Heavy Quark Physics and CP Violation*

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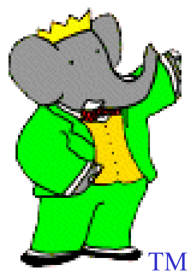
$$\begin{bmatrix} u \\ \end{bmatrix}\begin{bmatrix} c \\ s \end{bmatrix}\begin{bmatrix} \\ b \end{bmatrix}$$



TM

XIII Mexican School of Particles and Fields
Oct. 2 - 11, 2008

* along with a few other random topics I feel like talking about

Outline

- **Lecture 1**
  - **Remarks on learning and doing experimental particle physics**
  - **Constants, natural units, and order-of-magnitude estimates**
  - **Overview of *B* physics**
  - **CP violation as an interference effect**
  - **Production of *B* mesons in e^+e^- collisions**
  - **The *BABAR* experiment and PEP-II**

Try to mix discussion of experiment and theory.

Learning Particle Physics

- **My knowledge of particle physics was very scattered when I was a graduate student.**
- **Some things I have learned:**
  1. **Look for explanations that are as physical as possible, not just mathematical.**
  2. **Don’t be afraid to ask lots of questions, including “stupid” ones. Questions are the foundation of research.**
  3. **The amount of effort required to obtain the correct result (the “truth”) can be painful, but this is what it is all about.**
  4. **Being a scientist is a lot more than knowing physics.**
  5. **Most of particle physics is not yet known. There is plenty left to do!**

Doing Particle Physics

- **I have worked on the following experiments:**
  - **Mark III at SLAC (J/ψ, charm mesons)**
  - **UA1 at CERN (W, Z,...)**
  - **Mark II at SLAC (Z)**
  - **SLD at SLAC (Z)**
  - **CLEO at Cornell (B mesons)**
  - **BaBar at SLAC (B mesons, CP violation)**
  - **CMS at CERN (SUSY? Higgs?...)**

1. Build an operate and experiment that produces high quality, well-controlled data sample (fundamental!)
2. Isolate and measure properties of a particular class of processes.

Constants, natural units, and order-of-magnitude estimates (a few examples)

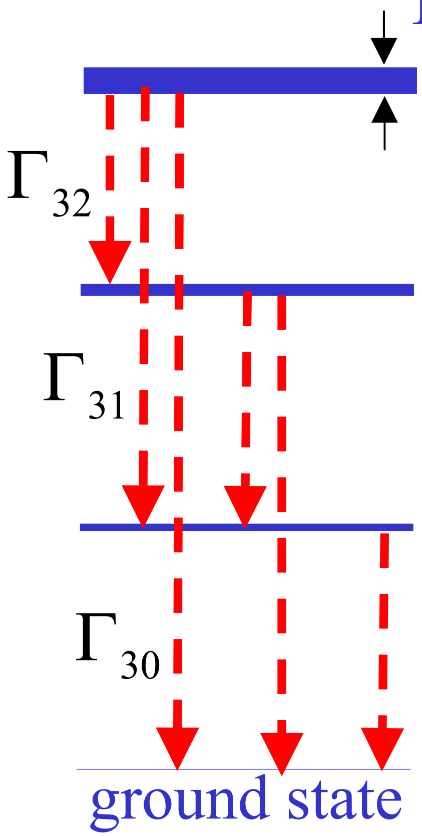
All physicists know that

$$\hbar = c = 1$$

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

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

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



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

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

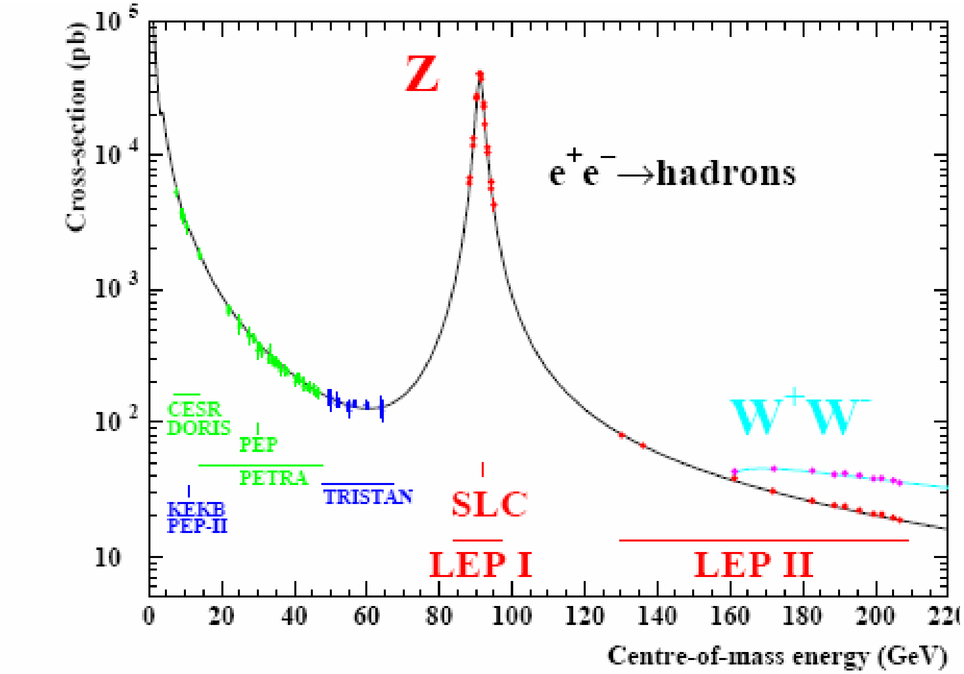
10^{-23} s = 1 strong sec $\approx r_{had}/c$ = 1 fm/c

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

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

no $t\bar{t}$ bound states

Line shape of the Z resonance



http://lepewwg.web.cern.ch/
LEPEWWG/1/physrep.pdf

Precision Electroweak Measurements on the Z Resonance

The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1]
the LEP Electroweak Working Group,[2]
the SLD Electroweak and Heavy Flavour Groups

Much effort was dedicated to the determination of the energy of the colliding beams. A precision of about 2 MeV in the centre-of-mass energy was achieved, corresponding to a relative uncertainty of about $2 \cdot 10^{-5}$ on the absolute energy scale. This level of accuracy was vital for the precision of the measurements of the mass and width of the Z, as described in Chapter 2. In particular the off-peak energies in the 1993 and 1995 scans were carefully calibrated employing the technique of resonant depolarisation of the transversely polarised beams [14,15]. In order to minimise the effects of any long-term instabilities during the energy scans, the centre-of-mass energy was changed for every new fill of the machine. As a result, the data samples taken above and below the resonance are well balanced within each year, and the data at each energy are spread evenly in time. The data recorded within a year around one centre-of-mass energy were combined to give one measurement at this "energy point".

The build-up of transverse polarisation due to the emission of synchrotron radiation [16] was achieved with specially smoothed beam trajectories. Measurements with resonant depolarisation were therefore only made outside normal data taking, and typically at the ends of fills. Numerous potential causes of shifts in the centre-of-mass energy were investigated, and some unexpected sources identified. These include the effects of earth tides generated by the moon and sun, and local geological deformations following heavy rainfall or changes in the level of Lake Geneva. While the beam orbit length was constrained by the RF accelerating system, the focusing quadrupoles were fixed to the earth and moved with respect to the beam, changing the effective total bending magnetic field and the beam energy by 10 MeV over several hours. Leakage currents from electric trains operating in the vicinity provoked a gradual change in the bending field of the main dipoles, directly affecting the beam energy. The collision energy at each interaction point also depended for example on the exact configuration of the RF accelerating system. All these effects are large compared to the less than 2 MeV systematic uncertainty on the centre-of-mass energy eventually achieved through careful monitoring of the running conditions and modelling of the beam energy.

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

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

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

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

tiny compared to size of hadron/nucleon

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

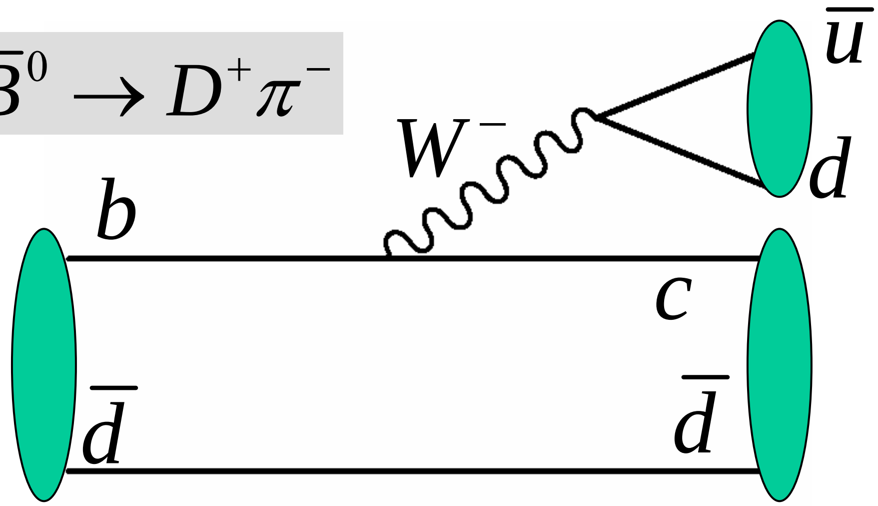
comparable to size of hadron/nucleon

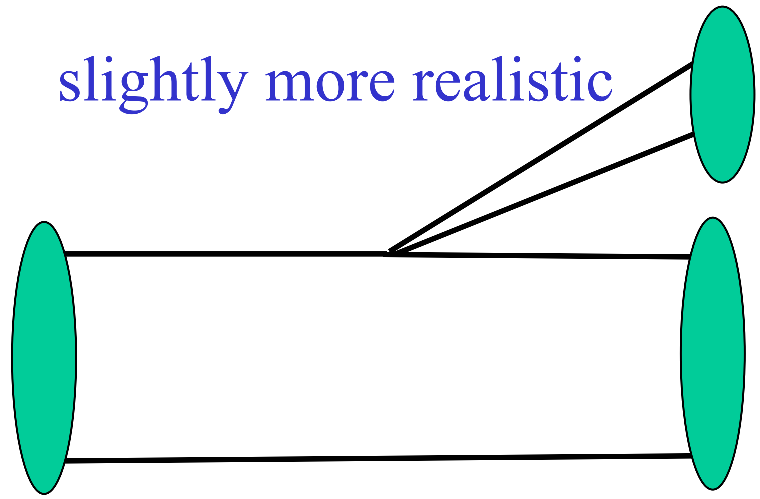
Size of the H-atom involves both the electon mass and the EM coupling.

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

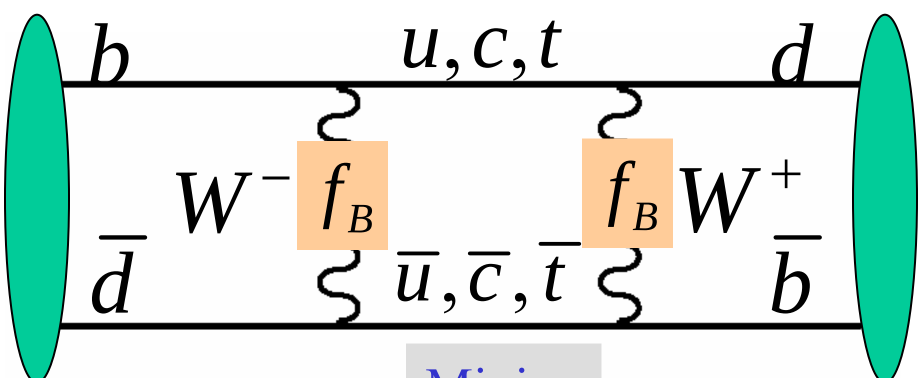
Range of the W is tiny compared to size of meson: Feynman diagrams can be misleading

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

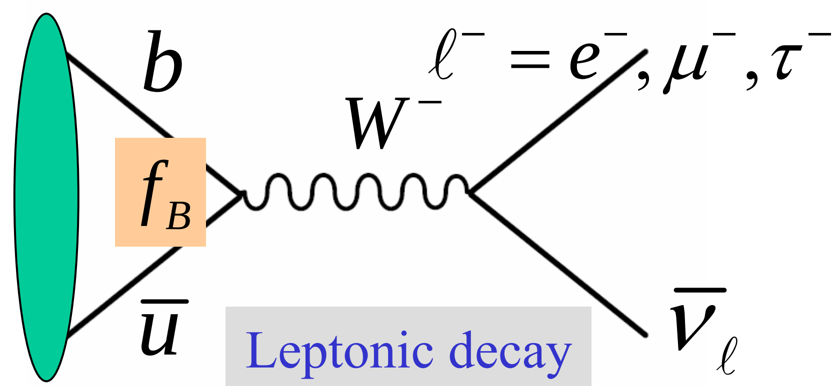




Quarks must be very close to <u>exchange</u> W: amplitude for quarks to have zero separation is described by the B meson decay constant f_B



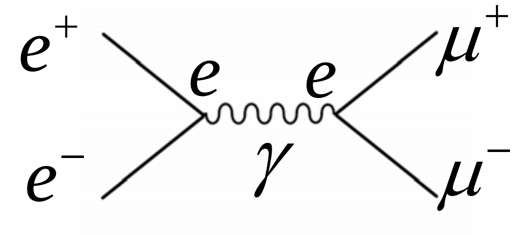
Mixing



Leptonic decay

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.)

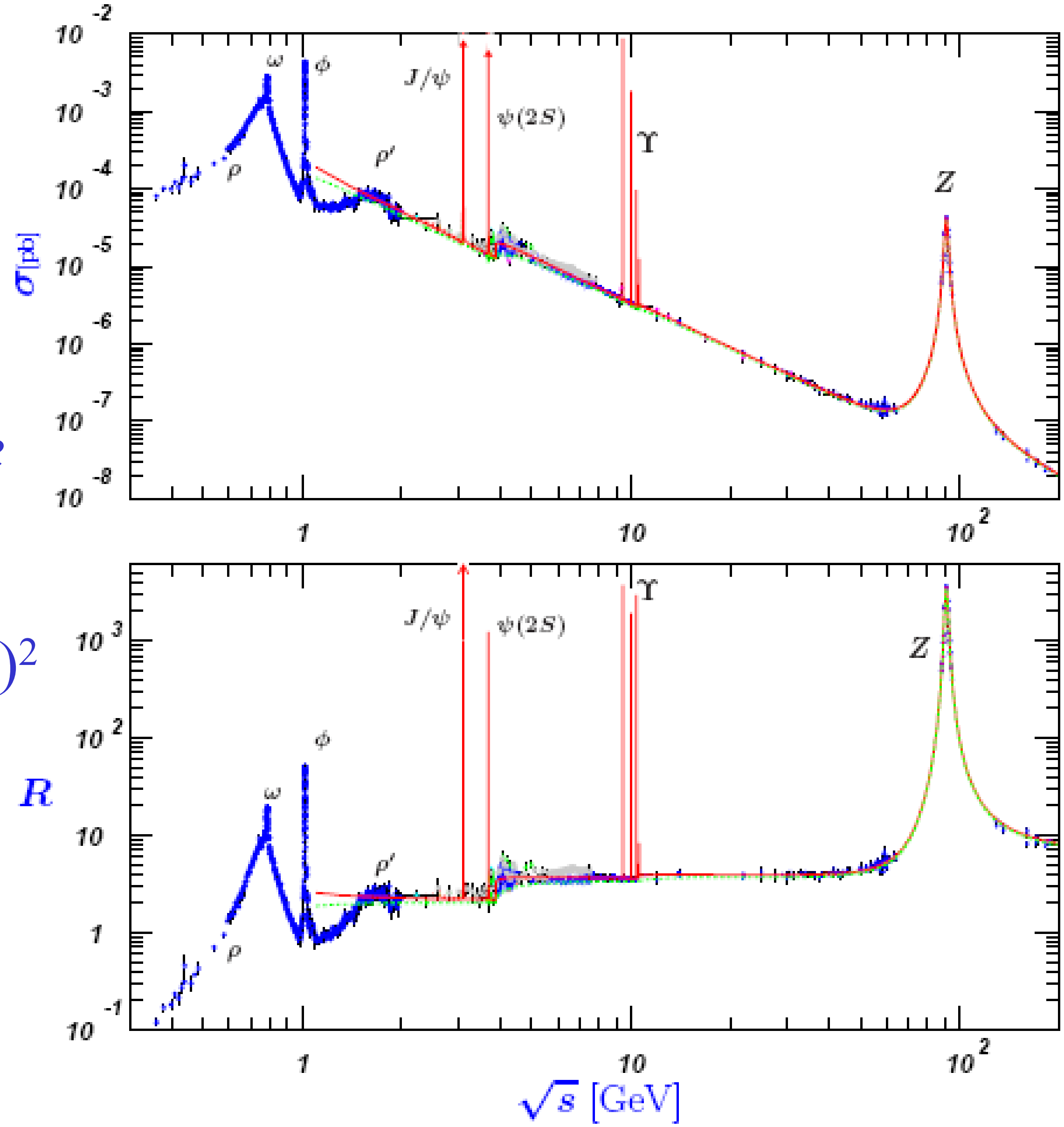
$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi}{3}\frac{\alpha^2(\hbar c)^2}{s} = \frac{86.8 \text{ nb}}{s(\text{GeV}^2)}$$

