# Flavor Physics Measurements - I

Presented at HCPSS24

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# Outline – Lecture I

- B physics background for experimenters
  - Nature's fight against flavor changing neutral currents
  - Yukawa coupling, the Higgs etc
  - The CKM Matrix
  - B decays, mixing, and CP violation
- Producing states with heavy quarks – the experimental landscape
- Experimental techniques
  - Physics quantities, physics objects, and
  - requirements on experiments at different machines

# Outline – Lecture II

- Four Case studies of physics investigations
  - $B^o_{(s,d)} \rightarrow \mu^+\mu^-$ , branching fraction and lifetime for $B_s$ , search for $B_d$
  - $b \rightarrow s\ \mu^+\mu^-$ decays. The characteristics that make these decays promising ones for observing New Physics (NP) and current status-
  - CPV in the $B_s$ system – recent results
  - Violation of Lepton flavor universality in B decays
- A few comments on areas not covered (if time)

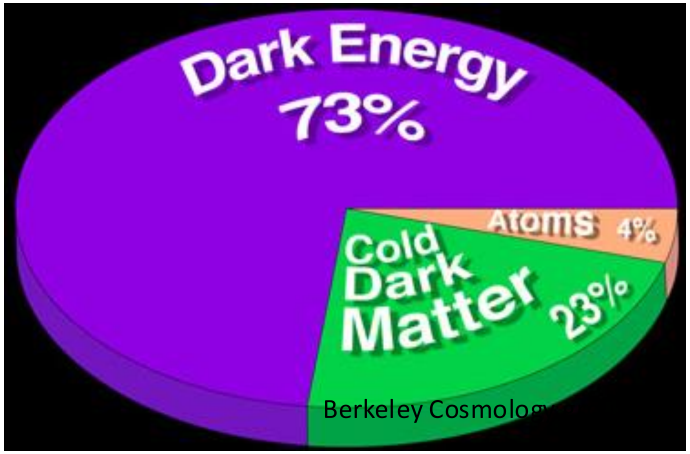
# The Standard Model Report Card

**The good news**

- **Explains the interactions of elementary particles via the EWK interaction with incredible accuracy**

**The bad news**

- **Does not explain the stability of the Higgs to higher order quantum effects (Higgs is too light);**
- **Does not explain the Baryon Asymmetry of the universe (predicts too little matter);**
- **Does not explain why there are three generations of quarks and leptons or their mass values (the "Flavor Problem");**
- **Offers no explanation for neutrino masses; and**
- **Provides no Dark Matter candidate and therefore does not explain 85% of the matter in the universe.**
- **Does not explain dark energy or bridge the gap between gravity and quantum field theory**




Explaining particle interactions via EWK and strong forces: **GRADE = A+++**
Explaining the matter and energy of the universe as it today: **GRADE = INCOMPLETE**

**Need for additional physics "Beyond the Standard Model (BSM)"**

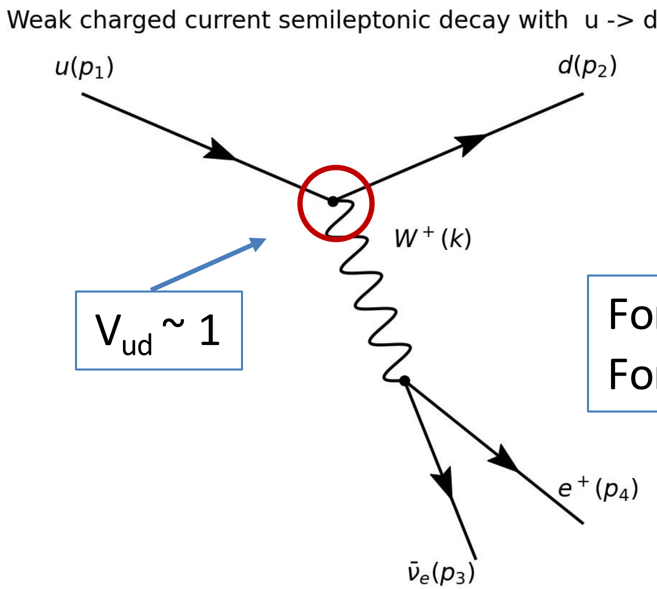
# Flavor – I: Strangeness and the Cabibbo Model, Suppression of Flavor-changing Neutral Currents

- The weak interaction is understood to be a four-fermion interaction with a charged particle, the W boson, transmitting the weak force
- Flavor was "born" when "Strange" new particles were seen in cosmic rays with longer lifetimes (~$10^{---10}$s), than particles decaying via strong interaction (~$10^{-23}$s)
- It was shown by production at accelerators that these "strange" particles are
  - created in pairs by the strong force ➔ Strangeness is conserved in strong interactions
  - but may decay into non-strange particles by the weak interaction ➔ strangeness not conserved in weak interactions
- This was quickly translated to the quark level and explained by the Cabibbo model of quark mixing:
- The d- and s- quarks mix, so the s-quark can become a d-quark part of the time, from which it can decay
  - Can also think of this as a small "flavor-changing" coupling of the W

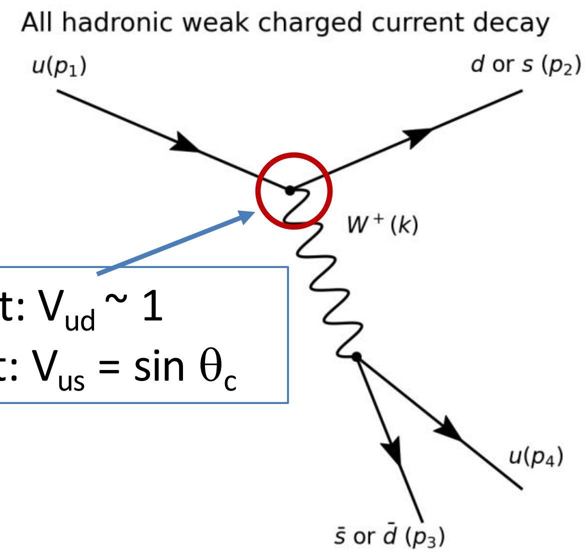
$$\overset{Leptons}{\begin{Bmatrix} \mu \\ \nu \end{Bmatrix} \begin{Bmatrix} e \\ \nu \end{Bmatrix}}, \quad \overset{Quarks}{\begin{Bmatrix} u \\ d_C \end{Bmatrix} = \begin{Bmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{Bmatrix}}$$

**$\sin\theta_c = 0.225$ ($\theta = 13.02^o$), from exp.**

# Charged Current, Four Fermion Interaction




$V_{ud} \sim 1$

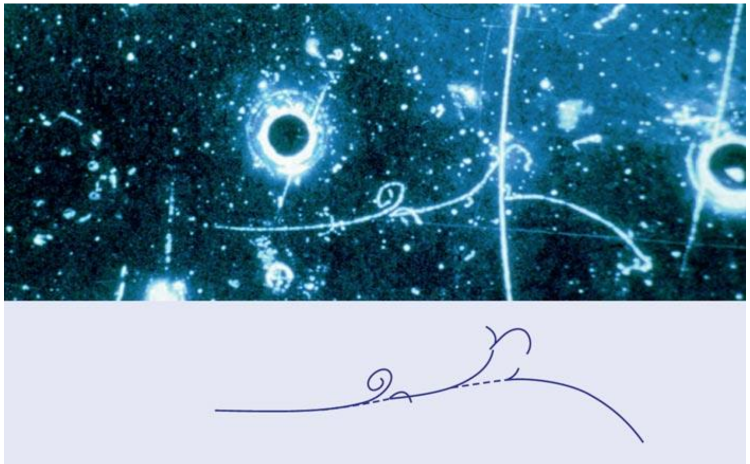



For d-quark out: $V_{ud} \sim 1$

For s-quark out: $V_{us} = \sin \theta_c$

The left side diagram describes semi-leptonic nuclear beta decay. Many other hyperon decays follow the same pattern but with an s-quark instead of a u-quark on the top legs and a charge 2/3 outgoing quark. The decays of mesons, each composed of a quark and an anti-quark, also can decay by this charged current interaction. On the right side the leptons at the lower vertex are replaced by a quark-antiquark pair, so this is a diagram for a weak all hadronic decay.

# Neutral Currents (NC) and suppression of FCNC



The first leptonic neutral current event. An anti-neutrino coming from the left knocks an electron forwards, creating a characteristic shower of electron-positron pairs..

A hadronic neutral current event, where the interaction of the neutrino from the left produces three secondary particles, all clearly identifiable as hadrons, as they interact with other nuclei in the liquid. There is no charged lepton.

- It was anticipated that there could also be weak neutral current interactions, mediated by a neutral boson, named the Z
- The Z boson can couple to electrons, positrons, neutrinos and also quarks of the same sign e.g.

$$Z \rightarrow u\bar{u}, \quad d\bar{d}, \quad s\bar{s}$$

- **But can it have flavor-changing couplings, like the charged current?**

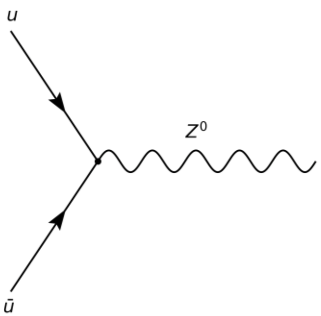
$$Z \rightarrow d\bar{s}$$

- **Answer: NO!**
  - **As demonstrated by experiment:**

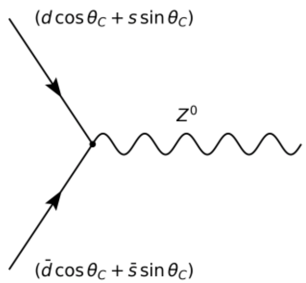
$$\frac{K^+ \rightarrow \pi^+ \nu\bar{\nu}}{K^+ \rightarrow \pi^0 \mu^+ \nu_\mu} < 10^{-5}$$

# Suppression of Flavor Changing Neutral Currents, the GIM Mechanism, Charm

u quark coupling to the Z boson




d quark cabibbo model coupling to the Z boso




$$\underbrace{u\overline{u} + (d\overline{d}\cos^2\theta_C + s\overline{s}\sin^2\theta_C)}_{\Delta S=0} + \underbrace{(s\overline{d} + \overline{s}d)\sin\theta_C\cos\theta_C}_{\substack{\Delta S=1 \\ \neq 0}}.$$

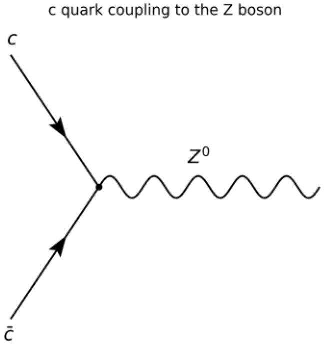
- To suppress unwanted flavor-changing neutral currents, introduce a new quark, charm, with charge 2/3

Mass eigenstate Propagation

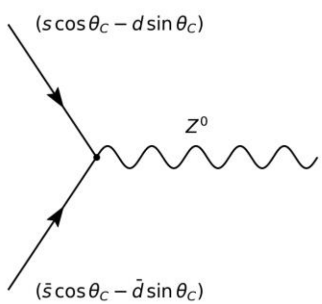
$$\begin{Bmatrix} u \\ d_C \end{Bmatrix} = \begin{Bmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{Bmatrix}, \begin{Bmatrix} c \\ s_C \end{Bmatrix} = \begin{Bmatrix} c \\ s\cos\theta_C - d\sin\theta_C \end{Bmatrix}$$

Mass eigenstate Propagation

c quark coupling to the Z boson




d quark GIM model coupling to the Z boson




$$\underbrace{u\overline{u} + c\overline{c} + (d\overline{d} + s\overline{s})\cos^2\theta_C + (s\overline{s} + d\overline{d})\sin^2\theta_C)}_{\Delta S=0} + \underbrace{(s\overline{d} + \overline{s}d - \overline{s}d - s\overline{d})\sin\theta_C\cos\theta_C}_{\substack{\Delta S=1 \\ =0.}}.$$

# The GIM mechanism
# Charm

- We began with a four-fermion charged current interaction
- We observed the production of pairs of "strange" particles
- We partially explained the weak decay of strange particles to more conventional particles with the Cabibbo model
- **We discovered neutral currents, basis of EWK unification**
- We then encountered the strong suppression of flavor changing neutral currents
  - While very strong it was not absolute.
    - We did observe the result of flavor changing neutral currents in "rare" decays such as $K_L \rightarrow \mu^+\mu^-$ small, but non-zero, level.
- This puzzle was addressed by the GIM mechanism, proposed in 1970, which required a new "charmed" quark, with charge 2/3!
  - Soon found - 1974

# The CKM matrix and flavor mixing

- Flavor changing neutral currents are suppressed and the charged current interaction, based on the mixing of charged 1/3 quarks, is flavor changing according to the following mixing matrix, which required a new doublet and a new "charmed" quark:

$$J^{+}_{weak} = \{\overline{u} \quad \overline{c}\} \begin{Bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{Bmatrix} \begin{Bmatrix} d \\ s \end{Bmatrix}$$

- The mass of the new quark had to be around 1.5 GeV to provide the needed amount of suppression, but not more . It was discovered in 1974
- **However, CP violation had ALREADY been discovered in the decays of neutral kaons in 1964. To get CP violation, there would need to be an interference effect, which implies some non-zero phase. The mixing matrix with two quarks is purely real.**
- **What can give us at least one phase that can produce interference in weak decays or flavor mixing? Another quark doublet!!!**

# More quarks and the Higgs Yukawa coupling to fermions

- **The Higgs field spontaneously breaks SU(2) X U(1) → U(1), gives masses to the weak bosons, leaves the photon massless, and creates the Higgs boson. THAT does not give masses to the fermions.**
- For that, there is an additional interaction which is "penned in", namely a **Yukawa interaction of the Higgs boson with the fermions** of the SM , namely the leptons and the quarks.
  - **This interaction is not be arbitrary. It must satisfy many requirements to be a candidate for**

In the SM the Lagrangian has the overall form

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A,\psi) + \mathcal{L}_{Higgs}(A,H) + \mathcal{L}_{Yukawa}(H,\psi)$$

where A are the gauge fields, H are the Higgs (or scalar) fields, and $\psi$ are the fermion fields.

$$-\mathcal{L}_{Yukawa} = (Y_D)_{ab}\overline{Q}^a_L H d^b_R + (Y_U)_{ab}\overline{Q}^a_L H_c u^b_R + (Y_E)_{ab}\overline{L}^a_L H e^b_R + h.c.$$

$$\overline{(u_1 u_2 u_3)} M^u \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} + hc; \qquad \overline{(d_1 d_2 d_3)} M^d \begin{Bmatrix} d_1 \\ d_2 \\ d_3 \end{Bmatrix} + h.c \quad \Rightarrow \quad \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix}_{L,R} = U_{L,R} \begin{Bmatrix} u \\ c \\ t \end{Bmatrix}_{L,R} \qquad \begin{Bmatrix} d_1 \\ d_2 \\ d_3 \end{Bmatrix} = D_{L.R} \begin{Bmatrix} d \\ s \\ b \end{Bmatrix}_{L,R}$$

$$U_R^{-1} M^u U_L = \begin{Bmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{Bmatrix} \qquad D_R^{-1} M^d D_L = \begin{Bmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{Bmatrix} \qquad \overline{(u_1\ u_2\ u_3)}\gamma_\mu \begin{Bmatrix} d_1 \\ d_2 \\ d_3 \end{Bmatrix}_L = \overline{(u\ c\ t)} U_L^\dagger D_L \gamma_\mu \begin{Bmatrix} d \\ s \\ b \end{Bmatrix}_L$$

$$J^+_{L\mu} = \overline{u,c,t)}_L \gamma_\mu V \begin{Bmatrix} d \\ s \\ b \end{Bmatrix} \qquad \boxed{V \equiv U_L^\dagger D_L}$$

# Phase counting in unitary matrices

- For N families, an N x N unitary matrix has
  - $N^2$ complex elements
  - The N charged quarks, q(i), each have an arbitrary, phase, $\varepsilon^{\phi(q(i))}$, that can be adjusted to remove phases from the matrix. One overall phase cannot be removed. Removing 2N-1 phases leaves
    - $(N-1)^2$ parameters
  - There are N(N-1)/2 parameters that correspond to rotation angles in N-dimensional flavor space of dimension N. These angles are real numbers
  - The number phases is: (N-1)[(N-1)-N/2) = 1/2 (N-1)(N-2)
    - For N = 2 families, the number of phases is 0, **so no CP violation**
    - For N = 3 families, the number of phases is 1
    - For N = 4 families, the number of phases is 3

CP violation in the SM requires 3 or more families, indicating at least one more quark doublet and one more "family" of fermions

# The CKM Matrix

- The third quark family was found with the discovery of the Upsilon, a bound state of the b-quark and b anti-quark, in 1978 and the observation of the top quark in 1995
- The charged current interaction now looks like

$$J^{+}_{weak} = \{\bar{u} \quad \bar{c} \quad \bar{t}\} \begin{Bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{Bmatrix} \begin{Bmatrix} d \\ s \\ b \end{Bmatrix}$$

- The 3x3 matrix is the Cabibbo-Kobayashi-Masakawa matrix.
- The matrix must be unitary
  - It has one complex phase
  - It has three Euler angles corresponding to rotations in a three-dimensional flavor space
- **The actual values of the CKM matrix are not determined by theory and must be extracted from measurement of decays that involve them**

# CKM via Rotation matrices in flavor space

$$\begin{array}{cccc} R_{23}(\theta_y,0) & R_{31}(-\theta_z,\phi) & R_{12}(\theta_x,0) & V_{CKM} \end{array}$$

$$\begin{Bmatrix} 1 & 0 & 0 \\ 0 & c_y & s_y \\ 0 & -s_y & c_y \end{Bmatrix} \times \begin{Bmatrix} c_z & 0 & s_z e^{-i\phi} \\ 0. & 1 & 0 \\ -s_z e^{i\phi} & 0 & c_z \end{Bmatrix} \times \begin{Bmatrix} c_x & s_x & 0 \\ -s_x & c_x & 0 \\ 0 & 0 & 1 \end{Bmatrix} = \begin{Bmatrix} c_x c_z & s_x c_z & s_z e^{-i\phi} \\ -s_x c_y - c_x s_y s_z e^{i\phi} & c_x c_y - s_x s_y s_z e^{i\phi} & s_y c_z \\ s_x s_y - c_x c_y s_z e^{i\phi} & -c_x s_y - s_x c_y s_z e^{i\phi} & c_y c_z \end{Bmatrix}$$

where $R_{ij}(\theta,\phi)$ is a unitary rotation in the $ij$–plane by the angle $\theta$ and the phase $\phi$.

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

**The three rotation angles and one phase are not given by the SM but must be determined from data on weak decay processes.** This was a long program that took many years. Multiple approaches and redundant measurements test the consistency of the SM and look for deviations that would mean new physics.

