# $B_0$ and $B_s$ mixing
# $|V_{td}/V_{ts}|$

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290E presentation

# Bigger picture!

- Matter-antimatter asymmetry
  - Visible universe is made out of matter
  - In the early universe, without CP violation, we expect equal number of baryons and anti-baryons
  - To explain the asymmetry, following Sakharov conditions need to be met:
    - Baryon number violation
    - C and CP violation
    - Departure from thermal equilibrium

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# CP violation in Standard Model

- The mass and weak eigen states of quarks are not the same
- Historical note:
  - This was first proposed for first and second generation
  - Goal was to explain why the $G_F$ was different for us ($K^+ \rightarrow \mu^+ \nu_\mu$) and ud ($\pi^+ \rightarrow \mu^+ \nu_\mu$) vertices
  - Explained by Cabibbo hypothesis

Weak eigenstates

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

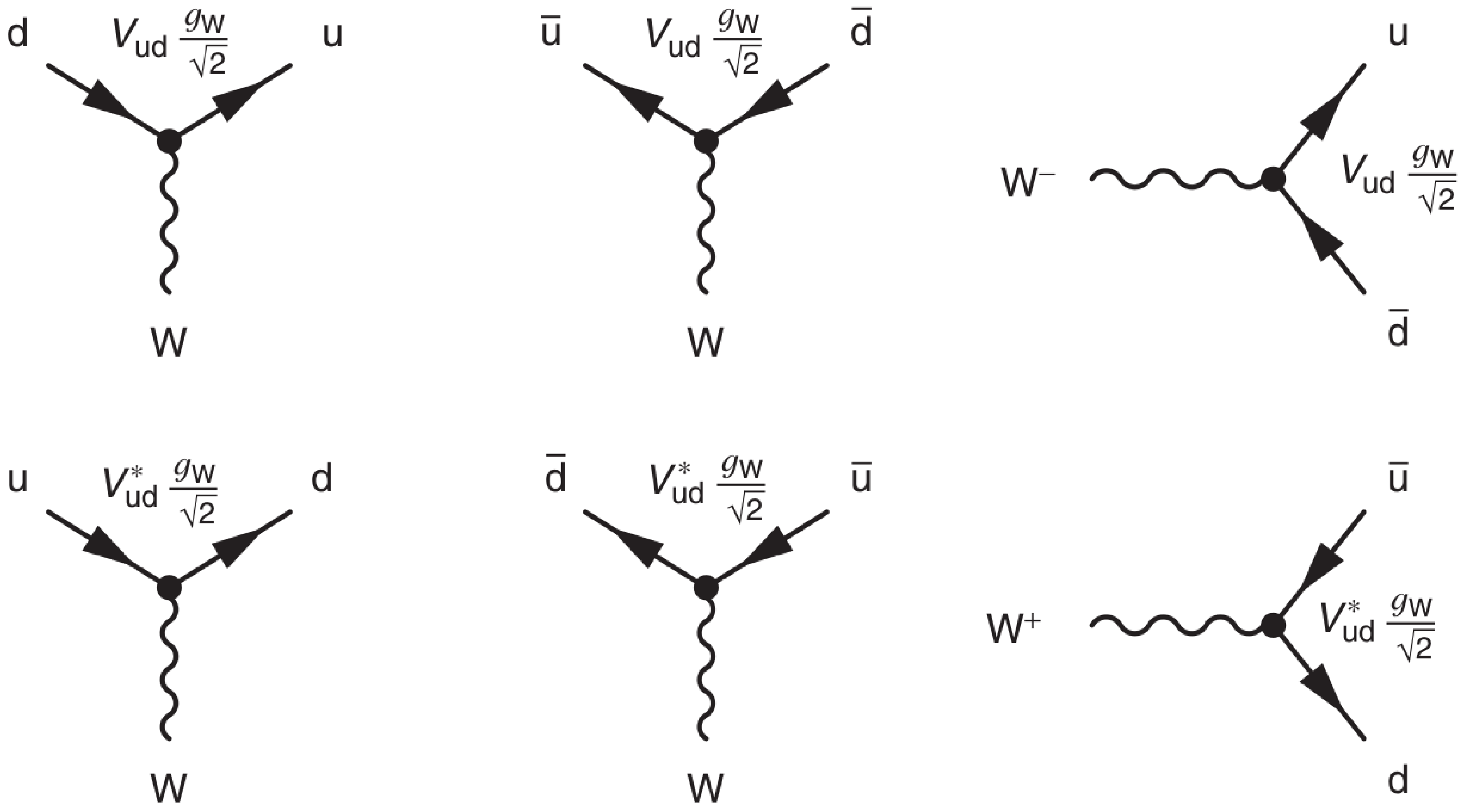
Mass eigenstates

# Extending to three generations

- Mixing in three generations is described by unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix

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

# Explains the $G_F$ mystery



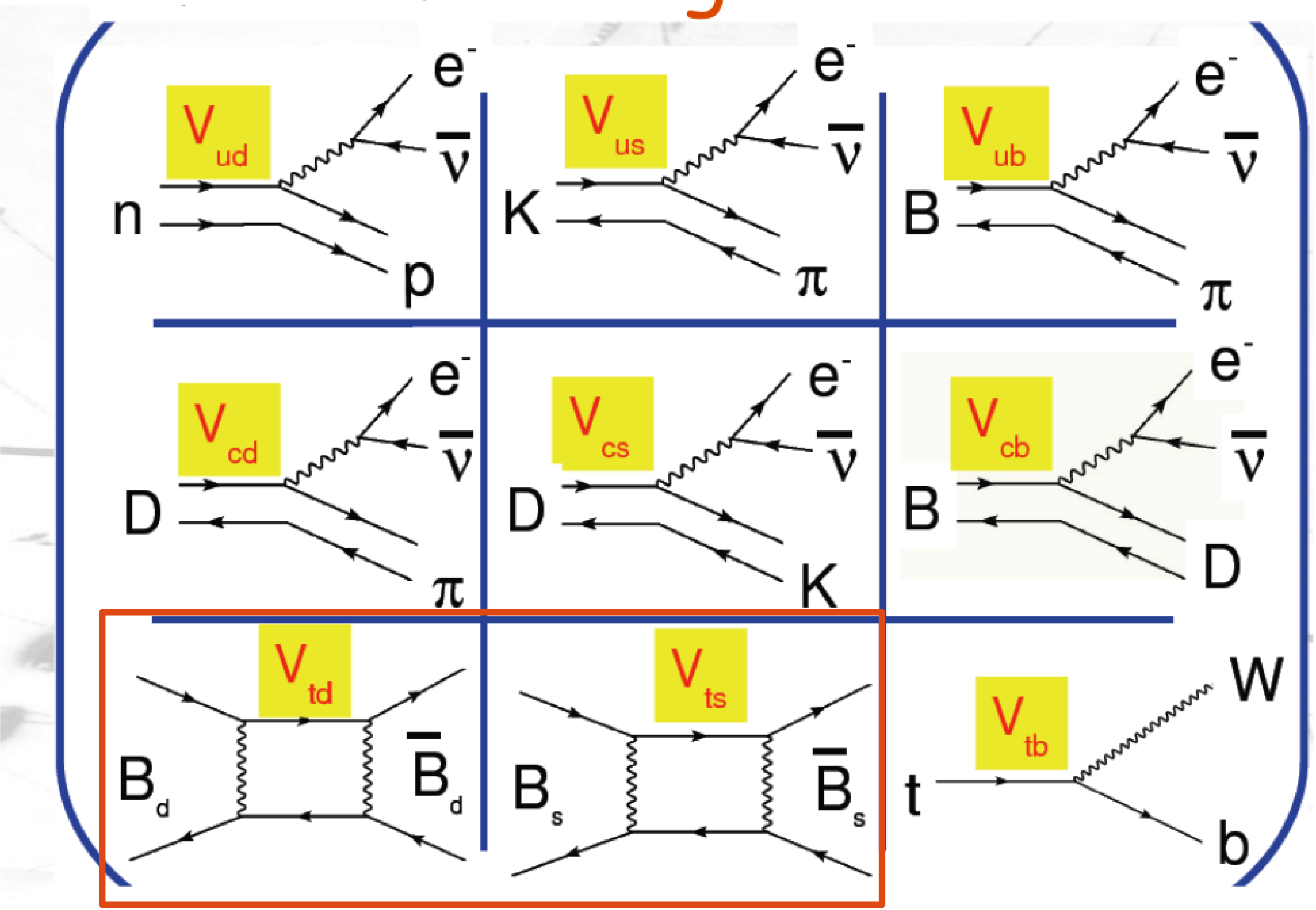
Ref: Thomson, Figure 14.5

# Near diagonal matrix

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ \multicolumn{2}{c}{\boxed{|V_{td}| \quad |V_{ts}|}} & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix}$$

- Today’s talk will focus on how we measure $|V_{td}|$ and $|V_{ts}|$
- Note: Cannot use direct top decays as almost always it decays to W and b

# CKM Magnitudes



Slides from F. Di Lodovico @ ICHEP2008

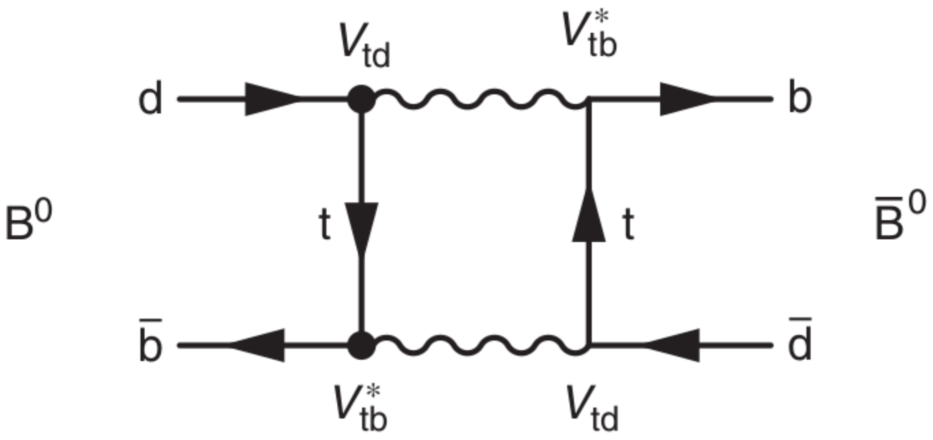
Phys226

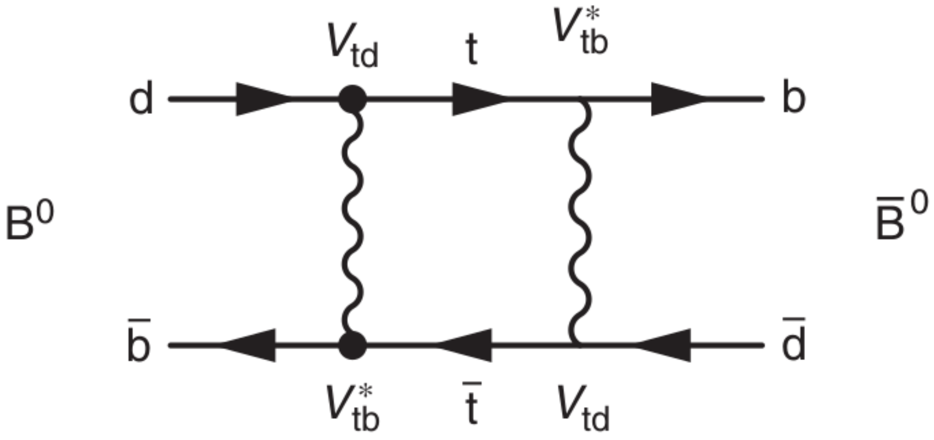
Prof. Kolomensky's slide

Yury Kolomensky: CKM Physics

# A little theory

- $B^0$ and $B^0$bar mixing dominated by two top quarks in the loop as $|V_{tb}| \sim 1$
- If you produce $B^0$ in an experiment, then it oscillates into $B^0$bar and vice versa





See Thomson for complete discussion

# A little more theory

- Using CKM matrix physical B meson states can be written as

$$|\mathrm{B}_L\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{B}^0\rangle + e^{-i2\beta}|\overline{\mathrm{B}}^0\rangle\right) \quad \text{and} \quad |\mathrm{B}_H\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{B}^0\rangle - e^{-i2\beta}|\overline{\mathrm{B}}^0\rangle\right).$$

where

$$V_{\mathrm{td}} = |V_{\mathrm{td}}|e^{-i\beta}, \quad \text{and} \quad \xi = e^{-i2\beta}.$$

# Tad bit more theory

- If you produce B0 in an experiment at t=0:

$$|\mathrm{B}^0\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{B}_L\rangle + |\mathrm{B}_H\rangle\right)$$

Flavor eigen state

Mass eigen states

- Over time,

$$|\mathrm{B}(t)\rangle = \frac{1}{\sqrt{2}}\left[\theta_L(t)|\mathrm{B}_L\rangle + \theta_H(t)|\mathrm{B}_H\rangle\right]$$

where

$$\theta_L = e^{-\Gamma t/2} e^{-im_L t} \quad \text{and} \quad \theta_H = e^{-\Gamma t/2} e^{-im_H t}.$$

**$m(B_H)$-$m(B_L)$ proportional to $|(V_{td}V_{tb}^*)^2|$**

- Oscillation probability:

$$P(\mathrm{B}^0_{t=0} \to \mathrm{B}^0) = |\langle \mathrm{B}(t)|\mathrm{B}^0\rangle|^2 = \tfrac{1}{4}e^{-\Gamma t}|\theta_+|^2 = e^{-\Gamma t}\cos^2\left(\tfrac{1}{2}\Delta m_{\mathrm{d}} t\right),$$

