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Finding New Physics using heavy flavor decays

Fermilab Academic Lectures, May, 2014

What is Heavy Flavor Physics ?

- Define Heavy Flavor Physics
  - Flavor Physics: Study of interactions that differ among flavors: (quark flavors are u, d, c, s, b, t)
  - Heavy: Not SM neutrino's or u or d quarks, maybe s quarks, concentrate here on b quarks (some c), t too heavy

u, d, ν's

too light

s, μ

maybe

c & b, τ; ν_M's ?

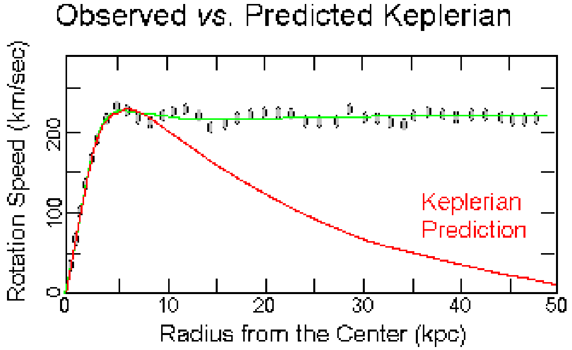
just right

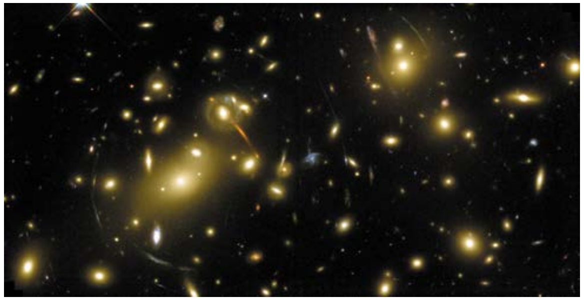
t

too heavy

Physics Beyond the Standard Model

- Baryogenesis: From current measurements can only generate $(n_B-\bar{n}_B)/n_\gamma$ =~10^{-20} but ~6×10^{-10} is needed. Thus New Physics must exist to generate needed CP Violation
- Dark Matter

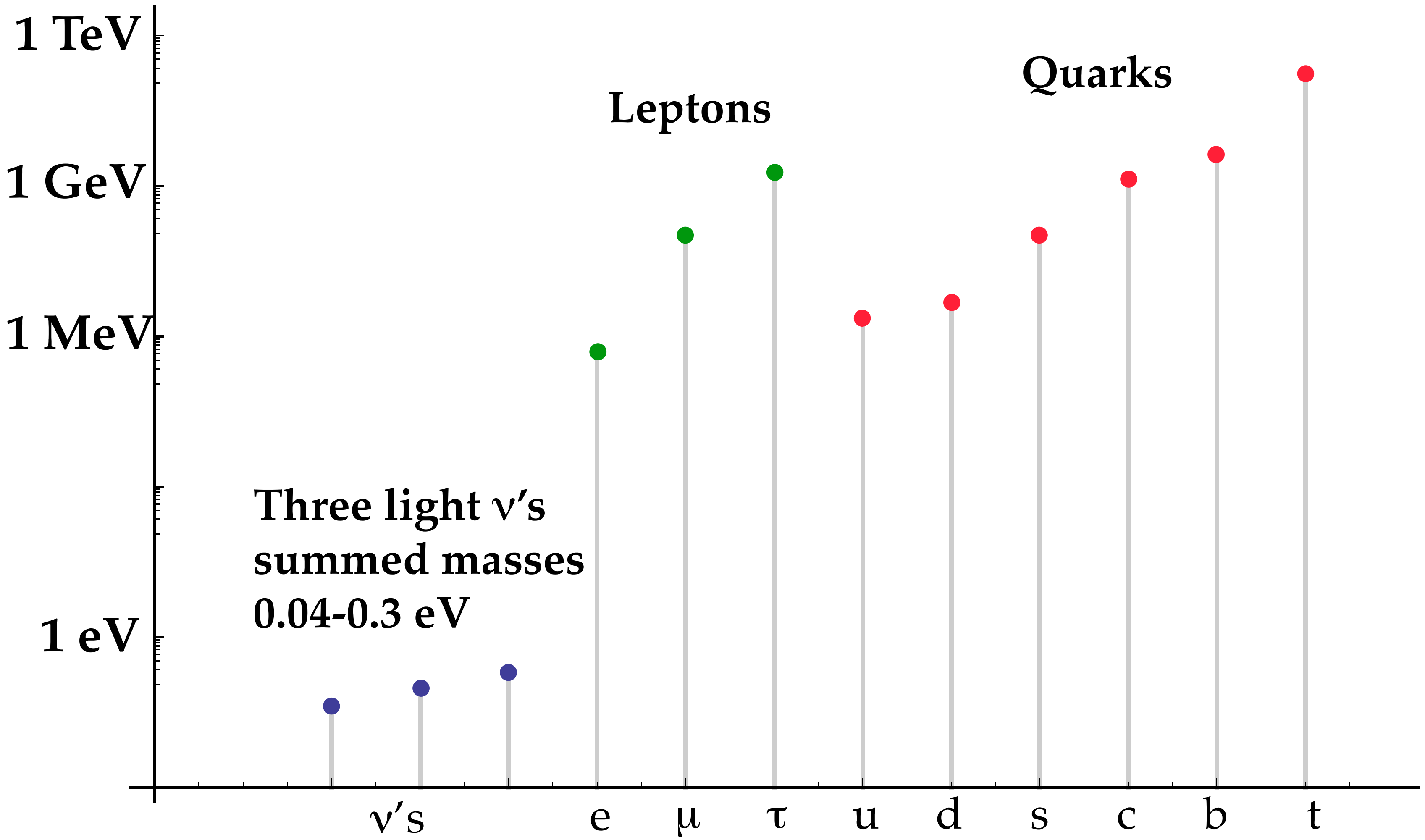




Gravitational lensing

- Hierarchy Problem: We don't understand how we get from the Planck scale of Energy ~10^{19} GeV to the Electroweak Scale ~100 GeV without "fine tuning" quantum corrections

Masses



12 orders of magnitude differences not explained; t quark as heavy as Tungsten

Formalism

- Standard model fermions

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L , \qquad u_R,\ d_R,\ c_R,\ s_R,\ t_R,\ b_R$$

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}_L , \quad e_R^-,\ \mu_R^-,\ \tau_R^-,\ \nu_{eR},\ \nu_{\mu R},\ \nu_{\tau R}.$$

- SM gauge bosons: γ, $W^{\pm}$, Z^0 & H^0.
- Lagrangian for charged current interactions is

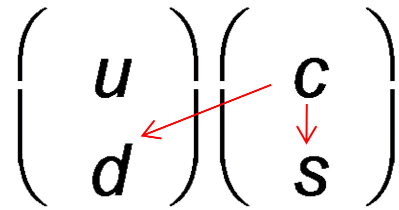
$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{\dagger}_{\mu} + h.c.,$$

- where

$$J^{\mu}_{cc} = (\bar{\nu}_e,\ \bar{\nu}_\mu,\ \bar{\nu}_\tau)\, \gamma^\mu V_{MNS} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} + (\bar{u}_L,\ \bar{c}_L,\ \bar{t}_L)\, \gamma^\mu V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

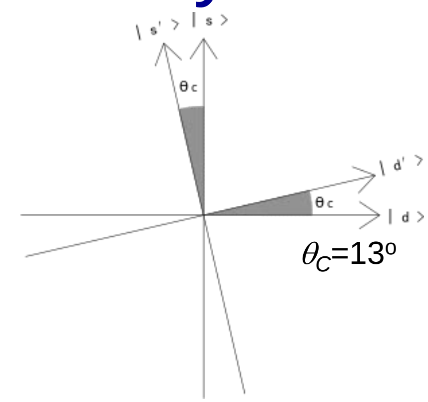
Quark Mixing

- Consider the charm quark. It forms a 2nd generation doublet with the strange quark (c,s). Yet it also decays into the d quark which is in the first generation with the u quark (u,d).



- We say this happens because the s & d quarks are "mixed" i.e. their wave functions really are described by a rotation matrix

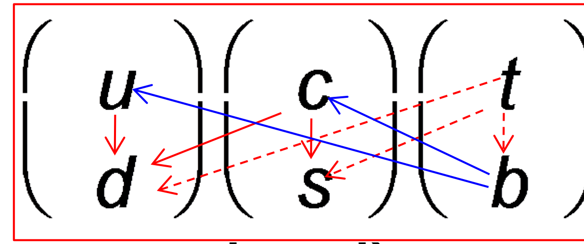
$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$



where the s´ couples to c

Quark Mixing & CKM Matrix

- All 3 generations of -1/3 quarks (d, s, b) are mixed



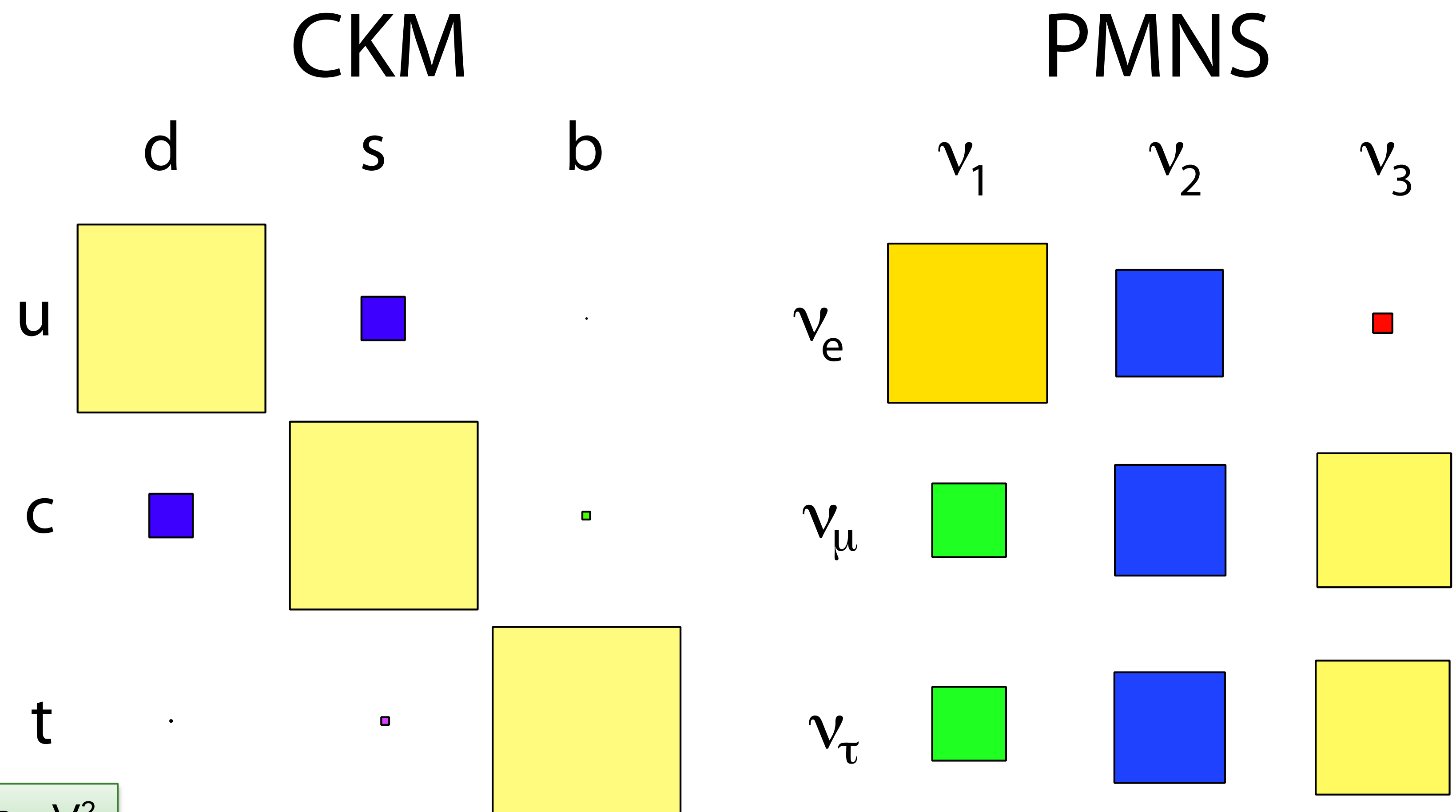
- Described by CKM matrix (also ν are mixed)

$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)}=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}=\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2+A\lambda^4(1/2+(\rho-i\eta)) & 1-A^2\lambda^4/2 \end{pmatrix}$$

Shown to order λ^4

- Unitary 3x3 matrix can be described by 4 parameters λ=0.225, A=0.8, constraints on ρ & η
- These are fundamental constants of nature in the Standard Model

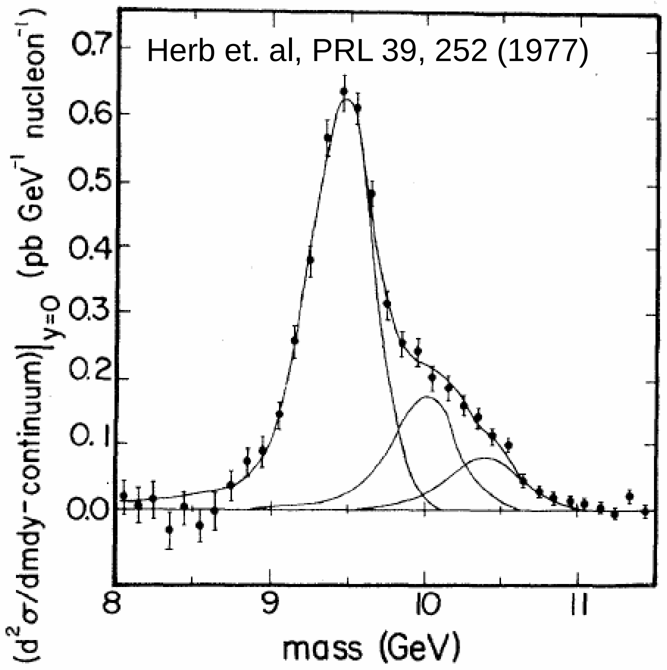
CKM vs. PMNS

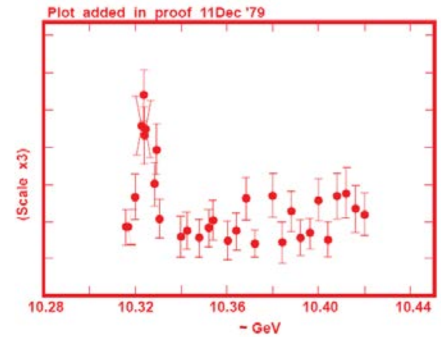


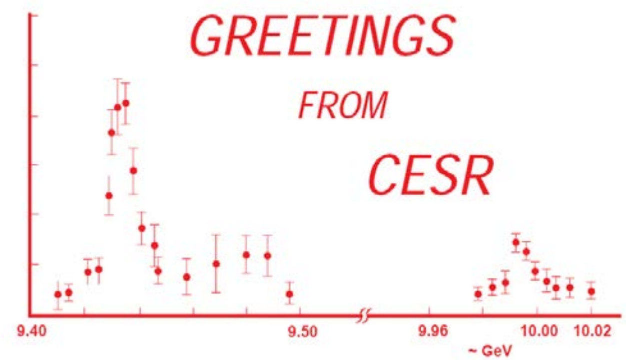
Area ~V^2

Why these values? Are the two related? Are they related to masses?

A bit of history



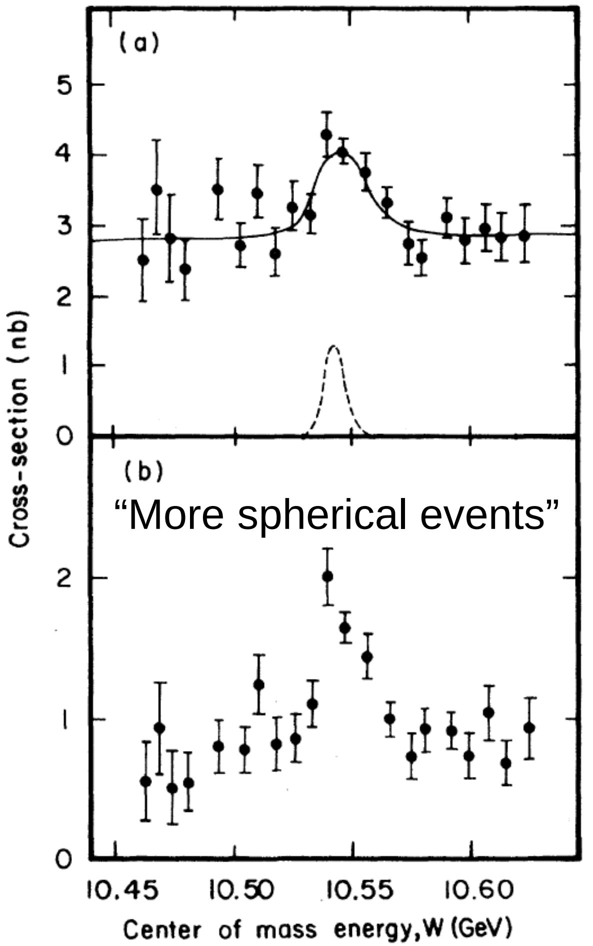




- Υ, formed of $b\bar{b}$ quarks, found at Fermilab in the $\mu^+\mu^-$ chanel
- Followed by Doris Υ, $\Upsilon 2$; CLEO & CUSB that distinctly observed all 3 states, & published on the 1979 Xmas card

Discovery of Υ(4S)

- The Υ states were narrow, their observed widths were consistent with the experimental mass resolution, so below the threshold to decay into $B\bar{B}$
- Another resonance was found that was ~20 MeV wide, & subsequently shown to decay into either B^+B^- or $B^0\bar{B}^0$

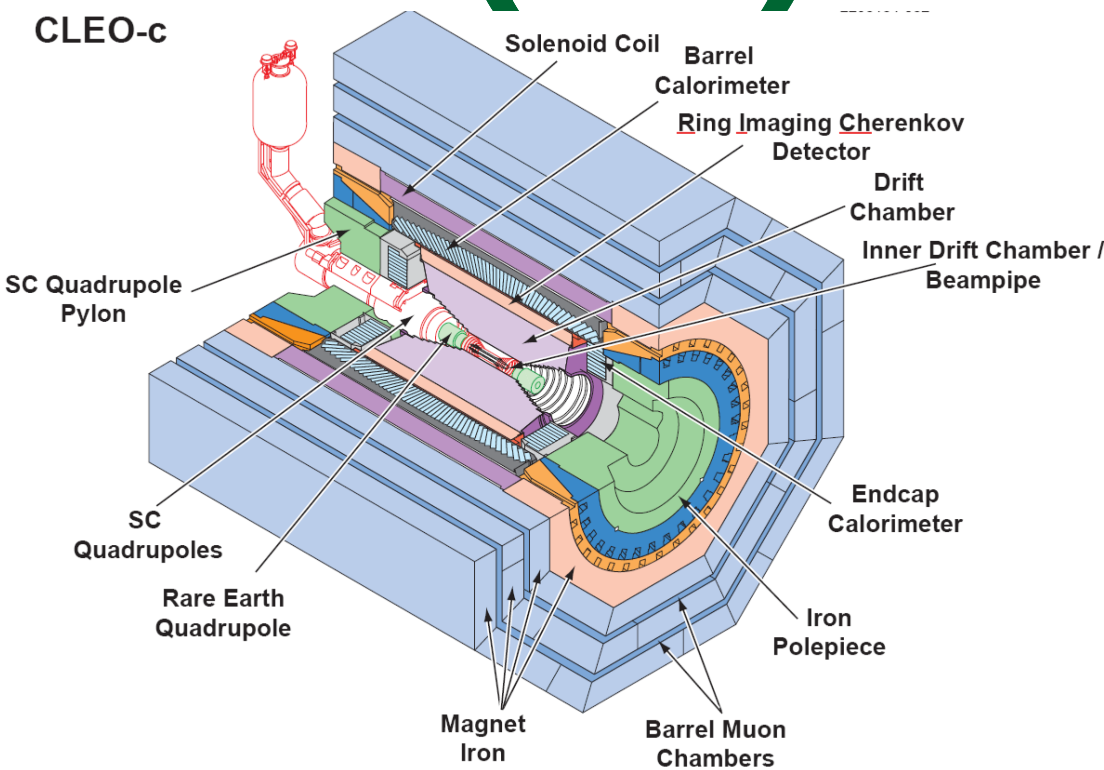


B Experiments

- e^+e^- at Υ(4S) ARGUS, CLEO, BaBar, & Belle
- e^+e^- at Z^0, LEP & SLC
- CDF & D0, 1.8 TeV $p\bar{p}$
- LHCb, CMS & ATLAS, 7-8 TeV pp

