The Uncertainty Principle, the Quarks, and the Search for New Physics

Andrei Gritsan

Johns Hopkins University

March 29, 2007

JHU Physics Colloquium

Outline

- The Quarks

  what we know and do not know in particle physics

- The Uncertainty Principle

  quantum mechanics with elementary particles

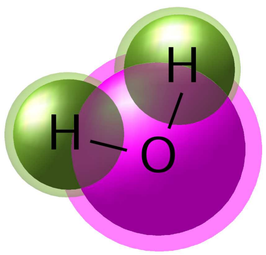
- The Search for New Physics

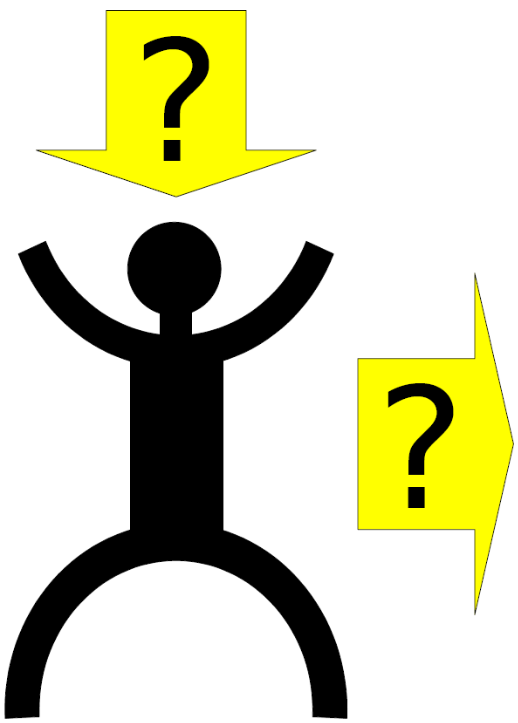
  set up an experiment with spin correlations

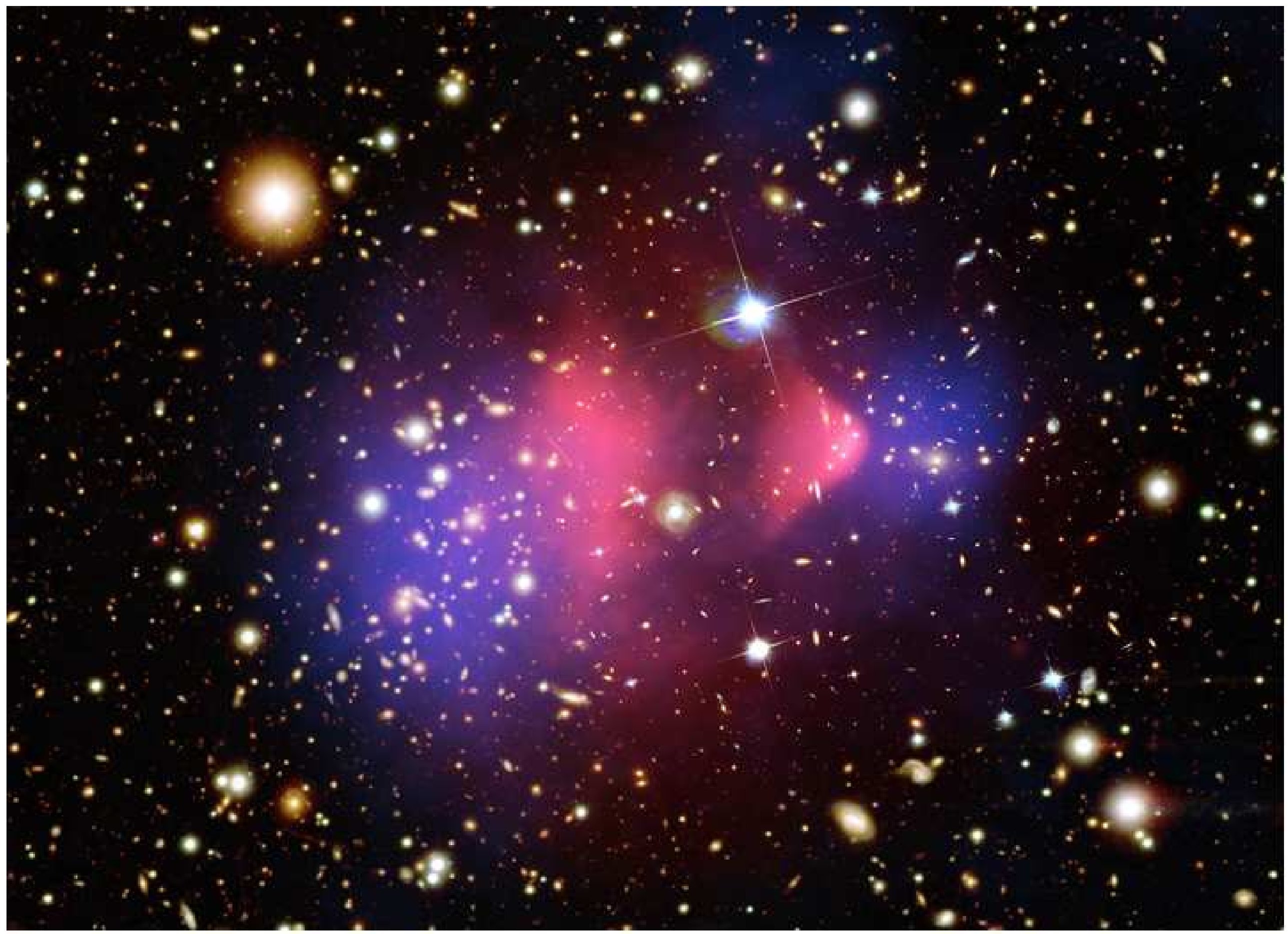
Particle Physics: Trying to Reach Deep

- On the smallest and largest scale:

  what are we made of and why





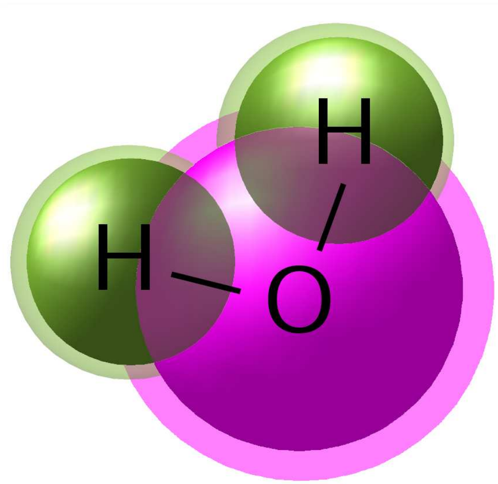


(Galaxy cluster 1E 0657-66: X-ray, Optical, Grav. Lensing)

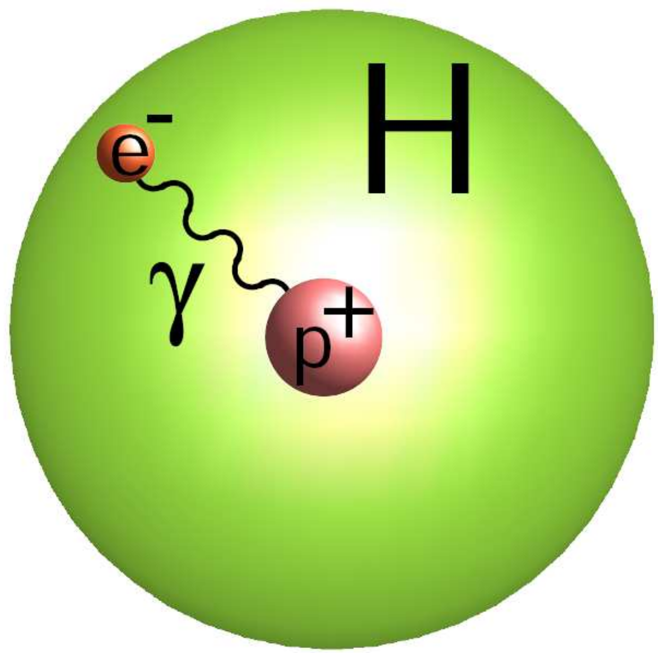
Particle Physics
What We Already Know

From Molecules to Quarks

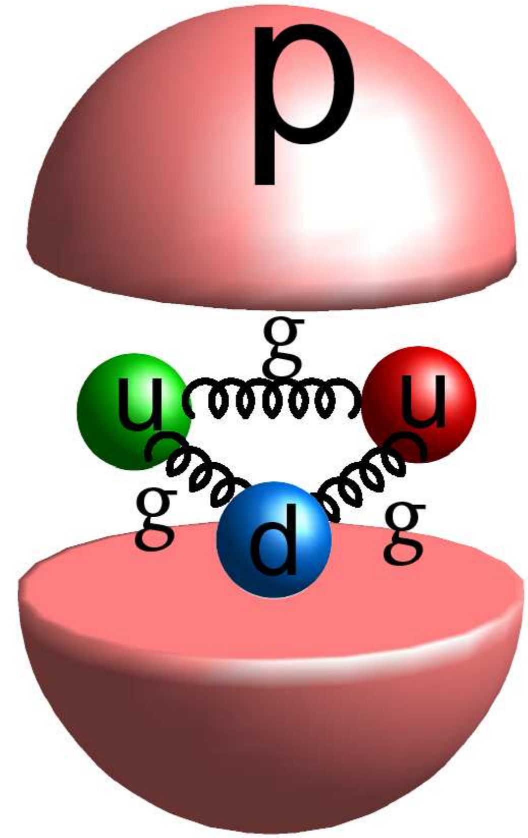
- XXth century: reaching deep into matter, Quarks



Chemistry



Atomic Physics



Particle Physics

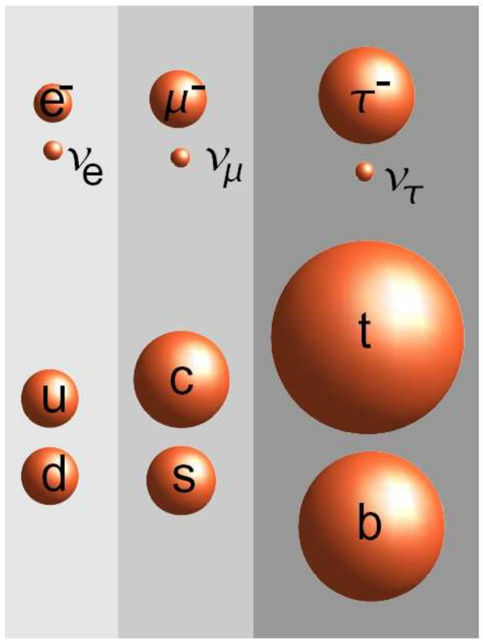
Elementary Particles

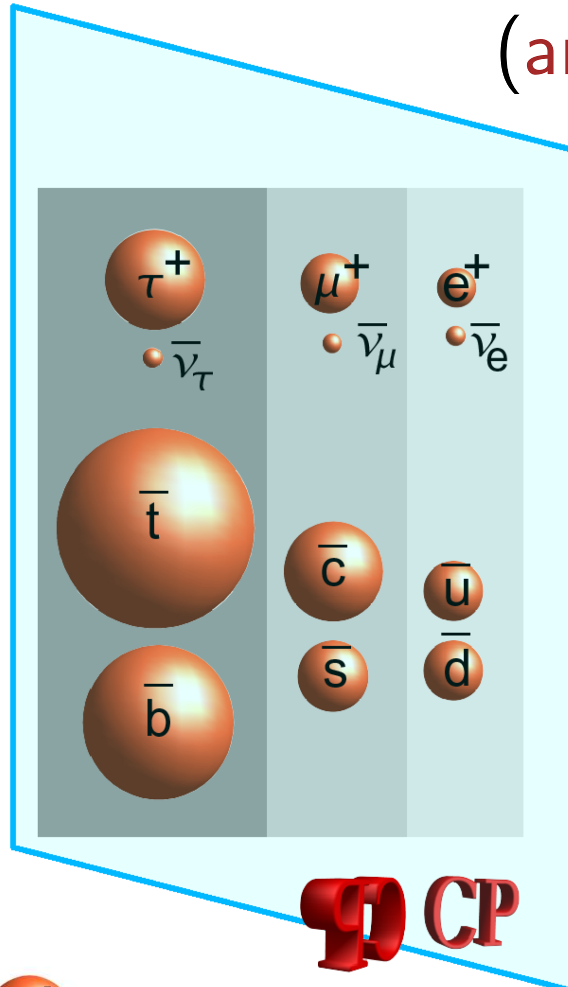
(anti-matter)

- Fermions $S = \frac{\hbar}{2}$ (matter)

leptons

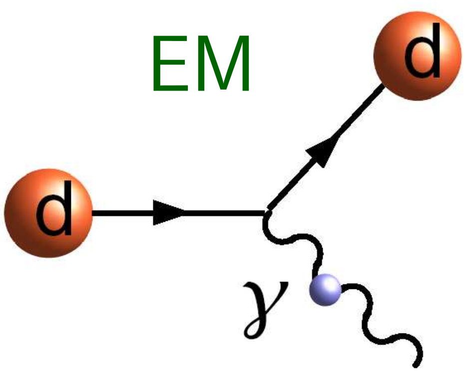
quarks



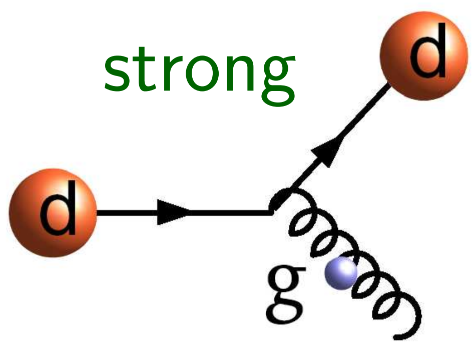


- Bosons $S = \hbar$ (force carries):

EM



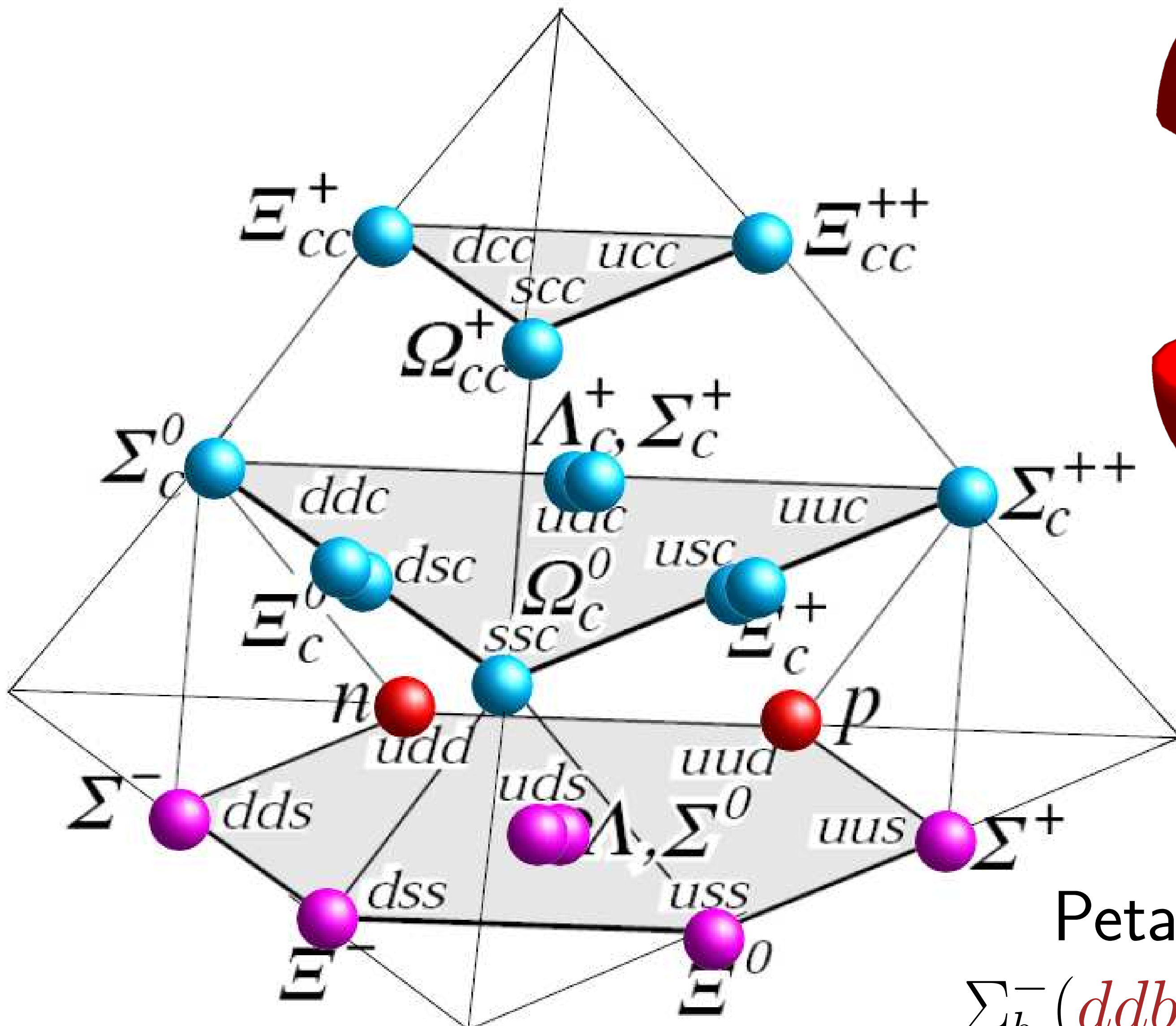
strong

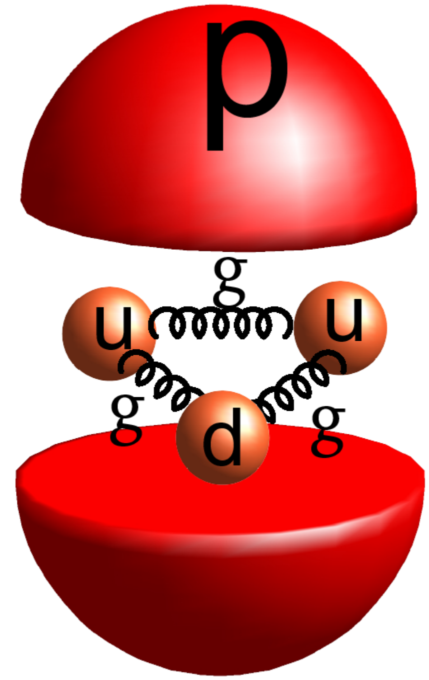


(weak force later)

"Periodic Table" of Baryons: Proton, Neutron,...

