Indirect BSM searches

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Exothiggs: PSI Summer School
Lyceum Alpinum, Zouz, Aug 14-20 2016

Indirect searches includes a very broad range of measurements:

- Charged Lepton Flavour Violation
- Kaon, B-meson, D-meson physics
- Non SM CP Violation searches
- EDM, g-2, ...
- Neutrino physics

In these two lectures I will concentrate on b-physics... and on the present

- Introduction

- CP Violation searches:
  - CPV in B-decays and the UT triangle
  - Facilities and measurements

- Rare B-decays:
  - Flavour Changing Neutral Currents
  - LFU test with rare decays

Some of the material is taken from the Flavour Physics course of 2015 (Steinkamp/Serra) and Flavour Physics course of 2016 (Isidori/Serra), also have a look at the Habilitationsschrift by Steinkamp

Introduction

- Indirect searches of BSM is basically the measurement of decays of existing particles

- Precision measurement of particle's decay allow to infer about the virtual particles interacting with SM particles: are there other gauge interaction? Are they family blind? …

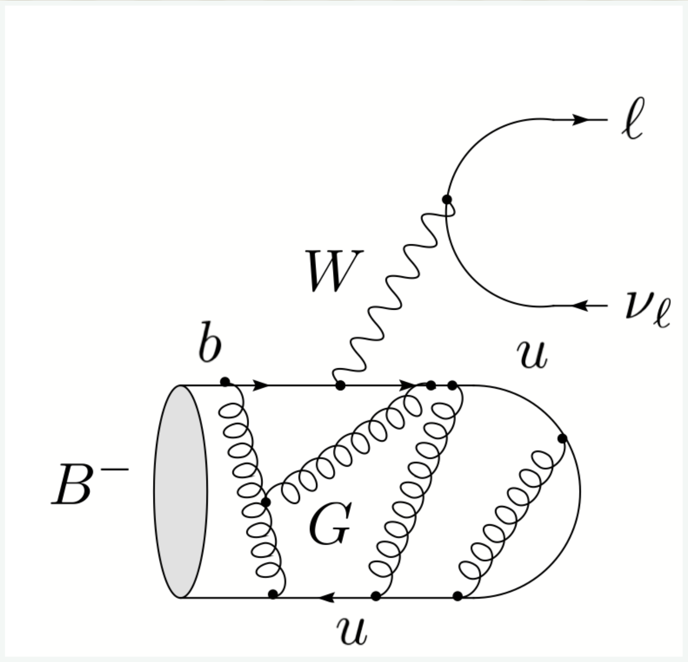
- Flavour Puzzle: why do we have three families which are identical wrt to the gauge interactions? <- In the SM!

- Particularly interesting is therefore the study of the third family (B-hadrons, tau-leptons) which is much less constrained than the first two families

Introduction

- Since new particles might enter as virtual particles, energies much larger than those reachable at colliders can be probed

- Let's take the simple example of a leptonic decay of a B-meson, which in the SM is mediated by the W



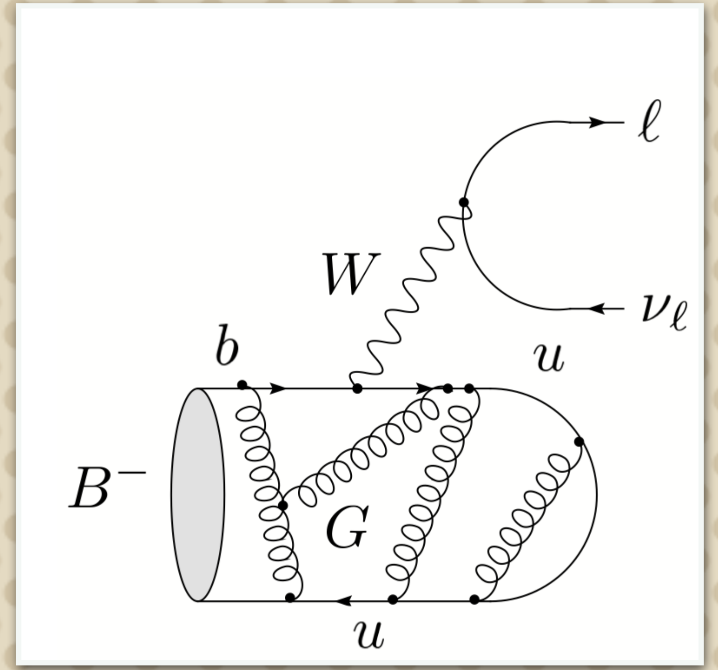
$$\Gamma(B^- \to \ell\bar{\nu}_\ell) = \frac{G_F^2}{8\pi} M_B m_\ell^2 \left(1 - \frac{m_\ell^2}{M_B^2}\right)^2 f_B^2 |V_{ub}|^2,$$

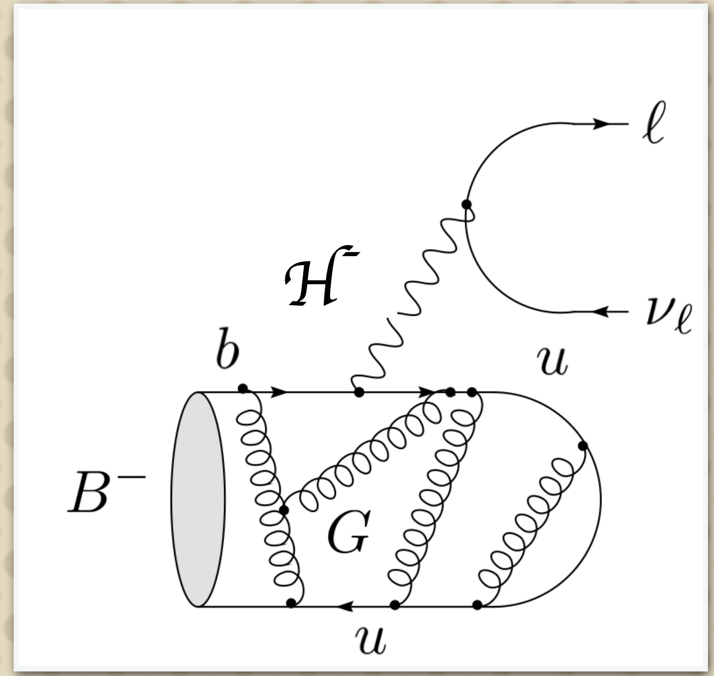
- G_F = Fermi Constant
- f_B decay constant determined by the B-wave function at the origin
- CKM element V_{ub}
- Helicity suppression

Introduction

- In extensions of the SM can be mediated by other new particles

- For instance in the 2HDM this decay can happen mediated by a charged Higgs

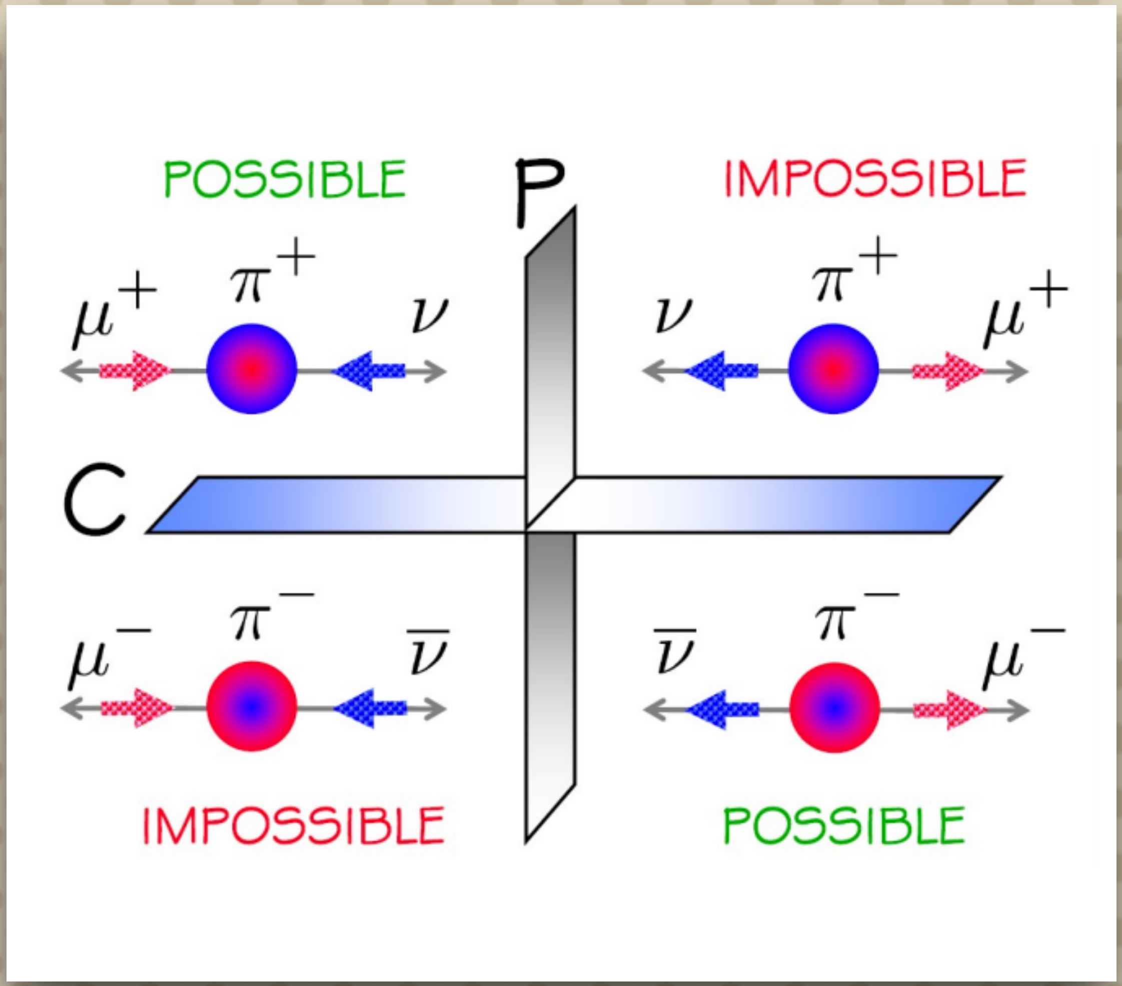




- Measurement of the BR gives you insight on the mediating particle, but you need to know f_b ... unless you use ratios or correlations with other decays

CP violation

CP symmetry



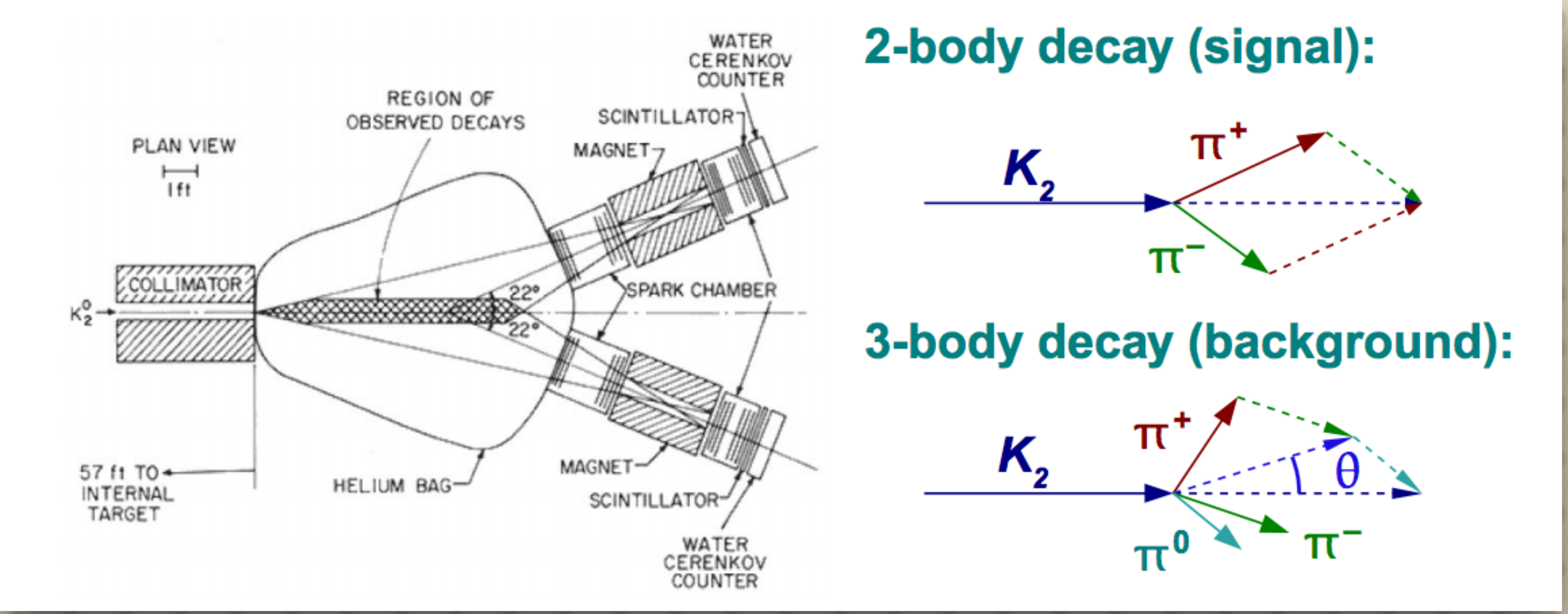
- Negative (positive) muons from leptonic pion decays are left-handed (right-handed)

- Parity and Charged conjugation symmetries are maximally violated in these decays but the combination of them (CP) is conserved

- Parity violation was first observed by Wu et al. in 1956, measuring the angular distribution of electrons from B-decays of $^{60}Co \longrightarrow {}^{60}Ni^*$

Discovery of CPV

Christenson, Cronin, Fitch, Turlay (1964) observed K_2 (K_L today) decaying into two pions



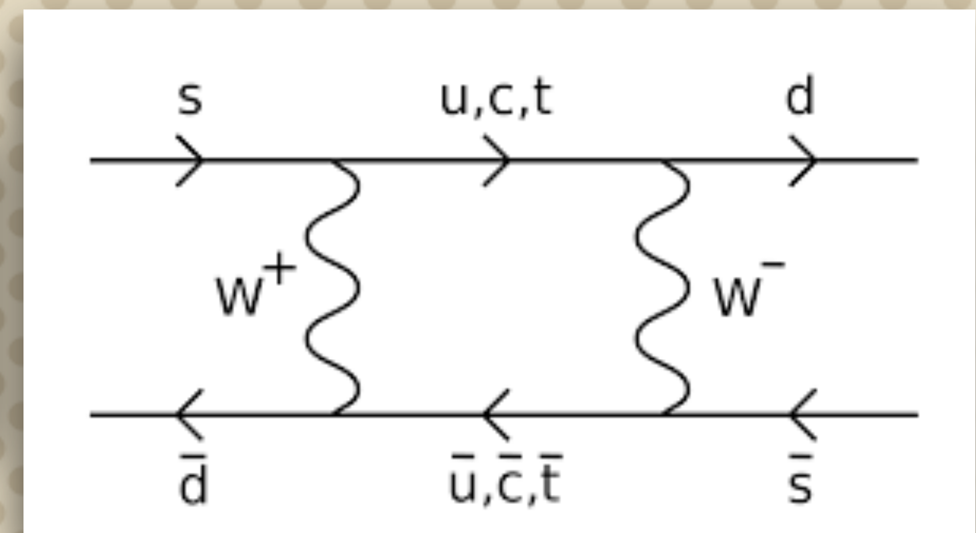
- Shoot proton into a target to produce neutral kaons
- Let them propagate in a vacuum pipe to eliminate the short living component
- Search for K_2 decays into two pions using the invariant mass and pointing

Discovery of CP Violation

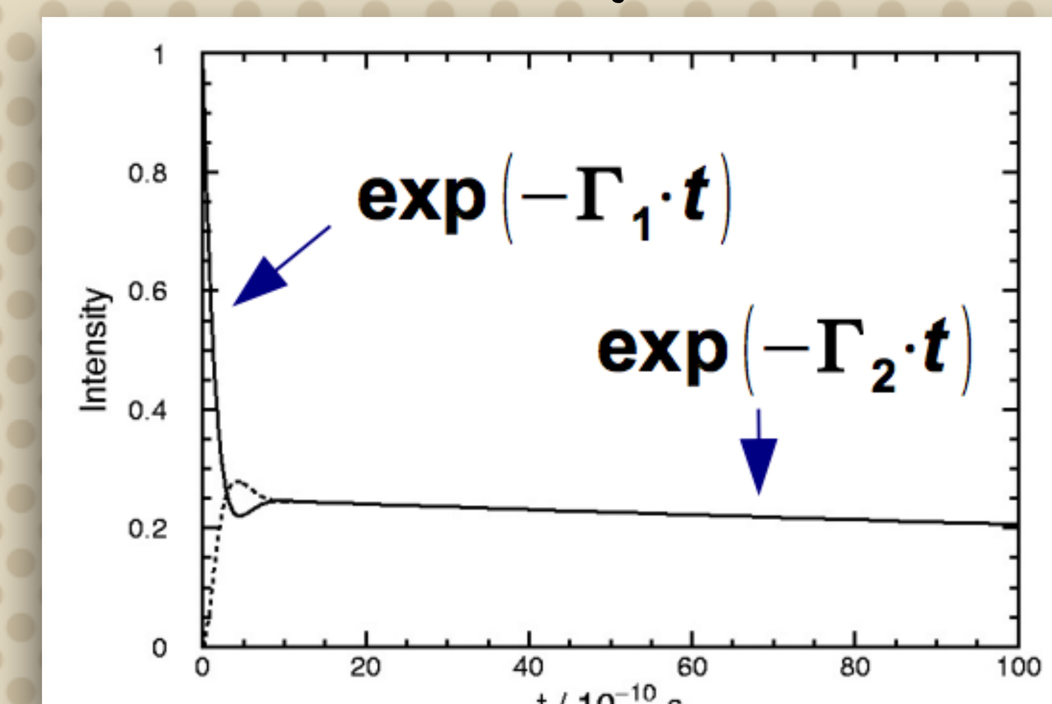
In neutral kaons we have two mass eigenstates which are not flavour eigenstates, due to CKM mixing

$$|K_1\rangle = \frac{1}{\sqrt{2}} \cdot \left\{ |K^0\rangle + |\bar{K}^0\rangle \right\} \quad \Rightarrow \quad CP\,|K_1\rangle = +\,|K_1\rangle$$

$$|K_2\rangle = \frac{1}{\sqrt{2}} \cdot \left\{ |K^0\rangle - |\bar{K}^0\rangle \right\} \quad \Rightarrow \quad CP\,|K_2\rangle = -\,|K_2\rangle$$



Mass eigenstates are known as K_L and K_S and they have a very different lifetime



If CP was conserved in weak interactions K_L and K_S would also be CP eigenstates

Pion P, CP

Looking at the wave function of neutral pions we obtain that they have neutral parity

$$P|\pi^0\rangle = |\bar{q}\downarrow q\uparrow\rangle - |\bar{q}\uparrow q\downarrow\rangle + |q\downarrow \bar{q}\uparrow\rangle - |q\uparrow \bar{q}\downarrow\rangle = -1\,|\pi^0\rangle$$

In the same way we can show that they are CP-odd

$$CP|\pi^0\rangle = -1\,|\pi^0\rangle \qquad CP|\pi^0\pi^0\rangle = (-1)^2\,|\pi^0\pi^0\rangle = +1\,|\pi^0\pi^0\rangle$$

The C operation changes positive pion to negative and the same the P, therefore the state with two charged pion has positive parity $CP|\pi^+\pi^-\rangle = \mathbb{1}|\pi^+\pi^-\rangle = +1\,|\pi^+\pi^-\rangle$

In addition

$$CP|\pi^0\pi^0\pi^0\rangle = (-1)^3\,|\pi^0\pi^0\pi^0\rangle = -1\,|\pi^0\pi^0\pi^0\rangle$$

$\pi^+\pi^-\pi^0$	-1	$(L_{(\pi^+\pi^-)\leftrightarrow\pi^0} = 0, 2, ..)$
	+1	$(L_{(\pi^+\pi^-)\leftrightarrow\pi^0} = 1, 3, ..)$

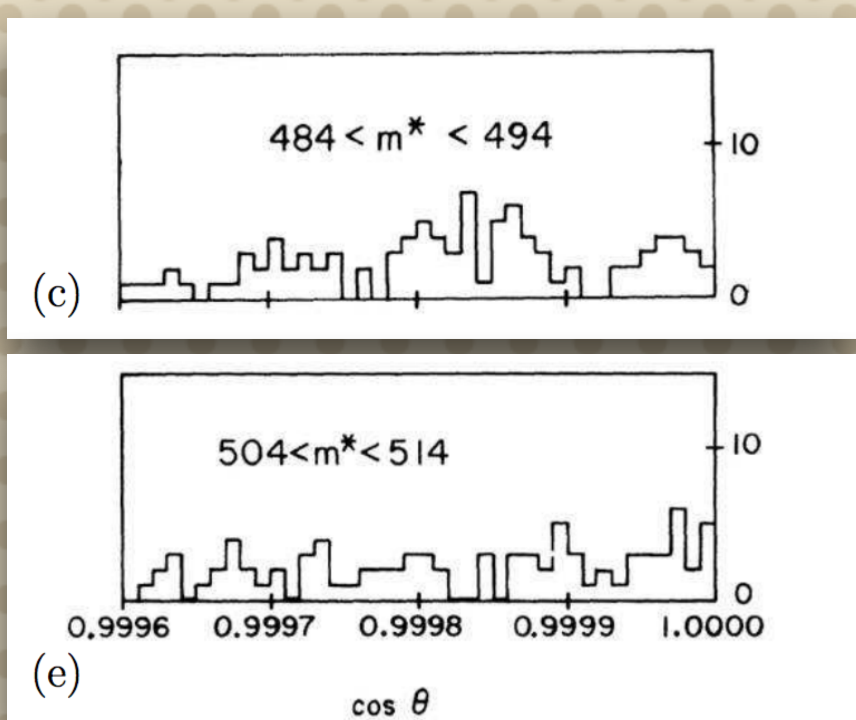
Discovery of CPV

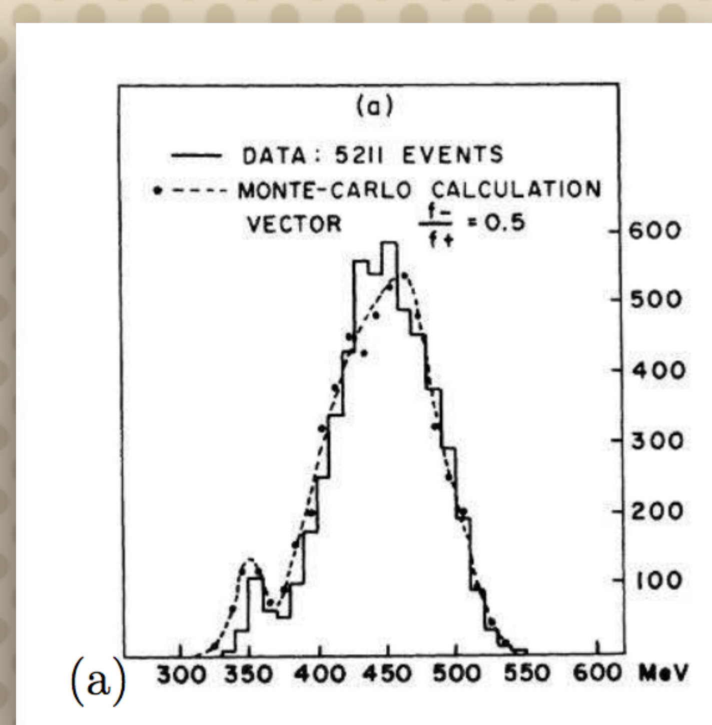
The background consists mainly of

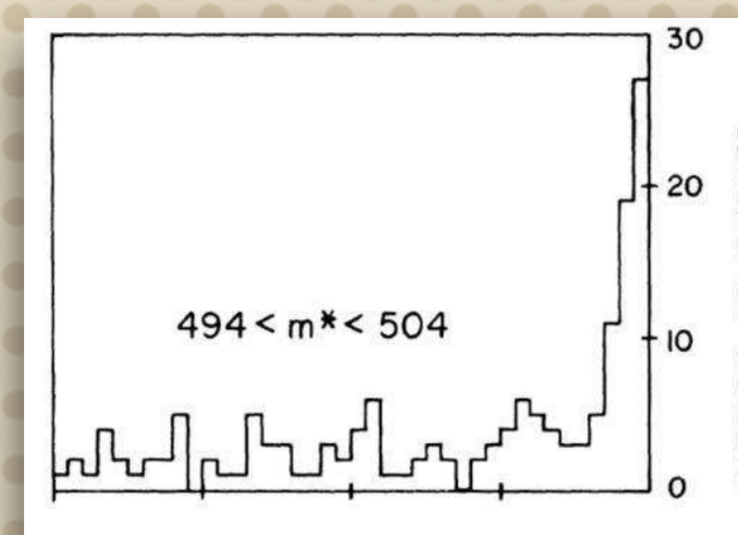
$K_L^0 \rightarrow \pi^+\pi^-\pi^0$ Low mass (peak around 350MeV)

$K_L^0 \rightarrow \pi\mu\nu$ and $K_L^0 \rightarrow \pi e\nu$ High mass

- No evident discrepancy in the invariant mass
- Excess of 49+/- 9 events when plotting the pointing angle in the kaon mass region







CP violation in neutral mesons

Neutral Meson Mixing

- State at time t is a linear combination of B^0 and anti-B^0
- Time evolution given by the Schrödinger equation

$$|\psi(t)\rangle = a(t)|B^0\rangle + b(t)|\bar{B}^0\rangle$$

$$-i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

- Since meson can decay H as an imaginary component
- Can be decomposed into two hermetian parts

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

$$\left\{\begin{array}{lllll} M & \equiv & M_{11} & = & M_{22} \\ \Gamma & \equiv & \Gamma_{11} & = & \Gamma_{22} \end{array}\right.$$

- Assuming CPT

$$M_{21} = M_{12}^* \;\; ; \;\; \Gamma_{21} = \Gamma_{12}^*$$

- Eigenvalues are given by

$$\omega_{H,L} = M - \frac{i}{2}\Gamma \pm \sqrt{\left(M_{12}-\frac{i}{2}\Gamma_{12}\right)\left(M_{12}^*-\frac{i}{2}\Gamma_{12}^*\right)} \equiv m_{H,L} - \frac{i}{2}\Gamma_{H,L}$$

Neutral Meson Mixing

- The eigenstates are

$$|B_{H,L}\rangle = p\,|B^0\rangle \mp q\,|\bar{B}^0\rangle$$

$$\frac{q}{p} = -\sqrt{\frac{H_{21}}{H_{12}}} = -\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

- Time evolution of B_H and B_L (they are not particle/antiparticle) but they have well-defined masses and lifetimes

$$|B_H(t)\rangle = \left(p \cdot |B^0\rangle - q \cdot |\bar{B}^0\rangle\right) \cdot e^{-i m_H t} \cdot e^{-\Gamma_H t/2}$$

$$|B_L(t)\rangle = \left(p \cdot |B^0\rangle + q \cdot |\bar{B}^0\rangle\right) \cdot e^{-i m_L t} \cdot e^{-\Gamma_L t/2}$$

