Physics Lessons from Heavy Flavour Physics

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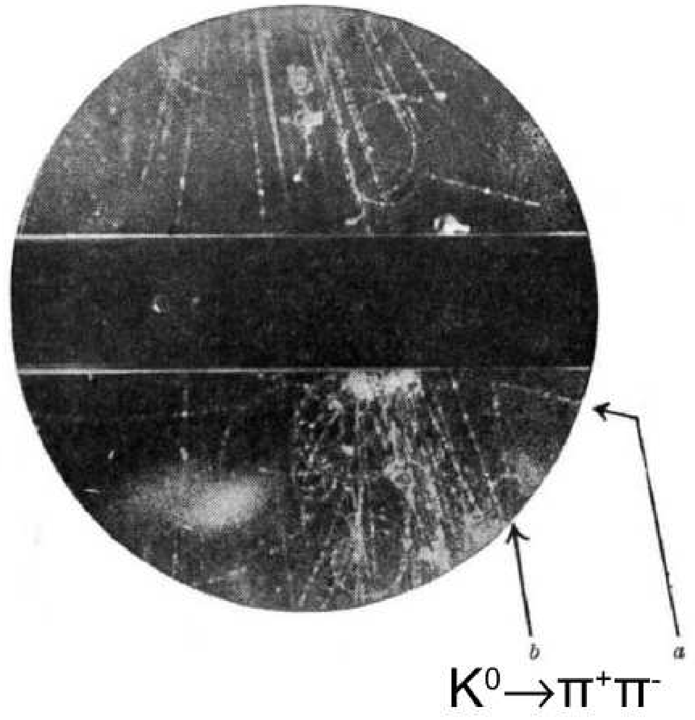
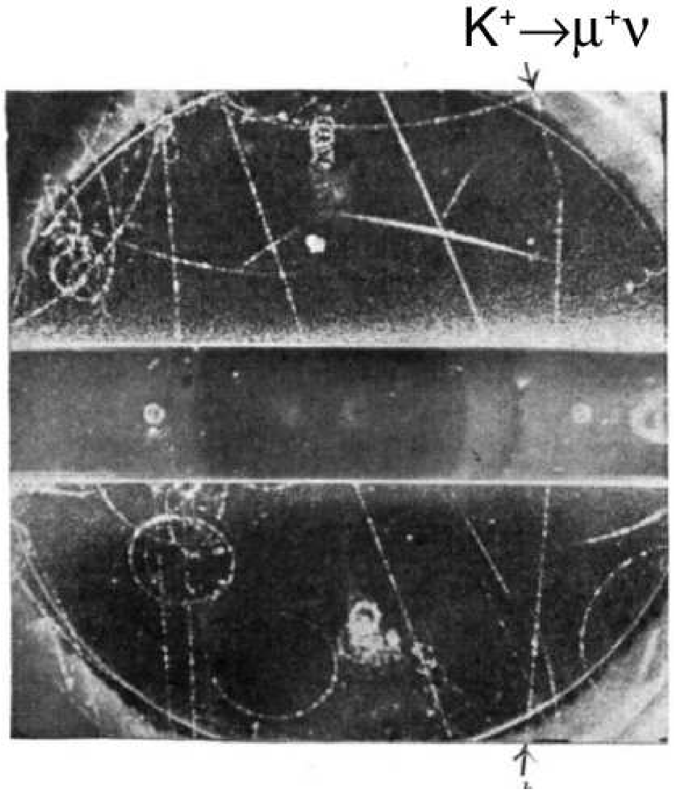
Birthday of Heavy Flavour

- 1947, G. D. Rochester and C. C. Butler, discovered kaons in cloud chamber studying cosmic rays



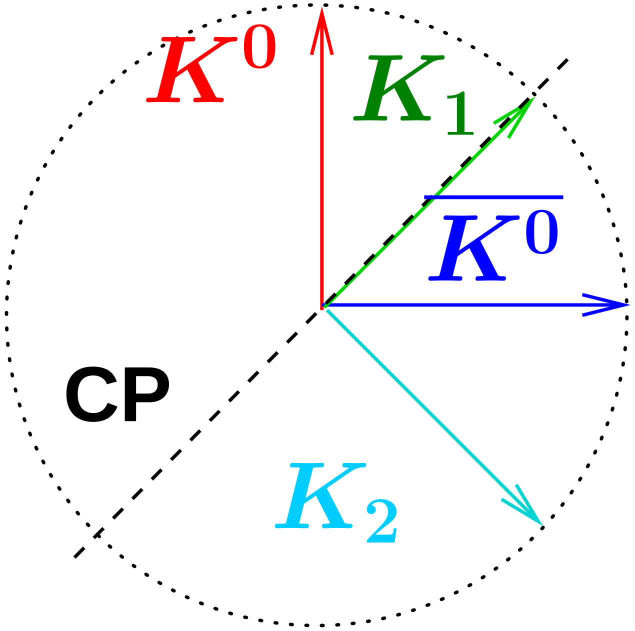


- 1953: new quantum number "strangeness" (Gellmann & Pais): conserved in strong IA, not conserved in weak IA

Idea of Neutral Meson Mixing

$$CP(K^0) = \overline{K^0}$$
$$CP(\overline{K^0}) = K^0$$

$$|K^0> = |d\bar{s}>$$



$$K_1 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0})$$
$$CP(K_1) = +K_1$$
$$K_1 \rightarrow \pi\pi$$

$$K_2 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0})$$
$$CP(K_2) = -K_2$$
$$K_2 \rightarrow \pi\pi\pi$$

K^0, $\overline{K^0}$ are flavour eigenstates

K_1, K_2 are CP eigenstates

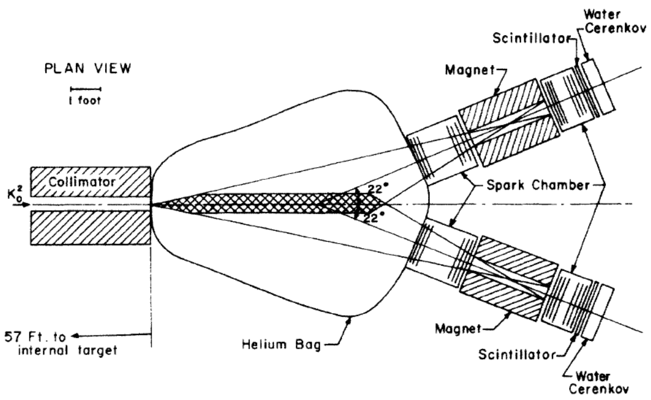
K_S, K_L are mass eigenstates

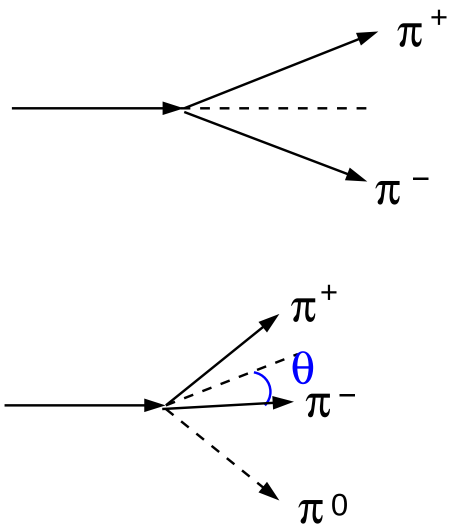
(with clear defined mass and lifetime, $\psi_{S/L}(t) = e^{-im_{S/L}t}e^{-\Gamma_{S/L}t/2}$)

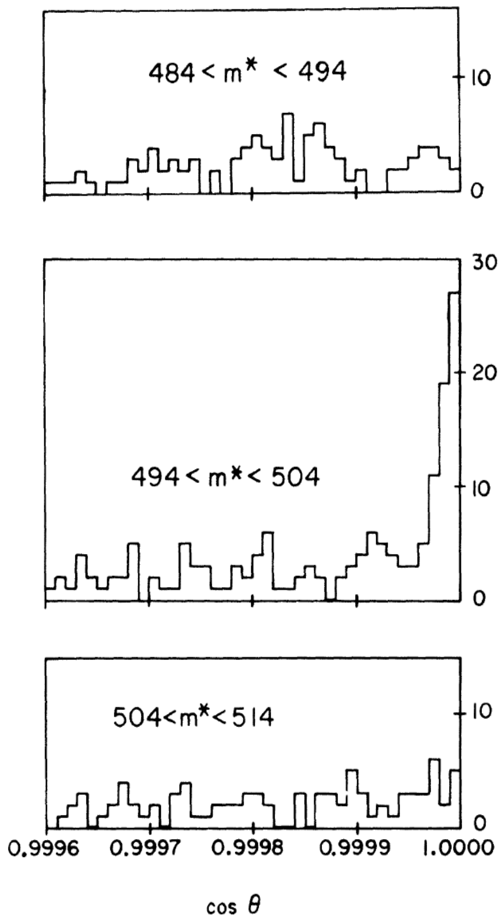
in absence of CPV: $K_S = K_1, K_L = K_2$

1964: Discovery of CPV

- produce K^0, wait long enough for K_S component to decay away $\longrightarrow$ pure K_L beam
- search for CP violation: $K_L \rightarrow \pi^+\pi^-$
  $\longrightarrow$ excess of 56 events: BR($K_L \rightarrow \pi^+\pi^-$) $\sim 2 \times 10^{-3}$







mass eigenstates are not CP eigenstates: $|K_L>= \frac{1}{\sqrt{1+|\epsilon^2|}}(|K_2> +\epsilon|K_1>)$

CP=-1 CP=+1

Nobel prize for Cronin and Fitch in 1980

After 40 years ...

$$|K_L> = \frac{1}{\sqrt{1+|\epsilon^2|}}(|K_2> + \epsilon|K_1>)$$

$\downarrow$ ε'

ππ

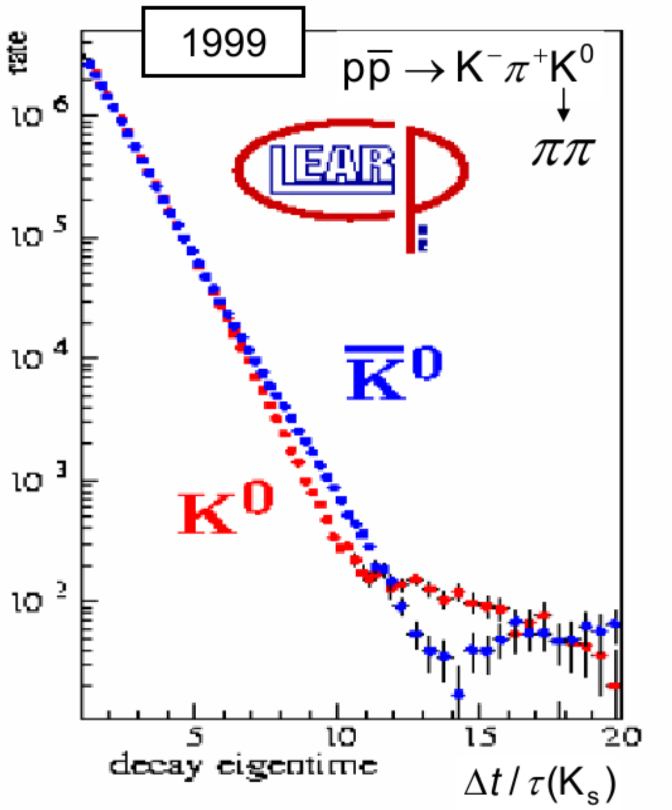
K_L mainly CP odd, a bit (ϵ) CP even ("CP in mixing")

CP odd state can decay in $\pi\pi$ with a tiny probability of ϵ'

$\longrightarrow$ CPV in decay

$$|\epsilon| = (2.284 \pm 0.014) \times 10^{-3}$$
$$Re(\epsilon'/\epsilon) = (1.67 \pm 0.26) \times 10^{-3}$$

Many precision measurement by NA48 (CERN), FNAL (kTeV) and CPLEAR (CERN).

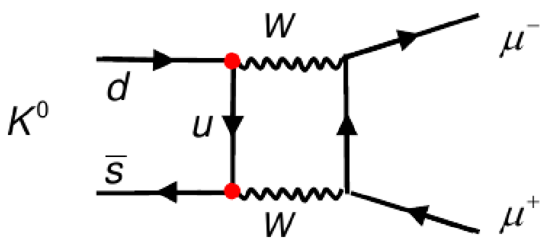


CPV in K system extremely difficult to interpret. Much easier to understand and predict/compute in the B system. CPV searches in D system just started.

1970: GIM Mechanism

Observed branching ratio $K_L \rightarrow \mu^+\mu^-$

$$\frac{BR(K_L \rightarrow \mu^+\mu^-)}{BR(K_L \rightarrow all)} = (7.2 \pm 0.5) \times 10^{-9}$$

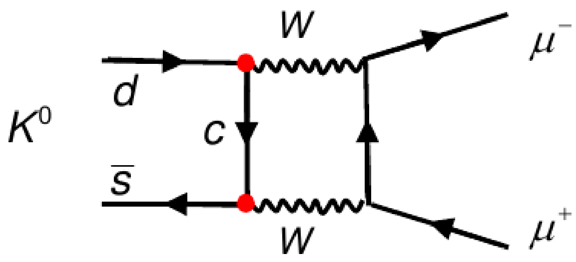


$M \sim \sin\theta_c \cos\theta_c$

In contradiction with theoretical

expectations in the 3 quark model

$(d' = d\cos\theta_c + s\sin\theta_c)$



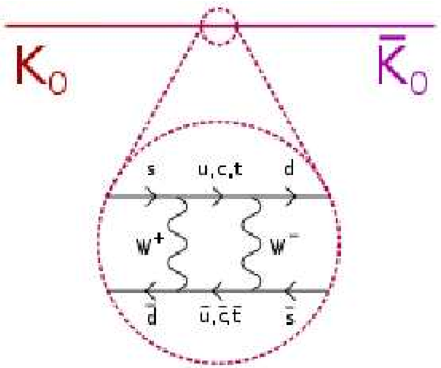
$M \sim -\sin\theta_c \cos\theta_c$

➡ Glashow, Iliopolus, Maiani (1970):

Prediction of a 2nd up type quark,

additional Feynman graph cancels

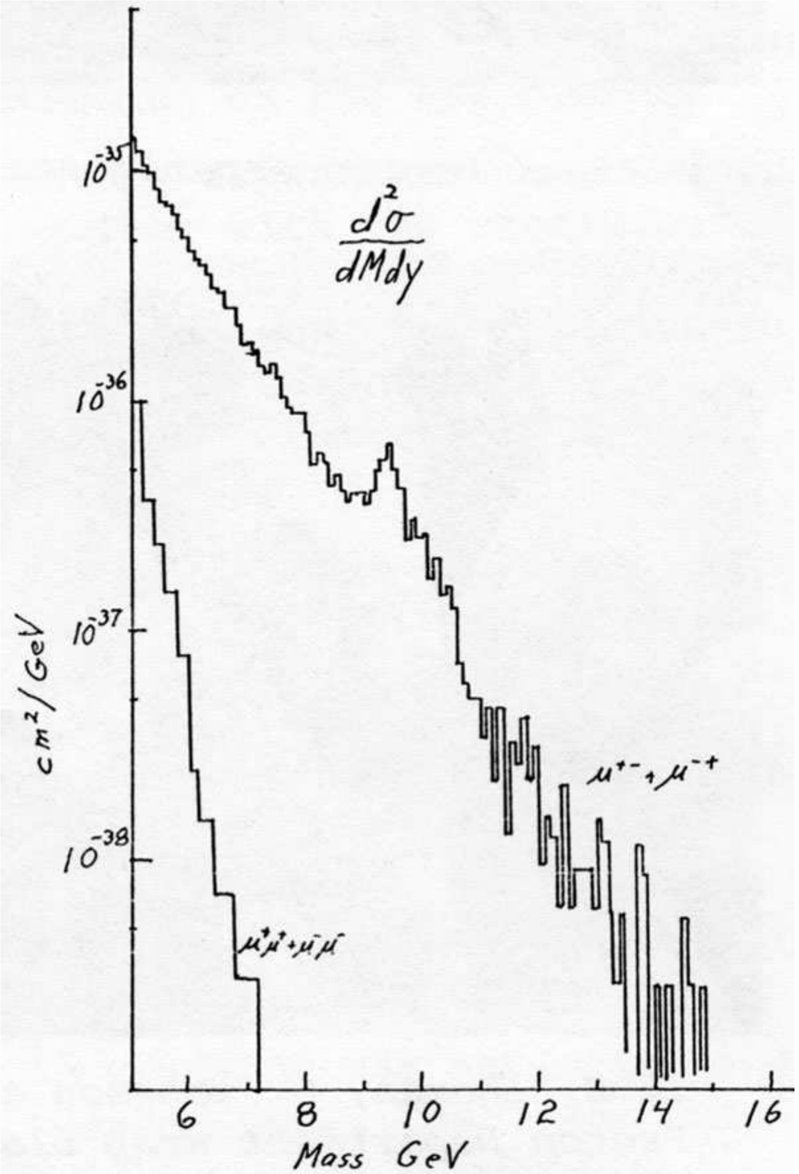
the “u box graph”



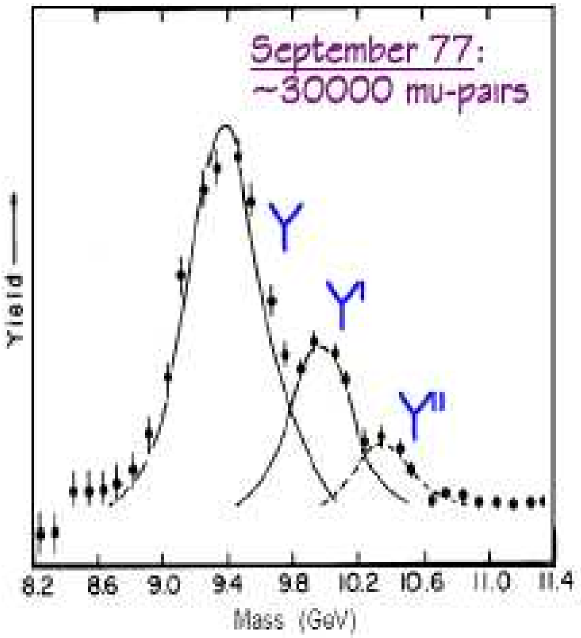
$\Delta m_K \rightarrow$ Prediction of m(c) $\approx$ 1.5 GeV

(J/Ψ Discovery in 1974)

1977: Bottom Quark



Leo Lederman



First surprises with B Lifetime

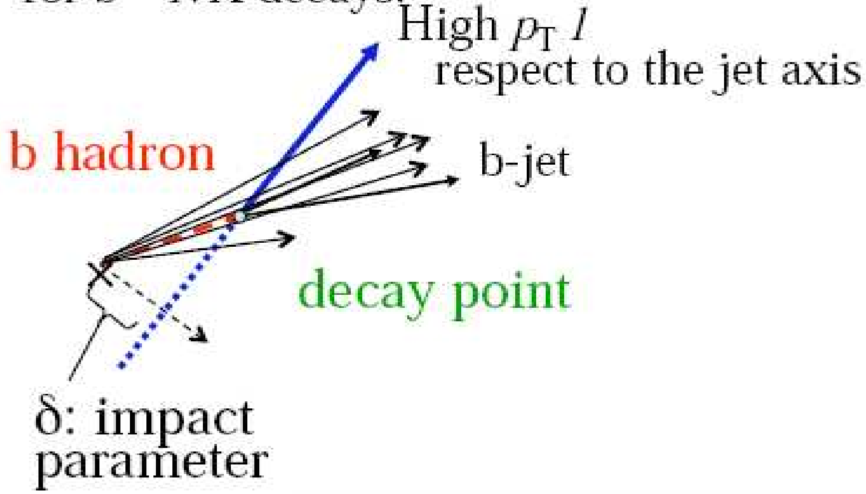
MAC

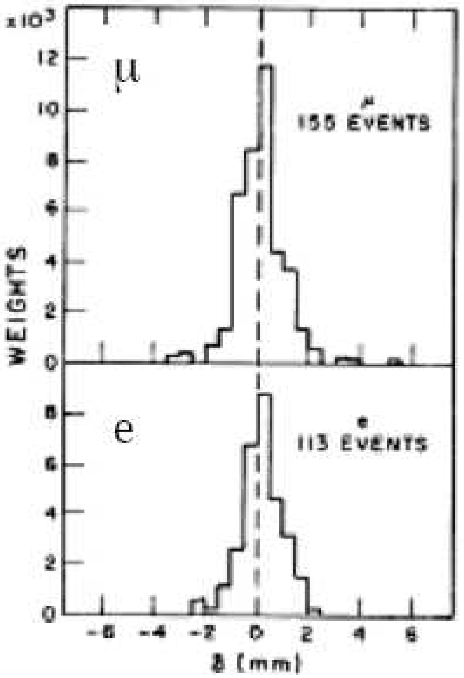
Phys. Rev. Lett. 51, (1983) 1022

Lifetime of Particles Containing *b* Quarks

From a sample of hadronic events produced in e^+e^- collisions, semileptonic decays of heavy particles have been isolated and used to obtain a measurement for the bottom-quark lifetime of $[1.8\pm0.6(\text{stat.})\pm0.4(\text{syst.})]\times10^{-12}$ *sec.*

Impact parameter distributions for $b\rightarrow l\nu X$ decays.