- Three quarks make up a Baryon:

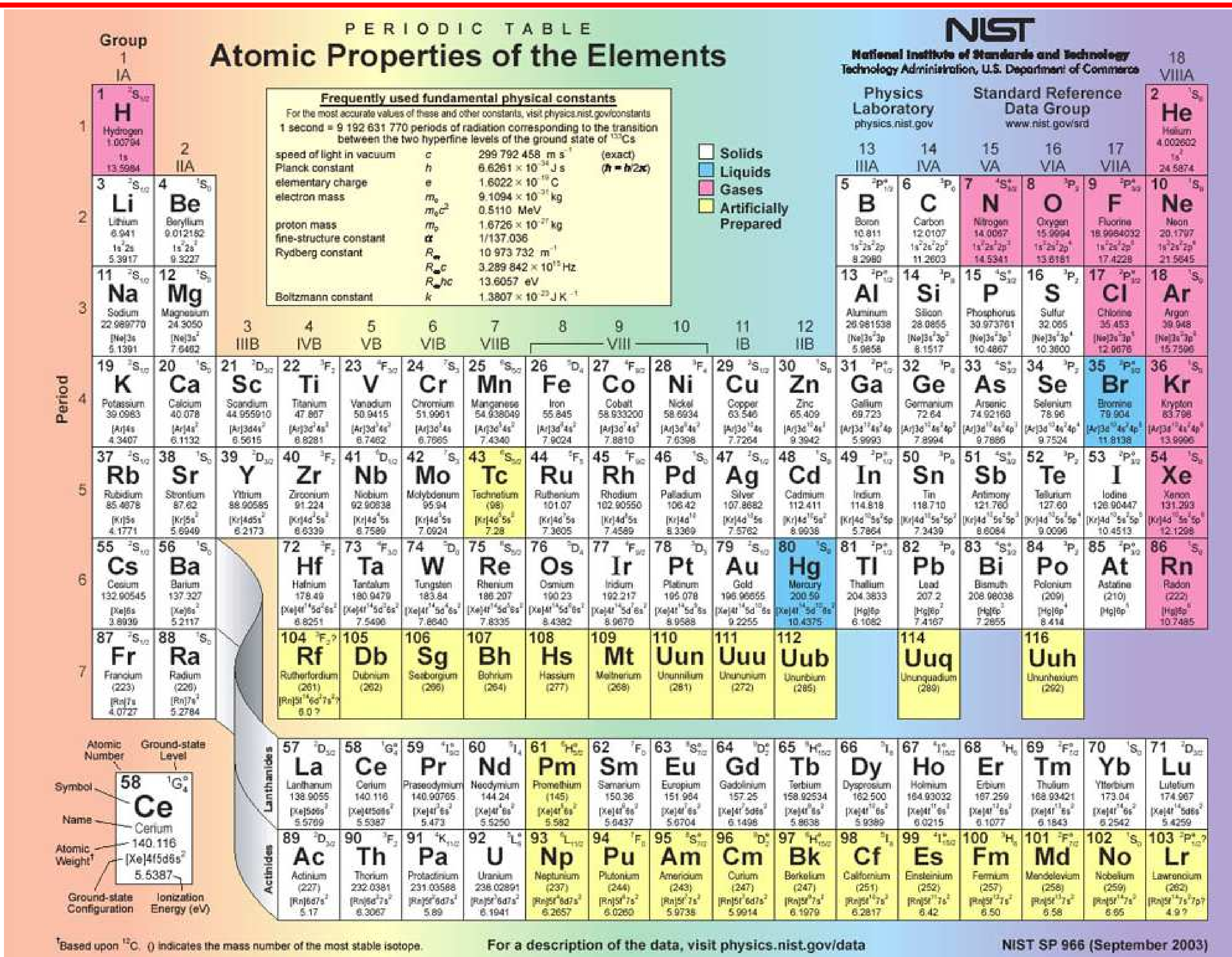




Petar's colloquium:

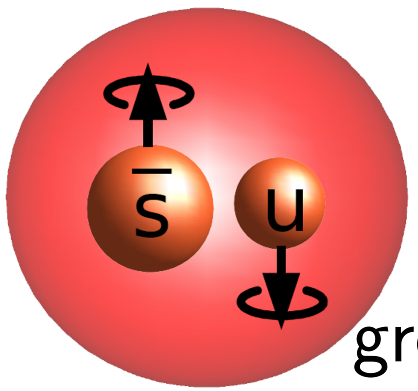
$\Sigma_b^-(ddb)$ and $\Sigma_b^+(uub)$

Like Periodic Table of Atoms



“Periodic Table” of Mesons

- Quark-antiquark make up a Meson:

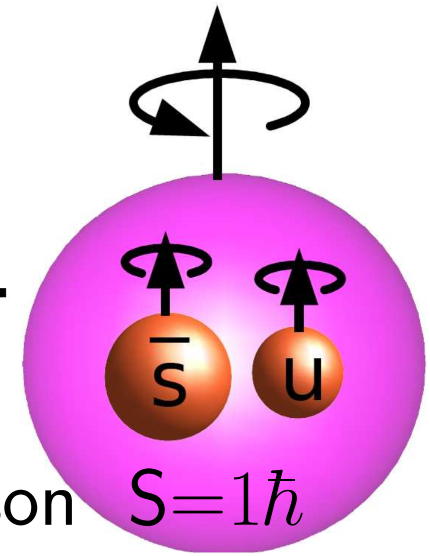


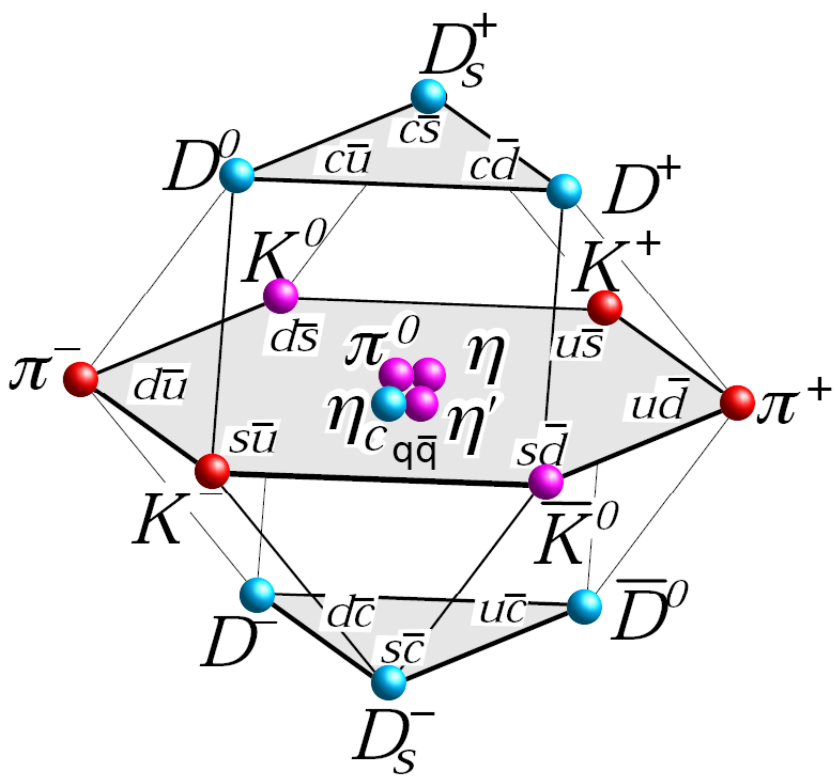
K^+

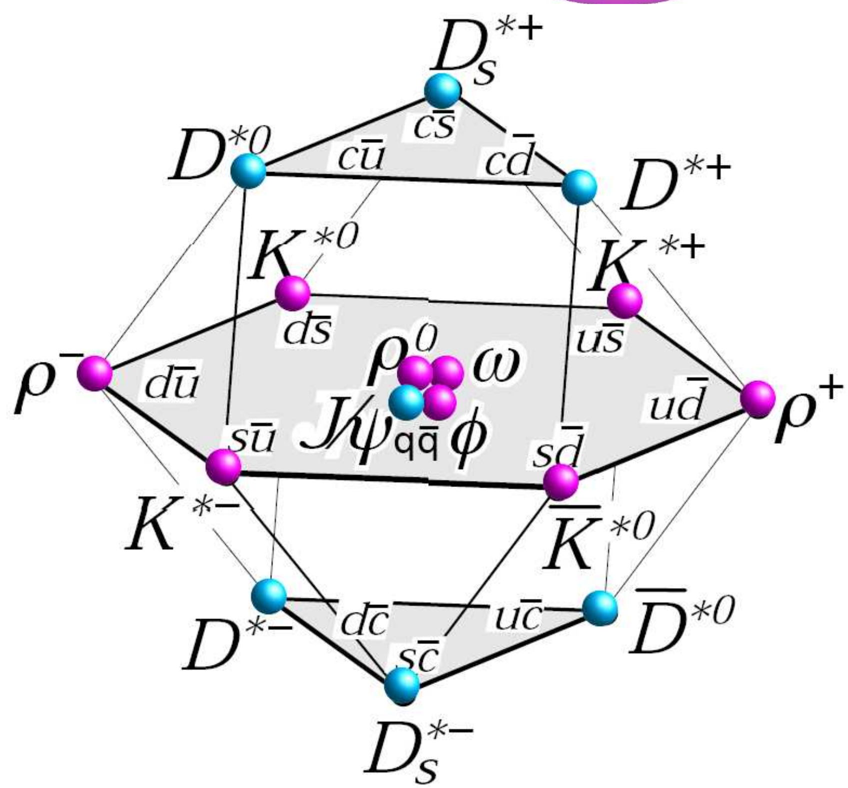
ground state (L=S=0)

K^{*+}

Vector meson S=1$\hbar$

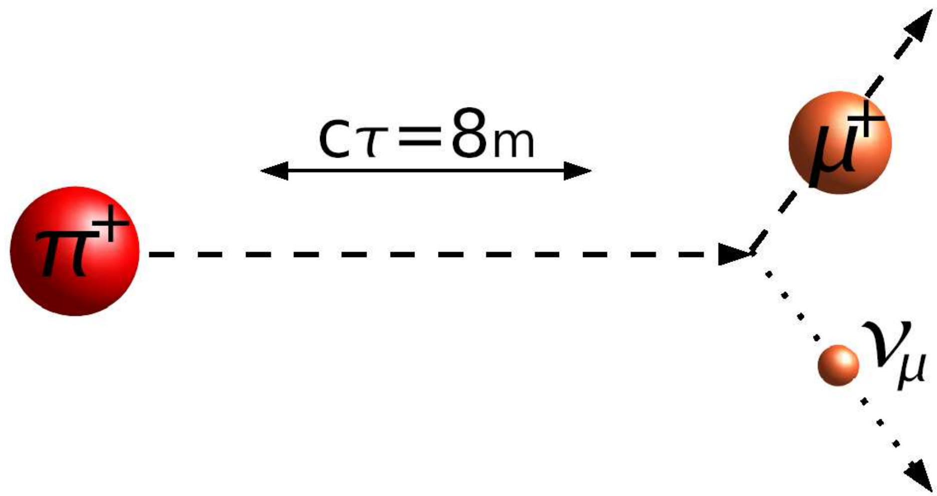




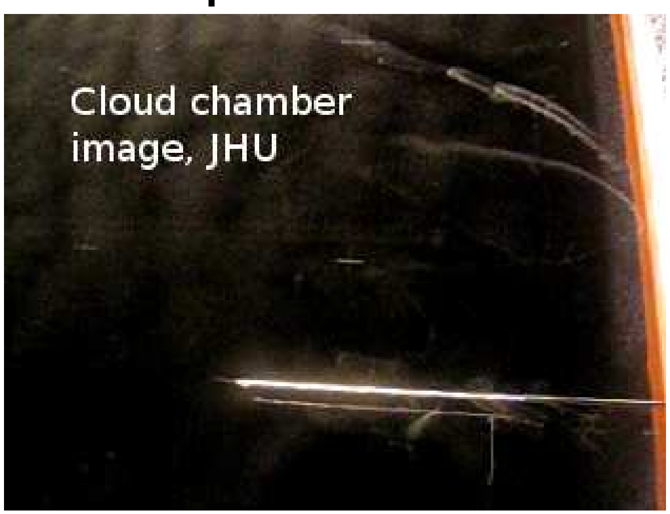


How do We "See" Particles

- We "see" semi-stable particles by "tracks" in matter:



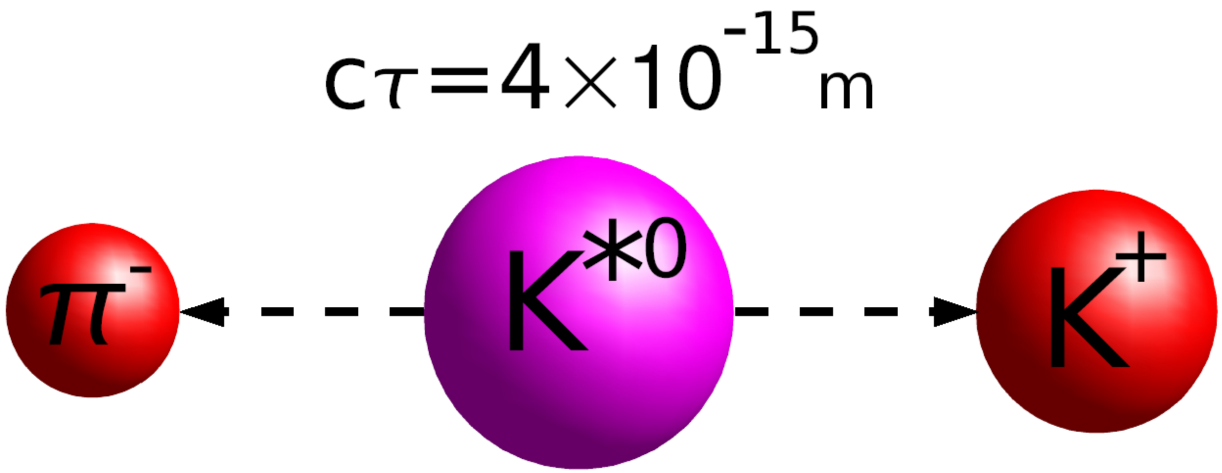
- Table-top illustrations



- Complex multi-ton detectors

How do We "See" Particles

- Most particles live too short to be "seen" directly
  - "see" decay products:



- Time (decay) and energy (resonance) amplitudes:

$$A(t) = A(0)e^{iE_0 t/\hbar}e^{-\Gamma_0 t/2\hbar} \quad \Rightarrow \quad |A(t)|^2 \propto e^{-\Gamma_0 t/\hbar} = e^{-t/\tau_0}$$

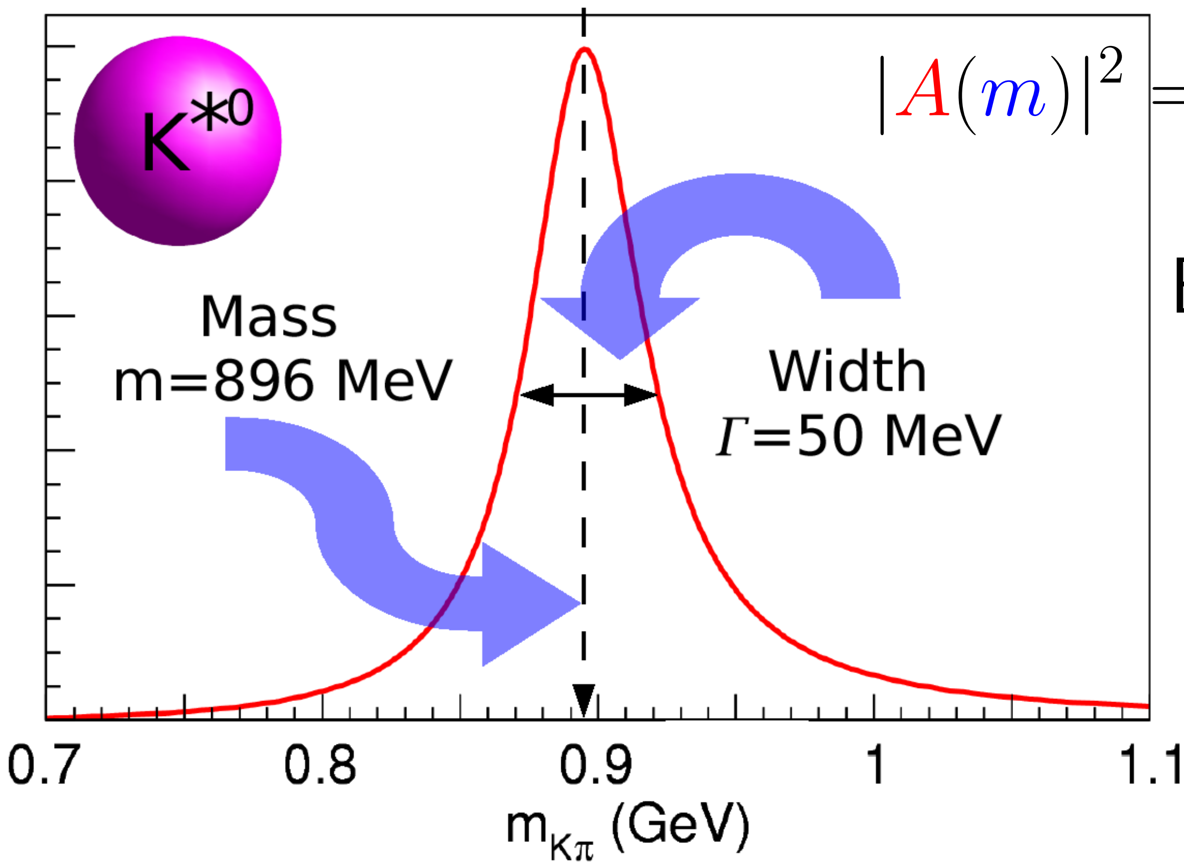
$$A(E) = \int A(t)e^{iEt/\hbar}\mathrm{d}t = \frac{C}{(E - E_0) - i\Gamma_0/2} \qquad \Gamma_0 = \frac{\hbar}{\tau_0}$$

Unstable Particles

- The Uncertainty Principle (part 1): $\Gamma_0 \times \tau_0 = \hbar$

  compare: $\Delta E \times \Delta t \sim \hbar$

- Probability $\propto \; |A(m)|^2$



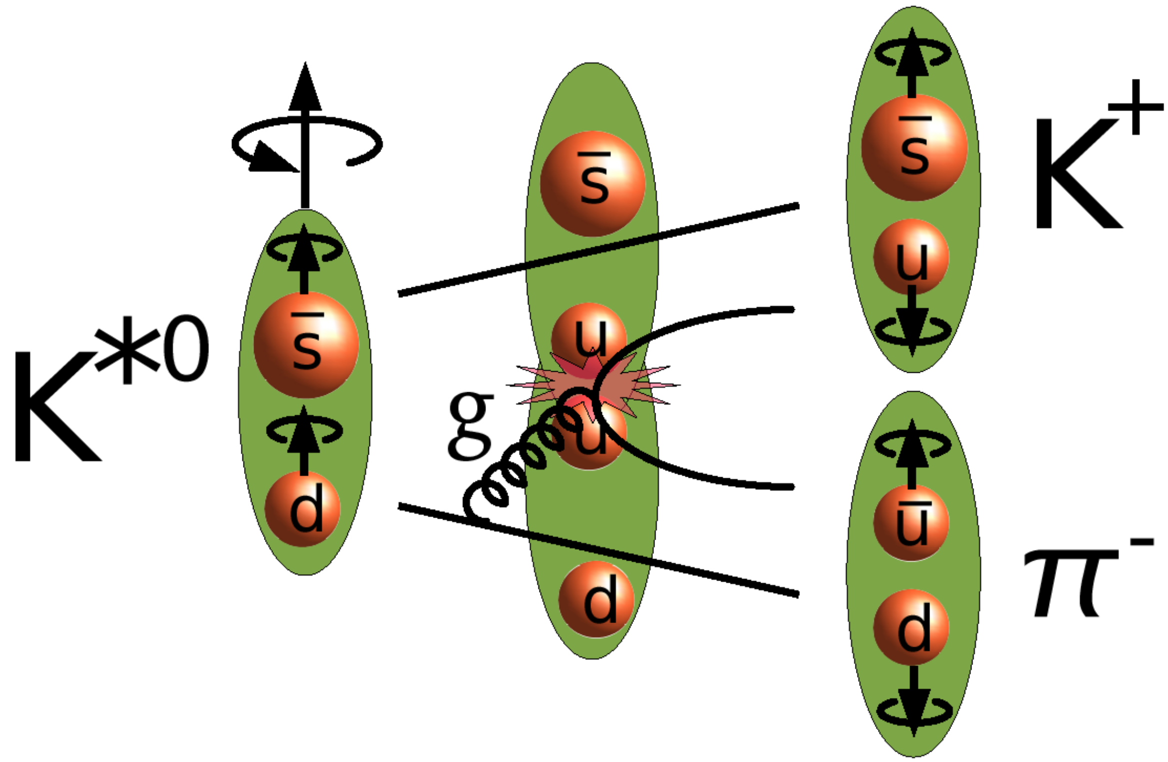
$$|A(m)|^2 = \left| \frac{C}{(m - m_0) - i\Gamma_0/2} \right|^2$$

