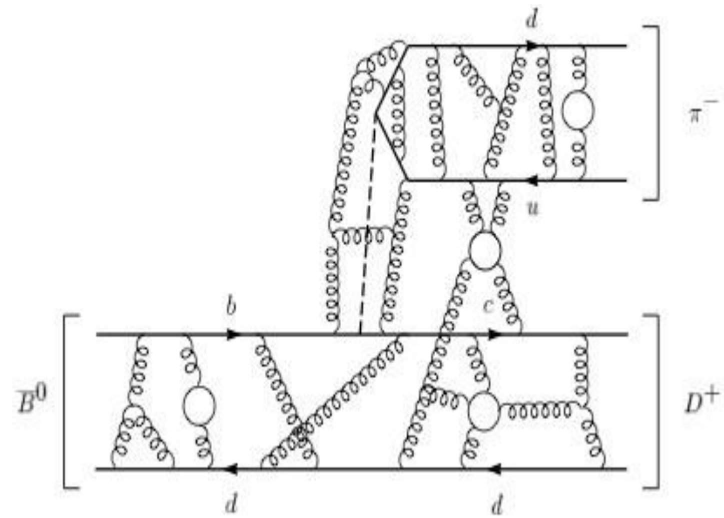
- ❑ No smoking gun yet … but **O(20%) NP contributions not excluded.**
- ❑ **Greater precision needed** -- **LHCb upgrade(s) and Belle II necessary.**
- ❑ Reduced theory errors on many inputs important & anticipated (LQCD)

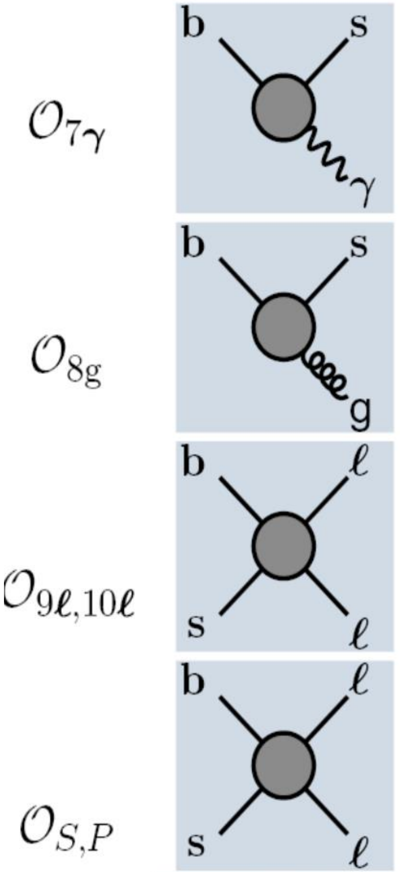
QCD in the Decays

- Things are not as easy as one wishes.
- While studying the weak interaction we can not switch off the strong interaction.
- Describe b→Dqq, b → Dg, b → Dγ transitions by an effective Hamiltonian.
- Long distance effects are absorbed in the definition of the operators O_i, while the short distance interactions are condensed in the Wilson coefficients C_i.

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p^{(D)} \left(C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3}^{10} C_i Q_i + C_{7\gamma} Q_{7\gamma} + C_{8g} Q_{8g} \right) + \text{h.c.},$$







b→s penguins

Slide from Frederic Teubert

If we focus into b → s transitions the relevant operators are

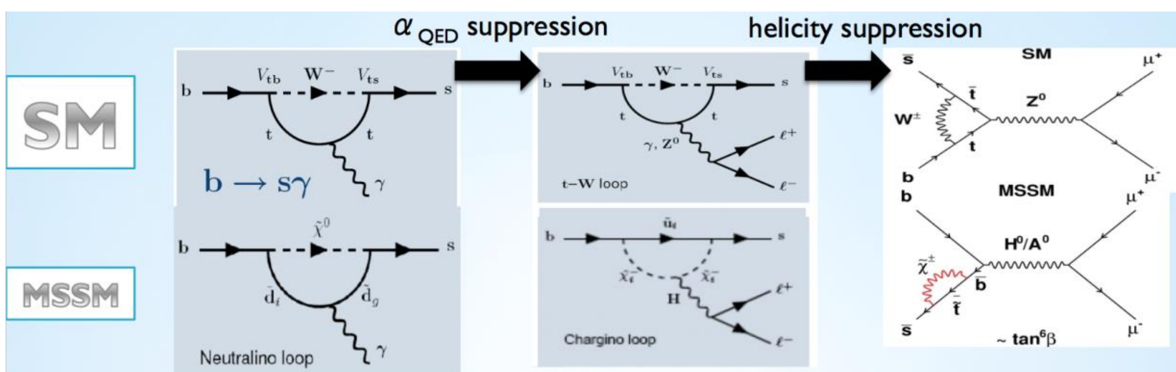
$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \quad O_8 = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\, a},$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \quad O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell),$$

$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell), \quad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell),$$

These appear in the so know rare decays with small SM contributions that could compete with comparable BSM.

