Introduction to Particle Physics

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HEP Summer Student Lectures

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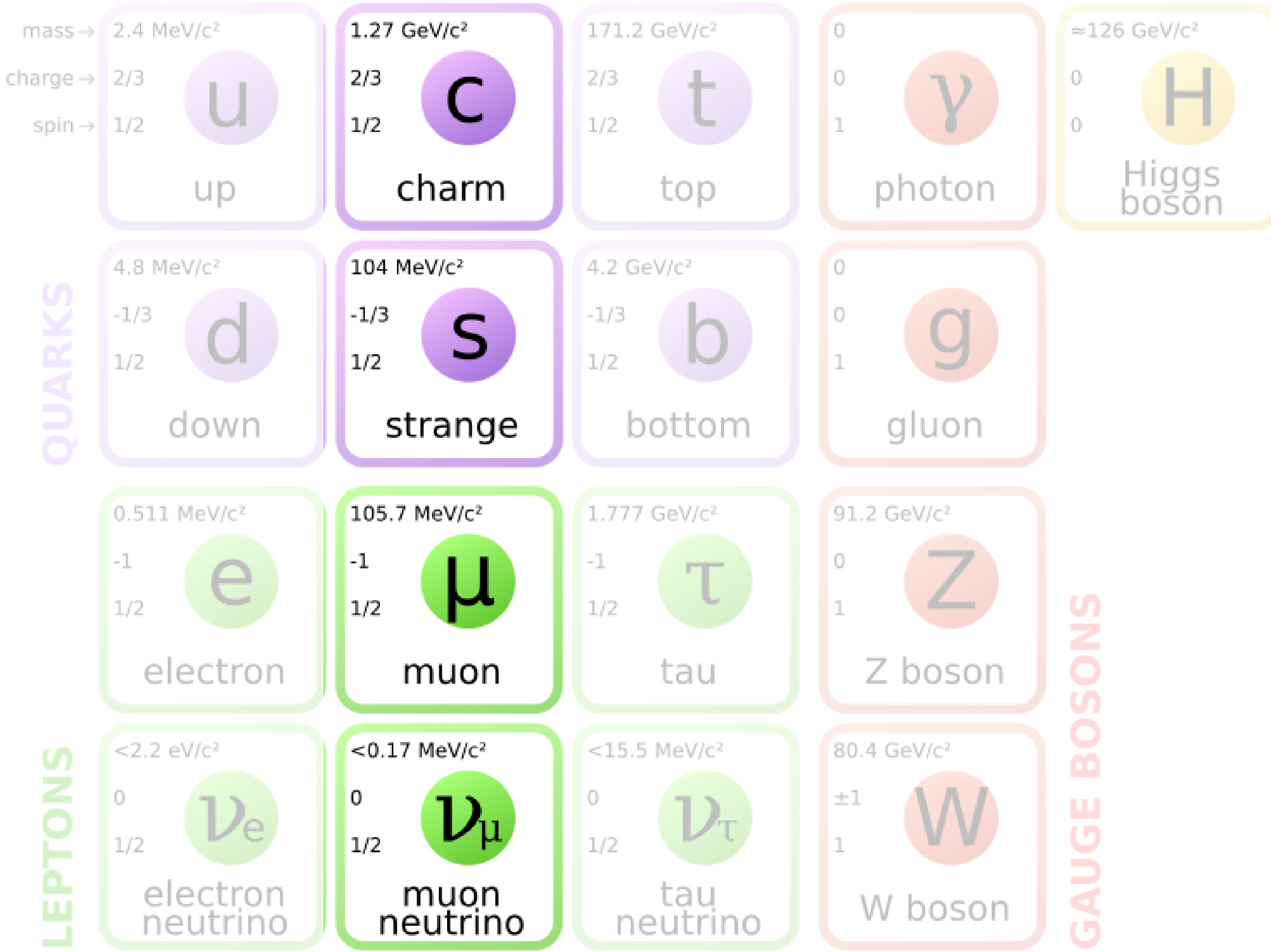
Overview

- Introduction
- Pre-requisites
  - relativistic kinematics
  - cross section measurement
  - symmetries and conserved quantities
  - Feynman diagrams
- Fermions
  - first generation
  - second generation
  - third generation
- Gauge Bosons / Forces
  - gluon
  - W and Z
  - Higgs
- Open Questions

Elementary Particles: Second Generation



Muon

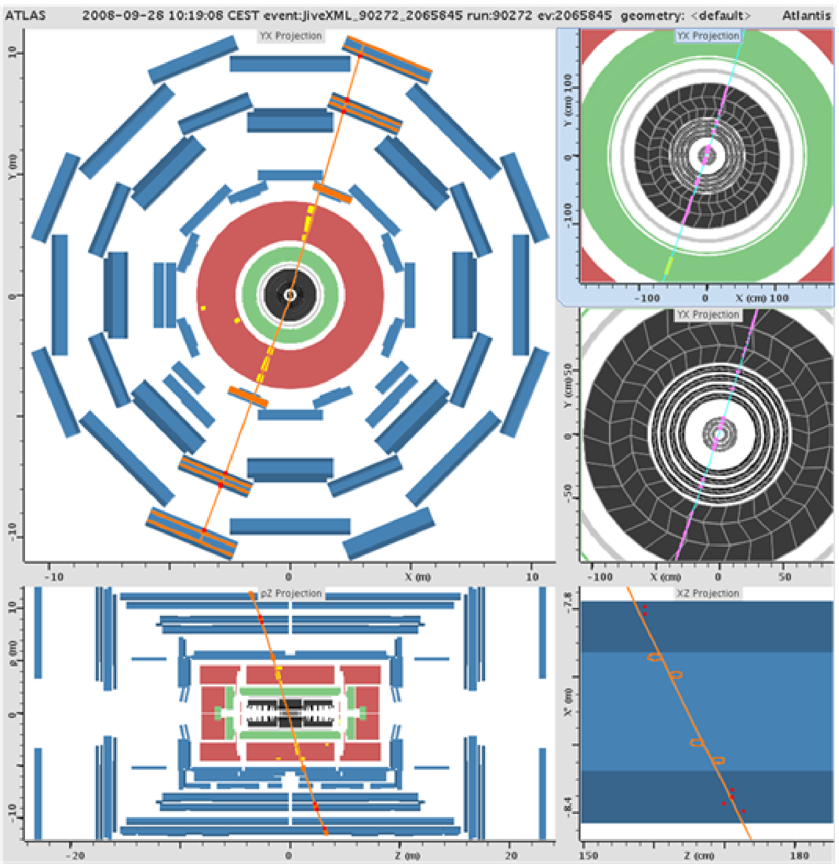
- was seen in cosmic rays and puzzled physicists since it didn't fit into the picture of protons, neutrons, electrons and their antiparticles
  - two types of electrons, one showering/stopping in lead, the other not???
- first estimate of mass≈100 MeV from curvature in magnetic field in a cloud chamber in 1936
  - originally called “mesotron”
  - identical to pion predicted in 1935 by Yukawa to describe (strong) interaction between protons and neutrons???
- but muon does not take part in strong interactions
- looks like a heavy electron, but $\mu \to e\gamma$ not observed

⇒ muon is really distinct from an electron, lepton family number conserved

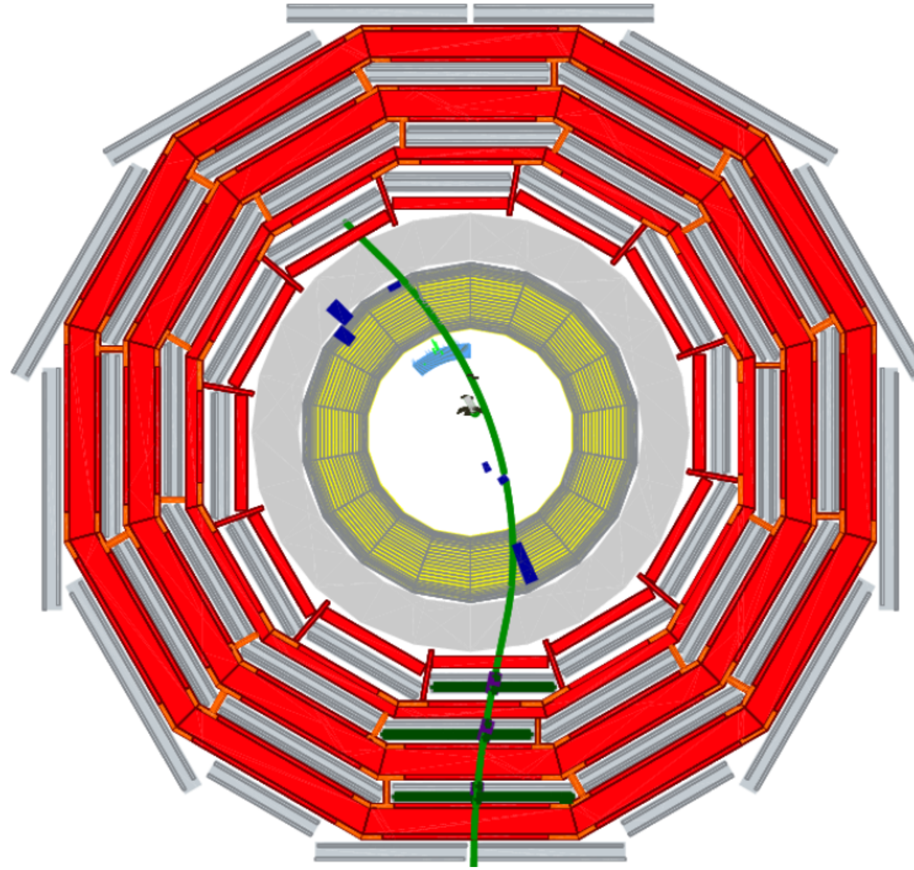
⇒ pion was found in 1947 (again in cosmic rays, photographic emulsion) Nobel prize 1949 for H. Yukawa

Muons from Cosmic Rays at LHC

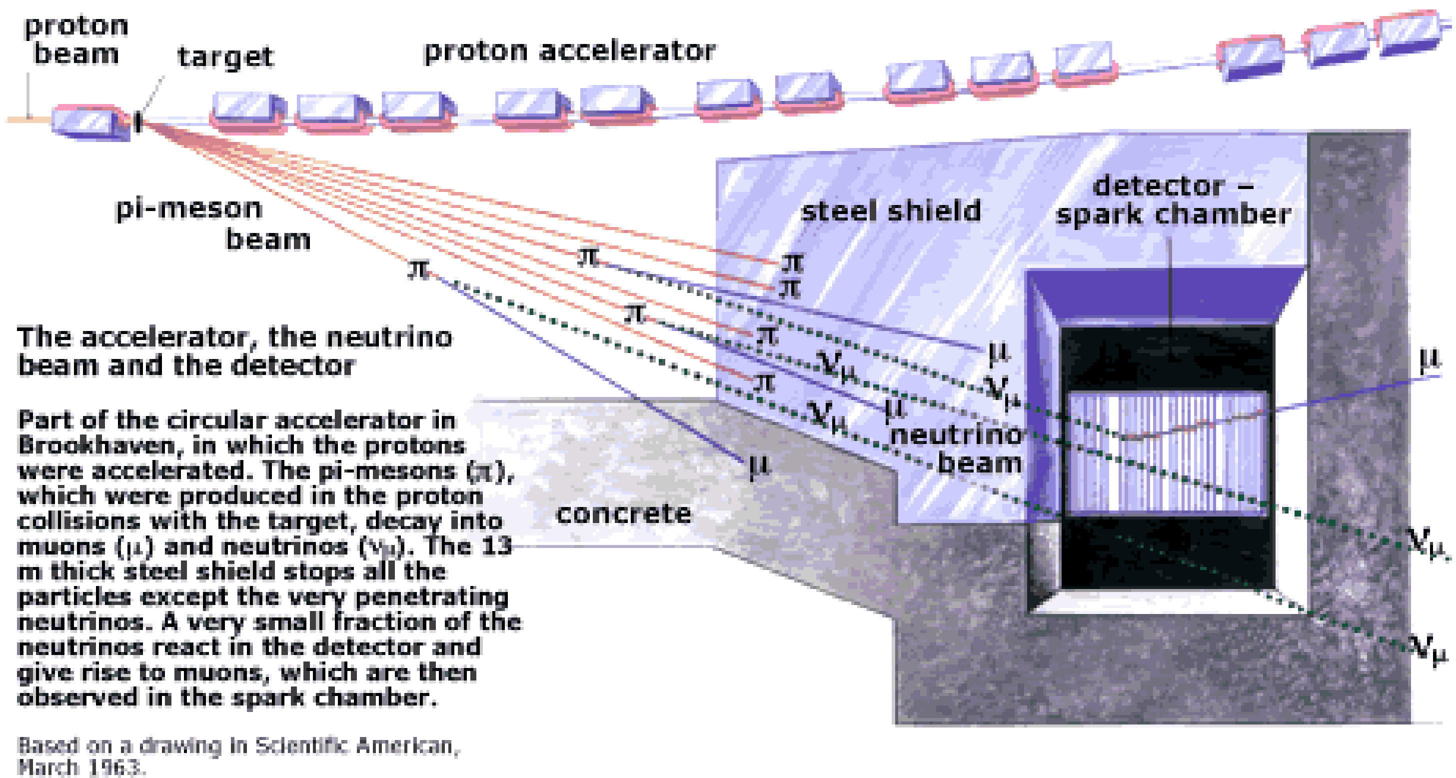
ATLAS

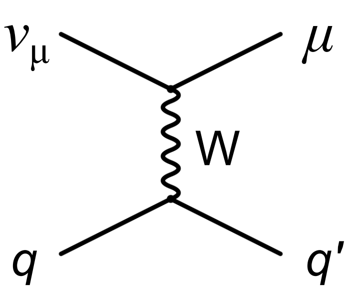


CMS



Muon Neutrino





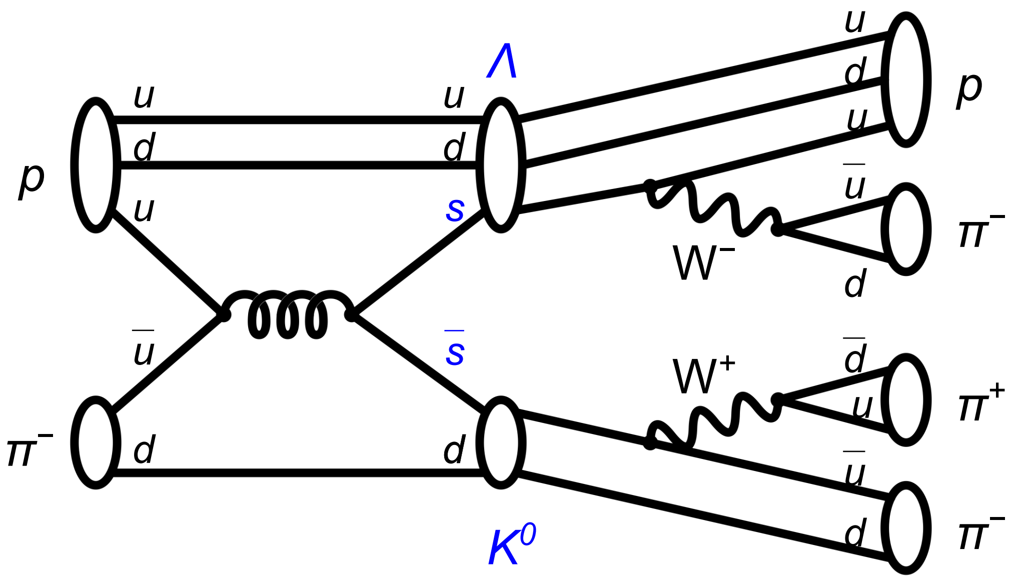
1962: first neutrino experiment at an accelerator

experimental challenge: reduce background from cosmic muons

Nobel prize 1988 for Lederman, Schwartz and Steinberger

Discovery of Strange Hadrons

- first strange particle, the kaon, discovered in 1947 in cosmic ray events (but strangeness as concept not yet known)
- features: “long” lifetime (10^{-10} s), about ½ proton mass
- later copiously produced in πp interactions:

