Particle Physics II

(LPHY2133)

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Section 2

The Higgs boson and the LHC design

The Higgs particle

$$L=\frac{1}{2}(\partial_\mu h)^2-\lambda v^2 h^2-\left(\lambda v h^3+\frac{1}{4}\lambda h^4\right)+const.$$

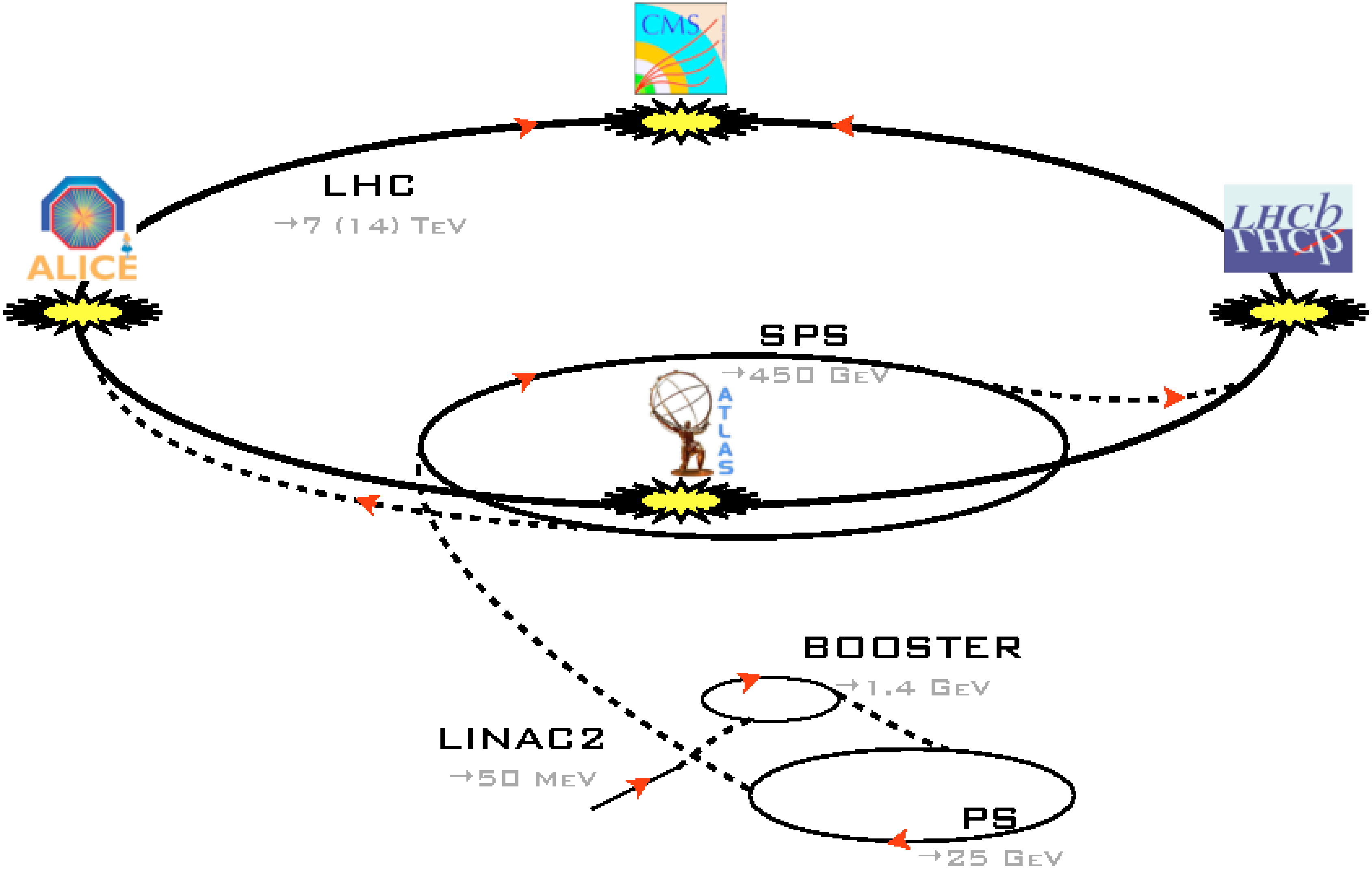
- Mass term for the new field h(x,y,z,t)
- This time it is real and positive, so it is actually physical:
  $m_H = \mathrm{sqrt}(2\lambda v^2) = \mathrm{sqrt}(-2\mu^2)$
- We call **Higgs particle** the quantum of the h field, which is more convenient to use than the ϕ field when we want to study the physical effects
- The ϕ field is more convenient to use when we want to see the symmetries of the lagrangian at first sight