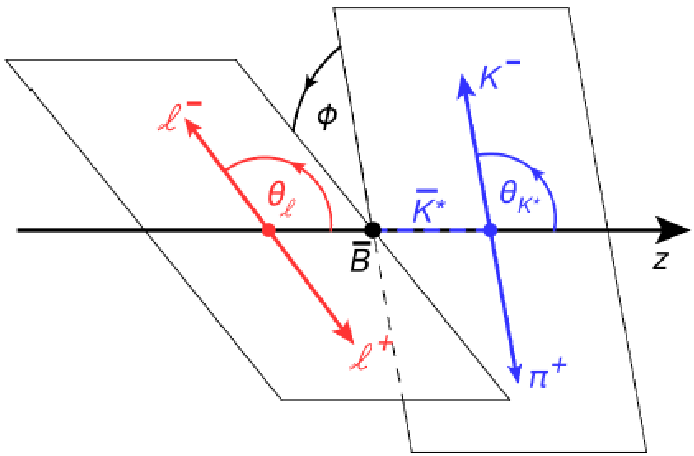
- Impact BRs, angular distributions
- C_{NP} could be complex → new CPV phases
- Could affect each generation differently, e.g. Lepton Universality



Angular analysis of $B^0 \to K^* \ell^+ \ell^-$

Slide from S Blusk

- Decay described by 3 angles $\Omega=(\theta_\ell, \theta_{K^*}, \phi)$ and q^2.



$$\frac{1}{\mathrm{d}(\Gamma+\bar\Gamma)/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar\Gamma)}{\mathrm{d}q^2\,\mathrm{d}\vec\Omega} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

19

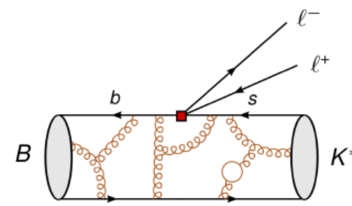
Fraction of longitudinal polarisation of the K*

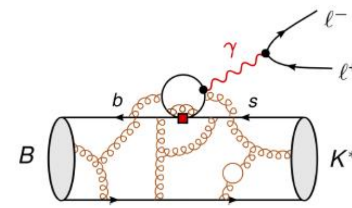
Forward-backward asymmetry of the dilepton system

- S_i, F_L, A_{FB} sensitive to $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$
- Non-perturbative uncertainties (FF, charm loops)
- Additional observables can be built, which are less sensitive to FF uncertainties

B→K* form factors (LQCD)

Non-factorizable corrections (charm loops, broad *cc* reson)



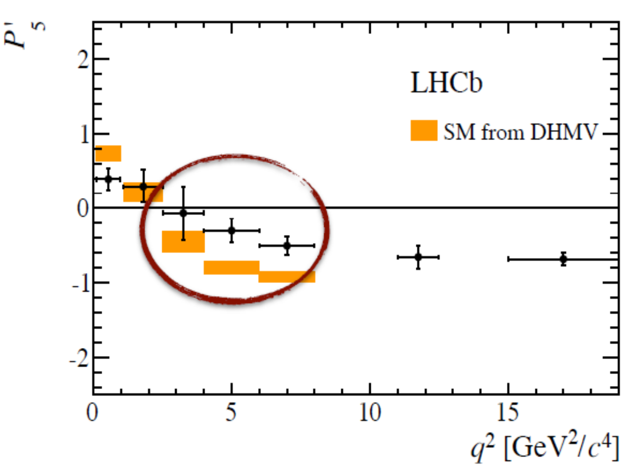


eg: $$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$ [Descotes-Genon, JHEP 05 (2013) 137]

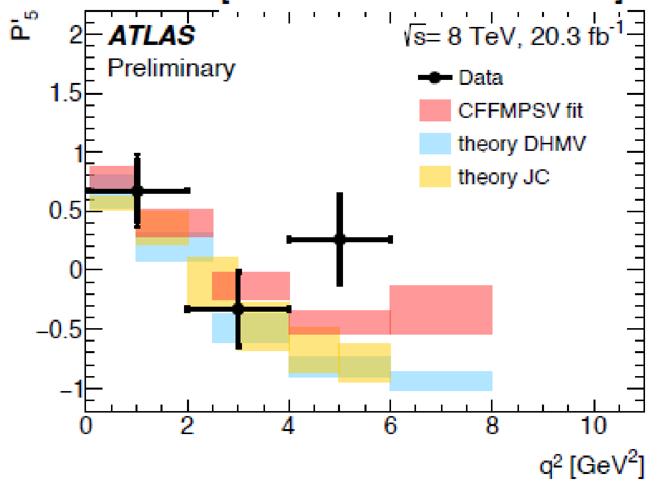
Angular analysis of $B^0 \rightarrow K^*\ell^+\ell^-$

Slide from S Blusk

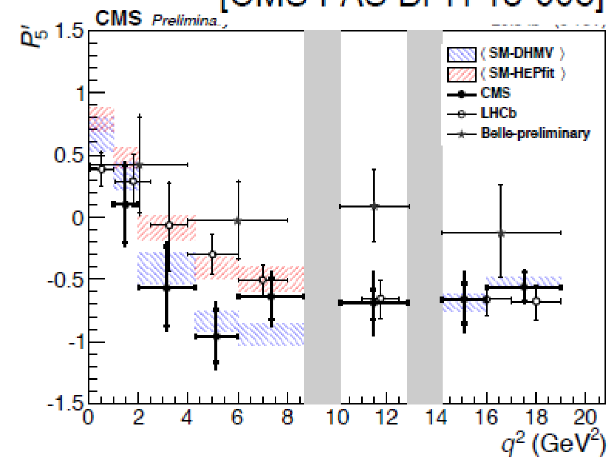
[JHEP 02 (2016) 104]



[ATLAS-CONF-2017-023]

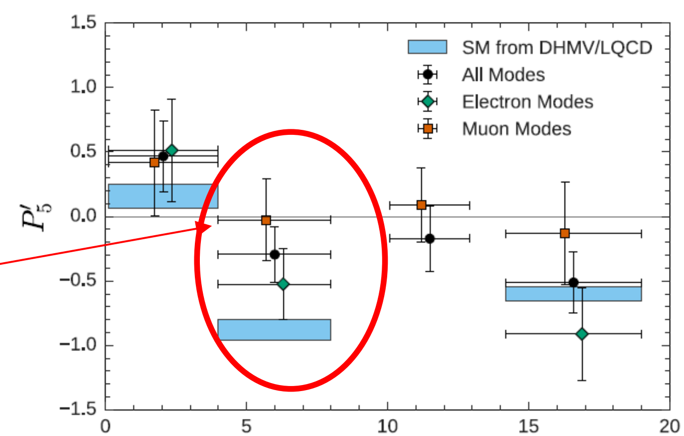


[CMS PAS BPH-15-008]



- LHC*b* ATLAS, Belle show tension in P_5' with SM predictions.