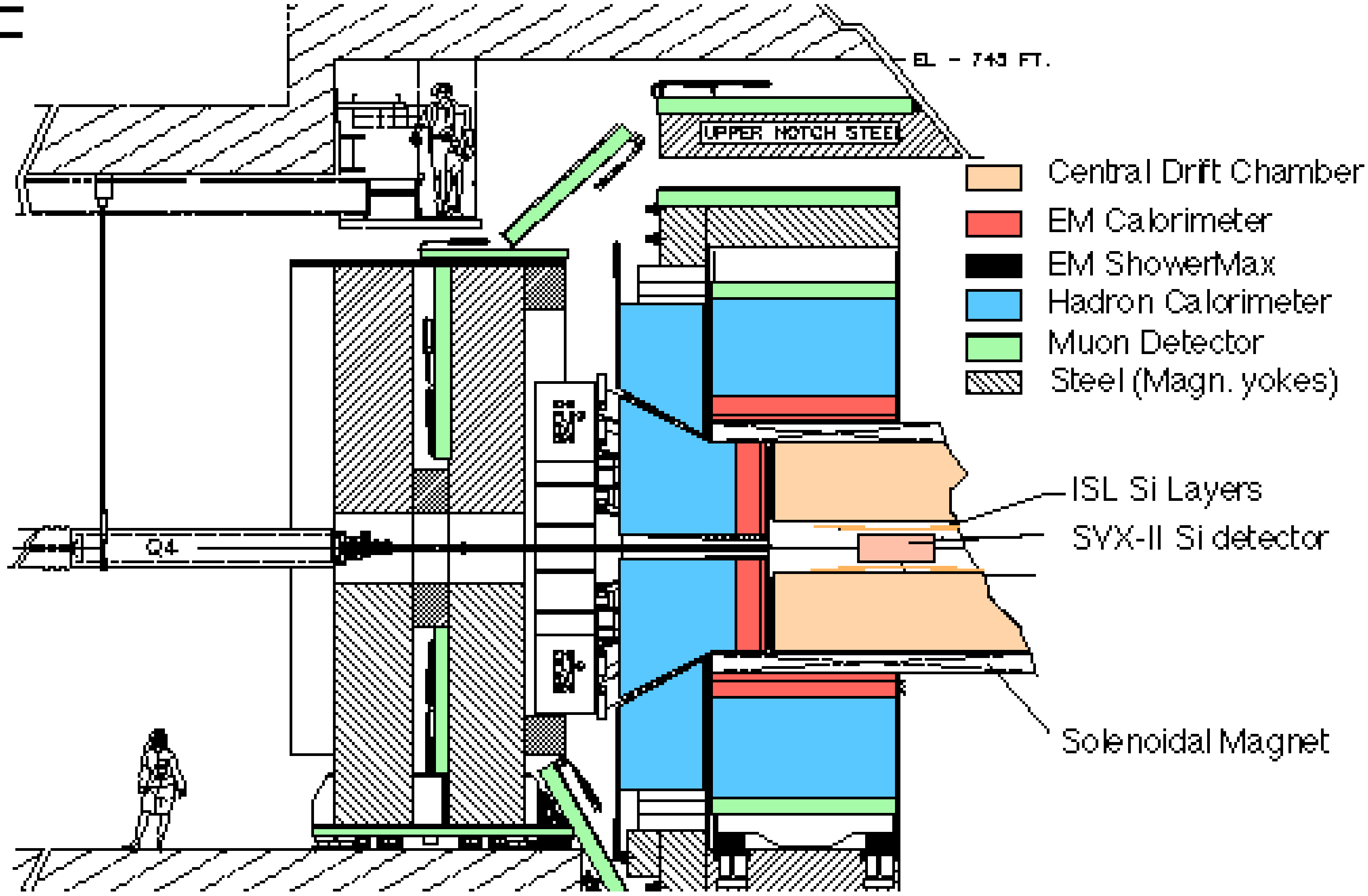
e^+e^- at $\Upsilon(4S)$

- All detectors have cylindrical geometries with common elements
- Key: PID, CsI ecal
- Vertex detector usually Si strips, to measure B & B vertex separations, possible since beams in Belle & Babar have different energies; causes boost along beam direction. Typical resolutions on τ_B ~900 fs.



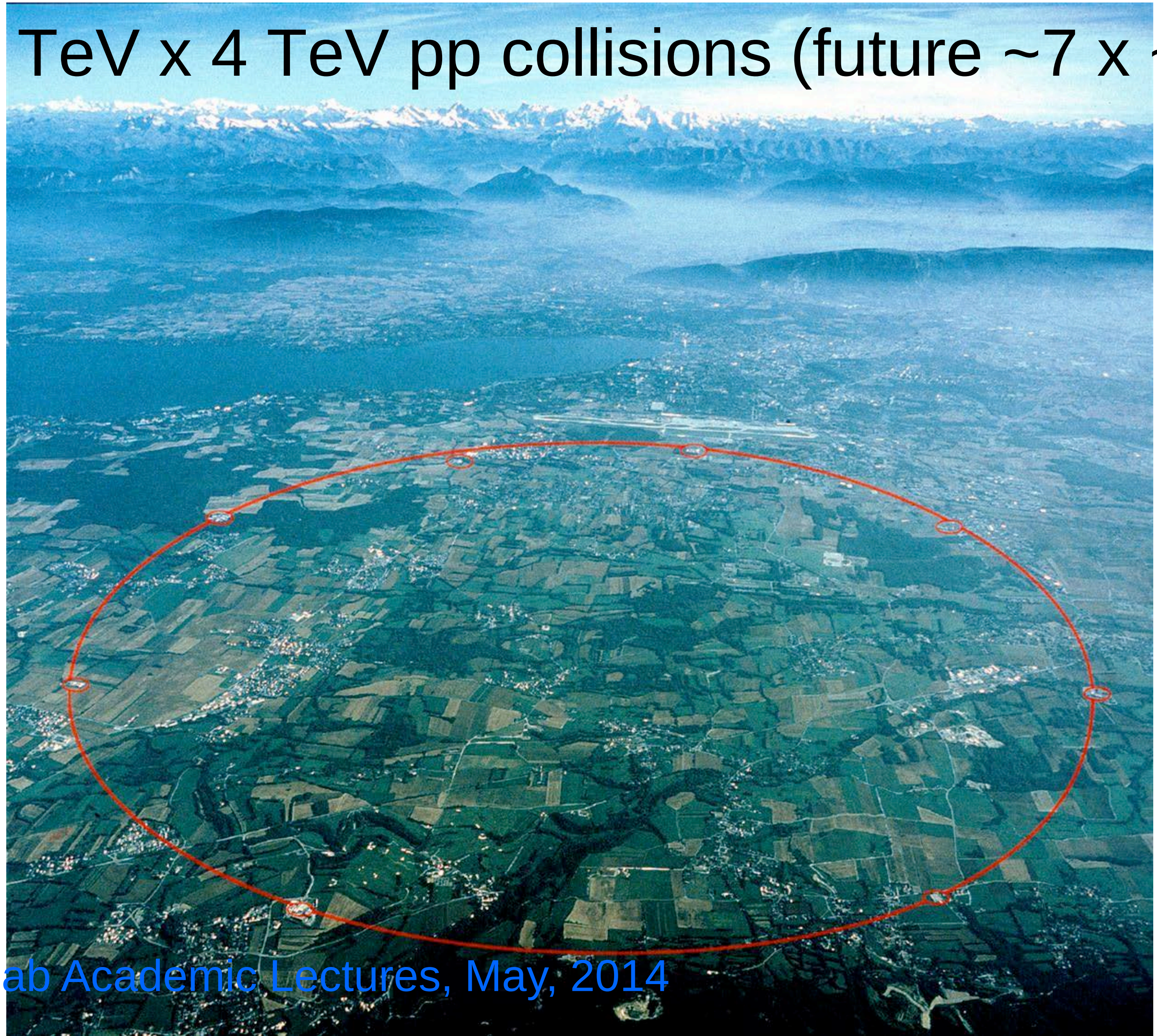
Central detectors at $p\overset{(-)}{p}$

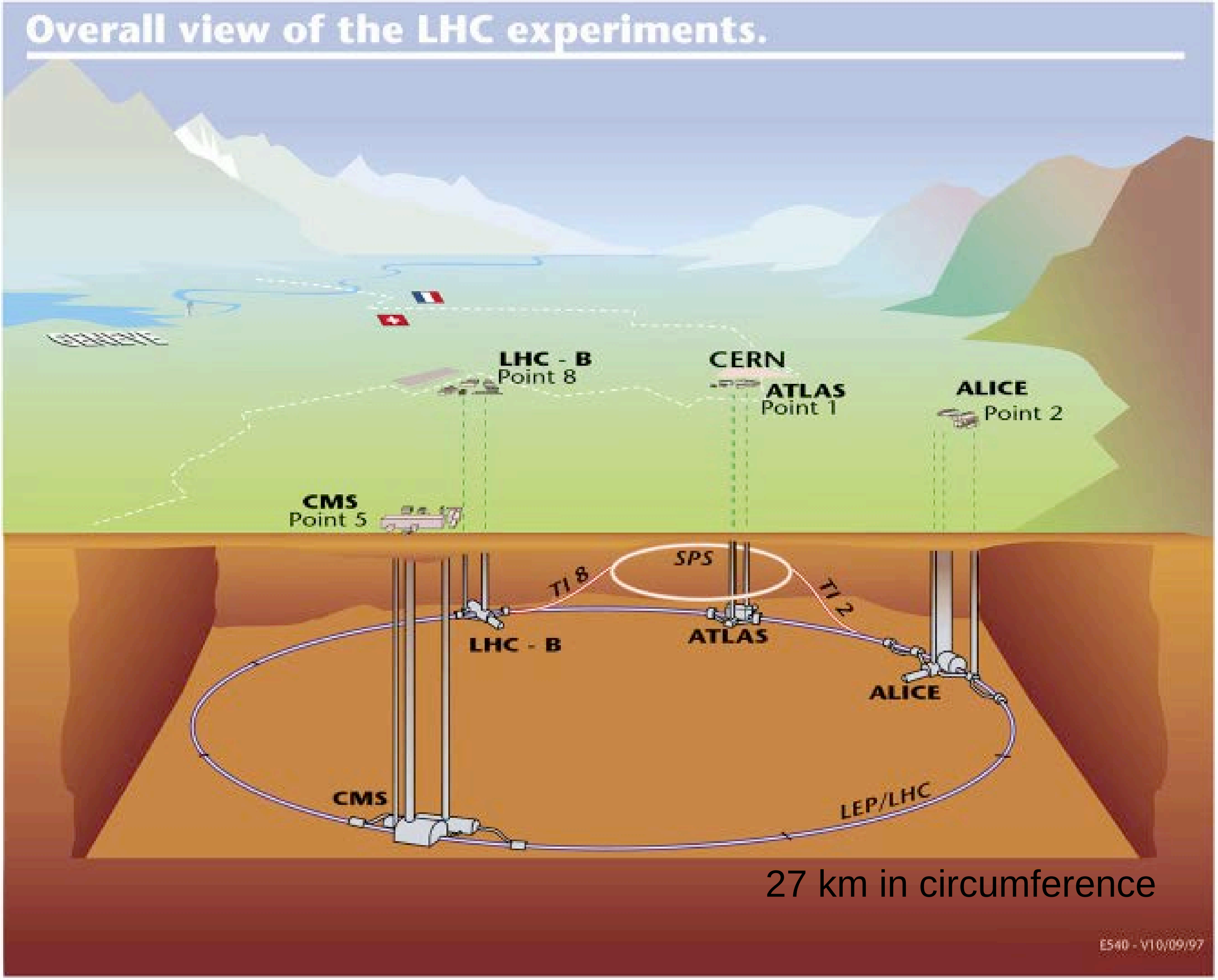
CDF



The LHC

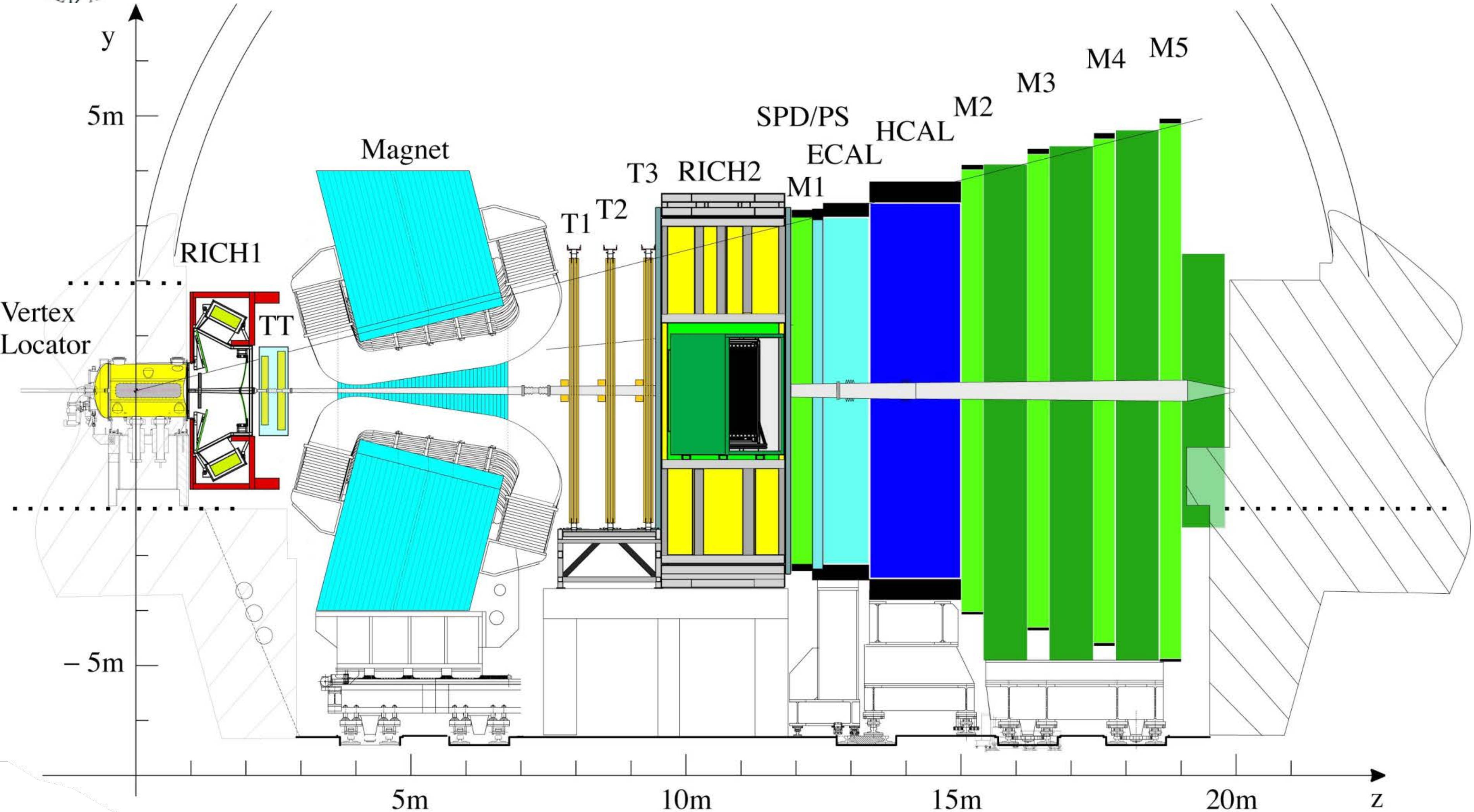
- 4 TeV x 4 TeV pp collisions (future ~7 x ~7)





