FYST17 LECTURE 1

The Standard Model

Recommended reading: chap 1

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 <u>not</u> allowed?

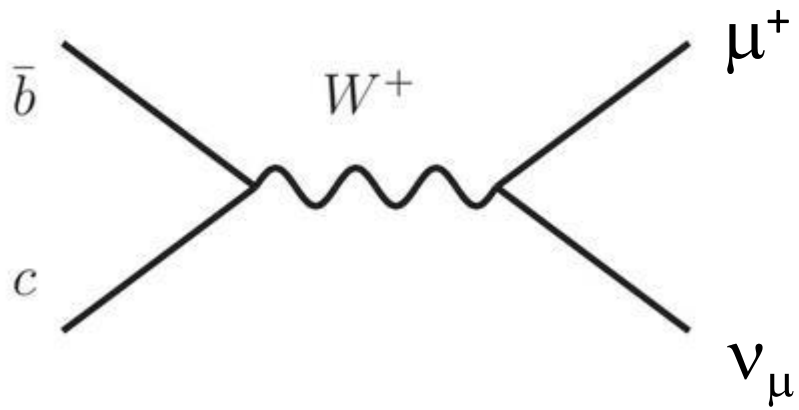
A) $\tau^+ \longrightarrow \pi^+ + \nu_\tau$

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

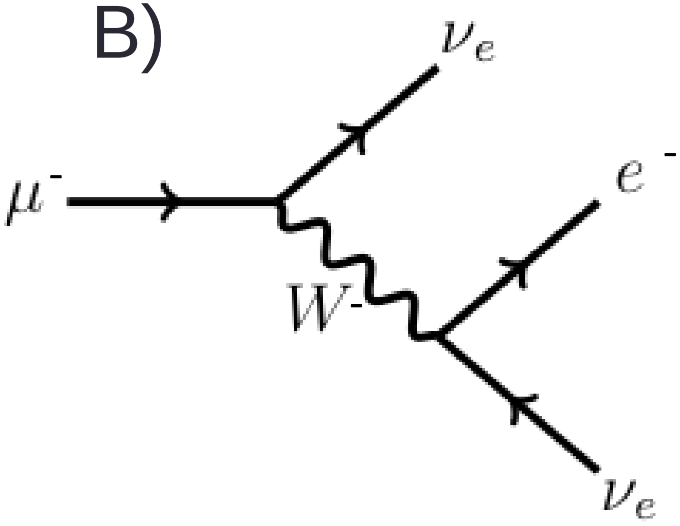
C) $K^+ \longrightarrow \pi^0 + \mu^+ + \nu_\mu$

Q4: Which is an allowed Feynman diagram?

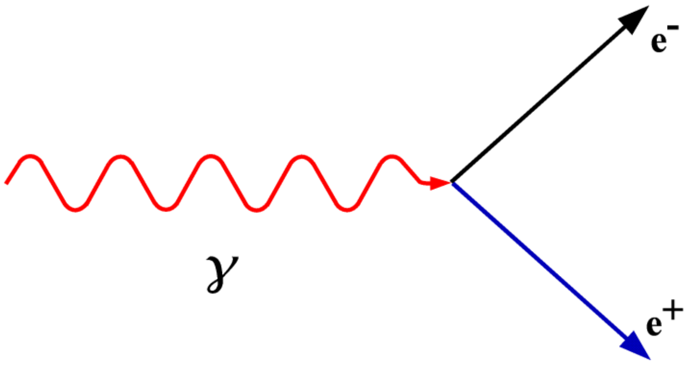
A)



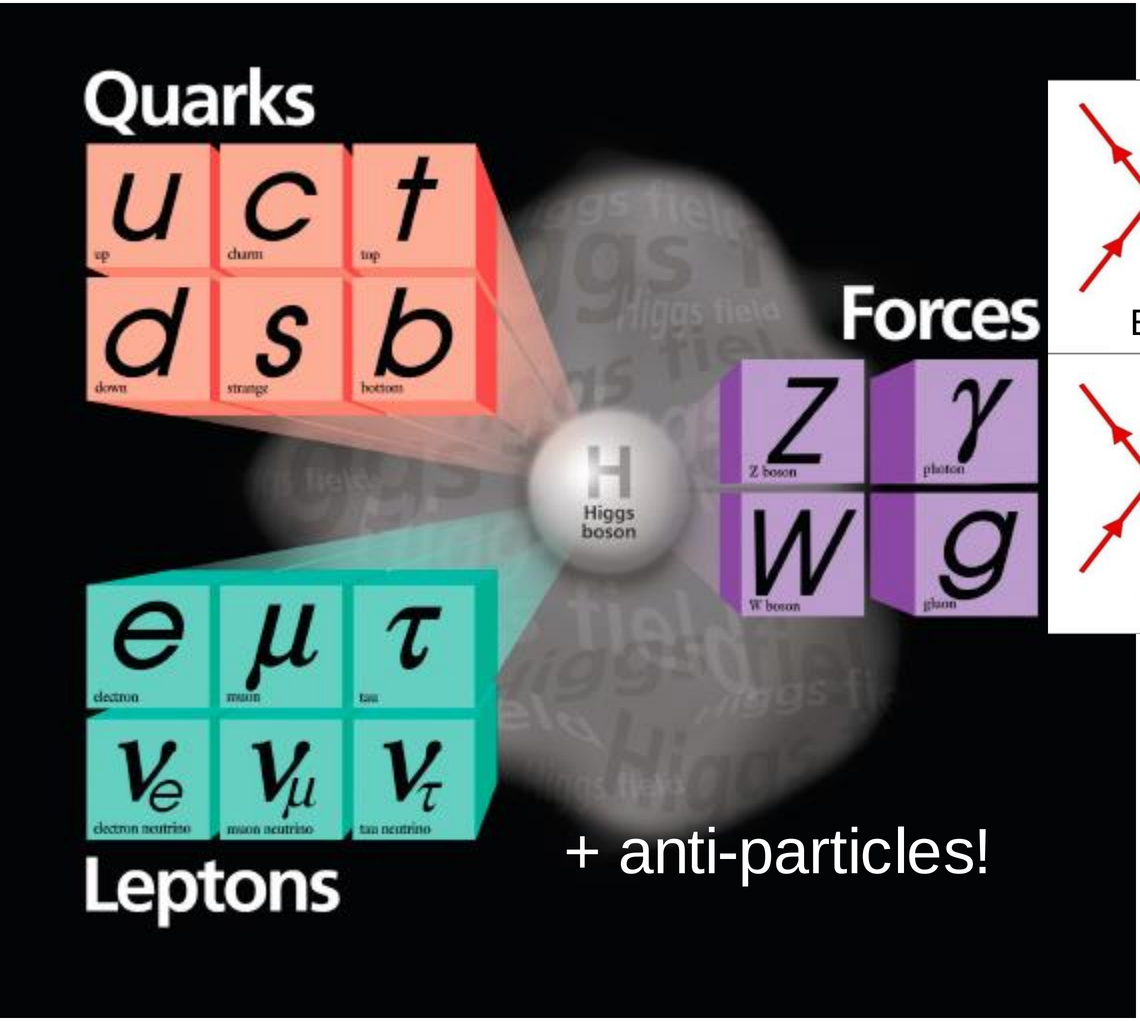
B)

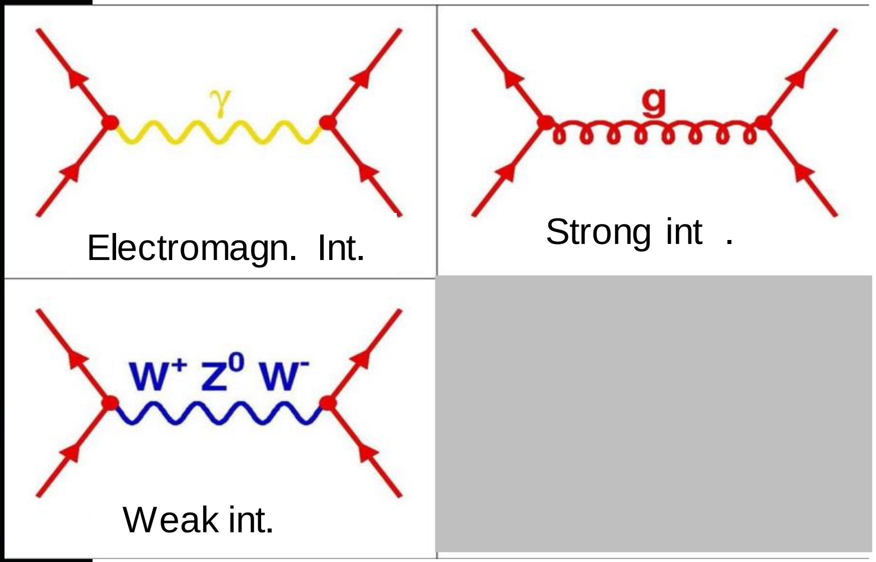


C)