The CKM matrix has an invariant, the Jarlskog invariant which is related to the determinant of the matrix, and therefore an "area". All CP violation is connected to A, which is found experimentally to be small

$$2A = J = c_{12} c_{13}^2 c_{23} s_{12} s_{23} \sin\delta = \mathcal{O}\left(10^{-5}\right) .$$

# Cross-generational communications – the Wolfenstein parametrization

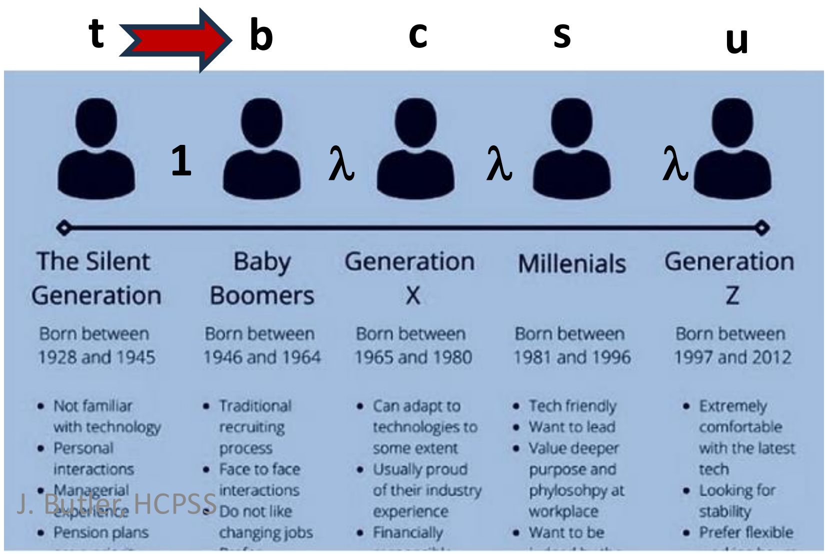
$$\begin{aligned} \lambda &\doteq s_{12} \\ A\lambda^2 &\doteq s_{23} \\ A\lambda^3(\rho - i\eta) &\doteq s_{13}\exp^{-i\delta} \end{aligned}$$

$$V_{CKM} = \begin{Bmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda + O(\lambda^7) & A\lambda^3(\overline{\rho}-i\overline{\eta}) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\overline{\rho}+i\overline{\eta})] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2+O(\lambda^8) \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\overline{\rho}+i\overline{\eta})] & 1-\frac{1}{2}A^2\lambda^4 \end{Bmatrix}$$

where $\overline{\rho} = \rho(1-\lambda^2/2) + O(\lambda^4)$ and $\overline{\eta} = \eta(1-\lambda^2/2) + O(\lambda^4)$

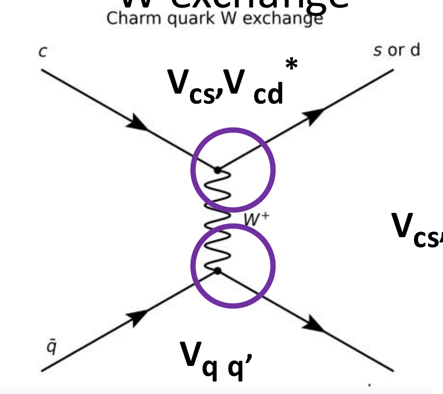
**From experiment, $s_{12}$ ~0.23 ($\theta$ =13°), so all off-diagonal elements are small. The charged weak current transitions are suppressed roughly by a power of $\lambda$ as the generation separation increases.**

$$V_{CKM} \approx \begin{Bmatrix} 1- & \lambda & \lambda^3 e^{-i\delta'} \\ -\lambda & 1- & \lambda^2 \\ \lambda^3 e^{i\delta'} & -\lambda^2 & 1- \end{Bmatrix}$$

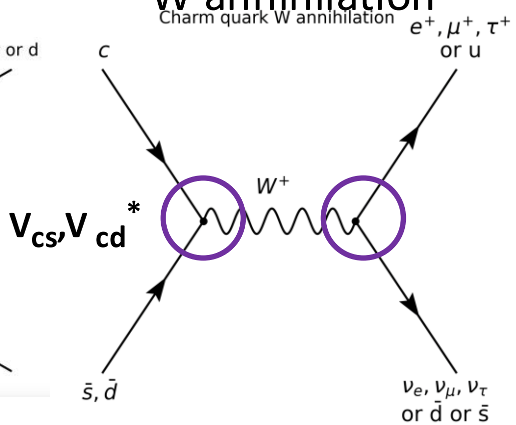


# Charm decays

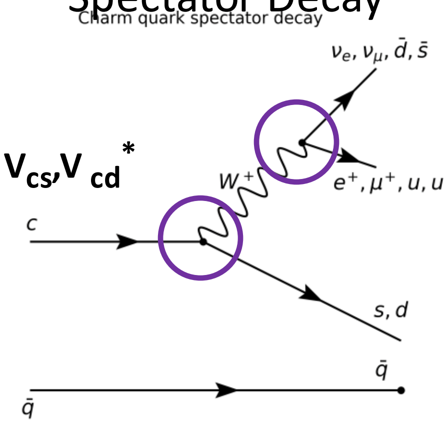
W exchange



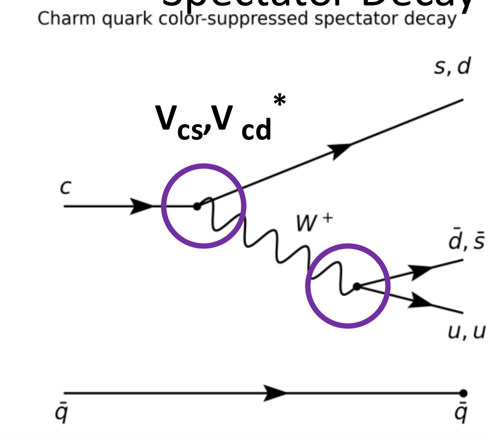

W annihilation




Spectator Decay




Color-suppressed Spectator Decay

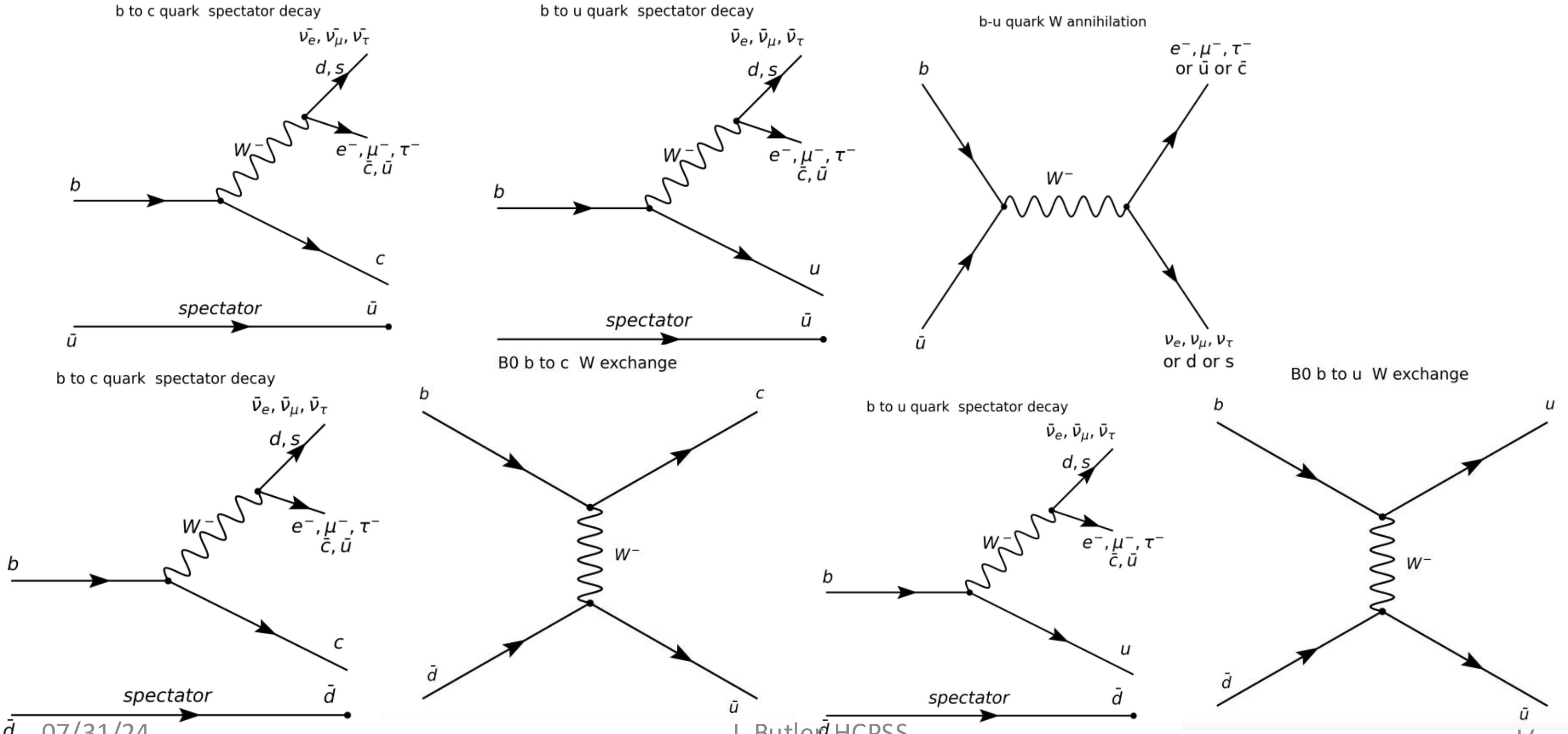



The relatively low mass of the charm quark allows these diagrams to interfere and leads to a relatively large variations in the mean lifetimes from >1ps ($D^+$) to ~300 fs ($D^0$)

# B decays

| Particle | Lifetime [ps] |
|---|---|
| $B^+$ | $1.638 \pm 0.004$ |
| $B^0$ | $1.519 \pm 0.004$ |
| $B_s^0$ | $1.516 \pm 0.006$ |
| $B_{sL}^0$ | $1.427 \pm 0.007$ |
| $B_{sH}^0$ | $1.616 \pm 0.010$ |
| $B_c^+$ | $0.510 \pm 0.009$ |
| $\Lambda_b^0$ | $1.471 \pm 0.009$ |
| $\Xi_b^-$ | $1.572 \pm 0.040$ |
| $\Xi_b^0$ | $1.480 \pm 0.030$ |
| $\Omega_b^-$ | $1.64^{+0.18}_{-0.17}$ |

- Spectator decays dominate since the other diagrams are very helicity suppressed because the mass of $M_b$. All particles with light quarks and b-quarks have ~ same lifetime of ~1.5ps.



# CKM Unitarity relations

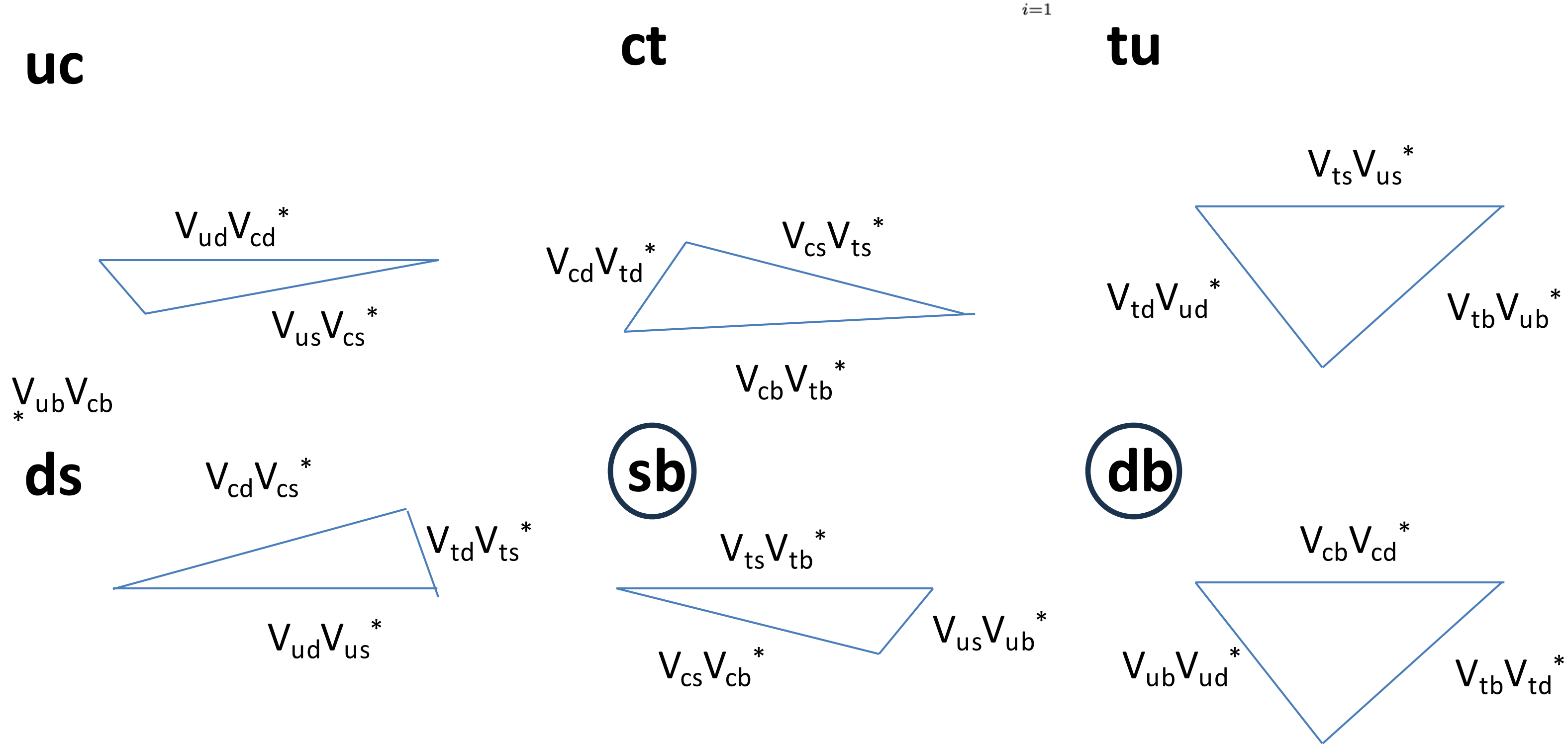
$$V^\dagger V = 1$$

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

$$\sum_{i=1}^{3} |V_{ij}|^2 = 1, j = 1,2,3$$

$$\sum_{i=1}^{3} VjiV_{ki}^* = 0, \quad j,k = 1,2,3, j \neq k$$

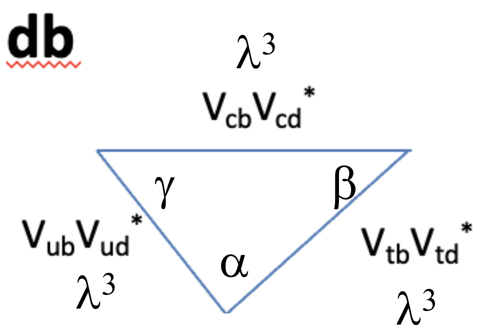
$$\sum_{i=1}^{3} VijV_{ik}^* = 0, \quad j,k = 1,2,3, j \neq k$$




**These the sides of these triangles, expressed as figures in a complex plane, must sum to 0 to satisfy the unitarity condition.**

# Establishing the unitarity of the CKM matrix

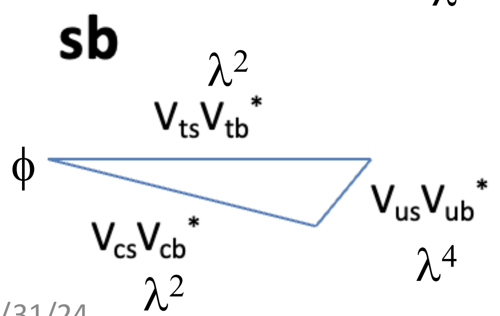
- Each of the 6 triangles represents a constraint equation – the CKM element products on the sides must sum to zero.
  - Since the CKM products appear in physical processes, these processes can be used to determine the CKM matrix elements and check that they obey unitarity
  - Matrix elements can be determined from all the processes that are involved in weak decays of of hadrons containing quarks - branching fractions, lifetimes, flavor mixing parameters, and CP violation
  - The angles of the CKM triangles are related to CP violation and mixing
  - The easiest triangles to explore are those whose sides are all approximately equal




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

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + 1 = 0$$

Angles $\alpha, \beta, \gamma$ are related to CP violation in $B^0$ and are large



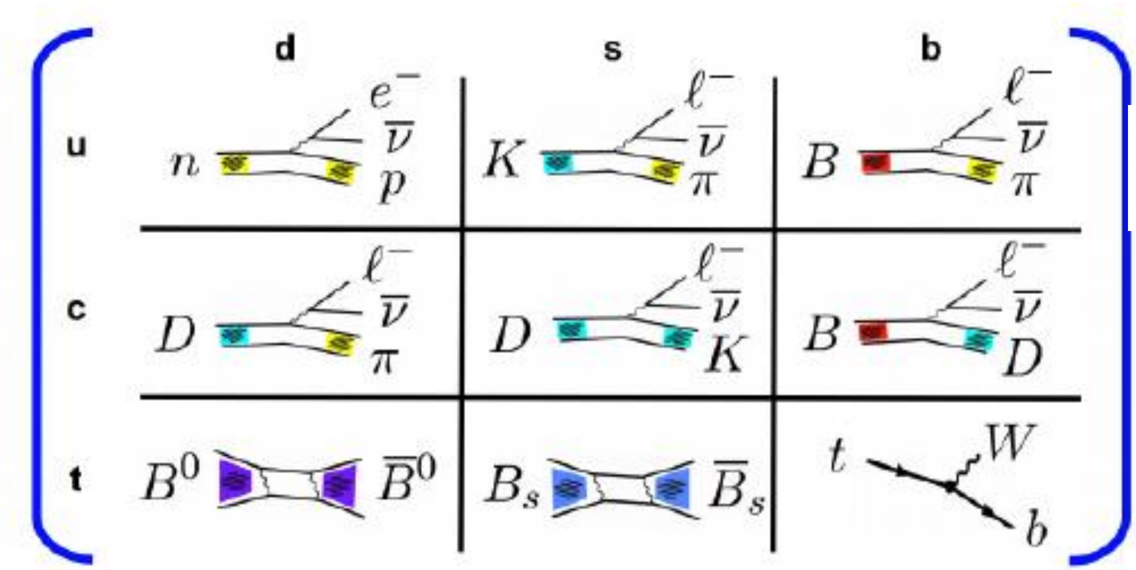

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$$\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*} + \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} + 1 = 0$$

Angle $\phi$ is related to CP violation in $B_s$ and is small

# Experimentally determined quantities

- CKM elements




Use of semileptonic decays reduces hadronic uncertainties

$$\begin{pmatrix} 0.97401 \pm 0.00011 & 0.22650 \pm 0.00048 & 0.00361^{+0.00011}_{-0.00009} \\ 0.22636 \pm 0.00048 & 0.97320 \pm 0.00011 & 0.04053^{+0.00083}_{-0.00061} \\ 0.00854^{+0.00023}_{-0.00016} & 0.03978^{+0.00082}_{-0.00060} & 0.999172^{+0.000024}_{-0.000035} \end{pmatrix}$$

Values of CKM matrix elements

## Wolfenstein Parameters

$$\lambda = 0.22650 \pm 0.00048\,, \qquad A = 0.790^{+0.017}_{-0.012}\,,$$
$$\bar{\rho} = 0.141^{+0.016}_{-0.017}\,, \qquad \bar{\eta} = 0.357 \pm 0.011\,.$$

## Unitarity Triangle angles and phase

$$\sin\theta_{12} = 0.22650 \pm 0.00048\,, \qquad \sin\theta_{13} = 0.00361^{+0.00011}_{-0.00009}\,,$$
$$\sin\theta_{23} = 0.04053^{+0.00083}_{-0.00061}\,, \qquad \delta = 1.196^{+0.045}_{-0.043}\,.$$

## Masses of SM fermions

| | | |
|---|---|---|
| $m_u \approx 2$ MeV | $m_c \approx 1.3$ GeV | $m_t \approx 173$ GeV |
| $m_d \approx 4$ MeV | $m_s \approx 95$ MeV | $m_b \approx 4.2$ GeV |
| $m_e \approx 0.511$ MeV | $m_\mu \approx 105$ MeV | $m_\tau \approx 1.78$ GeV |

# Interplay of the Strong and Weak interactions: Hadronization

- Quarks are confined inside hadrons. The interaction of the quarks via the interquark potential leads to wavefunctions, or, in momentum space, form factors that determine how close the quarks have to be to each other to interact to form hadrons.
- These hadronic effects lead to uncertainties in the prediction of SM quantities and therefore limit the demonstration that a measurement is at odds with the SM.
  - Some can now be calculated by Lattice QCD or as well-described by a model
- The best way to measure CKM matrix elements is by using semileptonic decays since one vertex has no hadronic uncertainties

$$\frac{d\Gamma_D}{dw}(B \to D\ell\nu) = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \mathcal{K}_D(w) \mathcal{G}(w)^2,$$

Phase space factor

Form factor

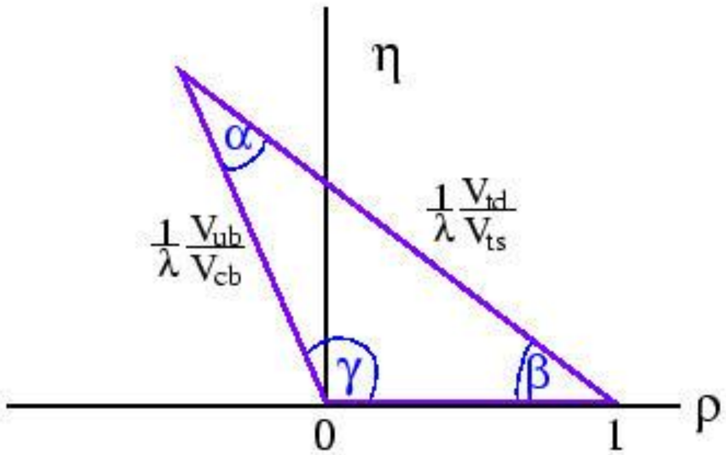
Decay rate measurements give the product of a CKM parameter and a hadronic form factor

# Where to look for BSM Physics

- The most valuable processes in which to search for BSM effects
  - very rare or forbidden by symmetry arguments or have SM predictions whose uncertainties are very low because of some other argument, e.g. isospin symmetries or Heavy Flavor symmetries
  - Since flavor-changing neutral currents are absent at the tree-level and highly suppressed at higher orders, these are among the best processes to study to look for BSM Physics
  - For some decays, the theory uncertainties may be low. These decays are called "golden modes" and are much studied
  - In some other cases, hadronic uncertainties may be eliminated by taking suitable ratios of states whose uncertainties might be large individually but cancel in the ratio.
- Since there is not enough CP violation in the SM to account for the observed antimatter-matter asymmetry, looking for anomalies in CPV which could suggest new sources is also an exciting strategy

