# B(eautiful) Physics I

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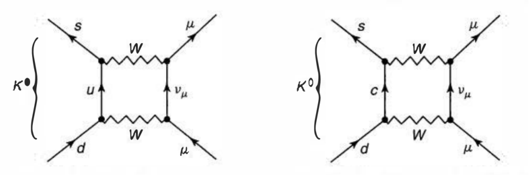
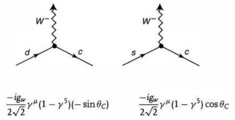
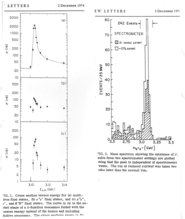
# A lesson from history - GIM mechanism

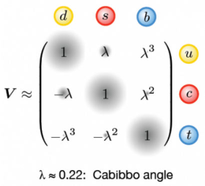


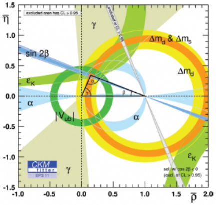

- Cabibbo angle was successful in explaining dozens of decay rates in the 1960s.
- There was, however, one that was not observed by experiments: $K^0 \to \mu^- \mu^+$.
- Glashow, Iliopoulos, Maiani (GIM) mechanism was proposed in the 1970 to fix this problem. The mechanism required the existence of a $4^{th}$ quark.
- At that point most of the people were skeptical about that. Fortunately in 1974 the discovery of the $J/\psi$ meson silenced the skeptics.



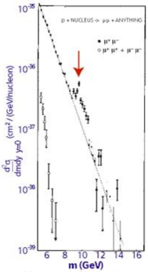



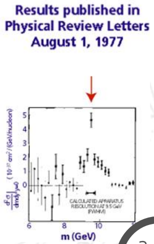
# A lesson from history - CKM matrix



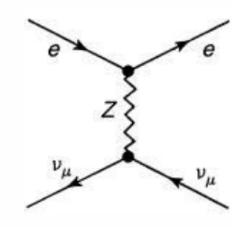



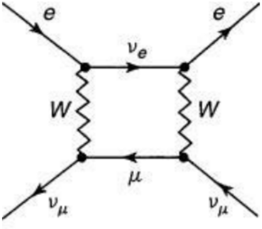

- Similarly, CP violation was discovered in 1960s in the neutral kaons decays.
- $2 \times 2$ Cabbibo matrix could not allow for any CP violation.
- For CP violation to be possible one needs at least a $3 \times 3$ unitary matrix
  ↬ Cabibbo-Kobayashi-Maskawa matrix (1973).
- It predicts existence of *b* (1977) and *t* (1995) quarks.



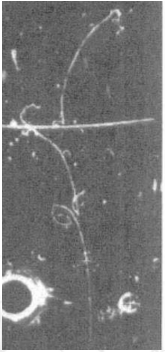



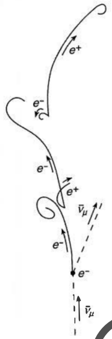
# A lesson from history - Weak neutral current




- Weak neutral currents were first introduced in 1958 by Buldman.
- Later on they were naturally incorporated into unification of weak and electromagnetic interactions.
- 't Hooft proved that the GWS models was renormalizable.
- Everything was there on theory side, only missing piece was the experiment, till 1973.



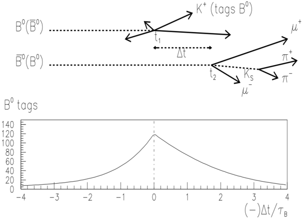


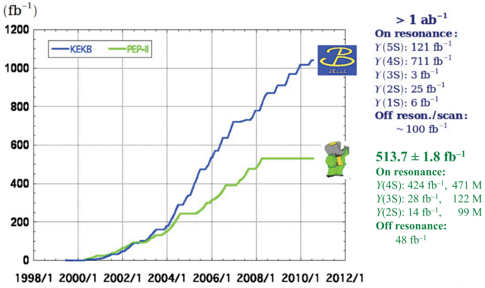
# *B*-factories

⇛ There were many *B* factories: HERA-B, CLEO, ARGUS.