The Standard Model in one slide

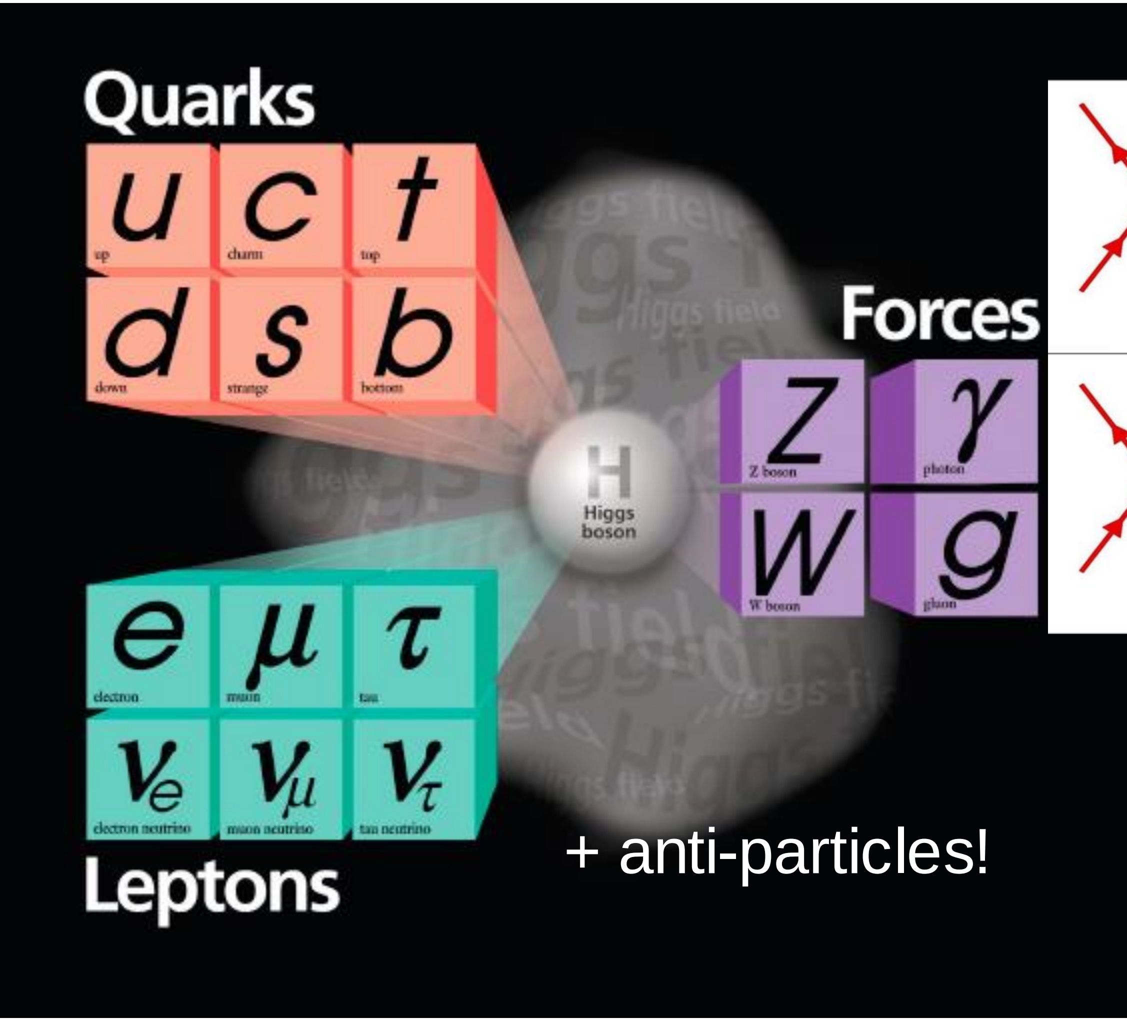


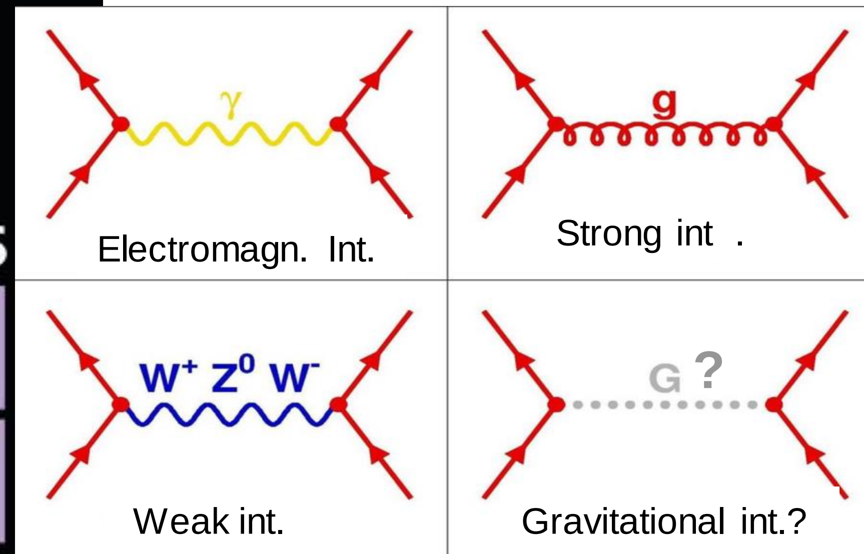


Existence of **Higgs boson** to give mass to the other particles

2. and 3. generation unstable
Decay via weak interaction

The Standard Model in one slide





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

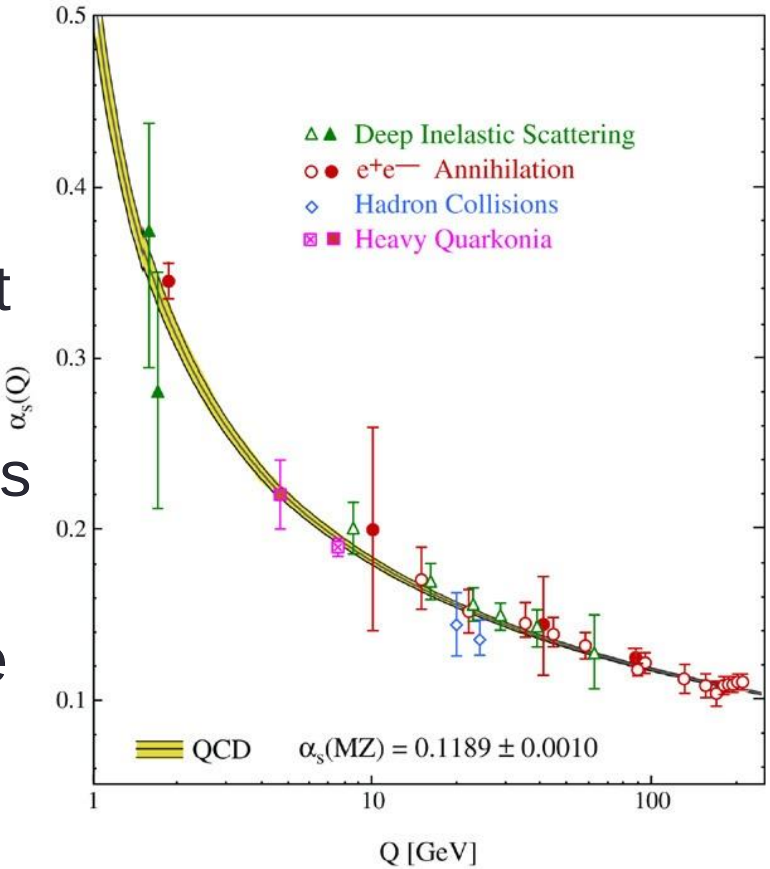
2. and 3. generation unstable
Decay via weak interaction

OK, two slides

- Quarks and gluons interact **strongly** – color charge
- Electrically 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 eV/c^2, and the unit of momentum is 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:

$x'^{\mu} = \Lambda^{\mu}_{\upsilon}\, x^{\nu}$ 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 first pages in chapters 2.4 & 6.1)

Why is Lorentz invariance important?

Let’s try an example

Feynman diagram reminders

To calculate probabilities/ cross sections:

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

Each matrix element is calculated from a Feynman diagram

Each vertex contribute factor $\propto$ coupling constant

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

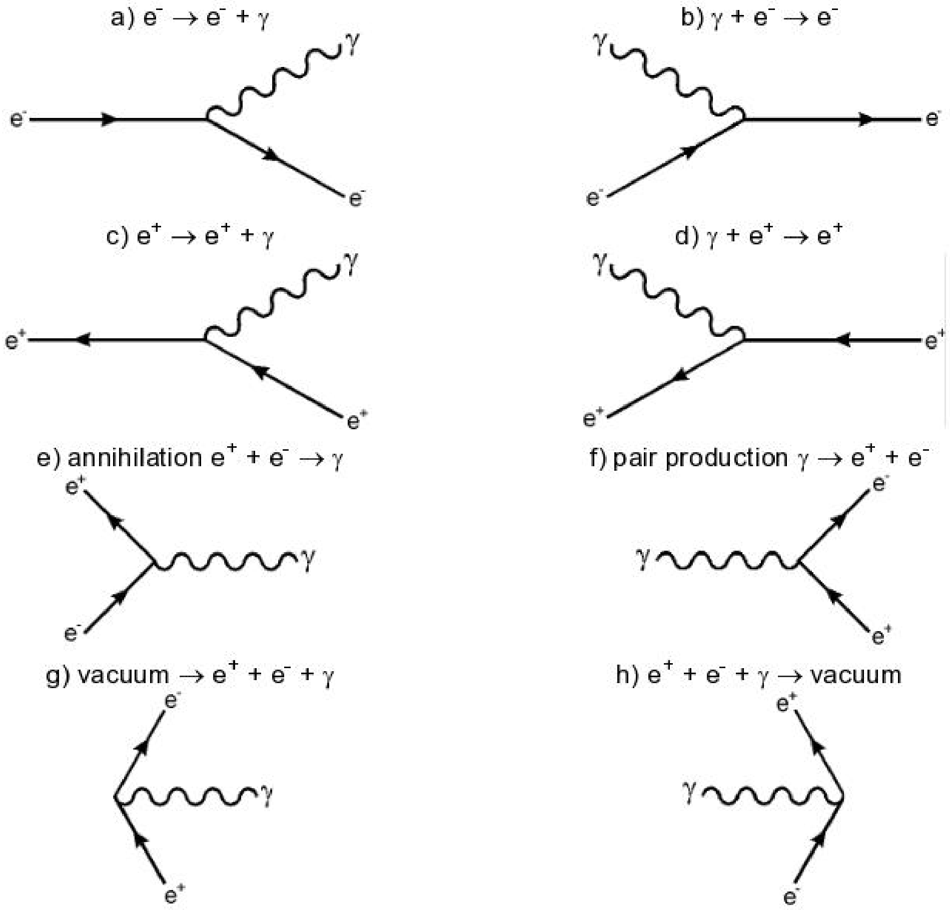
factor $\alpha_{EM} \propto 1/137 \Rightarrow$