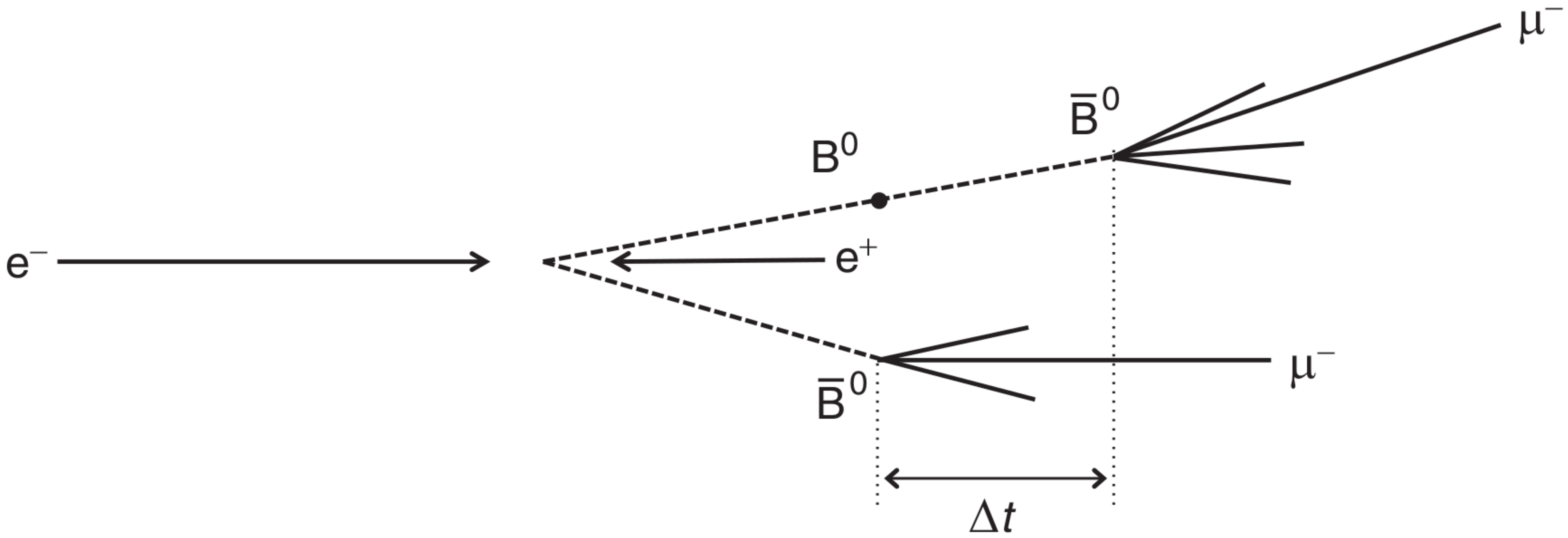
$$P(\mathrm{B}^0_{t=0} \to \overline{\mathrm{B}}^0) = |\langle \mathrm{B}(t)|\overline{\mathrm{B}}^0\rangle|^2 = \tfrac{1}{4}e^{-\Gamma t}|\xi\theta_-|^2 = |\xi|^2 e^{-\Gamma t}\sin^2\left(\tfrac{1}{2}\Delta m_{\mathrm{d}} t\right).$$

# B factories

m~5.3 GeV

- e+e- → Υ(4S) → $B^0B^0$bar
- Center-of-mass energy needed ~ 10.6 GeV
- Why are asymmetric B factories a thing?
  - Colliding at 10.6 GeV implies B mesons produced with low velocities
  - τ~10E-12 s → B mesons will travel small distance before decaying
  - So we cannot distinguish between both B mesons
  - Hence we need asymmetric B factories to get boosted B mesons

# Boosted B mesons

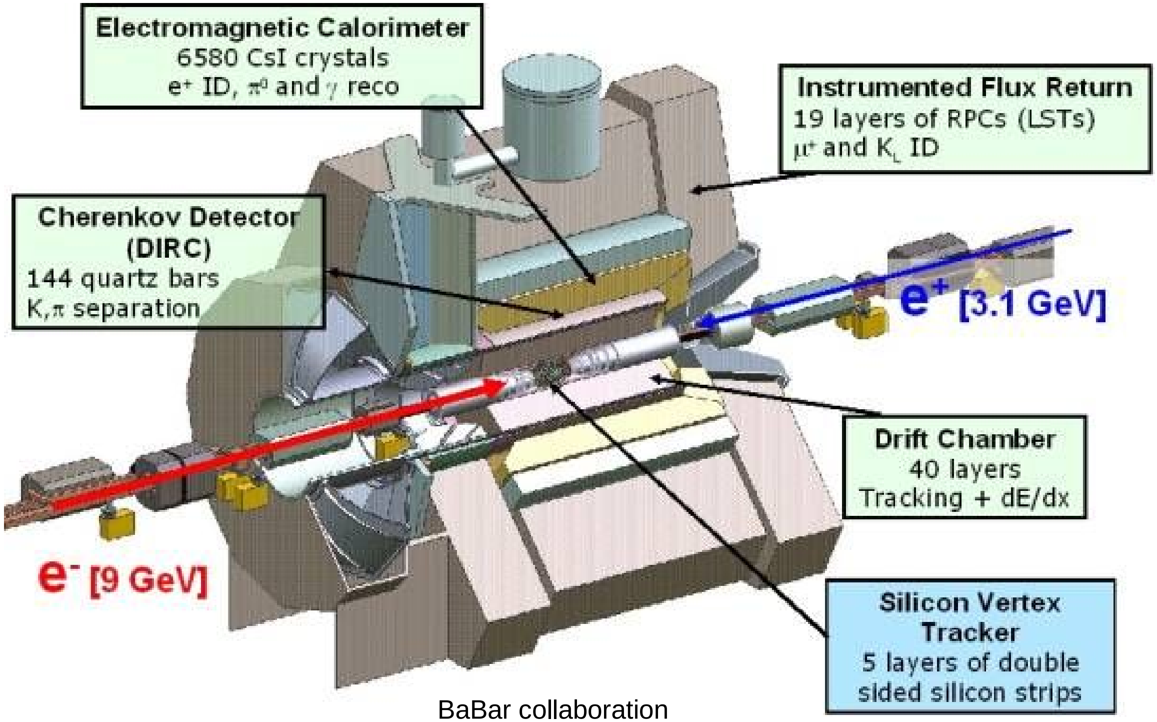


- B meson decays:

$$\boxed{B^0}(\bar{b}d) \to D^-(\bar{c}d)\boxed{\mu^+}\nu_\mu \quad \text{and} \quad \boxed{\bar{B}^0}(b\bar{d}) \to D^+(c\bar{d})\boxed{\mu^-}\bar{\nu}_\mu.$$

# BaBar experiment

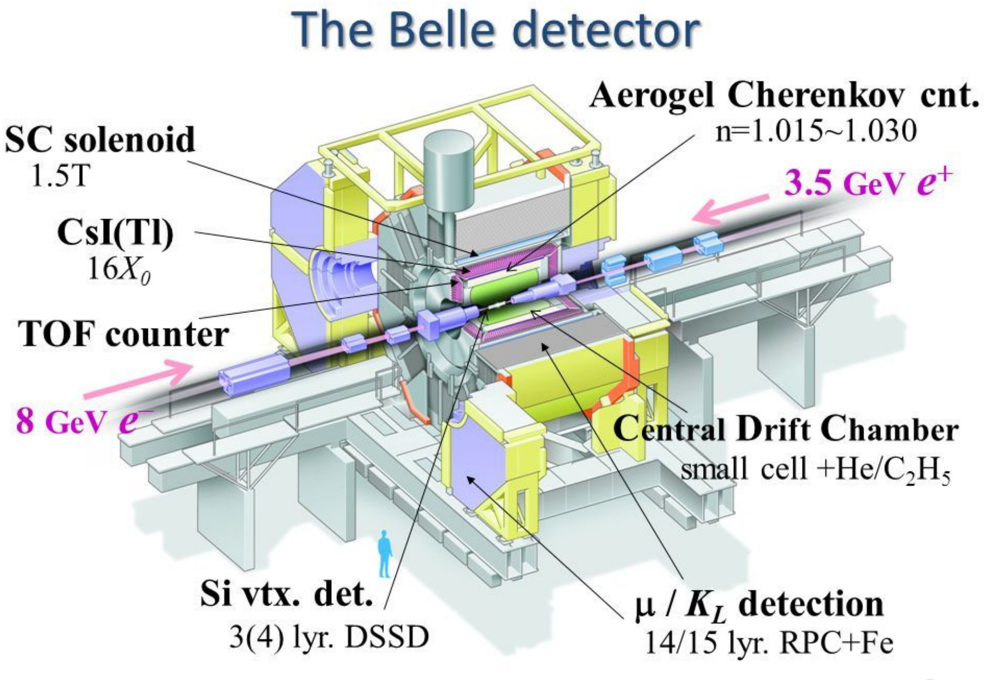
- Used high luminosity PEP II and KEKB collider at SLAC
- 9 GeV e- and 3.1 GeV e+ beams give B mesons βγ~0.56
- Mean distance between two B decays in Δz~200μm
- Detector has high precision silicon vertex detector to measure this