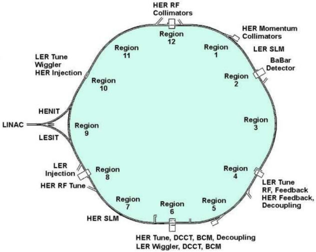
⇛ How ever in present when people talk about *B*-factories they mean BaBar and Belle experiments.

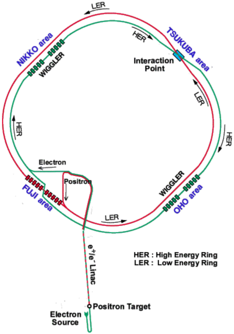
⇛ Both of them were asymmetric *B*-factories:



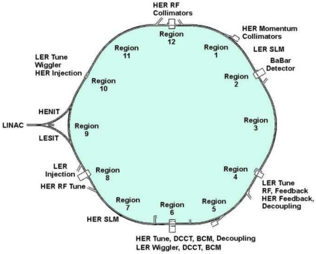
# *B*-factories

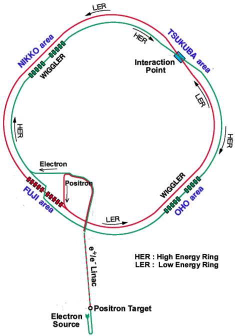



| Parameters | | | PEP-II | KEKB |
|---|---|---|---|---|
| Beam energy | | (GeV) | 9.0 ($e^-$), 3.1 ($e^+$) | 8.0 ($e^-$), 3.5 ($e^+$) |
| Beam current | | (A) | 1.8 ($e^-$), 2.7 ($e^+$) | 1.2 ($e^-$), 1.6 ($e^+$) |
| Beam size at IP | $x$ | ($\mu$m) | 140 | 80 |
| | $y$ | ($\mu$m) | 3 | 1 |
| | $z$ | (mm) | 8.5 | 5 |
| Luminosity | | (cm$^{-2}$ s$^{-1}$) | $1.2 \times 10^{34}$ | $2.1 \times 10^{34}$ |
| Number of beam bunches | | | 1732 | 1584 |
| Bunch spacing | | (m) | 1.25 | 1.84 |
| Beam crossing angle | | (mrad) | 0 (head-on) | $\pm 11$ (crab-crossing) |

# $B$-factories

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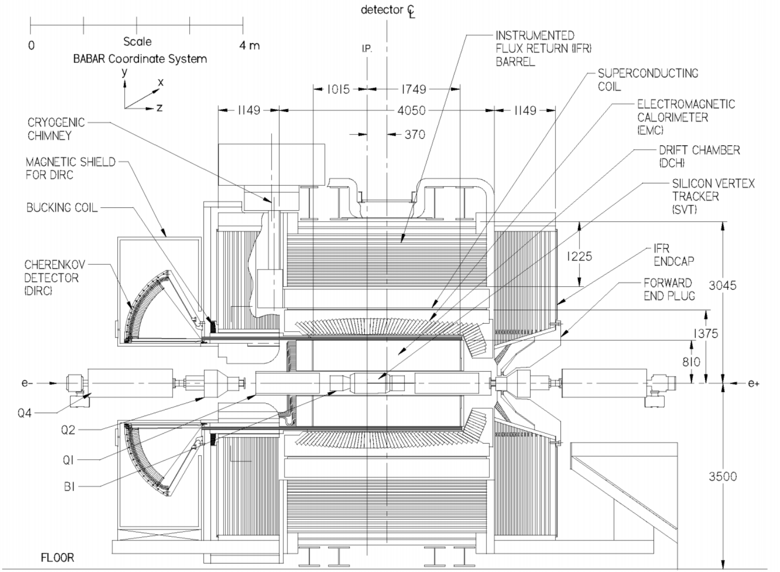
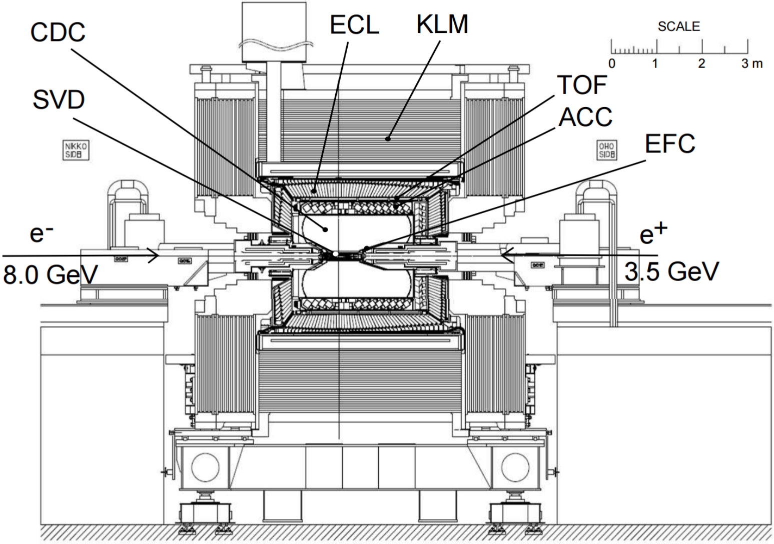
# *B*-factories, detectors