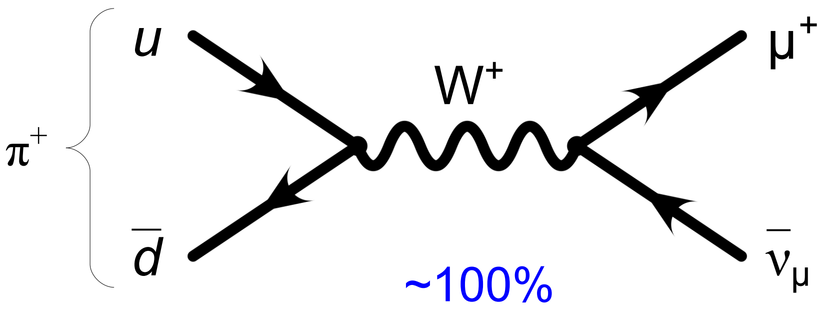


intermediate strange particles reconstructed by calculating invariant masses of proton and pions

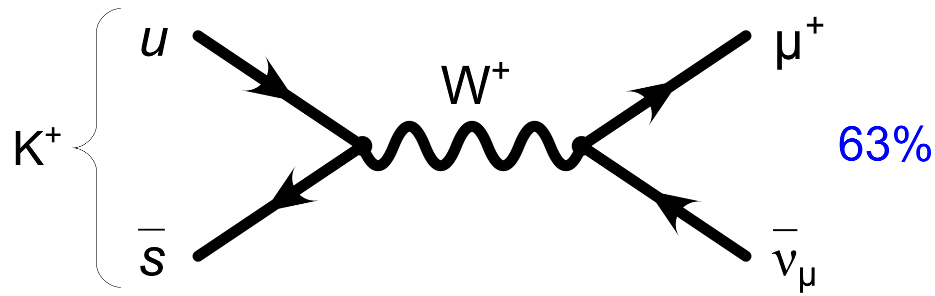
⇒ interpretation: strangeness conserved in strong production (always pairs of strange particles produced), but violated in weak decay

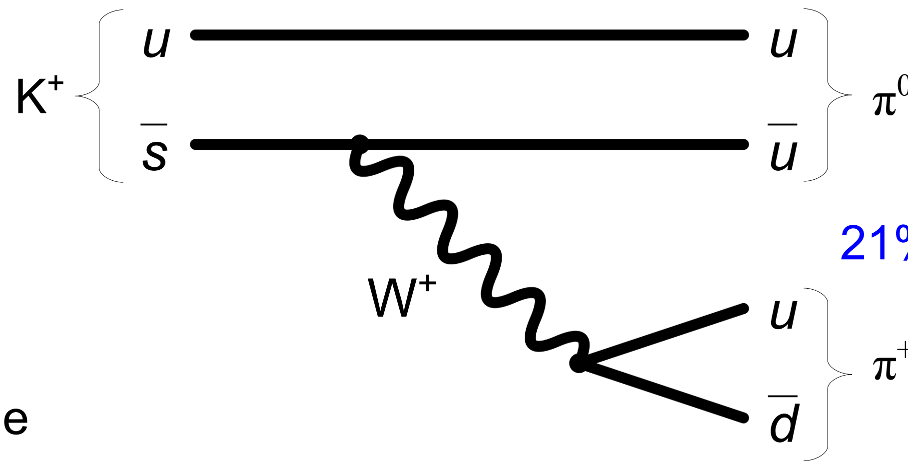
Comparison of Pion and Kaon Decay

$\tau_\pi = 2.6 \cdot 10^{-8}$ s

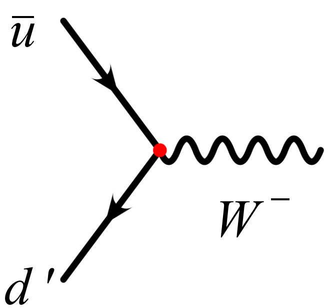


$\tau_K = 1.2 \cdot 10^{-8}$ s





- kaon (494 MeV) is much heavier than pion (135 MeV), why is not $\tau_K \ll \tau_\pi$?
- generation changing CC weak coupling is suppressed:



θ_C: Cabbibo angle

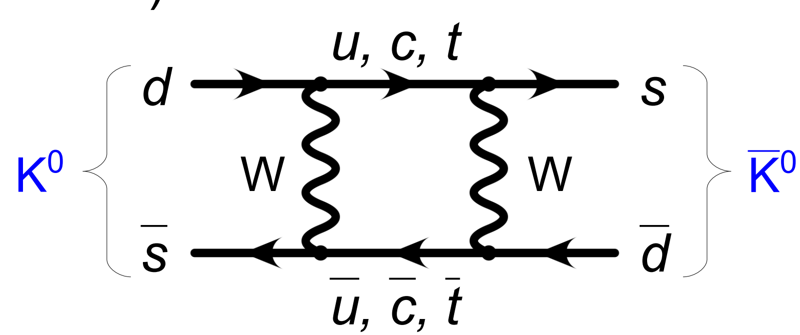
$$d' = d\cos\theta_C + s\sin\theta_C$$

~0.97 ~0.22

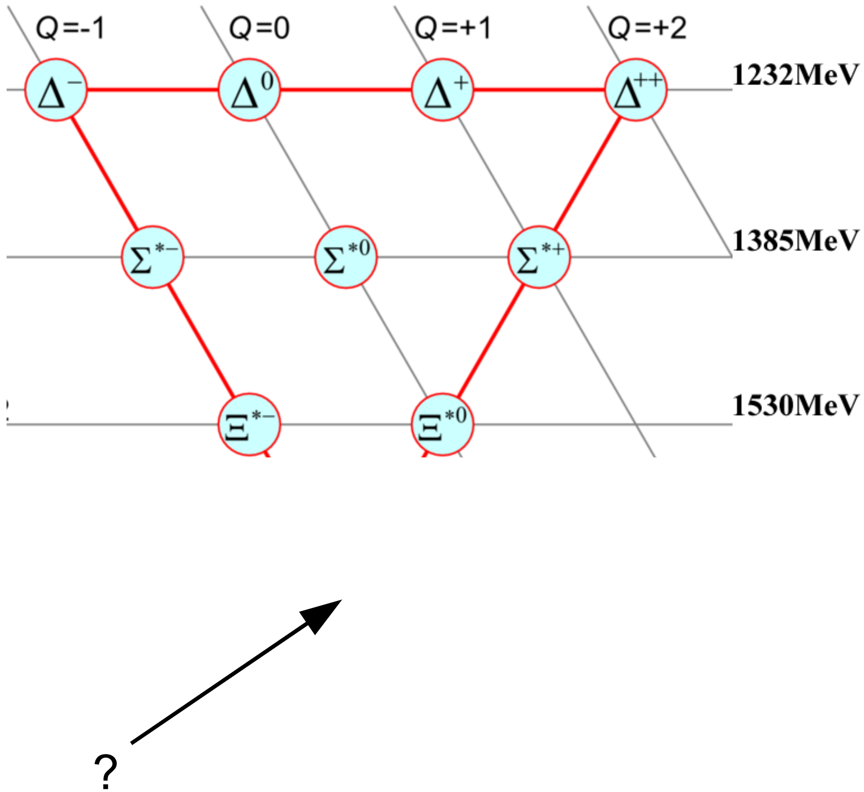
Kaons

- if you look into the PDG, you will find the following 4 entries:
  - $K^+ = u\bar{s}$, antiparticle: $K^- = \bar{u}s$, $\tau = 1.2 \cdot 10^{-8}$ s ($c\tau = 3.7$ m)
  - $K^0 = d\bar{s}$, antiparticle: $\bar{K}^0 = \bar{d}s$
  - K^0_S, $\tau = 9.0 \cdot 10^{-11}$ s ($c\tau = 2.7$ cm)
  - K^0_L, $\tau = 5.1 \cdot 10^{-8}$ s ($c\tau = 15$ m)
- K^0 and $\bar{K}^0$ are eigenstates of the strong interaction (which conserves strangeness) while K^0_S and K^0_L are eigenstates of the weak interaction
- since kaons decay weakly, only the weak eigenstates have a lifetime
- K^0_S and K^0_L are (nearly) CP eigenstates, the different accessible final states (2π for CP=+1, 3π for CP=−1) lead to the different lifetimes
- K^0 and $\bar{K}^0$ can turn from one into the other:

  "oscillation"



Baryon Decuplet

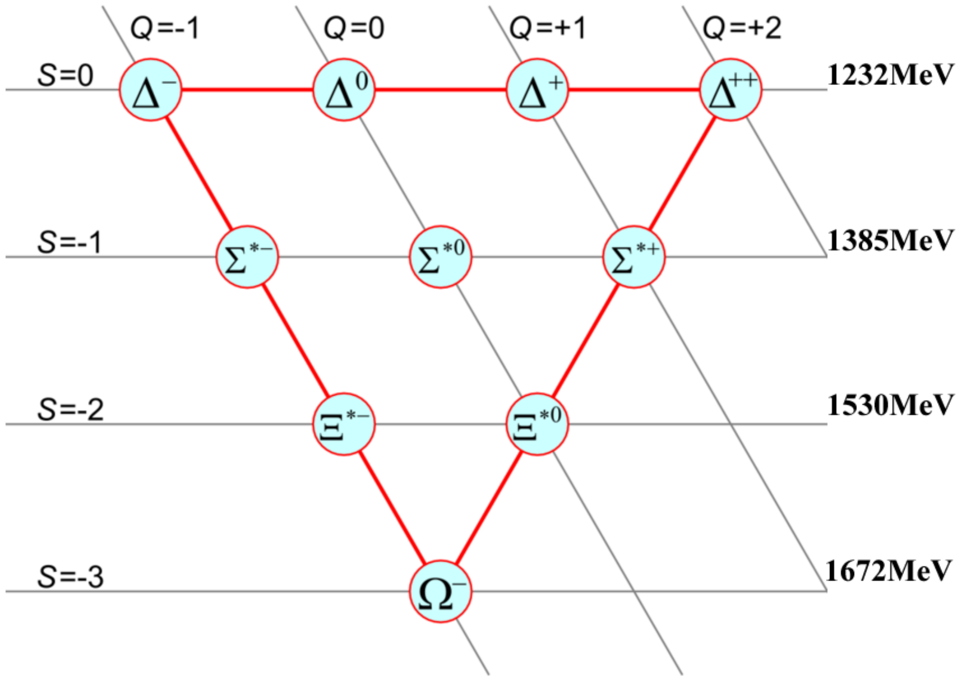


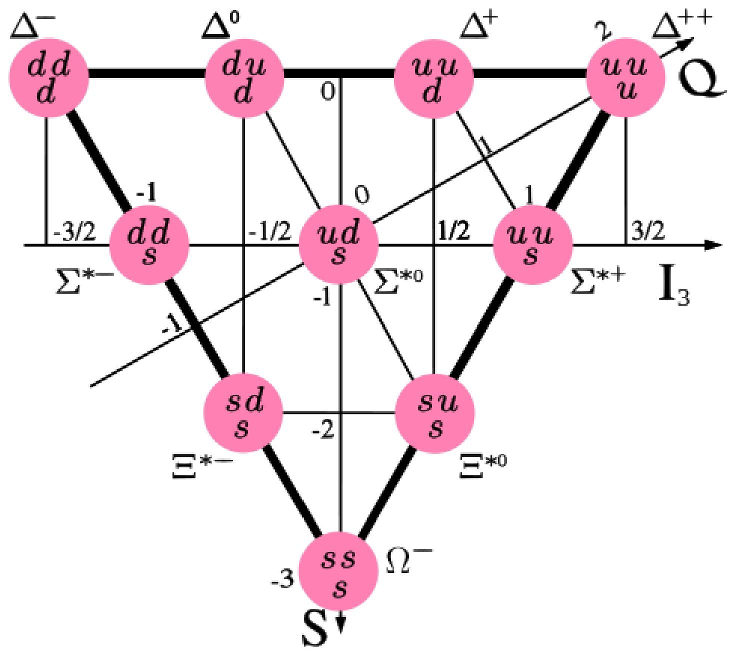
- by the early 1960's many new particles found ("particle zoo")
- try to find ordering principles
- e.g. order all spin-3/2 baryons by mass (or isospin) and charge
- lead to the postulate of quarks
- 1963: prediction of a baryon with isospin 0 at the lower tip

Baryon Decuplet: Omega Discovery

- 1964: Ω^- found, triumph of quark model

Nobel Prize 1969
for M. Gell-Mann





- “identical” states for all three quarks for Λ^-, Λ^{++} and Ω^- lead to proposal of colour charge