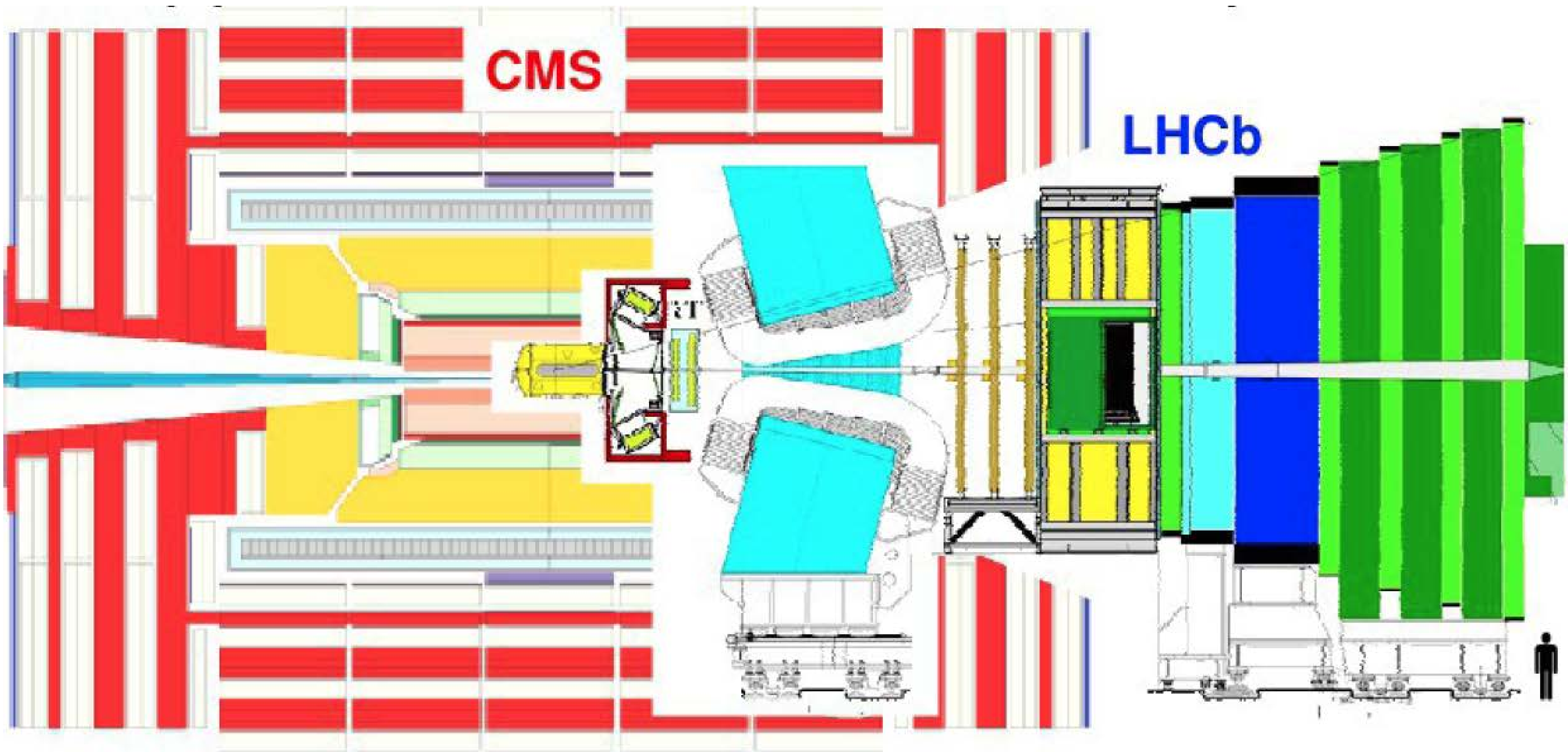
27 km in circumference

The LHCb Detector



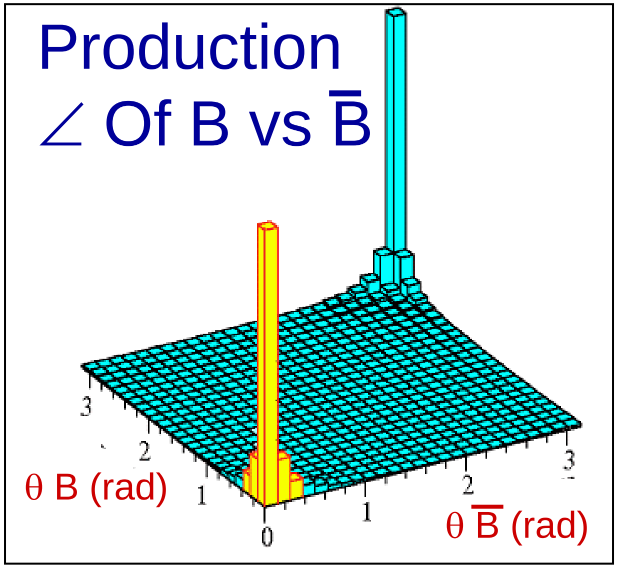
Detector Geometry

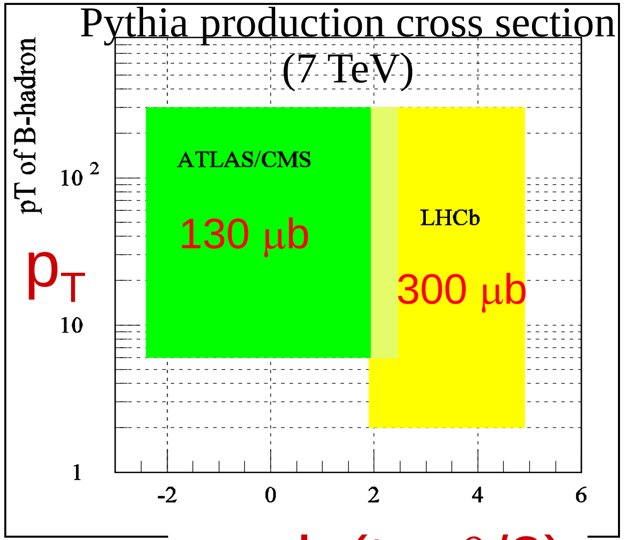
- Complementary to ATLAS & CMS
- Much less expensive



The Forward Direction at the LHC

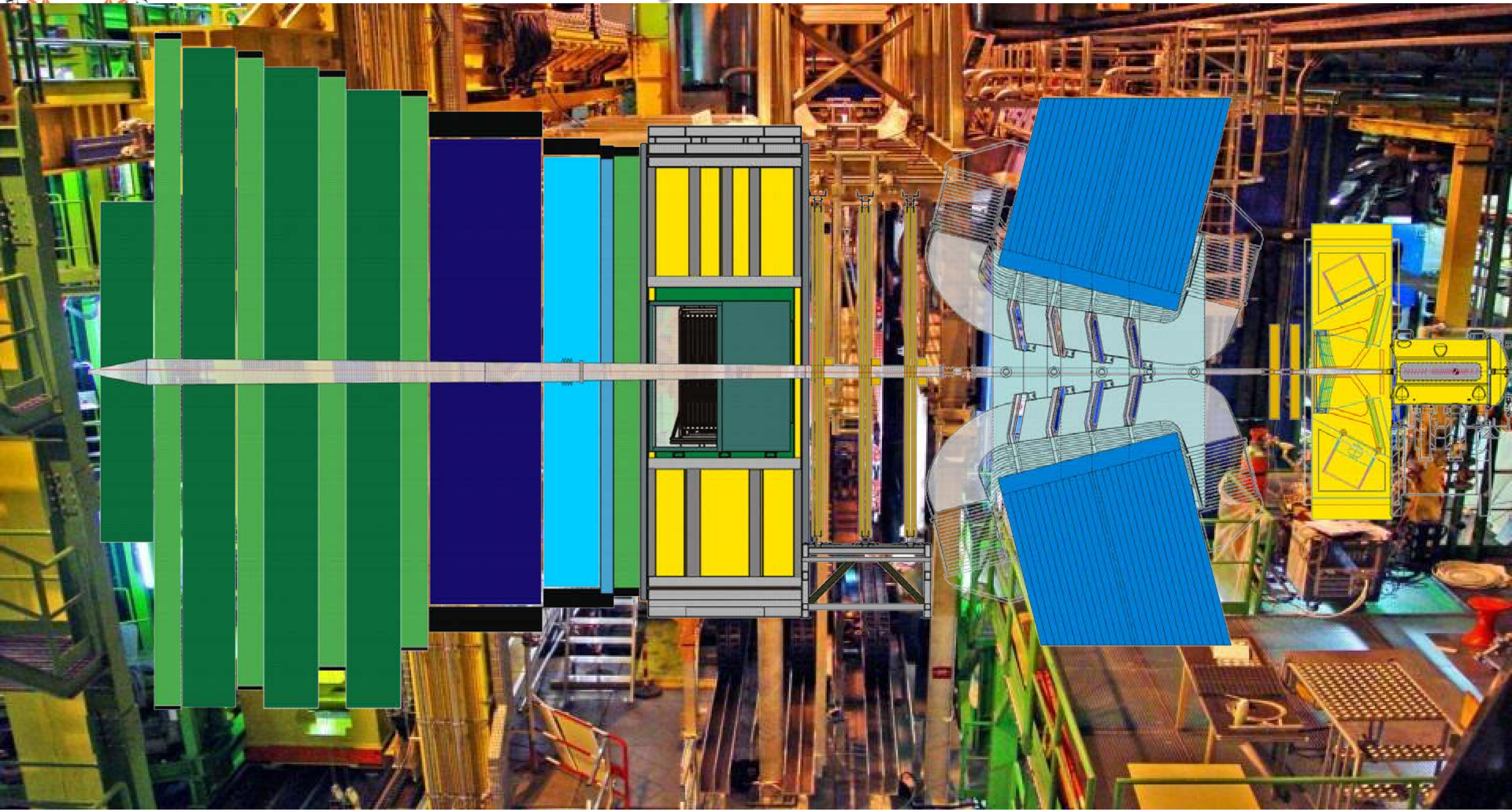
- The primary pp collision produces a pair of $b\bar{b}$ quarks. They then form hadrons. In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for knowing if a neutral B meson started out as a B^0 or $\bar{B}^0$, determined by "flavor tagging"
- At $\mathcal{L}$=2x10^{32}/cm^2-s, we get ~10^{12} B hadrons in 10^7 sec





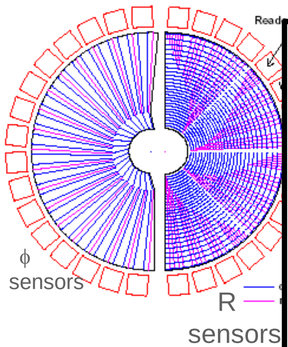
$\eta = -\ln(\tan\theta/2)$

Detector Workings

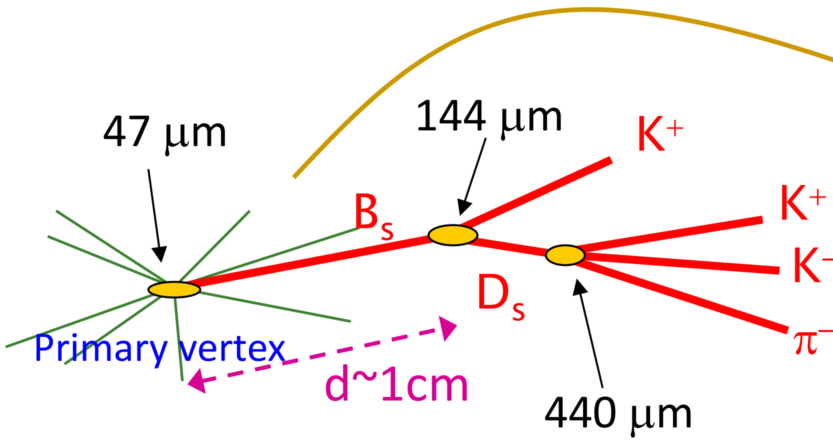


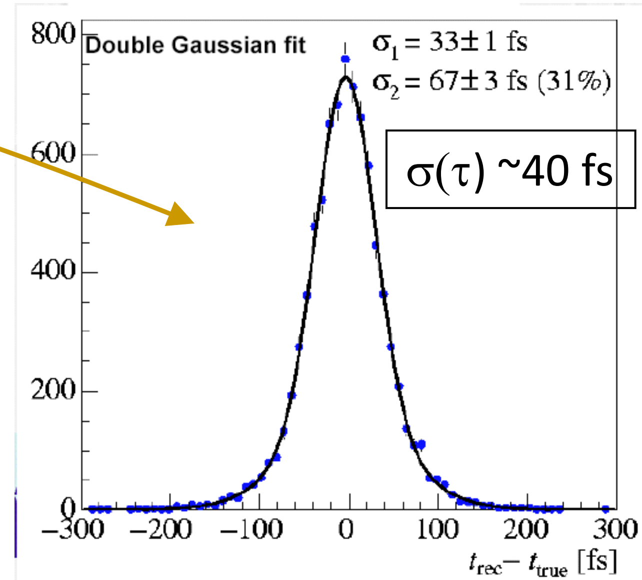
LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

B-Vertex Measurement

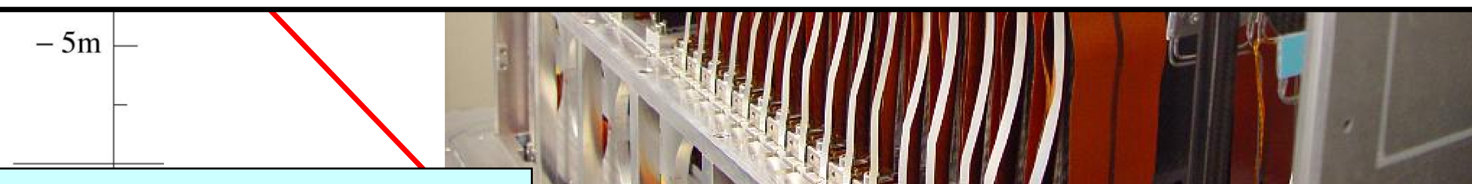


Example: $B_s \rightarrow D_s K$





Decay time resolution = 40 fs



Vertex Locator (Velo)

Silicon strip detector with

~ 5 μm hit resolution

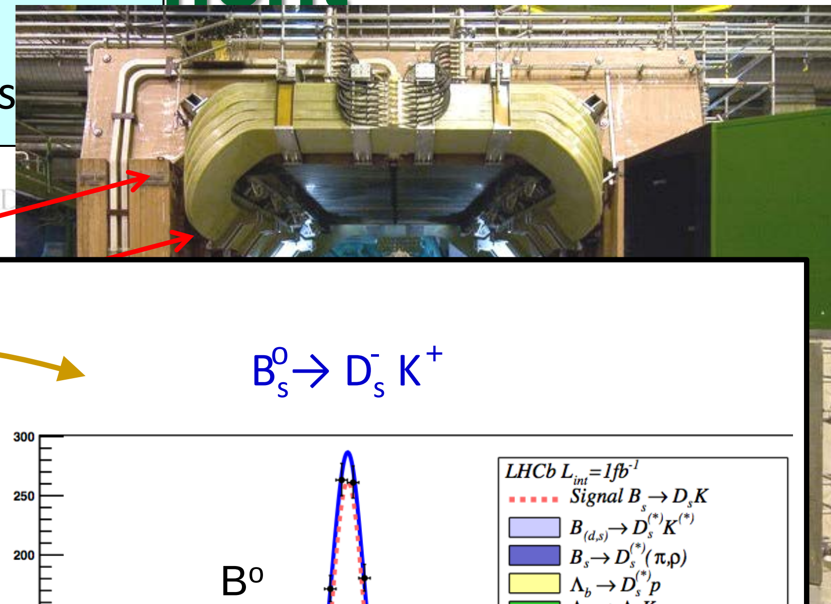
→ 30 μm IP resolution

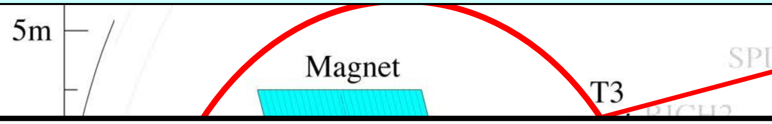
Vertexing:

- trigger on impact parameter
- measurement of decay distance & decay time=d/v=md/p

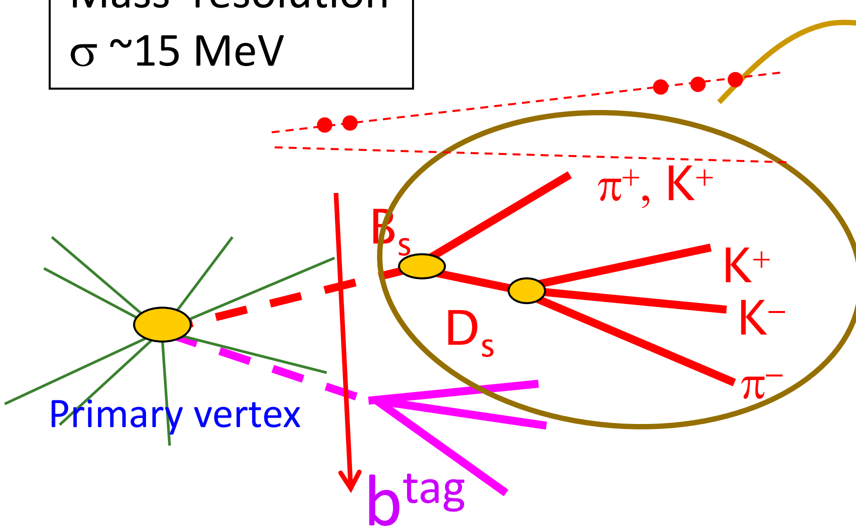
Momentum and Mass measurement

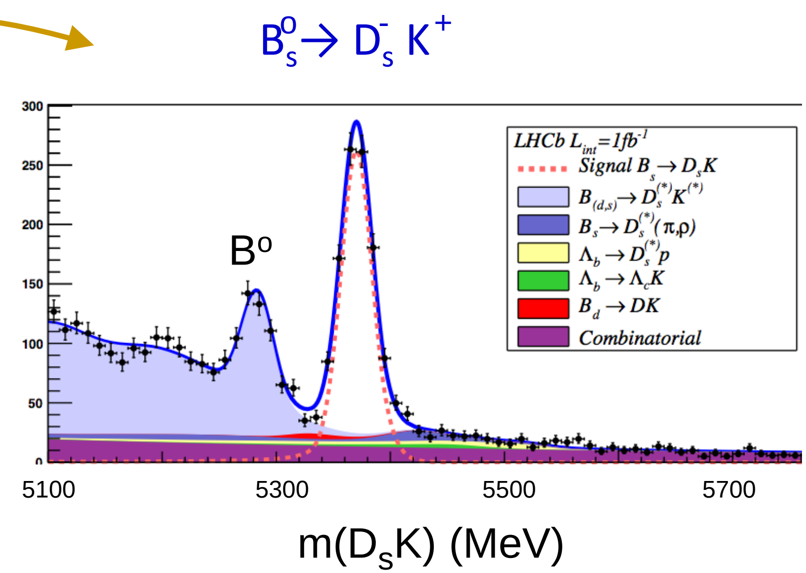
Momentum meas. + direction (VELO):
Mass resolution for background suppres





