The Uncertainty Principle and the Quarks

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JHU Quarknet Meeting

Outline

- The Uncertainty Principle

  quantum mechanics with elementary particles

- The Quarks

  what we know and do not know in particle physics

The Uncertainty Principle

- Heisenberg uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

  - key concept of Quantum Mechanics
  - tiny $\hbar = 10^{-34}$ J·s

- Consequence

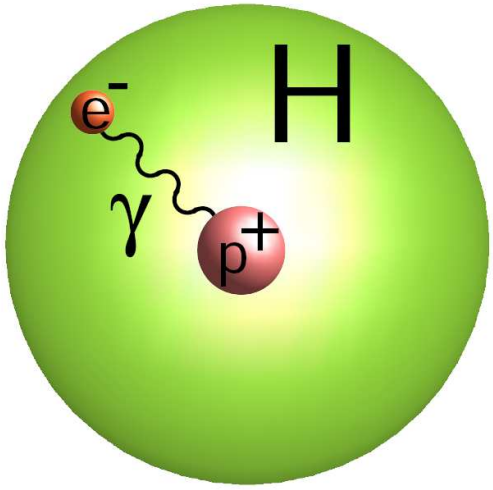
  - physics at small scale (quantum $\hbar$) is not deterministic!
  - operate with probabilities instead
  - cannot know exact position and momentum at the same time

- Counterintuitive, even Einstein was wrong:

"I cannot believe that God would choose to play dice with the universe."

The Uncertainty Principle

- Example: electron around a nucleus
  - only probability function (wave function)
  - no circular orbits
  - quantized (discrete) energies



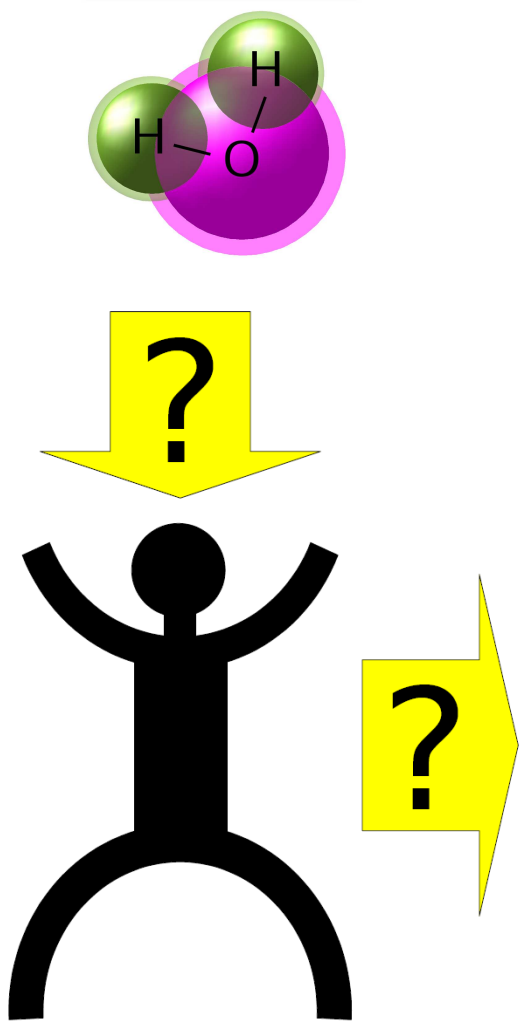
- Quantization of angular momentum:
  - orbital $\mathbf{L} = \mathbf{r} \times \mathbf{p} = \hbar \cdot n$
  - spin (internal) $\mathbf{S} = \frac{\hbar}{2} \cdot n$

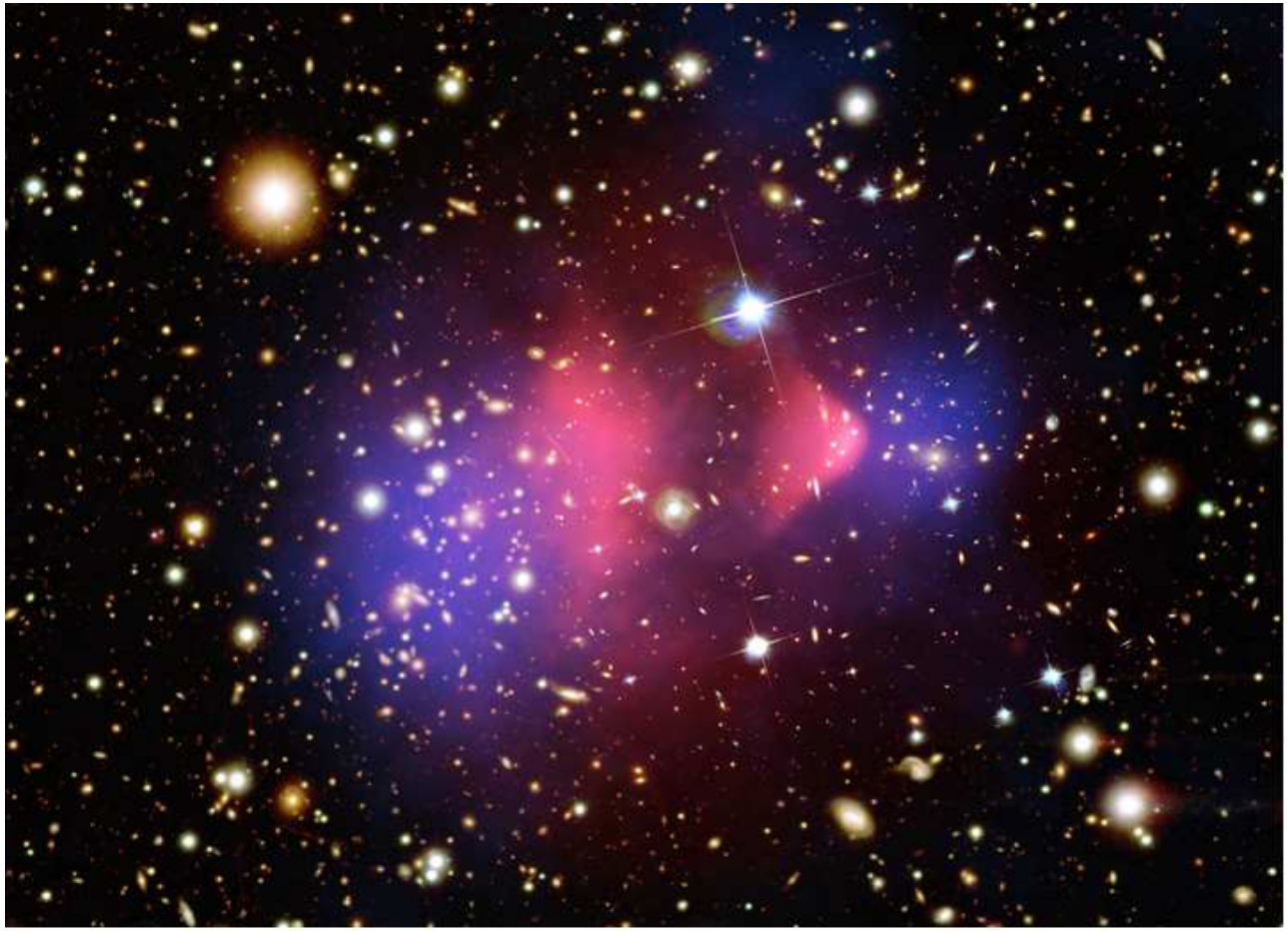
- Counterintuitive, but Einstein was right (photoelectric effect):
  - light quanta from Planck's $E = \hbar\omega$ (photon)

The "Quarks": from the Smallest to the Largest

- On the smallest and largest scale:

  what are we made of and why



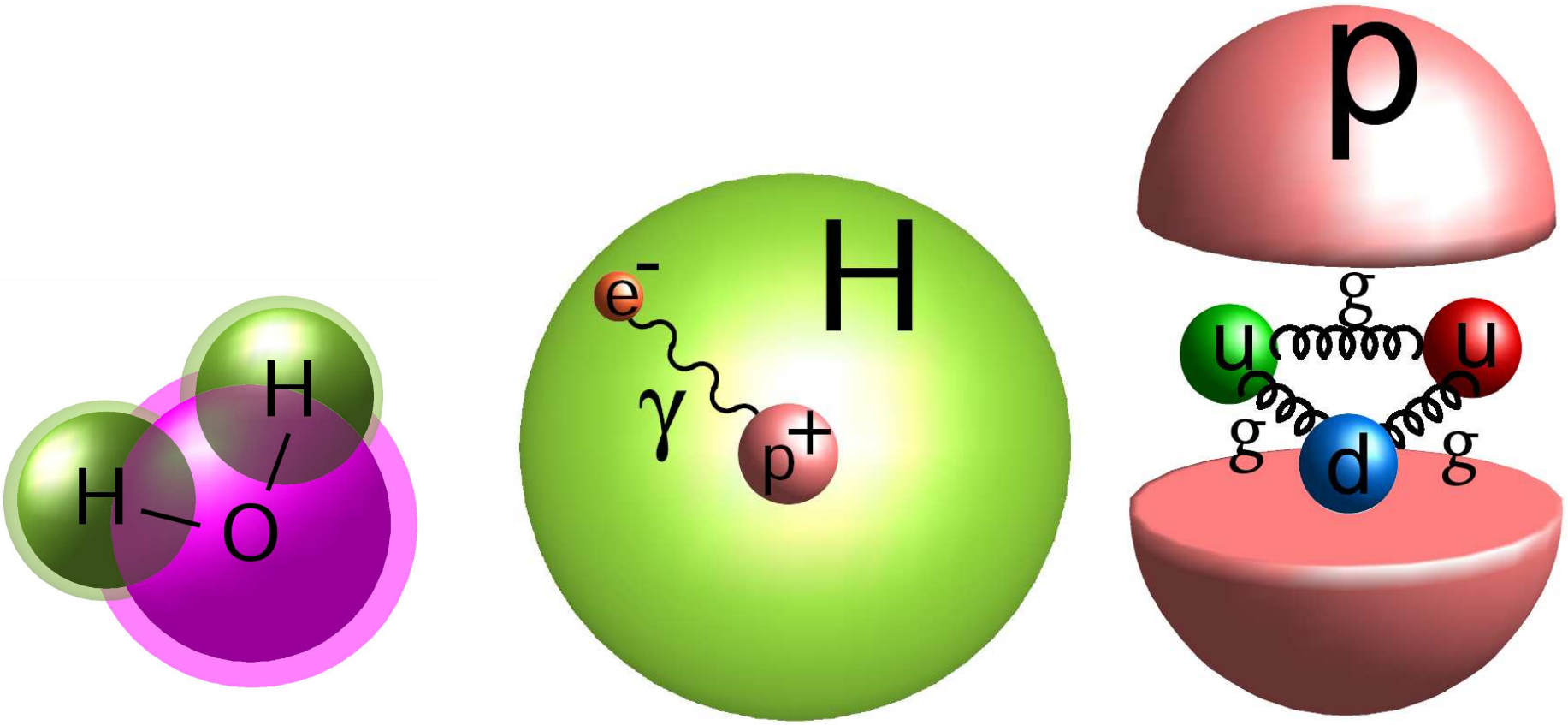


(Galaxy cluster 1E 0657-66: X-ray, Optical, Grav. Lensing)

Particle Physics
What We Already Know

From Molecules to Quarks

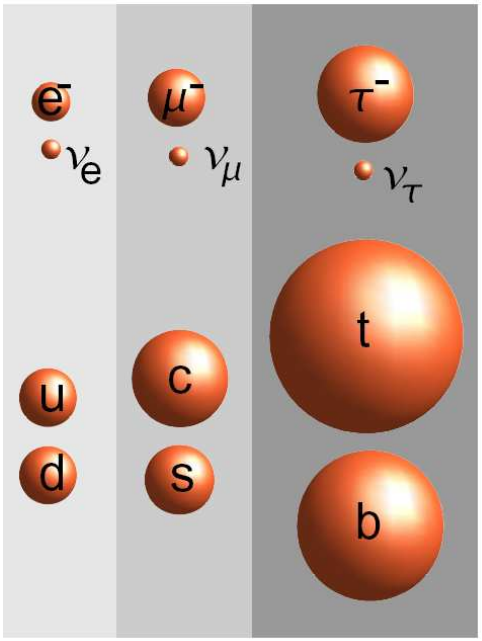
- XXth century: reaching deep into matter, Quarks



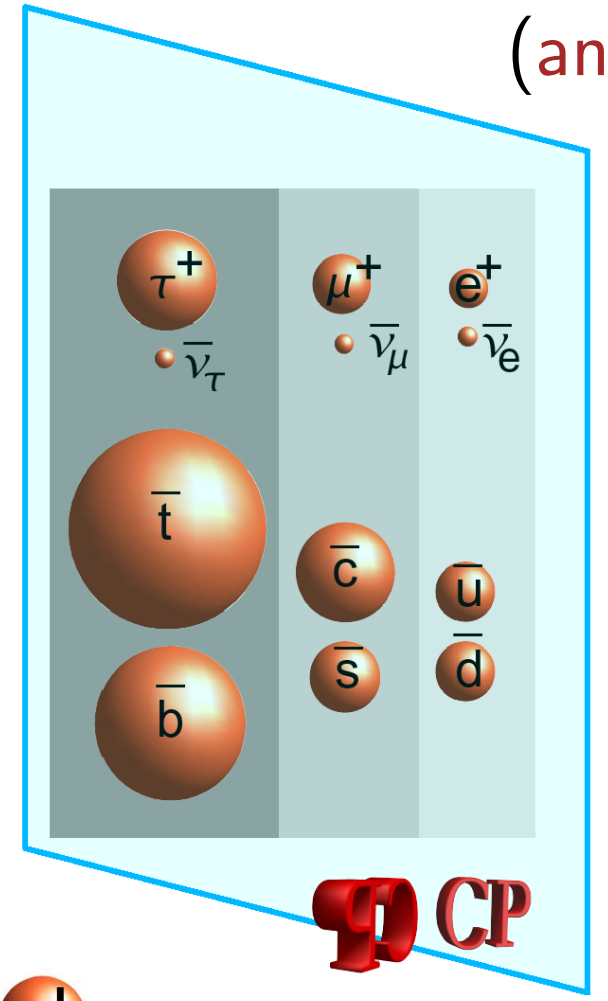
Chemistry Atomic Physics Particle Physics

Elementary Particles

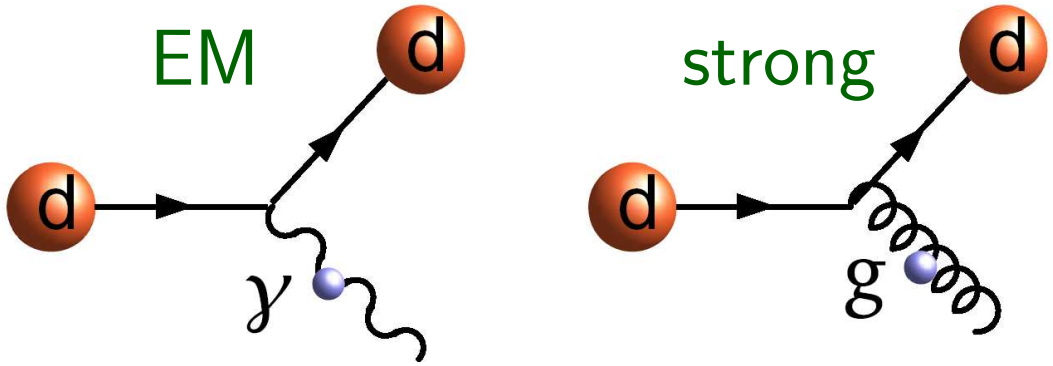
- Fermions $S = \frac{\hbar}{2}$ (matter)



