

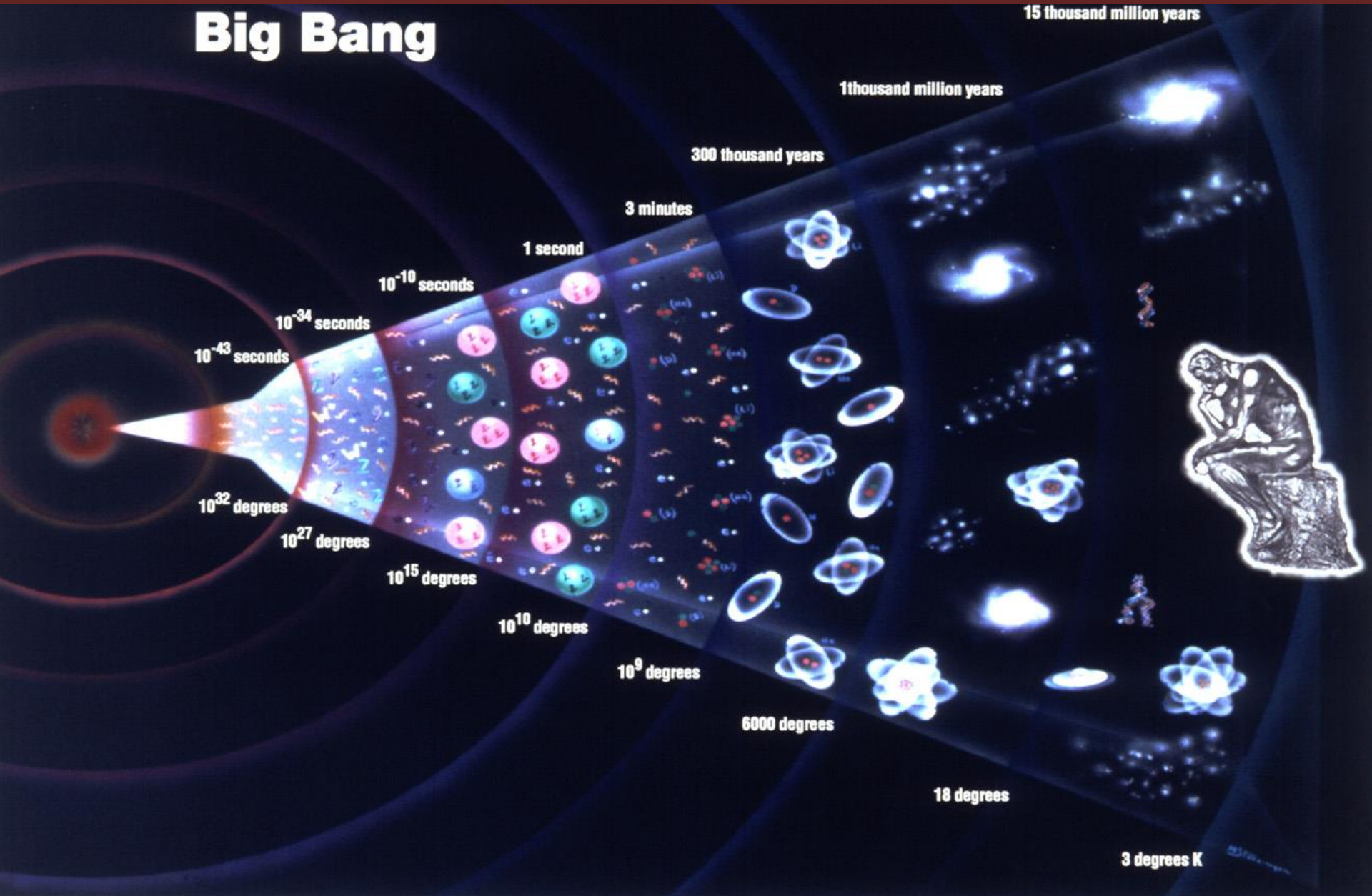
# FYST17 LECTURE 1

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The Standard Model

# About particle physics

## Big Bang



# Some questions to be answered

What happens at high energies  
where our model breaks down?

What is mass?

Do the forces unify ?

Where does gravity fit in?

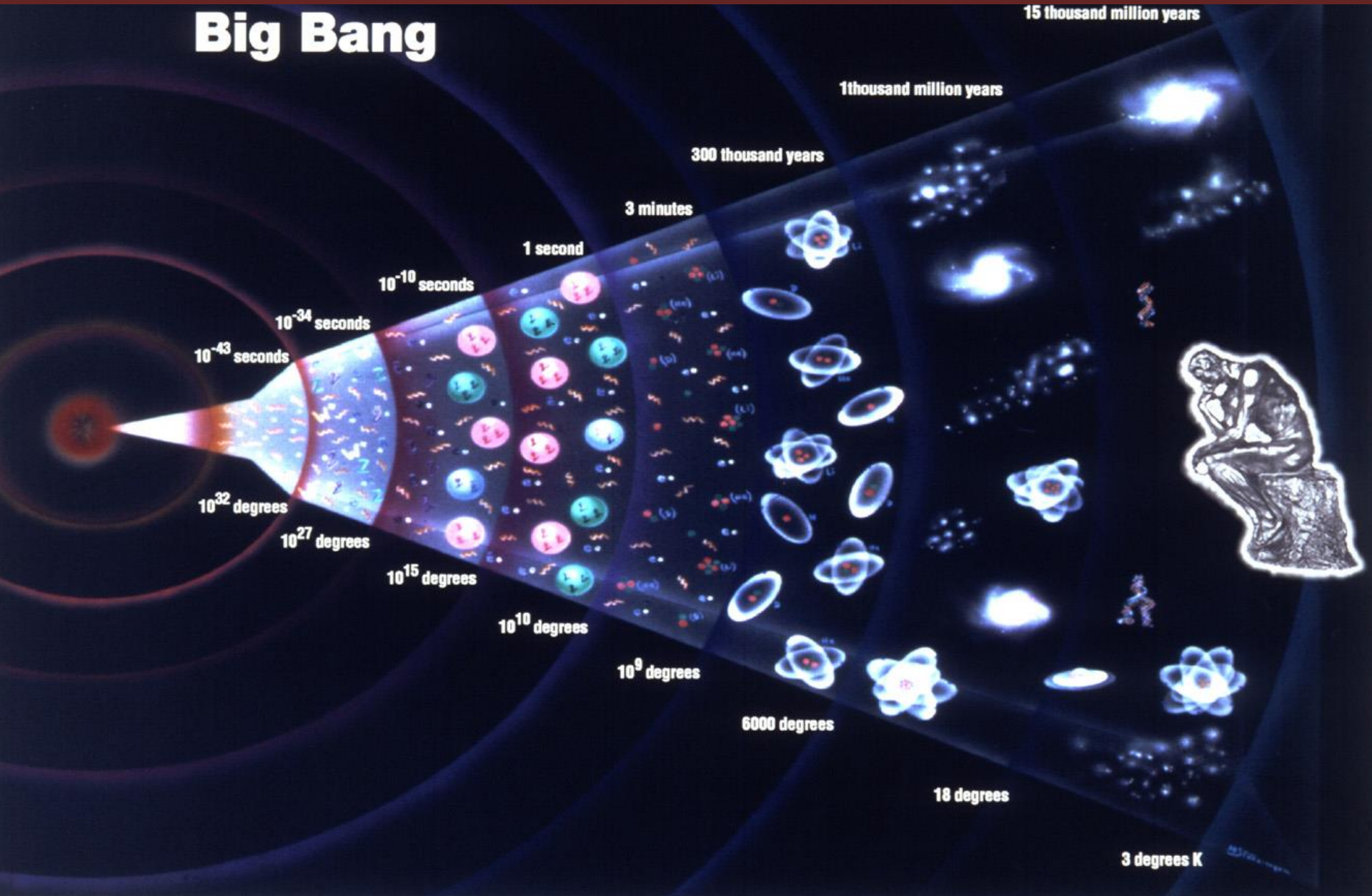
Where has all the anti-matter gone?

Is dark matter a particle?

Are there new space-time symmetries?

# Where to find answers

## Big Bang

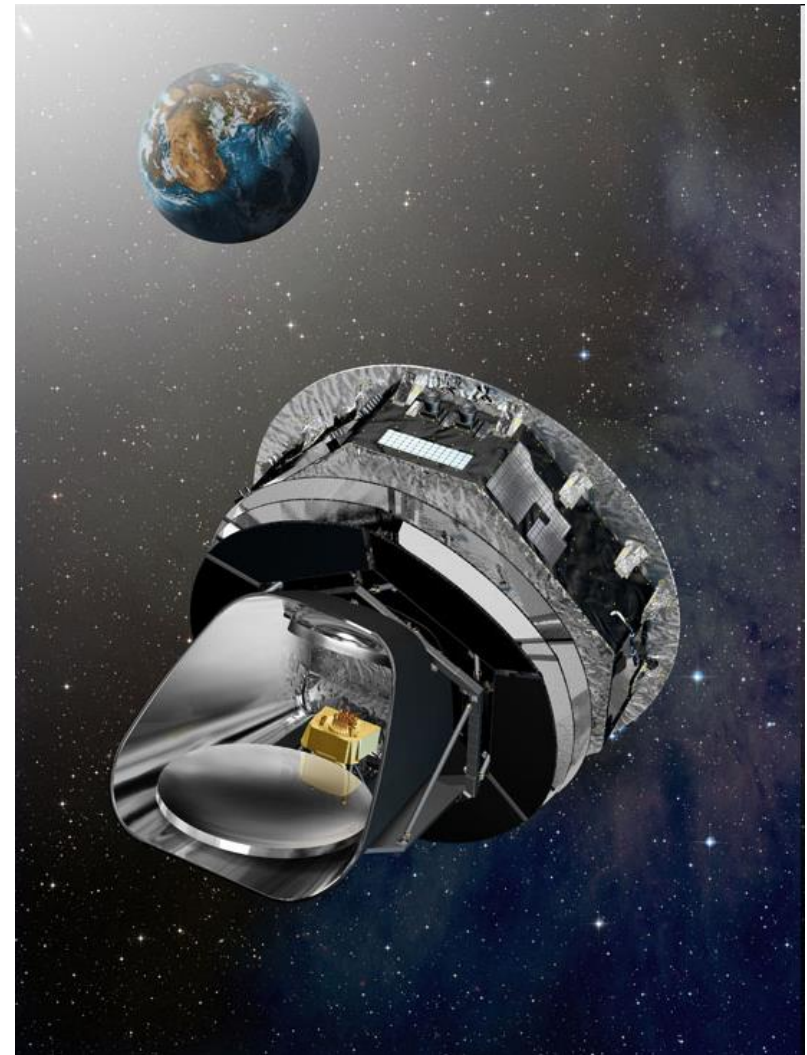


# Two standard approaches



Courtesy Fermilab Visual Media Services

FERMILAB 198-1348D



ESA's Planck satellite, courtesy ESA 5

# Today will be about reminders mostly

- 1) Mini-quiz
- 2) Standard model constituents, short overview
- 3) 4 vectors and kinematics
- 4) Feynman diagrams
- 5) More on hadrons