The SM is a sort of "fog" or "floor" to BSM physics

# Key Measurements of the CKM matrix in B Decays




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

$$\chi = \arg\left(-\frac{V_{cs}^*V_{cb}}{V_{ts}^*V_{tb}}\right) \qquad \chi' = \arg\left(-\frac{V_{ud}^*V_{us}}{V_{cd}^*V_{cs}}\right)$$

overall consistent picture within $O(10\%)$ uncertainties

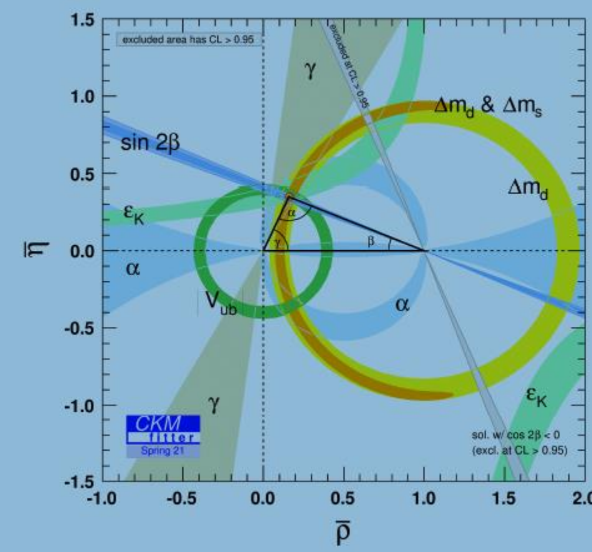
$\lambda = 0.2254^{+0.0004}_{-0.0003}$

$A = 0.823^{+0.007}_{-0.014}$

$\bar{\rho} = 0.150^{+0.012}_{-0.006}$

$\bar{\eta} = 0.354^{+0.007}_{-0.008}$

http://ckmfitter.in2p3.fr/
http://www.utfit.org/

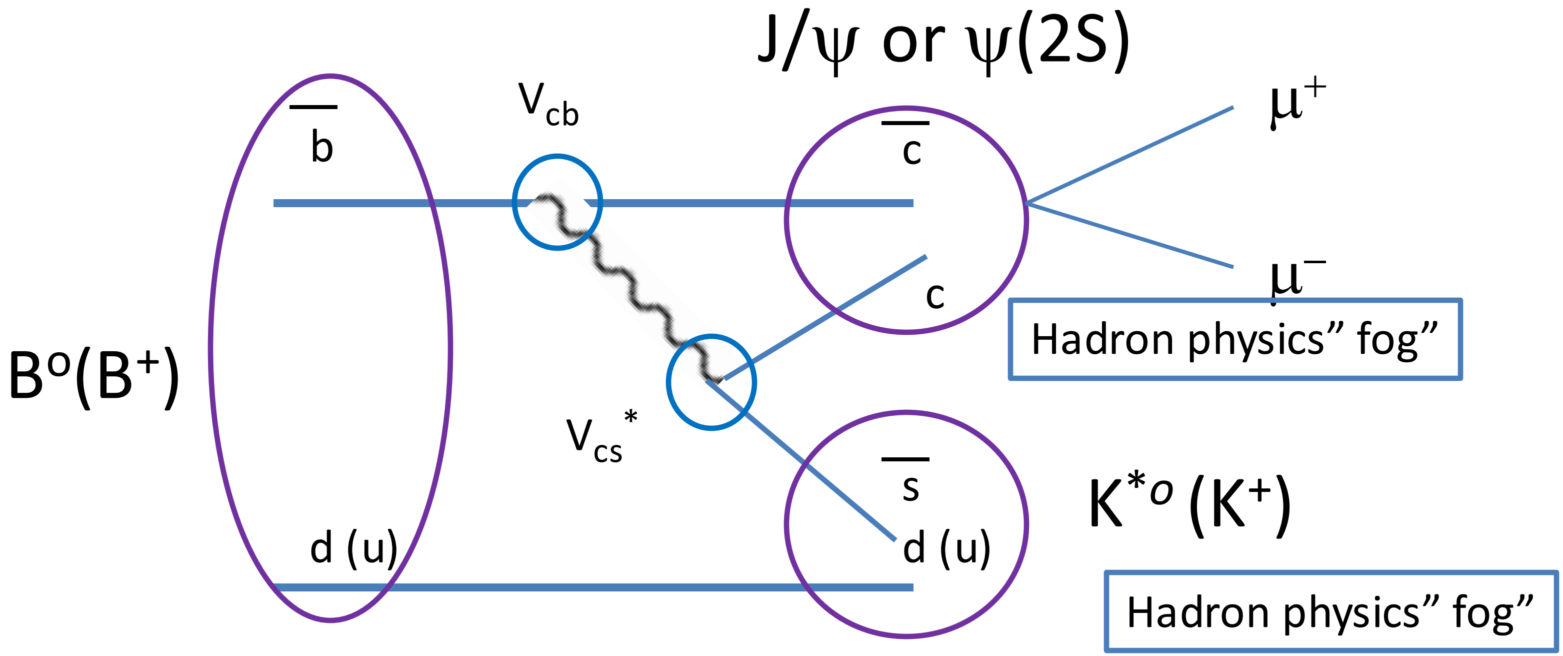



The CKM matrix has an area, its determinant, which is an invariant, the Jarlskog invariant. It turns out the all CPV is related to it. All angles must be non-zero.

$$2A = J = c_{12}c_{13}^2c_{23}s_{12}s_{23}\sin\delta = \mathcal{O}\left(10^{-5}\right) \; .$$

**About 1/2 of the key measurements are in $B_s$ decays!**

# A useful weak decay

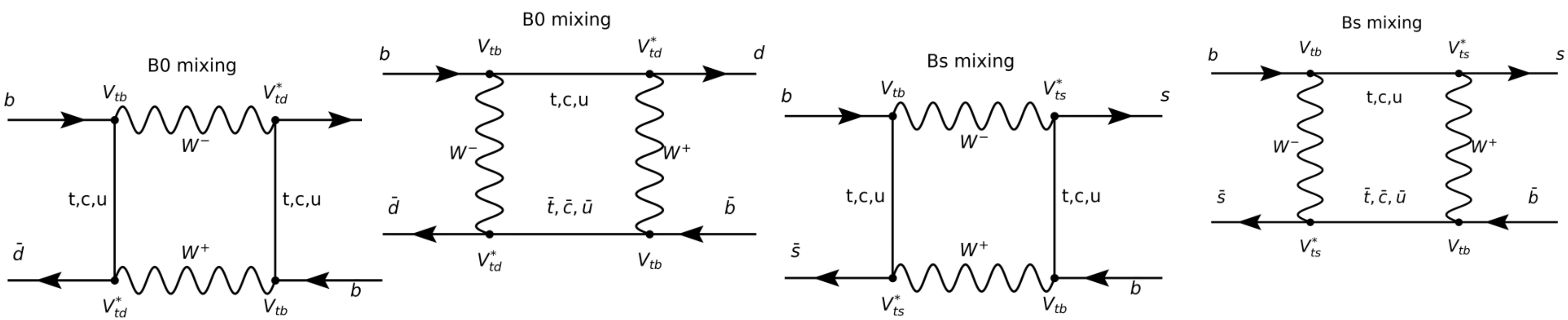



The anti-b quark does not decay through a loop diagram. These are CKM and Cabibbo favored decays that, far from being suppressed, have high branching fractions. The $J/\psi$ or $\psi(2S)$ decay into a $\mu^+\mu^-$ creates the **resonant contribution** that is excluded by the $q^2$ cuts in the $B^o \rightarrow K^{*o}\, \mu^+\mu^-$ analysis. The $B^+ \rightarrow J/\psi\, K^+$ is used as a normalization channel in the $B_{s,d} \rightarrow \mu^+\mu^-$ for its similarity to the signal decay (one extra particle, same muon content).

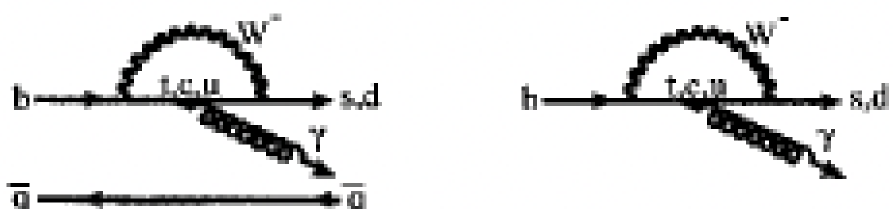
# Higher order: loops, boxes in B decays

These processes can produce FCNC:

I. B mixing (a.k.a. Box diagrams) that swap b and d or b and s




II. Penguin diagrams (a.k.a. Loops)



# Types of CP violation in b decays

- Asymmetries (differences) between particle and anti-particle decay rates occur because of interference effects:
  - **"Direct" CPV: interference between two or more decay amplitudes** (Feynman diagrams) with a role for strong interaction, which does exhibit CPV
    - Hard to predict because of the involvement of strong interaction phase shifts
    - $|\Delta$ flavor $| = 1$
    - Charged or neutral B hadrons
  - **"Indirect" CPV: CP violation in flavor mixing alone**
    - Neutral mesons only
    - $|\Delta$ flavor $| = 2$
    - Interference between the various contributions to "flavor" mixing from "box" diagrams
    - Prominent in kaon physics – historically the theatre for understanding flavor mixing and first observing CP violation
    - Long struggle to establish "direct" CPV in kaon decays ended with the observation of non-zero $\boldsymbol{\varepsilon_K'/\varepsilon}$
  - **"Mixing-induced CPV:**
    - Interference between mixing paths and decay amplitudes – decays following different mixing histories
    - Neutral mesons only
    - Can use with self-conjugate decays
    - Requires "flavor tagging" of initial production of the B mesons
    - $|\Delta$ flavor $| = 2$

# "Direct" CP Violation

CP violation directly in the decay amplitudes

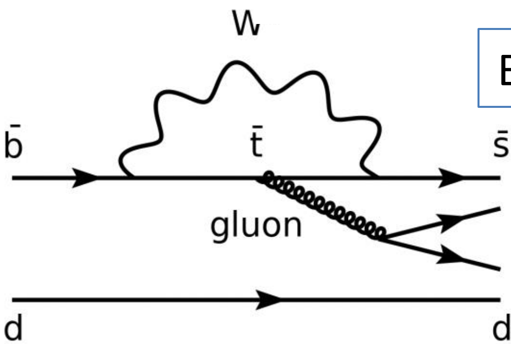
- Leads to a time independent difference in $B \to f$ and $\overline{B} \to \overline{f}$
- Can occur in either charged or neutral b hadrons
- Requires two decay diagrams to interfere
  - At least one must have the CP violating CKM phase, either $V_{ts}$ or $V_{ub}$, which change sign between b to bbar
  - Some strong phase shifts that do not change sign under CP because the strong interaction does not violate CP . They can come from final state interactions, hadronization of the final state quarks, ..., which makes these difficult to calculate

$$M^+ \equiv < f^+|\mathcal{L}|B^+ > \; = \; g_1 M_1 e^{i\delta_1} + g_2 M_2 e^{i\delta_2}$$
$$M^- \equiv < f^-|\mathcal{L}|B^- > \; = \; g_1^* M_1 e^{i\delta_1} + g_2^* M_2 e^{i\delta_2}$$

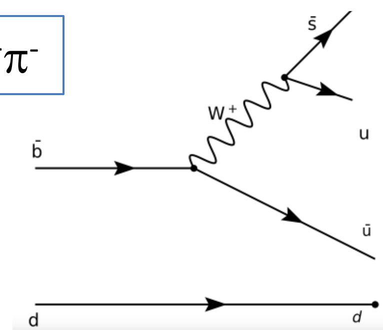
$g_1$ and $g_2$ are the weak couplings, including the complex CKM matrix elements, $\delta_1$ and $\delta_2$ are the appropriate strong (or EM) phase shifts final state interactions, and M1 and M2 are real.

Squaring these amplitudes and taking the difference gives a CP violating asymmetry of

$$|M^+|^2 - |M^-|^2 = 4 M_1 M_2 Im(g_1 g_2^*) \sin(\delta_2 - \delta_1)$$




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

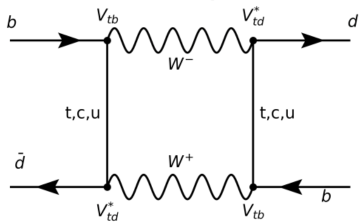



These show how an asymmetry can arise between $B^0 \to K\pi$ and $B^0$bar to $K\pi$. The hadronization of the final state could also result in a $\rho$ meson or a K* or both. This diagram also describes $B_s$ asymmetries if the spectator is replaced by an s-quark. Many such asymmetries have been detected.

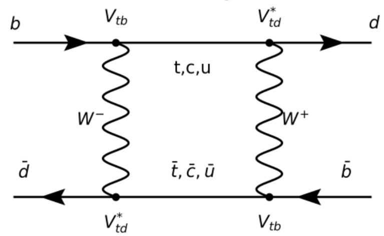
Recent results (LHCb): Phys. Rev. D 108(2023) 012008
CPV in various local parts of 3 body Dalitz plots

# Flavor mixing

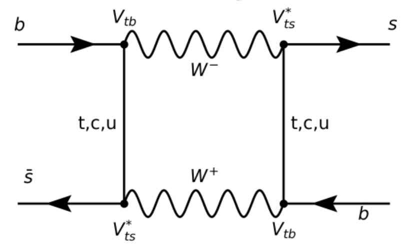
B0 mixing



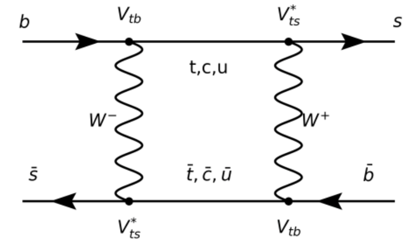

B0 mixing




Bs mixing




Bs mixing




$$i\frac{d}{dt}\begin{Bmatrix} a \\ \overline{a} \end{Bmatrix} = \begin{Bmatrix} m - \frac{1}{2}i\Gamma & m_{12} - \frac{1}{2}i\Gamma_{12} \\ m^*_{12} - \frac{1}{2}i\Gamma^*_{12} & m - \frac{1}{2}i\Gamma \end{Bmatrix} \begin{Bmatrix} a \\ \overline{a} \end{Bmatrix}$$

$$m_j - \frac{1}{2}i\Gamma_j = m - \frac{1}{2}i\Gamma \pm [(m_{12} - \frac{1}{2}i\Gamma_{12})(m^*_{12} - \frac{1}{2}i\Gamma^*_{12})]^{\frac{1}{2}}$$

$$|B_j> = \begin{Bmatrix} (m_{12} - \frac{1}{2}i\Gamma_{12})^{\frac{1}{2}}/(m_{12} + m^*_{12} - \frac{1}{2}i\Gamma_{12} - \frac{1}{2}i\Gamma^*_{12})^{\frac{1}{2}} \\ \pm(m^*_{12} - \frac{1}{2}i\Gamma^*_{12})^{\frac{1}{2}}/(m_{12} + m^*_{12} - \frac{1}{2}i\Gamma_{12} - \frac{1}{2}i\Gamma^*_{12})^{\frac{1}{2}} \end{Bmatrix}$$

Without CP violation, $m_{12} = m^*_{12}$ and $\Gamma_{12} = \Gamma^*_{12}$, that is both are real. We then have

$$|B_1> = \frac{1}{\sqrt{2}}\begin{Bmatrix} 1 \\ 1 \end{Bmatrix},\ m_1 = m + m_{12},\ \Gamma_1 = \Gamma + \Gamma_{12}$$

$$|B_2> = \frac{1}{\sqrt{2}}\begin{Bmatrix} 1 \\ -1 \end{Bmatrix},\ m_2 = m - m_{12},\ \Gamma_2 = \Gamma - \Gamma_{12}$$

$$\begin{aligned} |B_1> &= |B> + |\overline{B}> \text{ CP even} \\ |B_2> &= |B> - |\overline{B}> \text{ CP odd} \end{aligned}$$

$$\begin{aligned} |B> &= [|B_1> + |B_2>] \\ &\to \frac{1}{\sqrt{2}}\sum_{j=1,2} \exp(-im_j t - \frac{1}{2}\Gamma_j t)|B_j> \\ &= a(t)|B> + \overline{a}(t)|\overline{B}> \end{aligned}$$

$$a(B \to B) = \frac{1}{-}[exp(-im_1 t - \frac{1}{2}\Gamma_1 t) + exp(-im_2 t - \frac{1}{2}\Gamma_2 t)]$$

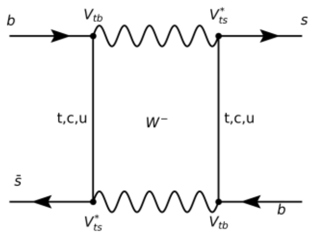
$$:p(-im_1 t - \frac{1}{2}\Gamma_1 t) - exp(-im_2 t - \frac{1}{2}\Gamma_2 t)]$$

Neglecting CP violation for the moment, we get for mixing:

$$(\frac{|\Delta m|}{\Gamma})_q = (\frac{2|m_{12}|}{\Gamma})_q = \tau_{B_q}\frac{BG^2_F}{6\pi^2} f^2_{B_q} m_{B_q} \eta_{QCD} |(V_{tq}V^*_{tb})^2)| I \qquad (1.41)$$

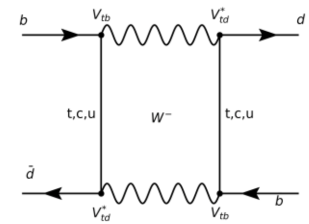
where $q = dors$, $\tau_{B_q}$ and $m_{B_q}$ are the lifetime and mass of the $B_q$-meson, $B$ is a factor to account for quark confinement, $f_{B_q}$ is the meson decay constant, related to the value of the wavefunction at the origin, $\eta_{QCD}$ is the short distance factor, and $I$ is the value of the box-integral.

Bs mixing




# Flavor Oscillations and “Indirect” CP Violation

B0 mixing




The strong interaction produces eigenstates of flavor, in pairs. The weak interactions through box diagrams, turn a state with flavor, F, into its opposite, -F, giving a $\Delta F = 2$ transitions. There are several diagrams that can interfere and $V_{td}$ or $V_{ub}$ can provide the complex phase that leads to CPV.

$$i\frac{d}{dt}\begin{Bmatrix} a \\ \bar{a} \end{Bmatrix} = \begin{Bmatrix} m - \frac{1}{2}i\Gamma & m_{12} - \frac{1}{2}i\Gamma_{12} \\ m_{12}^* - \frac{1}{2}i\Gamma_{12}^* & m - \frac{1}{2}i\Gamma \end{Bmatrix} \begin{Bmatrix} a \\ \bar{a} \end{Bmatrix}$$

CPT invariance requires $m_{11} = m_{22} = m$ and $\Gamma_{11} = \Gamma_{12} = \Gamma$ and the hermeticity of the dispersive and absorptive parts of the matrices further require $m_{21} = m^*_{12}$ and $\Gamma_{21} = \Gamma^*_{12}$.

The eigenvalues are: $$m_j - \frac{1}{2}i\Gamma_j = m - \frac{1}{2}i\Gamma \pm [(m_{12} - \frac{1}{2}i\Gamma_{12})(m_{12}^* - \frac{1}{2}i\Gamma_{12}^*)]^{\frac{1}{2}}$$

The eigenvectors are: $$|B_j> = \begin{Bmatrix} (m_{12} - \frac{1}{2}i\Gamma_{12})^{\frac{1}{2}}/(m_{12} + m_{12}^* - \frac{1}{2}i\Gamma_{12} - \frac{1}{2}i\Gamma_{12}^*)^{\frac{1}{2}} \\ \pm(m_{12}^* - \frac{1}{2}i\Gamma_{12}^*)^{\frac{1}{2}}/(m_{12} + m_{12}^* - \frac{1}{2}i\Gamma_{12} - \frac{1}{2}i\Gamma_{12}^*)^{\frac{1}{2}} \end{Bmatrix}$$

$$|B_1> = |B> + |\overline{B}> \text{ CP even}$$
$$|B_2> = |B> - |\overline{B}> \text{ CP odd}$$

Without CPV, $m_{12} = m_{12}^*$, $\Gamma_{12} = \Gamma_{12}^*$

$$|B_1> = \frac{1}{\sqrt{2}}\begin{Bmatrix} 1 \\ 1 \end{Bmatrix},\ m_1 = m + m_{12},\ \Gamma_1 = \Gamma + \Gamma_{12}$$
$$|B_2> = \frac{1}{\sqrt{2}}\begin{Bmatrix} 1 \\ -1 \end{Bmatrix},\ m_2 = m - m_{12},\ \Gamma_2 = \Gamma - \Gamma_{12}$$

Neglecting CPV, mixing is given by $$(\frac{|\delta m|}{\Gamma})_q = (\frac{2|m_{12}|}{\Gamma})_q = \tau_{B_q}\frac{BG_F^2}{6\pi^2}f_{B_q}^2 m_{B_q}\eta_{QCD}|(V_{tq}V_{tb}^*)^2)|I$$

$$r = P(B \to \overline{B})$$
$$\bar{r} = P(B \to B)$$

$$a_{FS} \equiv \frac{r - \bar{r}}{r = \bar{r}} = \frac{a}{2} - \frac{a}{2} \times \frac{\exp^{-\Gamma t}\cos(\Delta m t)}{\exp^{-\Gamma t}\cosh(\Delta\Gamma\frac{t}{2})}$$

$$r = \frac{1}{2}exp^{-1/2\Gamma t}[1 + \cos(\Delta m t)]$$
$$\bar{r} = \frac{1}{2}exp^{-1/2\Gamma t}[1 - \cos(\Delta m t)]$$

$\frac{N(++) + N(--)}{N} > 0$ No CPV $\frac{N(++) - N(--)}{N} \approx 0$ CPV, non-zero $\frac{N(++) - N(--)}{N}$ $\frac{r - \bar{r}}{r + \bar{r}} = 2\cos(\Delta(mt))$

# Indirect CP violation

- Mixing
  - Consider collisions in which B, B are produced. Consider the semileptonic decays, b→ c $\ell^- \nu$ and c.c.
  - Then, without mixing all decays would have $N_{+-}$.
  - With mixing then( $N_{++}$ + $N_{--}$) /Ntot >0
- Mixing and CPV

$$\epsilon = \frac{1-\eta}{1+\eta}$$

$$|B_1> = p|B> +q|\overline{B}> \text{ CP even}$$
$$|B_2> = p|B> -q|\overline{B}> \text{ CP odd}$$

$$|B_1> = \frac{|B> +\eta|\overline{B}>}{\sqrt{1+|\eta|^2}}$$
$$|B_2> = \frac{|B> -\eta|\overline{B}>}{\sqrt{1+|\eta|^2}}$$

$$\eta = [\frac{(m_{12}^* - \frac{1}{2}i\Gamma_{12}^*)}{(m_{12} - \frac{1}{2}i\Gamma_{12})}]^{\frac{1}{2}}$$

$$\eta = \frac{1-\epsilon}{1+\epsilon} \approx 1 - 2\epsilon$$

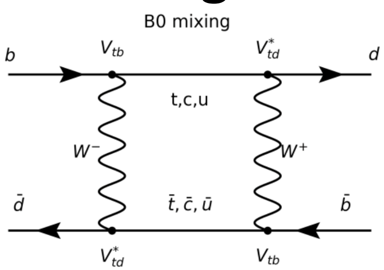
The time-integrated CPV asymmetry is

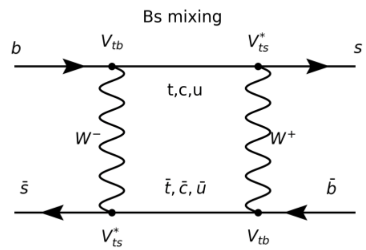
$$\mathcal{A} = \frac{|\eta|^2 - \frac{1}{|\eta|^2}}{|\eta|^2 + \frac{1}{|\eta|^2}} = \frac{|\eta|^4 - 1}{|\eta|^4 + 1} \approx 4\mathcal{R}](\epsilon)$$

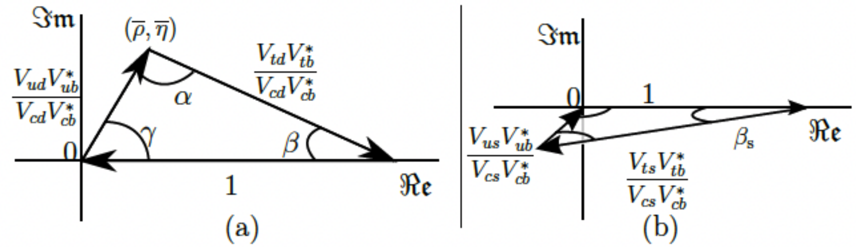
$\epsilon$ has only been measured in the $K^0 - \overline{K^0}$, where it was found that $re\epsilon$ $1.5 \times 10^{-3}$.