# $B$-factories, detectors



# $B$-factories, Physics

⇛ The $B$-factories had enormous physics program:

- CKM matrix:
  - $V_{ub}$ and $V_{cb}$ from semi-leptonic be decays.
  - $V_{td}$ and $V_{ts}$ from $B_{s,d}$ mixing.
  - Charmless $B$ decays.
  - $B$ mixing.
  - Electro-weak penguin decays.
- Quarkonium physics
- Charm physics
- $\tau$ physics

# $B$-factories, $V_{ub}$, $V_{cb}$

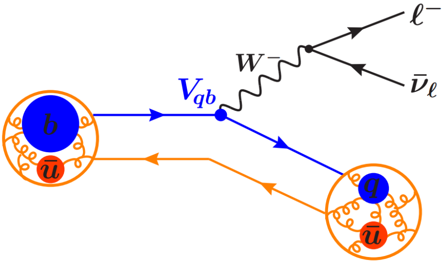
⇛ The decays of $B^0$ and $B^+$ that process via leading order tree decay involving a lepton in the final state $\ell = e, \mu$ are free from non SM contributions.

⇛ They can be used to probe the CKM-matrix elements: $V_{cb}$ and $V_{ub}$.

⇛ In addition the measurement of $\frac{|V_{ub}|}{|V_{cb}|}$ determines the angle $\phi_1$.

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{qb}^2|}{192\pi^3 m_B^3} \mathcal{K}(m_B^2, m_M^2, q^2) \times \mathcal{F}^{(2)}(q^2)$$

⇛ From theory point of view the only thing that is not well known are the from factors: $\mathcal{F}^{(2)}(q^2)$. There are now many theoretical ideas to calculate them and reduce the errors.



# B-factories, $V_{ub}$, $V_{cb}$

$\Rrightarrow$ Measurement of semi-leptonic decays are very challenging, because of missing neutrino!

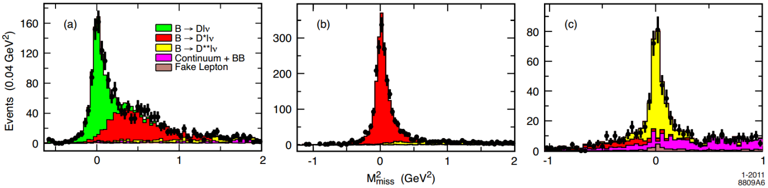
$\Rrightarrow$ We start from calculating the missing 4-momentum:

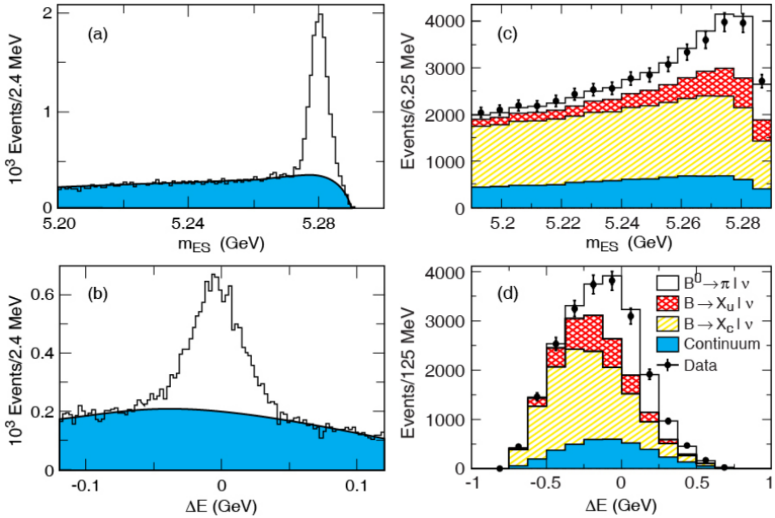
$$(E_{miss}, p_{miss}) = (E_0, p_0) - \sum_i (E_i, p_i)$$

