Flavour Physics (II)
History and recent progress at LHC

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Standard Model Flavour Framework

flavour eigenstatetates	$\Rightarrow$	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-strong and EM interactions		-weak interactions
-flavour conservation		-flavour changing

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right),\ \hat{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$

$A \approx 0.8$

$\rho^2 + \eta^2 \approx 0.3$

$(1 - \hat{\rho})^2 + \hat{\eta}^2 \approx 0.9$

$b \rightarrow s\gamma$ decays and B_s^0-$\overline{B}_s^0$ oscillations for $|V_{ts}|$

Standard Model Flavour Framework

- By the early 90's, the Standard Model model description of "flavour" through the Cabibbo-Kobayashi-Maskawa mass mixing matrix established well enough (nuclear β decays, kaon decays, charm decays and b decays, in particular with ε_K and Δm_d with little uncertainty from the still unmeasured m_t), to make a firm statement such as
  - If CPV is generated by the CKM phase, CPV in the $B \to J/\psi K_S$ decays must be observed with $>5\sigma$ within a few years of running with an asymmetric B factory with a luminosity of $\sim 10^{33} cm^{-2} s^{-1}$

→ This was the main motivation for asymmetric B factories

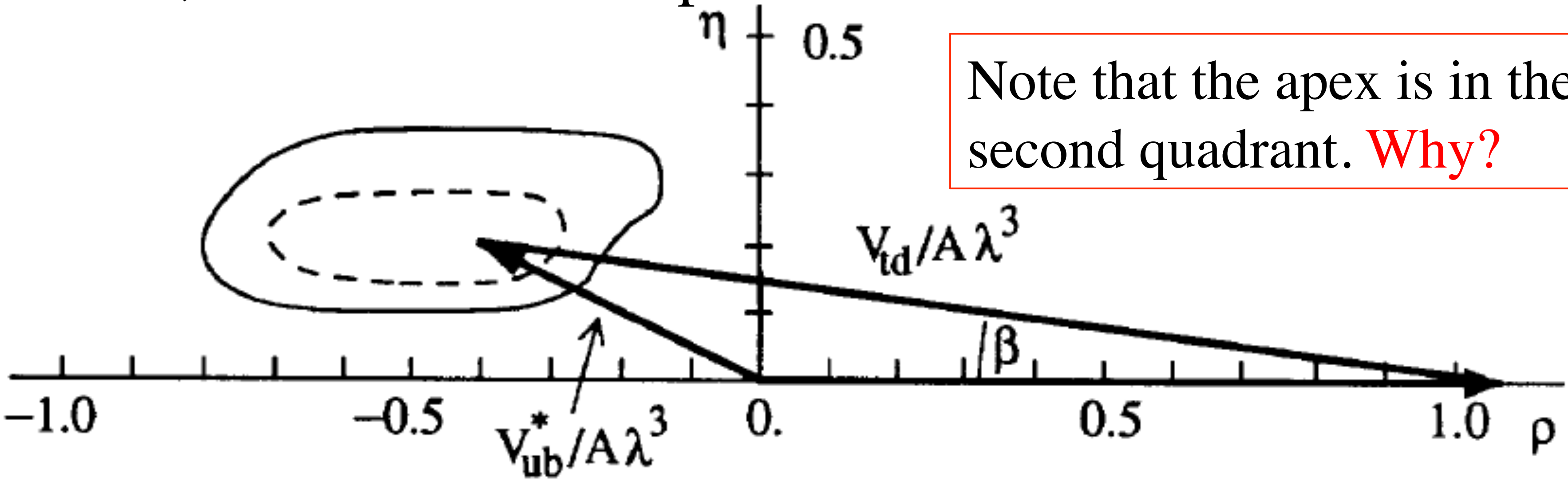
Standard Model Flavour Framework

- For example

$$\mathrm{Im}(\lambda) \approx \frac{2\sqrt{2}|\varepsilon|}{A^2 S_c^4}\left(\frac{\Delta m_K}{\Delta m_B}\right)\left(\frac{m_B}{m_K}\right)\left(\frac{\eta_B}{\eta_3}\right)\left(\frac{f_B^2 B_B}{f_K^2 B_K}\right)$$
$$\approx 0.3\cdot\left(\frac{1}{A^2}\right)\cdot\left(\frac{f_B^2 B_B}{f_K^2 B_K}\right).$$

f_B was considered to be $\approx$ 110 MeV at that time
Now $\approx$ 230 MeV

- From "Feasibility study for a B-meson factory in the ISR tunnel", CERN Yellow Report CERN 90-02



Note that the apex is in the second quadrant. Why?

Some details on V_{CKM}

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

First 2×2 sub-matrix: four $|V_{ij}|$ are measured by nucleus, pion, kaon and charm hadron decays

It is "almost" unitary with one single parameter

$\lambda \ (\equiv \sin\theta_{\mathrm{Cabibbo}}) = |V_{us}| = 0.2252 \pm 0.0009$ (PDG 2012)

$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1 & \lambda & V_{ub} \\ -\lambda & 1 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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$|V_{cb}|$ and $|V_{ub}|$ measured by semileptonic B_u and B_d decays

$$|V_{cb}| = \begin{cases} (41.9 \pm 0.7)\times 10^{-3} \text{ inclusive} \\ (39.6 \pm 0.9)\times 10^{-3} \text{ exclusive} \end{cases}$$

2.0σ discrepancy

(PDG 2012)

-errors limited theoretically-

$$|V_{ub}| = \begin{cases} (4.41 \pm 0.15\ {}^{+0.15}_{-0.19})\times 10^{-3} \text{ inclusive} \\ (3.23 \pm 0.31)\times 10^{-3} \text{ exclusive} \end{cases}$$

~3σ discrepancy

(PDG 2012)

-errors very limited theoretically-

Exclusives systematically smaller than inclusive?

Better QCD calculations needed.

Some details on V_{CKM}

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$\arg V_{cb} = 0$ by a phase convention

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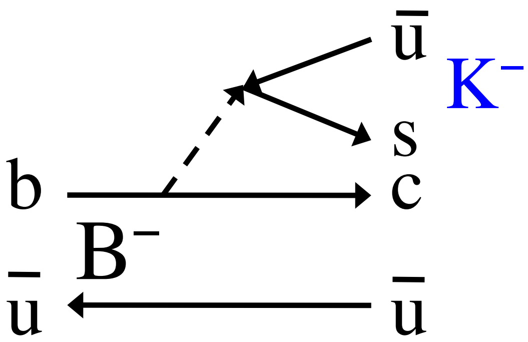
$\arg V_{ub}$ by CP violation in $B \rightarrow DK$

Some details on V_{CKM}

arg V_{ub} so called angle "γ" or "ϕ_1"

two decay diagrams producing identical final states



$V_{cb}V_{us}^*$

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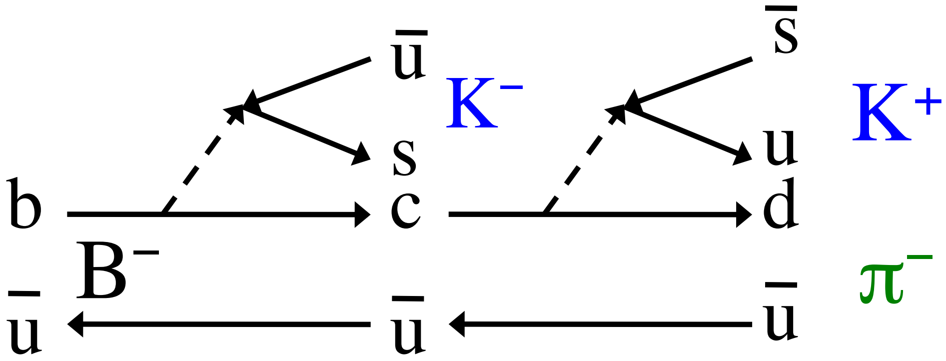

$V_{cb}V_{us}{}^{*}V_{cd}{}^{*}V_{us}$

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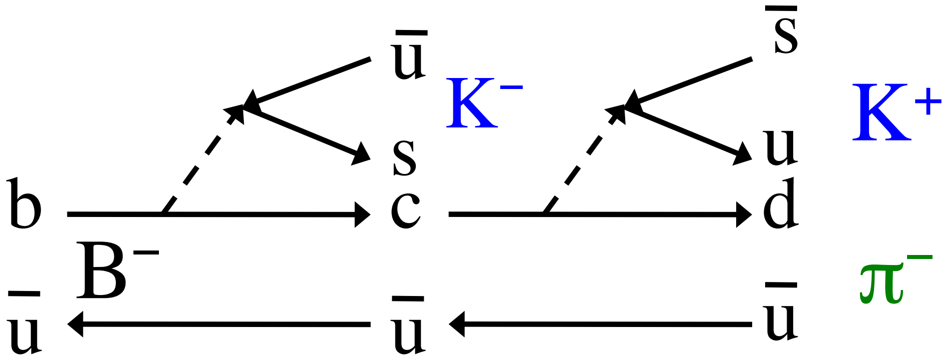
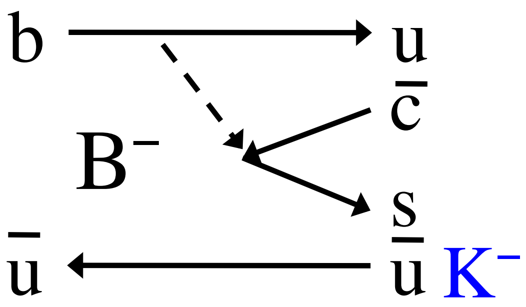


$V_{cb}V_{us}^*V_{cd}^*V_{us}$



$V_{ub}V_{cs}^*$

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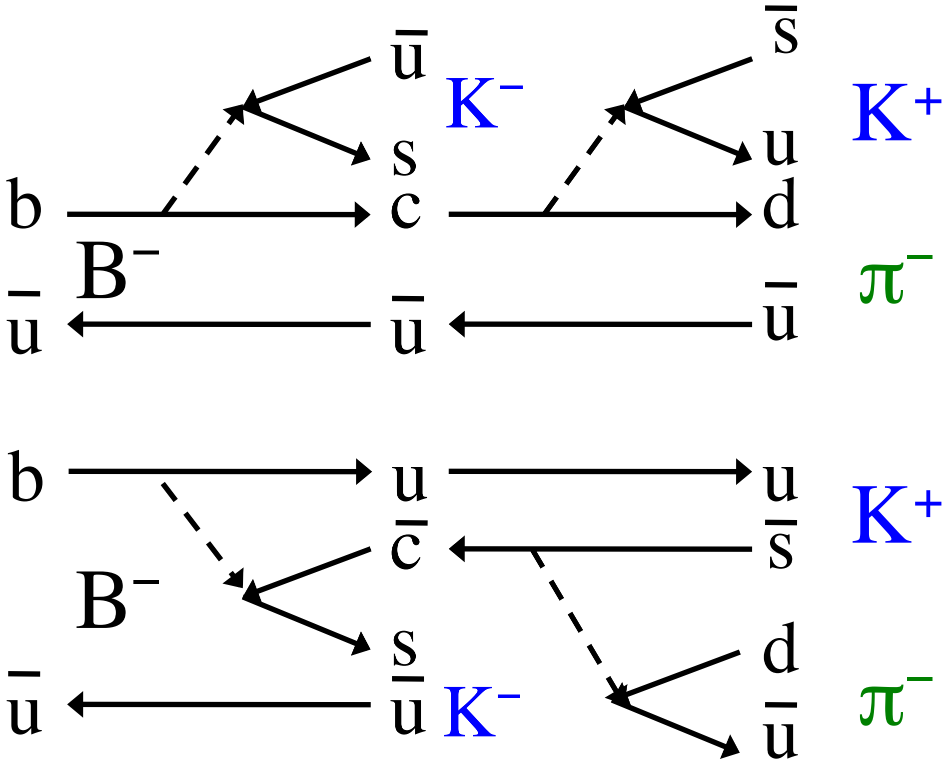