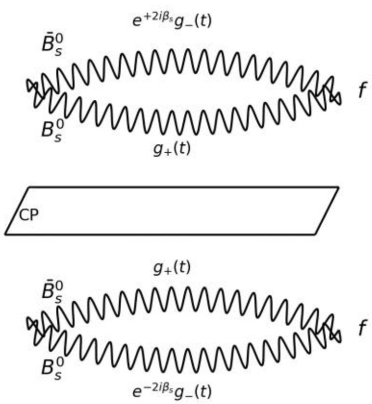
# “Mixing-induced” CP Violation

can also have CPV even if the mixing amplitude has |p/q|=1 and A(f)/A(f) =1, if there is a phase difference between them – ”mixing induced CPV”




Mixing induced CP violation: The upper part of the figure describes the decay of the $B_s^0$ to a CP conjugate state, $f$. The lower part shows the $\overline{B}_s^0$ decaying to the same final state $f$. The key point is that the upper decay occurs with a phase of $+2i\beta_s$ while the lower decay occurs with the opposite phase, $-2\beta_s$. This difference in the sign of the phase is what produces the CP violation.

- $B_d$ depends on $V_{td}$
  - extra CKM suppression keeps mixing frequency low
  - Since it carries the CKM phase, mixing-induced CP violation can be significant
  - Can discover and measure CPV and mixing in SM
- $B_s$ depends on $V_{ts}$
  - Larger value, less CKM suppression, makes mixing frequency high
  - Since it does not carry CKM phase, CP violation in SM will be very small
  - Must work to observe fast oscillations but can discover new sources of CPV with low SM background

# Observation of CP violation in $B^0$

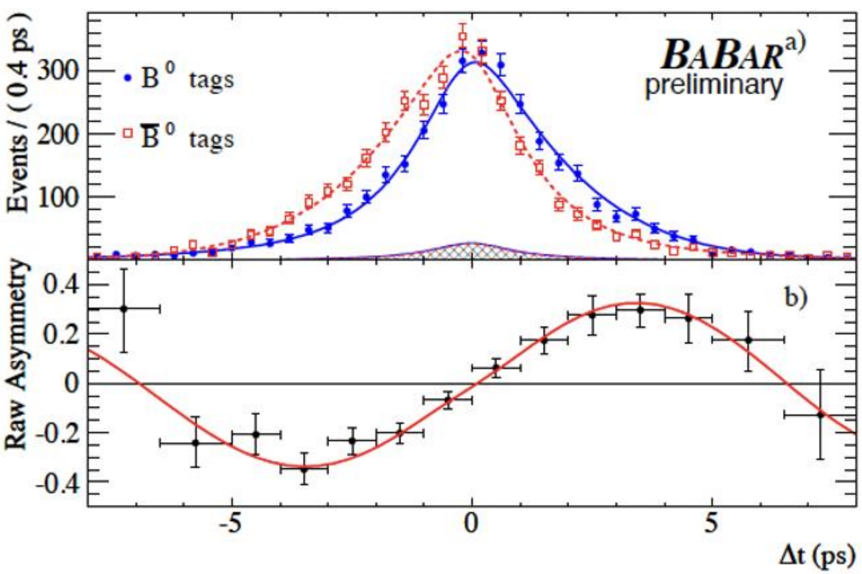
final-state CP eigenvalue

CP violation

flavor oscillations

$$a_{CP}(t) = \frac{-\eta_{fs}\sin(\phi_s)\sin(\Delta m_s t)}{\cosh(\frac{1}{2}\Delta\Gamma_s t) - \eta_{fs}\cos(\phi_s)\sinh(\frac{1}{2}\Delta\Gamma_s t)}$$

1.




For $B^0$, the relevant CKM angle is $2\beta$ and $\Delta\Gamma$ is ~0.

$$IM \frac{(V_{tb}^* V_{td})^2}{|V_{tb}V_{td}|^2}\frac{(V_{cb}V_{cs}^*)^2}{|V_{cb}V_{cs}|^2} \times F = -\frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2} \approx \sin 2\Phi$$

Figure 8: (a) The number of $J/\psi K_s$ candidates in the signal region with either a $B^0$ tag ($N_{B^0}$), or a $\overline{B}^0$ tag ($N_{\overline{B}^0}$) as a function of $\Delta t$. (b) The raw asymmetry, $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$. The solid (dashed) curves represent the fit projections as functions of $\Delta t$ for both $B^0$ and $\overline{B}^0$ tags. The shaded regions represent the estimated background contributions.

$\frac{\overline{A}(f)}{A(f)} \neq 1$ Direct CPV

$\Phi_{CPV}(f) \equiv \frac{q}{p}\bar{\rho}(f)$, where $\bar{\rho}(f) \equiv \frac{\overline{A}(f)}{A(f)}$

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

Phase of $\frac{p}{q}$ w.r.t $\bar{\rho}(f) \neq 0$

Mixing Induced CPV

$B_s$ mixing and CPV is very different in detail and will be discussed in the second of these lectures

# PRODUCING STATES WITH HEAVY QUARKS – THE EXPERIMENTAL LANDSCAPE

# Looking for BSM in all the right places: Disfavored, rare, and forbidden decays

- The flavor sector is complex and closely connected to the Higgs boson
- Nature, i.e. the SM, works overtime to eliminate FCNC at the tree level
  - FCNC can occur in the SM at higher order through loop and box diagrams
  - Models of BSM physics are severely constrained by the need to avoid FCNC
    - Technicolor models were challenged by this for quite some time
- This has consequences for experimental studies.
- Looking for new physics in rare B and CPV decays, especially if they have FCNC contributions beyond the SM, is a likely winning strategy
    - Forbidden decays are the best
    - The more suppressed a decay is in the SM the better since the SM is an annoying background to identifying BSM physics, the better it is
    - Since a SM contribution is eventually encountered, SM fog or floor, having a good theory prediction (control??) for it is important, especially as experiments approach the SM level
      - **New physics might contribute only a fraction to the SM rate**

We need lots of experimenters to do precise measurements, many theorists to calculate the SM backgrounds, give us well motivated BSM models to guide ourwork, and to help identify new observables to discriminate BSM from SM.

But we especially need a copious supply of B decays!

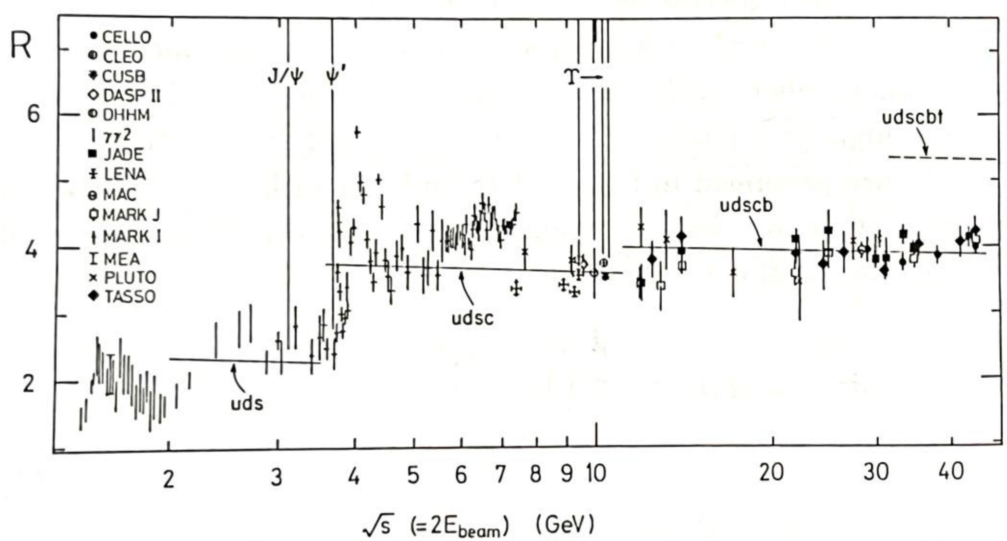
# B meson studies in $e^+e^-$ collisions

The cross section for production of hadrons is usually expressed as follows

$$\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}. \equiv \sigma_{QED} = 21.7\text{nb}/[E(GeV)]^2$$

$$R \equiv \frac{\sigma(e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)} = \frac{\sigma(e^+e^- \to \gamma^* \to q\bar{q})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)} = N_c \sum_q e_q^2$$

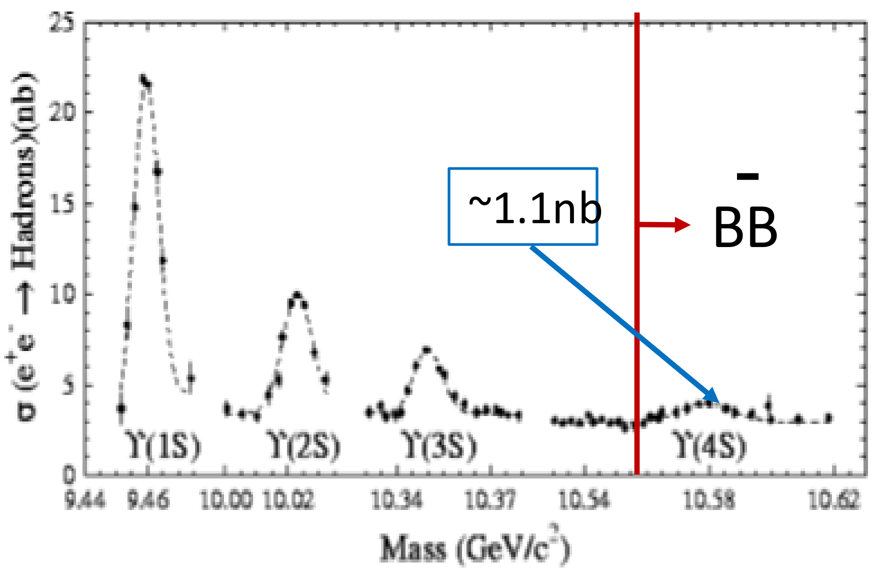
where the sum runs over all quarks whose $m_q < \sqrt{s}/2$, $e_q$ is the quark charge in units of $|e|$ and $N_c$ is the number of colors which is taken as 3. At energies over $\sqrt{s} > m_b$ but well below the Z-pole, the $b-$ quark contributes 1/3 of a unit out of 11/3 to $R$, so $b$-quark production is large.

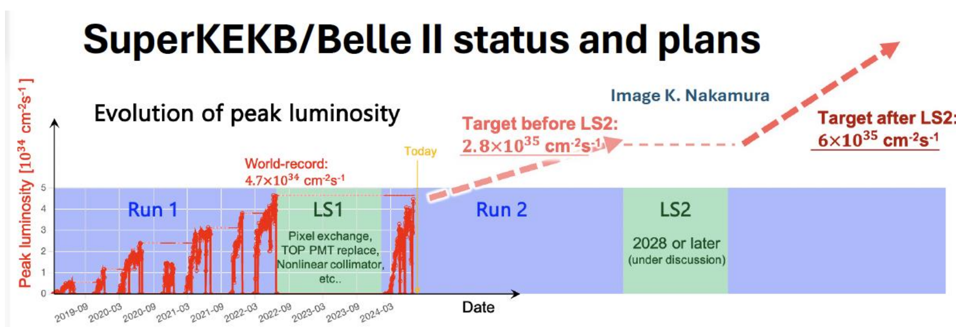


# $e^+e^-$ at the Upsilon(4S)

An ideal energy to study B° and B+/- decays is just above BB threshold on the Υ(4S) resonance, at a mass of 10.579 GeV/$c^2$.

- The cross section is about 1.1 nb, so relatively large
- An event can be either $e^+e^- \rightarrow B^+B^-$ or $B^0B^0$
- The "background from other hadronic production (u,d,s,c quarks) is only about 5 times higher, so relatively favorable compared to production at hardon colliders
- For time dependent studies, the beams can be run asymmetrically so the Υ is moving in the lab frame and the boost allows time-dependent measurements
  - Asymmetric beams of 3.5 and 8 GeV result in βγ for the Upsilon of 0.45
- Luminosities of $10^{35}$ have been achieved and 5 x$10^{35}$ are planned at KEK




- Run 2 is long – end 2028 or later
  - Steady accumulation at ~2 x $10^{35}$ $cm^{-2}s^{-1}$ for several $ab^{-1}$ – 2nd generation
  - After Run 2 – upgrade proposal for reach design luminosity and tens of $ab^{-1}$

# Good and bad of $e^+e^-$ b-factories on the Upsilon(4S)

- The good:
  - Flavor tagging is relatively simple
  - The knowledge of the CoM energy provides constraints that allow you to infer, e.g., the energy of a single undetected neutrino and to constrain the kinematics of two undetected neutrinos
  - Particle id is challenging but doable
  - Triggering, if needed at all, is simple
- The bad
  - Can only study $B^0$ and $B^{+,-}$
  - **The B factories have produced much more luminosity than even their optimistic supporters believed possible. Still, many key CPV studies are statistics limited and many rare decays simply require more B production than will ever be achieved**

# B Physics on the peak at $e^+e^-$ Z factories

- The hadronic cross section at the Z-peak is ~30 nb.
  - ~ 22% of this is production of states with b-quarks and 17% c-quarks
  - All types of b-mesons and baryons, are produced with production fractions given in the table
  - The average boost is large, so time-dependent mixing and CPV studies are possible
  - The tagging efficiency can be quite large
  - The fraction of times that two interactions or more occur in the same bunch crossing (pileup) is very low

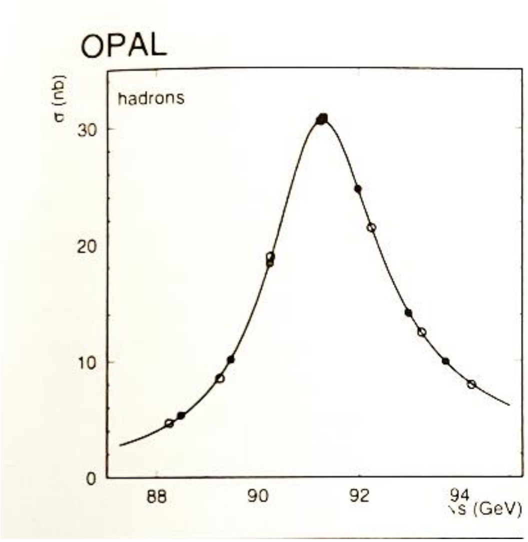



Table 1-3. *LEP/SLD $R_b$ and $R_c$ measurements*

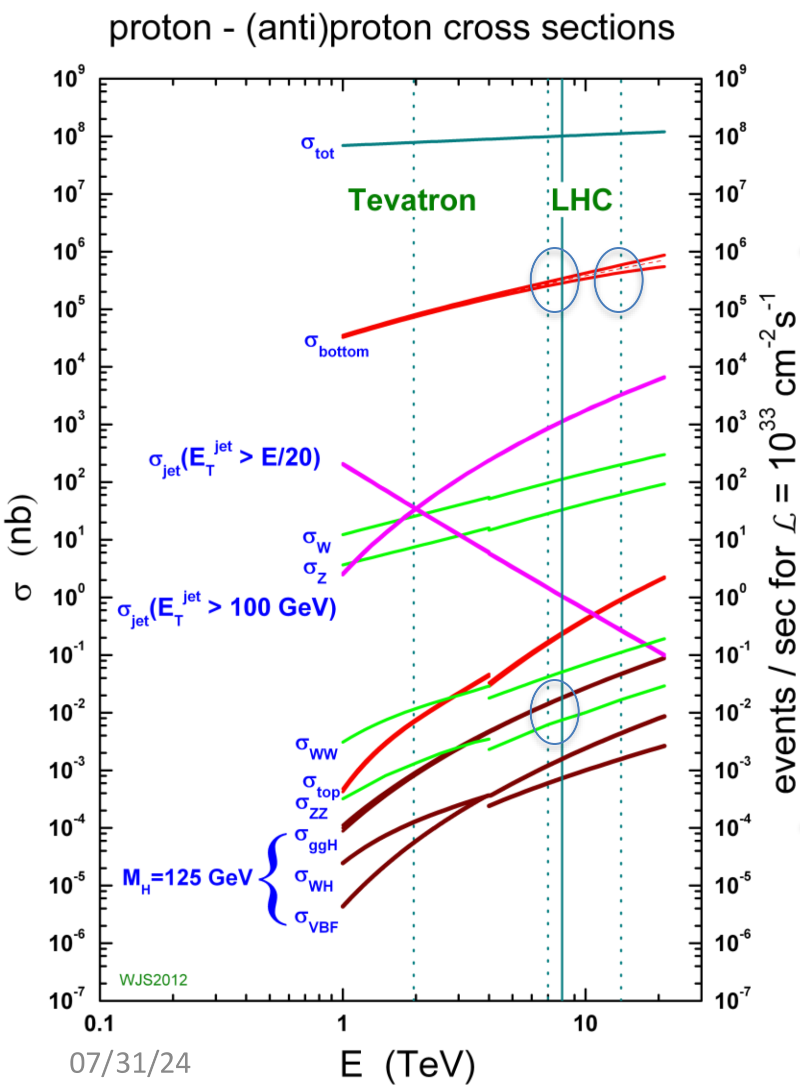
| | LEP/SLD | SM |
|---|---|---|
| $R_b$ | $0.2170 \pm 0.0009$ | $0.2157 \pm 0.0002.$ |
| $R_c$ | $0.1734 \pm 0.0048$ | $0.1722 \pm 0.0001$ |

*Summary of b-hadron production fractions at Z peak*

| b-hadron | Fraction (%). |
|---|---|
| $f(b \to B^-)$ | 37.8±2.2 |
| $f(b \to \overline{B}^0)$ | 37.8±2.2 |
| $f(b \to \overline{B}^0_s)$ | $11.2^{+1.8}_{-1.9}$ |
| $f(b \to \Lambda_b)$ | 13.2±4.1 |

- LEP recorded ONLY ~195 $pb^{-1}$ of data on the Z, providing each of its 4 experiments with about $4\text{x}10^6$ events/experiment with Zs decaying to hadrons
  - Peak luminosity was ~$10^{30}$.
- The proposed FCC-ee which would begin to operate after 2045 and would achieve in 4 years $1.82\text{X}10^{36}$ or 87 $ab^{-1}$/yr (for 4 ips combined)
  - **348 $ab^{-1}$ total ➔TeraZ!**
  - An ILC-type machine cannot achieve comparable rates on the Z peak

# B Production at the LHC




LO – Pair creation

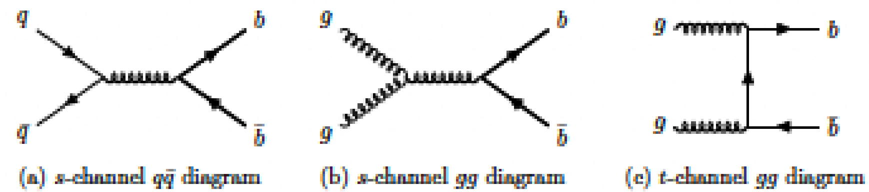
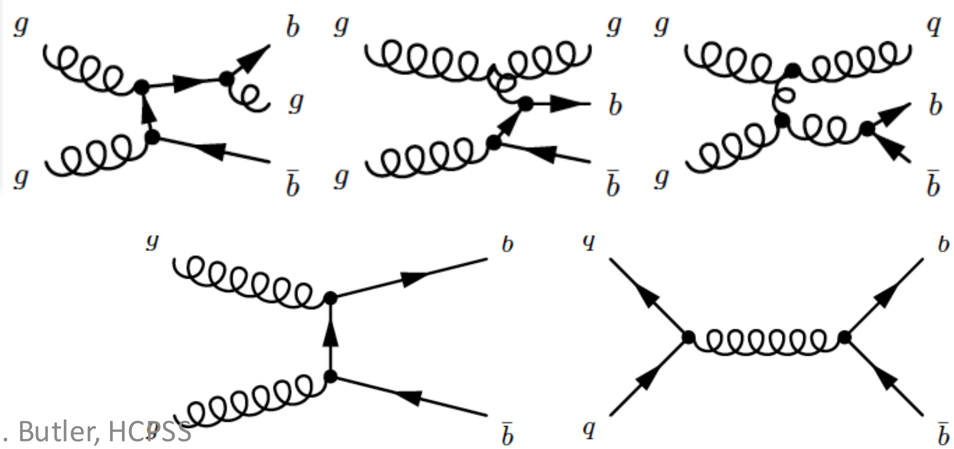
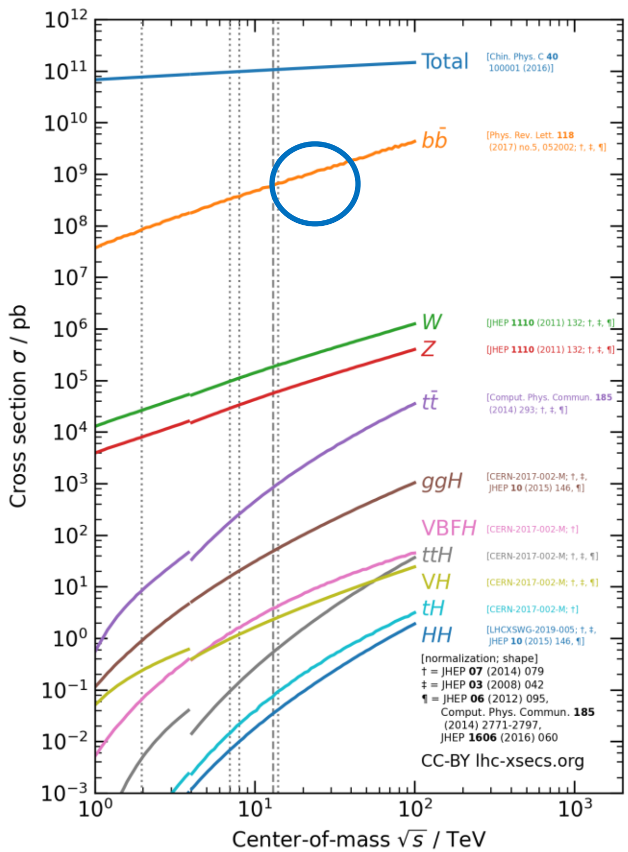



Figure 1: Feynman diagrams for the process $pp \to b\bar{b}$ at LO.

