Things I wish I'd known when I was a graduate student...that are related to particle physics

Jeffrey D. Richman

University of California, Santa Barbara

TM

***BABAR* Physics Analysis School**

Feb. 12 – 13, 2008

Outline

- **Lecture 1**
  - **Constants, natural units, and order-of-magnitude estimates**
  - **Overview of *B* physics**
  - **CP violation as an interference effect**
  - **3 kinds of CP violation**
  - **Direct CP violation**
- **Lecture 2**
  - **Thinking about symmetries**
  - **Meson oscillations**
  - **Time-dependent CP violation in *B* decays**
  - **Conclusions**

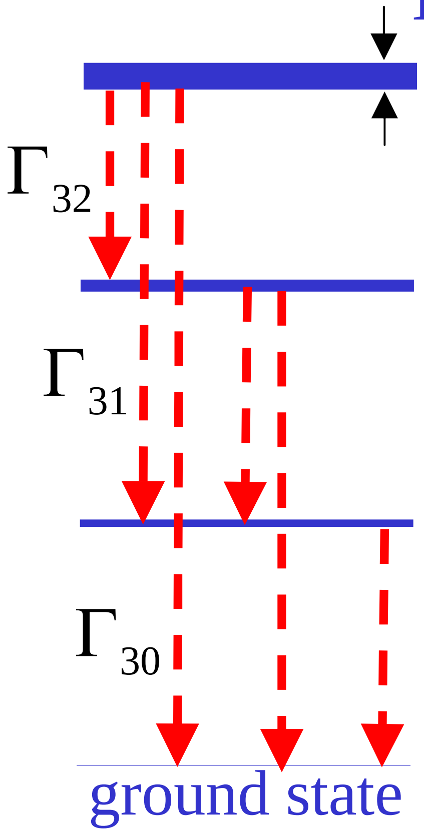
Learning Particle Physics

- **My knowledge of particle physics was very scattered when I was a graduate student.**
- **Main things I learned:**
    1. **Look for explanations that are as physical as possible, not just mathematical. Then, <u>remember</u> the explanation.**
    2. **Don't be afraid to ask stupid questions. Research is ultimately based on asking questions.**
- **This may not seem like much progress...but it's a pretty hard subject.**
- **<u>Remember: most of particle physics is not yet known!</u>**

$$\hbar = 66 \text{ MeV} \times 10^{-23} \text{ s}$$

In a quantum system, spontaneous transitions between states induce a spread in the energies (masses) of any unstable state.

Breit-Wigner line width = $\Gamma = \Gamma_{32} + \Gamma_{31} + \Gamma_{30}$



$$\Gamma_{\text{energy spread}} = \hbar \Gamma_{\text{decays/sec}}$$

$$\tau = \frac{\hbar}{\Gamma} \cong \frac{65.8 \text{ MeV} \cdot 10^{-23} \text{ s}}{\Gamma}$$

10^{-23} s = 1 strong sec = r_{had}/c =1 fm/c

$$\tau_{\rho\ meson} = \frac{65.8 \text{ MeV} \cdot 10^{-23} \text{ s}}{150 \text{ MeV}} \approx 0.4 \cdot 10^{-23} \text{ s}$$

$$\tau_{\text{t-quark}} = \frac{65.8 \text{ MeV} \cdot 10^{-23} \text{ s}}{1.5 \text{ GeV}} \approx 4 \cdot 10^{-25} \text{ s}$$

no $t\bar{t}$ bound states

$$\hbar c \approx 0.2\ \text{GeV}\cdot\text{fm}$$

$(= 0.1973\ \text{GeV}\cdot\text{fm})$

Sets the distance scale over which quantum fluctuations propagate from their source.

$$\Delta E\cdot\Delta t \approx mc^2\cdot\Delta t \approx \hbar \quad \Rightarrow c\cdot\Delta t \approx \frac{\hbar c}{mc^2}$$

$$V(r) = \frac{1}{4\pi r}e^{-mr}$$

A. Zee, p. 26 (n.u.)

Compton wavelengths

$$\frac{1}{m_W} \rightarrow \frac{\hbar c}{m_W c^2} \simeq \frac{0.2\ \text{GeV}\cdot\text{fm}}{81\ \text{GeV}} \simeq 2.5\cdot 10^{-3}\ \text{fm}$$

tiny compared to size of hadron/nucleon

$$\frac{1}{m_\pi} \rightarrow \frac{\hbar c}{m_\pi c^2} \simeq \frac{0.2\ \text{GeV}\cdot\text{fm}}{0.14\ \text{GeV}} \simeq 1.4\ \text{fm}$$

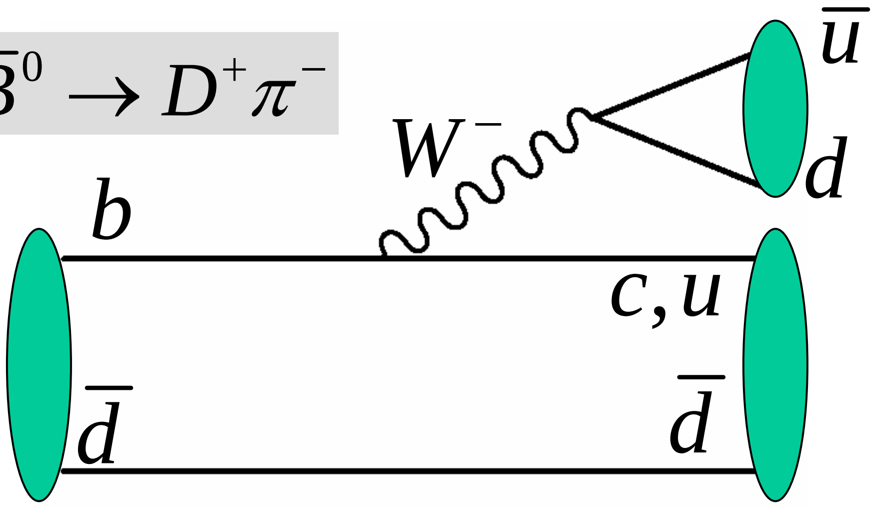
comparable to size of hadron/nucleon

Size of the H-atom involves both the electon mass and the EM coupling.

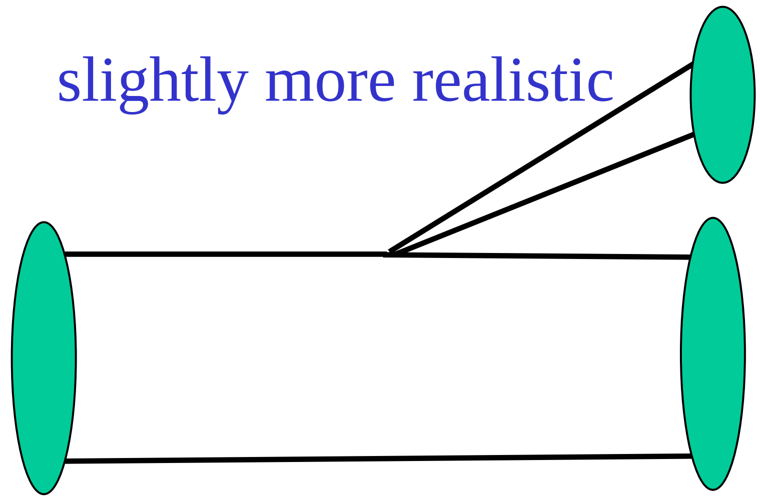
$$a_0 = \frac{1}{m_e\alpha} \rightarrow \frac{\hbar c}{m_e c^2\alpha} \simeq \frac{197.3\ \text{MeV}\cdot\text{fm}}{0.511\ \text{MeV}\cdot\frac{1}{137}} \simeq 5.29\cdot 10^4\ \text{fm} \simeq 0.53\ \text{A}$$

Range of the W is tiny compared to size of meson: Feynman diagrams can be misleading

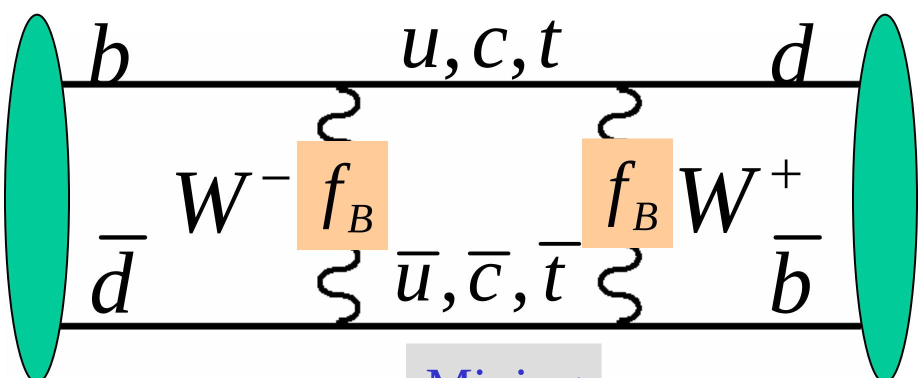
$\overline{B}^0 \rightarrow D^+ \pi^-$



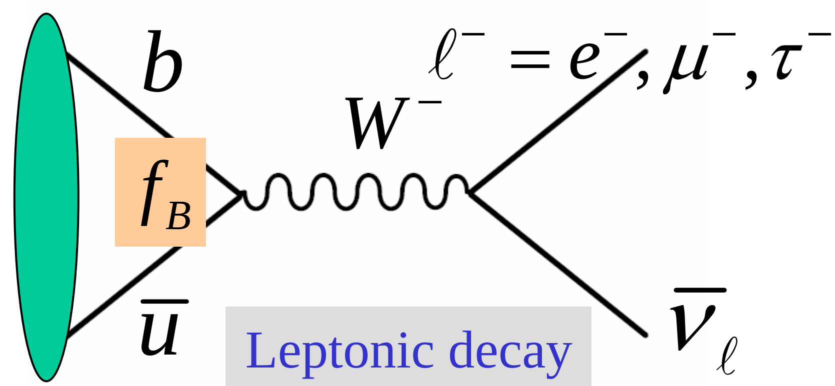
slightly more realistic



Quarks must be very close to <u>exchange</u> *W*: amplitude for quarks to have zero separation is described by the *B* meson decay constant f_B



Mixing



Leptonic decay

$\hbar$, natural units, and simple estimates

- **Often trade in M, L, & T for M, V=L/T, and A=MVL. Why???**
- **Natural scales are set for both V and A by physical constants of nature ($\hbar$ and c)!**

Ordinary dimensions (e.g., used in SI units)	Dimensions used for natural units	Transformations
M (mass)	M (mass)	M = M
L (length)	V (velocity)	$V = LT^{-1}$ $L = M^{-1} V^{-1} A$
T (time)	*A* (angular mom. = action)	$A = M L^2 T^{-1}$ $T = M^{-1} V^{-2} A$

Natural Units (n.u.)

Arbitrary quantity has dimensions

$$M^{\alpha}L^{\beta}T^{\gamma} = M^{\alpha}(M^{-1}AV^{-1})^{\beta}(M^{-1}AV^{-2})^{\gamma}$$
$$= M^{\alpha-\beta-\gamma}A^{\beta+\gamma}V^{-\beta-2\gamma}$$

Numerical quantity is of the form

$$a \cdot M^{\alpha-\beta-\gamma}\hbar^{\beta+\gamma}c^{-\beta-2\gamma} \underset{\hbar=c=1}{\longrightarrow} a \cdot M^{\alpha-\beta-\gamma}$$

Measuring
- ang. mom in units of $\hbar$
- velocity in units of c

$$L \underset{n.u.}{\longrightarrow} M^{0-1-0} = M^{-1} \qquad \sigma = L^2 \to M^{-2}$$
$$T \underset{n.u.}{\longrightarrow} M^{0-0-1} = M^{-1}$$

Easiest way to evalute: $m \rightarrow mc^2$; then insert powers of $\hbar c$, $\hbar$, or c to get correct dimensions of L and T.

$$\frac{GMm}{r} \sim E \Rightarrow GMm \sim \hbar c \Rightarrow M_{PL} = \sqrt{\frac{\hbar c}{G}} = 1.2 \cdot 10^{19}\ \text{GeV}/c^2$$

Planck mass

Dimensional analysis of cross sections

$$e^+e^- \to \mu^+\mu^-$$

$$(\sqrt{s} = E_{CM} \ll m_Z)$$

Total cross section (not differential) must have following dependence:

$$\sigma \sim \alpha^2 f(s, m_e, m_\mu)$$

For $s \gg m_\mu^2$, $\sigma \sim \alpha^2 f(s)$

$$\sigma \sim L^2 \Rightarrow \sigma \sim \frac{\alpha^2}{E^2} \sim \frac{\alpha^2}{s}$$

Compare with the actual answer:

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi}{3}\frac{\alpha^2}{s}$$ (n.u.)