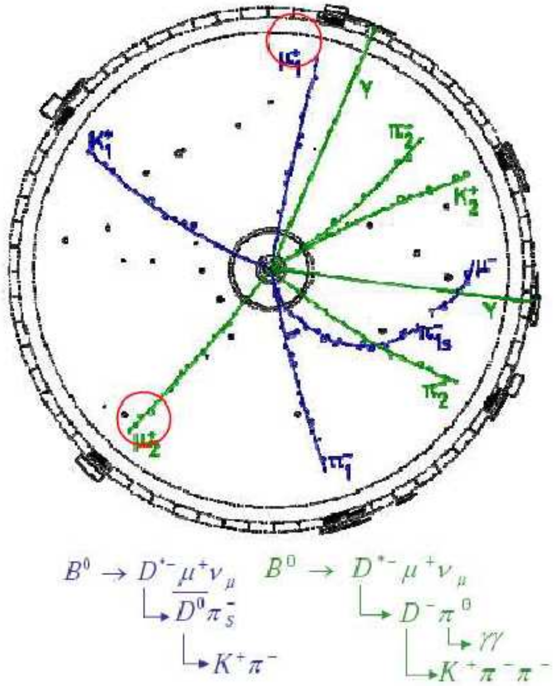


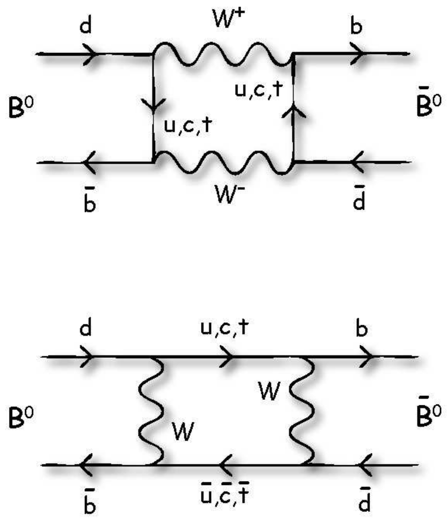


Relative long lifetime, opens up interesting possibilities for B mesons, e.g. oscillations, CP violation

1986: B^0 Oscillation at ARGUS

$$e^+e^- \to \Upsilon(4S) \to B^0\overline{B^0}$$





Time integrated mixing rate: χ_d = 0.17 $\pm$ 0.05

25 mixed events:

$$B^0\overline{B^0} \to \ell^-\ell^-$$

$$B^0\overline{B^0} \to \ell^+\ell^+$$

250 unmixed events:

$$B^0\overline{B^0} \to \ell^+\ell^-$$

First indication for a heavy top quark $m_t > 40$ GeV!

Precision Meteorology of CKM Matrix

....

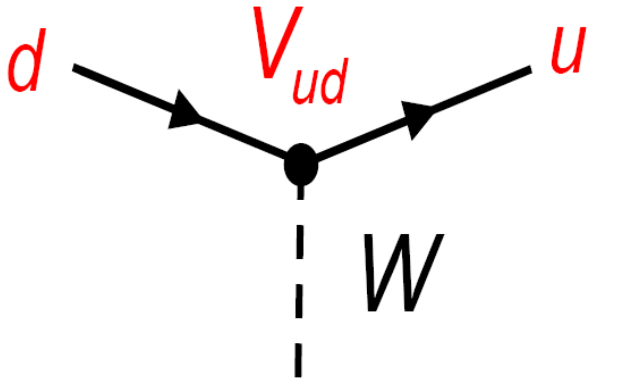
CKM Matrix

CKM matrix is consequence of introduction of Yukawa term to Lagrangian:

Charged currents: $J_\mu^+ \propto \left(\bar{u}, \bar{c}, \bar{t}\right)\left(1-\gamma_5\right)\gamma_\mu V_{CKM}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$

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

flavour CKM matrix mass



18 parameters (9 complex elements)

-5 relative quark phases (unobservable)

-9 unitarity conditions

——————————-

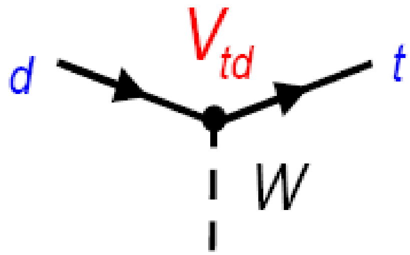
= 4 independent parameters 3 Euler angles and 1 Phase

CKM phase: only source of CPV in SM, third quark family required!

CKM under CP Transformation

Quarks

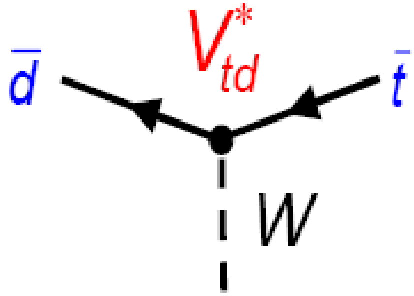
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



----- CP -----

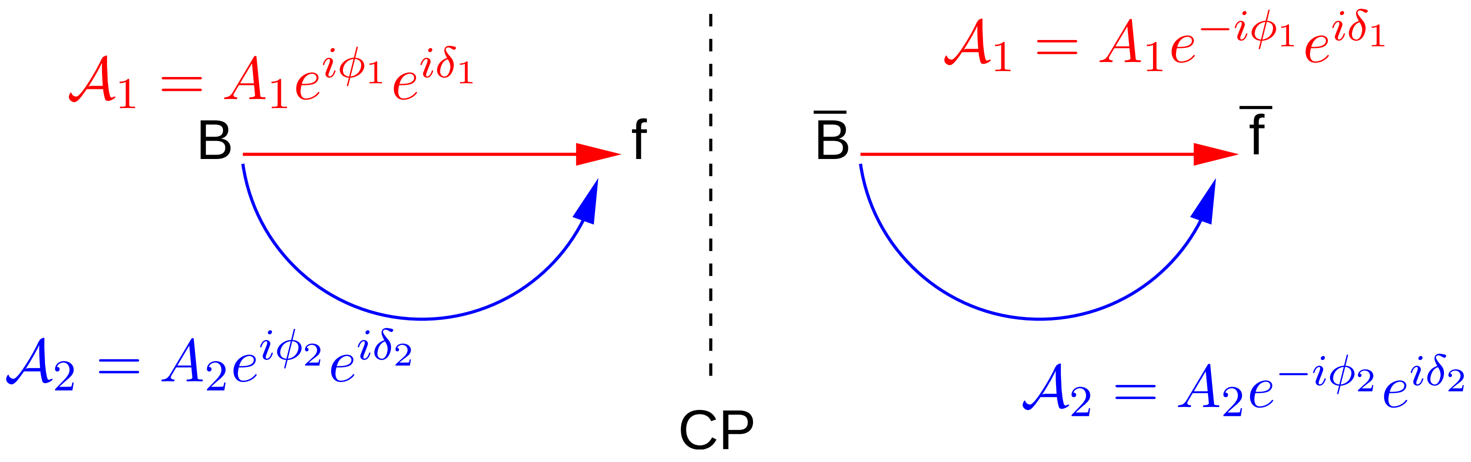
Anti-quarks:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$



Weak (CKM) phases change sign under CP transformation!

CP Violation



$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi + \Delta\delta)$$

$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(-\Delta\phi + \Delta\delta)$$

$\mathcal{A}_1$ and $\mathcal{A}_2$ need to have different weak phases ϕ and different strong phases δ.

(strong phase doesn't change sign under CP, e.g. from hadronization or phase π from mixing probability)

For sizeable (measurable) effects both amplitudes should have about same size,

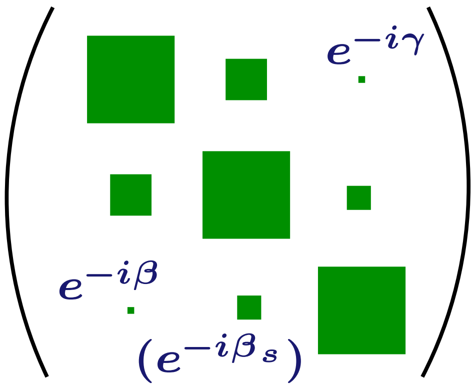
and both phase differences have to be sizeable.

To conclude on weak phases, strong phases need to be known/measured.

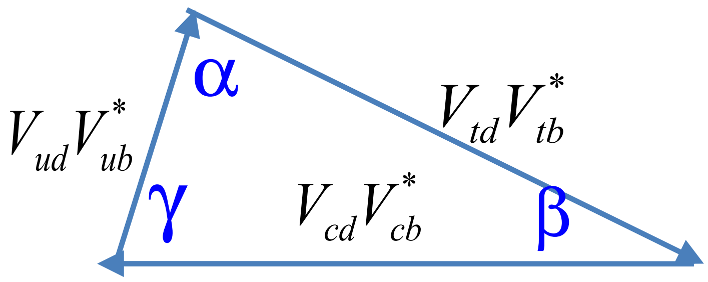
B-System and CKM Angles

size of box, illustrates absolute value

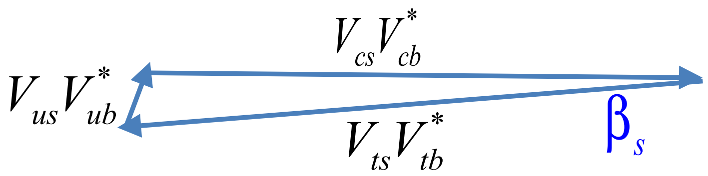
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim$$



B_d triangle:



B_s triangle:



+ B system: access to 4 out of 9 CKM matrix elements

+ b is heaviest quark which hadronizes ... huge phase space

+ largest complex contributions in CKM matrix involved in b decays

(D and K decays, mainly involve upper 2x2 matrix ($V_{tb} \sim 1$) ... no CPV)

CP Violation Primer

Mass eigenstates:

$$B_L = p|B^0> +q|\overline{B^0}> \text{ w. } m_L, \Gamma_L$$
$$B_H = p|B^0> -q|\overline{B^0}> \text{ w. } m_H, \Gamma_H$$

$|p^2| + |q^2| = 1,$ complex coefficients

Flavour eigenstates:

$$B^0 = \frac{1}{2p}(|B_L> +|B_H>)$$
$$\overline{B^0} = \frac{1}{2q}(|B_L> -|B_H>)$$

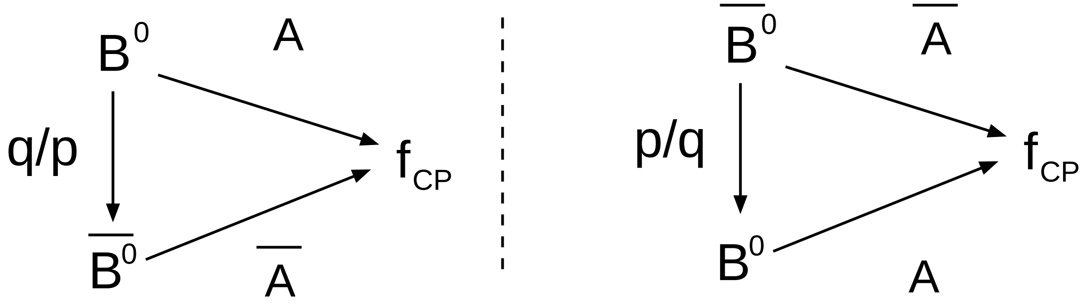
- CP Violation in mixing

  If $|\frac{q}{p}| \neq 1$; mass eigenstates are no CP eigenstates;

  $\rightarrow P(B^0 \rightarrow \overline{B^0}) \neq P(\overline{B^0} \rightarrow B^0)$

- CP violation in decay $|A(B \rightarrow f)| \neq |\overline{A}(\overline{B} \rightarrow \overline{f})|$

- CP violation in interference of mixing and decay: $Im(\frac{q}{p}\frac{\overline{A}}{A}) \neq 0$

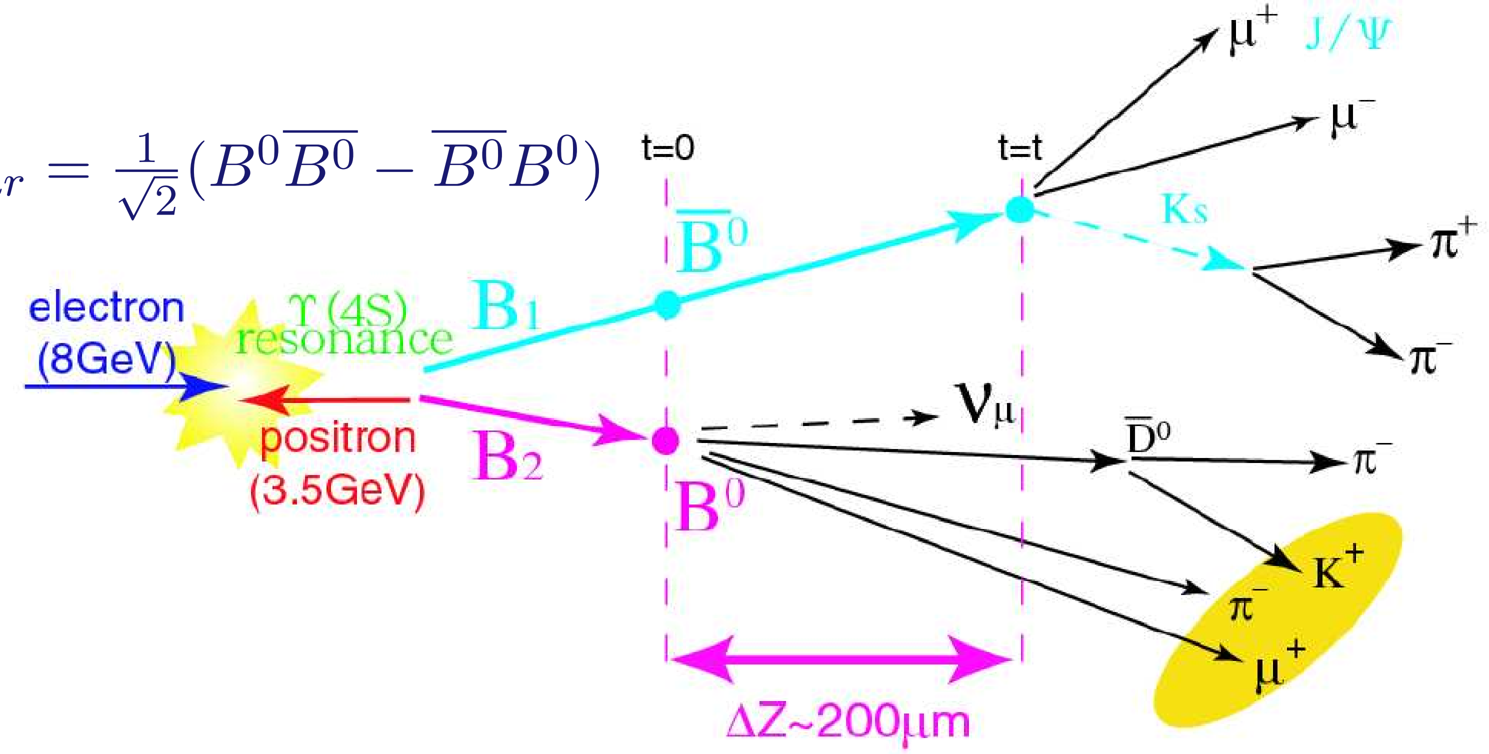


Idea of Asymmetric B Factory

To measure $t = L/p$ require B mesons to be moving
$\longrightarrow e^+e^-$ at threshold with asymmetric collisions (Oddone)

Other possibilities considered
$\longrightarrow$ fixed target production?
$\longrightarrow e^+e^-$ at high energy?
$\longrightarrow$ hadron collider?

$$\Psi_{flavour} = \frac{1}{\sqrt{2}}(B^0\overline{B^0} - \overline{B^0}B^0)$$

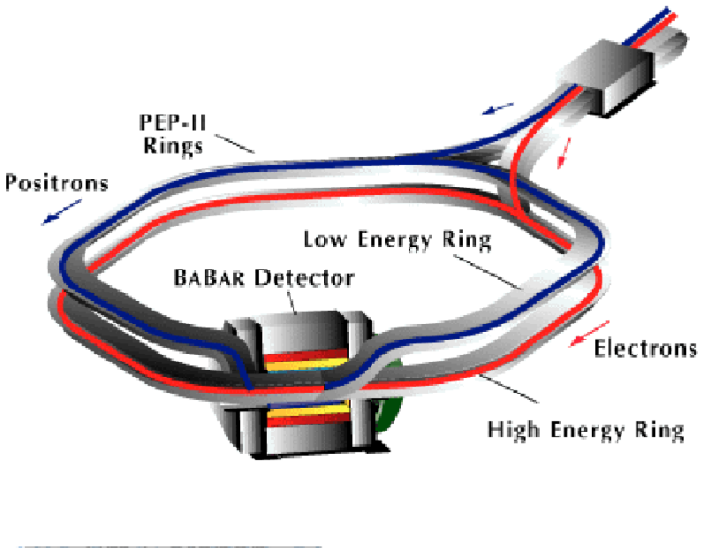


B Factories

2000-2008

PEPII at SLAC

9.0 GeV e⁻ on 3.1 GeV e⁺



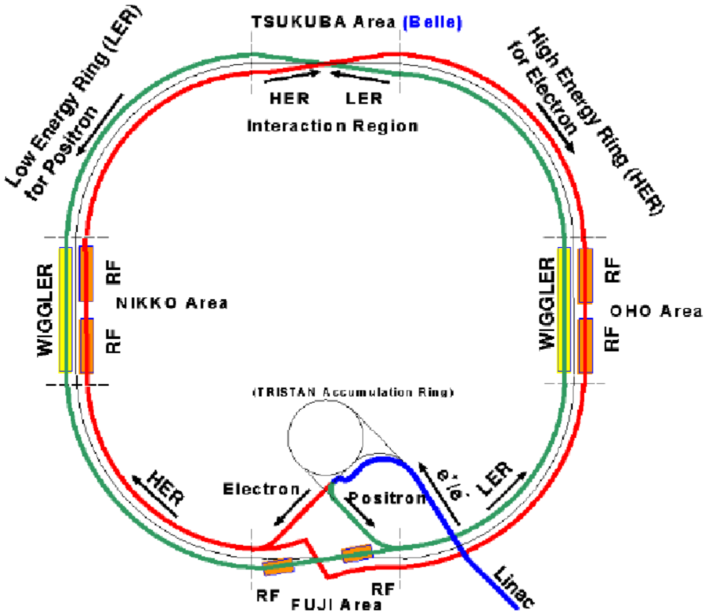
Babar

430 fb^{-1} Y(4S)

2000-2010

KEKB at KEK

8.0 GeV e⁻ on 3.5 GeV e⁺

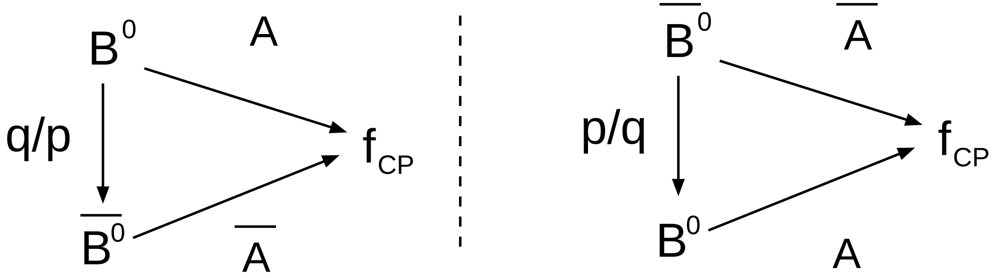


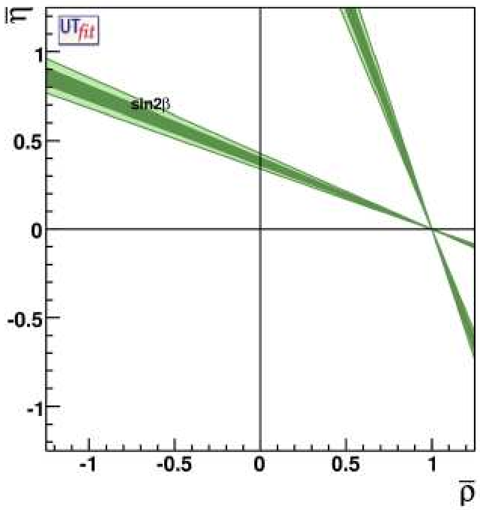
Belle

710 fb^{-1} Y(4S)

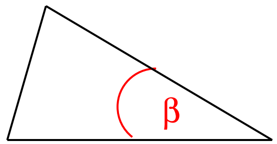
together 10^9 $B\overline{B}$ pairs detected