Q1: If a process can process through all three interactions, which interaction is the most likely:

- A) Strong
- B) Weak
- C) Electromagnetic

## Q2: Which quantity is Lorentz invariant?

- A) The total energy
- B) The 4 momentum  $P$
- C) The 4 momentum squared  $P^2$
- D) The total sum of 4 momentum



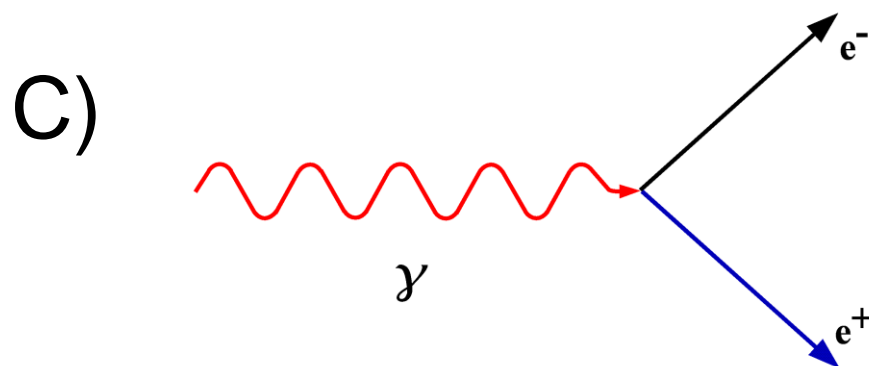
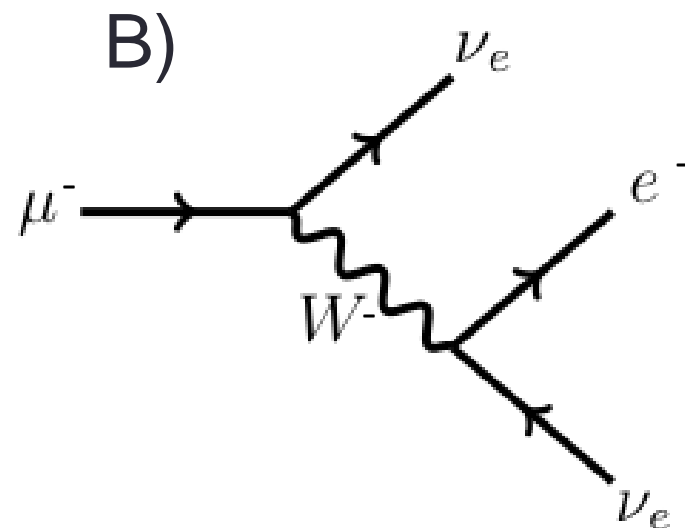
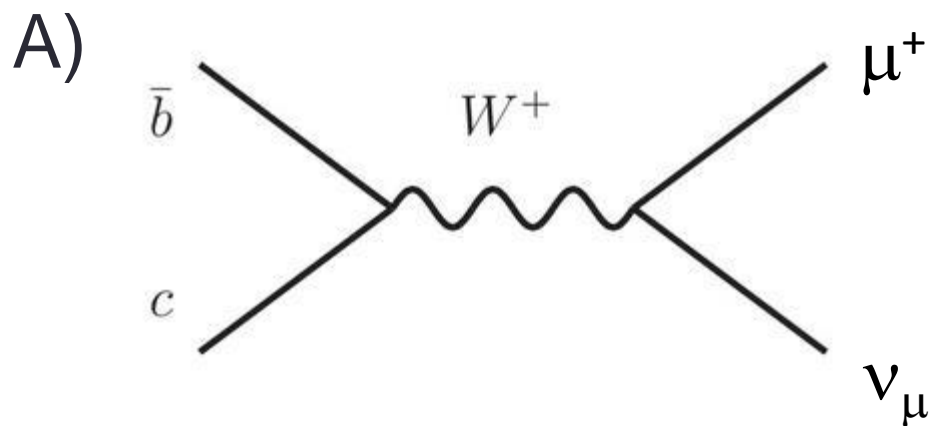
Q3: Which process is not allowed?

A)  $\tau^+ \rightarrow \pi^+ + \nu_\tau$

B)  $\pi^0 \rightarrow \gamma + \gamma$

C)  $K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$

# Q4: Which is a real Feynman diagram?



# The Standard Model in one slide

## Quarks



## Forces

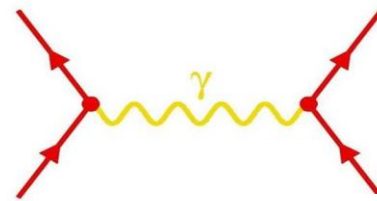


H  
Higgs  
boson

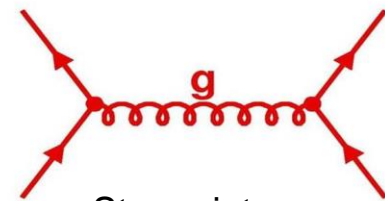


## Leptons

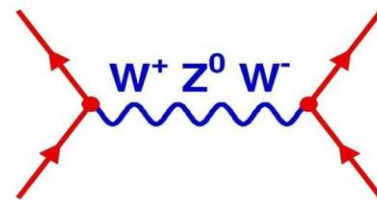
+ anti-particles!



Electromagn. Int.



Strong int .



Weak int.

Existence of **Higgs boson**  
to give mass to the other  
particles

2. and 3. generation unstable  
Decay via weak interaction

# The Standard Model in one slide

## Quarks

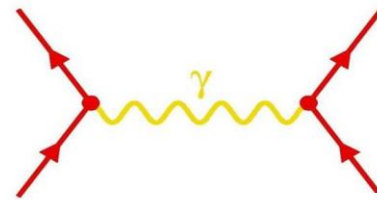


## Forces



## Leptons

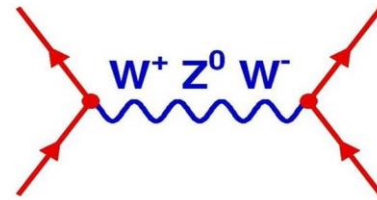
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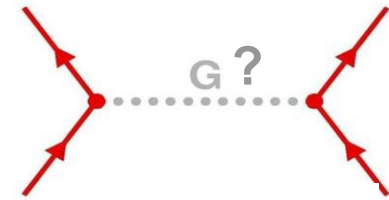
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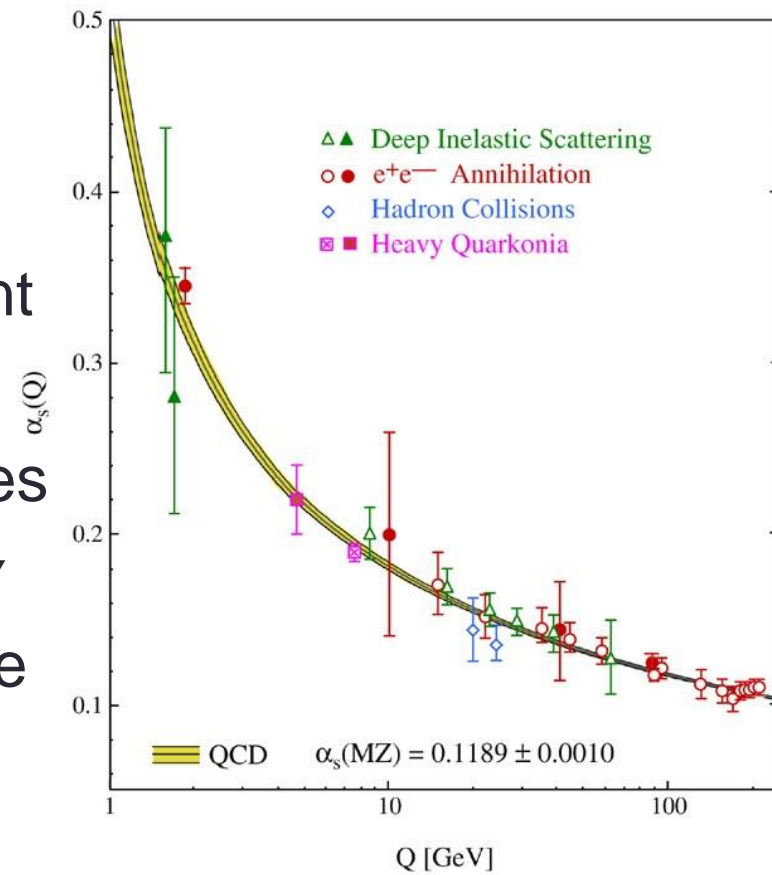
2. and 3. generation unstable  
Decay via weak interaction

# Ok two slides

- Quarks interact **strongly** – color charge
- Charged particles interact via **EM** interactions
- All fermions have a **weak** charge as well

Coupling constants are not actually constant. The strong force exhibits asymptotic freedom and confinement

The weak and electromagnetic forces described in the *Electroweak theory* (Higgs boson is crucial to explain the massive exchange particles)



# Reminder on units

## Units and dimensions

- ❖ Particle energy is measured in *electron-volts*:

$$1 \text{ eV} \approx 1.602 \times 10^{-19} \text{ J}$$

⌘ 1 eV is energy of an electron upon passing a voltage of 1 Volt.