Cross section for e^+e^- Scattering

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

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

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

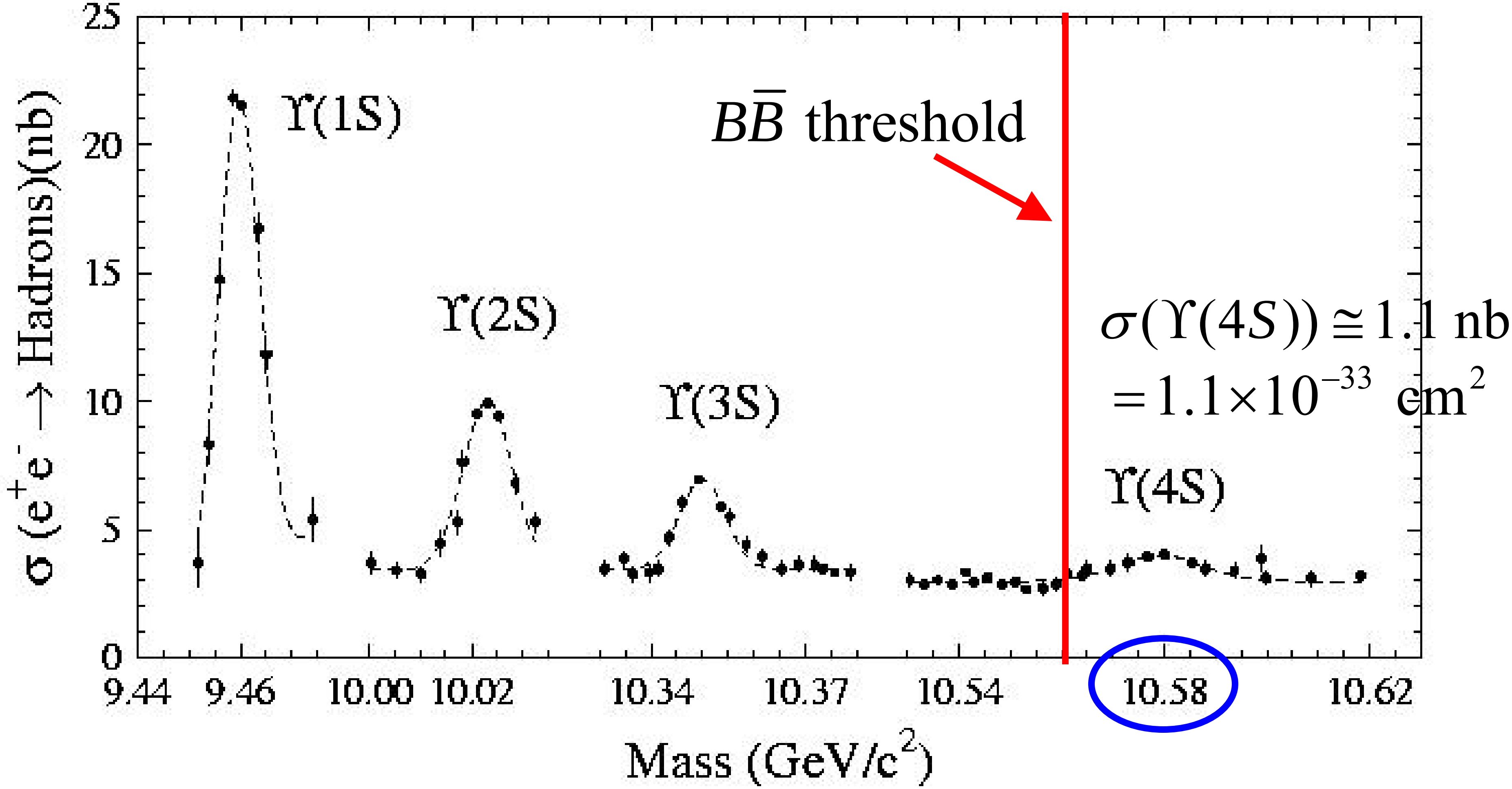


PDG 2005

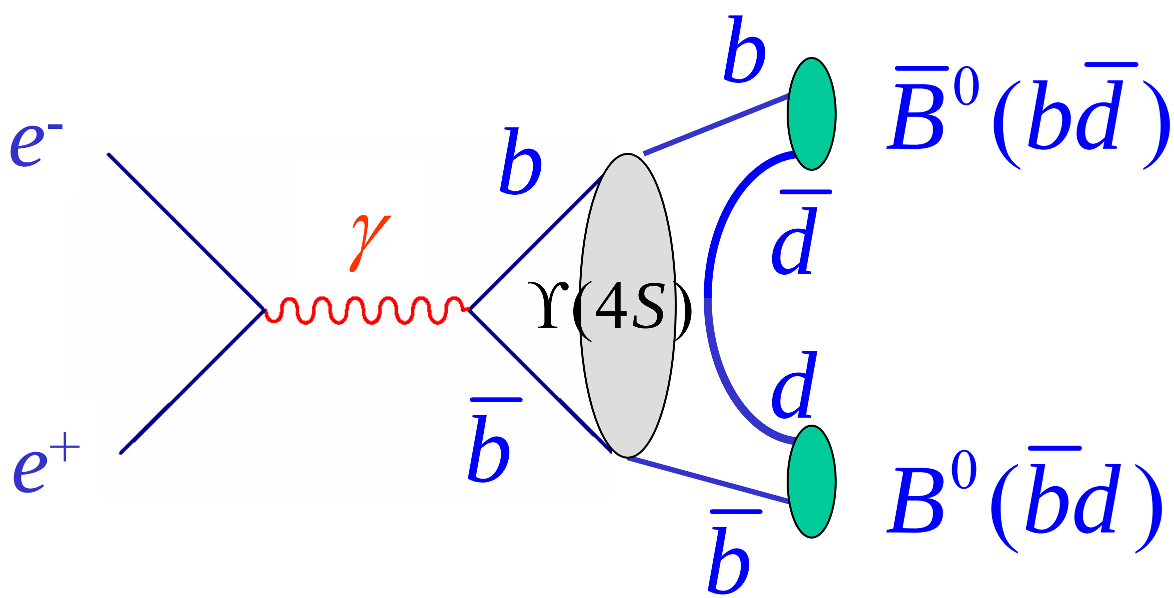
B production at the $Y(4S)$: cross section

$$e^+e^- \to \gamma \to b\bar{b} \to \Upsilon(4S) \to B^0(\bar{b}d)\bar{B}^0(b\bar{d}) \\ \to B^+(\bar{b}u)B^-(b\bar{u})$$

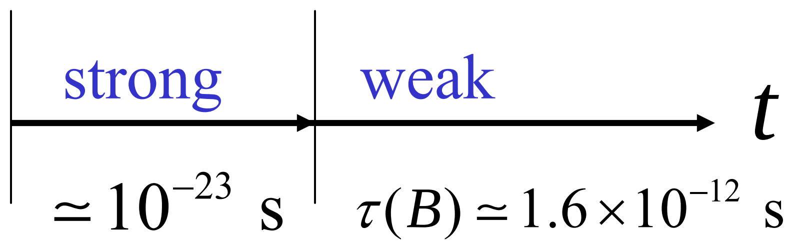
No additional pions!



Production of B mesons in e^+e^- collisions



$$m_B = 5.28 \text{ GeV}$$
$$m_b \approx 4.6 \text{ GeV}$$



$e^+e^- \to \gamma \to b\bar{b} \to \Upsilon(4S) \to B^0(\bar{b}d)\bar{B}^0(b\bar{d})$ $\quad B^+(\bar{b}u)B^-(b\bar{u})$

$e^+e^- \to \gamma \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

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

$$= 18 \text{ cm}$$ (Meas. value = 16.8 cm)

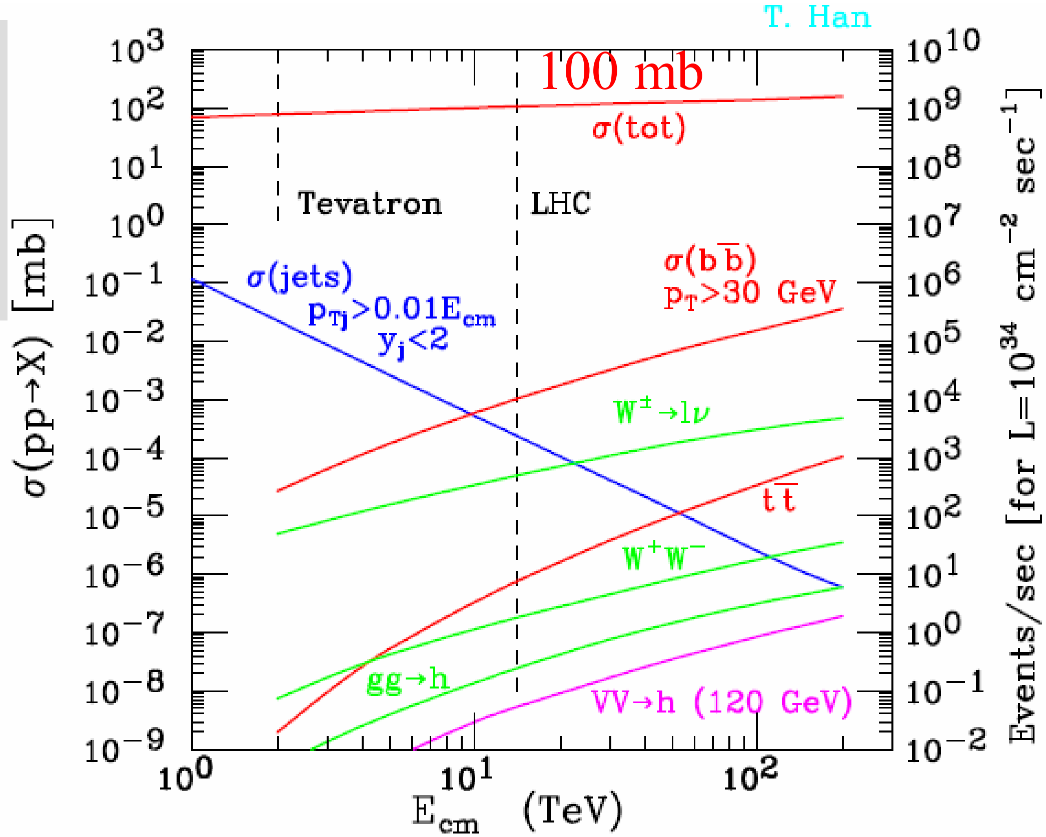
pp cross section

LHC interaction rate from inelastic scattering

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

BABAR interaction rate from e+e- → hadrons

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

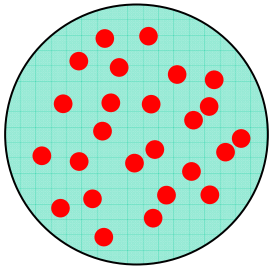


Huge range of cross sections at LHC!

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.

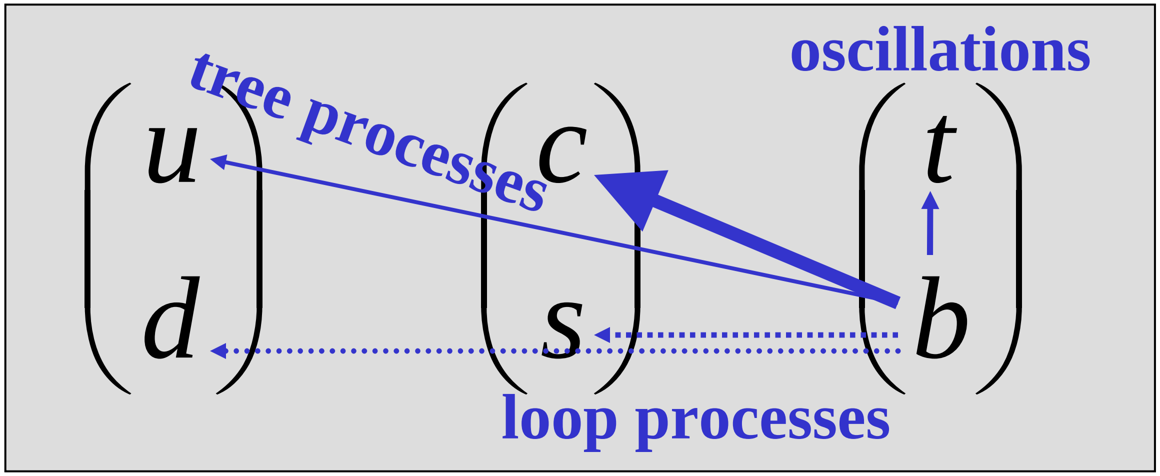
  A plant substance, for example, is mixed in alcohol to obtain a tincture. One drop of the tincture is mixed with 99 drops of alcohol (to achieve a ratio of 1:100) and the mixture is strongly shaken. This shaking process is known as succussion. The final bottle is labeled as "1C." One drop of this 1C 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?

Overview of B Physics:

What’s so special about the b quark?

Perspective on the *b* quark



1. **Mass**: The *b* quark is the heaviest quark that forms hadronic bound states. m_B=5.28 GeV
2. **Lifetime**: It must decay outside of its own quark generation → all decays are suppressed → relatively long lifetime (1.6 ps)
3. **Decay modes**: *b*→*c* decay is dominant; large mass→ many accessible final states. Many processes: trees, loops, oscillations.
4. ***CP* violation**: Cabibbo-Kobayashi-Maskawa matrix → very large *CP* asymmetries [O(1)] in some *B* decays. Confirmed by expt.!

What can we learn from heavy quark physics?

Phases of CKM elements from CP violating observables : 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
- Exotic hadrons?

Interaction between theory and experiment is crucial!