Measurement of $\sin(2\beta)$: golden channel $B_d \to J/\psi K_s$





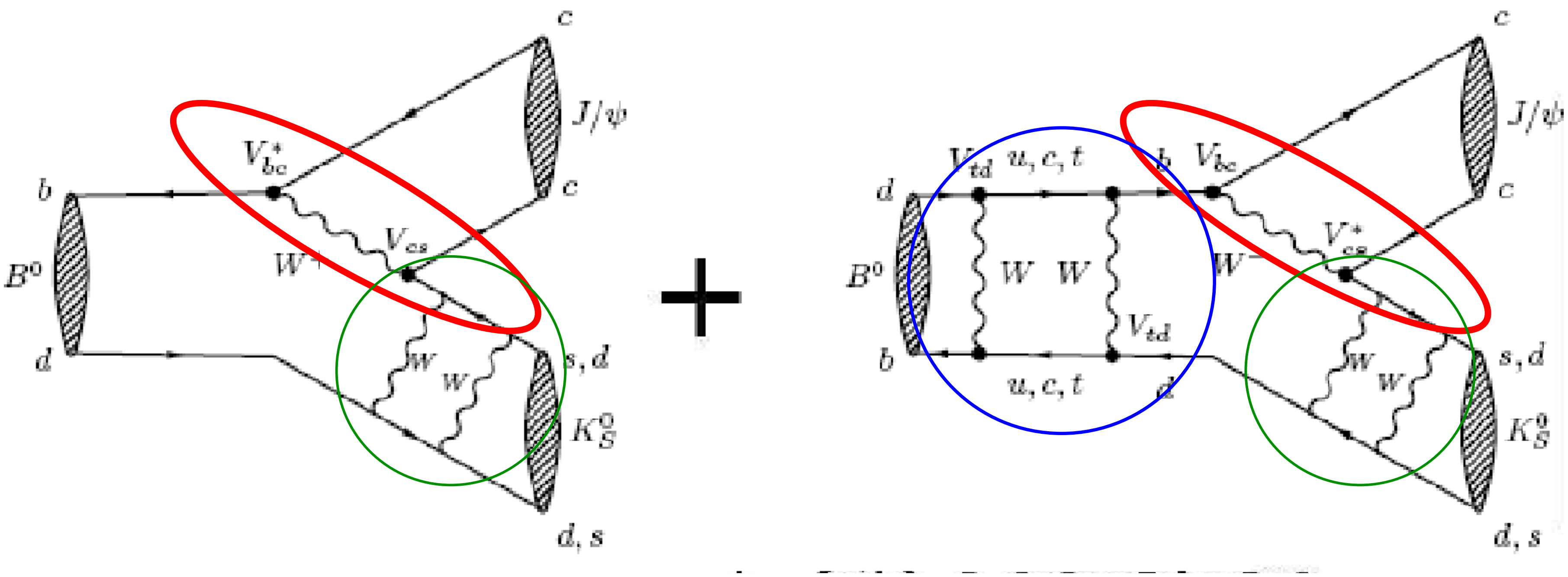
$$V_{td} = |V_{td}| e^{-i\beta}$$



Weak phase: $Im(\frac{q}{p}\frac{\overline{A}}{A})$

$B_d \rightarrow J/\Psi K^0$

Reach same final state through decay & mixing + decay



$$\mathcal{A}_1 = \mathcal{A}_{mix}(B^0 \rightarrow B^0) * \mathcal{A}_{decay}(B^0 \rightarrow J/\Psi K^0) = \cos(\frac{\Delta mt}{2}) * A * e^{i\omega} * A_K * e^{i\xi}$$

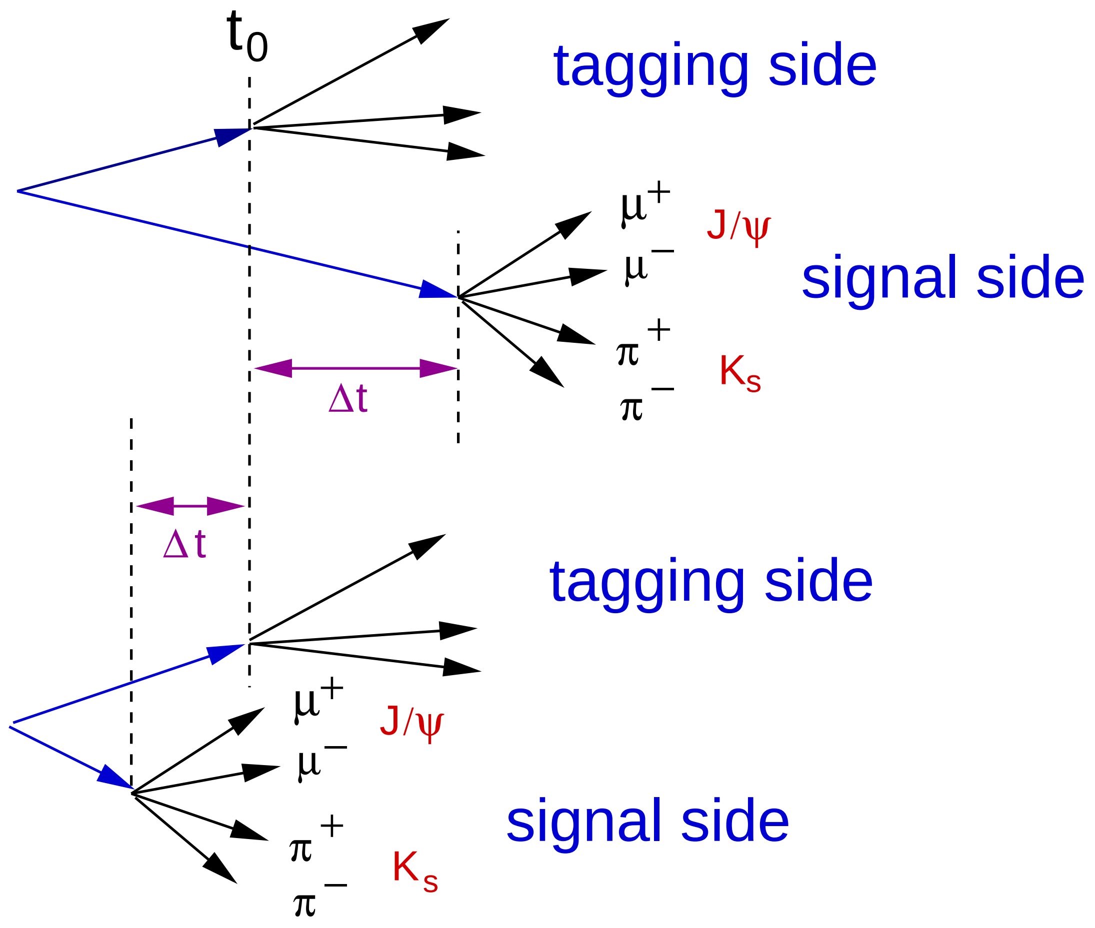
$$\mathcal{A}_2 = \mathcal{A}_{mix}(B^0 \rightarrow \overline{B^0}) * \mathcal{A}_{decay}(\overline{B^0} \rightarrow J/\Psi K^0) = i \sin(\frac{\Delta mt}{2}) * e^{+i\phi} * A * e^{-i\omega} A_K * e^{-i\xi}$$

$$\Delta\phi = \phi - 2\omega - 2\xi \sim \phi = 2arg(V_{td}) = 2\beta$$

$\Delta\delta = \pi/2 \Leftarrow$ mixing introduces second phase difference

Correlated B Production

$$A(t) = \frac{N(\overline{B}\to J/\psi K_s)(t) - N(B\to J/\psi K_s)(t)}{N(\overline{B}\to J/\psi K_s)(t) + N(B\to J/\psi K_s)(t)} = \eta_{CP}\sin(2\beta)\sin\Delta m_d t$$



$B - \overline{B}$ pair produced on Y(4S) resonance with well defined quantum numbers.

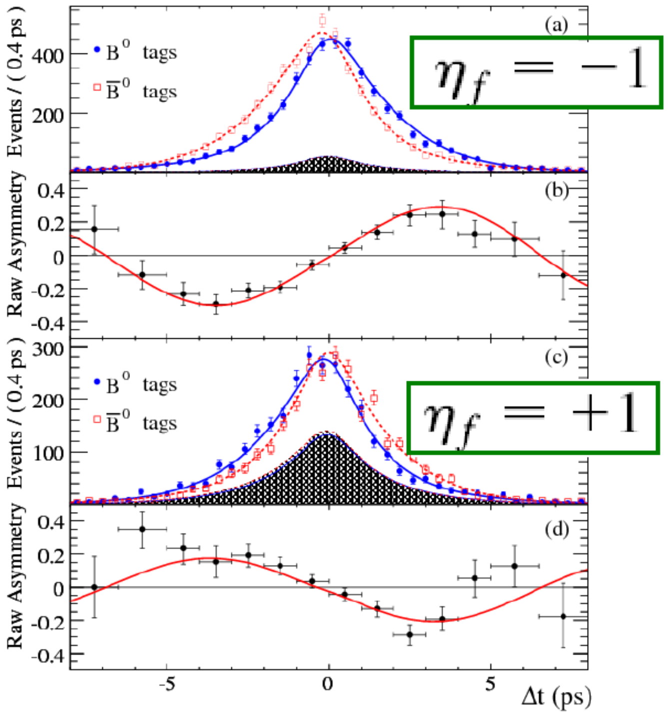
$\rightarrow$ Correlated $B - \overline{B}$ state till the time of the decay of the first B.

CPV in $B_d \to J/\psi K^0$

Golden mode $B \to J/\psi K^0$

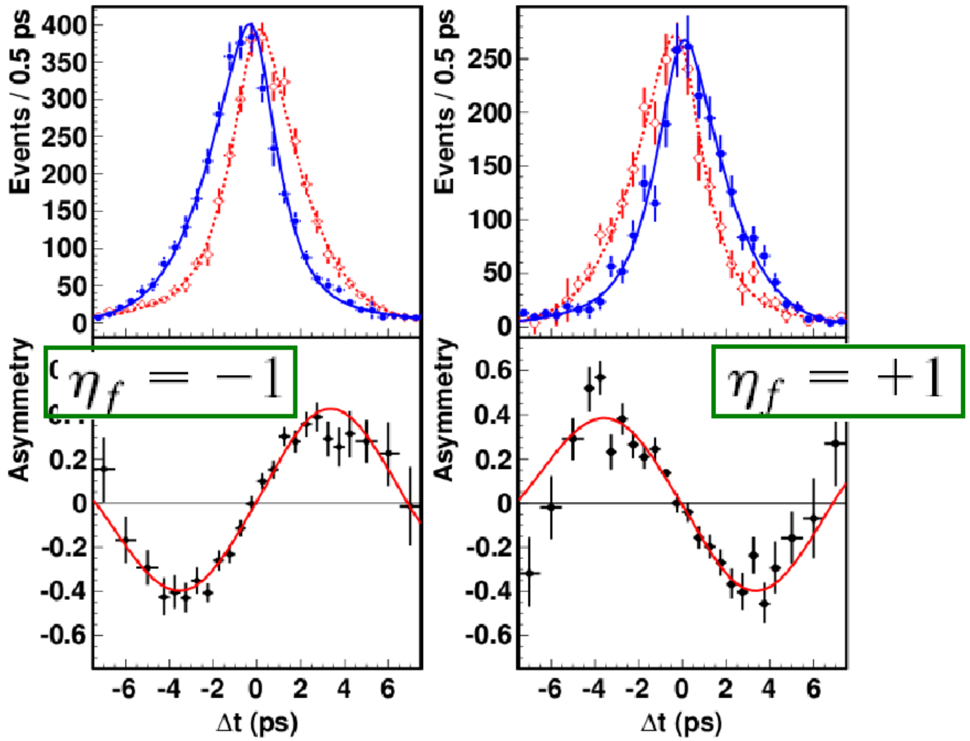
WA: $\sin 2\beta$ = 0.679 $\pm$ 0.20

BABAR

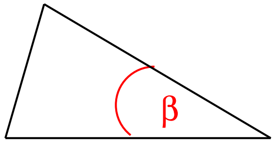


PRD 79 (2009) 072009

BELLE



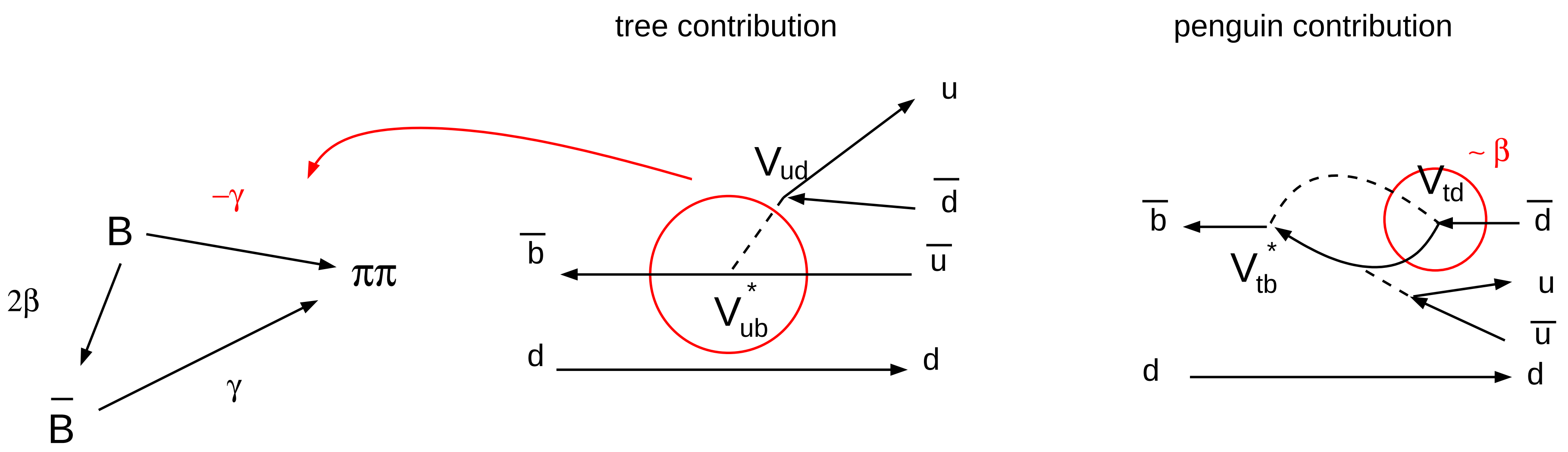
PRL 108 (2012) 171802



$\sin(2\beta) \neq 0$ was measured first in 2001.

Huge success for Babar and Belle, they were build for this purpose!

CKM angle α



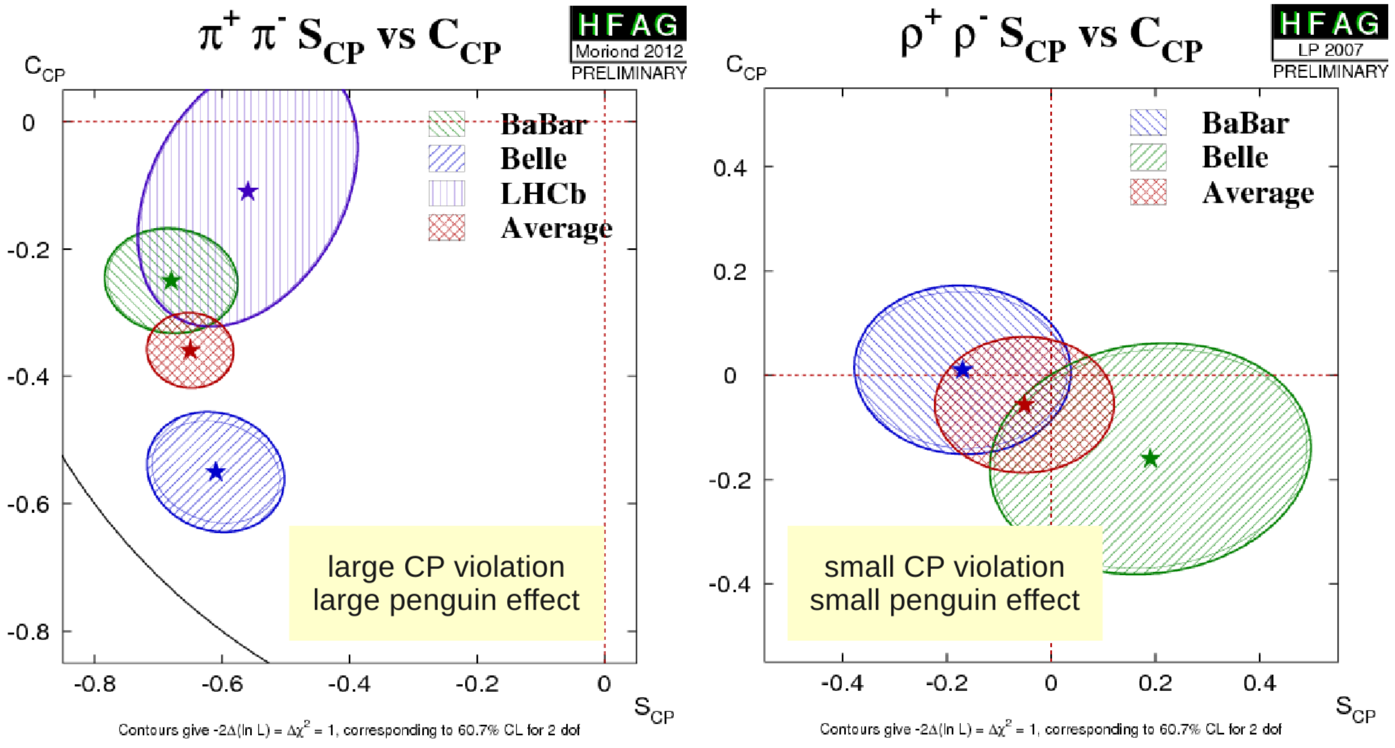
$\Delta\omega = 2\beta + 2\gamma = -2\alpha$

- Very same analysis idea, then $B_d \to J/\psi K^0$
- In absence of penguins, weak phase difference: $2\beta + 2\gamma = -2\alpha$
- However sizeable contributions from penguin decays (come in with phase β)
- Two approaches:

  1) use isospin relations w. other $B \to \pi\pi$ modes to determine T vs. P rate

  2) use alternative mode with little P contribution (e.g. $B^0 \to \rho^0\rho^0$)

$B_d \to \pi^+\pi^- / \rho\rho$



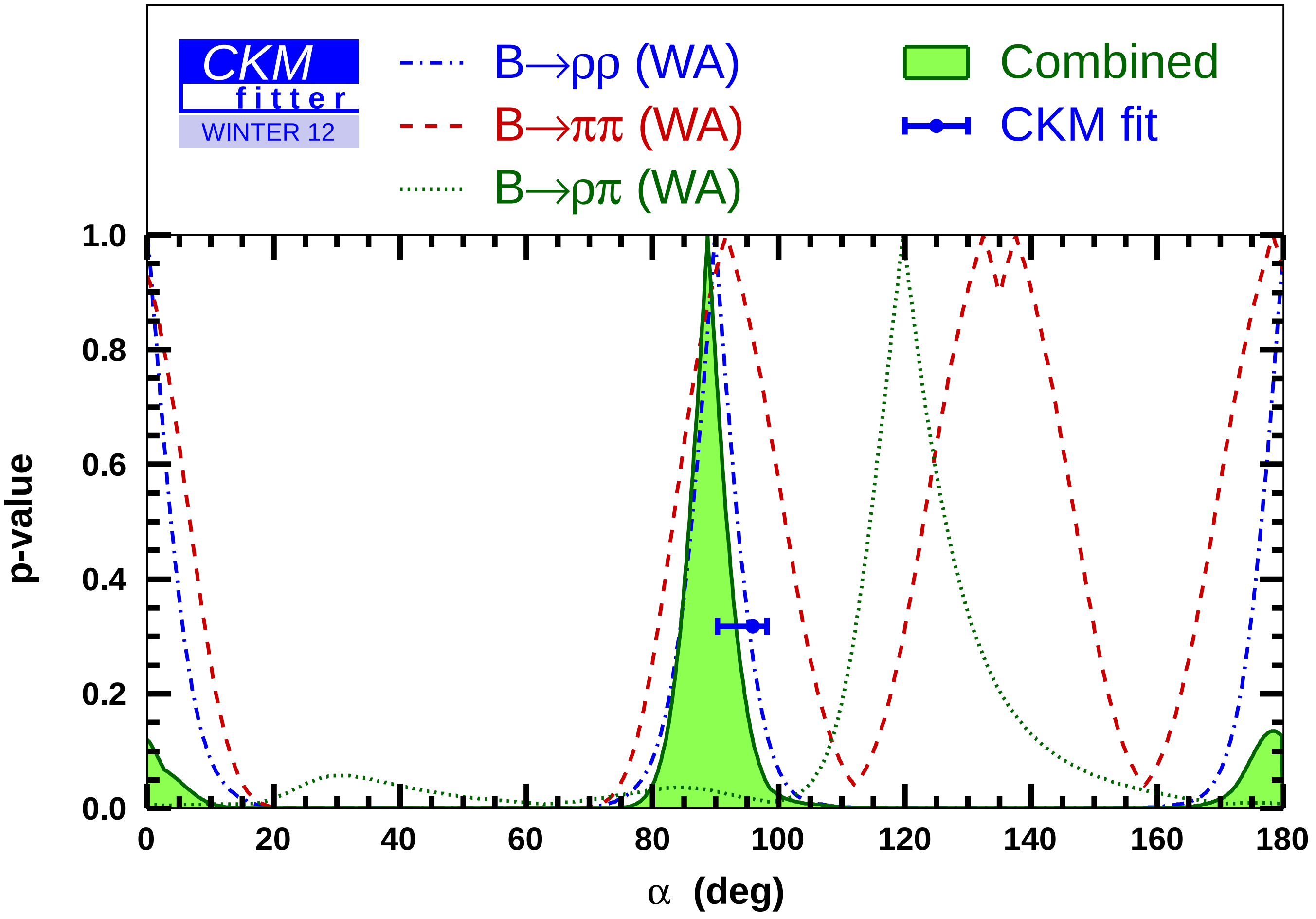
$$\Gamma(B^0 \to f_{CP}(t)) \approx e^{-\Gamma t}(1 - (S\sin(\Delta m t) - C\cos(\Delta m t)))$$

$$\Gamma(\overline{B^0} \to f_{CP}(t)) \approx e^{-\Gamma t}(1 + (S\sin(\Delta m t) - C\cos(\Delta m t)))$$

$$S = \frac{2Im(\lambda_{CP})}{1+|\lambda_{CP}^2|}, \quad C = \frac{1-|\lambda_{CP}^2|}{1+|\lambda_{CP}^2|}, \quad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