NLO –
pair creation, Flavor Excitation, Gluon splitting



# How to produce enough b-quarks to study rare processes-hadron machines




F. Sauerburger, *LHC cross section plot*, https://lhc-xsecs.org/

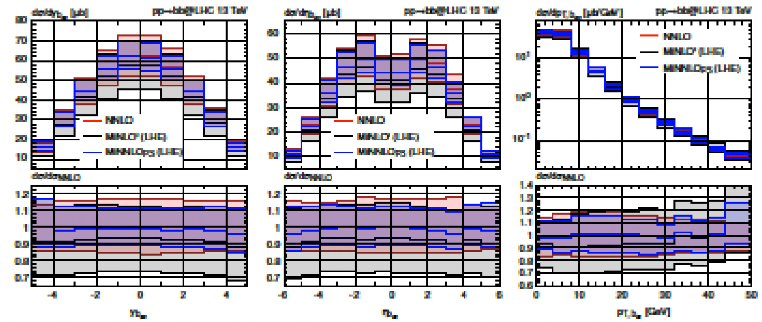



Figure 2: Validation of MiNNLO$_{PS}$ predictions against NNLO QCD results. See text for details.

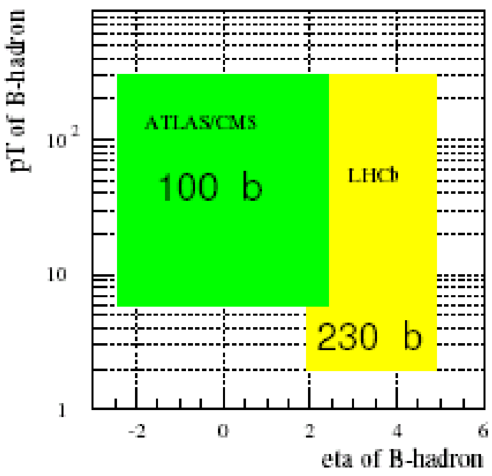
| Analysis | Energy | Process | Measured cross section ($\mu b$) | MiNNLO$_{PS}$ ($\mu b$) |
|---|---|---|---|---|
| ATLAS [12] | 7 TeV | $pp \to B^+ + X$ | $10.6 \pm 0.3_{(stat)} \pm 0.7_{(syst)} \pm 0.2_{(lumi)} \pm 0.4_{(bf)}$ | $10.17(5)^{+13.3\%}_{-14.0\%}$ |
| CMS [16] | 13 TeV | $pp \to B^+ + X$ | $15.3 \pm 0.4_{(stat)} \pm 2.1_{(syst)} \pm 0.4_{(lumi)}$ | $11.47(6)^{+11.3\%}_{-13.2\%}$ |
| LHCb–1 [19] | 7 TeV | $pp \to B^\pm + X$ | $38.9 \pm 0.3_{(stat)} \pm 2.5_{(syst)} \pm 1.3_{(bf)}$ | $42.2(1)^{+13.9\%}_{-11.4\%}$ |
| | | $pp \to B^0 + X$ | $38.1 \pm 0.6_{(stat)} \pm 3.7_{(syst)} \pm 4.7_{(bf)}$ | $42.3(1)^{+14.7\%}_{-11.3\%}$ |
| | | $pp \to B^0_s + X$ | $10.5 \pm 0.2_{(stat)} \pm 0.8_{(syst)} \pm 1.0_{(bf)}$ | $9.32(6)^{+13.6\%}_{-11.5\%}$ |
| LHCb–2 [21] | 7 TeV | $pp \to B^\pm + X$ | $43.0 \pm 0.2_{(syst)} \pm 2.5_{(stat)} \pm 1.7_{(bf)}$ | $42.2(1)^{+13.9\%}_{-11.4\%}$ |
| | 13 TeV | $pp \to B^\pm + X$ | $86.6 \pm 0.5_{(stat)} \pm 5.4_{(syst)} \pm 3.4_{(bf)}$ | $78.5(3)^{+9.0\%}_{-9.3\%}$ |
| LHCb–3 [20] | 7 TeV | $pp \to B + X$ | $72.0 \pm 0.3_{(stat)} \pm 6.8_{(syst)}$ | $65.3(1)^{+12.6\%}_{-10.5\%}$ |
| | 13 TeV | $pp \to B + X$ | $144 \pm 1_{(stat)} \pm 21_{(syst)}$ | $116.2(3)^{+7.6\%}_{-12.3\%}$ |

Table 1: Fiducial cross sections for the production of different $B$ hadron final states for various LHC analyses and compared against MiNNLO$_{PS}$ predictions. See text for details.

Total b cross section ~ 480 μb

# B Physics at LHC

- **B cross section huge: ~ 500 μb**
- Design luminosity is ~ $10^{34}$/cm$^2$-s
  - With an average of ~23 interactions/crossing (crossing interval= 25 ns)
  - Total interaction rate ~$10^9$/s
- Radiation damage prevents running vertex detectors too close to the IR
- Triggering at these rates is very difficult. Bandwidth to tape is only ~ hundred/s
  - Single muon trigger with $P_t$ threshold on the muon
  - Dimuon trigger with lower $P_t$ thresholds but on each muon
  - Some attempt to use electron triggers (but conversions, smearing due to bremsstrahlung)
- **Early running will be at ~$10^{33}$/cm$^2$-s. Most of the "general B physics" for ATLAS/CMS will be done at these "low" luminosities**
  - **At $10^{34}$/cm$^2$-s, will focus on very rare decays involving muons, for which reasonable triggers, mainly DIMUON, can be developed**
- **LHCb covers the forward rapidity region and is rate limited by the detector and trigger. It expects to run at around 2x $10^{32}$/cm$^2$-s,**



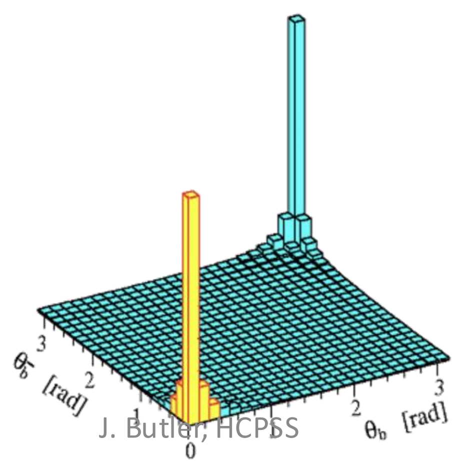
# B Physics with CMS and ATLAS

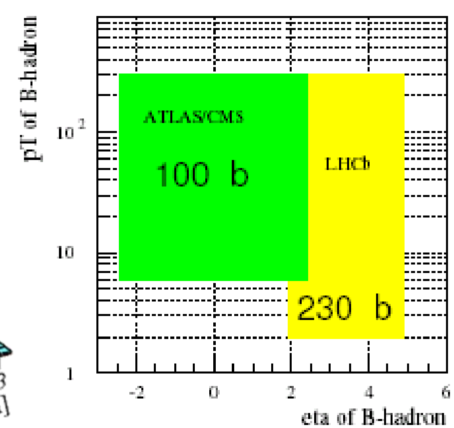
- Detectors aimed at physics frontier at high mass and high transverse momentum: Higgs, SUSY, new vector bosons, leptoquarks, new dynamics …
- They are equipped with many features that enable B physics
  - Vertex detectors – needed for B and $\tau$ jet tagging, important signatures of new physics
  - Muon and electron detection
  - Photon detection
- But they are not ideally equipped for B physics
  - No particle identification
  - Triggering problems – limited bandwidth already mostly oversubscribed by "high $P_t$ physics."

# B Physics: "General Purpose (i.e. high $P_t$)" Detectors vs Dedicated B Detectors

- **Detectors aimed at studying high mass or high $P_t$ phenomena focus on the central region, where the acceptance is high**
- **There is plenty of B production into this acceptance, but**
  - **The triggering problems in these detectors force a choice between B physics and other "discovery physics"**
- **The high energy, large time dilation and lower multiple scattering, and the availability of good particle identification techniques in the forward direction offer some advantages for dedicated B experiments. Good particle identification requires space and is more compatible with a forward geometry.**

**•LHCb is the first dedicated B detector at a hadron collider.**
**•For both central and forward detectors triggering is a problem and one that still needs work**



# FEATURES OF SELECTED OBSERVABLES AND OBJECTS NEEDED TO DETECT B DECAYS

# Requirements on Hadron Collider B Experiments

- **Ability to run at high luminosity with high efficiency and operate for long periods of time in high radiation fields without performance degradation**
- **A magnetic spectrometer with good acceptance for B decays products, signal and tags, and good momentum and mass resolution for isolating B signals with low background**
- **Superb vertex resolution for background rejection and for measuring rapid oscillations and small lifetime differences in the $B_s$ system**
- **A very efficient trigger for a wide variety of "hadron-only" final states with "hadron-only" tags and of course good lepton triggers**
- **An excellent particle identification system to avoid kinematic reflections and to do efficient flavor tagging**
- **Ability to reconstruct individual photons, $\pi^o$'s, and $\eta$'s with high efficiency for the many interesting states containing neutrals.**
- **A very high speed, high-capacity data acquisition system**

# Lifetime Measurements

- Measurement of the proper decay time (derived from the distance, L, of the decay vertex from the primary interaction vertex and the momentum derived from the decay products) is essential
  - To measure the time dependent asymmetries, mixing parameters, and lifetimes of B decays
  - To identify particles with vertices detached from the main interaction vertex as a way of reducing "prompt" background
    - The decays of the lightest B mesons and baryons have lifetimes of ~1.5 ps, i.e. fairly long-lived
    - The degree of detachment $L/\sigma(L)$ needed in each analysis depends on the magnitude and types of backgrounds one is trying to defeat. Typically, 5 is good number
  - Some oscillation parameters especially in $B_s$ decays are quite rapid, requiring much better resolution than needed for lifetime measurements or for background rejection

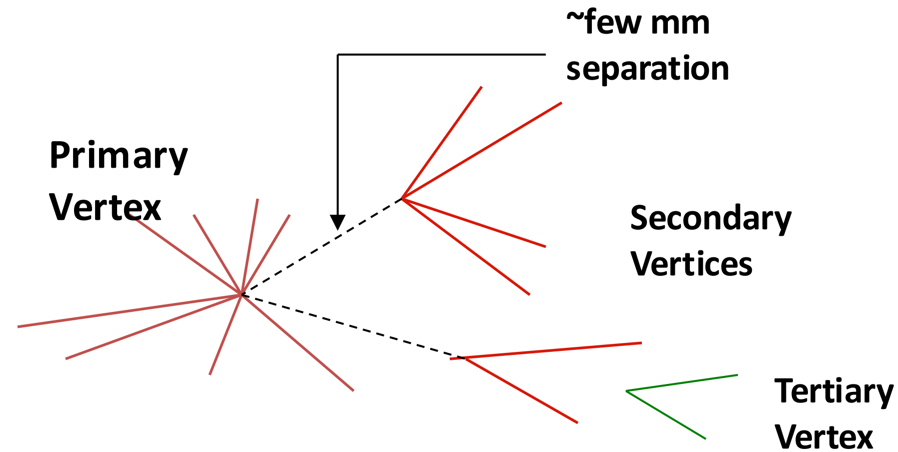
# Fundamentals: Decay Time Resolution

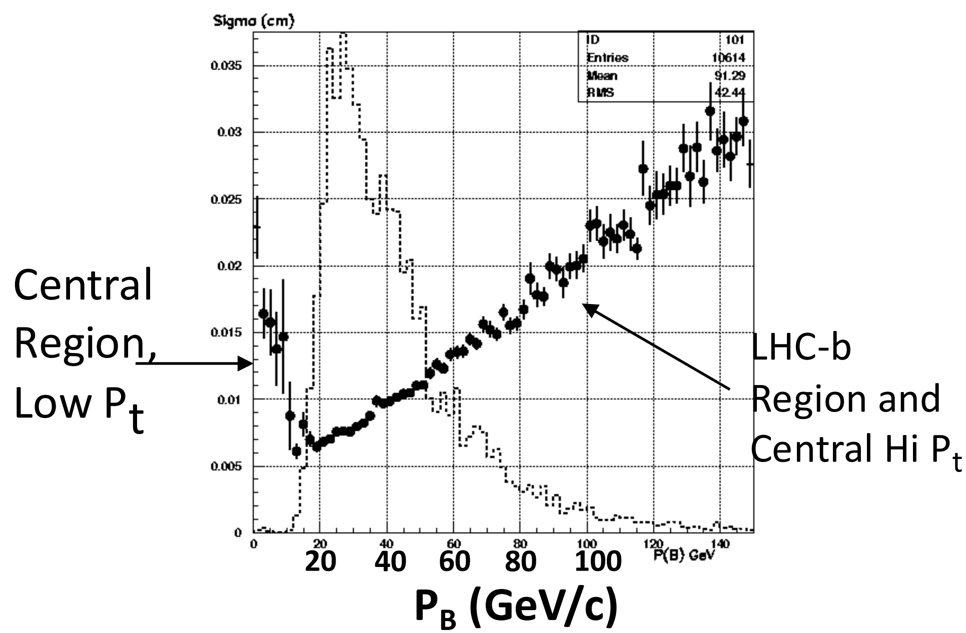
- Excellent vertex resolution
  - Separation of primary, secondary, tertiary vertices
    - **Suppresses combinatoric background**
    - **Permits measurement of proper decay times**
    - **Allows detached vertex trigger**
- **The average decay distance and the uncertainty in the average decay distance are functions of B momentum:**

$\langle L \rangle = \gamma\beta c\tau_B = 480\ \mu m \times p_B/m_B$

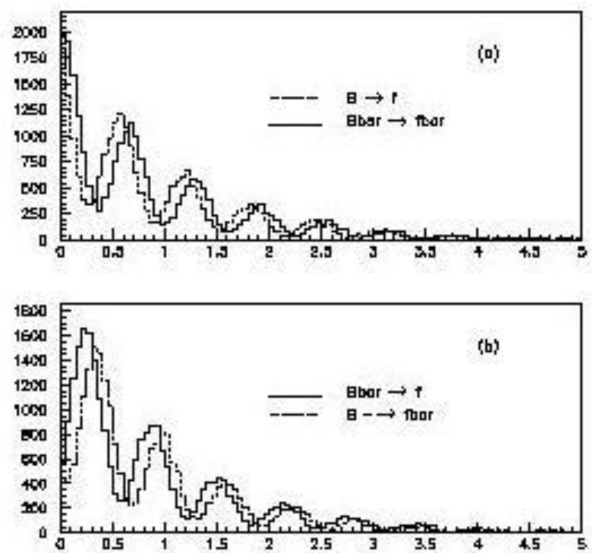
$\langle\sigma\rangle_L \sim 1/(\text{opening angles}) \sim \gamma_B \sim P_B$

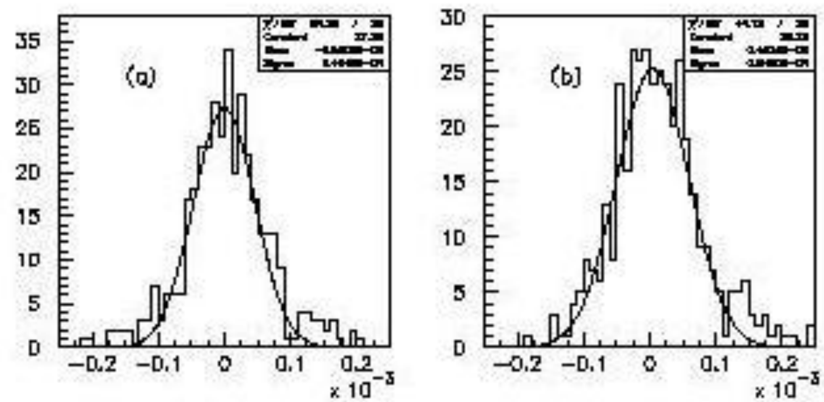
  - **L/σ(L)= significance of detachment is ~independent of momentum.**
  - **Degraded by multiple scattering.**
  - Momentum uncertainty also enters
- In 3D, you need to find the correct vertex out of ~40-60 (CMS, ATLAS) or can use 2D and the transverse beam spot. In fact, the experiments use both.



# Measurement of Time Evolution



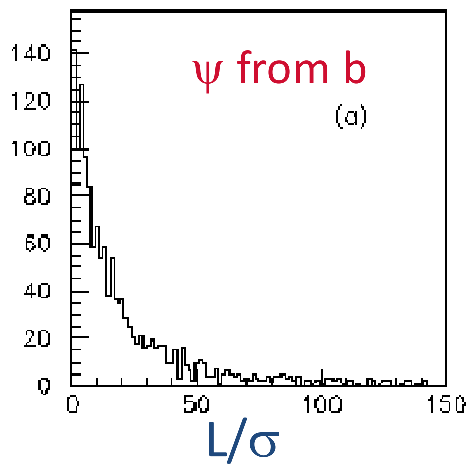

$$\text{For } x_s = \frac{\Delta M_s}{\Gamma_s} = 20, \text{ period is} \sim 500\, fs$$

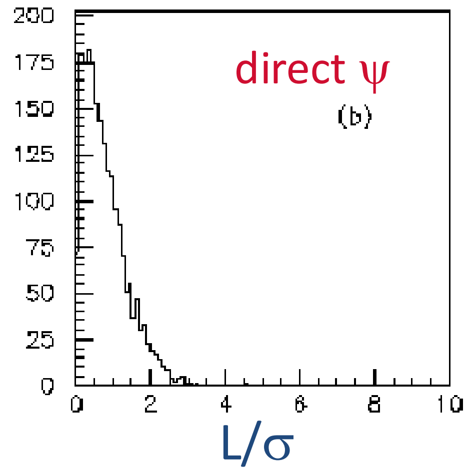
$$\frac{x_s}{x_d} = \frac{|V_{ts}{}^2|}{|V_{td}{}^2|}\ (\text{SM}: X_s = 20-28)$$

**Most experiments have silicon microstrip vertex detectors or pixel detectors and achieve resolutions in proper time ~ 45-65 fs!**

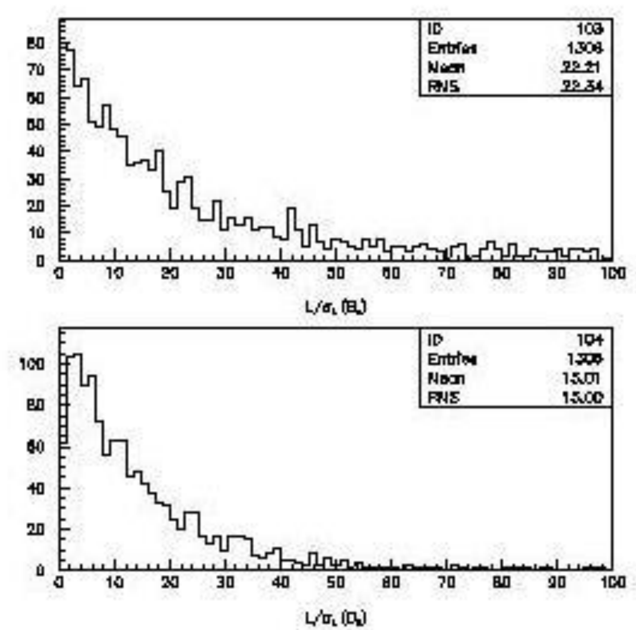
**$B_s$ mixing properties set the time resolution requirements for hadronic B experiments**. The lifetime difference between the $B_s^H$ and $B_s^L$ is expected to be about 10% of the $B_s$ lifetime, or about 160 fs. The rapid $B_s$ oscillation have a period of about 350 fs so excellent resolution is needed for these two studies.