Reminder on decay rates and branching fractions

Total width, partial widths, lifetime

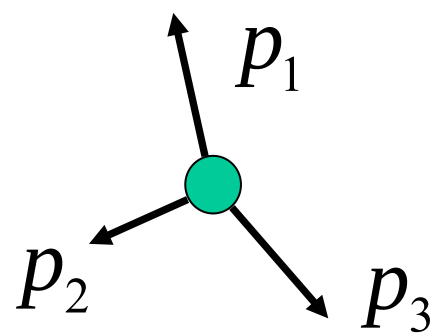
$$\Gamma = \sum_f \Gamma_f = \frac{1}{\tau}$$

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*

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

Comparison of π, *K*, τ, *D*, and *B* Decays

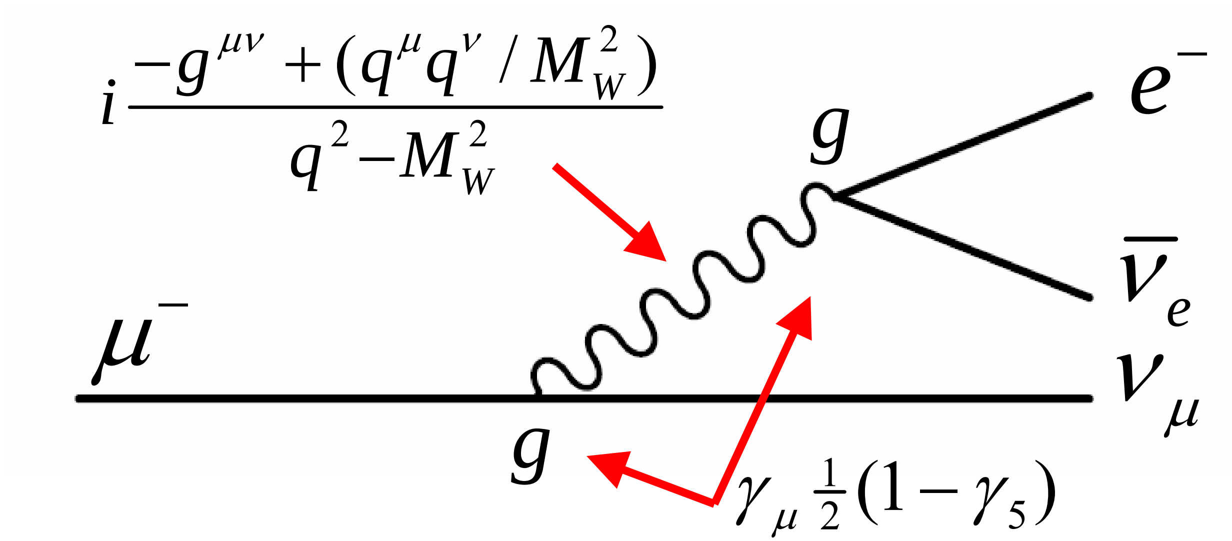
	Largest B.F.		Lifetime
π^-	$\pi^- \to \mu^- \bar{\nu}_\mu$	$(99.98770 \pm 0.00004)\%$	$(26.033 \pm 0.005) \times 10^{-9}$ s
K^-	$K^- \to \mu^- \bar{\nu}_\mu$	$(63.43 \pm 0.17)\%$	$(12.384 \pm 0.024) \times 10^{-9}$ s
	$K^- \to \pi^- \pi^0$	$(21.13 \pm 0.14)\%$	
τ^-	$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	$(17.84 \pm 0.06)\%$	$(290.6 \pm 1.1) \times 10^{-15}$ s
	$\tau^- \to \pi^- \nu_\tau$	$(11.06 \pm 0.11)\%$	$(0.2906 \pm 0.0011) \times 10^{-12}$ s
D^-	$D^- \to \bar{K}^0 e^- \bar{\nu}_e$	$(6.6 \pm 0.8)\%$	$(1.051 \pm 0.013) \times 10^{-12}$ s
	$D^- \to K^- \pi^+ \pi^+$	$(9.1 \pm 0.6)\%$	
B^-	$B^- \to D^{*0} e^- \bar{\nu}_e$	$(5.3 \pm 0.8)\%$	$(1.674 \pm 0.018) \times 10^{-12}$ s
	$B^- \to D^{*0} \rho^+$	$(1.55 \pm 0.31)\%$	

Leptonic decays are rare for *D* and *B*!

$$\tau_B > \tau_D > \tau_\tau$$

Muon decay: a prototype low-energy weak decay

W-mediated *b*-quark transitions have several key features in common with muon decay.



$$q^2 \le m_\mu^2 \ll M_W^2$$

$$\frac{G_F}{\sqrt{2}} \equiv \frac{g^2}{8M_W^2}$$

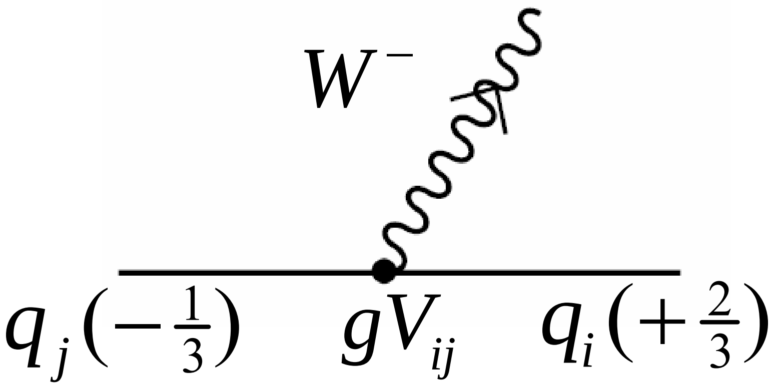
Very strong dependence of decay rate on mass!

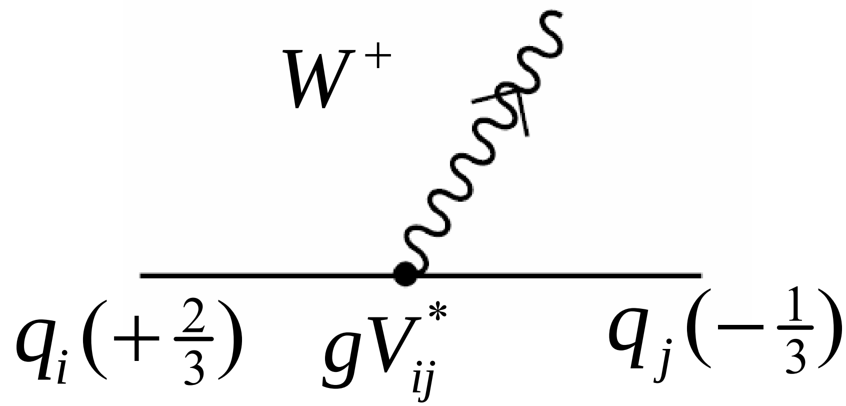
$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}\cdot(1-8x+8x^3-x^4-12x^2\ln x)$$

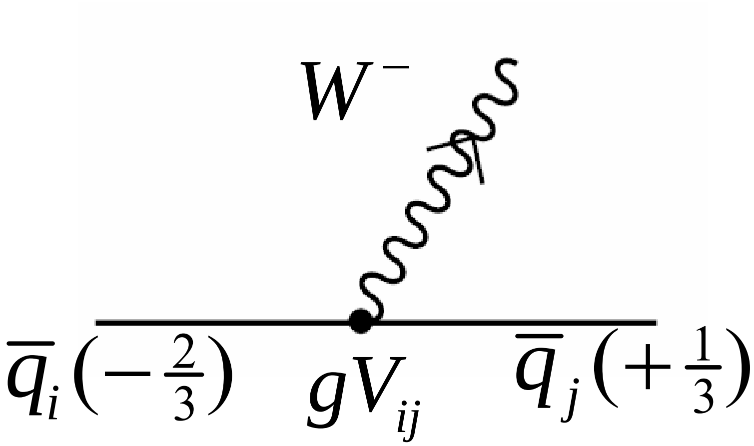
(ignoring QED radiative corrections)

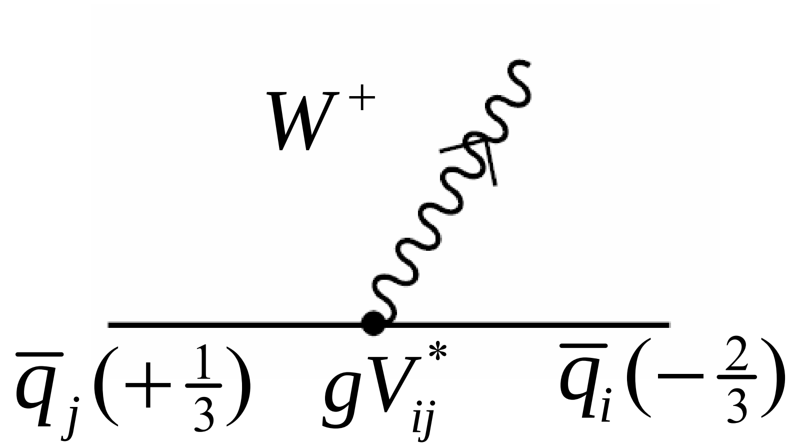
$$x \equiv \frac{m_e^2}{m_\mu^2}$$

Quark Couplings in *W*-mediated processes







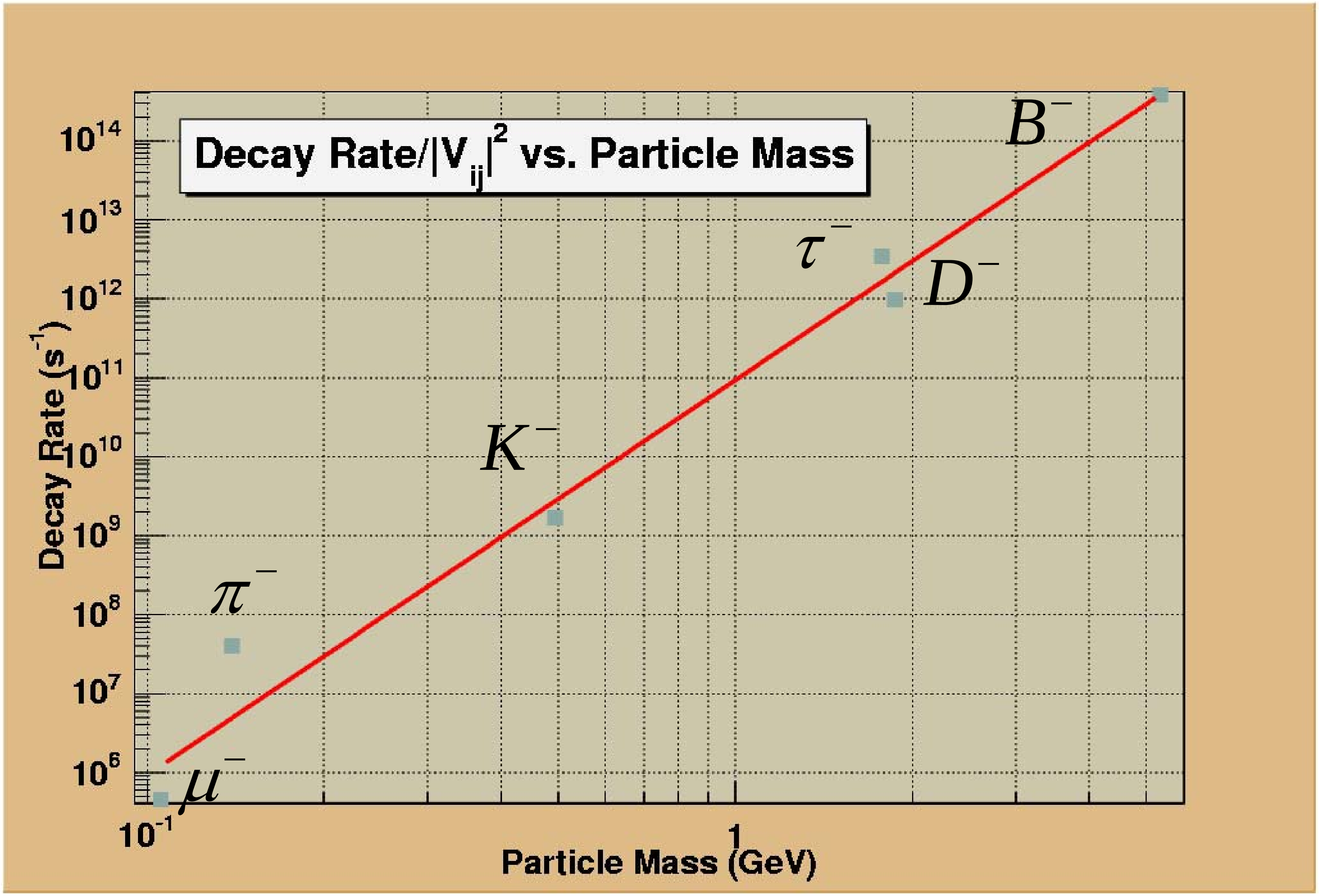


Universal weak coupling g must be multiplied by element of CKM matrix V_{ij}.

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

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

Mass dependence of weak decay rates (correcting for CKM elements)



Origin and implications of the "long" *B* lifetime

All *B* decays are CKM suppressed, with $b \to c$ decays dominant

$$\Gamma \propto G_F^2 \left|V_{cb}\right|^2 m_b^5 \qquad \left|V_{cb}\right| \simeq 0.04 \qquad \left|V_{cb}\right|^2 \simeq 1.6 \times 10^{-3}$$

$$c\tau_B = (3 \times 10^8 \text{ ms}^{-1})(1.6 \times 10^{-12} \text{ s}) = 0.48 \text{ mm}$$

How far will *B* mesons travel before decaying?

$$\left.\begin{aligned} \Delta\ell_{\text{lab}} &= v \cdot \Delta t_{\text{lab}} = \beta c \cdot \Delta t_{\text{lab}} \\ \Delta t_{\text{lab}} &= \gamma \cdot \Delta t_{\text{B rest}} \\ \Rightarrow \Delta\ell_{\text{lab}} &= \beta\gamma \cdot c\Delta t_{\text{B rest}} \end{aligned}\right\}$$

average over decays

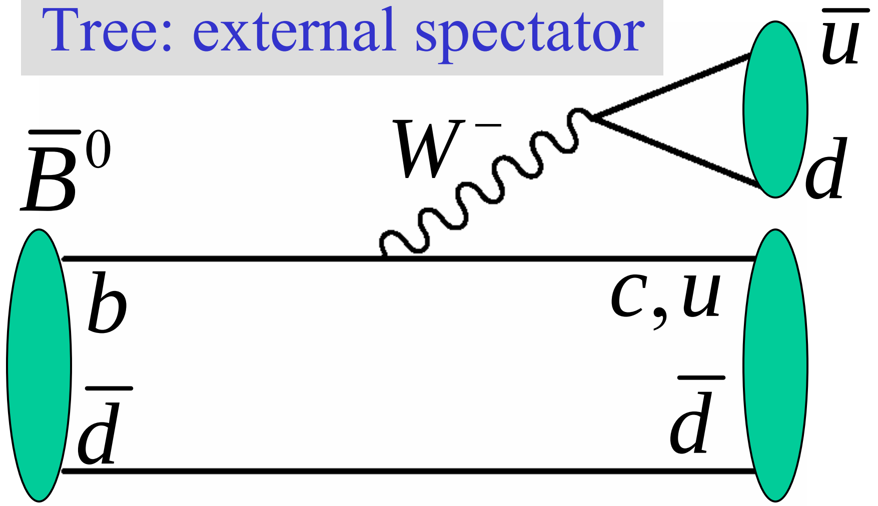
$$\begin{aligned} \left\langle \Delta\ell_{\text{lab}} \right\rangle &= \beta\gamma \cdot c \left\langle \Delta t_{\text{B rest}} \right\rangle \\ &= \underbrace{\beta\gamma}_{} \cdot c\tau_B \end{aligned}$$

0.56 in BaBar

→1/4 mm

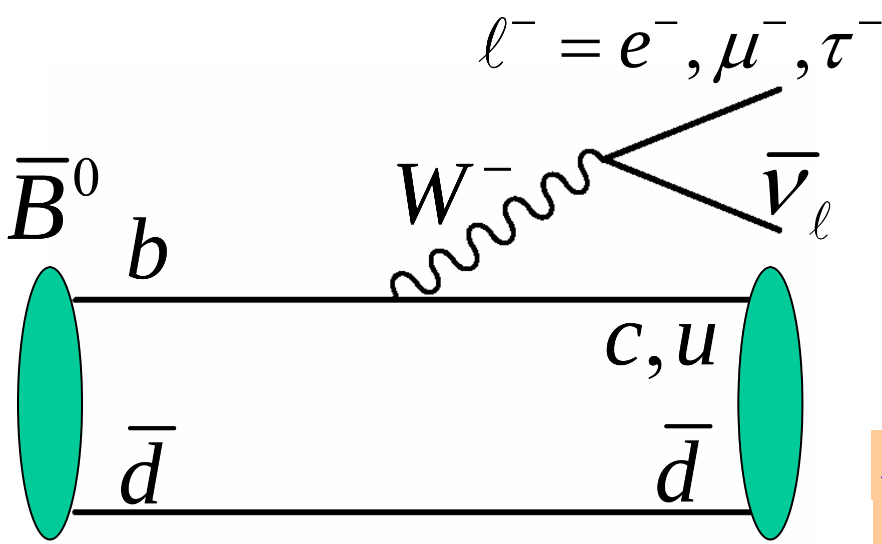
Weak transitions underlying *B* decay (I)