Belle, PRL, 118, 111801 (2017)

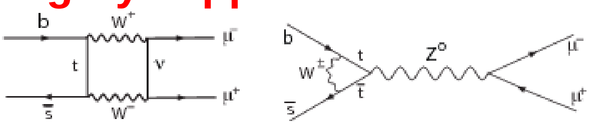


- New analysis by Belle, separately for *e* and μ!
  2.6σ deviation for K*μμ
  1.1σ deviation for K**ee*

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

Slide from S Blusk

- **Highly suppressed in the SM.**

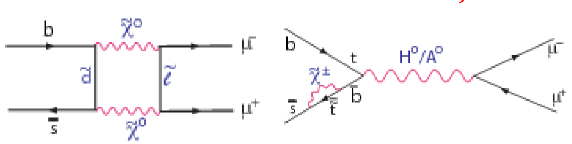


$$B_{SM}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23)\times 10^{-9}$$

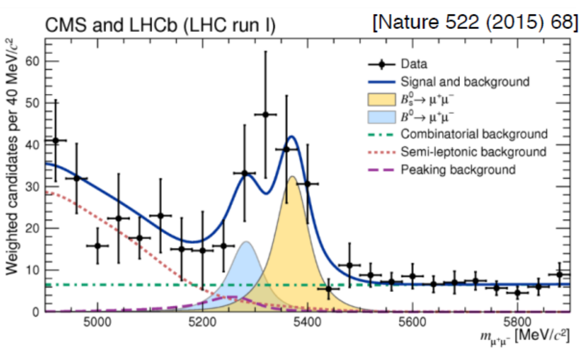
$$B_{SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09)\times 10^{-10}$$

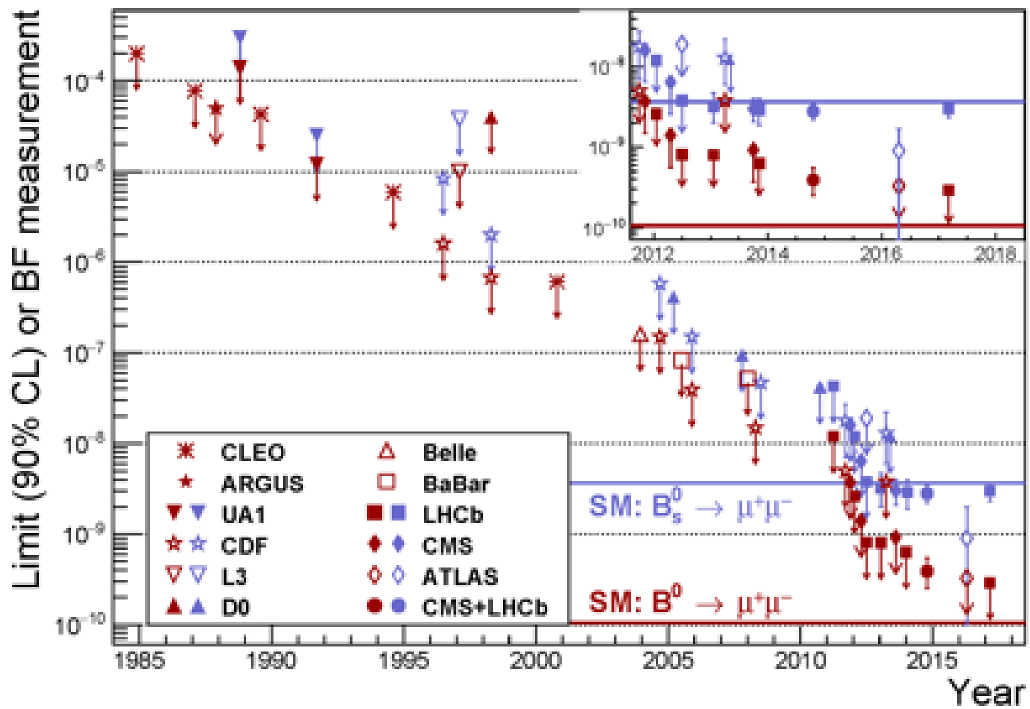
[Bobeth et. al, PRL112, 101801 (2014)]:

- **Sensitive to NP in C_{10} & $C_{S,P}$.**



- **Ratio of BFs stringent test for NP.**



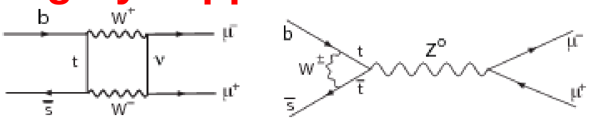


Slide from S Blusk

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

Recent updates

- **Highly suppressed in the SM.**

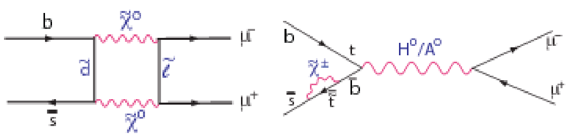


$$B_{SM}(B_s^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

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

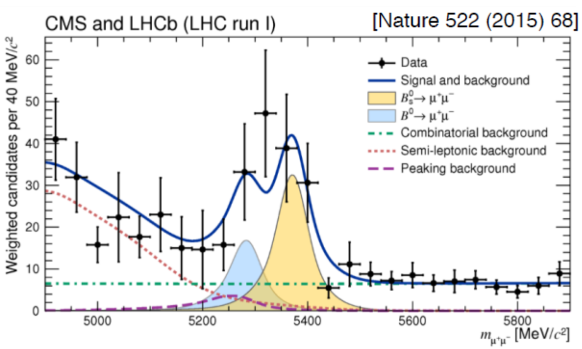
[Bobeth et. al, PRL112, 101801 (2014)]:

- **Sensitive to NP in C_{10} & $C_{S,P}$.**

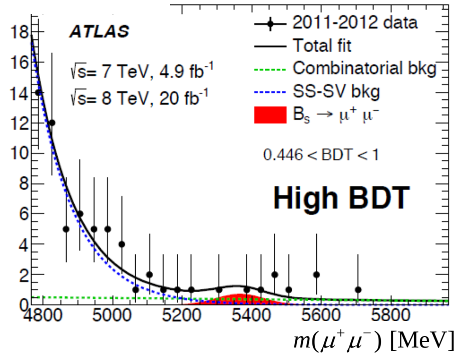


- **Ratio of BFs stringent test for NP.**

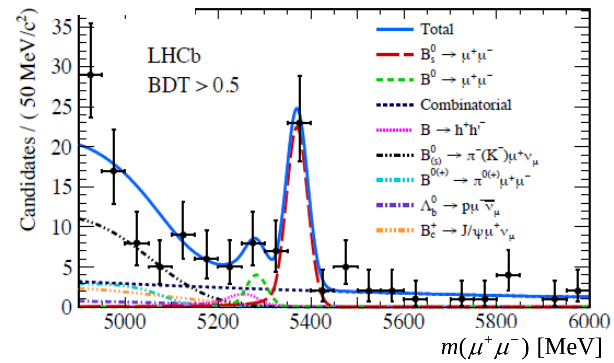
[Nature 522 (2015) 68]



ATLAS [EPJ C76 (2016) 9, 513]



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



	ATLAS	LHCb
$B(B_s^0 \rightarrow \mu^+\mu^-)$	$(0.9^{+1.1}_{-0.8}) \times 10^{-9}$	$(3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
$B(B^0 \rightarrow \mu^+\mu^-)$	$< 4.2 \times 10^{-10}$ @95% CL	$< 3.4 \times 10^{-10}$ @95% CL

- ❑ Signal in B_s clearly established, no anomalously large BF.
- ❑ Observing & measuring $B^0 \rightarrow \mu^+\mu^-$ high priority & steadily improve precision on $B_s \rightarrow \mu^+\mu^-$.
- ❑ Expect update from CMS soon..