- Made of terms in v^2 and v^4 with no dependence on the field
- Constant terms in the lagrangian have no physical effects: what matters is the eq.of motion, that you get by taking the derivative

Take-home messages

- The Standard Model is built from a mix of theory considerations (e.g., renormalizability) and experimental constraints (e.g., parity violation, need to explain masses, etc.)
- It was a big conceptual progress, as it explains previously disconnected phenomena with a small set of lagrangian terms
- However, several pieces look arbitrary, for example the values of the fundamental parameters are not explained (and some of them look "weird", e.g., the fermion mass hierarchy)
- General consensus: the SM is an incomplete theory, most probably the low-energy limit of the true theory

The LHC



Picture taken from https://inspirehep.net/record/1119569

LHC goals

- Confirmation (or not) of the Brout-Englert-Higgs mechanism
  - CMS&ATLAS (Higgs groups)
- Confirm the Dark Matter hypothesis / study Dark Matter
  - CMS&ATLAS (SUSY and Exotica groups)
- Study the quark-gluon plasma that filled the early Universe
  - ALICE; also CMS&ATLAS (Heavy Ions groups); dedicated runs
- Explain the matter/anti-matter imbalance of the Universe
  - LHCb; also CMS&ATLAS (Heavy Flavours groups)
- Search for additional particles, forces, dimensions of space
  - CMS&ATLAS (Exotica groups)
- Precisely measure the properties of the known particles
  - CMS&ATLAS&LHCb&ALICE (Top, Electro-Weak, QCD, ... groups)

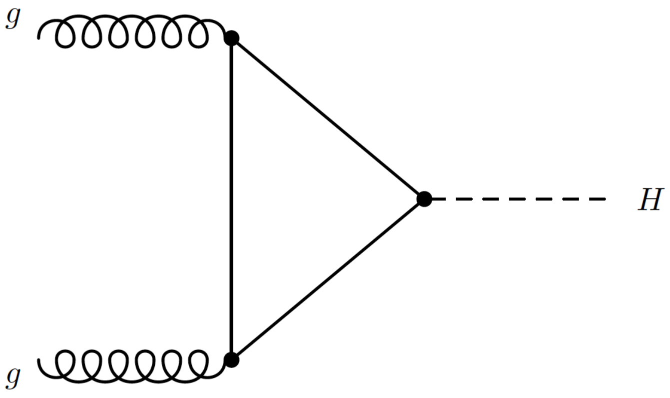
LHC goals

- The mission of the research area called "Particle Physics" can be summarized very simply: finding (or at least getting closer to) the "true theory" of fundamental interactions
- Two main directions for finding the true theory: searches for new particles, and precise tests of the SM predictions
- This course is mostly about the second; although until the end of LHC Run-1 the Higgs boson was a "new particle"! But in a sense, that was still in the category of "tests of SM predictions"
- The LHC has several goals but one was used as a benchmark to decide its design parameters: giving a YES/NO answer to the question "does the SM Higgs boson exist?"
- Now that we know the answer, precise studies of its properties are performed because they may be the door to "new physics"