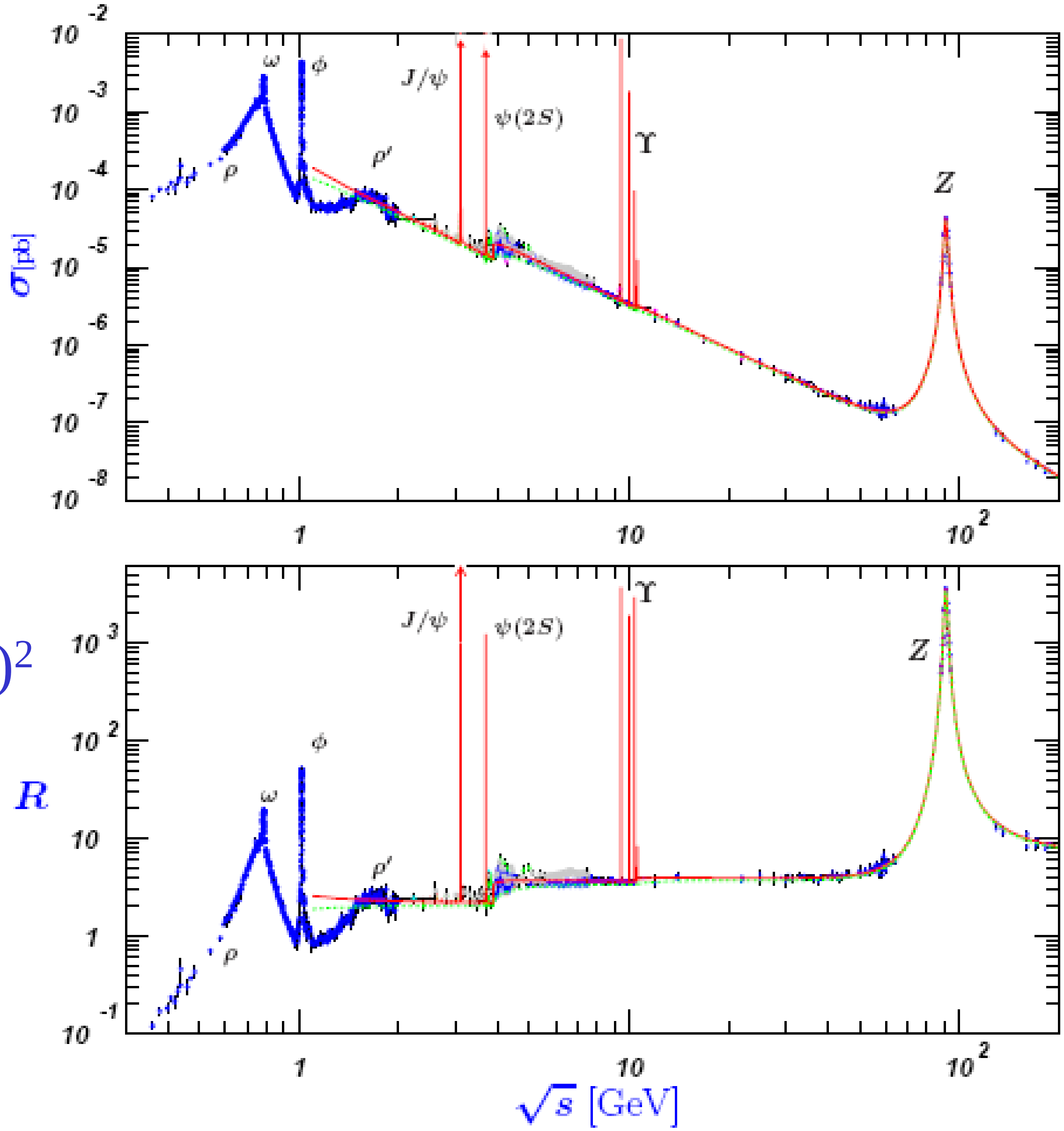
$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi}{3}\frac{\alpha^2(\hbar c)^2}{s} = \frac{86.8 \text{ nb}}{s(\text{GeV}^2)}$$

e^+e^- Scattering

$$\sigma(e^+e^- \rightarrow hadrons)$$

- Resonant peaks due to quarkonium states.
- $e^+e^- \rightarrow q\bar{q}$ continuum has *same energy dependence* as $e^+e^- \rightarrow \mu^+\mu^-$.
- Extra factor for each $q\bar{q}$: (3 colors)*(quark charge)^2

$$R \equiv \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$



PDG 2005

pp cross section (relevant for LHC)

Naïve calculation based on geometric cross secton

$$\sigma_{nucleon} \approx \pi r_{nucleon}^2 \approx \pi (1 \text{ fm})^2 \approx \pi (10^{-13} \text{ cm})^2 \approx 30 \text{ mb}$$

pp cross sections (LHC)

$$\sigma_{tot} \simeq 100 \text{ mb}$$

$$\sigma_{inelastic} \simeq 80 \text{ mb}$$

Approximate size of nucleus: $r_{nucleus} \simeq 1.2 \text{ fm}\, A^{1/3}$

Use to estimate nuclear interaction length (relevant for hadronic calorimeter or absorber for muon system)

$$\lambda_{\text{int}} = \frac{1}{N\sigma} = \frac{1}{(\rho N_{avo} / A) \cdot \sigma} = \frac{56}{(7.9 \text{ g cm}^{-3}) \cdot (6.65 \cdot 10^{-25} \text{ cm}^2) \cdot (6.02 \cdot 10^{23} \text{ g}^{-1})}$$

scattering centers/volume

$= 18$ cm (Meas. value = 16.8 cm)

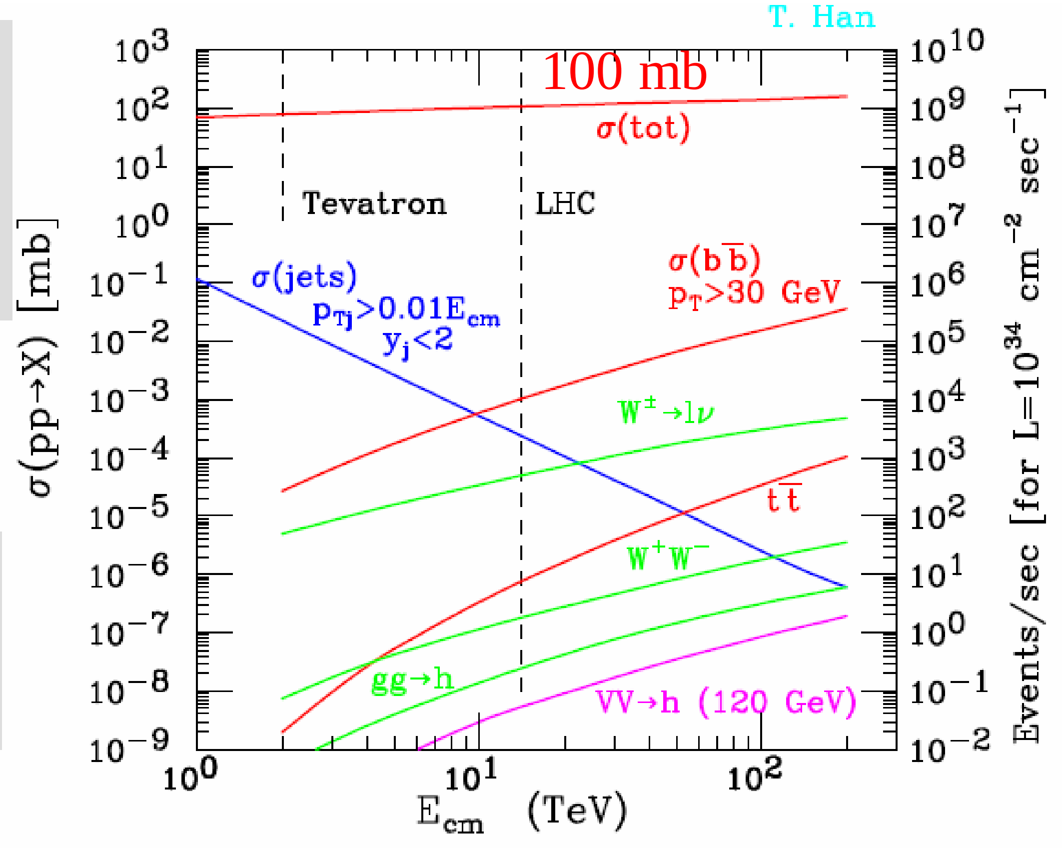
pp cross section

LHC interaction rate from inelastic scattering

$$\frac{dN}{dt} = L \cdot \sigma$$
$$= 10^{34}\ \text{cm}^{-2}\text{s}^{-1} \cdot 100 \cdot 10^{-3} \cdot 10^{-24}\ \text{cm}^2$$
$$= 10^9\ \text{s}^{-1}$$

BABAR interaction rate from e+e- → hadrons

$$\frac{dN}{dt} = 10^{34}\ \text{cm}^{-2}\text{s}^{-1} \cdot 4 \cdot 10^{-9} \cdot 10^{-24}\ \text{cm}^2$$
$$= 40\ \text{s}^{-1}$$

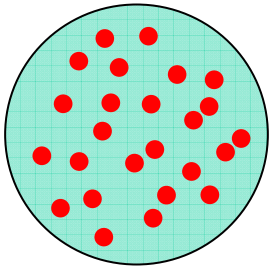


Huge range of cross sections at LHC!

Where does Avogradro's Number come from?, or: Why I became a physicist and not a chemist, or: Why I don't believe in homeopathic medicine.

Chemist's version

$$N_A = 6.02 \cdot 10^{23} \text{ particles/mole}$$



$$N_{\text{little objects}} = \frac{M_{\text{total}}}{m_{\text{little object}}}$$

Physicist's version: Avogradro's number is just $1/m_{proton}$(g) !

$$N_A = \frac{1}{m_{\text{bound nucleon}}(\text{g})} \simeq \frac{1}{m_{\text{proton}}(\text{g})} \simeq \frac{1}{m_{\text{neutron}}(\text{g})}$$

$$\simeq \frac{1}{1.67 \cdot 10^{-24}\,\text{g}} \simeq 6 \cdot 10^{23} \text{ nucleons/g}$$

$$N_{atoms} = \frac{M_{sample}}{m_{atom}} = \frac{M_{sample}}{A_{nucleons/atom} \cdot m_{nucleon}} = \frac{M_{sample}}{A_{nucleons/atom}} \cdot N_A$$

http://supplementspot.com/home.html

- **4. What are homeopathic medicines? Homeopathic medicines are drug products made by homeopathic pharmacies in accordance with the processes described in the Homeopathic Pharmacopoeia of the United States, the official manufacturing manual recognized by the FDA. The substances may be made from plants such as aconite, dandelion, plantain; from minerals such as iron phosphate, arsenic oxide, sodium chloride; from animals such as the venom of a number of poisonous snakes, or the ink of the cuttlefish; or even from chemical drugs such as penicillin or streptomycin. These substances are diluted carefully until little if any of the original remains.**

  A plant substance, for example, is mixed in alcohol to obtain a tincture. One drop of the tincture is mixed with 99 drops of alcohol (to achieve a ratio of 1:100) and the mixture is strongly shaken. This shaking process is known as succussion. The final bottle is labeled as "1C." One drop of this 1C is then mixed with 99 drops of alcohol and the process is repeated to make a 2C. By the time the 3C is reached, the dilution is 1 part in 1 million! Small globules made from sugar are then saturated with the liquid dilution. These globules constitute the homeopathic medicine. Dilutions or potencies commonly used (with their corresponding dilutions) include:
- **Dilution/Potency Dilution factor**
- **6C 10-12**
- **30C 10-60**
- **200C 10-400**
- **1M or 1000C 10-2000**

How big would the pill be if 1 atom in 10^{60} was the original substance?

What can we learn from heavy quark physics?

Standard Model CP parameters
measure/overconstrain Unitarity Triangle: α,β,γ (ϕ_3, ϕ_1,ϕ_2).

Magnitudes of CKM elements
V_{cb}, V_{ub}, V_{td}, V_{ts}

Effects of new physics
look for unexpected
- branching fractions
- patterns of CP asymmetries
- kinematic distributions

Studies of decay dynamics
- Test predictions of heavy-quark expansions
- Test QCD predictions: lattice, SCET, etc.
- Semileptonic, hadronic, and rare decays.

Searches for new particles
- Charm spectroscopy
- Charmonium spectroscopy
- Exotics ???

Interaction between theory and experiment is crucial!