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 γ



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

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

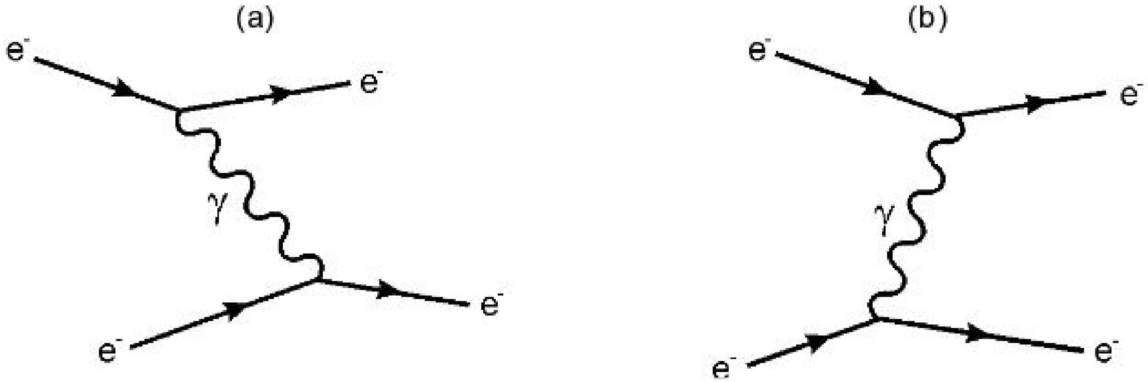


Figure 6: Electron-electron scattering, single photon exchange

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

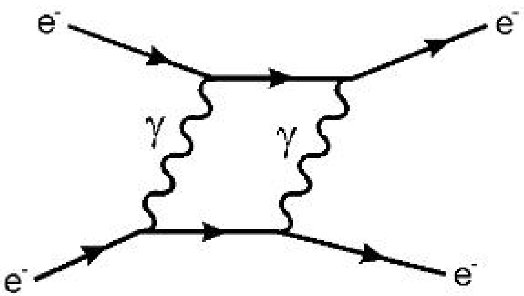
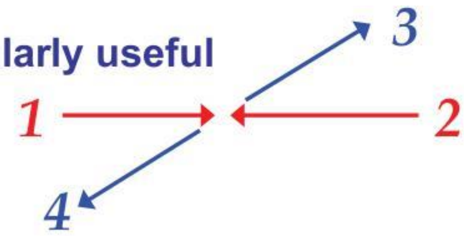


Figure 7: Two-photon exchange contribution

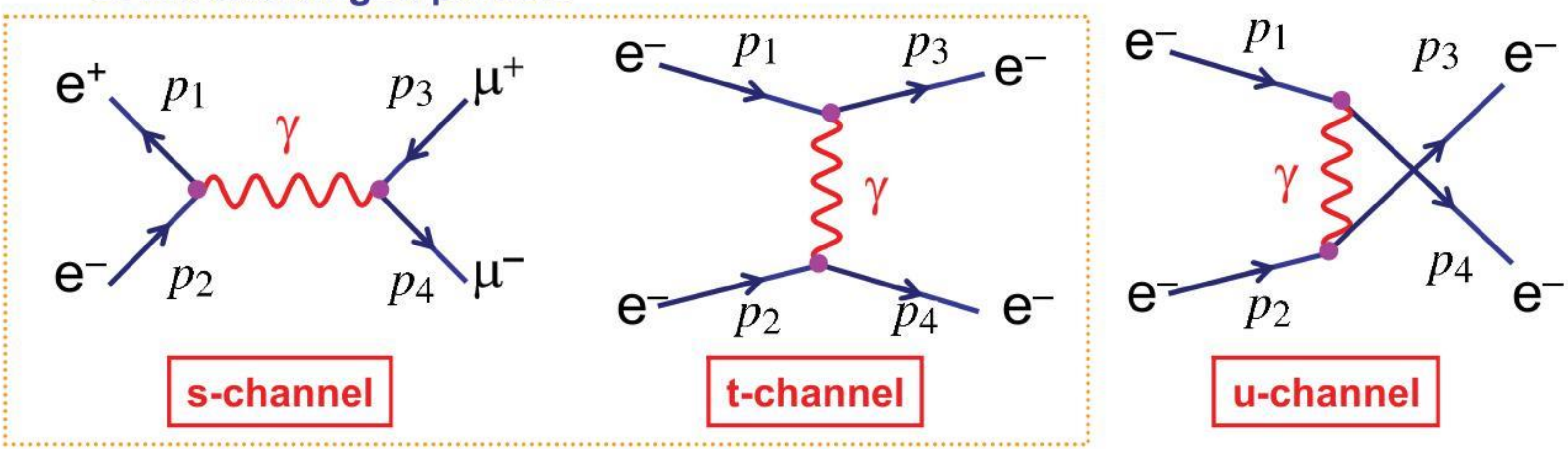
s, t and u variables

★ 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)

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

s, t and u variables

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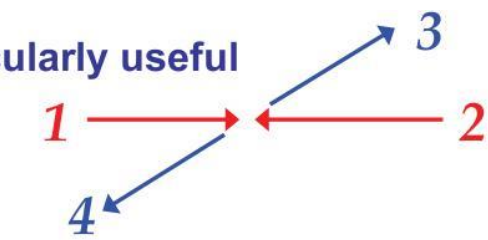

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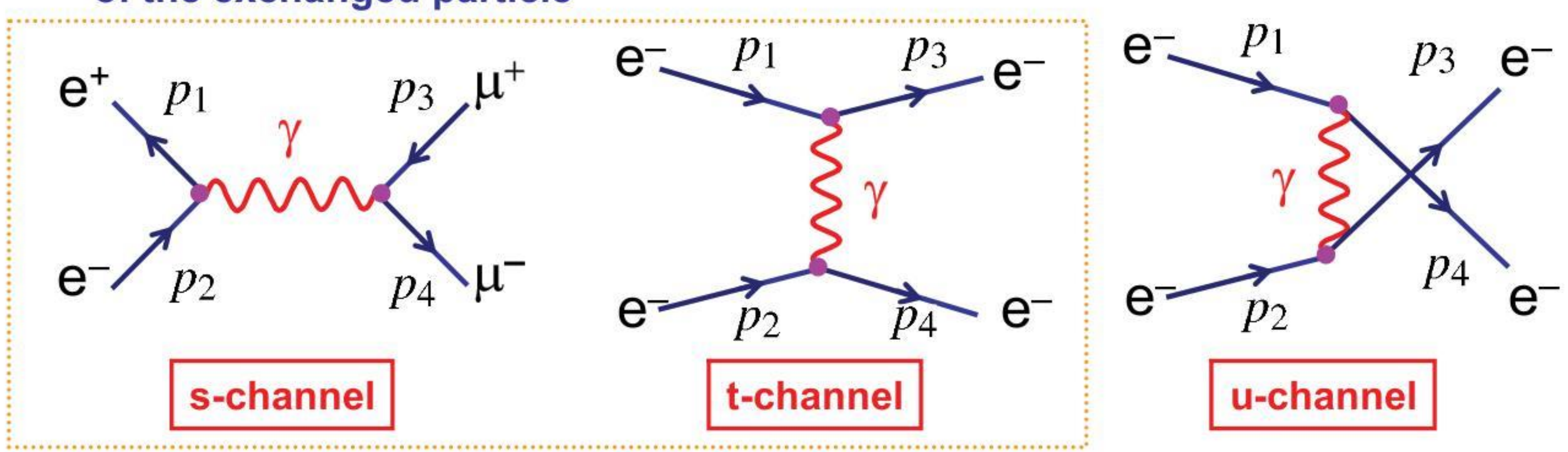

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$$\boxed{s = (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_1 - p_4)^2}$$

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

s, t and u variables

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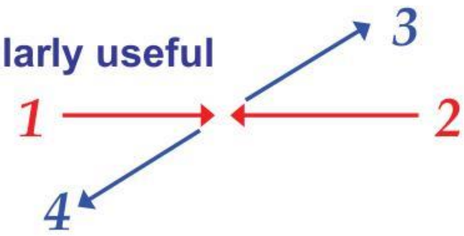
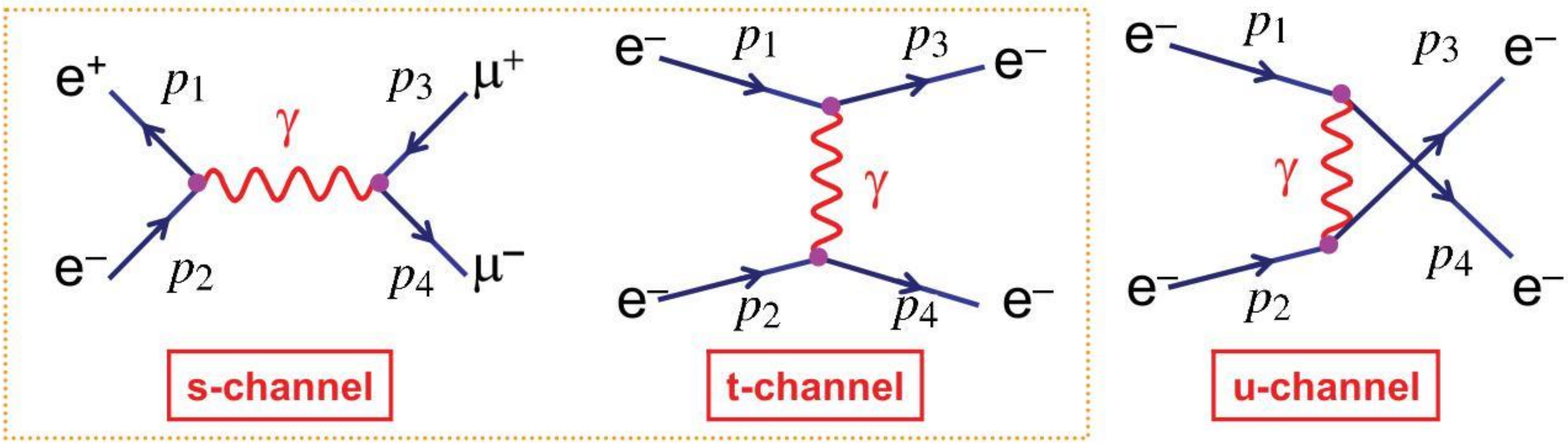


★ Consider the scattering process $1 + 2 \to 3 + 4$

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



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

What is
s+t+u = ?