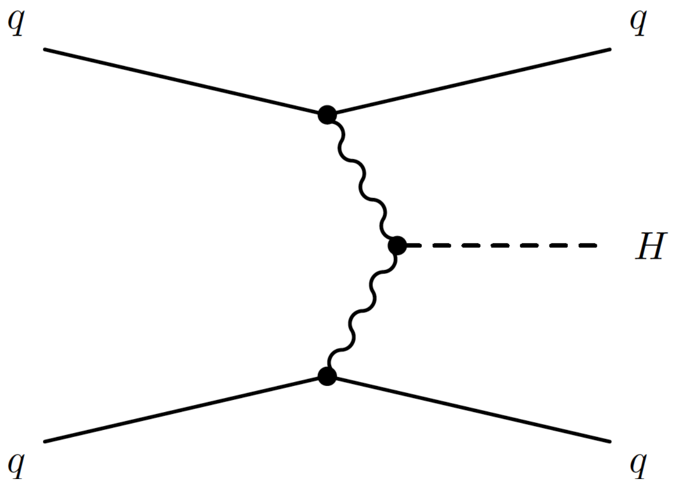
What m_H range had to be probed

- Main problem: the Standard Model does not make any prediction about the Higgs mass
  - It is given by sqrt($2\lambda v^2$), but this does not help much, because also for λ there is no prediction
- Before LHC, the mass boundaries were:
  - Theoretical upper limit from unitarity of HH→HH: O(1 TeV)
  - Direct experimental limits: ~110 GeV from LEP
  - Indirect experimental limits from "global fits": maximally model dependent (only valid if SM is true)
- Note that even after discovering a "light" Higgs, we are still interested in searching up to ~1 TeV. Several "beyond-SM" models predict more than one Higgs (e.g., 5 in SUSY)