⌘ 1 keV =  $10^3$  eV; 1 MeV =  $10^6$  eV; 1 GeV =  $10^9$  eV

- ❖ The reduced *Planck constant* and the *speed of light*:

$$\hbar \equiv h / 2\pi = 6.582 \times 10^{-22} \text{ MeV s}$$

$$c = 2.9979 \times 10^8 \text{ m/s}$$

and the “*conversion constant*” is:

$$\hbar c = 197.327 \times 10^{-15} \text{ MeV m}$$

- ❖ For simplicity, *natural units* are used:

$$\hbar = 1 \quad \text{and} \quad c = 1$$

thus the unit of mass is  $\text{eV}/c^2$ , and the unit of momentum is  $\text{eV}/c$

## 4 vectors reminders

- In natural units:  $x = (t, \vec{x})$ ,  $p = (E, \vec{p})$ ,  $a = (a_0, \vec{a})$
- Often written as:  $A^\mu = (A_0, \vec{A})$  **contravariant**  
 $B_\mu = (B_0, -\vec{B})$  **covariant**
- Product:  $A \bullet B = A^\mu B_\mu = A_\mu B^\mu = A_0 B_0 - (\vec{A} \bullet \vec{B})$
- **Important Lorentz invariant:  $A^2 = A_\mu A^\mu$**   
*[Prove this if you haven't!]*
- Invariant mass:  $P^2 = E^0 E^0 - (\vec{p} \bullet \vec{p}) = E^2 - p^2 = m^2$

# The Lorentz transformation

In 4-vector notation the space-time rotations can be written as:

$x'^{\mu} = \Lambda^{\mu}_{\nu} x^{\nu}$  where

$$\Lambda = \begin{bmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

*Check these results for the 4-momentum!* (See chapters 2 & 6)

Why is Lorentz invariance important?



# Feynman diagram reminders

To calculate probabilities/ cross sections:

$$\mathcal{P}(\text{process}) = |\mathcal{M}_1 + \mathcal{M}_2 + \dots + \mathcal{M}_N|^2$$

Each matrix element is calculated from a Feynman diagram

Each vertex contribute factor  $\propto$  coupling constant

**For instance EM** lowest contribution is two vertices  $\Rightarrow$

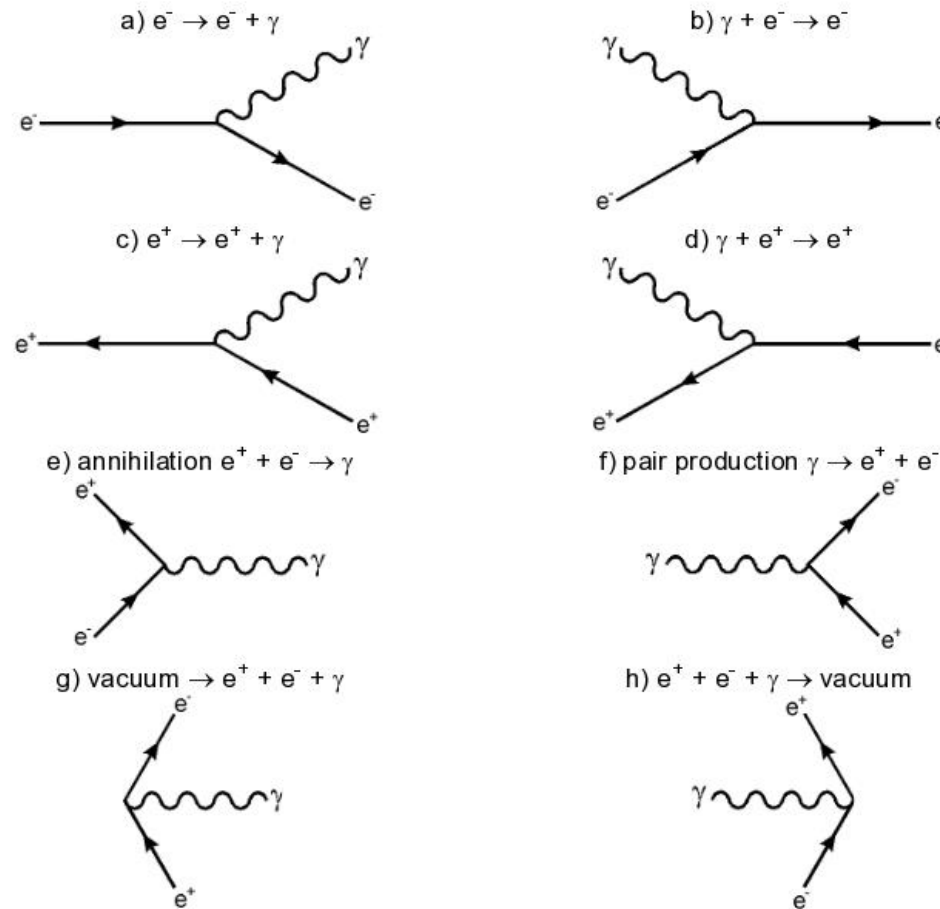
factor  $\alpha_{\text{EM}} \propto 1/137 \rightarrow$

diagrams with many vertices less important

***This is the assumption behind Feynman calculus!***

It is true for EM and weak interactions but not always for strong interactions (confinement at low energies)

# Example building blocks with $e^+$ , $e^-$ and $\gamma$



These are all **virtual** , energy conservation doesn't apply

- ❖ A real process demands energy conservation, is a combination of virtual processes:

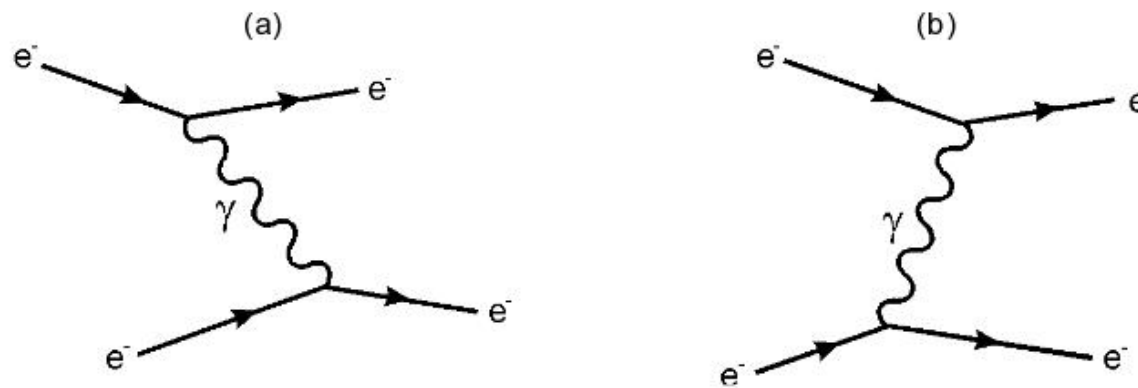


Figure 6: Electron-electron scattering, single photon exchange

- ❖ Any real process receives contributions from *all the possible* virtual processes:

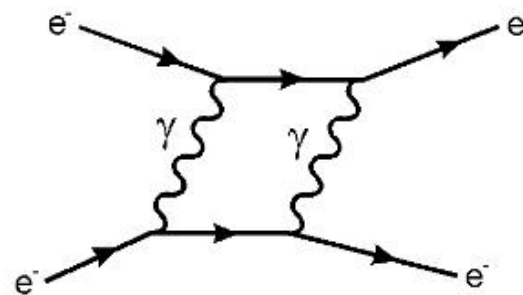
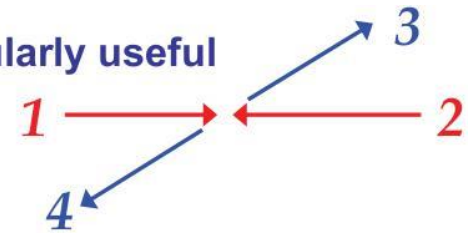