(anti-matter)



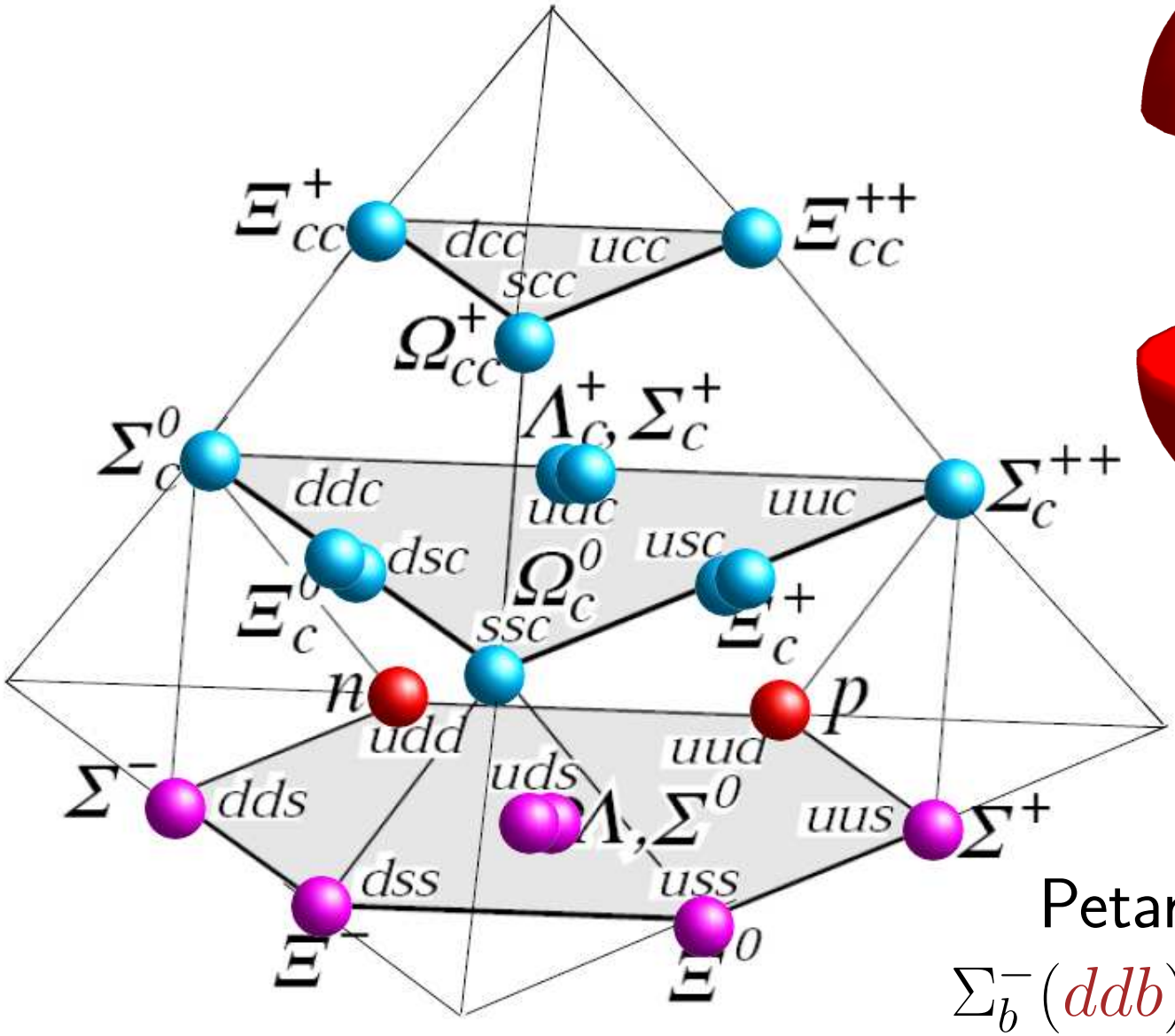
- Bosons $S = \hbar$ (force carries):

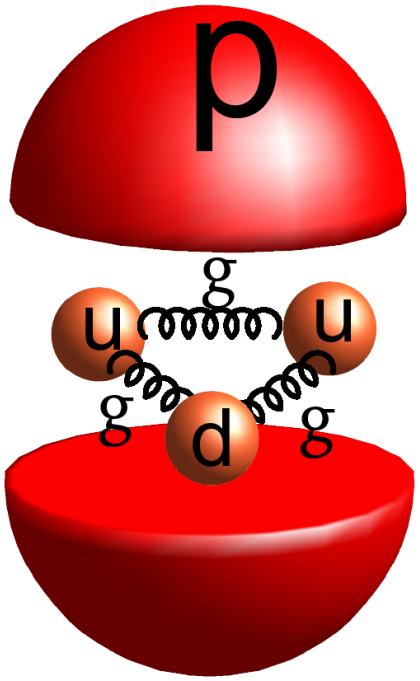


(weak force later)

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

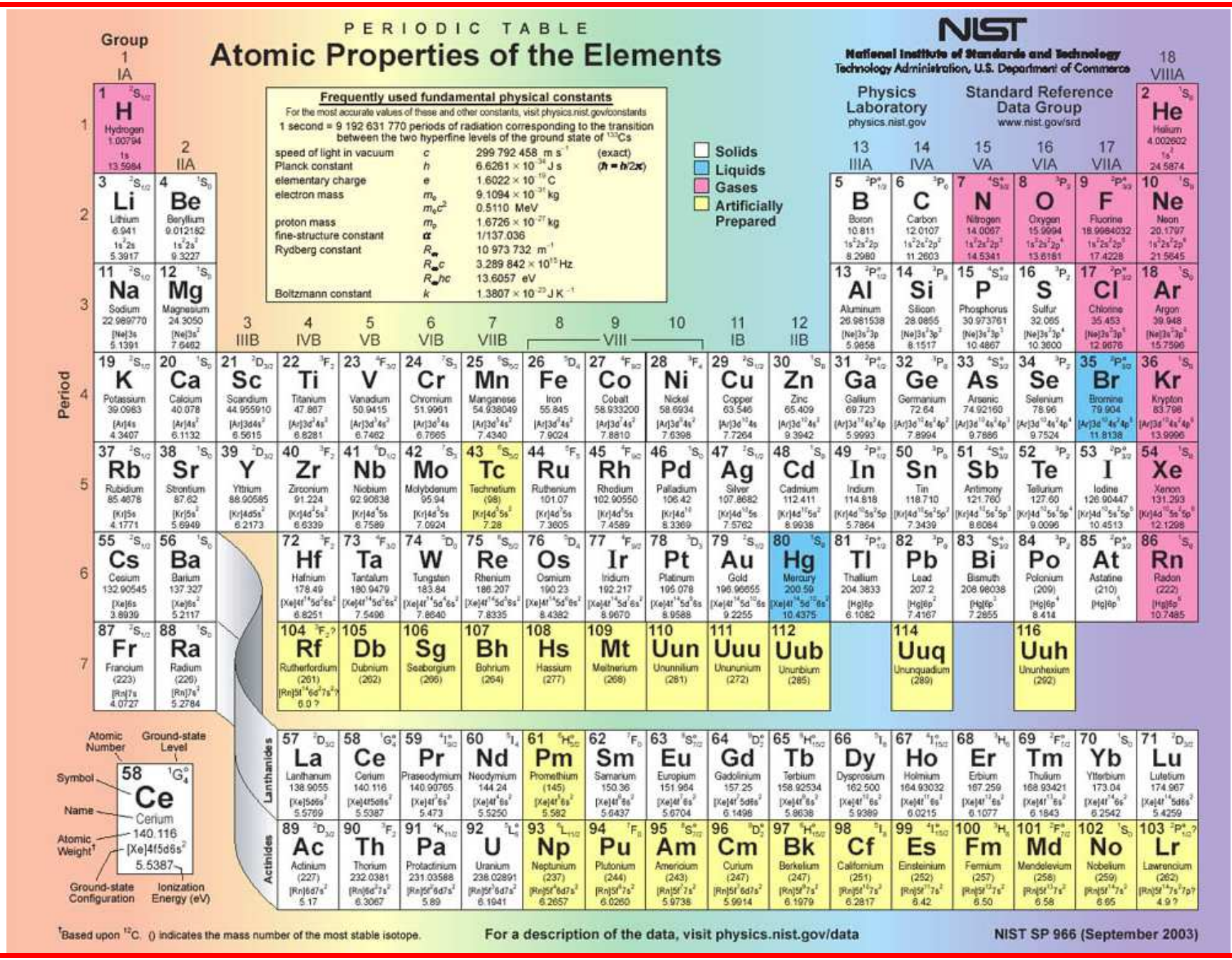
- Three quarks make up a Baryon:





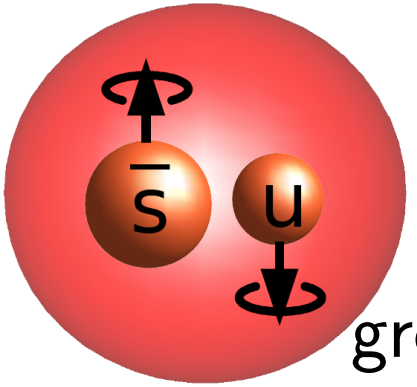
Petar's discovery:
$\Sigma_b^-(ddb)$ and $\Sigma_b^+(uub)$

Like Periodic Table of Atoms



"Periodic Table" of Mesons

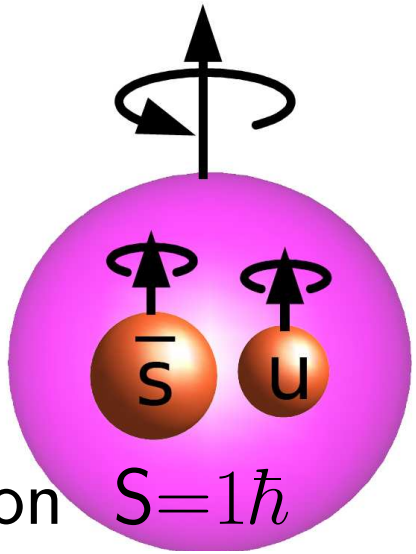
- Quark-antiquark make up a Meson:



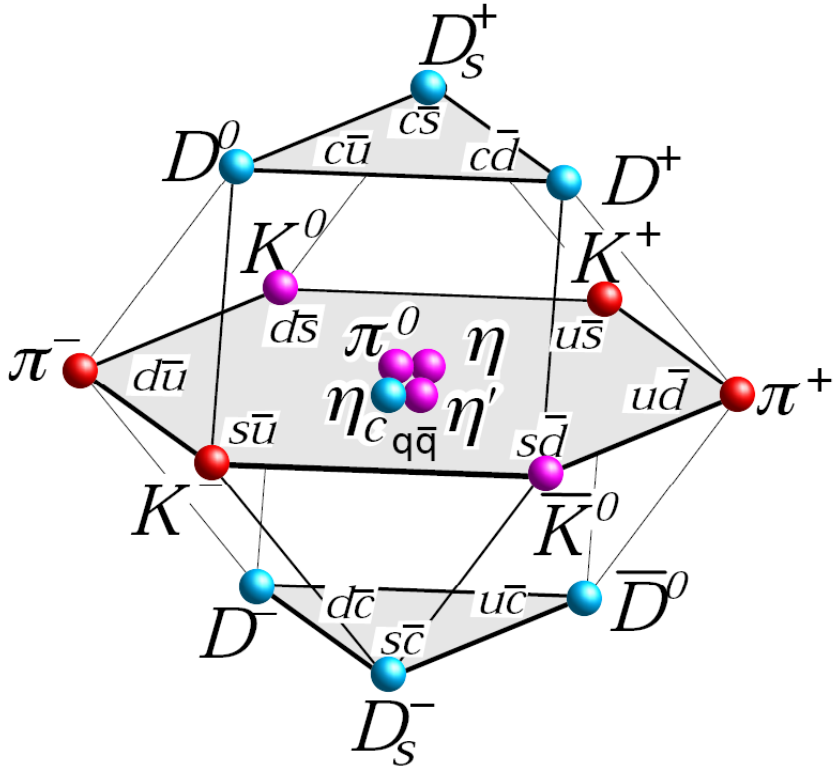
K^+

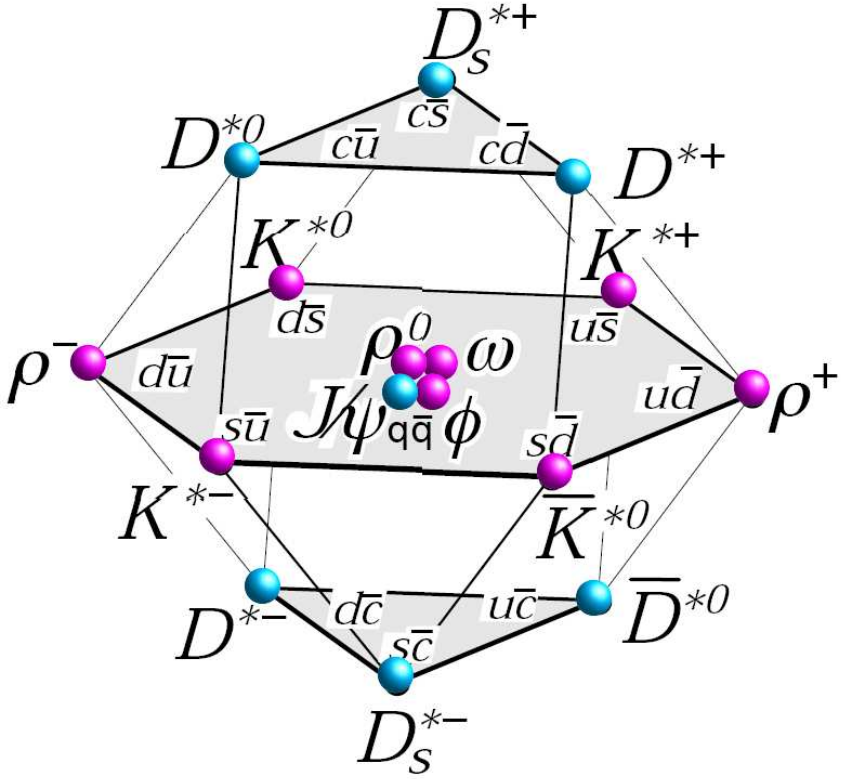
ground state (L=S=0)