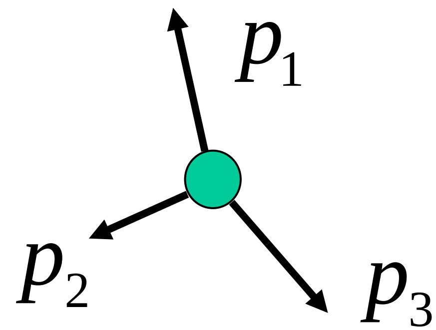
Reminder on decay rates and branching fractions

Branching fractions (B_f)

$$1 = \sum_{f=1}^{m} \frac{\Gamma_f}{\Gamma} = \sum_{f=1}^{m} B_f$$

Differential decay rate for mode *i* (in diff. region of phase space)

$$d\Gamma_f = \frac{(2\pi)^4}{2M} \left| \mathcal{M}_f \right|^2 d\Phi_n(P; p_1, \ldots, p_n)$$



sum of amplitudes for specified final state

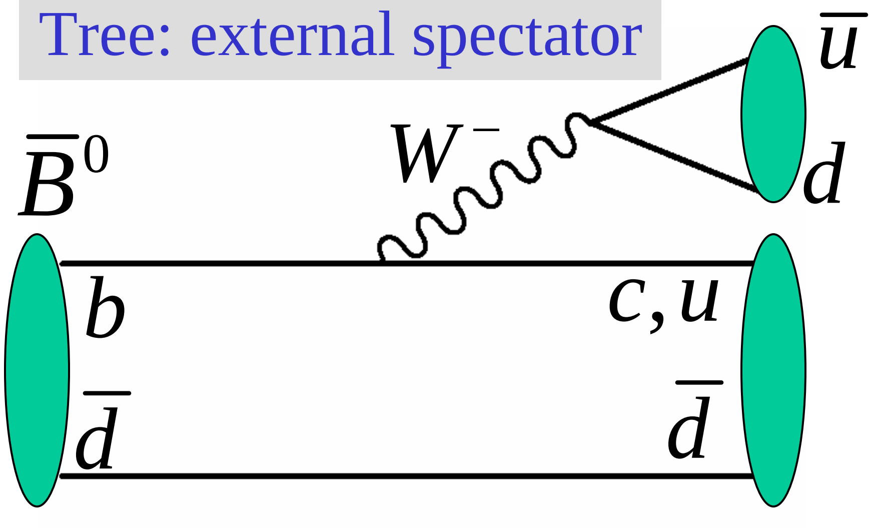
$$\mathcal{M}_f = \mathcal{M}_{f1} + \mathcal{M}_{f2} + \ldots$$

*phase space factor: integrate it over kinematic configurations consistent with (E,**p**) conservation*

$$d\Phi_n(P; p_1, \ldots, p_n) = \delta^4(P - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 (2E_i)}$$

Weak transitions underlying B decay (I)

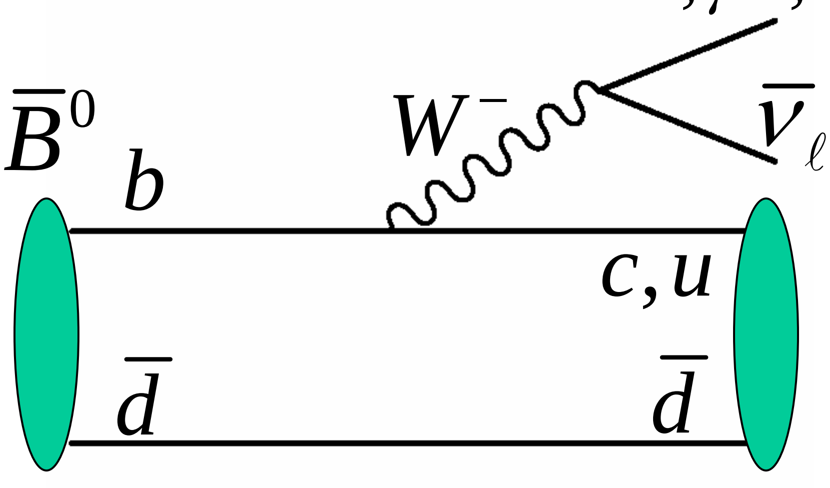
Tree: external spectator



Hadronic decay:

- External spectator diagram
- b→c is dominant
- Upper vertex can also produce $\bar{u}s, \bar{c}s, \bar{c}d$
- Typical mode:

$B(\bar{B}^0 \to D^-\pi^+) = 2.7 \cdot 10^{-3} \simeq 0.3\%$



Semileptonic decay:

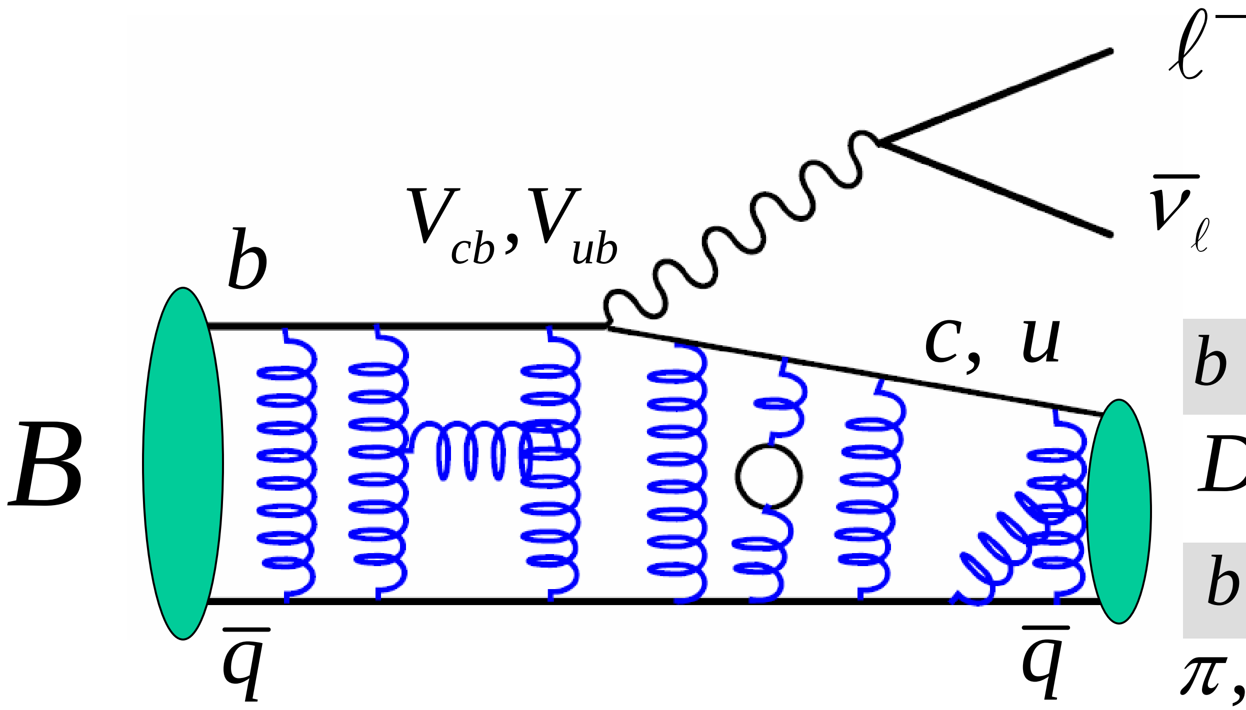
-Charge of lepton is correlated w/charge of b ($\bar{b}$) quark: tagging

-Largest B branching fraction

$B(B \to X \ell \bar{\nu}) \simeq 10.3\%$ (ℓ=e or μ, not sum)

$B(B \to D^* \ell \bar{\nu}) \simeq 5\%$ (ℓ=e or μ, not sum)

Decay dynamics: semileptonic B decays



$b \to c:$

$D,\ D^*,\ D^{**}$

$b \to u:$

$\pi,\ \rho,\ \eta,\ \eta',\ \omega,\ a_1, \ldots$

- Key application: determination of $|V_{cb}|$ and $|V_{ub}|$.
- In contrast to CKM phases, which we extract from CP *asymmetries*, need to measure (and predict) *decay rates*.

$$A(M_{Q\bar{q}} \to X_{q'\bar{q}}\ \ell^- \bar{\nu}) = -i \frac{G_F}{\sqrt{2}} \cdot V_{q'Q} \cdot L^\mu H_\mu$$

amplitude factorizes

Semileptonic decay form factors

The leptonic current can be calculated exactly:

$$L_\mu = \overline{u}_\ell \ \gamma_\mu (1-\gamma_5) \ v_\nu$$

Hadronic current describes complex, non-perturbative QCD effects

- Initial-state meson is perturbed by the momentum transfer from the decay
- Daughter- and spectator quarks exchange gluons to hold the meson together

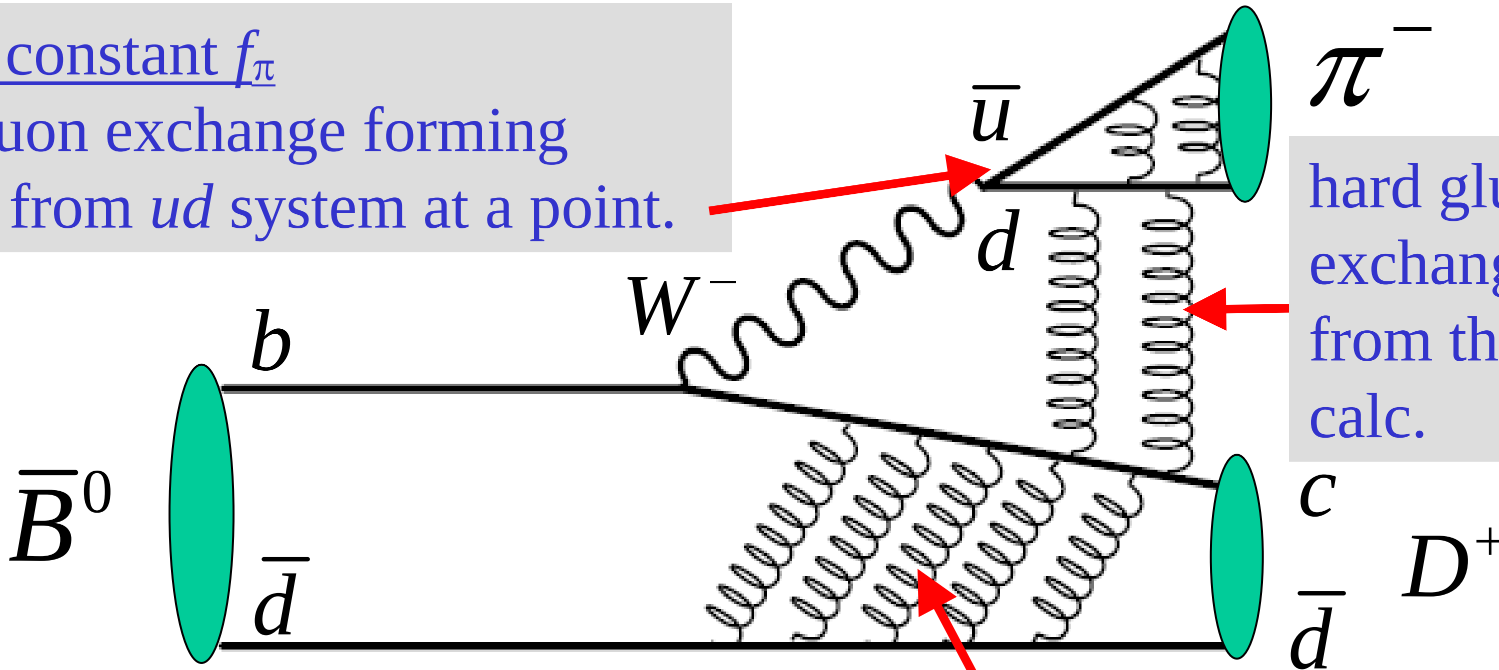
$$H_\mu = \left\langle X_{q'\overline{q}} \middle| \overline{q}' \ \gamma_\mu (1-\gamma_5) Q \middle| M_{Q\overline{q}} \right\rangle$$

Use **Lorentz invariance** to construct the hadronic current from the available four-vectors (momenta and polarization vectors) and form factors (Lorentz invariant functions).

$$\left\langle P'(p') | V^\mu \middle| P(p) \right\rangle = F_1(q^2)\left[(p+p')^\mu - \frac{M^2 - m_{P'}^2}{q^2} q^\mu \right] + F_0(q^2) \frac{M^2 - m_{P'}^2}{q^2} q^\mu$$

A simple model of hadronic *B* decays

Decay constant f_π
soft-gluon exchange forming meson from *ud* system at a point.



hard gluon exchange: a_1 from theory calc.