- Time evolution of B^0 and anti-B^0

$$|B^0_{t=0}(t)\rangle = g_+(t) \cdot |B^0\rangle + \frac{q}{p} \cdot g_-(t) \cdot |\bar{B}^0\rangle$$

$$|\bar{B}^0_{t=0}(t)\rangle = g_+(t) \cdot |\bar{B}^0\rangle + \frac{p}{q} \cdot g_-(t) \cdot |B^0\rangle$$

$$g_\pm(t) = \frac{1}{2} e^{-i\bar{m}t} e^{-\frac{\bar{\Gamma}t}{2}} \left(e^{i\frac{\Delta m\, t}{2}} e^{+\frac{\Delta\Gamma\, t}{4}} \pm e^{-i\frac{\Delta m\, t}{2}} e^{-\frac{\Delta\Gamma\, t}{4}} \right)$$

$$\begin{aligned}
\bar{m} &\equiv (m_H + m_L)/2 \\
\bar{\Gamma} &\equiv (\Gamma_H + \Gamma_L)/2 \\
\Delta m &\equiv m_H - m_L \quad > 0 \\
\Delta\Gamma &\equiv \Gamma_H - \Gamma_L
\end{aligned}$$

Neutral Meson Mixing

- Mixing probabilities

$$P(B^0 \to B^0, t) = \frac{1}{2} \cdot e^{-\bar{\Gamma} t} \cdot \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) + \boxed{\cos(\Delta m\, t)} \right\}$$

$$P(\bar{B}^0 \to \bar{B}^0, t) = P(B^0 \to B^0, t)$$

$$P(B^0 \to \bar{B}^0, t) = \frac{1}{2} \cdot \left|\frac{q}{p}\right|^2 \cdot e^{-\bar{\Gamma} t} \cdot \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) - \boxed{\cos(\Delta m\, t)} \right\}$$

$$P(B^0 \to \bar{B}^0, t) = \frac{1}{2} \cdot \left|\frac{p}{q}\right|^2 \cdot e^{-\bar{\Gamma} t} \cdot \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) - \boxed{\cos(\Delta m\, t)} \right\}$$

- Time dependent asymmetries

$$a_{mix}(t) \equiv \frac{N(B^0 \to B^0) - N(B^0 \to \bar{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \bar{B}^0)} = \frac{\cos(\Delta m\, t) + \delta \cdot \cosh(\Delta\Gamma\, t/2)}{\cosh(\Delta\Gamma\, t/2) + \delta \cdot \cos(\Delta m\, t)}$$

$$\bar{a}_{mix}(t) \equiv \frac{N(\bar{B}^0 \to \bar{B}^0) - N(\bar{B}^0 \to B^0)}{N(\bar{B}^0 \to \bar{B}^0) + N(\bar{B}^0 \to B^0)} = \frac{\cos(\Delta m\, t) - \delta \cdot \cosh(\Delta\Gamma\, t/2)}{\cosh(\Delta\Gamma\, t/2) - \delta \cdot \cos(\Delta m\, t)}$$

$$\boxed{\begin{aligned} x &\equiv \Delta m/\bar{\Gamma} \\ y &\equiv \Delta\Gamma/2\bar{\Gamma} \end{aligned}}$$

- If δ =0 then no CPV in the mixing

$$\delta \equiv \frac{1 - |q/p|^2}{1 + |q/p|^2}$$

$$a_{mix}(t) = \bar{a}_{mix}(t) = \frac{\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2)} = \frac{\cos(x \cdot \bar{\Gamma} t)}{\cosh(y \cdot \bar{\Gamma} t)}$$

Neutral Meson Mixing

- Neutral Kaons

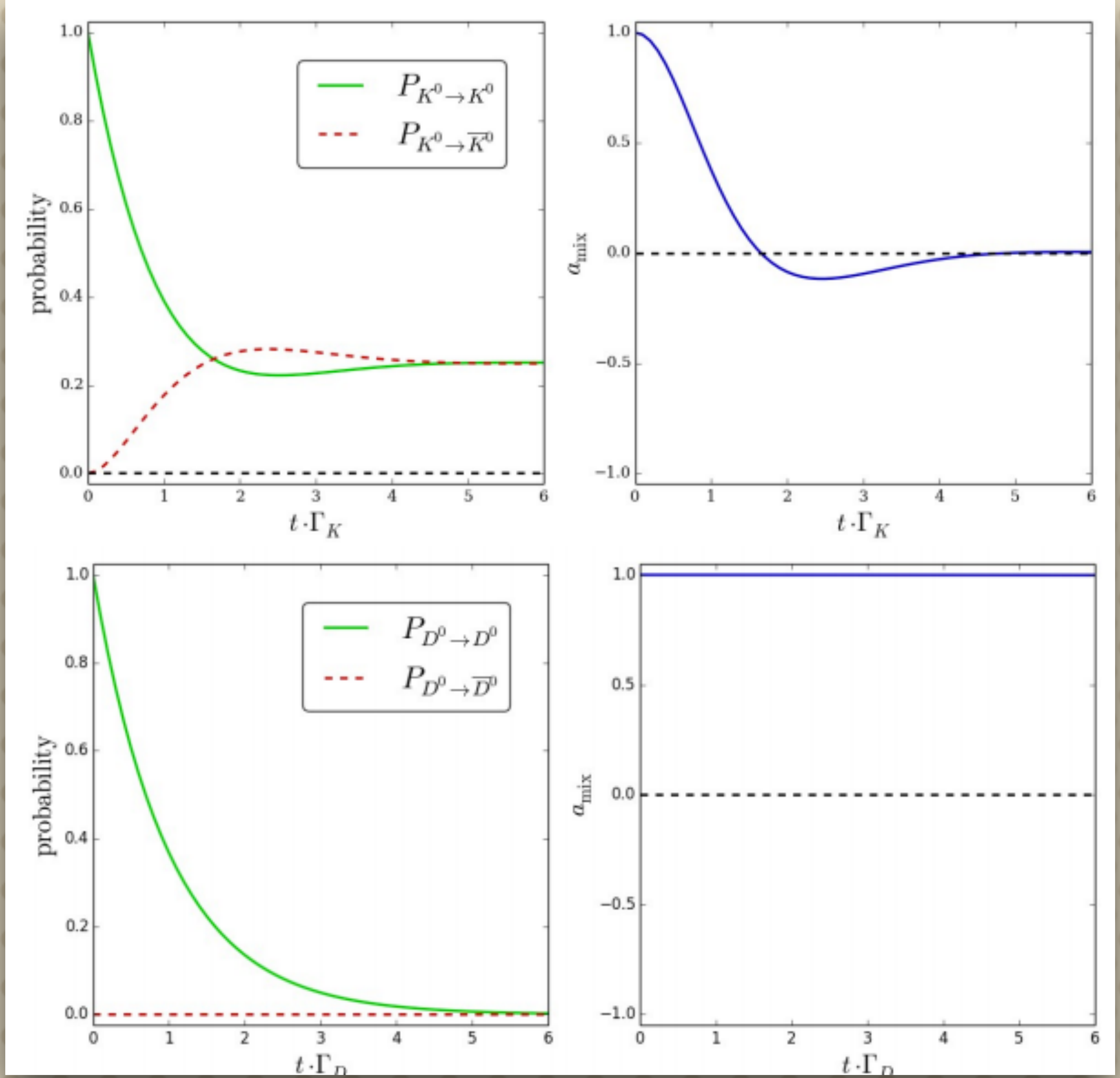
$x_K \approx 0.95$
$y_K \approx -1$

- Strong damping, only K_L are left after 1 oscillation

- D^0/anti-D^0 system

$x_D \approx 5 \times 10^{-3}$
$y_D = (7.15 \pm 0.09) \times 10^{-3}$

- Very small mixing



Neutral Meson Mixing

- B^0/anti-B^0 system

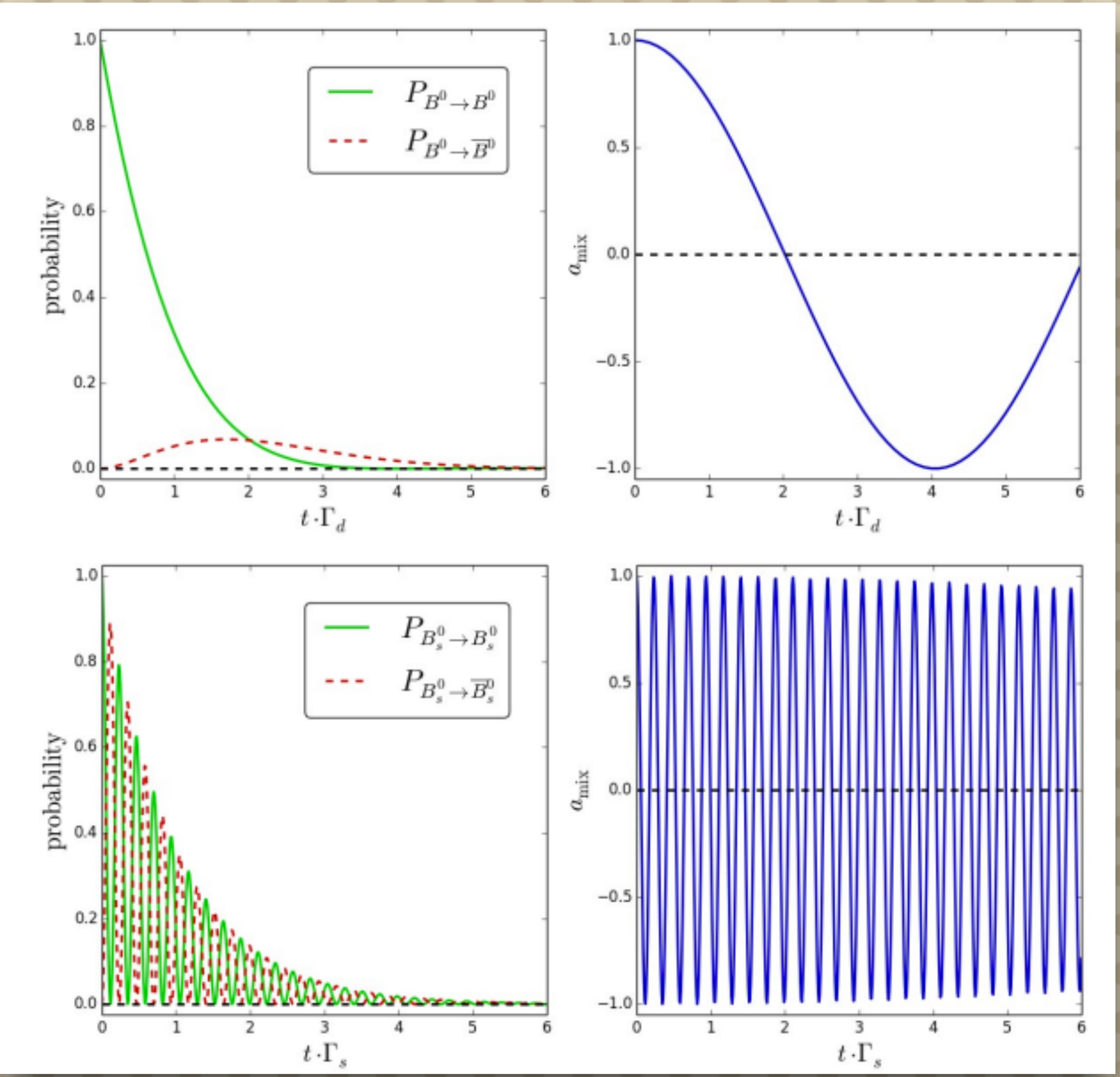
$x_d = 0.775 \pm 0.006$
$y_d = 0.007 \pm 0.009$

- Small damping and significant mixing

- B_s^0/anti-B_s^0 system

$x_s = 26.82 \pm 0.23$
$y_s = 0.058 \pm 0.010$

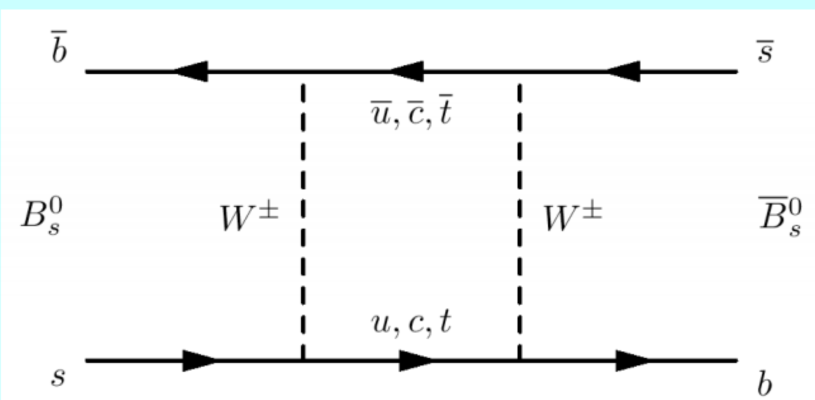
- Fast oscillations and complete mixing



CP Violation

CPV in mixing

("indirect *CP* violation")

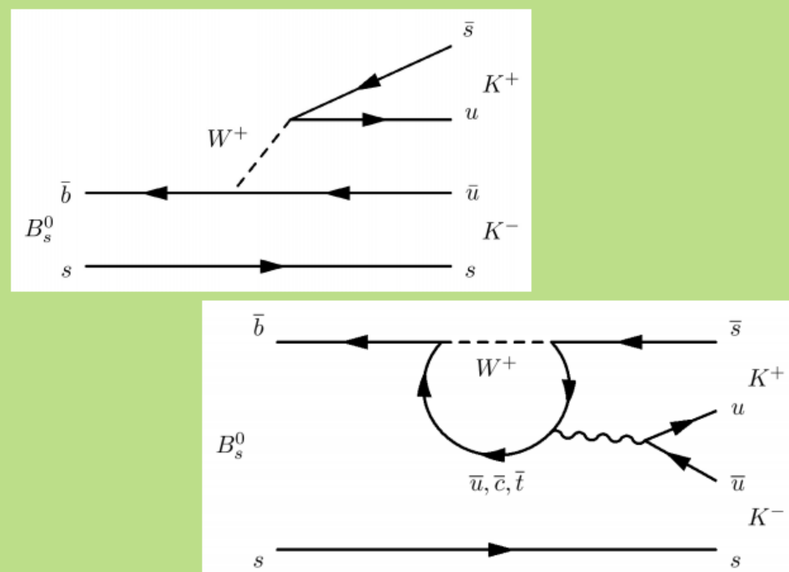


- interference of absorp-tive and dispersive part of mixing amplitude
- different mixing rate

  $B^0_{(s)} \rightarrow \overline{B}^0_{(s)}$ vs $\overline{B}^0_{(s)} \rightarrow B^0_{(s)}$
- small in Standard Model

CPV in decay

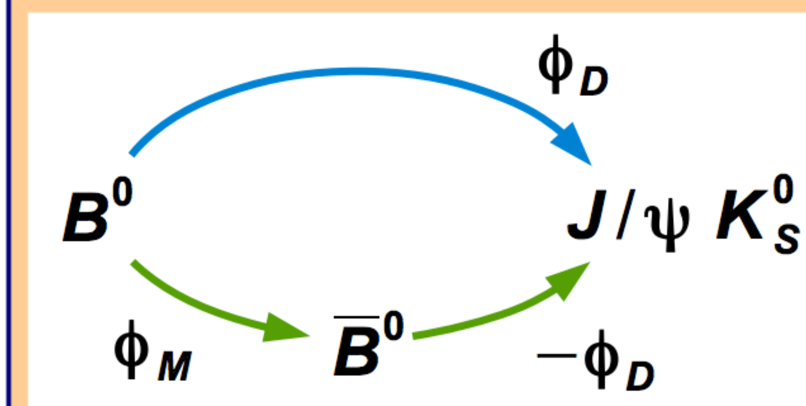
("direct *CP* violation")



- interference of decay diagrams with different weak and strong phases
- different decay rates

  $B \rightarrow f$ vs $\overline{B} \rightarrow \overline{f}$
- beware of strong phases

CPV in interference of mixing and decay



- interference between direct decay and decay after mixing
- different decay rates

  $B^0_{(s)} \rightarrow f_{CP}$ vs $\overline{B}^0_{(s)} \rightarrow f_{CP}$
- "golden modes"

The Unitarity Triangle(s)

The CKM matrix describes the relation between flavour and mass eigenstates

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

Weak Universality Relations

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

These relations represents triangles in the complex plane

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

$$\begin{aligned} V_{ud}^*V_{us} + V_{cd}^*V_{cs} + V_{td}^*V_{ts} &= 0 \\ \boxed{V_{ud}^*V_{ub} + V_{cd}^*V_{cb} + V_{td}^*V_{tb} = 0} \\ V_{us}^*V_{ub} + V_{cs}^*V_{cb} + V_{ts}^*V_{tb} &= 0 \end{aligned}$$

$J = \pm\mathrm{Im}(V_{us}V_{cb}V^*_{ub}V^*_{cs})$ = 2Area of triangles (prop to CPV)

Euler Angles

c_{ij} = cos of the angle between the i and j family
s_{ij} = sin of the angle between the i and j family

$$V_{CKM} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} =$$

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

We chose the phase to appear between the 1st and 3rd family

CKM parametrisations

Wolfenstein parametrisation

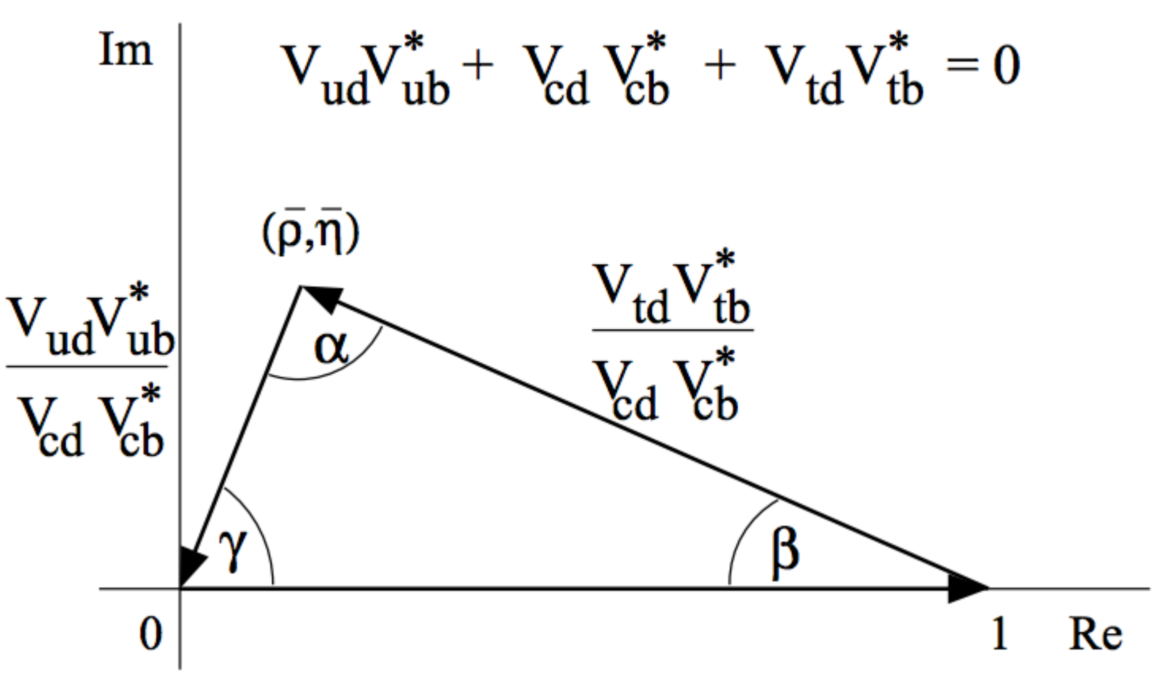
$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

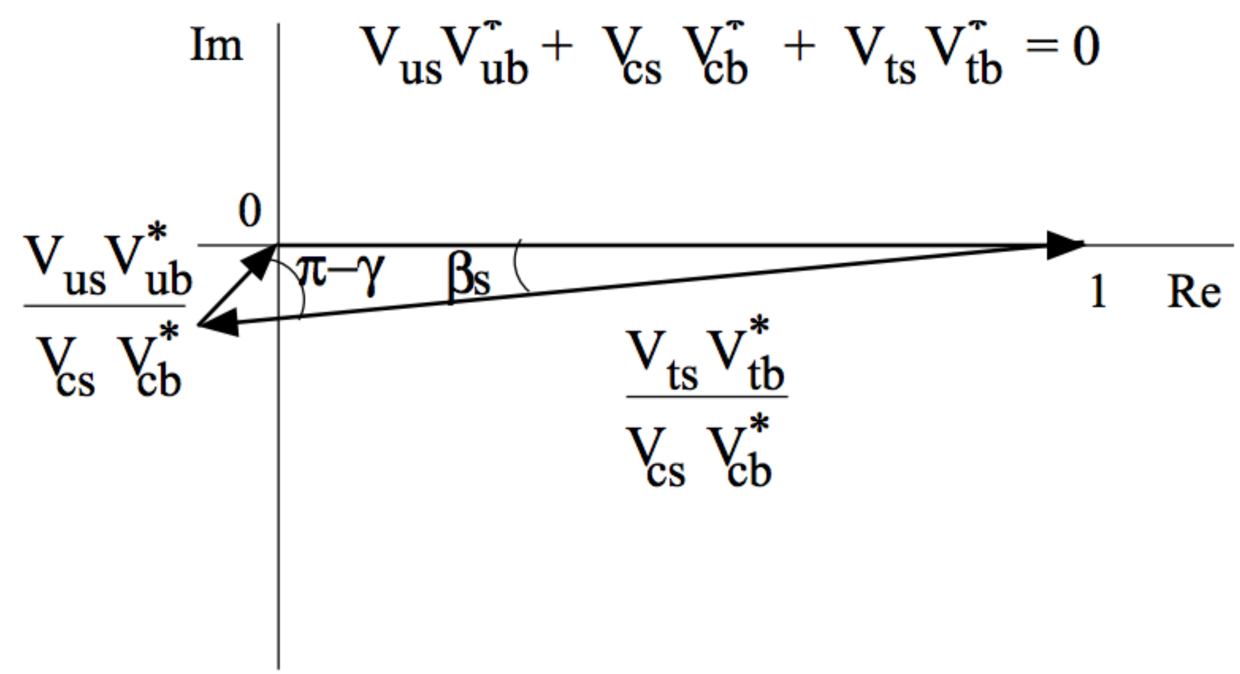
Where

$$\begin{aligned} \sin\theta_{12} &= \lambda \\ \sin\theta_{23} &= A\lambda^2 \\ \sin\theta_{13}e^{-i\delta_{13}} &= A\lambda^3(\rho - i\eta) \end{aligned}$$