K^{*+}



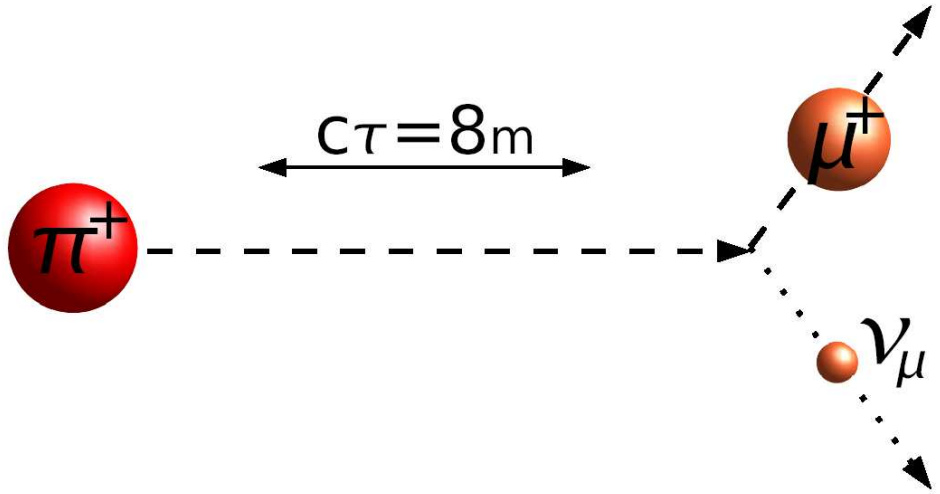
Vector meson $S=1\hbar$



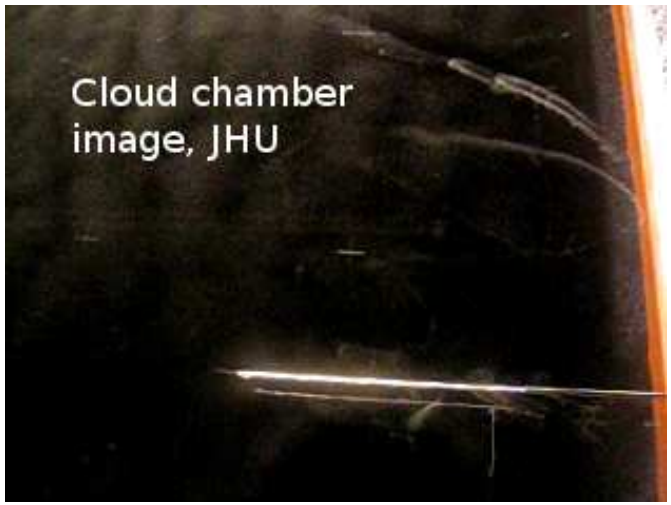


How do We "See" Particles

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



- Table-top illustrations

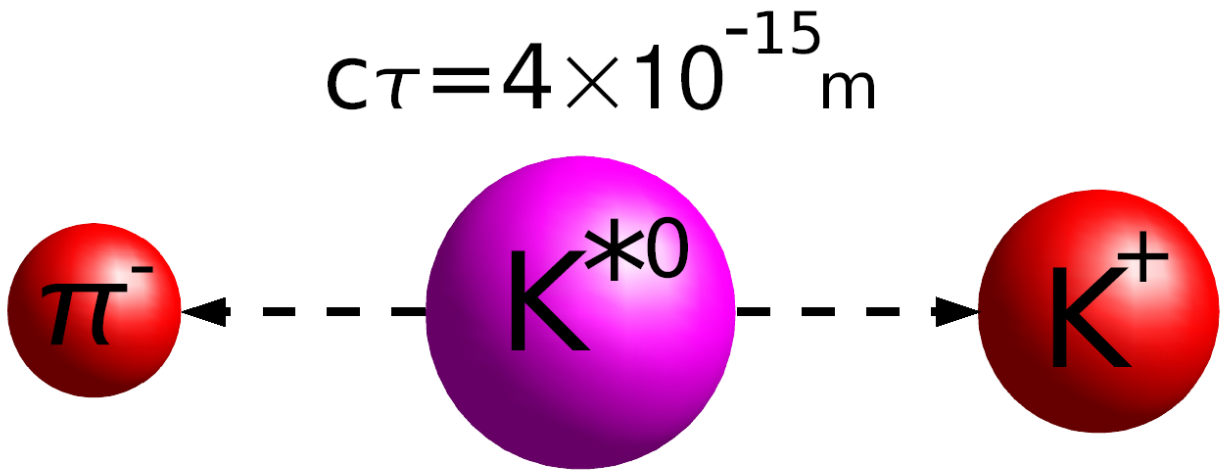


- Complex multi-ton detectors

Movie ?

How do We "See" Particles

- Most particles live too short to be "seen" directly
  - "see" decay products (c=3×10^8m/s):



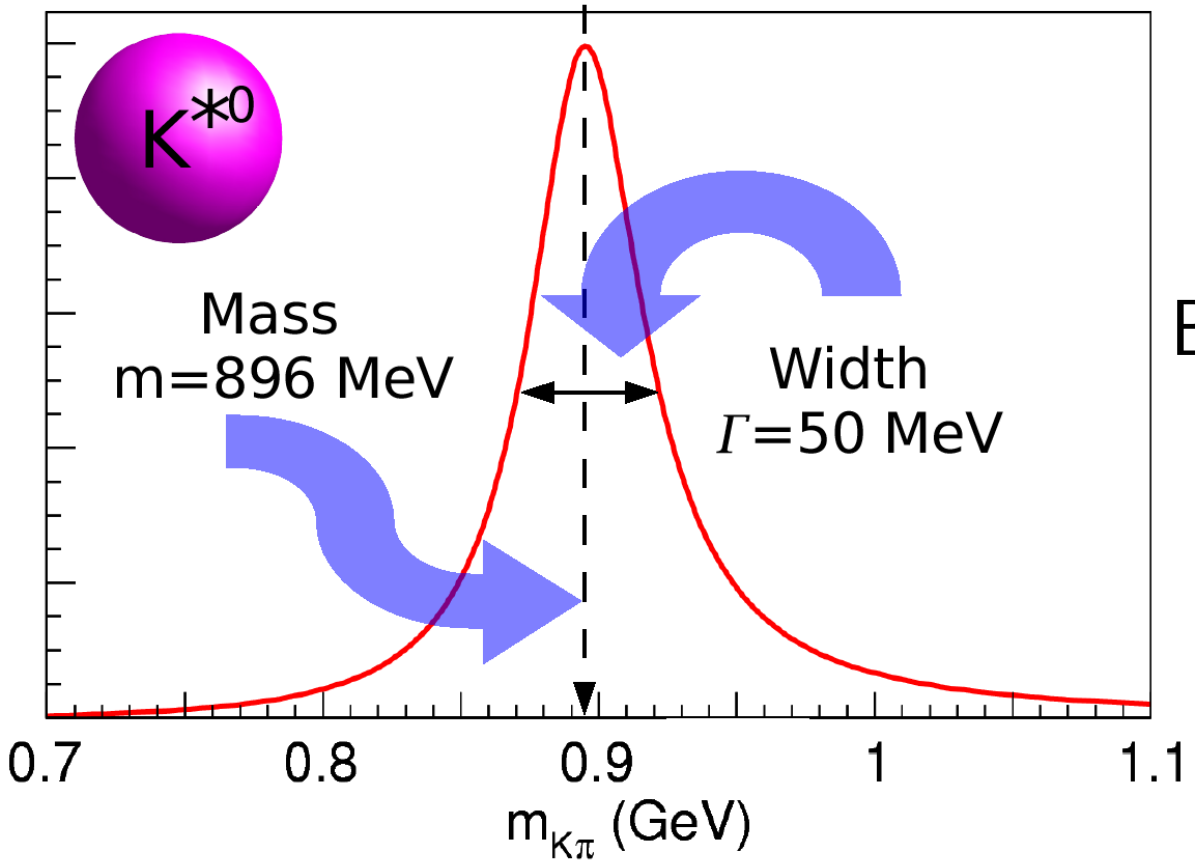
- life-time and energy (mass) uncertainty of a "resonance":
  - the Uncertainty Principle (part 2): $\Delta t \times \Delta E \sim \hbar$

Unstable Particles

- The Uncertainty Principle (part 2): $\Gamma_0 \times \tau_0 = \hbar$

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

- Probability (1 GeV $\simeq 2 \times 10^{-27}$ kg $\sim$ proton mass)

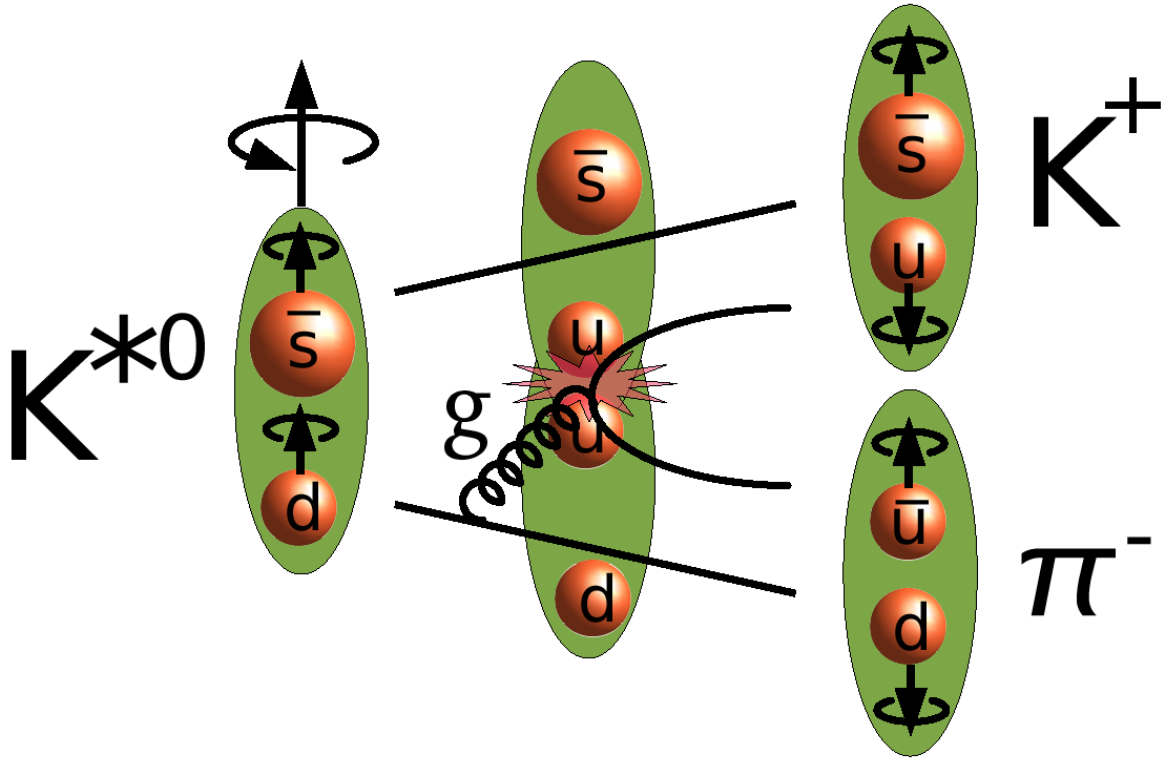


Breit-Wigner resonance

Decay Dynamics

- Unstable particles decay

  Feynman diagram:

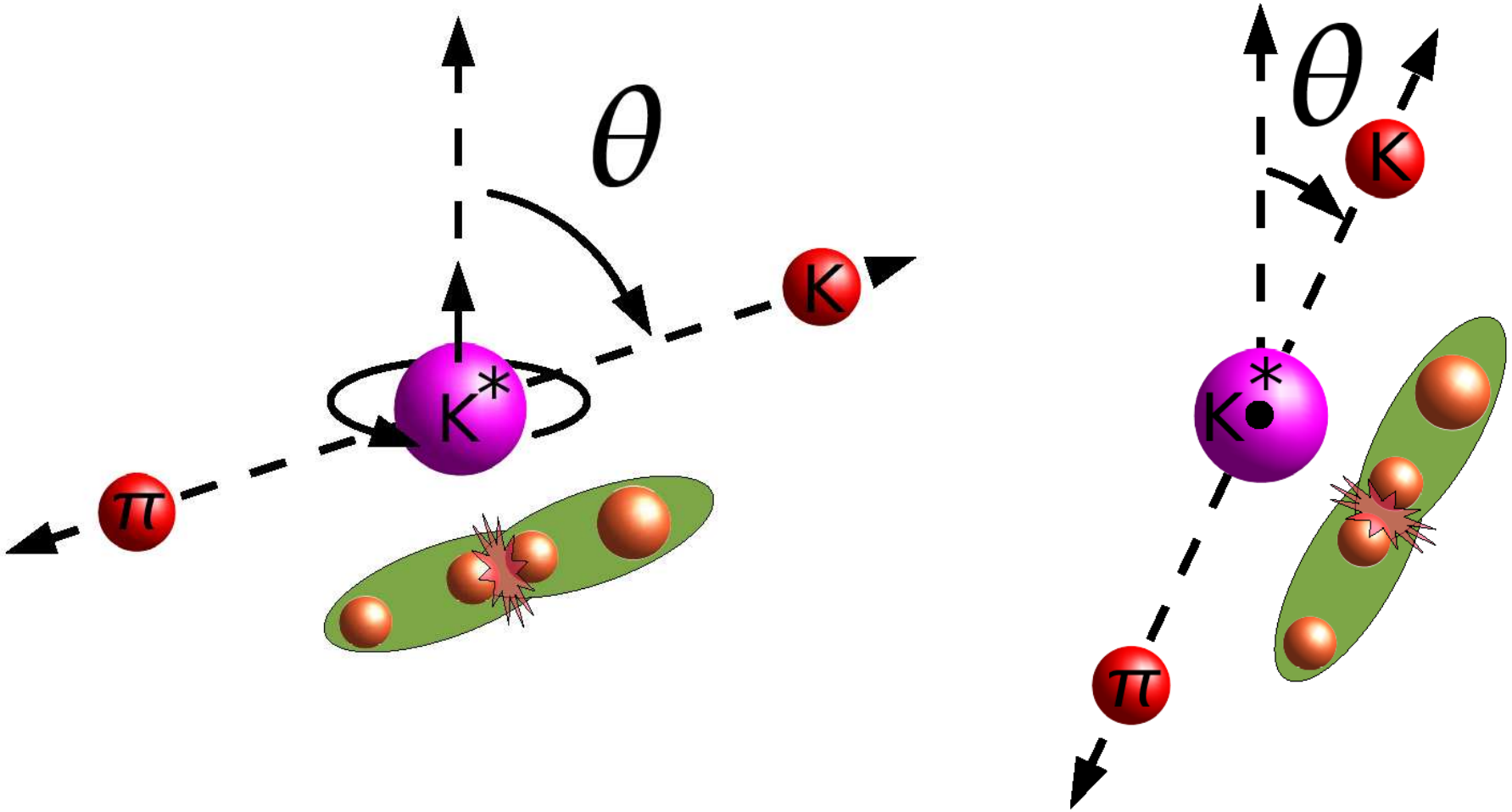


- Decay ⇒ study elementary particles and interactions

  (this "strong" decay is mostly understood)