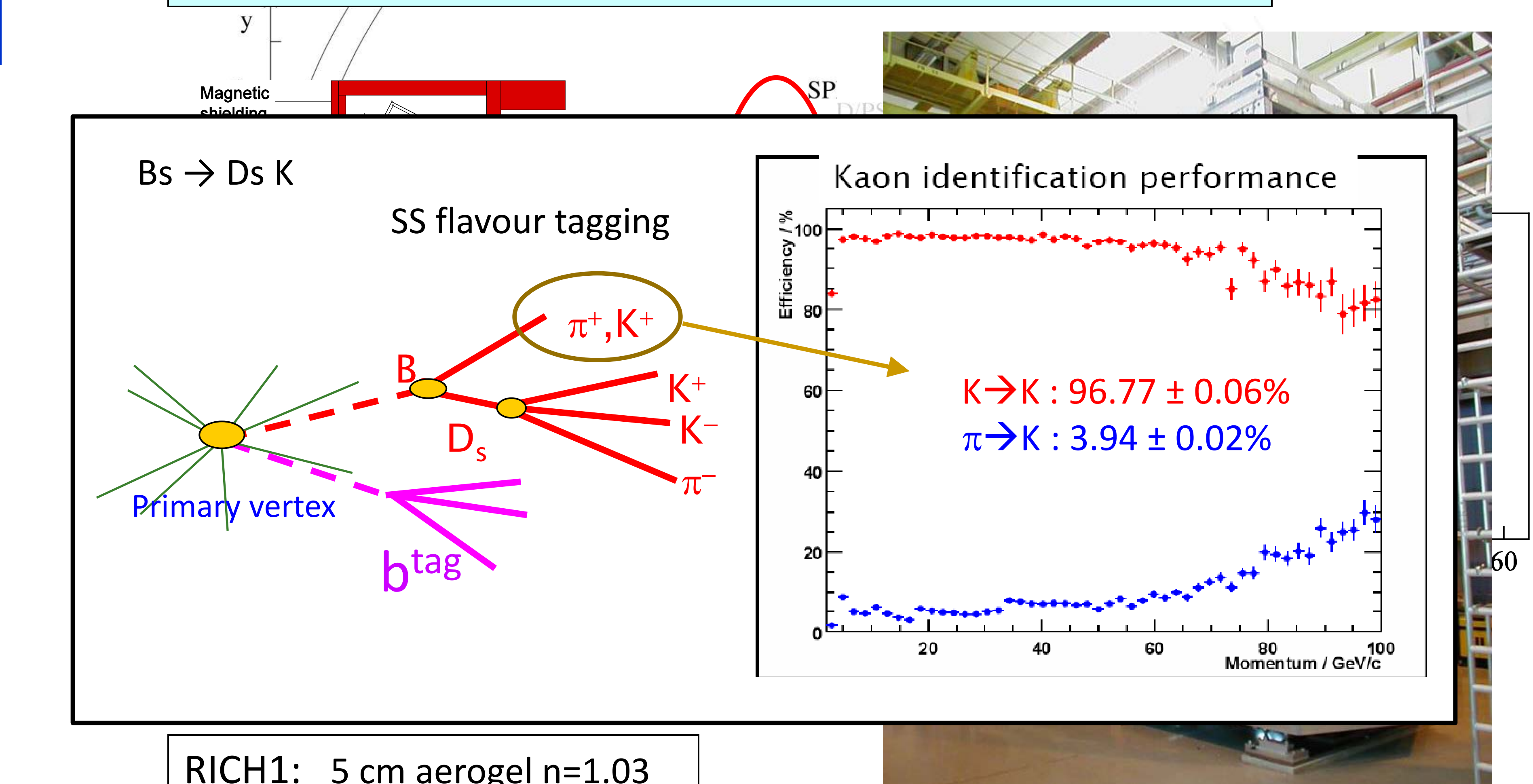
Mass resolution
σ ~15 MeV





Hadron Identification

RICH: K/π identification using Cherenkov light emission angle

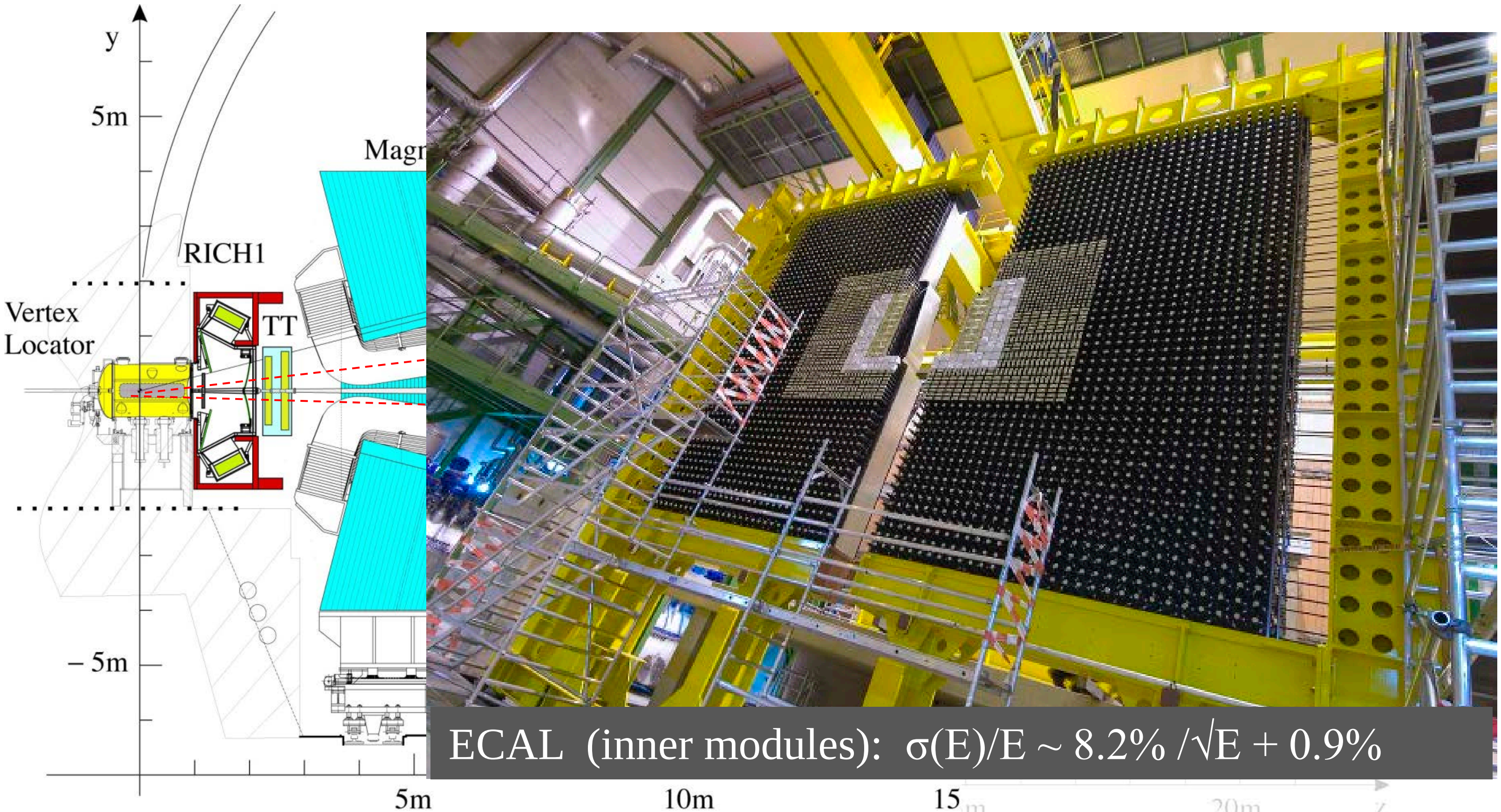


RICH1: 5 cm aerogel n=1.03

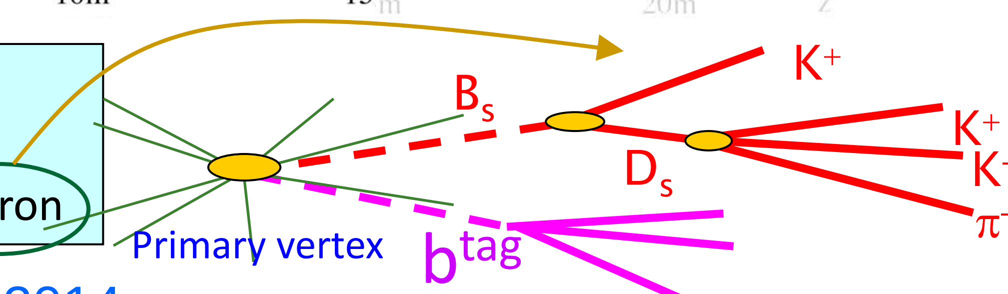
4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m3 CF_4 n=1.0005

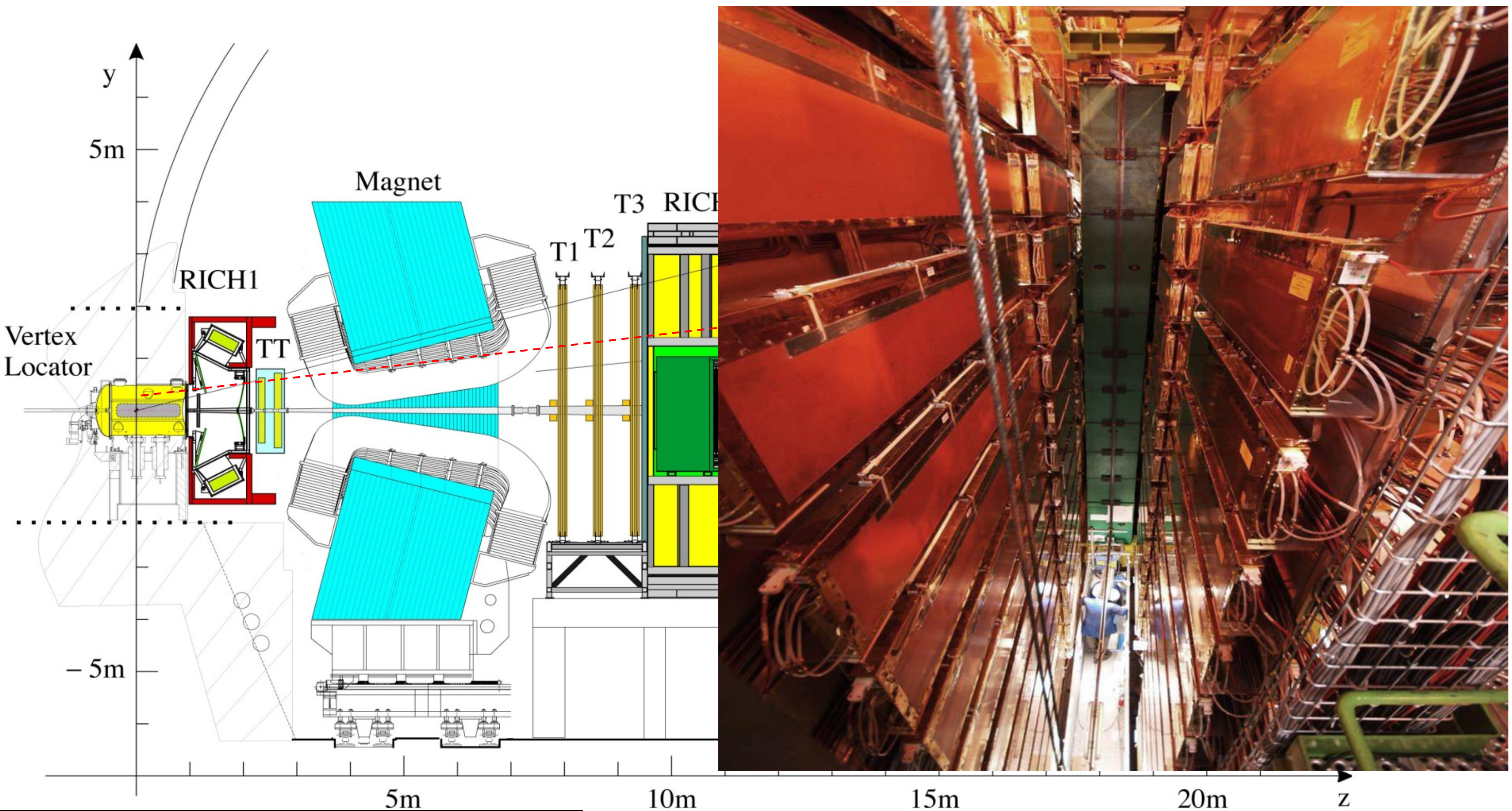
Calorimetry and L0 trigger



Calorimeter system :
- Identify electrons, hadrons, π^0 ,γ
- Level 0 trigger: high E_T electron and hadron

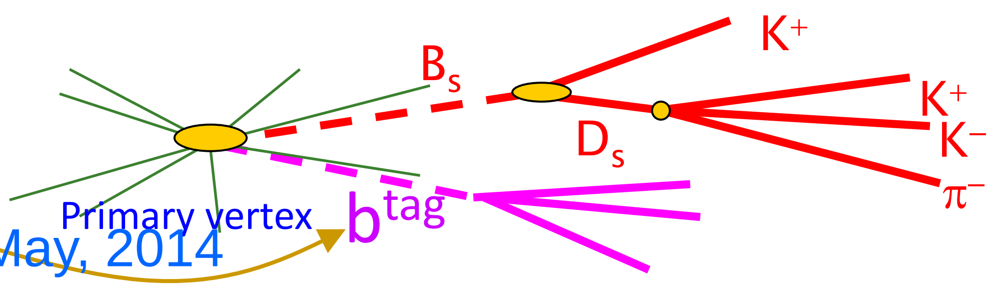


Muon identification and L0 trigger

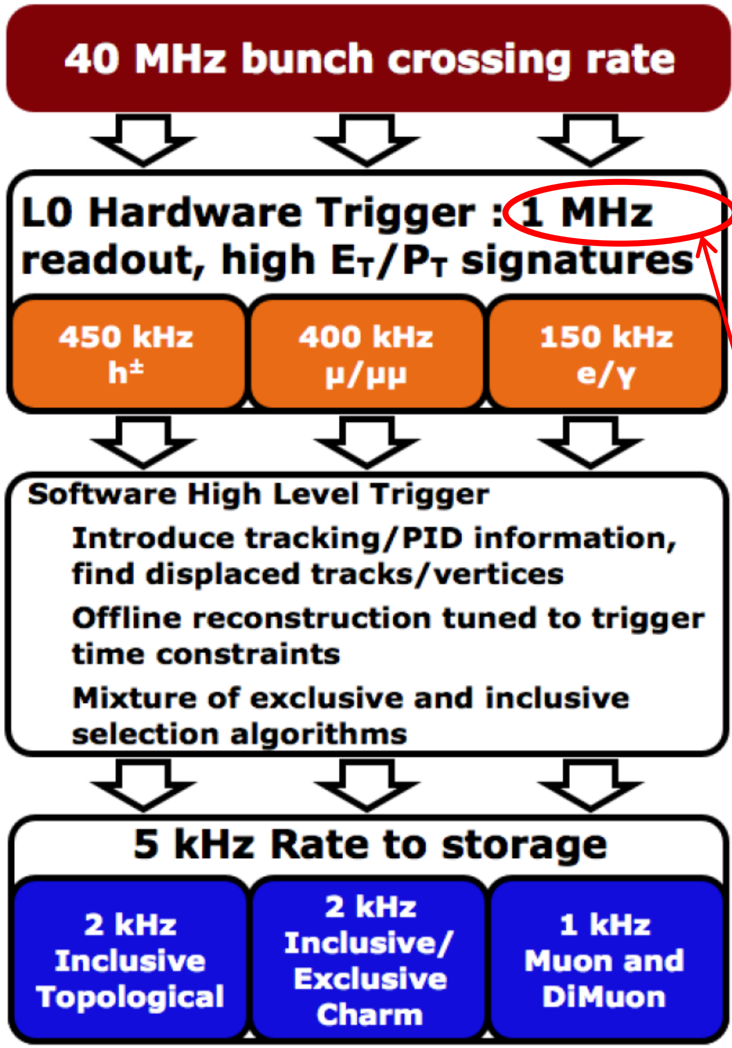


Muon system:

- Level 0 trigger: High P_t muons
- OS flavour tagging



Triggering



Trigger is crucial as $\sigma_{b\bar{b}}$ is less than 1% of total inelastic cross section and B decays of interest typically have B ranching ratios of <10^{-5}

Hardware level (L0)

Search for high-p_T μ, e, γ and hadron candidates

Software level (High Level Trigger, HLT)

Farm with $\mathcal{O}$(29000) multi-core processors)

Very flexible algorithms, writes ~5 kHz to storage

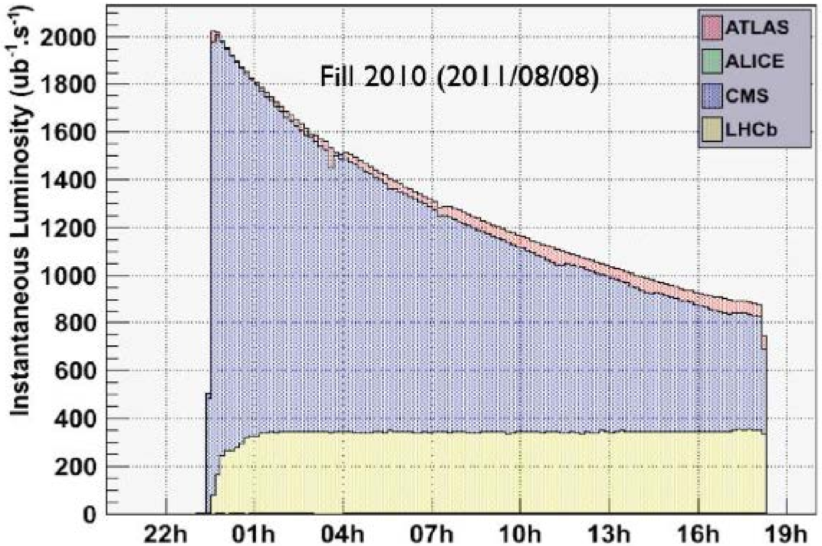
This is the bottleneck

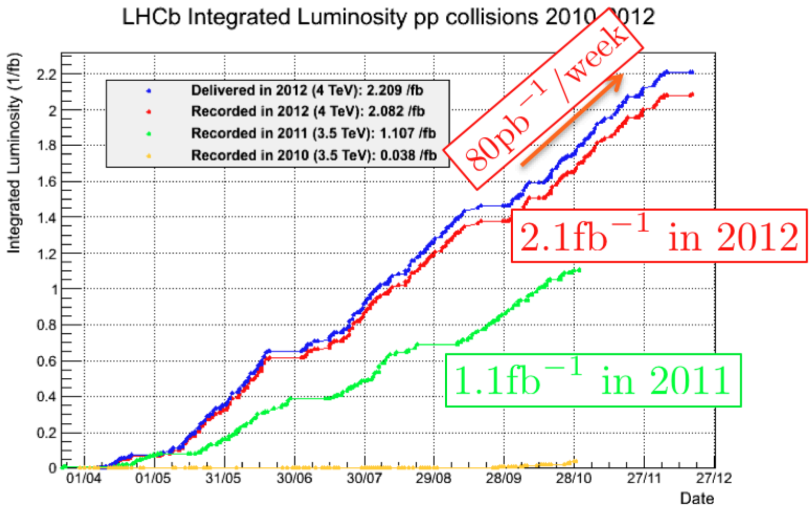
Detector Performance

- Detector works better than expected
- Run at 4x10^{-32} cm^{-2}/s instead of 2x10^{32}, with fewer bunches in the machine which is more difficult ~<1.5> interactions/crossing
- Detector efficiency >95% for all systems
- Problems: Vertex resolution slightly worse, flavor tagging somewhat poorer
- Luminosity is leveled – small changes of L with time; beams are brought closer together when currents decrease

Luminosity Leveling

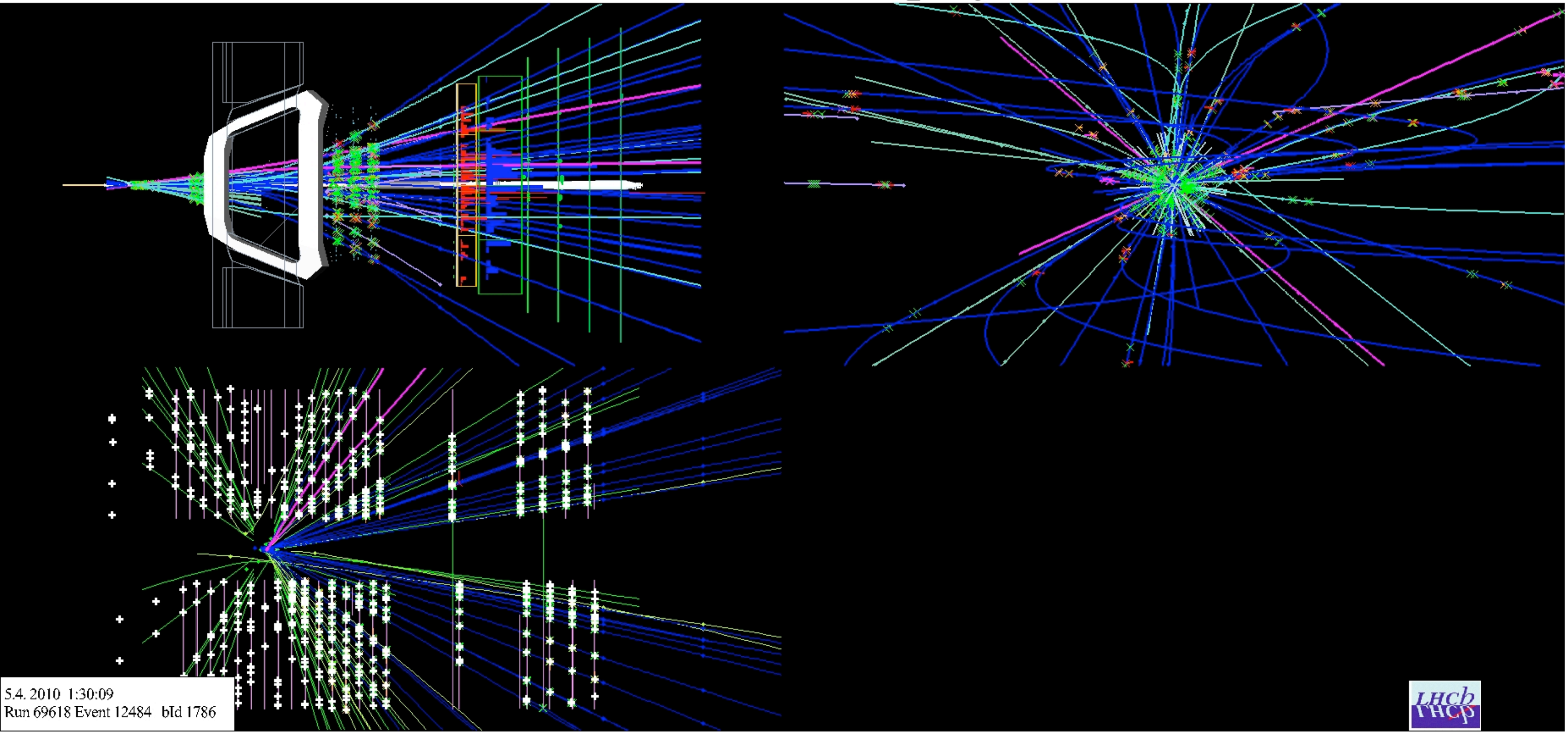
- Luminosity is maintained as at a constant value of ~4x10^{32}/cm·s by displacing beams transversely
- Integral L is 1/fb in 2011, collected 2/fb more in 2012