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

On the path from diagrams to physics

Or matrix element to observables

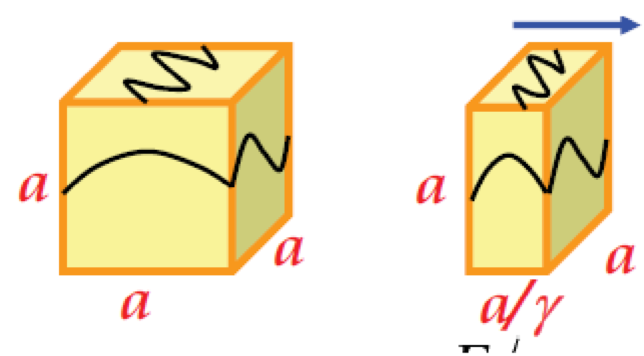
Phase space describes #states/ unit energy:

Decay width Γ 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

Don't forget relativistic conditions!



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

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

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

Composite particles: Hadrons

Baryons qqq: p, n, Λ, Σ+ (uus)

Mesons $q\bar{q}$: π0, π+, K-, B_c^+

Lifetimes: Depends on mechanism:

Strong decay $\Rightarrow$ short lifetime ~ 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

<u>Strange hadrons:</u>

For instance Λ, K-, Σ+ 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/ψ, Y

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 Λ_c+ etc

”Beauty” hadrons

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

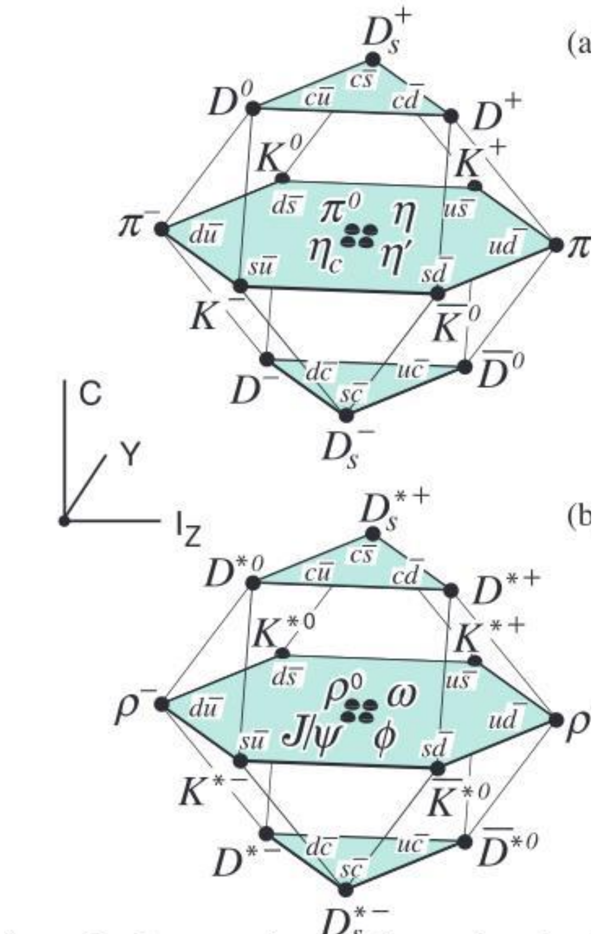
B baryons such as Λ_b (5461) = udb etc

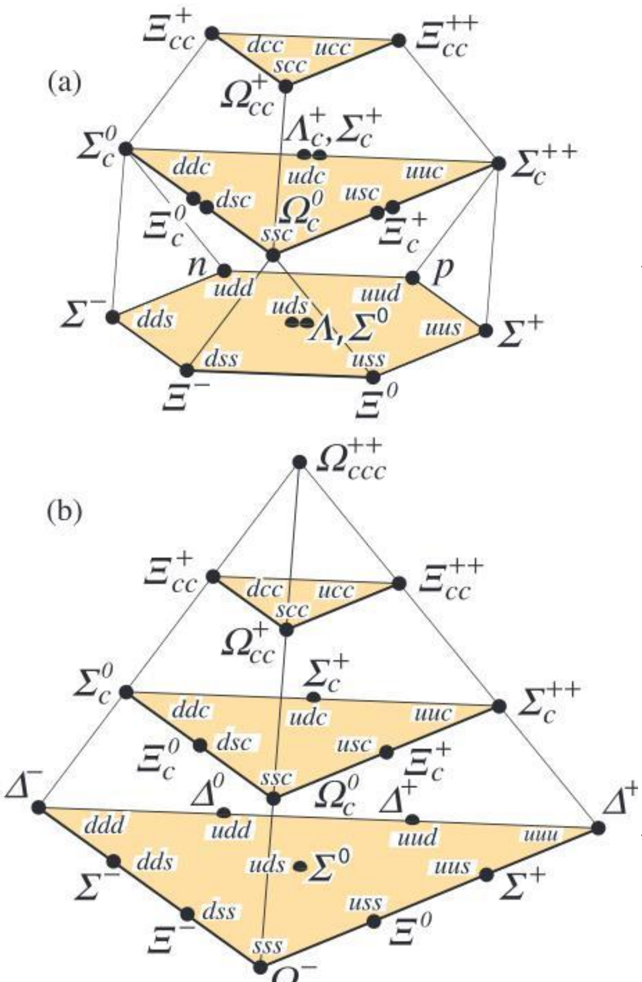
BUT NO TOP HADRONS

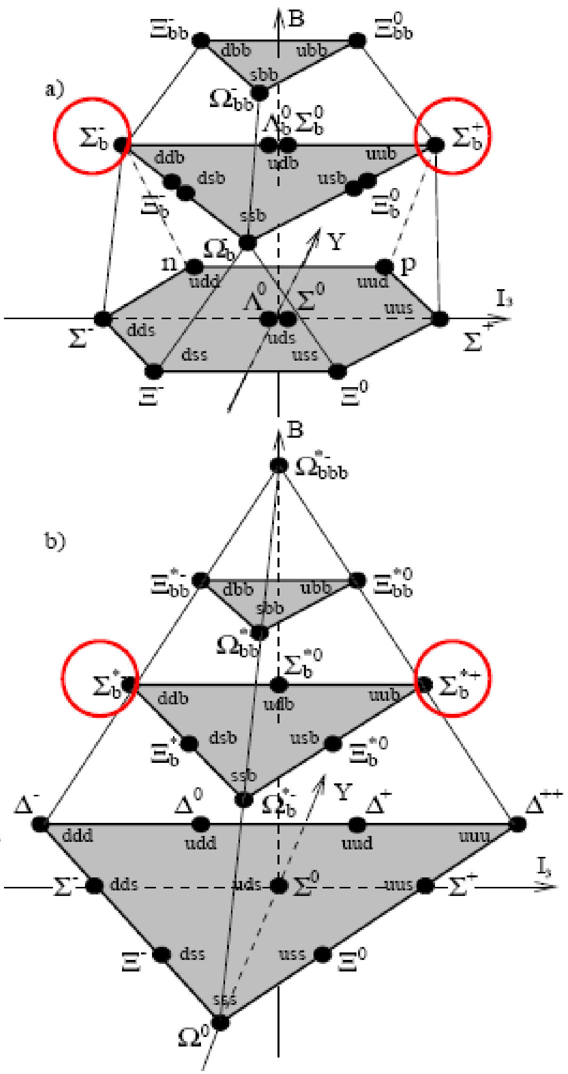
(one can still define a ”truth” quantum number)

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

Multiplets


(a
D_s^+
D^0
D^+
K^0
K^+
π^-
π^0 η
η_c η'
π^+
K^-
$\overline{K}^0$
D^-
$\overline{D}^0$
D_s^-
C
Y
I_Z
(b
D_s^{*+}
D^{*0}
D^{*+}
K^{*0}
K^{*+}
ρ^-
ρ^0 ω
J/ψ ϕ
ρ^+
K^{*-}
$\overline{K}^{*0}$
D^{*-}
$\overline{D}^{*0}$
D_s^{*-}


(a)
Ξ_{cc}^+
Ξ_{cc}^{++}
Ω_{cc}^+
Σ_c^0
Λ_c^+, Σ_c^+
Σ_c^{++}
Ξ_c^0
Ω_c^0
Ξ_c^+
n
p
Σ^-
Λ, Σ^0
Σ^+
Ξ^-
Ξ^0
(b)
Ω_{ccc}^{++}
Ξ_{cc}^+
Ξ_{cc}^{++}
Ω_{cc}^+
Σ_c^0
Σ_c^+
Σ_c^{++}
Ξ_c^0
Ξ_c^+
Δ^-
Δ^0
Ω_c^0
Δ^+
Δ^{++}
Σ^-
Σ^0
Σ^+
Ξ^-
Ξ^0
Ω^-


a)
B
Y
I_3
b)
B
Y
I_3

What about light flavor symmetries?

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

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

Nuclear force is ≈ 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:

$$p = \binom{1}{0};\ n = \binom{0}{1}$$

Analogous to spin angular momentum:

$p = | \tfrac{1}{2}\ \tfrac{1}{2} >$ ”isospin up”

$n = | \tfrac{1}{2}\ -\tfrac{1}{2} >$ ”isospin down”

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

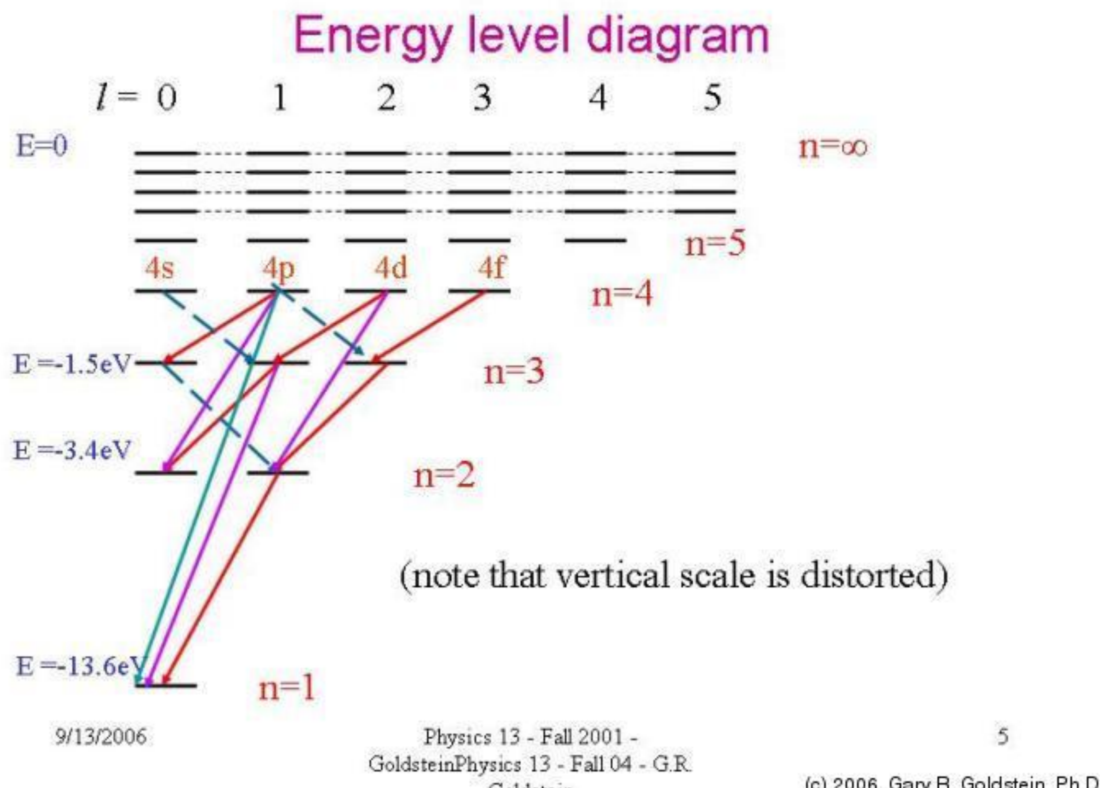
Physics (i.e. strong force) invariant under rotation in ”isospin space” assuming equal masses