# Signal Reconstruction, Elimination of Background



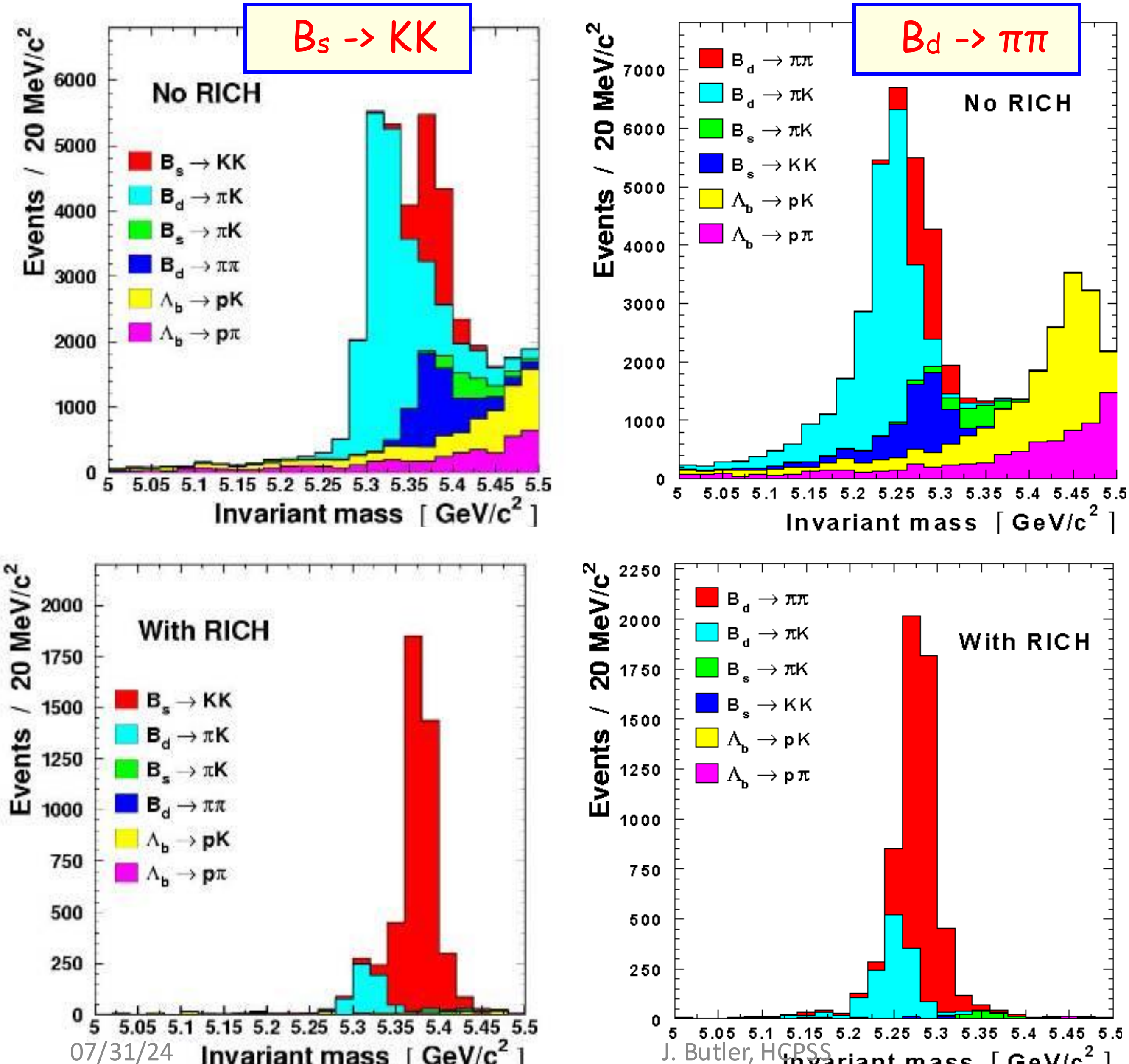




**L/σ> 3,4 rejects prompt "background"**



**$\langle L \rangle / \langle \sigma \rangle_L$ for $B_S$ (top) and $D_S$ daughter (bottom)**

# Particle Identification:Avoiding Kinematical Reflections (LHCb)

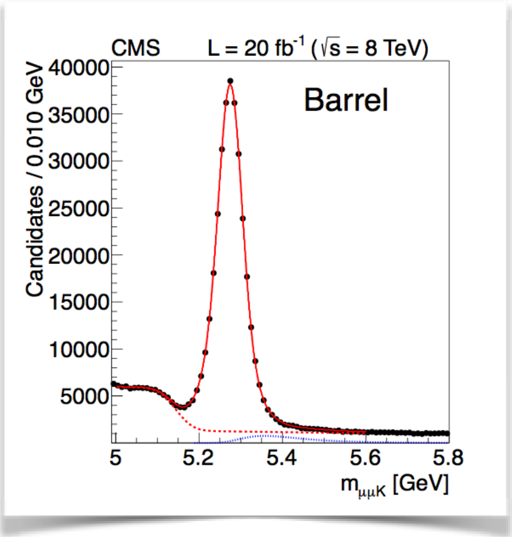



**Mis-assigning mass values can result in a broad background or, even worse, a peaked background, in the vicinity of the signal.**

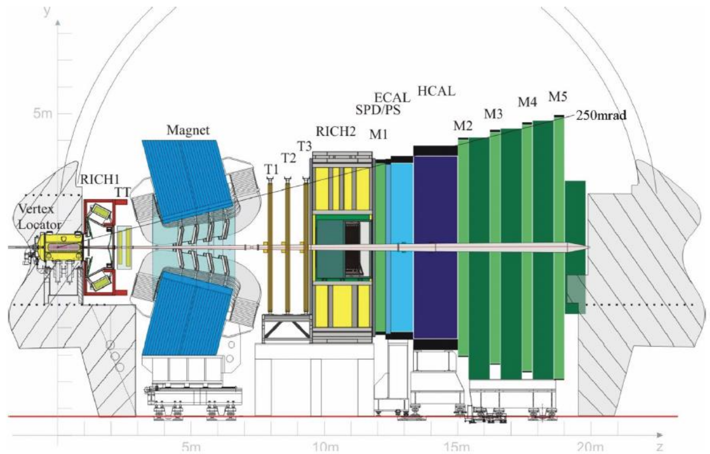
- **Central detectors have space(radial) limitations and at best have dE/dx and TOF for PID. Usually not effective above ~ 1-2 GeV/c**
- **Forward detectors have room (longitudinal) for Gas-Ring Imaging Cerenkov detectors**

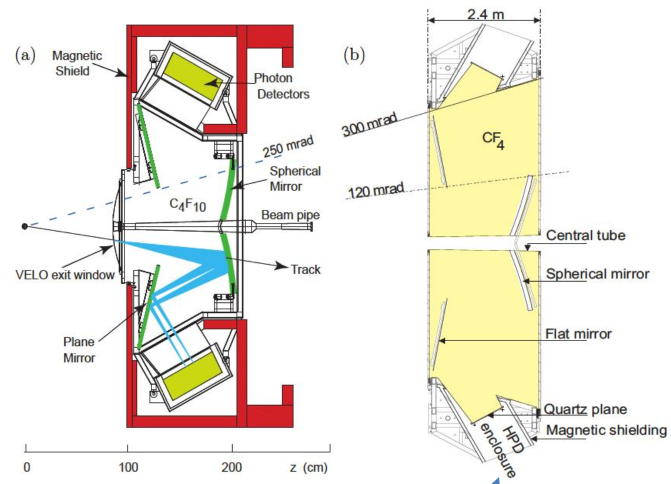
# Example of $B+ \rightarrow J/\psi\ (\mu^+\mu^-)K^+$ in CMS

- Early 8 TeV result

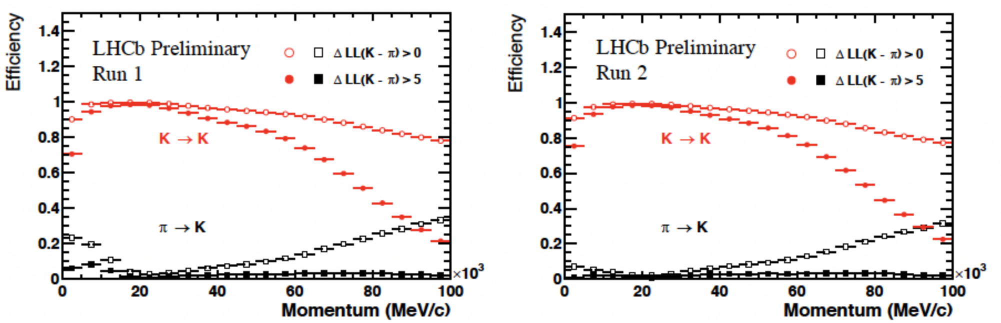


# LHCb Particle ID – 2 to 100 GeV




he optical system of (a) RICH1 and (b) RICH2 [2].



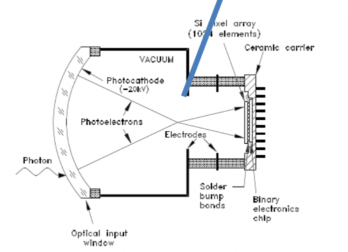




Figure 3: Kaon identification efficiencies (red markers) and $\pi \to K$ mis-identification (black markers) probabilities during (left) Run 1 and (right) Run 2, for two different values of $\Delta \log \mathcal{L}(K-\pi)$ requirement: (empty markers) looser requirement and (filled markers) tighter requirement.

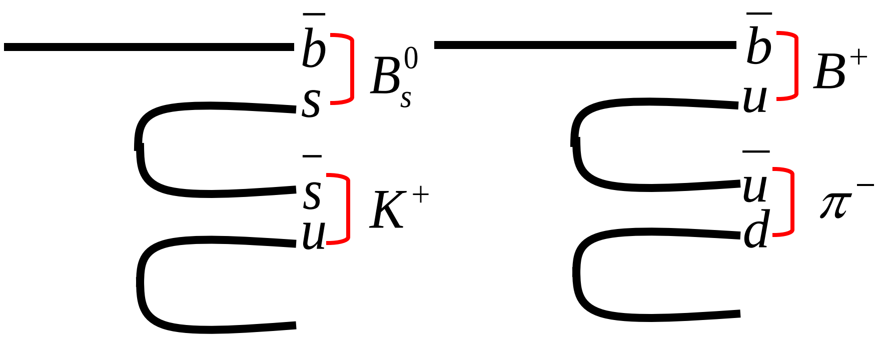
# Importance of Particle Identification
# Flavor Tagging

**To compare the time evolution of a B meson and its anti-particle, must determine the "flavor" of the particle "at birth". This is called "flavor tagging."**

**• "Away-side" method – use properties of the "other B" in the Event to determine its probable flavor, so the B you are observing must have the opposite flavor (beware of "away side Mixing"). The following properties have been used classically**

- **Lepton (muon, electron) charge from semi-leptonic decay**
- **Jet charge**
- **Kaon charge (PARTICLE ID crucial)**

**• "Same-side" method – use properties of fragmentation tracks produced with "signal side particle." (PARTICLE ID crucial). "Same" means close in rapidity.**



# The General Triggering Problem for Hadron Colliders Detectors

- **The inelastic cross section is much larger than the b-cross section: x500 at the Tevatron and x200 at the LHC. Total interaction rate at LHC ~1 GHz (LHC at original design luminosity)**
- **Topologically, B events are not that different from large numbers of minimum bias (or "typical") inelastic events, except for the presence of secondary vertices from the B decays, 100 to 10000 microns from primary vertex.**
- **Output bandwidth to archival storage limits the amount of data you can store to ~500 Mbyte/s. This is of order a few hundred to a few thousand events/s**
- **High $P_t$ experiments look for very rare processes and therefore run at the highest possible rate, e.g. >2x$10^{34}$/cm$^2$-s for ATLAS and CMS.**
  - **~ 2 Billion interactions/s**
- **Severe triggering problem, both for the rejection required, the complexity of the "crossings", and the speed at which it must be done**

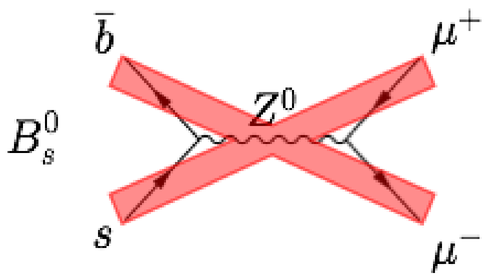
# The Muon Trigger and Beyond

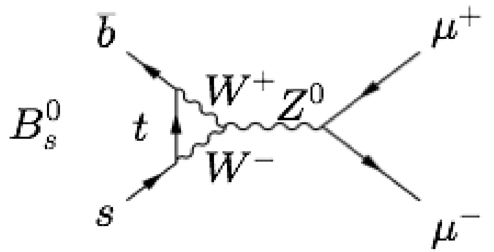
- Muons are a good Level 1 Trigger for B Physics in High $P_t$ experiments
  - **Large effective branching fraction for nearly all types of B decays due to large semimuonic branching ratio, 10%.**
  - **The "away side" opposite the semileptonic decay is unbiased with respect to final states**
  - **Signals from muon detectors are relatively straightforward to process in the short period of time allowed for the Level 1 trigger (typically a few microseconds).**
  - **Many interesting B states have two muons, e.g. states going to $J/\psi$, $B_{d,s} \to \mu^+\mu^-$, Penguin decays, such as $B \to K^* \mu^+\mu^-$.**
- But, muons have limitations
  - **Branching fractions – still take a big hit**
  - **$P_t$ cutoff**
    - **The $P_t$ dependence allows one to control the trigger rate at the cost of efficiency**
- **You have heard in these lectures about**
  - **New types of triggers beyond muons, such as displaced vertex triggers, that will be especially effective for B physics**
  - **New strategies for overcoming bandwidth, data, storage, and data processing techniques to accept more B events**
    - **Parking**
    - **Scouting**

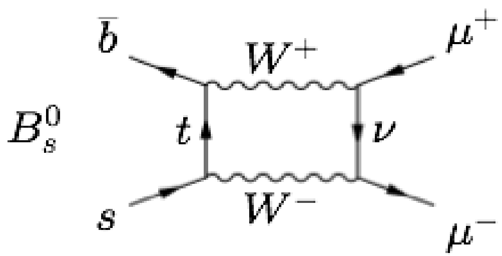
# $B_{s,d} \rightarrow \mu^+\mu^-$: the potential for New Physics

In the SM, $B_{s,d} \rightarrow \mu^+\mu^-$ decays are <u>**highly suppressed r**</u>esulting **tiny branching fractions**, but <u>are *robust SM theory predictions.*</u>

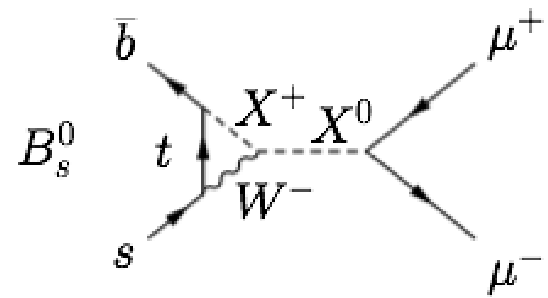
- Loop diagram + Suppressed SM + Theoretically clean ➔ <u>***An excellent place to look for new physics***</u>.

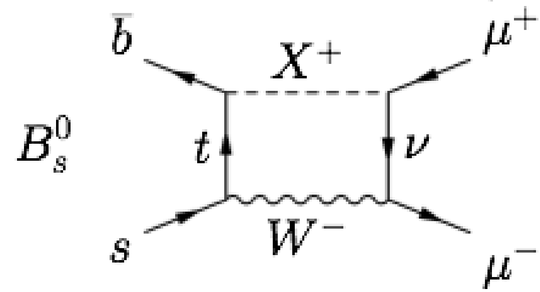



This will be the first case study in session 2




**Any difference in branching fraction from SM could provide a strong indication of new physics.**

Thank you for your attention! I will be glad to try to answer questions and hear your comments.

# Backup Slides

# Mixing-Induced CPV schematic

- A

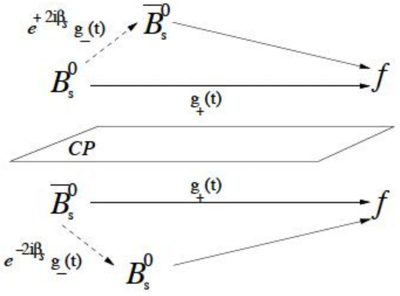
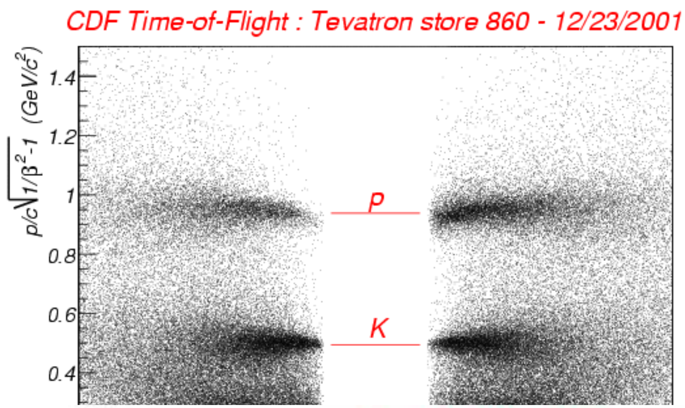
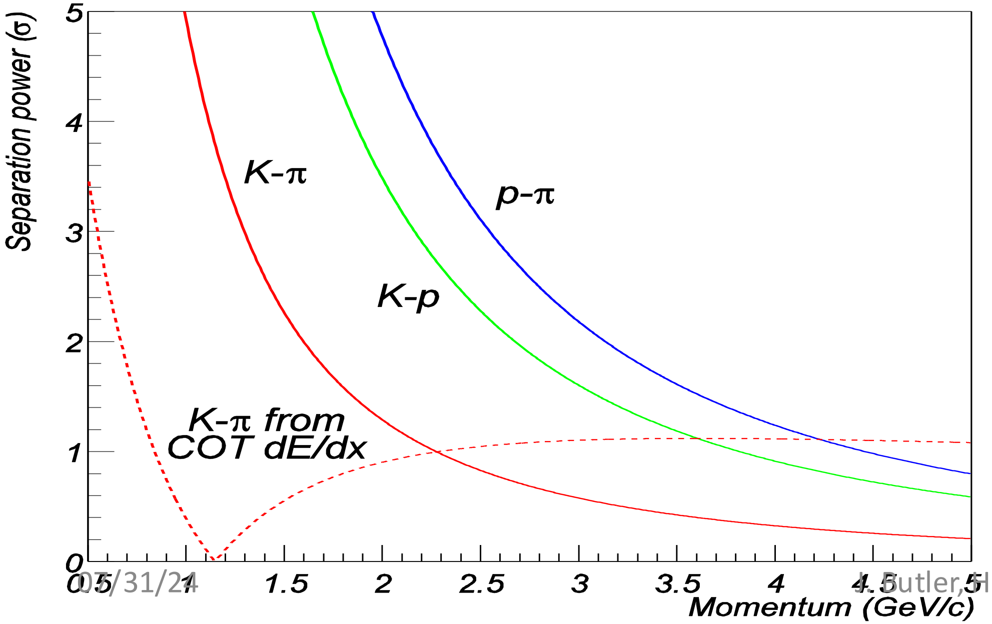


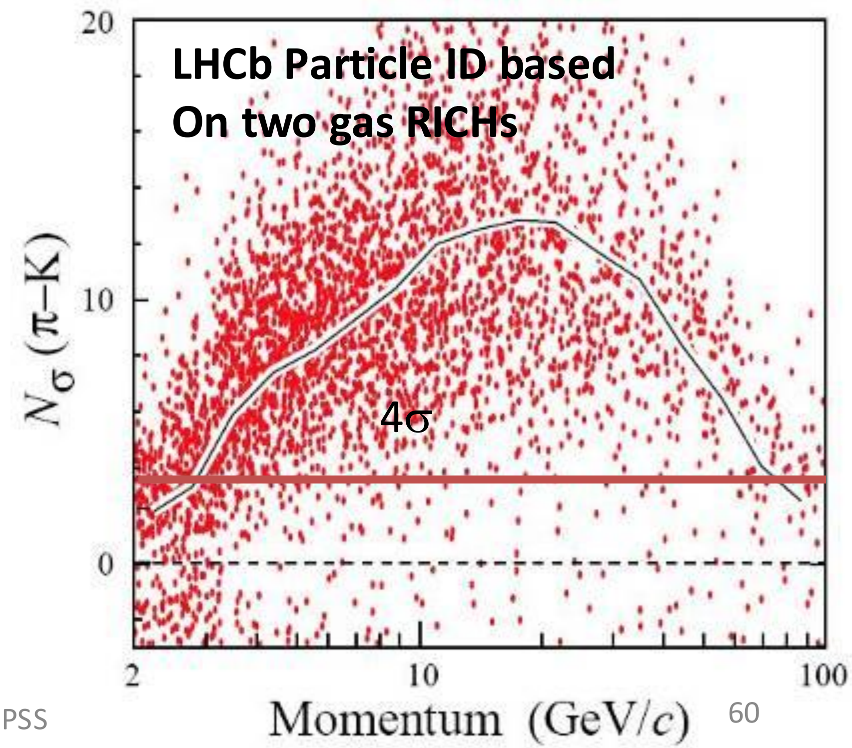

Figure 2.8: *CP violation from interference. The upper figure describes the decay of the* $B_s^0$ *meson to the CP-eigenstate* $f$*, the lower the CP-conjugated decay of the* $\bar{B}_s^0$ *to the same final state. The upper decay occurs with a weak phase* $+2\beta_s$*, the lower with* $-2\beta_s$

# Particle ID

- K/π/p separation improves S/B for B signal and flavor tagging
- Central Detctor
  - Time of Flight
    - $\sigma_t$ ~100 ps, L ~ 1.5 m
    - 2σ K/π separation for p~1.5 GeV
  - COT dE/dx
  - 1.3σ K/π separation for p > 2GeV
- Forward Detector
  - Gas Ring Imaging Cerenkov Counters



# Miscellaneous

| Particle | Lifetime [ps] |
|---|---|
| $B^+$ | $1.638 \pm 0.004$ |
| $B^0$ | $1.519 \pm 0.004$ |
| $B^0_s$ | $1.516 \pm 0.006$ |
| $B^0_{sL}$ | $1.427 \pm 0.007$ |
| $B^0_{sH}$ | $1.616 \pm 0.010$ |
| $B^+_c$ | $0.510 \pm 0.009$ |
| $\Lambda^0_b$ | $1.471 \pm 0.009$ |
| $\Xi^-_b$ | $1.572 \pm 0.040$ |
| $\Xi^0_b$ | $1.480 \pm 0.030$ |
| $\Omega^-_b$ | $1.64^{+0.18}_{-0.17}$ |

The study of the decay $B \to D\ell\nu$ poses new challenges from the experimental point of view. The differential decay rate for $B \to D\ell\nu$ can be expressed as [106]

$$\frac{d\Gamma_D}{dw}(B \to D\ell\nu) = \frac{G_F^2|V_{cb}|^2}{48\pi^3}\mathcal{K}_D(w)\mathcal{G}(w)^2, \quad (60)$$

where $\mathcal{K}_D(w)$ is the phase space factor and the form factor $\mathcal{G}(w)$ is generally expressed as the product of a normalization factor $\mathcal{G}(1)$ and a function, $g_D(w)$, constrained by dispersion relations [92]. The strategy to extract $\mathcal{G}(1)|V_{cb}|$ is identical to that used for the $B \to D^\star\ell\nu$ decay. However, $d\Gamma_D/dw$ is more heavily suppressed near $w=1$ than $d\Gamma_{D^\star}/dw$ due to the helicity mismatch between initial and final states. Moreover, this channel is much more challenging to isolate from the dominant background $B \to D^\star\ell\nu$ as well as from fake $D$-$\ell$ combinations. Table 4 shows the results of two-dimensional fits to $|V_{cb}|\mathcal{G}(1)$ and $\rho^2$ for different experiments and the world average.