Tree: external spectator



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

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



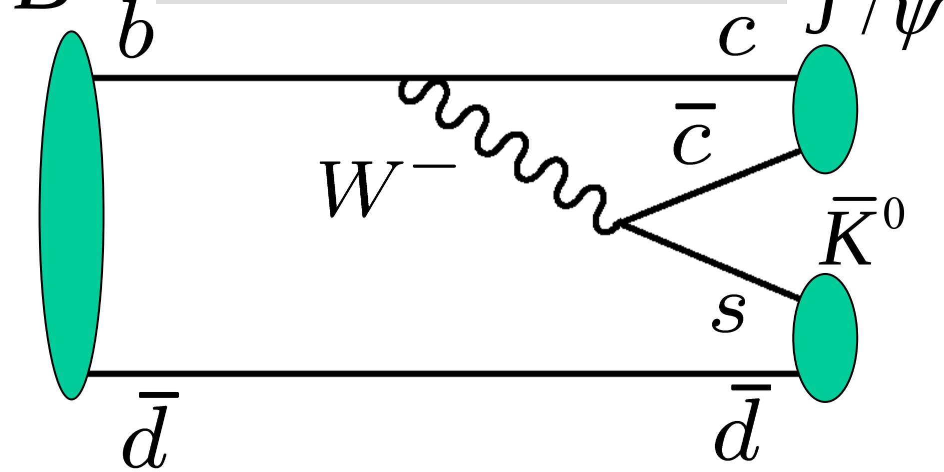
Semileptonic decay:
-Charge of lepton is correlated w/charge of *b* ($\overline{b}$) quark: tagging
-Largest B branching fraction

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

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

Weak transitions underlying B decay (II)

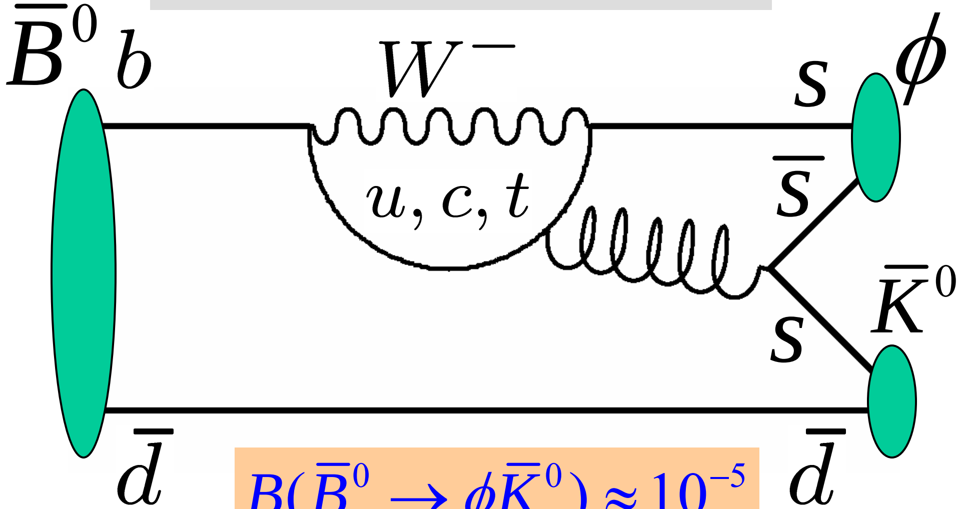
Tree: internal spectator



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

$B(\overline{B}^0 \to D^0\pi^0) = 2.6\cdot 10^{-4} \simeq 0.03\%$

Loop: gluonic penguin

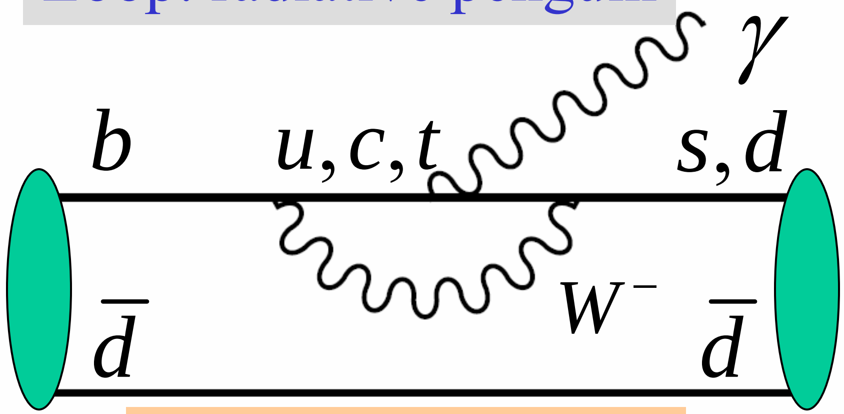


$B(\overline{B}^0 \to \phi\overline{K}^0) \approx 10^{-5}$

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.

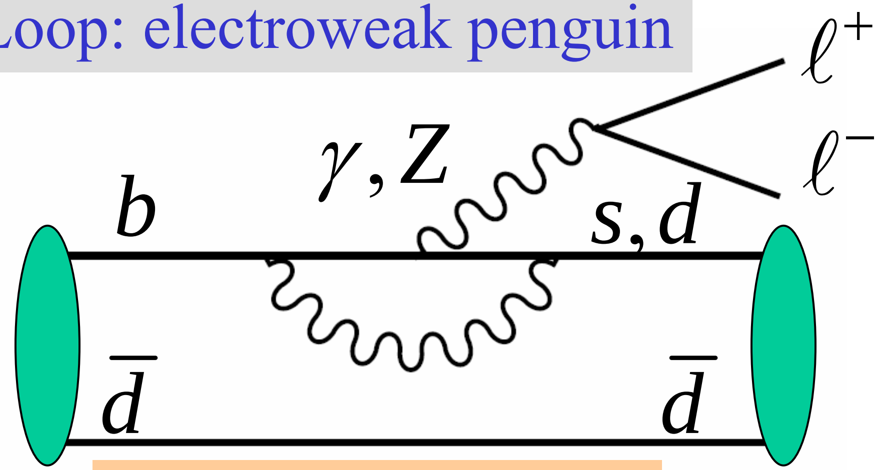
Weak transitions underlying *B* decay (III)

Loop: radiative penguin



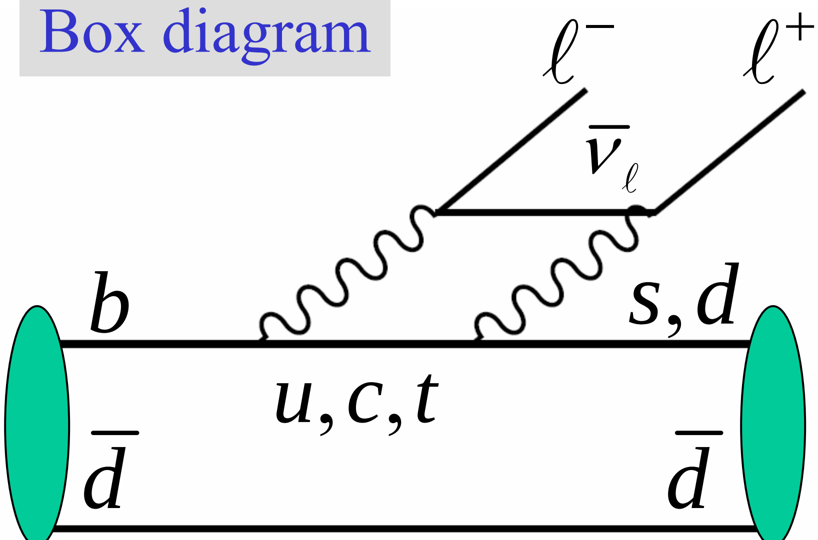
$B(\bar{B}^0 \to \bar{K}^{*0}\gamma) \simeq 4 \cdot 10^{-5}$

Loop: electroweak penguin



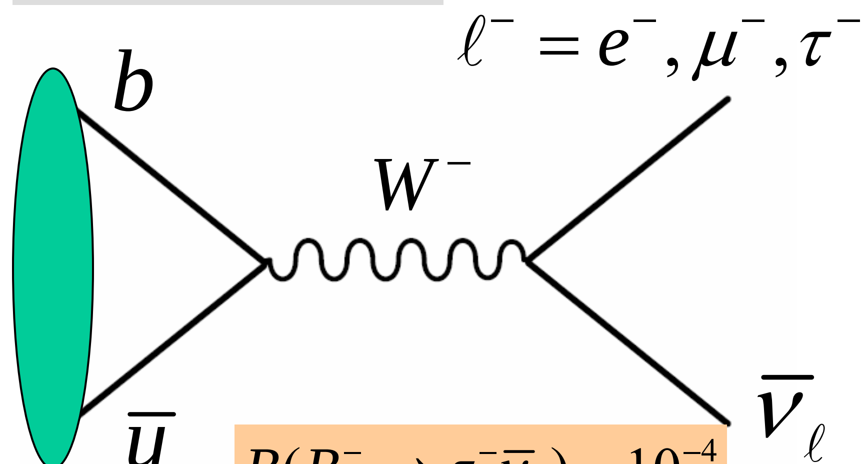
$B(\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-) \simeq 10^{-6}$

Box diagram



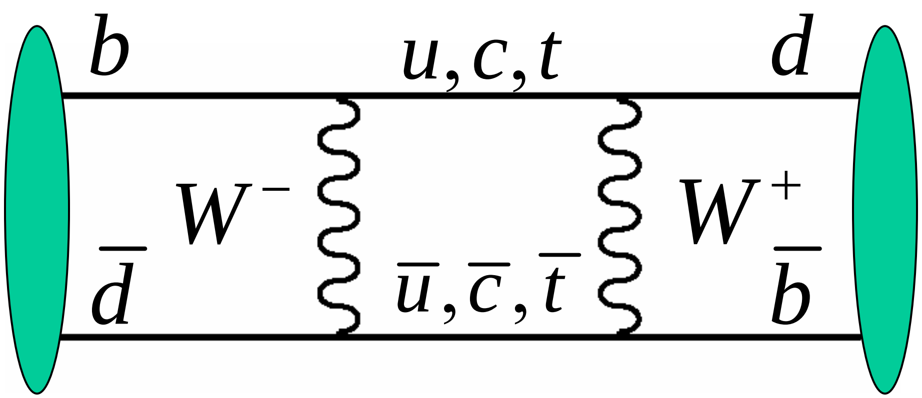
(part of previous process)

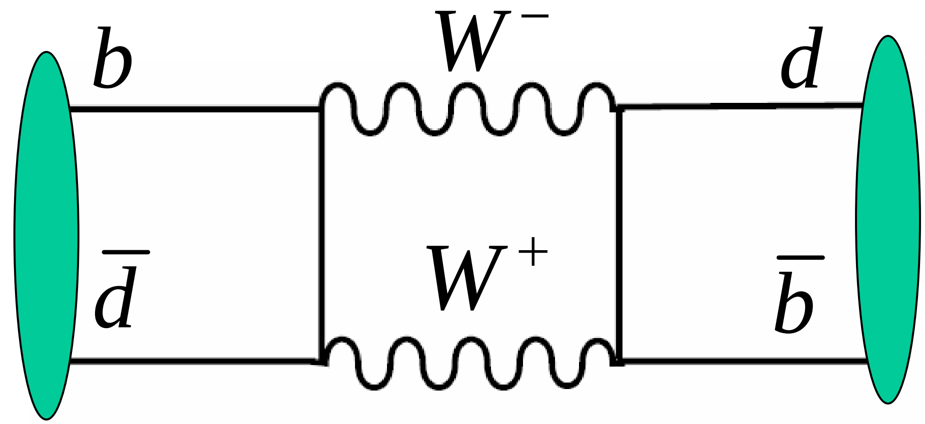
Leptonic decay



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

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



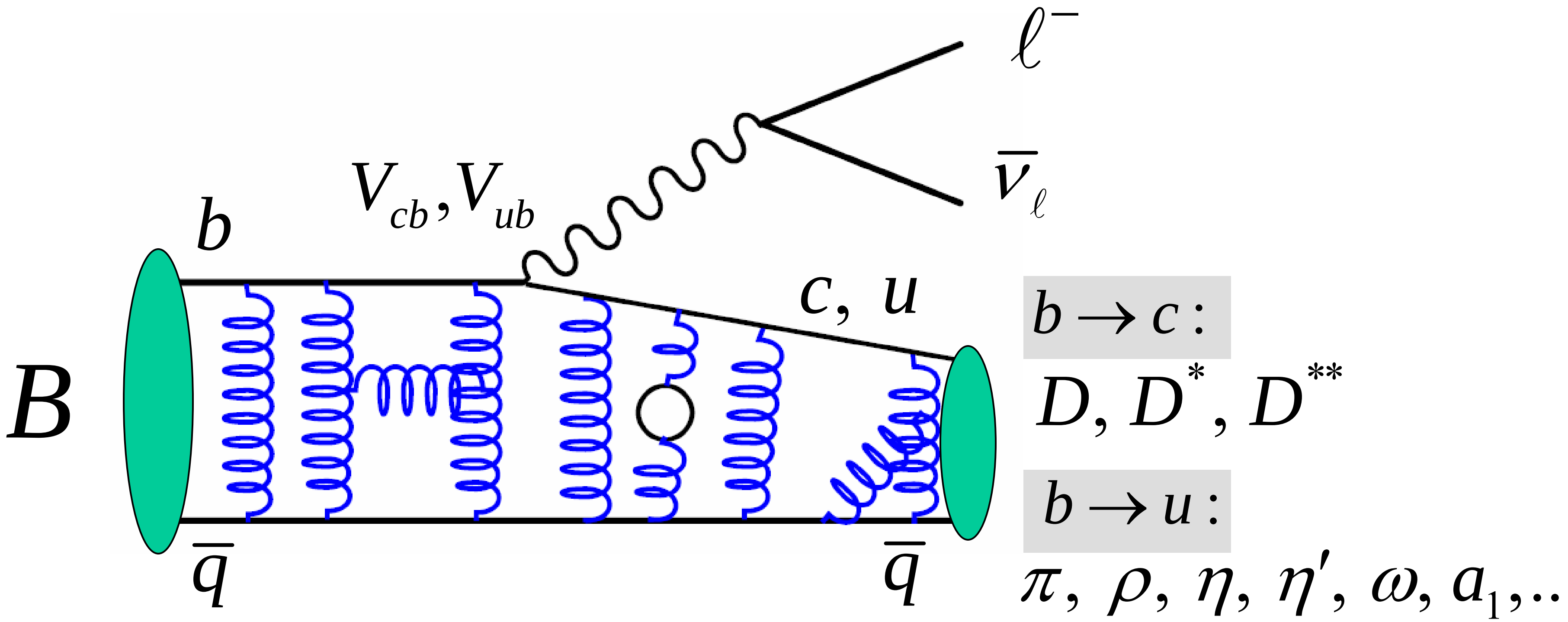


$$\left|B^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt}\left(\cos\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle + i\alpha\cdot\sin\frac{\Delta M\cdot t}{2}\left|\overline{B}^0\right\rangle\right)$$

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

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 $\overline{B}^0$.