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

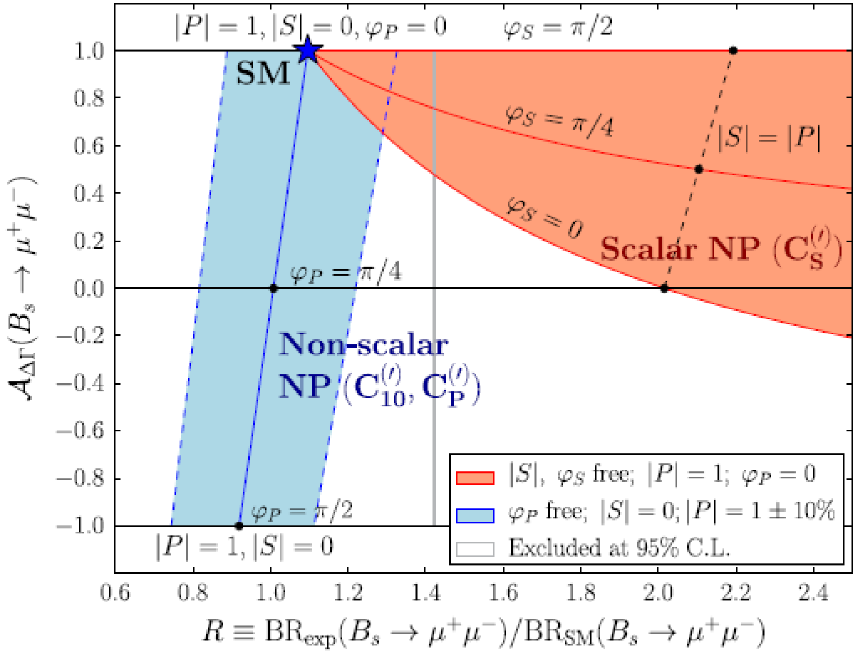
Slide from S Blusk

- Complementary probe of NP to BF

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

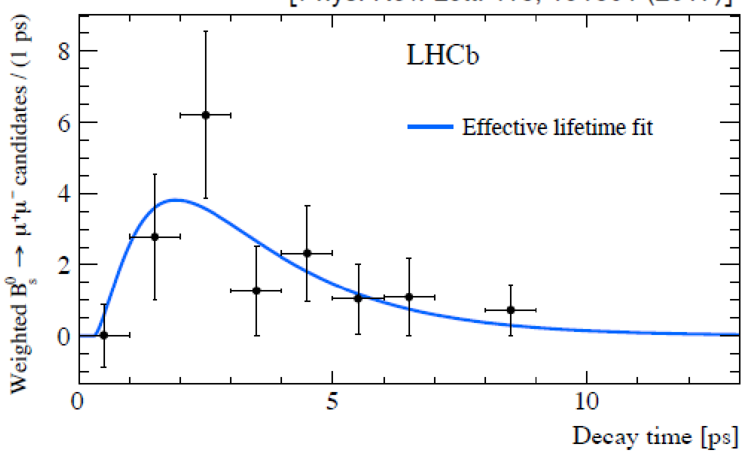
$$A_{\Delta\Gamma} = \frac{\Gamma(B_s^H \to \mu^+\mu^-) - \Gamma(B_s^L \to \mu^+\mu^-)}{\Gamma(B_s^H \to \mu^+\mu^-) + \Gamma(B_s^L \to \mu^+\mu^-)} = +1 \quad \text{(SM)}$$

➔ SM: $\tau_{\mu\mu} = \tau_H = 1.61 \pm 0.012$ ps



[De Bruyn et al., PRL 109, 041801 (2012)]

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



$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

- **A way to go here for a precision test**
- **Will require LHCb upgrade statistics**

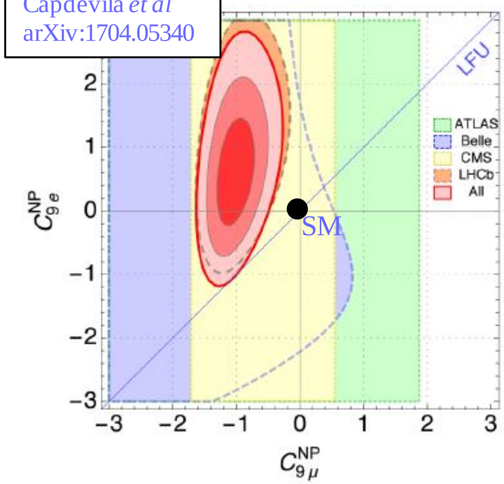
What is this all telling us?

Slide from S Blusk

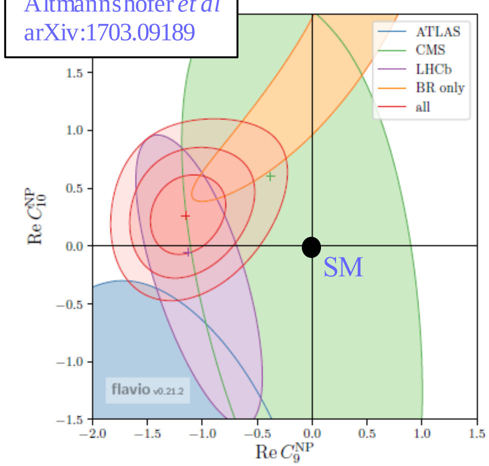
- Several global analyses performed to rare b decay data, assuming NP in one or more of the C_i's.
  - Tension in SM fits if no NP allowed.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left[\left[C_i^{SM} + C_i^{\ell} \right] O_i(\mu) + \left[C_i'^{SM} + C_i'^{\ell} \right] O_i'(\mu) \right]$$

Capdevila *et al* arXiv:1704.05340



Altmannshofer *et al* arXiv:1703.09189



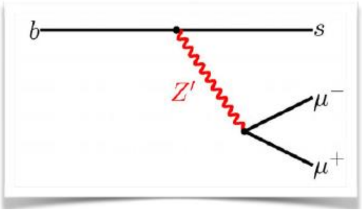
- $C_9^{(')}$ & $C_{10}^{(')}$ are Wilson coeff for EW penguins

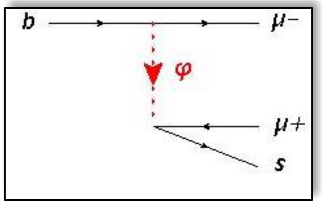
$$O_9^{(\prime)} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)\left(\bar{\ell}\gamma_\mu \ell\right), \qquad O_{10}^{(\prime)} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)\left(\bar{\ell}\gamma_\mu \gamma_5 \ell\right)$$

Vector **Axial vector**

Fits favor NP contribution to C_9, possibly C_{10}

- **Possibly NP in the vector couplings?**





Z′, Leptoquarks, composite models, ..

- **Larger samples should help illuminate the situation.**

Many more details at *Instant Workshop on B meson anomalies*, https://indico.cern.ch/event/633880/

Anomalies in the SM

Slide from S Blusk

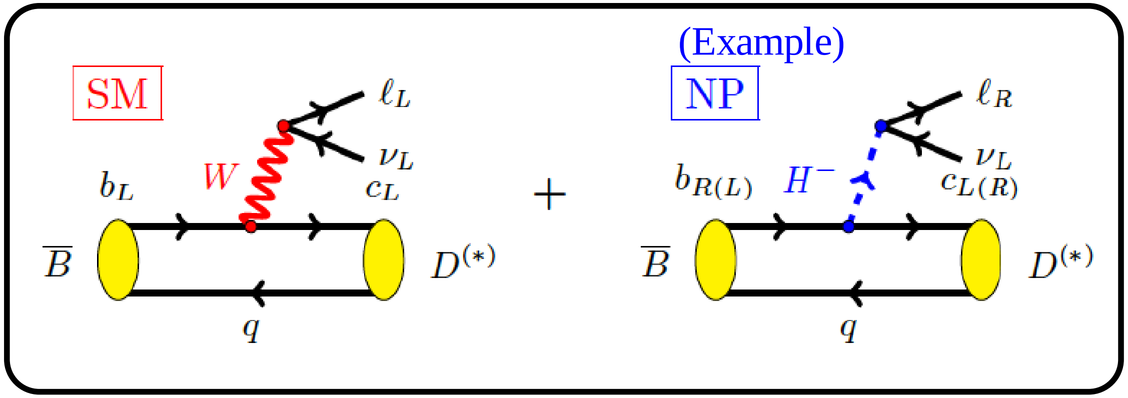
- **In the SM, coupling of $W^{\pm}$, Z^0 to e^-, μ^-, τ^- same → Lepton universality.**
  - Confirmed with high precision in $Z^0 \to \ell^+\ell^-$
  - Some "tension" here …