The matrix element for the weak decay is:

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} f_\pi q^\mu \left(\bar{u}_\mu \gamma^\mu \frac{1}{2}(1-\gamma^5) u_{\nu_\mu}\right)$$

where $f_\pi$ is the charged pion **decay constant**
(probability that quark-antiquark annihilate inside pion)

The matrix element squared in the rest frame of the pion is:

$$|\mathcal{M}|^2 = 4G_F^2 f_\pi^2 m_\mu^2 [p_3 \cdot p_4]$$

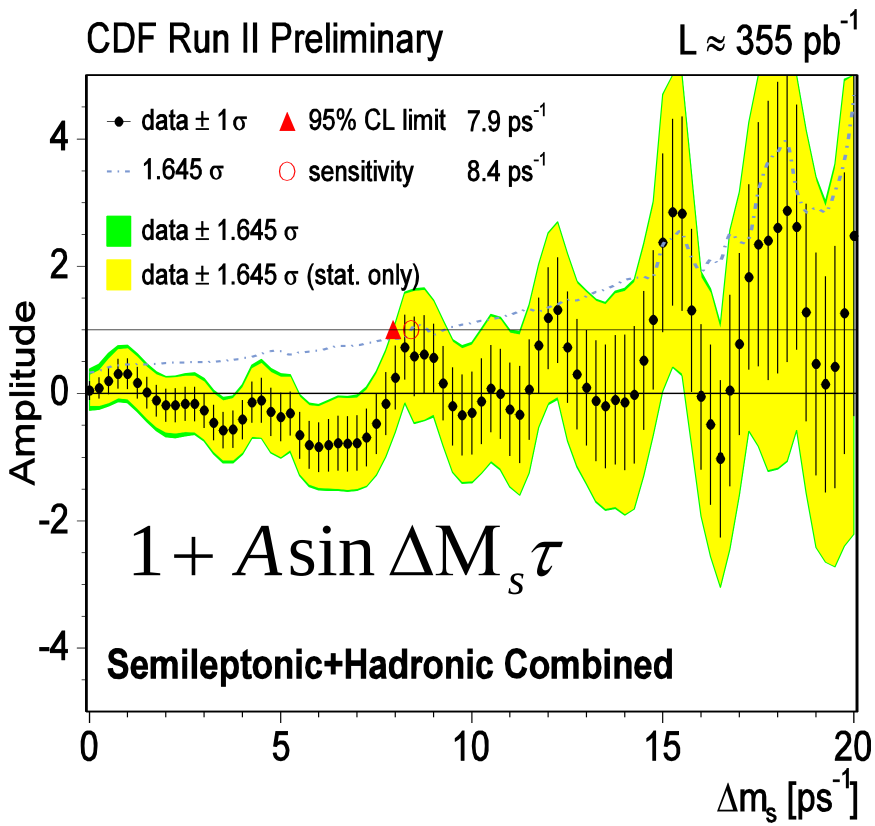
$$\Gamma_\pi = \frac{1}{\tau_\pi} = \frac{G_F^2}{8\pi} f_\pi^2 m_\pi m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2$$

Charged pion mass, lifetime and decay constant:

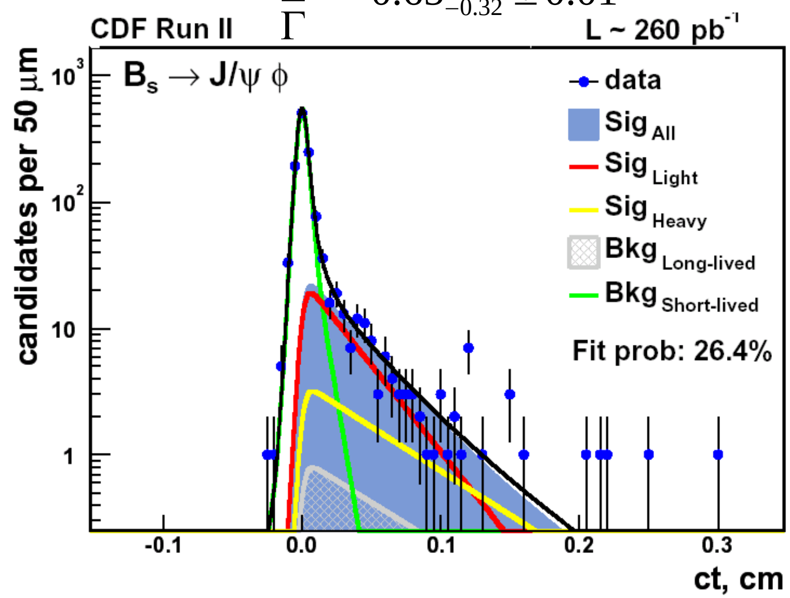
$m_{\pi+} = 139.6\text{MeV}$ $\quad \tau_{\pi+} = 26ns$ $\quad f_\pi = 131\text{MeV}$

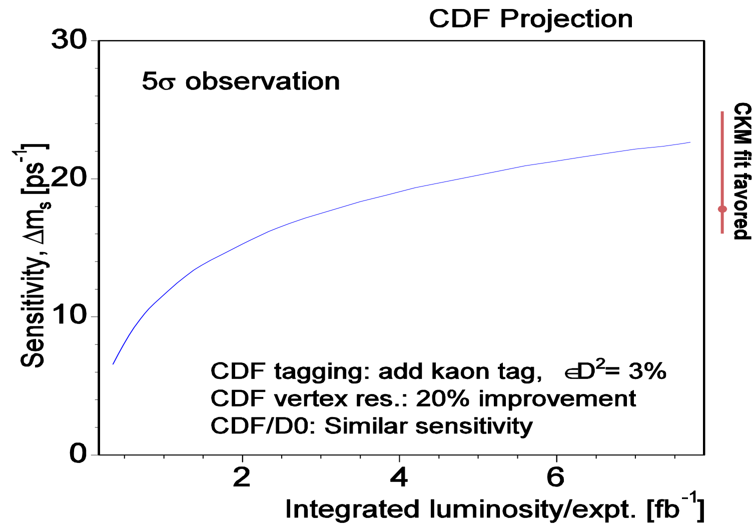
# CDF $B_s$ Mixing and $\Delta\Gamma_s$ Result

- **Semileptonic + Hadronic**
  - **Sensitivity: 7.4 → 8.4 $ps^{-1}$**
  - **Limit: 7.7 → 7.9 $ps^{-1}$**



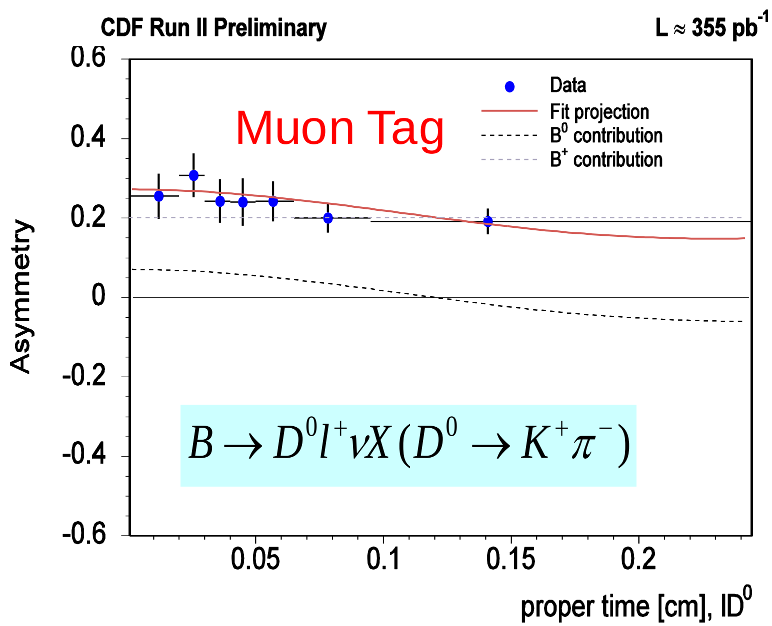

$$\frac{\Delta\Gamma_s}{\overline{\Gamma}} = 0.65^{+0.25}_{-0.32} \pm 0.01$$

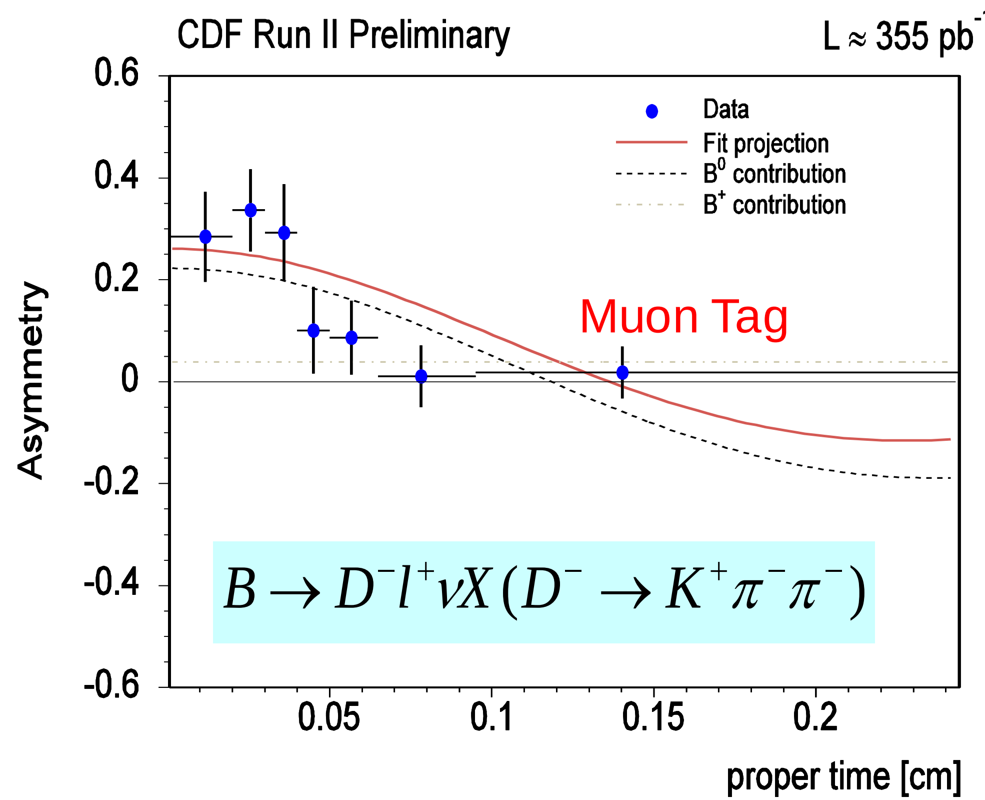


# $B^0_d$ Mixing (Semileptonic)

- **Validation of the flavor tag calibration using $B^0$ and $B^+$ sample**
  - **$B^0 \rightarrow D^- l\nu$, $B^+ \rightarrow D^0 l\nu$**
- **Measured $\Delta m_d$**
  - **$(0.498 \pm 0.028 \pm 0.015)\ ps^{-1}$**
  - **WA: $(0.510 \pm 0.005)\ ps^{-1}$**



# Summary Key of Detector Features for B Physics at Hadron Colliders

| Physics Quantity | Decay Mode | Vertex Trigger | K/π sep | γ det | Decay time σ |
|---|---|---|---|---|---|
| $\sin(2\alpha)$ | $B^o \to \rho\pi \to \pi^+\pi^-\pi^o$ | ✓ | ✓ | ✓ | |
| $\sin(2\alpha)$ | $B^o \to \pi^+\pi^-$ & $B_s \to K^+K^-$ | ✓ | ✓ | | ✓ |
| $\cos(2\alpha)$ | $B^o \to \rho\pi \to \pi^+\pi^-\pi^o$ | ✓ | ✓ | ✓ | |
| $\mathrm{sign}(\sin(2\alpha))$ | $B^o \to \rho\pi$ & $B^o \to \pi^+\pi^-$ | ✓ | ✓ | ✓ | |
| $\sin(\gamma)$ | $B_s \to D_s K^-$ | ✓ | ✓ | | ✓ |
| $\sin(\gamma)$ | $B^o \to D^o K^-$ | ✓ | ✓ | | |
| $\sin(\gamma)$ | $B \to K\pi$ | ✓ | ✓ | ✓ | |
| $\sin(2\chi)$ | $B_s \to J/\psi\eta'$, $J/\psi\eta$ | | ✓ | ✓ | ✓ |
| $\sin(2\beta)$ | $B^o \to J/\psi K_s$ | | | | |
| $\cos(2\beta)$ | $B^o \to J/\psi K^*$ & $B_s \to J/\psi\phi$ | | | | |
| $x_s$ | $B_s \to D_s\pi^-$ | ✓ | ✓ | | ✓ |
| $\Delta\Gamma$ for $B_s$ | $B_s \to J/\psi\eta'$, $K^+K^-$, $D_s\pi^-$ | ✓ | ✓ | ✓ | ✓ |

Note how many important states have γ's in them!!!

# Hierarchical Trigger Scheme

- The large rate of "typical interactions" compared to "interesting" ones leads to a "hierarchical" trigger scheme
  - Level 1 is usually has "fixed latency" and must inspect every beam crossing, almost always with specialized, custom trigger hardware.
    - **"Latency" is defined as the time between the beam crossing and the time when the trigger decision is returned to the front end electronics and readout is started. It is the time during which data must be stored while the trigger decision is being made. Trigger decisions must be made at the beam crossing rate, but the time permitted to make each one is the latency. Latencies for Level 1 triggers are typically a few microseconds.**
  - **Level 2 deals with a much smaller number of events and can take correspondingly longer, so can have more advanced hardware (DSP, FPGA) or standard CPUs. It may have fixed or variable latency and may have hundreds of microseconds or milliseconds to handle a single event.**
  - **Level 3 deals with even smaller number of events and uses commercial off the shelf CPUs to do an almost full offline type analysis for the final selection**

# CMS Trigger for B→ $\mu^+\mu^-$ Analysis

"The events used in this analysis were collected with a set of dimuon triggers designed to select events with :

$$B \rightarrow \mu^+\mu^-,\ B^+ \rightarrow J/\psi K^+,\ \text{and}\ B^o_s \rightarrow J/\psi\phi(1020)$$

To achieve an acceptable trigger rate, the **first-level trigger** required two high-quality oppositely charged muons restricted to $|\eta| < 1.5$.

At the **high-level trigger**, a high-quality dimuon secondary vertex (SV) was required and the events were restricted to mass ranges of *4.5–6.0 GeV* and *2.9–3.3 GeV* for the *B and J/ψ* mesons, respectively. The J/ψ triggers additionally required the SV to be displaced from the beam spot (defined as the average interaction point in the plane transverse to the beams) and the displacement vector to be aligned with the dimuon momentum."

# Test of Use of Future Absolute $B_s$ Branching Fraction for Normalization

- "We also estimate the branching fractions using the $B^o{}_s \rightarrow J/\psi\phi(1020)$ decays for the normalization.

- While this result is free from the explicit systematic uncertainty in the fs/ fu ratio, it depends on the $B^o{}_s \rightarrow J/\psi\phi(1020)$ branching fraction.
  - At the moment, this branching fraction measurement uses the fs/ fu ratio measurement as an input, but this dependence may be eliminated when new independent measurements of the $B^o{}_s \rightarrow J/\psi\phi(1020)$ branching fraction become available, such as the measurement planned by the Belle II Collaboration at the KEKB $e^+e^-$ collider [using the $Y(5S)$) data. Experimentally, the measurement based on the $B^o{}_s \rightarrow J/\psi\phi(1020)$ normalization channel has slightly larger systematic uncertainties due to the presence of the second kaon in the final state."
    - Work will need to be done to reduce this this source of uncertainty.

# BELLE Branching Fraction Measurements on Υ(5S)

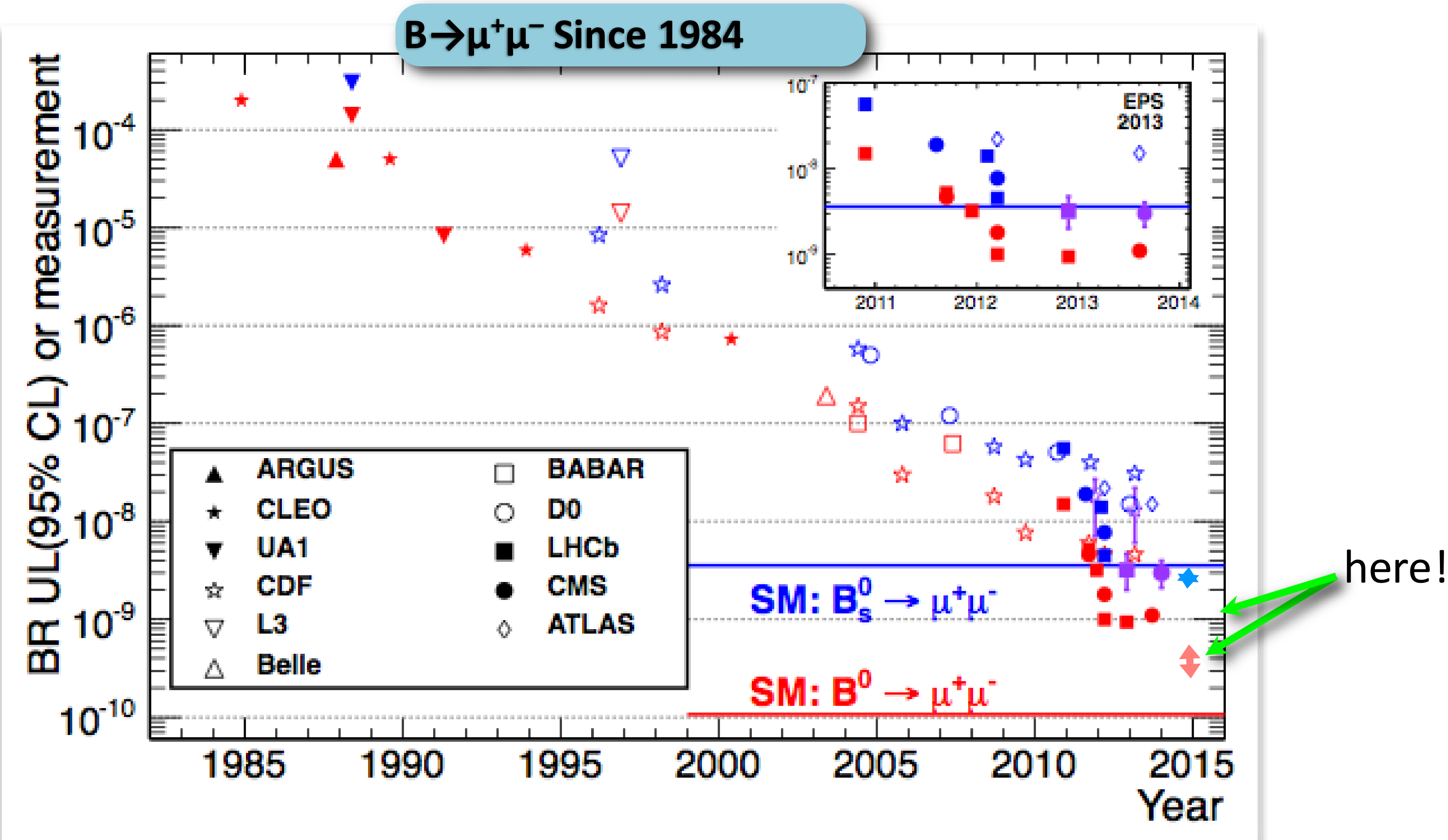
[17] Belle collaboration, F. Thorne *et al.*, *Measurement of the decays $B_s^0 \to J/\psi\phi(1020)$, $B_s^0 \to J/\psi f_2'(1525)$ and $B_s^0 \to J/\psi K^+K^-$ at Belle*, Phys. Rev. **D88** (2013) 114006, arXiv:1309.0704.