$V_{cb}V_{us}{}^{*}V_{cd}{}^{*}V_{us}$

$V_{ub}V_{cs}{}^{*}V_{ud}{}^{*}V_{cs}$

Some details on V_{CKM}

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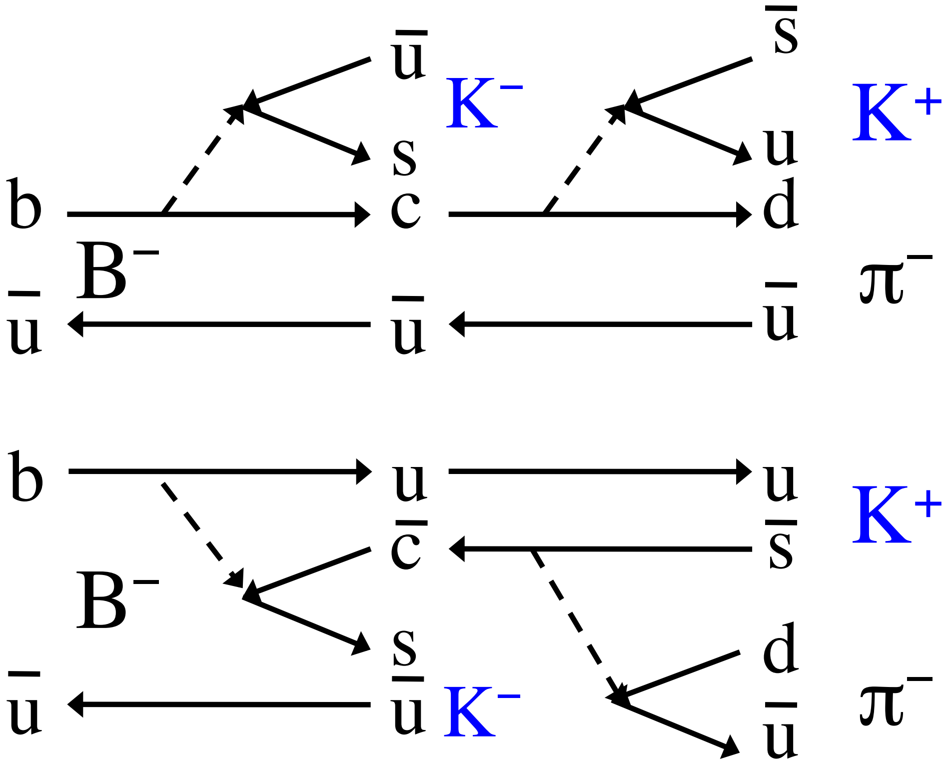


$V_{cb}V_{us}{}^{*}V_{cd}{}^{*}V_{us}$

$V_{ub}V_{cs}{}^{*}V_{ud}{}^{*}V_{cs}$

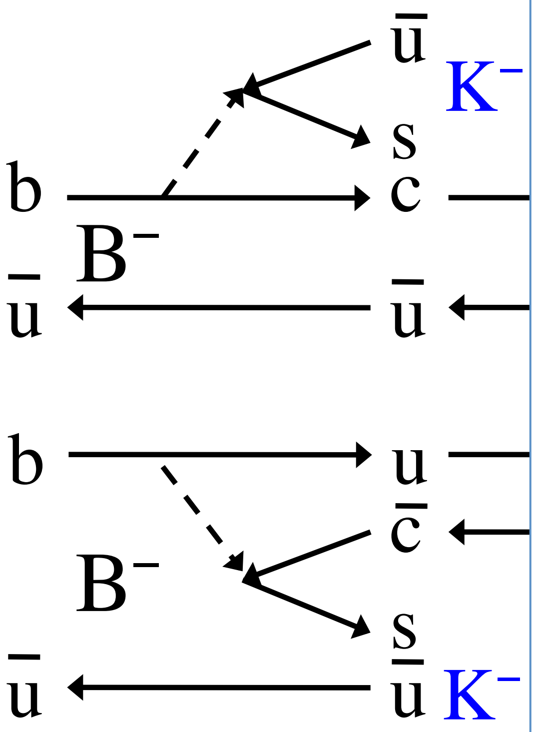
interfere → CPV $F(\arg V_{ub})$

$\mathrm{Br}\,(B^- \to [K^+\pi^-]_{D\text{-mass}}\,K^-) \neq \mathrm{Br}\,(B^+ \to [K^-\pi^+]_{D\text{-mass}}\,K^+)$

Some details on V_{CKM}

arg V_{ub} so called angle "γ" or "ϕ_1"

two decay diagrams producing identical final states



What kind of diagrams?

$V_{cd}^*V_{us}$

$V_{ud}^*V_{cs}$

interfere

→ CPV

$F(\arg V_{ub})$

Br ($B^-\rightarrow[K^+\pi^-$ … $[K^-\pi^+]_{D\text{-mass}}\ K^+$)

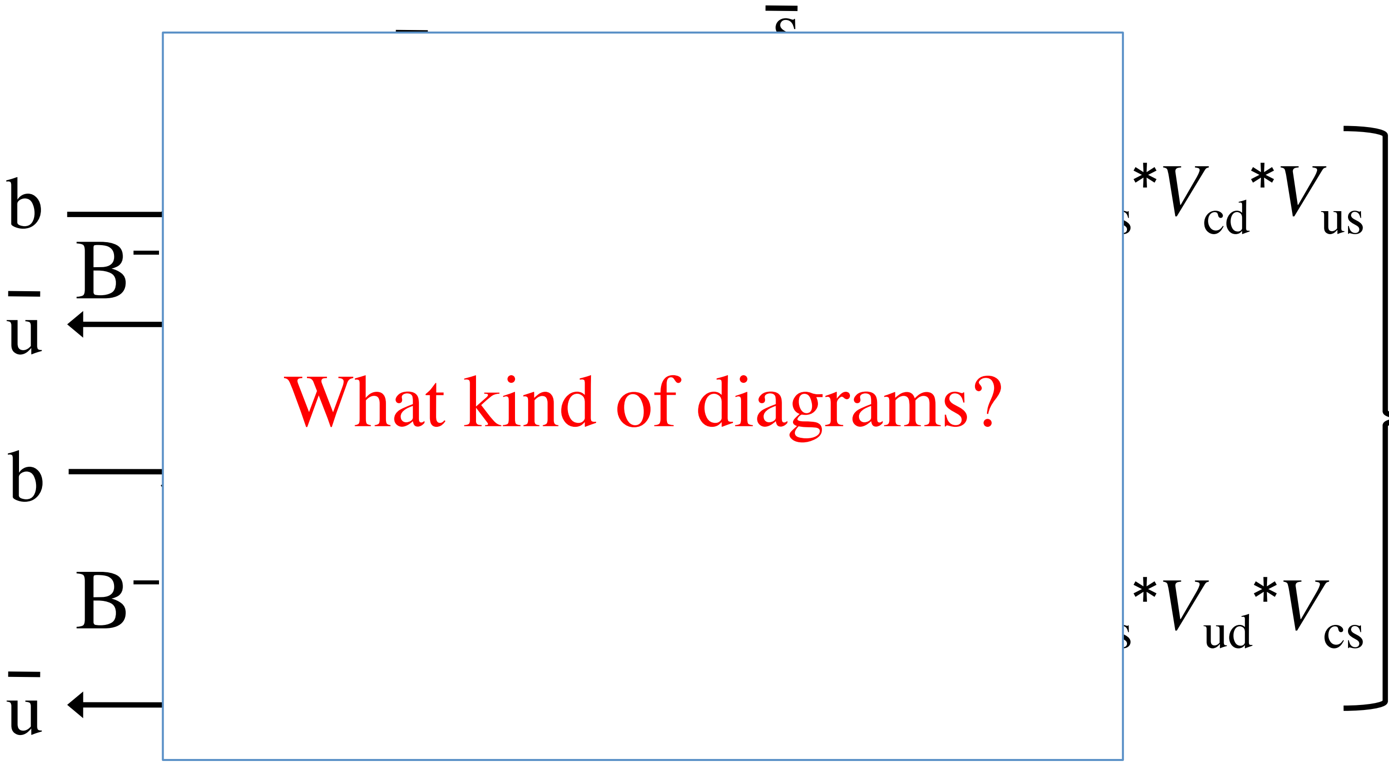
and also

Br ($B^-\rightarrow[K^-\pi^+]_{D\text{-mass}}\ K^-$) ≠ Br ($B^+\rightarrow[K^+\pi^-]_{D\text{-mass}}\ K^+$)

Some details on V_{CKM}

arg V_{ub} so called angle "γ" or "ϕ_1"

two decay diagrams producing identical final states



interfere

$\rightarrow$ CPV

$F(\arg V_{ub})$

$Br\,(B^- \rightarrow [K^+K^-]_{D\text{-mass}}\,K^-) \neq Br\,(B^+ \rightarrow [K^+K^-]_{D\text{-mass}}\,K^+)$

$Br\,(B^- \rightarrow [\pi^+\pi^-]_{D\text{-mass}}\,K^-) \neq Br\,(B^+ \rightarrow [\pi^+\pi^-]_{D\text{-mass}}\,K^+)$

Some details on V_{CKM}

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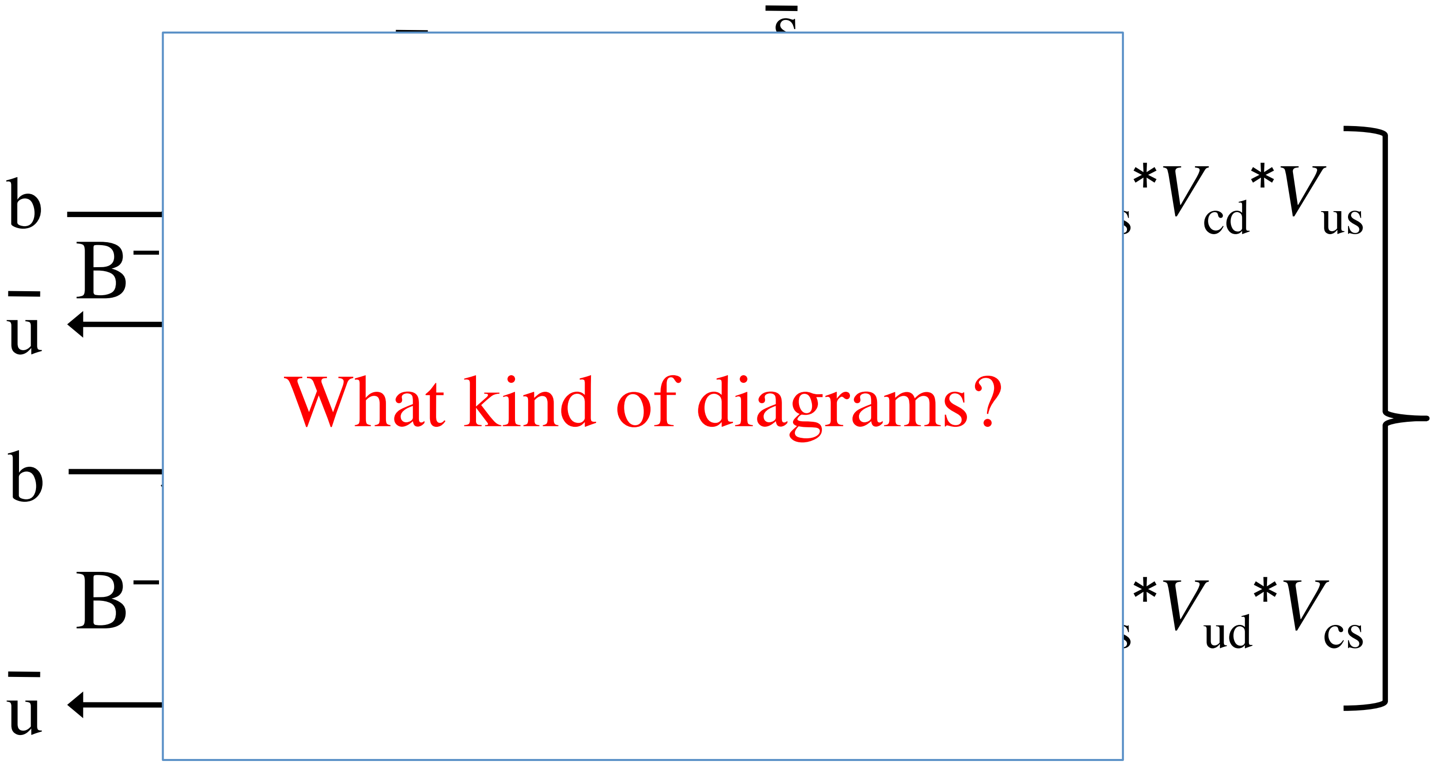

interfere

→ CPV

$F(\arg V_{ub})$

Br $(B^- \to [K_S\pi^+\pi^-]_{D\text{-mass}} K^-) \neq$ Br $(B^+ \to [K_S\pi^+\pi^-]_{D\text{-mass}} K^+)$