Figure 7: Two-photon exchange contribution

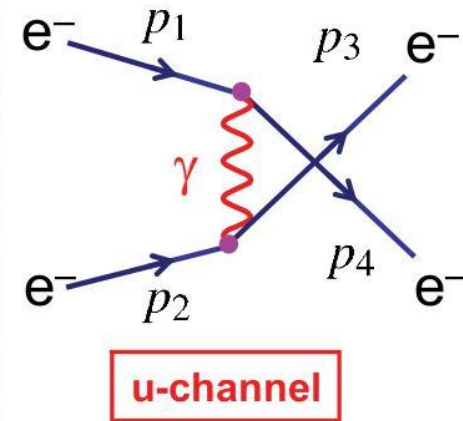
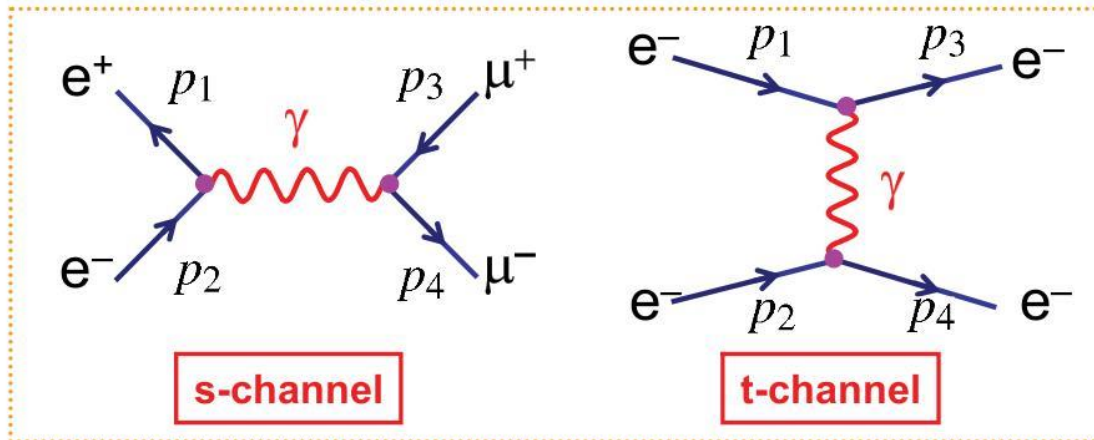
# s, t and u variables

- ★ In particle scattering/annihilation there are three particularly useful **Lorentz Invariant** quantities: **s, t and u**

- ★ Consider the scattering process  $1 + 2 \rightarrow 3 + 4$



- ★ (Simple) Feynman diagrams can be categorised according to the four-momentum of the exchanged particle



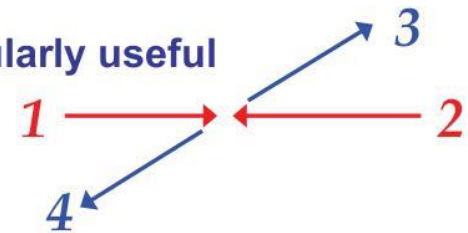
- Can define **three** kinematic variables: **s, t and u** from the following four vector scalar products (squared four-momentum of exchanged particle)

$$s = (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_1 - p_4)^2$$

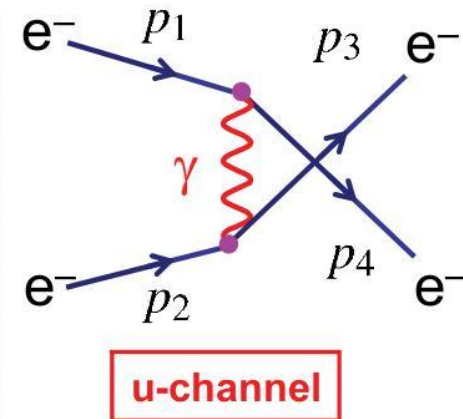
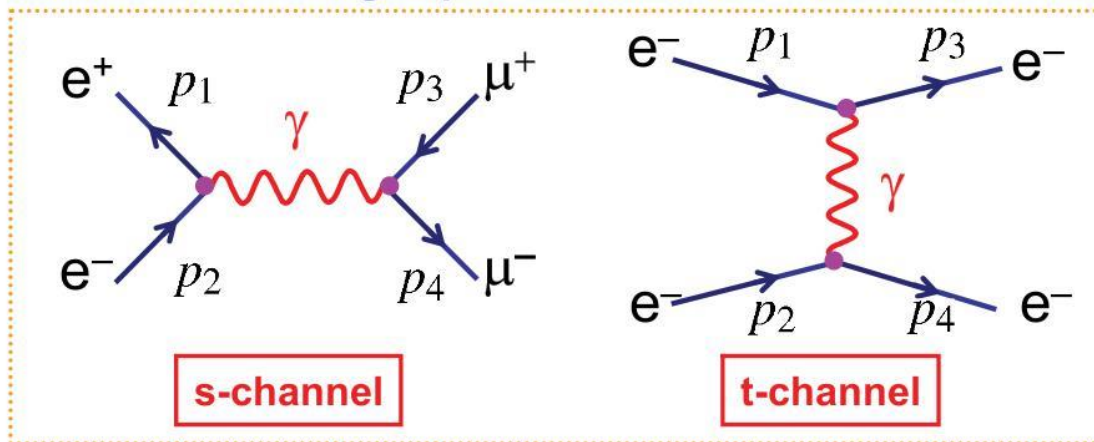
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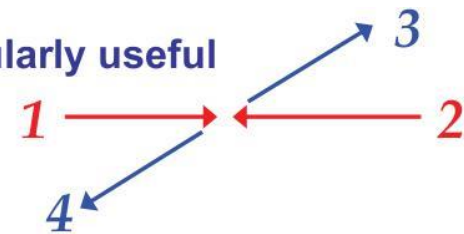
$$s = (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_1 - p_4)^2$$

*S* is often called the center-of-mass energy  $s = E_{cm}^2$

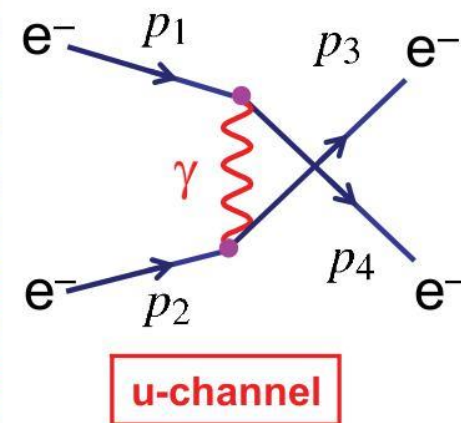
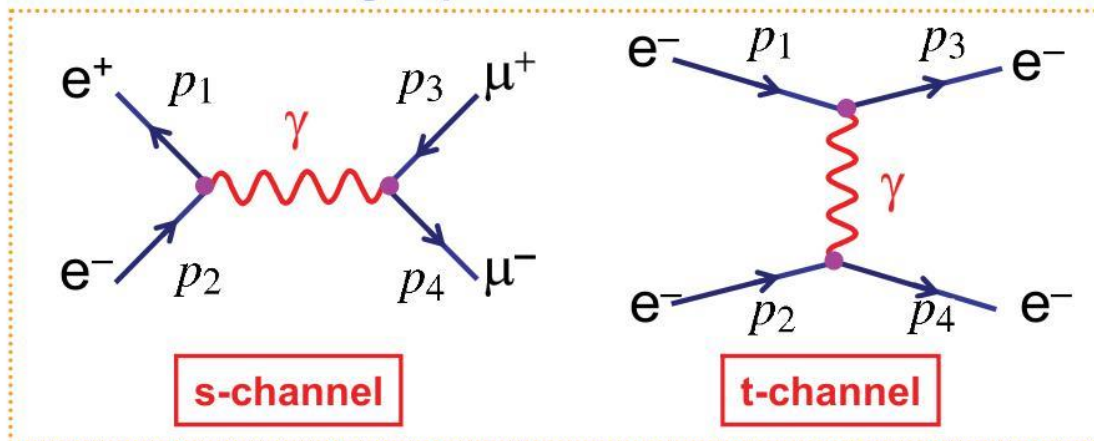
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*S* is often called the *center-of-mass energy*  $s = E_{cm}^2$

What is  
 $s+t+u = ?$

# On the path from diagrams to physics

Or matrix element to observables

*Phase space* describes #states/ unit energy:

Decay width  $\Gamma$  of process : (from Fermi's golden rule)

$$d\Gamma = 2\pi |\mathcal{M}^2| \times d\varphi_n$$

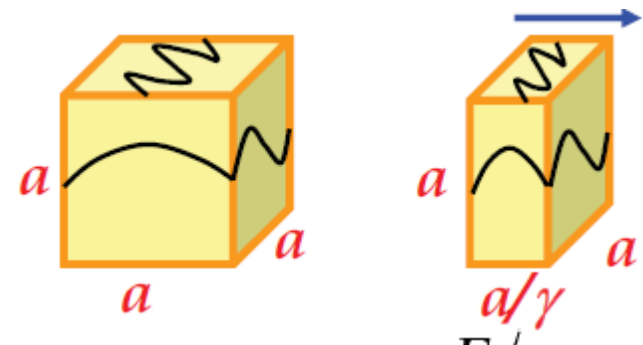
Rates depend on MATRIX ELEMENT and DENSITY OF STATES

Turns out all 2-body decays can be written on the form:

$$\frac{1}{\tau} = \Gamma = \frac{|\vec{p}^*|}{32\pi^2 m_i^2} \int |M_{fi}|^2 d\Omega$$

$$p^* = \frac{1}{2m_i} \sqrt{[(m_i^2 - (m_1 + m_2)^2) [m_i^2 - (m_1 - m_2)^2]]}$$

Don't forget relativistic conditions!



# Composite particles: Hadrons

Baryons  $qqq$ :  $p$ ,  $n$ ,  $\Lambda$ ,  $\Sigma^+$  ( $uus$ )

Mesons  $q\bar{q}$ :  $\pi^0$ ,  $\pi^+$ ,  $K^-$ ,  $B_c^+$

Lifetimes: Depends on mechanism:

Strong decay  $\Rightarrow$  short lifetime  $\sim 10^{-23}$  s

EM decay  $\Rightarrow 10^{-16} - 10^{-21}$  s

Weak decay  $\Rightarrow 10^{-7} - 10^{-13}$  s



These are sometimes called "long-lived"

***Only stable hadron is the proton***

Strange hadrons:

For instance  $\Lambda$ ,  $K^-$ ,  $\Sigma^+$  first discovered in cosmic rays

New quantum number strangeness  $S$  ( $S=+1$  for  $\bar{s}$ ) conserved in EM and strong interactions



# Heavy hadrons

**"Charmed" hadrons:** First seen as resonances,  $J/\psi$ ,  $\Upsilon$

But also as D mesons:  $D^+(1869) = c\bar{d}$ ;  $D^0(1865) = c\bar{u}$

$D^-(1869) = d\bar{c}$ ;  $\bar{D}^0(1865) = u\bar{c}$

And D baryons, for instance  $\Lambda_c^+$  etc

**"Beauty" hadrons**

B mesons such as  $b\bar{b}$ ,  $B^+ = u\bar{b}$ ,  $B_c^+ = c\bar{b}$  etc

B baryons such as  $\Lambda_b^- (5461) = udb$  etc

*BUT NO TOP HADRONS*

*(one can still define a "truth" quantum number)*

How do we know if we have found all the hadrons?