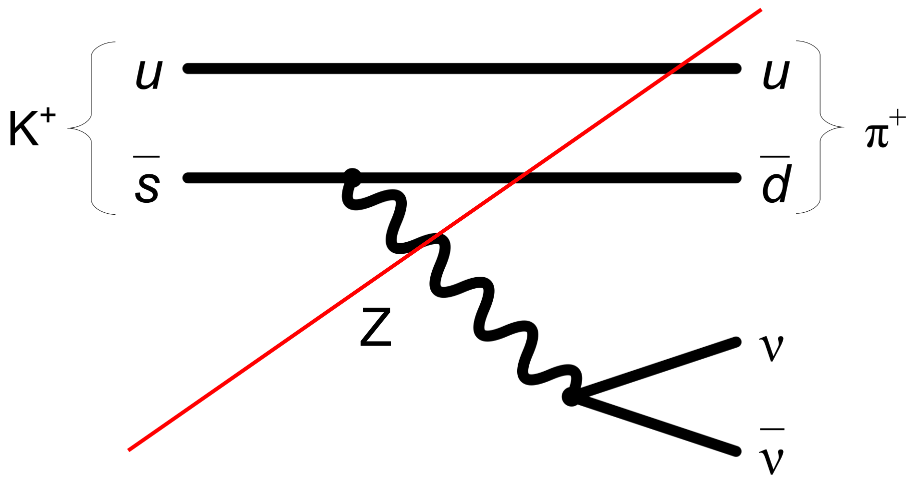
“Reality” of Quarks

- originally, when proposed in 1964 by Gell-Mann and Zweig, “quarks” were considered by many physicists just a principle for ordering the new-found particle zoo
- if the quarks really correspond to constituents of the hadrons was not clear
- in 1968, deep inelastic electron-proton scattering at SLAC showed that the proton consisted of smaller constituents, then called “partons” by Feynman
- only slowly it was accepted that the partons in the proton correspond to the *u* and *d* quarks

  → Quark-Parton-Model (QPM)

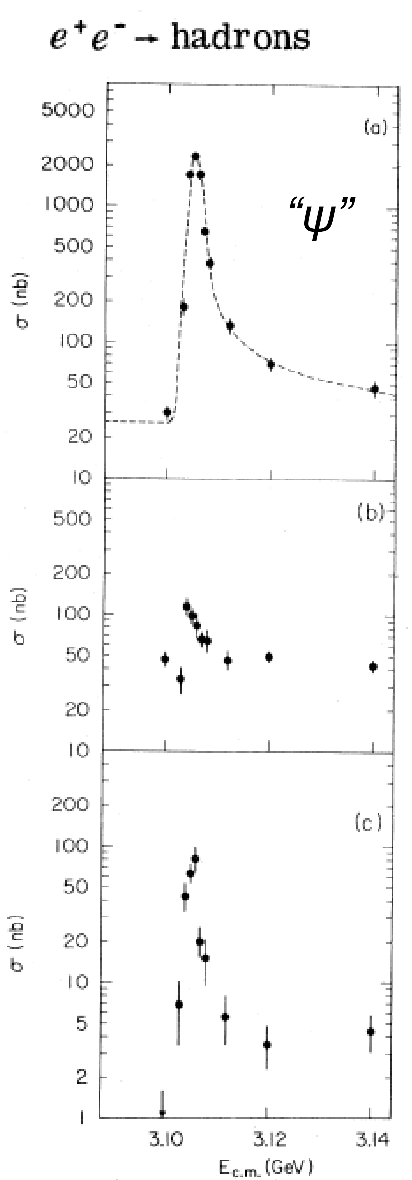
Charm Quark

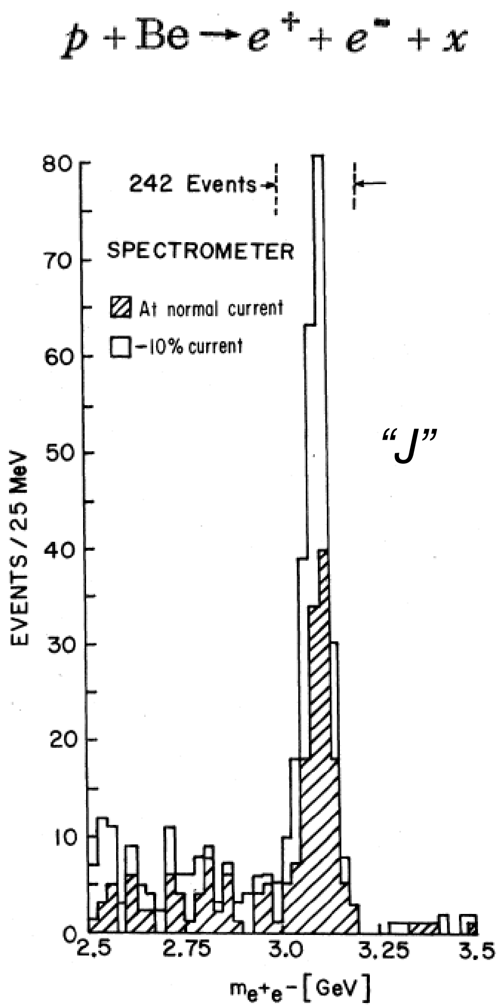
- Glashow, Iliopoulos and Maiani proposed charm quark as partner of the $s' = s\cos(\theta_C) - d\sin(\theta_C)$ combination
- analogous to u being partner of $d' = d\cos(\theta_C) + s\sin(\theta_C)$
- charm allows to prevent "flavour changing neutral currents" (FCNC) in the theory, which were observed to be extremely rare, e.g. $K^+ \to \pi^+ \nu \bar{\nu}$



- with d' and s' you get a destructive interference of the mixed $s\bar{d}$ and $\bar{s}d$ terms in the coupling to the Z

J/ψ Discovery



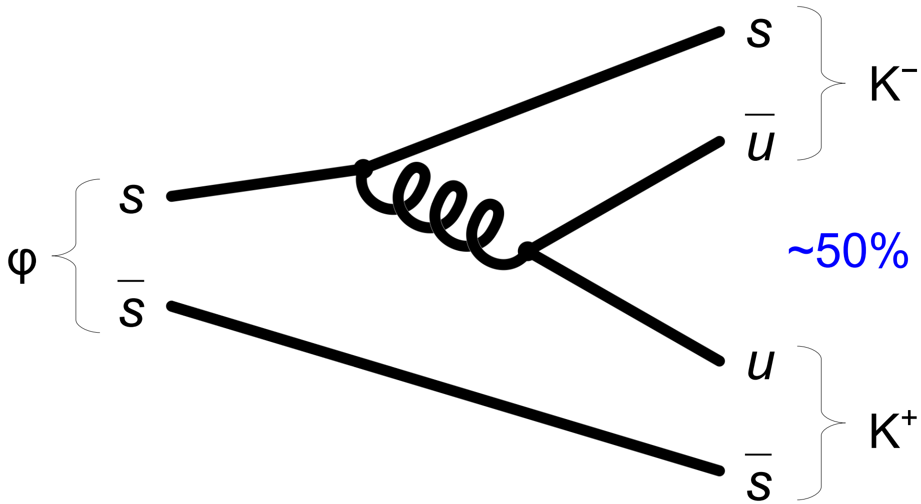


Nobel Prize 1976
for Richter and Ting

- the 1974 November revolution in HEP
- new particle with m=3.1 GeV and narrow width found at the same time by Ting et al. in collisions of a proton beam on a beryllium target and by Richter et al. in e^+e^- collisions in the SPEAR ring
- identified as bound charm-anti-charm state

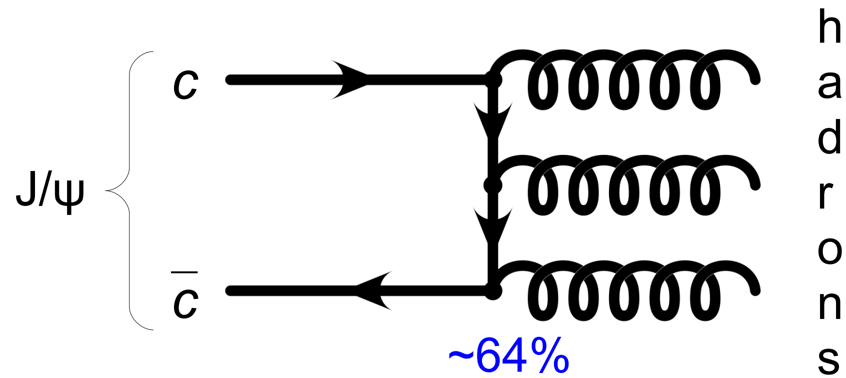
Why is the J/ψ so narrow?

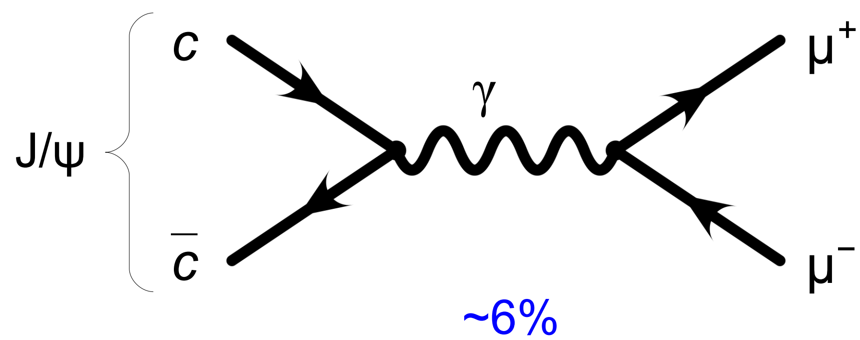
φ: m = 1020 MeV
Γ = 4.3 MeV



$\varphi \rightarrow \mu^+ \mu^-$: 0.03%

J/ψ: m = 3097 MeV
Γ = 0.09 MeV

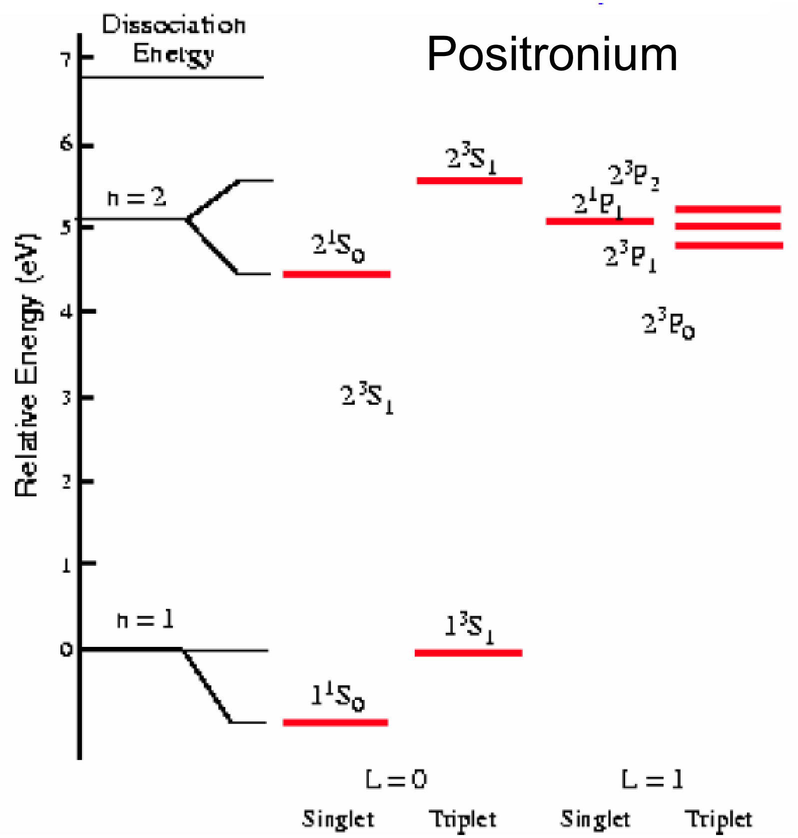


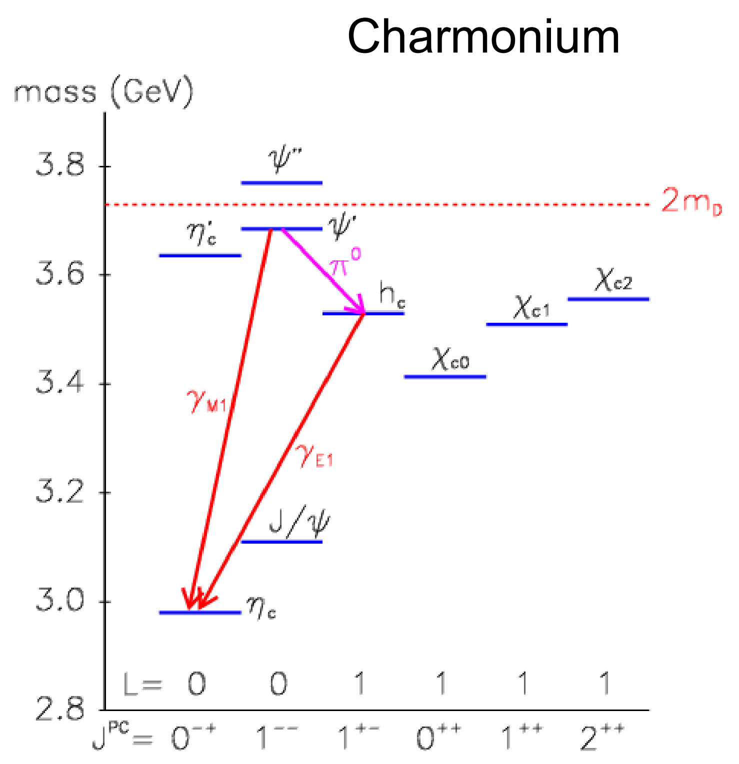


- J/ψ is too light to decay into 2 charm mesons (D mesons)
- "easiest" strong decay is via 3 gluons, higher order, heavily suppressed