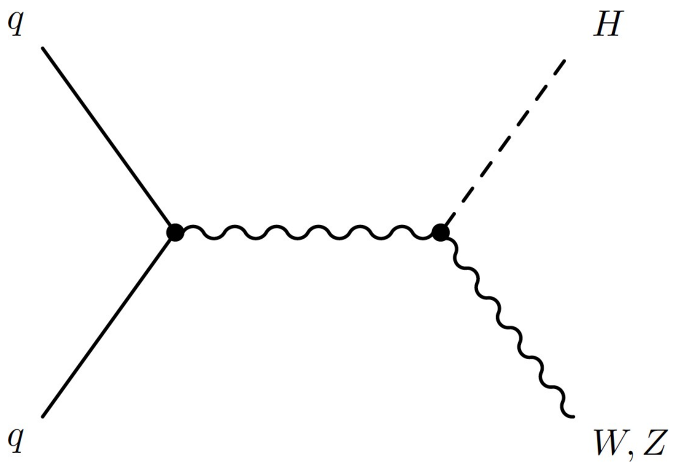
How to produce a Higgs boson



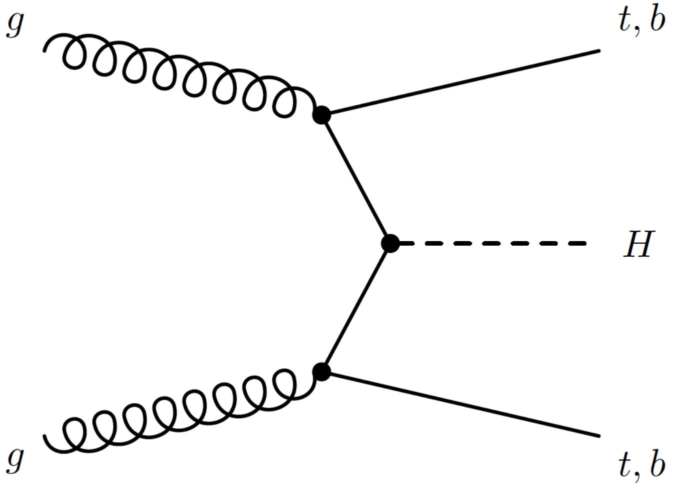
Gluon-gluon fusion



Vector-boson fusion



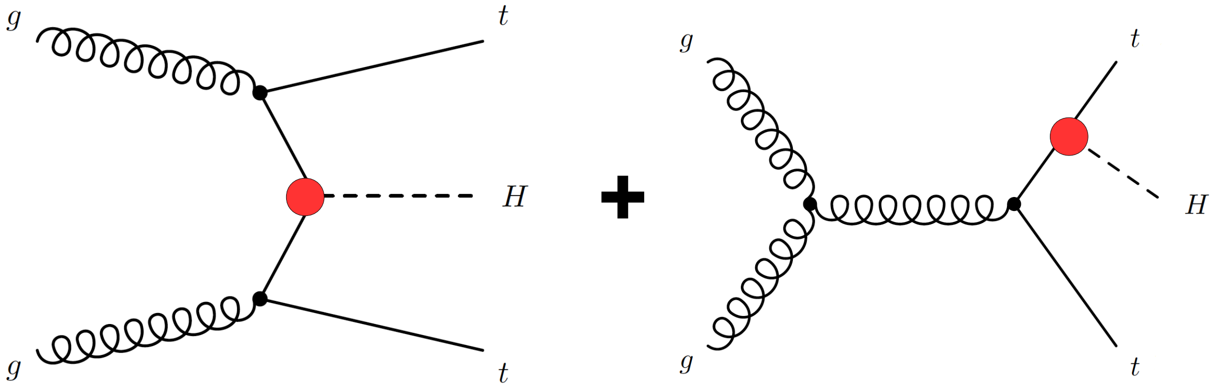
Higgs-strahlung



Top(bottom)-associated

Relationship between coupling and cross section

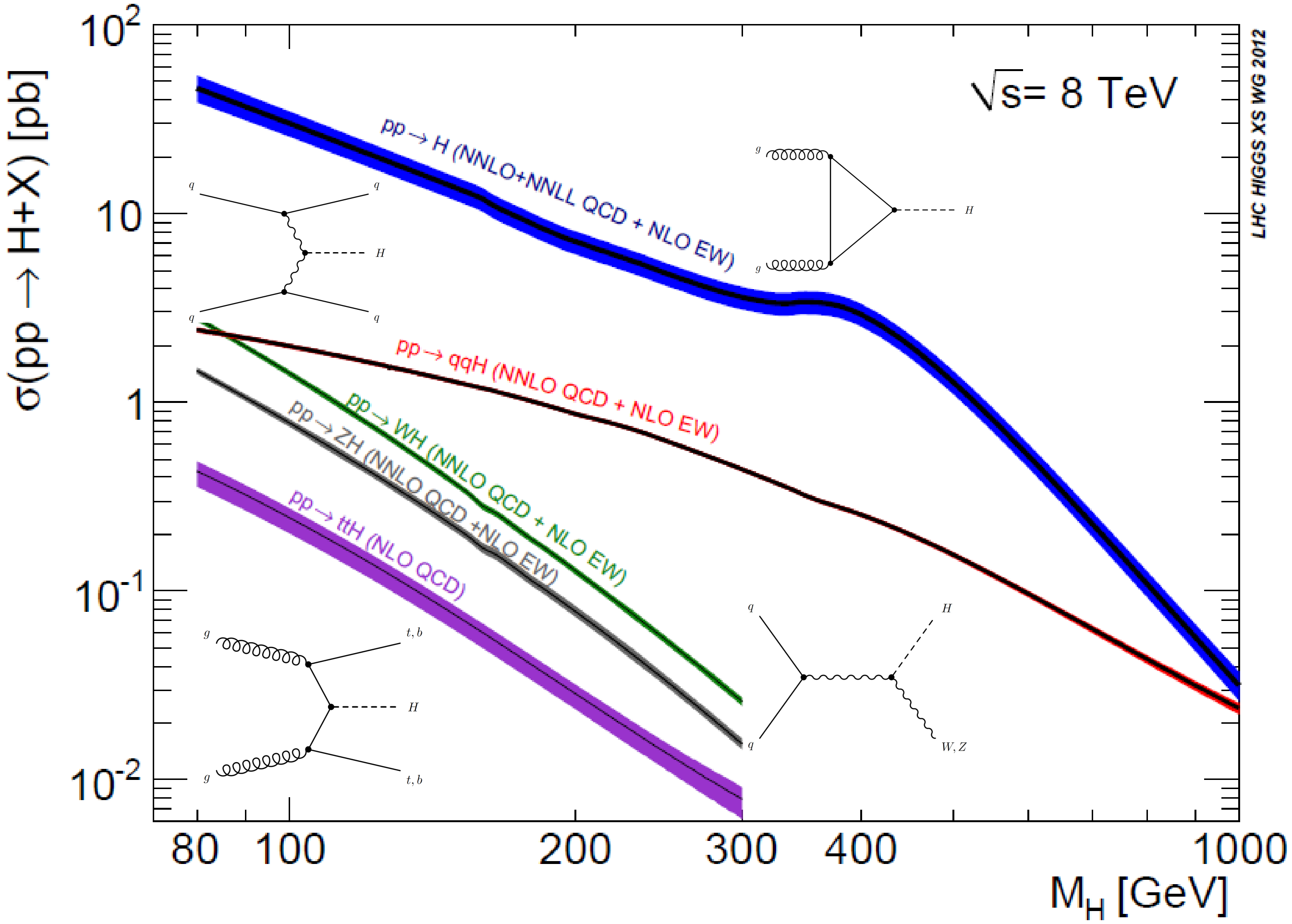
Example, for the ttH case:



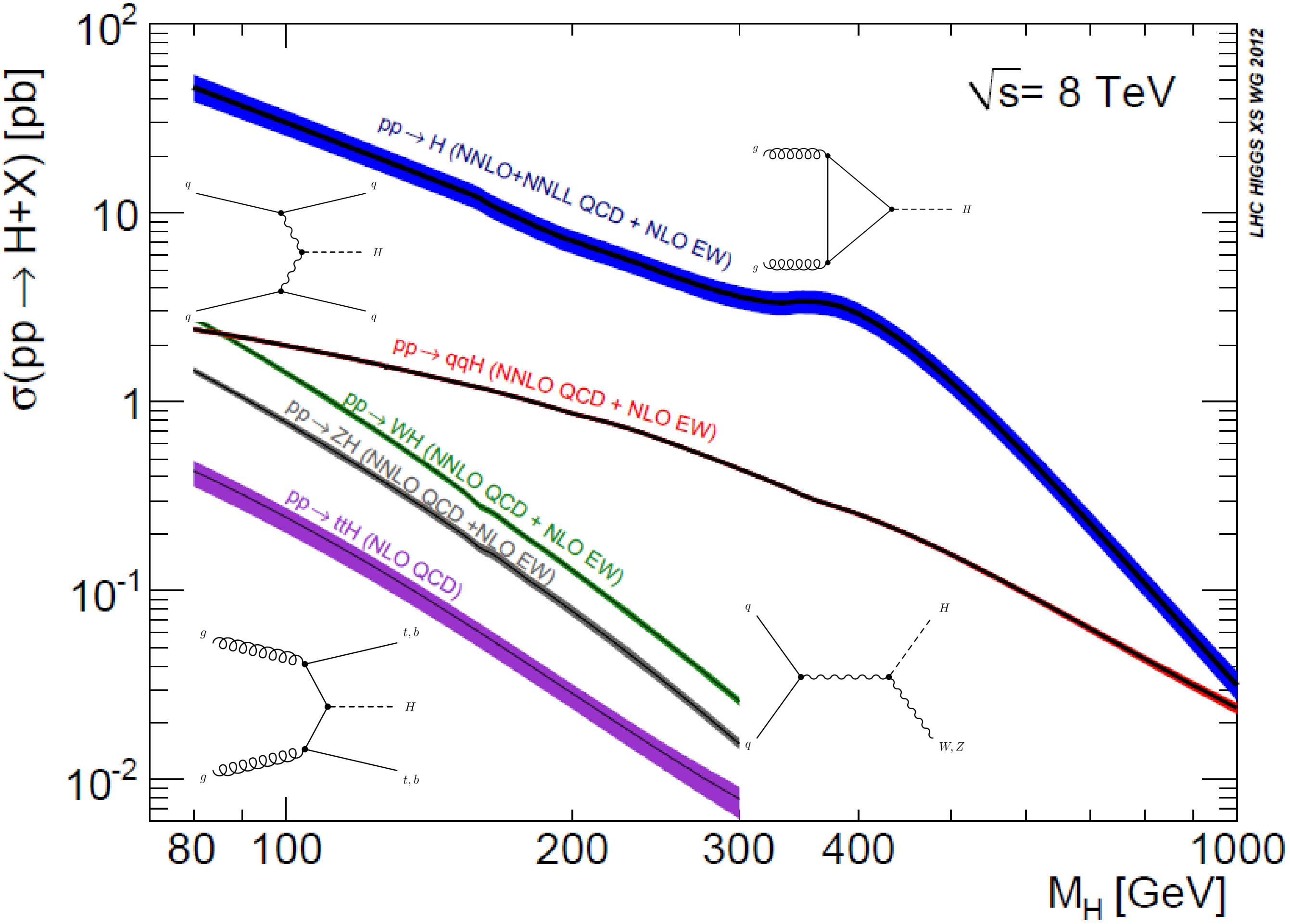
$$\sigma(t\bar{t}H) \propto \left| \quad + \quad + \ldots \right|^2 \propto |y_t|^2$$

Couplings of the H are proportional to the mass of the particles it couples to. Masses are precisely known ⇒ in general, measuring Higgs production cross sections can be seen as testing the mass-coupling relationship.