# What about light flavor symmetries?

No up or down quantum number – instead *isospin*:

$$m_{\text{neutron}} \approx m_{\text{proton}} \quad \text{and} \quad V_{pp} \approx V_{np} \approx V_{nn}$$

Nuclear force is  $\approx$   
charge-  
independent

If we could turn off electric charge we would not be able to distinguish!

The strong forces experienced by n and p identical

Heisenberg proposed them as two states of single particle, the nucleon:

$$p = \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \quad n = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Analogous to spin angular momentum:

$$p = | \frac{1}{2} \frac{1}{2} \rangle \text{ "isospin up"}$$

$$n = | \frac{1}{2} -\frac{1}{2} \rangle \text{ "isospin down"}$$

These form isospin doublet with total  $I = \frac{1}{2}$  and third component  $I_3 = \pm \frac{1}{2}$

Physics (i.e. strong force) invariant under rotation in "isospin space" assuming equal masses

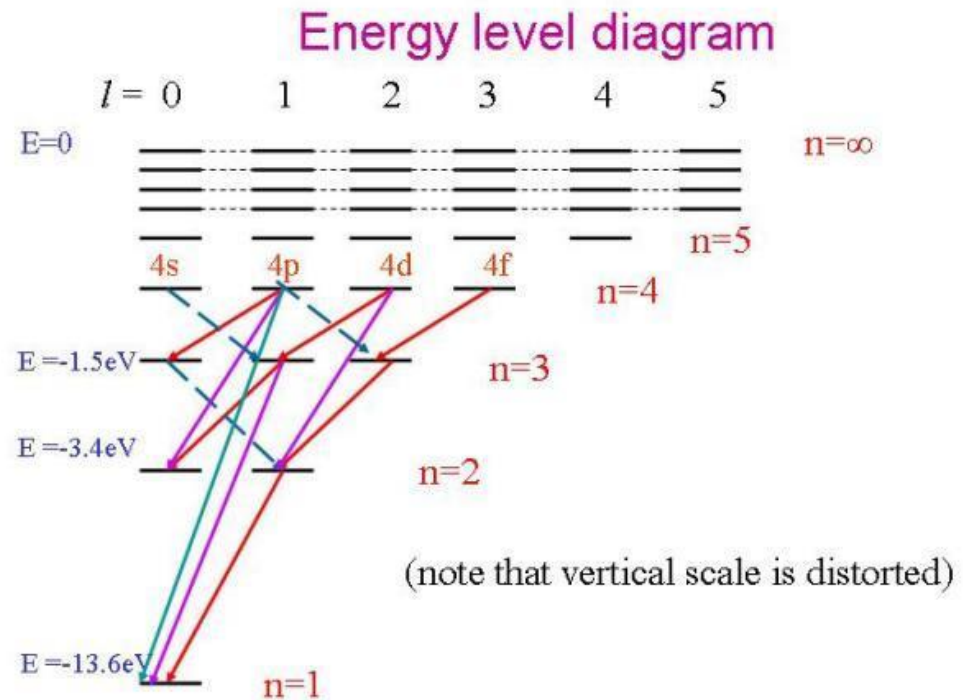
Isospin conserved in all strong interactions

# Spectroscopy

For combination of heavy quarks, the  $q - \bar{q}$  system is essentially non-relativistic ( $m_q \gg E_{kin}$ )

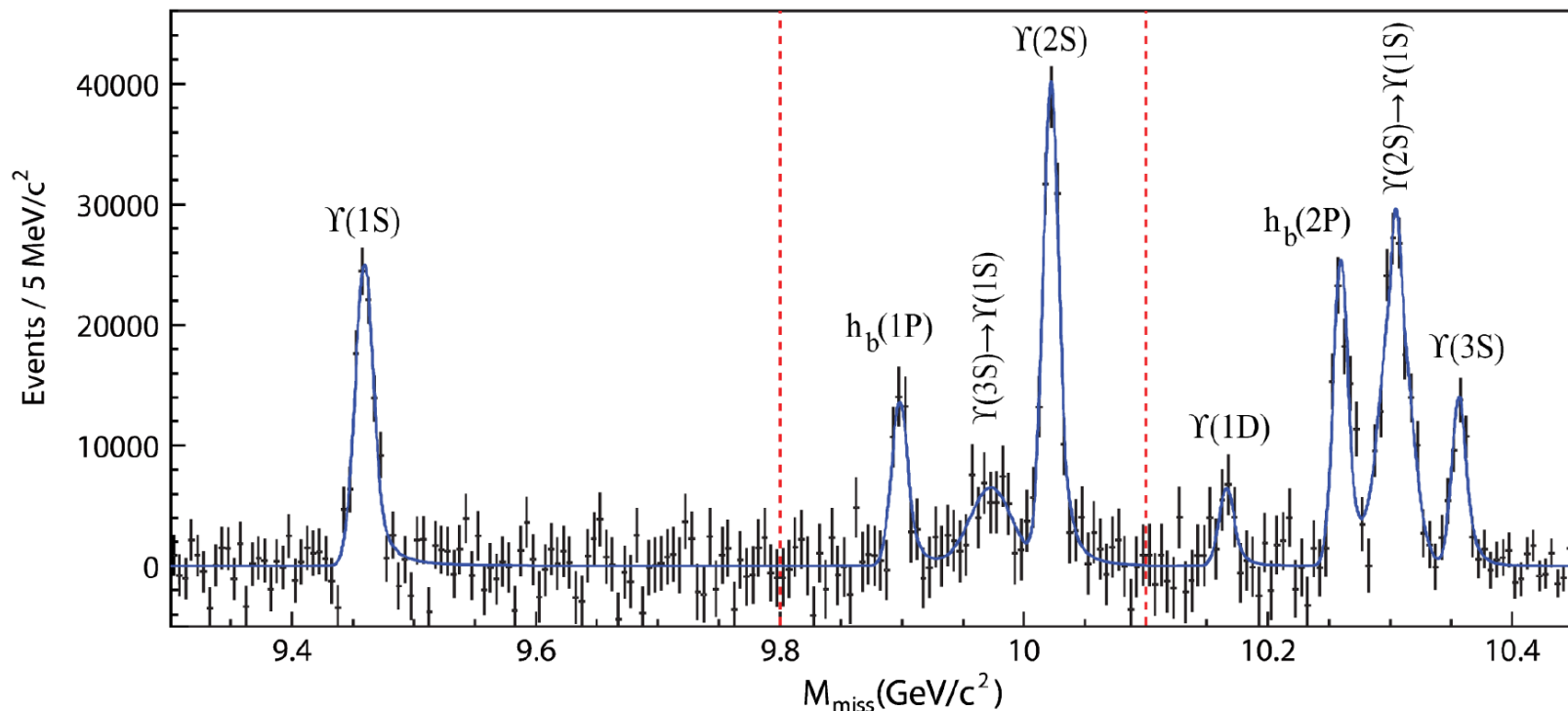
Quarkonium ( $c\bar{c}$ ,  $b\bar{b}$ ) analogous to hydrogen atom with several energy levels