The elegant simplicity of semileptonic B decays



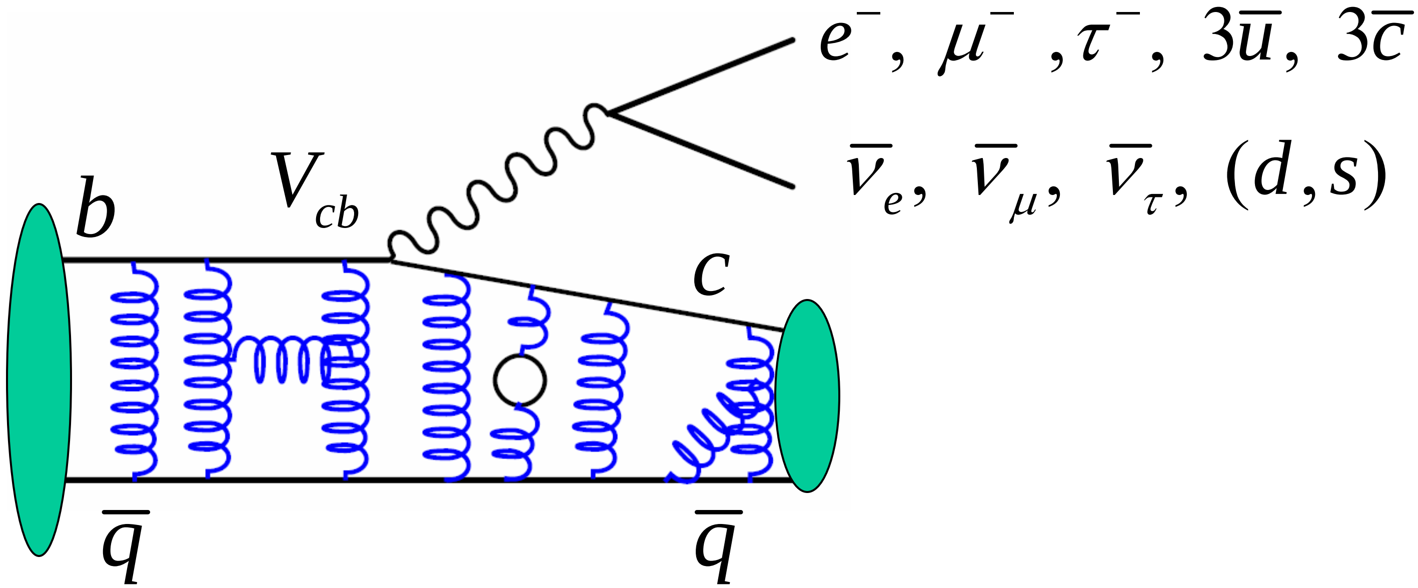
- Key application: determination of $|V_{cb}|$ and $|V_{ub}|$.
- In contrast to CKM phases, which we extract from CP *asymmetries*, need to measure (and predict) *decay rates*.

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

amplitude factorizes

Simplest ("naïve") branching fraction estimate

- Let's try to estimate the semileptonic branching fraction using the simplest assumptions (free quark model).

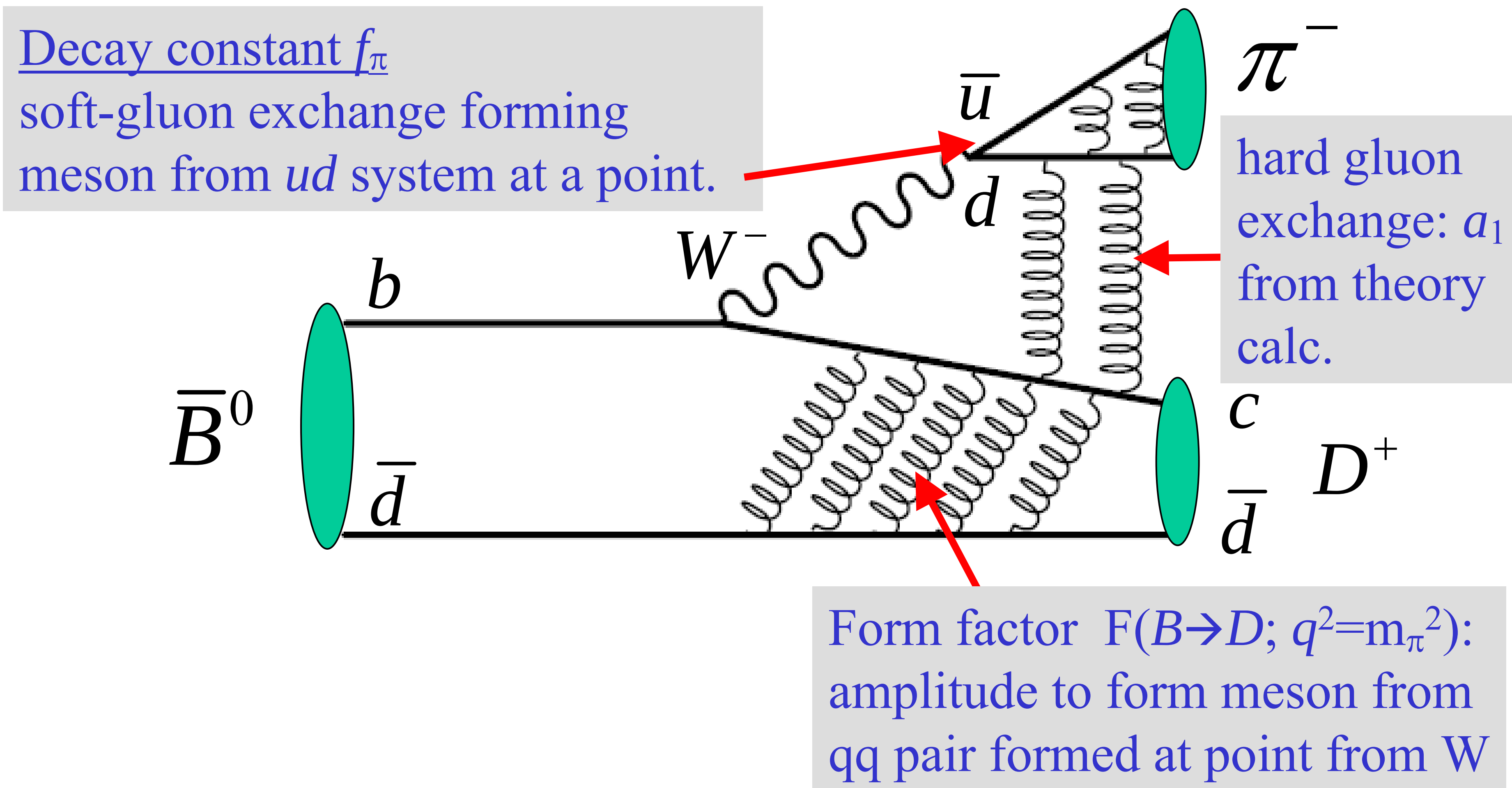


$$B_{SL} = \frac{\Gamma(b \to c e^- \bar{\nu}_e)}{2\Gamma(b \to c e^- \bar{\nu}_e) + \Gamma(B \to c\tau^- \bar{\nu}_\tau) + \Gamma(b \to c\bar{u}d + c\bar{u}s) + \Gamma(b \to c\bar{c}s + c\bar{c}d)}$$

$$\approx \frac{1}{2 + 0.2 + 3(1) + 3(0.31)} \approx 16\%$$ (with phase space estimates)

Measured value (PDG 04): $(10.73 \pm 0.28)\%$

A simple model of hadronic B decays



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

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).

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

Testing our model for hadronic decays

Predict

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

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

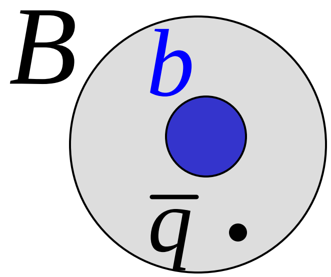
$$\approx 2.5$$

Measure

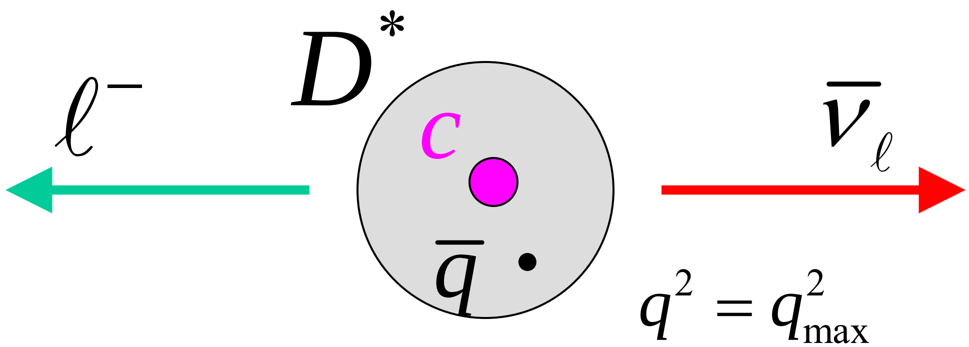
$$\frac{\Gamma(\bar{B}^0 \to D^+\rho^-)}{\Gamma(\bar{B}^0 \to D^+\pi^-)} = \frac{7.5 \cdot 10^{-3}}{2.7 \cdot 10^{-3}} = 2.8$$

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

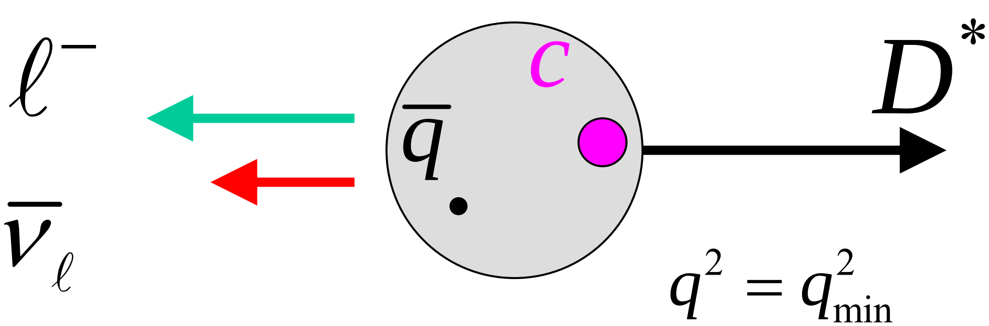
Physical meaning of q^2



B meson before decay



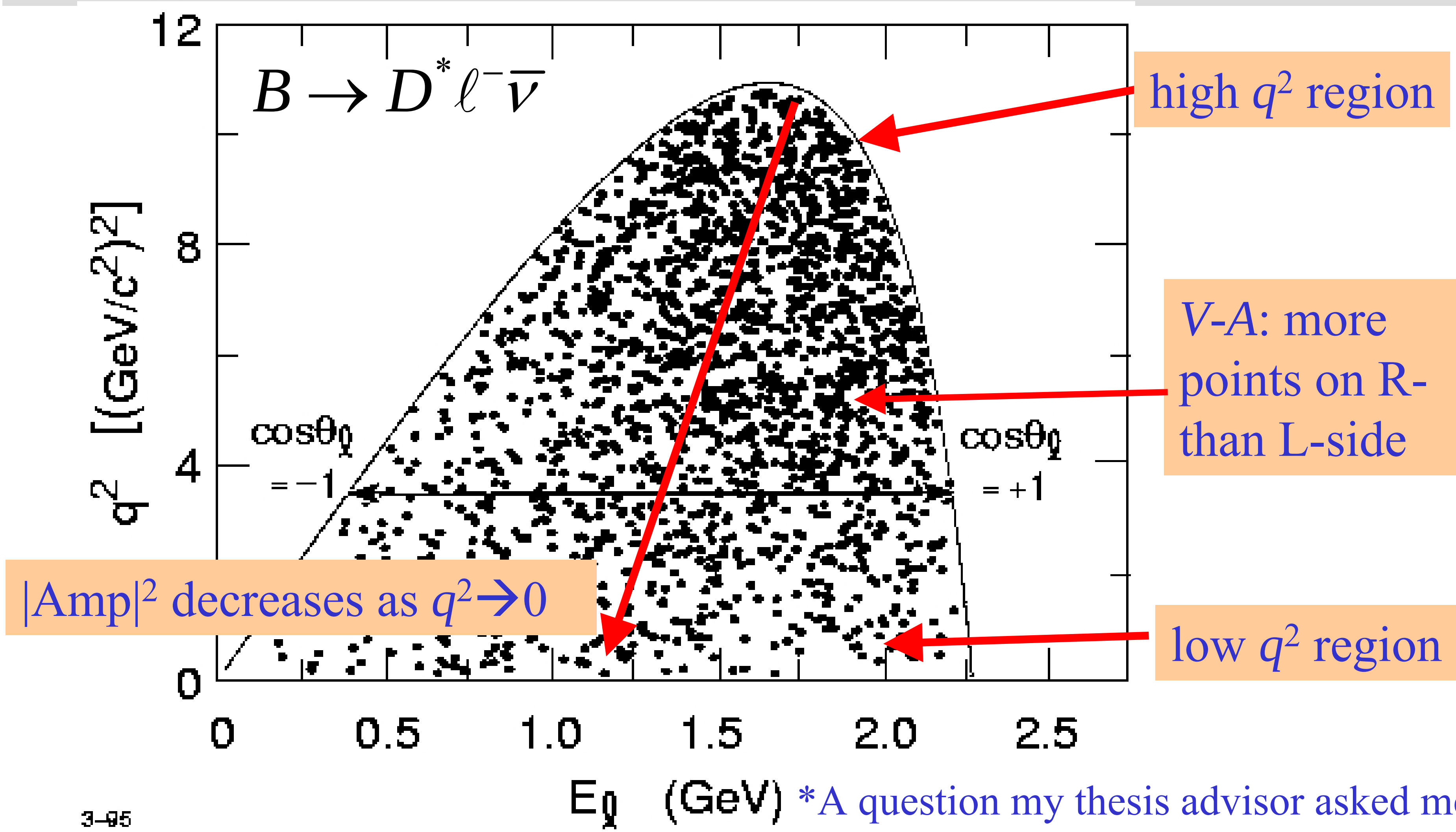
After decay: high q^2 configuration. Zero recoil of daughter hadron.



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.



*A question my thesis advisor asked me.

A first look at *CP* Violation

- What conditions are needed to produce *CP*-violating effects? (Lec 1)
- The three kinds of CP violation (Lec 2)
- Observations of CP violation (Lecs 2, 3)

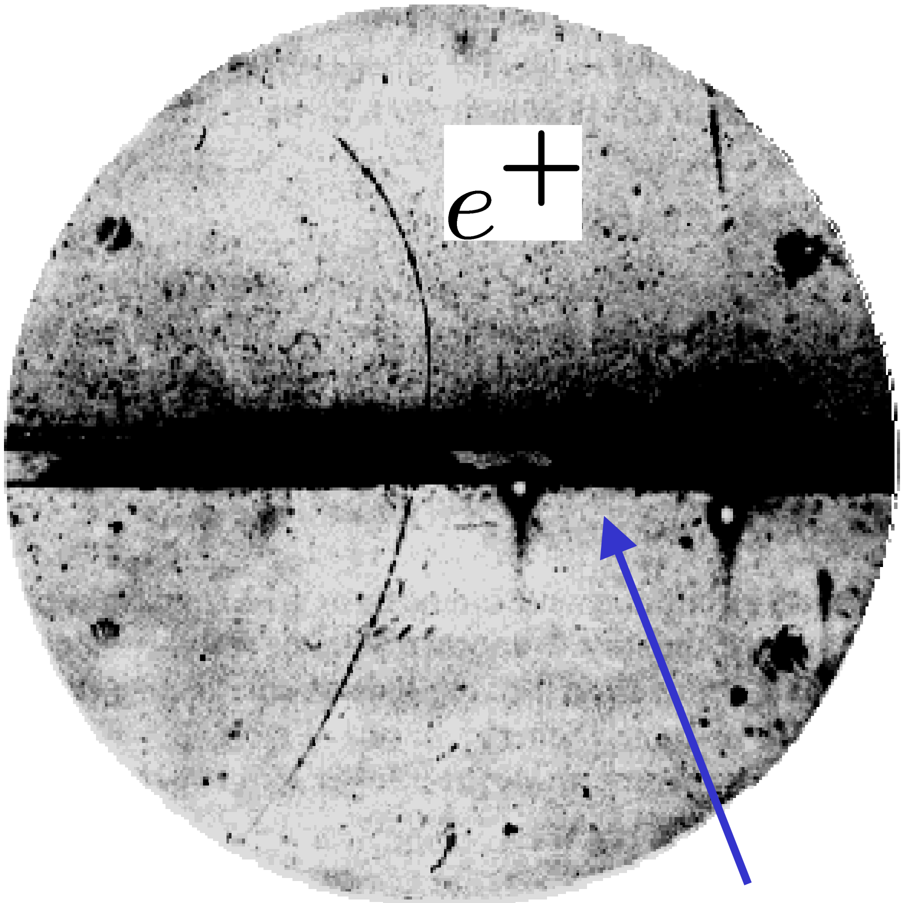
Discovery of antimatter

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

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

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

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



$\otimes \vec{B}$

Pb: 6 mm thick

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

Discrete Symmetry Transformations

Discrete symmetry transformations cannot be written in terms of a continuous parameter. Such transformations must be performed in a single “jump.”