Form factor F($B \rightarrow D$; $q^2 = m_\pi^2$): amplitude to form meson from qq pair formed at point from W

$$Amp(\bar{B}^0 \to D^+\pi^-) = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* \cdot (m_B^2 - m_D^2) \cdot a_1 \cdot f_\pi \cdot F_0^{B\to D}(q^2 = m_\pi^2)$$

Testing our model for hadronic decays

Predict

$$\frac{\Gamma(\bar{B}^0 \to D^+\rho^-)}{\Gamma(\bar{B}^0 \to D^+\pi^-)} = \left[\frac{a_1 \cdot f_\rho \cdot F(B \to D; q^2 = m_\rho^2)}{a_1 \cdot f_\pi \cdot F(B \to D; q^2 = m_\pi^2)}\right]^2$$

$$\approx \left[\frac{f_\rho}{f_\pi}\right]^2 = \left(\frac{208\ \text{MeV}}{131\ \text{MeV}}\right)^2$$

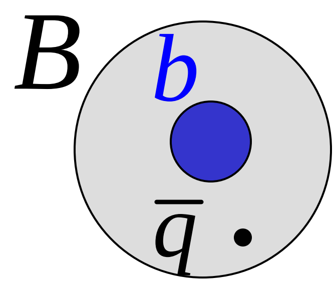
$$\approx 2.5$$

Measure

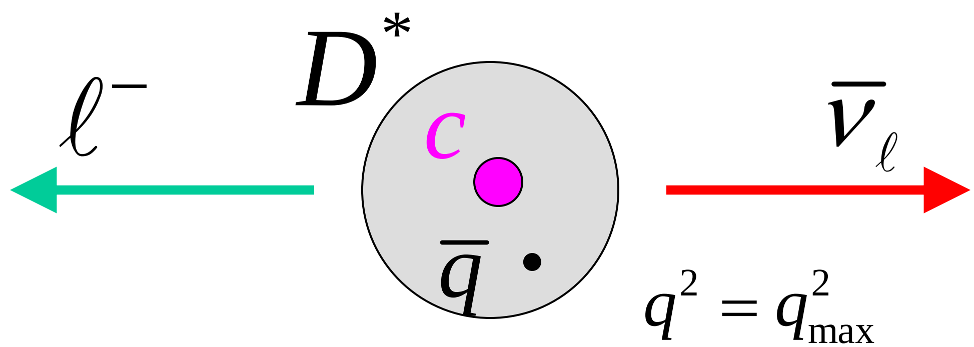
$$\frac{\Gamma(\bar{B}^0 \to D^+\rho^-)}{\Gamma(\bar{B}^0 \to D^+\pi^-)} = \frac{7.5 \cdot 10^{-3}}{2.7 \cdot 10^{-3}} = 2.8$$

Not due to extra spin degrees of freedom of ρ, since helicity=0 !

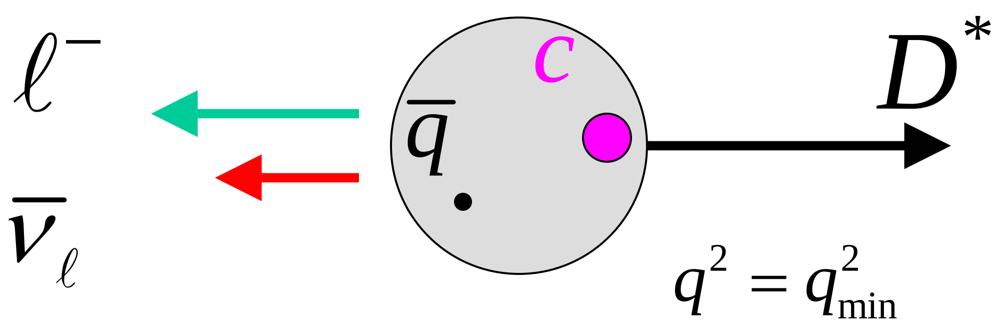
Physical meaning of q^2



B meson before decay



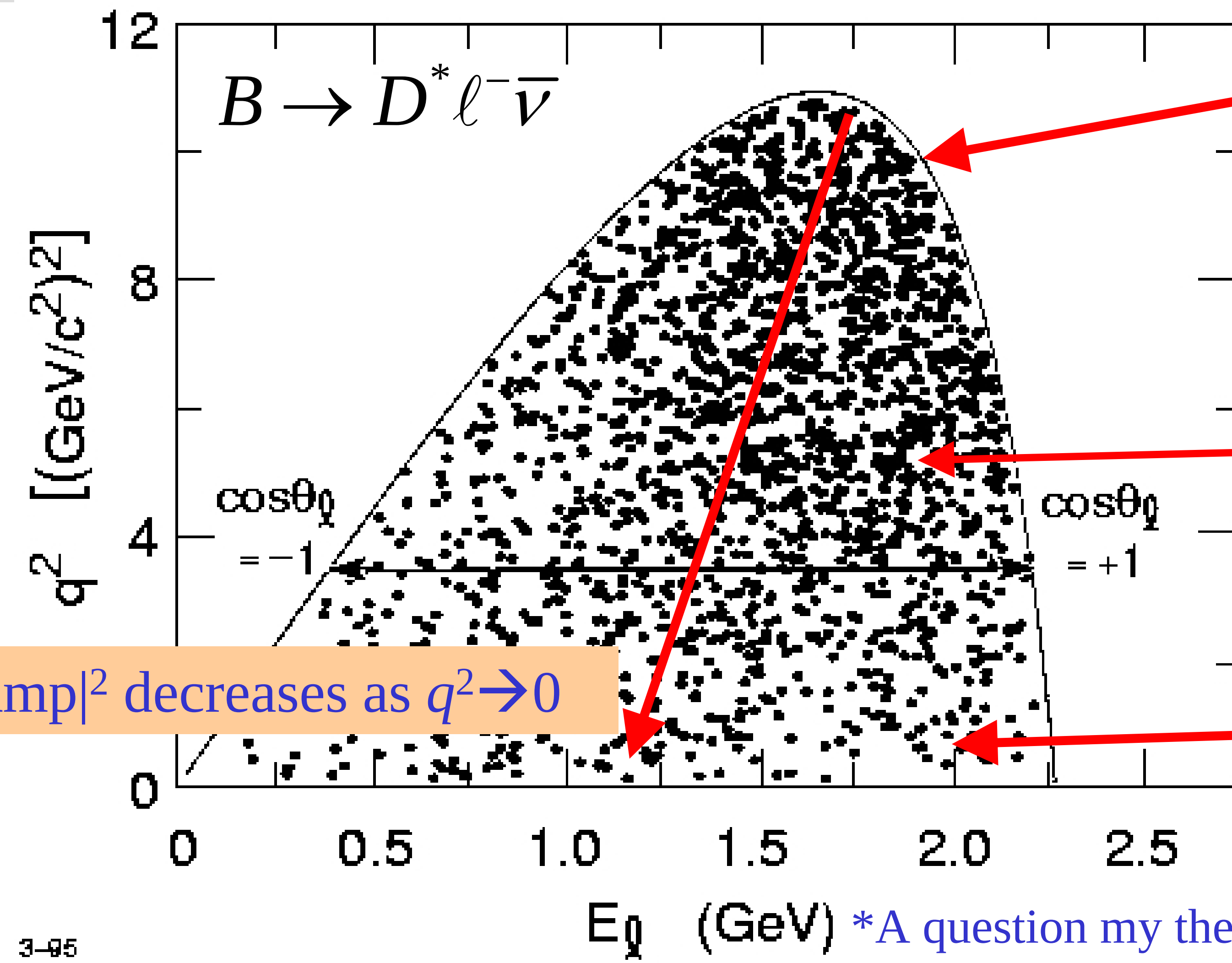
After decay: high q^2 configuration. Zero recoil of daughter hadron.



After decay: low q^2 configuration. Fast recoil of daughter hadron.

What is a Dalitz Plot?*

Dalitz plot variables: m^2 or E → Density of points shows $|\mathrm{Amp}|^2$. In a Dalitz plot, $|M|^2$=const would give uniform distribution of points.



high q^2 region

V-A: more points on R-than L-side

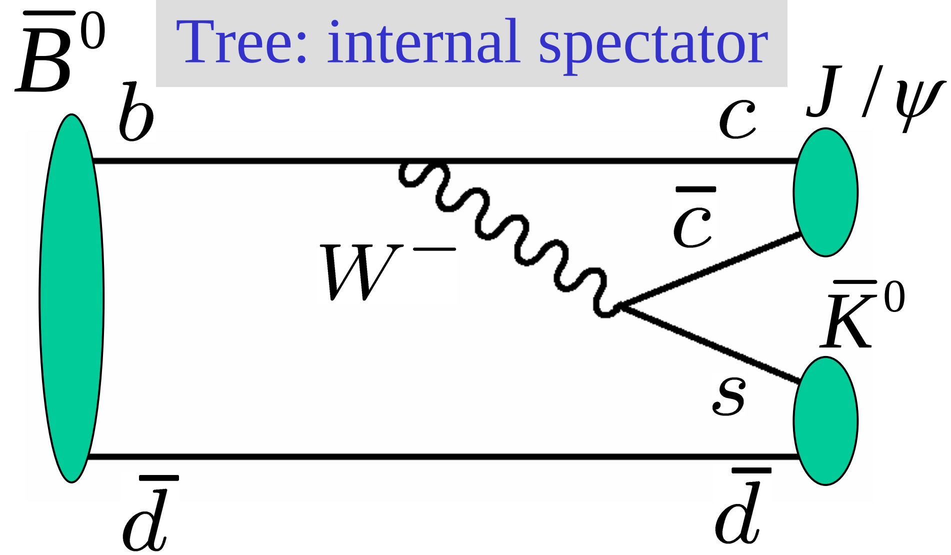
$|\mathrm{Amp}|^2$ decreases as $q^2 \to 0$

low q^2 region

*A question my thesis advisor asked me.

Weak transitions underlying *B* decay (II)

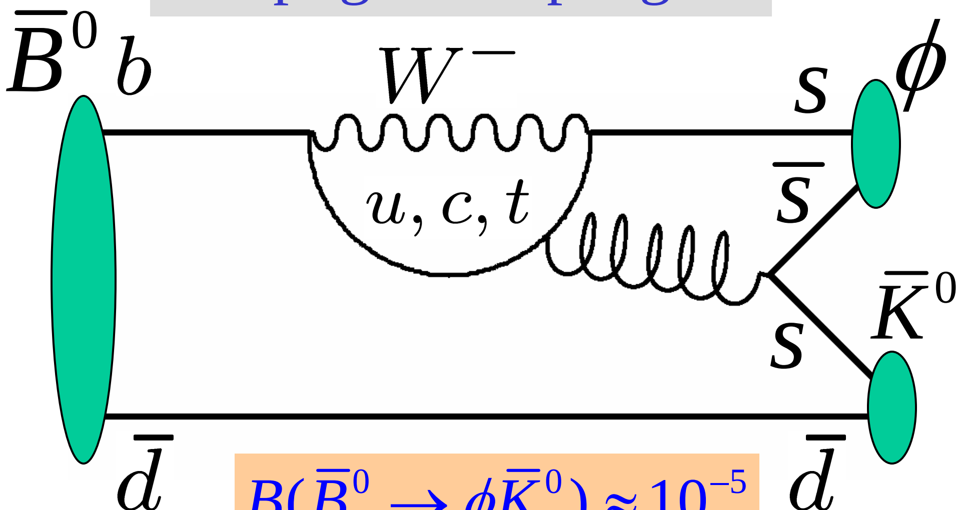
Tree: internal spectator



Hadronic decay:
- "Internal" spectator diagram
- Color suppressed
- In B^0 decays, can interfere with ext. spectator diagram.

$B(\overline{B}^0 \to D^0\pi^0) = 2.6\cdot10^{-4} \simeq 0.03\%$

Loop: gluonic penguin

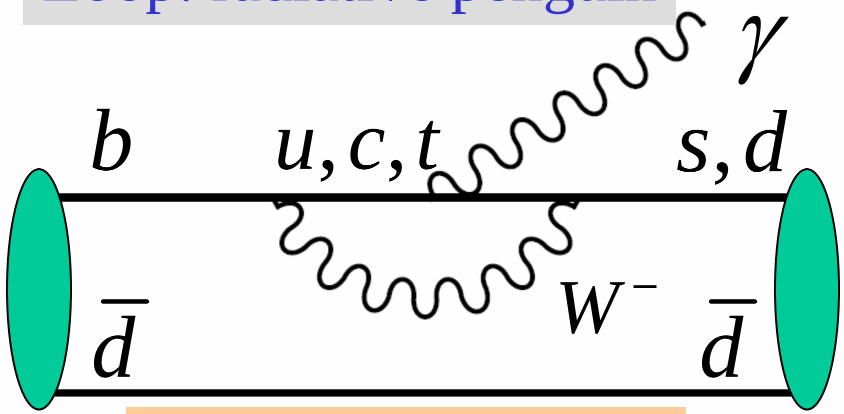


$B(\overline{B}^0 \to \phi\overline{K}^0) \approx 10^{-5}$

Hadronic decay:
- Gluonic penguin diagram
- Many such modes have now been observed! BF: 10^{-6}-10^{-5}
- Loop diagrams are suppressed in SM→ good place to search for new physics amplitudes.