BaBar collaboration

# Belle experiment

- Used KEKB collider in Japan
- 8 GeV e- and 3.5 GeV e+ beams give B mesons βγ ~ 0.425
- Upgraded Belle II working from 2018 and expected to collect 50x more data compared to Belle



Belle collaboration

# How to calculate $|V_{td}|$?

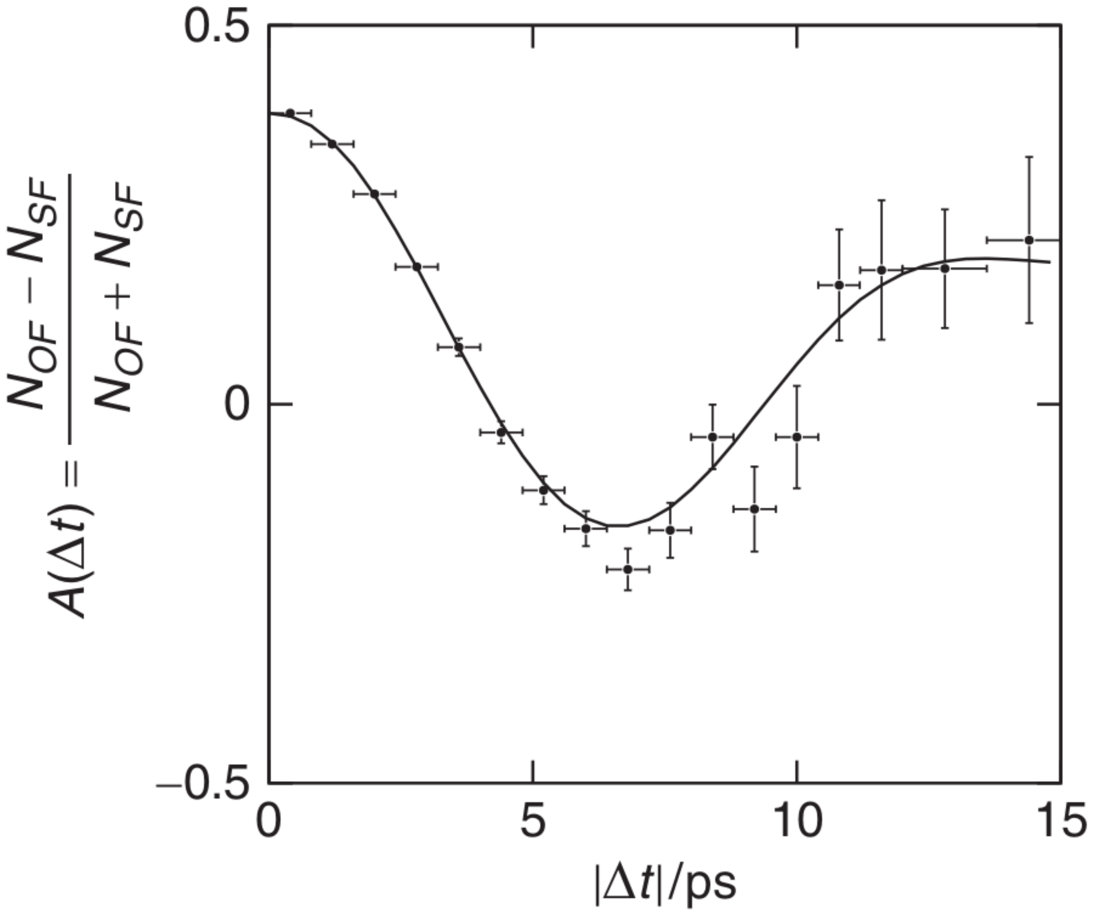
Mass difference is measured from lepton flavor asymmetry

$$A(\Delta t) = \frac{N_{OF} - N_{SF}}{N_{SF} + N_{OF}}$$

$$A(\Delta t) = \frac{[P(\mathrm{B}^0_{t=0} \rightarrow \mathrm{B}^0) + P(\overline{\mathrm{B}}^0_{t=0} \rightarrow \overline{\mathrm{B}}^0)] - [P(\mathrm{B}^0_{t=0} \rightarrow \overline{\mathrm{B}}^0) + P(\overline{\mathrm{B}}^0_{t=0} \rightarrow \mathrm{B}^0)]}{[P(\mathrm{B}^0_{t=0} \rightarrow \mathrm{B}^0) + P(\overline{\mathrm{B}}^0_{t=0} \rightarrow \overline{\mathrm{B}}^0)] + [P(\mathrm{B}^0_{t=0} \rightarrow \overline{\mathrm{B}}^0) + P(\overline{\mathrm{B}}^0_{t=0} \rightarrow \mathrm{B}^0)]},$$

$$A(\Delta t) = \cos^2\left(\tfrac{1}{2}\Delta m_{\mathrm{d}} t\right) - \sin^2\left(\tfrac{1}{2}\Delta m_{\mathrm{d}} t\right) = \cos\left(\Delta m_{\mathrm{d}} t\right)$$

# Experimental measurement



- Not a perfect cosine because of background, lepton charge misidentification and experimental Δt resolution

# Determining $|V_{td}|$

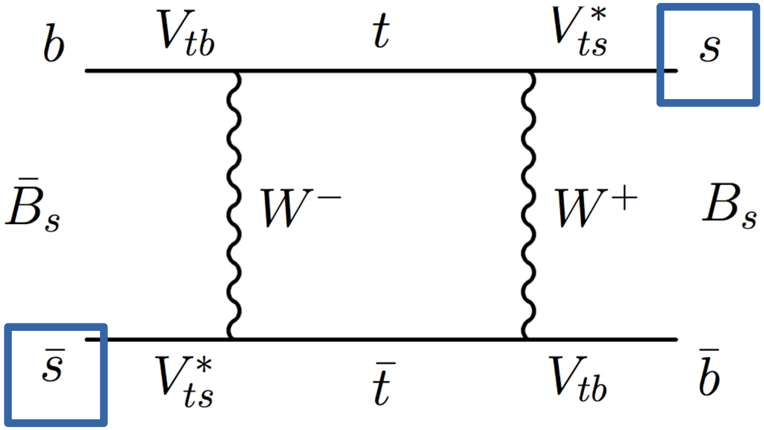
$$\Delta m_{\mathrm{d}} = (0.507 \pm 0.005)\,\mathrm{ps}^{-1} \equiv (3.34 \pm 0.03) \times 10^{-13}\,\mathrm{GeV}$$

- Recall $\Delta m_d = m(B_H)-m(B_L)$ proportional to $|(V_{td}V_{tb}{}^*)^2|$
- Using $V_{tb} \sim 1$, we get