Decay Kinematics

- We often understand decay dynamics through kinematics



Decay Kinematics

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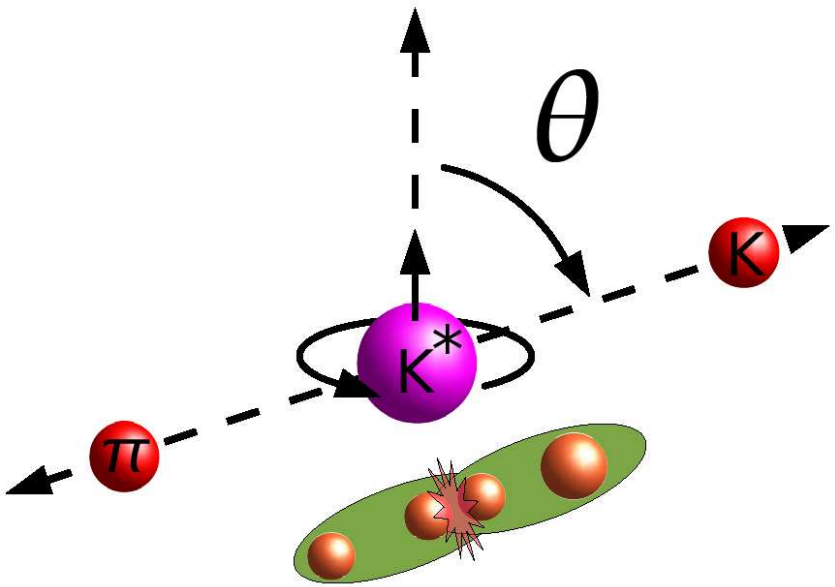
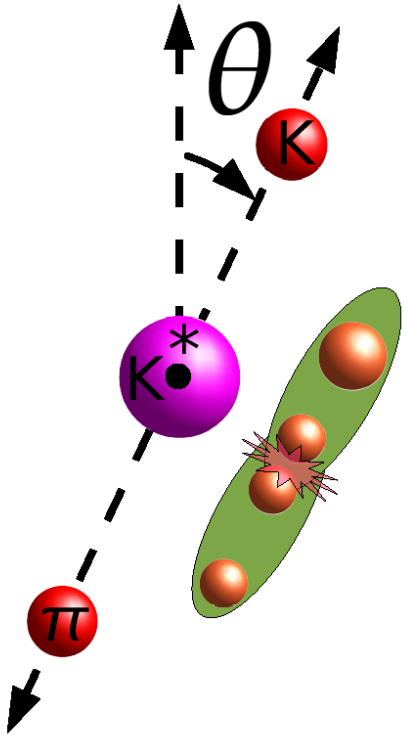
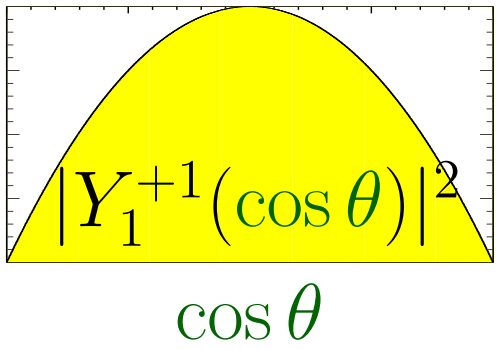


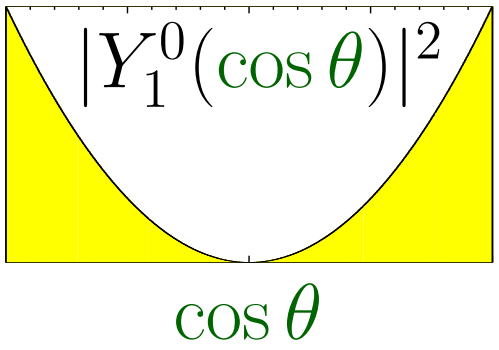


- Conservation of orbital momentum:

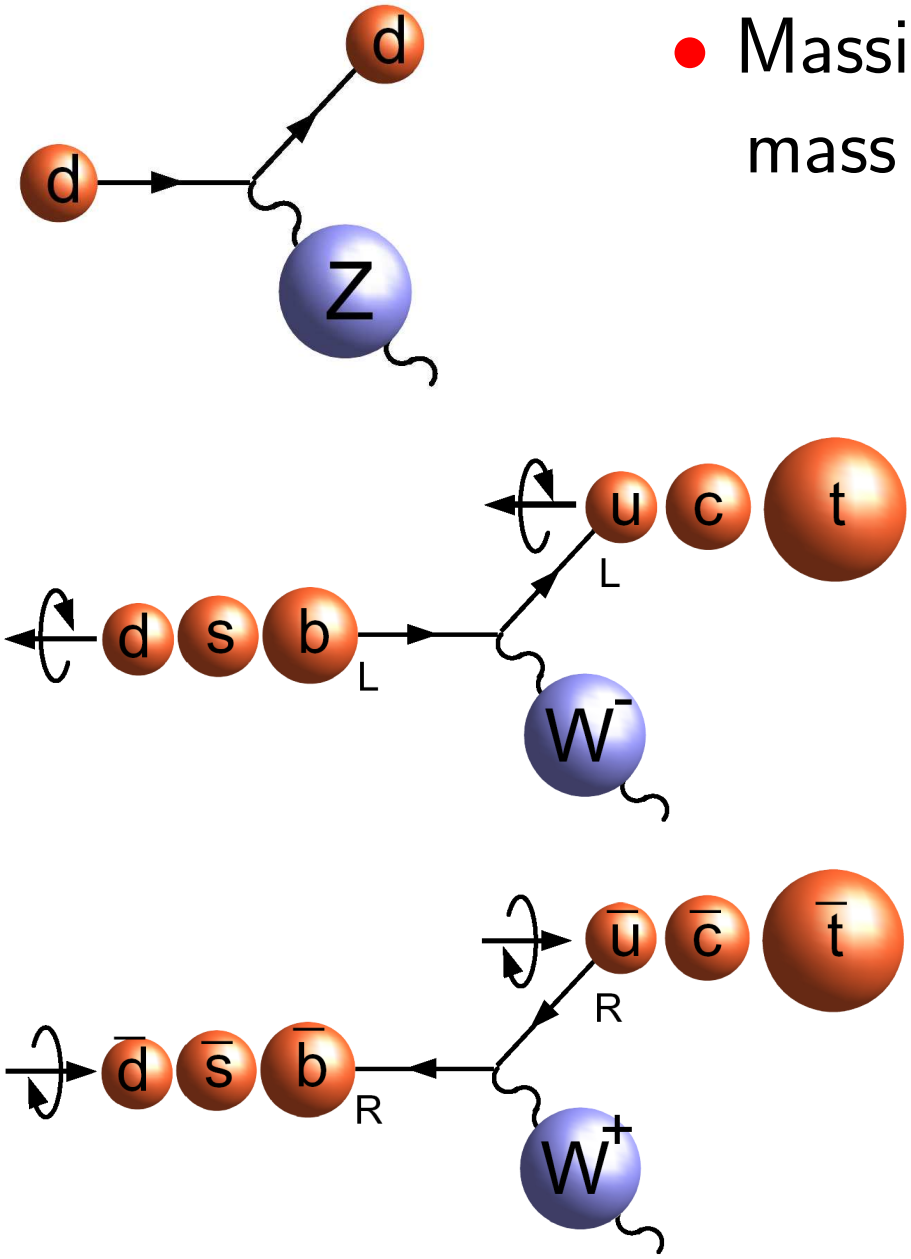
$L_z = +1$



$L_z = 0$



Weak Interactions



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

- Special interactions:

  change type of quark

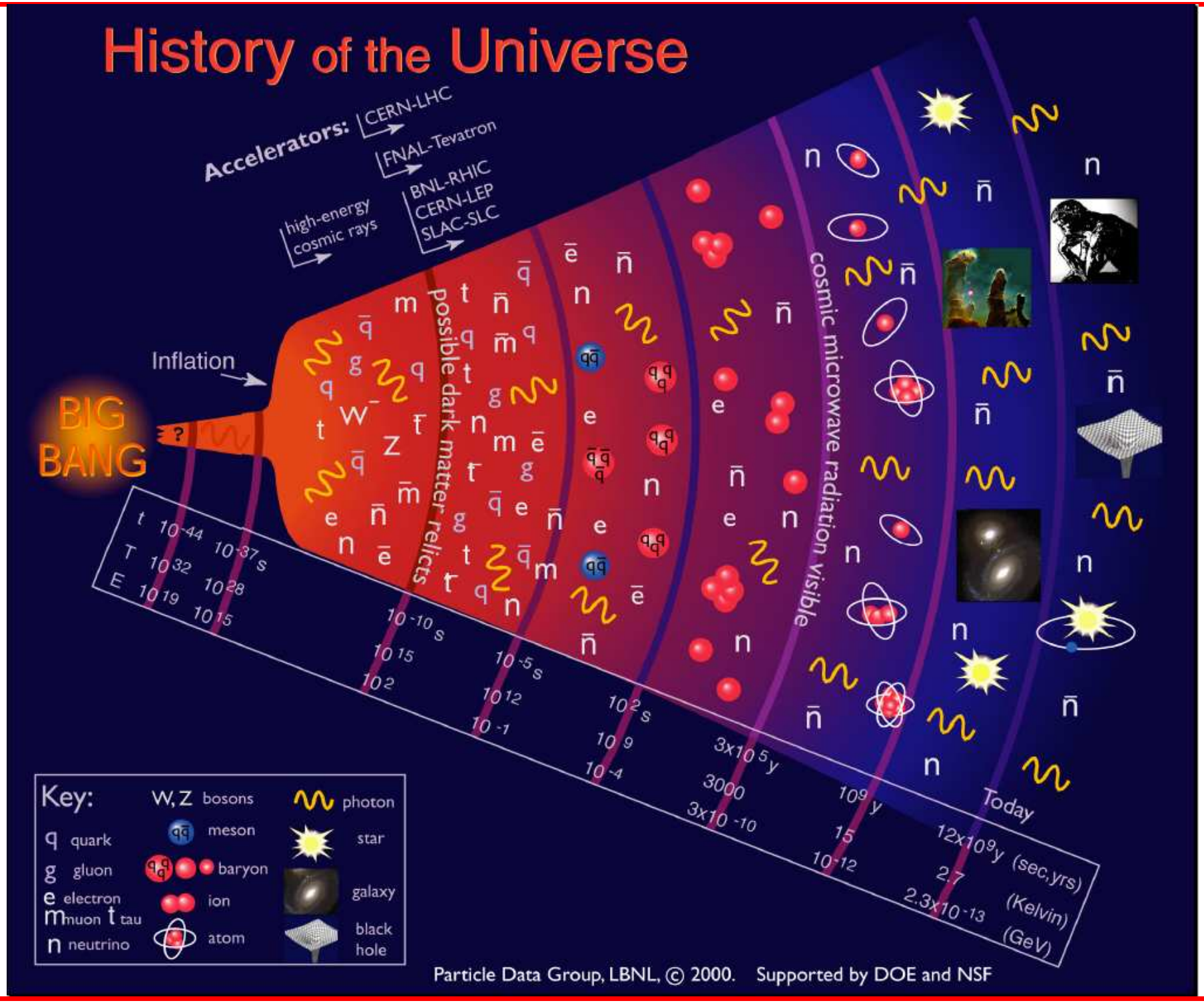
  change families

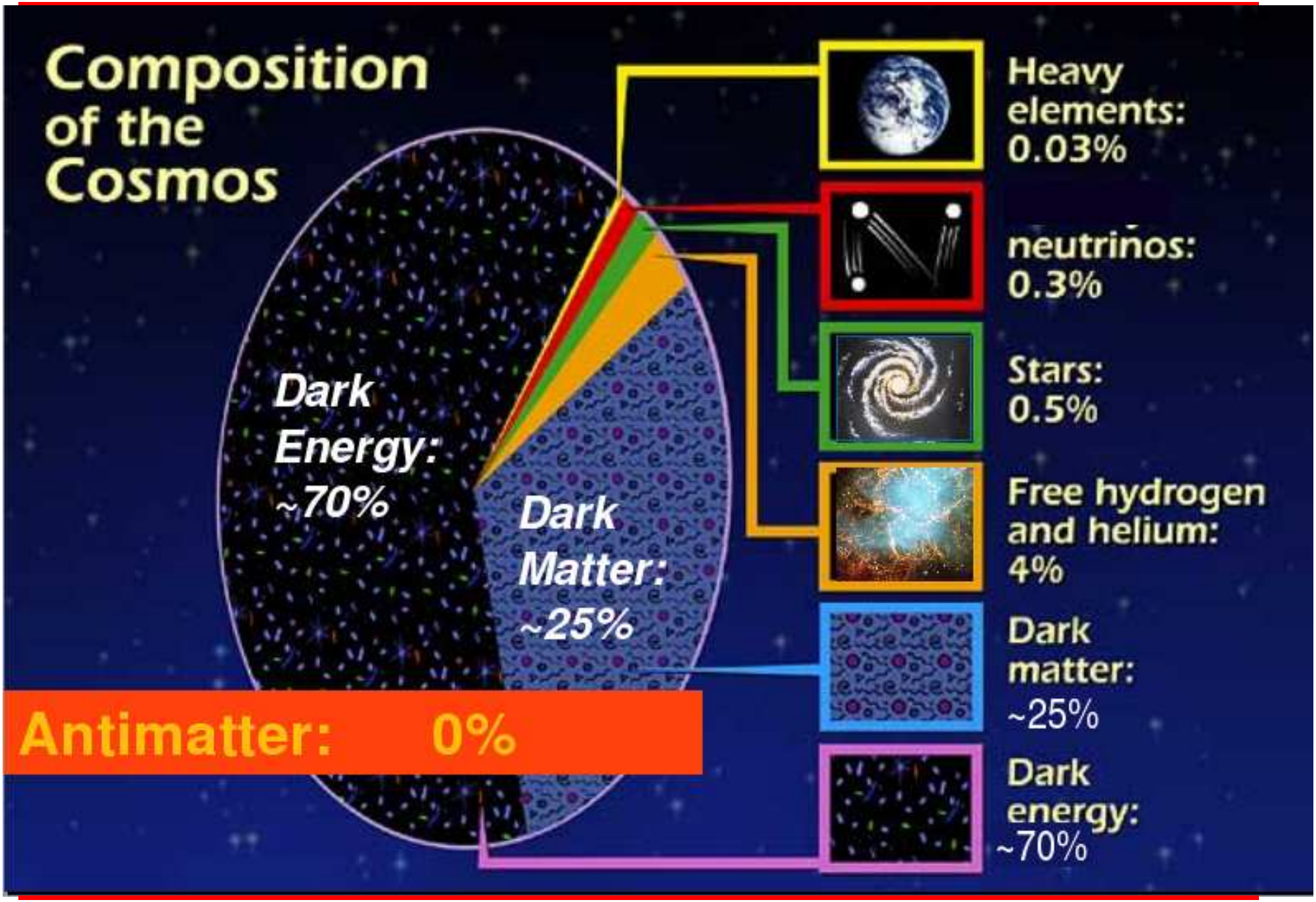
  left-handed fermions

  violate Parity and C

  violate CP symmetry

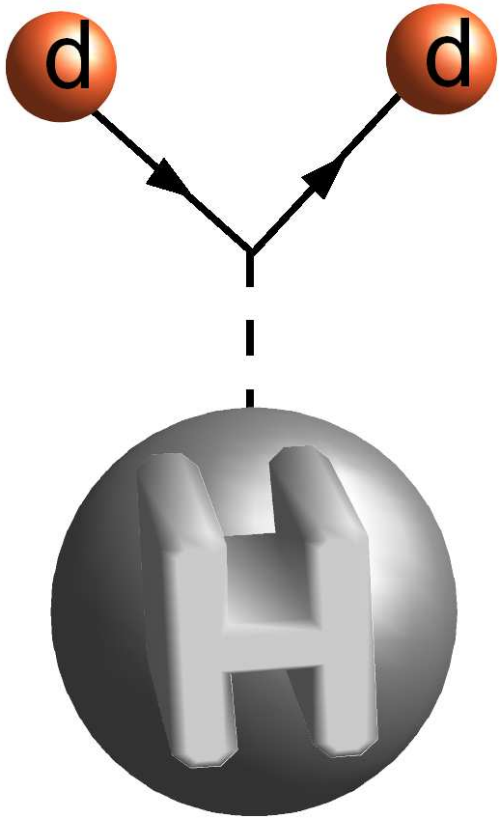
Particle Physics
What We do not Know


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 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Today
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