Breit-Wigner resonance

Decay Dynamics

- Unstable particles decay

  Feynman diagram:

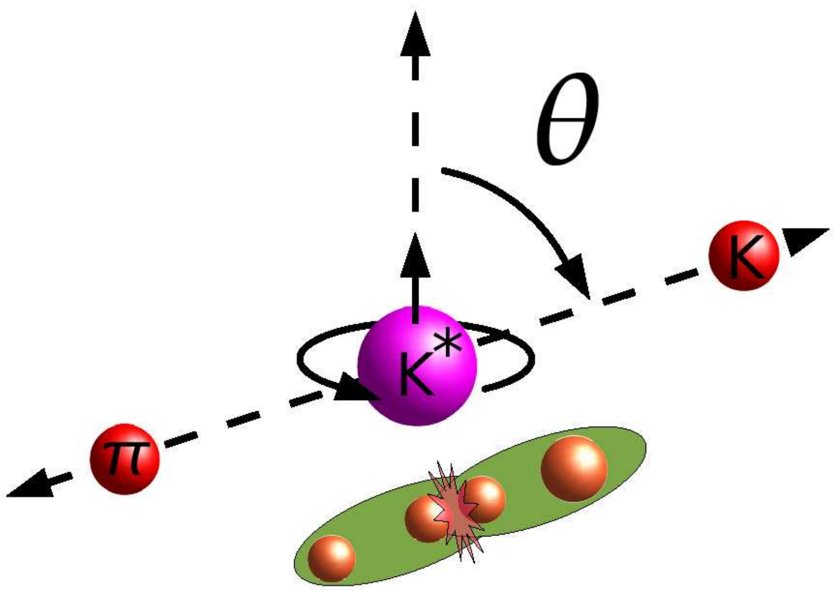


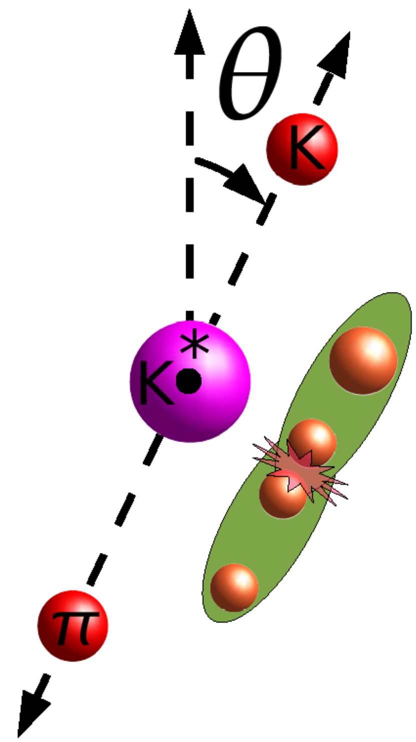
- Decay ⇒ study elementary particles and interactions

  (this "strong" decay is mostly understood)

Decay Kinematics

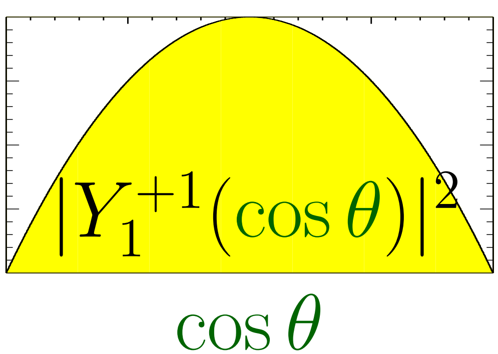
- We often understand decay dynamics through kinematics



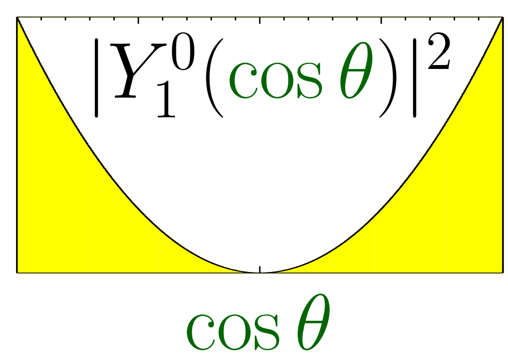


- Conservation of orbital momentum:

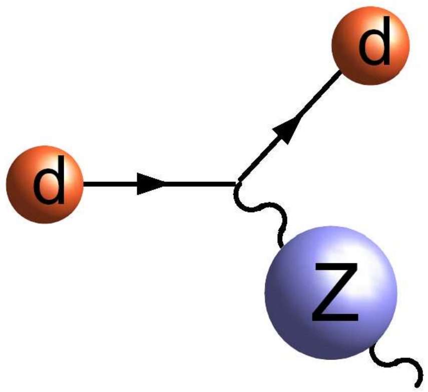
$L_z = +1$



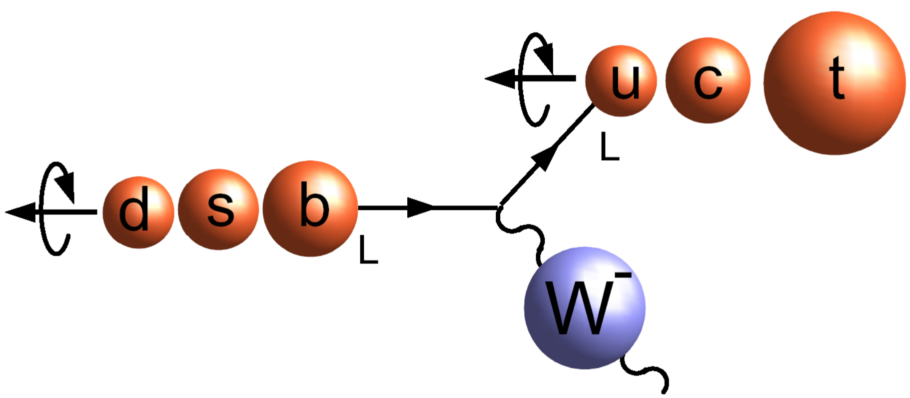
$L_z = 0$

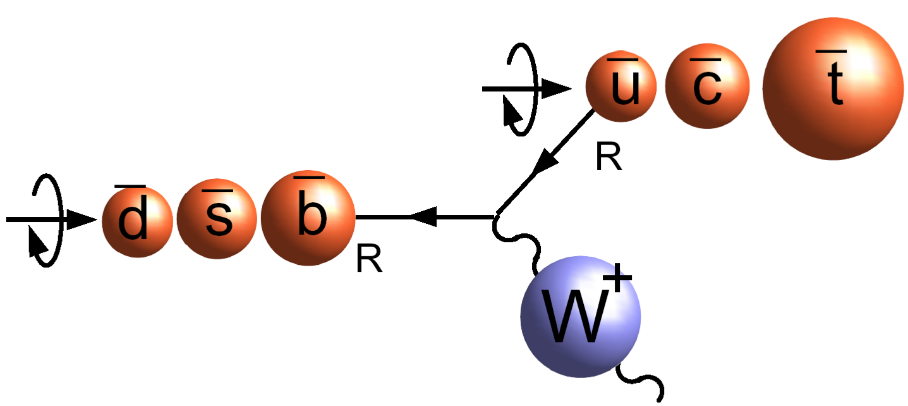


Weak Interactions



- Massive carries $\Rightarrow$ weak (short-range)
  mass $\sim$ 80-90 GeV





- <u>Special interactions:</u>

  change type of quark

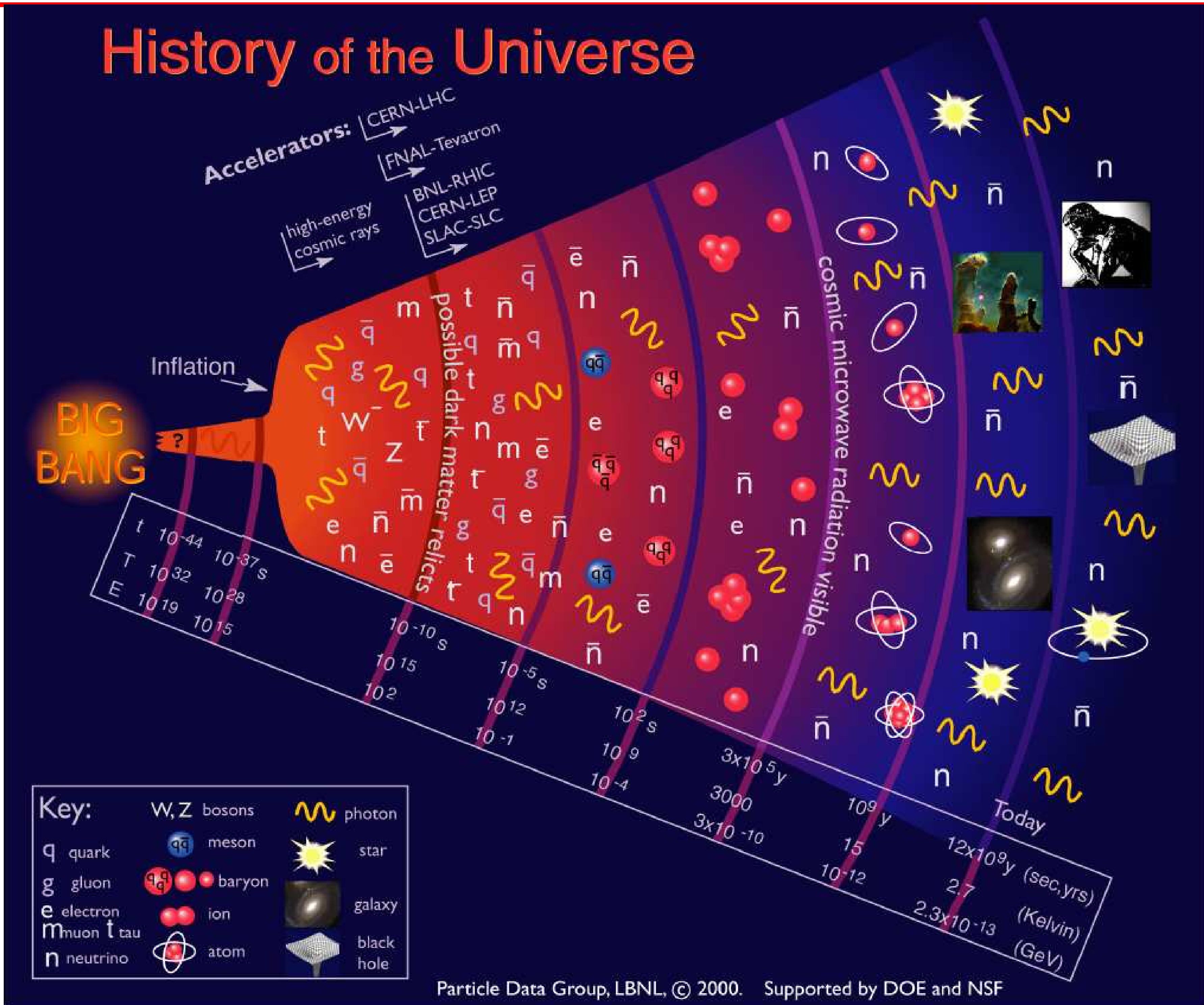
  change families

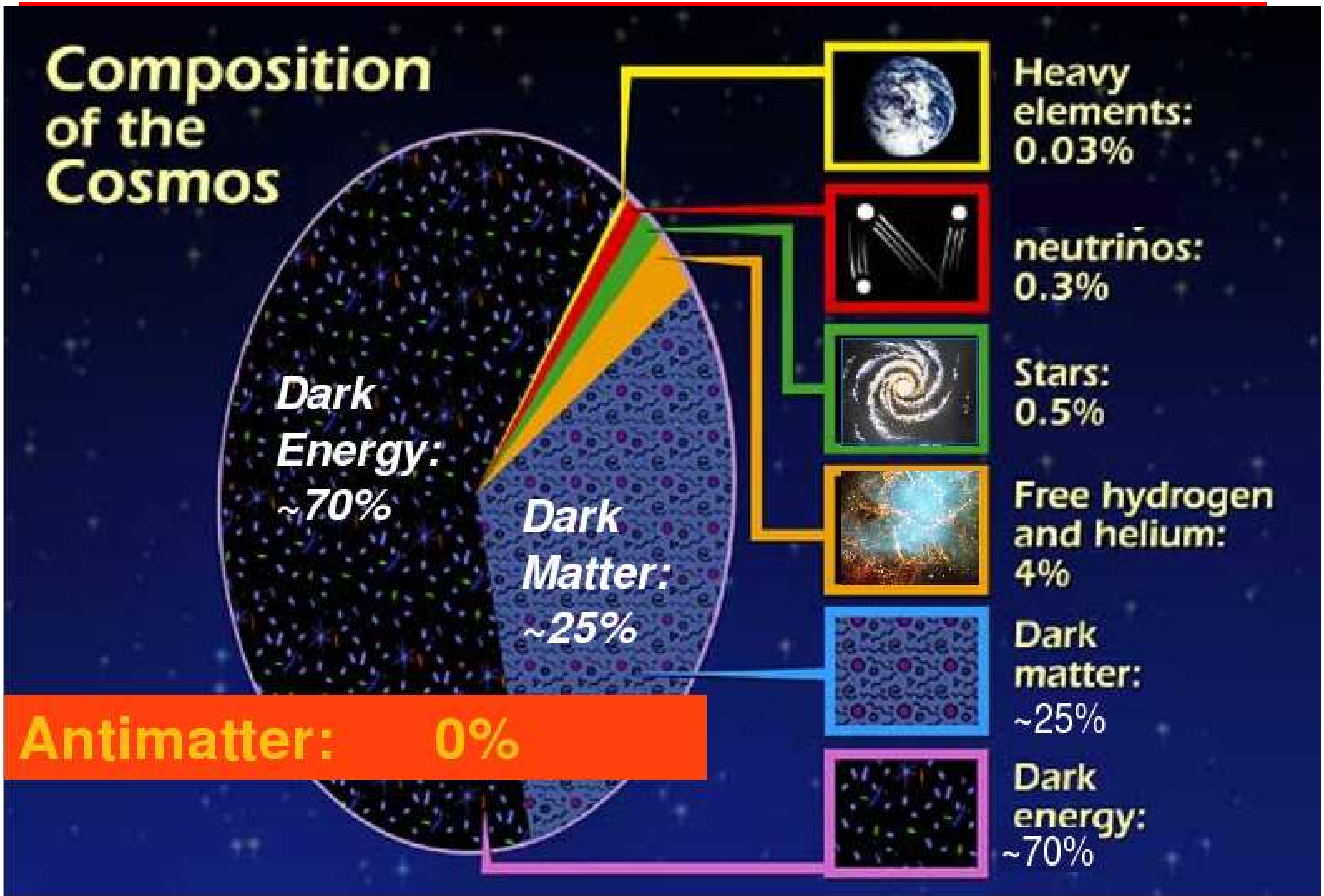
  left-handed fermions
  $\bar{q}\gamma^{\mu}(1-\gamma^{5})q$

  violate Parity and C

  violate CP symmetry

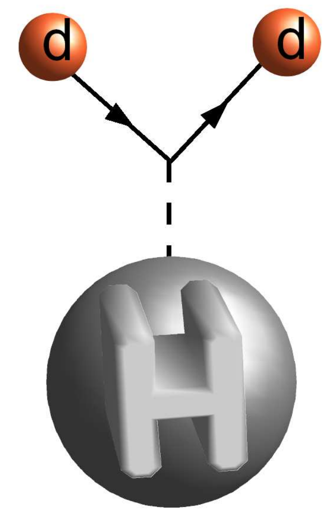
Particle Physics
What We do not Know


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


Composition of the Cosmos
Dark Energy: ~70%
Dark Matter: ~25%
Antimatter: 0%
Heavy elements: 0.03%
neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: ~25%
Dark energy: ~70%

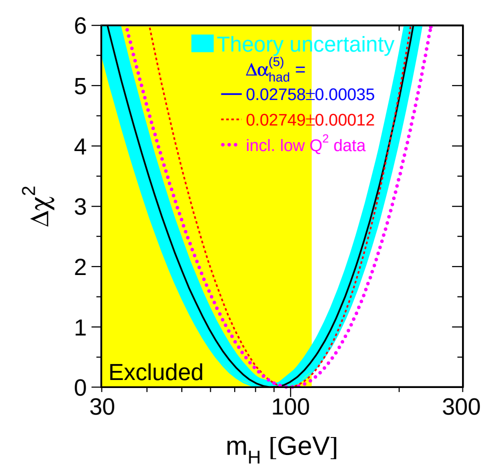
Look Beyond the Standard Model

- Why does matter dominate (Sakharov):
  - CP-asymmetry
  - baryon non-conservation
  - non-equilibrium



- Mysterious Higgs field
  - gives mass to particles

- Need something beyond the SM
  - large CP-asymmetry
  - dark matter
  - light Higgs



Possible Extension: Super-Symmetry

- New (super)symmetry:

  Q|fermion⟩=|boson⟩

  Q|boson⟩=|fermion⟩

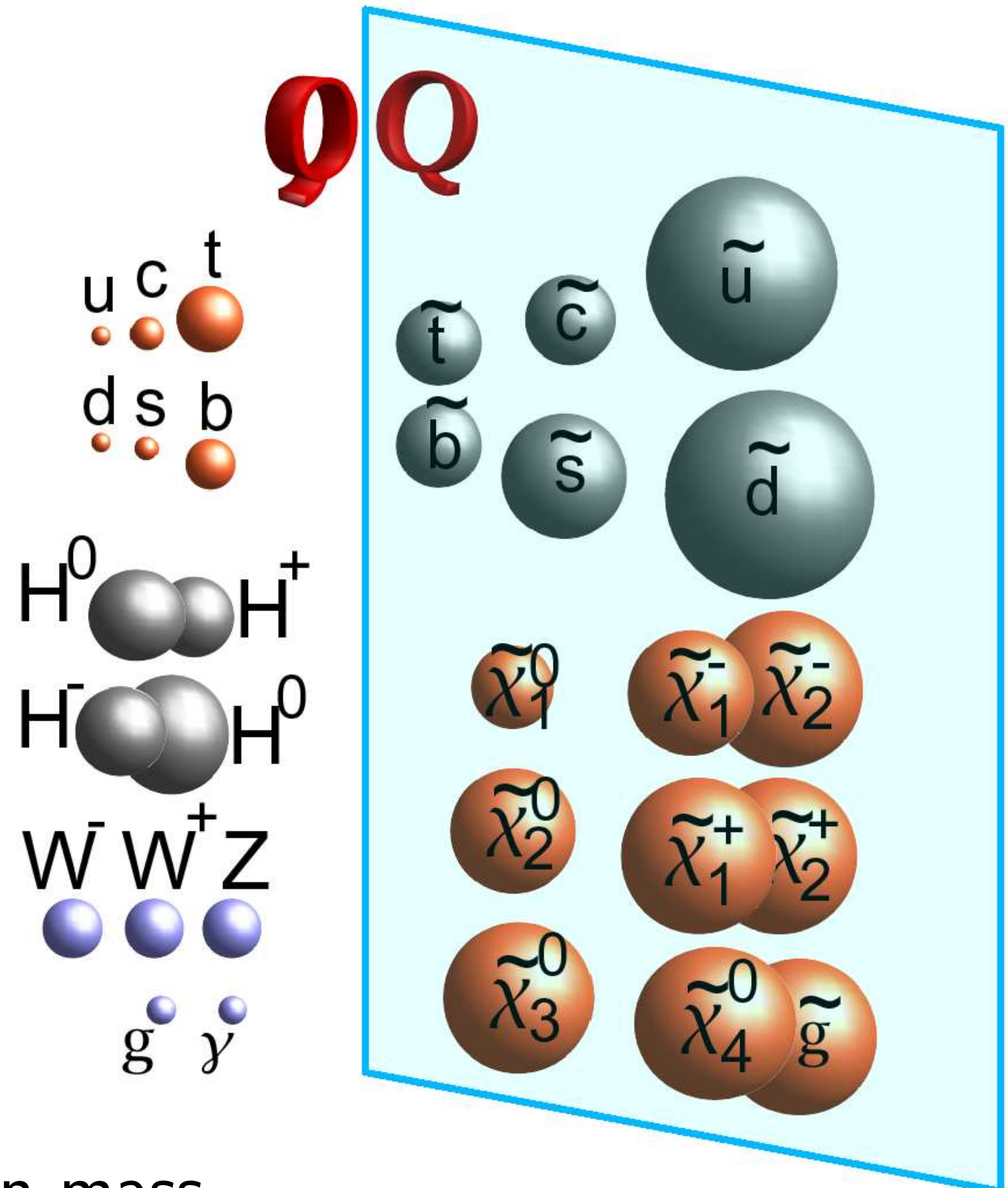
- Solve:

  (1) natural light *H*iggs fields

  (2) dark matter lightest $\tilde{\chi}_1^0$

  (3) large *CP* phases

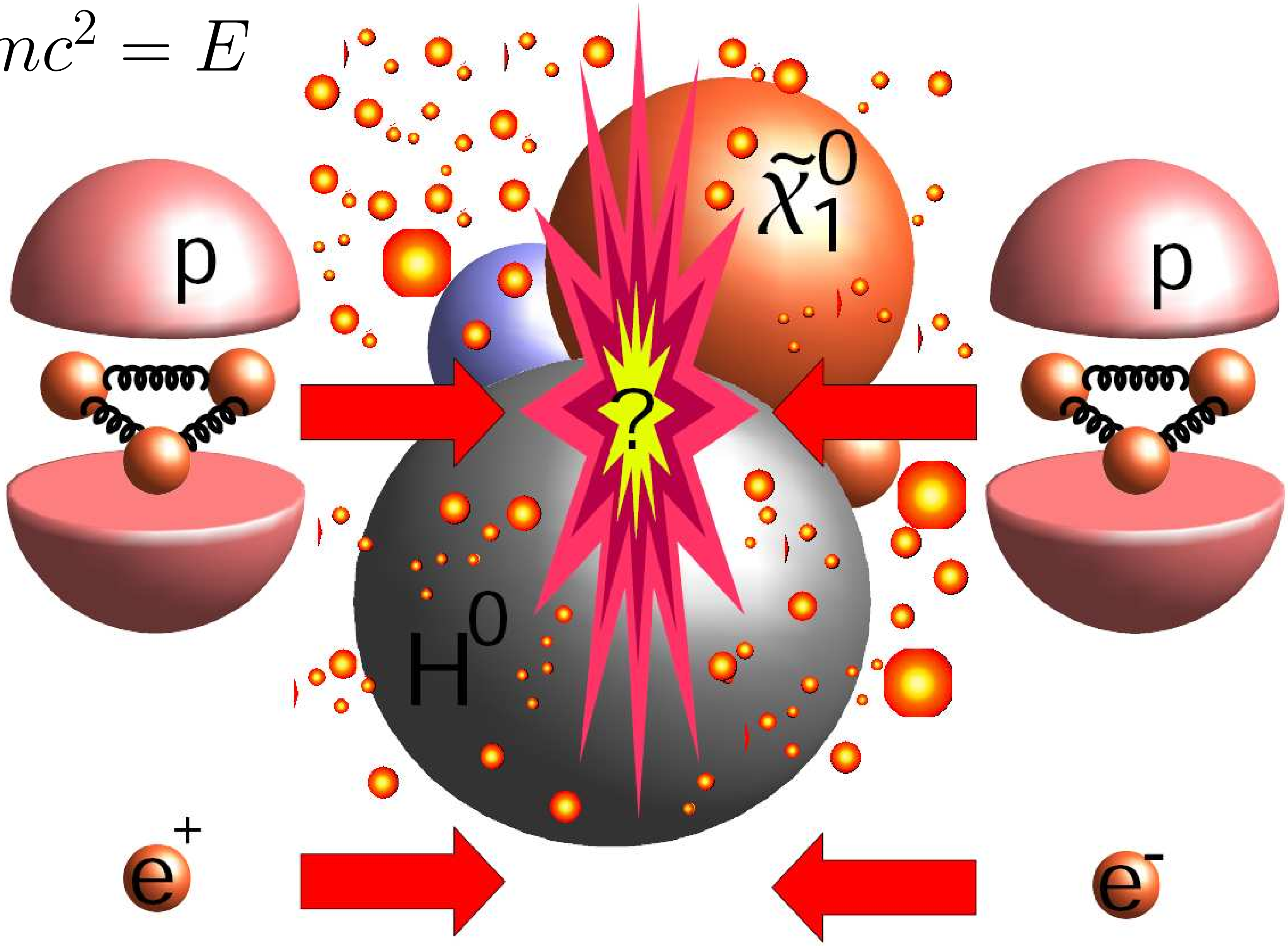
- Just around the corner in mass...



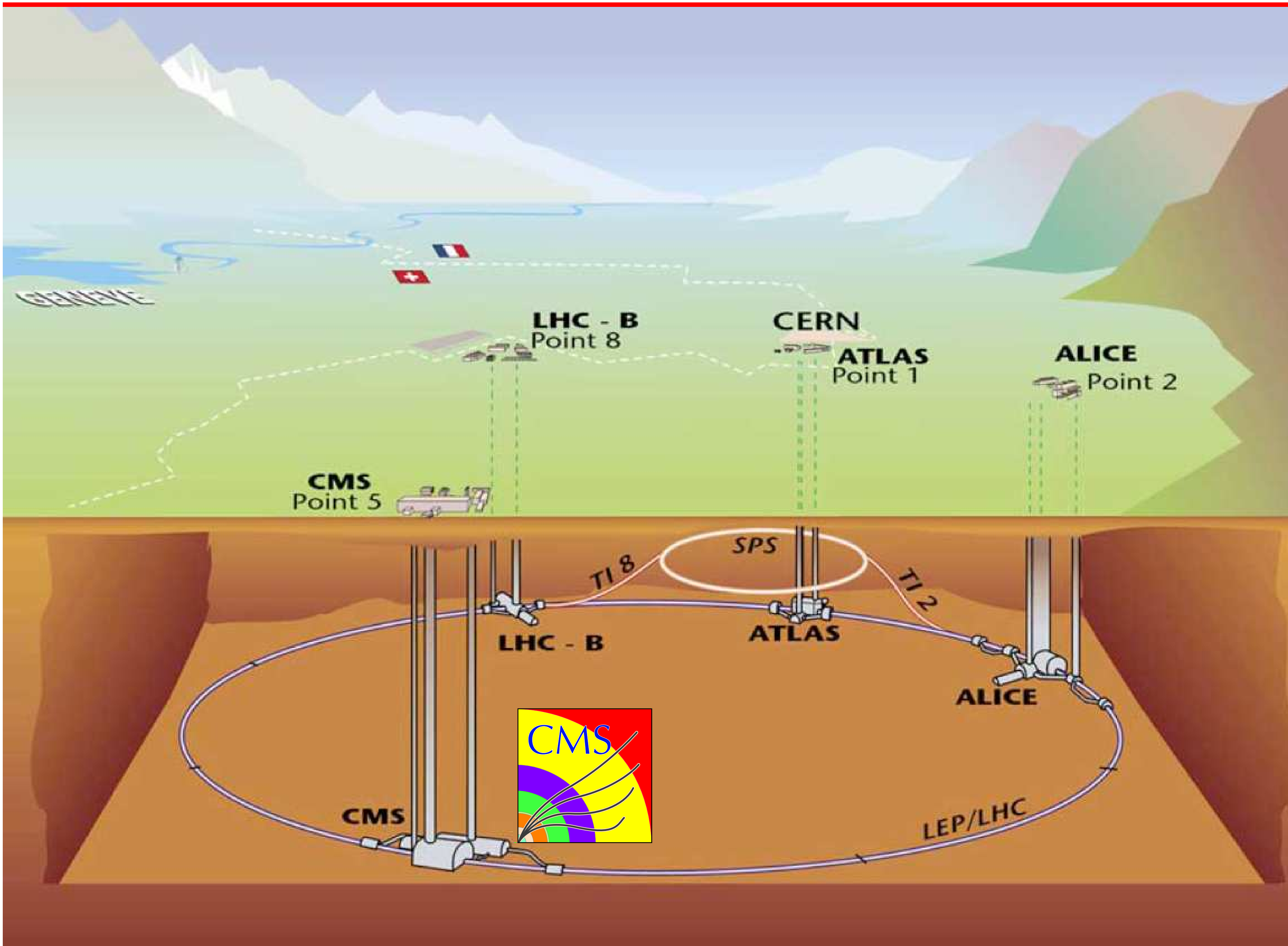
Particle Physics
How to Reach Beyond

Reaching Highest Energy

- $mc^2 = E$



Large Hadron Collider: 2008

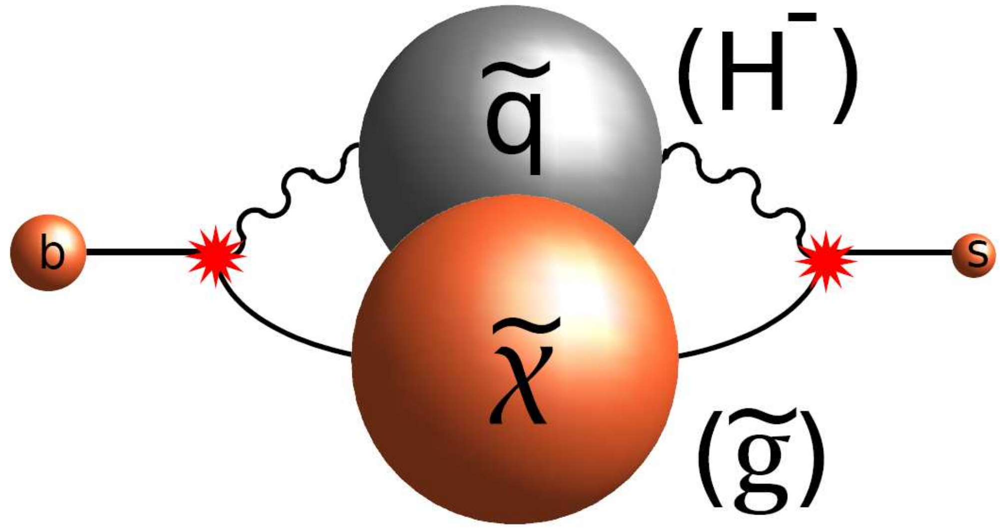


The Uncertainty Principle

- "Heavy" objects for a short instant Δt:

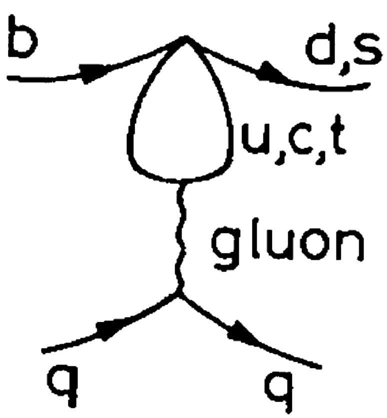
$$\Delta E \times \Delta t \sim \hbar$$

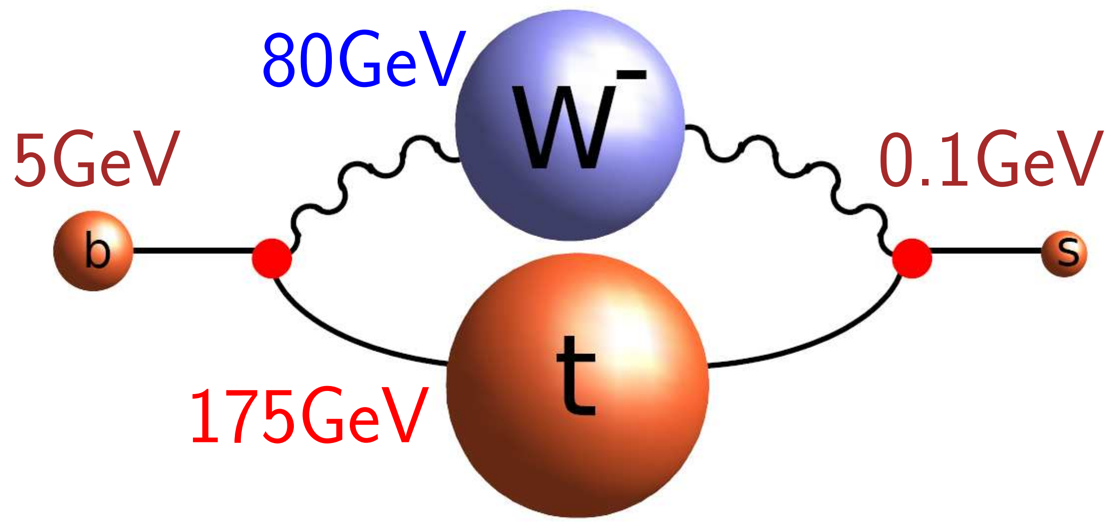
get $\tilde{m}c^2 \sim \Delta E \sim$500GeV



- Possible:

"penguin" loop

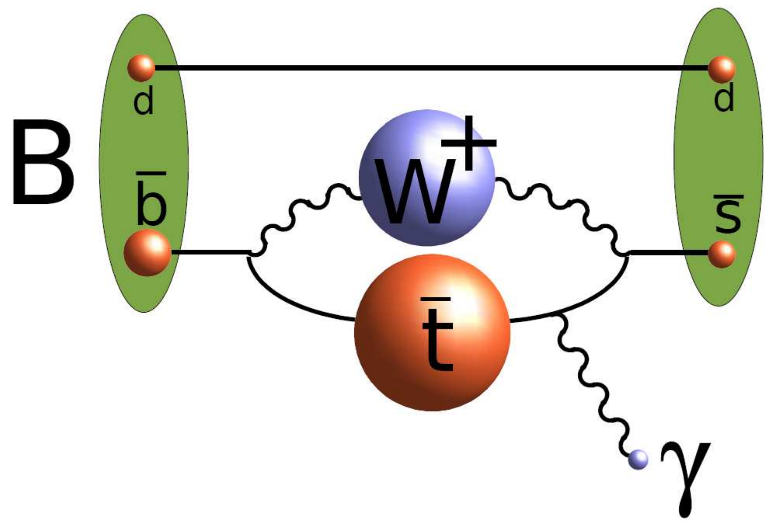




Observation of "Penguins"

- 1975: importance of "penguin", observation on CLEO-II:

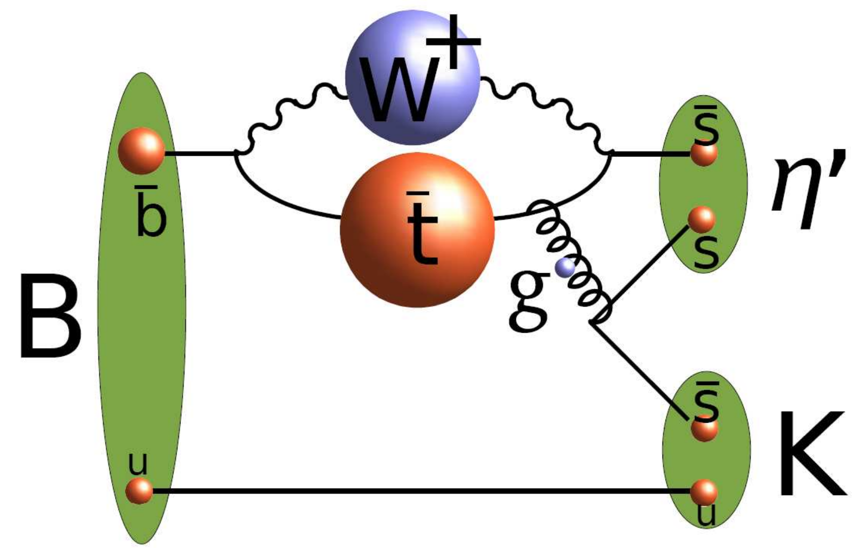
1993: EM "penguin"



- rate $\sim 3.5 \times 10^{-4}$

  best New Physics limits

1997: gluonic "penguin"



- harder due to gluons

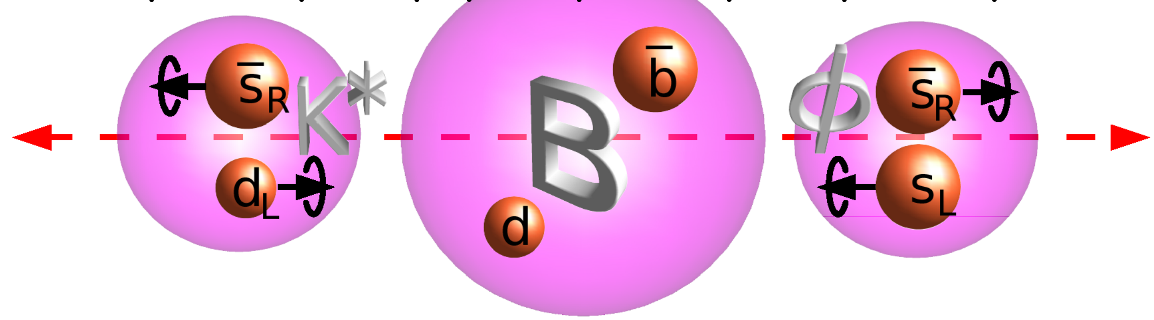
  fun Ph.D. discovery

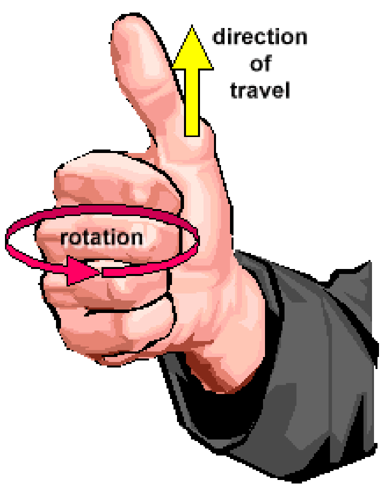
- "Physics Book:" measure size or phase of $A = |A| \times e^{i\phi}$

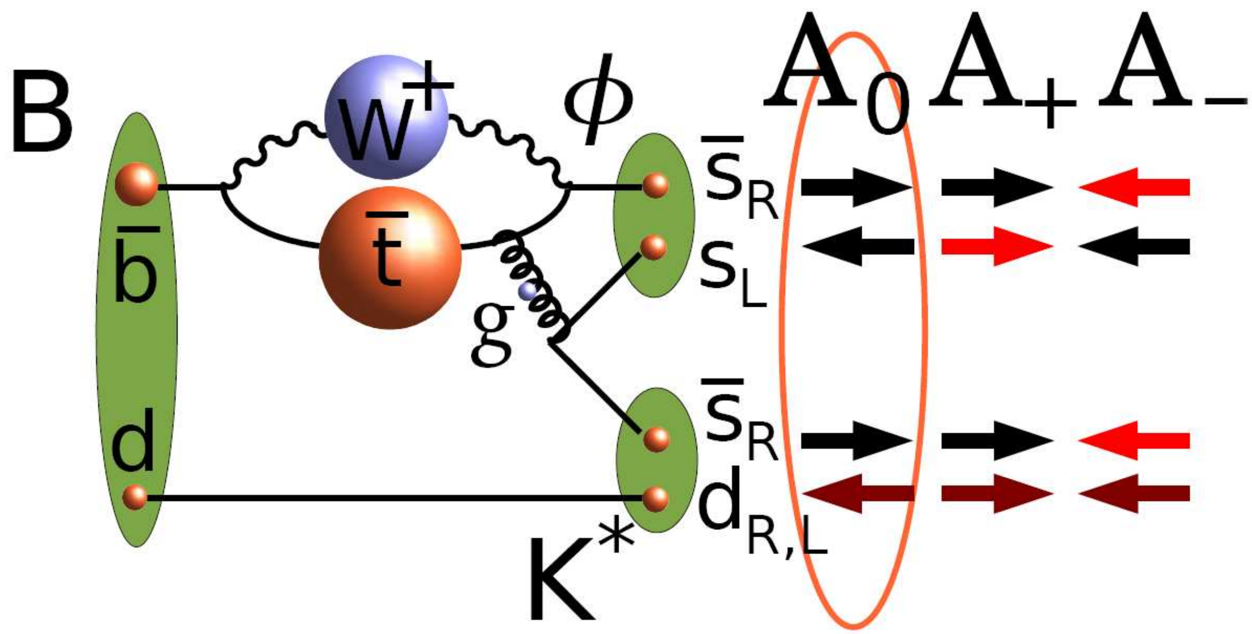
New Test: Polarization

- new "penguin" $B \to \phi K^*$ with vector mesons

$$|S, S_z\rangle = \quad |1,0\rangle \quad |i\rangle = |0,0\rangle \quad |1,0\rangle \quad \Rightarrow A_0$$