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

# What about $|V_{ts}|$?

- Similar analysis follows



Instead of d quark, we have s quark here

- From experiment,

$$\Delta m_s = 17.72 \pm 0.04 \text{ ps}^{-1}.$$

- We get

$$\boxed{|V_{ts}| = (4.3 \pm 0.3) \times 10^{-2}}$$

# Summarize so far..

- Results:

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

$$|V_{\mathrm{ts}}| = (4.3 \pm 0.3) \times 10^{-2}$$

- The uncertainties are dominated by theoretical calculations

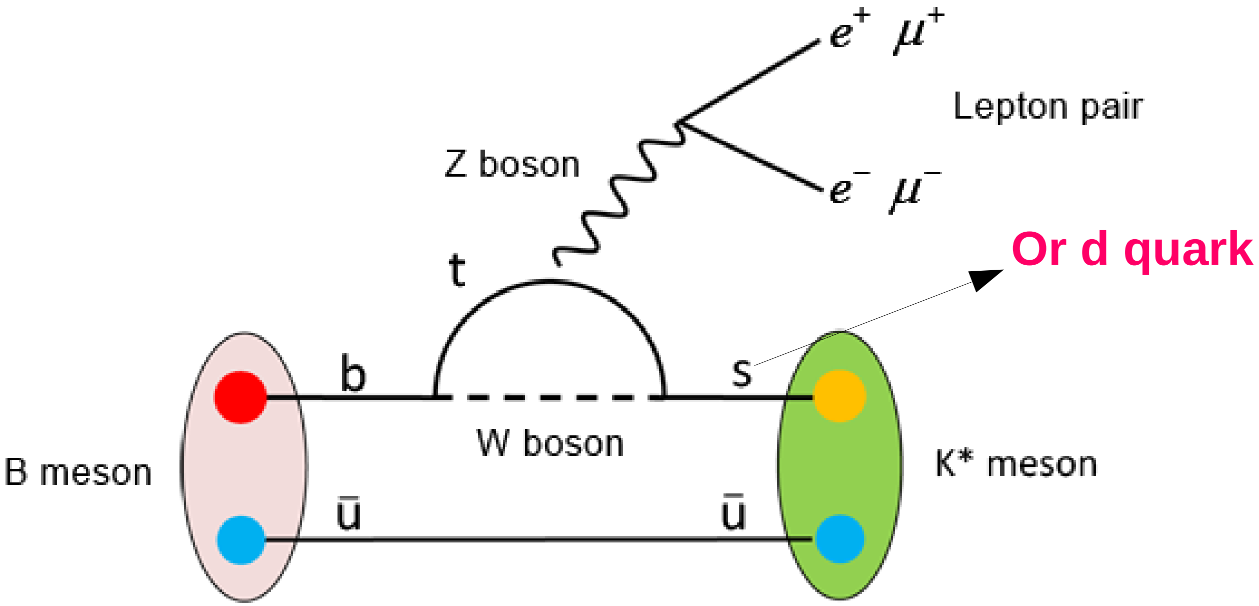
# $|V_{td}|/|V_{ts}|$

- Ratios are preferred for precision measurements.
- For example, $\Delta m_d/\Delta m_s$ is more reliably calculated in theory
- So measuring this will be a better handle to probe CP violation
- Using earlier results,

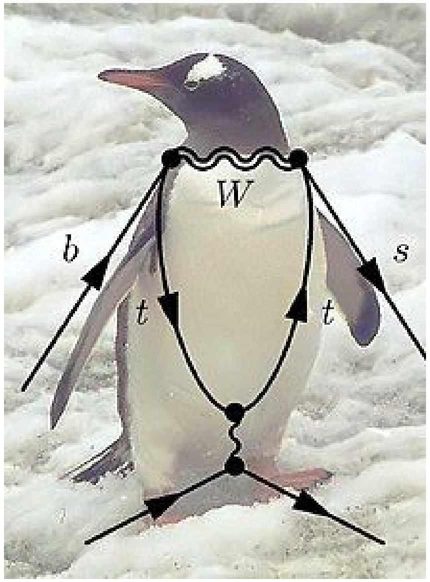
$$\left|V_{td}/V_{ts}\right| = 0.210 \pm 0.001 \pm 0.008.$$

# Alternate methods (Penguins!)

- b→ dγ and b→ sγ are not tree level processes in the standard model



Ref: https://phys.org/news/2009-09-belle-hint-physics-extremely-rare.html

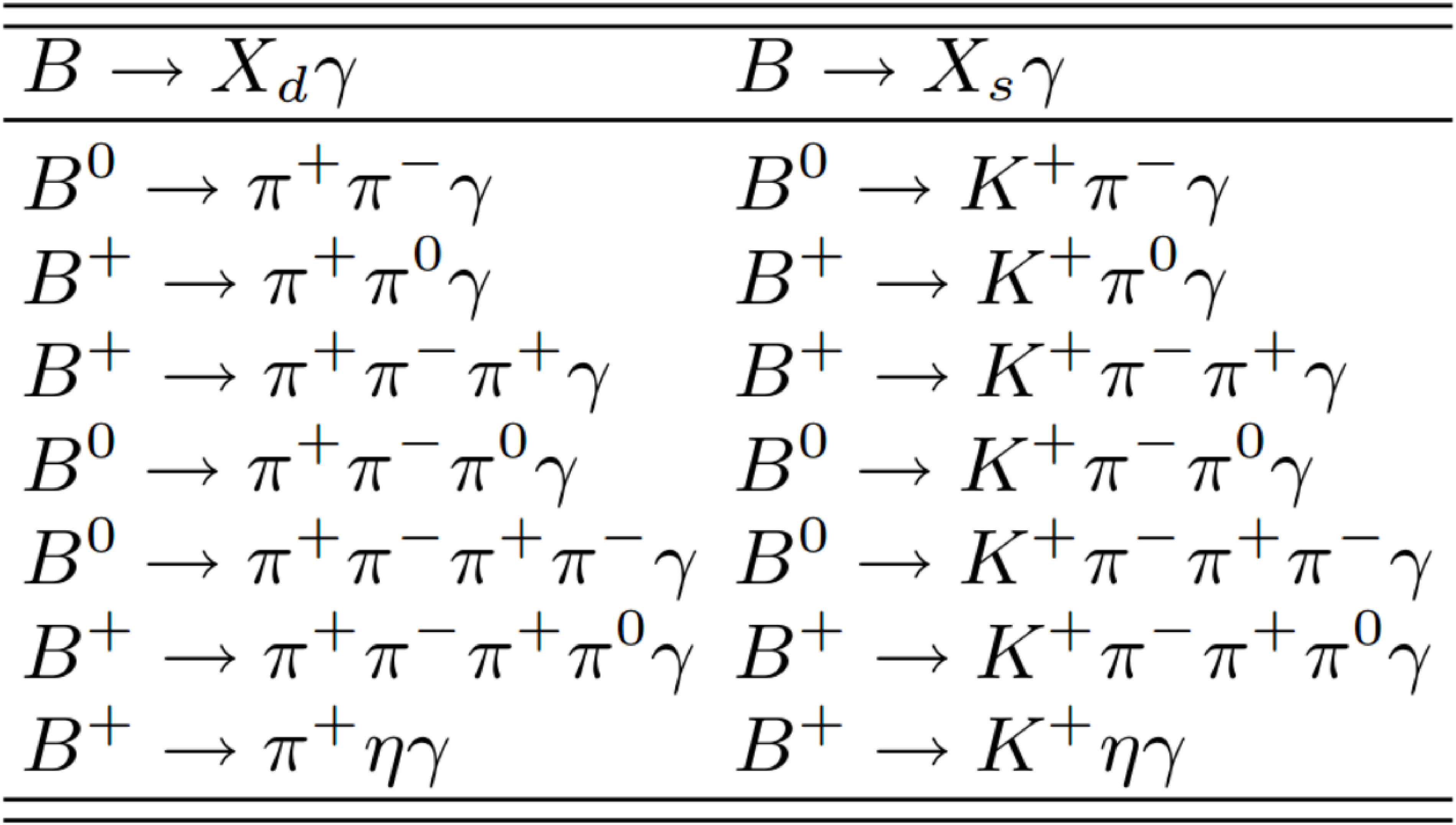


Ref: Wikipedia

- The inclusive decay of d vs. s quark is supressed by $(|V_{td}|/|V_{ts}|)^2$
- Ratio is sensitive to new physics coupling differently to d and s quarks