Comparison of Positronium and Charmonium

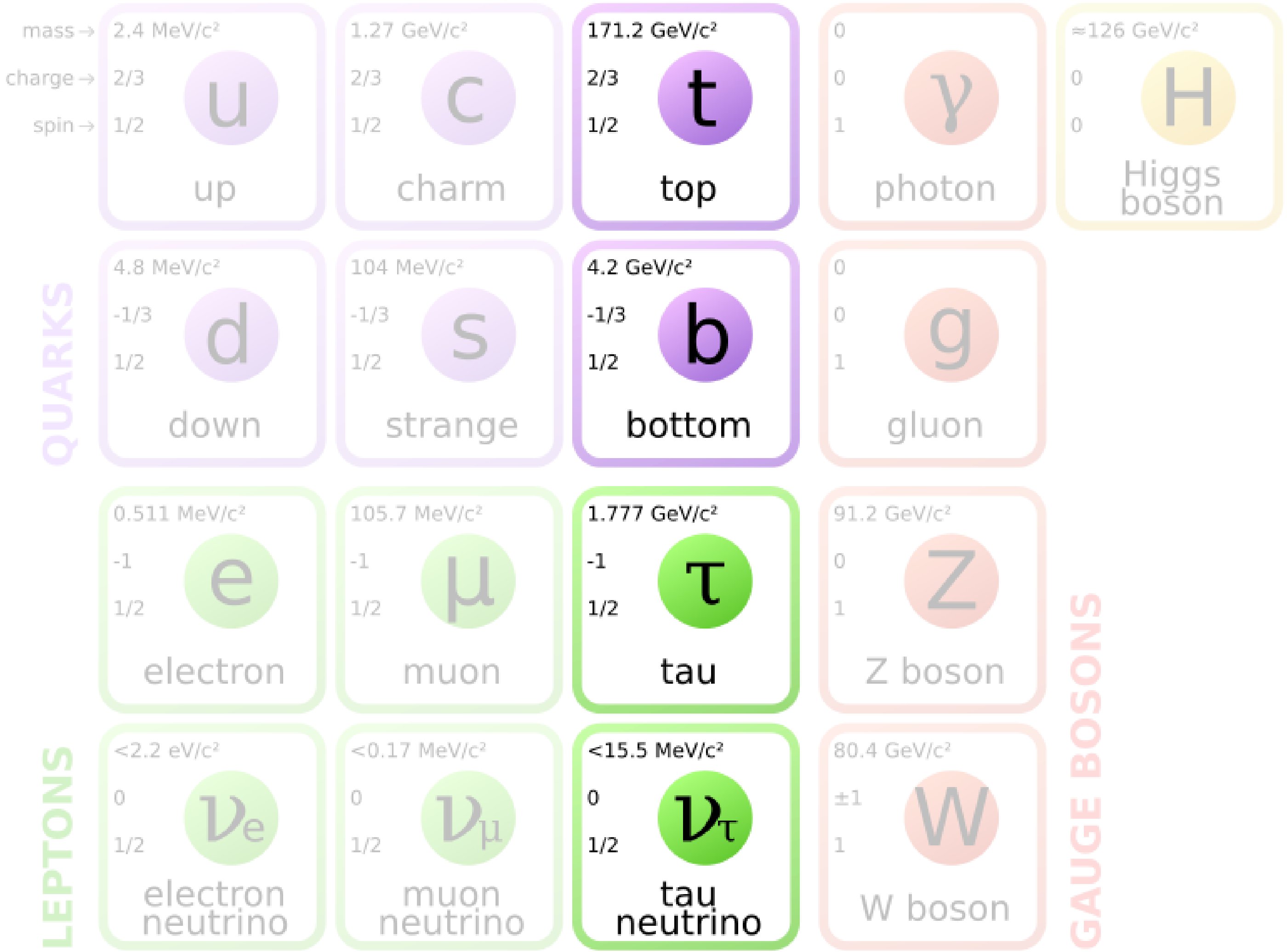
- positronium: e^+e^- bound state, elm. interaction, eV level spacing
- charmonium: $c\bar{c}$ bound state, strong interaction, GeV level spacing





Questions?

Elementary Particles: Third Generation



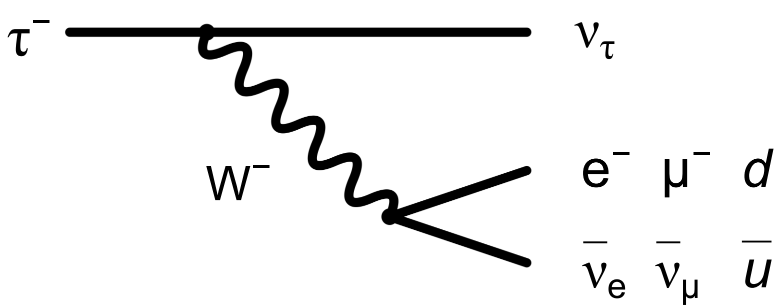
Tau

- τ was found in 1977 in e^+e^- collisions at SPEAR in the "anomalous" reaction: $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + *at least two undetected particles*

Nobel Prize 1995 for M. Perl

- interpretation: $e^+ + e^- \rightarrow \tau^+ + \tau^- \rightarrow e^\pm + \mu^\mp + 4\nu$
- mass: 1.8 GeV, lifetime $\tau = 0.3 \cdot 10^{-12}$ s, $c\tau = 87$ μm
- BR: 17% $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$
  17% $\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$
  66% $\tau^- \rightarrow \text{hadrons} + \nu_\tau$

τ is the only lepton that decays to hadrons

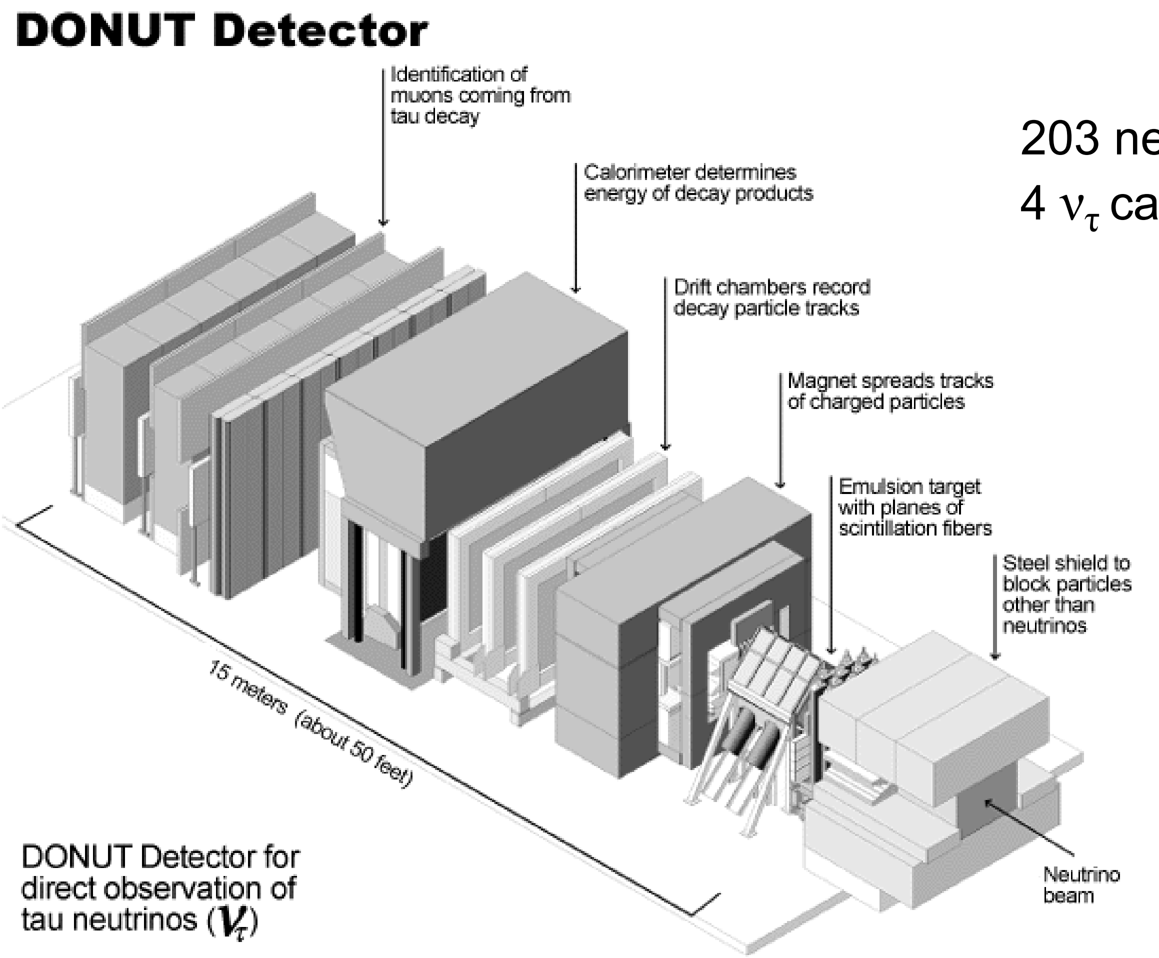


colour factor

$1 : 1 : 1{*}3 = 20\% : 20\% : 60\%$

Tau Neutrino

- first direct detection in 2000 in a dedicated experiment, DONUT, at Fermilab → “youngest” elementary particle (except Higgs?)

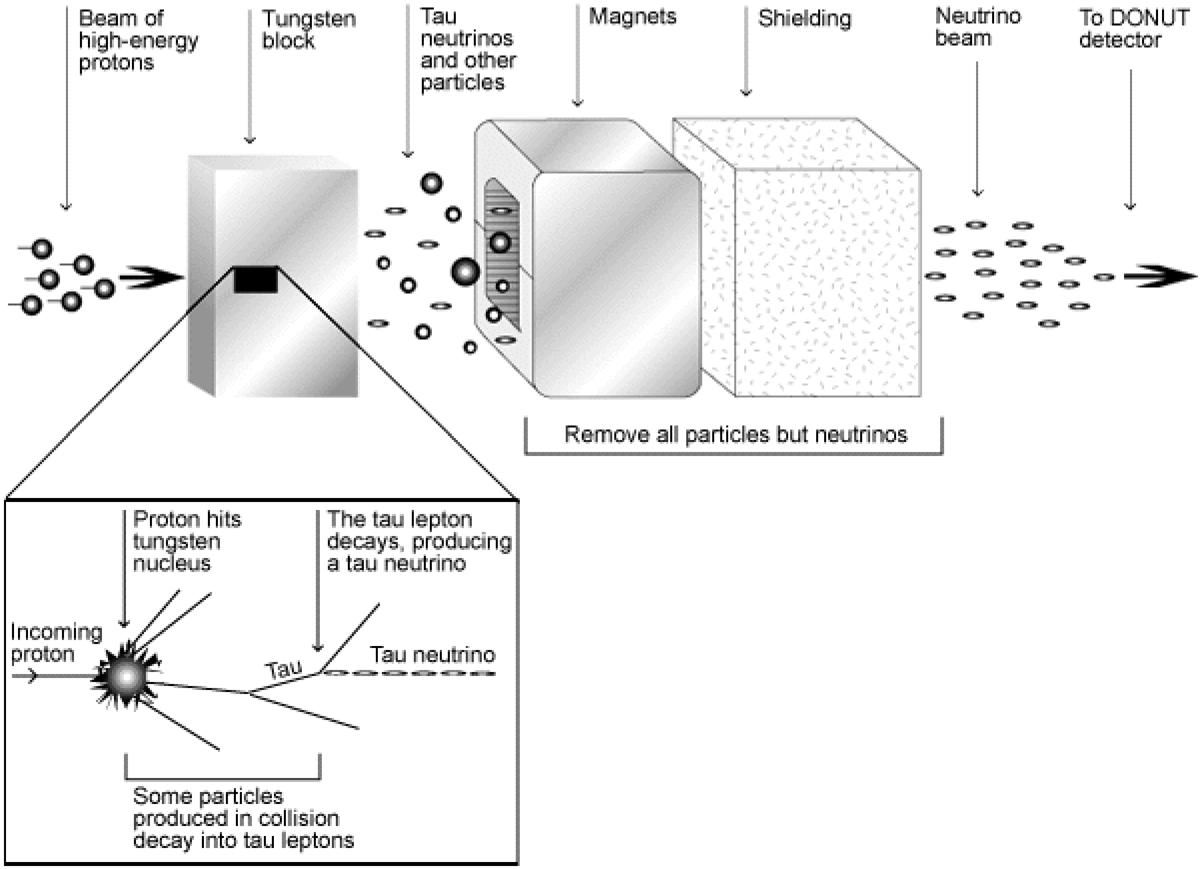


203 neutrino events

4 ν_τ candidates

Tau Neutrino

- one of the difficulties: produce a beam that contains enough ν_τ



Bottom Quark

- third generation of quarks proposed in 1973 by Kobayashi and Maskawa to explain CP violation (before the charm quark was found!)
- CKM Matrix, extension of Cabibbo angle to 3 families:

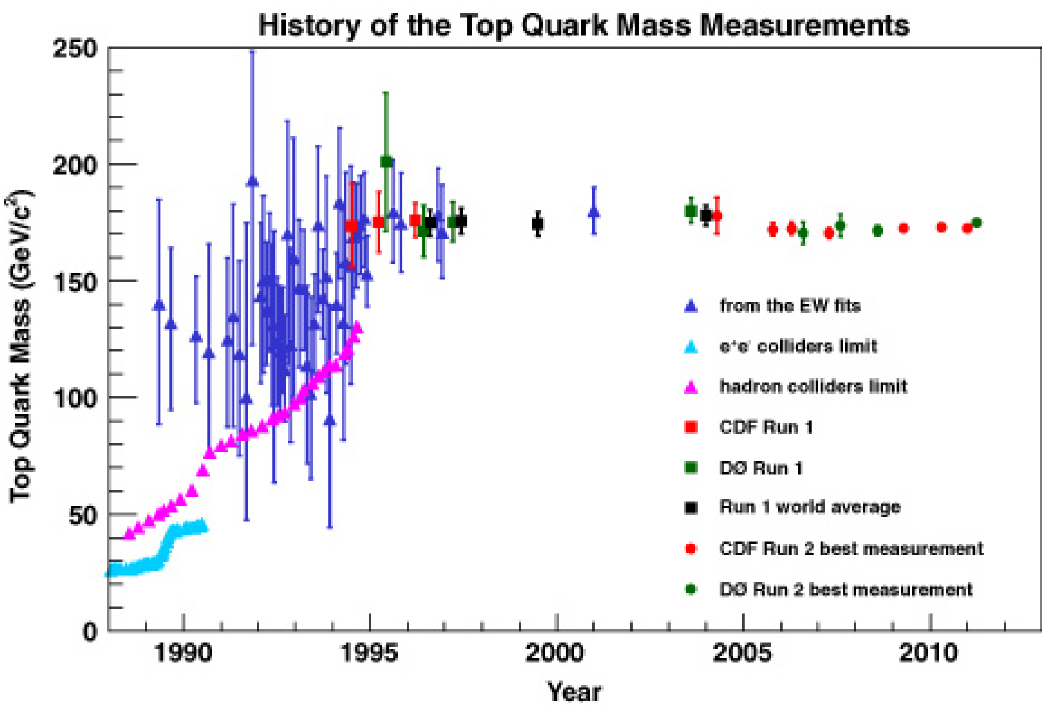
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- coupling of *b* to lighter quarks is very small
- consequence: "long" lifetime of B hadrons ($\tau \approx 1.5 \cdot 10^{-12}$ s, $c\tau \approx 450$ μm), experimentally important since this can be used to identify them: most detectors have very precise vertex detectors
- *b* quarks were discovered in 1977 when bottomonium (Υ mesons) was found in the $\mu^+\mu^-$ decay channel in collisions of a proton beam on a fixed target