$\Rrightarrow$ In case that the only missing particle in the detector is a neutrino the missing mass should be close to zero!

$\Rrightarrow$ We also use the:

$$\Delta E = E_B^* - E_{beam}^*, \qquad M_{ES} = \sqrt{(E_{beam}^*)^2 - (p_B^*)^2}$$

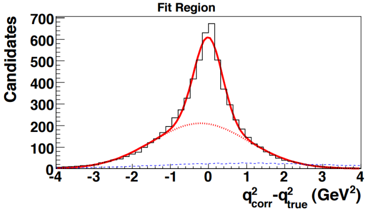


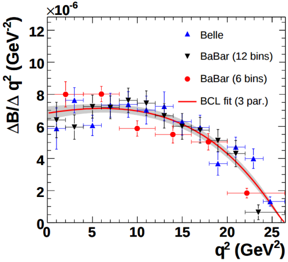


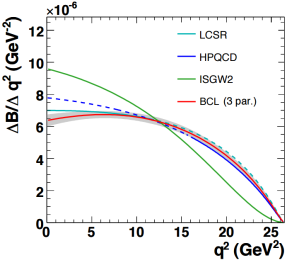
(a)
$10^3$ Events/2.4 MeV
$m_{ES}$ (GeV)
(b)
$10^3$ Events/2.4 MeV
ΔE (GeV)
(c)
Events/6.25 MeV
$m_{ES}$ (GeV)
(d)
Events/125 MeV
ΔE (GeV)
$B^0 \to \pi l \nu$
$B \to X_u l \nu$
$B \to X_c l \nu$
Continuum
Data

## $B$-factories, $V_{ub}$, $V_{cb}$

$\Rrightarrow$ Also the $q^2 = [(E_\ell, p_\ell) + (E_{miss}, p_{miss})]^2$ distribution was measured.



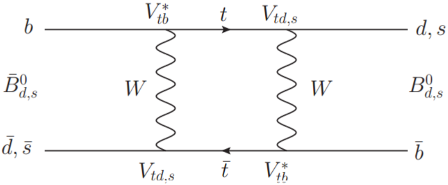



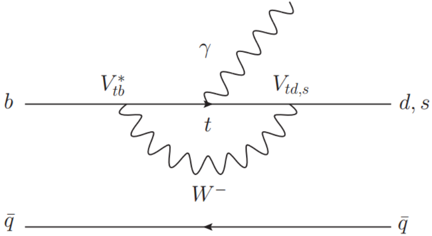
# $B$-factories, $V_{ts}$, $V_{tb}$

⇛ The CKM elements $V_{ts}$, $V_{tb}$ are problematic to determine. One can use:

- Rare radiative $K$ and $B$ decays
- $B^0$ and $B_s^0$ oscilations:




$$\Delta m_d = \frac{G_F^2}{6\pi^2} f_B^2 m_B m_W^2 \eta_B S_0 |V_{tb}^* V_{td}|^2 \hat{B}_B$$




⇛ Unfortunately the theory precision is limited by the QCD.