We report a measurement of the branching fraction of the decay $B_s^0 \to J/\psi\,\phi(1020)$, evidence and a branching fraction measurement for $B_s^0 \to J/\psi f_2'(1525)$, and the determination of the total $B_s^0 \to J/\psi\,K^+K^-$ branching fraction, including the resonant and non-resonant contributions to the $K^+K^-$ channel. We also determine the $S$-wave contribution within the $\phi(1020)$ mass region. The absolute branching fractions are $\mathcal{B}[B_s^0 \to J/\psi\,\phi(1020)] = (1.25 \pm 0.07\,(\text{stat}) \pm 0.08\,(\text{syst}) \pm 0.22\,(f_s)) \times 10^{-3}$, $\mathcal{B}[B_s^0 \to J/\psi f_2'(1525)] = (0.26 \pm 0.06\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.05\,(f_s)) \times 10^{-3}$ and $\mathcal{B}[B_s^0 \to J/\psi\,K^+K^-] = (1.01 \pm 0.09\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.18\,(f_s)) \times 10^{-3}$, where the last systematic error is due to the branching fraction of $b\bar{b} \to B_s^{(*)}B_s^{(*)}$. The branching fraction ratio is found to be $\mathcal{B}[B_s^0 \to J/\psi f_2'(1525)]/\mathcal{B}[B_s^0 \to J/\psi\,\phi(1020)] = (21.5 \pm 4.9\,(\text{stat}) \pm 2.6\,(\text{syst}))$. All results are based on a 121.4 fb$^{-1}$ data sample collected at the $\Upsilon(5S)$ resonance by the Belle experiment at the KEKB asymmetric-energy $e^+e^-$ collider.

$$(1.25 \pm 0.07 \pm 0.23) \times 10^{-3}$$

This seems to use $f_s$ to get the BR!

# Historical Summary




It took 30 years to finally measure the $B_s \to \mu^+\mu^-$ decay; The result turns out to be very close to the prediction and gives a stringent limit on the physics beyond the Standard Model. There is still a possibility of ~50% deviation from the SM, which will be resolved by more statistics in the next few years.

Note: I will add $\Gamma$ and $\tau$ numbers for completeness

# Some $B_s$, $B_d$ meson properties

- The $B_s$ meson is a $\bar{b}s$ bound state; the $B_d$ meson is a $\bar{b}d$ bound state
- The Mass of the $B_s$ is 5366.7 MeV/$c^2$ and the $B_d$ is 5279.55 MeV/$c^2$
    - $M_{B_s} - M_{B_d} = \sim 87$ MeV/$c^2$
- $B_s^0$ is a flavor eigenstate, not a mass eigenstate, and oscillates rapidly between $B_s$ and $\overline{B}_s$
- The interactions that produce mixing also can produce a difference in lifetimes between the two mass eigenstates $B_{sH}$ and $B_{sL}$ of about 10%
- The $B_d^0$ has weaker mixing, oscillates more slowly and there is almost no difference in the lifetimes of its two mass eigenstates
- Both $B_d$ and $B_s$ have mean lifetimes of 1.5ps, corresponding to $c\tau$ of ~450$\mu$ m
- The distance from the production (primary) vertex to the B decay (secondary) vertex can be measured and used to eliminate most prompt backgrounds

# Review: Properties of $B_s$ and $B_d$

| Property | $B_d$ | $B_s$ | Comment |
|---|---|---|---|
| Mass (MeV) | 5279.55 | 53667.7 | $M_{Bs} - M_{Bd}$=87.34 |
| $\Delta$ M $B_d$($10^{12}$ h/2$\pi$ $s^{-1}$) | 0.510 | | $\Delta$ [$M(B^0_H) - M(B^0_L)$] |
| $\Delta$ M $B_s$ ($10^{12}$ h/2$\pi$ $s^{-1}$) | | 17.769 | $\Delta$ [$M(B_{sH}) - M(B_{sL})$] |
| Mean Lifetime (ps) | 1.519 | 1.469 | |
| $B_{sH}$ mean life (ps) | | 1.70 | |
| $\Delta\Gamma$ ($B_d$) ($ps^{-1}$) | (42+/-10)x$10^{-4}$ $\Gamma$ | | $\Delta\Gamma(B_d)=\Gamma(B_{dL}) - \Gamma(B_{dH})$ |
| $\Delta\Gamma$ ($B_s$) ($ps^{-1}$) | | 0.091+/- 0.016 | $\Delta\Gamma(B_s)=\Gamma(B_{sL}) - \Gamma(B_{sH})$ |
| $\Delta M/\Gamma$ ($B_d$) | 0.774 | | |
| $\Delta M/\Gamma$ ($B_s$) | | 26.85 | |

| Observable | Current | LHCb-U1a | LHCb-U2 | ATLAS | CMS |
|---|---|---|---|---|---|
| $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ $(\times 10^9)$ | $\pm 0.46$ | $\pm 0.30$ | $\pm 0.16$ | $\pm(0.50)$ | $\pm 0.39$ |
| $\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$ | $\sim 70\%$ | $\sim 34\%$ | $\sim 10\%$ | $-$ | $\sim 21\%$ |
| $\tau_{\mu\mu}$ | $\sim 14\%$ | $\pm 0.16$ ps | $\pm 0.04$ ps | $-$ | $\pm 0.05$ ps |

Table 3: Summary of the current and expected experimental precision for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ observables. The expected uncertainty are reported for LHCb at $23\,\text{fb}^{-1}$ (LHCb-U1a) and $300\,\text{fb}^{-1}$ (LHCb-U2) while for ATLAS and CMS are evaluated at $3\,\text{ab}^{-1}$.

This is after Moriond 2021 so does not contain all recent results, view as illustrative only

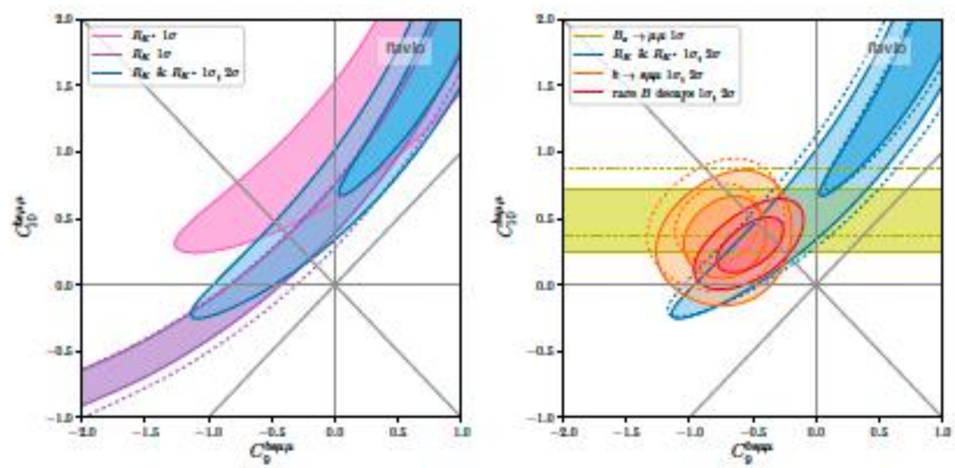


Figure 4: Constraints in the Wilson coefficient plane $C_9^{bs\mu\mu}$ vs. $C_{10}^{bs\mu\mu}$. Left: LFU ratios only. Right: Combination of LFU ratios, combination of $b \to s\mu\mu$ observables, $\text{BR}(B_s \to \mu^+\mu^-)$, and the global fit. The dashed lines show the constraints before the recent updates [11, 13, 14, 41].

https://arxiv.org/abs/2103.13370v3

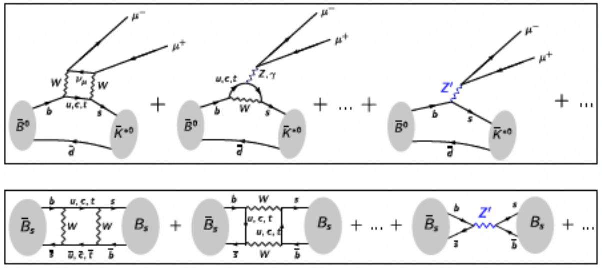


Figure 3: Schematic representation of the (top) $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$ decay and (bottom) $B_s^0$-$\overline{B}_s^0$ mixing amplitudes as sums over all possible Feynman diagrams. The diagrams on the left are examples of SM contributions, while the diagram on the right is an example of an NP contribution in theories with a flavor-changing neutral gauge boson $Z'$.

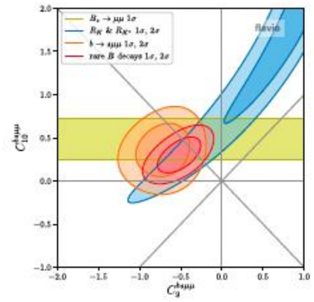
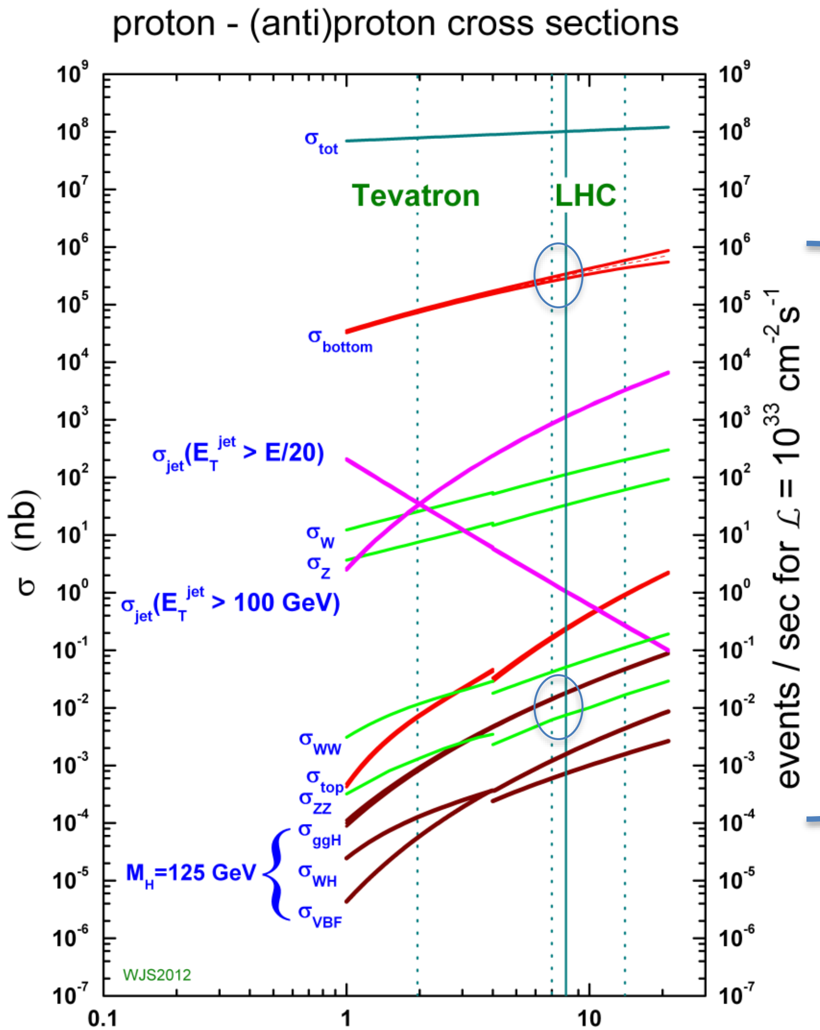


Figure 1: Constraints at $1\sigma$ (darker) and $2\sigma$ (lighter) in the plane $C_9^{bs\mu\mu}$ *vs.* $C_{10}^{bs\mu\mu}$ resulting from $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (yellow-green), combination of the lepton-flavor-universality ratios $R_K$ and $R_{K^{*0}}$ (blue), combination of $b \to s\mu^+\mu^-$ observables (orange), and global fit of rare $b$ decays (red) [9]. The Wilson coefficients $C_9^{bs\mu\mu}$ and $C_{10}^{bs\mu\mu}$ are the NP contributions to the couplings of the operators $O_9 = (\overline{s}\gamma_\mu b_L)(\overline{\mu}\gamma^\mu \mu)$ and $O_{10} = (\overline{s}\gamma_\mu b_L)(\overline{\mu}\gamma^\mu \gamma_5 \mu)$, respectively. The global fit result is inconsistent with the SM point (the origin) by $\sim 5\sigma$.

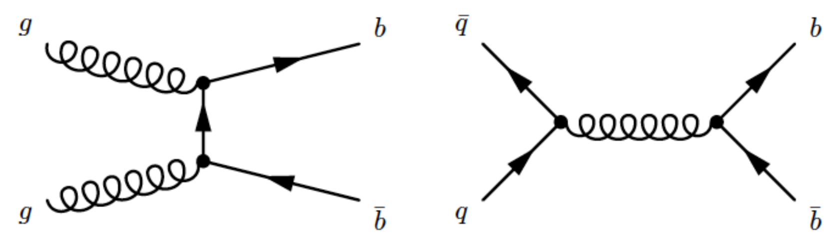
This is after Moriond Snowmass 2021 so does not contain all recent results, view as illustrative only

https://arxiv.org/abs/2208.05403v2

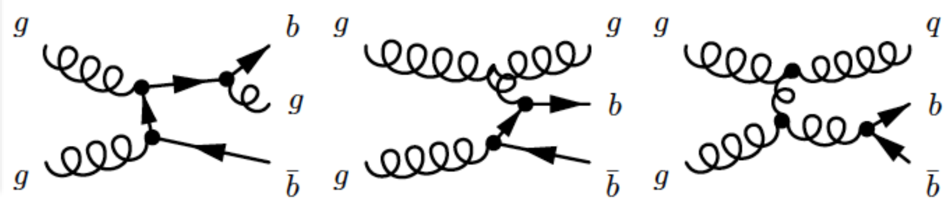
# B Production at the LHC




LO – Pair creation



NLO –
pair creation, Flavor Excitation, Gluon splitting



# FCC-ee Specs

| Parameter | Z | WW | H (ZH) | ttbar |
|---|---|---|---|---|
| beam energy [GeV] | 45 | 80 | 120 | 182.5 |
| beam current [mA] | 1280 | 135 | 26.7 | 5.0 |
| number bunches/beam | 10000 | 880 | 248 | 36 |
| bunch intensity [$10^{11}$] | 2.43 | 2.91 | 2.04 | 2.64 |
| SR energy loss / turn [GeV] | 0.0391 | 0.37 | 1.869 | 10.0 |
| total RF voltage 400/800 MHz [GV] | 0.120/0 | 1.0/0 | 2.08/0 | 4.0/7.25 |
| long. damping time [turns] | 1170 | 216 | 64.5 | 18.5 |
| horizontal beta* [m] | 0.1 | 0.2 | 0.3 | 1 |
| vertical beta* [mm] | 0.8 | 1 | 1 | 1.6 |
| horizontal geometric emittance [nm] | 0.71 | 2.17 | 0.64 | 1.49 |
| vertical geom. emittance [pm] | 1.42 | 4.34 | 1.29 | 2.98 |
| horizontal rms IP spot size [μm] | 8 | 21 | 14 | 39 |
| vertical rms IP spot size [nm] | 34 | 66 | 36 | 69 |
| luminosity per IP [$10^{34}$ $cm^{-2}s^{-1}$] | 182 | 19.4 | 7.3 | 1.33 |
| total integrated luminosity / year [$ab^{-1}/yr$] 4 IPs | 87 | 9.3 | 3.5 | 0.65 |
| beam lifetime (rad Bhabha + BS+lattice) | 8 | 18 | 6 | 10 |
| | 4 years<br>$5 \times 10^{12}$ Z<br>LEP x $10^5$ | 2 years<br>> $10^8$ WW<br>LEP x $10^4$ | 3 years<br>$2 \times 10^6$ H | 5 years<br>$2 \times 10^6$ tt pairs |

From Fabiola's talk

Currently assessing technical feasibility of changing operation sequence (e.g. starting at ZH energy)

- x 10-50 improvements on all EW observables
- up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- x10 Belle II statistics for b, c, τ
- indirect discovery potential up to ~ 70 TeV
- direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

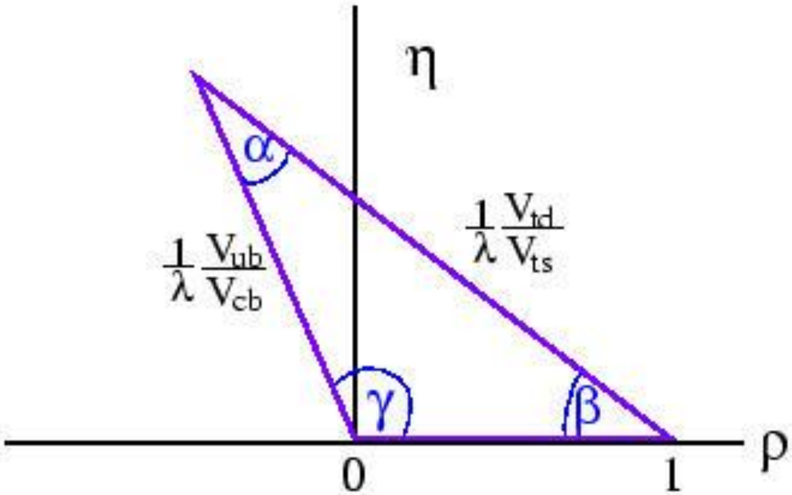
Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

9

# Resources (under development)

- http://ckmfitter.in2p3.fr/www/html/ckm_results.html

# Key Measurements of the CKM matrix in B Decays




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

$$\chi = \arg\left(-\frac{V_{cs}^*V_{cb}}{V_{ts}^*V_{tb}}\right) \qquad \chi' = \arg\left(-\frac{V_{ud}^*V_{us}}{V_{cd}^*V_{cs}}\right)$$

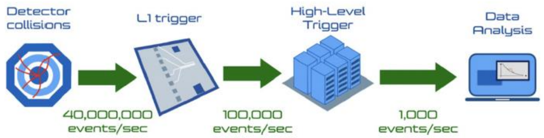
$\chi$

| Physics Quantity | Decay Mode |
|---|---|
| $\sin(2\alpha)$ | $B^o \to \rho\pi \to \pi^+\pi^-\pi^o$ |
| $\cos(2\alpha)$ | $B^o \to \rho\pi \to \pi^+\pi^-\pi^o$ |
| $\mathrm{sign}(\sin(2\alpha))$ | $B^o \to \rho\pi,\ B^o \to \pi^+\pi^-$ |
| $\sin(\gamma)$ | $B_s \to D_s K^-$ |
| $\sin(\gamma)$ | $B^+ \to D^o K^+$ |
| $\sin(\gamma)$ | $B \to K\pi$ |
| $\sin(\gamma)$ | $B \to \pi^+\pi^-,\ B_s \to K^+K^-$ |
| $\sin(2\chi)$ | $B_s \to J/\psi\eta',\ J/\psi\eta$ |
| $\sin(2\beta)$ | $B^o \to J/\psi K_s$ |
| $\sin(2\beta)$ | $B^o \to \phi K_s,\ \eta' K_s,\ J/\psi\phi$ |
| $\cos(2\beta)$ | $B^o \to J/\psi K^*,\ B_s \to J/\psi\phi$ |
| $x_s$ | $B_s \to D_s\pi^-$ |
| $\Delta\Gamma$ for $B_s$ | $B_s \to J/\psi\eta',\ K^+K^-,\ D_s\pi^-$ |

**About 1/2 of the key measurements are in $B_s$ decays!**

# What is Data Scouting?

## A detour to CMS trigger system:




- LHC Collide proton-proton bunches each __25ns__ with rate up to __40MHz__
- L1 (level 1) trigger: **40 MHz → 100kHz**.
  - Only simplified event information available (no tracker information)
- HLT (high level trigger): decreases rate to **1kHz** before data storage

***Too small rate for some physics analyses!***
***In most cases, we end up selecting events with high-$p_T$ objects***
***Events that are NOT selected by trigger system are lost, __forever__!!***

- **The actual limitation...**
  - *Trigger Bandwidth = Event Rate × Event Size*
    *~1 kHz × ~1 MB = ~1 GB / sec*

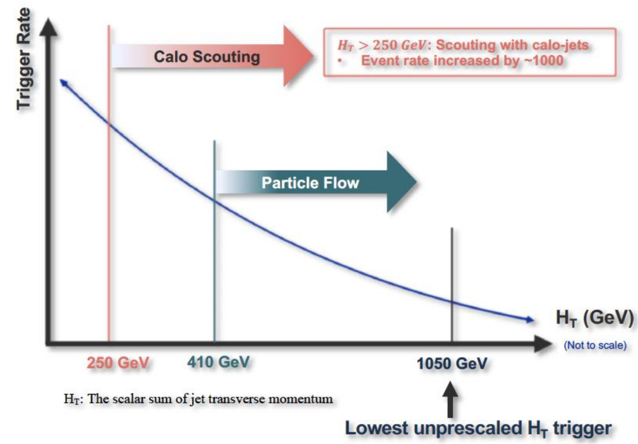
    ↑ *If we want to __increase__ the rate*

    ↓ *We need to __decrease__ the event size*

A Way Out!!

***This is the idea of data scouting!***
*Provides a major increase in the amount of physics data available for analysis*

*New Trigger Paradigm: Scouting Technique*




__Data scouting:__
- Higher rate with the suitable performance for physics analysis
  - Reduced amount of data per event → **~1.5kB event size**
  - Types: Particle Flow Scouting, Calo Scouting

__A drawback of Scouting & the idea of Parking:__

- **Full event information not available in scouting**
  - Difficult to fully characterize a potential signal (if seen)
- __Way out:__ **Parking of the full RAW data**
  - NO immediate offline reconstruction necessary
  - Reconstruct only in case of a discovery in the scouting data