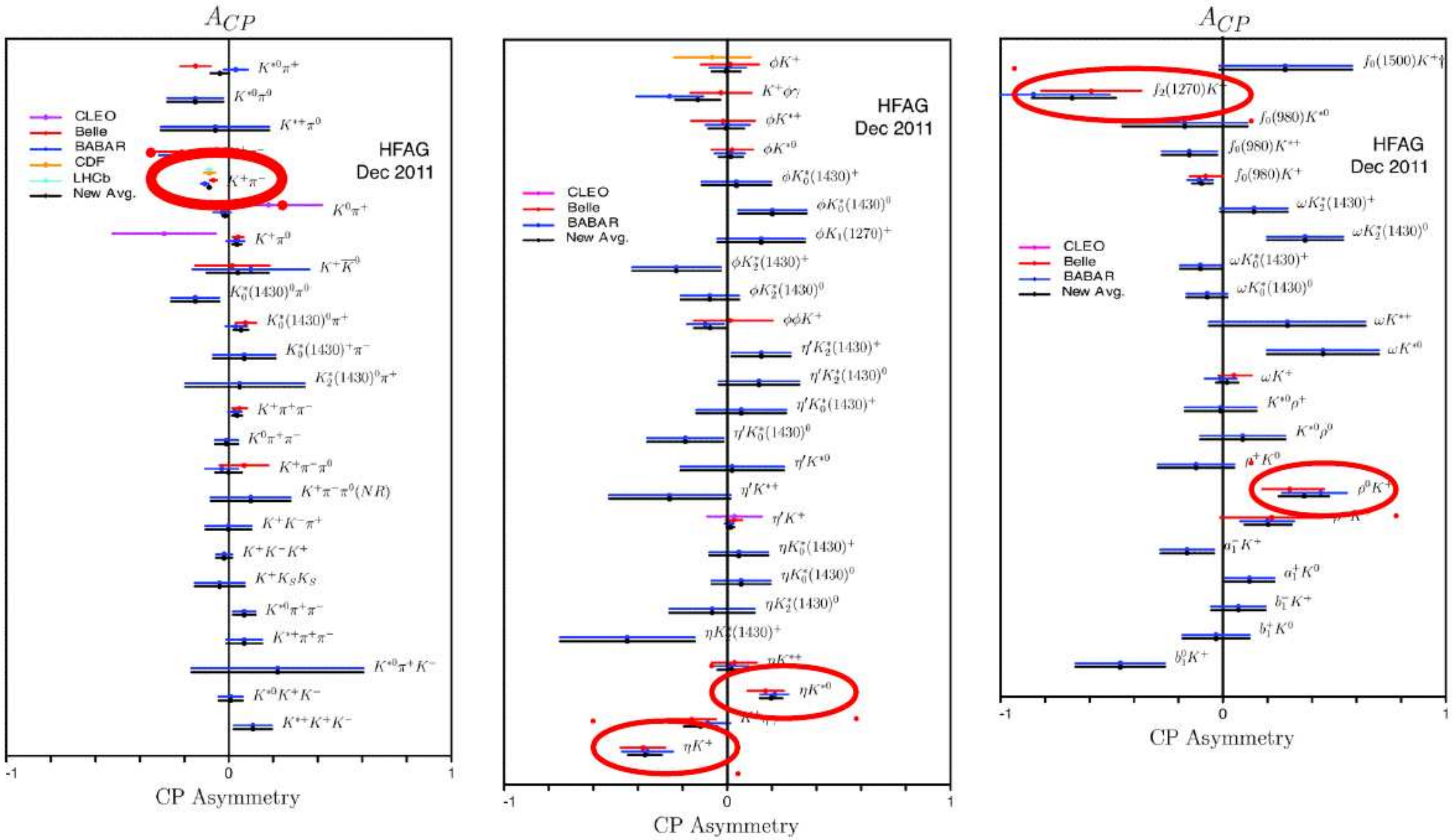
no CPV in mixing and decay: $|\lambda| = 1 \to C = 0$ (e.g. in $B_d \to J/\psi K^0$)

Constraints on α



$\alpha = 0$ and $\alpha = \pi$ excluded by branching ratio measurements

Lot’s of direct CPV ...

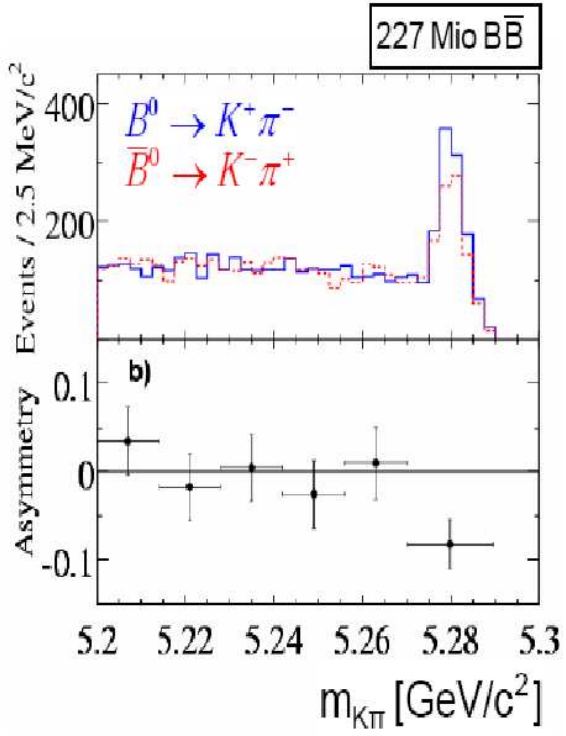


Due to strong phases, hard to relate asymmetries directly to CKM parameters.

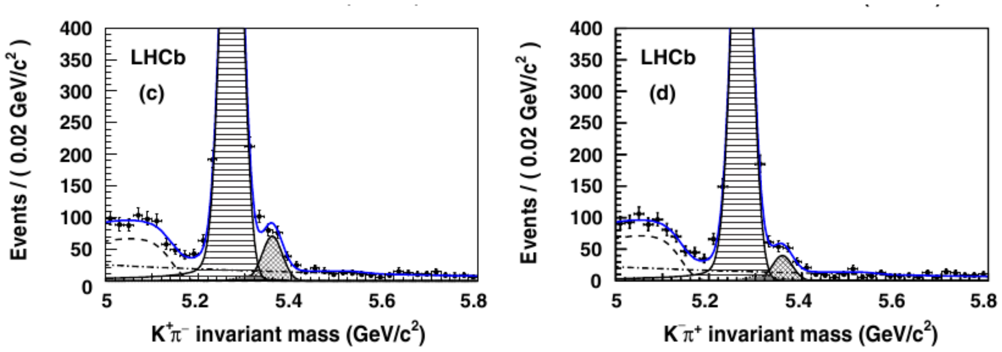
"The strong interaction can be seen either as the unsung hero or the villain in the story of quark flavour physics”; I. Bigi.

First direct CPV in ...

$B^0 \to K^+\pi^-$/$\overline{B^0} \to K^-\pi^+$



$B_s \to K\pi$



$A_{CP} = 0.27 \pm 0.08 \pm 0.02$ (LHCB);

$A_{CP} = 0.22 \pm 0.07 \pm 0.02$ (CDF);

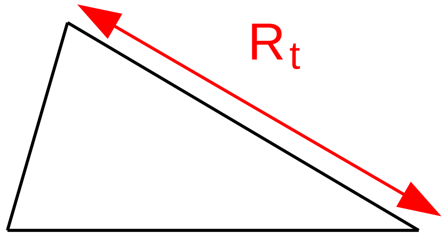
WA: $A_{CP} = -0.097 \pm 0.012$

First direct CPV in charged $B \to Dh$ observed by LHCb (5.8σ)

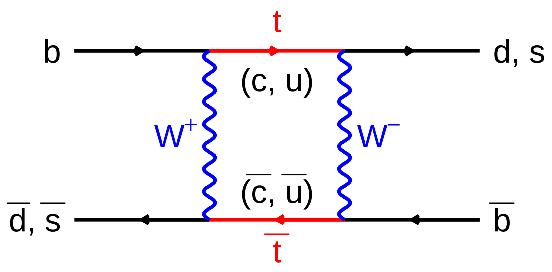
crucial input for measurment of γ

Constraint on R_t

$$R_t = |\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}|$$



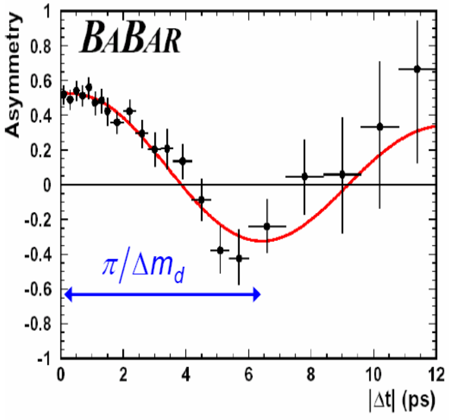
$$\Delta m_d = \frac{G_F^2 M_W^2 \eta S(m_t^2/m_W^2)}{6\pi^2} m_{B_d} f_{B_{B_d}}^2 |V_{td}^* V_{tb}|^2$$

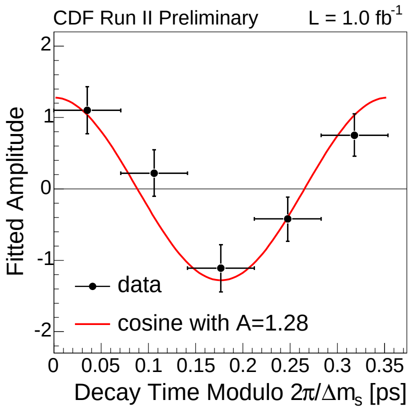


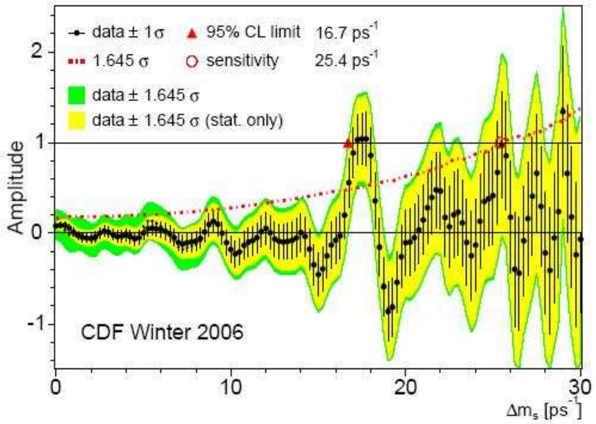
Hadronic uncertainties cancel in ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

ξ from lattice

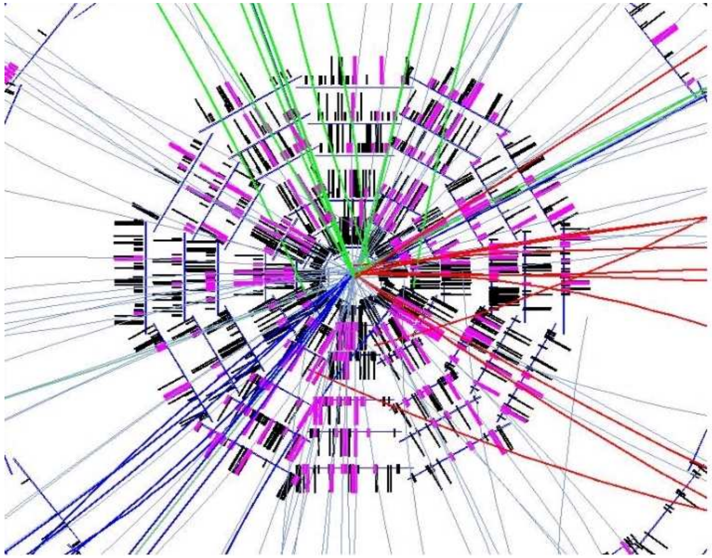


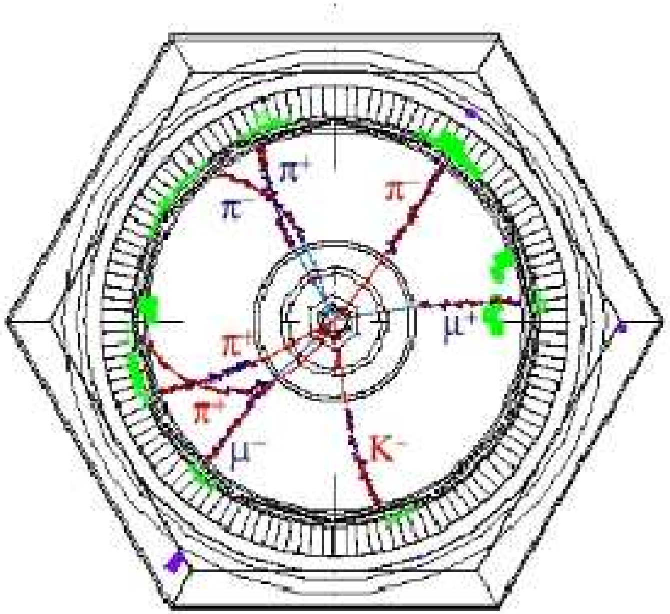


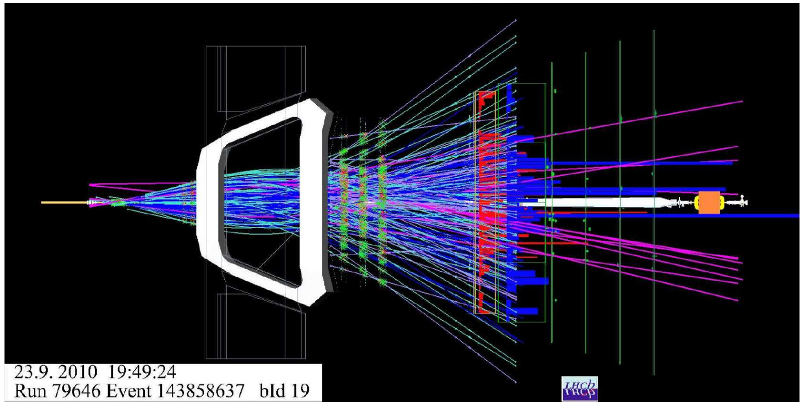


$\Delta m_d = 0.511 \pm 0.005 \pm 0.006$ ps^{-1} $\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1}

B Factories vs. Hadron Colliders

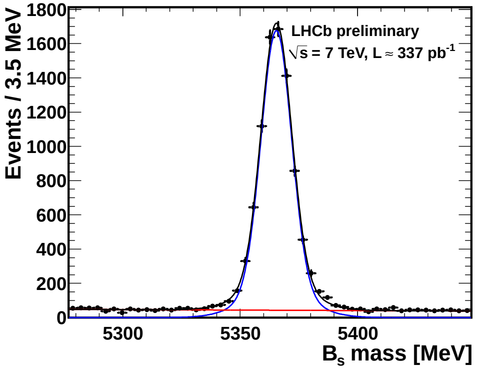






~~*Discoveries are done at hadron colliders, precision measurements at e^+e^-!*~~

Tevatron: high precision measurements are feasible at hadron colliders!



soft cut on decay length gives extremely clean signals

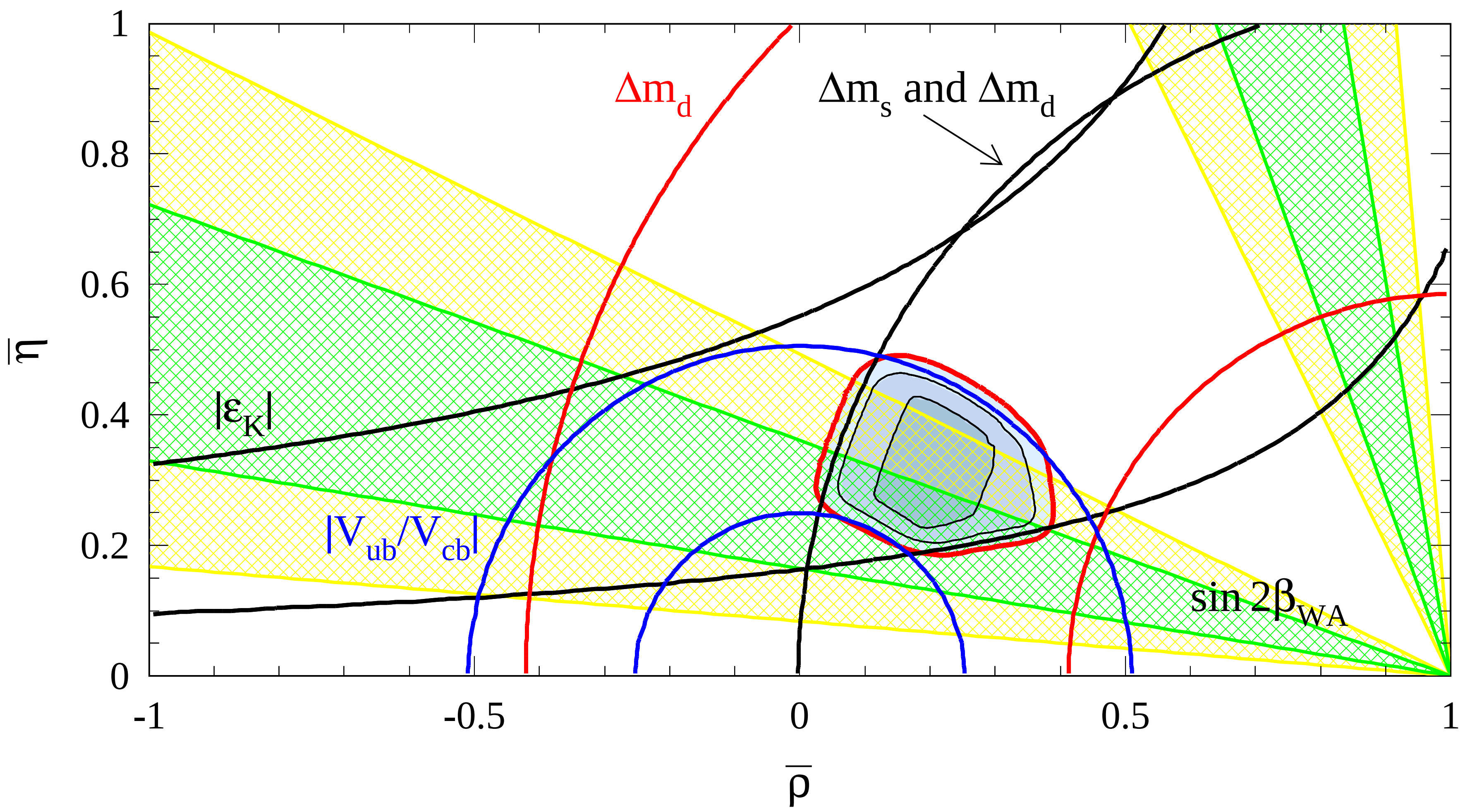
B Factories vs. Hadron Colliders

- clean events ($\sim$ 10 tracks/ev) + correlated $B\bar{B}$ production $\longrightarrow$ very good tagging: $\epsilon D^2 \sim 0.3$
- very busy events ($\sim$ 50-100 tracks/ev) $\longrightarrow$ very low tagging performance: $\epsilon D^2 \sim 0.03$ $\longrightarrow$ bad in decays with π^0, γ, ...
- particles almost produced at rest (DL $\sim$ 100 μm)
- excellent proper time resolution (boost, DL $\sim$ $\mathcal{O}(cm)$) crucial for fast B_s oscillation
- huge luminosity, but low $b\bar{b}$ cross-section $\mathcal{O}(nb)$
- huge $b\bar{b}$ cross-section $\mathcal{O}$(100μb), but huge inel. cross-section $\longrightarrow$ trigger
- at Y(4S), only access to B^0, $B^\pm$
- access to all B species

Not a priory clear, which approach works better, depend on decay channel

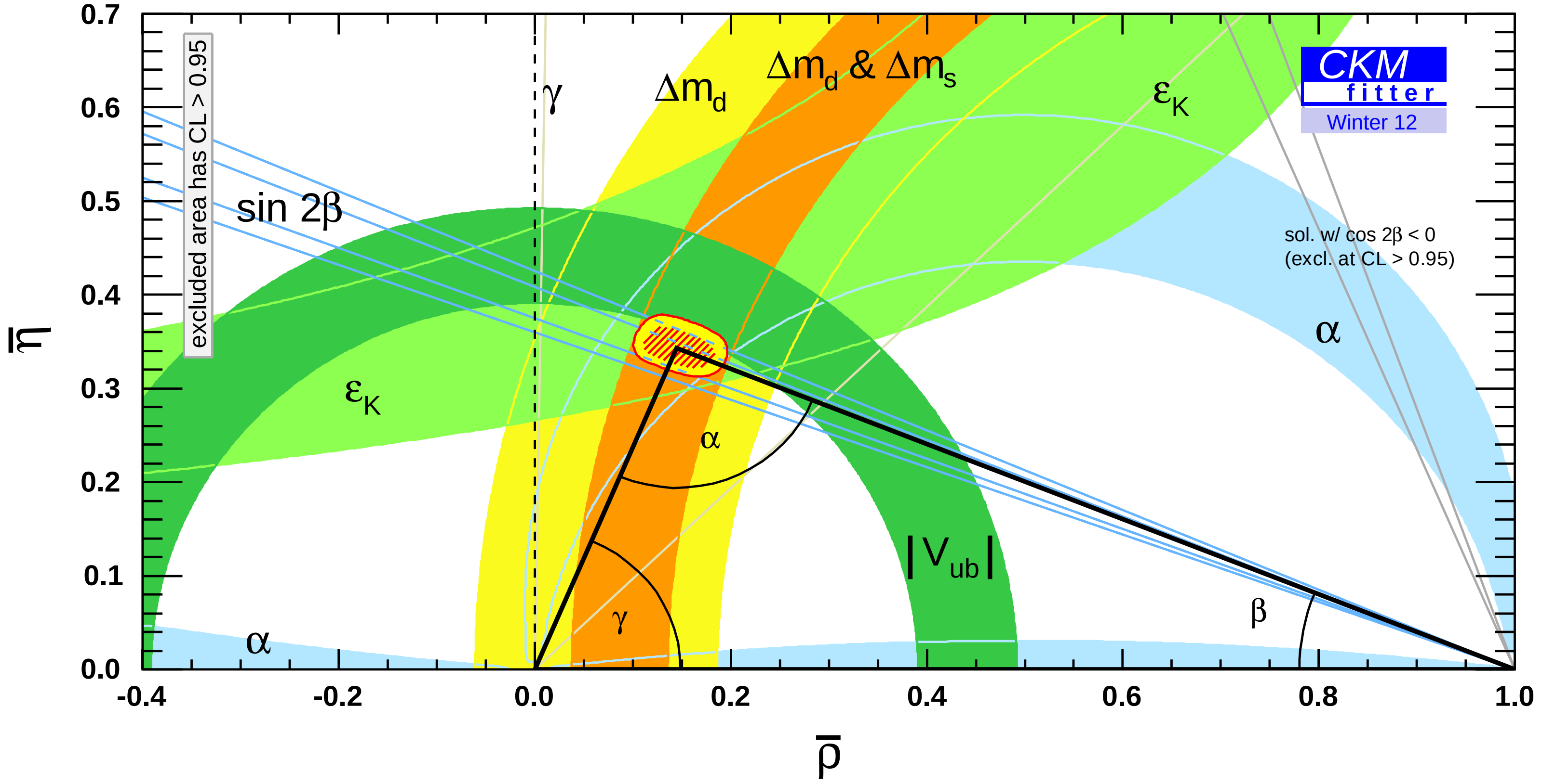
Summary of Current Understanding & Lessons Learned

Quark-Mixing 2001



CKM mechanism experimental not really constraint.