Top Quark

- proposed together with the *b* quark in 1973
- was expected to be “a bit heavier” than bottom, and to be found soon
- but it took 18 years to find it!
- first hints of production in 1992, final discovery in 1995 at Tevatron

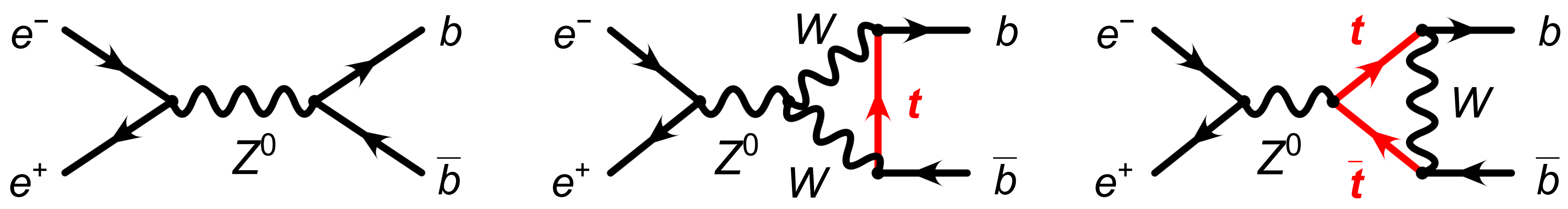
Figure 1 from Angela Barbaro Galtieri et al 2012 Rep. Prog. Phys. 75 056201



already several years before the top was finally found, the range of the top mass was known from electroweak fits

Top Mass from Electroweak Fits

- in various electroweak processes top quarks appear as virtual particles in higher order diagrams
- example: $e^+ e^- \rightarrow Z^0 \rightarrow b\,\bar{b}$ at LEP:



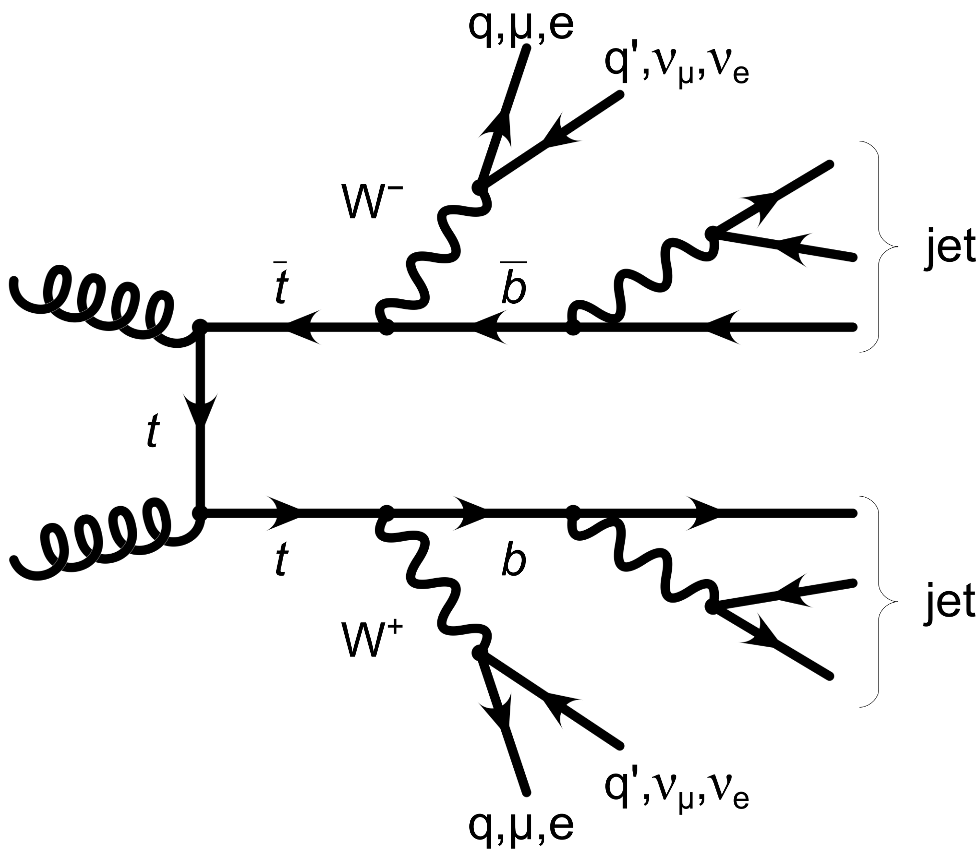
- top mass range allowed by LEP data (1993 prediction):

  $m_t = 170 \pm 20$ GeV

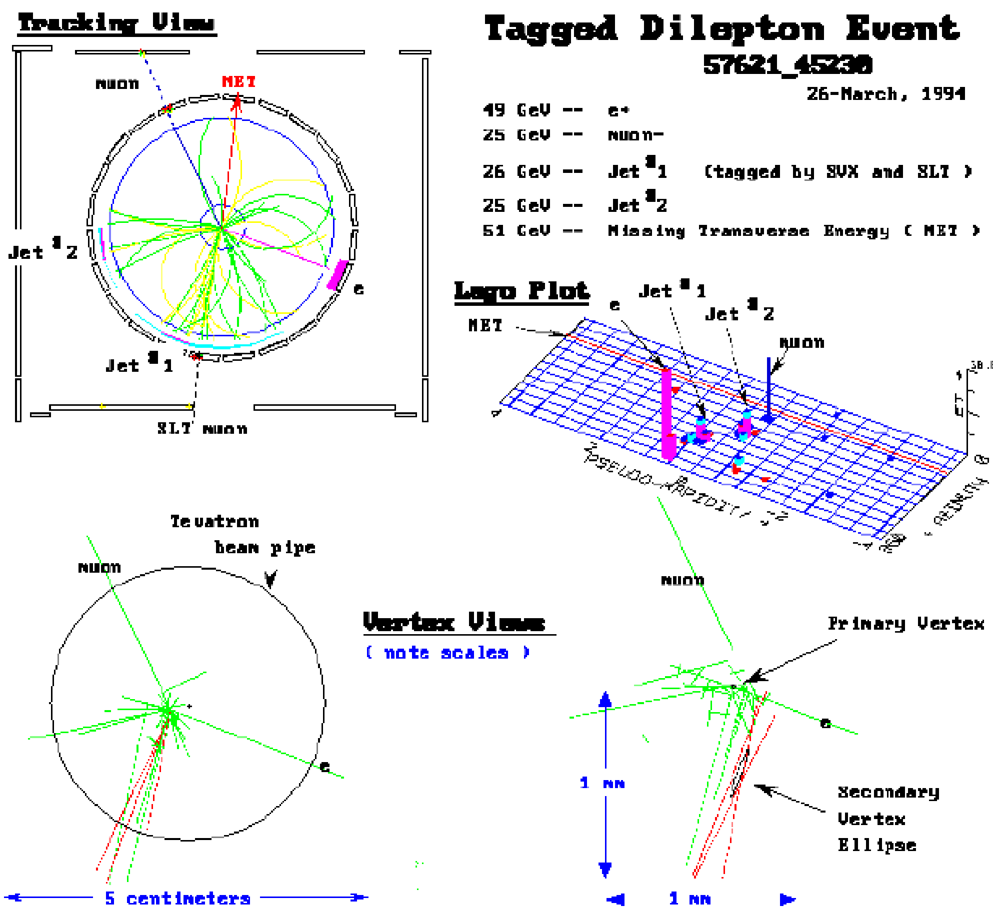
Top Production and Decay

- top is very heavy (173 GeV, about 35 times as heavy as b), and can decay weakly in the same generation, so very short lifetime of ~10^{-25} s
- top quarks decay before they hadronize → the only “free” quark, no *t* hadrons seen

t decays to almost 100% to *b* + *W*

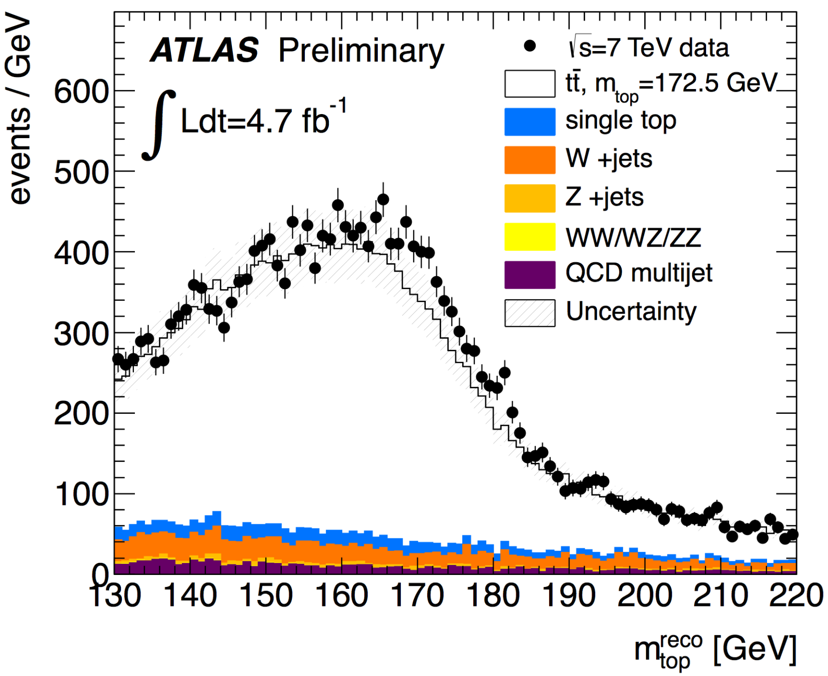


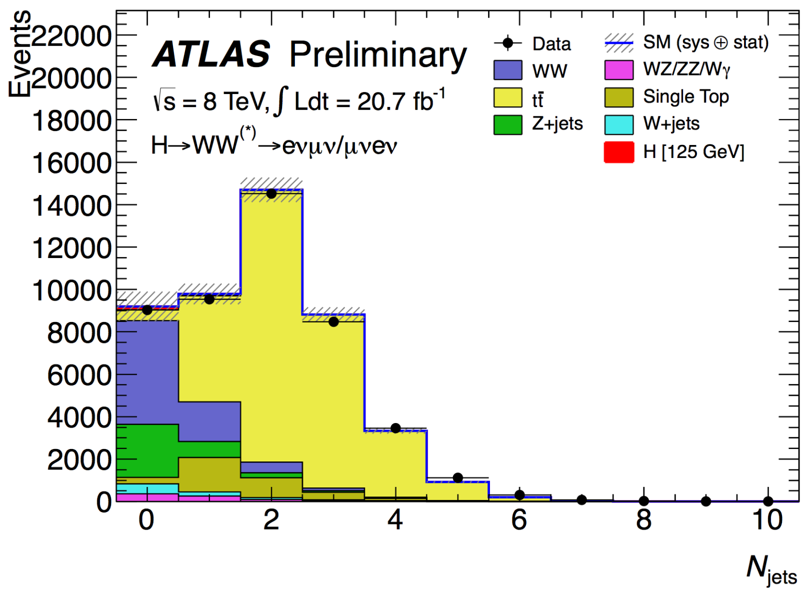
One of the first produced Top Candidates



Yesterdays Discovery is Todays Background

- at LHC, top quark pairs are copiously produced and are a major source of W pairs
- new top mass measurements profit from large statistics





- top pairs are one of the important backgrounds for the H → WW decay

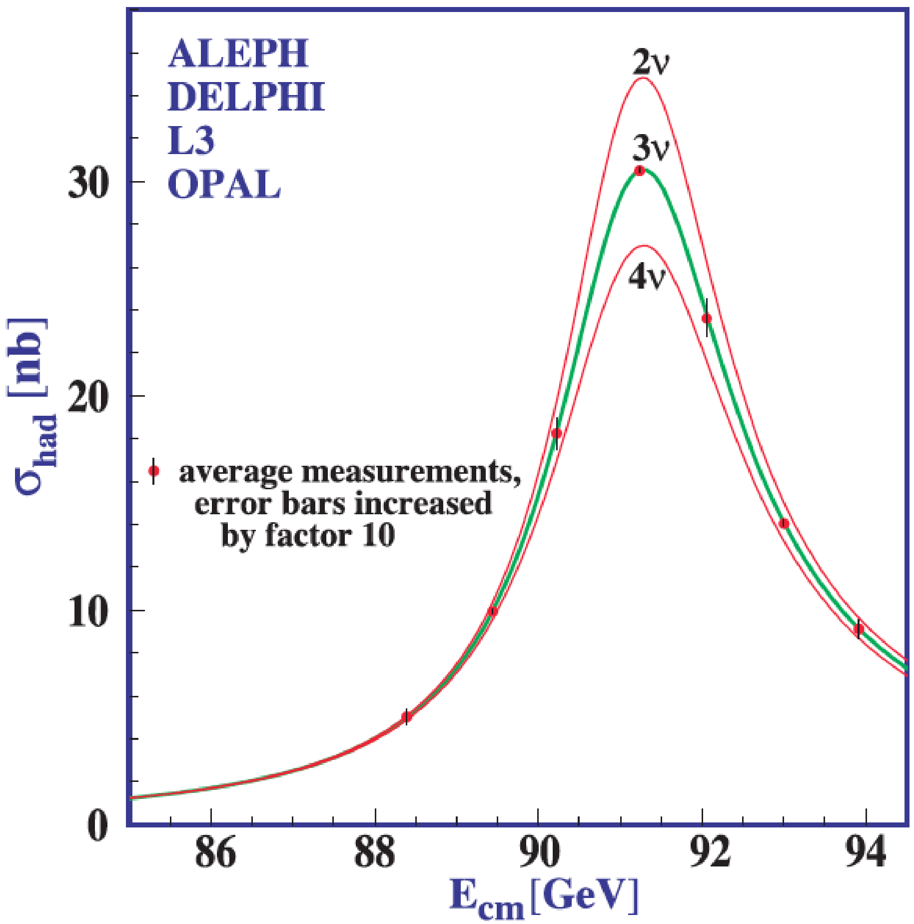
More Than 3 Generations?