$C: \; a \rightarrow \bar{a}$

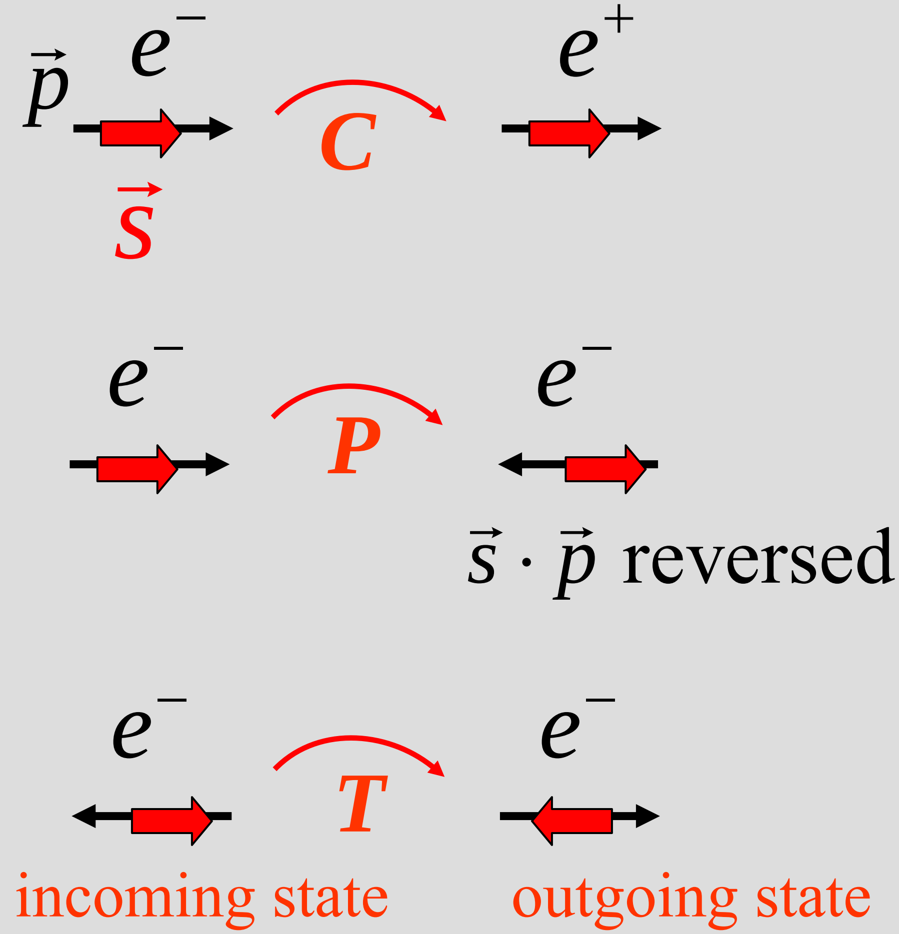
charge conjugation

$P: \; \vec{r} \rightarrow -\vec{r}$

parity

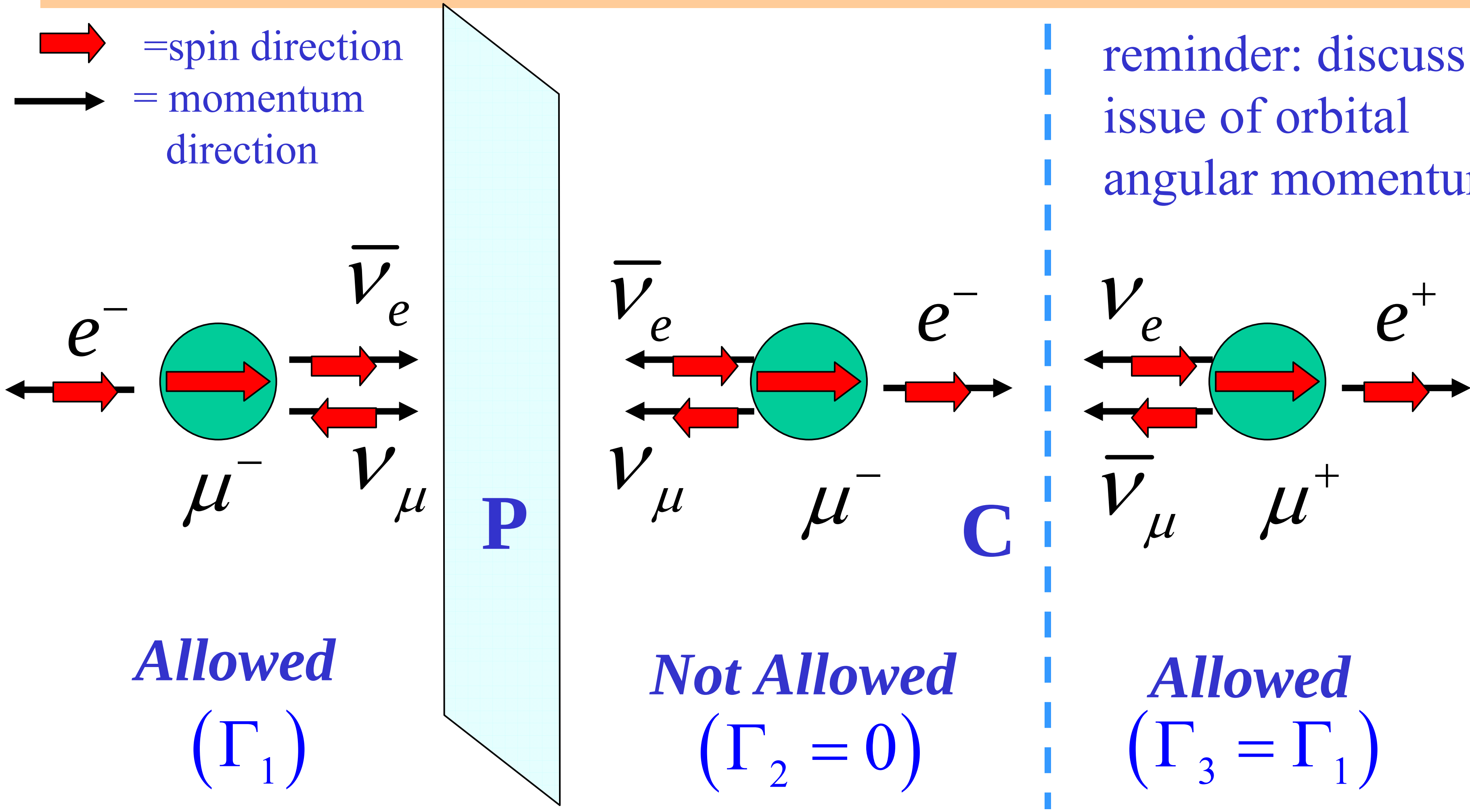
$T: \; t \rightarrow -t$

motion reversal



P and C violation in polarized muon decay

reminder: discuss issue of orbital angular momentum



P and C are individually violated <u>maximally</u> in the weak interactions, but combined CP is a good symmetry even for most weak processes!

Discovery of CP violation

- CP violation at a tiny level (10^{-3}) was first discovered in 1964 in the decays of neutral kaons (mesons with strange quarks).

$$B(K_L^0 \to \pi^+\pi^-) = (2.0 \pm 0.4)\times 10^{-3} \qquad \eta_{CP}(\pi^+\pi^-, L=0) = +1$$

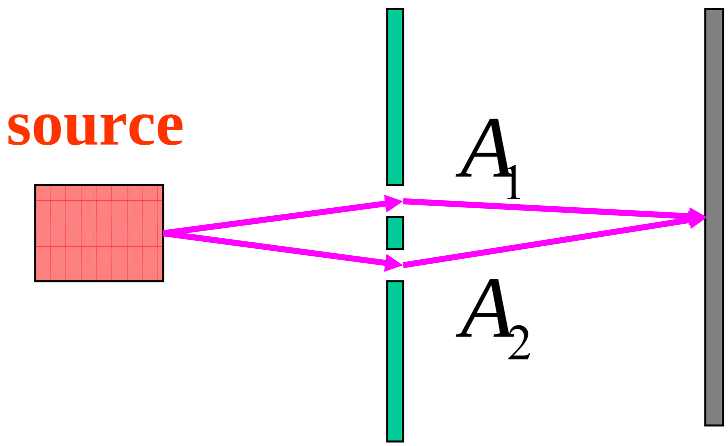
- Demonstrated that $K_L{}^0$ is not an eigenstate of CP: $[H, CP] \neq 0$

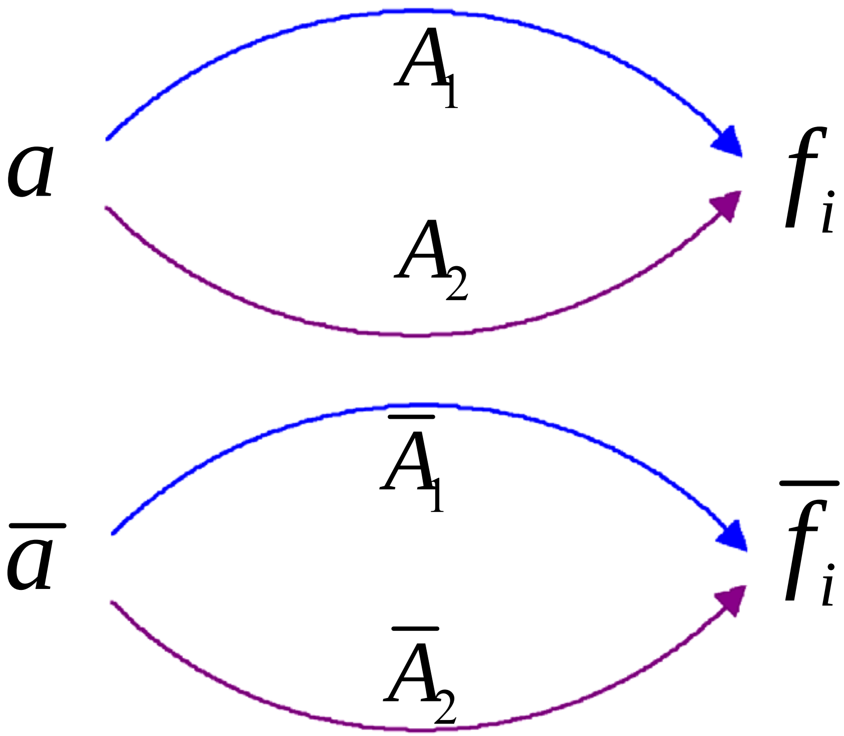
Jim Cronin's Nobel Prize lecture:

"...the effect is telling us that at some tiny level there is a fundamental asymmetry between matter and antimatter, and it is telling us that at some tiny level interactions will show an asymmetry under the reversal of time. We know that improvements in detector technology and quality of accelerators will permit even more sensitive experiments in coming decades. We are hopeful then, that at some epoch, perhaps distant, this cryptic message from nature will be deciphered."

How are CP violating asymmetries produced?

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





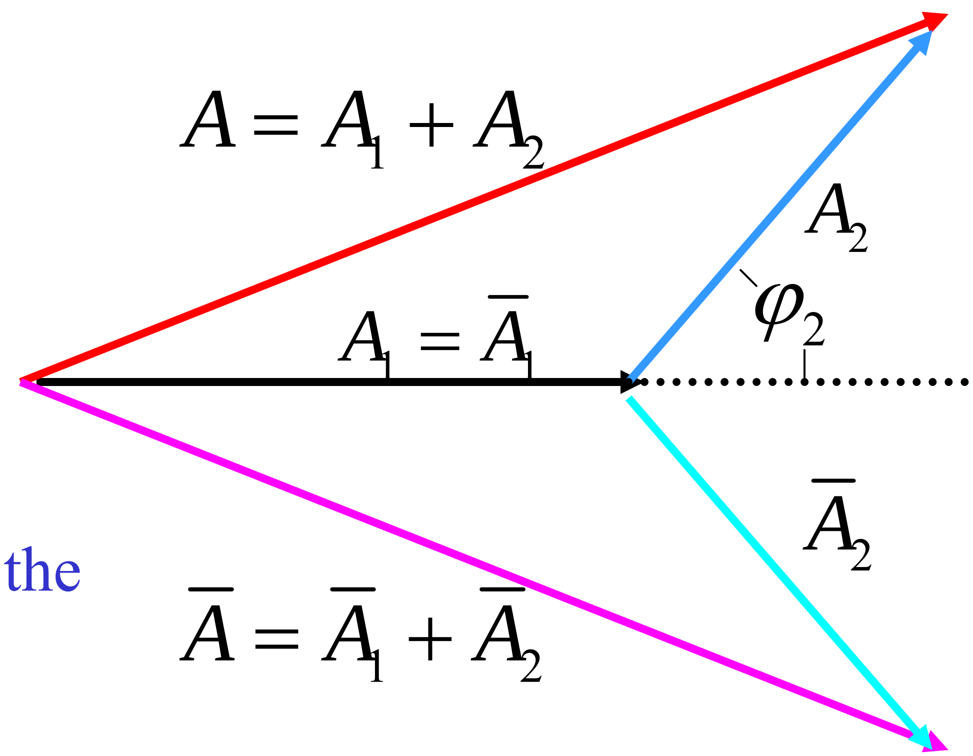
Double-slit experiment: if the final state does not distinguish between the paths, then the amplitudes A_1 and A_2 interfere!

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

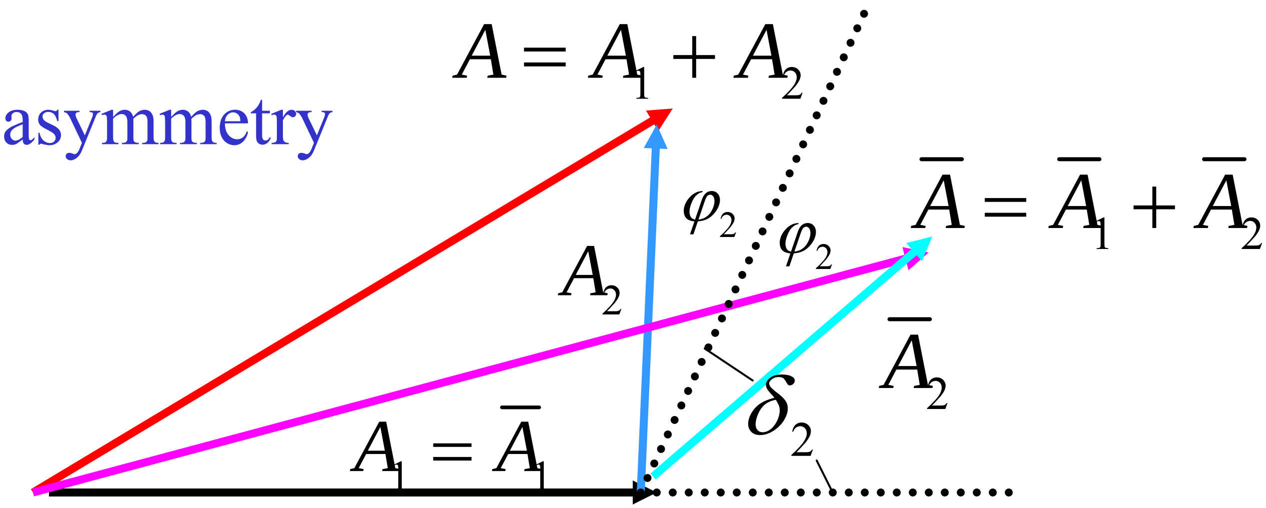
- Next, introduce a *CP-conserving* phase in addition to the *CP-violating* phase.