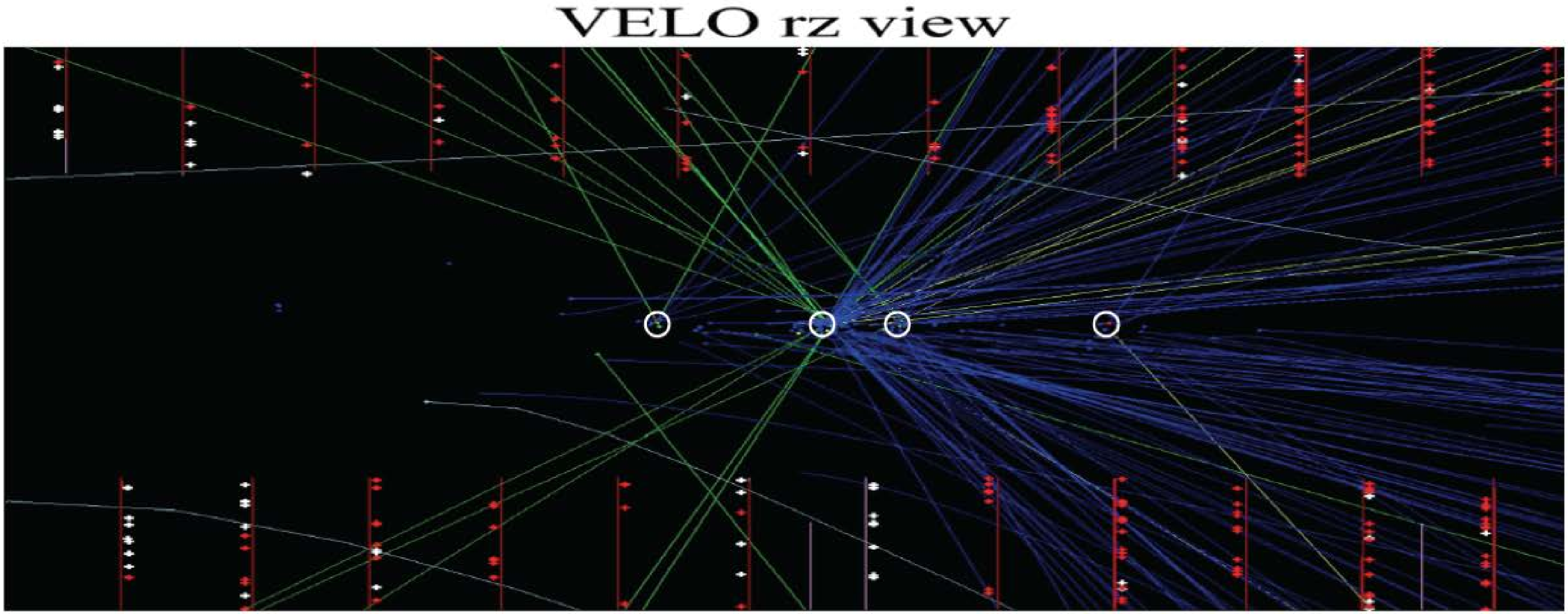


$B^- \rightarrow J/\psi\ K^-$

LHCb Event Display



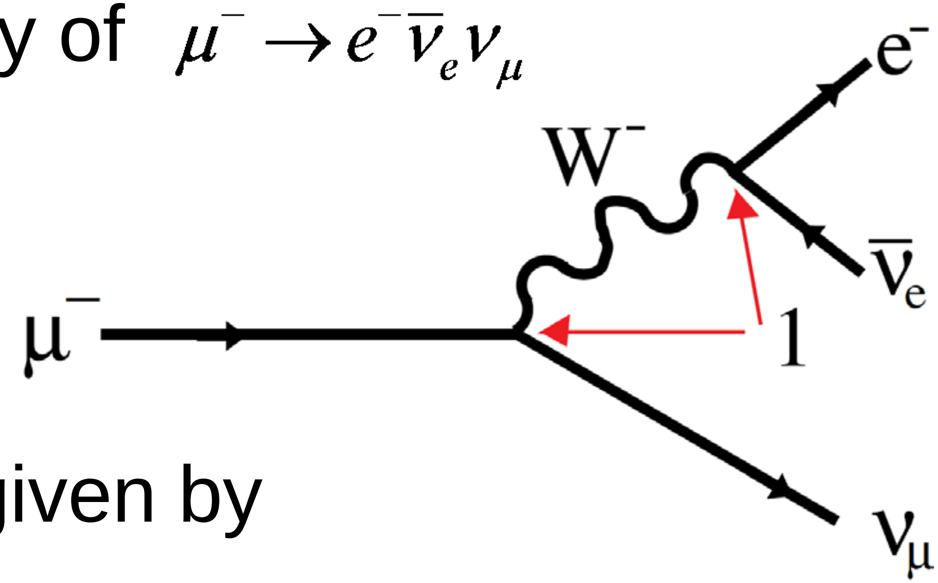
Running Conditions



- 20 MHz of bunch crossing (in 2012, with 50 ns bunch spacing) with an average of 1.5 pp interactions per bunch crossing → this level of pileup not an issue for LHCb

Weak decay constant

- Consider the b decay of $\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$



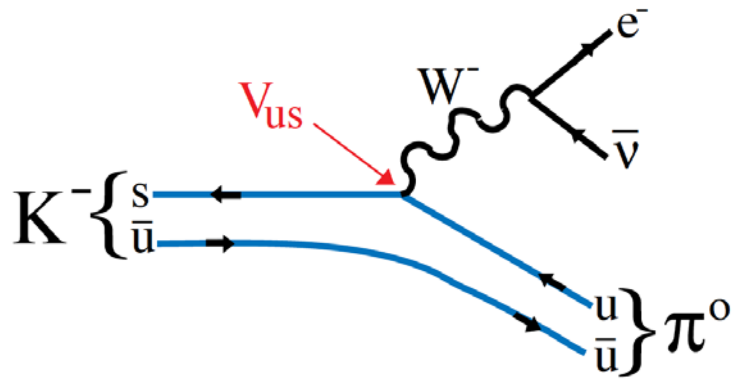
- The decay width is given by

$$\Gamma_\mu = \frac{G_F^2}{192\pi^3} m_\mu^5 \times (\text{phase space}) \times (\text{radiative corrections})$$

- Since $\Gamma_\mu \oplus \tau_\mu = \hbar$, measuring the muon lifetime determines G_F.

$|V_{us}|$

- $|V_{ud}|$ =0.97418±0.00026 is measured using nuclear β decays



- For $|V_{us}|$ use semileptonic kaon decays. The decay width is given by

$$\Gamma(K_{l3}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 \times I_{K,l}(\lambda)(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K,l}^{EM})$$

  - C_K is a Clebsch-Gordan coefficent =1/2
  - S_{EW} is the short-distance EW correction =1.0232
  - Δ's are SU(2) breaking & long-distance E&M corrects
  - $I_{K,l}(\lambda)$ is the phase space integral

$|V_{us}|$ II

- $f_+(0)$: Here we have quark transition, yet the quarks have to form a single hadron, the π^0
- The probability of this happening is parameterized in terms of the 4-momentum transfer squared, $q^2=(p-p')^2$. From the fact that the K→π weak transition must be Vector

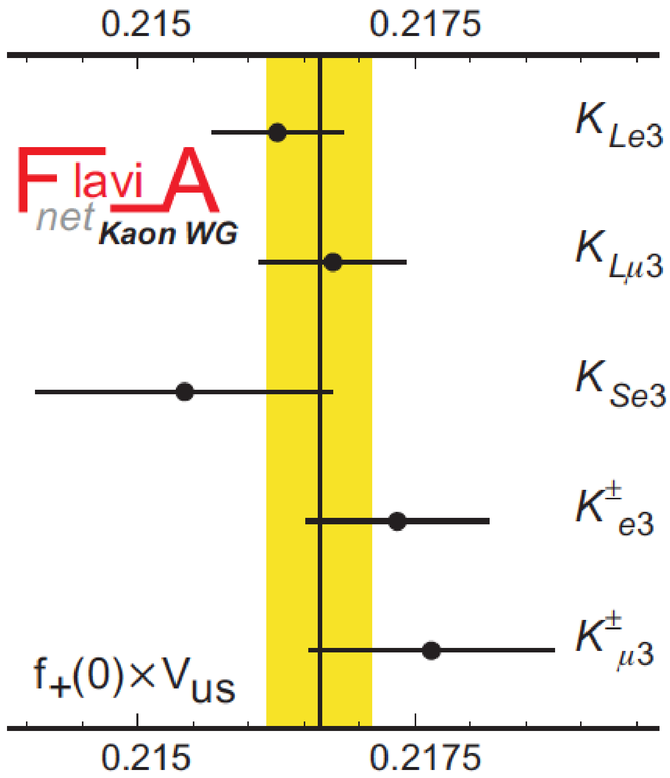
$$\left\langle \pi(p') \middle| V_\mu = \gamma_\mu(1+\gamma_5) \middle| K(p) \right\rangle = \left(p_\mu + p'_\mu\right) f_+(q^2) + \left(p_\mu - p'_\mu\right) f_-(q^2)$$

- For massless leptons the $f_-(q^2)$ term vanishes
- The shape of $f(q^2)$ can be measured, so only $f_+(0)$ remains to be calculated.

$|V_{us}|$ III

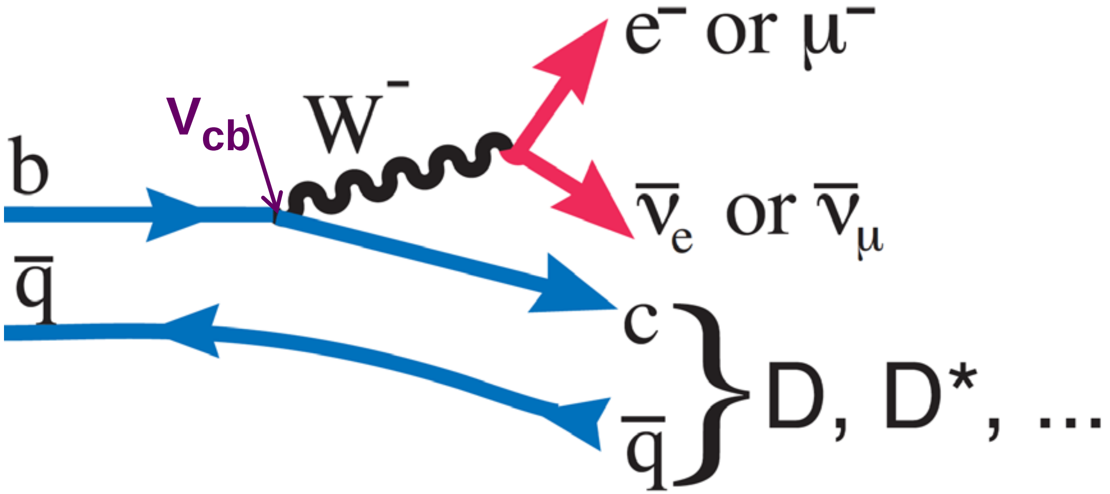
- Measurements of $f_+(0)|V_{us}|$
- $f_+(0)=0.964(5)$
- $\lambda=|V_{us}|=0.2246\pm0.0012$
- Experiment measures

K lifetime, shape of form-factor & value of the form-factor at $q^2=0$



$|V_{cb}|$

- Basic decay diagram:



- Two methods used to determine $|V_{cb}|$ from data: Exclusive, only a D or D* produced, & Inclusive, take all b→c decays
- If B→D one form-factor, for B→D*, have 3

Exclusive $|V_{cb}|$

- Based on HQET invented by N. Isgur & M. Wise
  - Idea is that there are spin & flavor symmetries between two ∞ heavy quarks; the b & c quarks are not quite that heavy, but corrections can be calculated in a controlled way. In HQET only 1 ff for B→D*, where there are 3 independent spin states
  - Consider the invariant 4-*velocity* transfer, ω. When ω=1, the b transforms into a c with the same velocity, so the form-factor is unity modulo some small corrections
  - Note $\omega = \left(m_B^2 + m_{D^{(*)}}^2 - q^2\right) / \left(2 m_B m_{D^{(*)}}\right)$

Exclusive $|V_{cb}|$ II

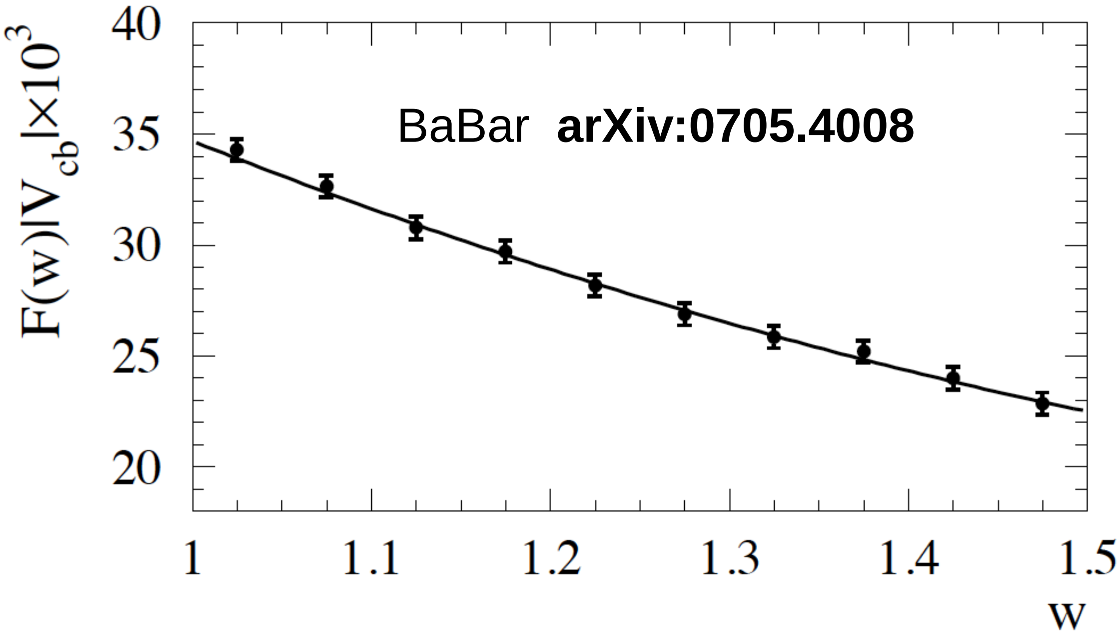
- F(ω) is the form-factor

$$\frac{d\Gamma(B \to D^* \ell \nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \mathcal{K}(w)\mathcal{F}(w)^2$$

- K(ω) is the phase space factor, which goes to zero as ω→, so data must be extrapolated. There are theoretical models for the shape of F(ω). All that's necessary is the lifetime, the value of the branching fraction at F(1), which determines $(F(1)|V_{cb}|)^2$, & the theoretically determined corrections to F(1) from 1

Exclusive $|V_{cb}|$ III

- Predictions of F(1)
  - Lattice (FNAL/MILC): 0.906±0.004±0.012
  - QCD sum rules 0.86±0.02



- $|V_{cb}|x10^3$=39.04±0.49$_{exp}$±0.53$_{QCD}$±0.19$_{QED}$ (Lattice)
- =41.6±0.6$_{exp}$±1.9$_{thy}$ (Sum rules)

Inclusive $|V_{cb}|$

- Here assume that the ensemble of exclusive $b \to c$ decays, $B \to Dl\nu$, $D^*l\nu$, $D^{**}l\nu$,… can be approximated by a continuum, called "duality". The model is called the Heavy Quark Expansion (HQE).
- The decay rate is related to $|V_{cb}|$ as

$$\Gamma(\overline{B} \to X_c \ell \bar{\nu}) = \frac{G_F^2 m_b^5 |V_{cb}|^2}{192\pi^3}\left(f(\rho) + k(\rho)\frac{\mu_\pi^2}{2m_b^2} + g(\rho)\frac{\mu_G^2}{2m_b^2} + d(\rho)\frac{\rho_D^3}{m_b^3} + l(\rho)\frac{\rho_{LS}^3}{m_b^3} + \mathcal{O}(m_b^{-4})\right),$$

where $\rho = m_c^2/m_b^2$, and μ_π^2, μ_G^2, ρ_D and ρ_{LS} are non-perturbative matrix elements of local operators

- We will not go into the details here see arXiv:0902.3743

Inclusive $|V_{cb}|$ II

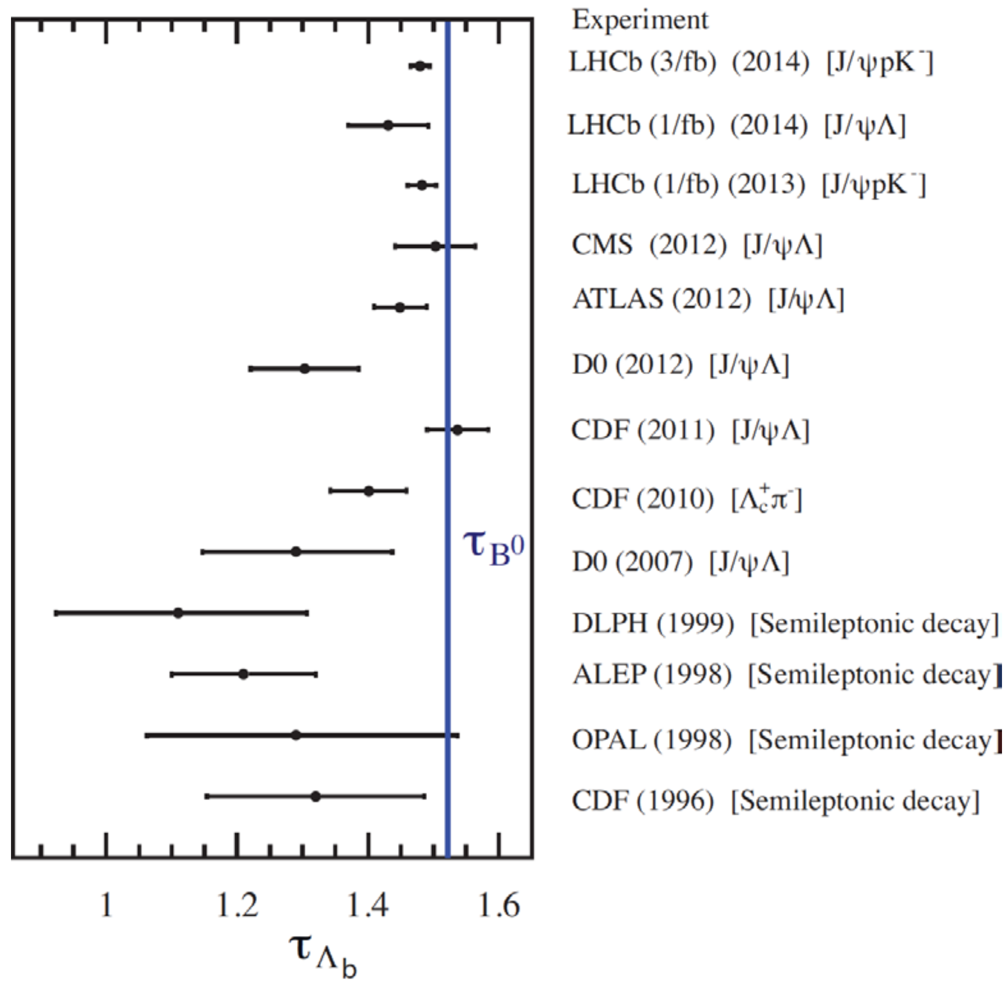
- Latest result: $|V_{cb}| \times 10^3 = 41.94 \pm 0.43_{fit} \pm 0.59_{thy}$
- $= 41.94 \pm 0.73$
- Exclusive (Lattice) $= 39.04 \pm 0.75$
- Difference has $\chi^2 = 3.8$ for 1 dof, prob=5%
- Could there be a problem here?
- Λ_b/B^0 lifetime ratio: HQE predicts that the lifetime ratio is almost equal, with Λ_b being shorter by a few %.