Dalitz $(K_S\pi^+\pi^-)$ plot analysis needed

Some details on V_{CKM}

arg V_{ub} so called angle "γ" or "ϕ_1"

two decay diagrams producing identical final states

Pre-LHC average = $(68 \,^{+10}_{-11})^{\circ}$ (PDG 2012)

-Determined by the "tree" level amplitude interference between V_{cb} and V_{ub} no "New Physics" effect

-Based on the e^+e^- B factory experiments: BABAR and BELLE

-LHCb contribution next lecture

Pre-LHC Status of V_{CKM}

$$V_{CKM} \approx \begin{pmatrix} 1 & \lambda & V_{ub} \\ -\lambda & 1 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{cb}|$ and $|V_{ub}|$ measured by semileptonic B_u and B_d decays

arg $V_{cb} = 0$ by a phase convention

arg V_{ub} by CP violation in $B \rightarrow DK$

$V_{tb} \approx 1$ if we assume V_{CKM} to be unitary

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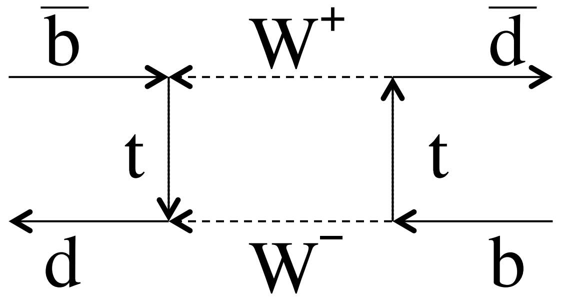
$V_{tb} \approx 1$ if we assume V_{CKM} to be unitary
$|V_{td}|\times|V_{tb}|$ by B^0-B^0 oscillation frequency (Δm_d)
$|V_{ts}|\times|V_{tb}|$ by B_s^0-B_s^0 oscillation frequency (Δm_s)

Some details on V_{CKM}

B-$\overline{\mathrm{B}}$ oscillation: dispersive part of the box diagram: M_{12}



$$\Delta m = 2|M_{12}| \propto |V_{td}|^2\,|V_{tb}|^2$$
$$= (0.507 \pm 0.004)\ \mathrm{ps}^{-1} \quad \text{(PDG 2012)}$$

Some details on V_{CKM}

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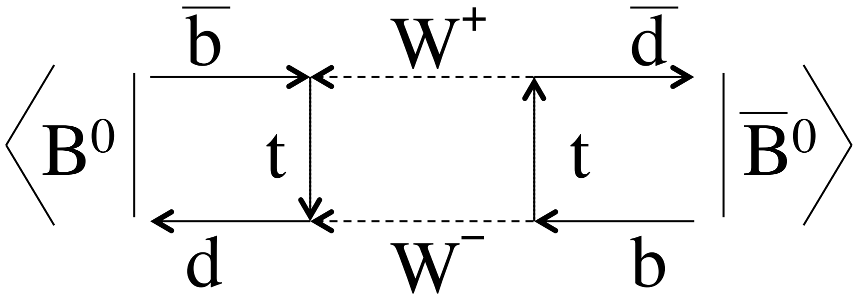

$$\Delta m = 2|M_{12}| \propto B_d f_d^{\,2} |V_{td}|^2\, |V_{tb}|^2$$
$$= (0.507 \pm 0.005)\ \mathrm{ps}^{-1}$$ (PDG 2010)

$Bf^{\,2}$: hadronic matrix elements

Some details on V_{CKM}

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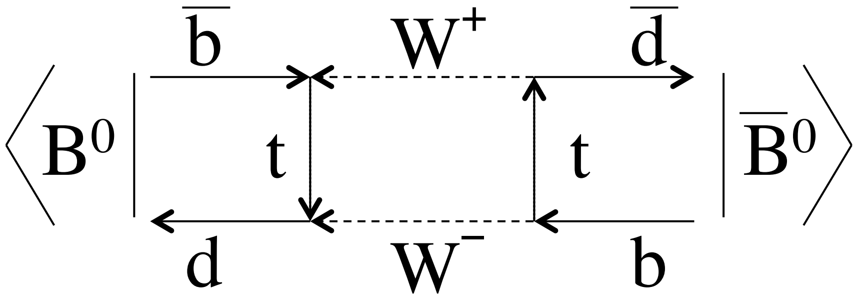

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$\arg = M_{12} = \arg\,(V_{td}{}^* V_{tb})^2 + \pi$

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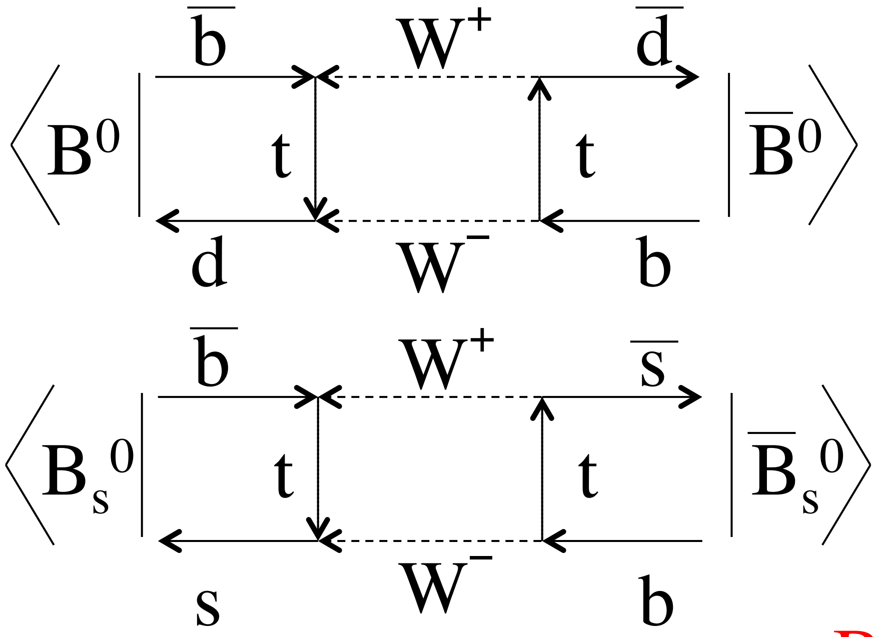
Some details on V_{CKM}

$B\text{-}\bar{B}$ oscillation: dispersive part of the box diagram: M_{12}



$$\Delta m = 2|M_{12}| \propto B_d f_d^2 |V_{td}|^2\ |V_{tb}|^2$$

$$= (0.507 \pm 0.005)\ \text{ps}^{-1} \quad \text{(PDG 2012)}$$

$$\arg = M_{12} = \arg\,(V_{td}{}^* V_{tb})^2 + \pi$$

$$\Delta m_s = 2|M_{12}| \propto B_s f_s^2 |V_{ts}|^2\ |V_{tb}|^2$$

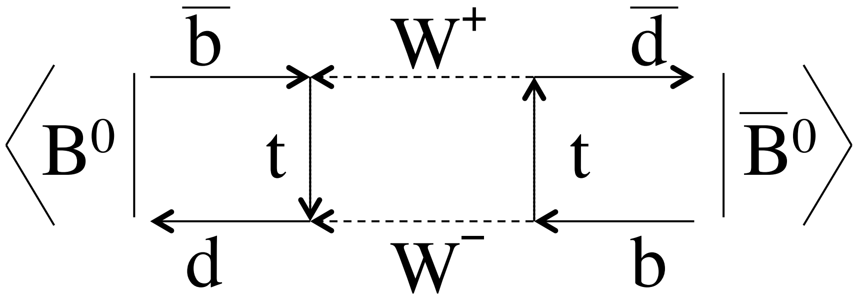
$$= (17.719 \pm 0.043)\ \text{ps}^{-1} \quad \text{(PDG 2012)}$$

$$\arg M_{12} = \arg\,(V_{ts}{}^* V_{tb})^2 + \pi$$

Bf^2: hadronic matrix elements

Some details on V_{CKM}

$\mathrm{B}\text{-}\overline{\mathrm{B}}$ oscillation: dispersive part of the box diagram: M_{12}



$\Delta m = 2|M_{12}| \propto B_d f_d^{\,2} |V_{td}|^2\,|V_{tb}|^2$

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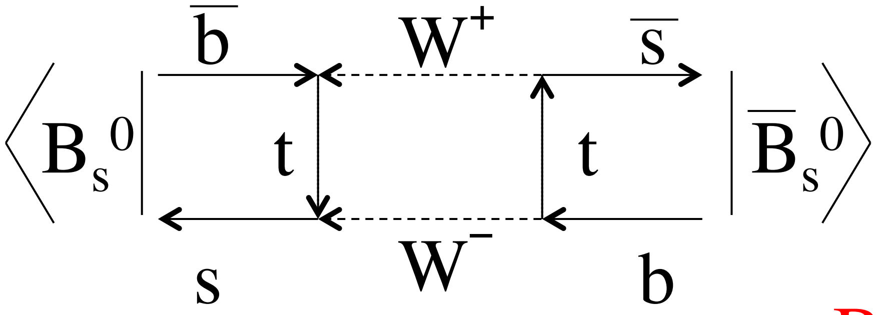


$\Delta m_s = 2|M_{12}| \propto B_s f_s^{\,2} |V_{ts}|^2\,|V_{tb}|^2$

$= (17.719 \pm 0.043)\ \mathrm{ps}^{-1}$ (PDG 2012)

$\arg M_{12} = \arg\,(V_{ts}{}^* V_{tb})^2 + \pi$

$Bf^{\,2}$: hadronic matrix elements

$|V_{td}| = (8.4 \pm 0.6)\times 10^{-3}$

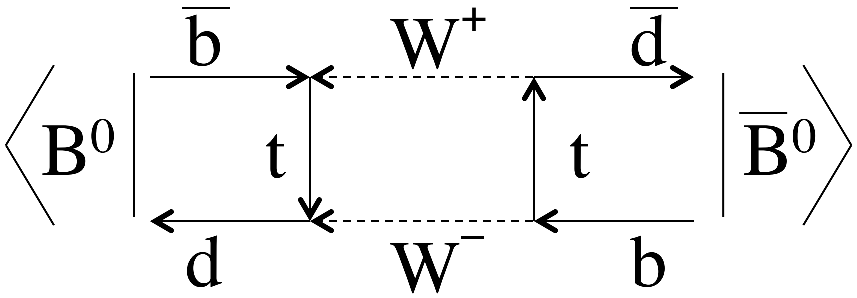
$|V_{ts}| = (42.9 \pm 2.6)\times 10^{-3}$

} errors are totally theoretical: $Bf^{\,2}$

(PDG 2012)

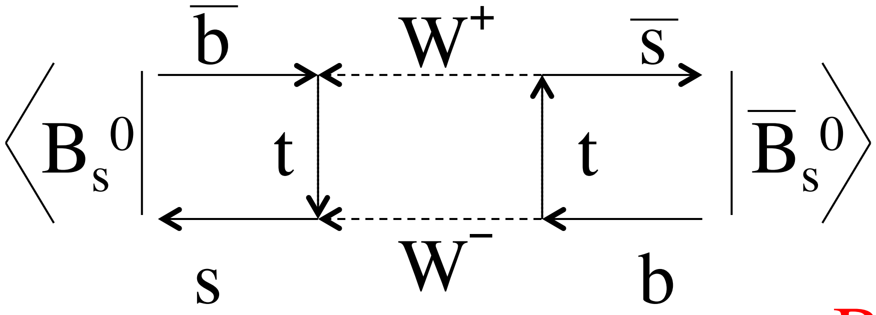
Some details on V_{CKM}

B-$\overline{\text{B}}$ oscillation: dispersive part of the box diagram: M_{12}



$$\Delta m = 2|M_{12}| \propto B_d f_d^{\,2} |V_{td}|^2\, |V_{tb}|^2$$
$= (0.507 \pm 0.005)$ ps^{-1} (PDG 2010)

$$\arg = M_{12} = \arg\, (V_{td}{}^{*} V_{tb})^2 + \pi$$



$$\Delta m_s = 2|M_{12}| \propto B_s f_s^{\,2} |V_{ts}|^2\, |V_{tb}|^2$$
$= (17.77 \pm 0.12)$ ps^{-1} (PDG 2010)

$$\arg M_{12} = \arg\, (V_{ts}{}^{*} V_{tb})^2 + \pi$$

$Bf^{\,2}$: hadronic matrix elements

$|V_{td}| = (8.4 \pm 0.6) \times 10^{-3}$
$|V_{ts}| = (38.7 \pm 2.1) \times 10^{-3}$
} errors are totally theoretical: $Bf^{\,2}$
(PDG 2012)