$\boxed{\text{Isospin conserved in all strong interactions}}$

Spectroscopy

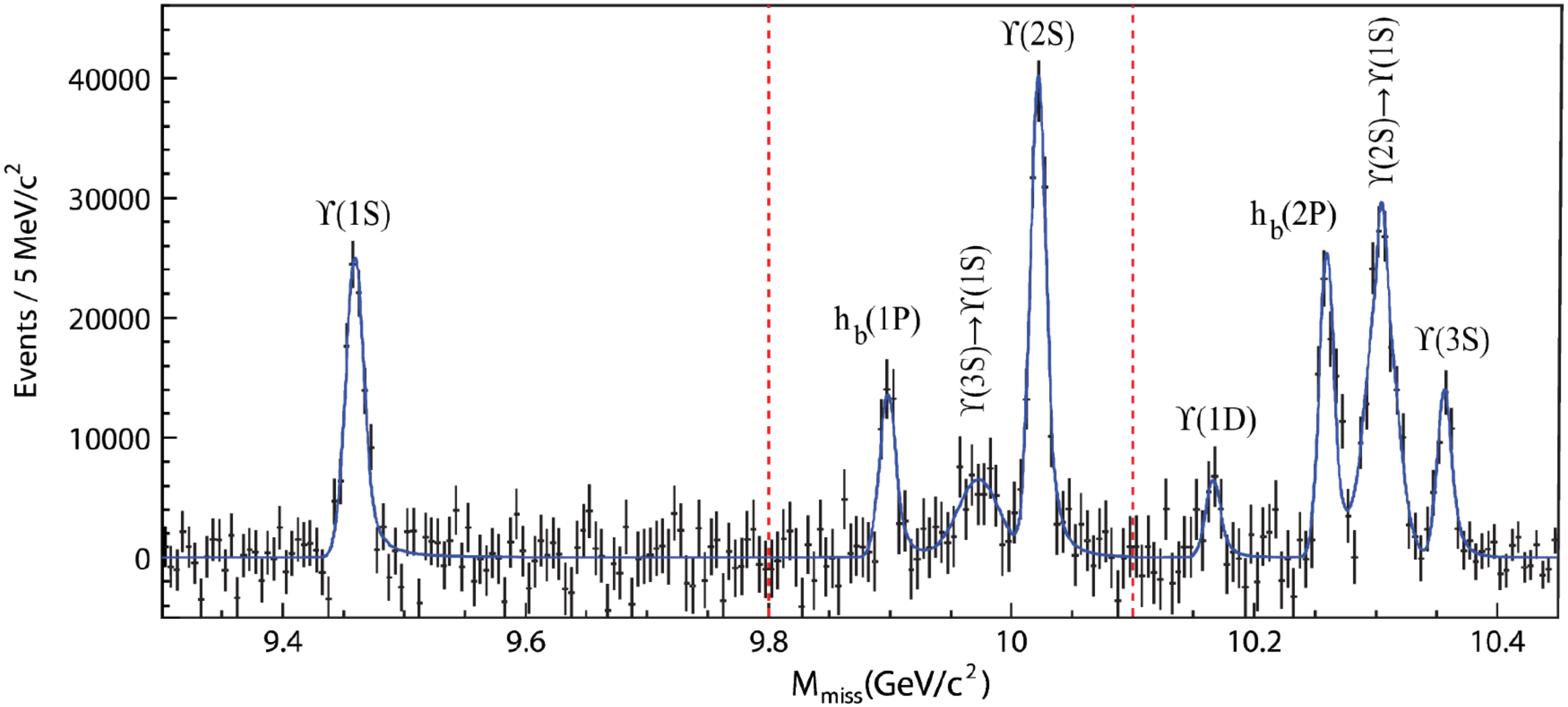
For combination of heavy quarks, the $q - \bar{q}$ system is essentially non-relativisic ($m_q \gg E_{kin}$)
Quarkonium ($c\bar{c}$, $b\bar{b}$) analogous to hydrogen atom with several energy levels

Important difference
the quarkonium system is dominated by the STRONG force



Quarkonia

Looks like several particles with different masses but same quark content



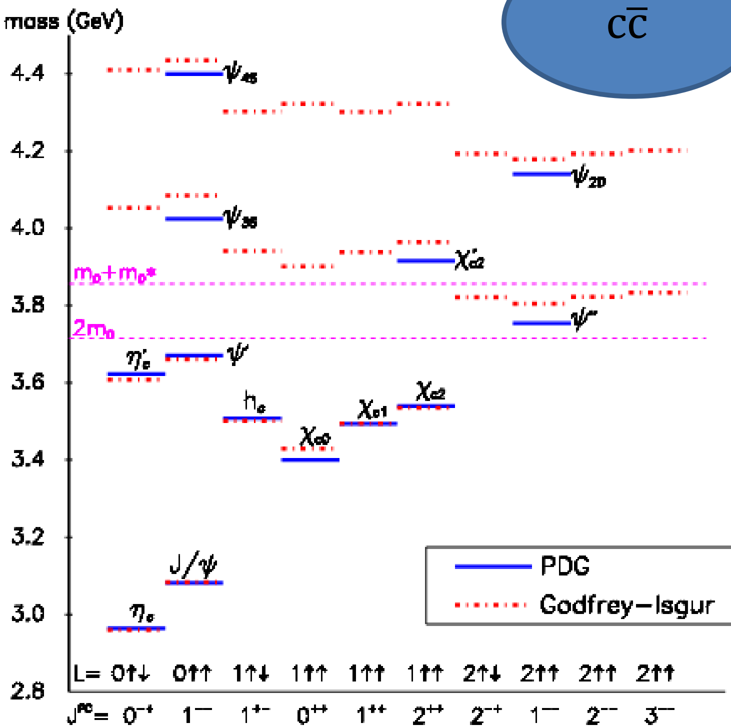
Just starting to measure experimentally the mixed systems $c\bar{b}$, $\bar{c}b$ (weakly produced)

Quarkonia spectroscopy

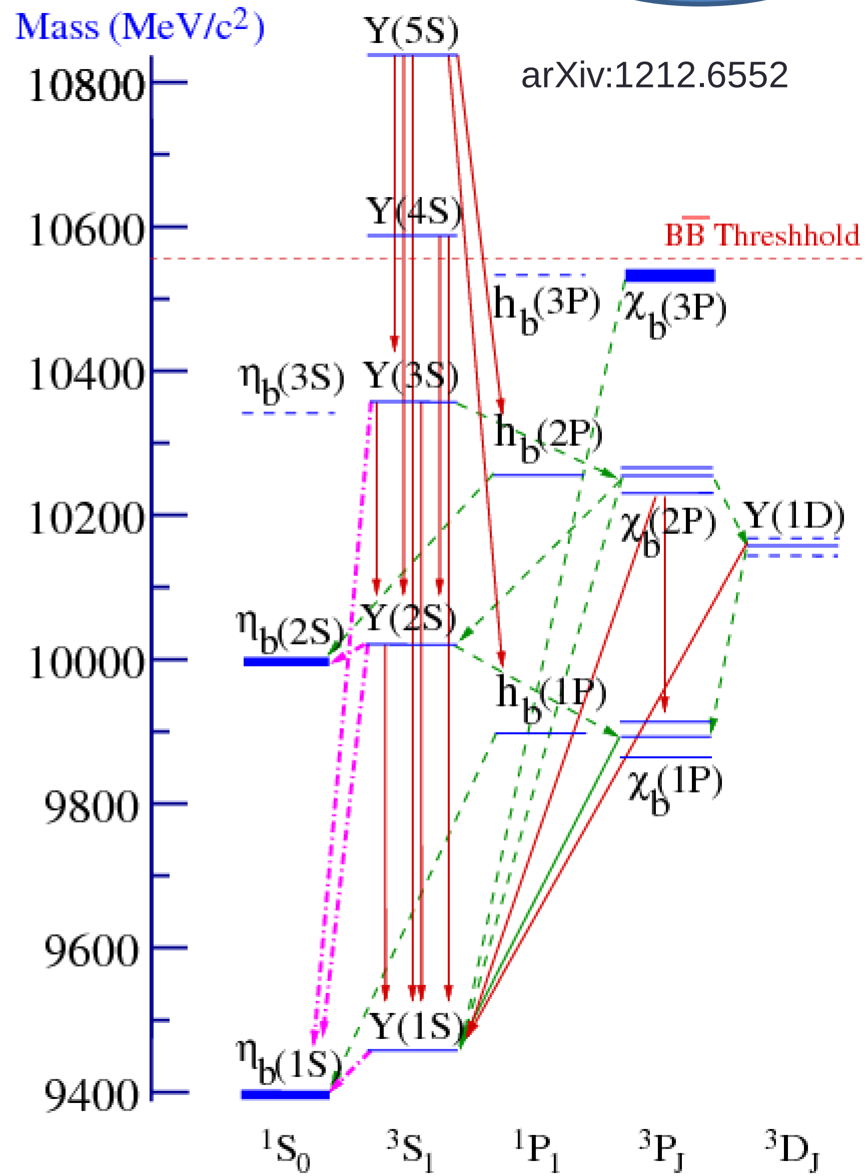
$b\bar{b}$

arXiv:1307.4139

$c\bar{c}$



arXiv:1212.6552



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)