Quark-Mixing 2012



Within uncertainties, flavor changing data well described by Standard Model!

B factories tremendously improved understanding of FP in the last decade

improved exp. input followed by improved theoretical calculations

2008 - Nobel Prize in Physics

The Nobel Prize in Physics 2008

"… for the discovery of the origin of broken symmetrie, which predict the existence of at least three quark families."

Lessons learned up to now ...

- Precision measurements are sensitive to new particles well before direct measurements, very successful history:
  - Prediction of c quark from GIM-suppressed K decays
  - Prediction of c mass from kaon mixing frequency (Δm_K)
  - Prediction of existance of third quark family to explain CPV
  - Prediction of a heavy top from B^0 oscillation
- B system is a rich environment to study CP violation
- High recision measurements feasible in hadronic environment!

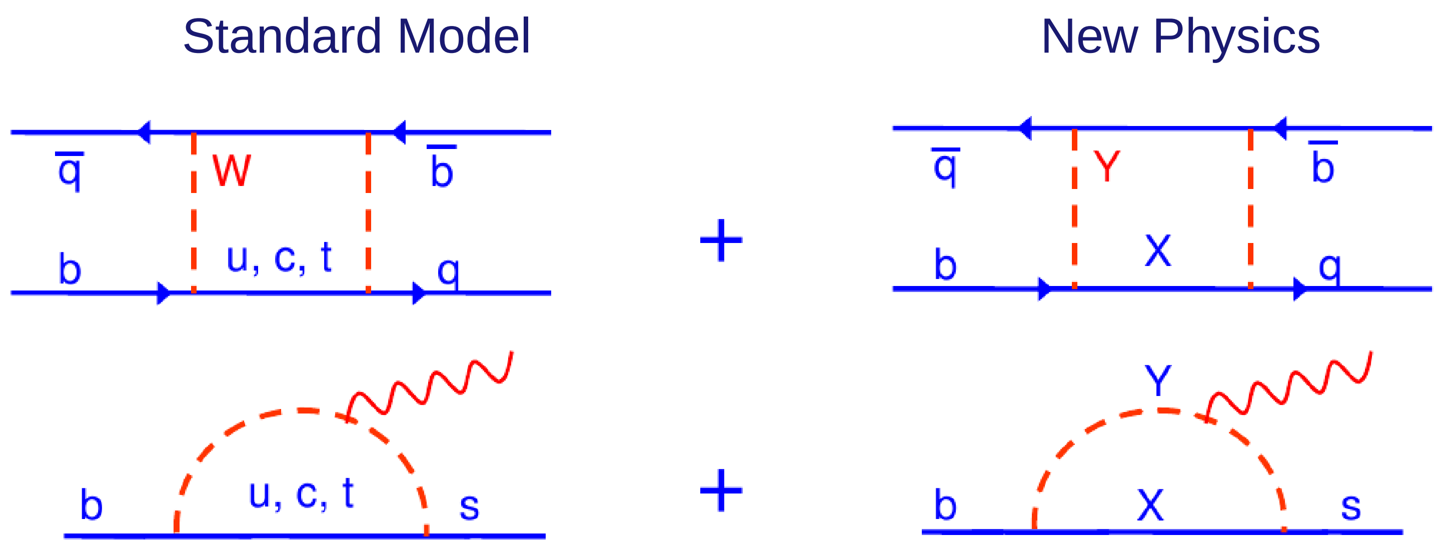
  e.g. Δm_s, ...
- CKM mechanism well established as major source of CPV

  it works very well :-), it works too good! :-(

  $\longrightarrow$ see Yossi's talk for more *quantitative* statements

New Physics in B decays

New Physics effects only appear as correction to leading SM terms.



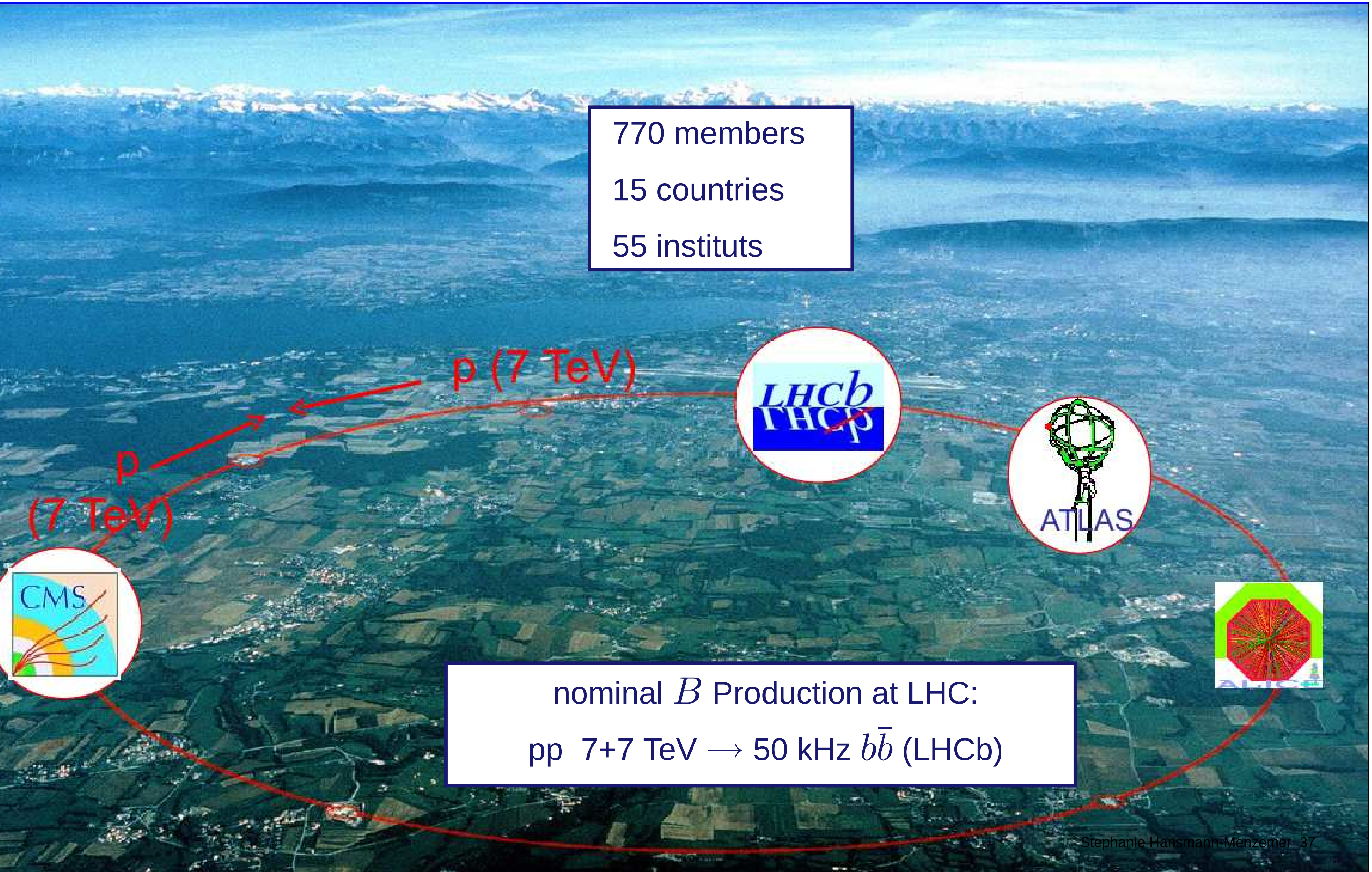
$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{C_{SM}}{m_W^2} + \frac{C_{NP}}{\lambda_{NP}^2} \right); \quad (C_{SM} = \frac{g_W^2}{4\pi} \sim \frac{1}{30}, \lambda_{NP} \sim 1 \text{ TeV (?))}$$

Flavour physics approach to new physics:

- study processes which are sensitive to quantum corrections:
  e.g. very rare (SM suppressed) decays, CPV

Current Hot Topics and near Future

The Large Hadron Collider



770 members

15 countries

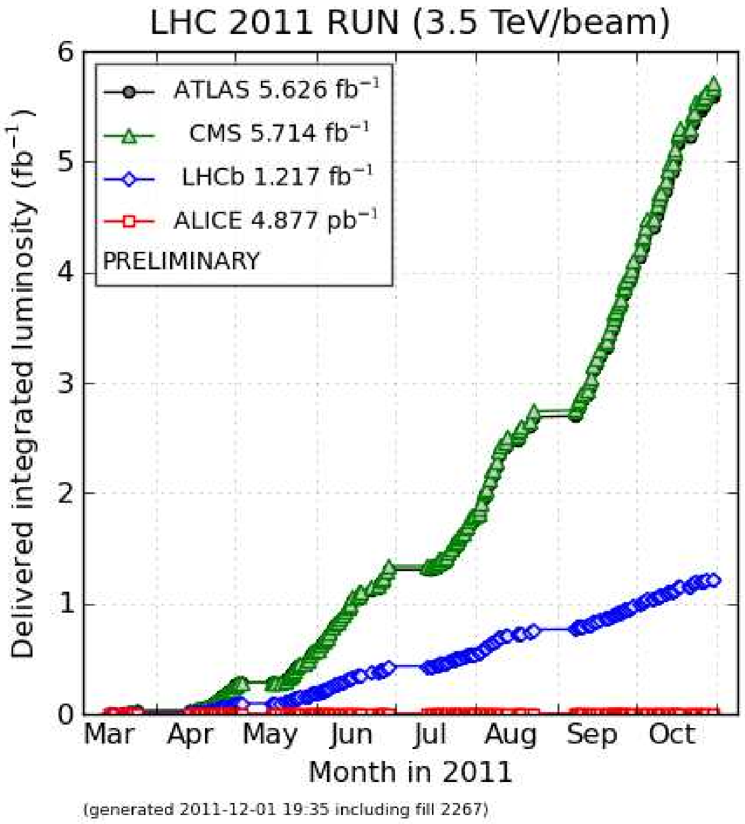
55 instituts

nominal B Production at LHC:

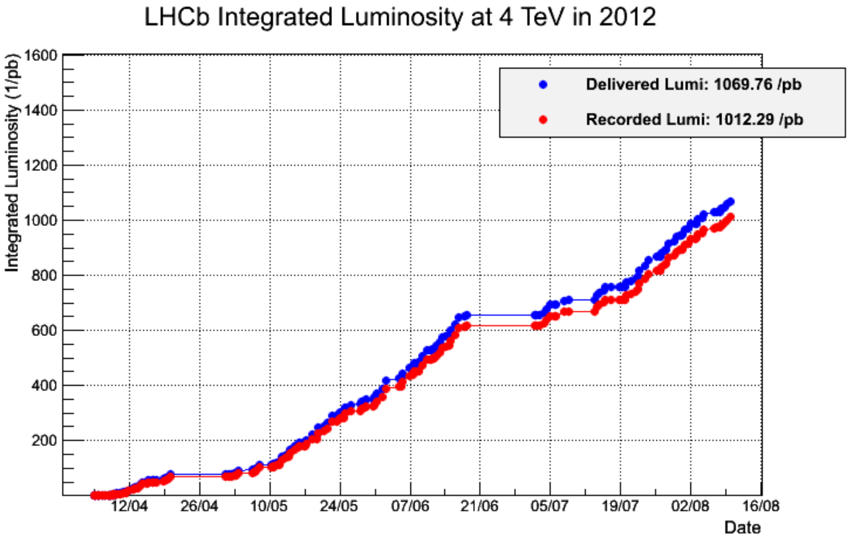
pp 7+7 TeV $\longrightarrow$ 50 kHz $b\bar{b}$ (LHCb)

LHC 2011 Performance

$\sim 1\ \text{fb}^{-1}$



$+ 1\ \text{fb}^{-1}$

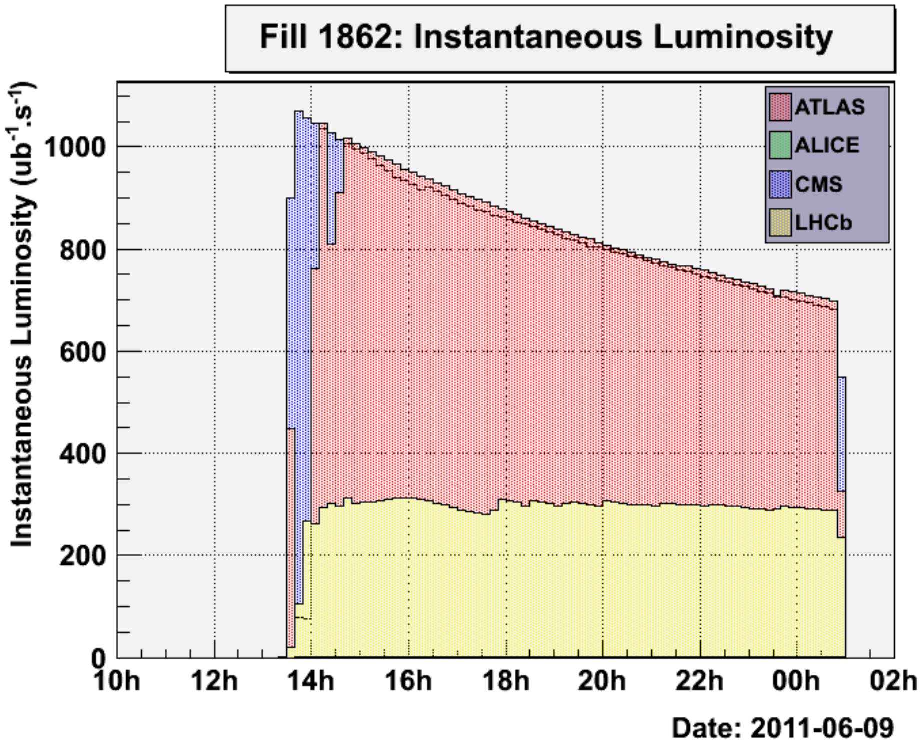


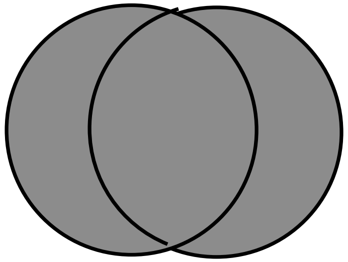
2011 data $\equiv 20\times10^{10}\ B$ pairs produced in the LHCb detector

LHCb Data Taking

LHCb adapt on the fly the interaction rate per BX

$\longrightarrow$ stabel running conditions during one fill





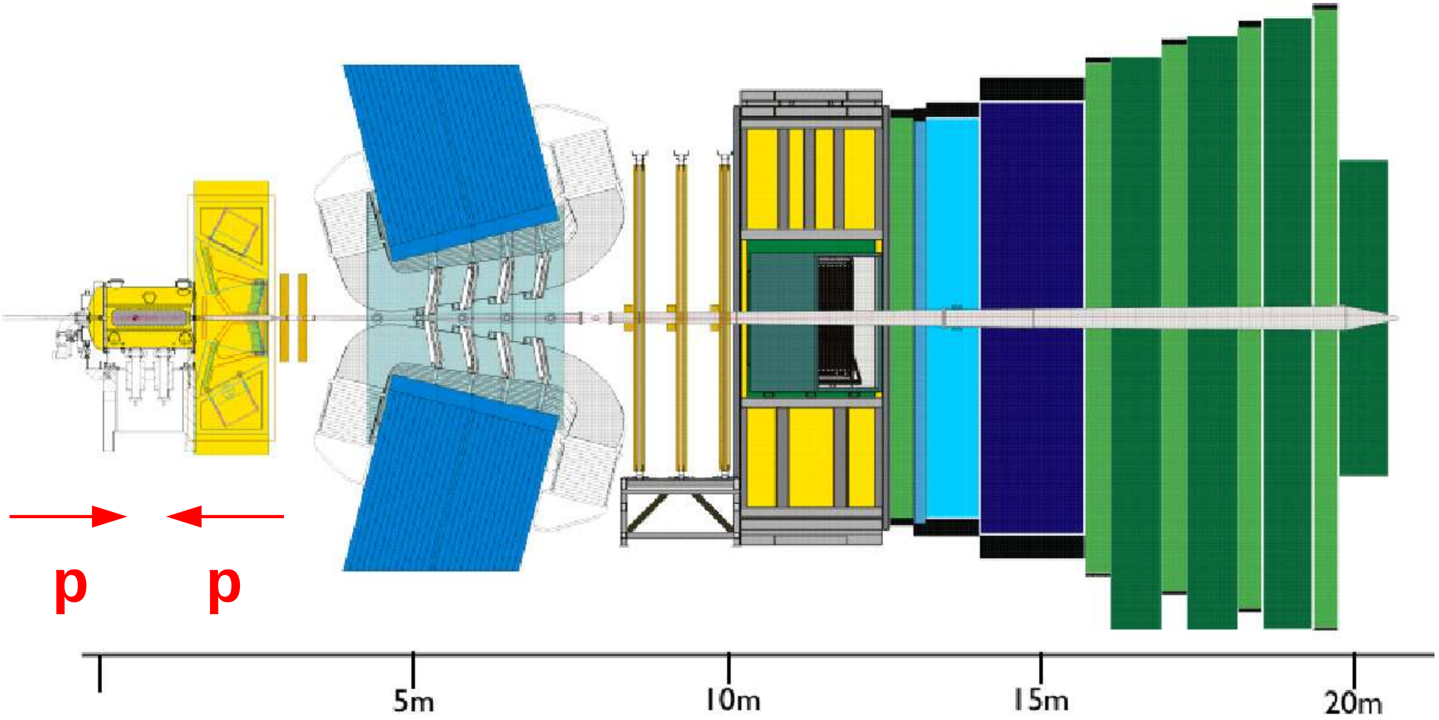
	bunch	WW/BX	luminosity
design	2835	0.5	2×10^{32}
2011+12	1380	1.6	3×10^{32}