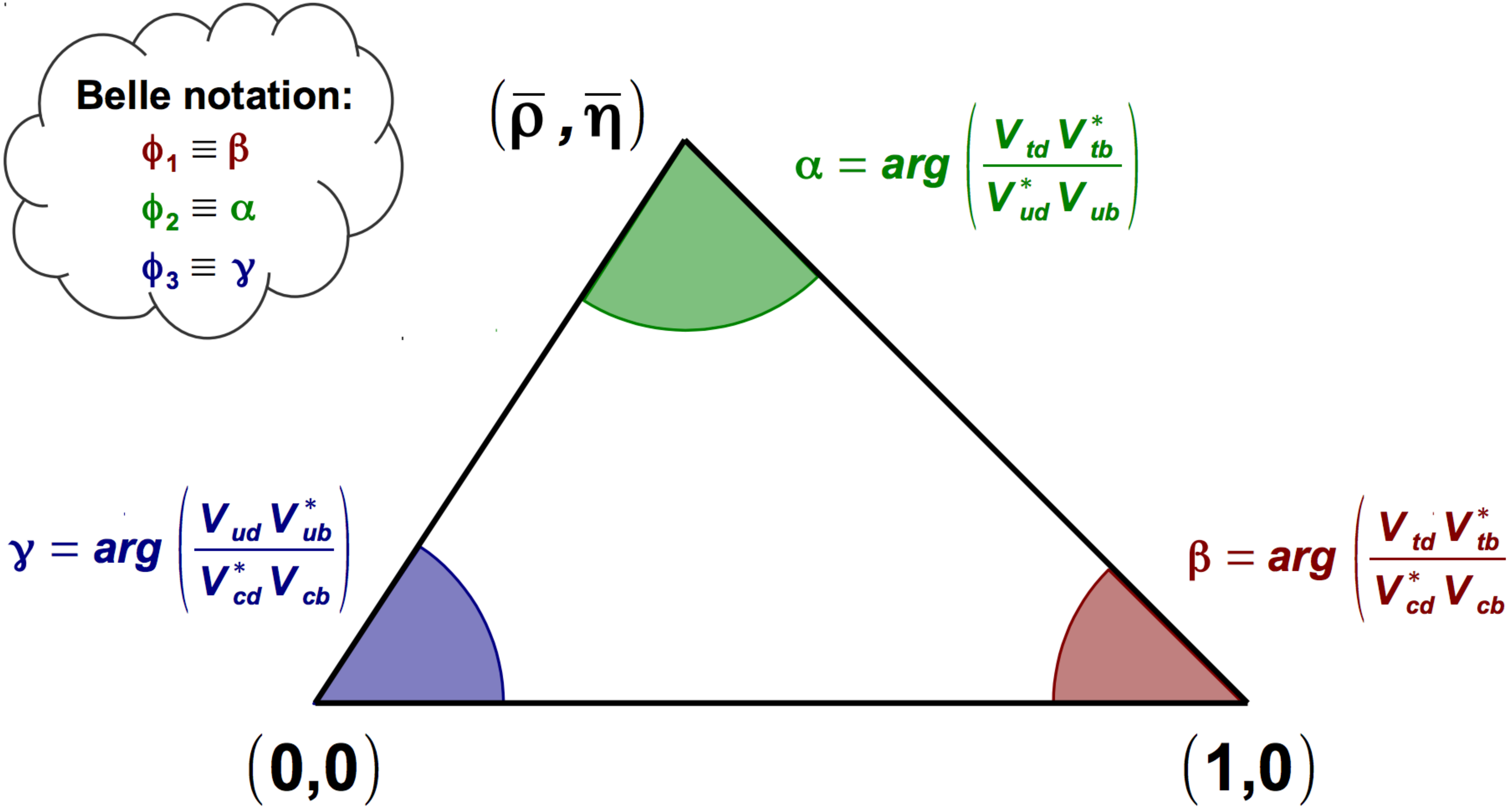
CKM parametrisations

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

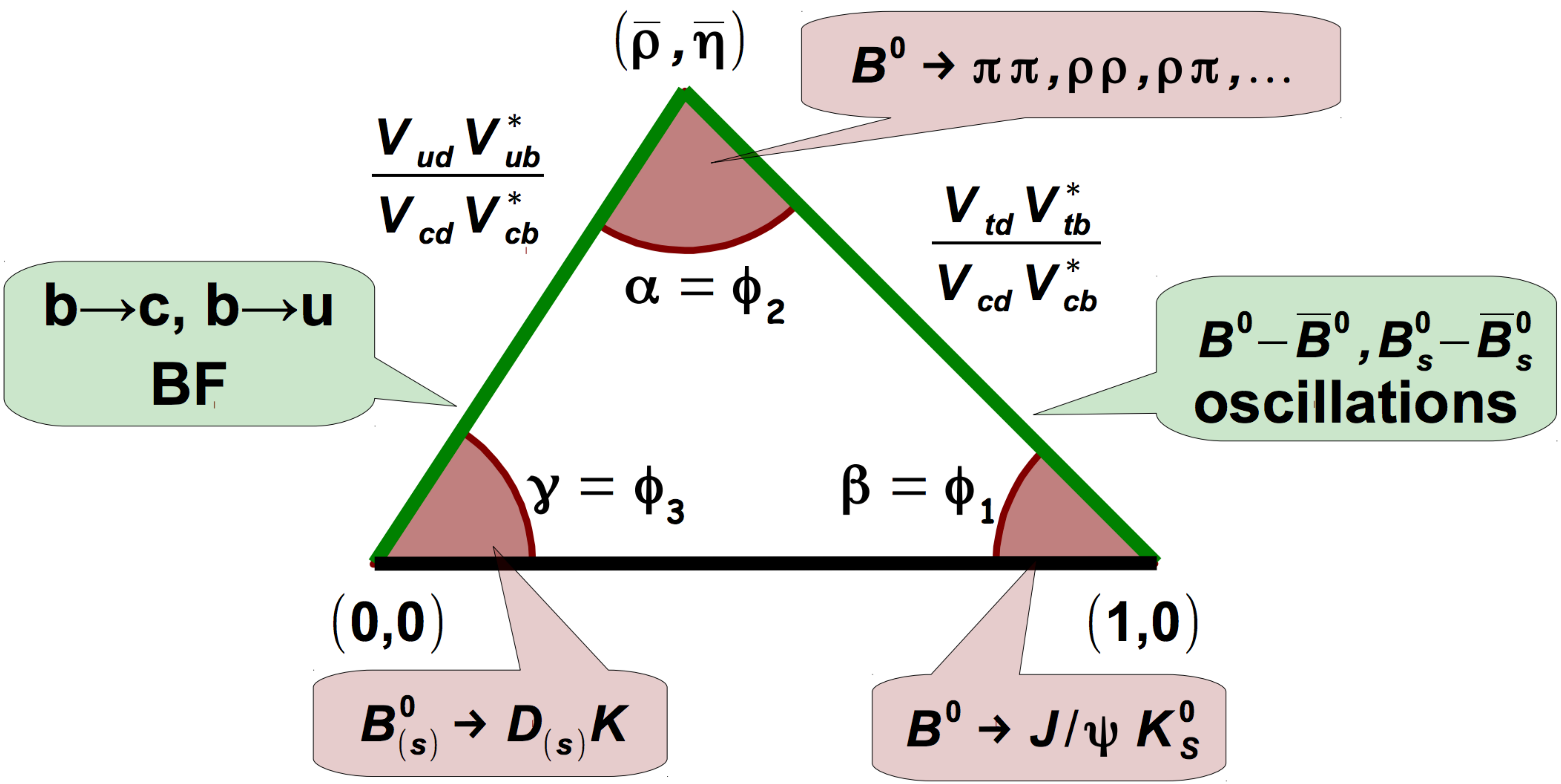




Unitarity Triangle



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



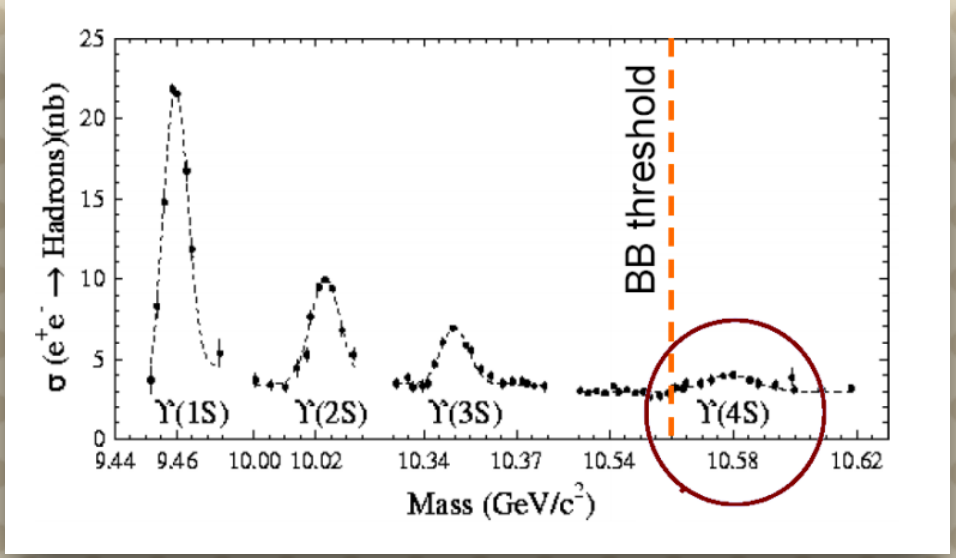
$(\bar{\rho}, \bar{\eta})$
$B^0 \to \pi\pi, \rho\rho, \rho\pi, \ldots$
$\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}$
$\alpha = \phi_2$
$\frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*}$
b→c, b→u
BF
$B^0 - \bar{B}^0, B_s^0 - \bar{B}_s^0$
oscillations
$\gamma = \phi_3$
$\beta = \phi_1$
$(0,0)$
$(1,0)$
$B^0_{(s)} \to D_{(s)} K$
$B^0 \to J/\psi K^0_S$

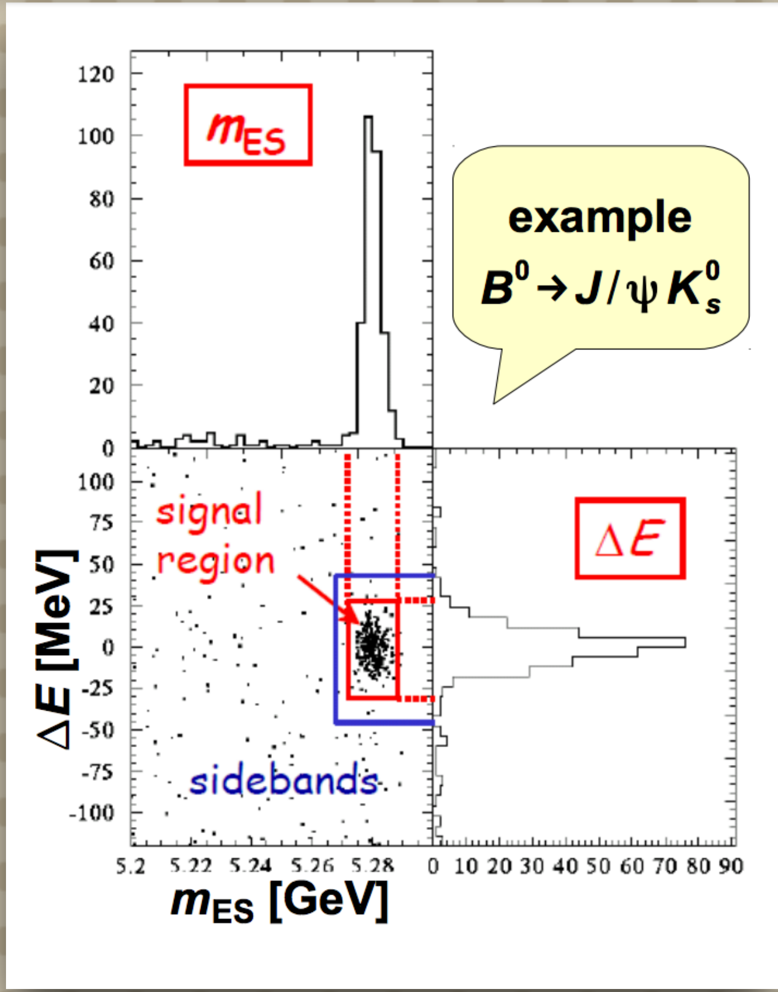
Facilities

B-factories

- Electron/position collider at the Υ(4S) resonance
- Υ(4s) decays in B^0/anti-B^0 (50%) and in B^+B^- (50%)
- 1fb^{-1} corresponds to about 10^6bbar pairs
- Clean events (only track from B)

E^*_{beam} = known beam energy
E^*_B = measured energy of *B* candidate
p_B^* = measured momentum of *B* candidate





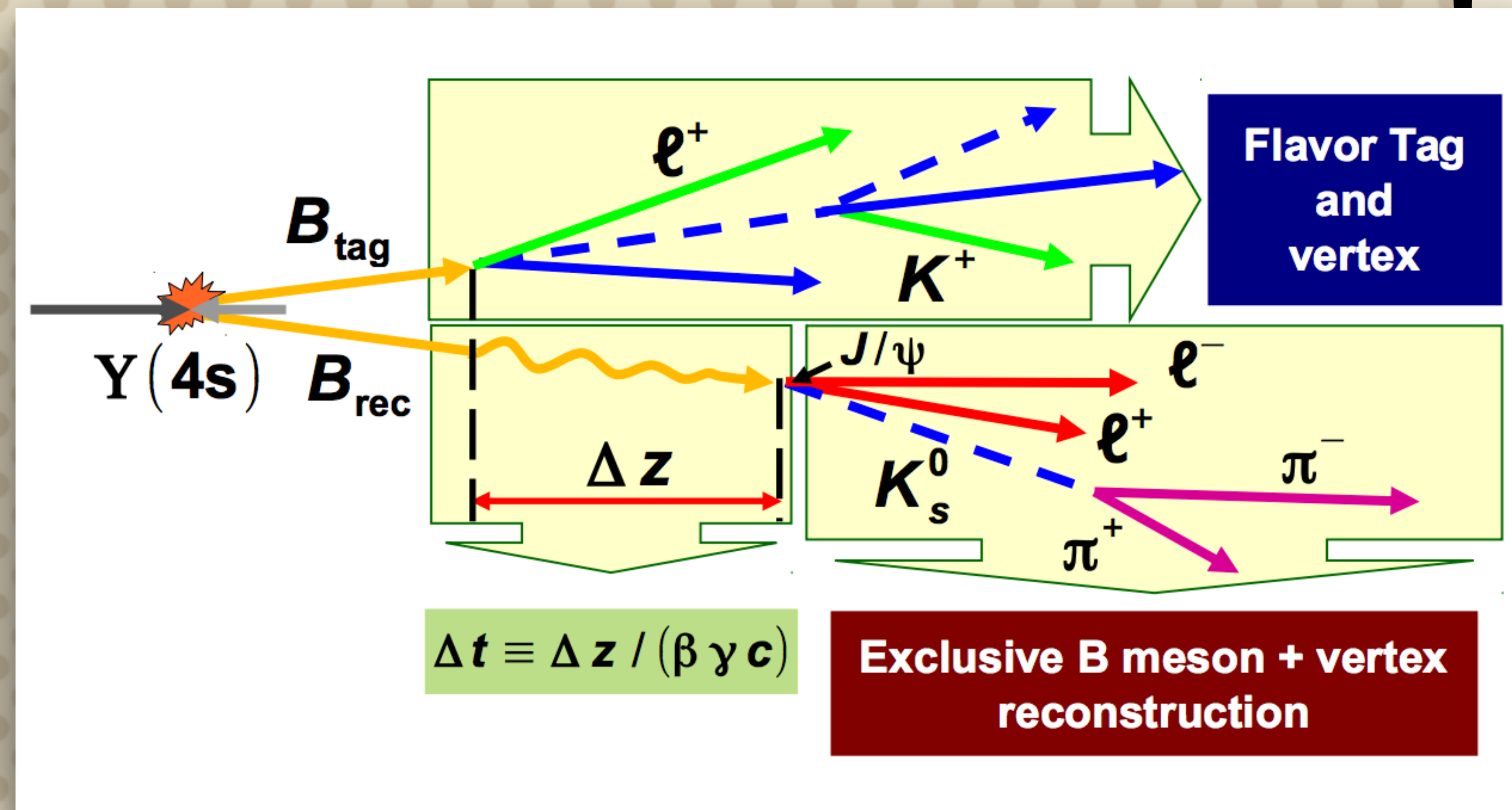
B-factories

- PEP-II: 9 GeV e^- + 3.1 GeV e^+

$$\beta\gamma = 0.56 \qquad \langle \Delta z \rangle \approx 260\ \mu m$$

- KEKB: 8 GeV e^- + 3.5 GeV e^+

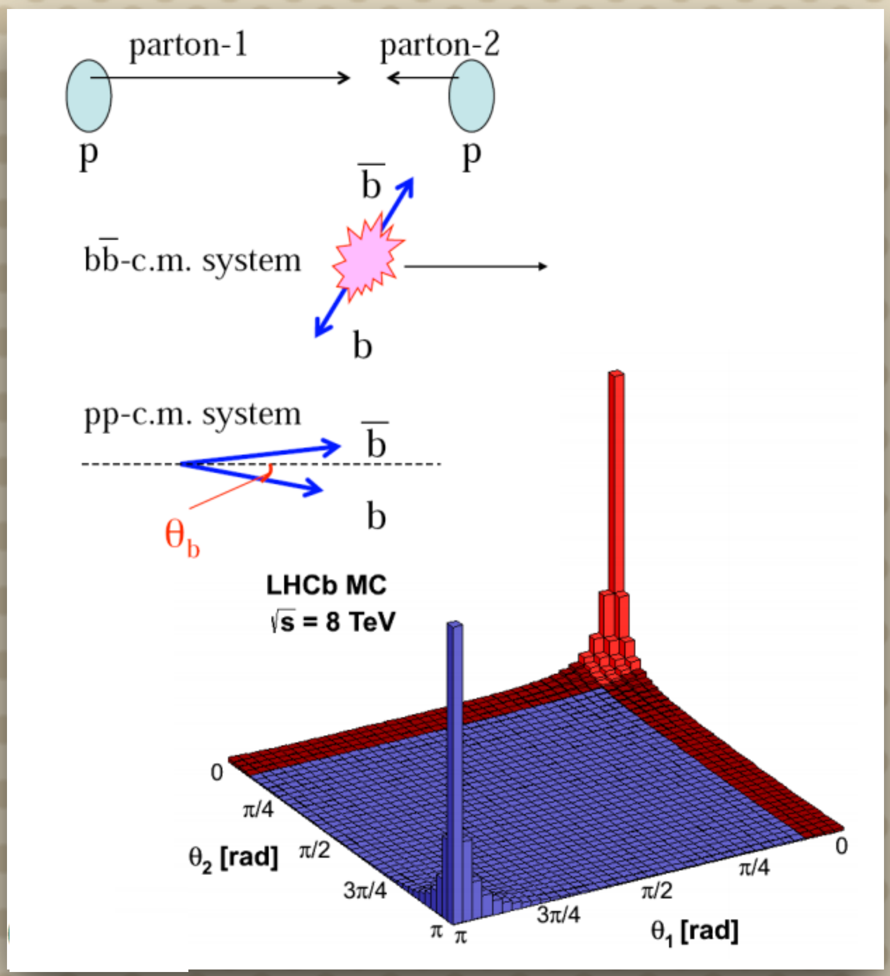
$$\beta\gamma = 0.425 \qquad \langle \Delta z \rangle \approx 200\ \mu m$$

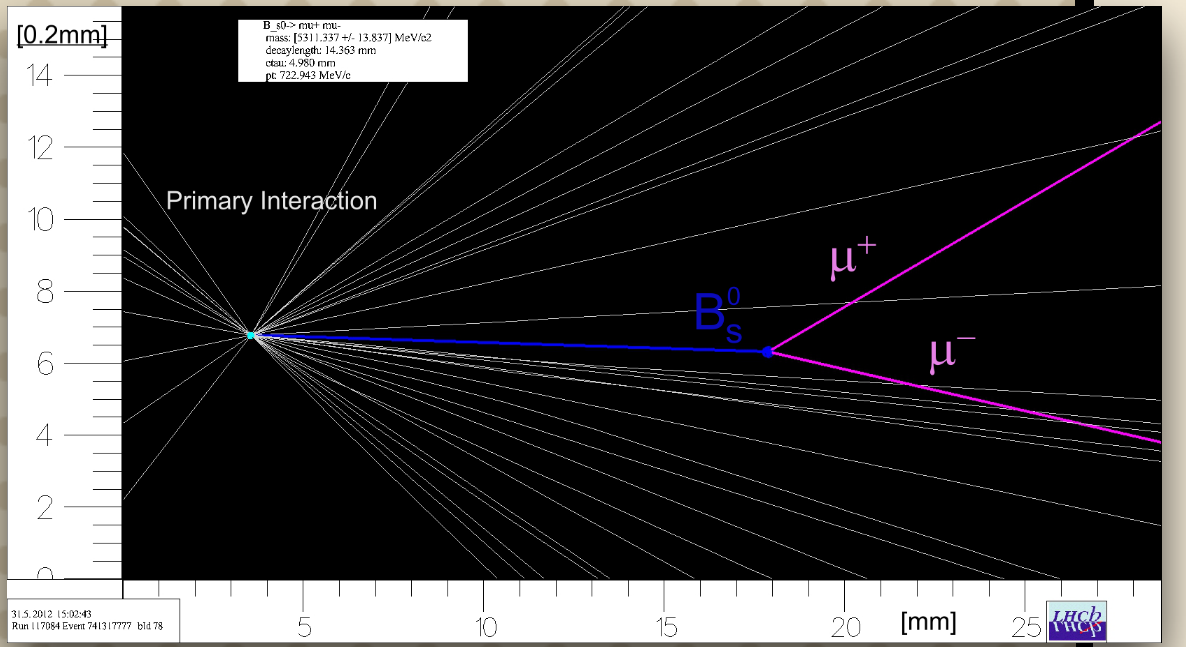


- Asymmetric beam to use boost to improve proper time resolution
- Possibility to use the other B for flavour tagging and background rejections for decays with neutrinos in the final state

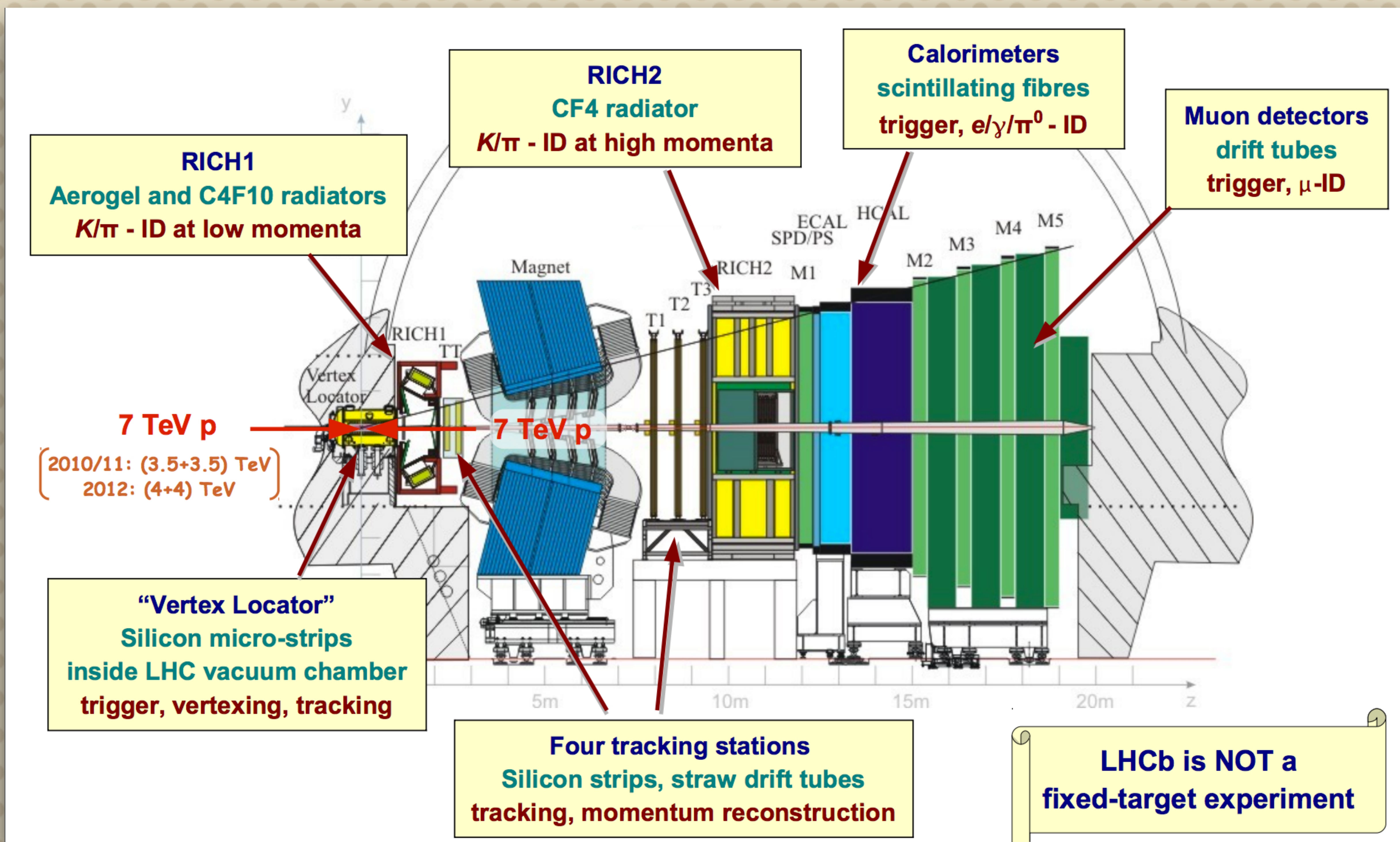
LHCb

- Proton-proton collider at LHC (max 14TeV)
- Produce all b-hadron species including B_s , B_c and b-baryons
- 1fb^{-1} corresponds to about 10^{12}bbar pairs
- "Dirty" events so the typical efficiency is per-mill (those selected events are very clean)
- Main selection variables are displacement from the PV and PT



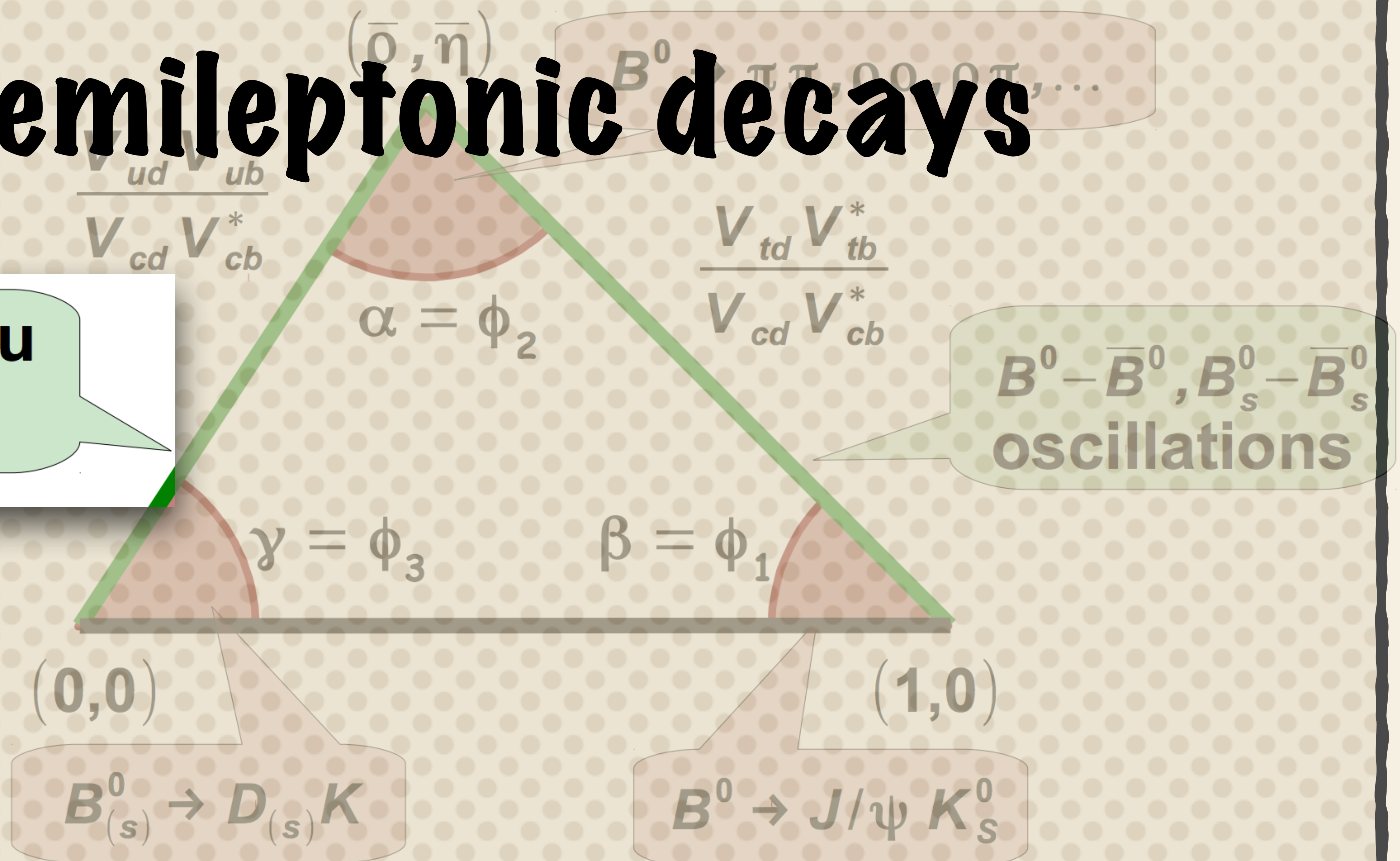


LHCb


RICH1
Aerogel and C4F10 radiators
K/π - ID at low momenta
RICH2
CF4 radiator
K/π - ID at high momenta
Calorimeters
scintillating fibres
trigger, e/γ/π⁰ - ID
Muon detectors
drift tubes
trigger, μ-ID
7 TeV p
2010/11: (3.5+3.5) TeV
2012: (4+4) TeV
7 TeV p
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
ECAL
SPD/PS
HCAL
M1
M2
M3
M4
M5
y
z
5m
10m
15m
20m
"Vertex Locator"
Silicon micro-strips
inside LHC vacuum chamber
trigger, vertexing, tracking
Four tracking stations
Silicon strips, straw drift tubes
tracking, momentum reconstruction
LHCb is NOT a
fixed-target experiment