Λ_b/B^0 lifetime ratio

- Λ_b lifetime measurements were much lower
- LHCb now finds

$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.974 \pm 0.006 \pm 0.004.$$

- Consistent with HQE original prediction. Credit Uraltsev



Exclusive $|V_{ub}|$

- No theory like HQET
- Must rely on Lattice & model calculations

See Ricciardi arXiv:1403.7750

Exclusive decays	$\|V_{ub}\| \times 10^3$
$\bar{B} \to \pi l \bar{\nu}_l$	
HPQCD ($q^2 > 16$) (HFAG)[97, 11]	$3.52 \pm 0.08^{0.61}_{0.40}$
Fermilab/MILC ($q^2 > 16$) (HFAG)[98, 11]	$3.36 \pm 0.08^{0.37}_{0.31}$
lattice, full q^2 range (HFAG)[11]	3.28 ± 0.29
LCSR ($q^2 < 12$) (HFAG)[100, 11]	$3.41 \pm 0.06^{+0.37}_{-0.32}$
LCSR ($q^2 < 16$) (HFAG)[101, 11]	$3.58 \pm 0.06^{+0.59}_{-0.40}$

Exclusive $|V_{ub}|$

- Use HQE. Here many final states possible

See Ricciardi arXiv:1403.7750

	Inclusive decays	$(\,|V_{ub}| \times 10^3\,)$		
Models:	BNLP [134],[135],[136]	GGOU [141]	ADFR [138],[139],[140]	DGE [137]
BaBar [133]	$4.28 \pm 0.24^{+0.18}_{-0.20}$	$4.35 \pm 0.24^{+0.09}_{-0.10}$	$4.29 \pm 0.24^{+0.18}_{-0.19}$	$4.40 \pm 0.24^{+0.12}_{-0.13}$
Belle [132]	$4.47 \pm 0.27^{+0.19}_{-0.21}$	$4.54 \pm 0.27^{+0.10}_{-0.11}$	$4.48 \pm 0.30^{+0.19}_{-0.19}$	$4.60 \pm 0.27^{+0.11}_{-0.13}$
HFAG [11]	$4.40 \pm 0.15^{+0.19}_{-0.21}$	$4.39 \pm 0.15^{+0.12}_{-0.20}$	$4.03 \pm 0.13^{+0.18}_{-0.12}$	$4.45 \pm 0.15^{+0.15}_{-0.16}$

- So take e.g. exclusive $(3.28 \pm 0.29) \times 10^{-3}$
- & inclusive $(4.20 \pm 0.25) \times 10^{-3}$
- These are inconsistent!
- No resolution in sight

$|V_{ub}|$

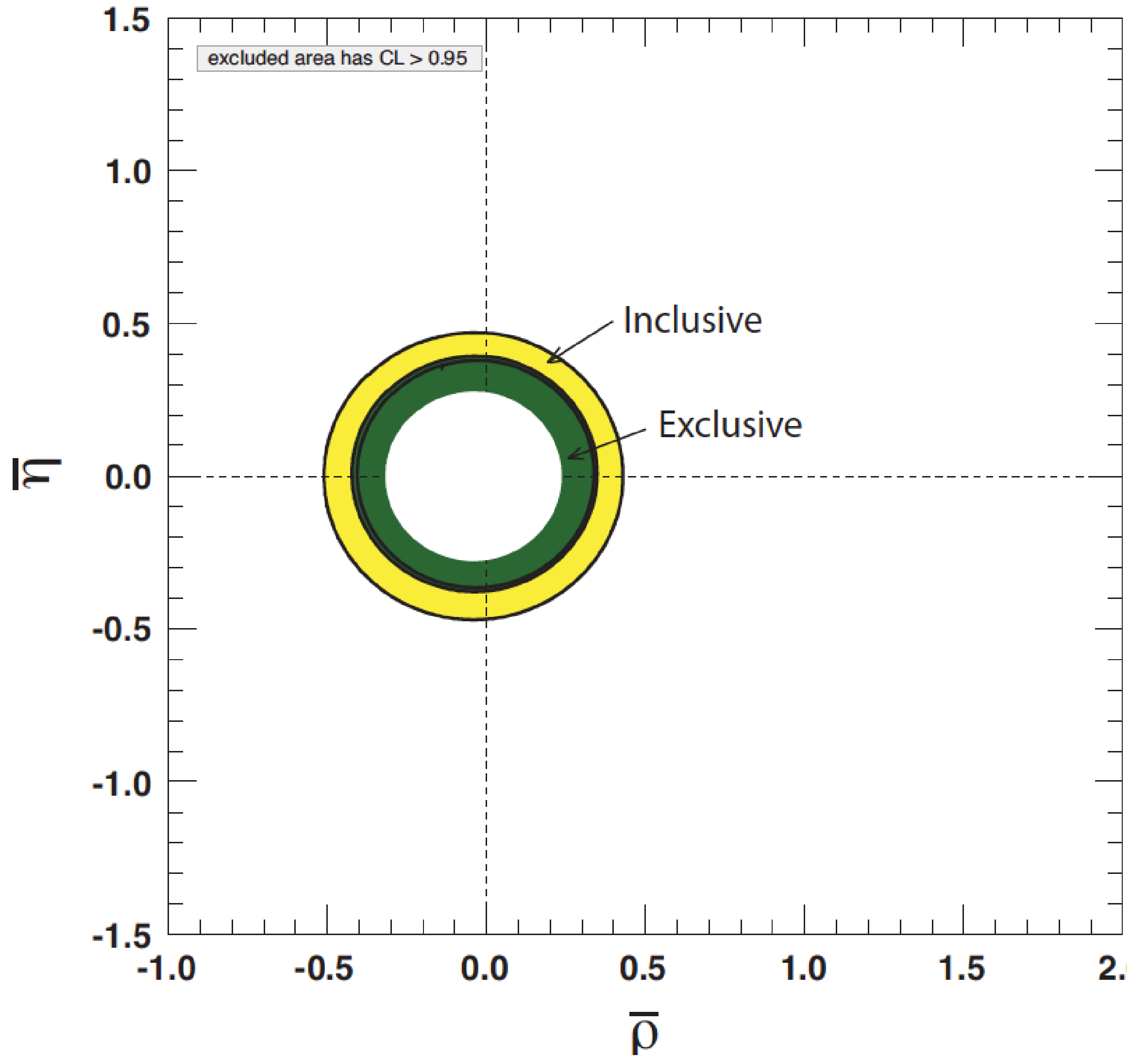
- Summary
- Note

$\bar{\rho}=\rho(1-\lambda^2/2)$

$\bar{\eta}=\eta(1-\lambda^2/2)$

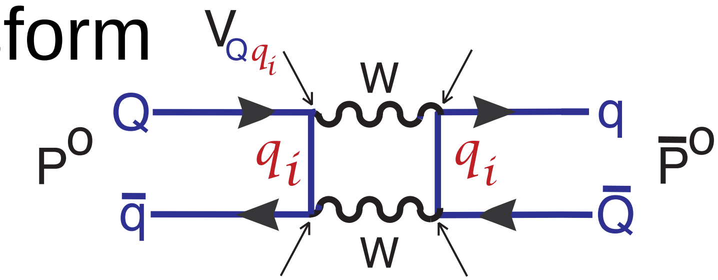
- Bands are

$\pm 2\sigma$



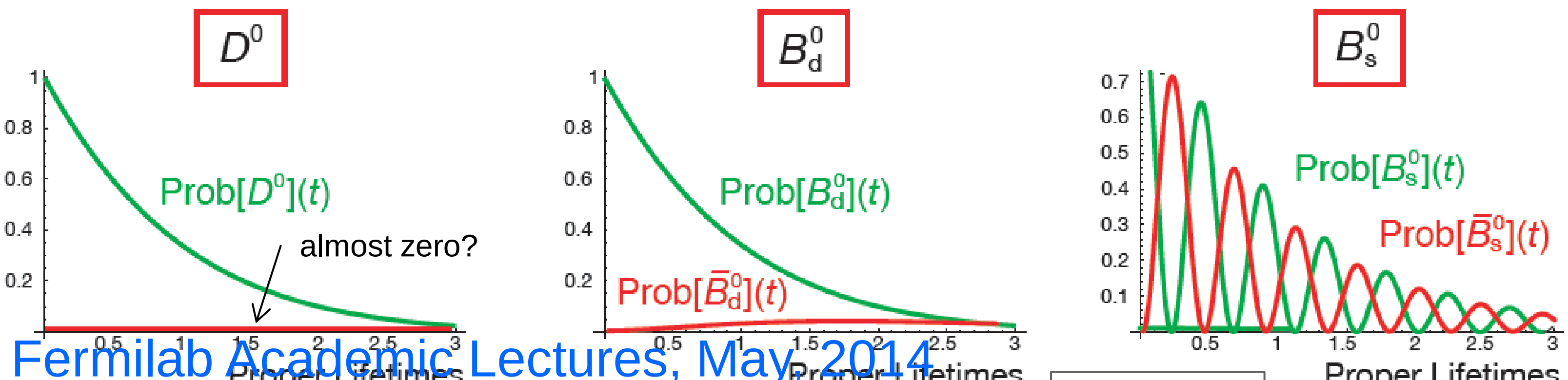
Neutral Meson Mixing

- Neutral heavy mesons can transform into their anti-particles via 2nd order weak interactions



New particles possible in the loop

- Short distance transition rate depends on
  - mass of intermediate q_i, the heavier the larger, favors mesons containing s & b, since t is allowed
  - CKM elements V_{ij}.



from Van Kooten

Mixing formalism

- Hamiltonian

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

- Schrodinger equation

$$i\frac{d}{dt}\begin{pmatrix} \mid B^0(t)\rangle \\ \mid \overline{B}^0(t)\rangle \end{pmatrix} = \mathcal{H}\begin{pmatrix} \mid B^0(t)\rangle \\ \mid \overline{B}^0(t)\rangle \end{pmatrix}$$

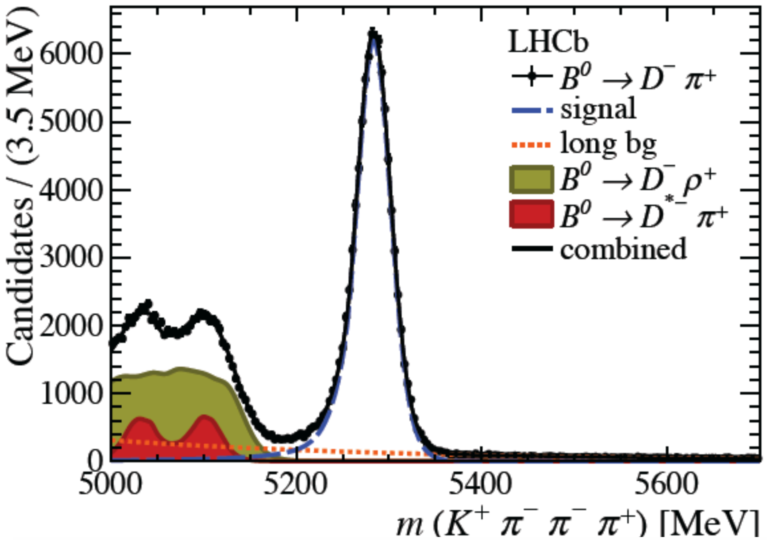
- Diagonalizing

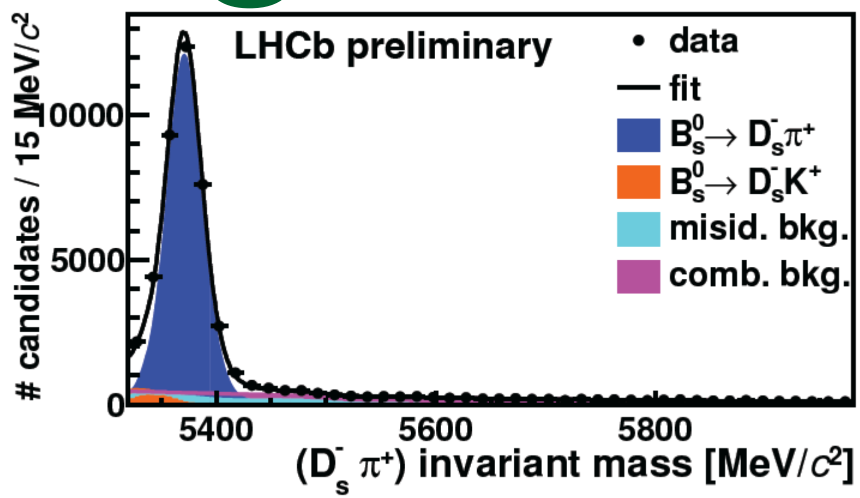
$$\Delta m = m_{B_H} - m_{B_L} = 2\,|M_{12}|$$

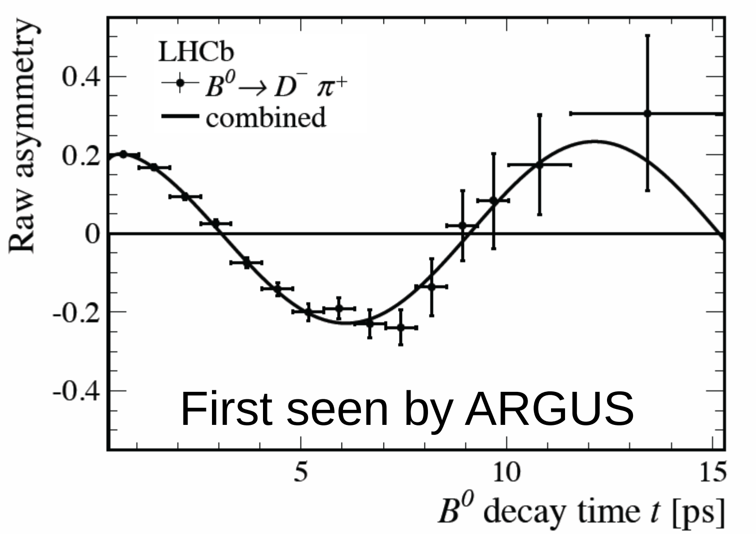
$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2\,|\Gamma_{12}|\cos\phi$$

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

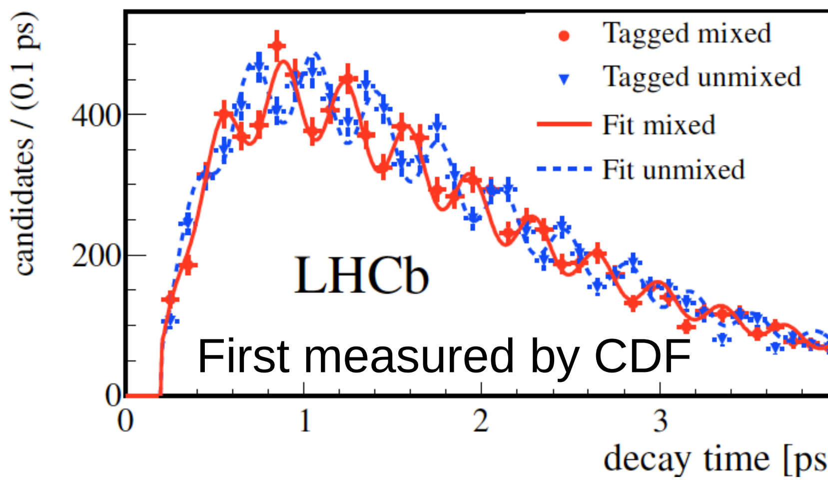
B Mixing data







$\Delta m_d = 0.5156 \pm 0.0051\,(\text{stat}) \pm 0.0033\,(\text{syst})\ \text{ps}^{-1}$



$\Delta m_s = 17.768 \pm 0.023\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$

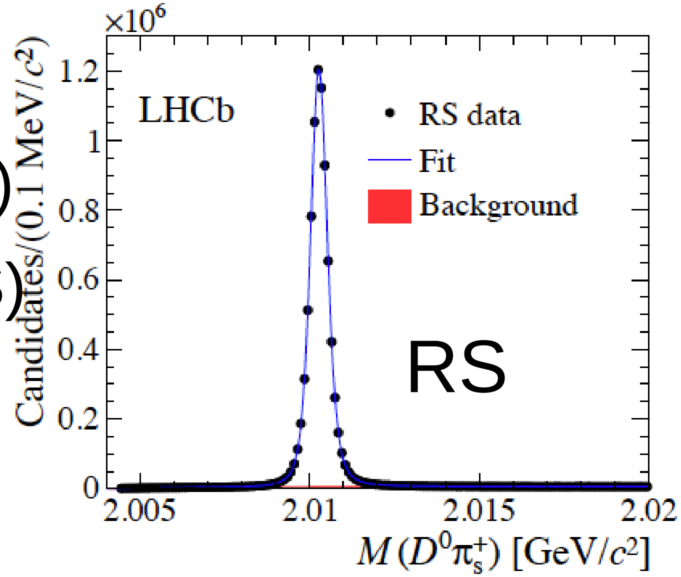
D^o-$\bar{D}^o$ Mixing

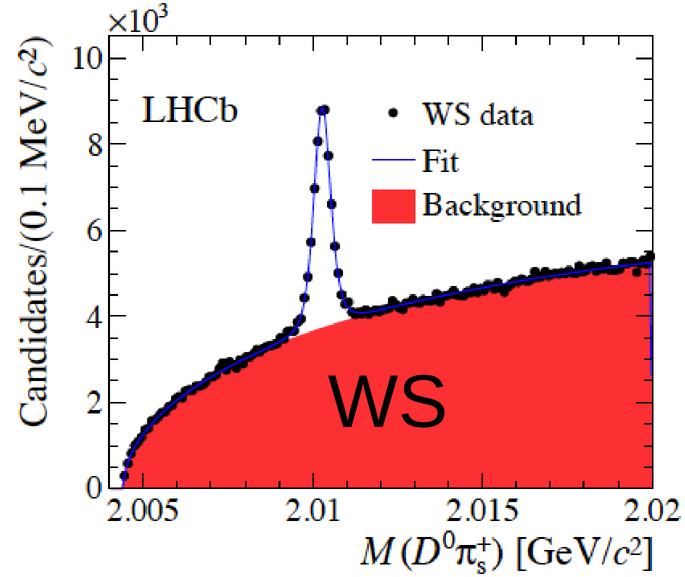
- $D^{*+} \rightarrow \pi^+ D^o$ provides an initial flavor tag
- "Wrong-sign" (WS) D^o can appear via mixing or a rare decay that gives the same final state called doubly-Cabbibo suppressed decay (DCS), where DCS follow ~exp($-t/\tau_{D^o}$). Mixing, however, depends on t in a more complicated way
- Define R_D=DCS/(Cabibbo favored). Mixing is parameterized as x´ & y´, functions of Δm & $\Delta\Gamma$.
- Measure Wrong-sign/Right-sign, R(t)= (WS/RS)