- plenty of searches for 4th generation quarks or leptons
- very strong hint of only 3 generations from $e^+e^- \to Z \to$ hadrons
- total Z width gets contributions from all possible decays:

$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{qq} + N_\nu \Gamma_{\nu\nu}$$

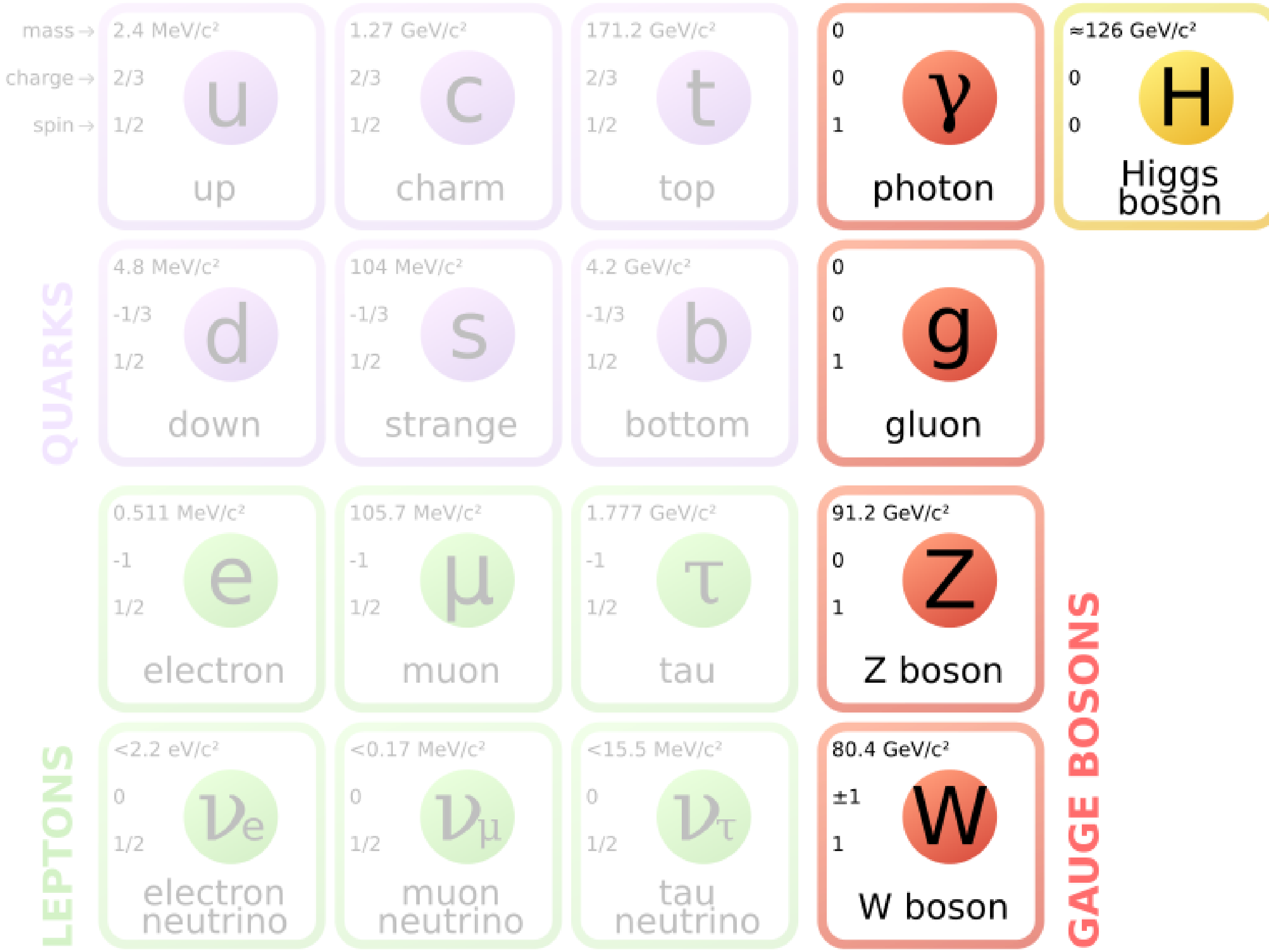
- number of light ($< \frac{1}{2} m_Z$) neutrinos:

  $N_\nu = 2.984 \pm 0.008$



Questions?

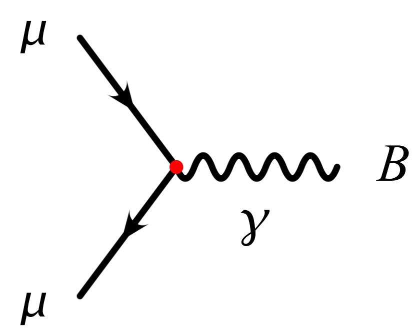
Elementary Particles: Gauge Bosons



Photon / QED

- quantisation of electromagnetic radiation proposed by Einstein in 1905
- QED formulated as first quantum field theory in 1930ies and 40ies
- experimentally the most precisely tested theory in physics
- example: anomalous magnetic moment of the muon (“g–2”)

$$\vec{\mu} = g\,\mu_B\,\vec{s} \qquad \text{with} \qquad \mu_B = \frac{e\hbar}{2mc}$$



- lowest order diagram: g=2
- higher order diagrams change the value of g by ~1‰, so the “anomaly” a=(g – 2)/2 is studied
- results: $a^{\mathrm{exp}} = (11\ 659\ 208.9 \pm 5.4 \pm 3.3)\cdot 10^{-10} \Rightarrow \quad \Delta a/a = 5\cdot 10^{-7}$

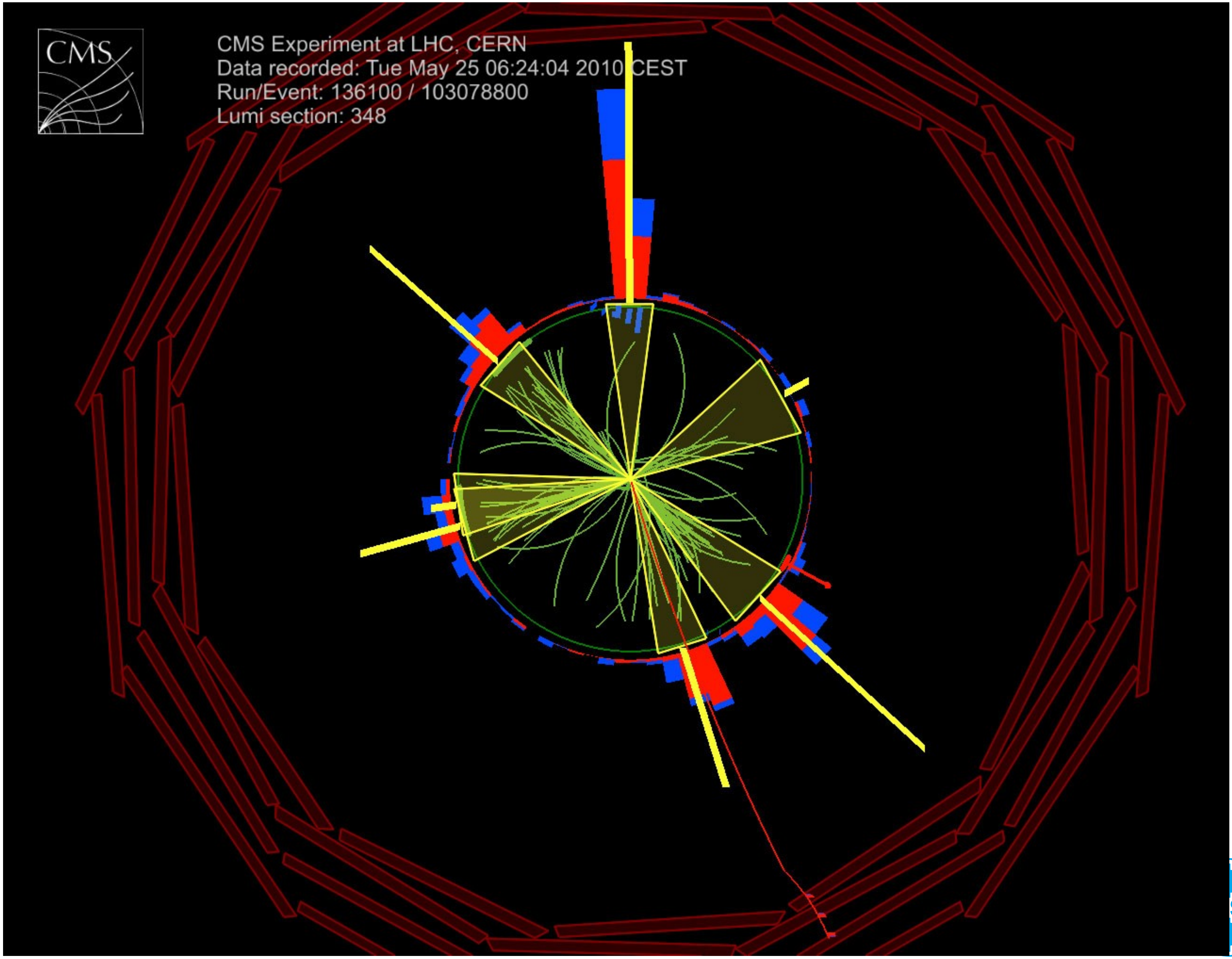
$$a^{\mathrm{SM}} = (11\ 659\ 180.2 \pm 0.2 \pm 4.2 \pm 2.6)\cdot 10^{-10}$$

3.6 σ difference

Gluon / QCD

- gluons proposed by Gell-Mann as vector meson field in 1962/1964
- experimental challenge to measure gluons:
  - not directly visible in detector, but always fragment into quarks and more gluons, which then hadronise and appear as bundle of hadrons, a jet, in the detector
  - but quarks do the same and also appear as jets
  - distinction between quark and gluon jets is difficult
  - but gluons have spin 1 while quarks have spin ½ which leads to differences in the angular dependence of the cross section
  - ➔ infer the presence of gluons from the possible processes and angular distributions

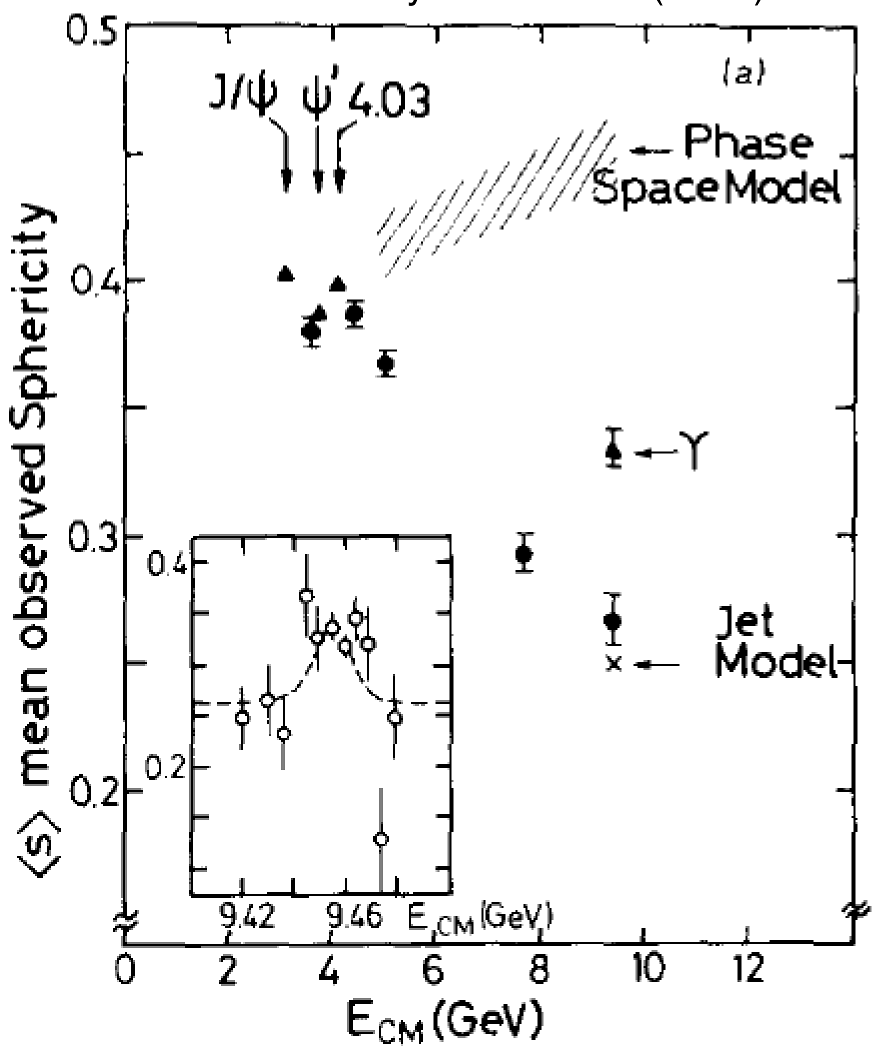
Jets in the CMS Detector



Gluon Discovery

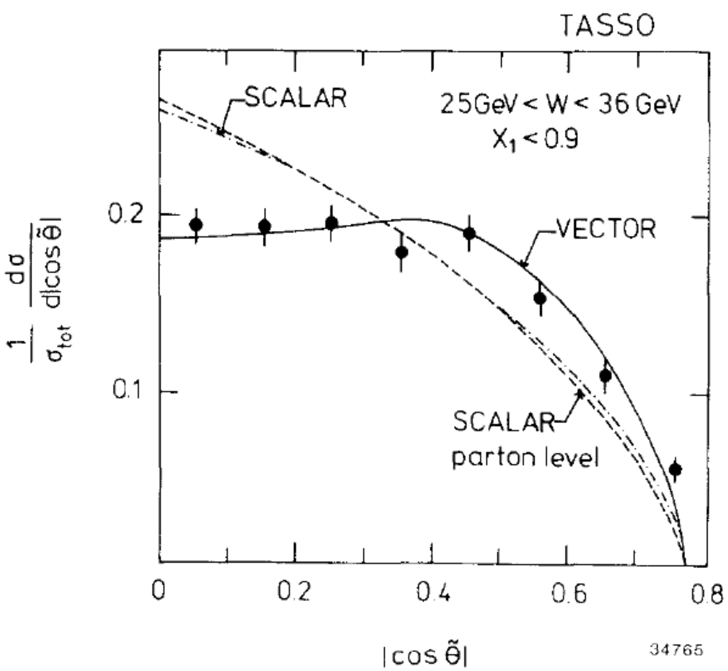
- 1978: first hints from the PLUTO experiment at the e^+e^- collider DORIS at DESY: $\Upsilon \rightarrow ggg$ decay
- Sphericity s: variable to classify shape of an event perfectly isotropic: s=1, perfectly back-to-back 2-jet: s=0
- jet model: $q\bar{q}$ di-jets does not describe the data at the Υ resonance
- no ggg model yet