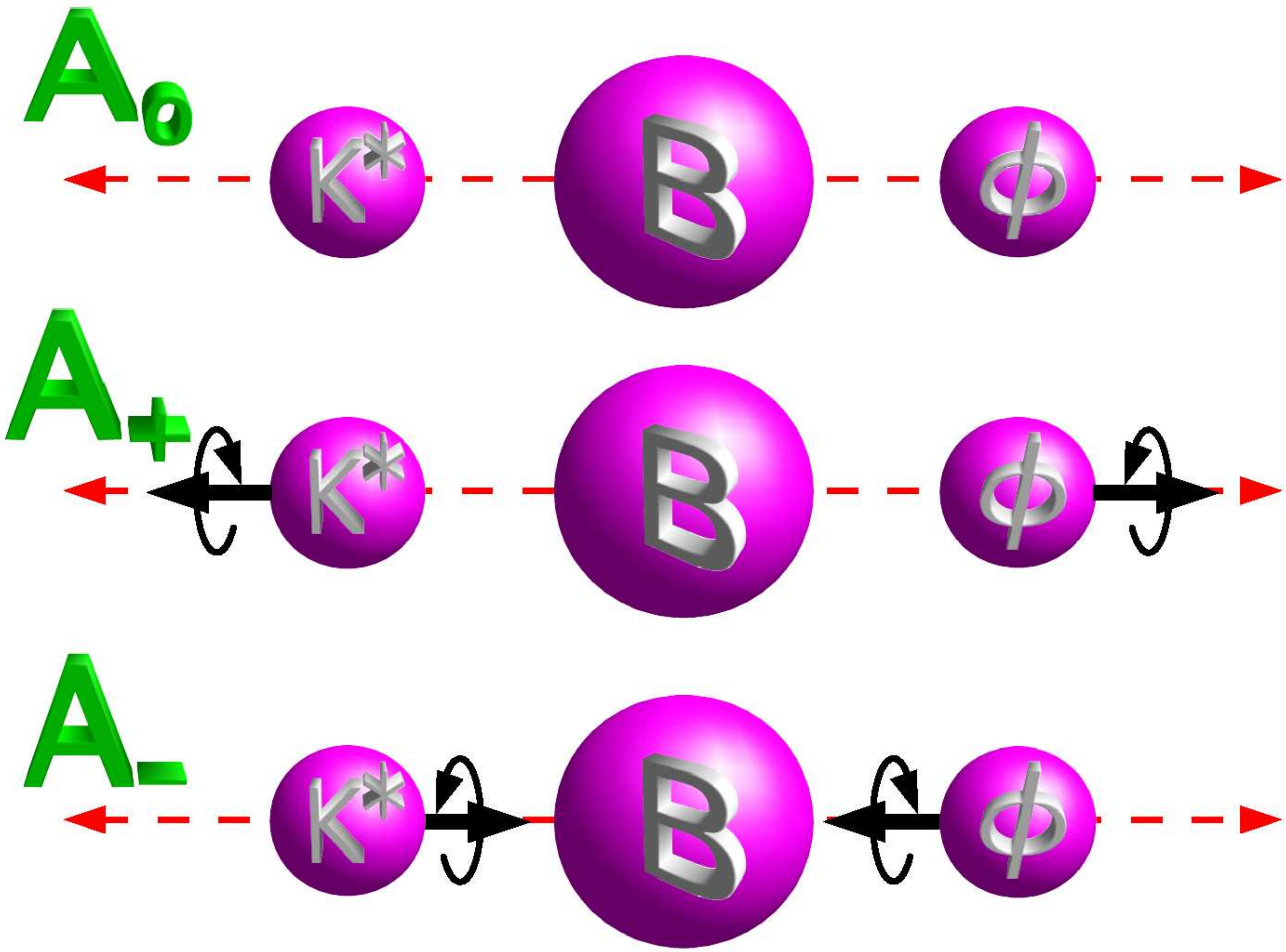


$|A_0|^2 \gg |A_+|^2 \gg |A_-|^2$ suppression $\sim (m_\phi/m_B)^2 \sim 1/25$

Polarization Experiment

- Goal: (1) find $B \to \phi K^*$, (2) find spin projections

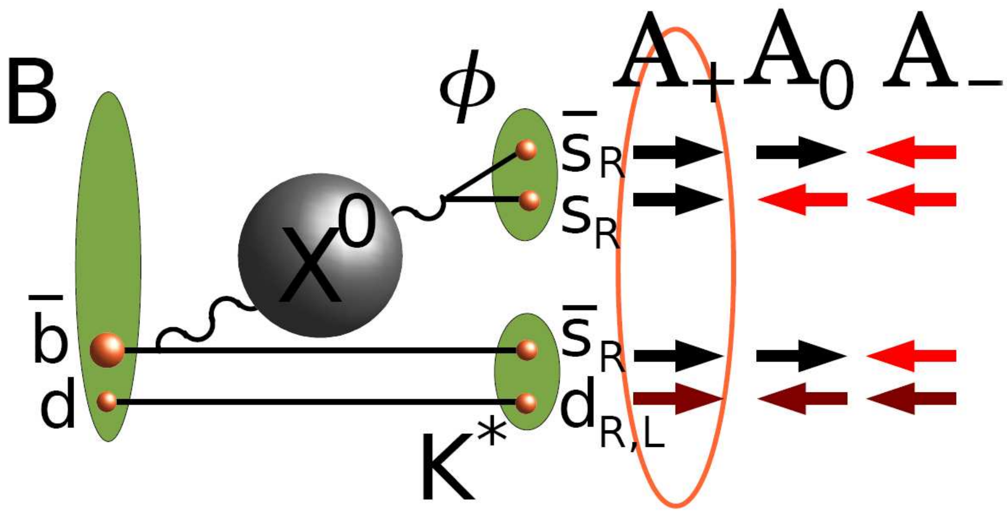
expected probability $\propto$ $|A_0|^2 \gg |A_+|^2 \gg |A_-|^2$



New Physics in Polarization

violate $|A_0|^2 \gg |A_+|^2 \gg |A_-|^2$

scalar interaction

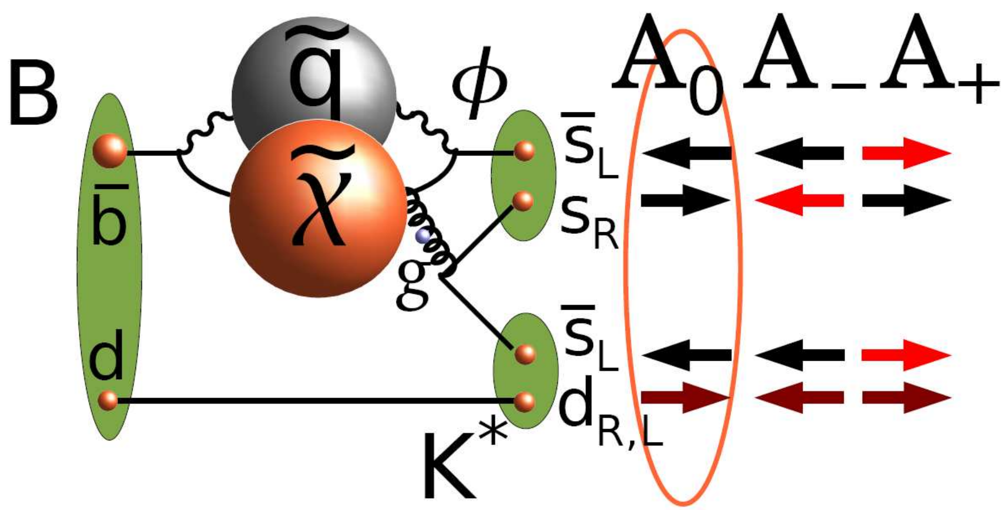


$\bar{q}\gamma^\mu(1-\gamma^5)q$

$|A_+|^2 \gg |A_0|^2 \gg |A_-|^2$

$\bar{q}(1+\gamma^5)q$

supersymmetry



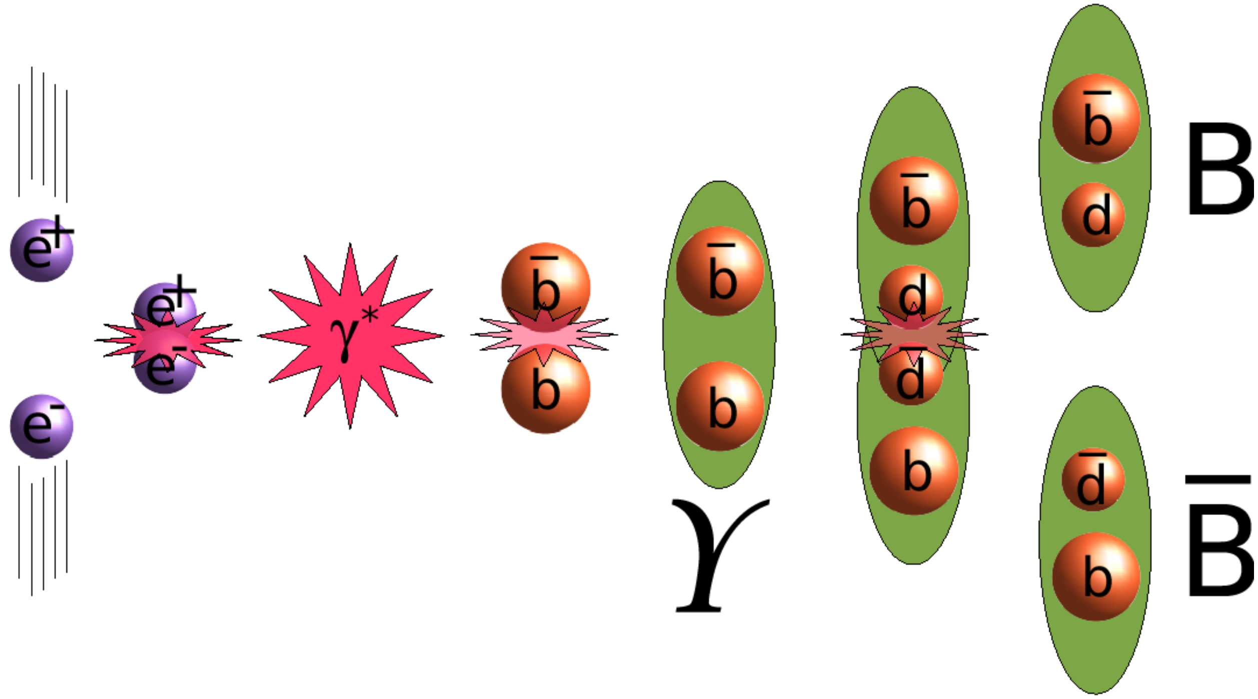
$|A_0|^2 \gg |A_-|^2 \gg |A_+|^2$

$\bar{q}\gamma^\mu(1+\gamma^5)q$

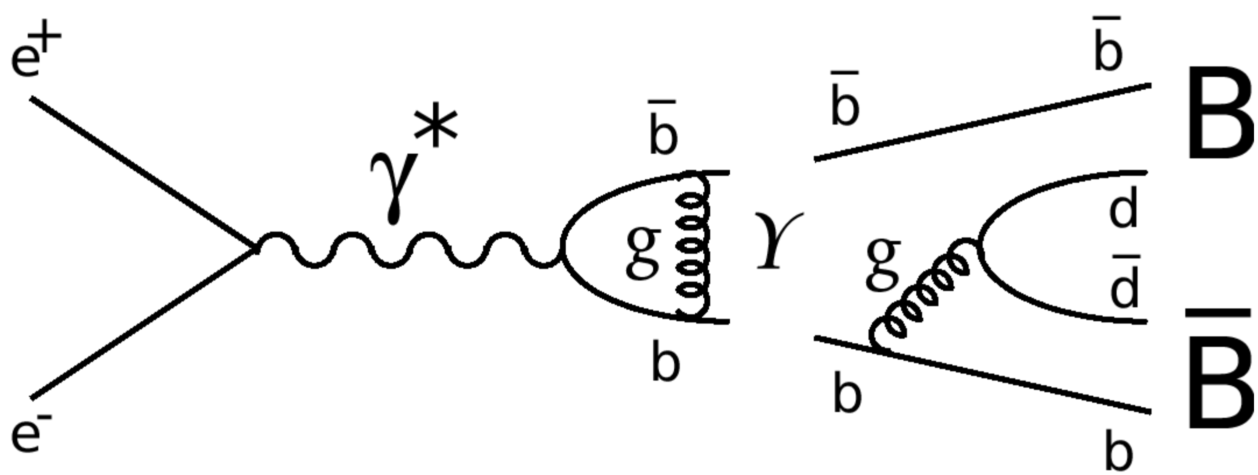
Particle Physics Laboratory

Producing the B Mesons

- Kinematics:



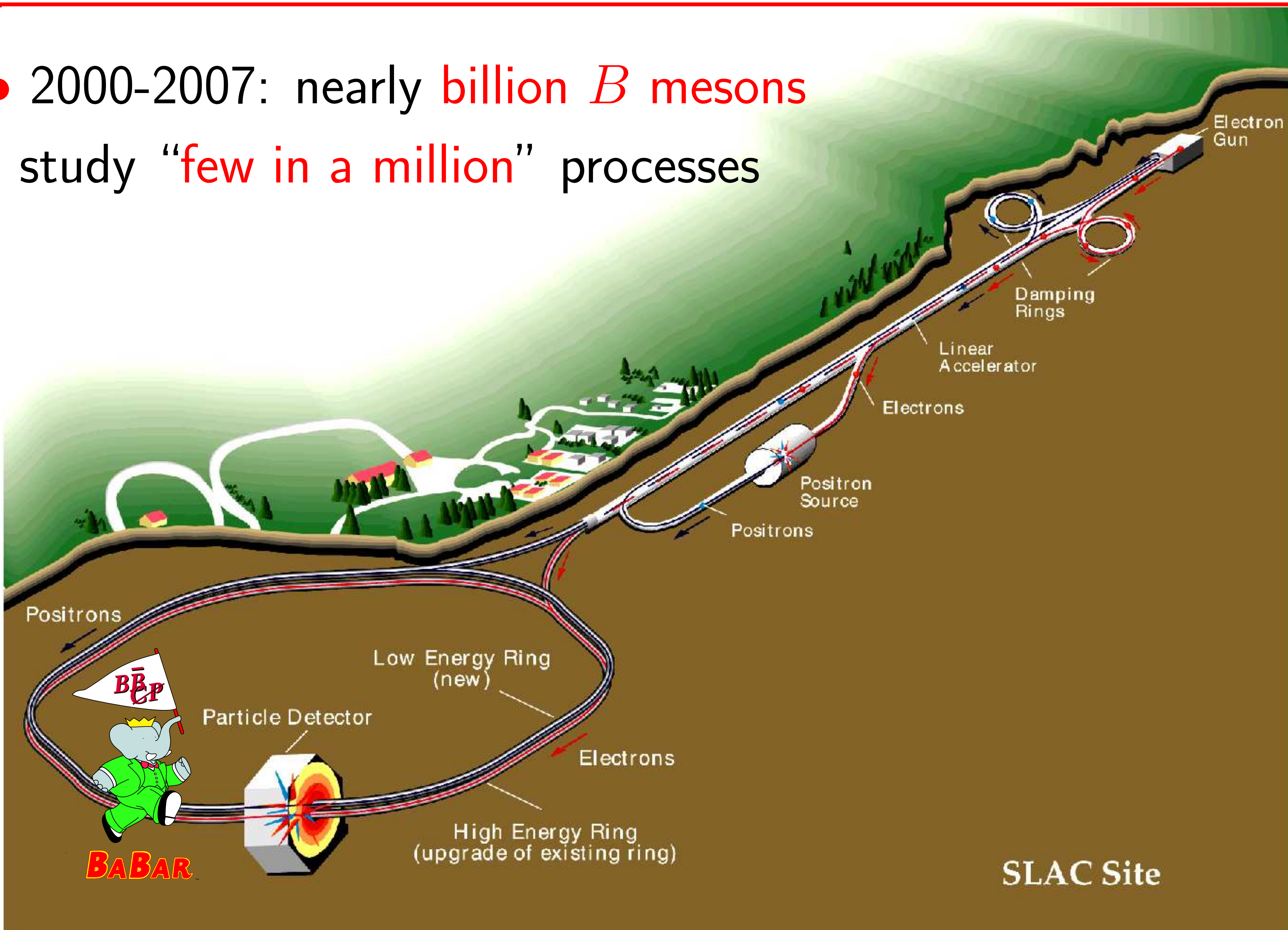
- Dynamics:



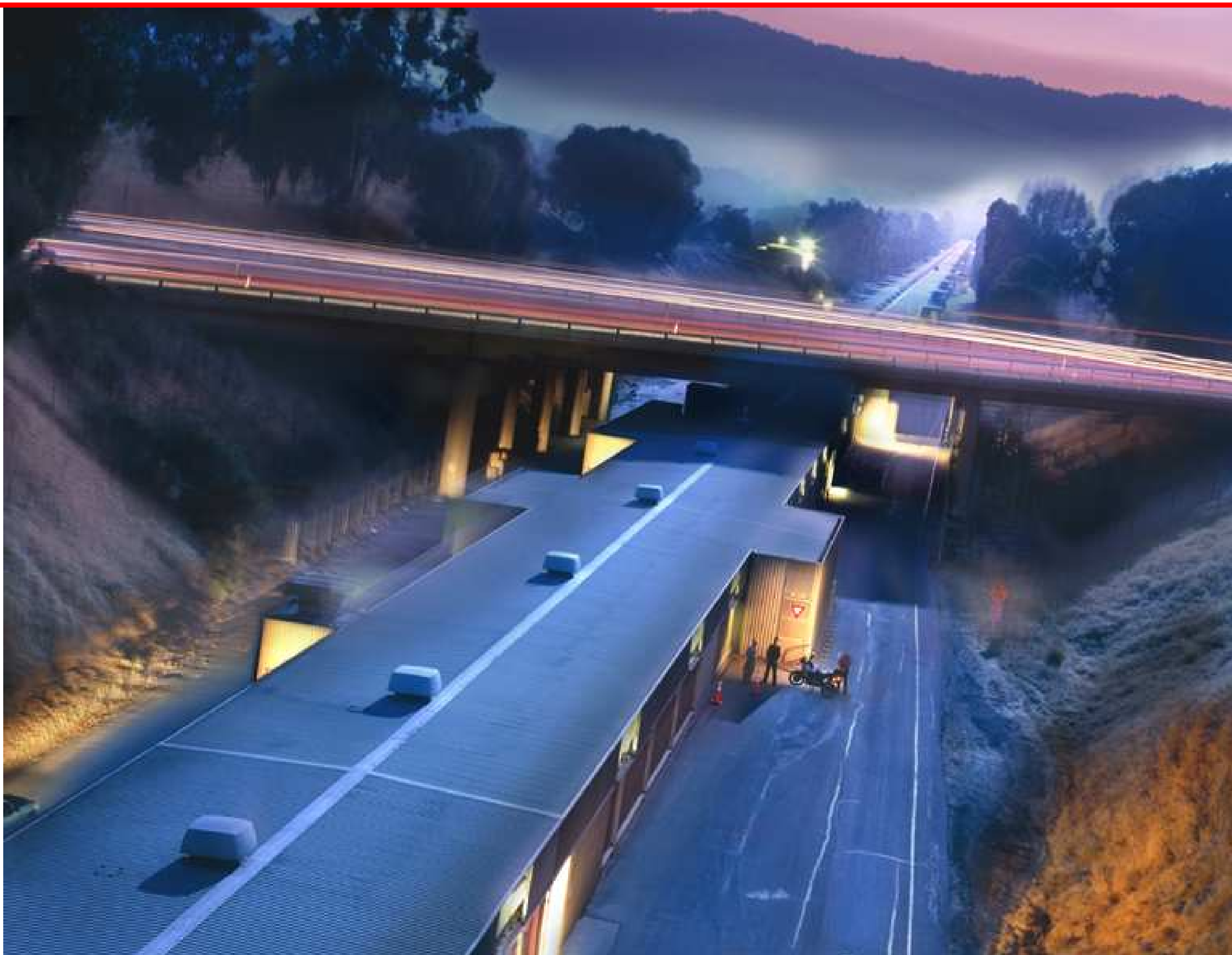
Producing the B Mesons

- 2000-2007: nearly billion B mesons

  study "few in a million" processes



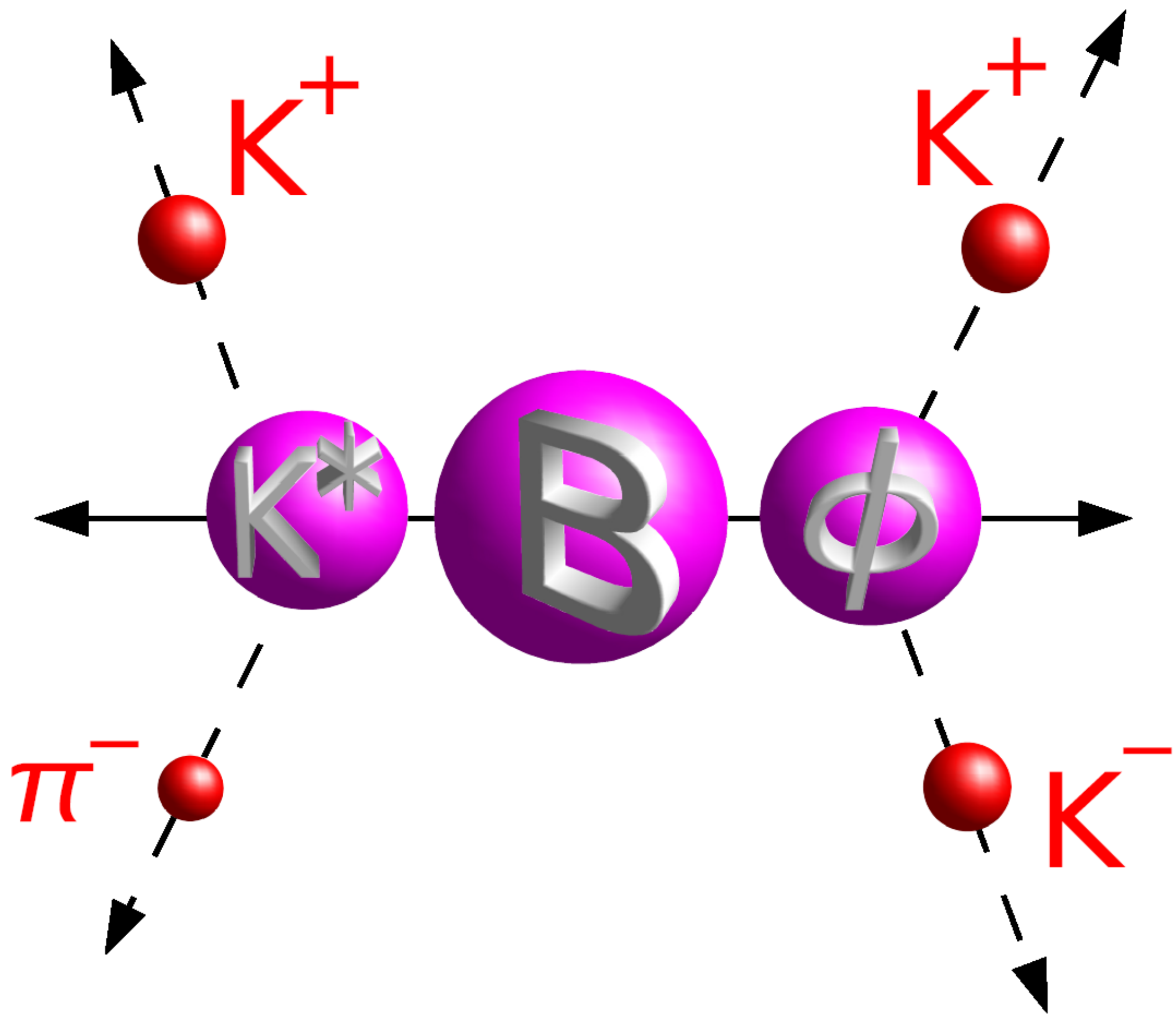
Producing the B Mesons



Kinematics of the Decay

- Find 4 "tracks": find $\sim$ 1-2/week

  $B^0 \to \phi K^{*0} \to (K^+K^-)(K^+\pi^-)$ rare $<$ 1 in 100,000

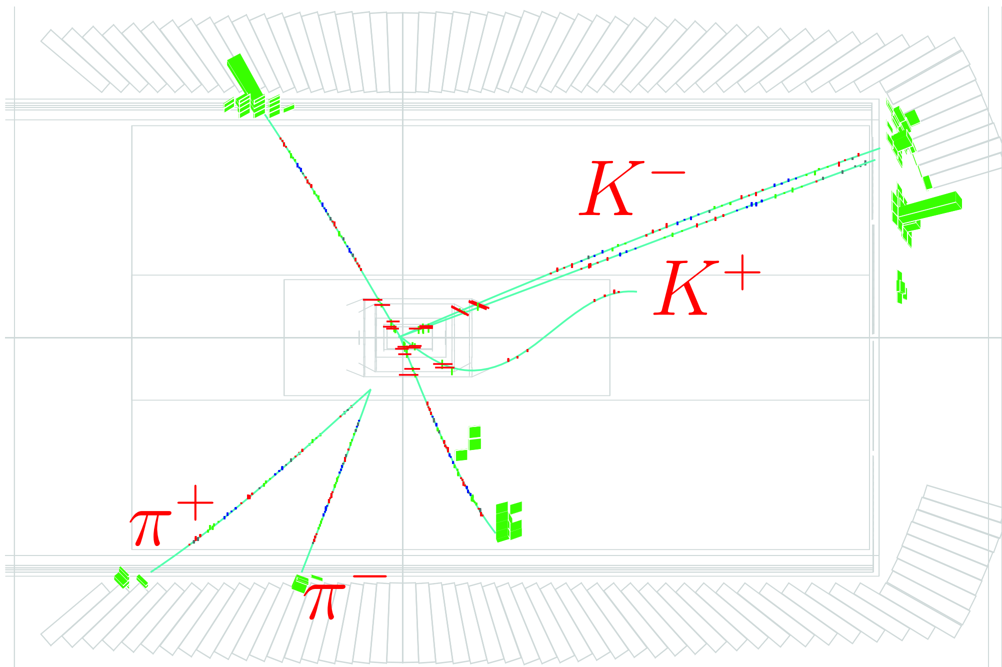


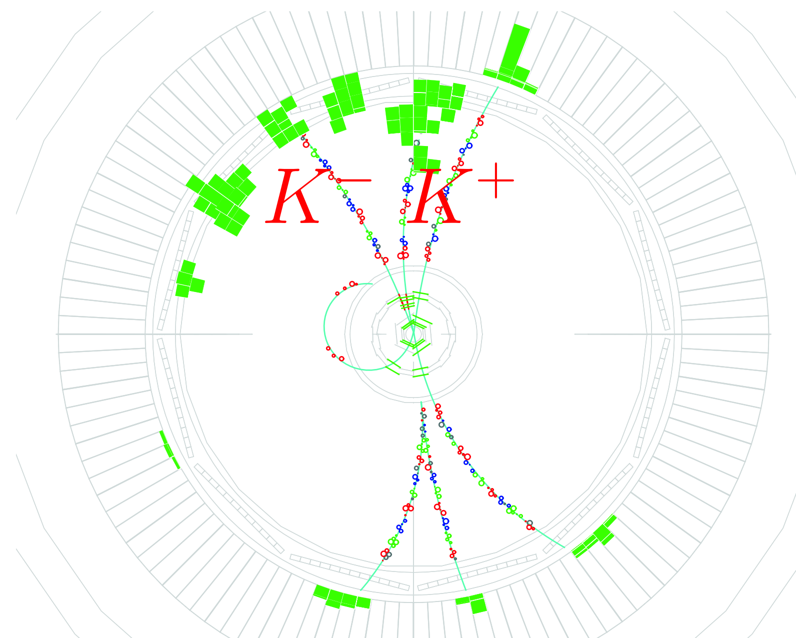
Reconstructing Kinematics in the Detector

- *BaBar* detector at SLAC:

$$B^0 \to \phi K^{*0} \to (K^+K^-)(K^+\pi^-)$$

$$B^0 \to \phi K^0 \to (K^+K^-)(\pi^+\pi^-)$$

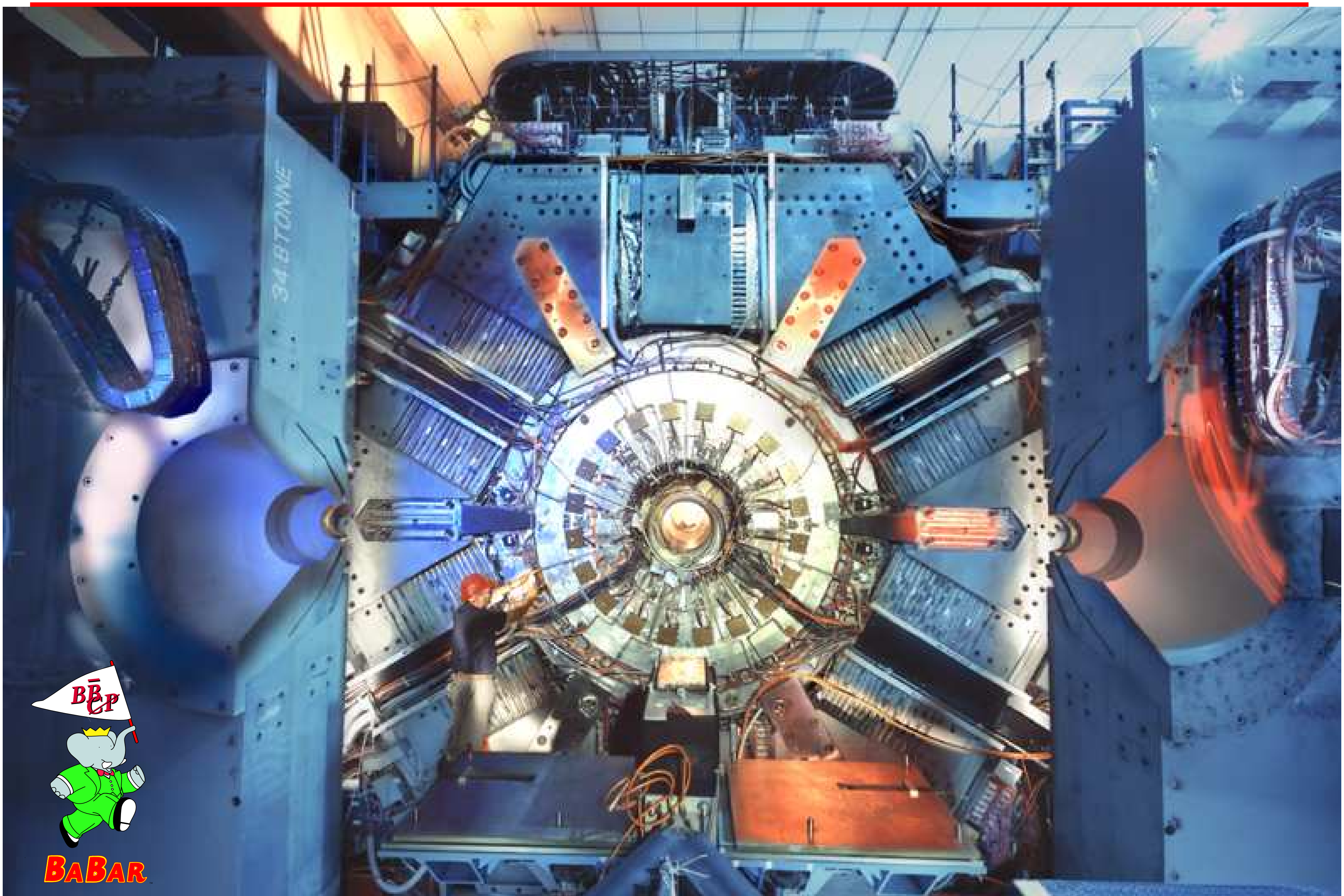




The Heart of the BABAR Detector

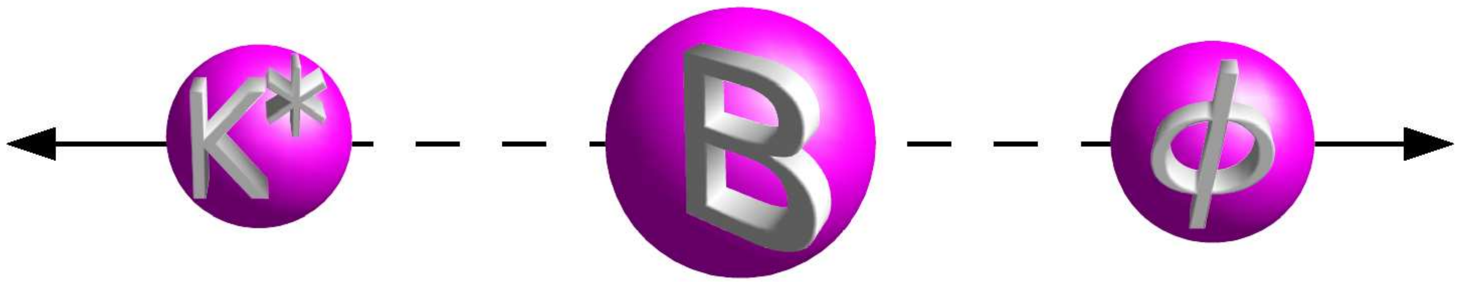
- Work on silicon detectors on BABAR and CMS

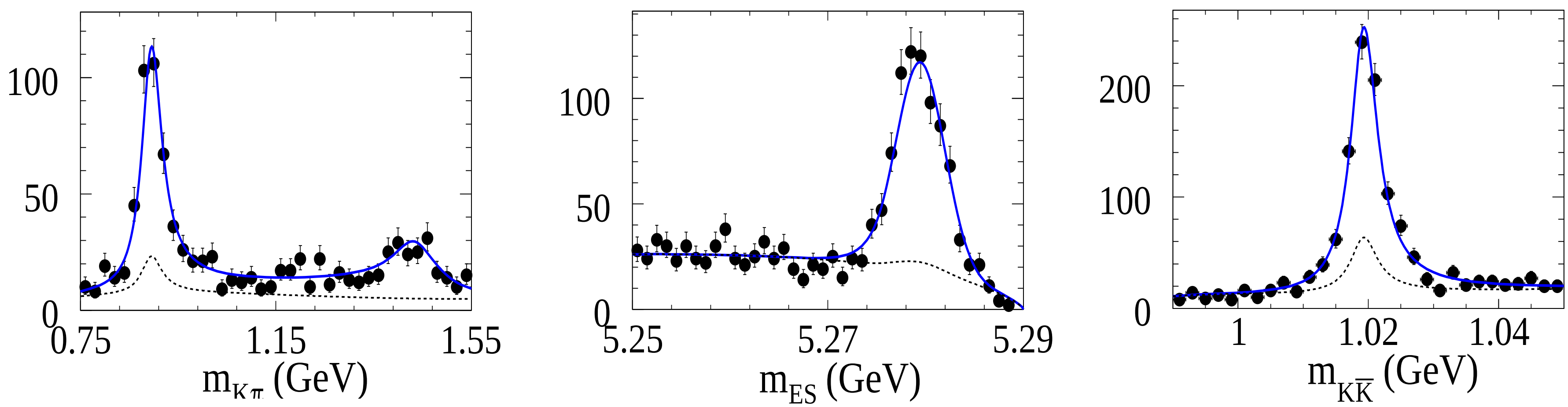
The *BaBar* Detector

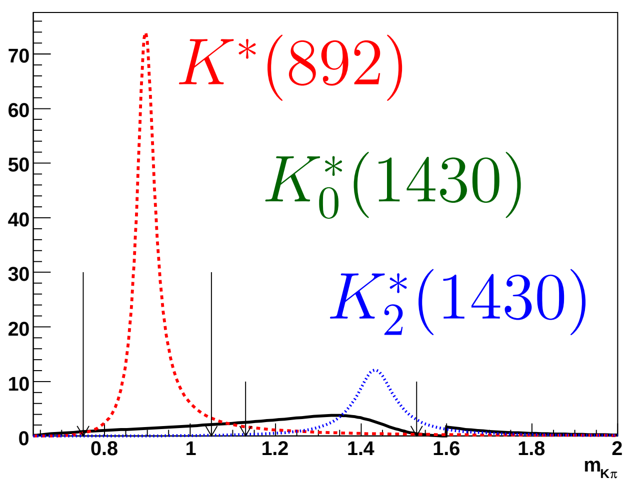


Polarization Experiment

Finding the Signal







406 ± 29 $\phi K^*(892)$ (spin 1)