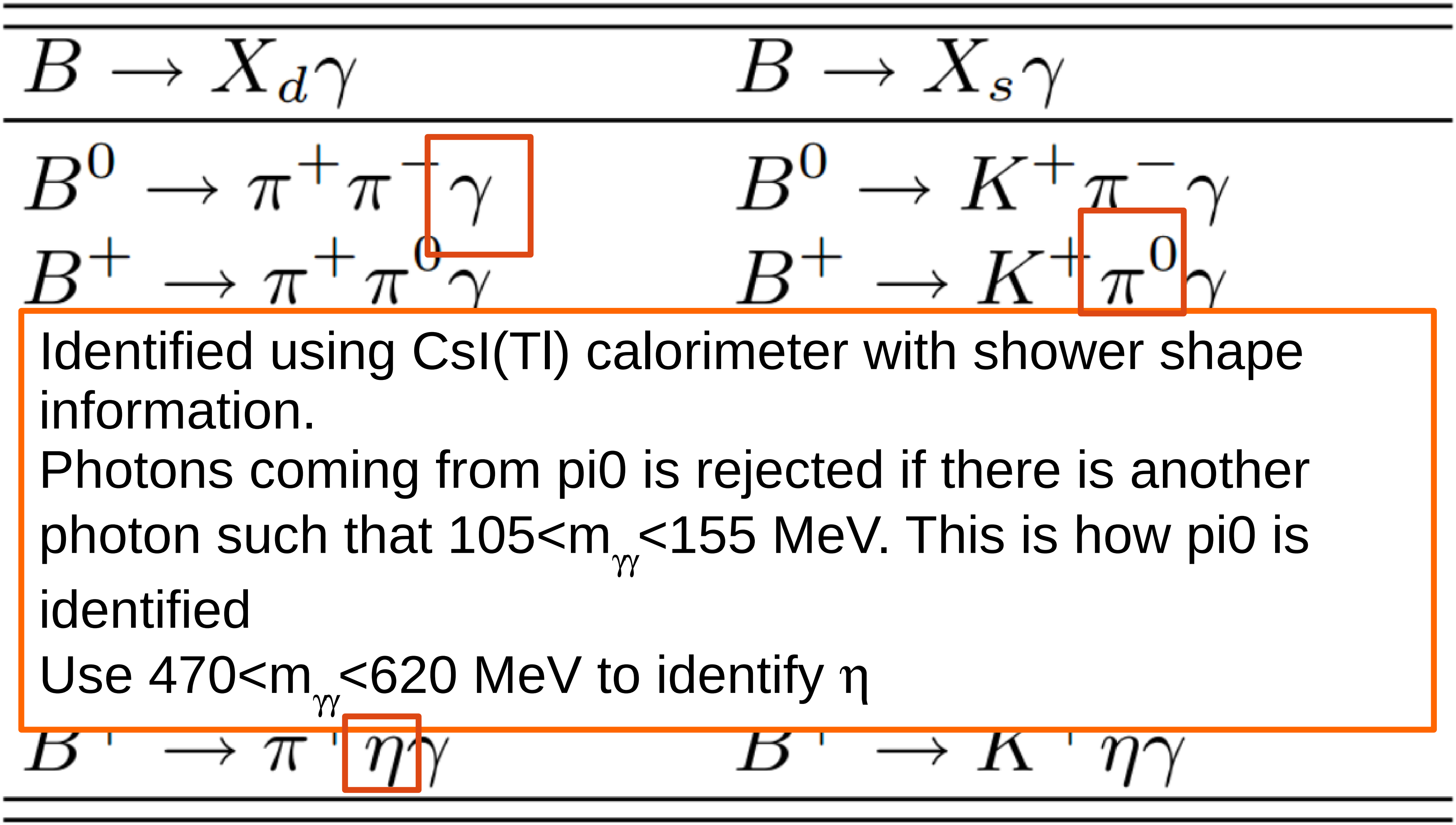
Reference

# Measure all decay modes



| $B \to X_d \gamma$ | $B \to X_s \gamma$ |
|---|---|
| $B^0 \to \pi^+ \pi^- \gamma$ | $B^0 \to K^+ \pi^- \gamma$ |
| $B^+ \to \pi^+ \pi^0 \gamma$ | $B^+ \to K^+ \pi^0 \gamma$ |
| $B^+ \to \pi^+ \pi^- \pi^+ \gamma$ | $B^+ \to K^+ \pi^- \pi^+ \gamma$ |
| $B^0 \to \pi^+ \pi^- \pi^0 \gamma$ | $B^0 \to K^+ \pi^- \pi^0 \gamma$ |
| $B^0 \to \pi^+ \pi^- \pi^+ \pi^- \gamma$ | $B^0 \to K^+ \pi^- \pi^+ \pi^- \gamma$ |
| $B^+ \to \pi^+ \pi^- \pi^+ \pi^0 \gamma$ | $B^+ \to K^+ \pi^- \pi^+ \pi^0 \gamma$ |
| $B^+ \to \pi^+ \eta \gamma$ | $B^+ \to K^+ \eta \gamma$ |

# Particle ID is essential



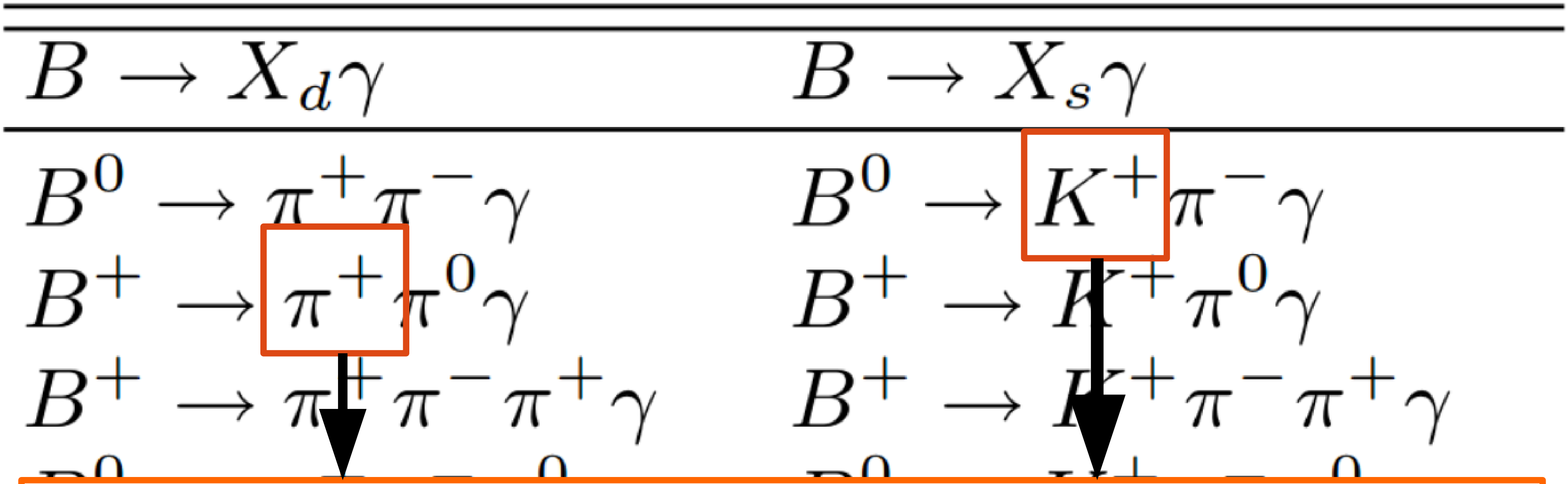
| $B \to X_d\gamma$ | $B \to X_s\gamma$ |
|---|---|
| $B^0 \to \pi^+\pi^-\gamma$ | $B^0 \to K^+\pi^-\gamma$ |
| $B^+ \to \pi^+\pi^0\gamma$ | $B^+ \to K^+\pi^0\gamma$ |
| $B^+ \to \pi^+\eta\gamma$ | $B^+ \to K^+\eta\gamma$ |