Semileptonic decays

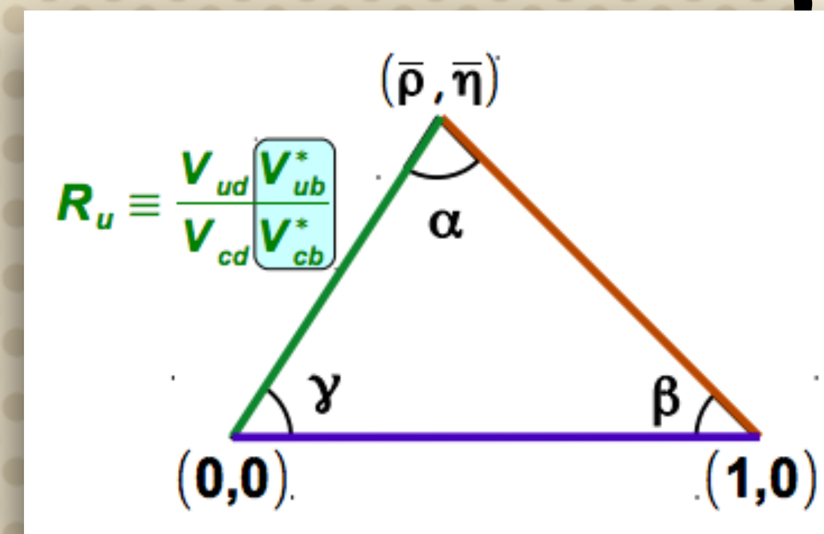
b→c, b→u
BF

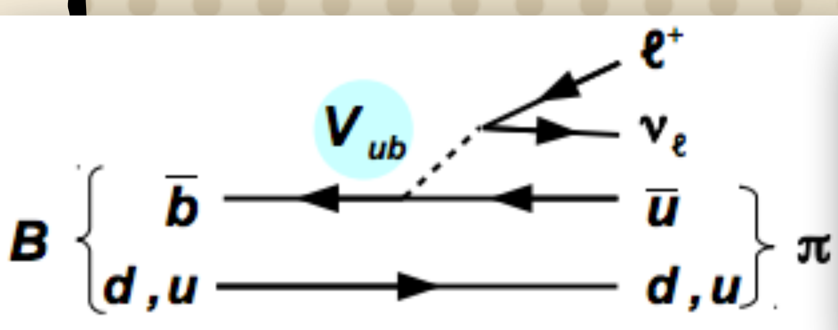


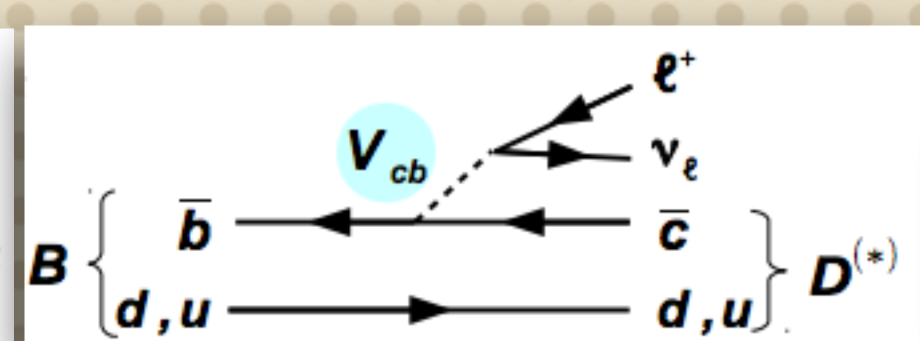
Semileptonic decays

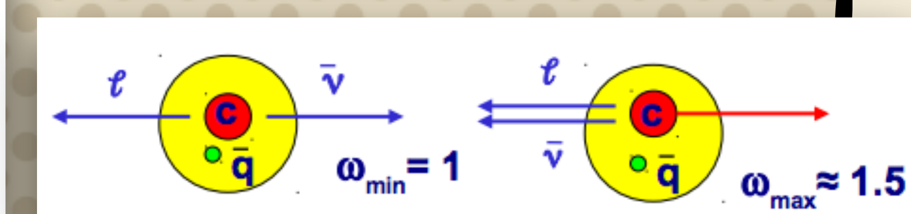
- Measure $|V_{ub}|$ from $\mathcal{B}(b \to u\ell^- \nu_\ell)$ and $|V_{cb}|$ from $\mathcal{B}(b \to c\ell^- \nu_\ell)$

- Exclusive decays:
  - Use decays such as $B \to \pi\ell\nu_\ell$ and $B \to D^{(*)}\ell\nu_\ell$
  - Theory uncertainty from QCD form factors
  - Relatively clean experimentally decays









$$\frac{d\Gamma}{d\omega}(B \to D^*\ell\nu_\ell) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2(m_B - m_{D^*})^2 m_{D^*}^3 \sqrt{\omega^2 - 1} PHS(\omega) F^2(\omega)$$

$$\frac{d\Gamma}{d\omega}(B \to D\ell\nu_\ell) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2(m_B - m_D)^2 m_D^3 (\omega^2 - 1)^{3/2} G^2(\omega)$$

Form factors

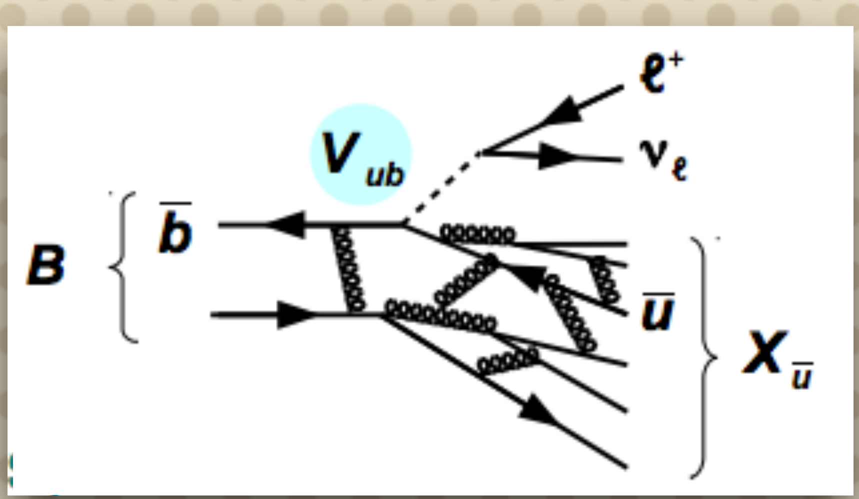
$$\omega = \frac{P_B \cdot P_{D^{(*)}}}{m_B m_{D^{(*)}}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$

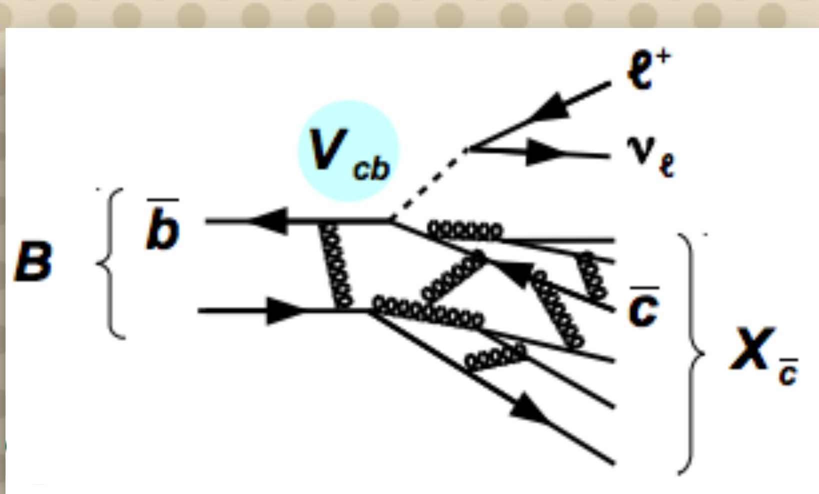
Semileptonic decays

Inclusive decays, i.e. measuring the rates of $B \to X_u \ell \nu_\ell$ and $B \to X_c \ell \nu_\ell$:

– Small theory uncertainty

– Challenging from experimental point of view





Difficult to disentangle $X_u \ell \nu_\ell$ final state and $X_c \ell \nu_\ell$:

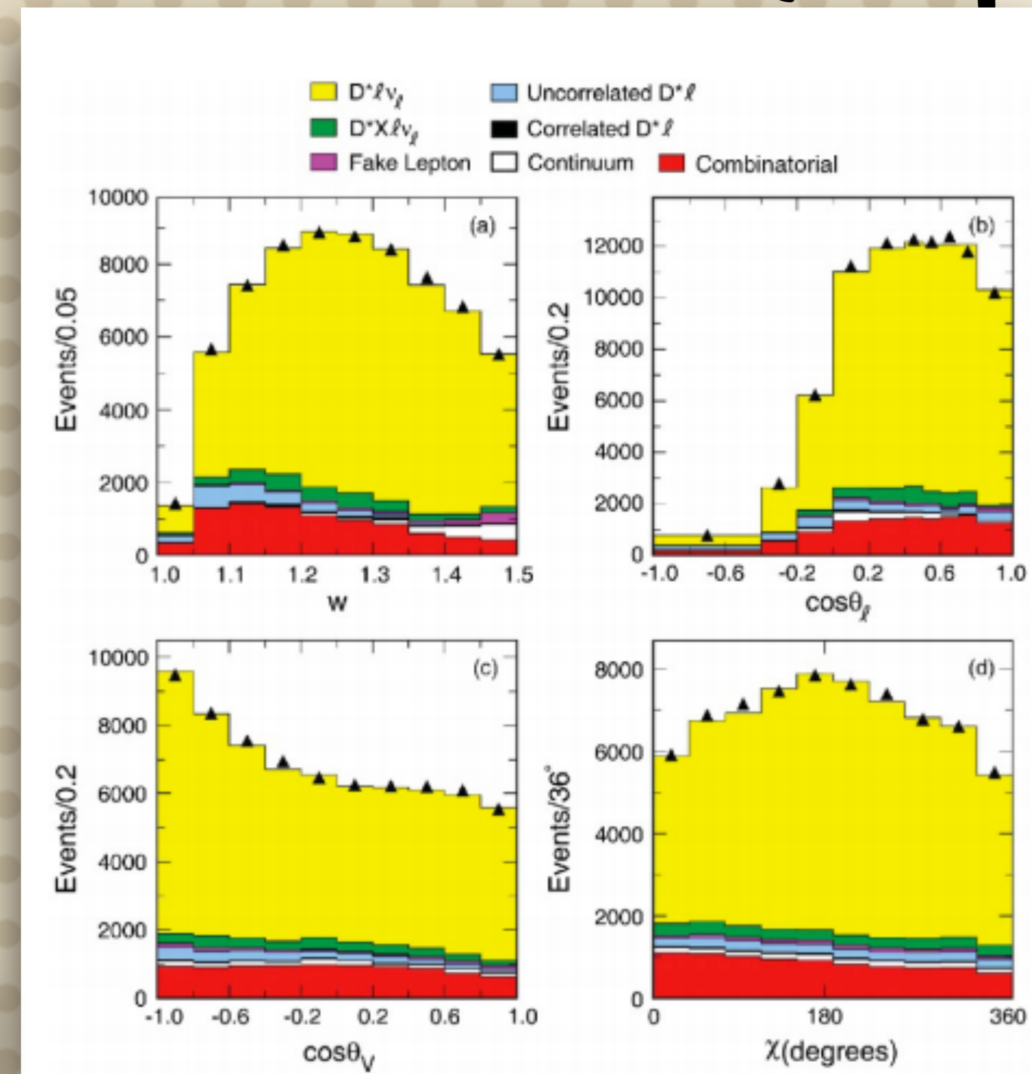
- Suppress background using tight kinematic cuts, but introduce form-factors dependent phase space corrections

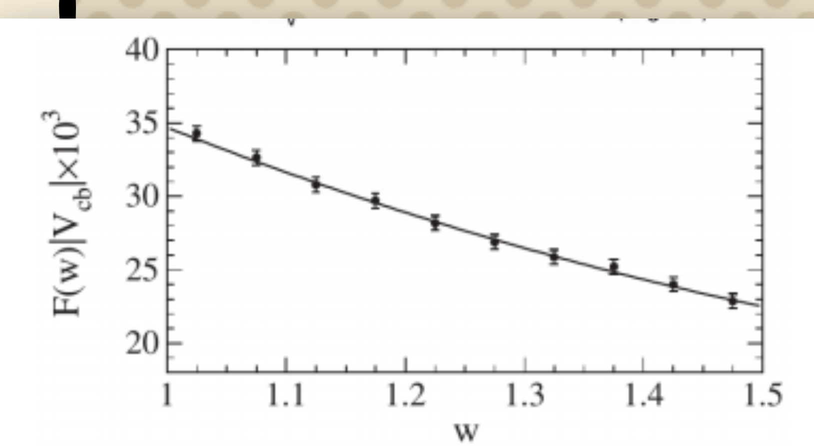
- Possible at B-factories fully reconstructing the other B-meson

Exclusive semileptonic decays

- tagged analysis (better resolution, lower statistics):
  - fully reconstruct the other B
  - Neutrino momentum from momentum imbalance

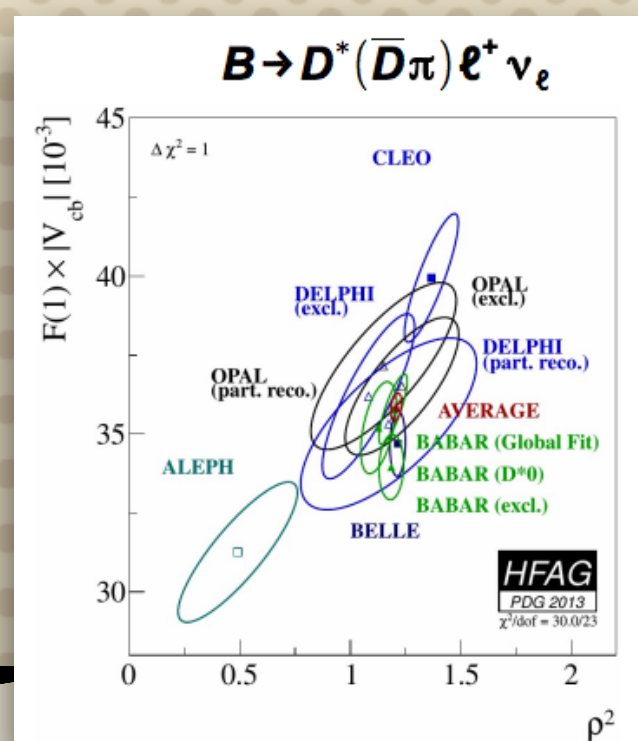
- untagged analysis:
  - higher statistics, but higher background and worse resolution

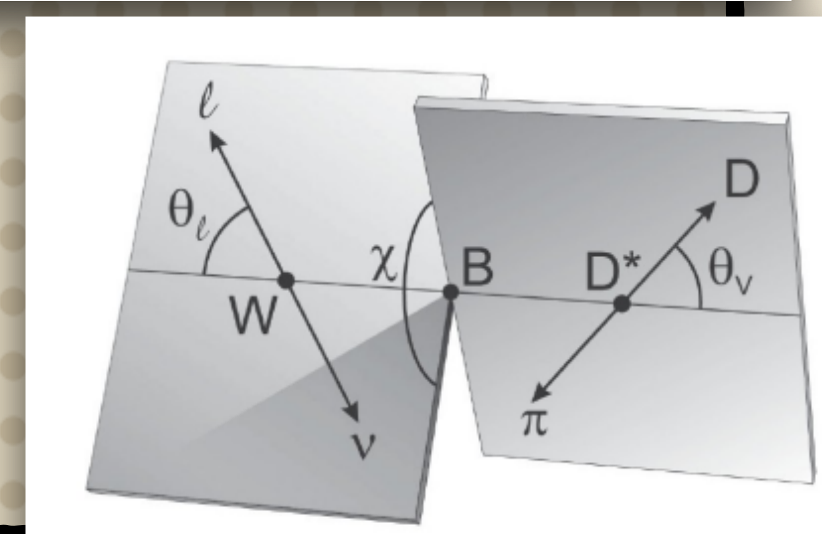




BaBar, $B^0 \to D^{*-}(\overline{D}^0\pi^-)\ell^+\nu_\ell$, untagged

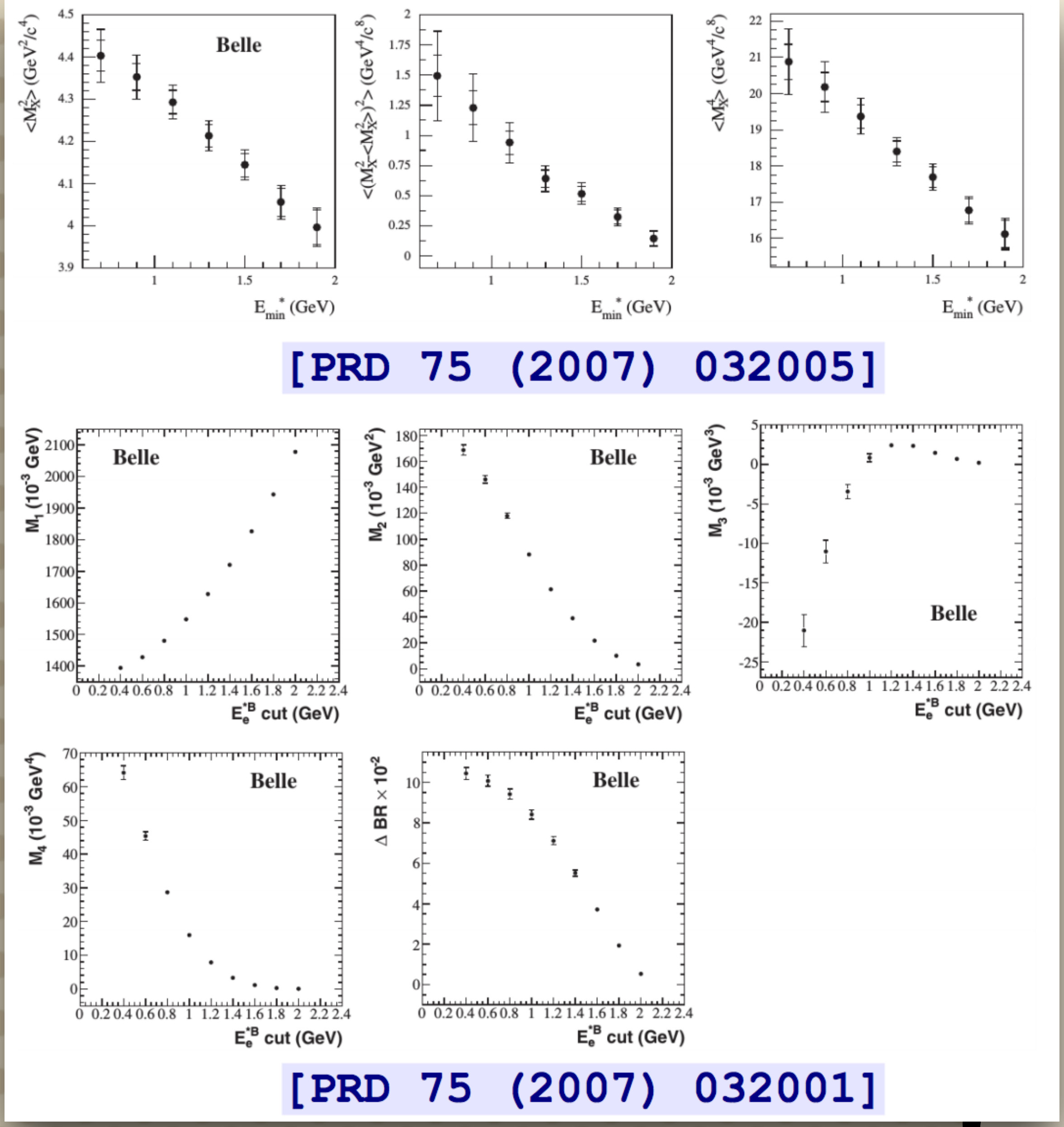
[PRD 77 (2008) 032002]





Vcb from inclusive decays

- tagged analysis:
  - fully reconstruct the other B-meson
  - Assign all remaining tracks and energy deposits to X_c
  - Require one charged lepton above a certain p_{min} threshold
  - Determine moments of the m(Xc) distribution
  - Do the same for a different value of p_{min}



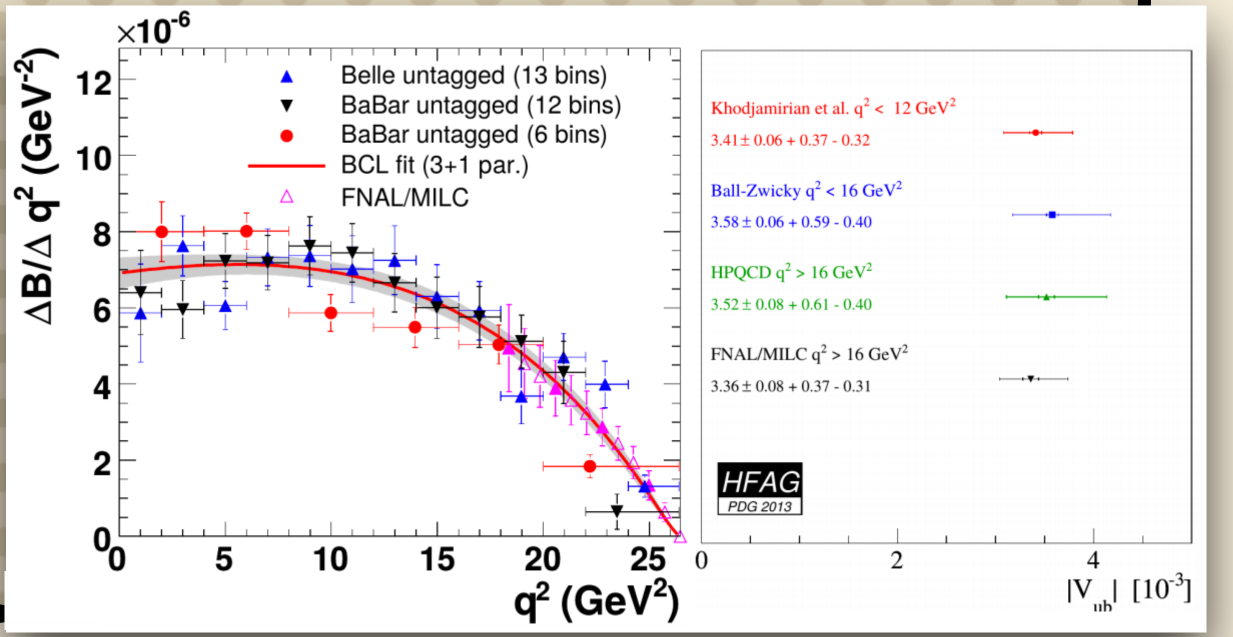
Moments of $E(\ell)$ and $m(X_c)$ distributions in $B \to X_c \ell \nu_\ell$ related to $|V_{cb}|$, m_b and m_c by HQET

Vub exclusive measurements

$$\frac{d\Gamma}{d\omega}(B \to \pi \ell \nu_\ell) = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 |p_\pi|^3 |f_+(q^2)|^2$$

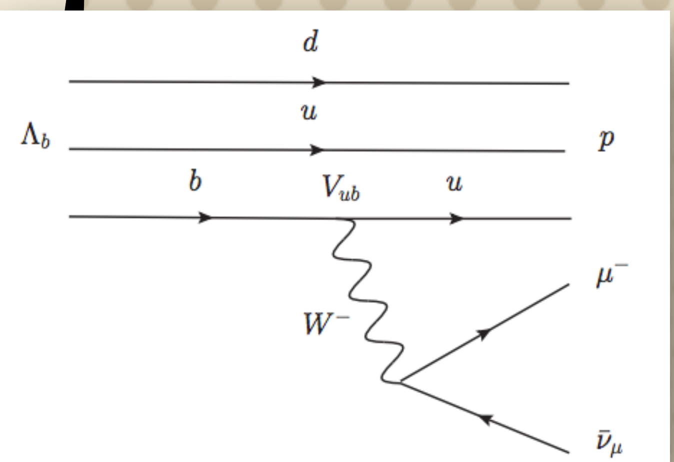
- Measurement done using untagged, hadronic tagged and semi-leptonic tagged analyses:
  - Untagged: larger statistics and worse resolution and more background
  - Semileptonic tagged: reconstruct the 2nd meson as $B \to D^{(*)} \ell \nu_\ell$ and use kinematic constraint in the center of mass
  - Hadronic tagged: fully reconstruct the other B-meson obtaining the neutrino momentum from momentum imbalance

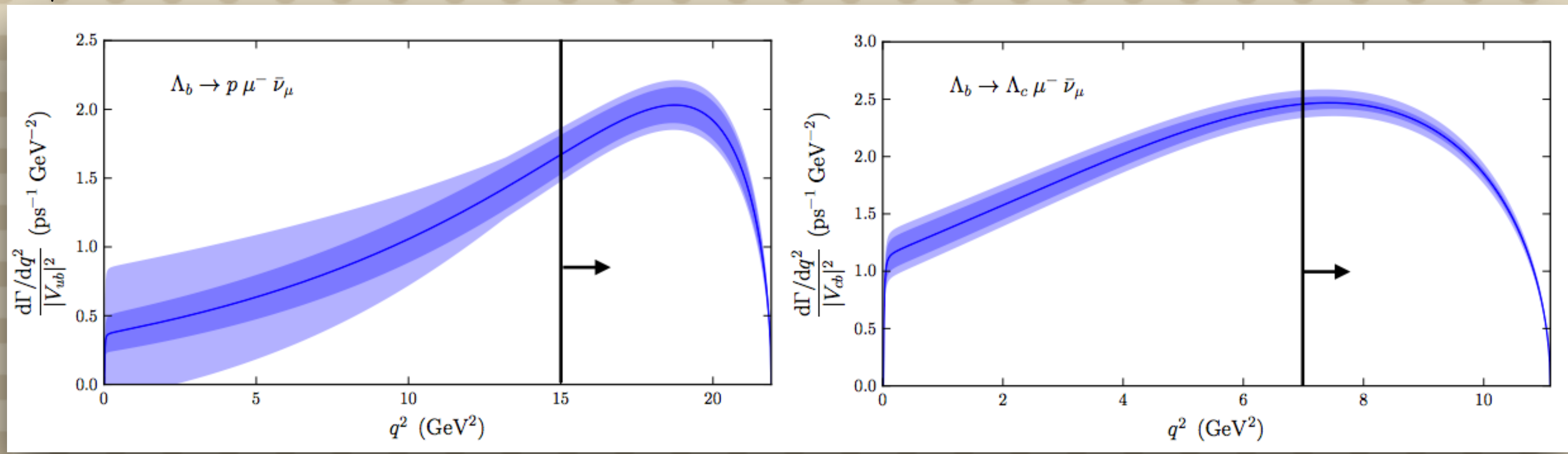
- Form factors at high q^2 from Lattice QCD
- Form factors at low q^2 from light-cone sum rules
- Various models to interpolate q^2 dependence in the two regions