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

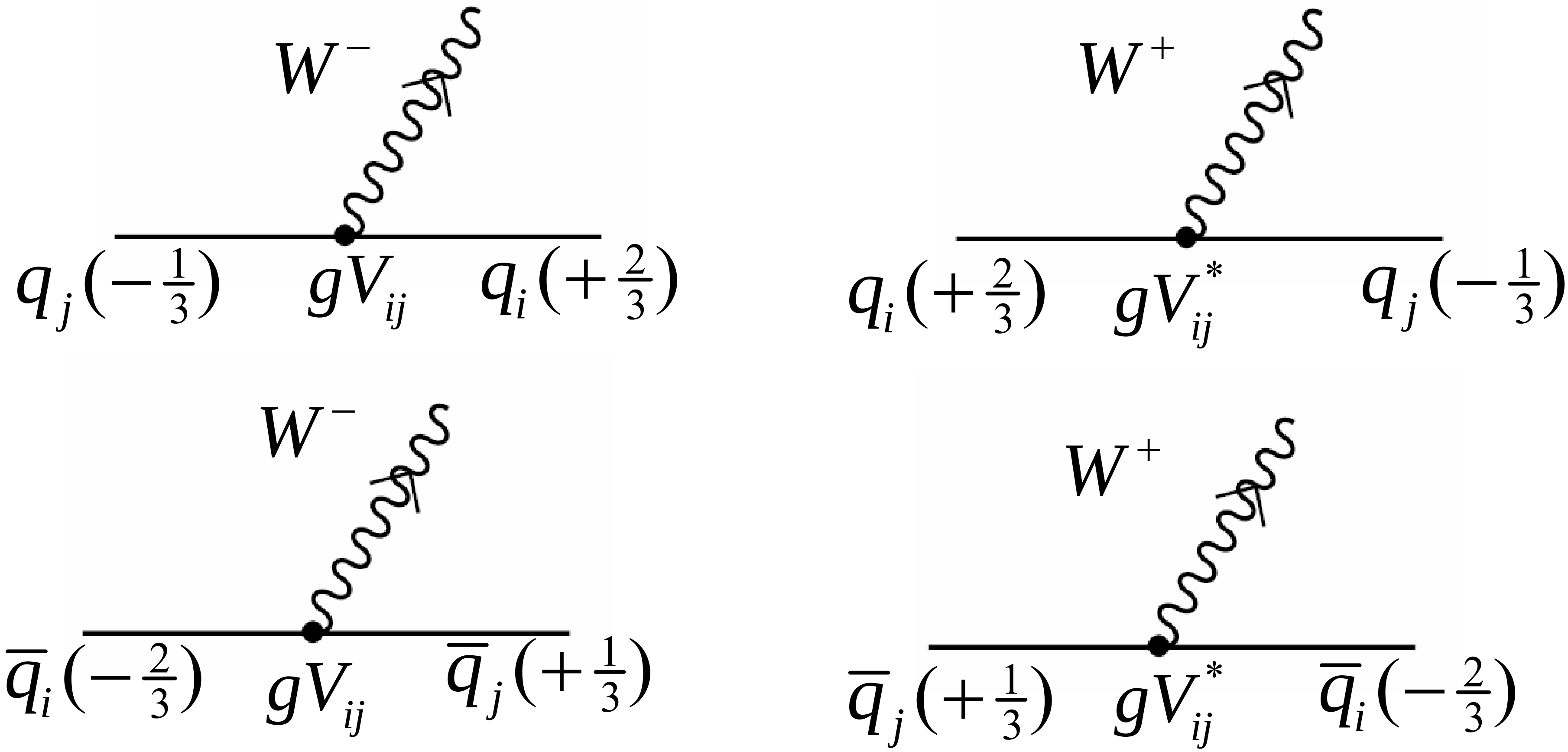
$$\bar{A} = A_1 + a_2 e^{i(-\varphi_2 + \delta_2)}$$

- 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 $W^- \Rightarrow V_{ij}^*$

A first look at a B physics experiment

Some questions to think about:

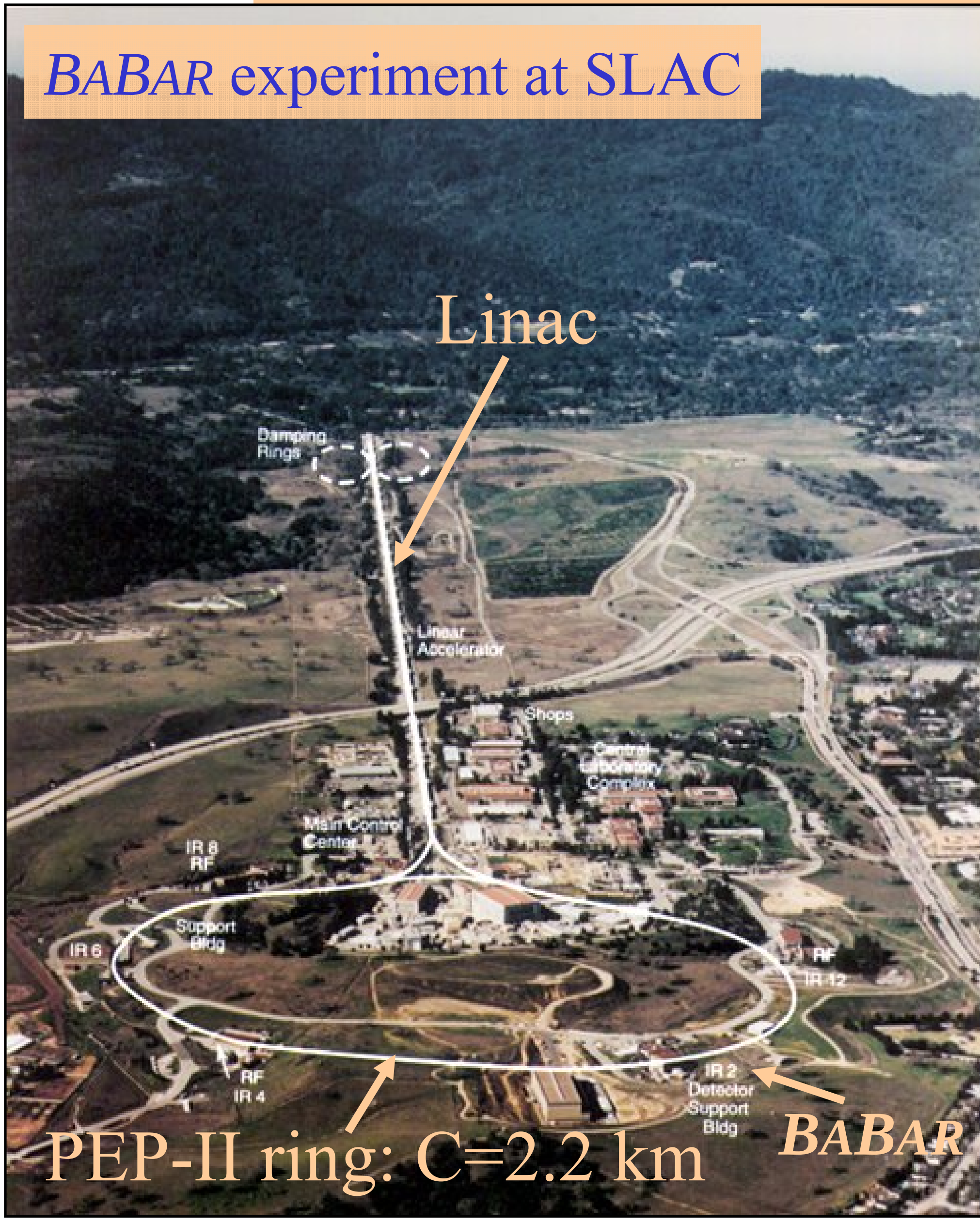
What sets the scale of the detector?

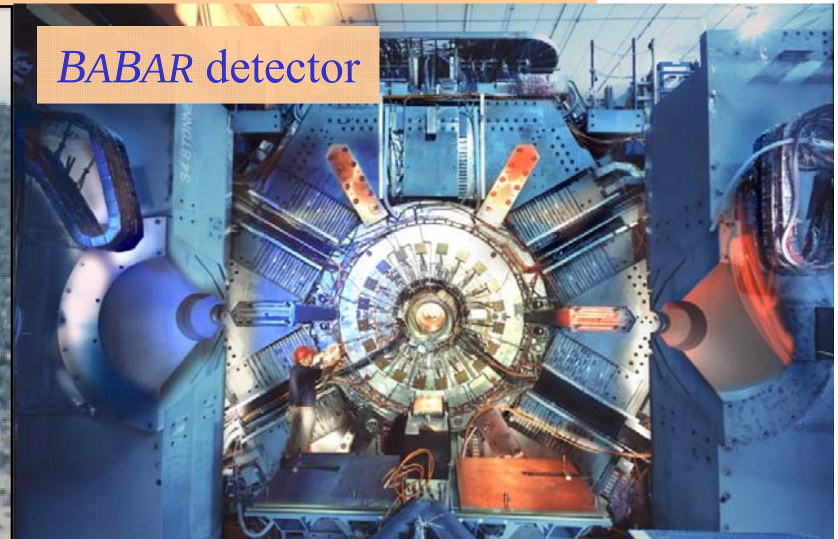
What are the detector requirements?

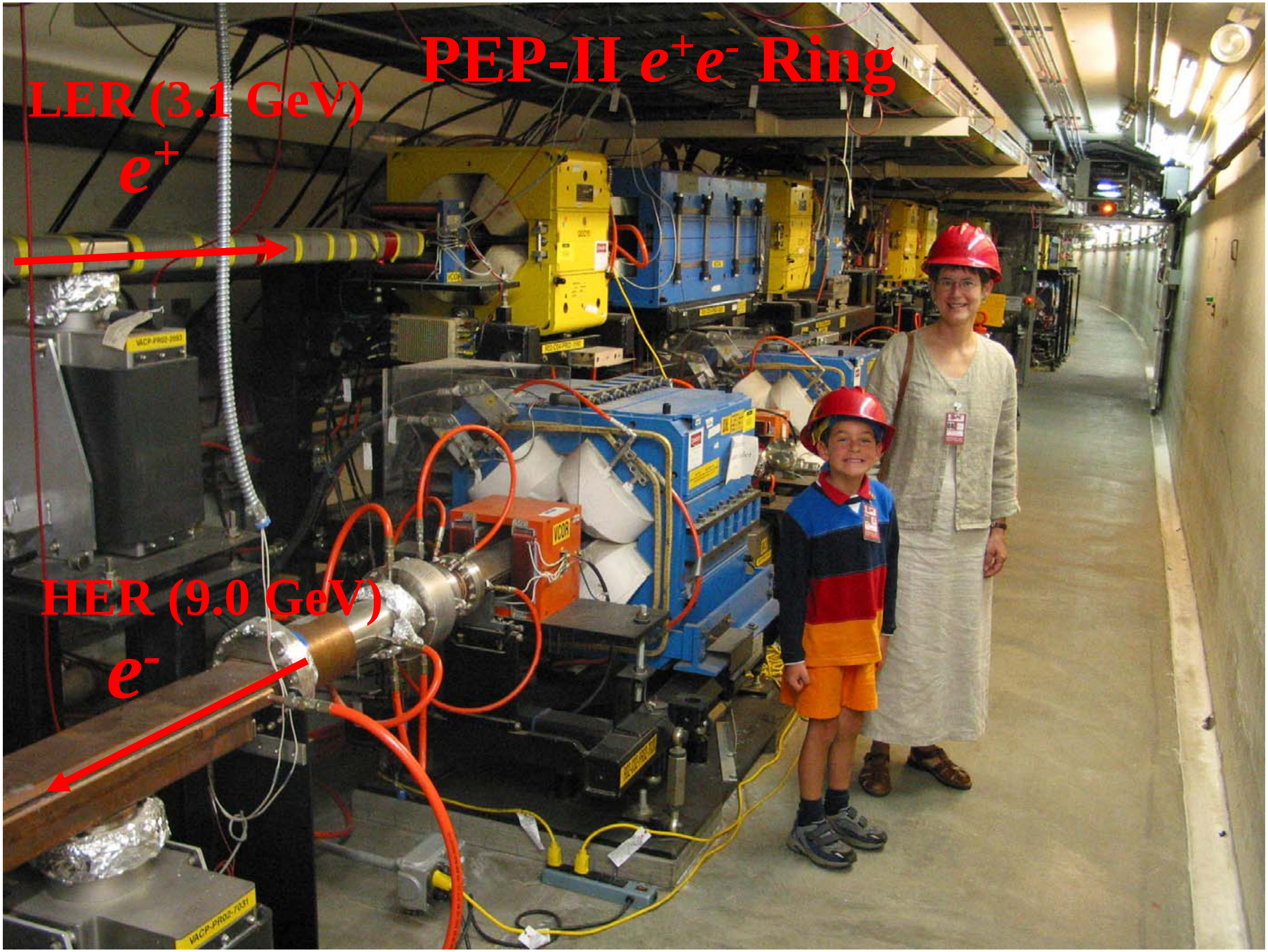
How many B mesons do you need?

A detector is an answer to many questions.

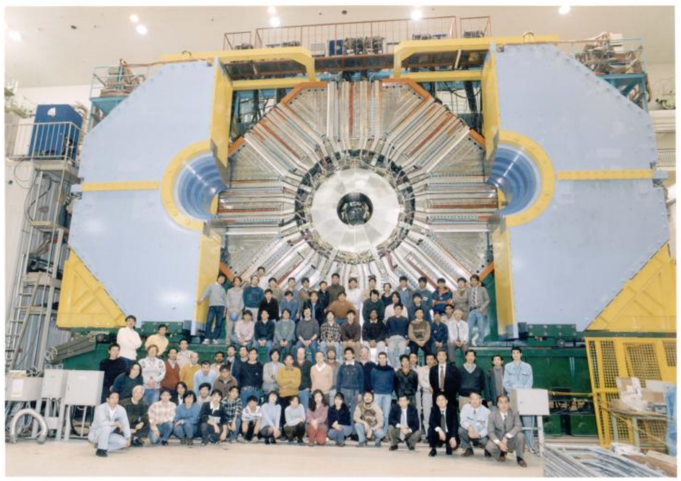
BABAR and PEP-II at SLAC

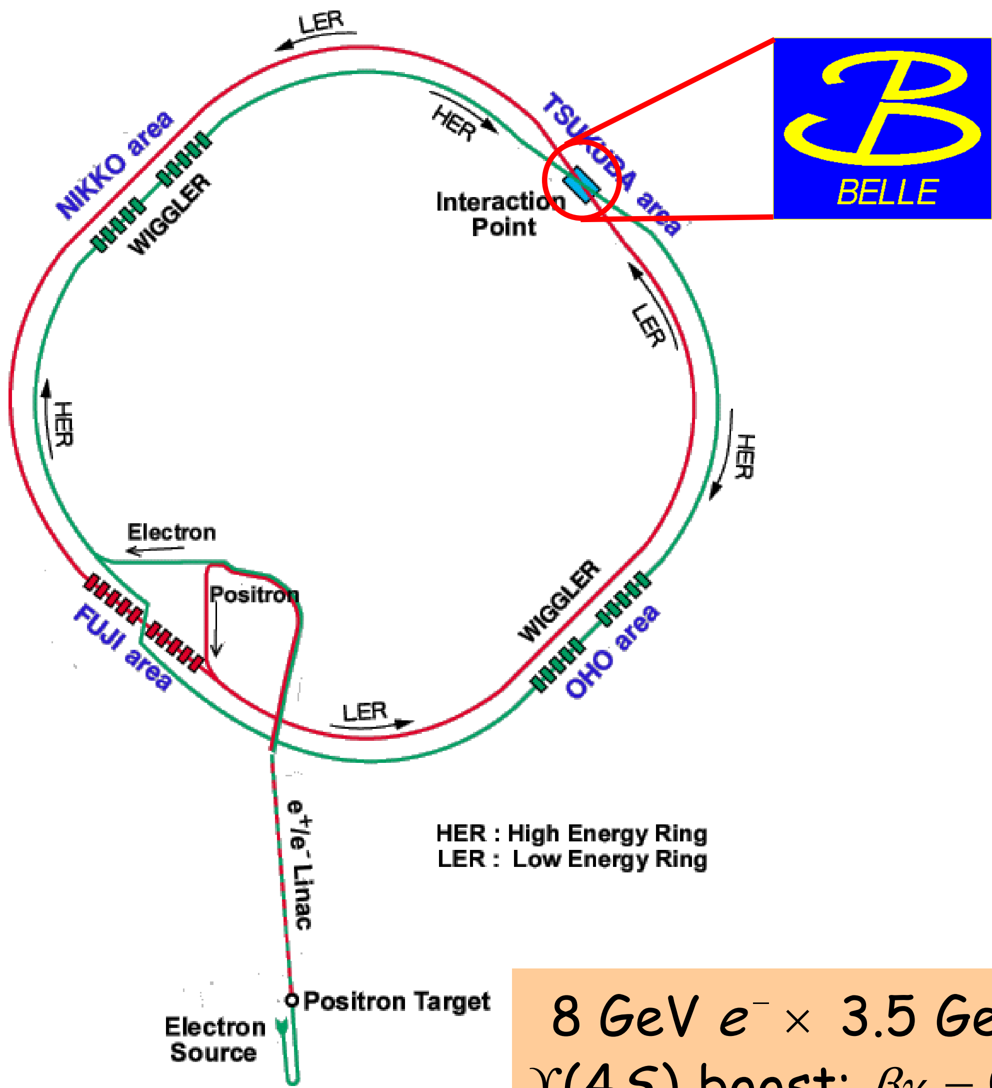





PEP-II e^+e^- Ring
LER (3.1 GeV)
e^+
HER (9.0 GeV)
e^-

KEKB & Belle (Japan)