How to produce a Higgs boson



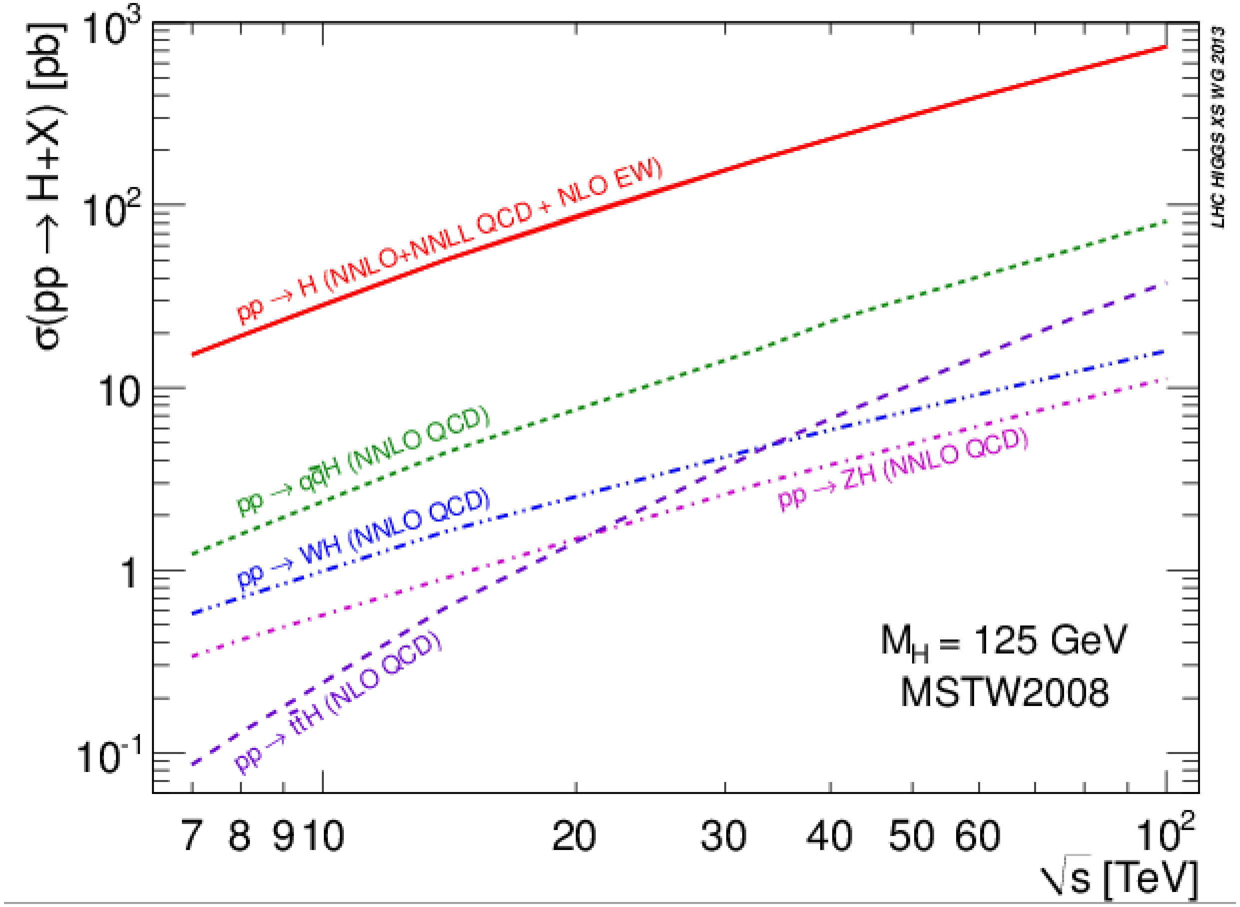
Some little quiz



- Why is gluon-gluon fusion more abundant than vector-boson fusion?
- Why is ttH production relatively rare?
- Why is WH more abundant than ZH production?
- What is the bump at around 350-400 GeV?