<u>Key feature: we only detect these by their decay products</u>

$\pi^- + p \rightarrow n + X$

$\quad\quad\quad\quad\quad\hookrightarrow A + B$

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

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

This will show a mass peak distribution

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

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

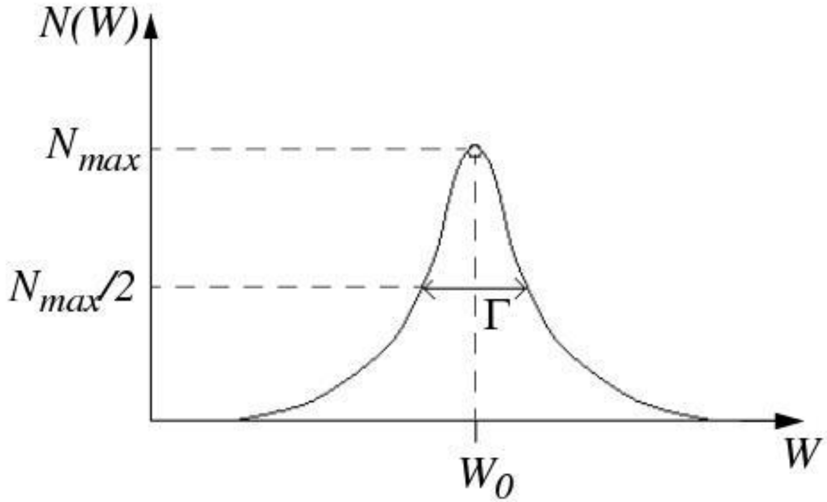


Figure 93: Breit-Wigner shape

- Mean value of the Breit-Wigner shape is the mass of a resonance: $M=W_0$
- Γ 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.

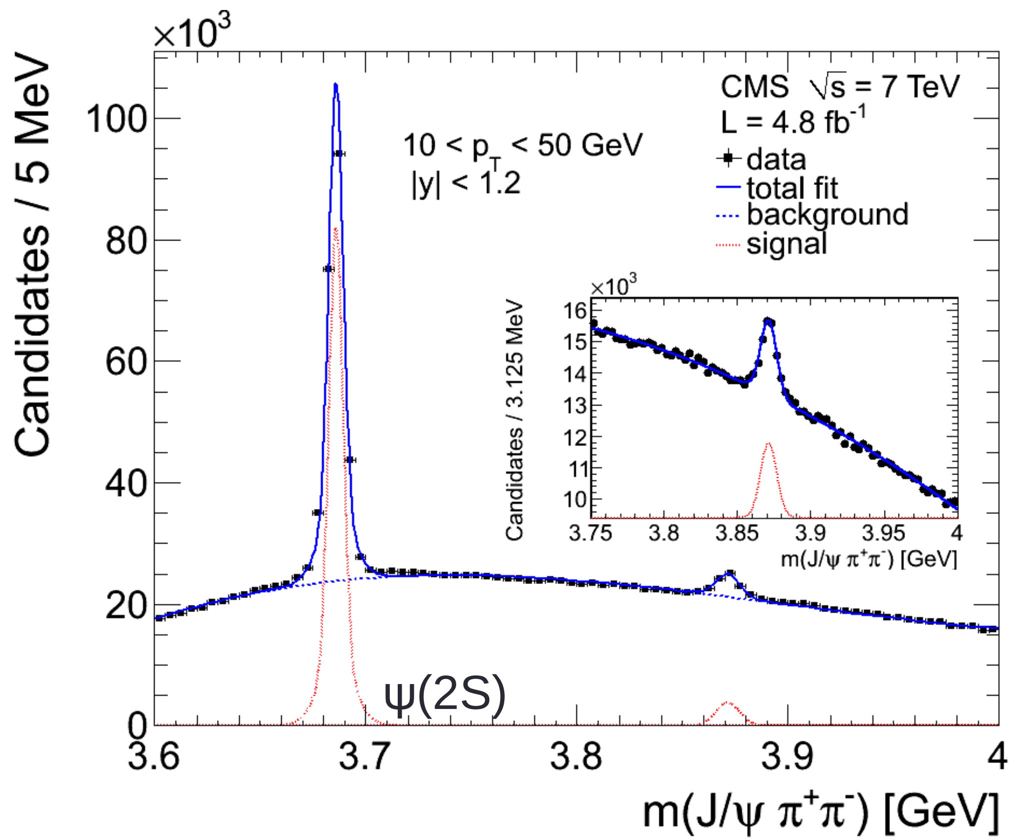
Still doesn't fit in

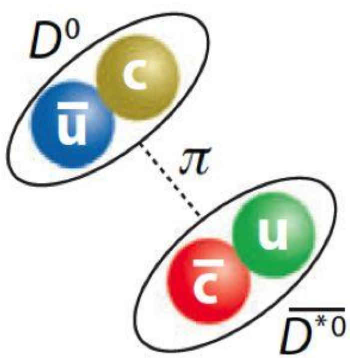
LHCb measured:

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

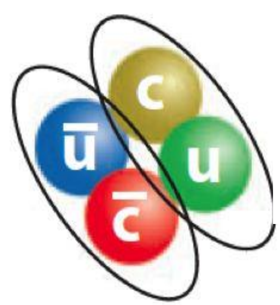
so not charmonium,

perhaps D-D* molecule?



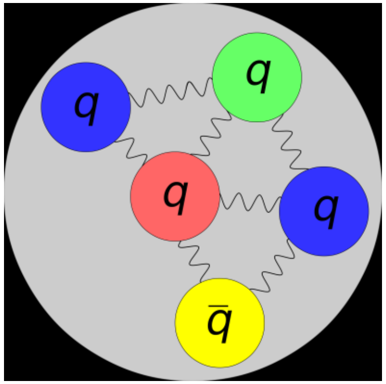


D^0–$\overline{D^{*0}}$ **"molecule"**



Diquark–diantiquark

Pentaquarks!



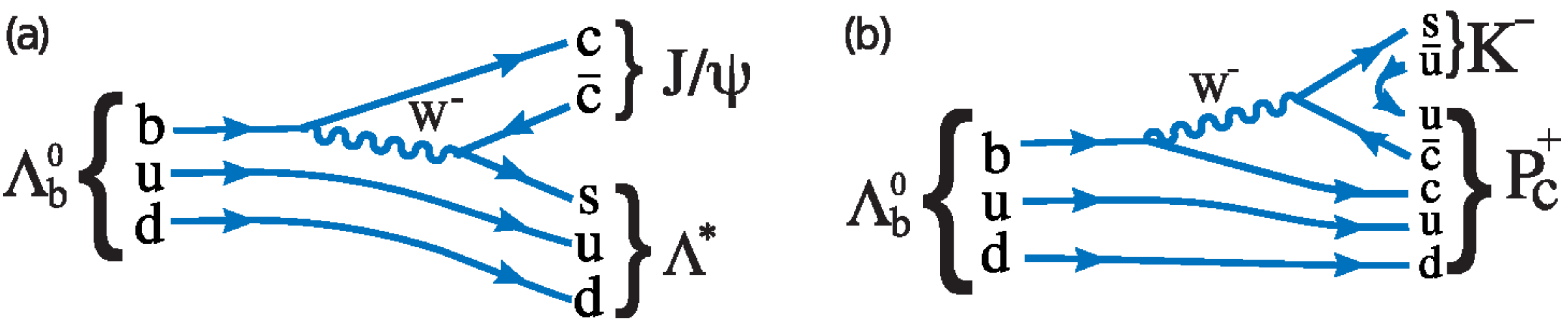
- The ”old” story:
- Proposed states with 5quarks (or 4q, 1$\bar{q}$)
- Discovered (?) 2003 by LEPS experiment:
  - Θ+ (uudd$\bar{s}$) , mass = 1,54 GeV.
  - Not very significant, little statistics

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

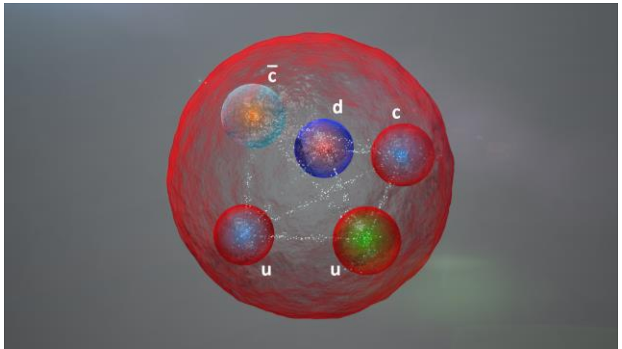
By 2006: High statistics collider searches for pentaquarks at LEP & Belle. These experiments see NOTHING
$\rightarrow$ the pentaquark is dead ?