$|V_{td}/V_{ts}| = 0.211 \pm 0.001 \pm 0.006$ $(B_d f_d^{\,2})/(B_s f_s^{\,2})$: smaller error
(PDG 2012) Δm_s measured only at the hadron machines

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$$V_{CKM} \approx \begin{pmatrix} 1 & \lambda & V_{ub} \\ -\lambda & 1 & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{cb}|$ and $|V_{ub}|$ measured by semileptonic B_u and B_d decays

$\arg V_{cb} = 0$ by a phase convention

$\arg V_{ub}$ by CP violation in $B \rightarrow DK$

$V_{tb} \approx 1$ if we assume V_{CKM} to be unitary

$|V_{td}| \times |V_{tb}|$ by B^0-B^0 oscillation frequency (Δm_d)

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$|V_{ts}| \times |V_{tb}|$ by $B_s{}^0$-$B_s{}^0$ oscillation frequency (Δm_s)

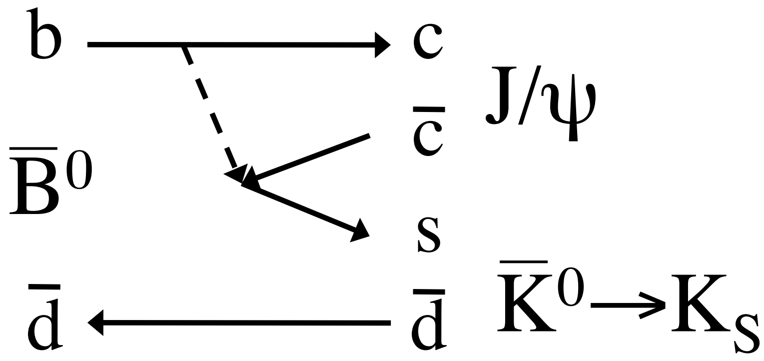
arg V_{td} by CP violation in $B_d \rightarrow J/\psi K_S$

arg V_{ts} by CP violation in $B_s \rightarrow J/\psi\phi$

Some details on V_{CKM}

$\overline{\mathrm{B}}^0 \longrightarrow \overline{\mathrm{B}}^0$ → $\mathrm{J}/\psi\ \mathrm{K_S}$

$\mathrm{b} \to \mathrm{c}+\bar{\mathrm{c}}\mathrm{s}$: $V_{\mathrm{cb}}V_{\mathrm{cs}}{}^* \propto e^{\iota 0}$

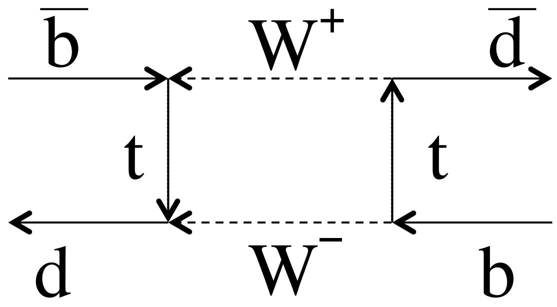


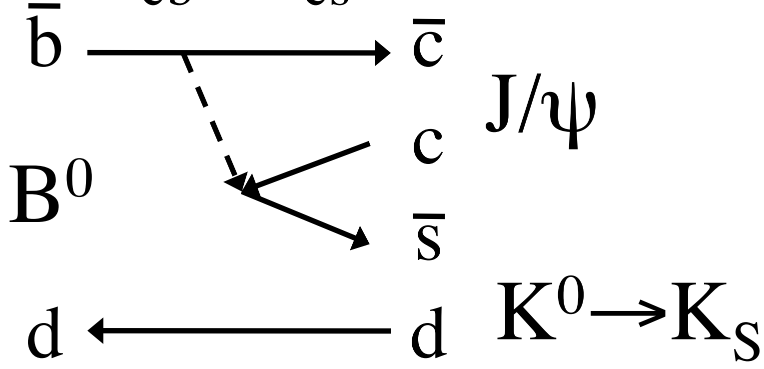
Some details on V_{CKM}

$\bar{B}^0 \rightarrow B^0 \rightarrow J/\psi\, K_S$

$M_{12} \propto -e^{2i\arg V_{td}}$

$\bar{b} \rightarrow \bar{c}+c\bar{s}:\ V_{cb}{}^{*}\, V_{cs} \propto e^{i0}$





Some details on V_{CKM}

$\bar{B}^0 \longrightarrow \bar{B}^0$ $\quad$ $b \to c+\bar{c}s$: $V_{cb}V_{cs}^* \propto e^{\iota 0}$

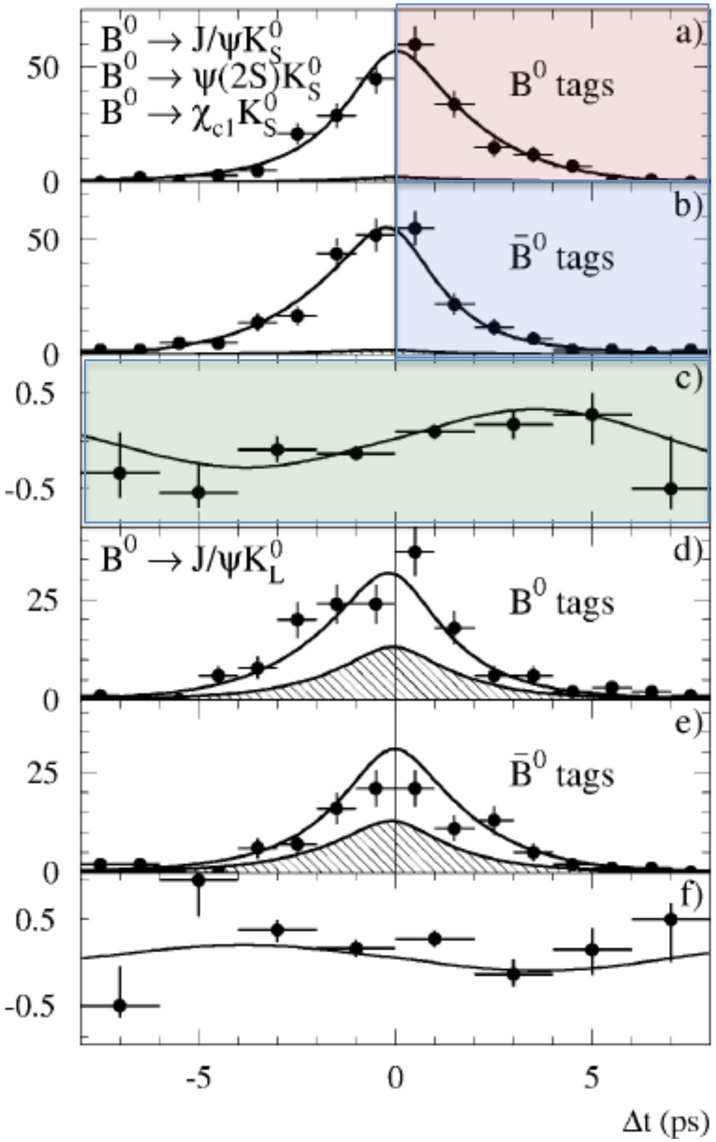
$\bar{B}^0 \to B^0$, $\quad \bar{B}^0 \to J/\psi\, K_S$, $\quad B^0 \to J/\psi\, K_S$

$J/\psi\ K_S$

$M_{12} \propto -e^{2i\arg V_{td}}$ $\quad B^0$ $\quad$ $\bar{b} \to \bar{c}+c\bar{s}$: $V_{cb}^* V_{cs} \propto e^{\iota 0}$