$$\left.\frac{B(W\to\tau\nu)}{0.5\times\left[B(W\to e\nu)+B(W\to\mu\nu)\right]}\right|_{LEP} = 1.077 \pm 0.026$$

PDG, see also
J. Park, hep-ph/0607280

  - A hint? Or a fluctuation?
  - $(g-2)_\mu \sim 3\sigma$ from SM ?

- **(Semi)leptonic decays**
  - **SM:** Universal coupling of $W^{\pm}$ to leptons
  - **NP:** Could violate lepton universality
    - Charged Higgs
    - New, heavy W (W′)
    - Leptoquarks
    - …



$B \to D^{(*)}\tau^-\nu$ / $B \to D^{(*)}\mu^-\nu$

Slide from S Blusk

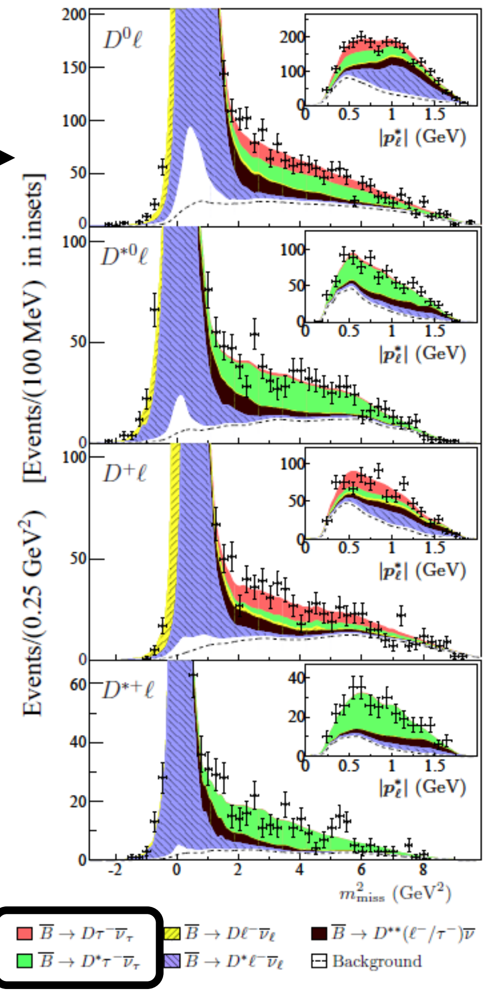
- **In 2012, BaBar reported ratios:**

$$R(D) = \frac{B(B \to D\tau^-\bar{\nu}_\tau)}{B(B \to D\mu^-\bar{\nu}_\mu)} = 0.440 \pm 0.058 \pm 0.042$$

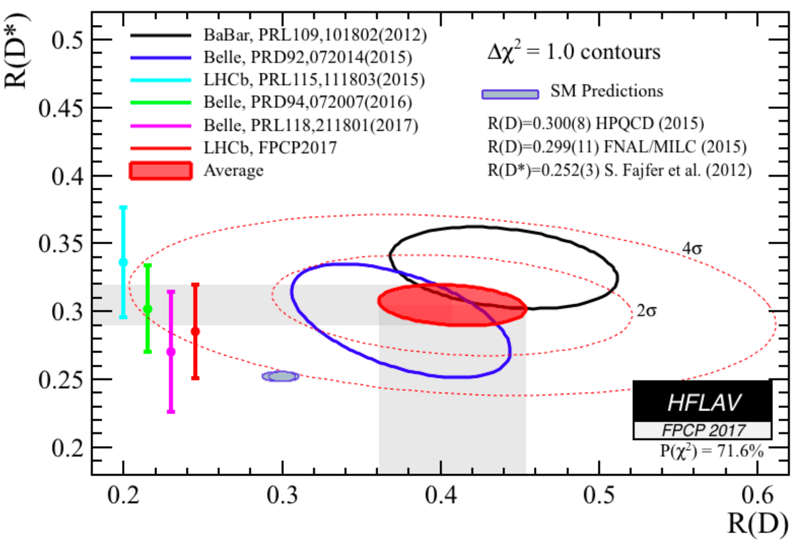
$$R(D^*) = \frac{B(B \to D^*\tau^-\bar{\nu}_\tau)}{B(B \to D^*\mu^-\bar{\nu}_\mu)} = 0.332 \pm 0.024 \pm 0.018$$

BaBar, PRL 109,101802 (2012) →

- Deviates from SM by 3.4σ!