Identified using CsI(Tl) calorimeter with shower shape information.

Photons coming from pi0 is rejected if there is another photon such that 105<$m_{\gamma\gamma}$<155 MeV. This is how pi0 is identified

Use 470<$m_{\gamma\gamma}$<620 MeV to identify η

# Charged particle identification

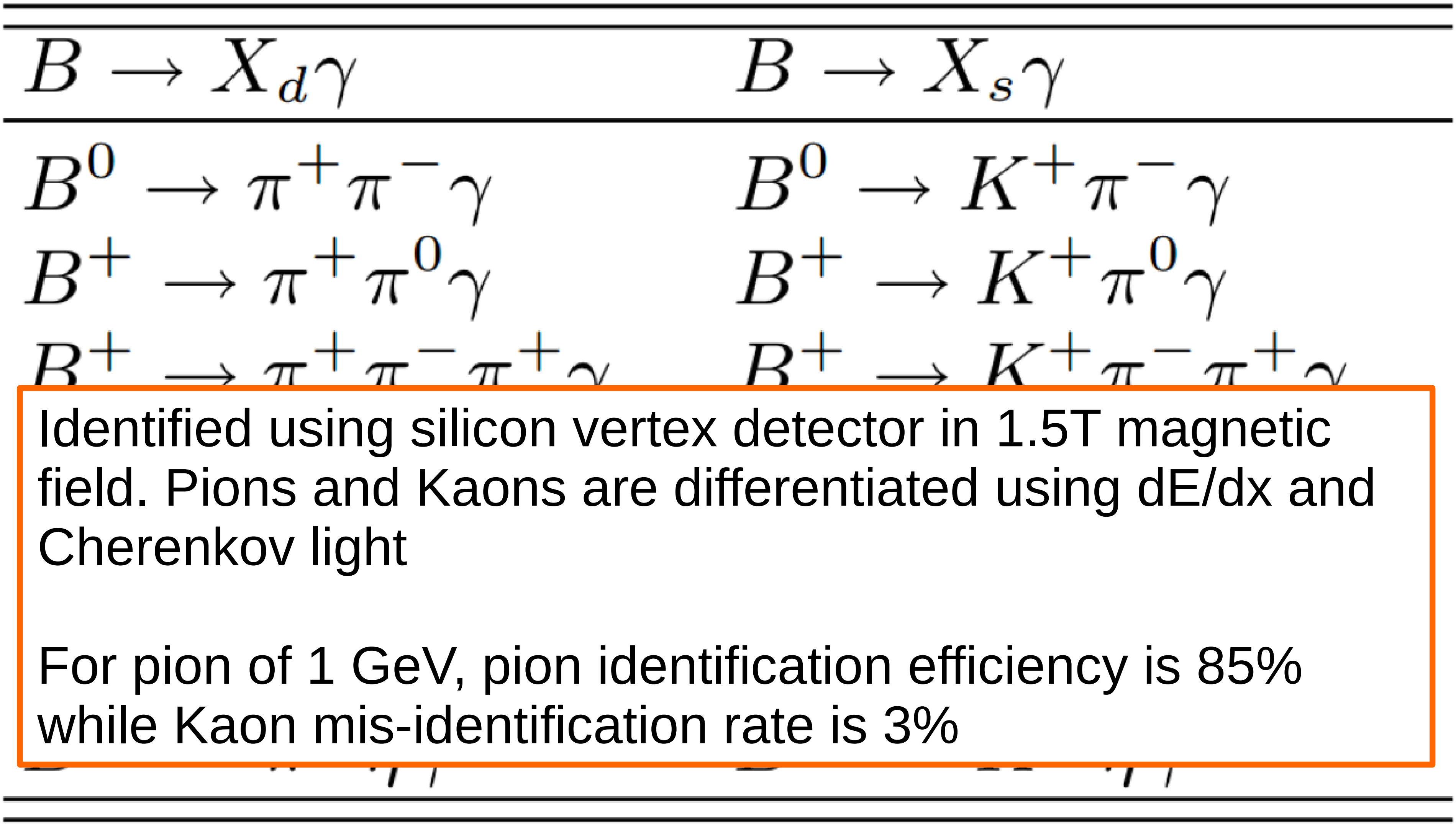


| $B \to X_d\gamma$ | $B \to X_s\gamma$ |
|---|---|
| $B^0 \to \pi^+\pi^-\gamma$ | $B^0 \to \boxed{K^+}\pi^-\gamma$ |
| $B^+ \to \boxed{\pi^+}\pi^0\gamma$ | $B^+ \to K^+\pi^0\gamma$ |
| $B^+ \to \pi^+\pi^-\pi^+\gamma$ | $B^+ \to K^+\pi^-\pi^+\gamma$ |

Identified using silicon vertex detector in 1.5T magnetic field. Pions and Kaons are differentiated using dE/dx and Cherenkov light

For pion of 1 GeV, pion identification efficiency is 85% while Kaon mis-identification rate is 3%