two processes interfere → CPV ∝ sin $2\arg V_{td}$

Some details on V_{CKM}

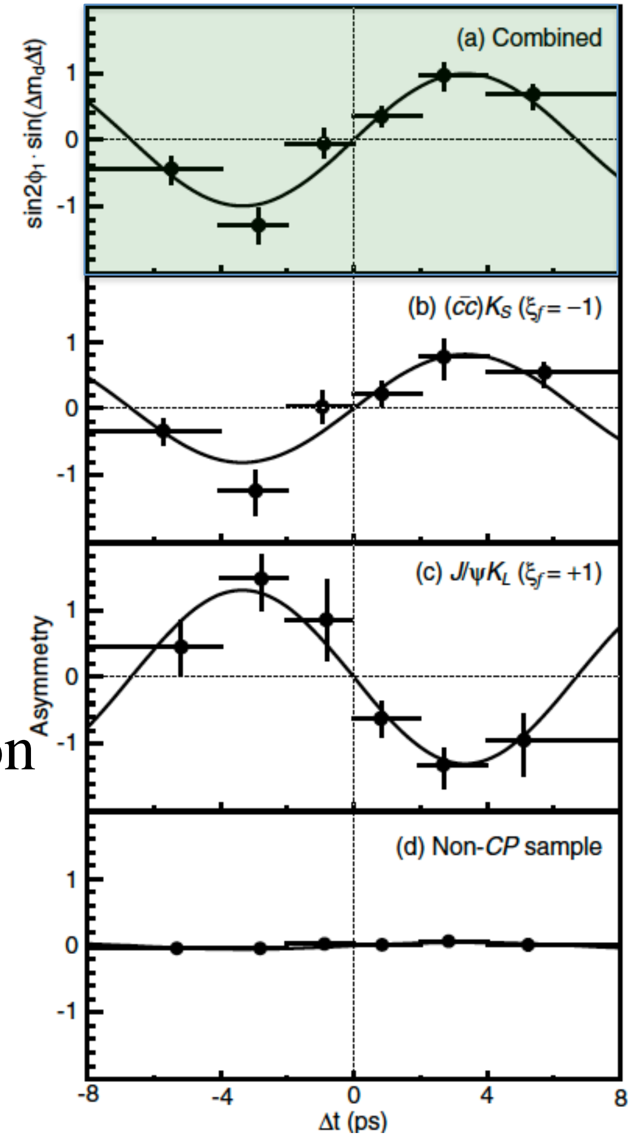


$\overline{B}^0_{t=0} \to J/\psi K_S(t)$

$B^0_{t=0} \to J/\psi K_S(t)$

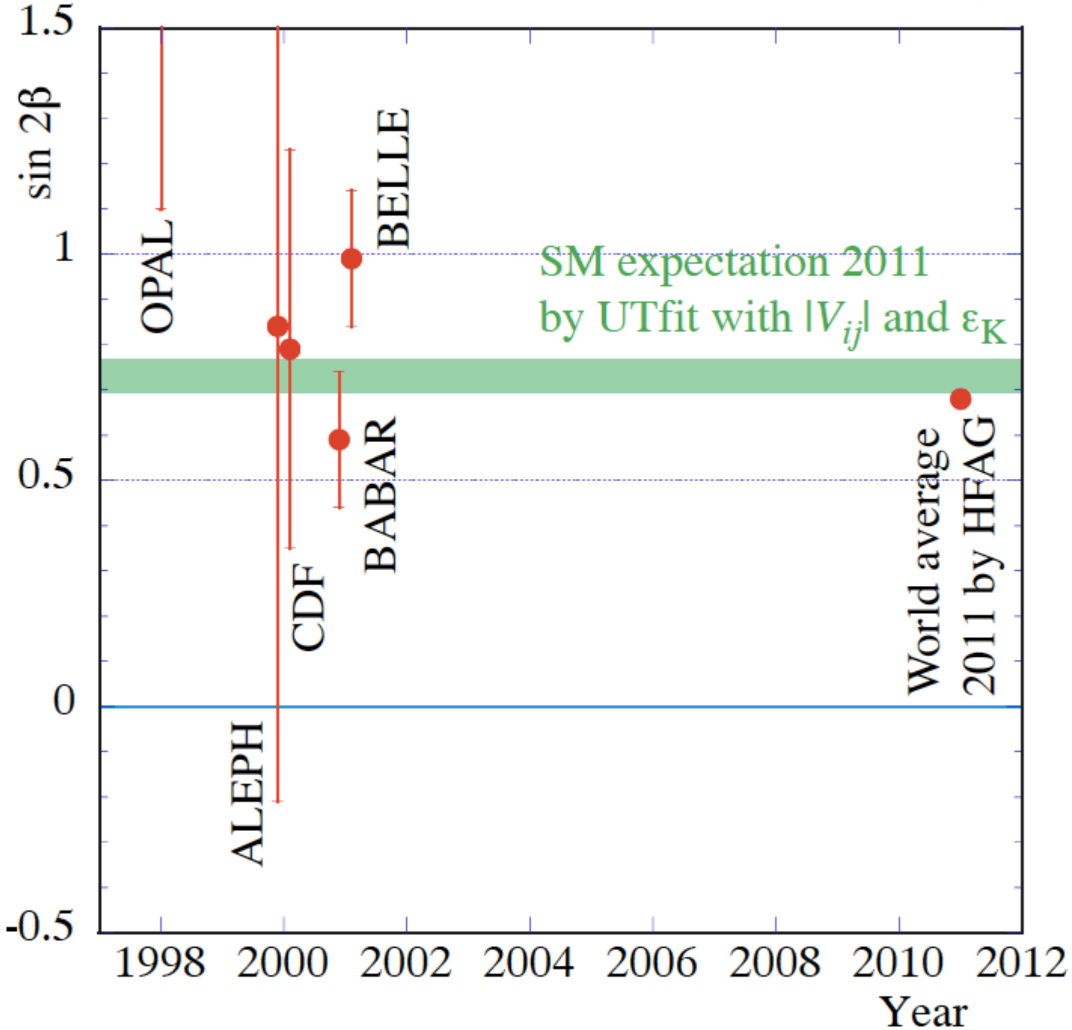
Time dependent CP asymmetries

The first observation
of CP violation
outside of
the kaon system
by the two
B factories



BABAR: Phys. Rev. Lett. 87, 091801 (2001) BELLE: Phys. Rev. Lett. 87, 091802 (2001)

Some details on V_{CKM}



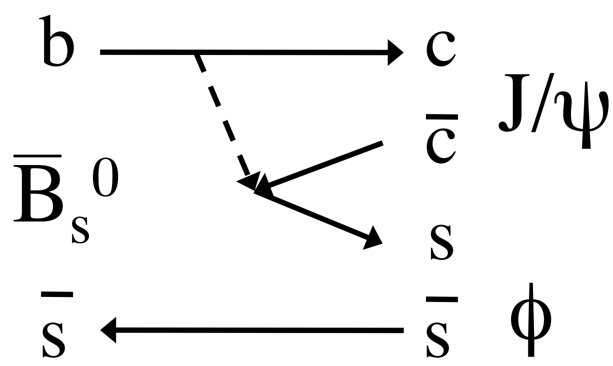
two processes interfere → CPV ∝ sin $2\arg V_{td}$

0.679 ± 0.020 (PDG 2012)

Some details on V_{CKM}

$\overline{B}_s^0 \longrightarrow \overline{B}_s^0 \longrightarrow J/\psi\phi$

$b \rightarrow c+\bar{c}s$: $V_{cb}V_{cs}^* \propto e^{\iota 0}$



Some details on V_{CKM}

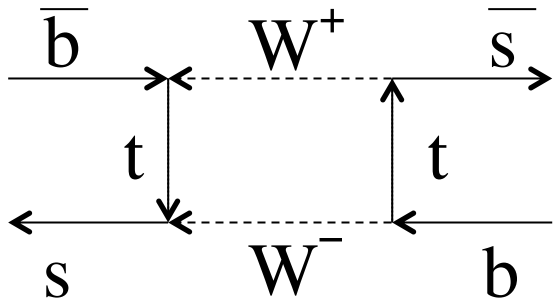
$\bar{B}_s^0$

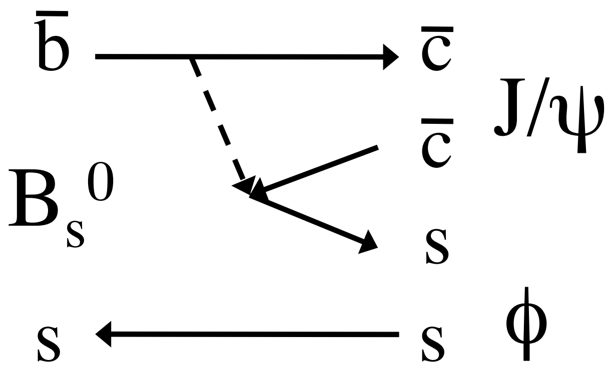
B_s^0 → J/ψ K_S or J/ψϕ

$M_{12} \propto -e^{2i\arg V_{td}}$

or $-e^{2i\arg V_{ts}}$

$\bar{b} \to \bar{c} + c\bar{s}$: $V_{cb}^* V_{cs} \propto e^{\iota 0}$





Some details on V_{CKM}

$\bar{B}_s^0 \longrightarrow \bar{B}_s^0$ $\quad b \to c+\bar{c}s$: $V_{cb}V_{cs}^* \propto e^{\iota 0}$

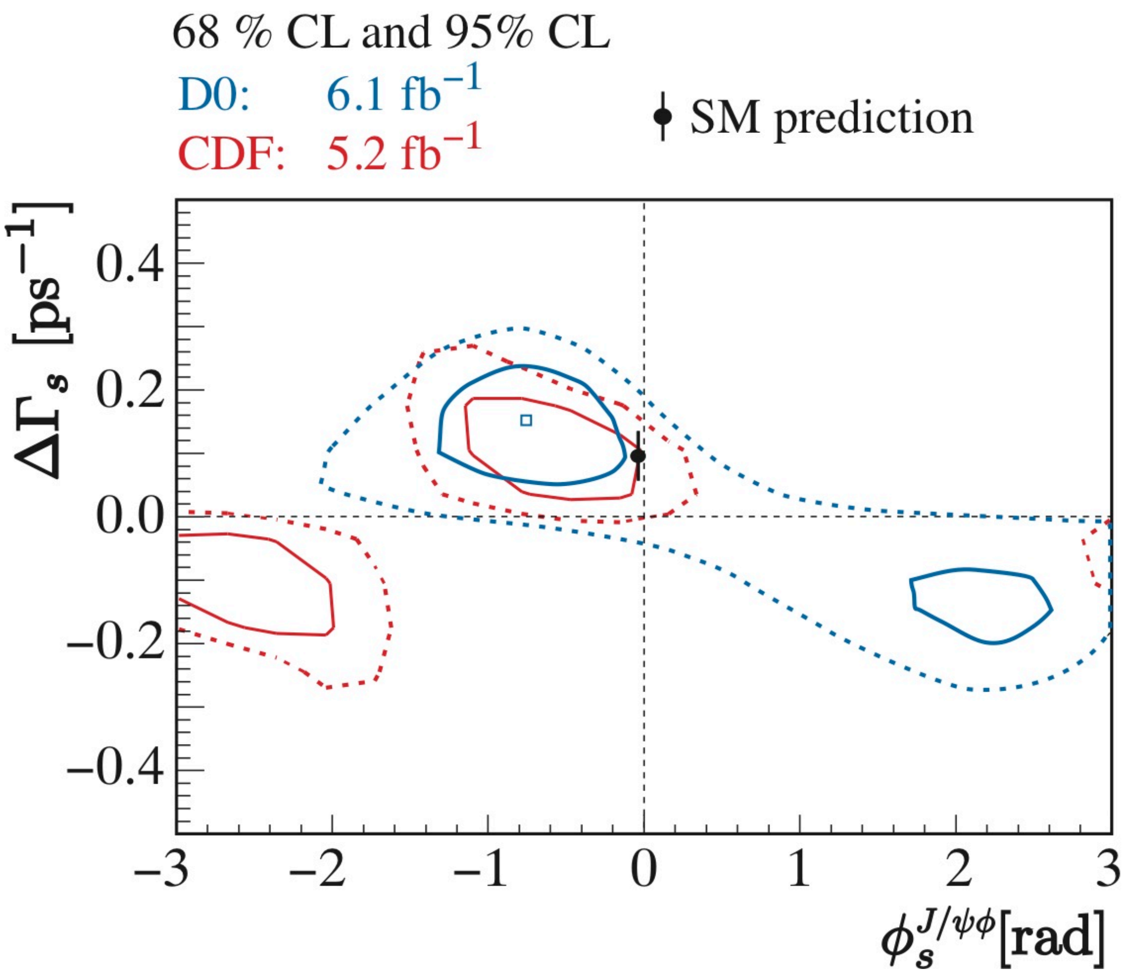
$\bar{B}_s^0 \searrow B_s^0$ $\quad \bar{B}_s^0, B_s^0 \to J/\psi\phi$

$M_{12} \propto -e^{2i\arg V_{ts}}$ $\quad B_s^0$ $\quad \bar{b} \to \bar{c}+c\bar{s}$: $V_{cb}^* V_{cs} \propto e^{\iota 0}$

two processes interfere → CPV ∝ sin $2\arg V_{ts}$

was not well measured before the start of LHCb

Some details on V_{CKM}



two processes interfere → CPV ∝ sin $2\arg V_{\mathrm{ts}}$

was not well measured before the start of LHCb

Some details on V_{CKM}

$$\approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right)$$

$$\hat{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

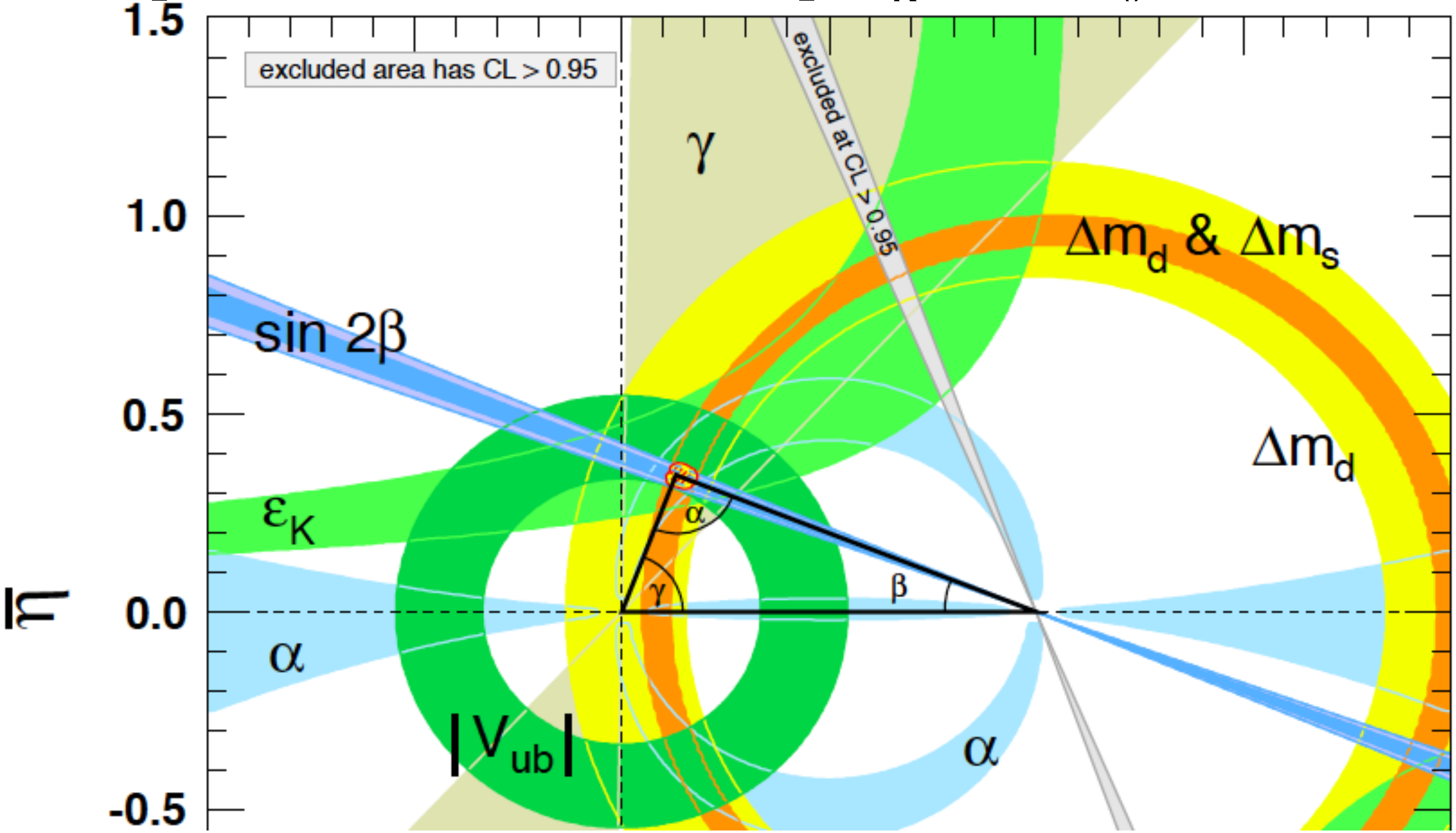
A from $|V_{\mathrm{cb}}|$, ρ and η from