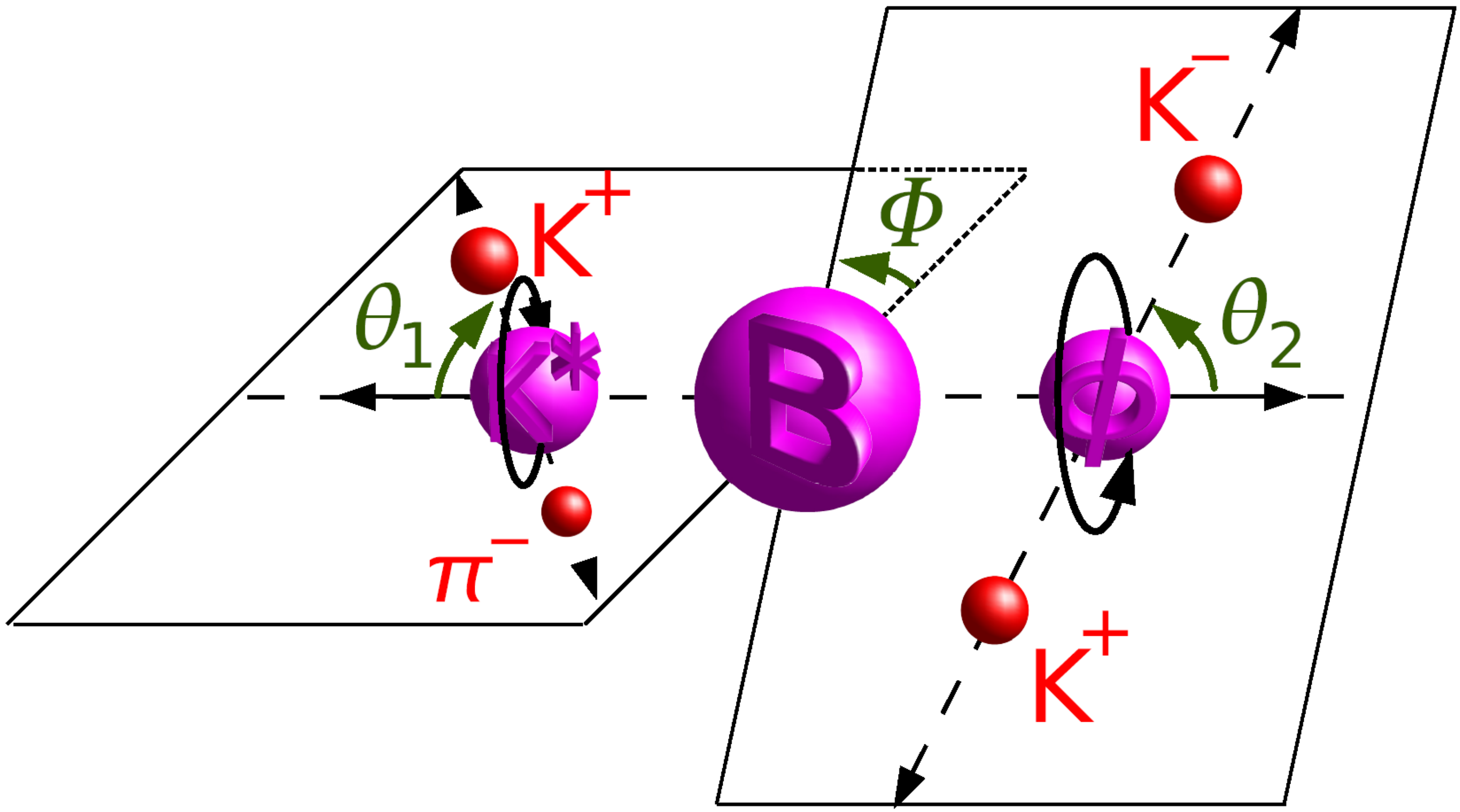
147 ± 23 $\phi K_0^*(1430)$ (spin 0)

133 ± 17 $\phi K_2^*(1430)$ (spin 2)

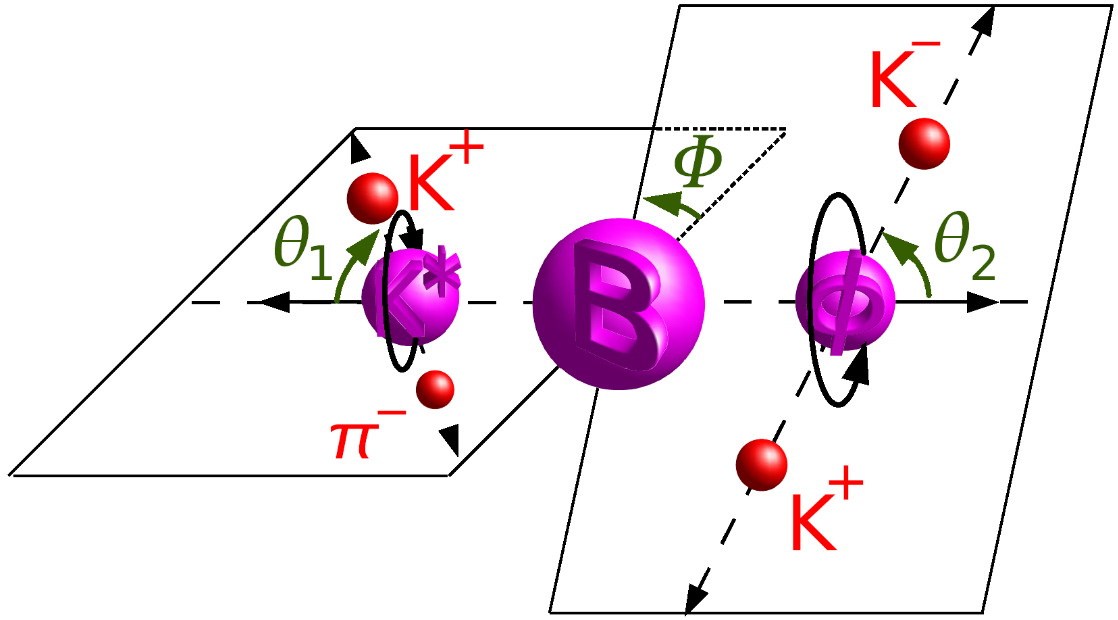
rate $\sim 10^{-5}$ of all B decays

Polarization Analysis

- Angular correlations $\Rightarrow$ spin projection



Angular Measurements



$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto \left| \sum_{\lambda=-1,0,+1} A_\lambda \times Y_{J_1}^{\lambda}(\theta_1,\Phi) \times Y_{J_2}^{-\lambda}(\pi-\theta_2,0) \right|^2$$

transverse — longitudinal

$$\propto \Big\{ \frac{1}{4} \sin^2\theta_1 \sin^2\theta_2 \left(|A_{+1}|^2 + |A_{-1}|^2\right) + \cos^2\theta_1 \cos^2\theta_2 |A_0|^2$$

$$+\frac{1}{2}\sin^2\theta_1\sin^2\theta_2\left[\cos 2\Phi\ \mathrm{Re}(A_{+1}A^*_{-1}) - \sin 2\Phi\ \mathrm{Im}(A_{+1}A^*_{-1})\right]$$

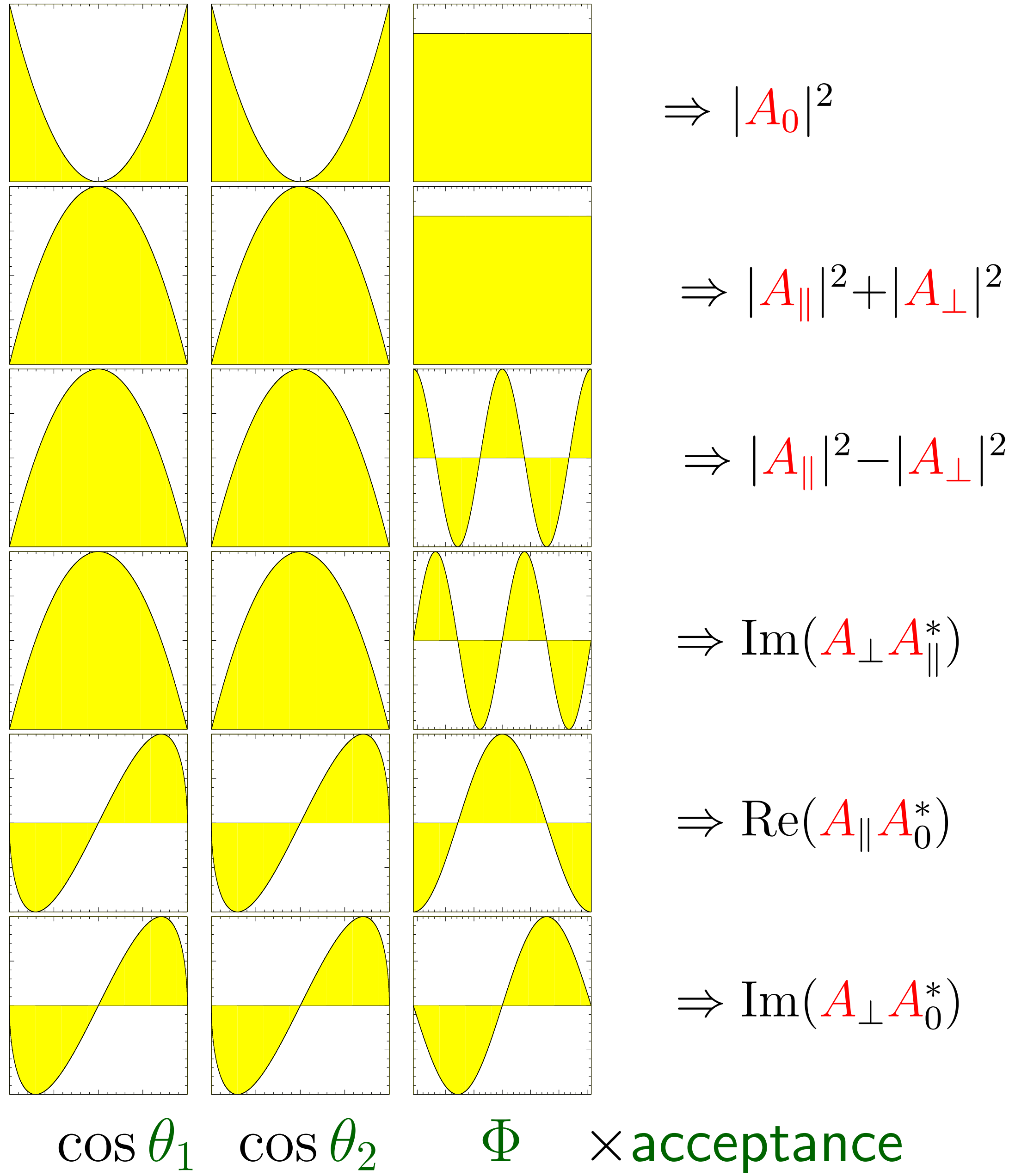
$$+\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 \left[\cos\Phi\ \mathrm{Re}\left(A_{+1}A_0^* + A_{-1}A_0^*\right) - \sin\Phi\ \mathrm{Im}\left(A_{+1}A_0^* - A_{-1}A_0^*\right)\right] \Big\}$$

Angular Distribution in Slices

- Expected only $|A_0|^2$

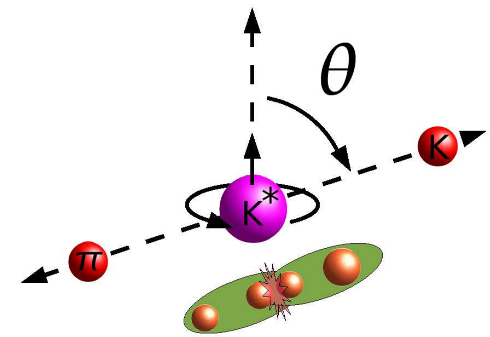
- Polarization basis (like photon)

$A_{\parallel,\perp} = (A_+ \pm A_-)/\sqrt{2}$

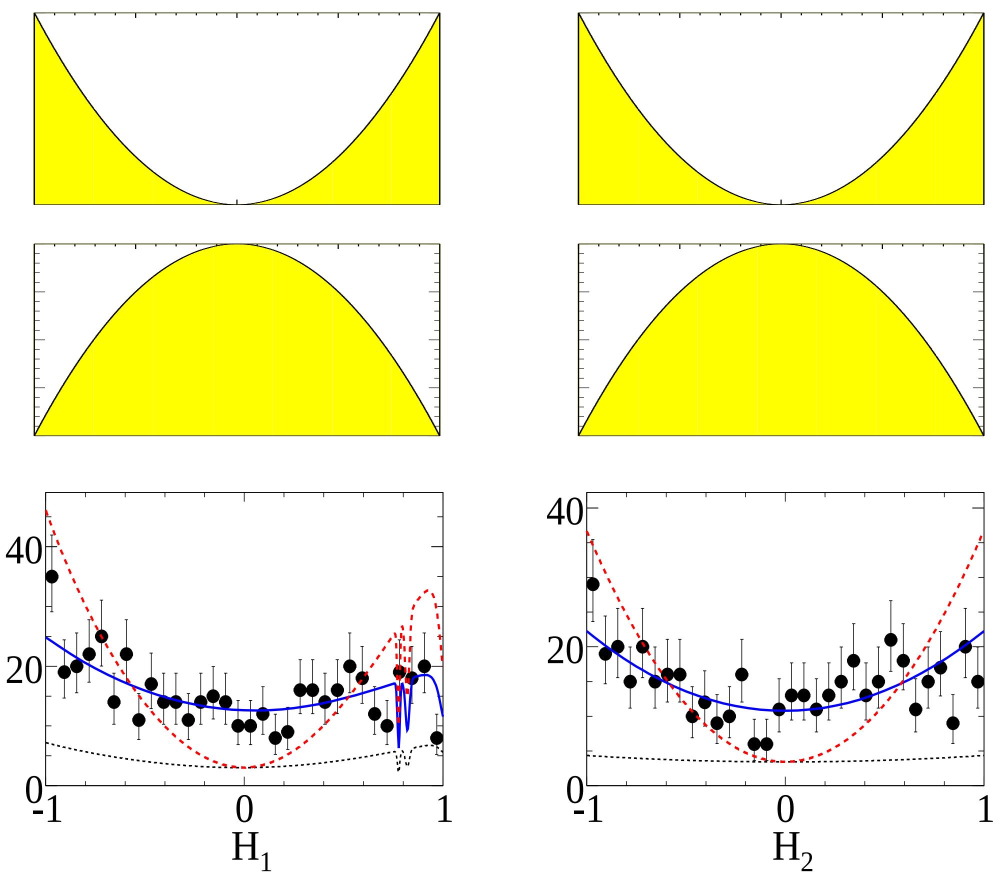


The Result: Polarization Anomaly

- With two angles:



$\cos\theta_1 \; (K^*)$ $\qquad$ $\cos\theta_2 \; (\phi)$



$|A_0|^2 \qquad \times |Y_1^0(\theta)|^2$

$|A_+|^2 + |A_-|^2 \quad \times |Y_1^{\pm 1}(\theta)|^2$

$\Rightarrow |A_0|^2 \simeq |A_+|^2 + |A_-|^2$

- Polarization anomaly:

$$|A_0|^2/(|A_+|^2 + |A_-|^2 + |A_0|^2) = 0.506 \pm 0.040 \pm 0.015 \quad \neq 1$$

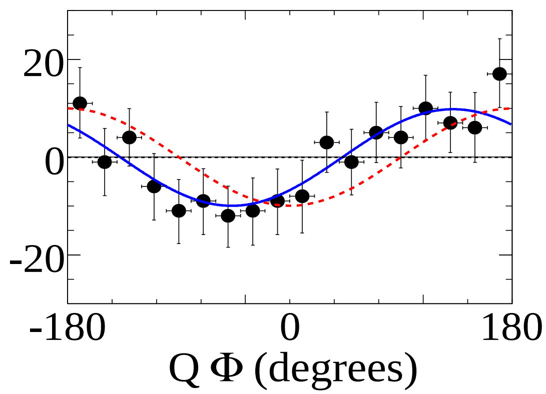
The Results

- Complex analysis with 12 independent results:

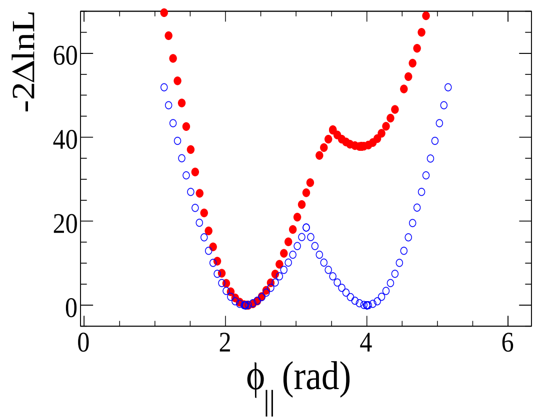
B (matter): $|A_0|, |A_+|, |A_-|, \arg(A_0), \arg(A_+), \arg(A_-)$

$\bar{B}$ (antimatter): $|\bar{A}_0|, |\bar{A}_+|, |\bar{A}_-|, \arg(\bar{A}_0), \arg(\bar{A}_+), \arg(\bar{A}_-)$

- Examples:



$\Rightarrow \arg(A_0) \neq \arg(A_\pm)$



$K^*(892)/K_0^*(1430)$ interference

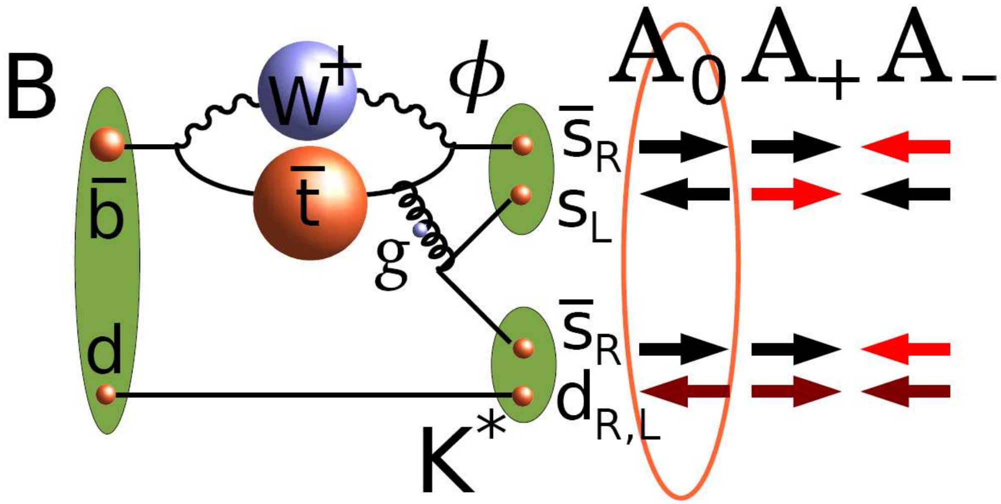
resolve $|A_+|^2 \gg |A_-|^2$

- Bottom line:

$$|A_0|^2 \simeq |A_+|^2 \gg |A_-|^2$$
$$\arg(A_0) \neq \arg(A_+)$$

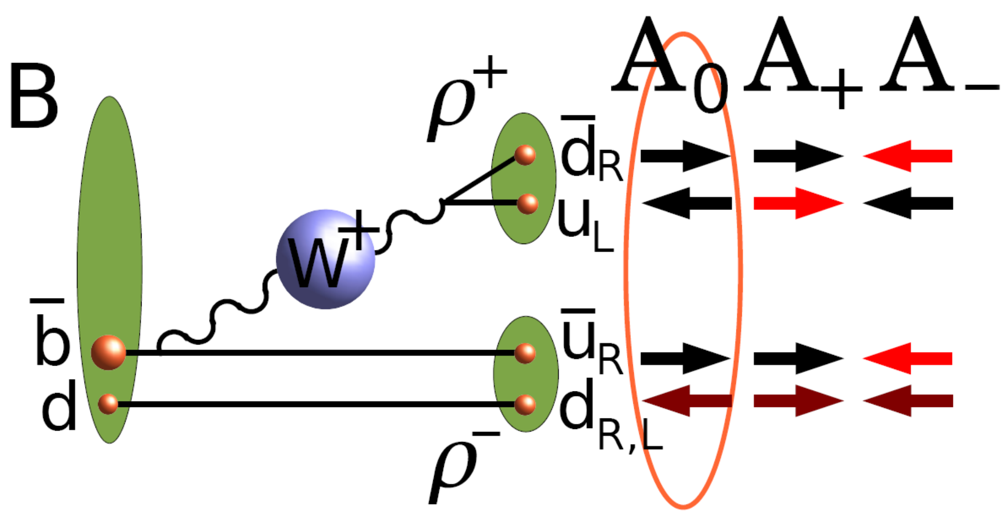
Spin Does Not Flip

- Observation $|A_0|^2 \simeq |A_+|^2 \gg |A_-|^2$ violates expectation



$|A_0|^2 \gg |A_+|^2 \gg |A_-|^2$

- It works: $B \to \rho^+\rho^-$ $|A_0|^2/(|A_+|^2 + |A_-|^2 + |A_0|^2) = 0.968 \pm 0.023$