- Mysterious Higgs field
  - gives mass to particles



- Need something beyond the SM
  - large matter-dominance
  - dark matter
  - light Higgs

Possible Extension: Super-Symmetry

- New (super)symmetry:

$Q|\text{fermion}\rangle = |\text{boson}\rangle$

$Q|\text{boson}\rangle = |\text{fermion}\rangle$

- Solve:

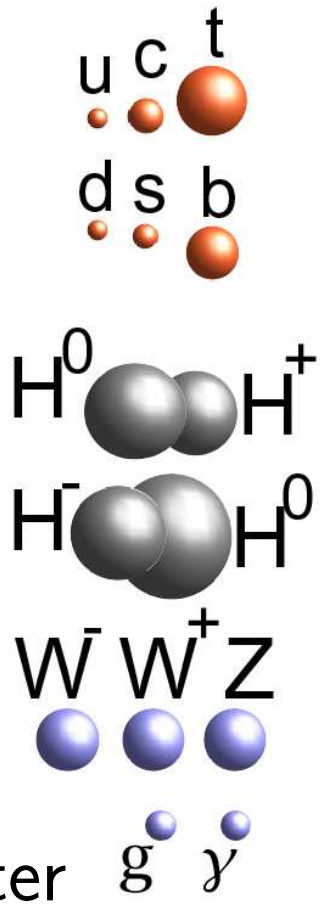
(1) natural light

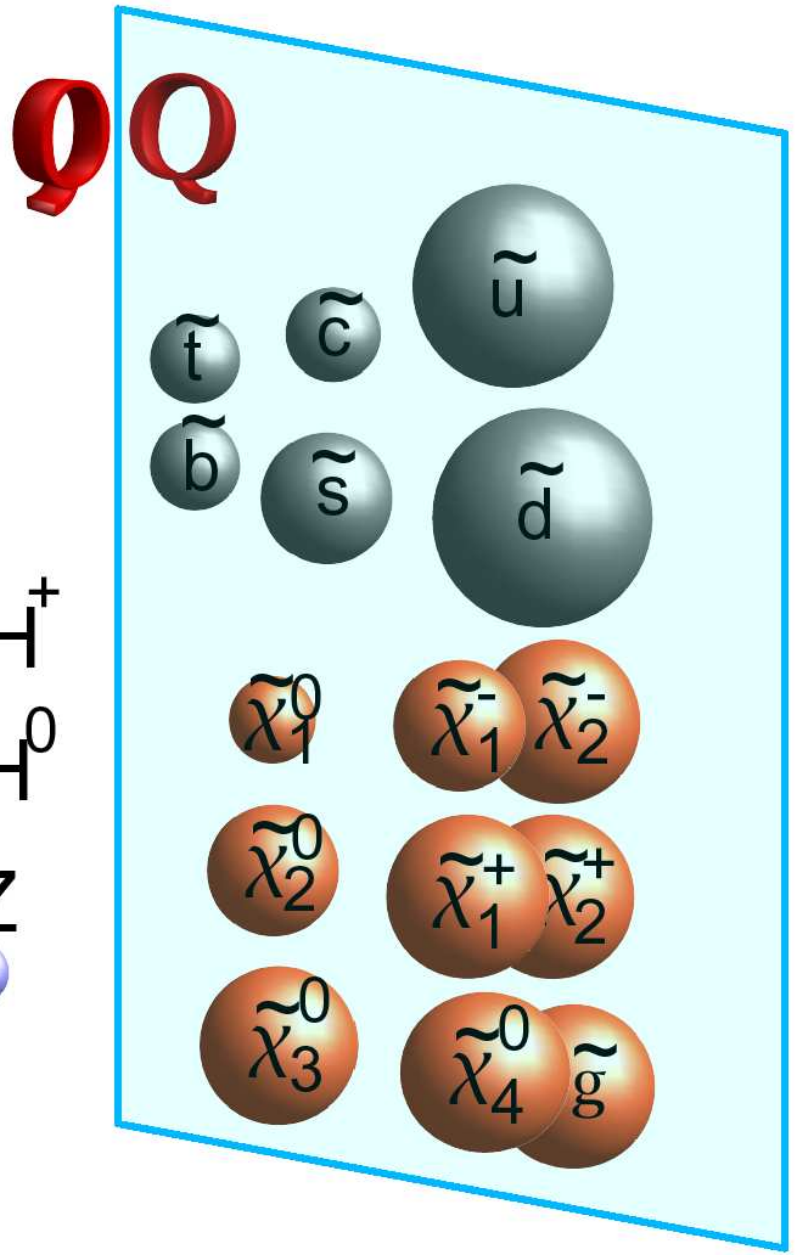
Higgs

(2) dark matter

lightest $\tilde{\chi}_1^0$

(3) large matter/antimatter



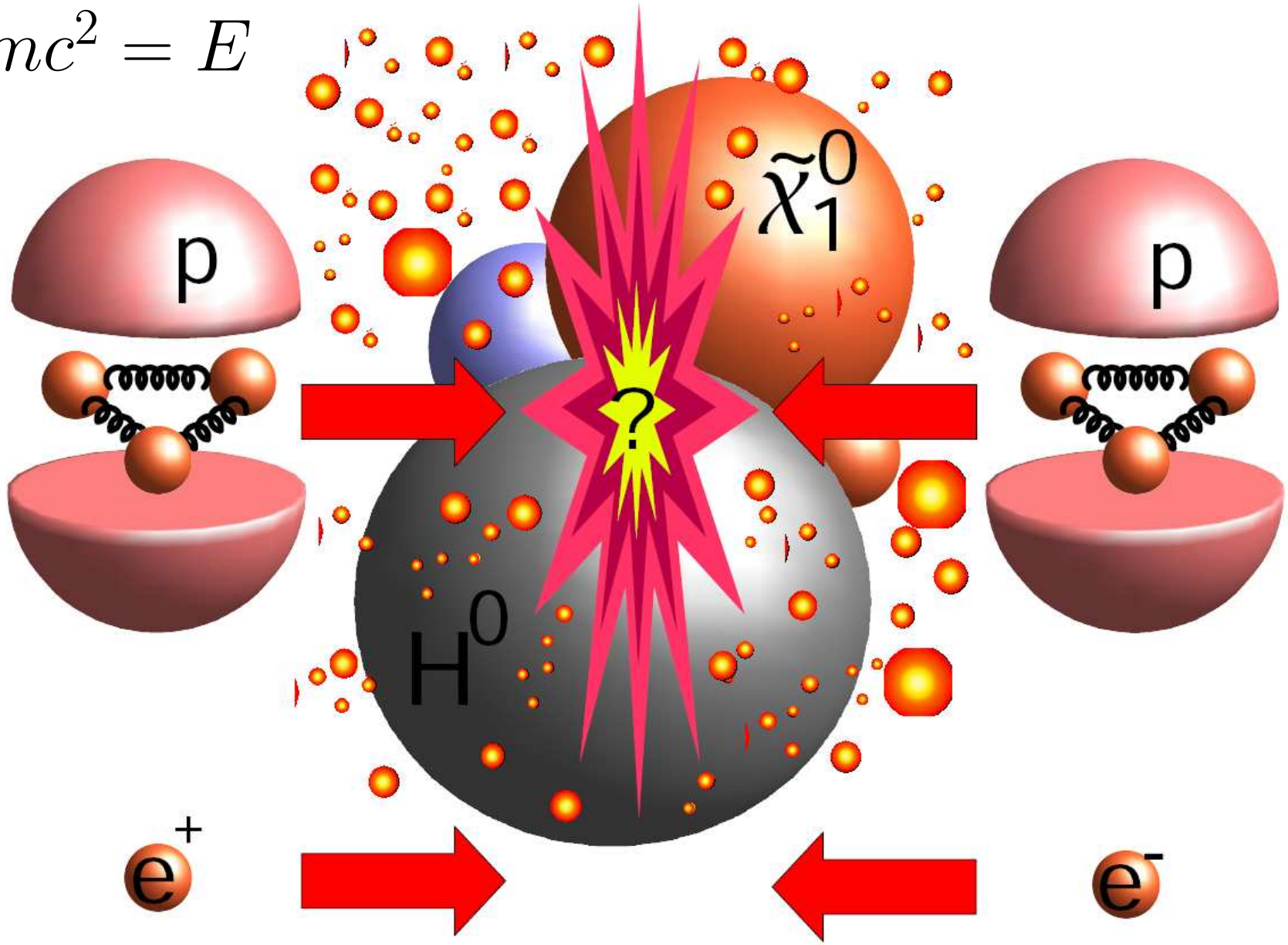


- Just around the corner in mass...

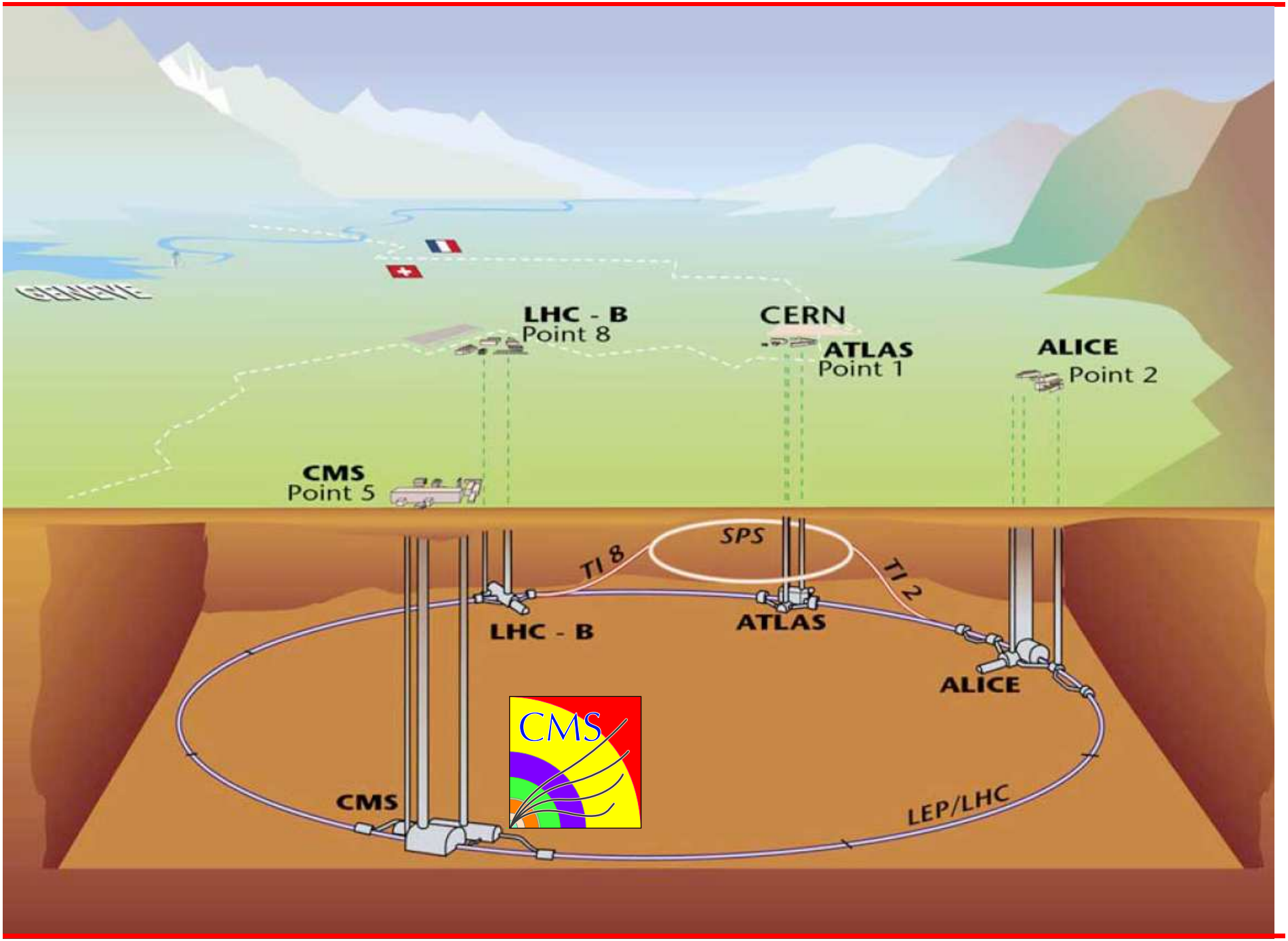
Particle Physics
How to Reach Beyond

Reaching Highest Energy

- $mc^2 = E$



Large Hadron Collider: 2008



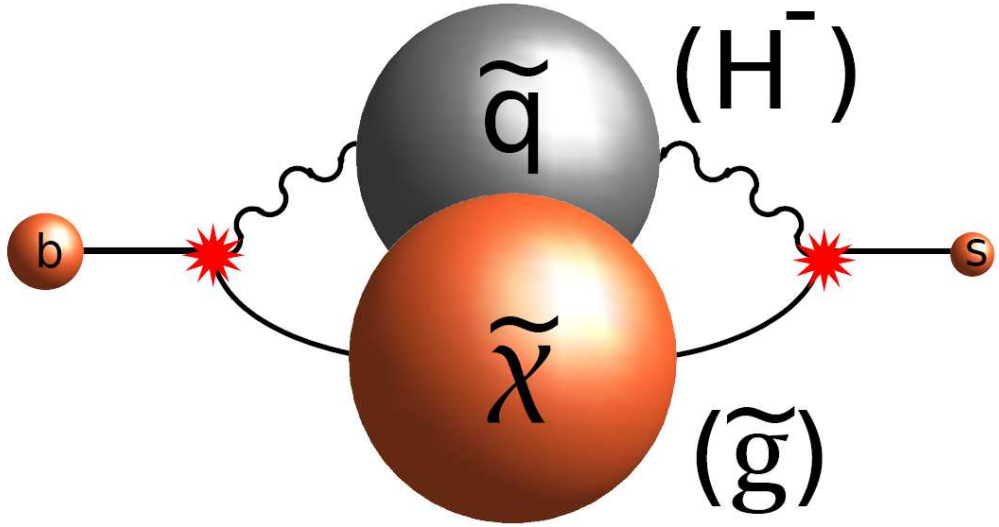
Movie ?