- **Since that time, several new measurements from Belle & LHCb**



- Including additional measurements, discrepancy of **4.1σ**.
- Several BSM scenarios possible (H⁺, W′, LQs), but must evade other expt constraints → **challenging**.
- **Better precision & additional modes to come! e.g. $R(\Lambda_c)$**

R_K

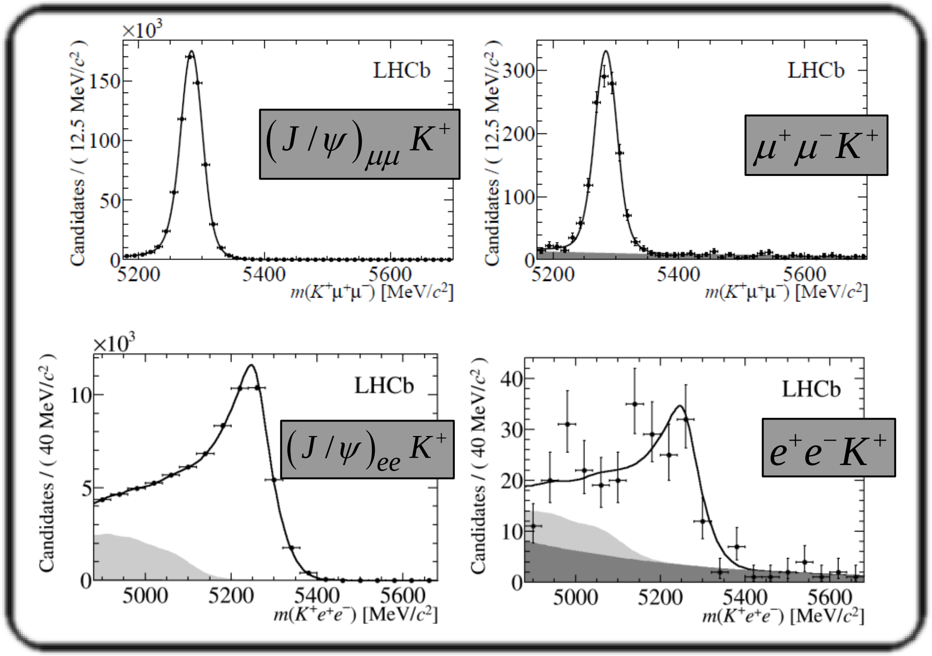
Slide from S Blusk

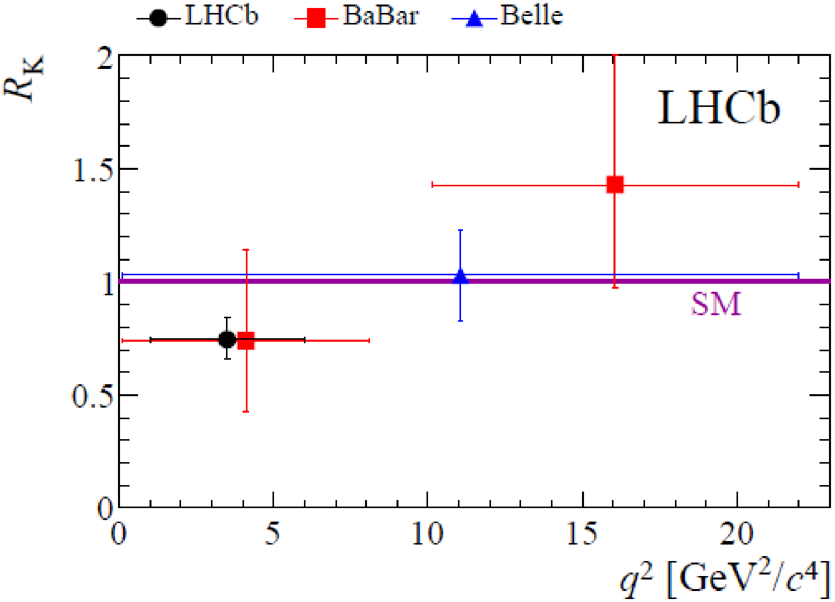
$$R_K \equiv \frac{B(B^+ \to K^+\mu^+\mu^-)}{B(B^+ \to K^+e^+e^-)}$$

- Theoretically clean
- Stringent test of LFU

LHCb: PRL 113, 151601 (2014)
BaBar: PRD 86, 032012 (2012)
Belle: PRL 103, 171801 (2009)

LHCb: PRL 113, 151601 (2014)





$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$ **LHCb**

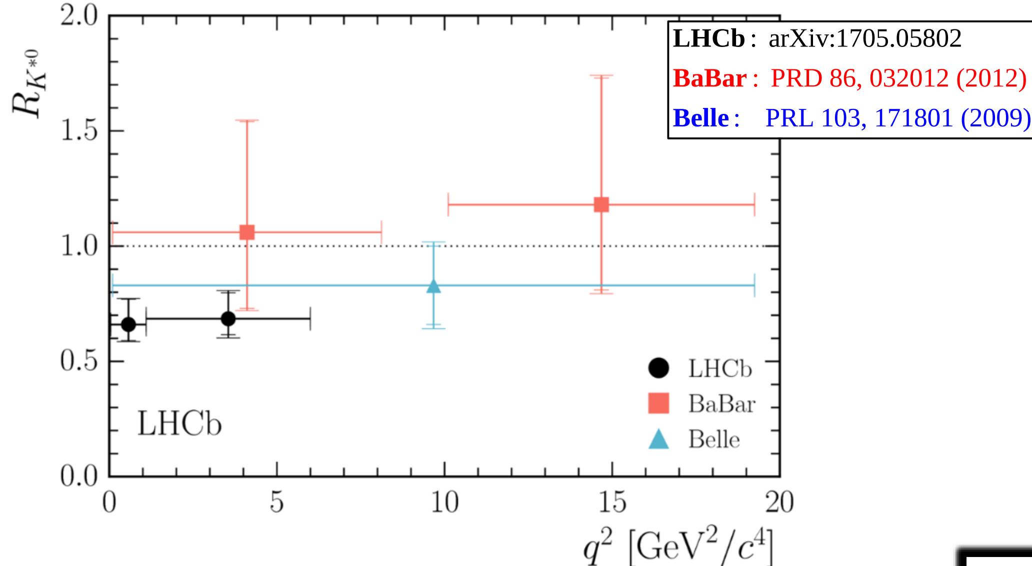
2.6 standard deviations from the SM prediction