Hints: M_W ~ 80 GeV, M_Z ~ 90 GeV, M_t ~ 175 GeV

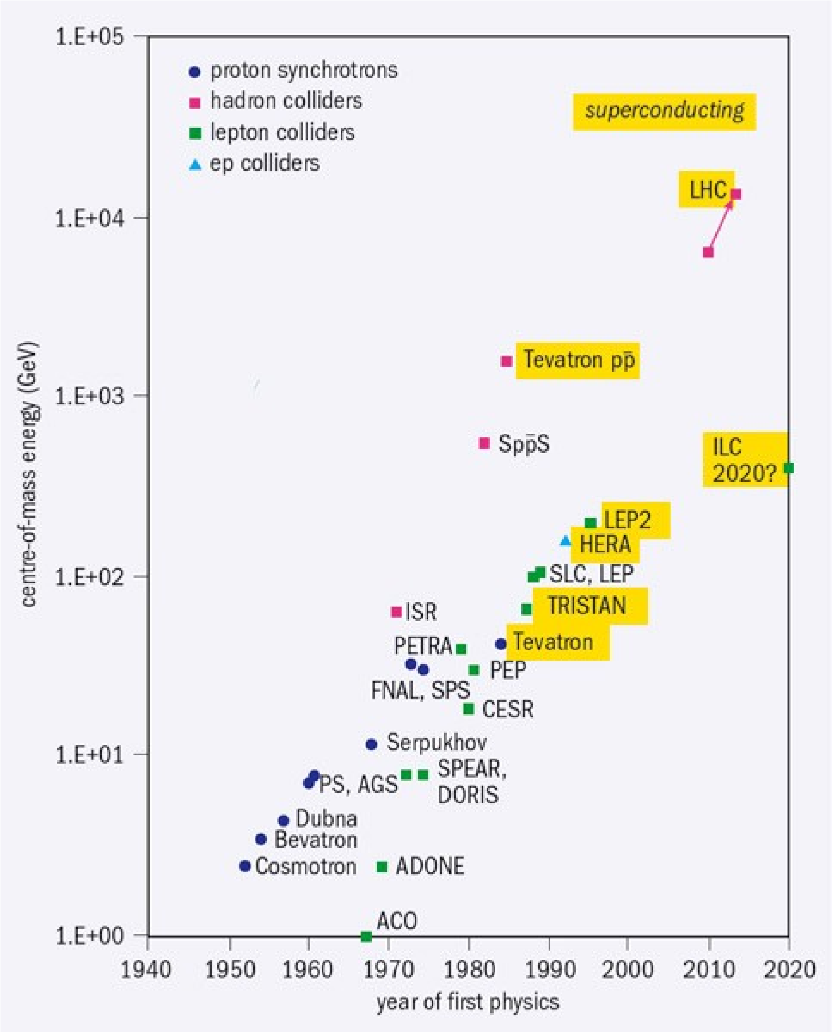
As function of collision energy



Q: explain the behavior of ttH

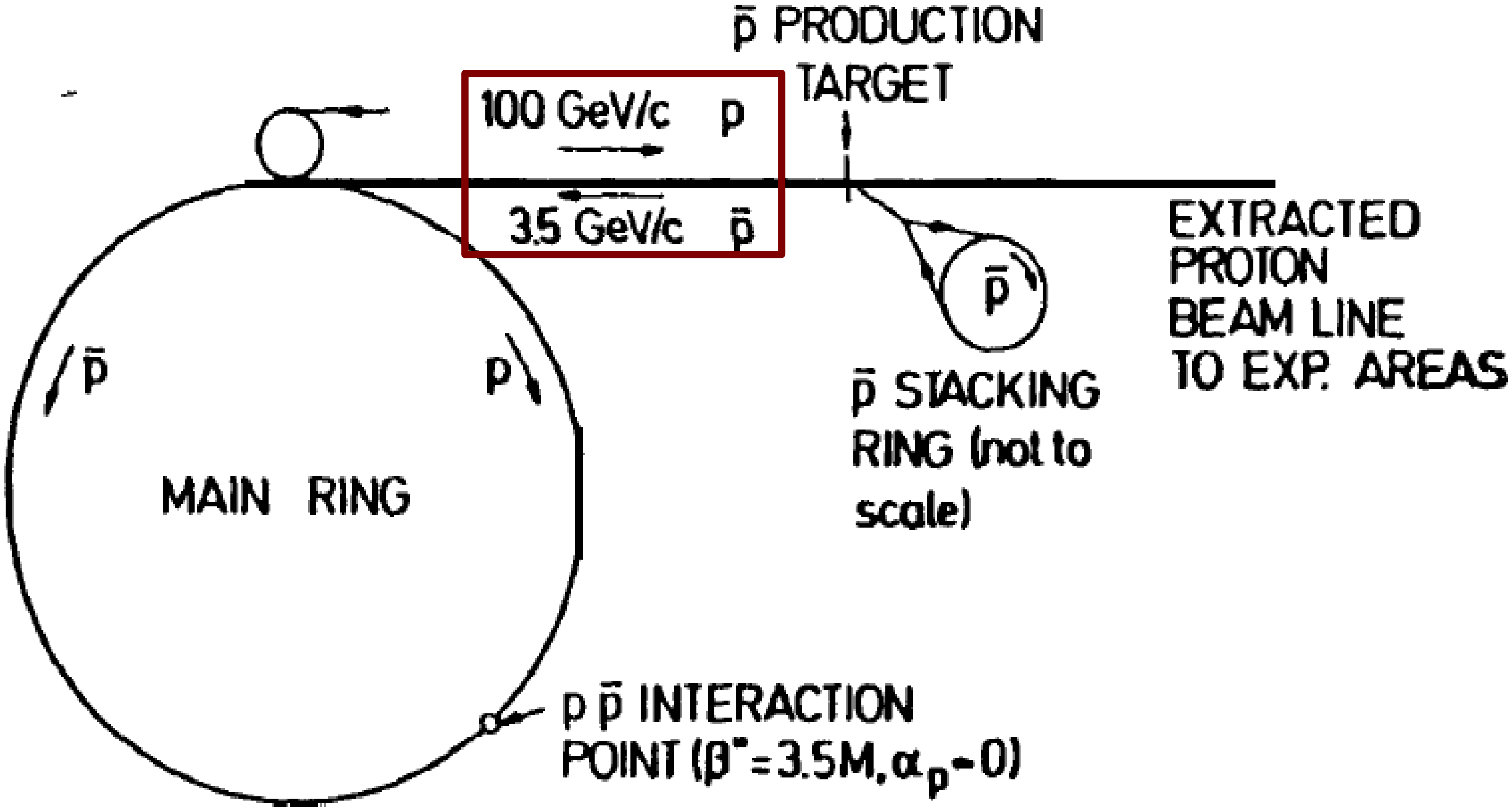
Colliding pp or $p\bar{p}$?