- $|V_{\mathrm{ub}}|$ and $\arg V_{\mathrm{ub}}$
- $|V_{\mathrm{tb}}|$ and $\arg V_{\mathrm{tb}}$
- $|V_{\mathrm{ub}}|$ and $|V_{\mathrm{tb}}|$
- $|V_{\mathrm{td}}|$ and $\arg V_{\mathrm{ub}}$

many way to get solutions i.e. consistency can be checked

Summary of the V_{CKM}

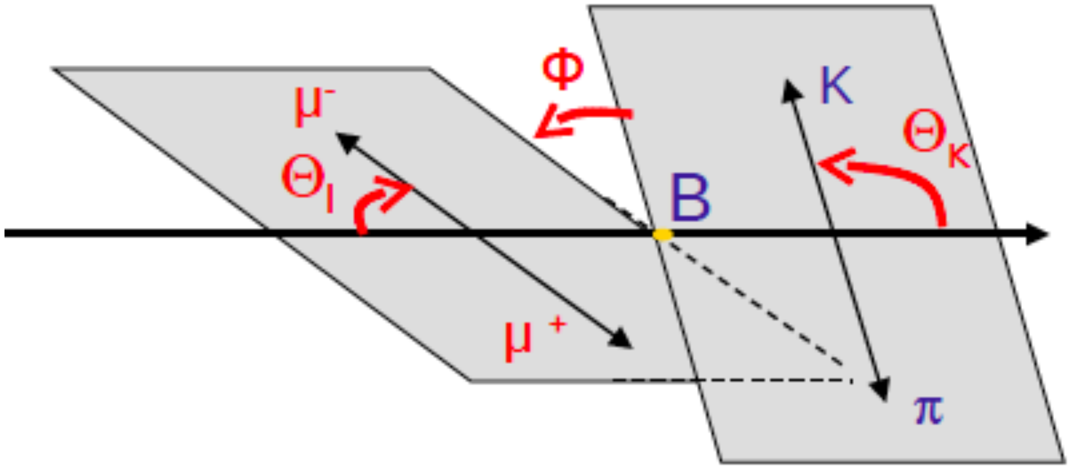
- All input from B factories, except ε_K and Δm_s

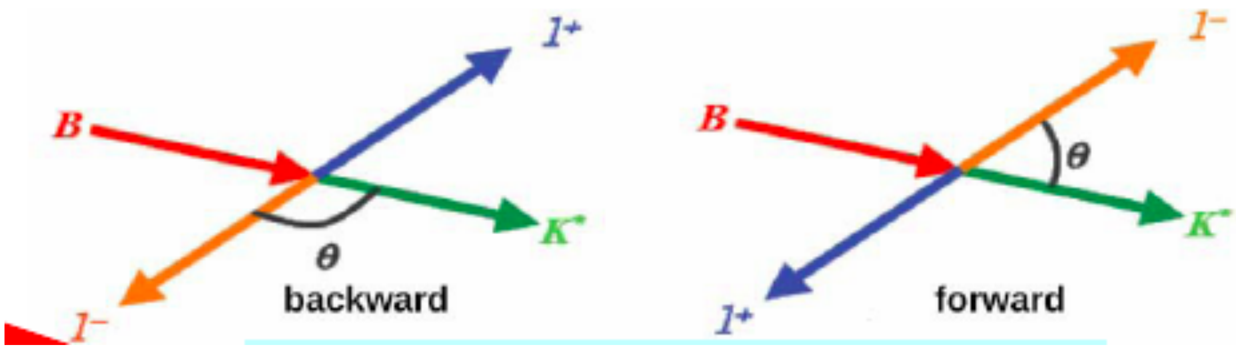


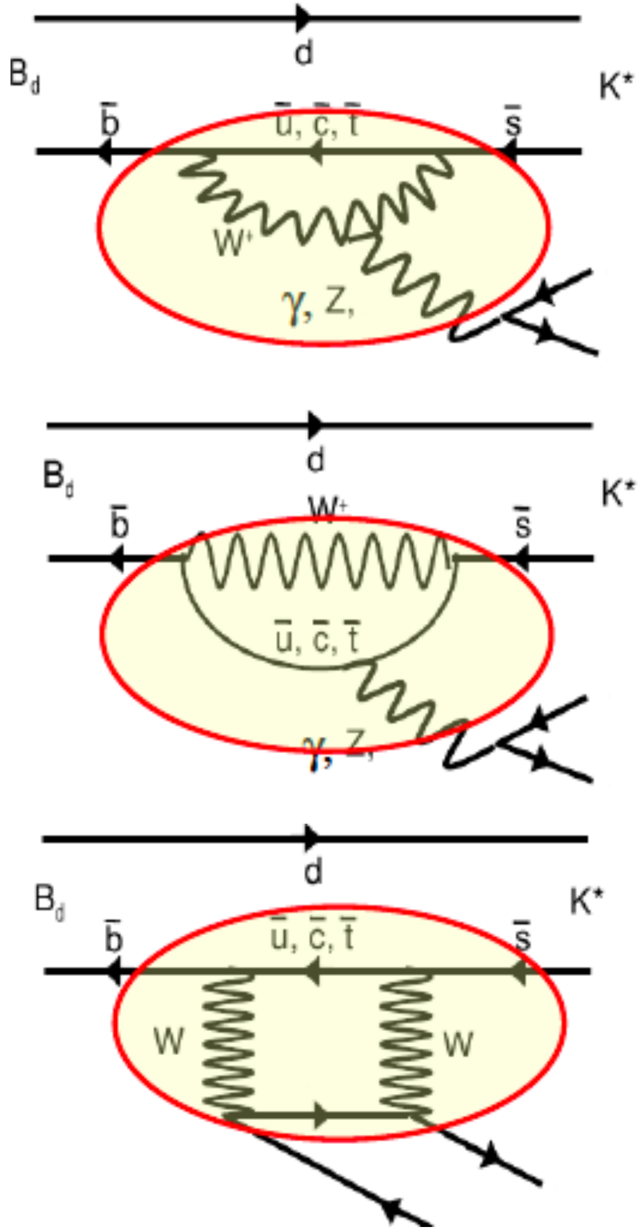
- All the measurements agree with the CKM framework

Lorentz structure of the loop

- Muon A_{FS} in $B^0 \rightarrow K^{*0}\mu^+\mu^-$





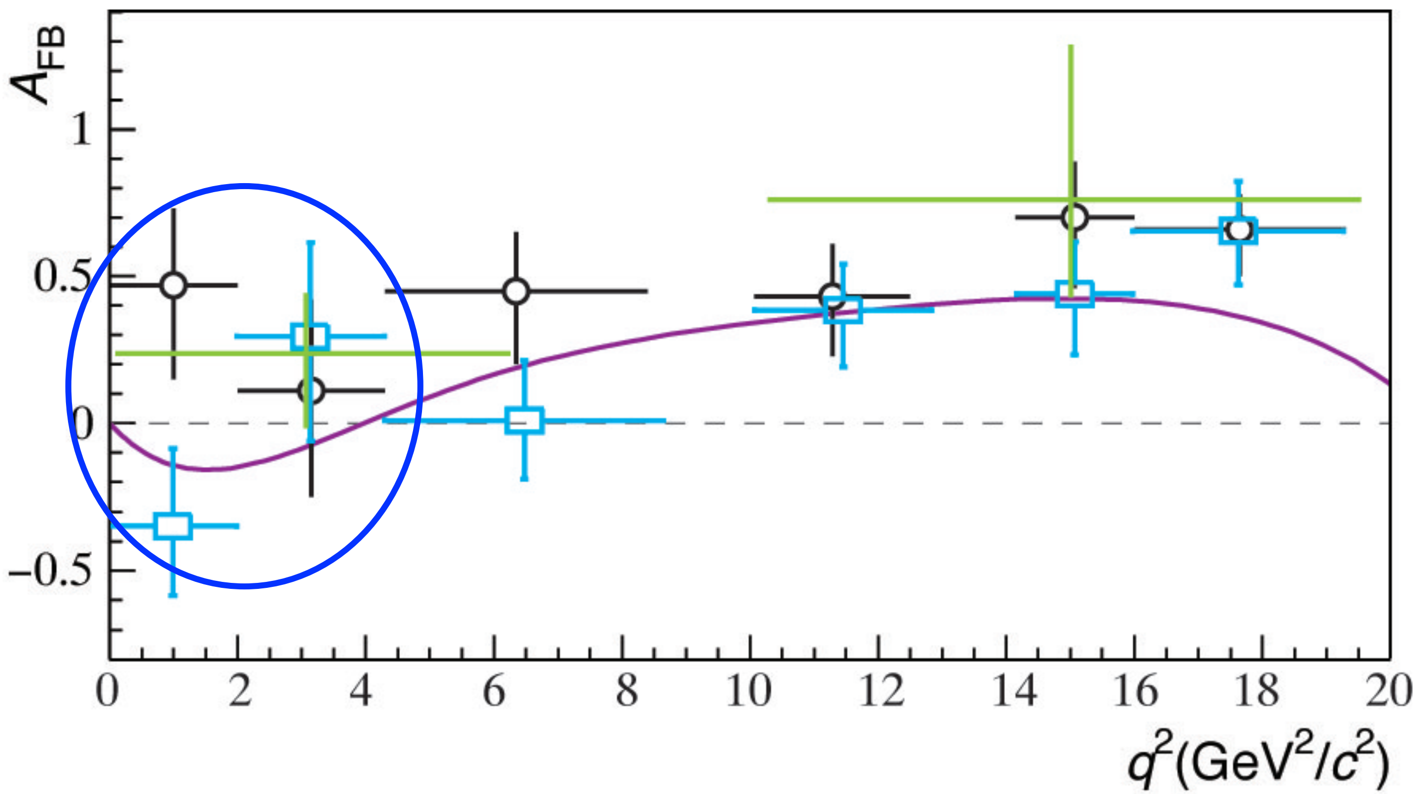


Lorentz structure of the loop

- Muon A_{FS} in $B^0 \to K^{*0}\mu^+\mu^-$

BELLE (PRL2009)
BABAR (PRD2009)
CDF (PRL2011)