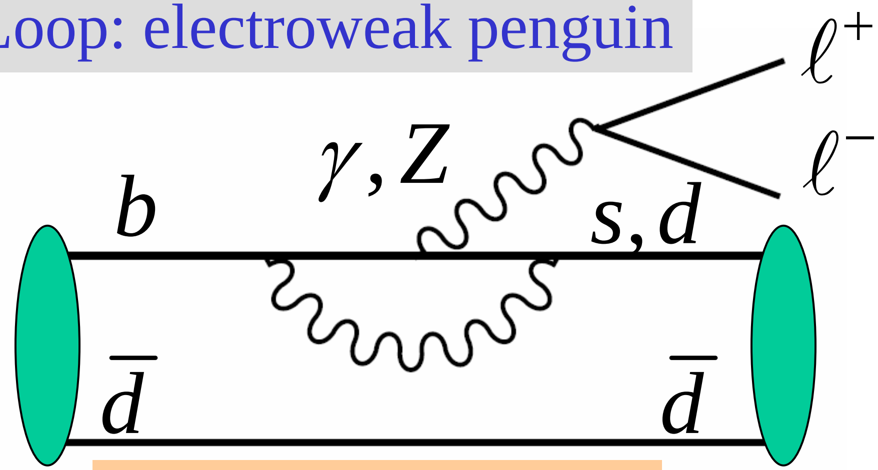
Weak transitions underlying *B* decay (III)

Loop: radiative penguin



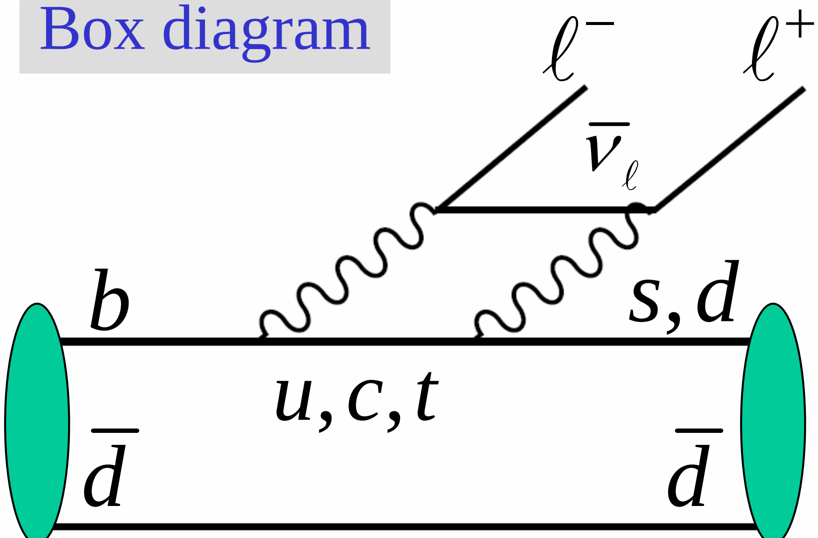
$B(\bar{B}^0 \to \bar{K}^{*0}\gamma) \simeq 4\cdot 10^{-5}$

Loop: electroweak penguin



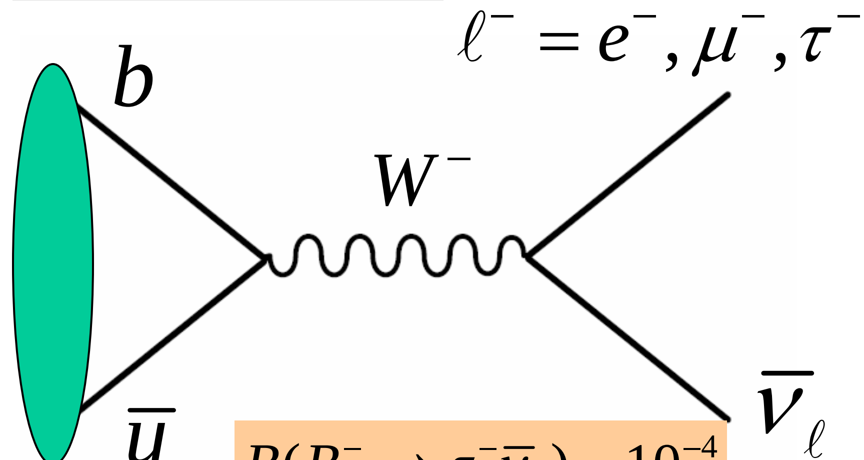
$B(\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-) \simeq 10^{-6}$

Box diagram



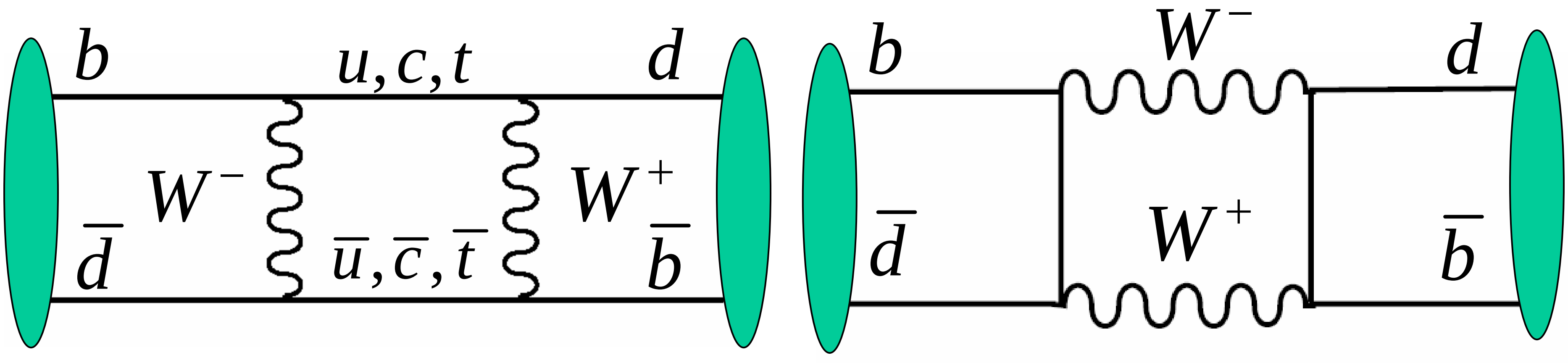
(part of previous process)

Leptonic decay



$B(B^- \to \tau^-\bar{\nu}_\tau) \simeq 10^{-4}$

Weak transitions underlying $B^0\,\overline{B}^0$ oscillations



$$\left|B^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt}\left(\cos\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle + i\alpha\cdot\sin\frac{\Delta M\cdot t}{2}\left|\overline{B}^0\right\rangle \right)$$

$$\left|\overline{B}^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt}\left(\frac{i}{\alpha}\sin\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle + \cos\frac{\Delta M\cdot t}{2}\left|\overline{B}^0\right\rangle \right)$$

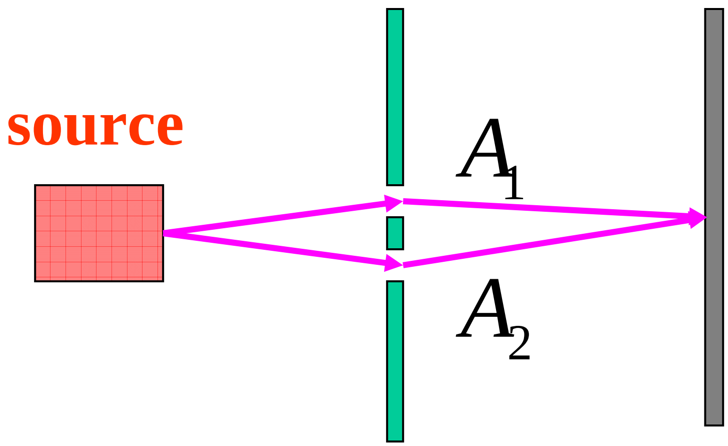
B^0 and $\overline{B}^0$ spontaneously evolve into each other. More precisely, a particle that is initially a B^0 evolves into a superposition of B^0 and $\overline{B}^0$.

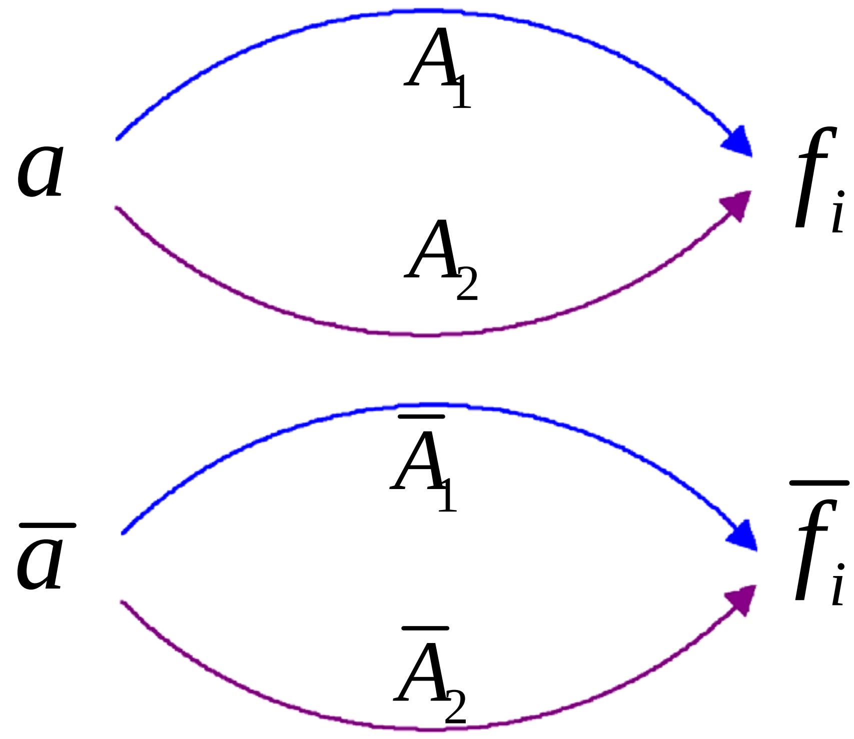
A 1st look at *CP* Violation

- What conditions are needed to produce *CP*-violating effects?
- What are the different ways to observe CP violation?
- How does CP violation in the *K*-meson system differ from CP violation in the *B*-meson sytem?

How are CP violating asymmetries produced?

The Standard Model predicts that, if CP violation occurs, it must occur through specific kinds of <u>quantum interference effects</u>..





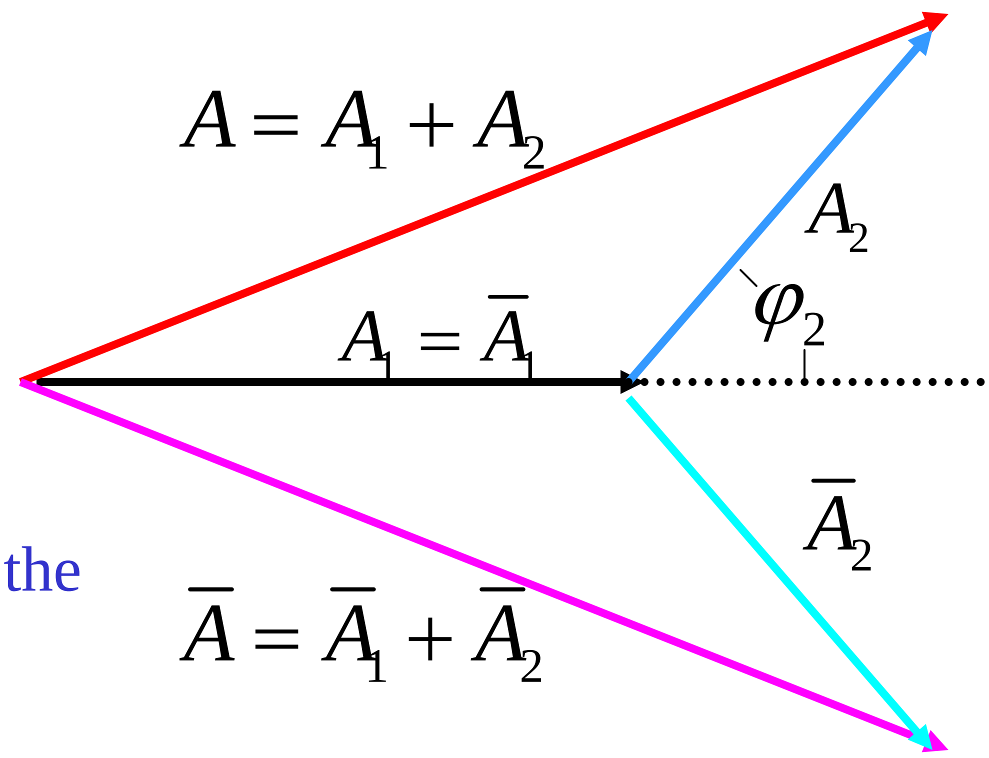
Double-slit experiment: if the final state does not distinguish between the paths, then the amplitudes A_1 and A_2 interfere!