The 2015 pentaquark ”accident”

- LHCb collaboration publishes in Phys.Rev.Letters (arXiv:1507:03414) July 2015: ”Observation of J/psi p resonances consistent with pentaquarks”



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

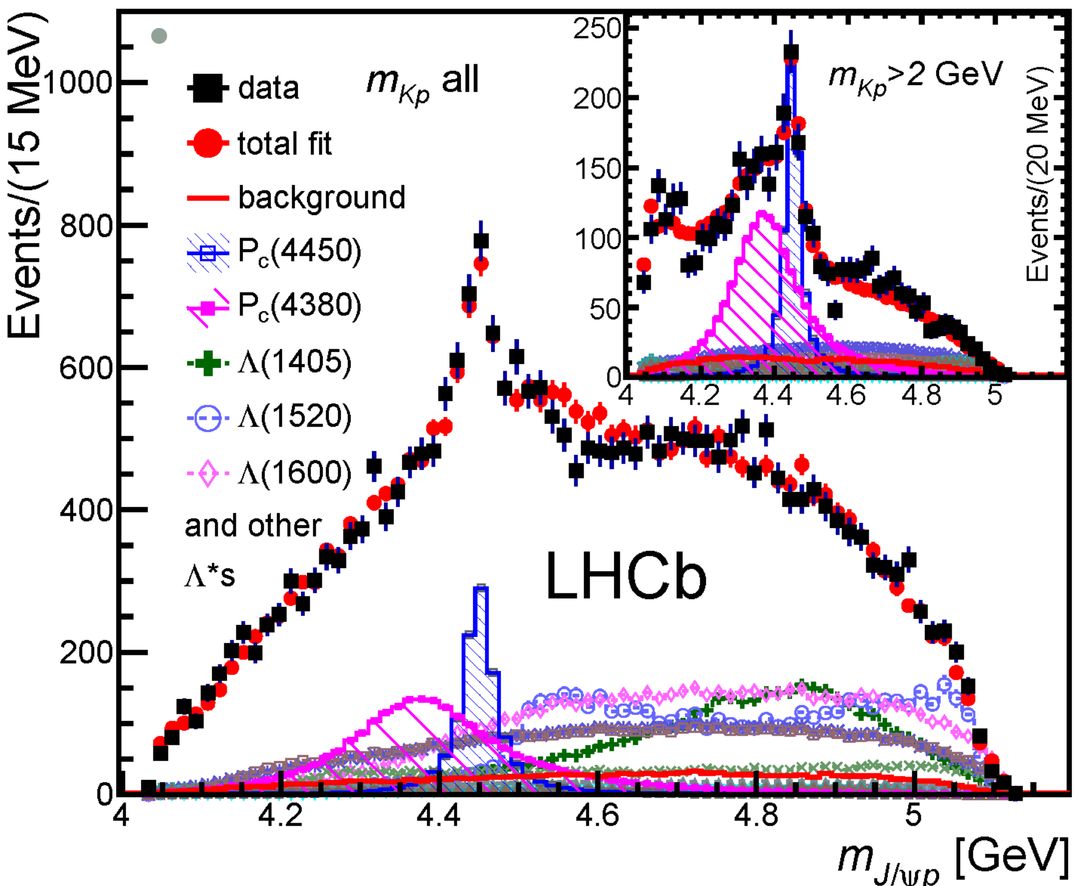


Best fit to data involves two new states with masses

- P_c+(4050) mass = 4449.8 ± 1.7 ± 2.5 MeV
- P_c+(4380) mass = 4380 ± 8 ± 29 MeV

Systematical uncertainty

Statistical uncertainty

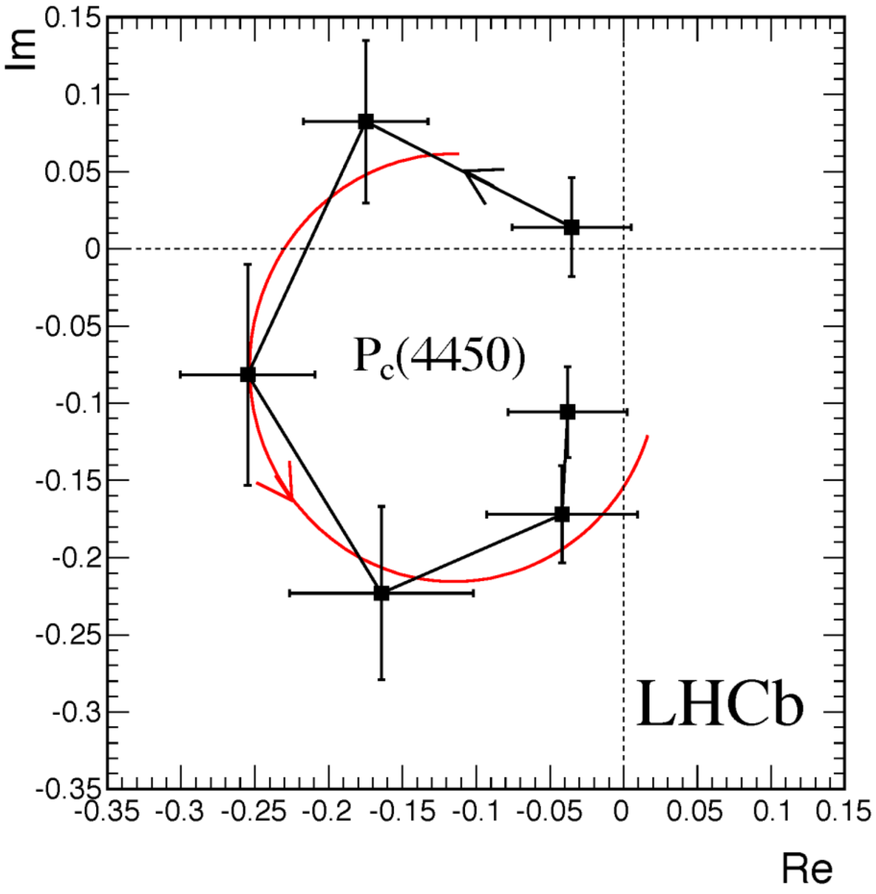


Significances 9-15 σ

2016 analysis confirms this

How do they know?

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



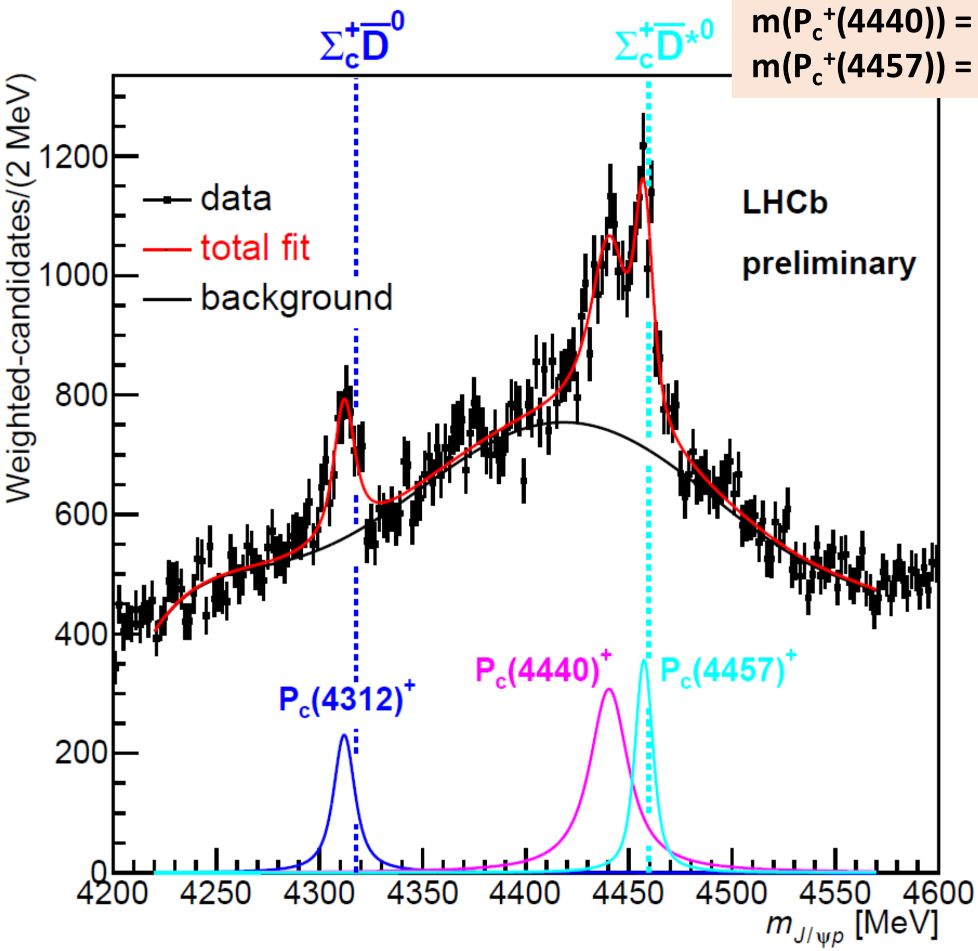
One of the tests:

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)

And more new pentaquarks in 2019!

m(P_c^+(4312)) = 4311.9±0.7+6.8/-0.6 MeV, Γ = 9.8±2.7+3.7/-4.5 MeV
m(P_c^+(4440)) = 4440.3±1.3+4.1/-4.7 MeV, Γ = 20.6±4.9+8.7/-10.1 MeV
m(P_c^+(4457)) = 4457.3±0.6+4.1/-1.7 MeV, Γ = 6.4±2.0+5.7/-1.9 MeV



Discovery of a new narrow pentaquark particle, $P_c(4312)^+$, decaying to a J//ψ and a proton, with a statistical significance of 7.3 σ!!

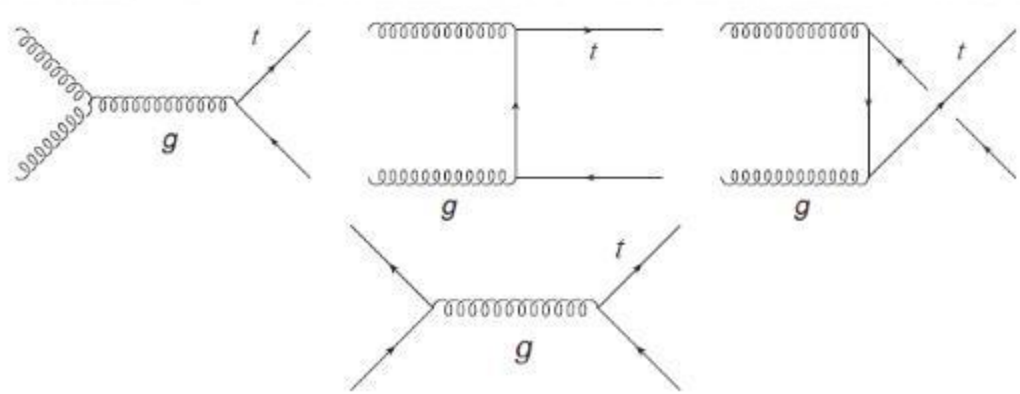
The $P_c(4450)^+$ pentaquark structure previously reported by LHCb is also confirmed, but a more complex structure consisting of two narrow overlapping peaks, $P_c(4440)^+$ and $P_c(4457)^+$
(The two-peak structure has statistical significance of 5.4 σ compared to a single-peak hypothesis).