Before the start of the LHC situation was not clear

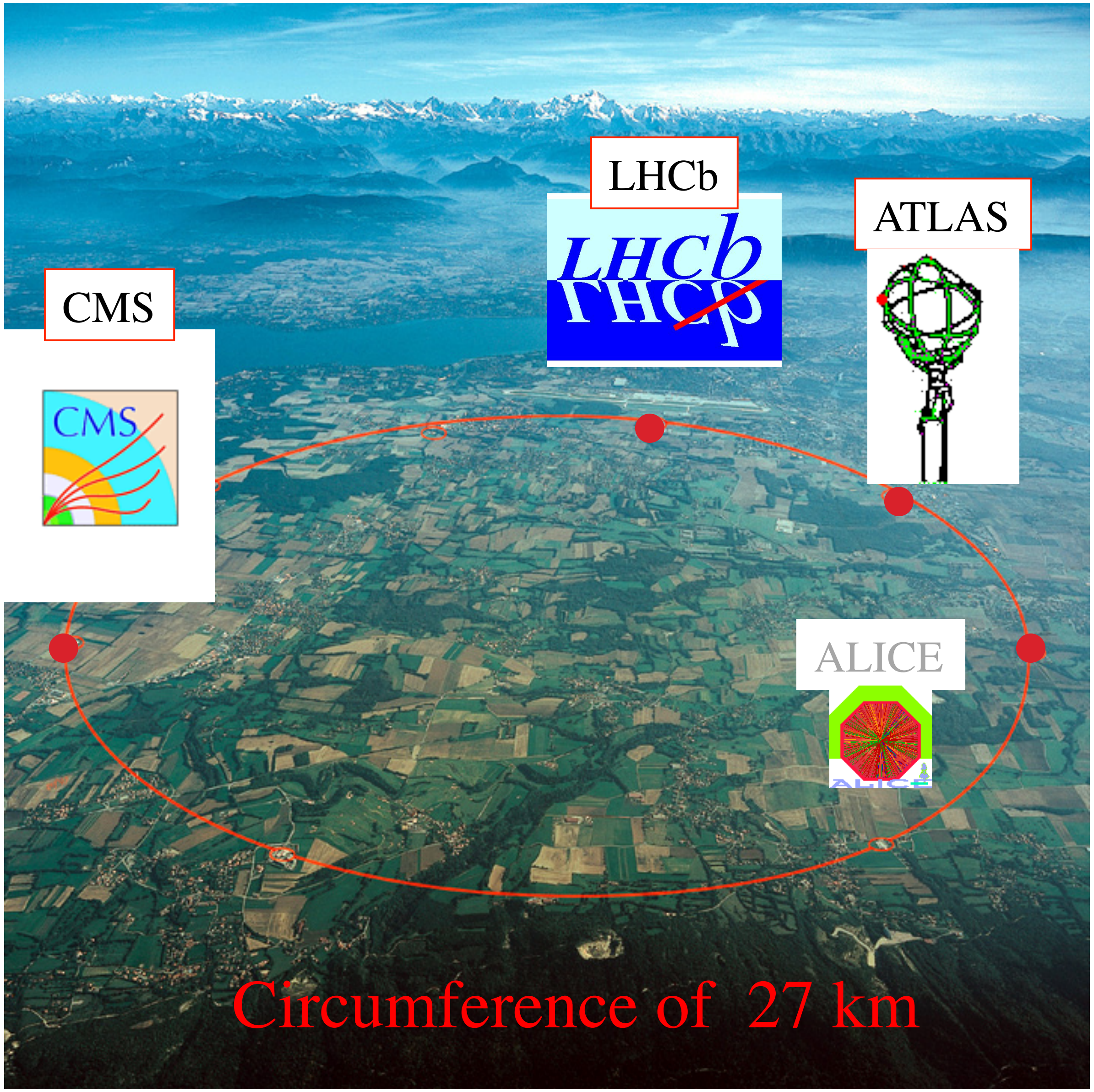


Standard model

Before the LHC start up

- BABAR and Belle, with high statistics B_u and B_d sample, successfully demonstrated that the quark flavour can be quantitatively well described by the CKM mechanism of the Standard Model, including CP violation. Their analysis went well beyond the original expectations, e.g. angle γ (ϕ_3) measurement.
- CDF and D0 have started to explore the B_s meson system: e.g. discovery of B_s-$\overline{B}_s$ oscillations:
- However, CP violation in the B_s system remained as a largely unexplored territory, as well as very rare decays, e.g. $B_{s,d}\to\mu^+\mu^-$, and high statistic decay topology studies of rare decays, e.g. $B_d\to K^{*0}\mu^+\mu^-$.
- Several evidences were seen for D-$\overline{D}$ oscillations, but statistics were not enough to explore CP violation.

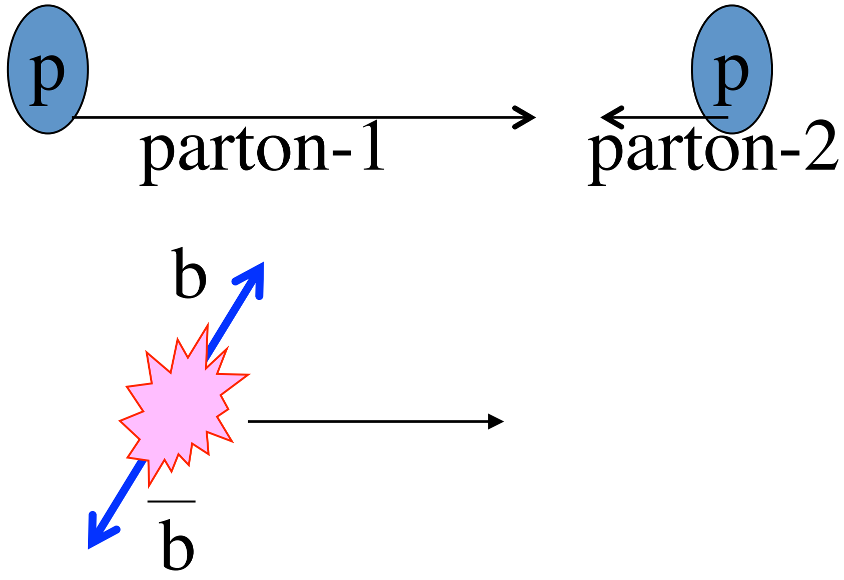
LHC with flavour relevant experiments



Flavour Physics at Hadron Machines

Production of heavy flavour

important input for designing an experiment



Flavour Physics at Hadron Machines

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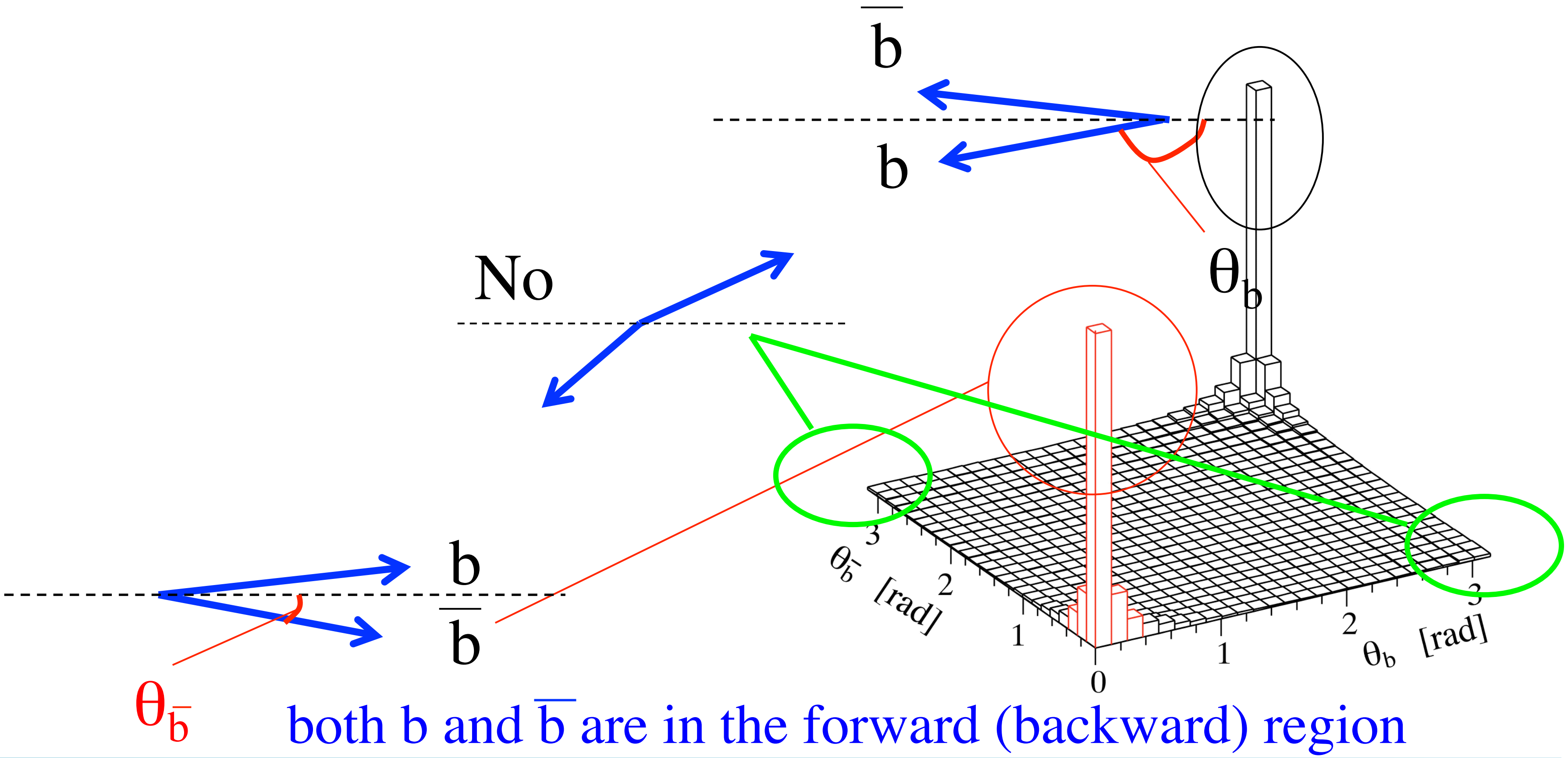
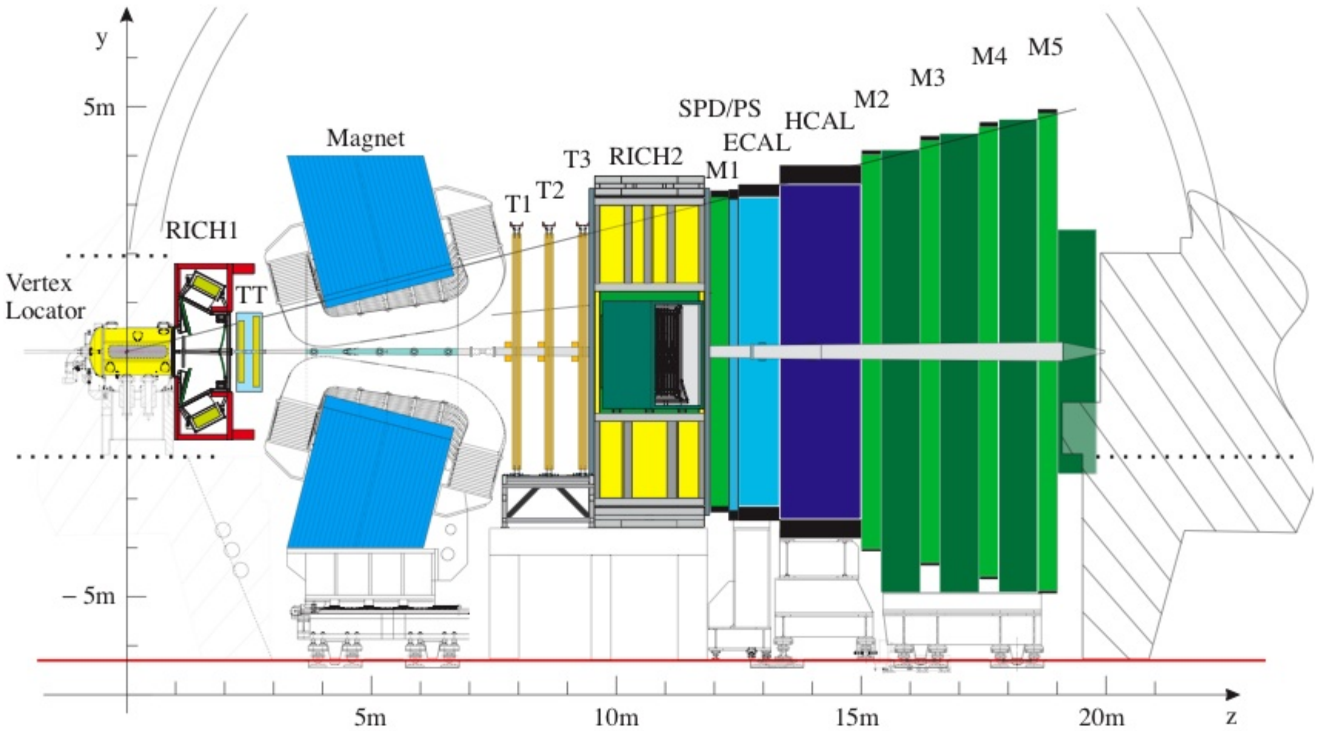