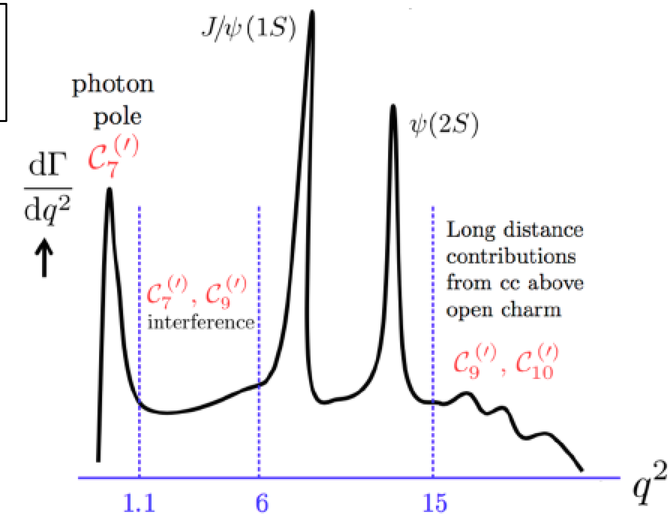
R_{K^*}

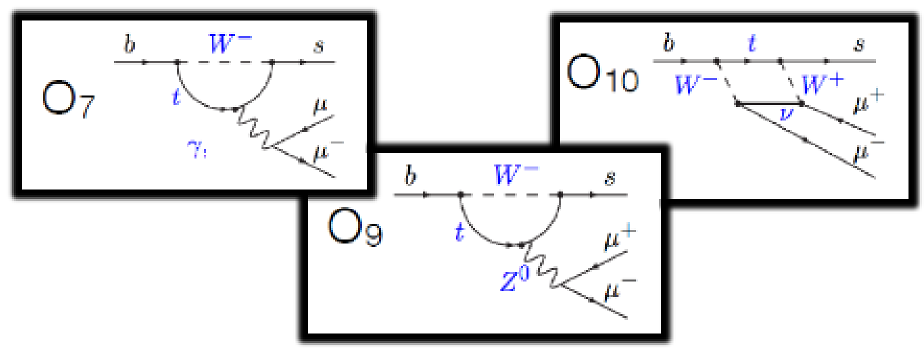
Slide from S Blusk

$$R_{K^*} \equiv \frac{B(B^0 \to K^{*0}\mu^+\mu^-)}{B(B^0 \to K^{*0}e^+e^-)}$$

- **Similar to R_K m'ment**
- **Double-ratio, wrt $B^0 \to J/\psi K^{*0}$**
- **Measured in two q^2 intervals**







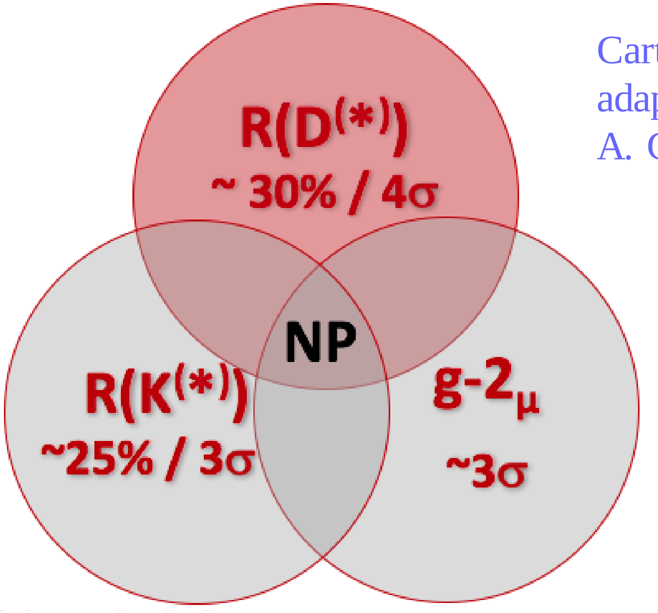
	low- q^2	central- q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$

- Compatibility with the SM prediction(s):
  - Low-q^2: 2.1 - 2.3 standard deviations
  - Central-q^2: 2.4 - 2.5 standard deviations

Summary of anomalies

Slide from S Blusk

- Several *tensions*
  - Other "tensions": $B(W\to\tau\nu)/B(W\to\mu\nu)$, ε'/ε (kaons)
- But, many constraints as well
  - No direct signatures from CMS or ATLAS
  - **B**($B_s \to \mu^+\mu^-$)
  - $B_{(s)}$ mixing.
  - **B**($b\to s\gamma$)
  - **B_c lifetime** (see Alonso at al, arXiv:1611.06676)
  - **B**($\tau\to(\mu,e)\nu\nu$), rare/forbidden τ decays, ..
  - + many others



Cartoon adapted from A. Crivellin

- A number of possibilities for NP to explain one or more of these deviations
  - Scalar or vector leptoquarks, H^+, Z', W'
  - Analysis of Wilson coefficients can help identify the form of the interaction.
  - Or, is it SM with theory and/or experimental errors underestimated ?
  - Extensive presentations at the Instant Workshop on B anomalies (May 17, 2017)
- **Improved precision (expt + theory) should provide some illumination here..**

FIN