from Phys. Lett. B 78 (1978) 176

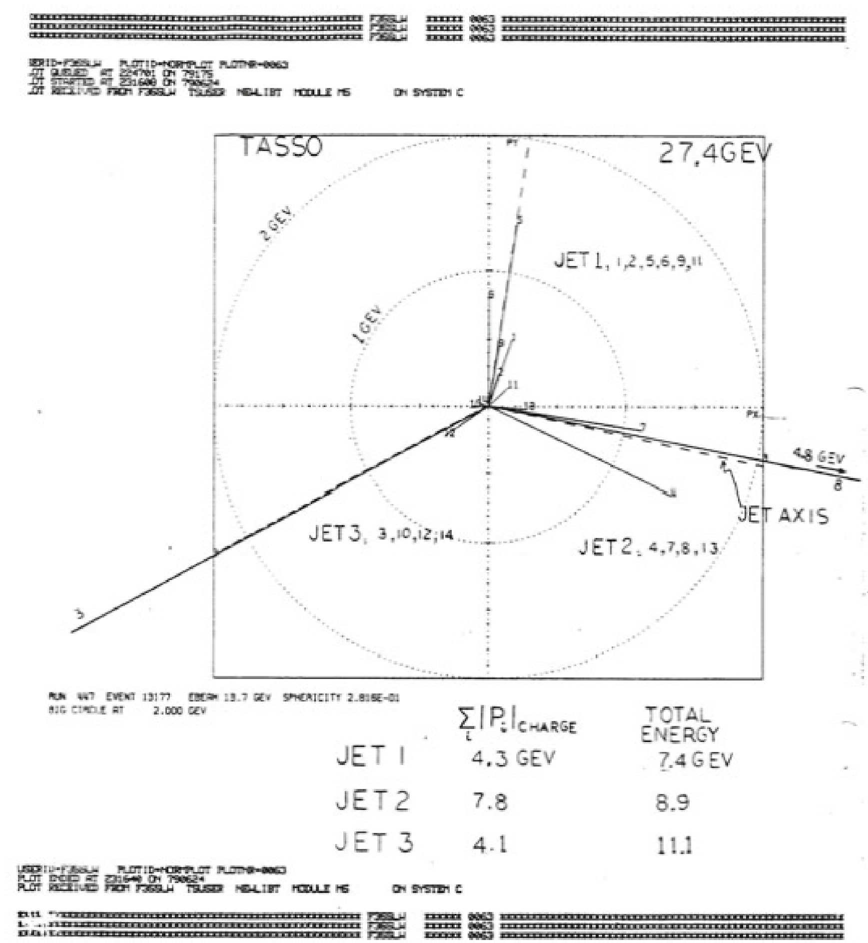


Gluon Discovery

- 1979: TASSO, MARK-J, PLUTO and JADE at the PETRA collider at DESY: 3-jets in $e^+e^- \rightarrow q\bar{q}g$
- 1980: demonstration that gluon has spin 1 (vector particle)



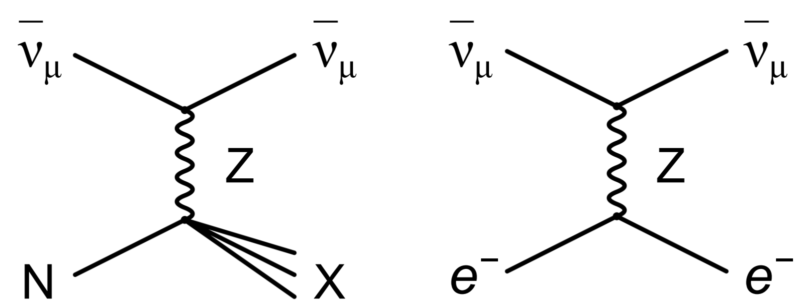
first 3-jet event from PETRA



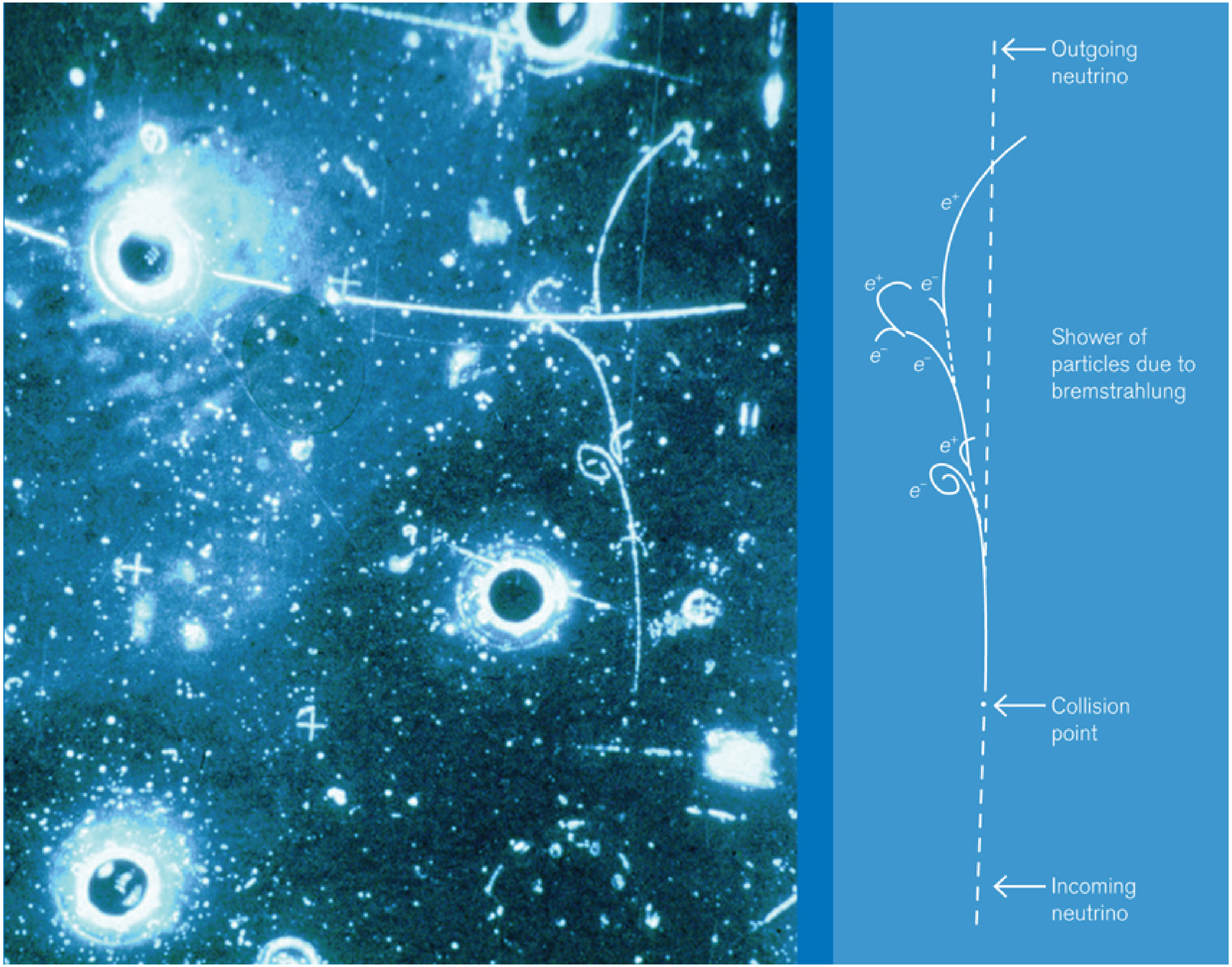
W & Z Boson

Nobel Prize 1979 for Glashow, Salam and Weinberg

- both W and Z first noticed as virtual particles in weak interactions
- predicted in the unified theory of electromagnetism and weak force by Glashow, Salam and Weinberg in 1964
- CC weak interactions were known (β decay, decay of strange particles)
- NC weak reactions are much more difficult to observe:
  - strange decays are forbidden, Z coupling does not change quark flavour
  - processes can also proceed via photons or gluons if charged particles or quarks are involved
  - best possibility: elastic scattering of neutrinos
- in 1973, the Gargamelle bubblechamber experiment at the CERN PS observed two types of NC processes:



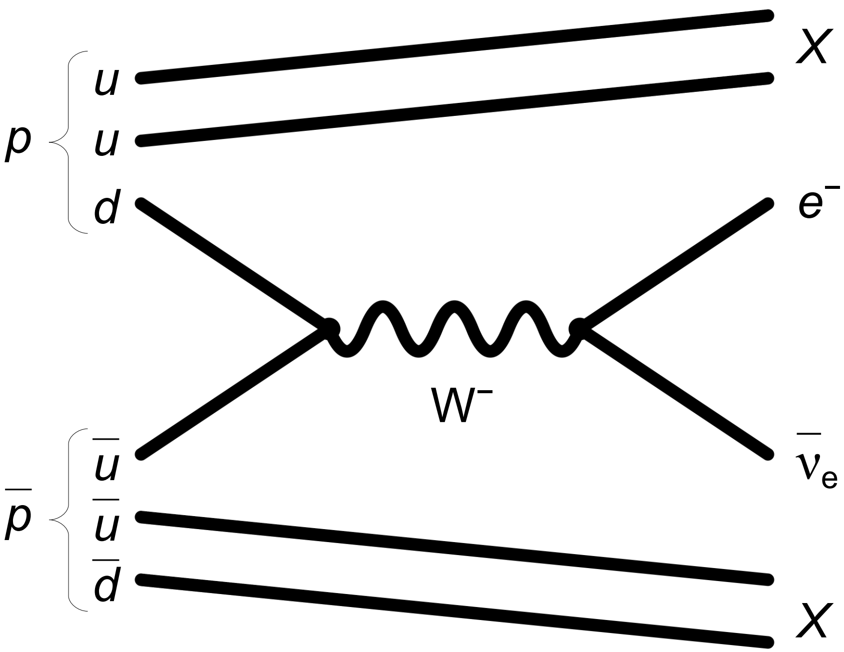
NC Example: $\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$

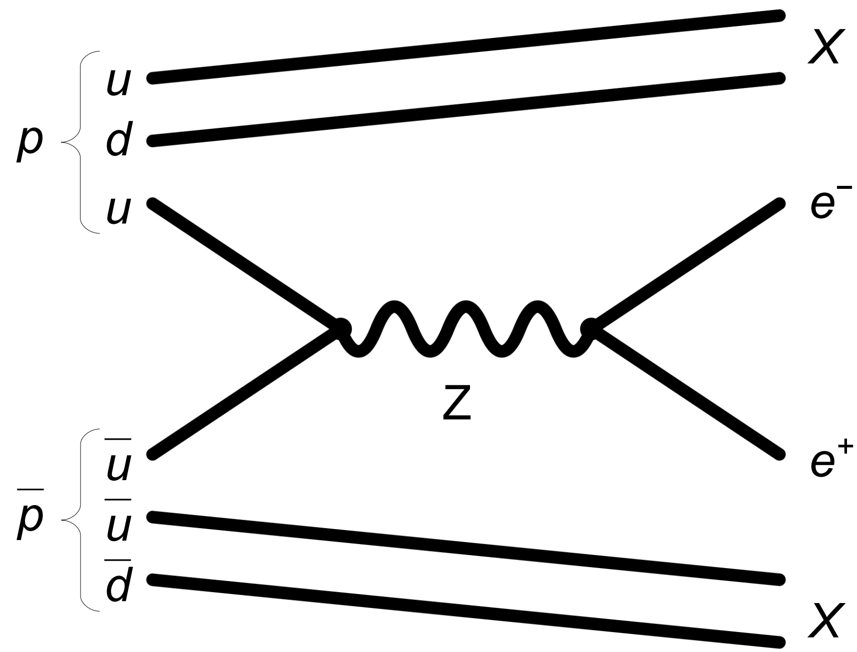


from Symmetry Magazine, courtesy of CERN

W & Z Bosons

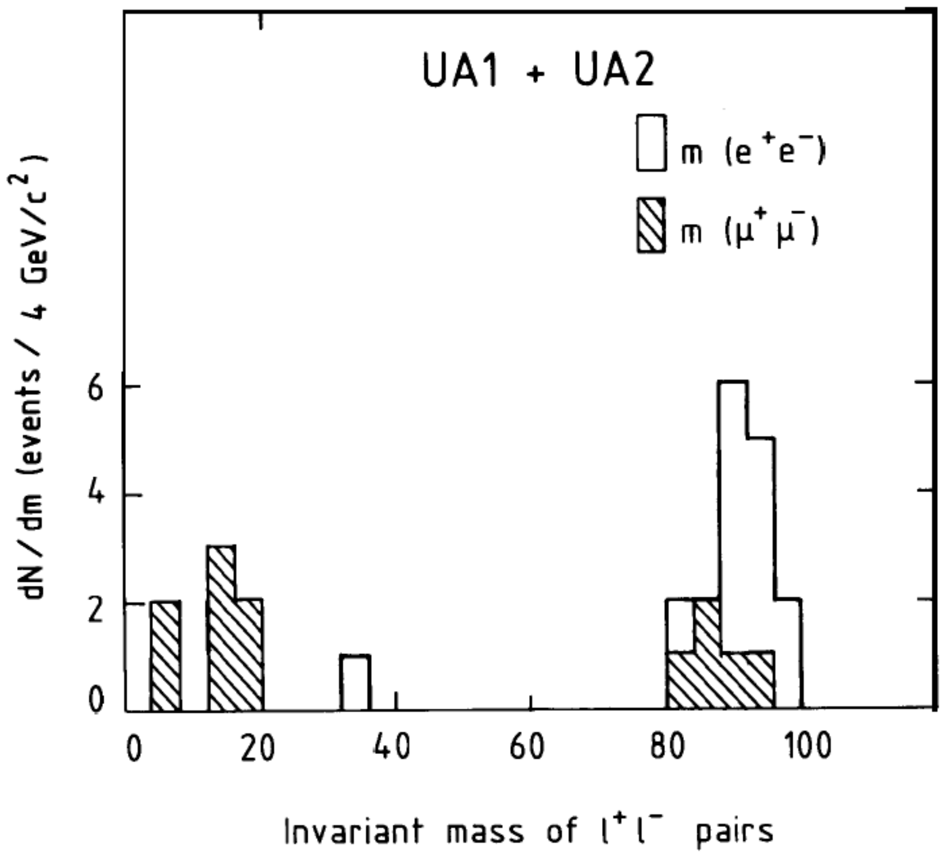
- first production of real W and Z bosons in 1983
- the SPS at CERN was used as first proton-antiproton collider ($Sp\bar{p}S$)
- stochastic cooling invented by van der Meer essential to produce the intense antiproton beam





W and Z Boson Discovery

- 1983: first signals with 6 W → eν and 4 Z → ee events
- 1984: Nobel prize for C. Rubbia (UA1) and S. van der Meer



from www.nobelprize.org

Questions?