**Important difference**  
the quarkonium system is dominated by the **STRONG** force



# Quarkonia

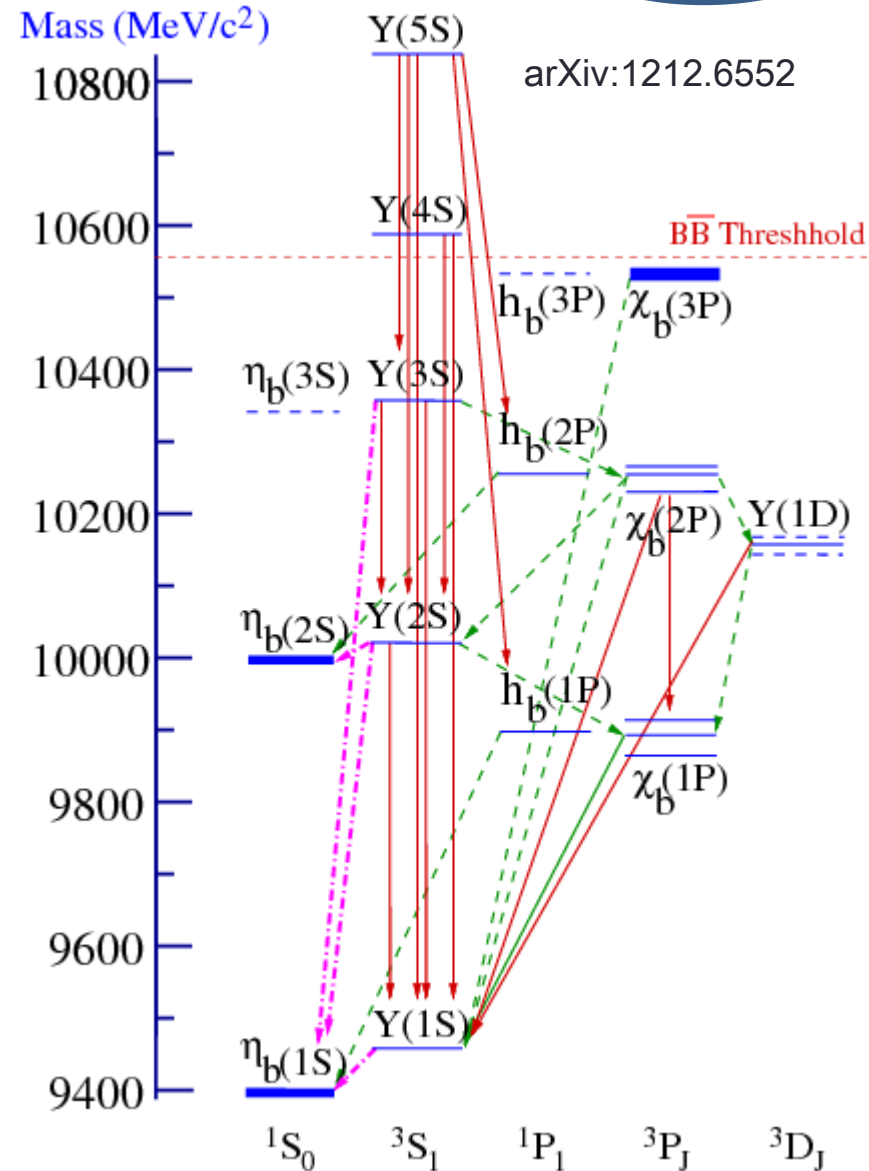
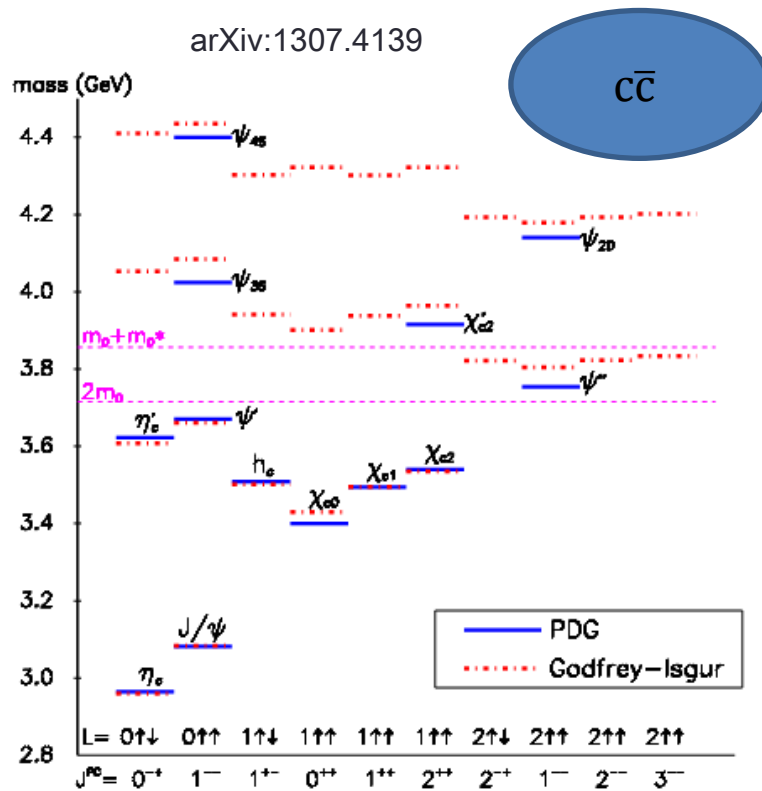
Looks like several particles with different masses but same quark content



Just starting to measure experimentally the mixed systems  $c\bar{b}$ ,  $\bar{c}b$  (weakly produced)

# Quarkonia spectroscopy

$b\bar{b}$

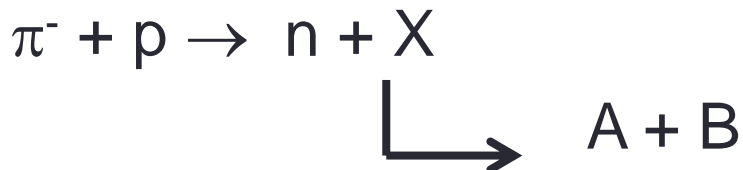


# Resonances

Unstable particles with very short lifetimes  $10^{-13} - 10^{-24}$  s

This could for instance be strong decay of excited state down to a ground state (that then decays weakly)

Key feature: we only detect these by their decay products



A typical way to detect these are using the invariant mass:

$$M^2_X = (E_A + E_B)^2 - (p_A + p_b)^2$$

This will show a mass peak distribution



Resonance peak shapes are approximated by the *Breit-Wigner* formula:

$$N(W) = \frac{K}{(W - W_0)^2 + \Gamma^2/4} \quad (103)$$

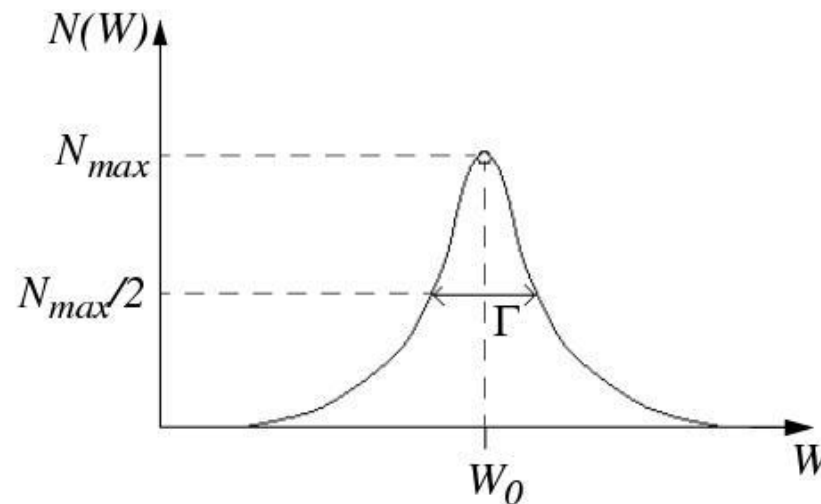


Figure 93: Breit-Wigner shape

- ☉ Mean value of the Breit-Wigner shape is the mass of a resonance:  $M=W_0$
- ☉  $\Gamma$  is the width of a resonance, and it has the meaning of inverse mean lifetime of particle at rest:  $\Gamma \equiv 1/\tau$

# Exceptions: X(3872)

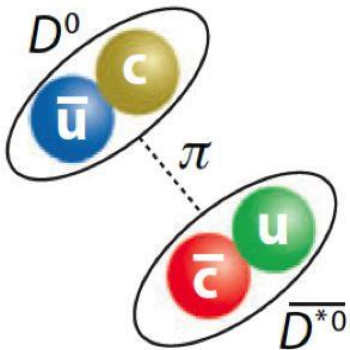
Discovered by the *Belle* experiment in 2003.

Still doesn't fit in

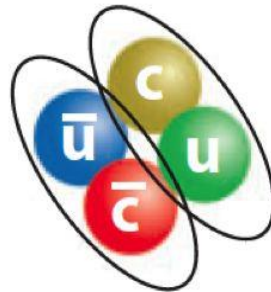
*LHCb* measured:

$$J^{PC} = 1^{++}$$

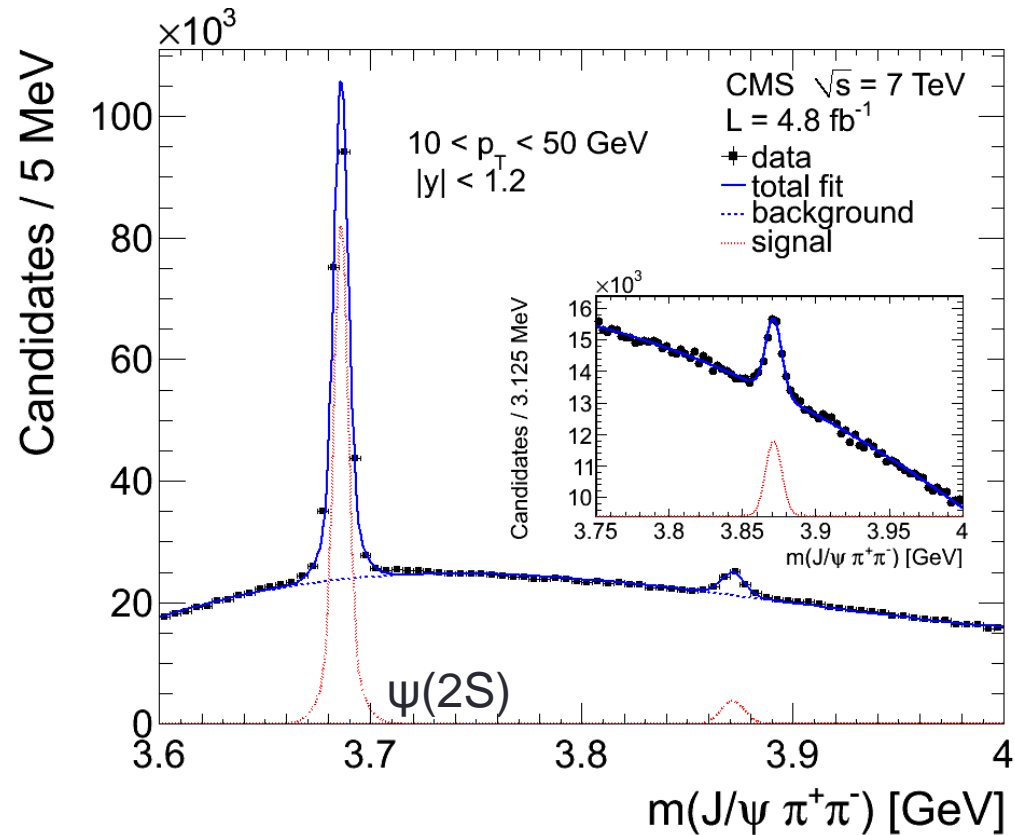
so not charmonium,  
perhaps D-D\* molecule?