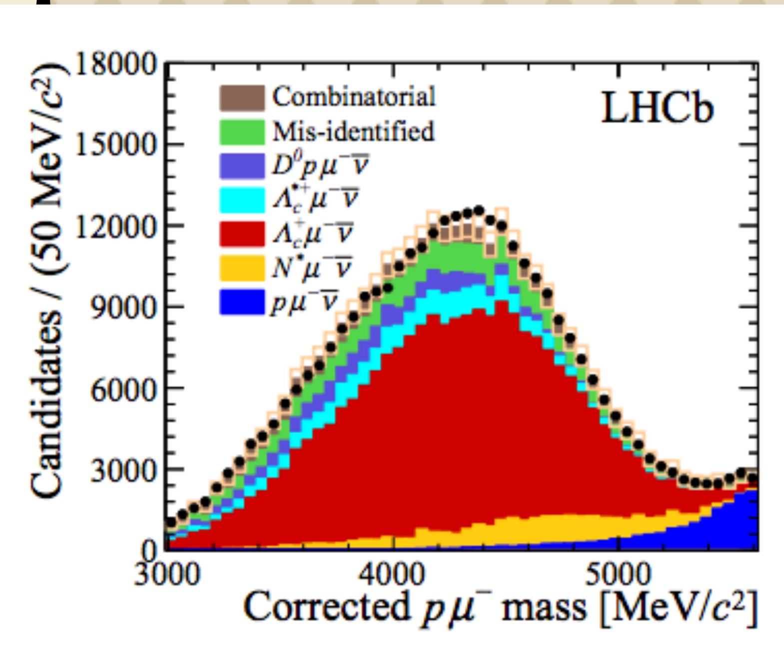
Vub exclusive measurements

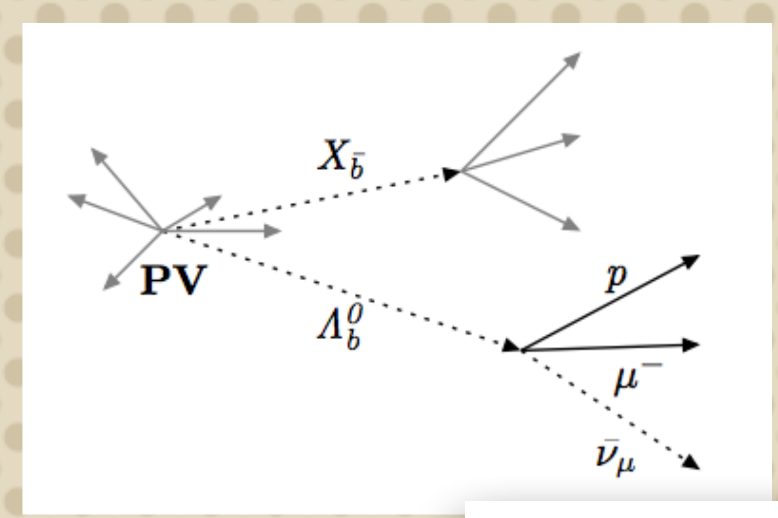
Determination of $\frac{|V_{ub}|^2}{|V_{cb}|^2}$ using the decays $\Lambda_b \to p\mu\nu$ and $\Lambda_b \to \Lambda_c\mu\nu$

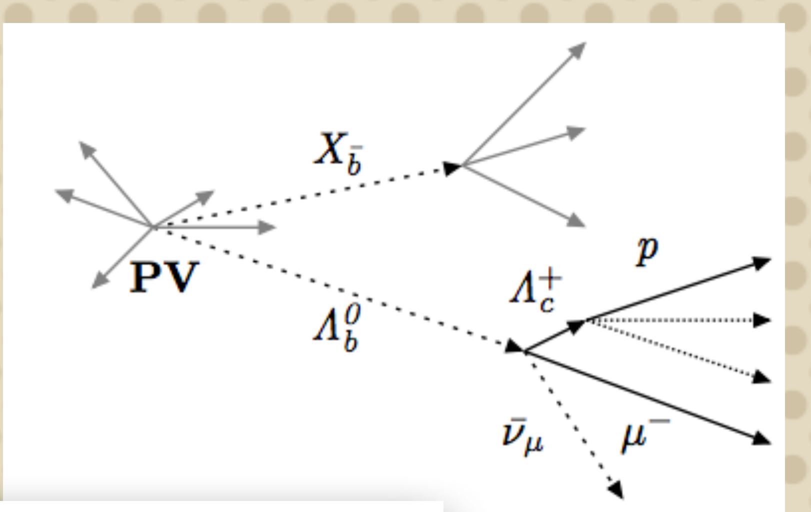




- The decay $\Lambda_b \to p\mu\nu_\nu$ is the baryonic version of the $B \to \pi\ell\nu_\ell$
- Cleaner at LHCb due to protons are rarer than kaon and pions
- Normalisation mode cancels the several systematic uncertainties



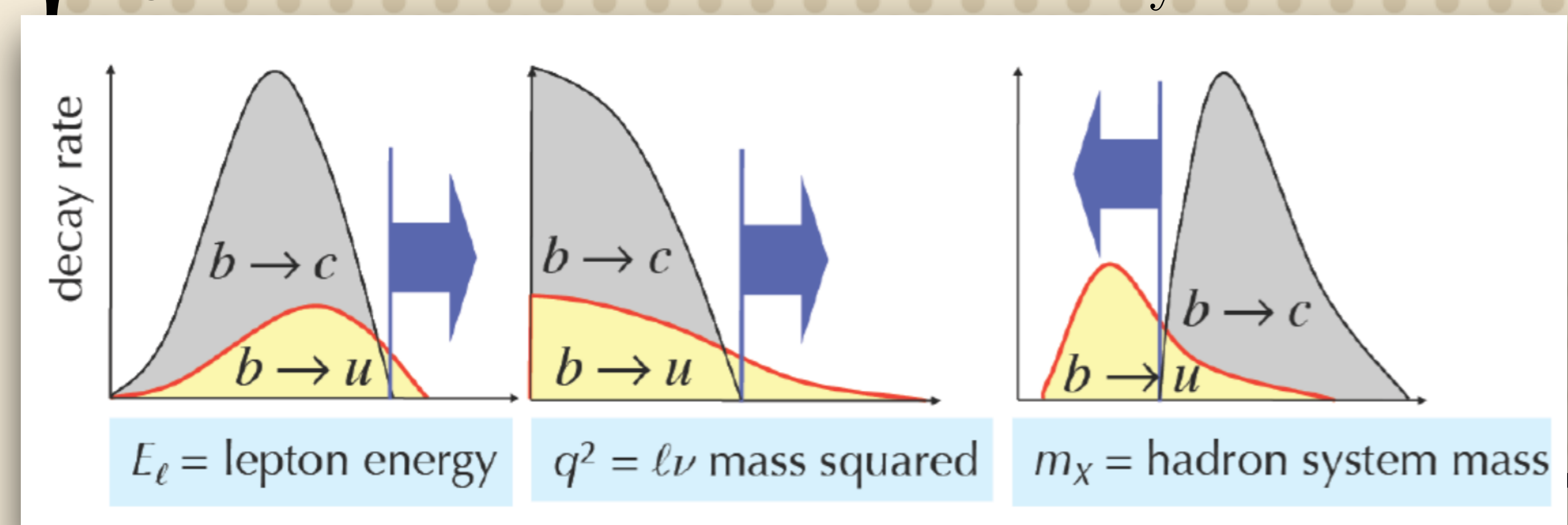




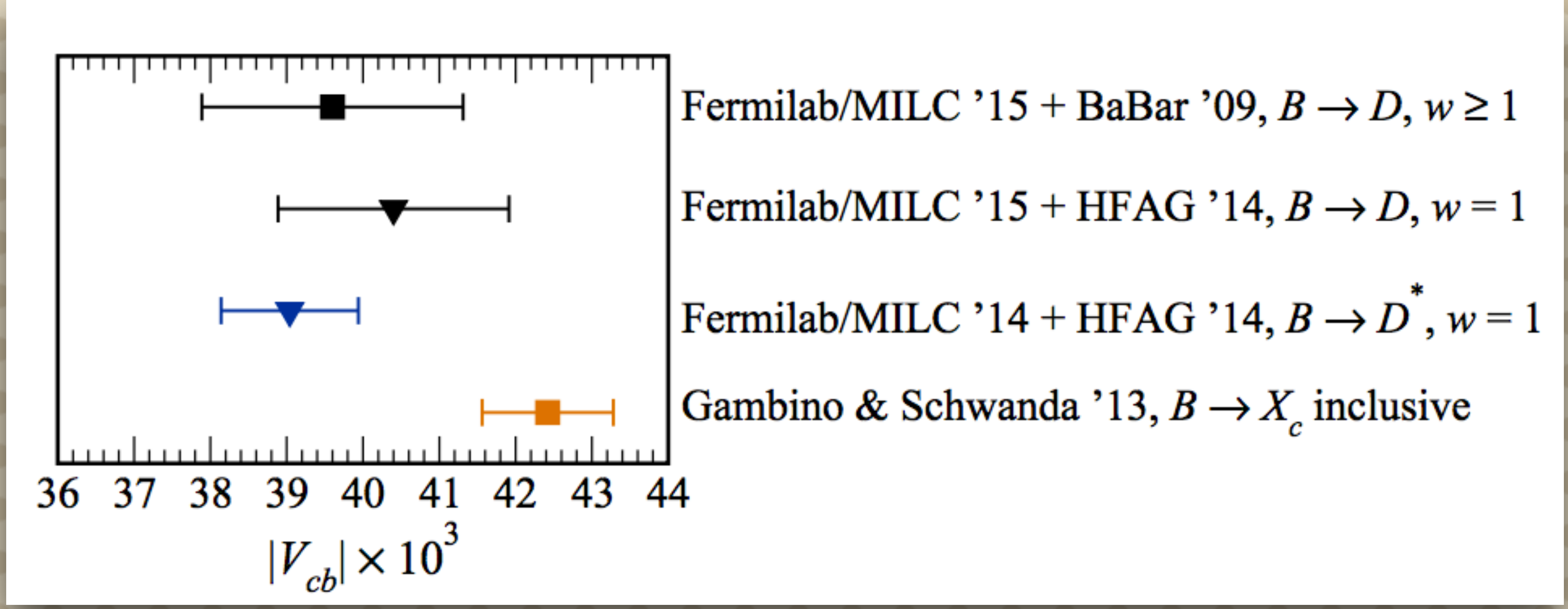
Nature Physics **11**, 743–747 (2015)

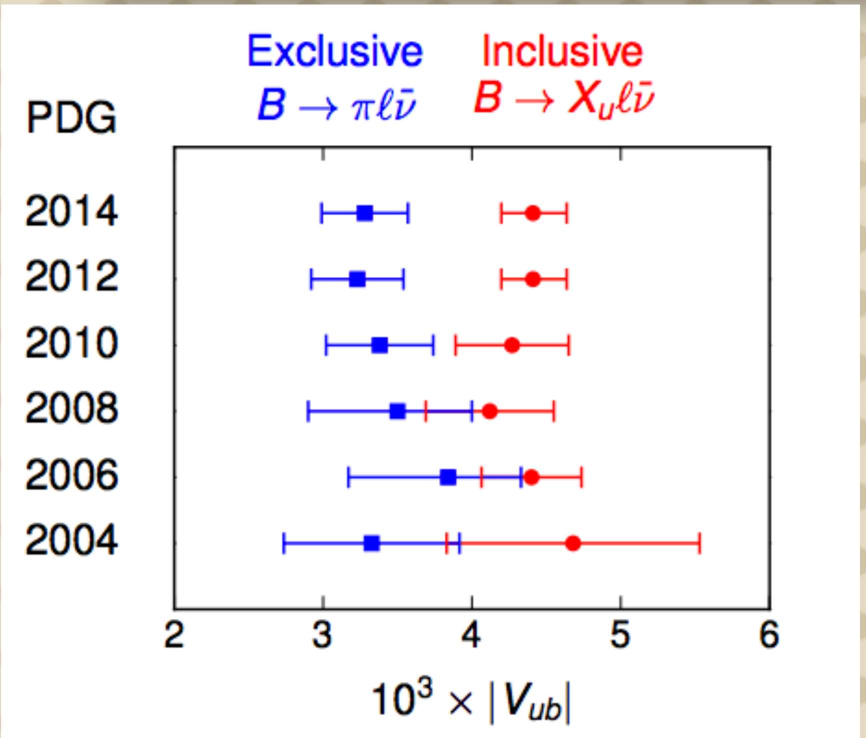
Vub inclusive measurements

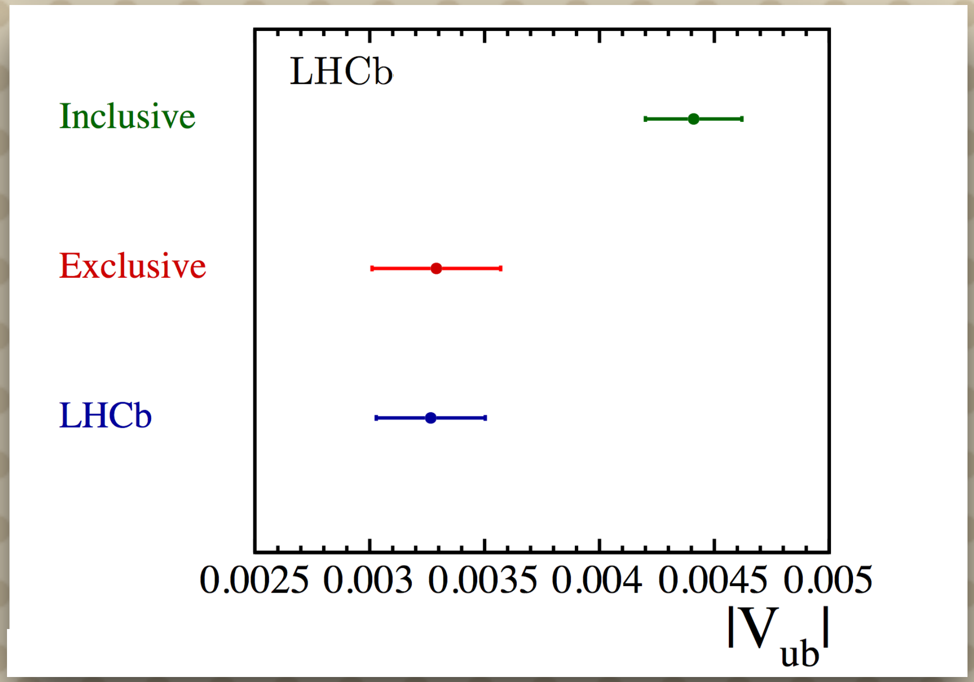
- Fully reconstruct the 2nd B-meson, assign remaining tracks to B_{rec}, require a charge lepton from B_{rec}
- Challenging background from $B \to X_c \ell \nu_\ell$ (about 50 times the signal)
- Suppress $b \to c$ background using:
  - Lepton energy: $E(\ell) > \frac{(m_B^2 - m_D^2)}{2m_B}$; Momentum transfer: $q^2 > (m_B - m_D)^2$; Invariant mass of X: $m_X < m_D$
- Other criteria: vetos for π_{sl} from $D^* \to D\pi_{sl}$, kaons from $b \to c \to s$, second lepton from $c \to s\ell\nu$, higher multiplicity in $b \to c$, ...
- Cut based selections or multivariate analysis



Inclusive VS Exclusive

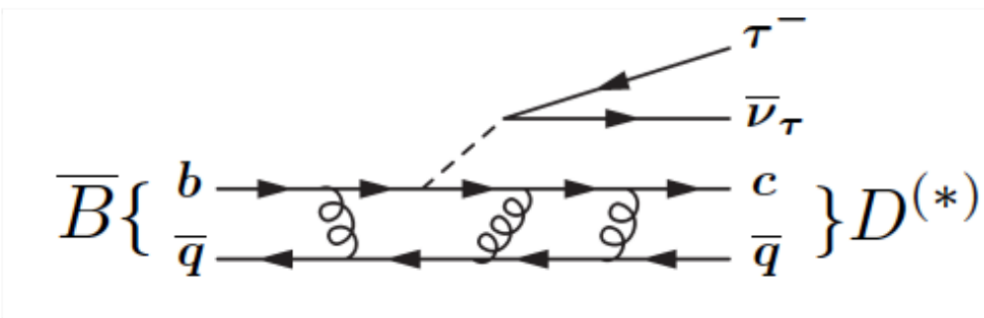






Semitaunic decays

Semitauonic decays



$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell\nu)} = \frac{\text{signal}}{\text{normalization}} \quad (\ell = e, \mu)$$

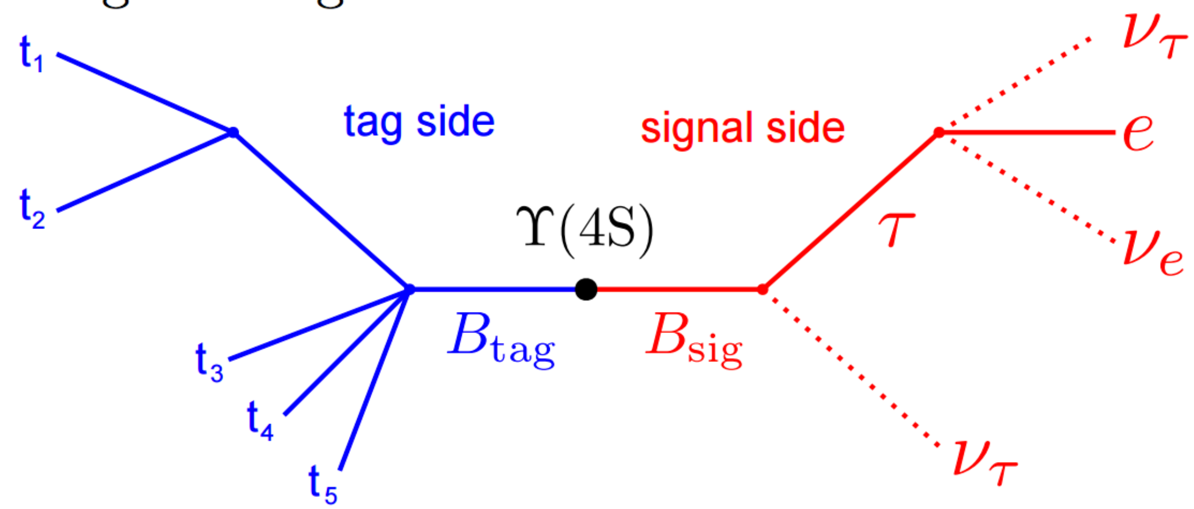
- B-factories measure tau->e,mu 2v
- LHCb measures tau->mu 2v

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2\,|V_{cb}|^2\,|\boldsymbol{p}^*_{D^{(*)}}|\,q^2}{96\pi^3 m_B^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^2 \Big[(|H_+|^2 + |H_-|^2 + |H_0|^2)\left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2}|H_s|^2\Big]$$

- Since the D-meson is a scalar $H_{+,-}$ vanish
- Amplitudes depend on 4 universal FFs extracted from data
- Four free parameters in the fit
- In the case of the e/mu H_s is suppressed by the mass, so this is only present in the channel with the tau (from HQET)

B-factory strategy

Tag- and signal-side of the full reconstruction

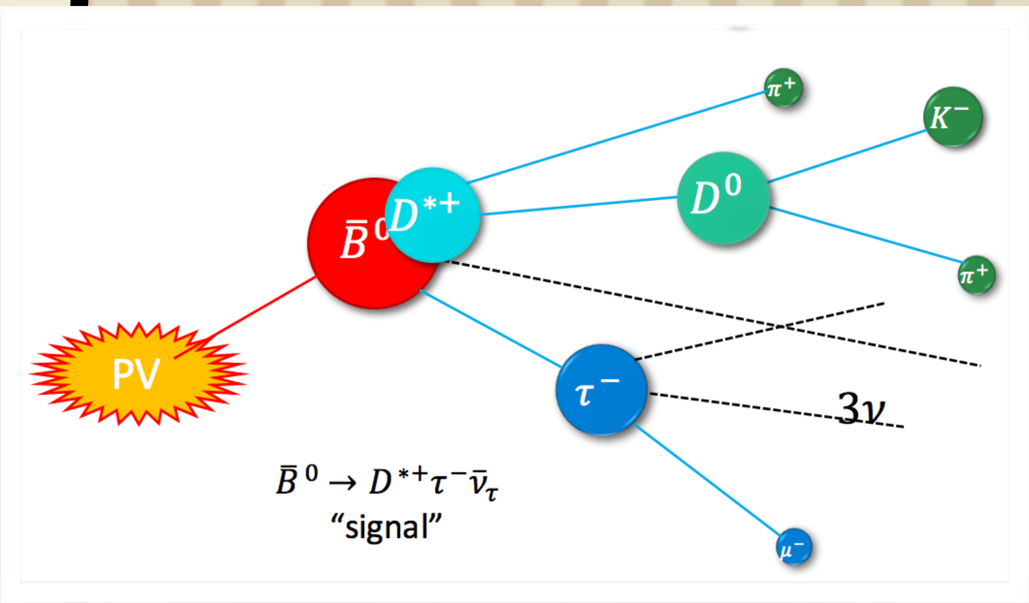


$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} = \frac{\int_{m_\tau^2}^{q^2_{\max}} \frac{d\Gamma_\tau}{dq^2}\, dq^2}{\int_{m_\ell^2}^{q^2_{\max}} \frac{d\Gamma_\ell}{dq^2}\, dq^2}$$

- Hadronic tag analyses:
  - Reconstruct tag B meson in all hadronic mode
  - Precise knowledge of kinematic of missing system
  - Kill background, but efficiency about 10^{-3}

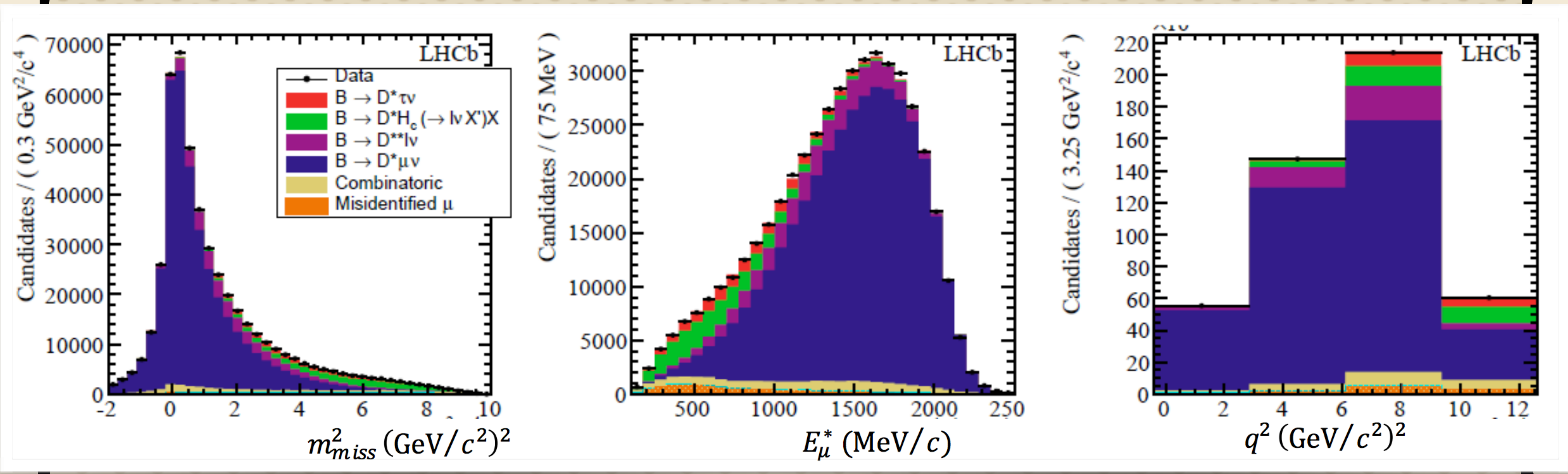
- Semileptonic analyses:
  - Tag B-meson in semileptonic channel
  - Selection: E_T, missing mass and angle between D*l and B

LHCb Strategy



$$(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu} \implies (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

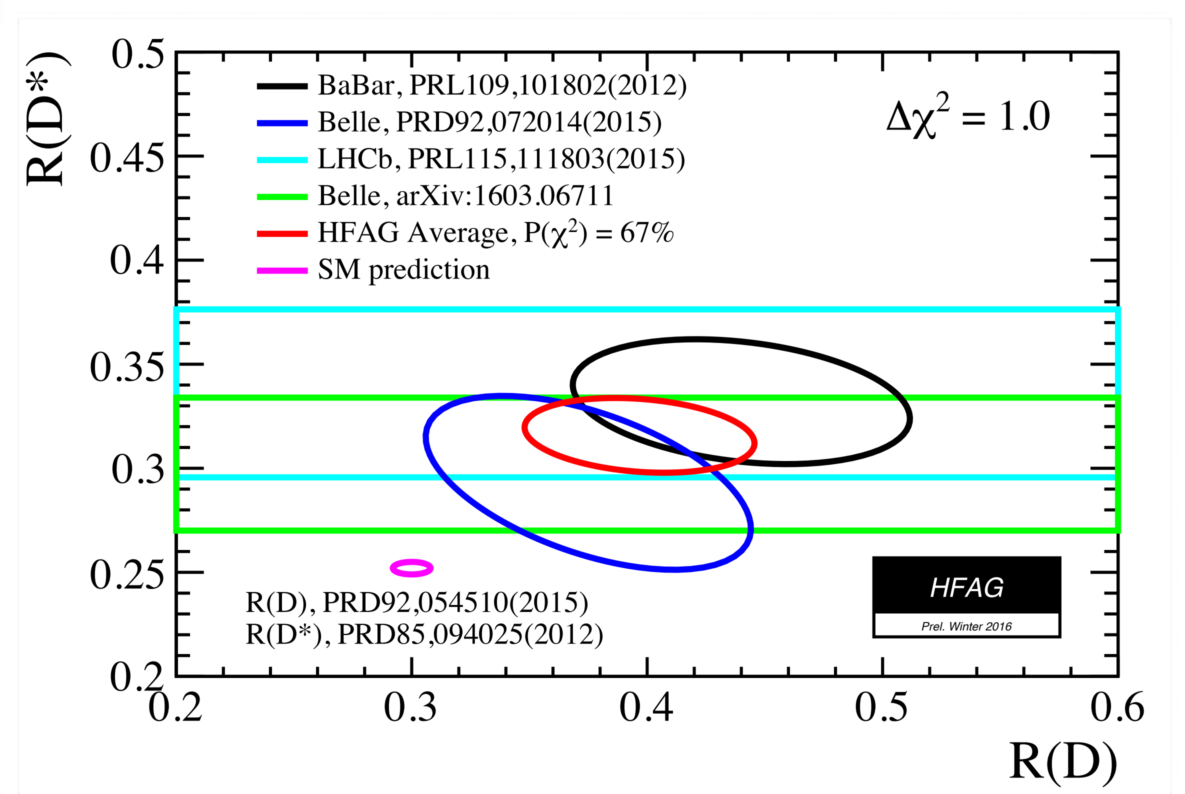
- B-direction given by PV-SV
- Full fit of the MM, E*, q²
- Muon, tau modes and bkg fit simultaneously