https://arxiv.org/abs/1904.03947

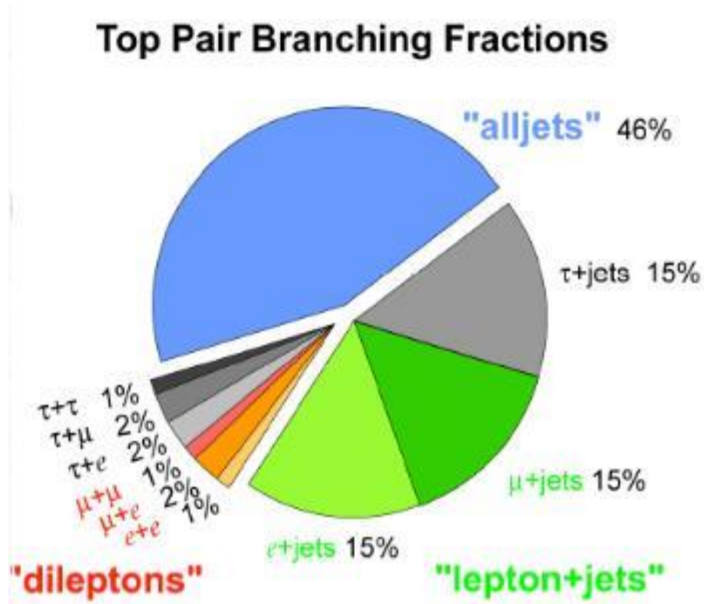
Top quarks

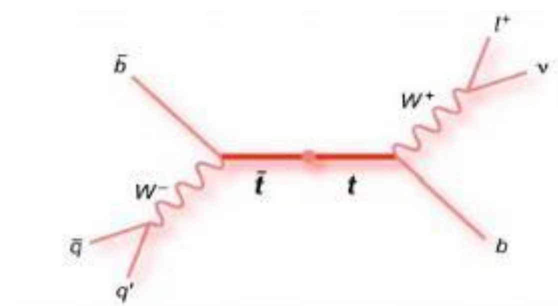
Only seen in hadron collisions so far

Pair production: qq and gg fusion

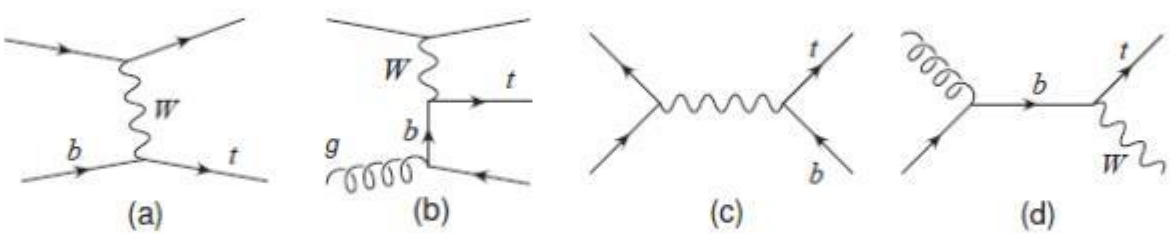


Top quark decays

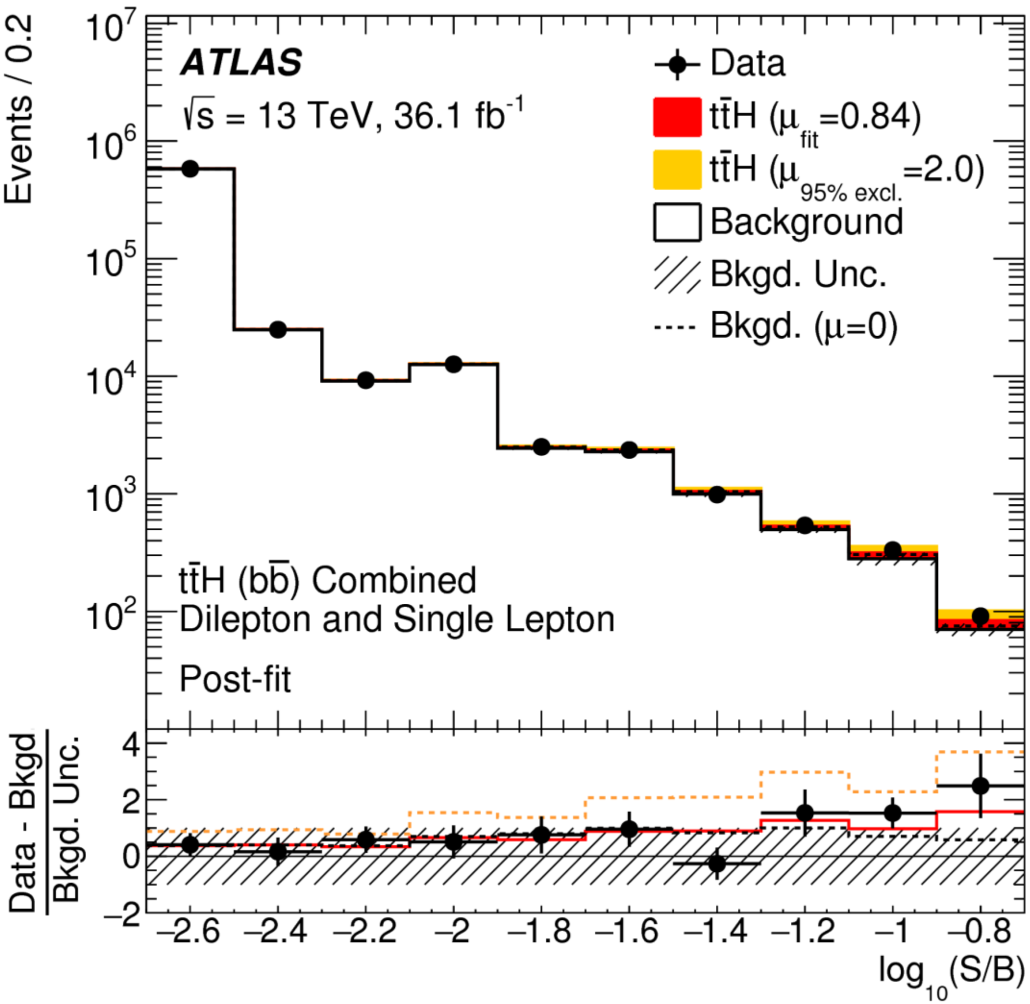




Single production: Drell-Yan and Wg fusion



Top quark properties

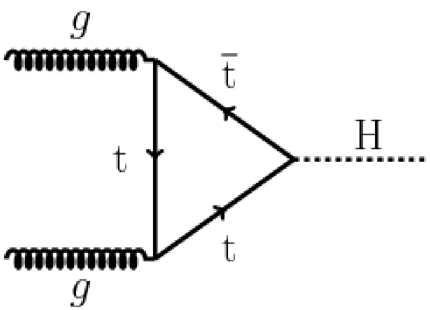


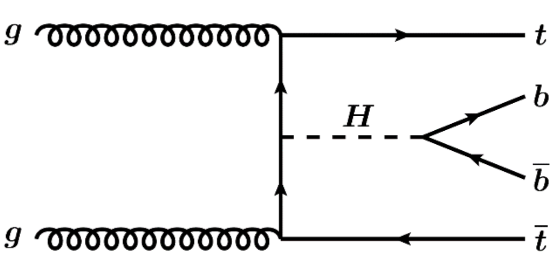
The LHC is a top factory:

Precision measurements of the mass and other properties

M_{top} = 173.34 ± 0.36 ± 0.67 GeV

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



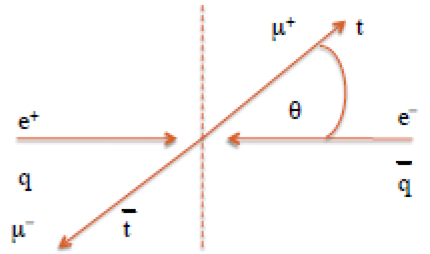


Top charge asymmetry?

Definitions

- Asymmetry defined for ee→μμ

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

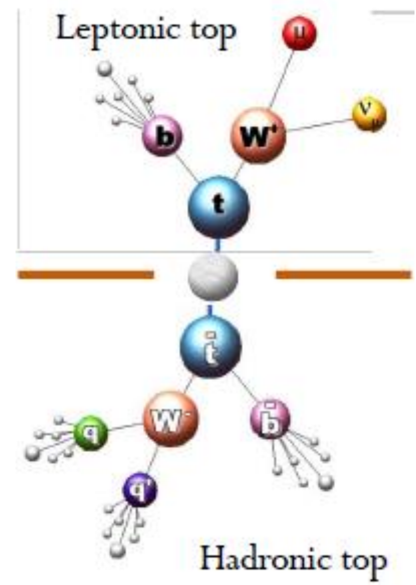


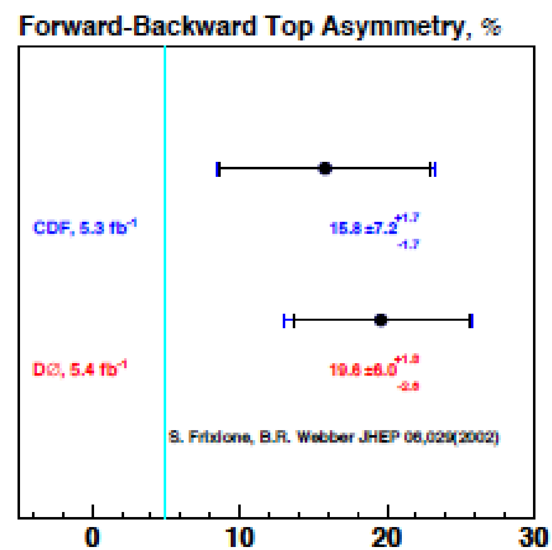
- In proton-antiproton collisions θ→y
- Δy is invariant to boosts along z-axis $\Delta y = y_t - y_{\bar{t}} = q_l(y_{leptonic} - y_{hadronic})$
- Asymmetry based on Δy is the same in lab and tt rest frame

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

- Asymmetry based on rapidity of lepton from top decay
  - Lepton angles are measured with a good precision

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





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

Unfortunately not confirmed by the LHC experiments