The Uncertainty Principle

- "Heavy" objects for a short instant Δt:

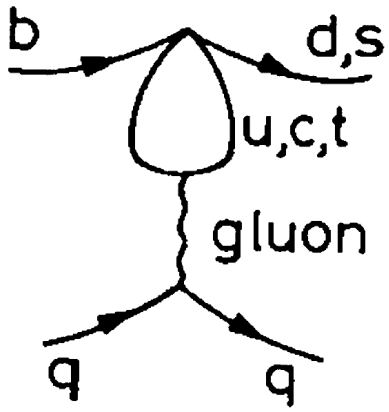
  $\Delta E \times \Delta t \sim \hbar$

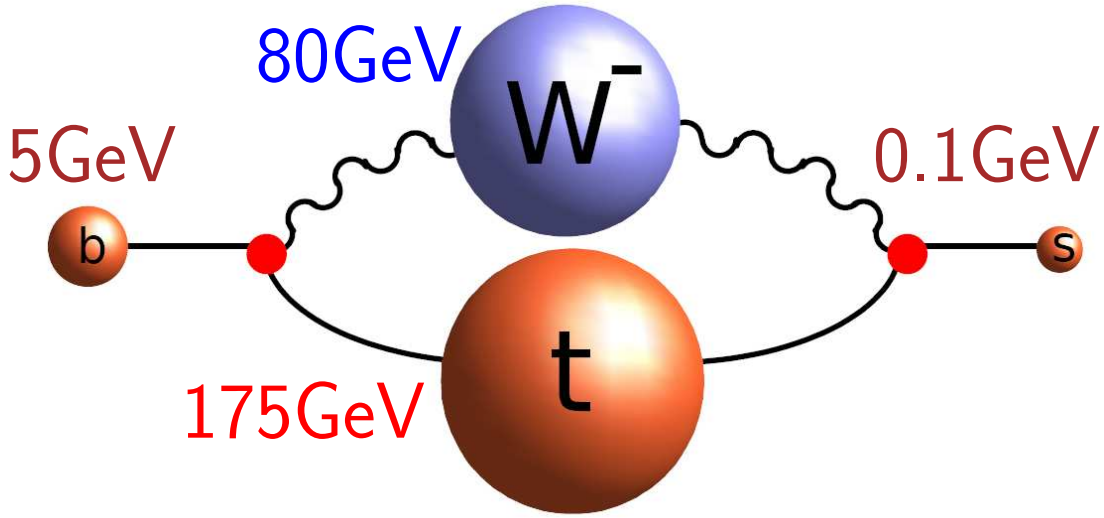
  get $\tilde{m}c^2 \sim \Delta E \sim$500GeV



- Possible:

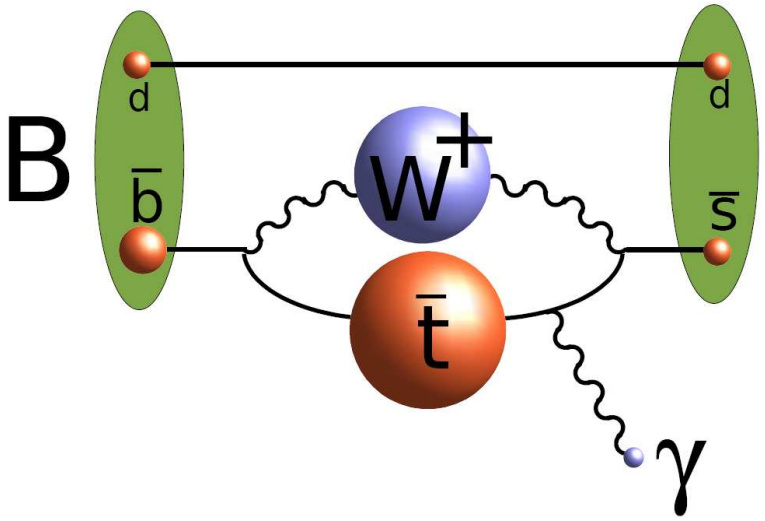
"penguin" loop





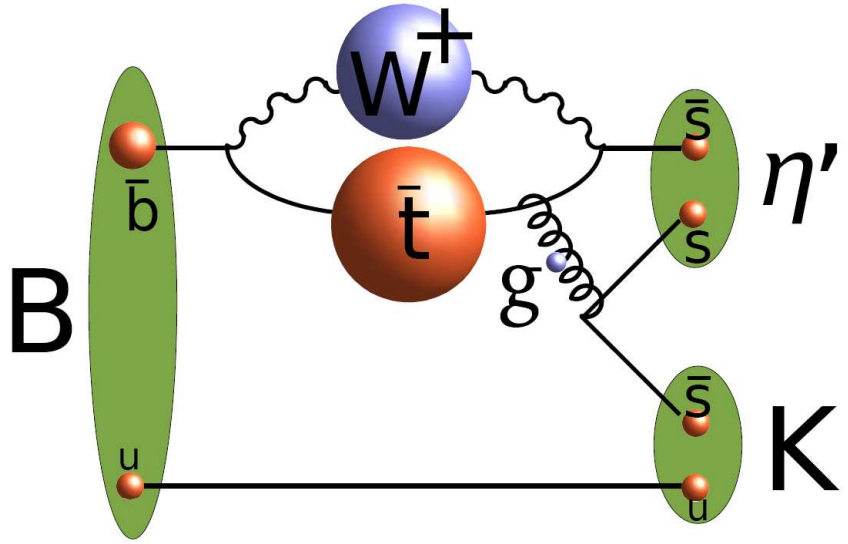
Types of "Penguins"

1993: EM "penguin"



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

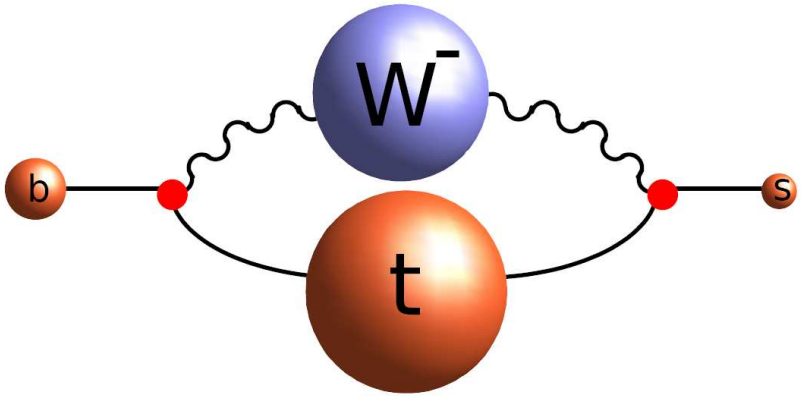
1997: gluonic "penguin"



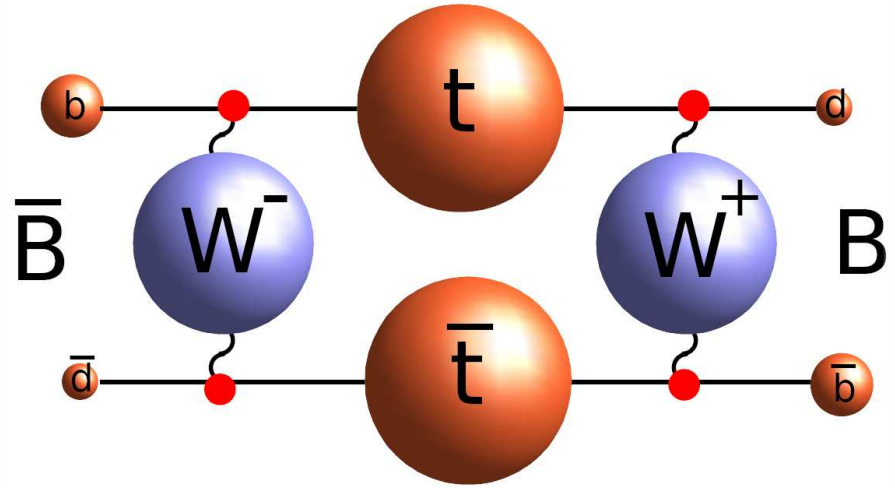
- harder due to gluons

Loops

"penguin" loop



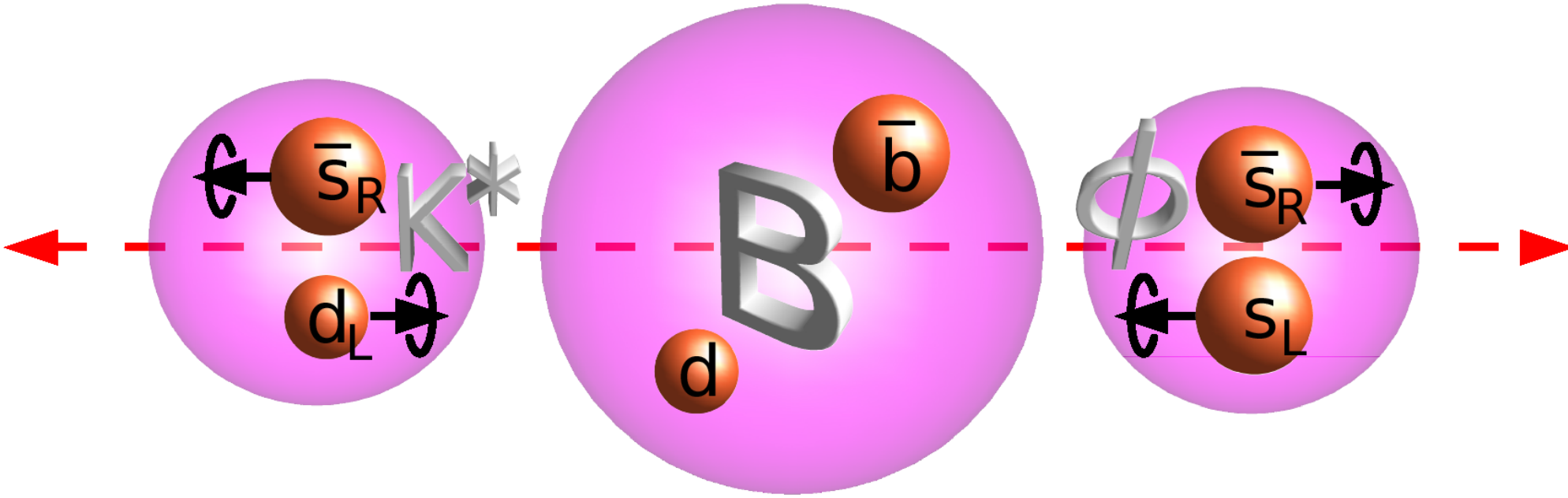
mixing "box"



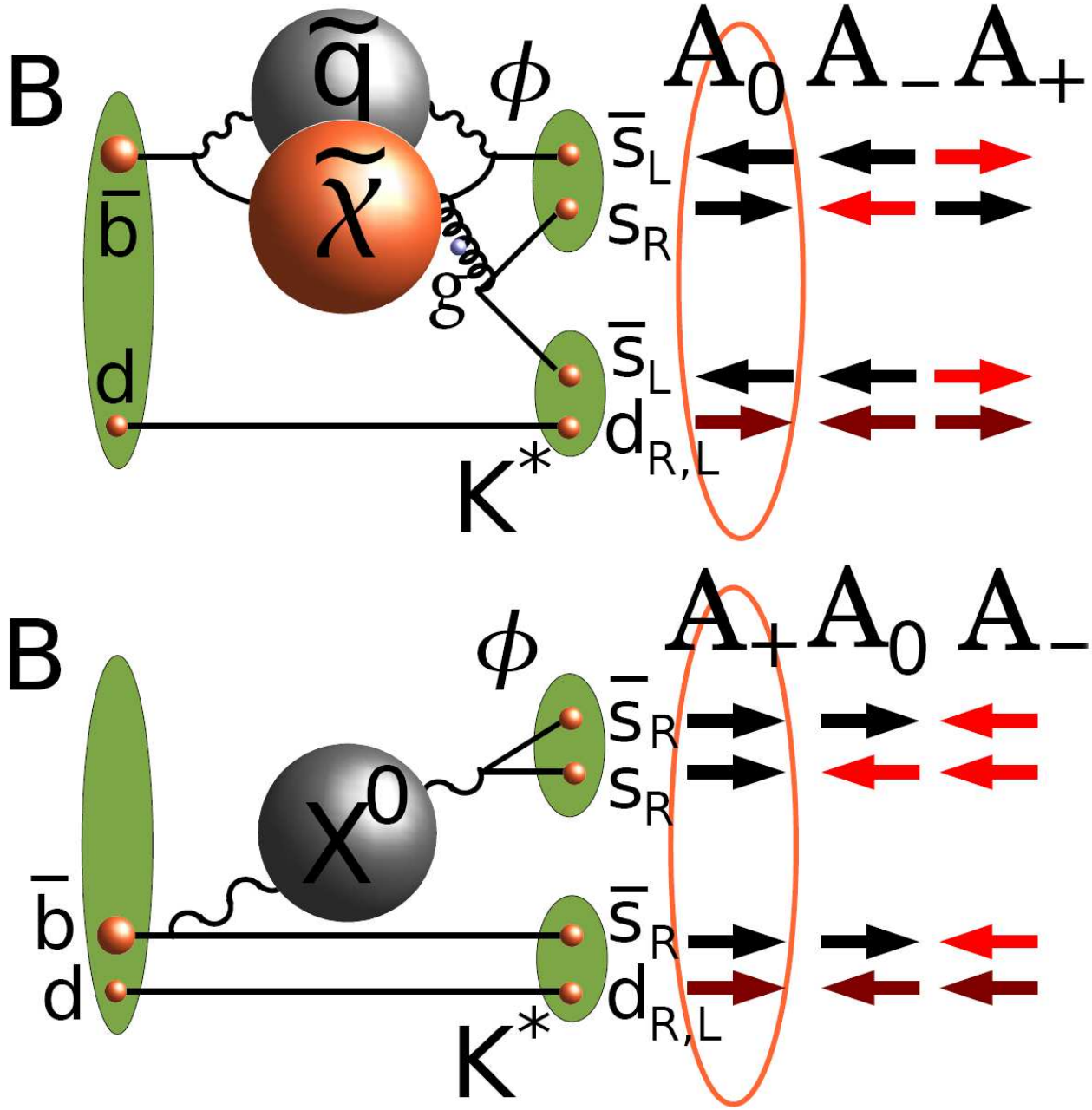
Best constraints on supersymmetry and New Physics