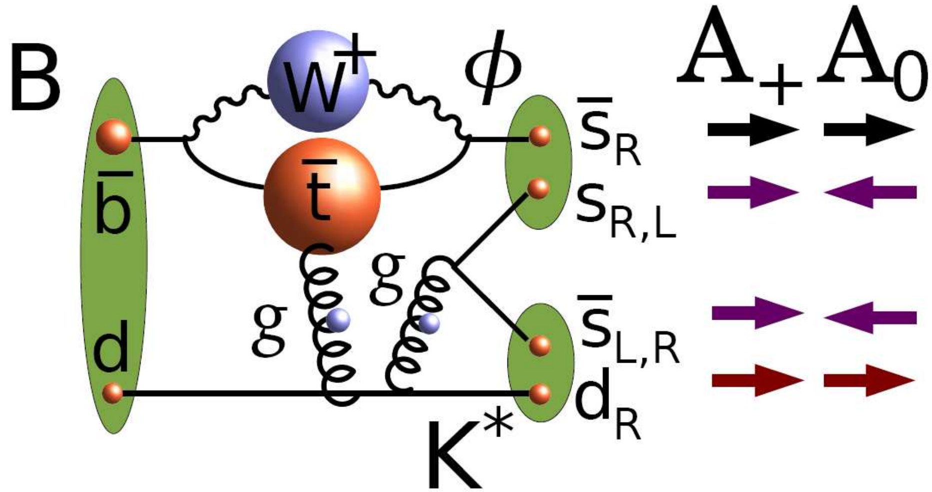


no loop contribution

ideal for CP studies in SM
(seminar last December)

Scrambling to Explain A_+

- "Annihilation" mechanism

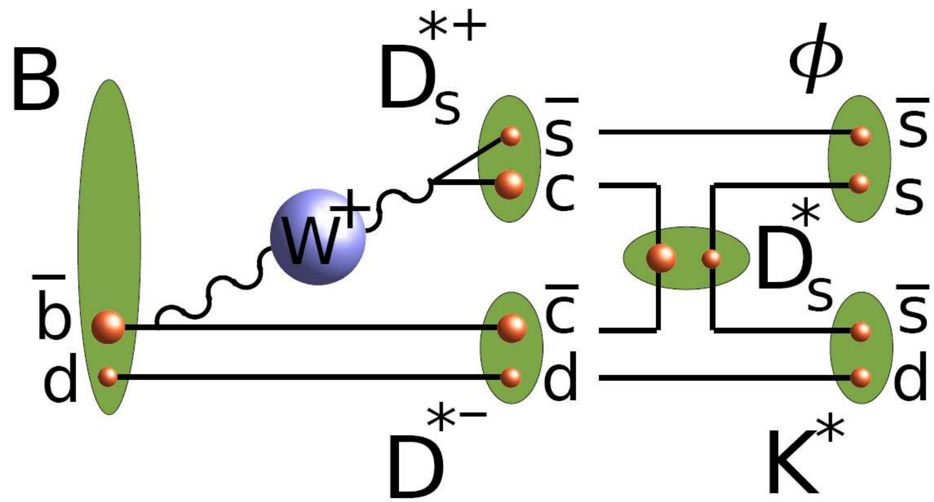


gluon to other quark

unlikely $\sim 1/m_B$

need to cancel A_0

- "Rescattering" mechanism (final state interaction)



spin-flip heavy > 2GeV states

violates both $|A_0|^2 \gg |A_\pm|^2$ and $|A_+|^2 \gg |A_-|^2$

- No satisfactory solution

Try Different Spin of K^*

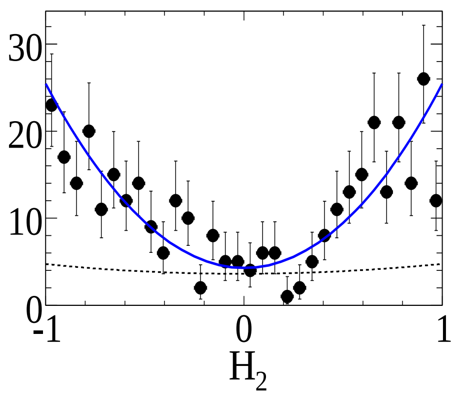
- $B^0 \to \phi K_2^*(1430)^0$ (spin-2)
  - would also expect "annihilation" or "rescattering"
- No anomaly:

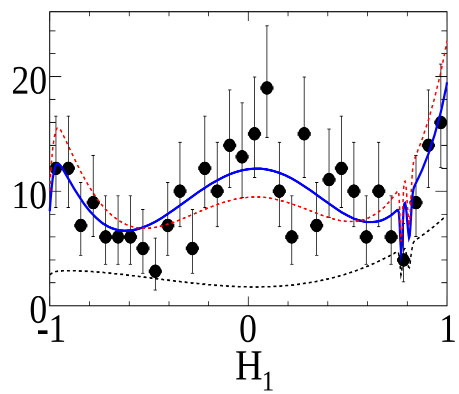
$$|A_0|^2/(|A_+|^2 + |A_-|^2 + |A_0|^2) = 0.853^{+0.061}_{-0.069} \pm 0.036 \gg 0.5$$

- Angular distribution:

$$|Y_1^{\lambda=\pm 1}(\theta_2, 0)|^2 \quad |Y_2^{\lambda=\pm 1}(\theta_1, \Phi)|^2 \quad \Rightarrow |A_+|^2 + |A_-|^2$$

$$|Y_1^{\lambda=0}(\theta_2, 0)|^2 \quad |Y_2^{\lambda=0}(\theta_1, \Phi)|^2 \quad \Rightarrow |A_0|^2$$

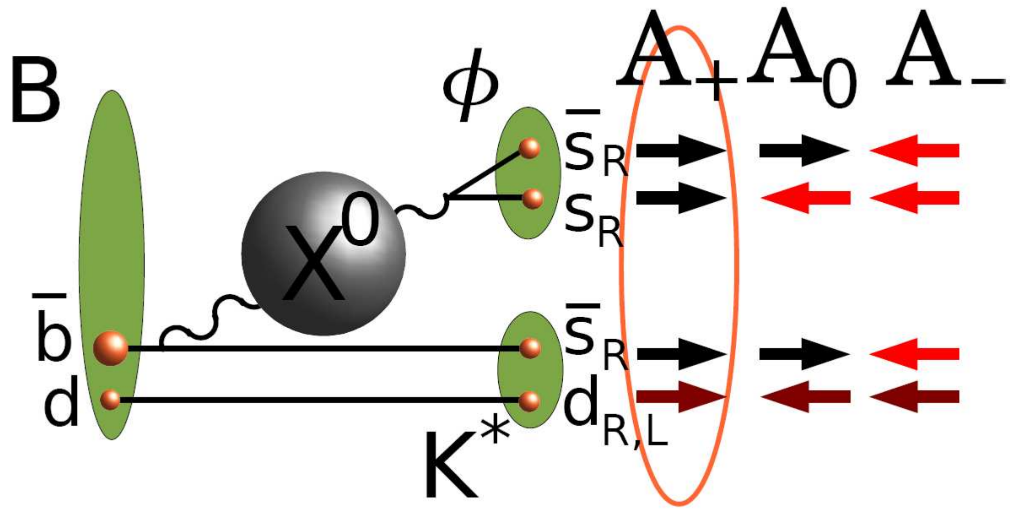




$$\Rightarrow |A_0|^2 \gg |A_+|^2 + |A_-|^2$$

Intriguing Possibility of New Physics

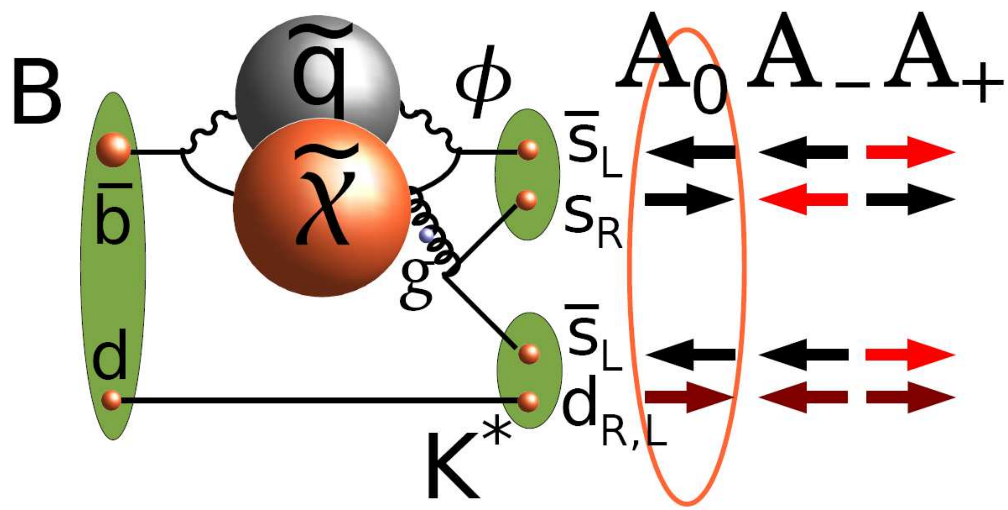
scalar (or tensor) interaction



ideal origin of A_+

exotic $\bar{q}(1+\gamma^5)q$

supersymmetry



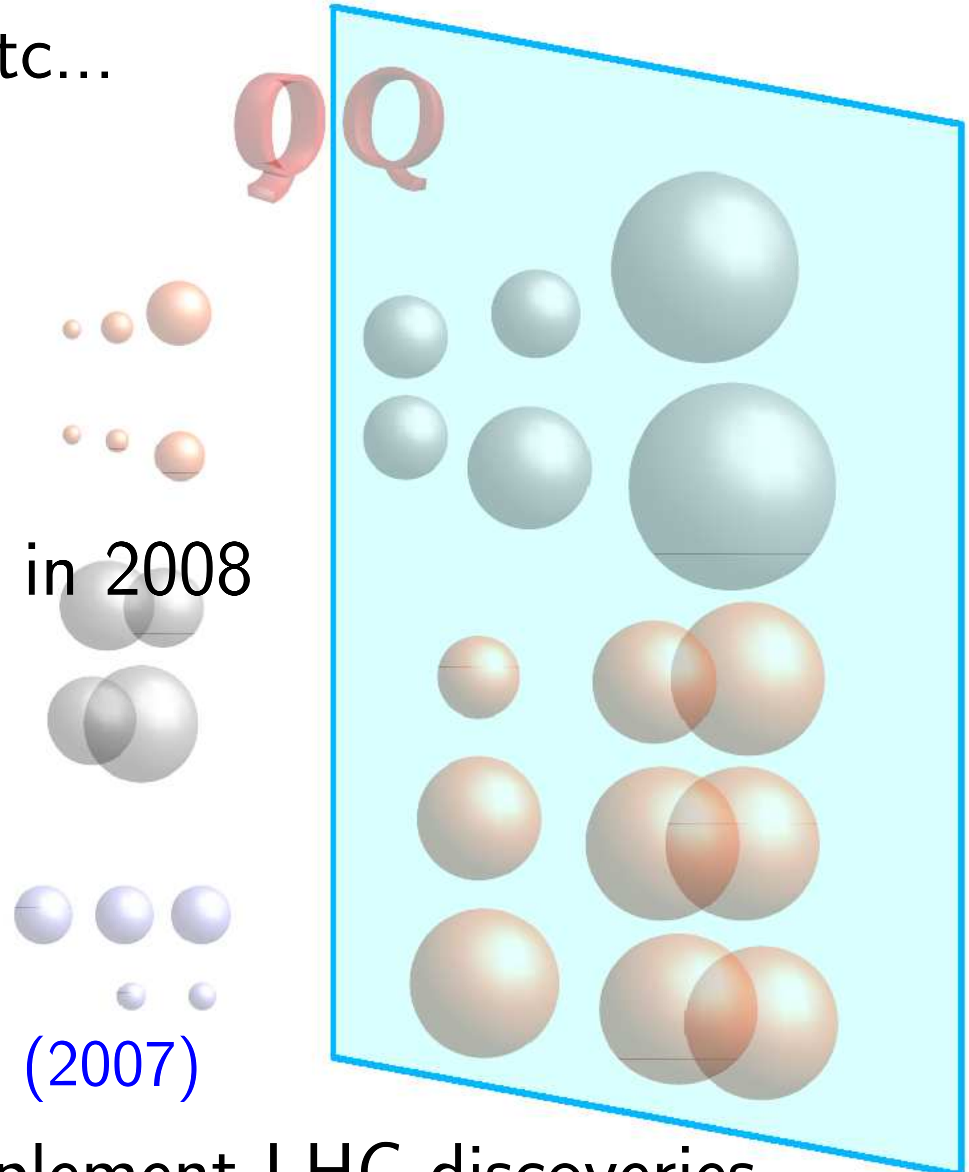
less ideal

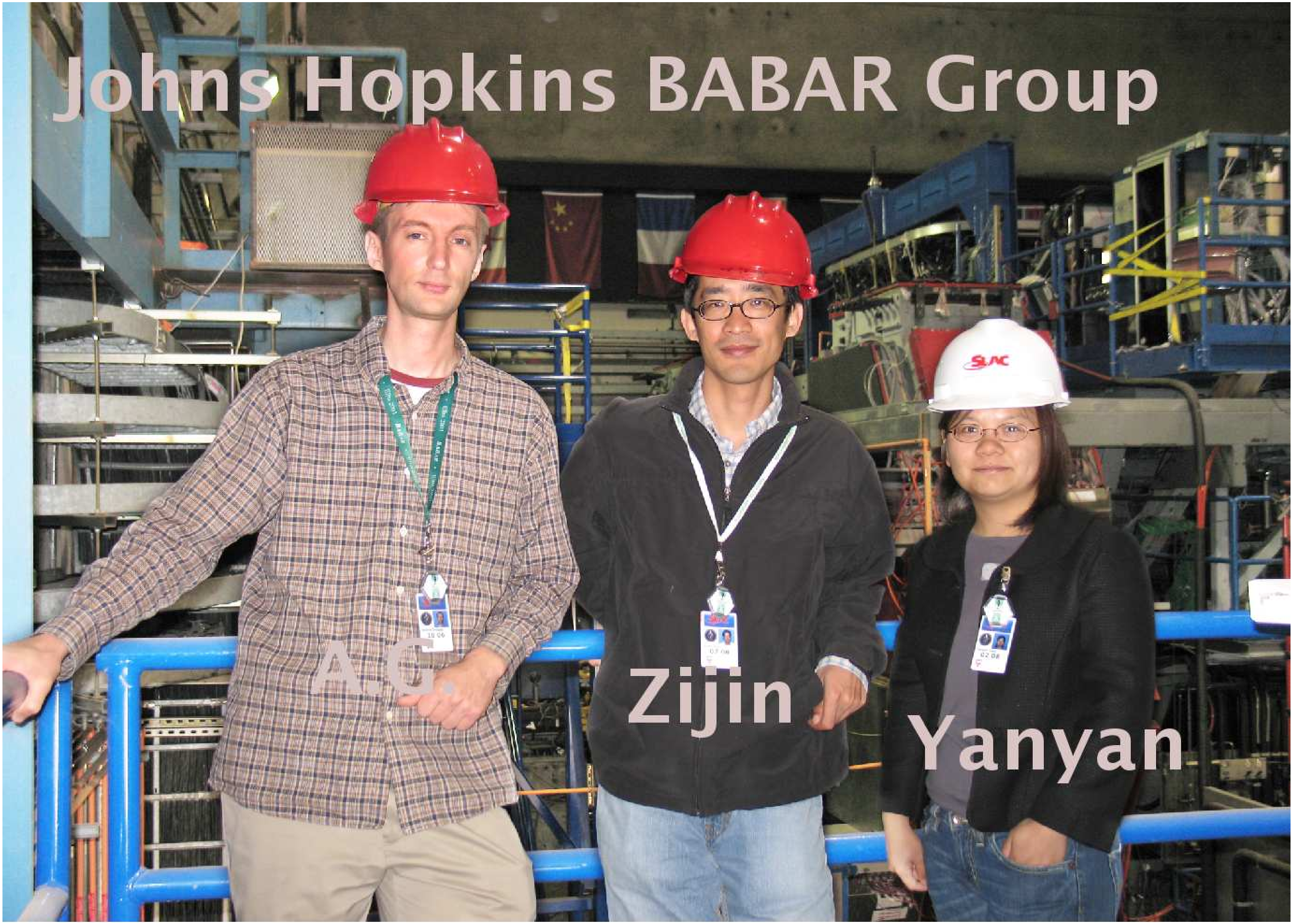
$\bar{q}\gamma^\mu(1+\gamma^5)q$

Summary: the Uncertainty Principle, the Quarks, and the Search for New Physics

- Particles physics: Quarks, etc...
  - very successful
  - incomplete
- Searching for New Physics
  - get to large mass at LHC in 2008
- Use Uncertainty Principle
  - look for hints
  - polarization puzzle

    Phys. Rev. Lett. 98, 051801 (2007)
  - first hints (?) would complement LHC discoveries

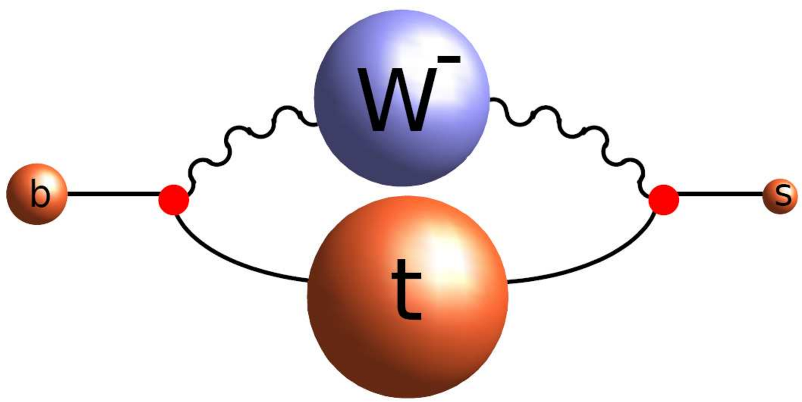



Johns Hopkins BABAR Group
A.G.
Zijin
Yanyan

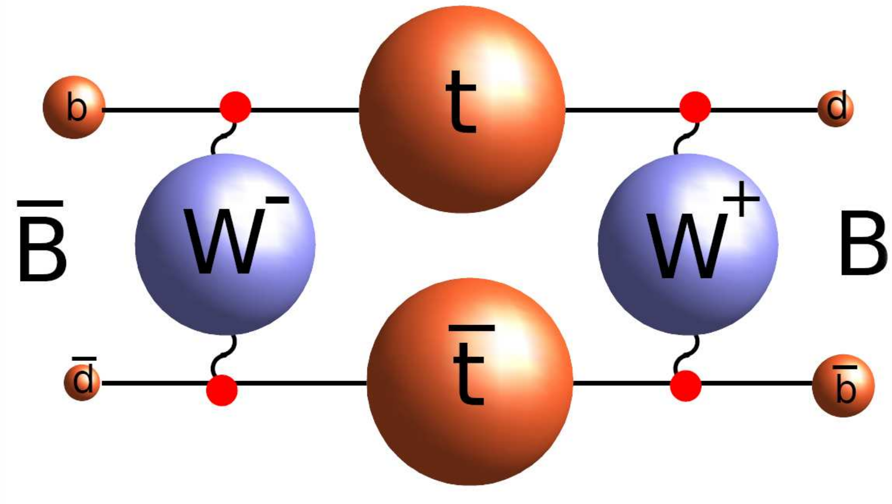
BACKUP SLIDES

Loops

"penguin" loop



mixing "box"



- B-meson physics: test $A = |A| \times e^{i\phi}$

  (1) transition rate $|A|^2$

  (2) phase ϕ=arg(A)

Best constraints on supersymmetry and New Physics

Computing and Analysis

- *BABAR* $\sim$ Petabyte of data

  $>$ billion "events" (B's are minority)

(1) Huge combinatorics, reduce to few 1000 events

$$\vec{x}_j = (m_B, m_\phi, m_{K^*}, \theta_1, \theta_2, \Phi, \ldots)$$

(2) Extract $\sim$ few 100 signal events and parameters

likelihood $\mathcal{L} = \exp\left(-\sum_i n_i\right) \prod_{j=1}^{N} \left(\sum_i n_i \mathcal{P}_i(\vec{x}_j; \vec{\xi}\,)\right)$ = maximum