Two amplitudes with a CP-violating relative phase

- Suppose a decay can occur through two processes, with amplitudes A_1 and A_2. Let A_2 have a CP-violating phase ϕ_2.

$$A = A_1 + a_2 e^{i\varphi_2}$$

$$\bar{A} = A_1 + a_2 e^{-i\varphi_2}$$



No CP asymmetry!
(But the decay rate is different from what it would be without the phase.)

Two amplitudes with CP-conserving & CP-violating phases

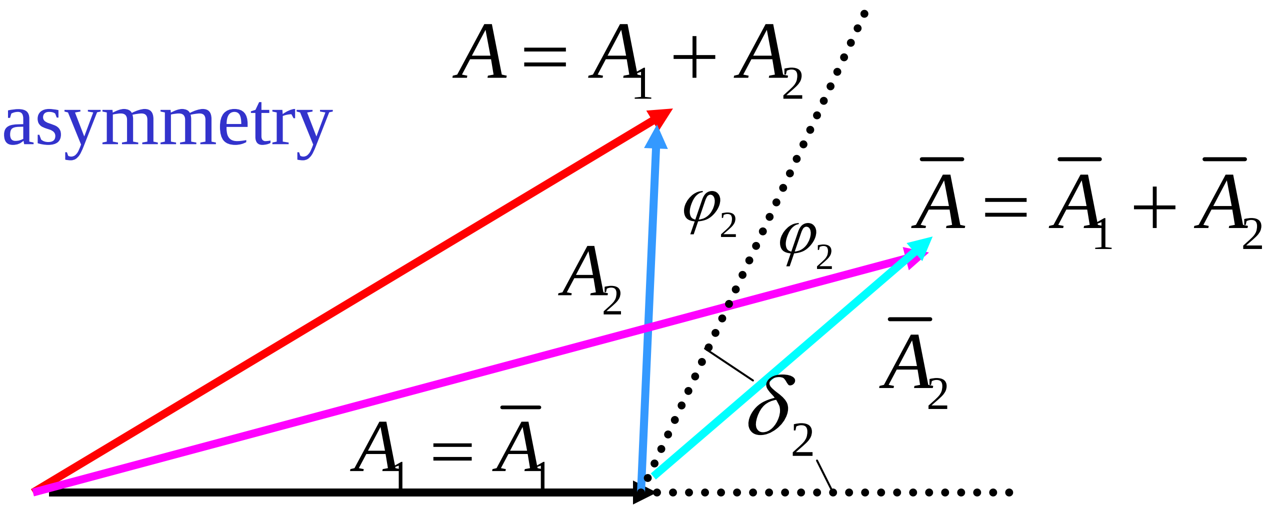
- Next, introduce a *CP-conserving* phase in addition to the *CP-violating* phase.

$$A = A_1 + a_2 e^{i(\varphi_2 + \delta_2)}$$

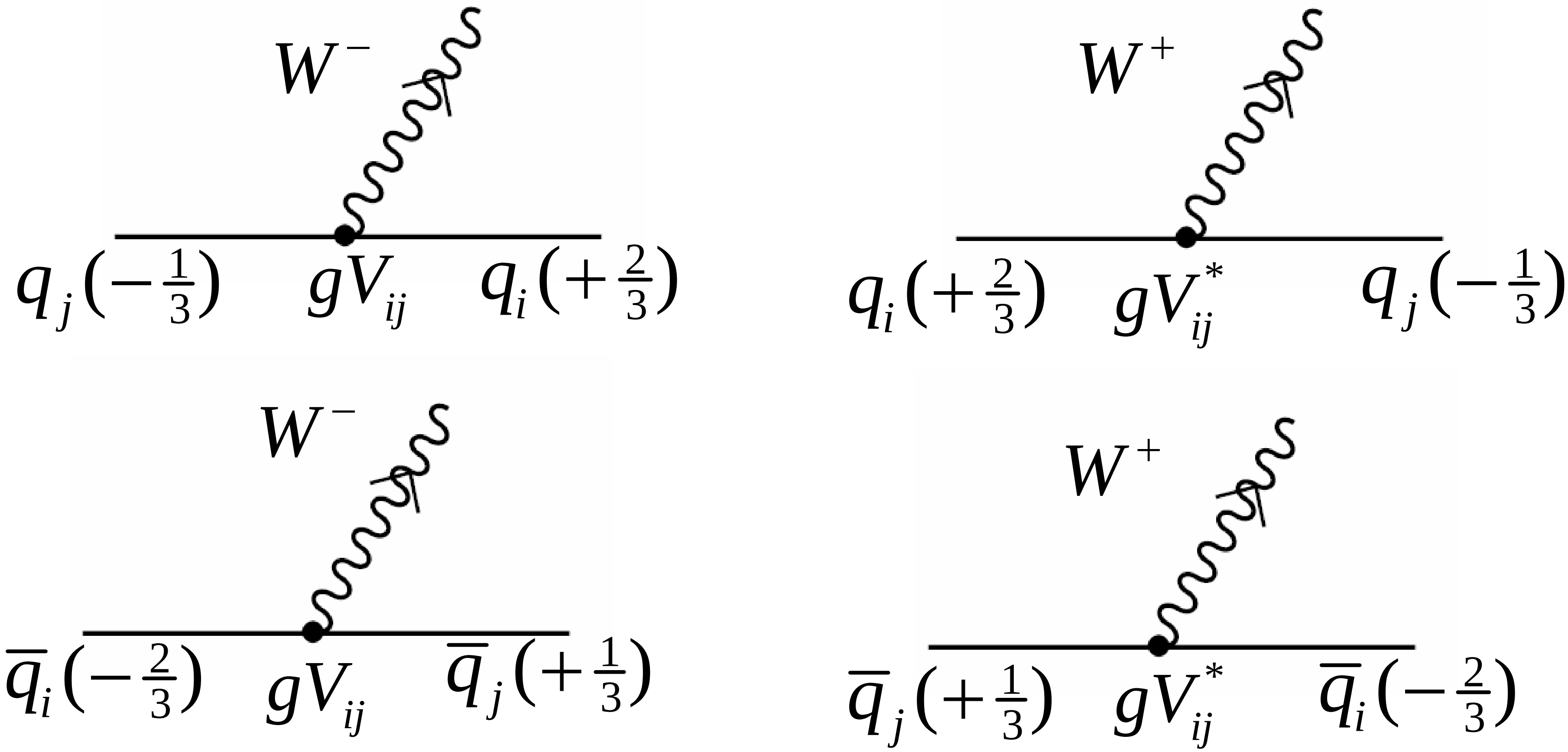
$$\bar{A} = A_1 + a_2 e^{i(-\varphi_2 + \delta_2)}$$

- Now have a CP asymmetry

$$|A| \neq |\bar{A}|$$



Origin of CP-violating phases in the Standard Model: Quark Couplings in *W*-mediated processes



Universal weak coupling g must be multiplied by element of CKM matrix V_{ij}.

emit W^- or absorb W^+ $\Rightarrow$ V_{ij}

emit W^+ or absorb W^- $\Rightarrow$ V_{ij}^*

Three Kinds of *CP* Violation

We have seen that CP violation arises as an interference effect.

- Need at least two interfering amplitudes
- Need relative CP-violating phase
- Need relative CP-conserving phase

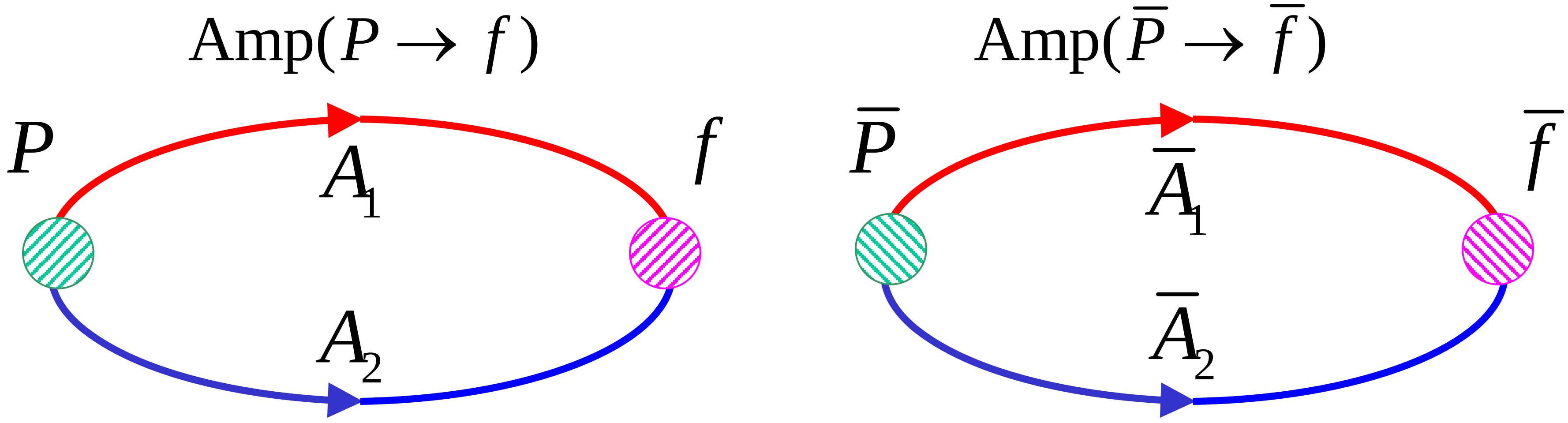
A single CP-violating amplitude will not produce observable CP violation!

Classification of CP-violating effects in particle transitions

(based on the sources of amplitudes that are present).

1. CP violation in oscillations ("indirect CP violation")
2. CP violation in decay ("direct CP violation")
3. CP violation in the interference between mixing and decay

Direct CP violation: interfering decay amplitudes



Direct CP violation seems the most straight-forward: it doesn't involve mixing to generate one of the amplitudes.

- Can occur in decays of both neutral & charged particles
- But the CP-conserving phases are from strong (QCD) interactions between the mesons ("final-state interactions"). These strong phases cannot be predicted reliably.

Amplitude analysis for direct CP violation

$$A = |A_1| e^{i(\varphi_1+\delta_1)} + |A_2| e^{i(\varphi_2+\delta_2)}$$

$$\bar{A} = (|A_1| e^{i(-\varphi_1+\delta_1)} + |A_2| e^{i(-\varphi_2+\delta_2)}) e^{-i[\theta(P)-\theta(f)]}$$

$$\text{Asymmetry} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\sin(\varphi_1-\varphi_2)\sin(\delta_1-\delta_2)}{\left|\frac{A_2}{A_1}\right| + \left|\frac{A_1}{A_2}\right| + \cos(\varphi_1-\varphi_2)\cos(\delta_1-\delta_2)}$$

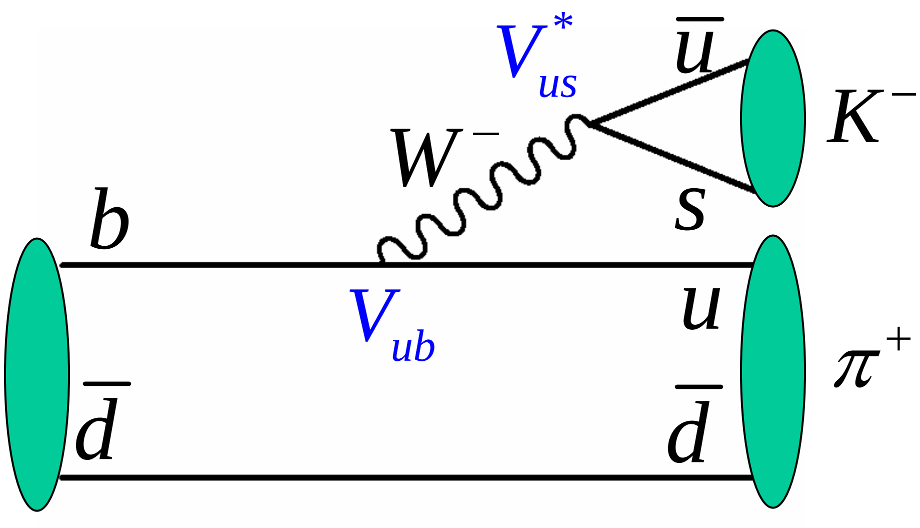
Problems with interpreting measurements of direct CP asymmetries:

1. we often don't know the difference δ_1-δ_2 , so we cannot extract ϕ_1-ϕ_2 from the asymmetry.
2. we often don't know the relative magnitude of the interfering amps.