$D^0-\bar{D}^{*0}$  "molecule"

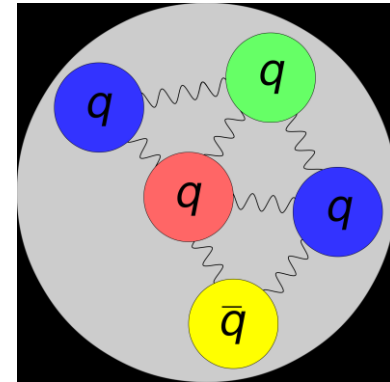


Diquark-diantiquark



# Pentaquarks!

- The "old" story:
- Proposed states with 5quarks (or  $4q, 1\bar{q}$ )
- Discovered (?) 2003 by LEPS experiment:
  - $\Theta^+$  ( $uudd\bar{s}$ ) , mass = 1,54 GeV.
  - Not very significant little statistics

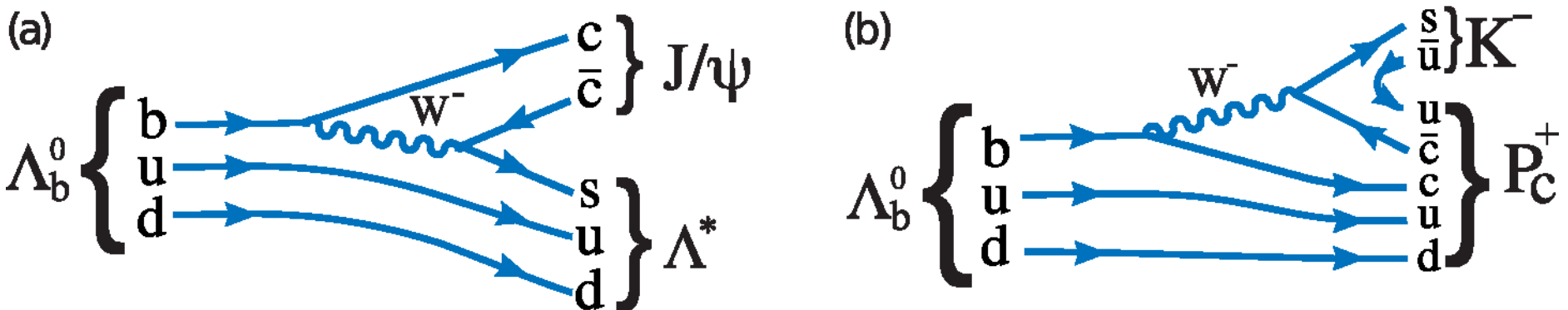


Over the next few years several other low statistics experiments report that they also see it

By 2006: High statistics collider searches for pentaquarks at LEP & Belle. These experiments see NOTHING  
 $\Rightarrow$  the pentaquark is dead ?

# The 2015 pentaquark "accident"

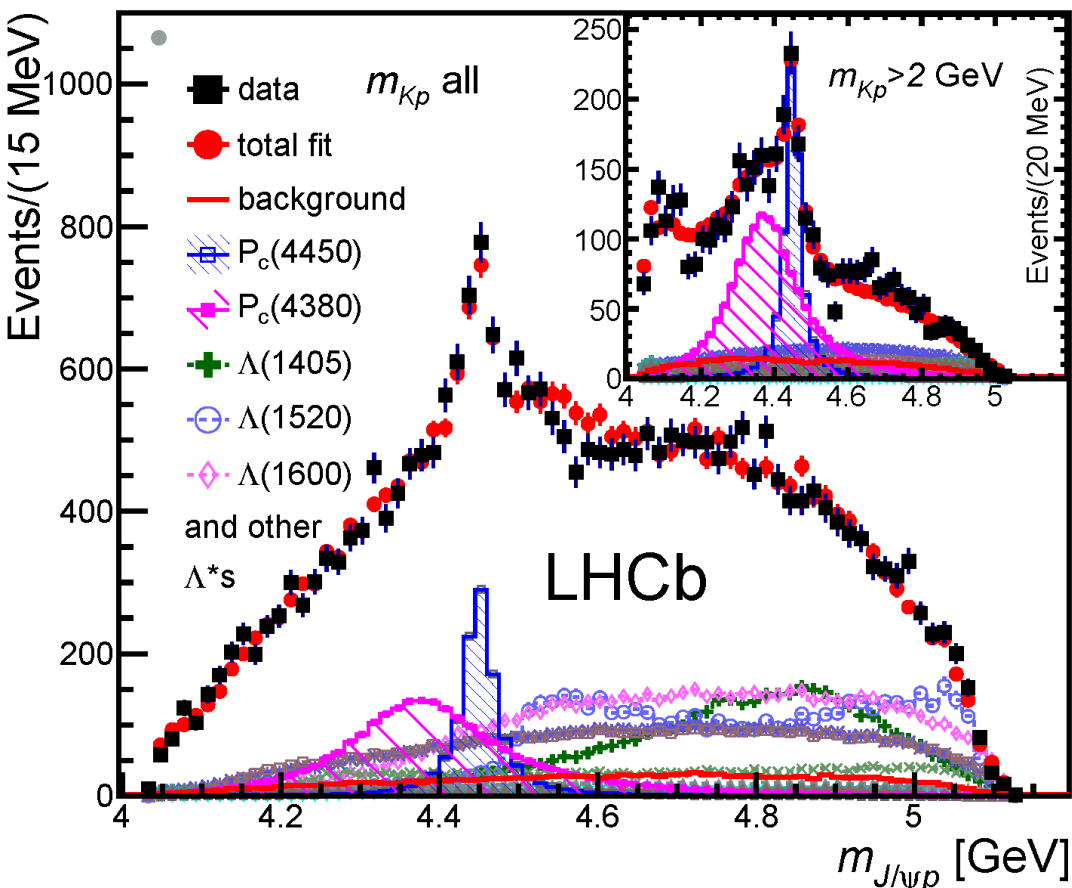
- Publication in Phys.Rev.Letters (arXiv:1507:03414) July 2015: "Observation of J/psi p resonances consistent with pentaquark"



- Proposed state would be  $uudc\bar{c}$

Best fit to data involves two new states with masses

- $P_c^+(4050)$  mass =  $4449.8 \pm 1.7 \pm 2.5$  MeV
- $P_c^+(4380)$  mass =  $4380 \pm 8 \pm 29$  MeV



Systematical uncertainty

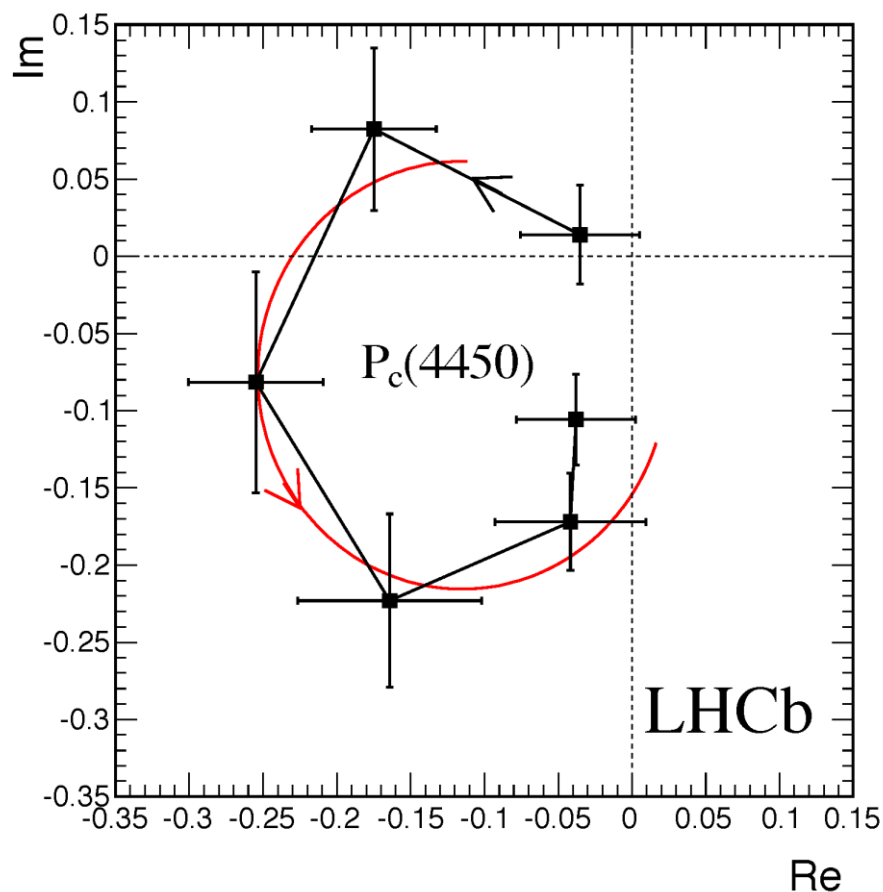
Statistical uncertainty

Significances 9-15  $\sigma$

2016 analysis confirms this

# How do they know?

That it is a new resonance particle (and not just a proton and a  $J/\psi$ ?)