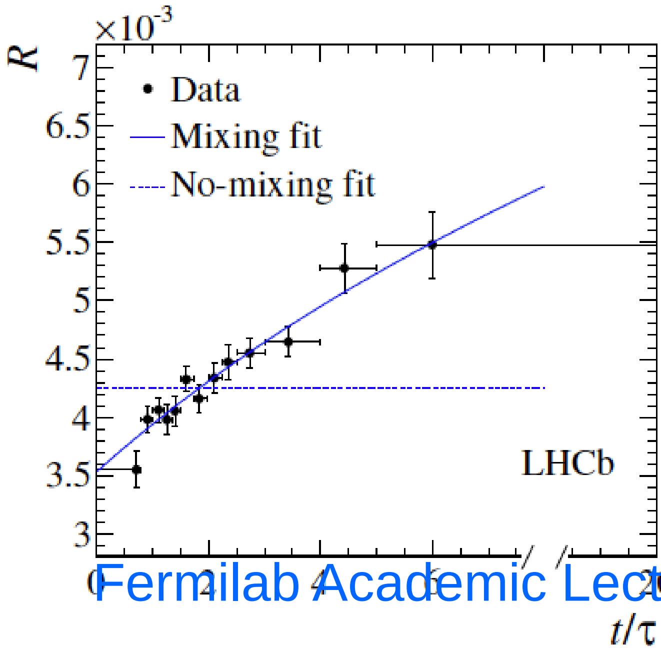
$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

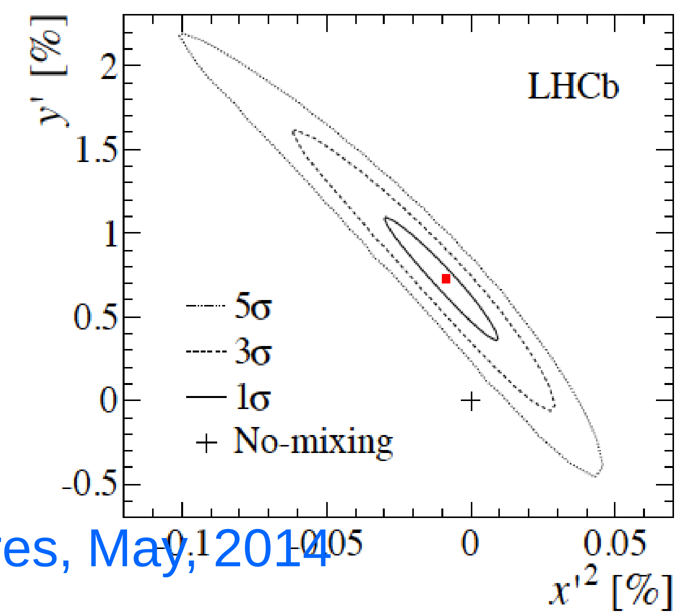
Charm mixing result

$D^{*+} \rightarrow \pi^+ D^o$,
$D^o \rightarrow K^- \pi^+$ (RS)
$\bar{D}^o \rightarrow K^+ \pi^-$ (WS)









No mixing excluded at 9.1σ, systematic errors are included
$y' = (7.2 \pm 2.4)\%$
$x'^2 = (-0.09 \pm 0.13)\%$

B mixing CKM constraints

- For B^0 mixing

$$\frac{\Delta m}{\Gamma} = \frac{G_F^2}{6\pi^2} B_{B_d} f_B^2 m_B \tau_B |V_{tb}^* V_{td}|^2 m_t^2 F\left(\frac{m_t^2}{M_W^2}\right)\eta_{QCD}$$

B_B is a theoretical parameter, f_B, the meson decay constant is also estimated theoretically though in principle measuring $B^- \to \tau\nu$ would determine $|V_{ub}|^2 f_B^2$. F is a known function & η_{QCD}~0.8

- Similar Eq. for B_s mixing. Errors cancel in

$$\frac{x_d}{x_s} = \frac{B_B}{B_{B_s}} \frac{f_B^2}{f_{B_s}^2} \frac{m_B}{m_{B_s}} \frac{\tau_B}{\tau_{B_s}} \frac{|V_{tb}^* V_{td}|^2}{|V_{tb}^* V_{ts}|^2}$$

B mixing & CKM constraints

- We have

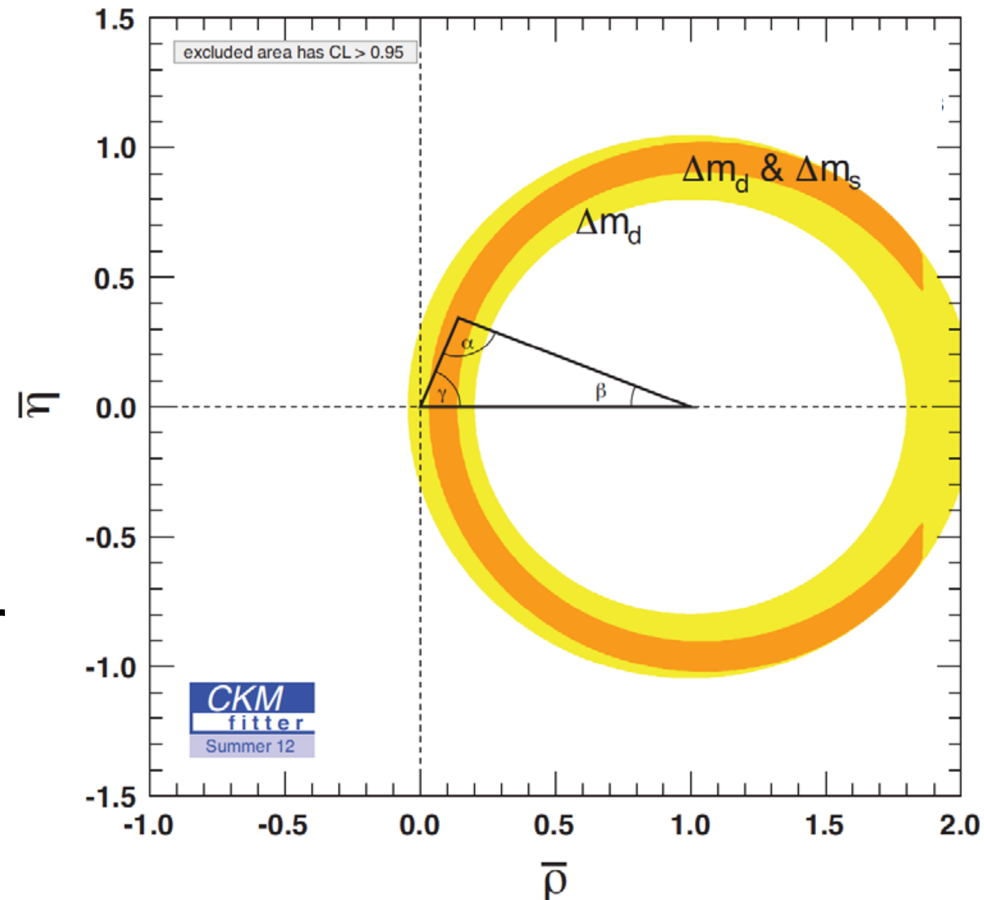
$$|V_{tb}^* V_{td}|^2 = A\lambda^3|(1-\rho-i\eta)|^2 = A\lambda^3(\rho-1)^2+\eta^2 \text{ and}$$

$$|V_{tb}^* V_{ts}|^2 = A\lambda^2 ,$$

- So the ratio gives

a circle in the ($\bar{\rho}$,$\bar{\eta}$) plane centered at (1,0).

- (Modulo small higher order corrections)



Sakharov conditions

- Big bang gave matter & anti-matter
- For the Universe to exist:
  1. Baryon # violation
  2. Departure from thermal equilibrium
  3. C & CP violation, where C is charge conjugation, e.g, C|p>=±|p>, & P is parity $P|\psi(\mathbf{r})\rangle = \pm|\psi(-\mathbf{r})\rangle$
  - 1. is satisfied as SM gives B violation at high T
  - 2. is satisfied from the EW phase transition
  - 3. C & CP are violated by weak interactions
- BUT amount of CPV is too small by 10^9, so new sources need to be found

CP formalism

- Basic idea: two interfering amplitudes that ultimately involve the CKM parameter η.

$$\Gamma(B \to f) = \left(|\mathcal{A}|\, e^{i(s_\mathcal{A}+w_\mathcal{A})} + |\mathcal{B}|\, e^{i(s_\mathcal{B}+w_\mathcal{B})}\right)^2$$

$$\Gamma(\overline{B} \to \overline{f}) = \left(|\mathcal{A}|\, e^{i(s_\mathcal{A}-w_\mathcal{A})} + |\mathcal{B}|\, e^{i(s_\mathcal{B}-w_\mathcal{B})}\right)^2$$

$$\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f}) = 2\,|\mathcal{A}\mathcal{B}|\sin(s_\mathcal{A} - s_\mathcal{B})\sin(w_\mathcal{A} - w_\mathcal{B})$$

- Favorable if **A** & **B** are about the same size
- Resulting rate difference depends on both a strong & weak phase difference

CP formalism

- Consider specifically $|B^0\rangle$, but this can be for any P^0: K^0, B^0, B^0_s, or D^0.
- $CP|B^0\rangle = |\overline{B}^0\rangle$. So these are not CP eigenstates, but
- $|B_1^0\rangle = \frac{1}{\sqrt{2}}\left(|B^0\rangle - |\overline{B}^0\rangle\right)$ & $|B_2^0\rangle = \frac{1}{\sqrt{2}}\left(|B^0\rangle + |\overline{B}^0\rangle\right)$ are with $CP|B_1^0\rangle = |B_1^0\rangle$ & $CP|B_2^0\rangle = -|B_2^0\rangle$
- To allow for CPV define

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle, \quad |B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

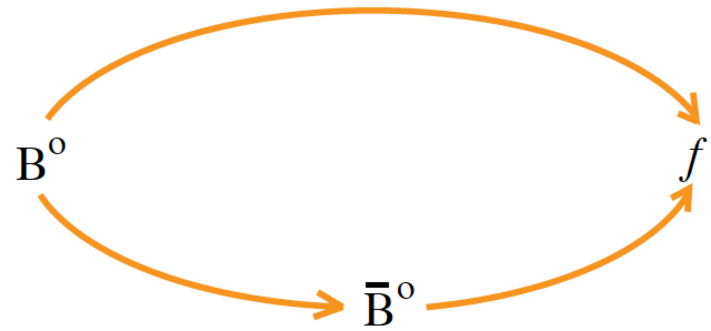
where CP is violated if $|p/q| \neq 1$

CPV via interference of mixing & decay

- Here we are interested in a final state that can be reached by either a $|P^0>$ or a $|\overline{P}^0>$
- Then we can utilize

mixing to provide another

Interfering amplitude



- f can be a CP eigenstate, $CP|f_{CP}\rangle = \pm|f_{CP}\rangle$ but it doesn't have to be
- Define $A = \langle f_{CP}|\mathcal{H}|B^0\rangle, \;\; \overline{A} = \langle f_{CP}|\mathcal{H}|\overline{B}^0\rangle$. If $\left|\frac{\overline{A}}{A}\right| \neq 1$

we have "direct" CPV, but all that is needed is for $\lambda = \frac{q}{p} \cdot \frac{\overline{A}}{A} \neq 1$ which can happen even if $\left|\frac{p}{q}\right| = \left|\frac{\overline{A}}{A}\right| = 1$

CPV for f_{CP}

- The asymmetry is given by

$$a_{f_{CP}} = \frac{\Gamma\left(B^0(t) \to f_{CP}\right) - \Gamma\left(\overline{B}^0(t) \to f_{CP}\right)}{\Gamma\left(B^0(t) \to f_{CP}\right) + \Gamma\left(\overline{B}^0(t) \to f_{CP}\right)}$$

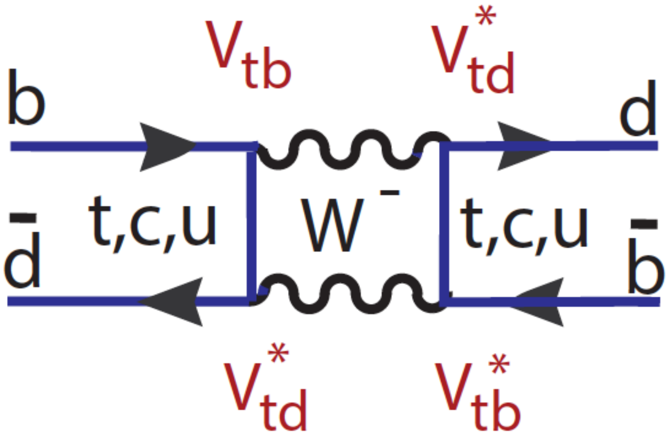
$$a_{f_{CP}} = \frac{\left(1-|\lambda|^2\right)\cos\left(\Delta m t\right) - 2\mathrm{Im}\lambda\sin(\Delta m t)}{1+|\lambda|^2}$$

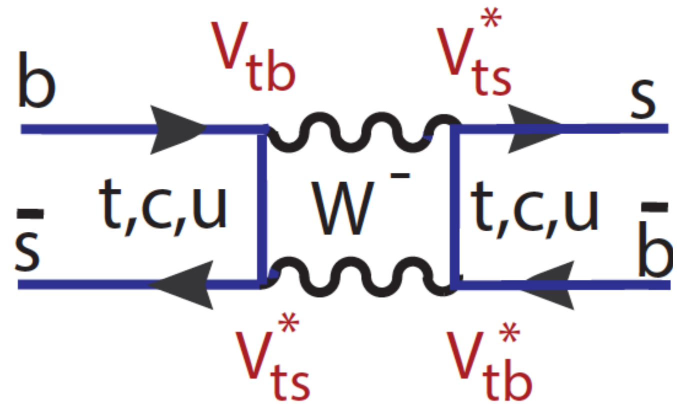
- For $|\lambda|=1$, we have

$$a_{f_{CP}} = -\mathrm{Im}\lambda\sin(\Delta m t)$$

CP mixing phase

- Depends on CKM elements in mixing or box diagram





- For B^0

$$\frac{q}{p}=\frac{\left(V^*_{tb}V_{td}\right)^2}{\left|V_{tb}V^*_{td}\right|^2}=\frac{\left(1-\rho-i\eta\right)^2}{\left(1-\rho+i\eta\right)\left(1-\rho-i\eta\right)}=e^{-2i\beta}$$

For B_s

$$\frac{q}{p}=\frac{\left(V^*_{tb}V_{ts}\right)^2}{\left|V_{tb}V^*_{ts}\right|^2}=1$$

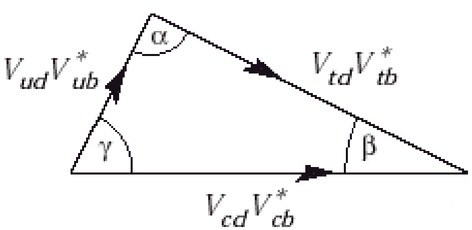
- arg(p/q)=β

arg(p/q)~0

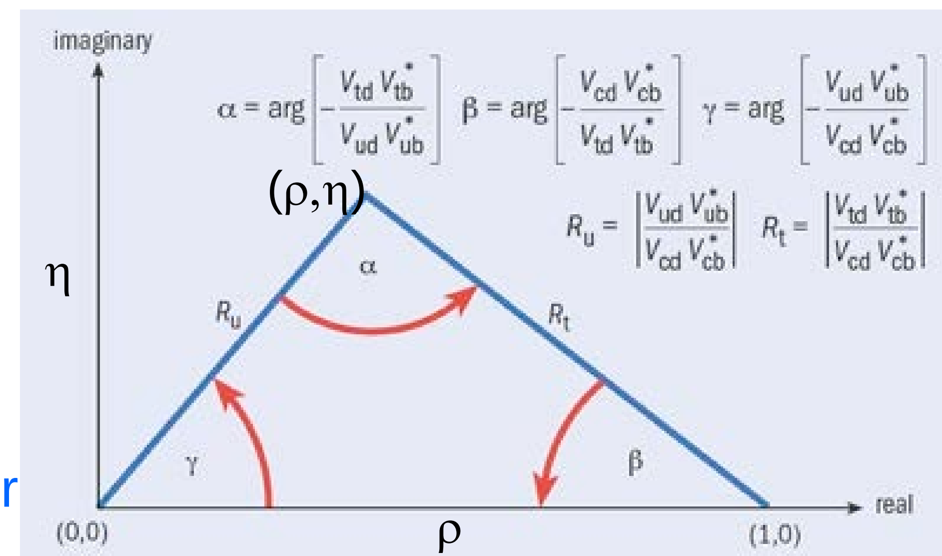
CPV for B^0

- Need p/q and $\bar{A}/A$. Choosing a suitable CP eigenstate forces $\bar{A}/A$=1. p/q comes from mixing $\frac{q}{p}=\frac{(V_{tb}^{*}V_{td})^2}{|V_{tb}V_{td}|^2}=\frac{(1-\rho-i\eta)^2}{(1-\rho+i\eta)(1-\rho-i\eta)}=e^{-2i\beta}$
- B^0:

$$\mathrm{Im}\frac{q}{p}=-\frac{2(1-\rho)\eta}{(1-\rho)^2+\eta^2}=\sin(2\beta)$$



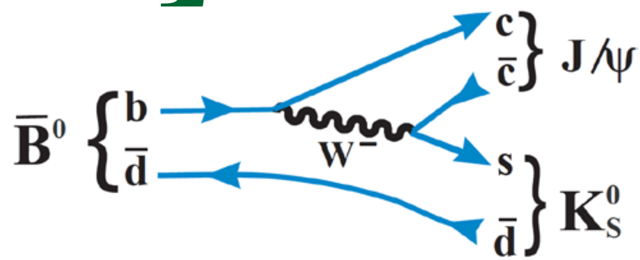
y

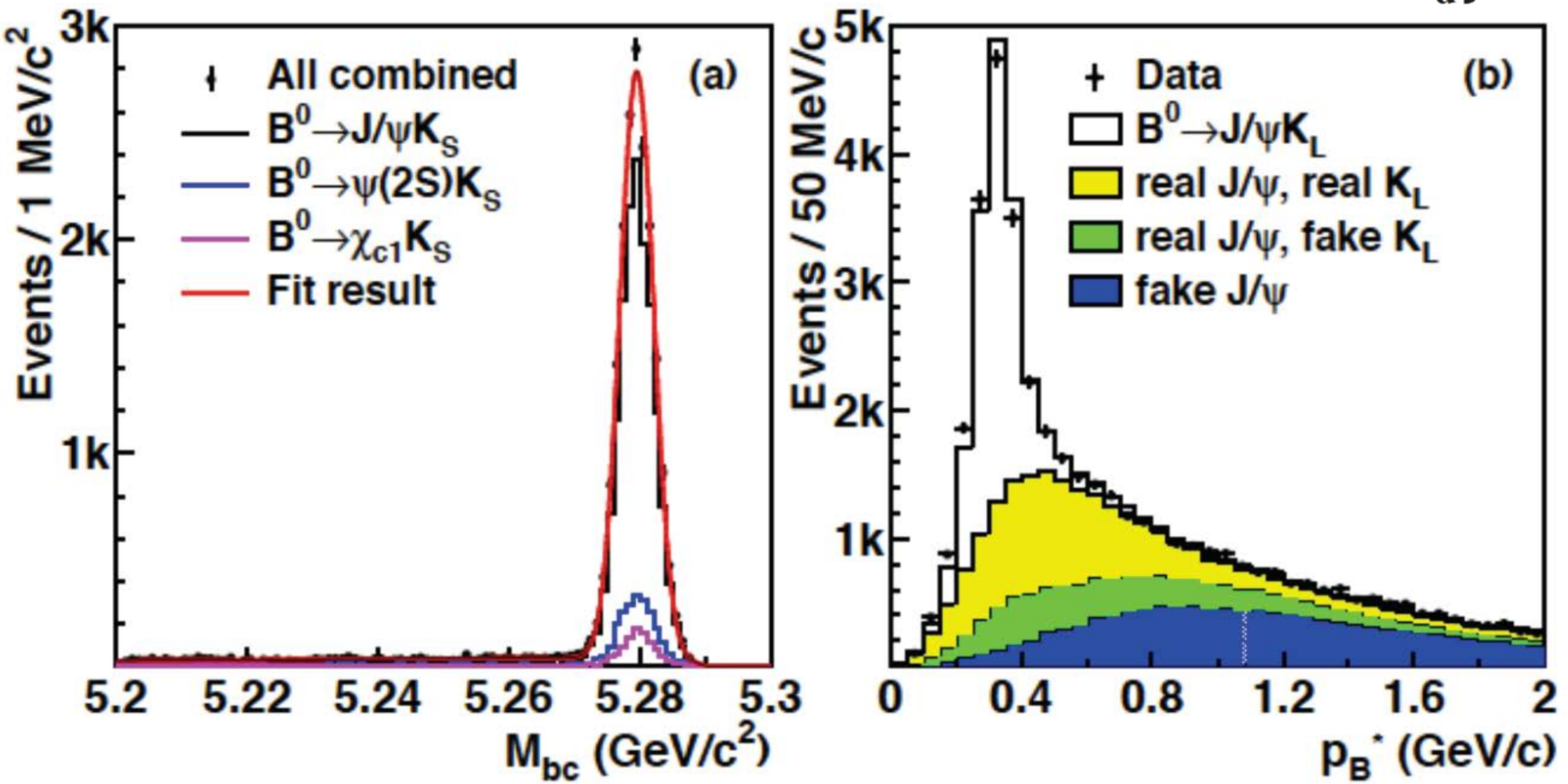


- This is SM

$B^0 \to \{c\bar{c}\}\, K^0$

- For charmonium final states (Belle)