both b and $\bar{b}$ are in the forward (backward) region

Flavour Physics at Hadron Machines

that is why LHCb is a forward spectrometer



Flavour Physics at Hadron Machines

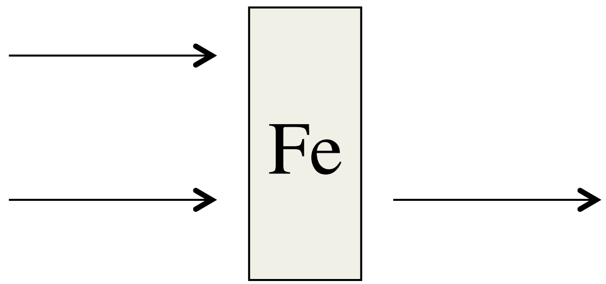
and additional advantage is

For triggering…. $p > p_{\mathrm{min}}$

muon: identification hadron: energy resolution

$p < p_{\mathrm{min}}$

$p > p_{\mathrm{min}}$



$\sigma_E/E \approx \sqrt{70\%}/\sqrt{E}$

Flavour Physics at Hadron Machines

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muon: identification

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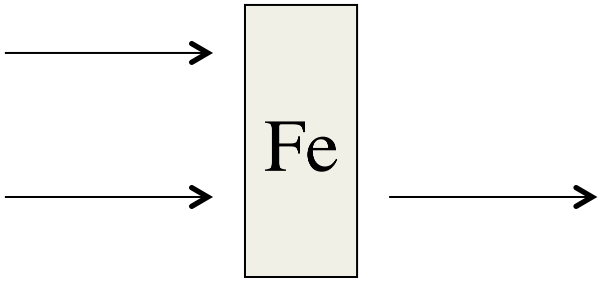
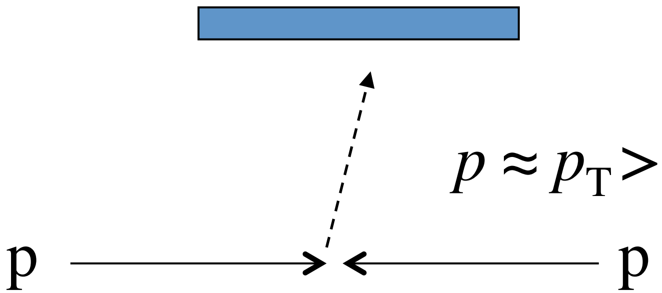


hadron: energy resolution

$\sigma_E/E \approx \sqrt{70\%}/\sqrt{E}$

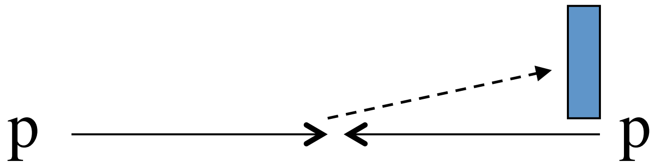
central detector



$p \approx p_T > p_{min}$

forward detector

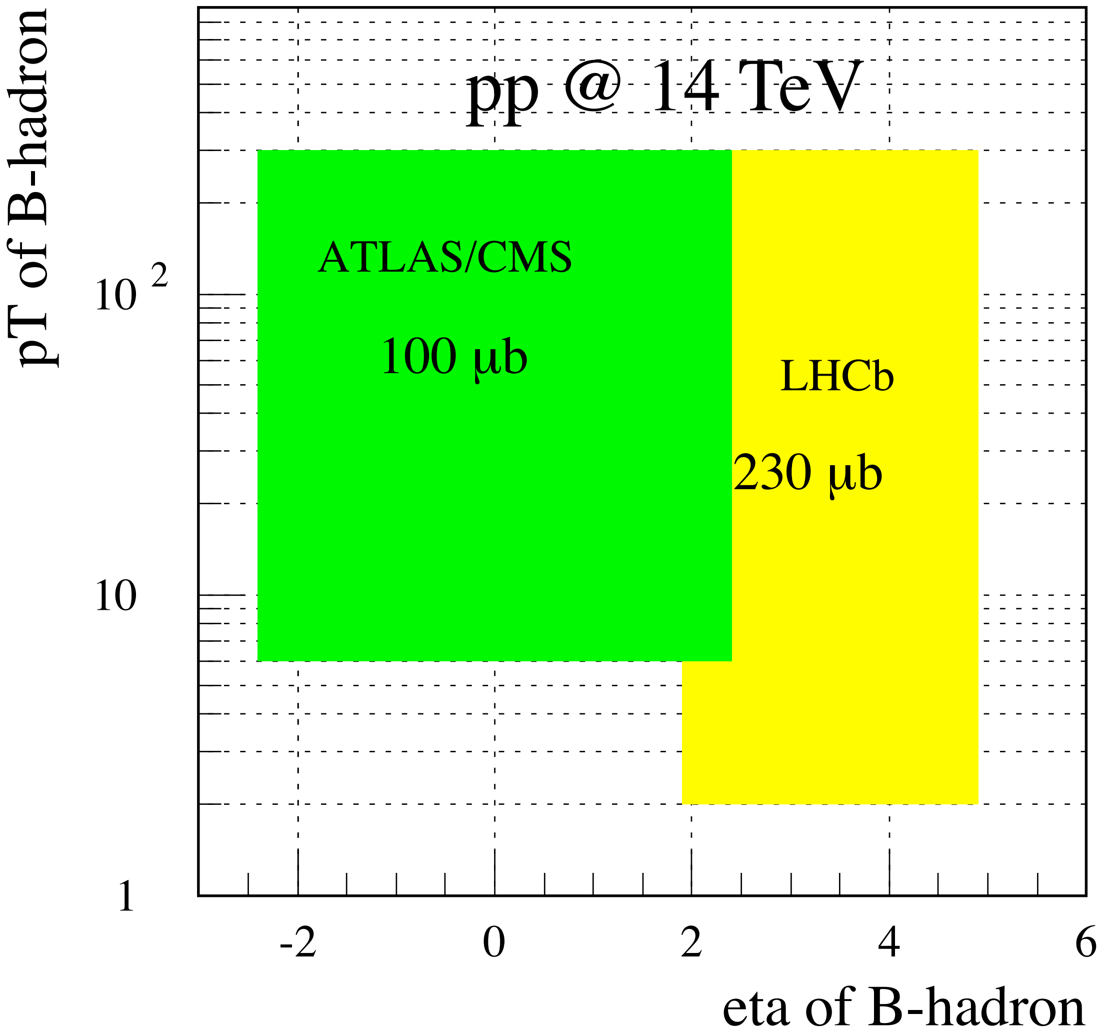
$p \approx p_L > p_{min}$



forward: p_T threshold can be set low: → high b efficiency

Flavour Physics at Hadron Machines

can exploit low p_T particles



Flavour Physics at Hadron Machines

Reconstruction of B **decay vertex with a good resolution** is essential to **reduce combinatorial background**:

decay vertex: >1 well reconstructed tracks
well reconstructed track =
- charged particle seen by vertex detector
- reconstructed particle from tracks measured by vertex detector

$D^0(K^-\pi^+)$, $D_s(K^+K^-\pi^+)$, etc., also K_S

examples are
$B_{(s)}{}^0 \to l^+l^-$, h^+h^-, $B_s{}^0 \to D_s(K^+K^-\pi^-)\,\pi^+$, $B^+ \to D(K_S\pi^+\pi^-)\,K^+$

Flavour Physics at Hadron Machines

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$B_{(s)}{}^0 \to l^+l^-$, h^+h^-, $B_s{}^0 \to D_s(K^+K^-\pi^-)\,\pi^+$, $B^+ \to D(K_S\pi^+\pi^-)\,K^+$

K_S not seen by the vertex detector, π^0 and γ can be **associated** to a reconstructed vertex (if not too many)

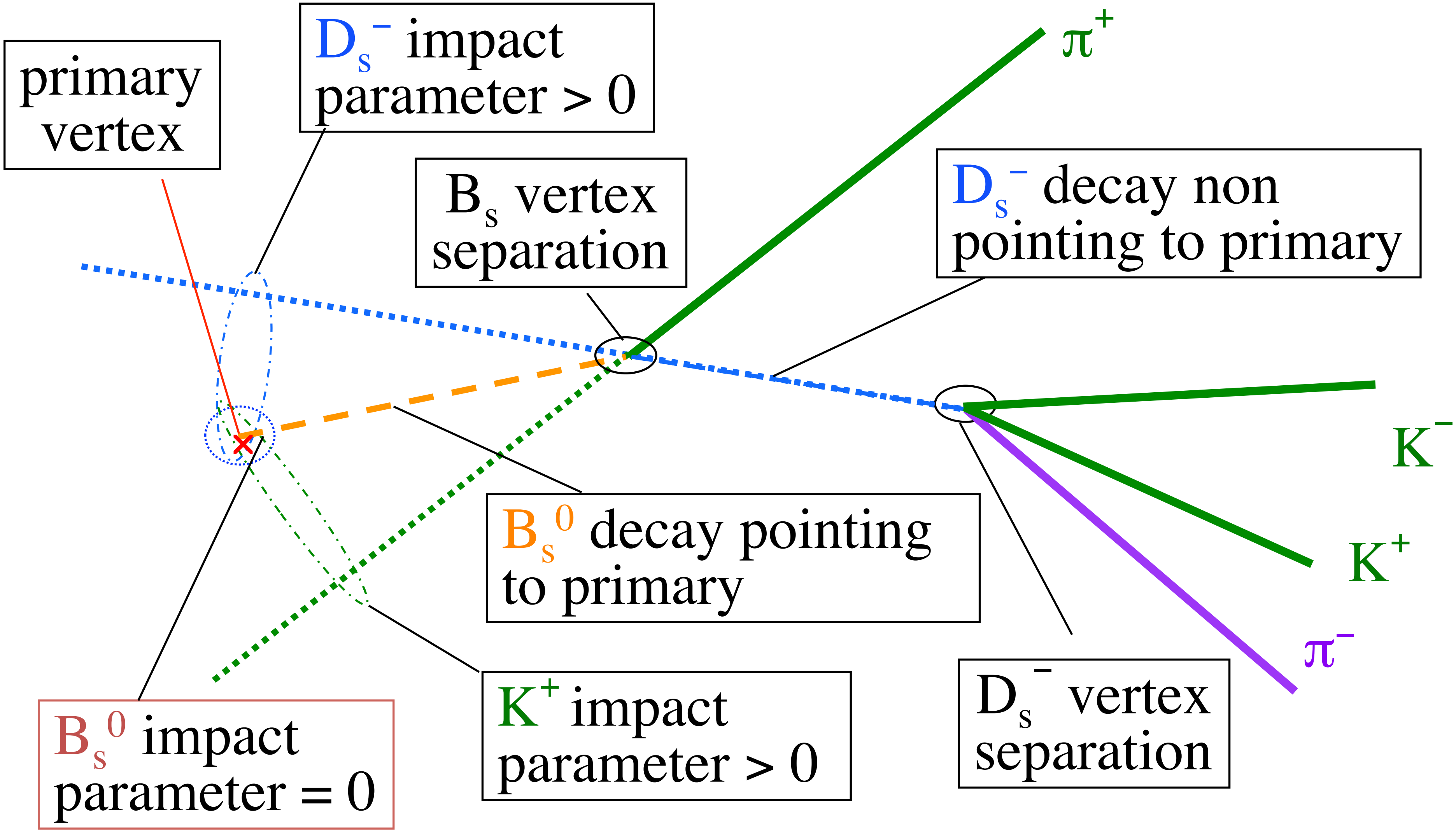
$B^0 \to J/\psi\,K_S$, $K^{*0}(K^+\pi^-)\gamma$, $\rho^0(\pi^+\pi^-)\pi^0$, etc. are possible

but not

$B^0 \to K_S\pi^0$, $\rho^+(\pi^+\pi^0)\pi^0$, $\pi^0\nu\nu$, etc.

$B^+ \to \mu^+\nu$, $K^+\nu\nu$, $\tau^+\nu$

Flavour Physics at Hadron Machines



plus p_T cut (LHCb) or isolation cut (ATLAS/CMS)
and for some cases, decay angle cut