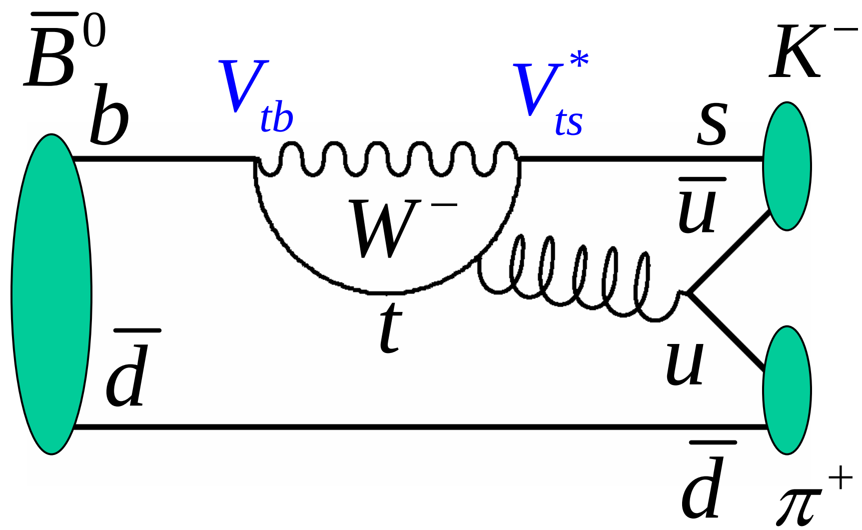
Direct CP violation in $B \rightarrow K^- \pi^+$

Interference between tree and penguin amplitudes produces a CP asymmetry in $B \rightarrow K^- \pi^+$. Both processes are suppressed!

External spectator



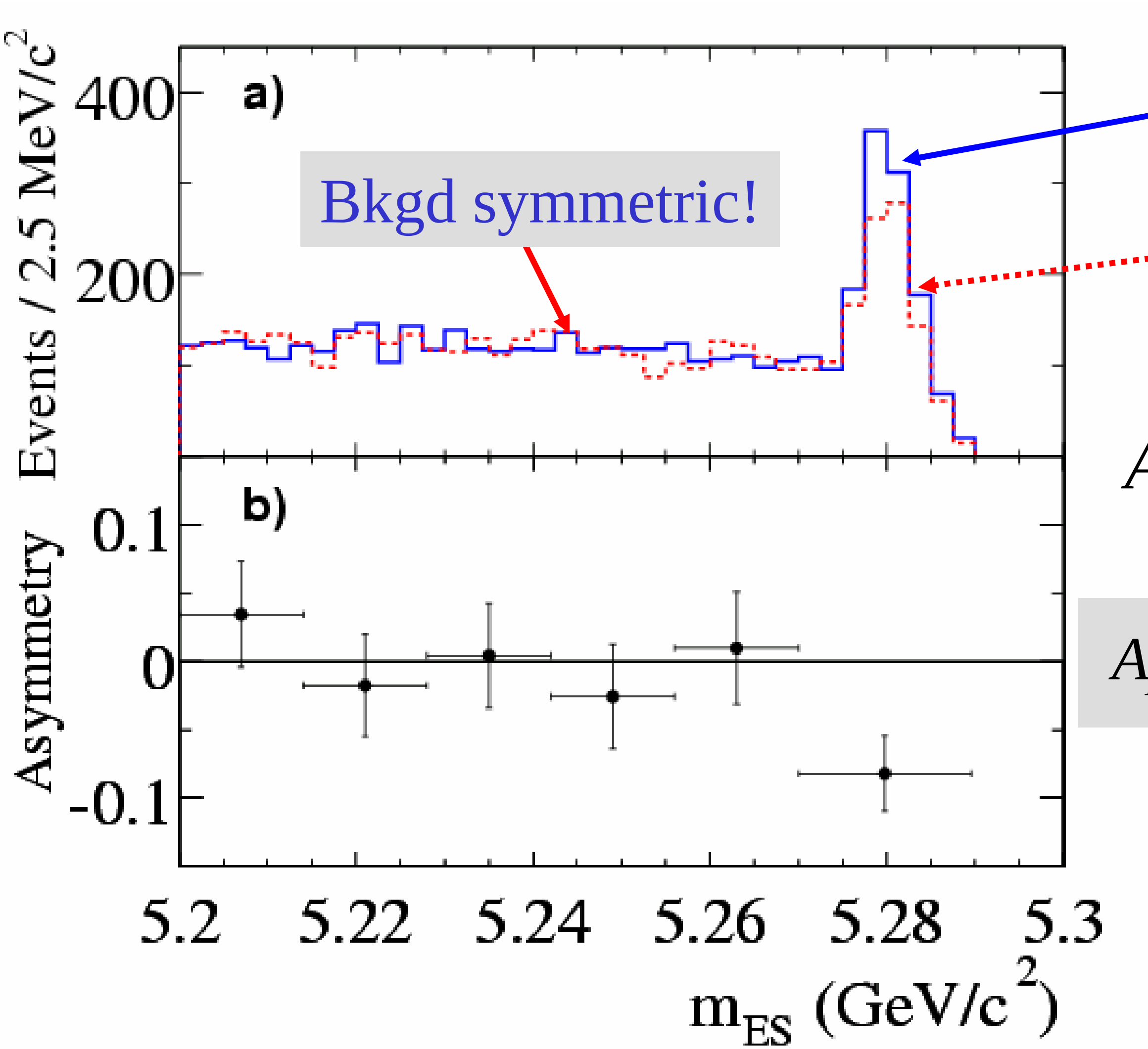
Gluonic penguin



In the Wolfenstein convention, the CP-violating phase factor comes from $V_{ub} \propto e^{-i\gamma}$.

"Direct" CP violation in $B^0 \to K^+\pi^-$ vs. $\bar{B}^0 \to K^-\pi^+$

$$N(B\bar{B}) = 227\times10^6 \qquad B(B\to K\pi)\approx 2\times10^{-5}$$



$$n\left(B^0\to K^+\pi^-\right) = 910$$

$$n\left(\bar{B}^0\to K^-\pi^+\right) = 696$$

$$A = \frac{696-910}{696+910} = -0.133$$

$$A_{K\pi} = -0.133\pm0.030\pm0.009$$

hep-ex/0408057

CP violation and aliens from outer space

We can use our knowledge of CP violation to determine whether alien civilizations are made of matter or antimatter without having to touch them.

$$A_{CP} = \frac{\Gamma(\overline{B}^0 \to K^- \pi^+) - \Gamma(B^0 \to K^+ \pi^-)}{\Gamma(\overline{B}^0 \to K^- \pi^+) + \Gamma(B^0 \to K^+ \pi^-)} \simeq -13\%$$

$b\overline{d}$ $\qquad$ $\overline{b}d$

We have these inside of us.

$$K^- = \overline{u}s$$

$$\pi^- = \overline{u}d$$

Finally: a practical application for particle physics!

Is the difference between matter and antimatter merely one of convention, or is there a difference in their behavior?

CPT symmetry guarantees

$$\begin{cases} m(a) = m(\overline{a}) \\ \Gamma(a) = \Gamma(\overline{a}) \\ \tau(a) = \tau(\overline{a}) \end{cases}$$

C violation by itself does not truly distinguish between matter and antimatter, because a parity flip would restore equality:

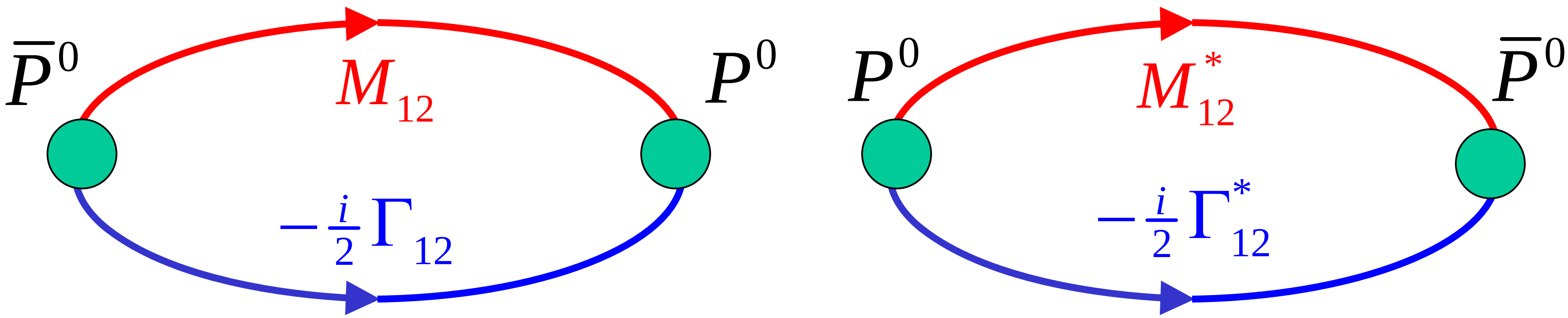
$$\sum_{\substack{\text{all final-state} \\ \text{helicities}}} \Gamma\left(\mu^- \to e^- \overline{\nu}_e \nu_\mu\right) = \sum_{\substack{\text{all final-state} \\ \text{helicities}}} \Gamma\left(\mu^+ \to e^+ \nu_e \overline{\nu}_\mu\right)$$

We want to observe a true decay-rate difference!

$$\underbrace{\Gamma_i(a \to f_i)}_{\text{rate (process)}} \neq \underbrace{\Gamma_i(\overline{a} \to \overline{f}_i)}_{\text{rate (anti-process)}}$$

} C *and* CP violation

CP Violation in Oscillations



$\mathrm{Amp}(\overline{P}^0 \to P^0)$ $\mathrm{Amp}(P^0 \to \overline{P}^0)$

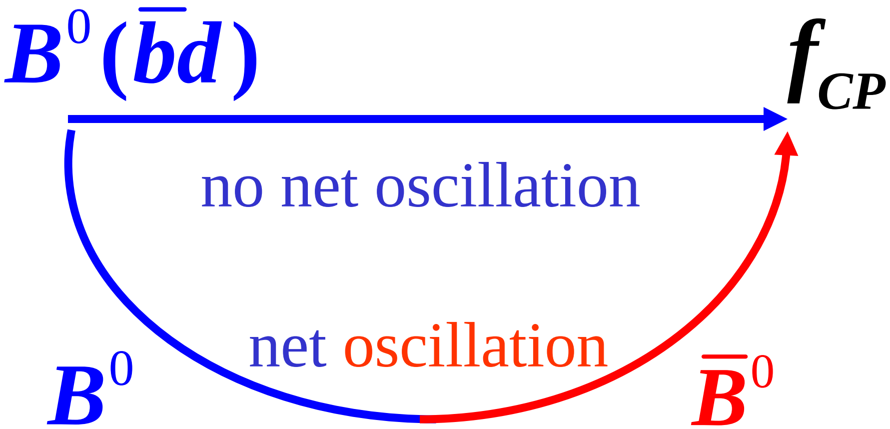
M_{12} = transition amplitude via intermediate states that are virtual (off-shell)

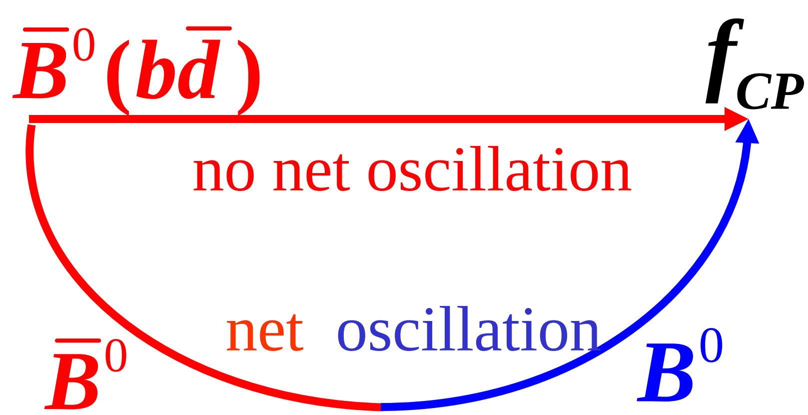
Γ_{12} = transition amplitude via intermediate states are are real (on-shell: both P^0 and $\overline{P}^0$ can decay into these!)

- The "-i" is a CP conserving phase factor. It doesn't change sign!
- M_{12} and Γ_{12} behave like CP-violating phase factors, as long as they are not relatively real.

Time-dependent CP asymmetries from the interference between mixing and decay amplitudes

By modifying the mixing measurement, we can observe whole new class of CP-violating phenomena: pick final states that both B^0 and $\bar{B}^0$ can decay into. (Often a CP eigenstate, but doesn't have to be.)