# Measure all decay modes



| $B \to X_d\gamma$ | $B \to X_s\gamma$ |
|---|---|
| $B^0 \to \pi^+\pi^-\gamma$ | $B^0 \to K^+\pi^-\gamma$ |
| $B^+ \to \pi^+\pi^0\gamma$ | $B^+ \to K^+\pi^0\gamma$ |
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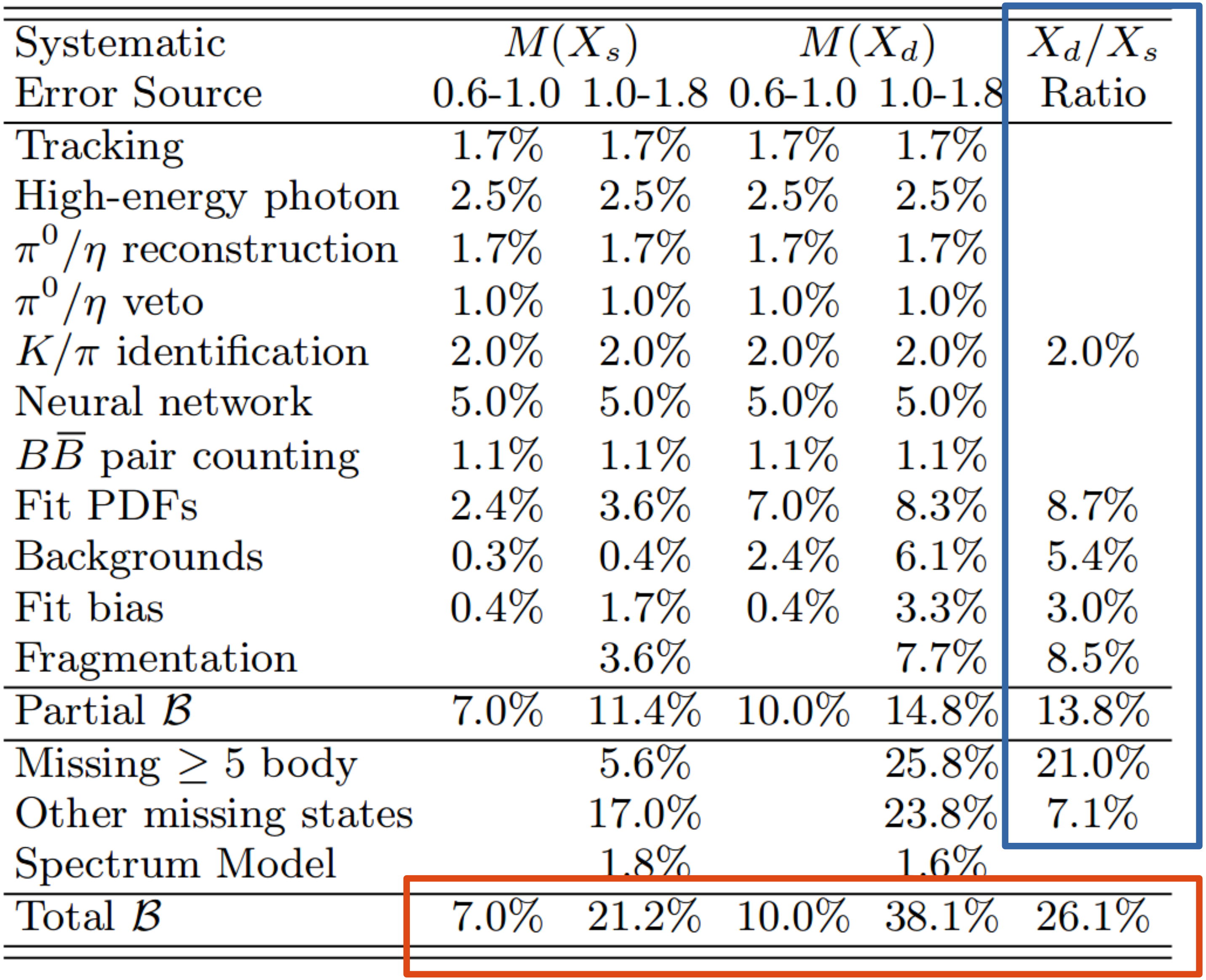
# Analysis details

- Identified particles are combined to form B meson candidates consistent with one of the 7 decay modes
- Background: e+e-→ qqbar and photon from ISR or FSR
- Angles, rates of K and lepton production are different in signal and background
- Use a neural network (NN) to distinguish signal from background

# Uncertainties



| Systematic | $M(X_s)$ | | $M(X_d)$ | | $X_d/X_s$ |
|---|---|---|---|---|---|
| Error Source | 0.6-1.0 | 1.0-1.8 | 0.6-1.0 | 1.0-1.8 | Ratio |
| Tracking | 1.7% | 1.7% | 1.7% | 1.7% | |
| High-energy photon | 2.5% | 2.5% | 2.5% | 2.5% | |
| $\pi^0/\eta$ reconstruction | 1.7% | 1.7% | 1.7% | 1.7% | |
| $\pi^0/\eta$ veto | 1.0% | 1.0% | 1.0% | 1.0% | |
| $K/\pi$ identification | 2.0% | 2.0% | 2.0% | 2.0% | 2.0% |
| Neural network | 5.0% | 5.0% | 5.0% | 5.0% | |
| $B\overline{B}$ pair counting | 1.1% | 1.1% | 1.1% | 1.1% | |
| Fit PDFs | 2.4% | 3.6% | 7.0% | 8.3% | 8.7% |
| Backgrounds | 0.3% | 0.4% | 2.4% | 6.1% | 5.4% |
| Fit bias | 0.4% | 1.7% | 0.4% | 3.3% | 3.0% |
| Fragmentation | | 3.6% | | 7.7% | 8.5% |
| Partial $\mathcal{B}$ | 7.0% | 11.4% | 10.0% | 14.8% | 13.8% |
| Missing $\geq 5$ body | | 5.6% | | 25.8% | 21.0% |
| Other missing states | | 17.0% | | 23.8% | 7.1% |
| Spectrum Model | | 1.8% | | 1.6% | |
| Total $\mathcal{B}$ | 7.0% | 21.2% | 10.0% | 38.1% | 26.1% |

# Result

- Measuring ratio of *total widths of d and s decay modes*, we get

$$|V_{td}/V_{ts}| = 0.177 \pm 0.043 \pm 0.001$$

Experimental uncertainty

Theoretical uncertainty

- Using cross-check with exclusive decays of B → $(\rho,\omega)\gamma$ and B → $K^*\gamma$, we get

$$|V_{td}/V_{ts}| = 0.214 \pm 0.046 \pm 0.028$$

# Summary

- $B^0$-$B^0$bar oscillations let us measure $|V_{td}|$ and $|V_{ts}|$ separately
- The ratio of these CKM matrix elements gives us more reliable measurement
- $|V_{td}/V_{ts}|$ is measured from penguin diagrams in various B decays
- Stay tuned for more precision measurements from Belle II and other experiments
- To conclude, B-physics provides a great experimental handle to study diverse physics phenomena

# References

- Most pictures and equations from Modern particle physics textbook
- Physics 226 lecture slides by Heather Gray (Fall 2017) https://sites.google.com/lbl.gov/gray-ph226-2017/home
- $|V_{td}/V_{ts}|$ measurement: http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-13340.pdf

# Back up

# Measuring the sides of the CKM Matrix PDG

- Nuclear beta decays: $|V_{ud}| = 0.97417 \pm 0.00021$
- Semileptonic kaon and hyperon decays: $|V_{us}| = 0.2248 \pm 0.0006.$
- Semileptonic charm decays+form factors: $|V_{cd}| = 0.220 \pm 0.005.$
- Semileptonic D or leptonic $D_s$ decays: $|V_{cs}| = 0.995 \pm 0.016$
- Semileptonic exclusive and inclusive B decays: $|V_{cb}| = (40.5 \pm 1.5) \times 10^{-3}$
- Endpoint spectrum in semileptonic B decays $|V_{ub}| = (4.09 \pm 0.39) \times 10^{-3}$
- The terms involving top quarks are more challenging
  - Unlikely to measure $|V_{td}|$ and $|V_{ts}|$ from tree-level processes with top quarks
  - Use B-$\overline{\text{B}}$ oscillations with top quarks in box diagrams

    $$|V_{td}| = (8.2 \pm 0.6) \times 10^{-3}, \qquad |V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}.$$
  - Clean measurement from $K^+ \rightarrow \pi^+ \nu\nu$
- |Vtb|: ratios of br. fractions in top decays or single top $|V_{tb}| = 1.009 \pm 0.031$