Measurements of sin2β

- Requires knowledge of B flavor at birth – use info from the other B in the event
- sin2β values

Belle

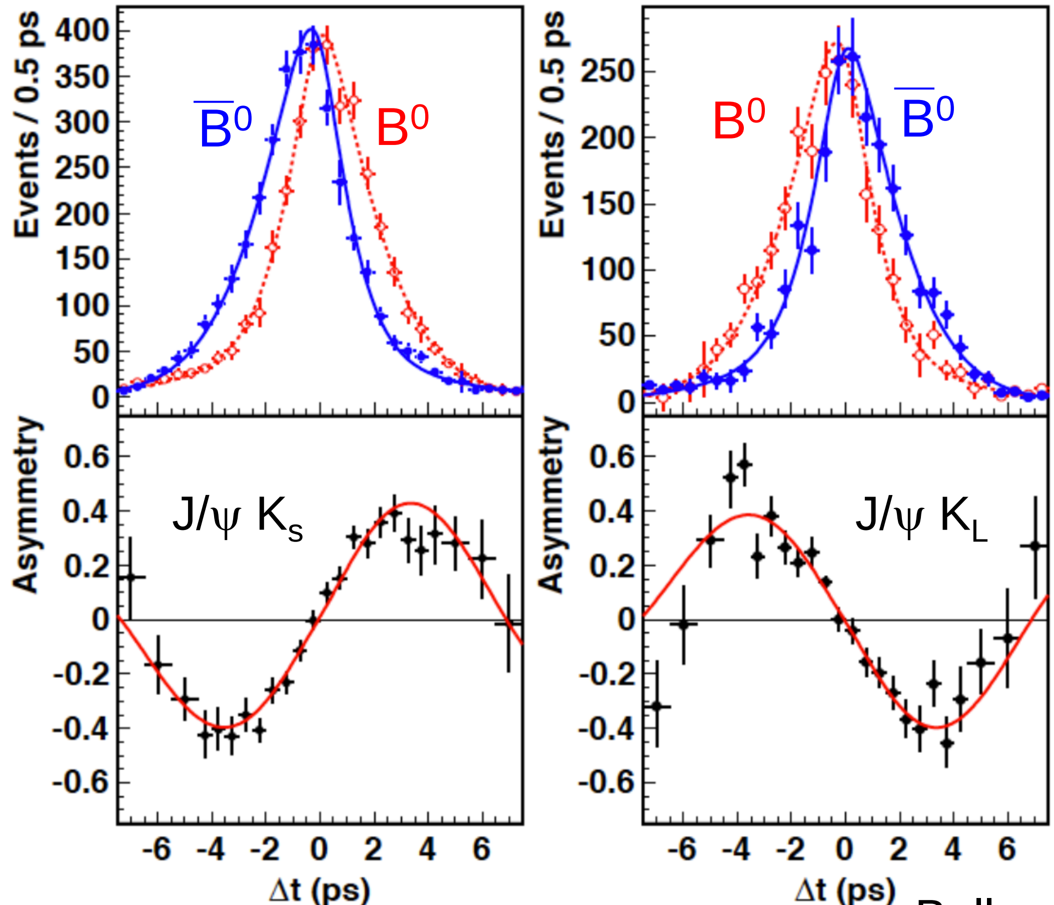
0.667±0.023±0.012

BaBar:

0.691±0.028±0.012

World Average:

0.682 ± 0.019

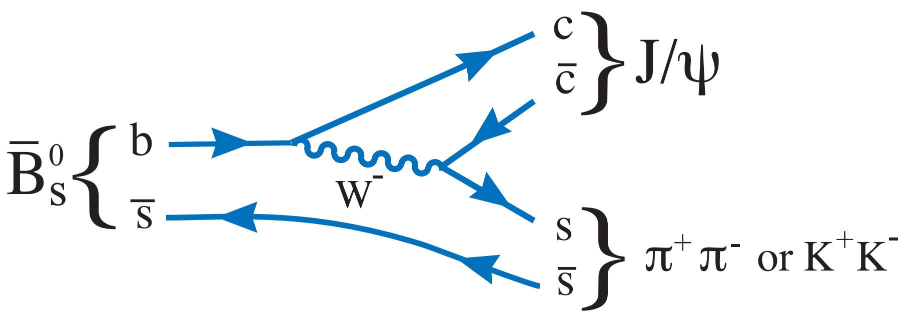


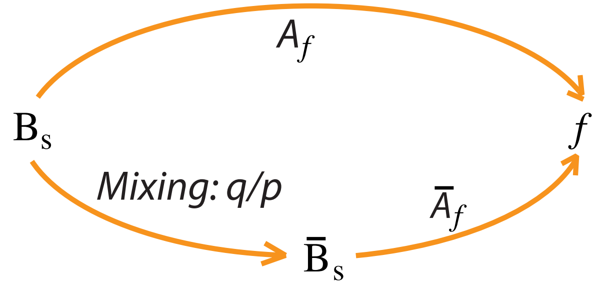
Belle Belle

$$\beta = \left(21.5^{+0.8}_{-0.7}\right)^{o} \text{ or } \left(68.5^{+0.7}_{-0.8}\right)^{o}$$

CPV in $B_s \rightarrow J/\psi\ X$

- For f =$J/\psi\ \phi$ or $J/\psi\ f_0$





- Small CPV expected, good place for NP to appear. Non zero due to CKM effects of order λ^4 in V_{ts}

$$\varphi_s^{SM} \equiv -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -2^{\circ}$$

- $J/\psi\phi$ not a CP eigenstate. Why? But can be used

CPV Time Evolution for B_S

- Consider $$a[f(t)] = \frac{\Gamma(\bar{M} \to f) - \Gamma(M \to f)}{\Gamma(\bar{M} \to f) + \Gamma(M \to f)}$$
- Define $$A_f \equiv A(M \to f),\ \bar{A}_f \equiv A(\bar{M} \to f), \quad \lambda_f = \frac{p}{q}\frac{\bar{A}_f}{A_f}$$
- Only 1 A_f & $\Delta\Gamma$=0 $\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(1 - \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$
- Then $a[f(t)] = -\mathrm{Im}\,\lambda_f$, & λ_f is a function of V_{ij} in SM
- For B^o, $\Delta\Gamma$H0, but there can be multiple A_f

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(\frac{1-|\lambda_f|^2}{2}\cos(\Delta M t) - \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$$

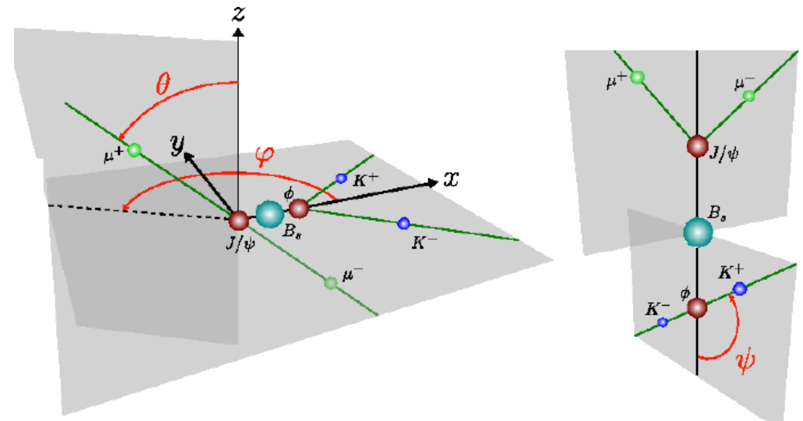
- If in addition $\Delta\Gamma$ 0, eg. B_s

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t}\left(\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma t}{2} + \frac{1-|\lambda_f|^2}{2}\cos(\Delta M t) - \mathrm{Re}\,\lambda_f \sinh\frac{\Delta\Gamma t}{2} - \mathrm{Im}\,\lambda_f \sin(\Delta M t)\right)$$

See Nierste
arXiv:0904.1869 [hep-ph]

Transversity

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4\Gamma}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)$$



k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

} for S-wave under ϕ predicted by Stone & Zhang PRD 79, 074024 (2009)

Transversity II

$$
\begin{aligned}
|A_0|^2(t) &= |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\parallel(t)|^2 &= |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)\right], \\
|A_\perp(t)|^2 &= |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_\parallel^*(t)\, A_\perp(t)) &= |A_\parallel||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta\_\|)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)\right], \\
\Re(A_0^*(t)\, A_\parallel(t)) &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. + \sin\phi_s \sin(\Delta m t)\right], \\
\Im(A_0^*(t)\, A_\perp(t)) &= |A_0||A_\perp| e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)\right], \\
|A_s(t)|^2 &= |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t\right], \\
\Re(A_s^*(t) A_\parallel(t)) &= |A_s||A_\parallel| e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel - \delta_s)\ \cos\phi_s \sin(\Delta m t)\right. \\
&\quad \left. + \cos(\delta_\parallel - \delta_s)\cos(\Delta m t)\right], \\
\Im(A_s^*(t) A_\perp(t)) &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin\phi_s \sin(\Delta m t)\right], \\
\Re(A_s^*(t) A_0(t)) &= |A_s||A_0| e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)\right. \\
&\quad \left. - \sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s)\cos(\Delta m t)\right].
\end{aligned}
$$

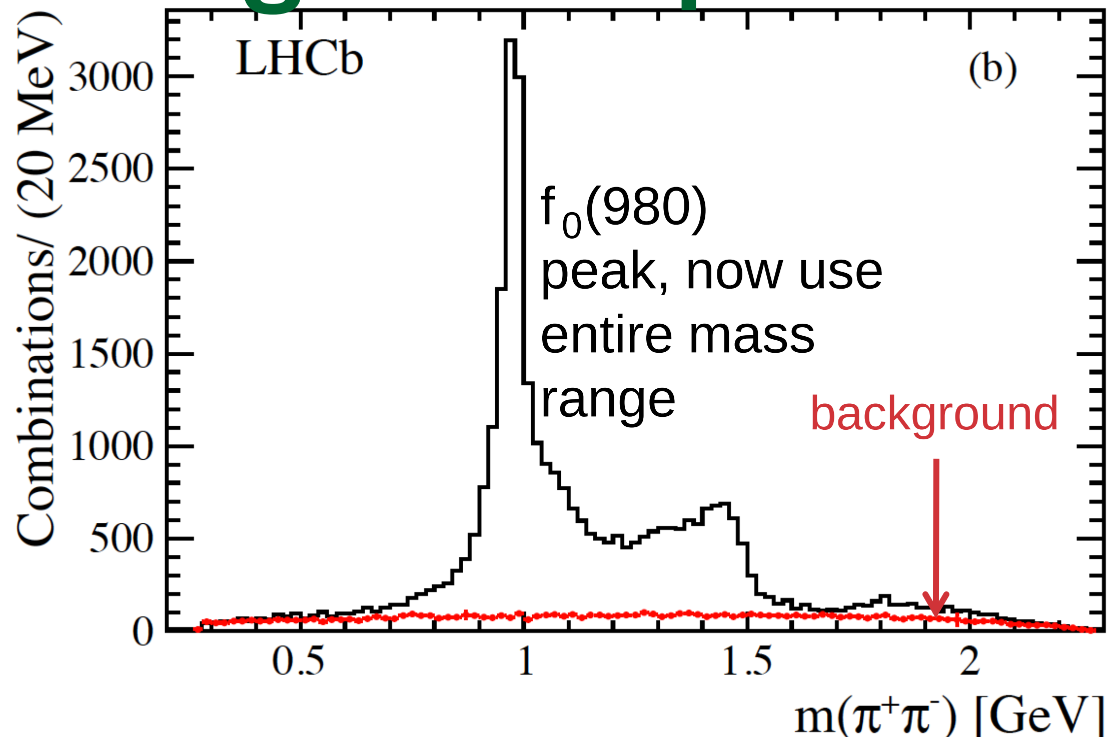
only term for $f=f_{cp}$

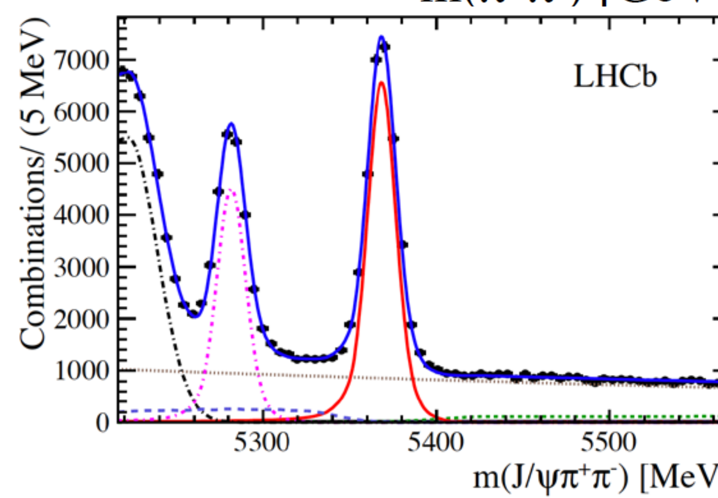
ϕ_s from $B_s \to J/\psi\pi^+\pi^-$

- Reconstructed $\pi^+\pi^-$ mass spectrum
- In region between arrows, measured to be >97.7% CP-odd @95% cl

$$a[f(t)] \square 2\sin\phi_s \sin(\Delta M t)$$

- $\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$ rad (1/fb)
- (uncertainty for 3/fb~0.070 rad)





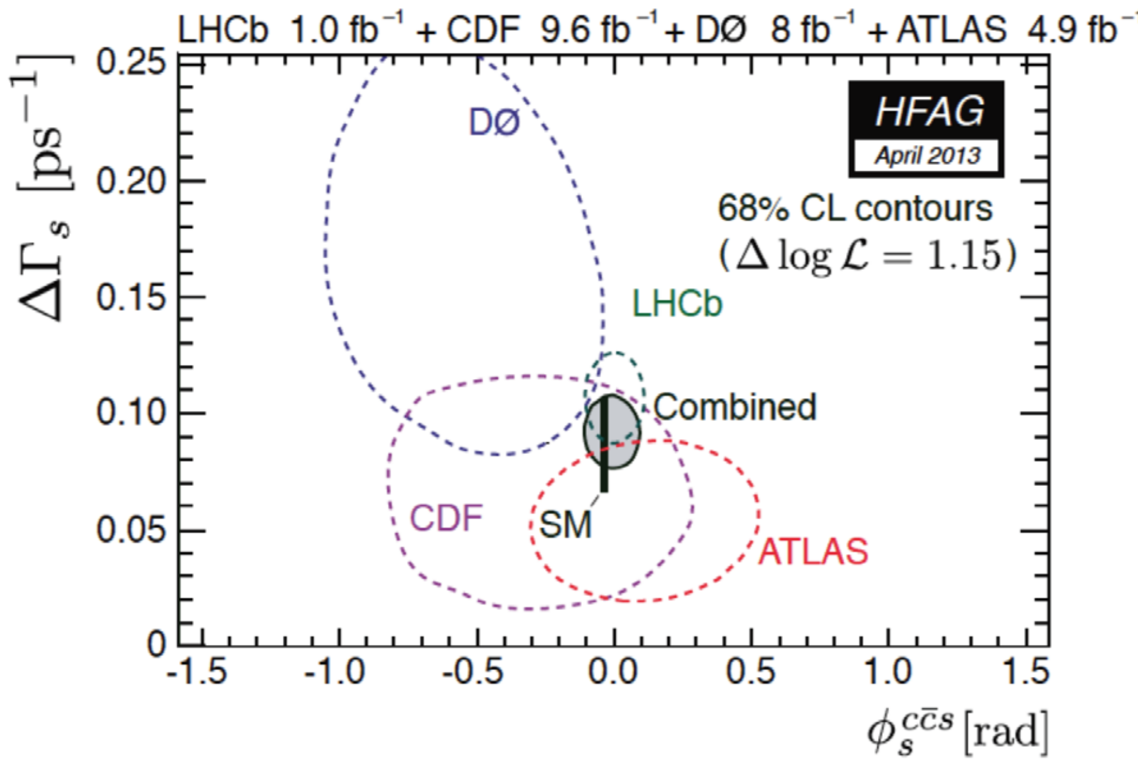
ϕ_s results from $J/\psi\phi$

LHCb values

$\Gamma = 0.6580 \pm 0.0054$
± 0.0066 (ps^{-1})

$\Delta\Gamma = 0.116 \pm 0.018$
± 0.006 (ps^{-1})

$\phi_s = 0.001 \pm 0.101$
± 0.027 (rad)



- Combining LHCb results:

$$\begin{aligned} \phi_s &= 0.01 \pm 0.07 \pm 0.01 \text{ rad} \\ \Gamma_s &= 0.661 \pm 0.004 \pm 0.006 \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.106 \pm 0.011 \pm 0.007 \text{ ps}^{-1} \end{aligned}$$