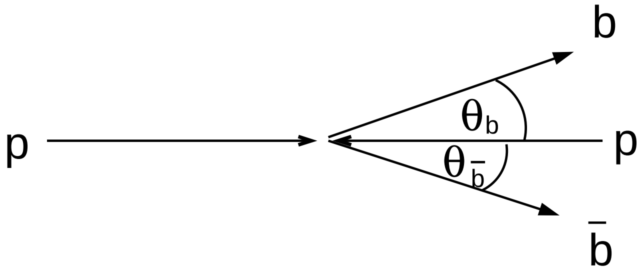
The LHCb Detector

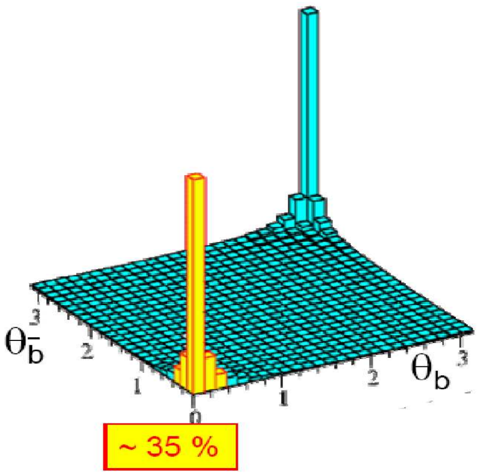
RICH 1 magnet tracking stations RICH 2 myon sytem

vertex detector

calorimeter



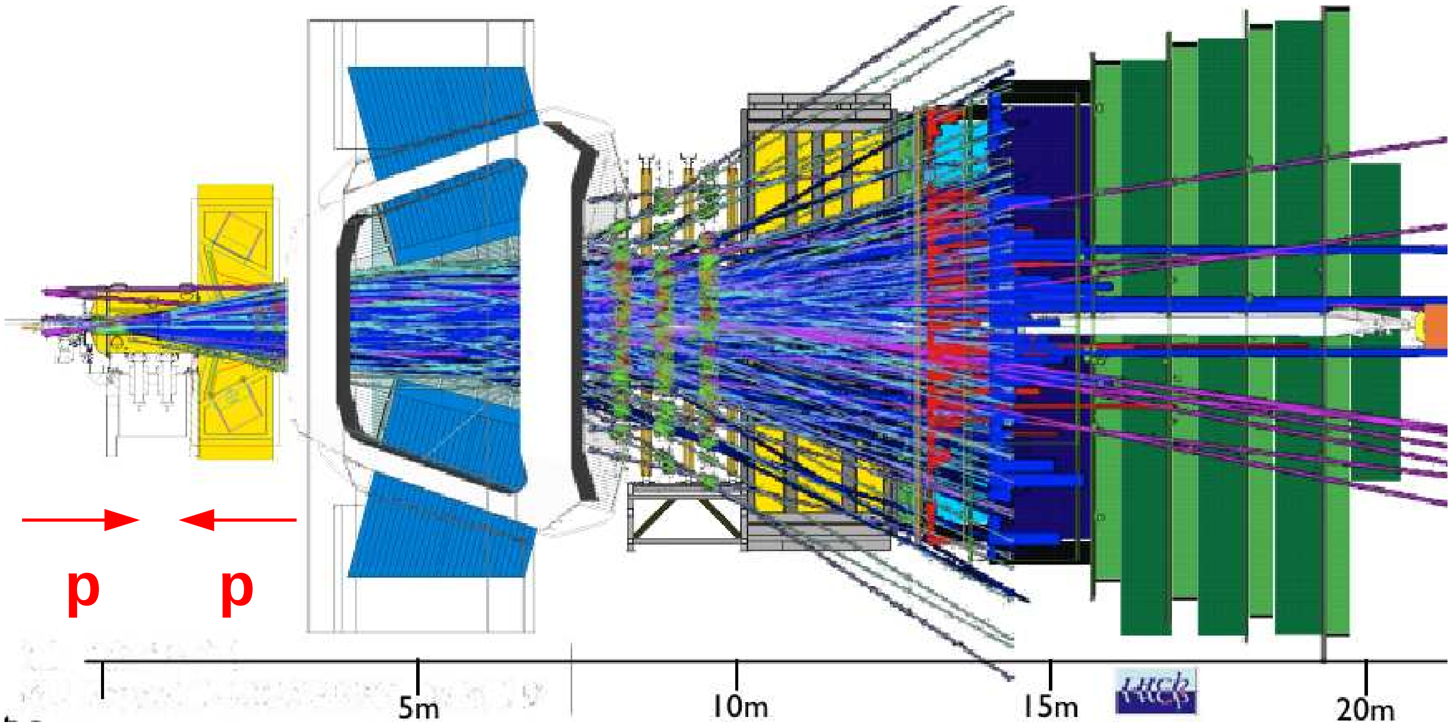


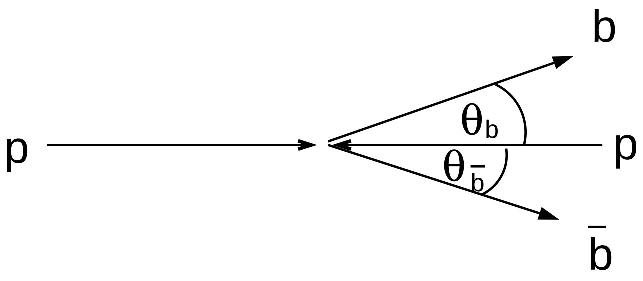


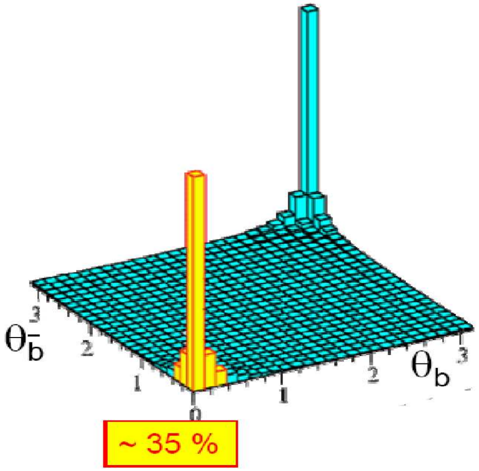
The LHCb Detector

RICH 1 magnet tracking stations RICH 2 myon system

Vertex-detector calorimeter







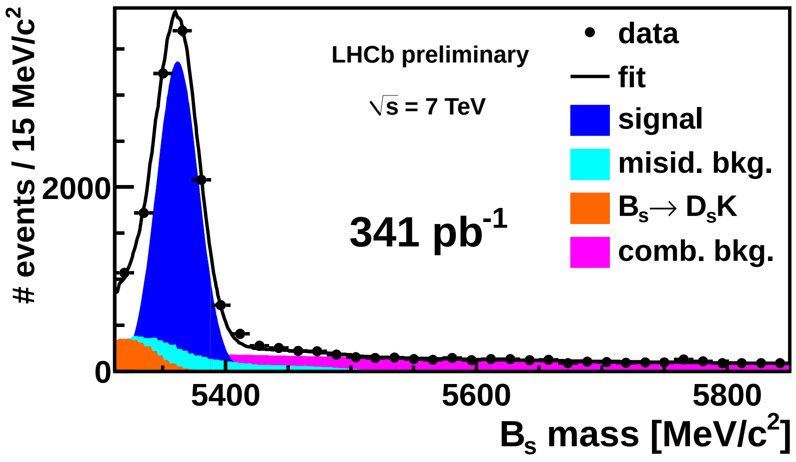
Hot Topics in the LHCb area ...

These are selected topics, many other examples exist!

- CPV in B_s mixing
  - mixing phase ϕ_s ("$\sin 2\beta$ of B_s system")
  - $A_{sl} : P(B^0 \to \overline{B^0}) \neq P(\overline{B^0} \to B^0)$
- Unexpected surprise: CP violation in charm
- Measurement of CKM angle γ (left over SM homework)
- $BR(B_s \to \mu^+\mu^-)$
- Observables in $B \to K^{(*)}\mu^+\mu^-$
- ...

$B_s - \bar{B}_s$ Mixing

decay mode	signal yield
$B_s^0 \to D_s^-(\phi\pi^-)\pi^+$	4371 ± 91
$B_s^0 \to D_s^-(K^*K^-)\pi^+$	2910 ± 89
$B_s^0 \to D_s^-\pi^+$ non-resonant	1908 ± 74

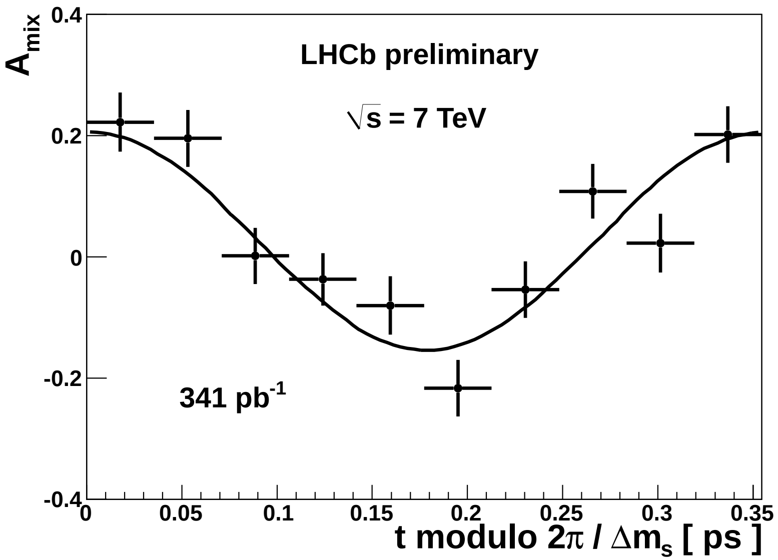


$\sim$ 9.250 B_s candidates in 3 decay modes

proper time resolution: σ_t = 45 fs

Δm_s = 17.725 $\pm$ 0.041 $\pm$ 0.026 ps^{-1}

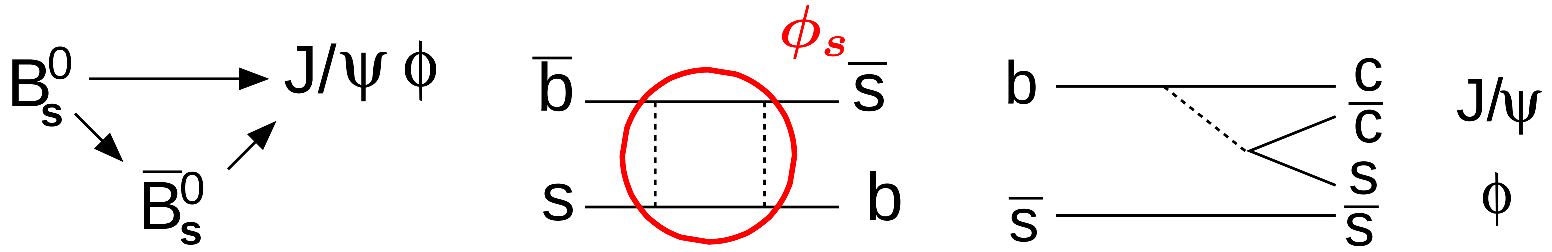
world best measurement!



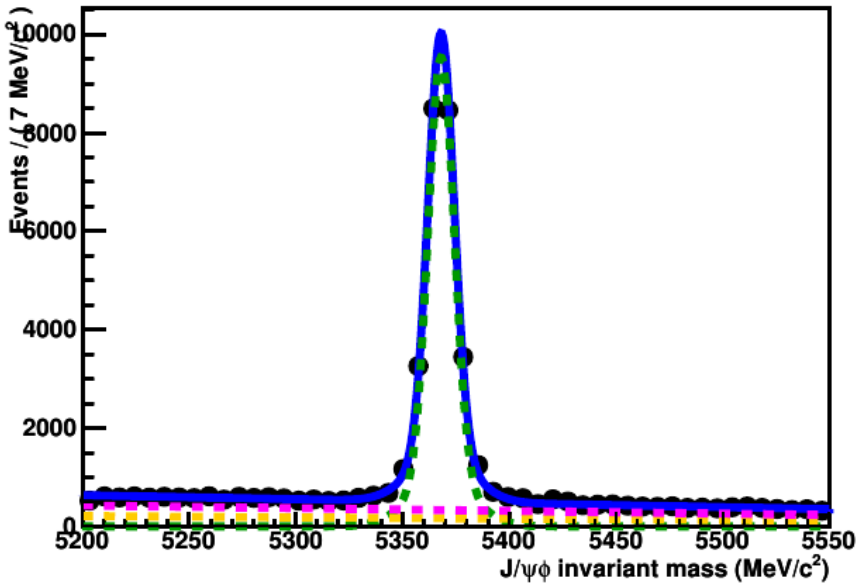
CDF: Δm_s = 17.77 $\pm$ 0.10 $\pm$ 0.07 ps^{-1} mit 1 fb^{-1}, $\sigma_t \sim$ 100 fs

Mixing phase $\phi_s \sim 2\beta$

CPV in interference of mixing and decay (analogous to $\sin 2\beta$ in $B^0 \to J/\psi K^0$):



golden mode: $B_s \to J/\psi\phi$: ($\sim$ 21.000 candidates in 1 fb^{-1})

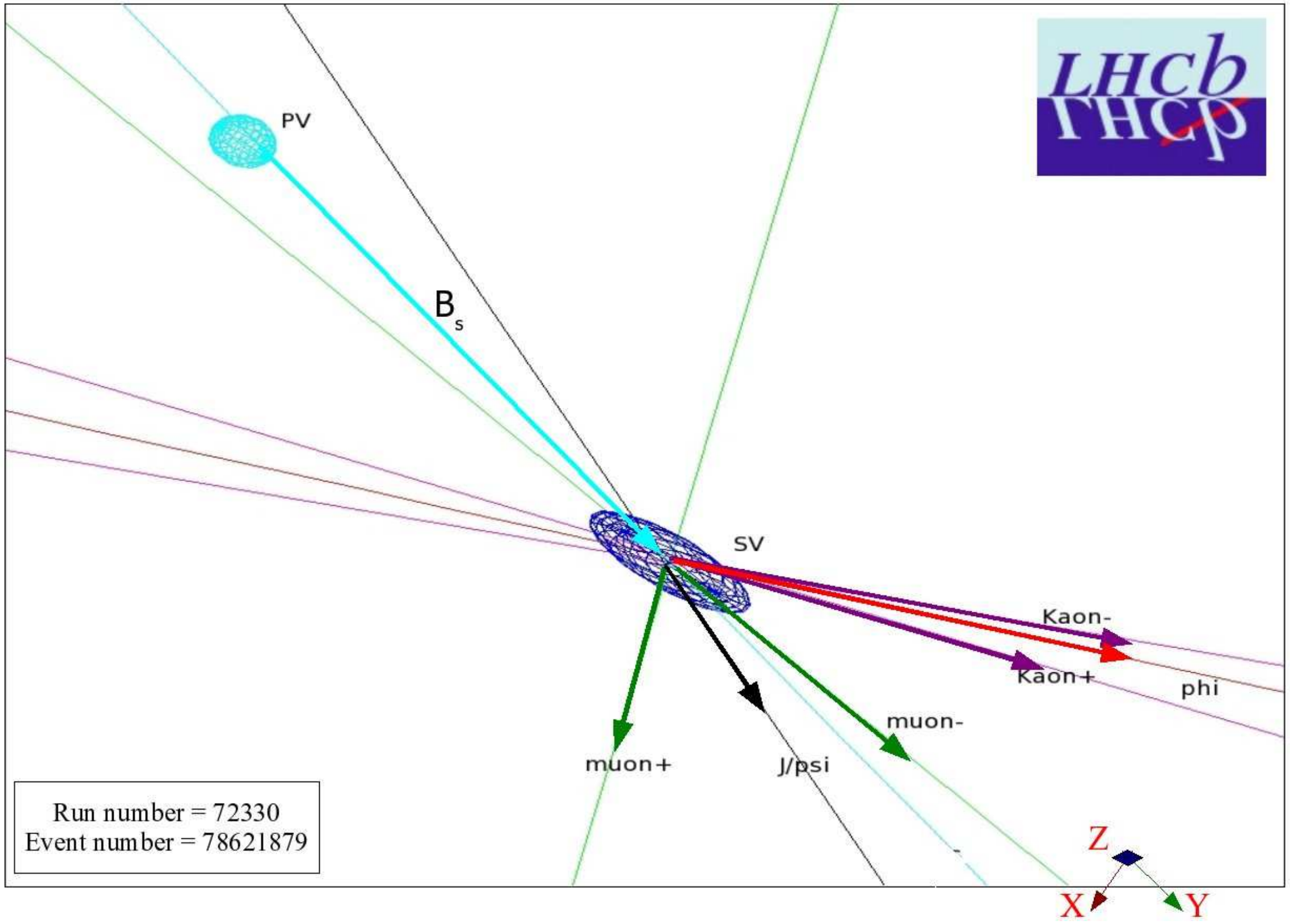


$$arg(V_{ts}) = \beta_s$$

in first order $2\beta_s \sim -\phi_s$

SM: ϕ_s = -0.003 rad

$B_s \to J/\psi\phi$



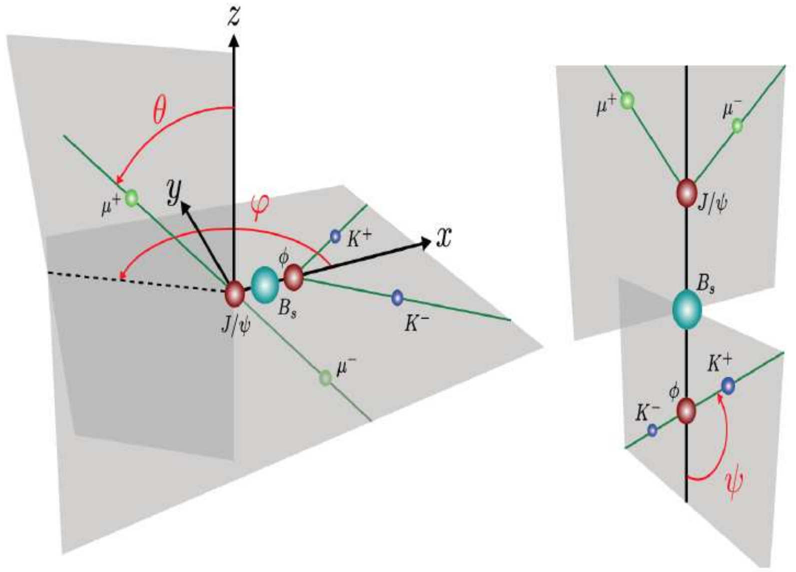
$m(\mu\mu) = 3072 MeV/c^2$
$m(KK) = 1020 MeV/c^2$
$m(\mu\mu KK) = 5343 MeV/c^2$

$x^2_{vtx}/nDOF = 0.8$
$t/\sigma(t) = 78 (L = 20mm!)$

Technical Complication

$J/\psi\phi$ is no CP eigenstate, but combination of CP even and CP odd states.

$J_B = 0$, $J_{J/\psi} = J_\phi = 1 \rightarrow$ L = 0,1,2

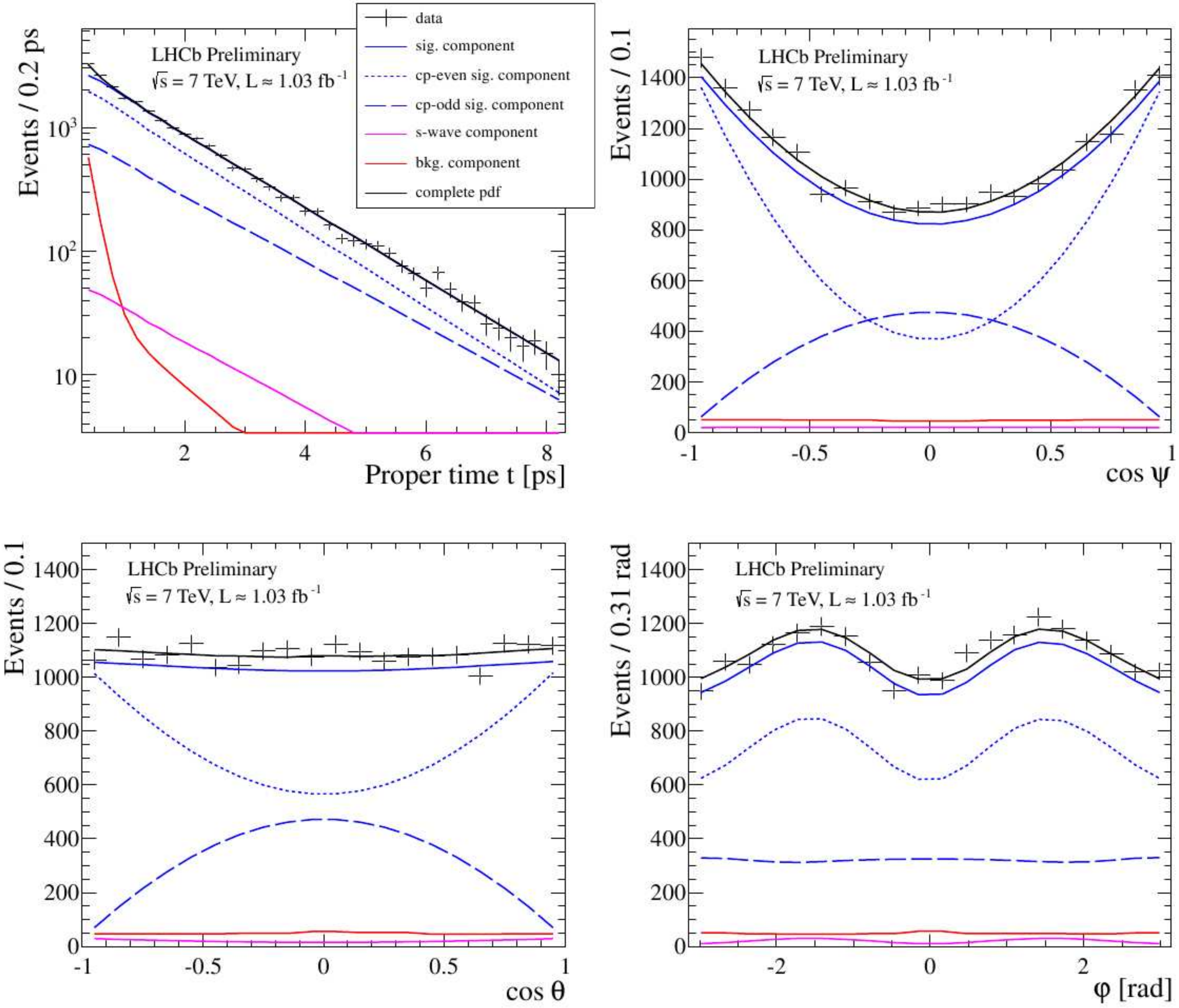


$$
\begin{aligned}
A_1 &= |A_0|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_2 &= |A_\parallel|^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_3 &= |A_\perp|^2 e^{-\Gamma_s t}[\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)] \\
A_4 &= |A_\parallel||A_\perp| e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_\parallel)\cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)] \\
A_5 &= |A_0||A_\parallel| e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)[\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)] \\
A_6 &= |A_0||A_\perp| e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_\perp - \delta_0)\cos(\Delta m t)] \\
A_7 &= |A_s|^2 e^{-\Gamma_s t}[\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] \\
A_8 &= |A_s||A_\parallel| e^{-\Gamma_s t}[-\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) \\
&\quad + \cos(\delta_\parallel - \delta_S)\cos(\Delta m t)] \\
A_9 &= |A_s||A_\perp| e^{-\Gamma_s t}\sin(\delta_\perp - \delta_S)[\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)] \\
A_{10} &= |A_s||A_0| e^{-\Gamma_s t}[-\sin(\delta_0 - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0 - \delta_S)\cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_0 - \delta_S)\cos(\Delta m t)]
\end{aligned}
$$