# $B$-factories, $V_{ts}$, $V_{tb}$

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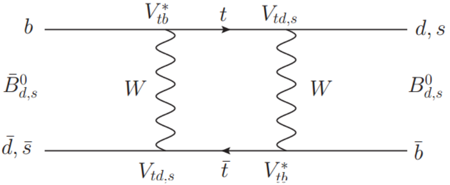
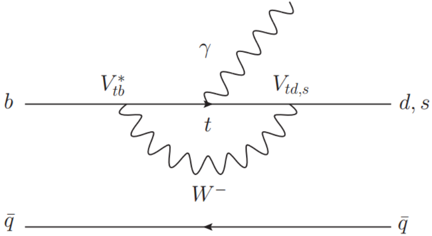
- Rare radiative $K$ and $B$ decays
- $B^0$ and $B^0_s$ oscillations:




$$\Delta m_d = \frac{G_F^2}{6\pi^2} f_B^2 m_B m_W^2 \eta_B S_0 |V_{tb}^* V_{td}|^2 \hat{B}_B$$

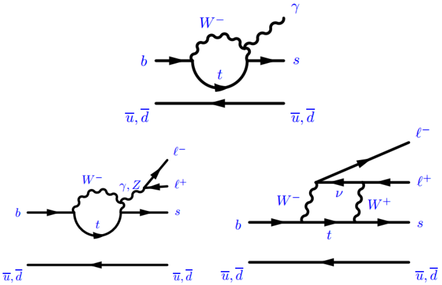



⇛ Unfortunately the theory precision is limited by the QCD.

# Electroweak penguins

- Rare EWP decays are THE most sensitive probes of NP in flavour physics.
- They are described by the effective Hamiltonian (see next lecture for more details):

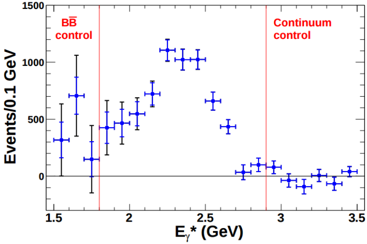
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\left[\lambda_q^t \sum_{i=1}^{10} C_i \mathcal{O}_i + \lambda_q^u \sum_{i=1}^{2} C_i(\mathcal{O}_i - \mathcal{O}_i^u)\right]$$

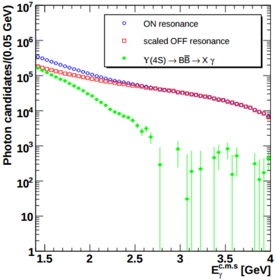


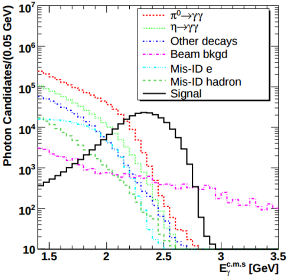
# Inclusive/Exclusive $b \to s\gamma$

$\Rrightarrow$ Measurement of inclusive modes is difficult. First attempt was done using sum of exclusive modes.

$\Rrightarrow$ Latter one used the leptonic tag.



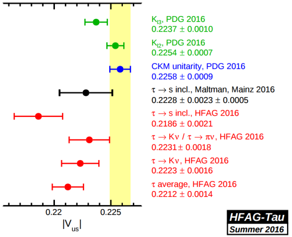
# $\tau$ Physics

$\Rrightarrow$ *B*-factories are also $\tau$ factories!

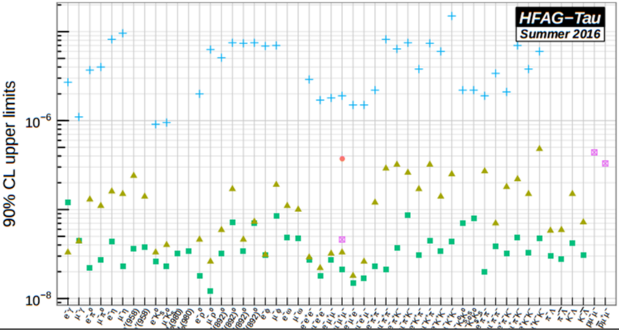
$\Rrightarrow$ $\tau$ leptons are very nice objects.

And allow 2 main things:

- Test of QCD in the harmonic decays.
- Search for NP ex. LFV.




$$B(\tau^- \to K^- \nu_\tau) = \frac{G_F^2 f_K^2 |V_{us}|^2 m_\tau^3 \tau_\tau}{16\pi\hbar}\left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 S_{EW}$$



# Warp up

⇛ The Physics reach of $B$-factories was enormous.

⇛ They robustness of their measurements because a text-book procedures when analysing the data.

⇛ Fief anomalies remain (next lecture), which are beeing tackled by current $B$-factories.

⇛ If you want to know more please read the ”Legacy” book: arxiv::1406.6311