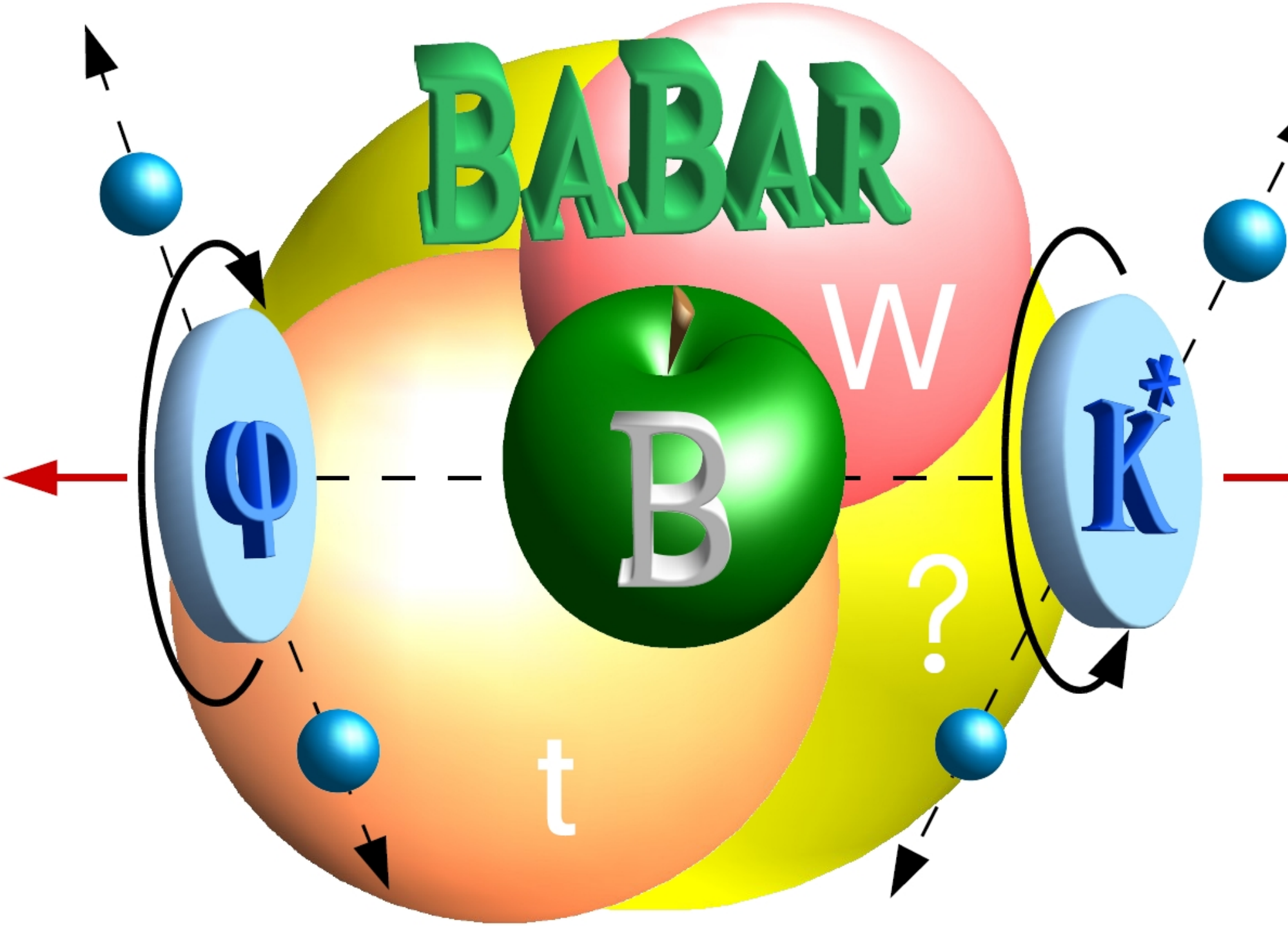
One Example

- Study "penguin" $B \longrightarrow \phi K^*$



New Particles through Uncertainty Principle ?



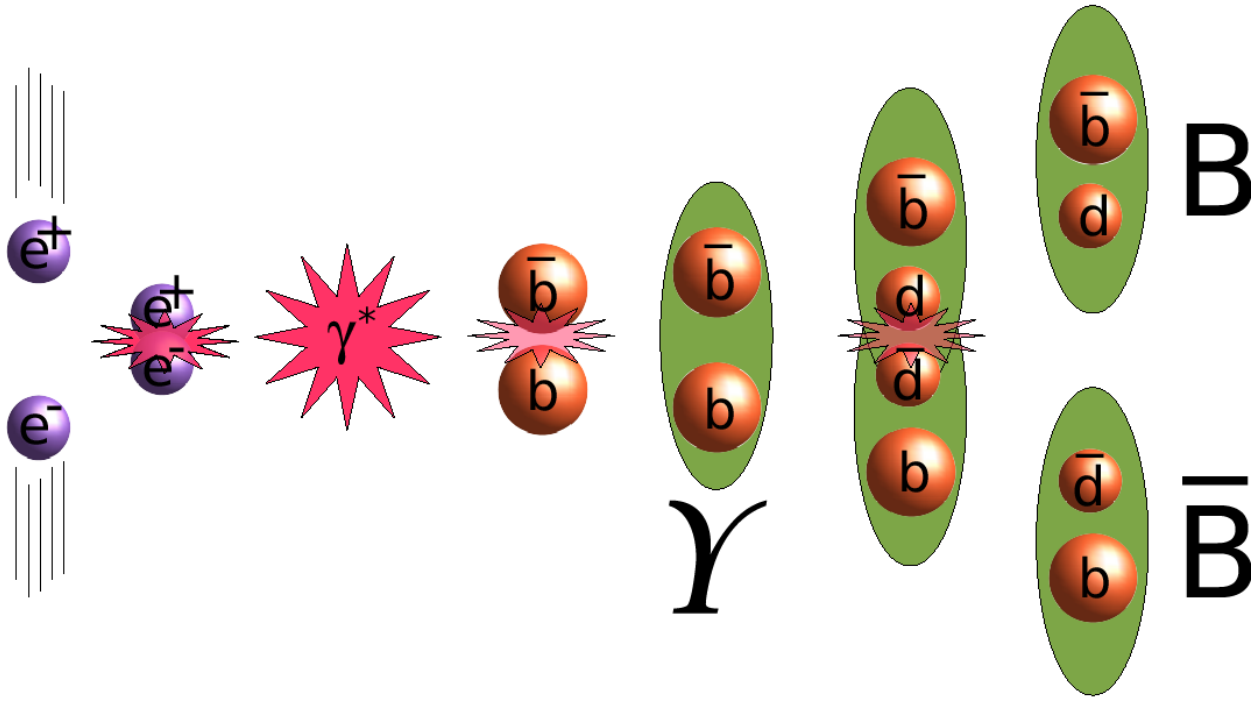


http://today.slac.stanford.edu/a/2006/10-26.htm

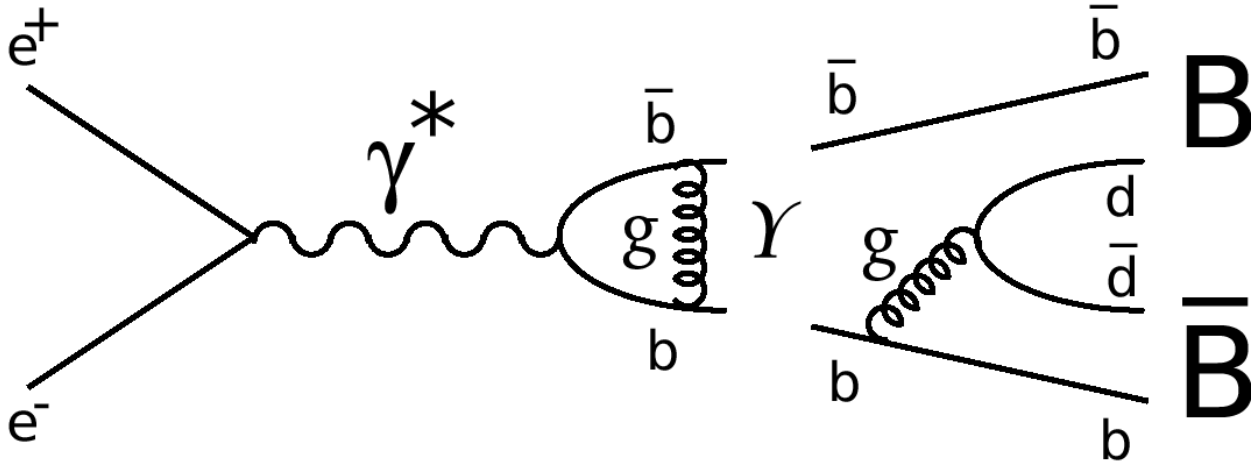
Particle Physics Laboratory

Producing the B Mesons

- Kinematics:



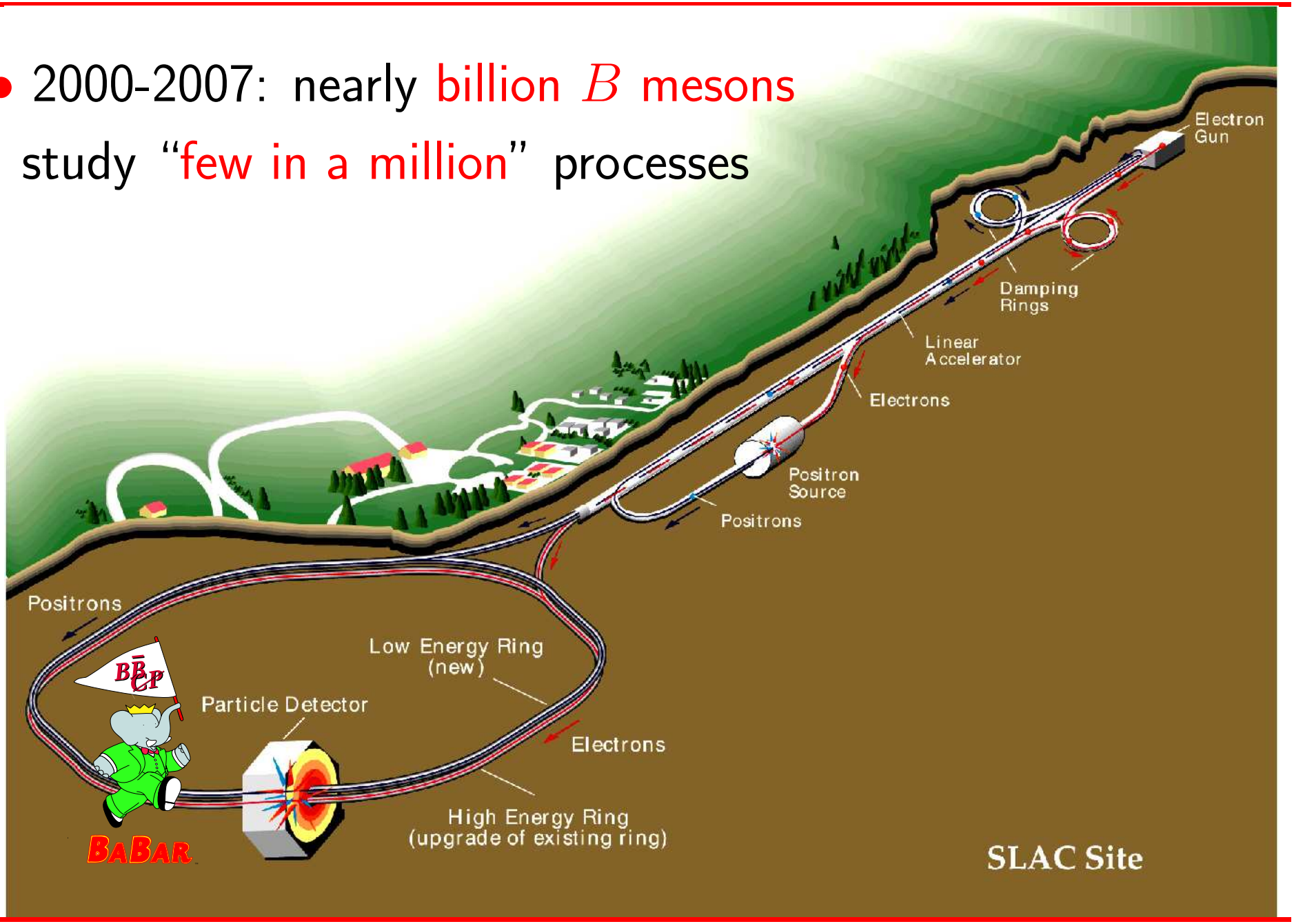
- Dynamics:



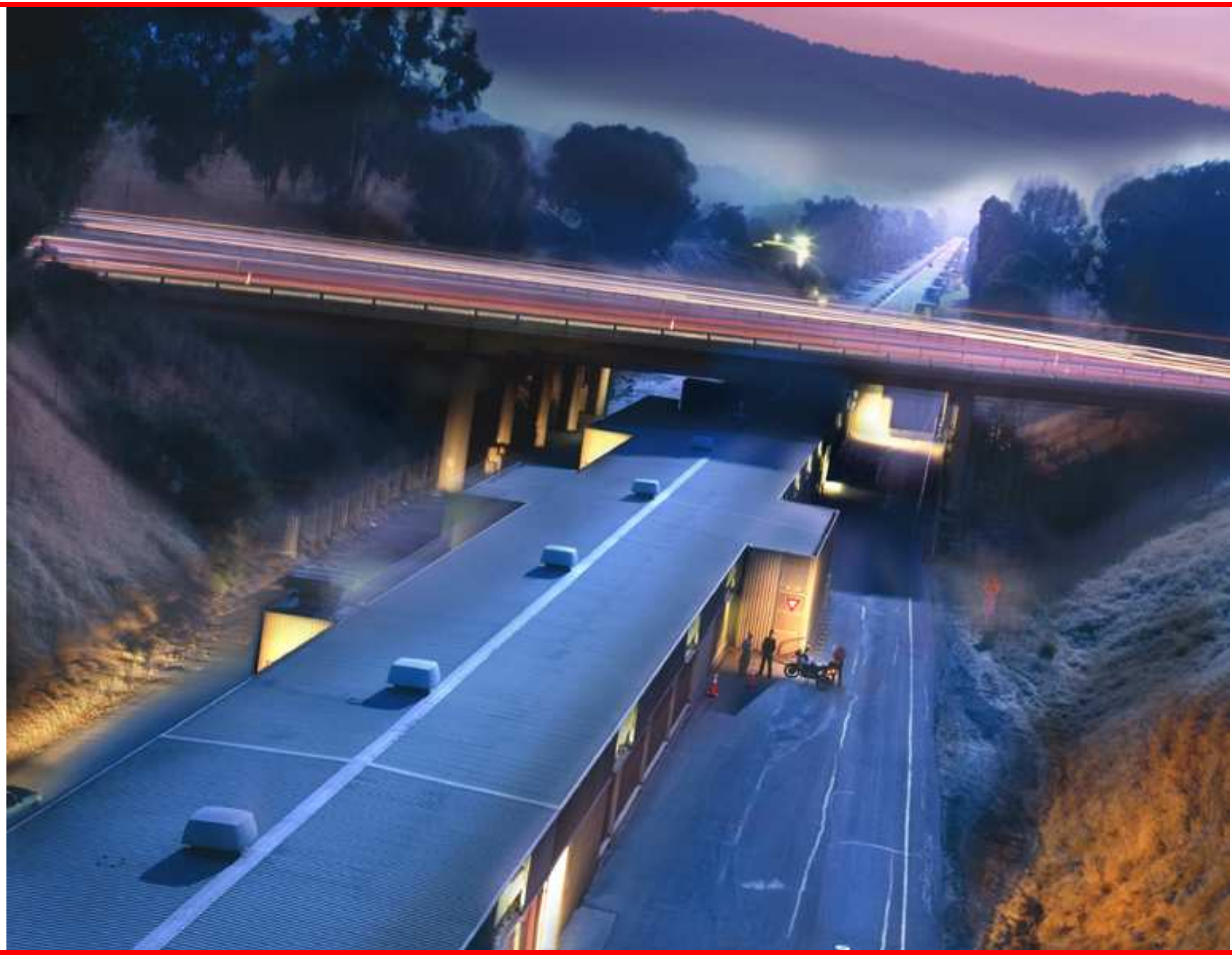
Producing the B Mesons

- 2000-2007: nearly billion B mesons

  study "few in a million" processes



Producing the B Mesons



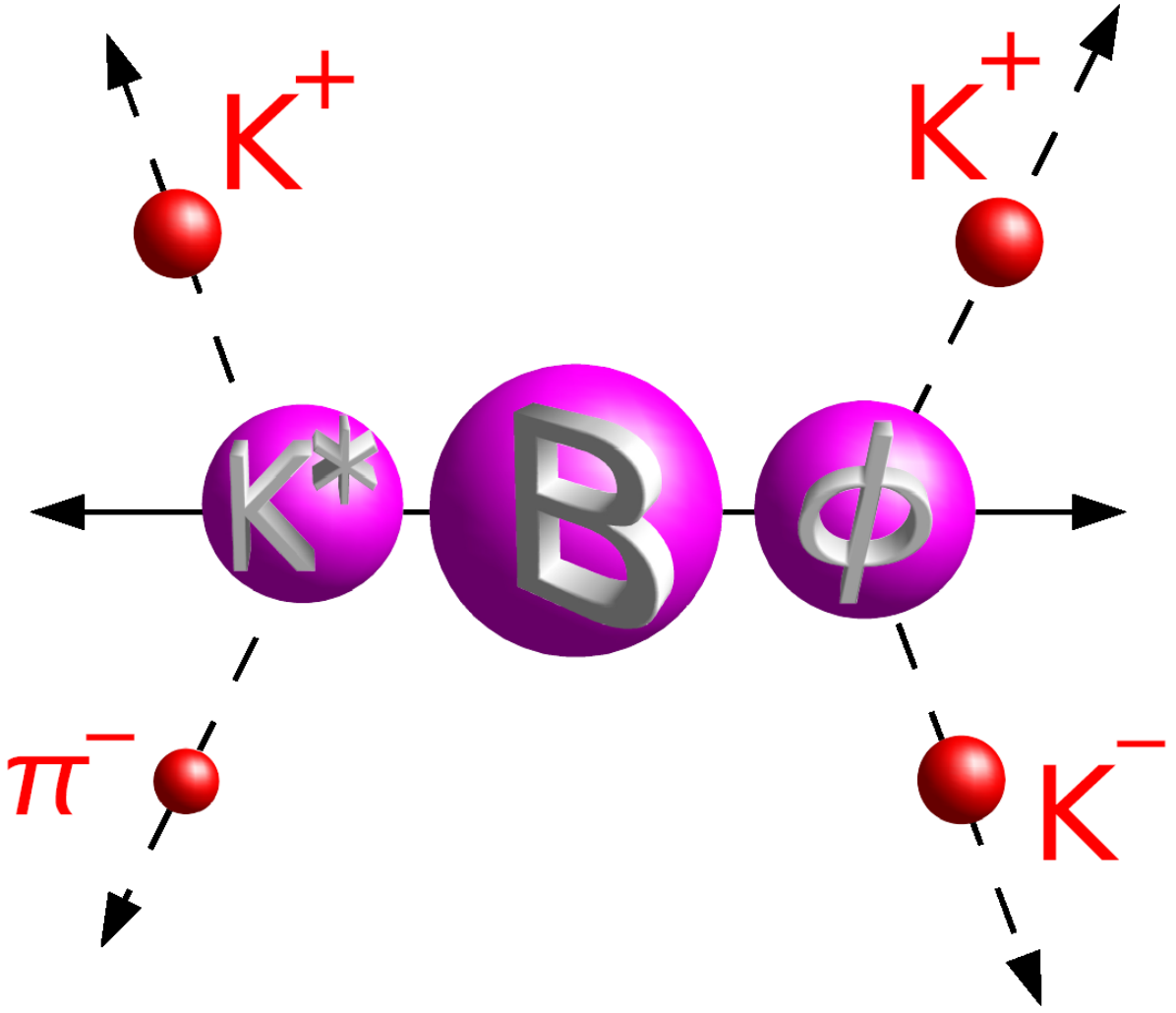
Kinematics of the Decay

- Find 4 "tracks":

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

  find $\sim$ 1-2/week

  rare $<$ 1 in 100,000

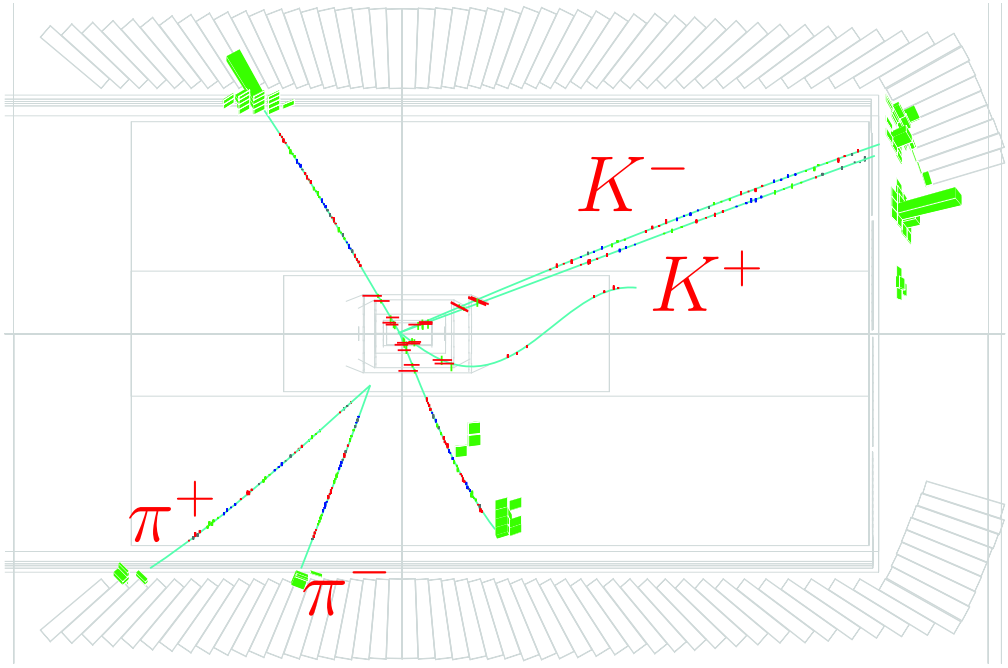


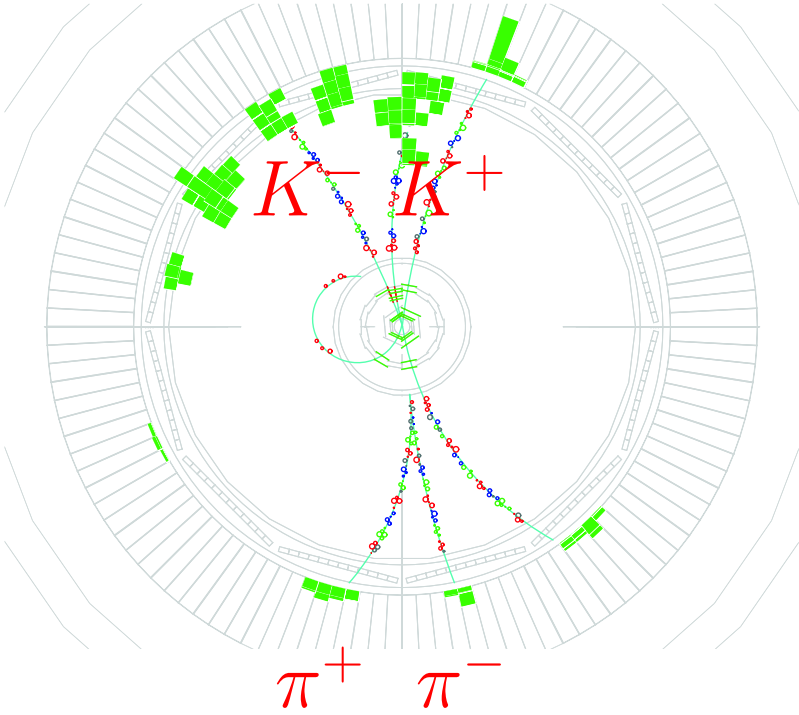
Reconstructing Kinematics in the Detector

- *BABAR* detector at SLAC:

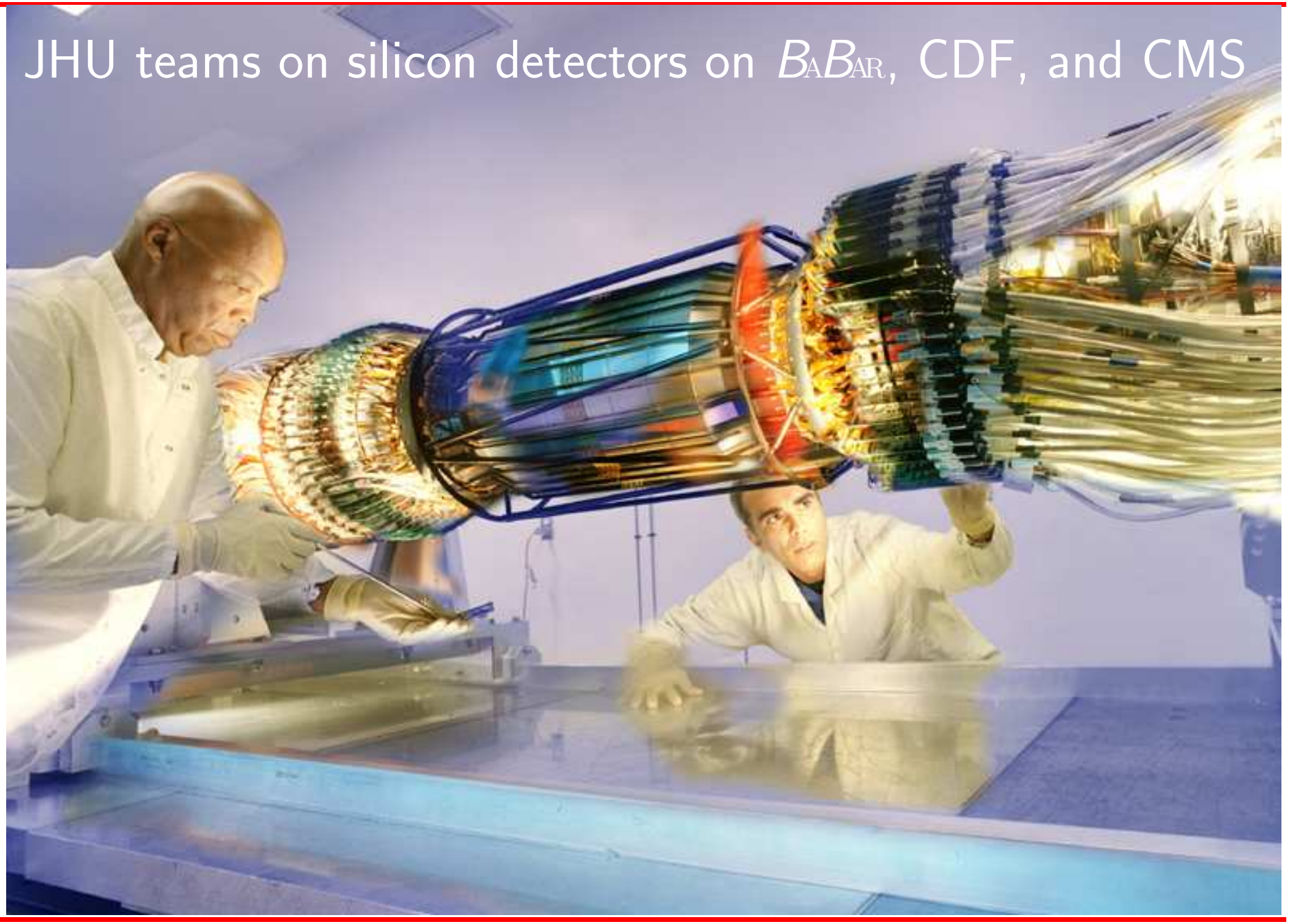
$$B^0 \to \phi K^{*0} \to (K^+K^-)(K^+\pi^-)$$

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

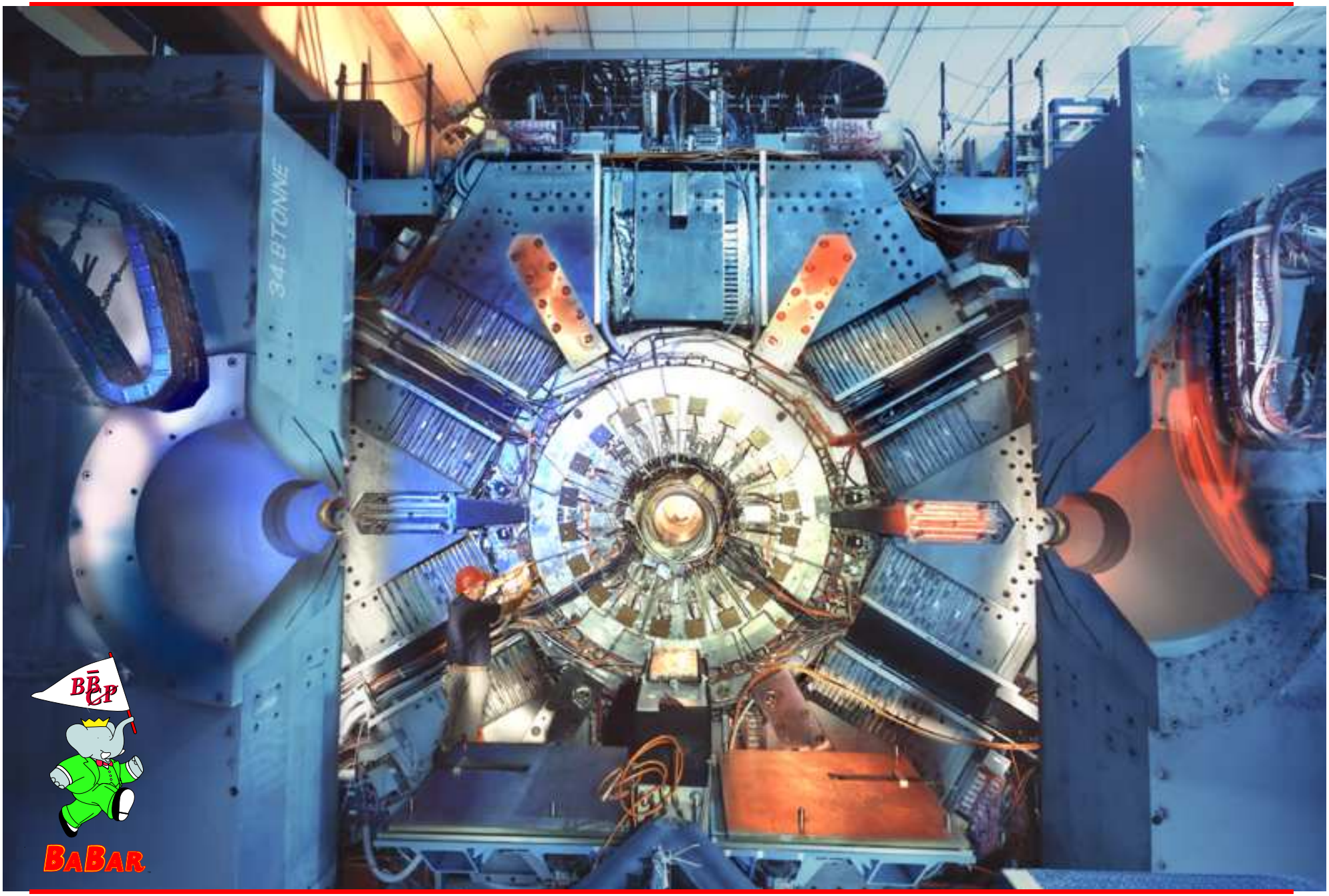




The Heart of the *BABAR* Detector



The *BABAR* Detector



Movie ?