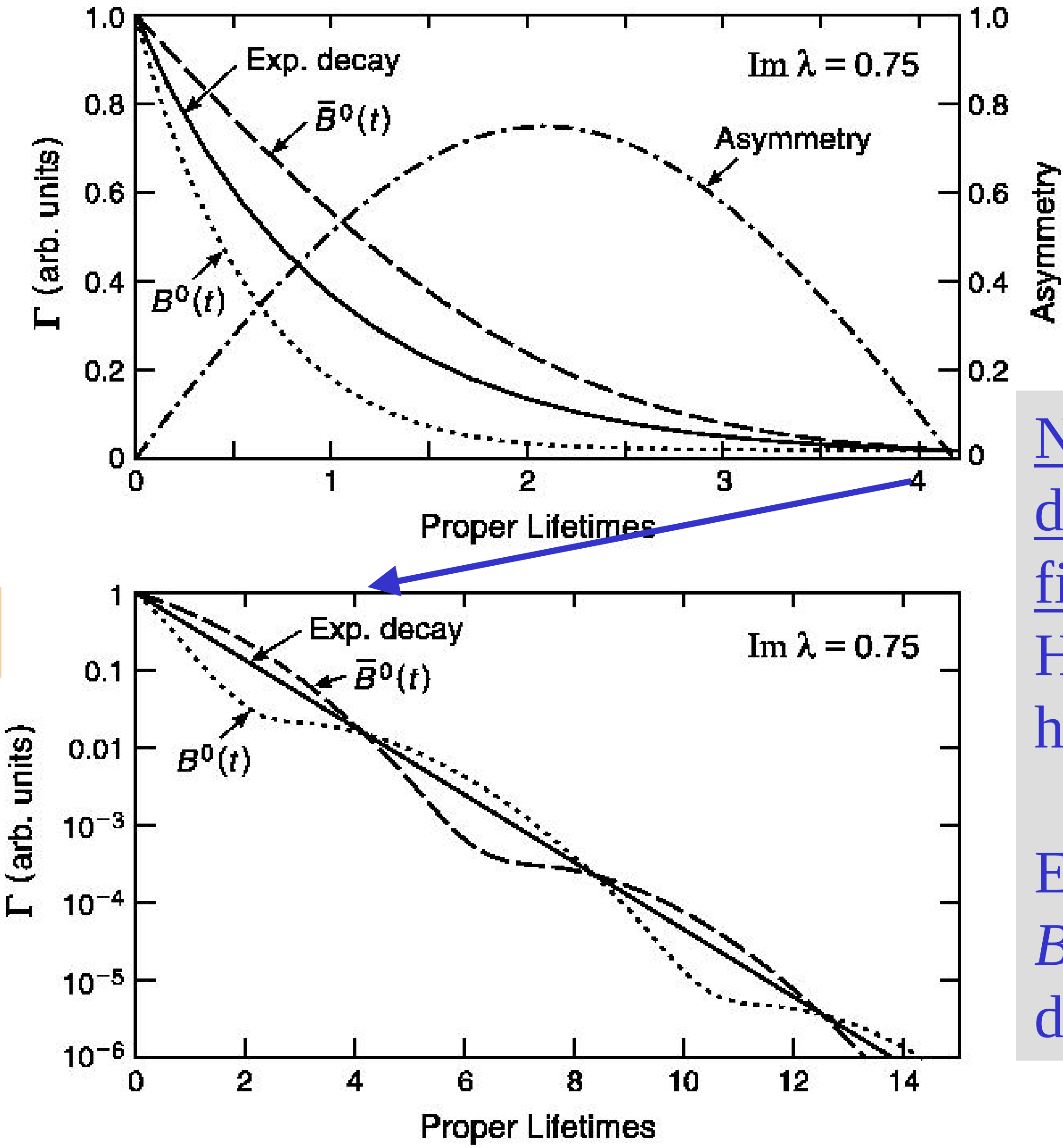
$$\Gamma(B^0_{phys}(t) \to f_{CP})$$

$$\Gamma(\bar{B}^0_{phys}(t) \to f_{CP})$$

Preview: the strange behavior of $B^0 \rightarrow J/\psi\ K_s$

Linear scale

Log scale



[Non-exponential decay law in this final state!]()

How does this happen?

Even stranger:

B^0 and $\bar{B}^0$ behave differently. Why?

Backup Slides

Homework Problem

A beam of optically polarized rubidium atoms is passed through a homogeneous magnetic field and a radio-frequency field. This is followed by a passage through a thin foil of magnetized iron and an adiabatic fast passage through an inhomogeneous electric field, two mutually perpendicular gravitational fields, a radio-frequency scalar meson field, and a wheat field.

Why?

A Random Walk in Science, R.L. Weber

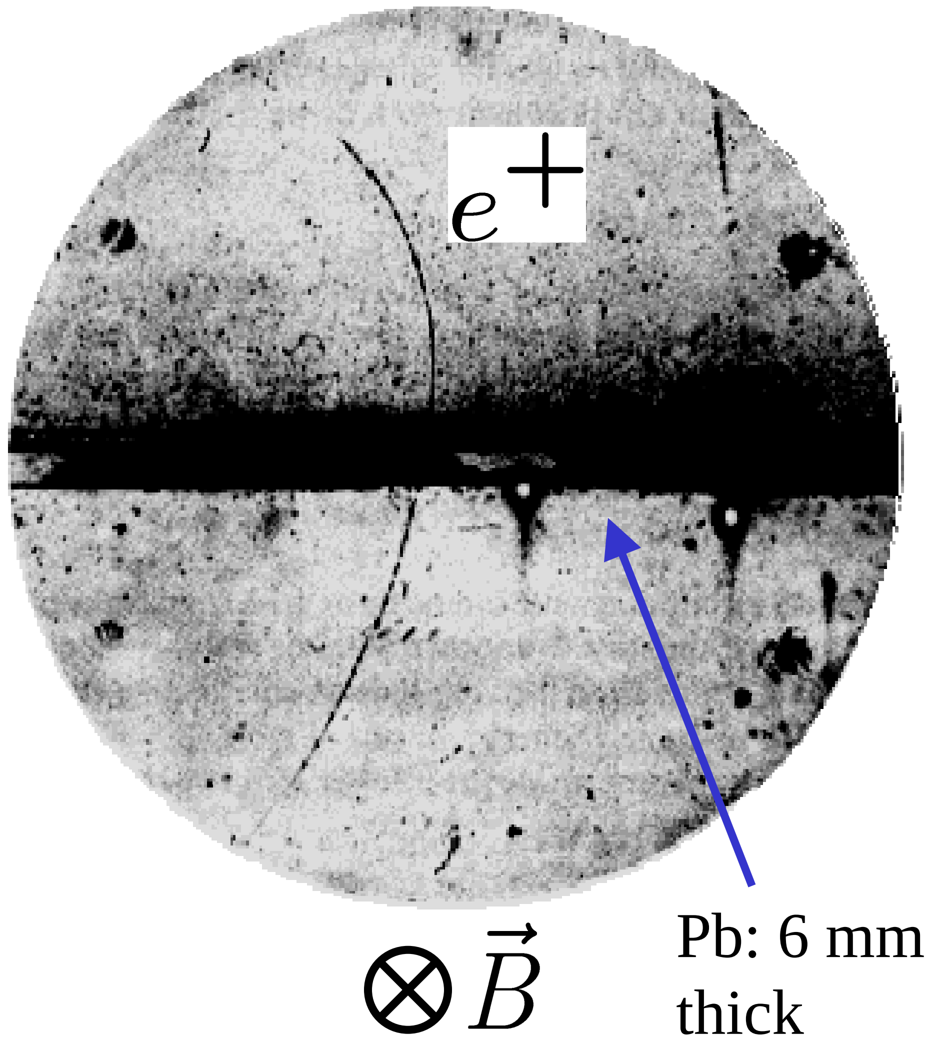
Discovery of antimatter

- **Dirac relativistic wave equation (1928): extra, "negative-energy" solutions. Positron interpretation confirmed by Anderson.**
- **A radical idea: doubling the number of kinds of particles!**

$$e^- \rightarrow e^+$$
$$p(udu) \rightarrow \bar{p}(\bar{u}\bar{d}\bar{u})$$
$$\gamma \rightarrow \gamma$$
$$\nu \rightarrow \bar{\nu}\ (= \nu?)$$

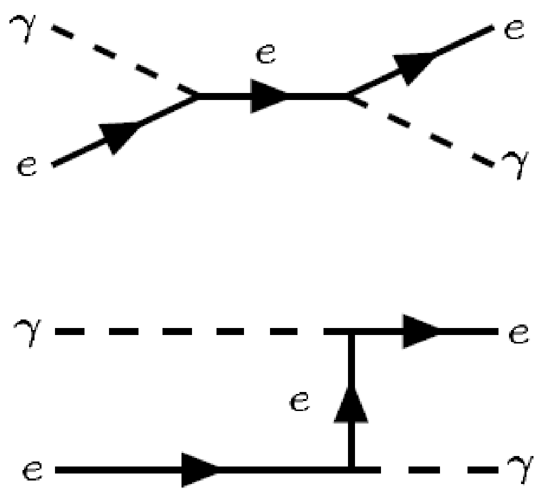
- **Supersymmetry: doubles the number of particles again!**

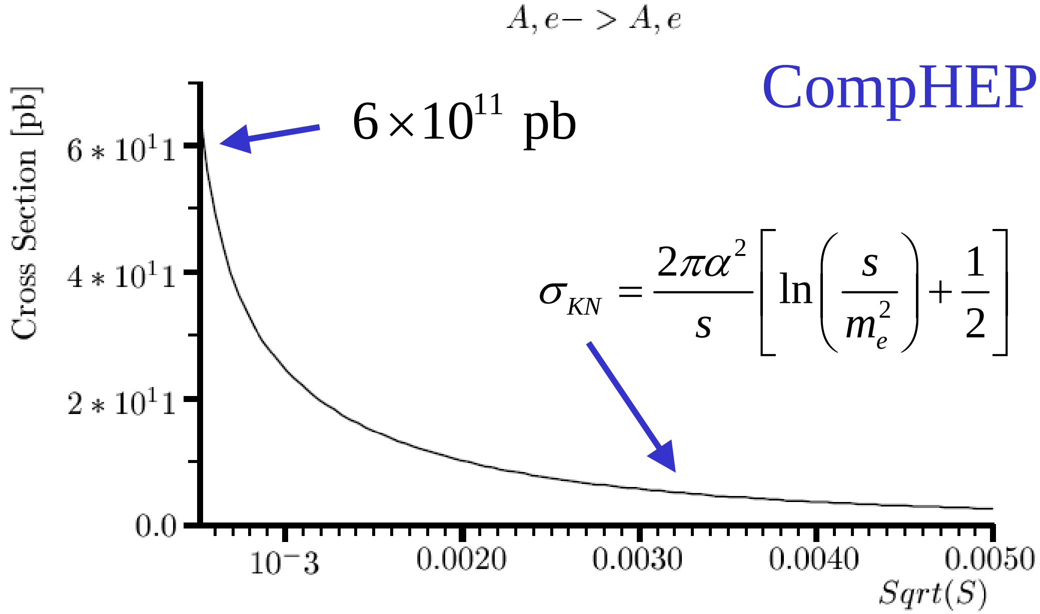
$$e^- \rightarrow \tilde{e}^-$$



P.A.M. Dirac, Proc. Roy. Soc. (London), **A117**, 610 (1928); ibid., **A118**, 351 (1928).
C.D. Anderson, Phys. Rev. **43**, 491 (1933).

$\gamma + e^- \rightarrow \gamma + e^-$ (Compton Scattering)





$$\sigma_{KN} = \frac{2\pi\alpha^2}{s}\left[\ln\left(\frac{s}{m_e^2}\right) + \frac{1}{2}\right]$$

Low energy photon-electron scattering; but E_γ is large relative to atomic binding energy, so electron is "free" particle.

Thomson scattering

$$\sigma = \frac{8\pi\alpha^2}{3m_e^2} \rightarrow \frac{8\pi\alpha^2(\hbar c)^2}{3(m_e c^2)^2}$$

$$= \frac{8\pi\left(\frac{1}{137}\right)^2 (1973\times10^{-6}\ \text{MeV}\cdot10^{-8}\ \text{cm})^2}{3(0.511\ \text{MeV})^2} \simeq 0.67\times10^{-24}\ \text{cm}^2$$

about a barn!

Conjugate amplitudes and direct CP violation

What is the relation between an amplitude and its conjugate?

$$\left.\begin{aligned} CP\left|P\right\rangle &= e^{i\theta(P)}\left|\overline{P}\right\rangle \\ CP\left|\overline{P}\right\rangle &= e^{-i\theta(P)}\left|P\right\rangle \\ (CP)^2\left|P\right\rangle &= \left|P\right\rangle \end{aligned}\right\}$$

Often, people choose a specific phase convention. I like to keep the non-physical CP phase explicit.

$$A = \left\langle f\middle|H\middle|P\right\rangle = \left\langle f\middle|(CP)^\dagger(CP)H(CP)^\dagger(CP)\middle|P\right\rangle$$

$$= \left\langle \overline{f}\middle|(CP)H(CP)^\dagger\middle|\overline{P}\right\rangle e^{i[\theta(P)-\theta(f)]}$$

assume $[H,CP]=0$

$$= \left\langle \overline{f}\middle|H\middle|\overline{P}\right\rangle e^{i[\theta(P)-\theta(f)]}$$

$$= \overline{A}e^{i[\theta(P)-\theta(f)]} \qquad \Rightarrow \left|\frac{\overline{A}}{A}\right| = 1$$

if CP conserved