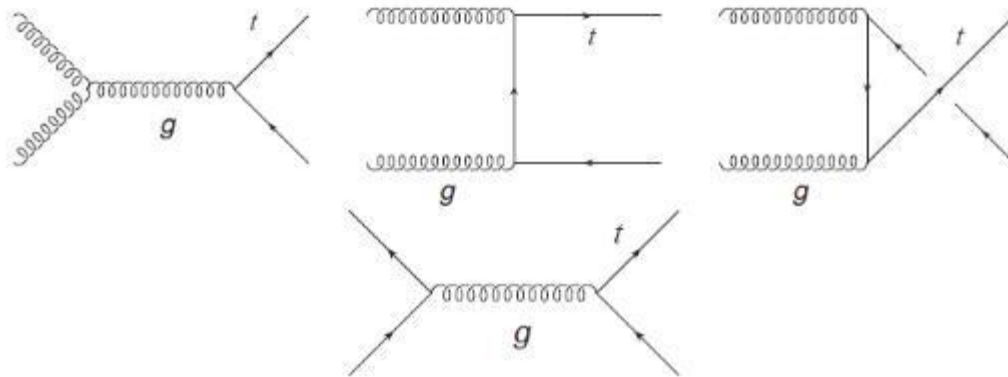
One of the tests:

A resonant particle should follow a circle in an Argand diagram ( F. Halzen and P. Minkowski, nuclear physics B, vol 14 Issue 3 (1969) p 522-530)

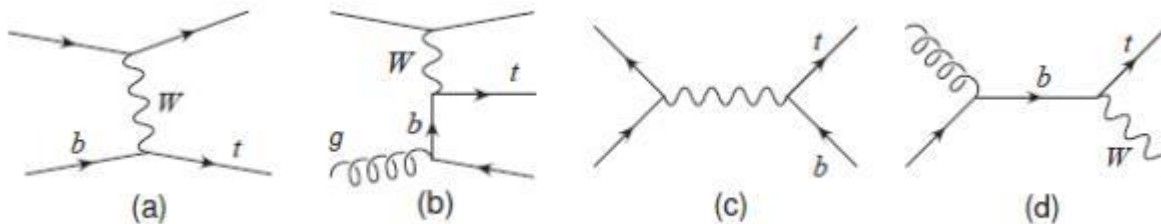
# Top quarks

Only seen in hadron collisions so far

Pair production:  $q\bar{q}$  and  $gg$  fusion

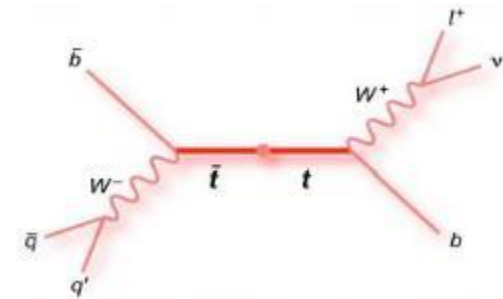
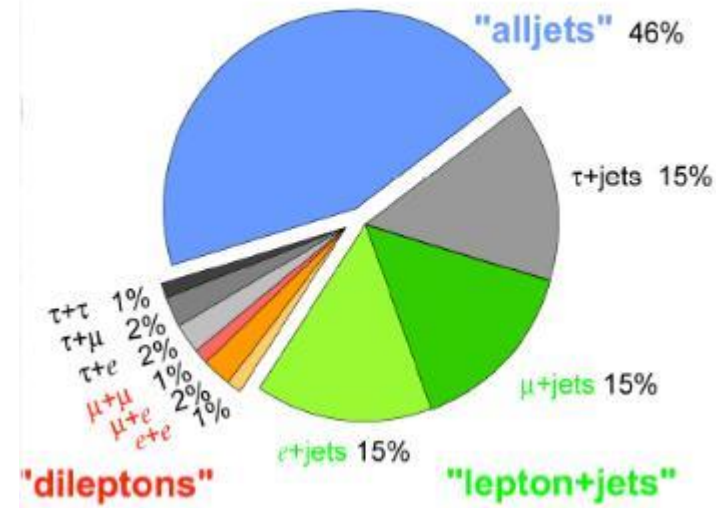


Single production: Drell-Yan and  $Wg$  fusion

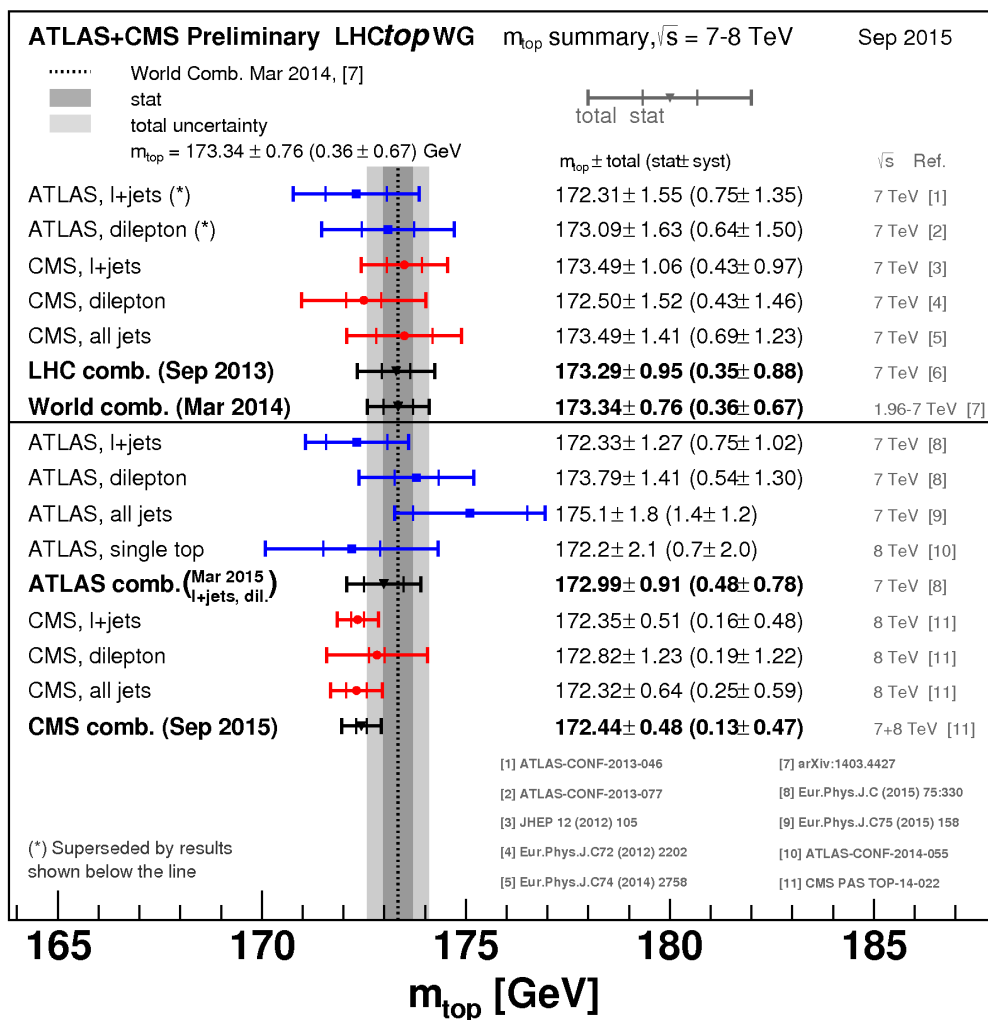


## Top quark decays

### Top Pair Branching Fractions



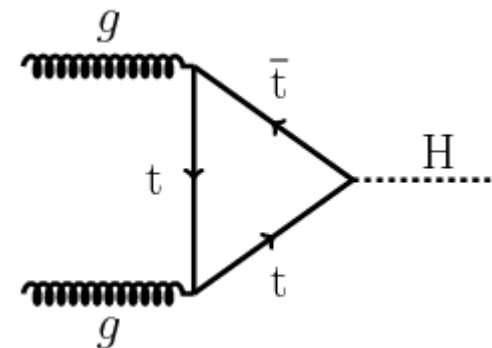
# Top quark properties



The LHC is a top factory:  
 Precision measurements  
 of the mass and other  
 properties

$$M_{\text{top}} = 173.34 \pm 0.36 \pm 0.67 \text{ GeV}$$

Investigating the  $Ht\bar{t}$   
 vertex:





# Top charge asymmetry?

## Definitions

- Asymmetry defined for  $ee \rightarrow \mu\mu$

$$A = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

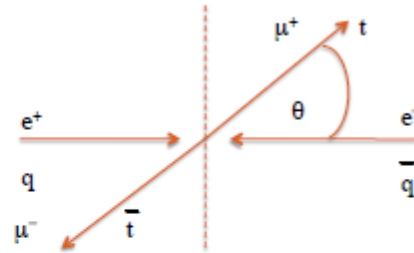
- In proton-antiproton collisions  $\theta \rightarrow y$

- $\Delta y$  is invariant to boosts along z-axis

- Asymmetry based on  $\Delta y$  is the same in lab and  $t\bar{t}$  rest frame

- Asymmetry based on rapidity of lepton from top decay

- Lepton angles are measured with a good precision



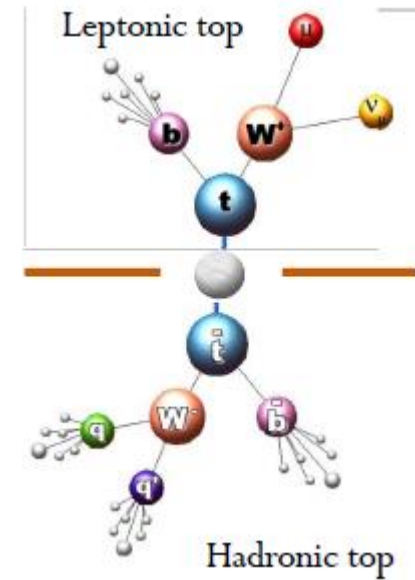
$$\Delta y = y_t - y_{\bar{t}} = q_t (y_{\text{leptonic}} - y_{\text{hadronic}})$$

$$A = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$A_l = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

Tevatron experiments saw larger asymmetry than expected (top quarks prefer the proton beam direction) which could indicate new physics

Unfortunately not confirmed by the LHC experiments



Forward-Backward Top Asymmetry, %