Results

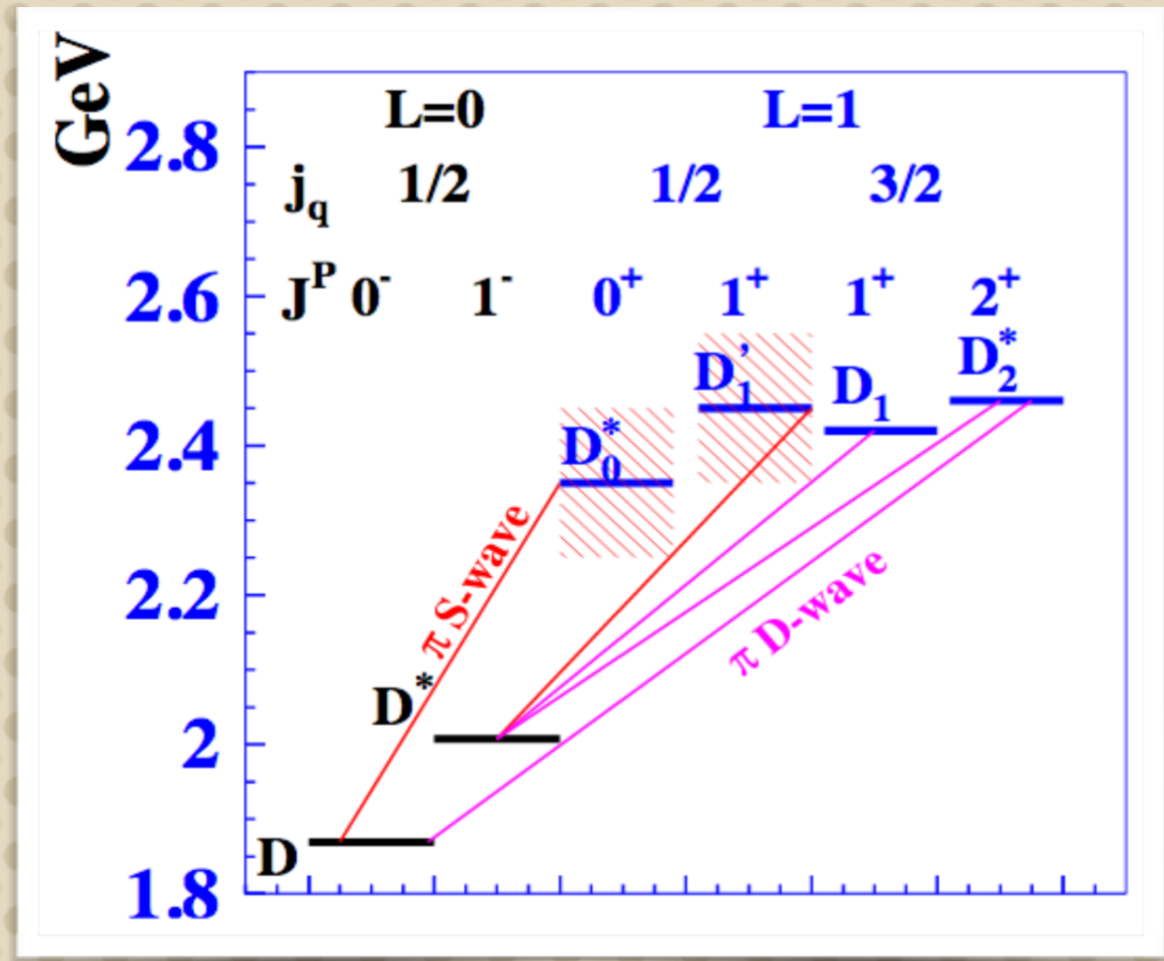
From HFAG webpage

Experiment	R(D*)	R(D)	Rescaled Correlation (stat/syst/total)	Parameters	Remarks
BaBar	0.332 +/- 0.024+/- 0.018	0.440 +/- 0.058 +/- 0.042	-0.45/-0.07/-0.27	input	Phys.Rev.Lett. 109,101802 (2012) [arXiv:1205.5442 [hep-ex]] Phys.Rev.D 88, 072012 (2013) [arXiv:1303.0571]
BELLE	0.293 +/- 0.038 +/- 0.015	0.375 +/- 0.064 +/- 0.026	-0.56/-0.11/-0.49	input	Phys.Rev.D 92, 072014 (2015) [arXiv:1507.03233 [hep-ex]]
BELLE	0.302 +/- 0.030 +/- 0.011	-	-	input	Preliminary at Moriond EW 2016 [arXiv:1603.06711 [hep-ex]]
LHCb	0.336 +/- 0.027 +/- 0.030	-	-	input	Phys.Rev.Lett.115,111803 (2015) [arXiv:1506.08614 [hep-ex]]
Average	**0.316+/- 0.016 +/- 0.010**	**0.397+/- 0.040 +/- 0.028**	**-0.21**	**chi2/dof = 2.38/4 (CL = 0.67)**	pdf png

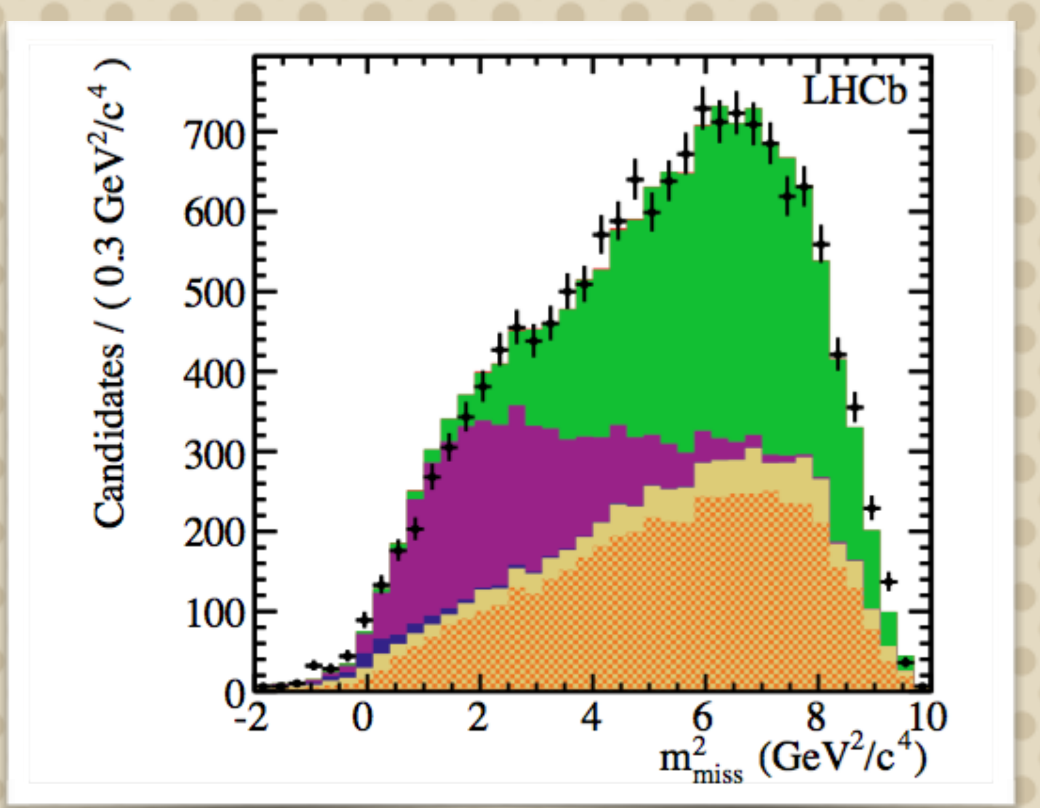


Deviation of about 4sigmas wrt SM predictions!

Experimental challenges

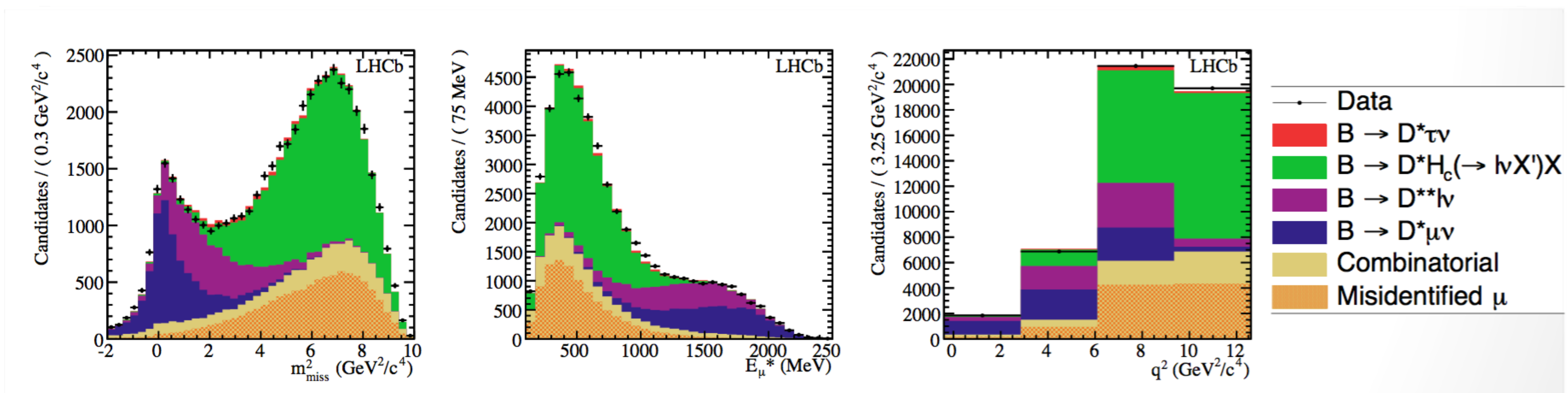


example B->D*pipi lv

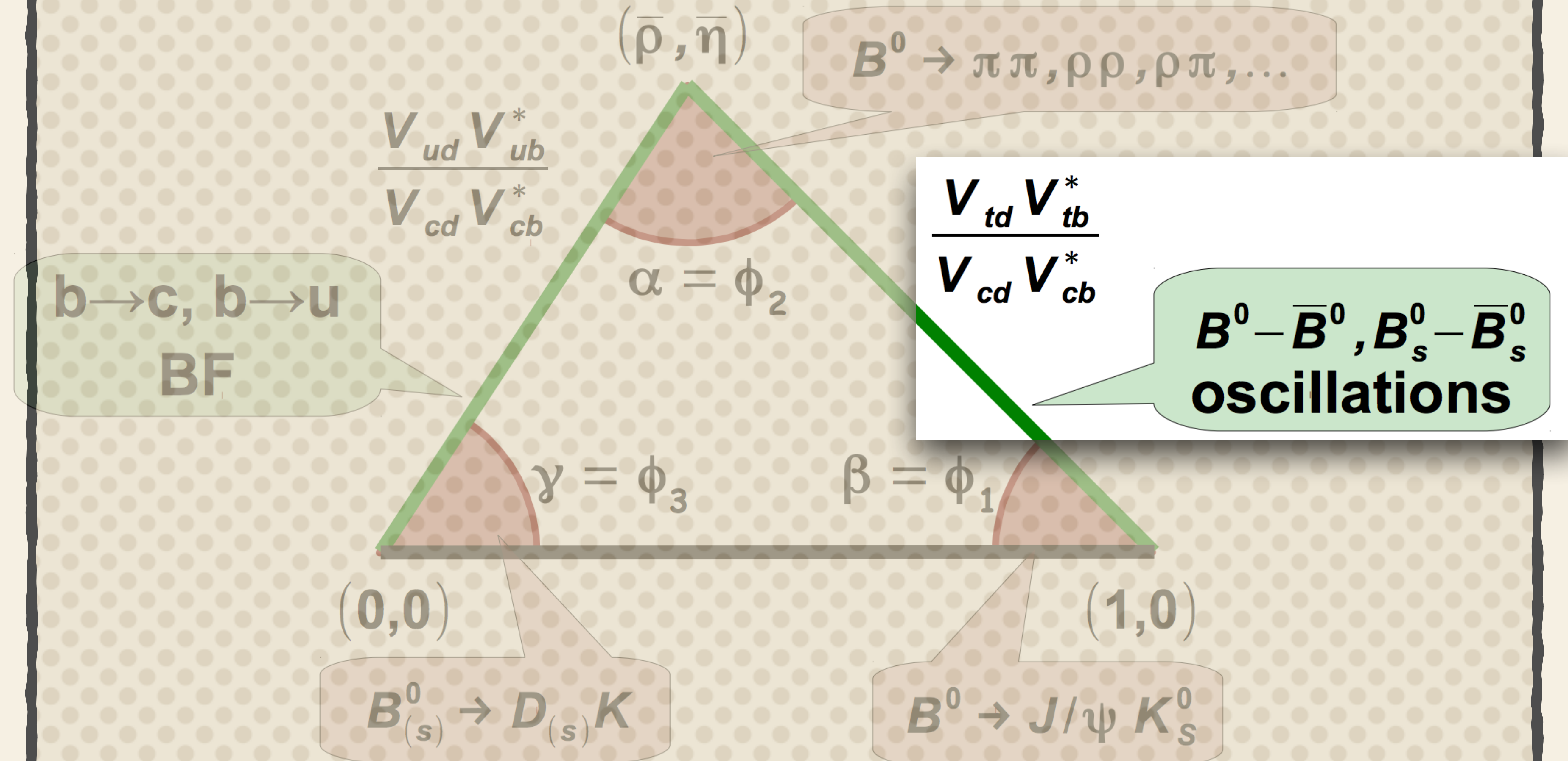


- Large contribution from excited D** states
- Narrow states ($D_1^{(')}$ and D_2^*) fit directly from data B->D*pi lv used as a control sample
- Higher D** excited states also fit from data and B->D pipi lv used as a control channel

Double Charm Bkg



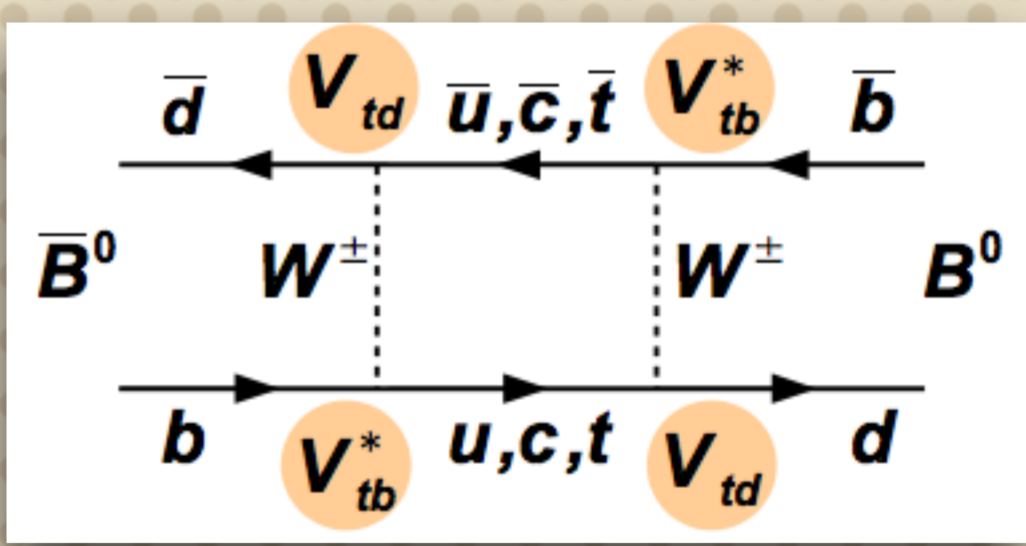
- As usual charm is a background for tau
- Bkg from D_s->tau nu, D ->K lv fit directly from data
- Control sample obtained reconstructing B->D* K lv

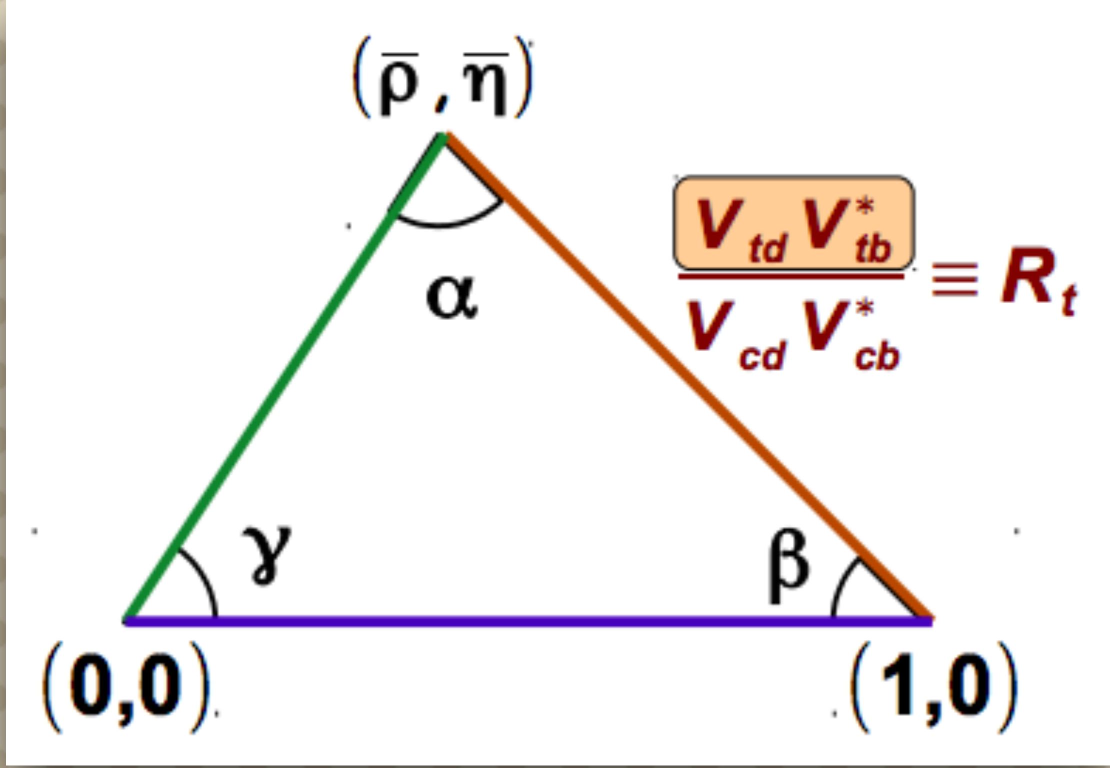


$(\bar{\rho},\bar{\eta})$
$B^0 \to \pi\pi, \rho\rho, \rho\pi, \ldots$
$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$
$\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$
$b \to c$, $b \to u$
BF
$\alpha = \phi_2$
$B^0 - \overline{B}^0, B_s^0 - \overline{B}_s^0$
oscillations
$\gamma = \phi_3$
$\beta = \phi_1$
(0,0)
(1,0)
$B^0_{(s)} \to D_{(s)} K$
$B^0 \to J/\psi\, K_S^0$

Neutral B-meson mixing

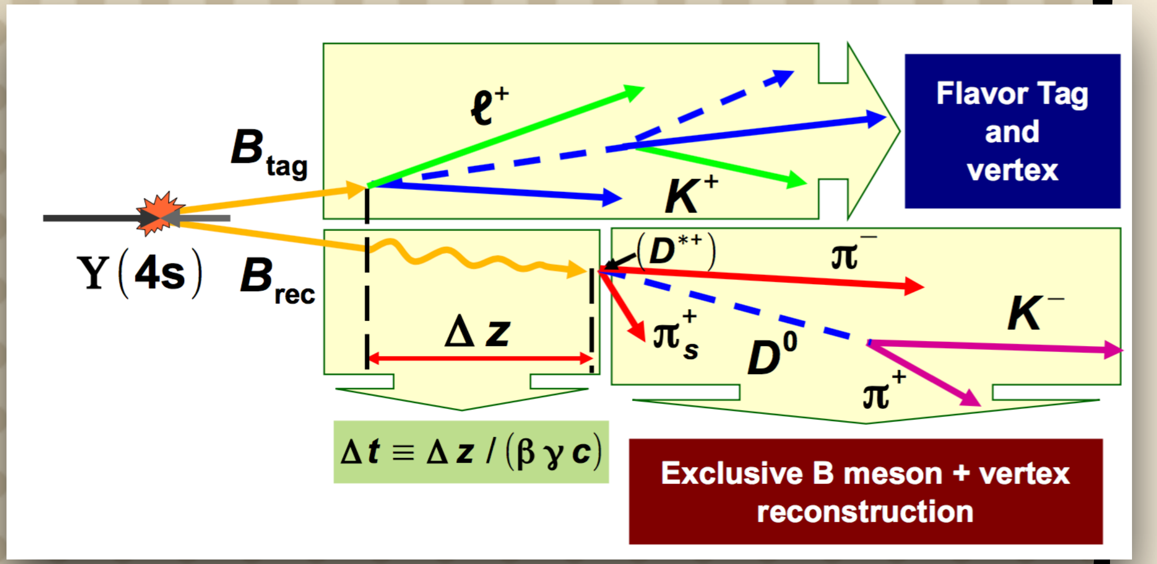
- $B^0 \leftrightarrow \overline{B}^0$ transitions due to off diagonal H_{12}
- $M_{12} \propto m_t^2 (V_{td} V_{tb}^*)^2$ dominated by off-shell intermediate state
- $\Gamma_{12} \ll M_{12}$ therefore the oscillation frequency is $\Delta M_d = 2|M_{12}| \propto |V_{td}|^2 |V_{tb}|^2$
- Best way to measure ΔM_d is via the time-dependent mixing asymmetry: $a_{mix}(t) = \overline{a}_{mix}(t) = \frac{\cos \Delta M_d \cdot t}{\cosh \Delta\Gamma \cdot t} \simeq \cos \Delta M_d \cdot t$

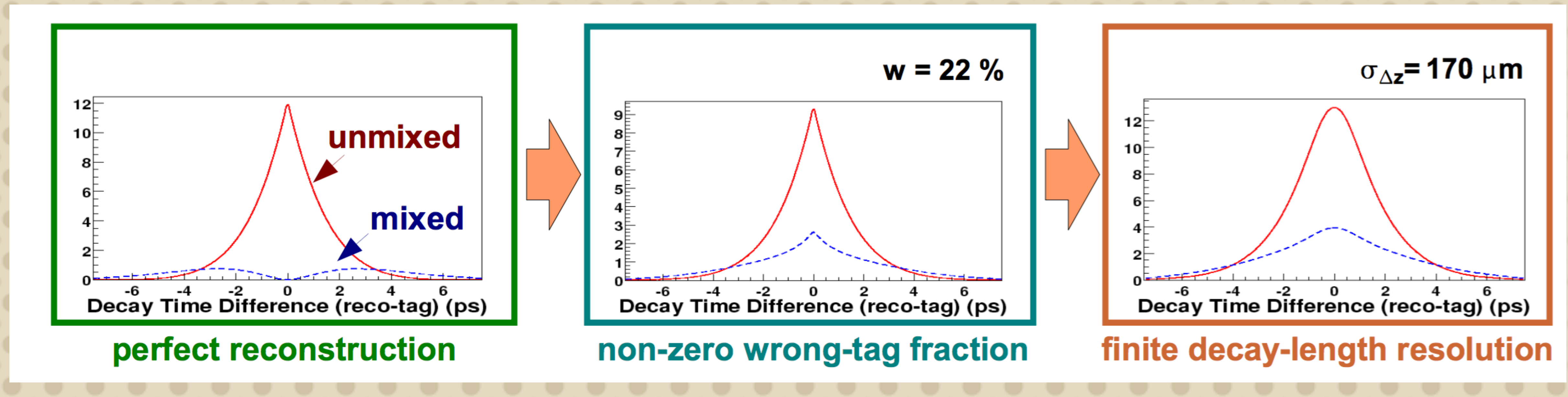




B-factories

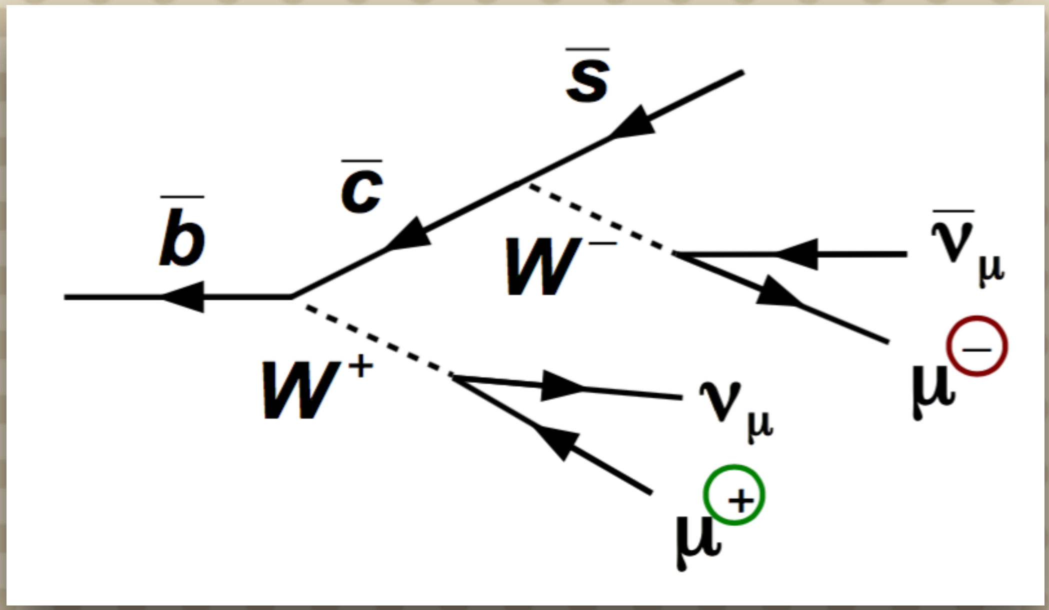
- Fully reconstruct B_{rec} in a flavour specific decay
- Measure momentum, decay vertex and flavour of B_{rec}
- Assign all remaining tracks to B_{tag}
- Infer the flavour of B_{rec} at production from the flavour of B_{tag}
- Decay time difference given by ΔZ and the B_{rec} momentum