$\rightarrow$ time dependent analysis of 3 relative decay angles of the B daughters

(add. non resonant KK S-wave contribution)

Time & Angular Distribution



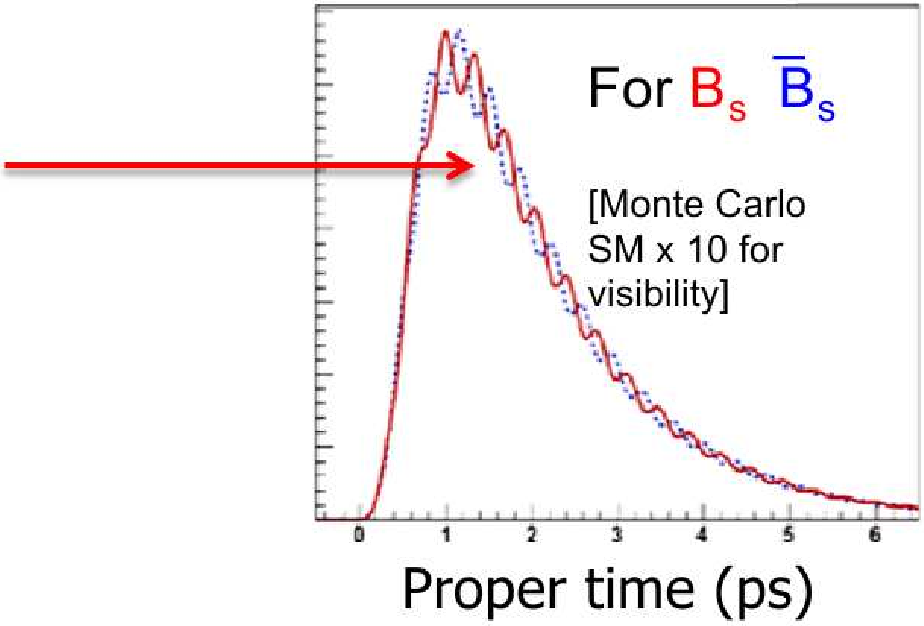
in case of no CPV:

$B_{CP=+1} = B_H$;

$B_{CP=-1} = B_L$

Measurement of ϕ_s

measurement of modulation
in decay time distribution



- amplitude of modulation is $\sin\phi_s$
- opposite sign for B_s and $\bar{B}_s$ (and for η_{CP})

physics observables: $A_\perp, A_\|, A_0, \delta_\|, \delta_\perp, \Gamma, \Delta\Gamma, \Delta m_s, m_B, \phi_s, \delta_S, F_S, \lambda_{CP}$

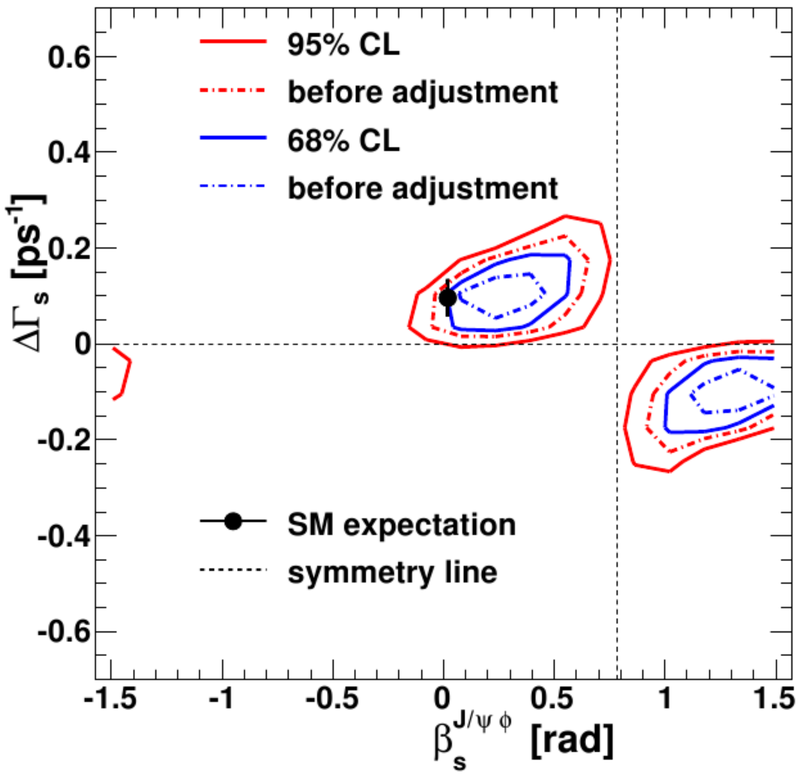
important tools: flavour tagging & decay time resolution

Inheritance from Tevatron

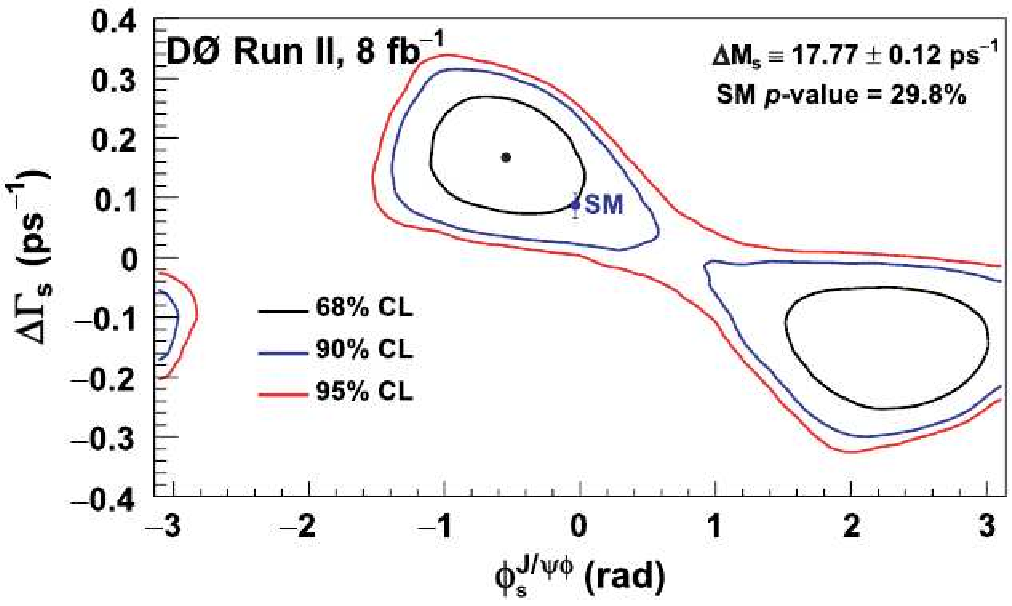
Tevatron experiments saw a deviation already in their early data, which stayed as well in the final results ...

CDF result (6 fb^{-1})

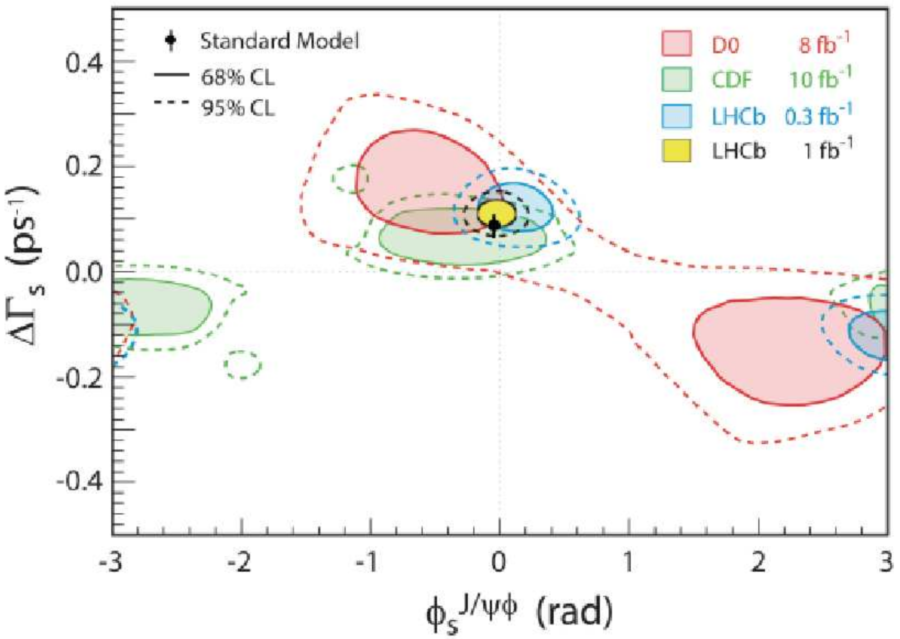
updated final result out already



D0 result



LHCb Result (1 fb^{-1})



[ambigious soluation elimated by LHCb study of phase difference $\delta_S - \delta_\perp$ in bin of KK mass.]

ϕ_s = -0.001 $\pm$ 0.101 (stat) $\pm$ 0.027 (syst) rad (SM: $\phi_s \sim -0.03$ rad)

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

(first 5σ observation of $\Delta\Gamma_s \neq 0$)

Message: no big non-SM effects in ϕ_s.

However a priori worth of observable for NP search remains. Must improve precision! By 2018 it should be similar to SM central value.

New Physics in B_s-Mixing?

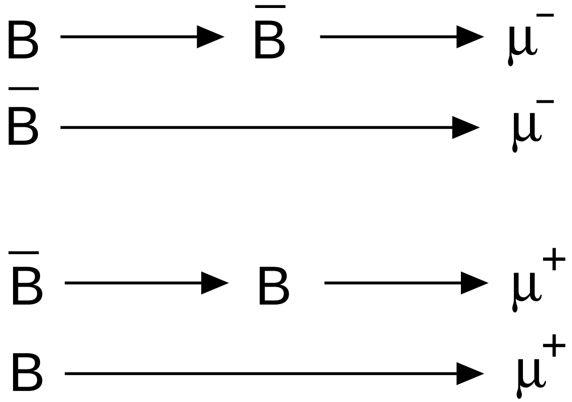
- $P(B \to \bar{B}) \neq P(\bar{B} \to B)$

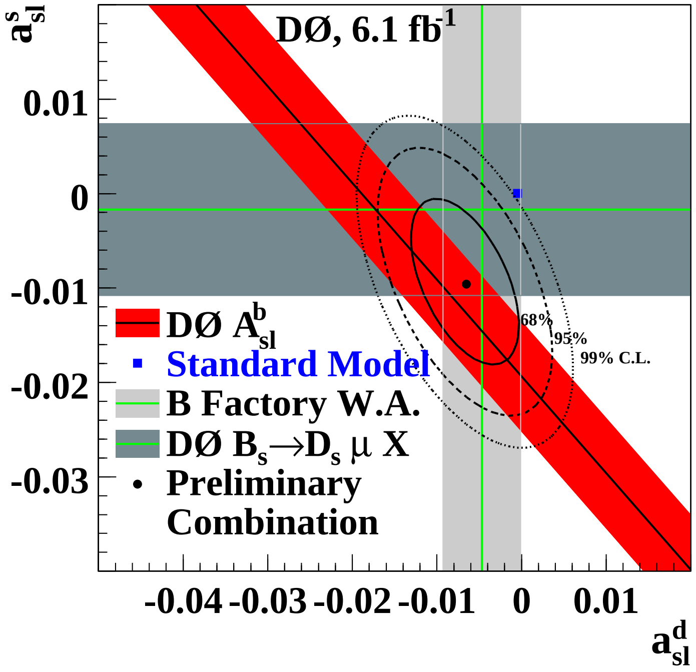
SM: A^b_{sl} = (-0.20 $\pm$ 0.03) $\times$ 10^{-3}

A. Lenz, U. Nierste, (2006/2011)

semileptonic asymmetry

$(B^0 + B_s)$





$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

$$a = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)}$$

A^b_{sl} = -0.957 $\pm$ 0.251 (stat) $\pm$ 0.14 (syst) %

(Phys. Rev. Lett 105, 081802 (2010))

$\longrightarrow$ 3.2σ deviation fromSM

LHCb Measurement of A_{sl}

Exploit partial reconstructed semileptonic decays, to measure contribution from B_s^0 only and to reject huge amount of background.

$$a_s = 1 - |\frac{q}{p}|^2$$

$$A_{sl}^s \equiv \frac{\Gamma(\overline{B_s^0} \to D_s^- \mu^+) - \Gamma(B_s^0 \to D_s^+ \mu^+)}{\Gamma(\overline{B_s^0} \to D_s^- \mu^+) + \Gamma(B_s^0 \to D_s^+ \mu^+)} = \frac{1-(1-a_s)^2}{1+(1-a_s)^2} \sim a_s$$

LHCb performs an untagged time integrated analysis, no information on production flavour used (due to very low tagging ...)!

$$A_{meas} \equiv \frac{\Gamma(D_s^- \mu^+) - \Gamma(D_s^+ \mu^-)}{\Gamma(D_s^- \mu^+) + \Gamma(D_s^+ \mu^-)} = \frac{a_{sl}^s}{2} + \left(a_p - \frac{a_{sl}^s}{2}\right) \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta m_s t) \epsilon(t) dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cosh(\Delta \Gamma_s t/2) \epsilon(t) dt} \sim \frac{a_{sl}^s}{2}$$

untagged semileptonic asymmetry

production asymmetry ... pp collider

prod. asymmetry washed out due to mixing ($\times$ 0.2%) ; works for B_s not for B_d

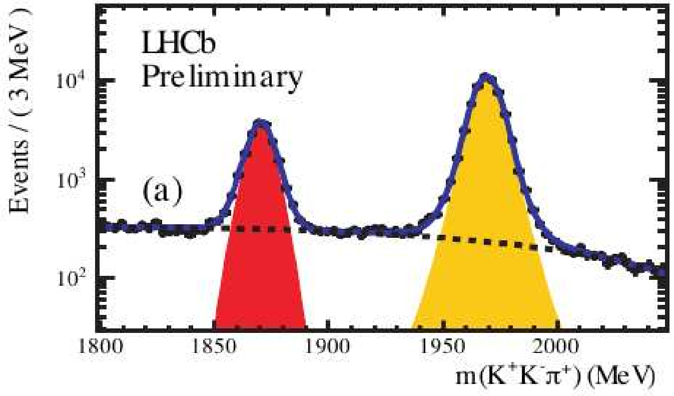
$\epsilon(t)$: decay time acceptance function

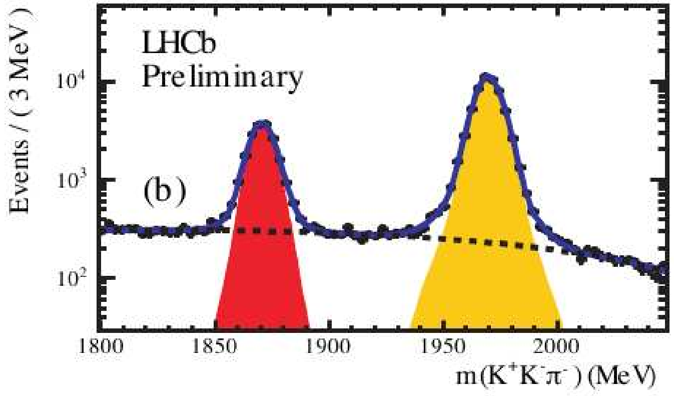
LHCb Measurement of A_{sl}

$$A_{meas} \equiv \frac{\Gamma(D_s^- \mu^+) - \Gamma(D_s^+ \mu^-)}{\Gamma(D_s^- \mu^+) + \Gamma(D_s^+ \mu^-)} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-) \times \frac{\epsilon(D_s^- \mu^+)}{\epsilon(D_s^+ \mu^-)}}{N(D_s^- \mu^+) + N(D_s^+ \mu^-) \times \frac{\epsilon(D_s^- \mu^+)}{\epsilon(D_s^+ \mu^-)}}$$

- aim for a permille level uncertainty (cannot trust MC to this precision)
- need to understand detection and background asymmetries (e.g. $D_s^- \to \phi\pi^-$ vs. $D_s^+ \to \phi\pi^+$ and μ^- vs. μ^+ detection asymmetry) advantage, we have magnet up and magnet down sample of almost equal size; many effects related to left/right detector asymmetries cancle

plots and numbers for magnet down samples only

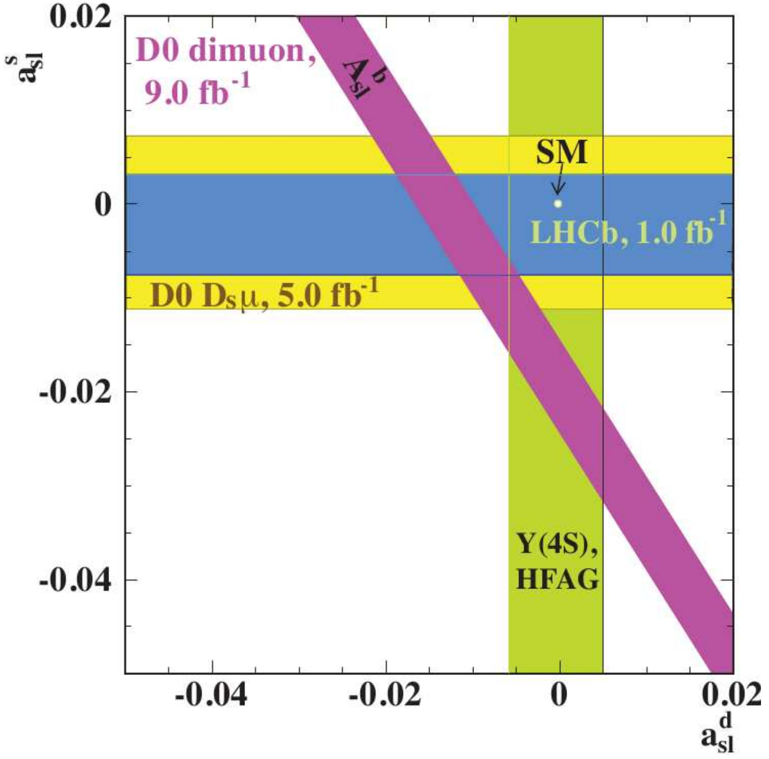




55,755 $\pm$ 278 $D_s^- \mu^+$ 56,447 $\pm$ 294 $D_s^+ \mu^-$

LHCb Results

a_{sl}^{s} = (-0.24 $\pm$ 0.54 $\pm$ 0.33) %



- consistent both with SM and with D0 result
- not yet the end of the story ... add more decay modes and more statistics
- work on time dependent asymmetry in B_d system ongoing

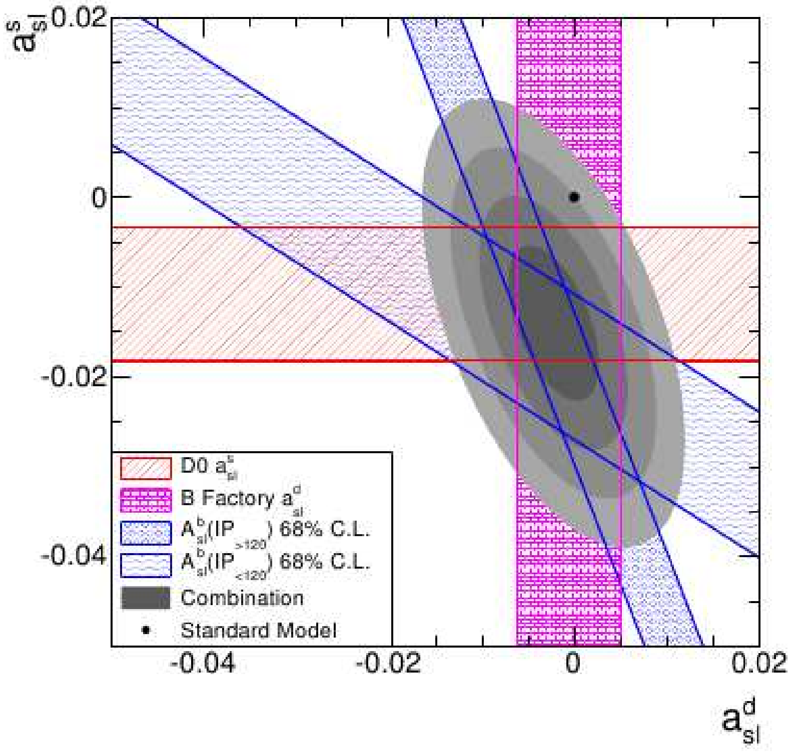
Updated D0 results

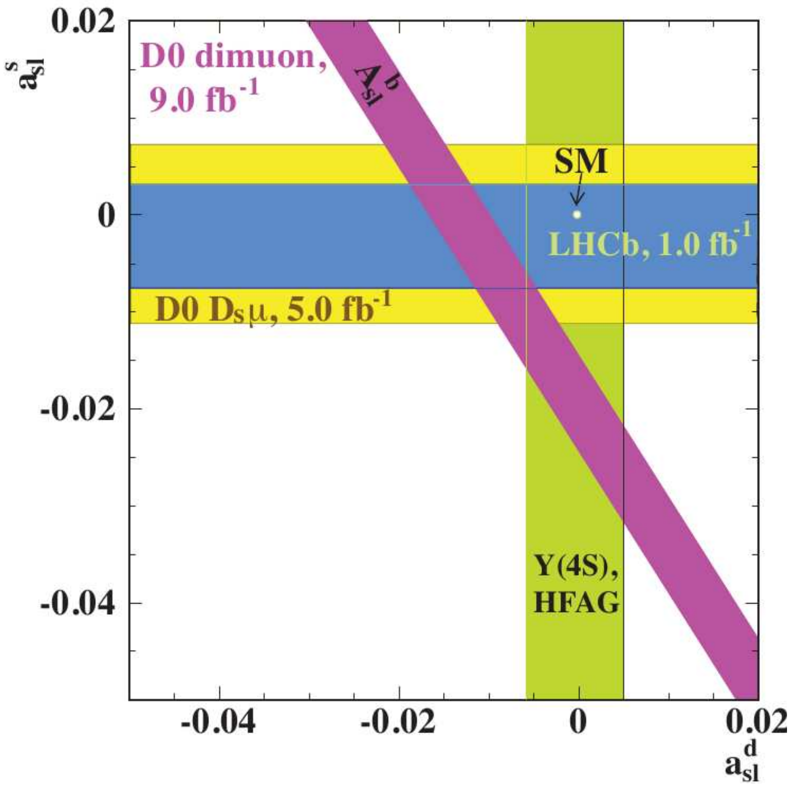
D0 updated results with 9 fb^{-1}

a^s_{sl} = (-1.08 $\pm$ 0.72 $\pm$ 0.17) %

LHCb result

a^s_{sl} = (-0.24 $\pm$ 0.54 $\pm$ 0.33) %





It stays interessting ...