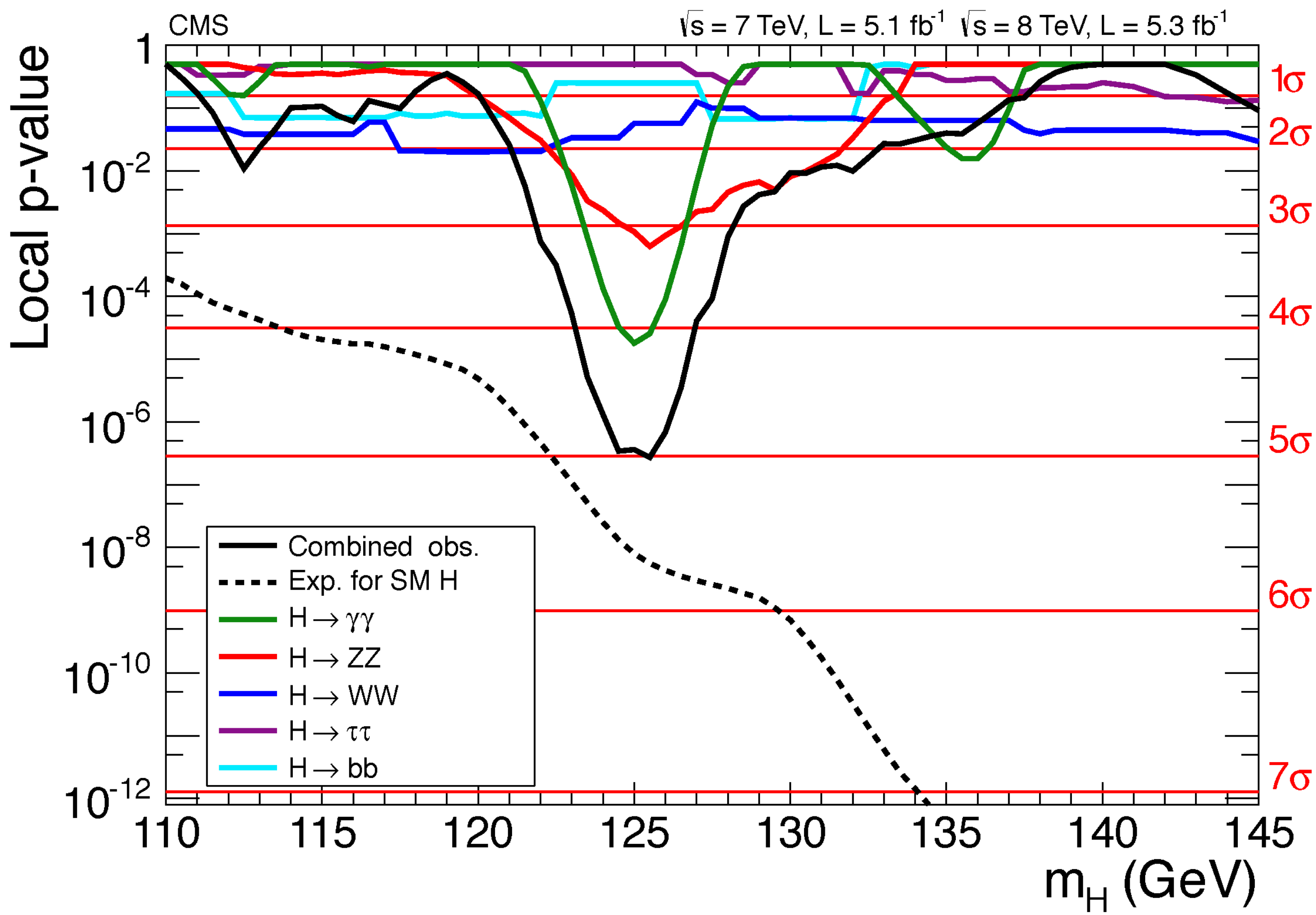
The Higgs

further contributions to theory of electroweak interaction:

- Veltman and 't Hooft showed 1971 that the theory is renormalizable (Nobel prize in 1999)
- but field quanta of Glashow-Salam-Weinberg theory should be massless
- in 1964, three independent papers proposing a mechanism how to break the symmetry and make W and Z bosons massive
  - Brout and Englert
  - Higgs (mentioning the existence of one or more scalar bosons)
  - Guralnik, Hagen and Kibble
- since then the Higgs boson was looked for by many experiments at colliders, e.g. at LEP, Tevatron, LHC
- Higgs searches are rather complicated since many different decay channels are combined to get significant results
  $\rightarrow$ dedicated lecture K. Tackmann

The Higgs: First Observation

- 4^{th} July 2012: both CMS and ATLAS reach 5σ significance



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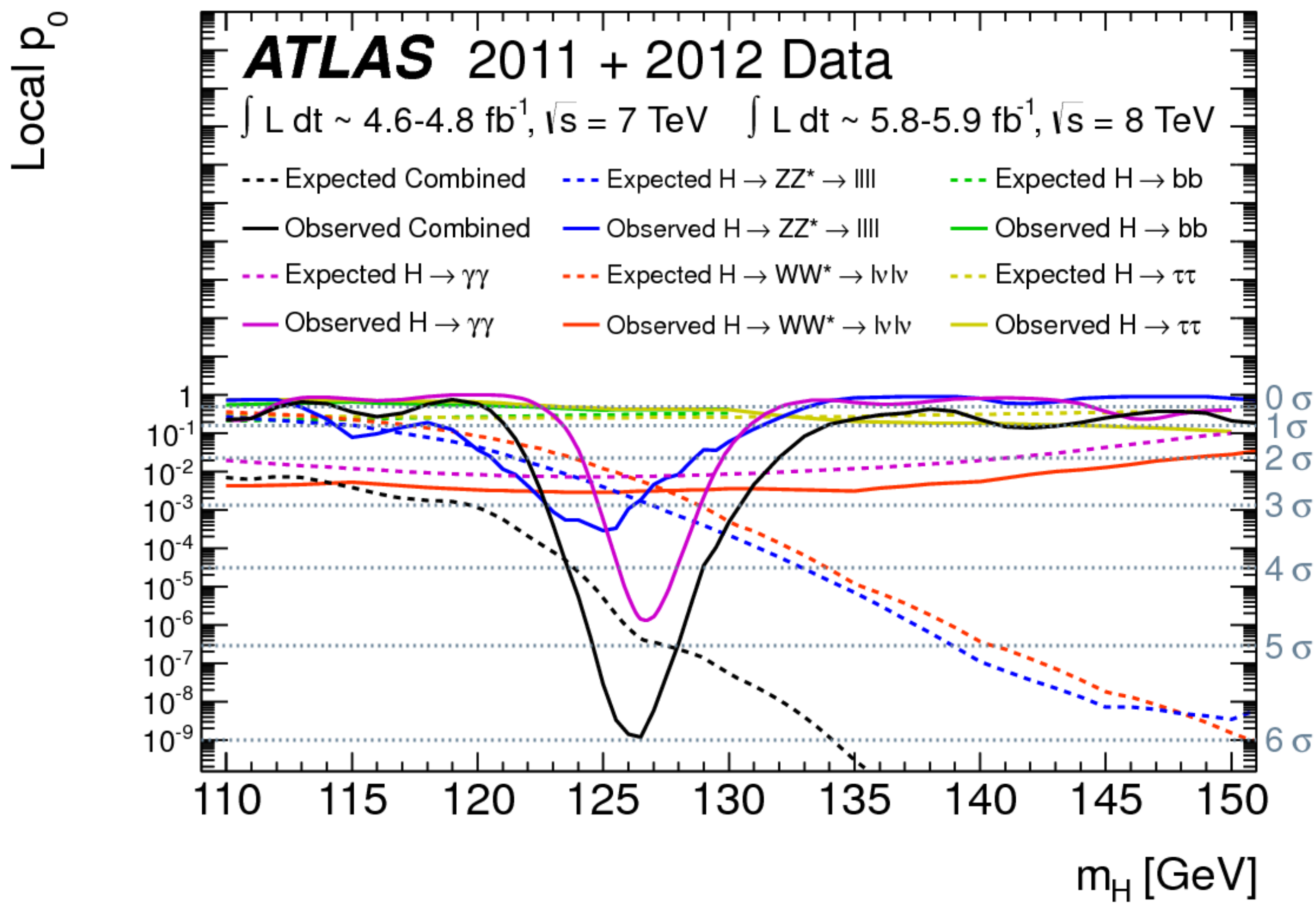
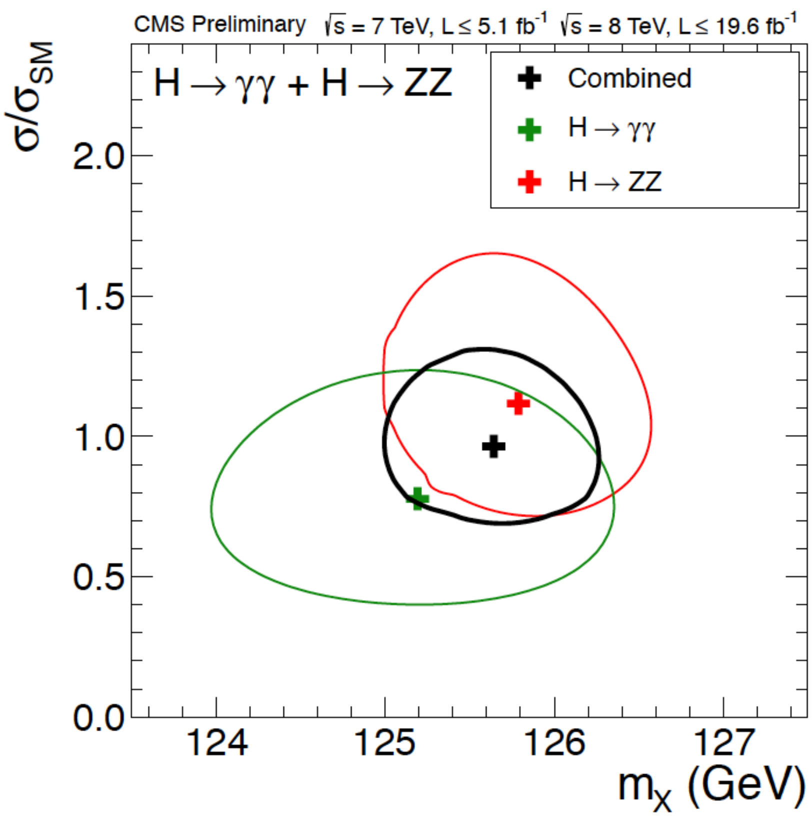
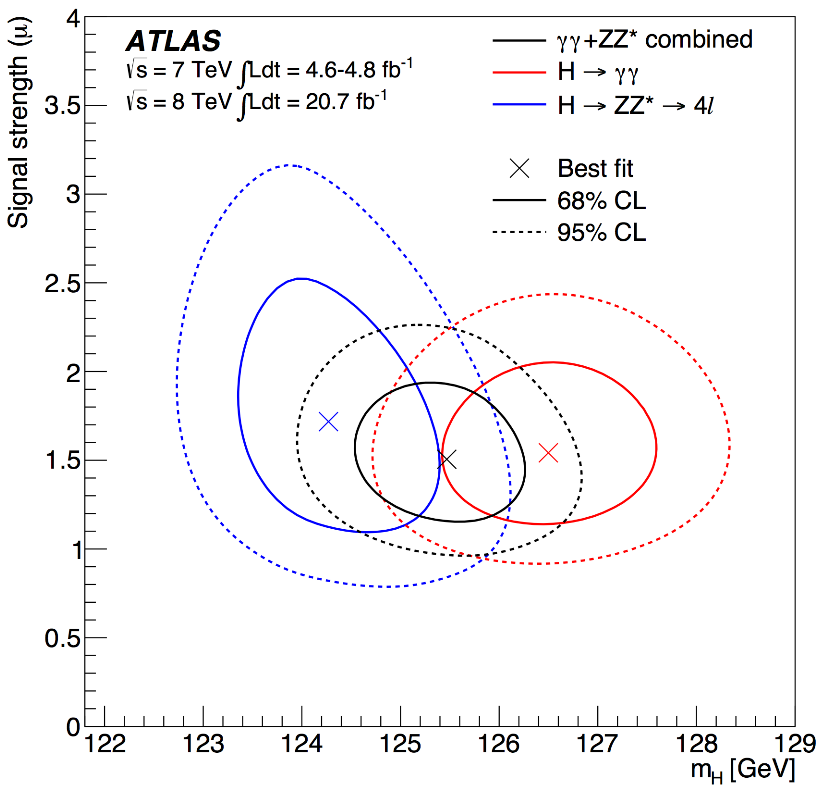


The Higgs: Status Today

- new boson with m ≈ 125 GeV firmly established, now concentrating on establishing that it is really the (only?) Higgs





- need to check cross section, branching ratios, spin, CP state, ...

Particle Discoveries: Geography

- fermions are discovered in the US
  - μ at Caltech in Pasadena
  - τ at SLAC in Stanford
  - charm at SLAC in Stanford and at BNL near New York
  - bottom at Fermilab near Chicago
  - top at Tevatron at Fermilab near Chicago
- bosons are discovered in Europe:
  - gluon at DORIS & PETRA at DESY in Hamburg
  - W and Z at Sp$\bar{p}$S at CERN in Geneva
  - Higgs (probably) at LHC at CERN in Geneva

Beyond the Standard Model

ANYTHING ELSE???

Shortcomings of the Standard Model (personal selection)

- connection between quarks and leptons is rather loose, but the numbers of families are the same, and the electrical charges are multiples of exactly the same number. WHY?
- Higgs mechanism is a nice way to explain masses of gauge bosons and fermions by couplings, but provides no explanation why the masses are so different. And there are more “arbitrary” numbers in the Standard Model (e.g. elements of CKM matrix)
- How do masses of neutrinos fit into the picture? In the SM neutrinos are massless, and violate P maximally (neutrinos are ONLY left-handed). But if they acquire masses by the Higgs mechanism like all other fermions, this maximal P violation is not possible

The End

Thank You for Your Attention!