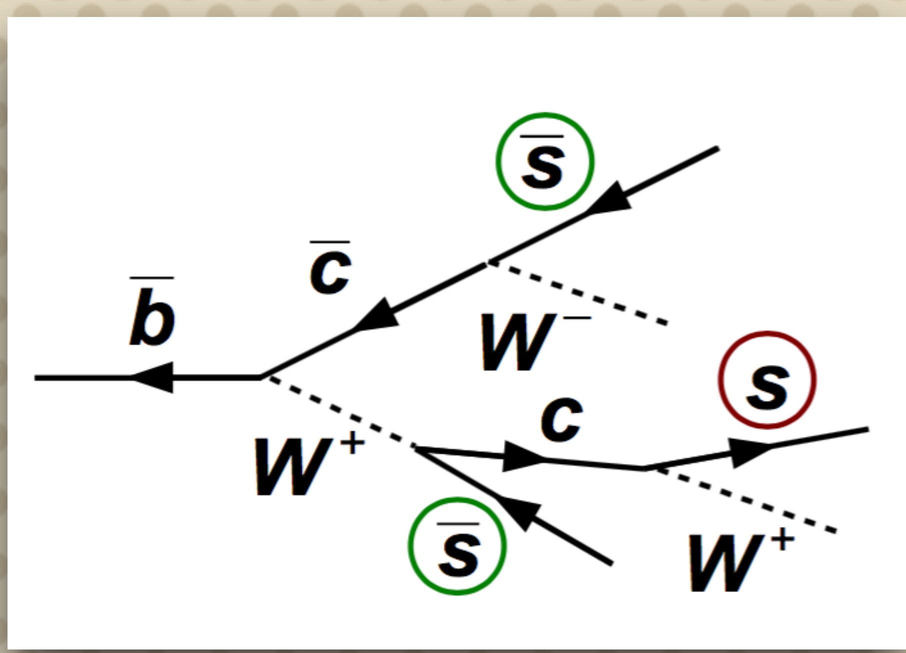




Flavour Tagging

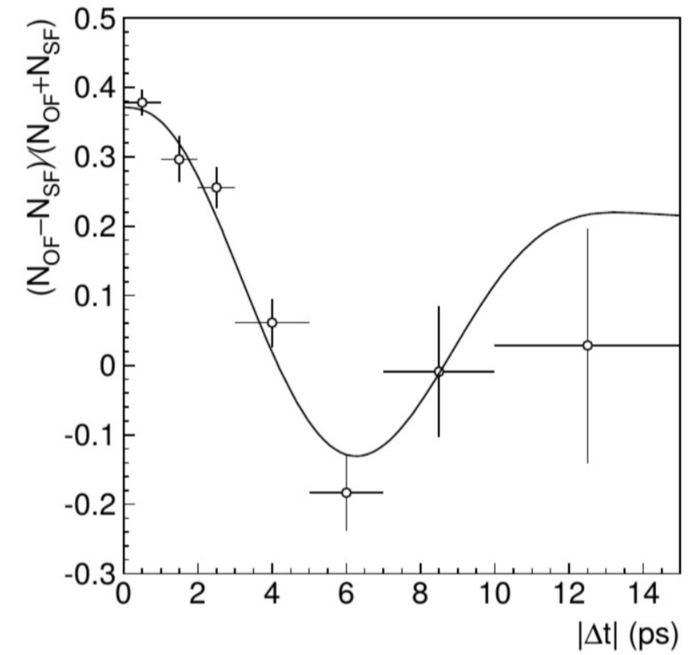
- Effect of tagging given by the tagging power: $Q = \epsilon D^2 = \epsilon(1-\omega)^2$, where ϵ, D and ω are the tagging efficiency, dilution and wrong fraction
  - Lepton: tagging has low mis-tag fraction, small efficiency, small contamination from
  - Kaons:higher efficiency, higher mis-tag fraction
  - Inclusive methods (e.g. vertex charge): high efficiency, high mis-tag fraction
- Typically several techniques are combined in a neural network





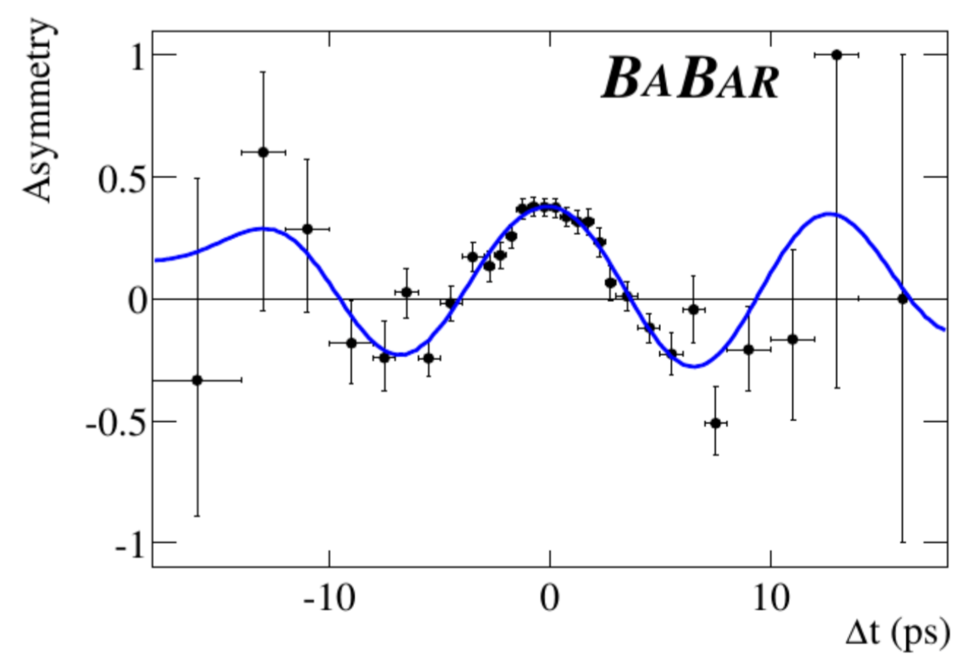
B-factory measurement

- Hadronic decays (e.g. $B^0 \to D^{(*)-}\pi^+$):
  - clean event (B_{rec} fully reconstructed)
  - flavour at decay from pion charge
  - small branching ratio



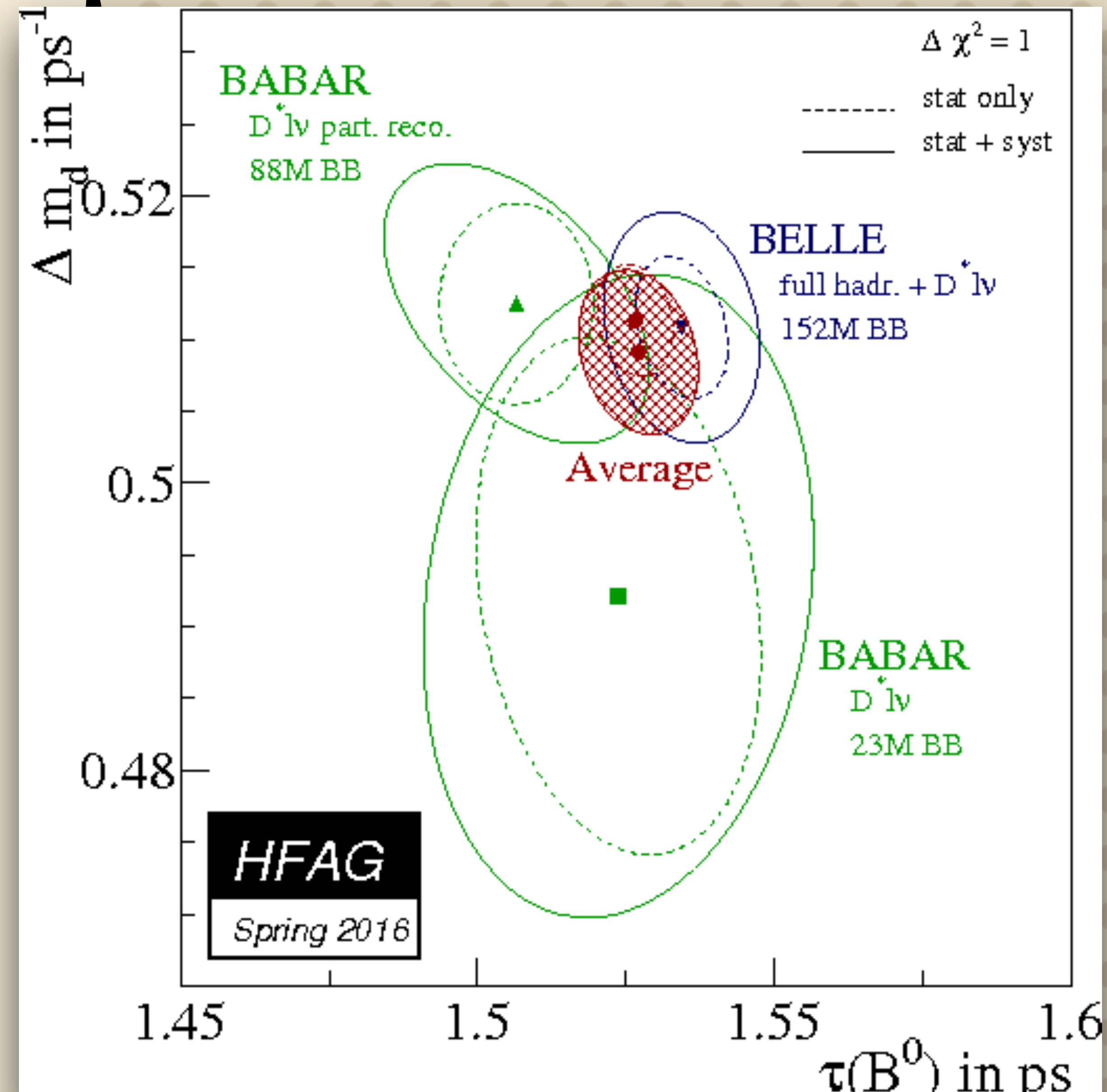
[PLB 542 (2002) 207]

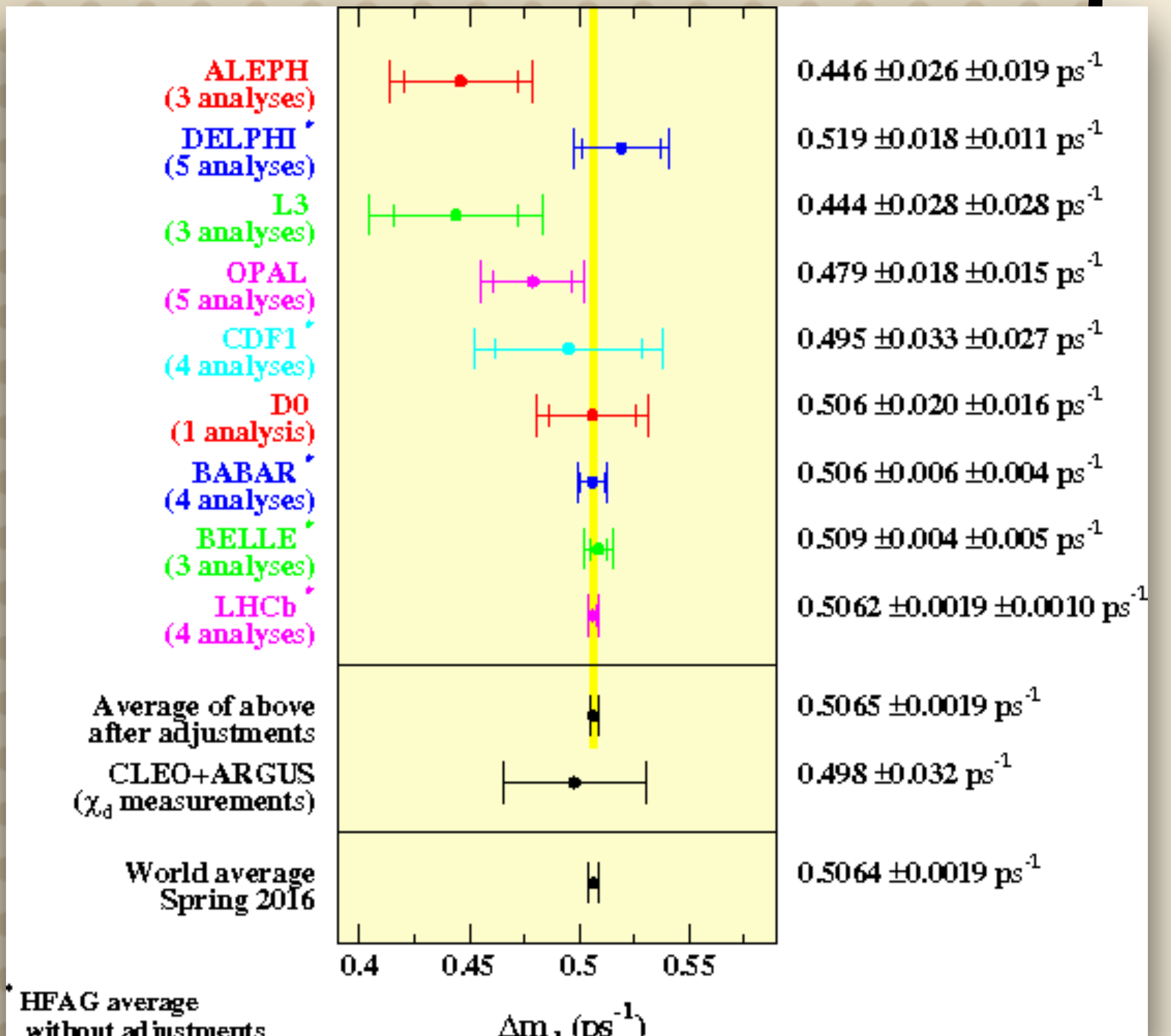
- Semi-leptonic decays (e.g. $B^0 \to D^{(*)-}\ell^+\nu_\ell$):
  - higher branching ratio
  - reasonably clean events
  - flavour from ℓ charge
  - neutrino missing, worse B-momentum resolution



[PRD 67 (2003) 072002]

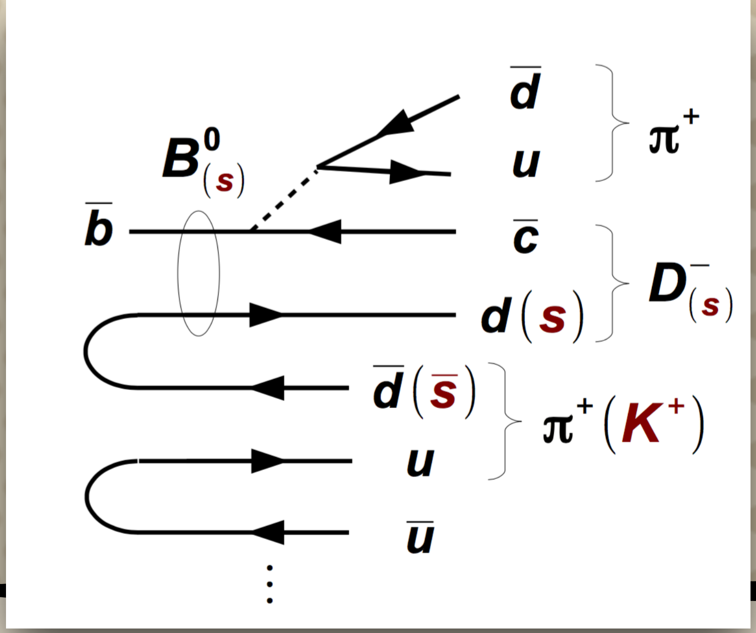
B⁰ mixing results

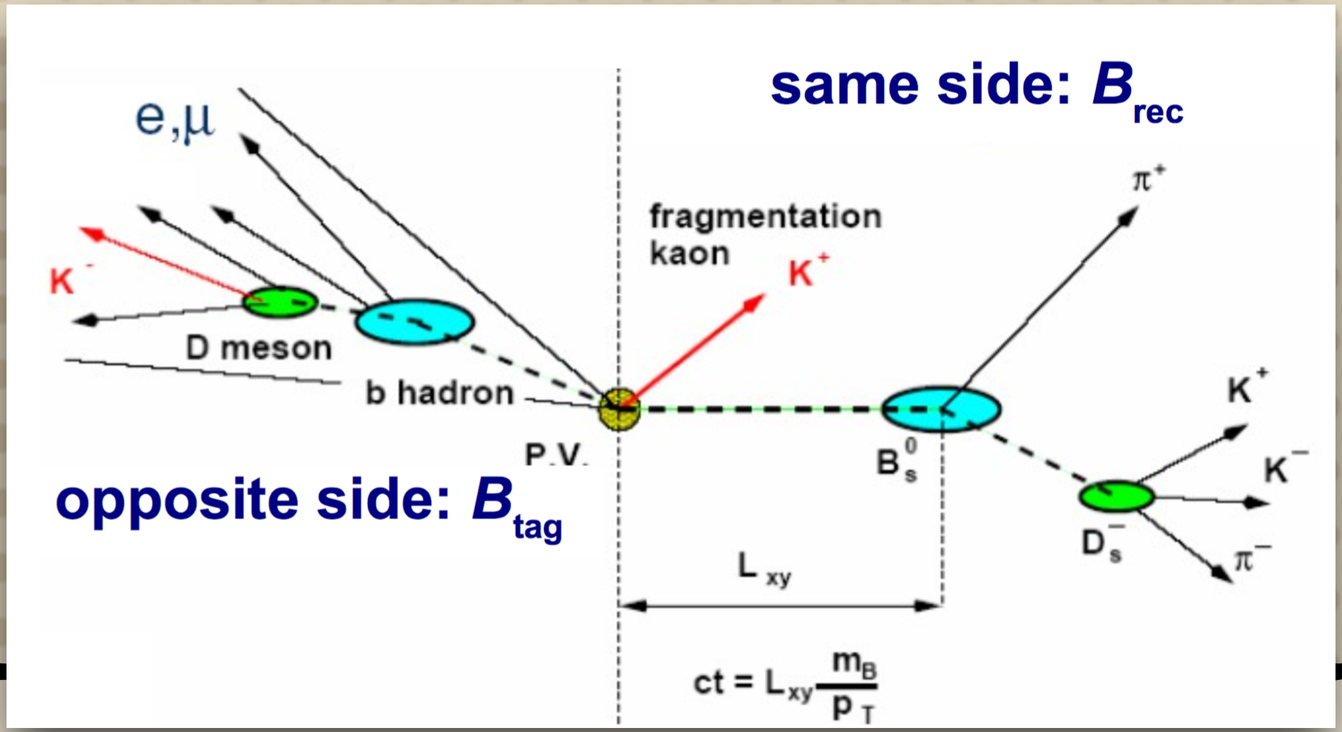




Tagging at hadron colliders

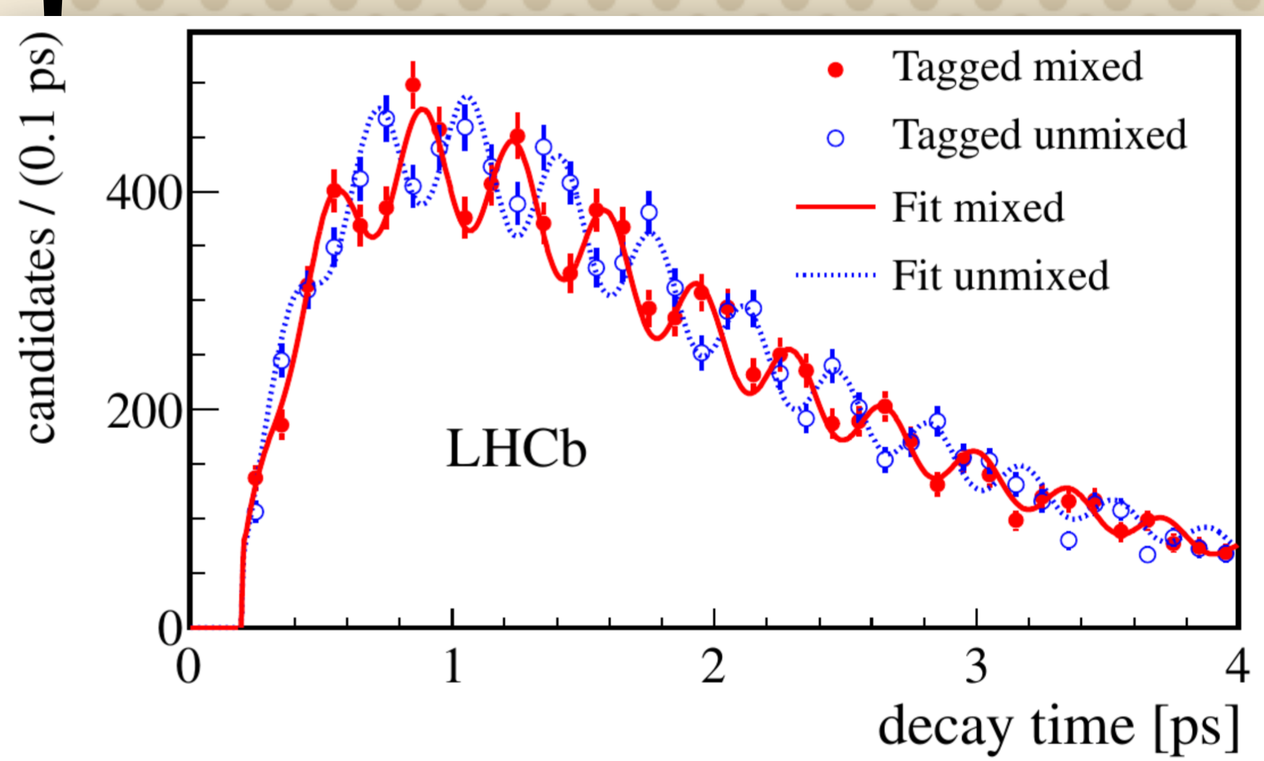
- ΔZ measured as the distance between PV and SV
- Flavour specific B_{rec} decay (e.g. $B_s^0 \to D_s^- \pi^+$)
- Flavour at production:
  - Opposite side tagging (lepton, kaon, jet/vertex charge):
  - Intrinsic dilution from mixing is about 40% for B^0 and 10% from B_s
  - Many more tracks imply larger wrong tag fraction wrt B-factories
- Same side tagging using pion or kaon close to B_{rec} in phase space
- In general tagging performances worse than B-factories



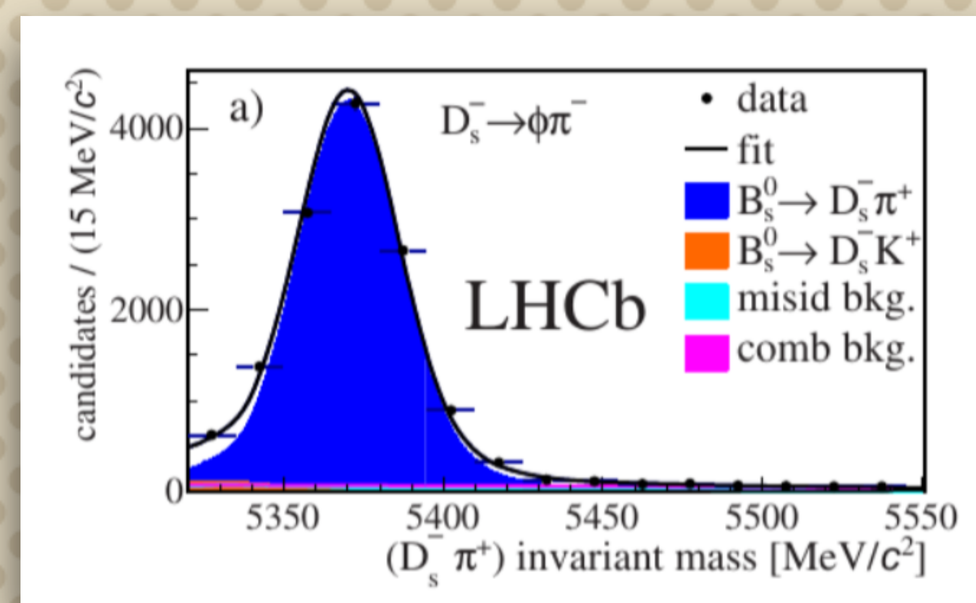


Mixing in B_s-system

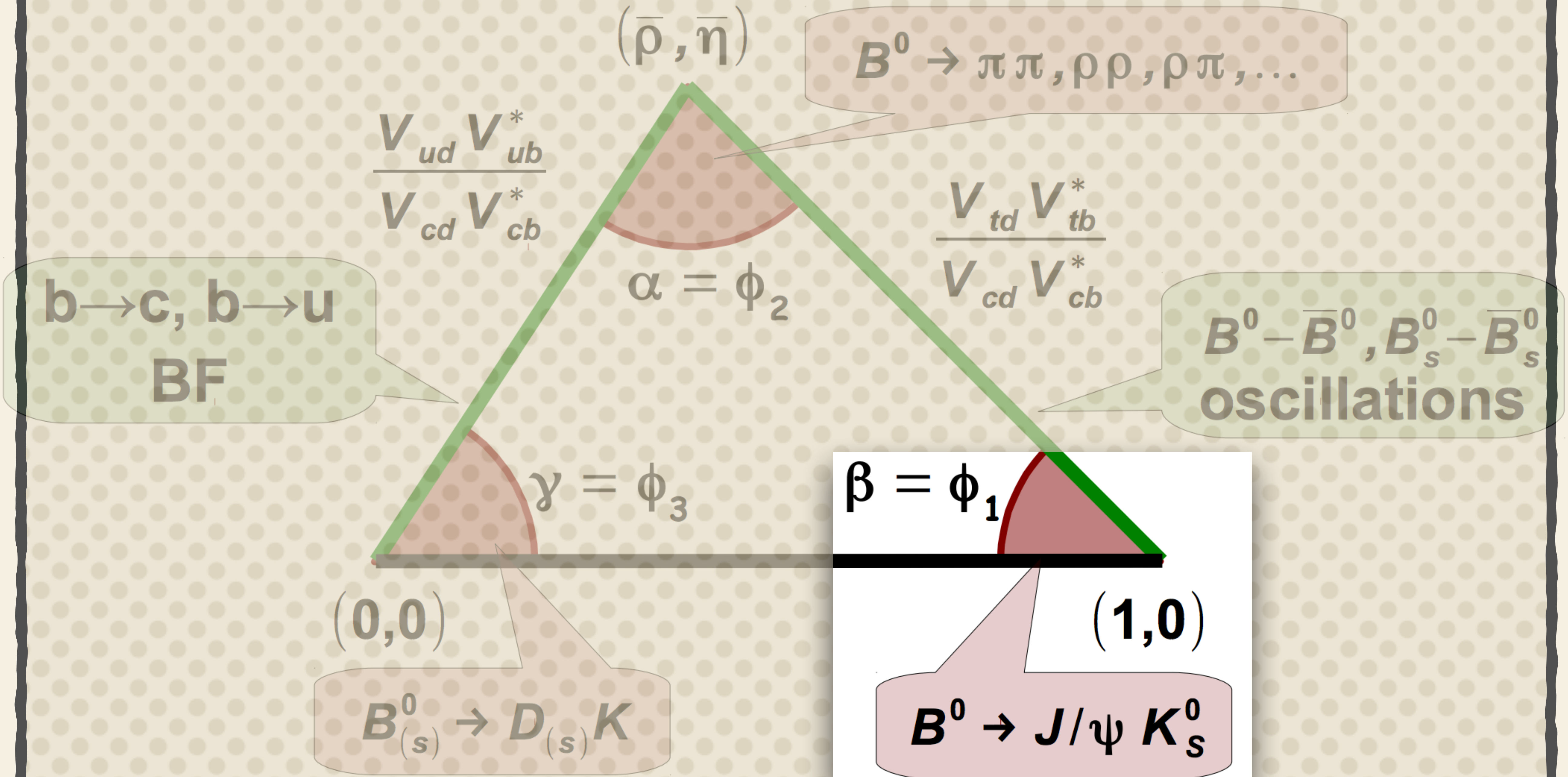
- First measurement of ΔM_s done at CDF
- Measurement at LHCb important test of detector performances (CDF measurement already better than theory uncertainty)
- LHCb vertex resolution important to resolve $B_s^0 - \overline{B}_s^0$ oscillations
- Analysis with $1 fb^{-1}$ (2011 dataset) using $B_s^0 \to D_s^- \pi^+$ about 34K signal events