$B_s \rightarrow \mu^+\mu^-$

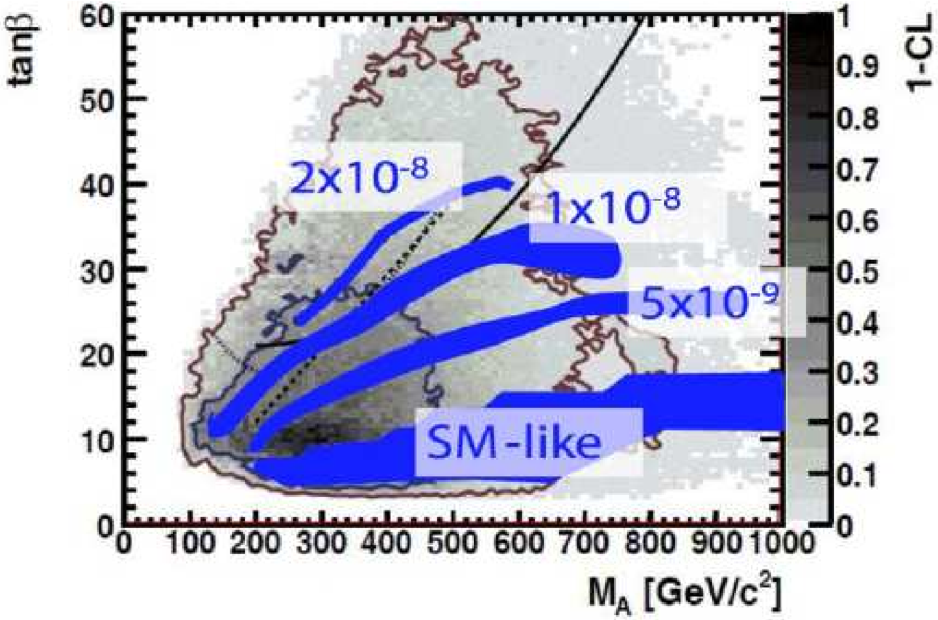
- B physics rare decay par excellence
- $\text{BR}_{SM}(B_s \rightarrow \mu^+\mu^-) = (3.6 \pm 0.2) \cdot 10^{-9}$

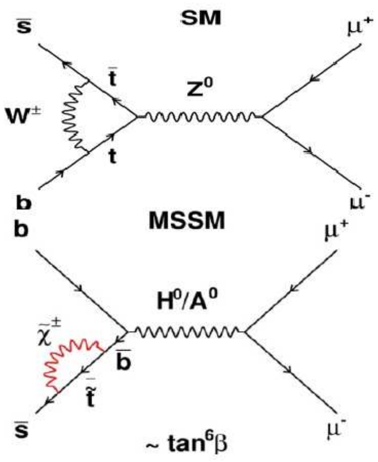
  [A. Buras, 2009]

  Very precise prediction (which will improve)!
- Very high sensitivity to NP, e.g. MSSM

  One example (O. Buchmüller et al)

  NUHM (= generalized version of CMSSM)





95% CL limits on

$B_s \rightarrow \mu^+\mu^-$

(status spring 2011:)

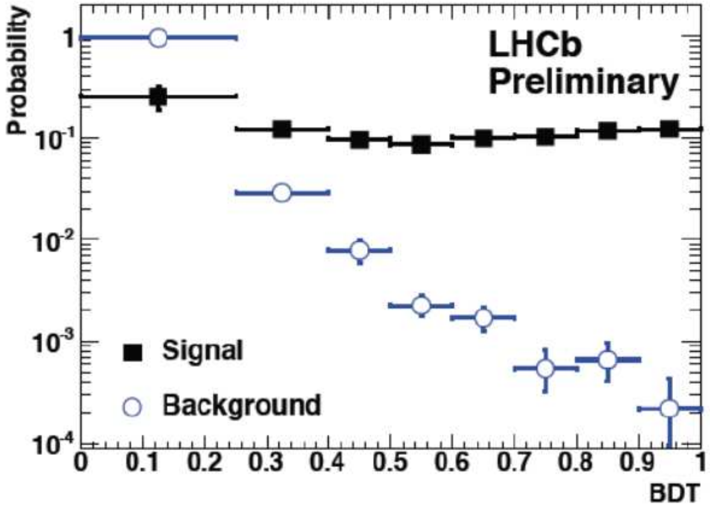
Experiment	Data set	Limit
CDF	3.7 fb^{-1}	4.3 x 10^{-8}
D0	6.1 fb^{-1}	5.1 x 10^{-8}
LHCb	0.036 fb^{-1}	5.6 x 10^{-8}

$\sim$ 15-20 $\times$ SM value,

plenty of room for NP

Analysis Strategy

3D analysis: mass $\times$ kinematic $\times$ muon-ID



- Build Boosted Decision Tree (BDT) out of 9 kinematical and topologial variables. train BDT on MC, but calibrate on data:
  - signal response: use $B \to hh$ decays
  - background response: use sidebands
- Calibrate muon-ID using tag & probe method (J/ψ))
- Calibrate signal mass shape/width on dimuon resonances from data
- Now look in a 9×8 grid of $\mu^+\mu^-$ invariant mass vs. BDT output
- Three normalisation channels for BR: $B^+ \to J/\psi K^+$, $B_s \to J/\psi\phi$ and $B^0 \to K\pi$, give all consistent results

$B_s \to \mu^+\mu^-$ Candidate

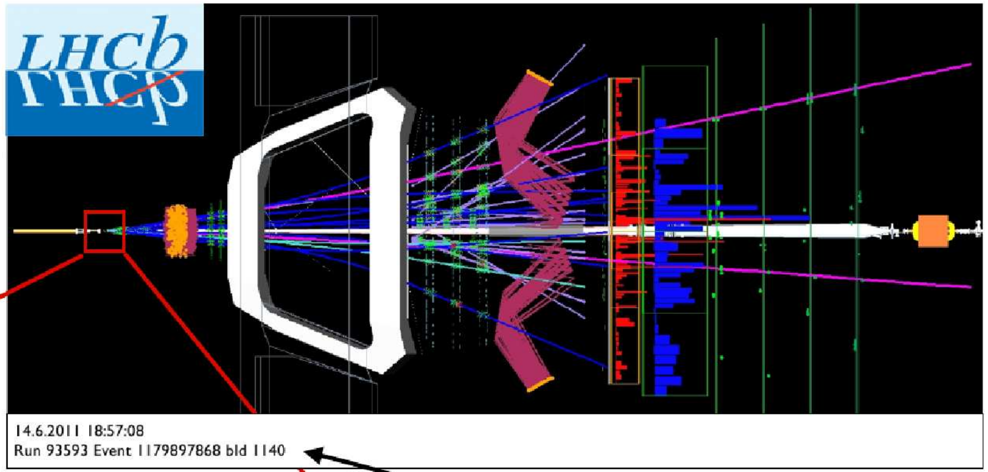
Even at the SM branching ratio, LHCB expects to accumulated $B_s \to \mu\mu$ decays in 2011 data ($\sim$ 12 after pre-selection). Indeed, plausible candidates are seen:

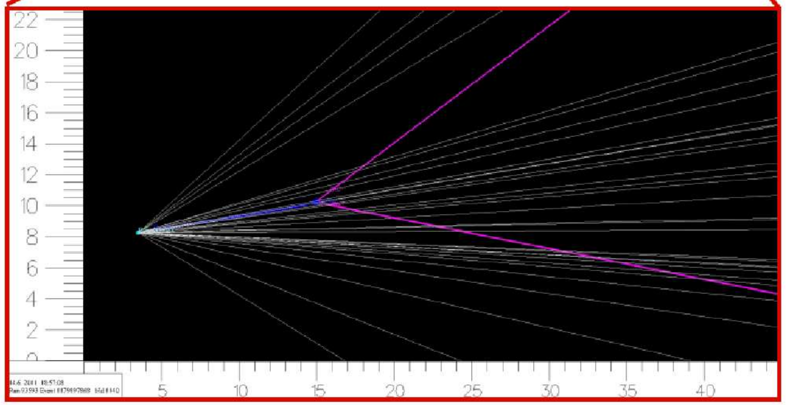
$m_{\mu\mu} = 5.347$ GeV/c^2

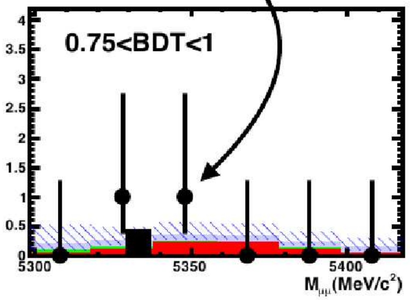
BDT = 0.9

decay length = 11.5 mm

only tracks w. $p_T >$0.5 GeV/c

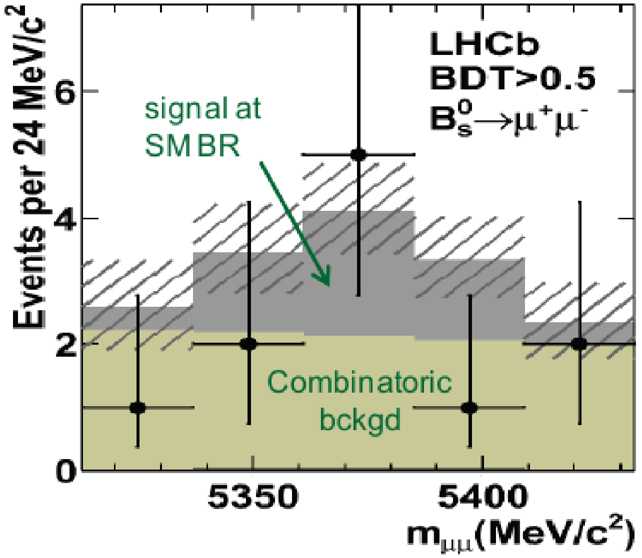




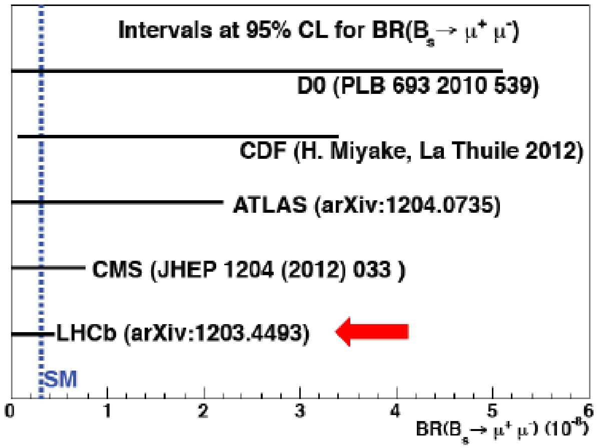


$B_s \to \mu^+\mu^-$ Result

No excess seen - e.g. for BDT>0.5 – limit is actually better than expected!



limit	at 95% CL
Exp. bkg + SM	7.2×10^{-9}
Exp. bkg	3.4×10^{-9}
Observed	4.5×10^{-9}



limit very close to SM - no large NP enhancement. Big consequences for NP parameter space.

Next step, perform a precision measurement to test if BR is *really* SM.

Potential for $\sim 15\%$ stat. error by 2018.

Data driven analysis equipped to controll all systematics.

Conclusion up to now

There seems to be no “low hanging fruit”, so we have to climb higher.

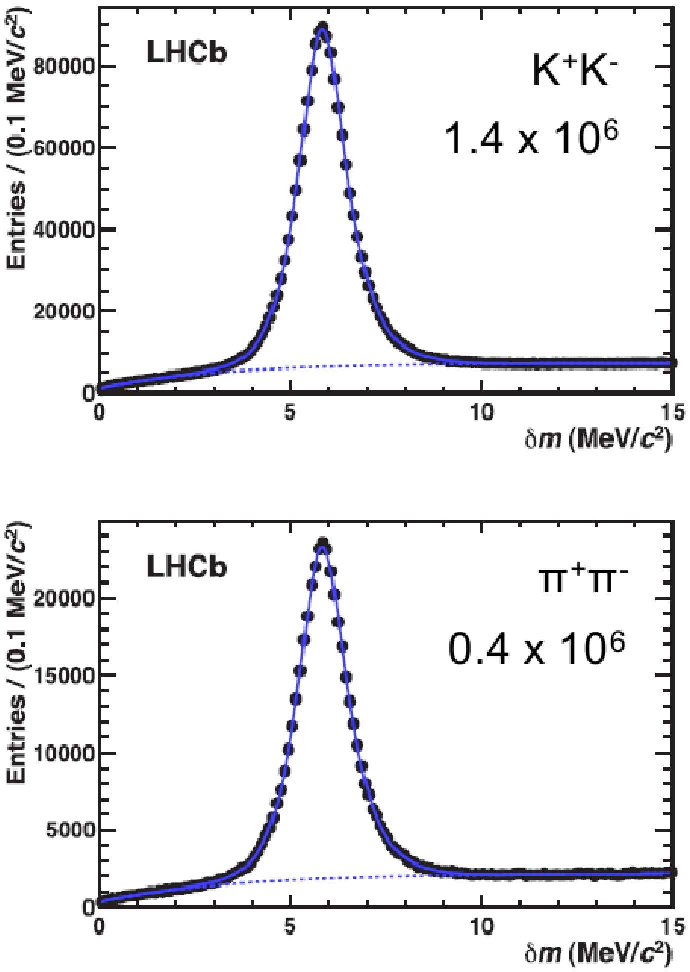
That’s OK, as the view will be better!

courtesy G. Wilkinson

Search for New Physics in Charm

- Same qualities which make LHCb a great B-physics detector also hold for charm ...
- + enourmous cross-section: 6.5 mb 7 TeV
  $\longrightarrow$ very large and clean event sample
  2011 data set about $\times$ 10 larger than total Babar+Belle data set
- physics programm: search for CPV in decay & mixing, searches for very rare decays, spectroscopy ...
- charm decays involves mainly upper 2x2 corner of CKM matrix, very small CPV expected;
  "CPV in SCS decays $\mathcal{O}(1\%)$ clear sign of new physics."

LHCb D^*-D^0-m_π [0.6 fb^{-1}]



Experimental challenge, controll systematic to $\sim$ 0.1%

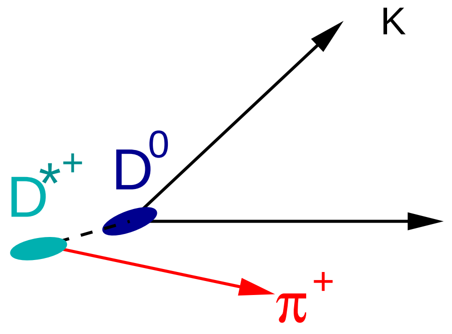
CPV in D^0 decays

$$A_{CP}(D^0 \rightarrow h^+h^-) = \frac{\#(D^0 \rightarrow h^+h^-) - \#(\overline{D^0} \rightarrow h^+h^-)}{\#(D^0 \rightarrow h^+h^-) + \#(\overline{D^0} \rightarrow h^+h^-)}$$

h^+h^-: K^+K^- or $\pi^+\pi^-$

$D^{*+} \longrightarrow D^0 \pi^+$

$D^{*-} \longrightarrow \overline{D}^0 \pi^-$



$$A_{raw} = A_{CP} + A_{reco\ \pi^\pm} + A_{prod\ D^{*\pm}}$$

$A_{reco\ \pi^\pm} \neq 0$ pion reconstruction

$A_{prod\ D^{*\pm}} \neq 0$ pp collision ist asymmetrical starting condition

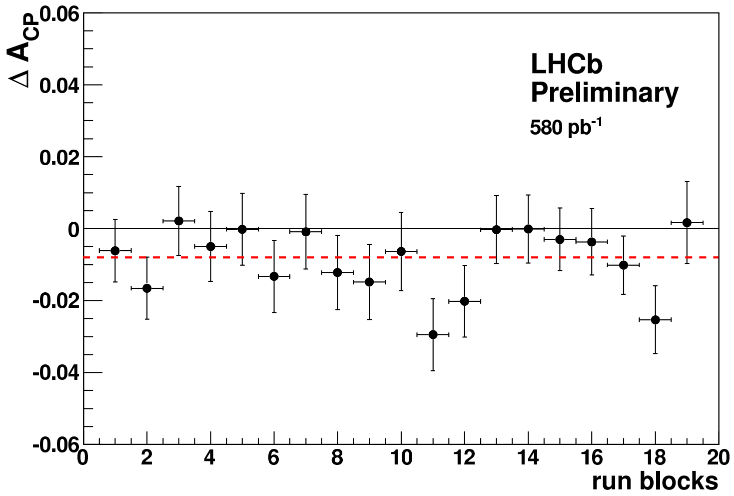
$\longrightarrow$ diff. D^{*+} and D^{*-} production rates

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$

Reconstruction and production asymmetries cancel in difference!

Result

many stability tests performed



ΔA_{CP} is an extremly robust quantity!

$$\Delta A_{CP} = [-0.82 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})]\%$$

First experimental evidence for CPV in charm system!

Most likely CPV in decay, as CPV in mixing and interference of mixing and decay cancels almost in difference.

in the mean confirmed by other experiments: -0.62 $\pm$ 0.21 $\pm$ 0.1 % (CDF); -0.87 $\pm$ 0.41 $\pm$ 0.06% (Belle)

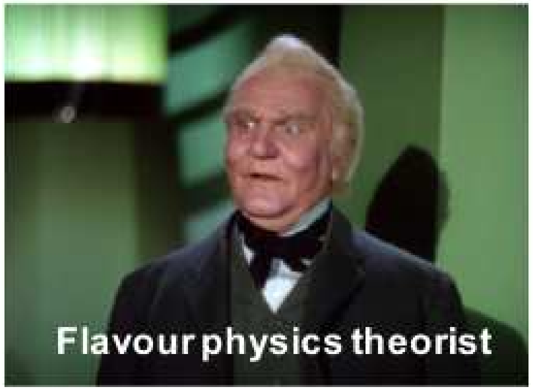
Update on 2 fb^{-1} & cross check with $B \to \mu D^0 X$ decays

(μ tag instead of D^* tag) on the way

Informing Collegues from Theory ...

Please, sir. We've done what you told us. We've brought you the broomstick of the Wicked Witch of the West. We melted her.

Oh... You liquidated her, eh? Very resourceful!



Yes, sir. So we'd like you to keep your promise to us, if you please sir.

Not so fast! I'll have to give the matter a little thought. Go away and come back tomorrow.

courtesy G. Wilkinson

$\longrightarrow$ "Stretching the SM one can explain the observed effect."

Need to establish ΔA_{CP} signal and study CPV in further SCS charm modes !

Summary

- Flavour physics/indirect measurements very successful in the past to discover/predict new particles.
- Precision measurements of B decays sensitive to quantum corrections is a powerful tool to search for BSM physics
- No striking hint for new physics found yet ... CKM works too well
  Still room for $\sim$ 20% effects.
- High precision measurements are challenging, excellent understanding of detector crucial!
- LHCb had a very successful start, many exciting results ahead!