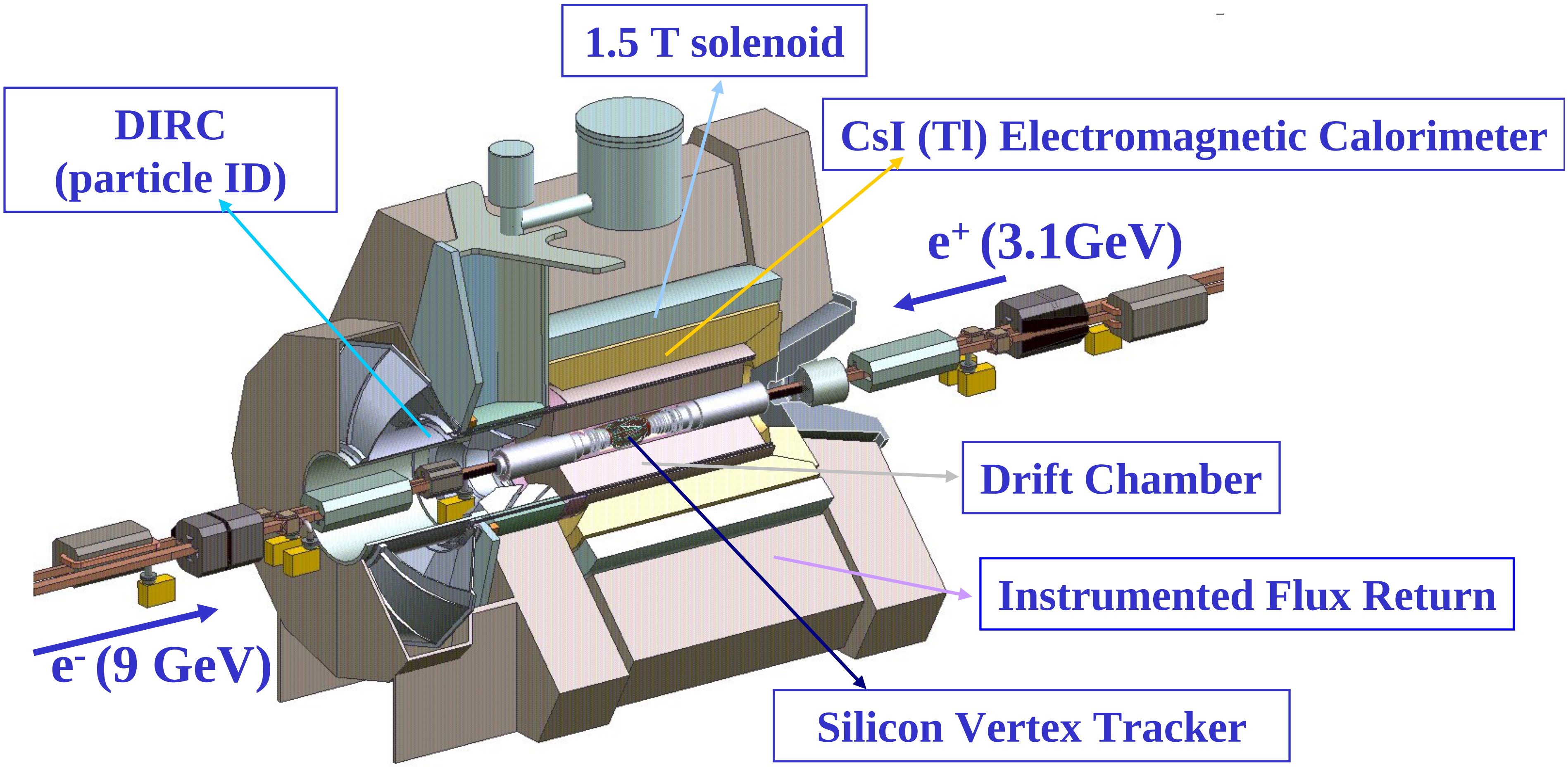


8 GeV $e^{-} \times$ 3.5 GeV e^{+}

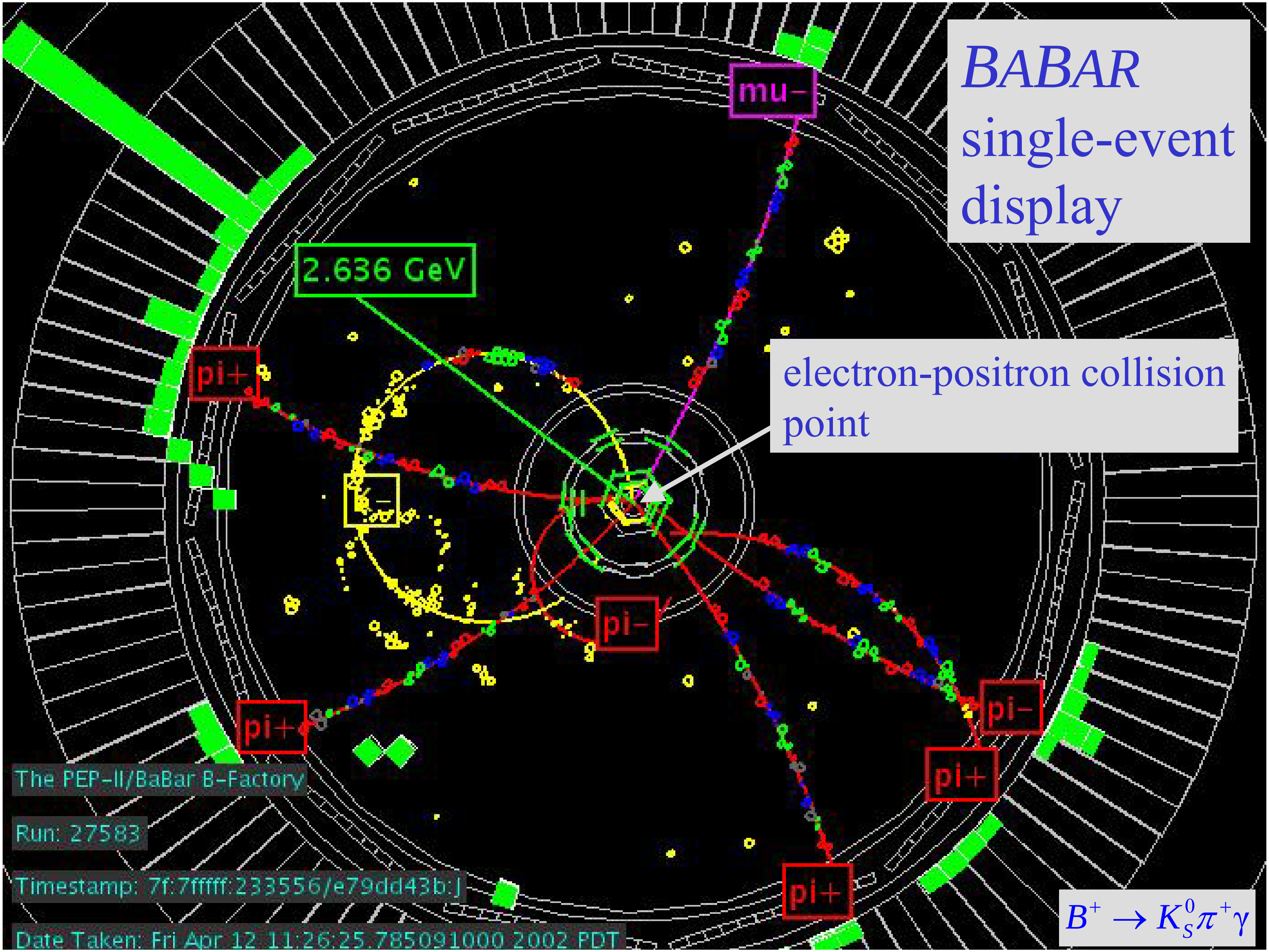
$\Upsilon(4S)$ boost: $\beta\gamma = 0.425$

± 11 mrad crossing angle

The *BaBar* Detector



- SVT: 97% efficiency, 15μm z resol. (inner layers, perpendicular tracks)
- Tracking : $\sigma(p_T)/p_T = 0.13\%\ P_T \oplus 0.45\%$
- DIRC : K-π separation >3.4σ for P<3.5GeV/c
- EMC: $\sigma_E/E = 1.33\%\ E^{-1/4} \oplus 2.1\%$



BABAR single-event display
2.636 GeV
mu-
pi+
K-
pi-
pi+
pi-
pi+
pi+
electron-positron collision point
The PEP-II/BaBar B-Factory
Run: 27583
Timestamp: 7f:7fffff:233556/e79dd43b:J
Date Taken: Fri Apr 12 11:26:25.785091000 2002 PDT
$B^+ \to K_S^0 \pi^+ \gamma$

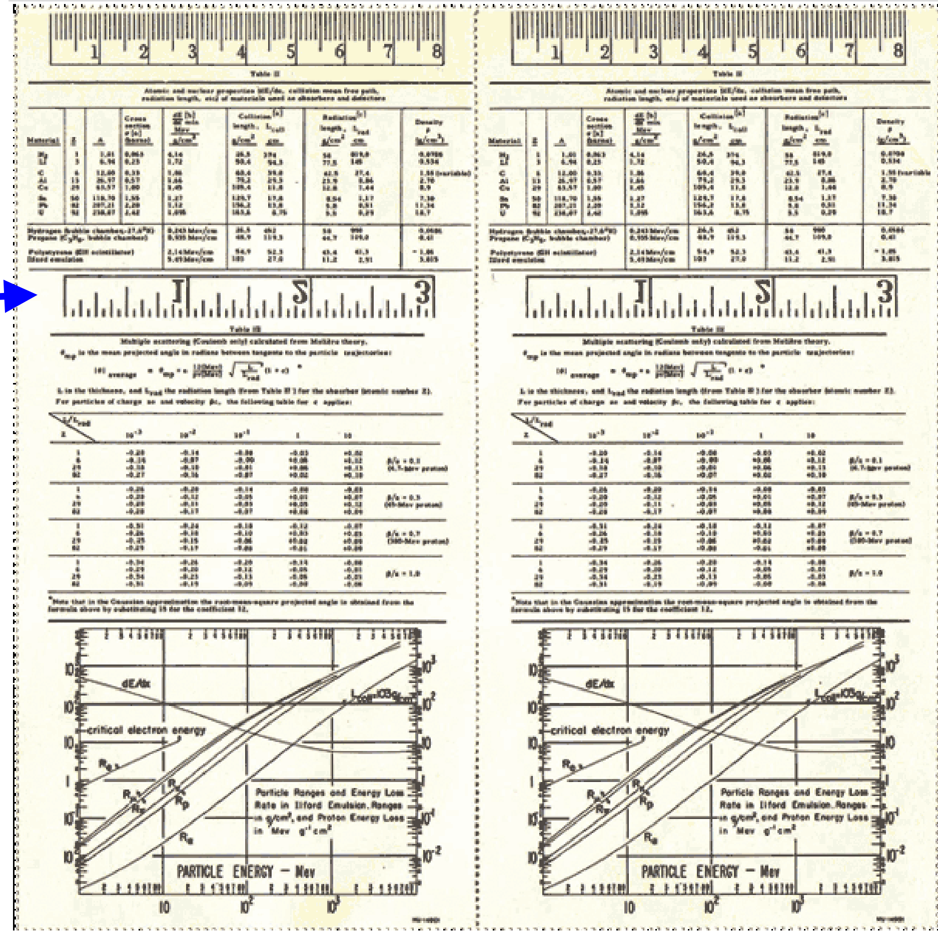
End of Lecture 1

Backup Slides

The Challenge of Data Quality

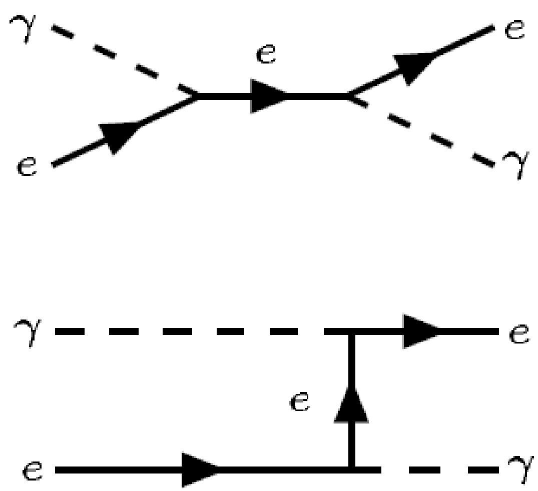
- Two aspects
  - Experimental/Technical issues.
  - Human behavior issues.
- Already had difficulties reproducing ruler in 1958!
- Particle physicists put a huge effort into maintaining the quality of data and the results derived from the data.
- This is fundamentally a hard problem: there are a lot more ways to things wrong than to do things right! (Entropy)

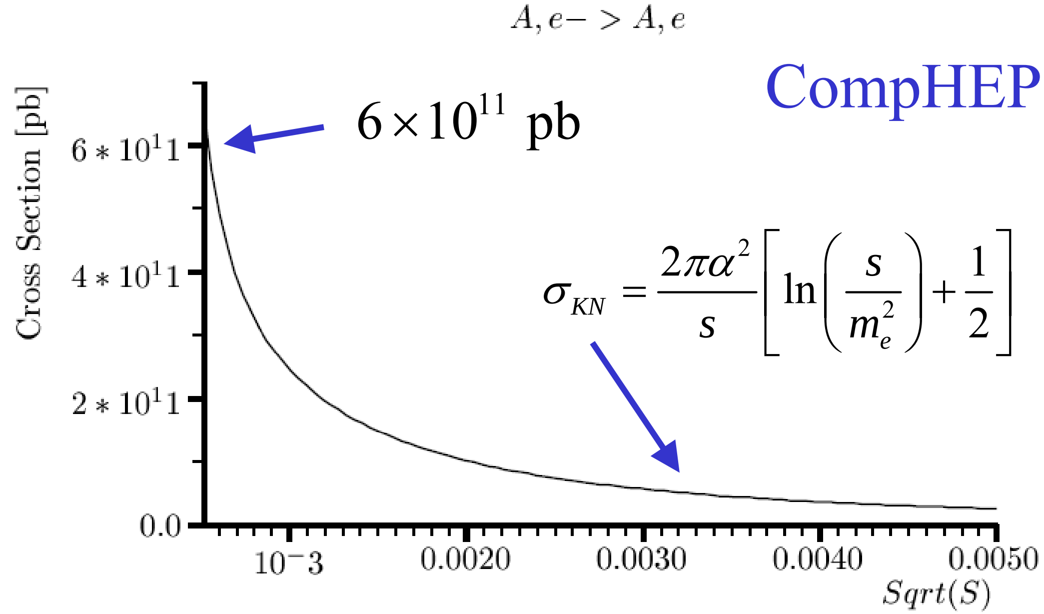
Particle Data Book, 1958
Lawrence Radiation Lab Report UCRL-8030



2006 edition has 1232 pages; 24,559 measurements!

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





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

Thomson scattering

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

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

about a barn!

$\hbar$, 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