[NJP 15 (2013) 053021]



$\Delta m_s = 17.757 \pm 0.021\ \text{ps}^{-1}$	CDF, LHCb



$(\bar{\rho},\bar{\eta})$
$B^0 \to \pi\pi, \rho\rho, \rho\pi, \ldots$
$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$
$\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$
$\alpha = \phi_2$
b→c, b→u
BF
$B^0-\bar{B}^0, B_s^0-\bar{B}_s^0$
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$\gamma = \phi_3$
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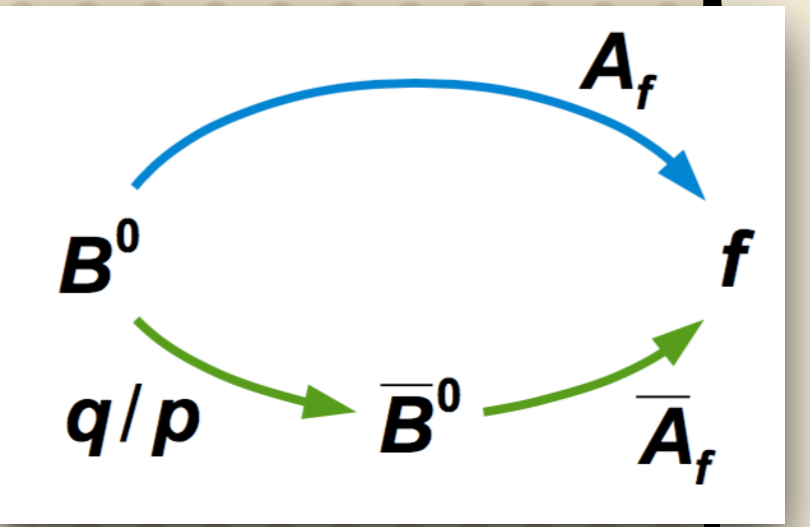
$(0,0)$
$(1,0)$
$B^0_{(s)} \to D_{(s)}K$
$B^0 \to J/\psi\, K_S^0$

CPV in the interference



Now we are also considering the decay

$$a_f(t) = \frac{N(B^0_{t=0}) - N(\overline{B}^0_{t=0})}{N(B^0_{t=0}) + N(\overline{B}^0_{t=0})} \simeq \frac{-C_f \cos(\Delta M \cdot t) + S_f \sin(\Delta M \cdot t)}{\cosh(\Delta\Gamma \cdot t/2) + \Omega_f \sinh(\Delta\Gamma \cdot t/2)}$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \;;\; S_f = \frac{2 \cdot \mathrm{Im}(\lambda_f)}{1 + |\lambda_f|^2}$$

$$\Omega_f = 1 - S_f^2 - C_f^2$$

- The CPV in the interference between mixing and decay can also happen if there is no CPV in the mixing and in the decay
- If one single decay amplitude dominates: $|\overline{A}_f / A_f| \Rightarrow |\lambda_f|$

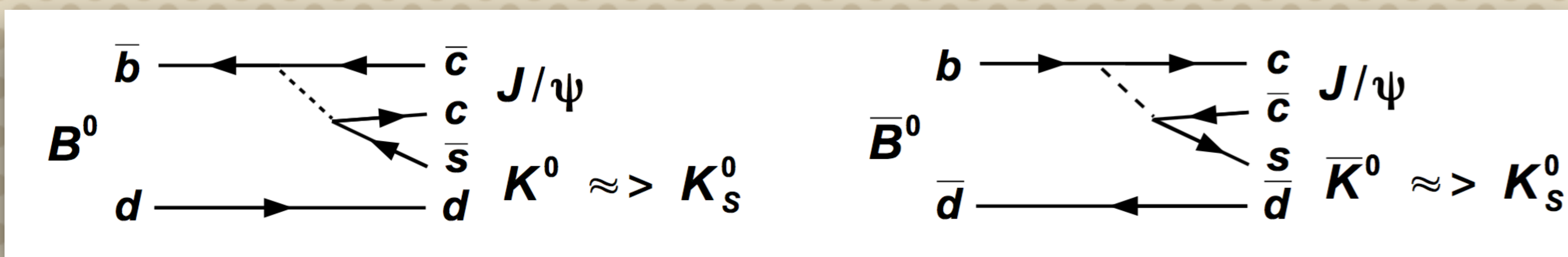
$$a(t)_f = \frac{\Im(\lambda_f) \cdot \sin(\Delta M \cdot t)}{\cosh(\Delta\Gamma \cdot t/2) + \Re(\lambda_f)\sinh(\Delta\Gamma \cdot t/2)}$$

In the B^0-system this simplifies to $a(t)_f \simeq \Im(\lambda_f) \cdot \sin(\Delta M_d \cdot t)$

CP is violated if $\Im(\lambda_f) \neq 0$

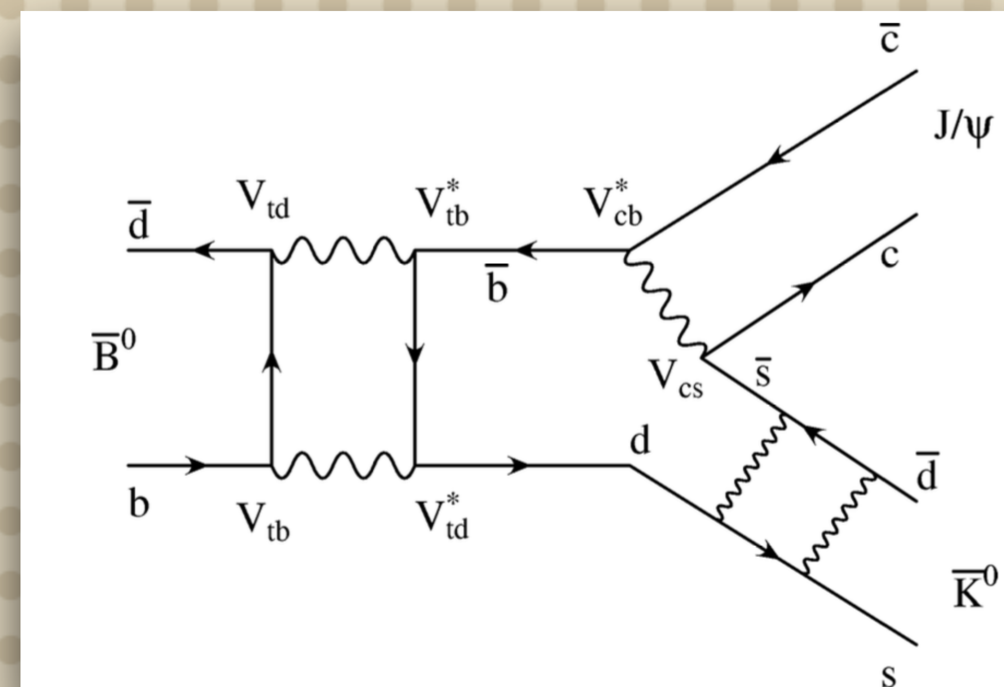
Measurement of Beta

The decay $B^0 \to J/\psi K^0_S$ is a CP eigenstate ($\eta_{CP} = -1$) and it is accessible from B^0 and $\overline{B}^0$



The decay is dominated by the tree amplitude $\Rightarrow$
$a_{J/\psi K^0_S}(t) = \Im(\lambda_{J/\psi K^0_S}) \cdot \sin(\Delta M_d \cdot t)$

$$\begin{aligned}
\lambda_{J/\psi K^0_s} &= \left(\frac{q}{p}\right)_{B^0} \cdot \left(\frac{\overline{A}_{J/\psi K^0}}{A_{J/\psi K^0}}\right) \cdot \left(\frac{q}{p}\right)_{K^0} \\
&= \left(\frac{V^*_{tb} V_{td}}{V_{tb} V^*_{td}}\right) \cdot \left(\frac{V^*_{cs} V_{cb}}{V_{cs} V^*_{cb}}\right) \cdot \left(\frac{V^*_{cd} V_{cs}}{V_{cd} V^*_{cs}}\right) \\
&= \left(\frac{V^*_{tb} V_{td}}{V^*_{cb} V_{cd}}\right) / \left(\frac{V_{tb} V^*_{td}}{V_{cb} V^*_{cd}}\right) \\
&= 2 \cdot \arg\left(\frac{V^*_{tb} V_{td}}{V^*_{cb} V_{cd}}\right) = 2 \cdot \beta
\end{aligned}$$

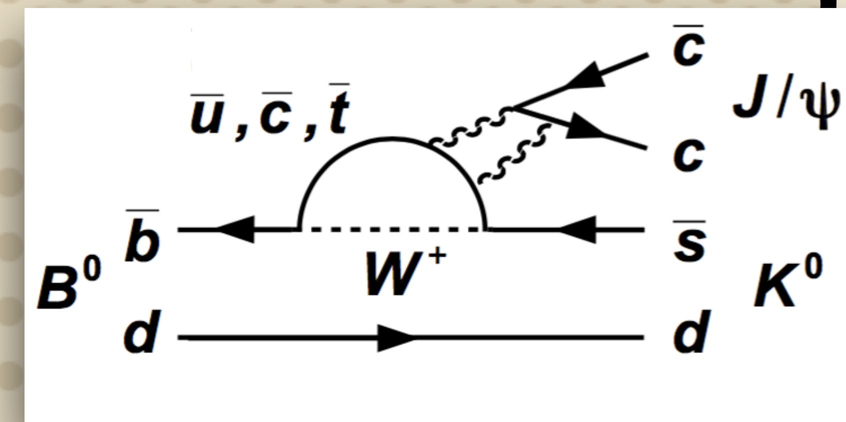


$$\boxed{a_{J/\psi K^0_s}(t) = \sin 2\beta \cdot \sin(\Delta m_d \cdot t)}$$

Measurement of Beta

For the unitarity of the CKM $V_{tb}^* V_{ts} = -V_{cb}^* V_{cs} - V_{ub}^* V_{us}$ therefore

$$\begin{aligned} A_{J/\psi K^0} &= P_t \cdot (V_{tb}^* V_{ts}) + (T + P_c) \cdot (V_{cb}^* V_{cs}) + P_u \cdot (V_{ub}^* V_{us}) \\ &= (T + \underbrace{P_c - P_t}_{\approx 0.1 \cdot T}) \cdot \underbrace{(V_{cb}^* V_{cs})}_{\propto \lambda^2} + (\underbrace{P_u - P_t}_{\approx 0.1 \cdot T}) \cdot \underbrace{(V_{ub}^* V_{us})}_{\propto \lambda^4} \end{aligned}$$



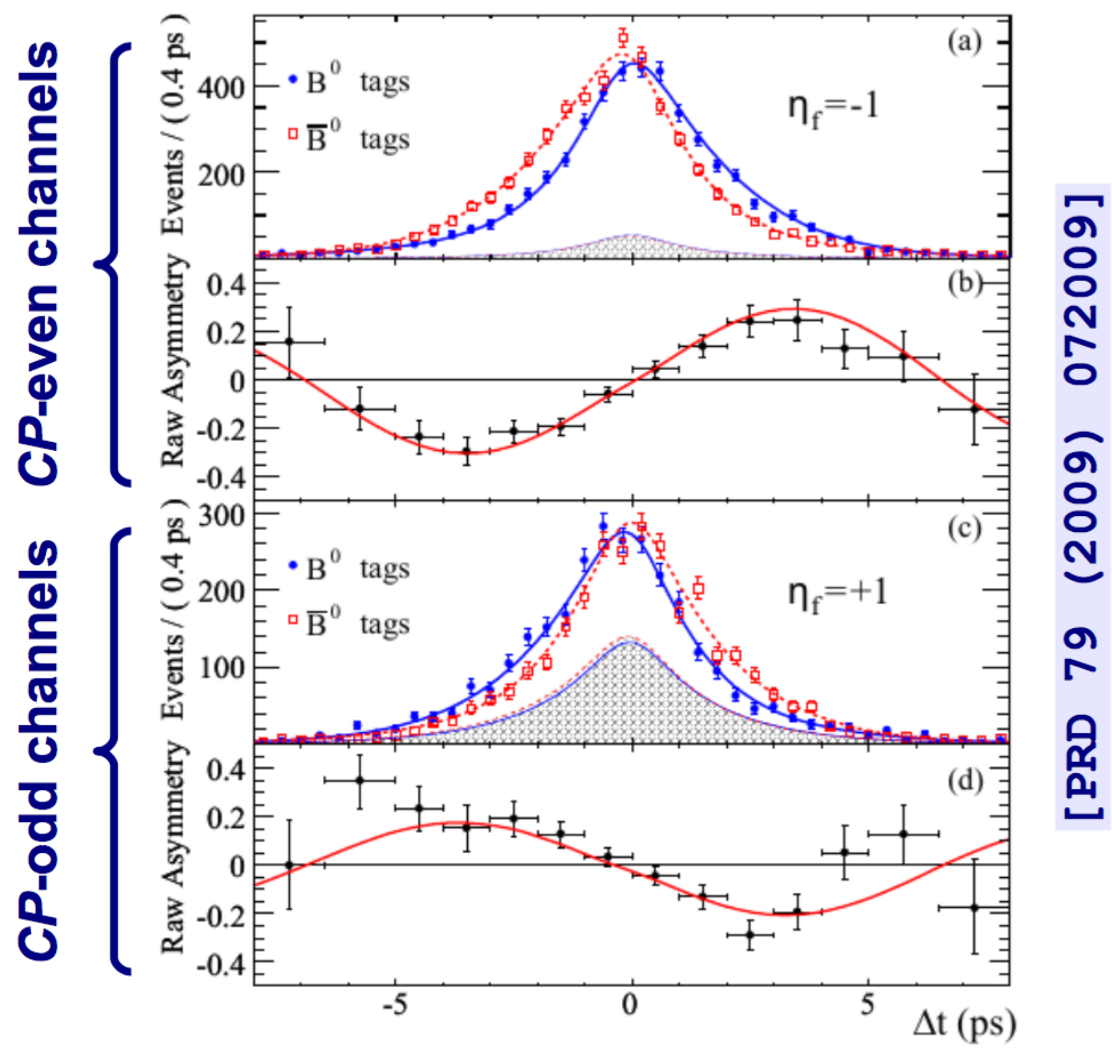
Contamination from $V_{ub}^* V_{us}$ smaller than 1% $\Rightarrow$ clean from theory point of view

Attractive from experimental point of view as well:

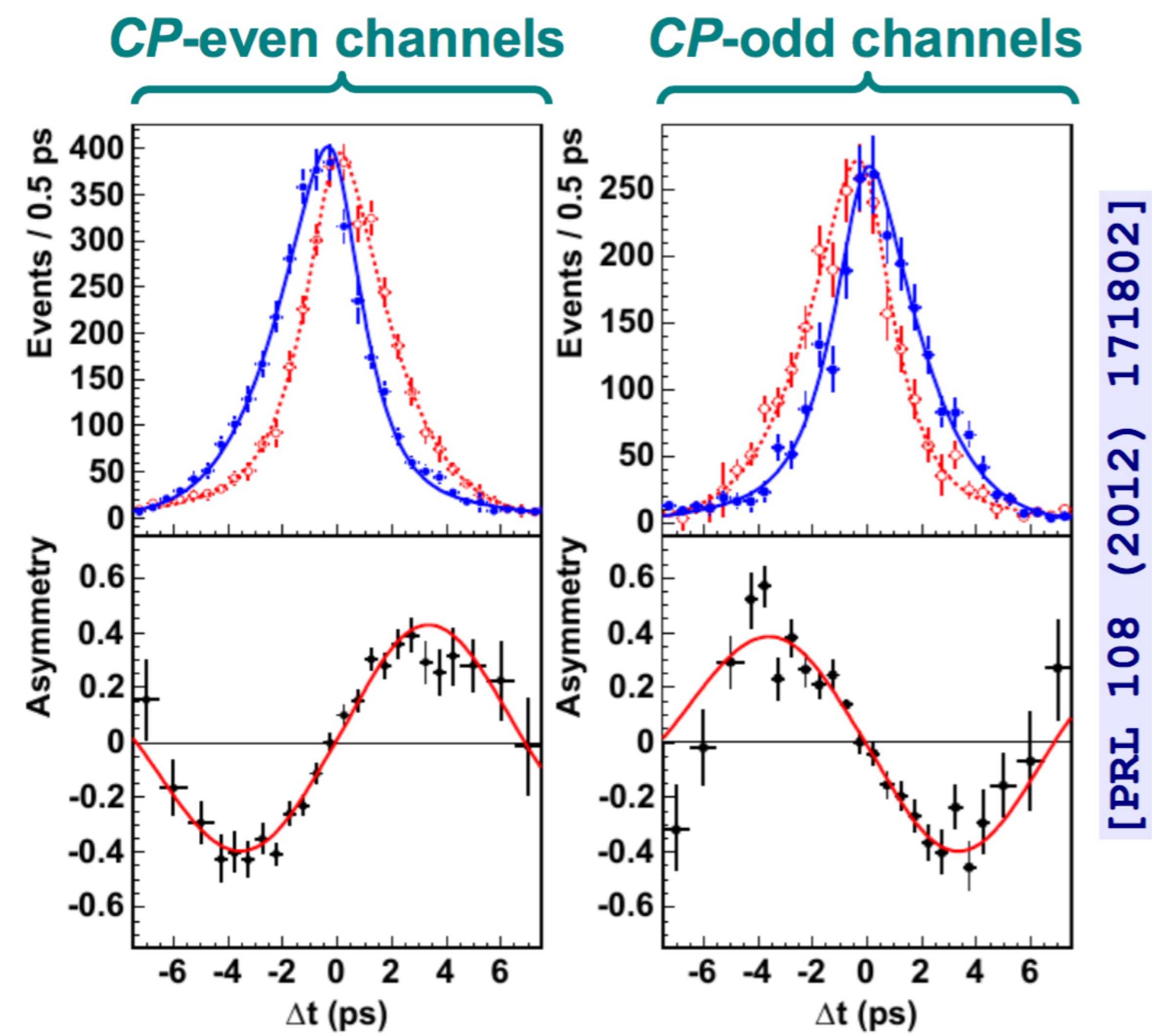
- Clear event signature with $J/\psi \to \ell^+ \ell^-$, second displaced vertex from K_S^0, invariant masses
- Similar strategy as for the measurement of ΔM_d
- Taking into account the dilution (D) and resolution ($R(\Delta t)$) we have: $a_{meas}(\Delta t) = (D \cdot \sin(2\beta) \cdot \sin(\Delta M_d \cdot \Delta t)) \otimes R(\Delta t)$
- Quantities are determined from data ($B^0 \to D^{(*)+}\pi^-$ and $B^0 \to J/\psi K^*$) and MC

Measurement of Beta

Babar (465M $B\bar{B}$ pairs):



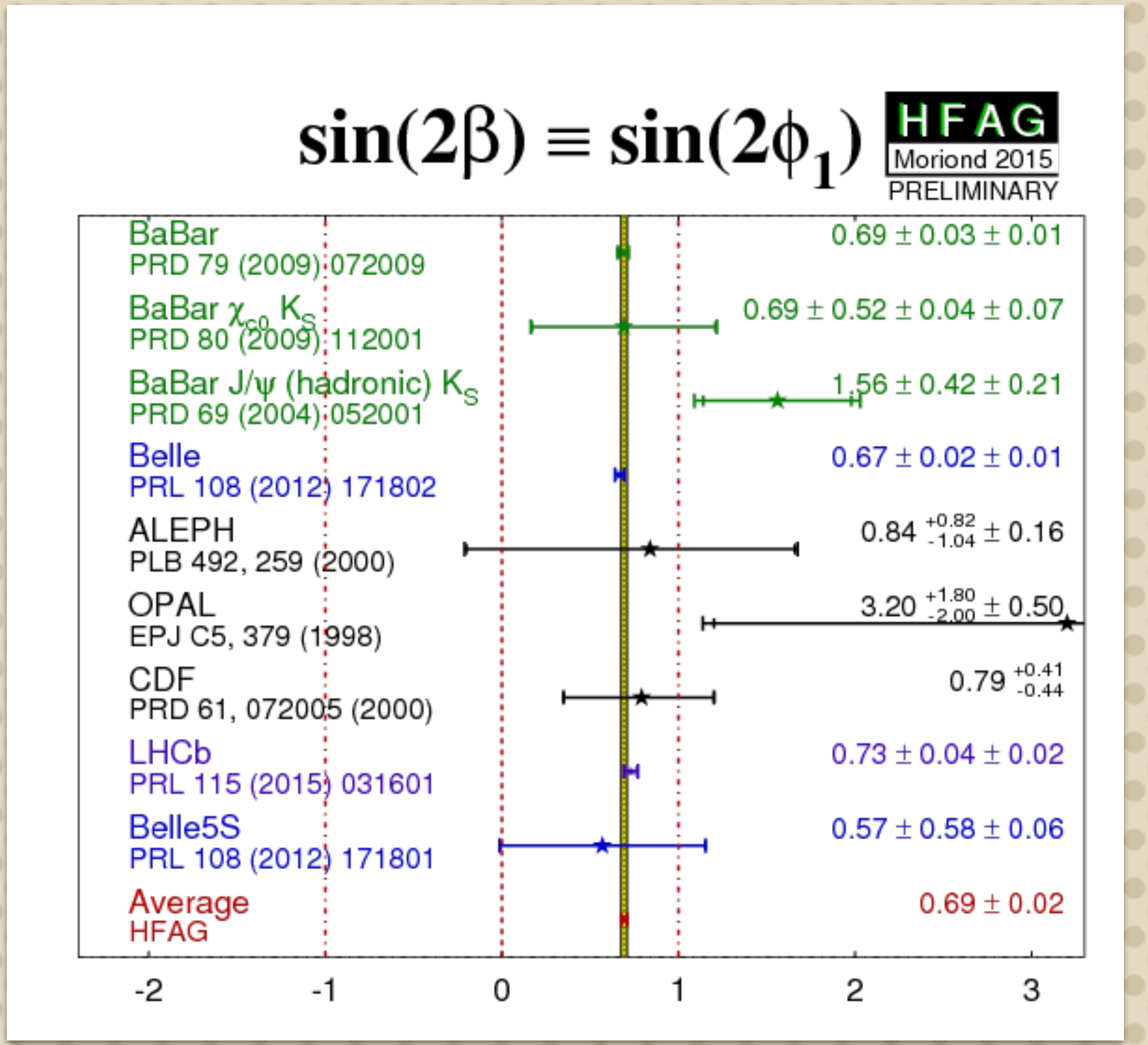
Belle (772M $B\bar{B}$ pairs):

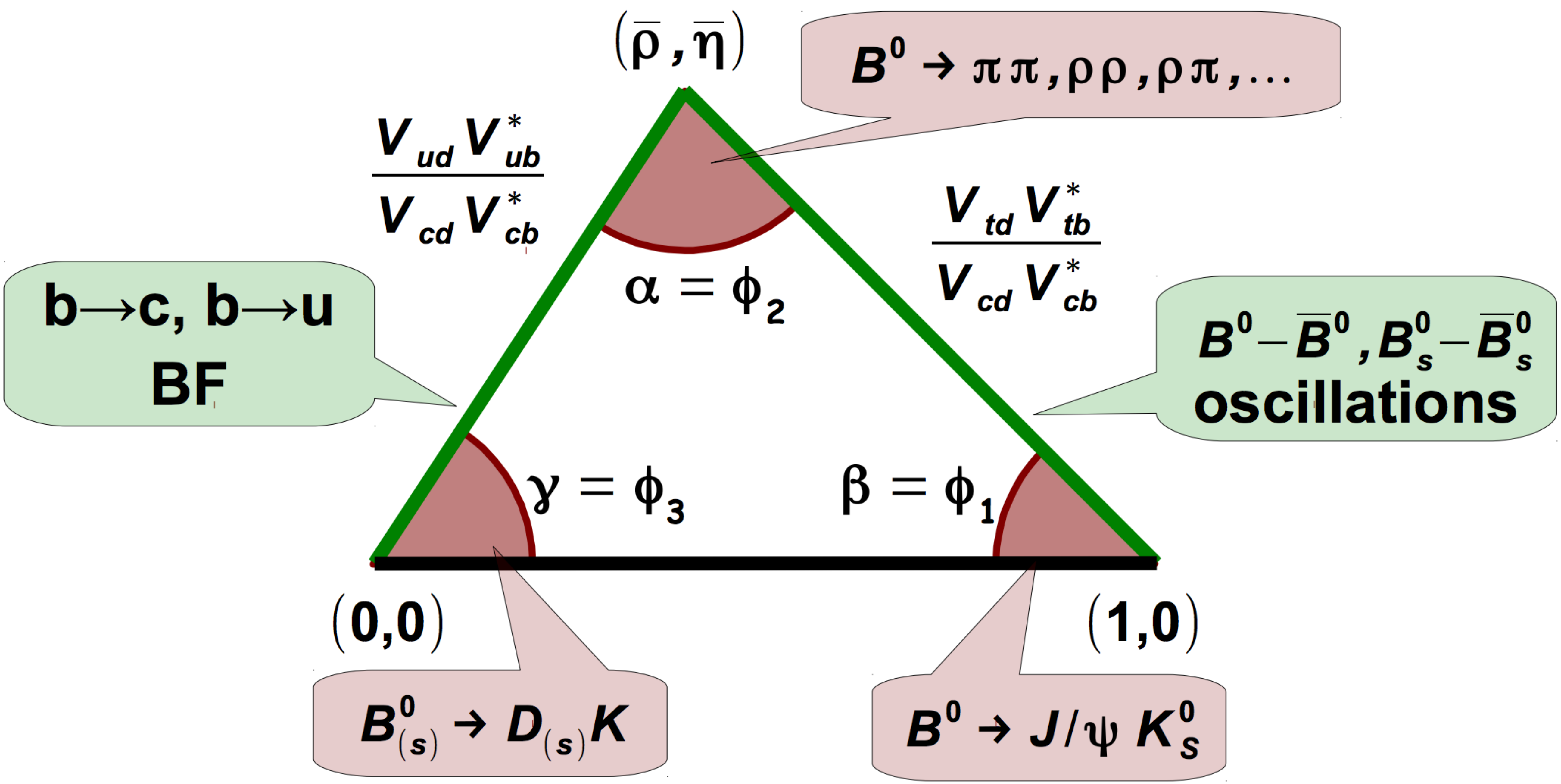


$$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$$

$$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$$

Measurement of Beta

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Status of the UT