- The precursors of LHC as highest-energy hadron colliders were the S$p\bar{p}$S at CERN and the Tevatron at Fermilab
- S$p\bar{p}$S (1981-1984): c.o.m. E = 540 GeV
  - Note: in 1976-1981 and 1984-present, called SPS and used for fixed-target experiments and as injector for LEP and then LHC
- Tevatron (1987-2011): c.o.m. E = 1.80 TeV, then upgraded to 1.96 TeV
- Both were $p\bar{p}$ colliders

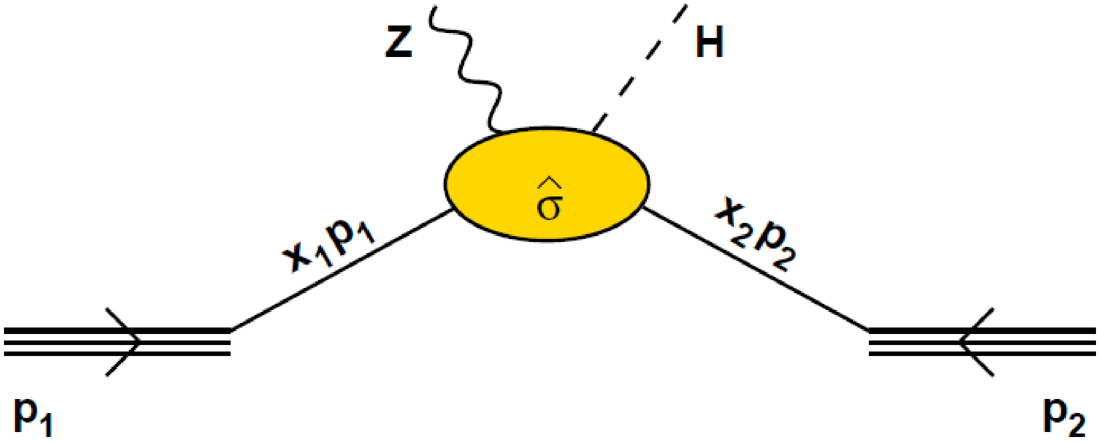


How to produce antiprotons

- Some of the protons are shot against a target, producing a lot of hadrons; among them, some antiprotons
- Magnetic selection of antiprotons by their mass and charge sign



Parton Density Functions



Factorization theorem:

$$\underbrace{\sigma}_{\uparrow} = \int \underbrace{dx_1 f_{q/p}(x_1,\mu^2) \int dx_2 f_{\bar{q}/\bar{p}}(x_2,\mu^2)} \, \underbrace{\hat{\sigma}}_{\uparrow}(x_1p_1, x_2p_2, \mu^2)\,, \qquad \hat{s} = x_1x_2s$$

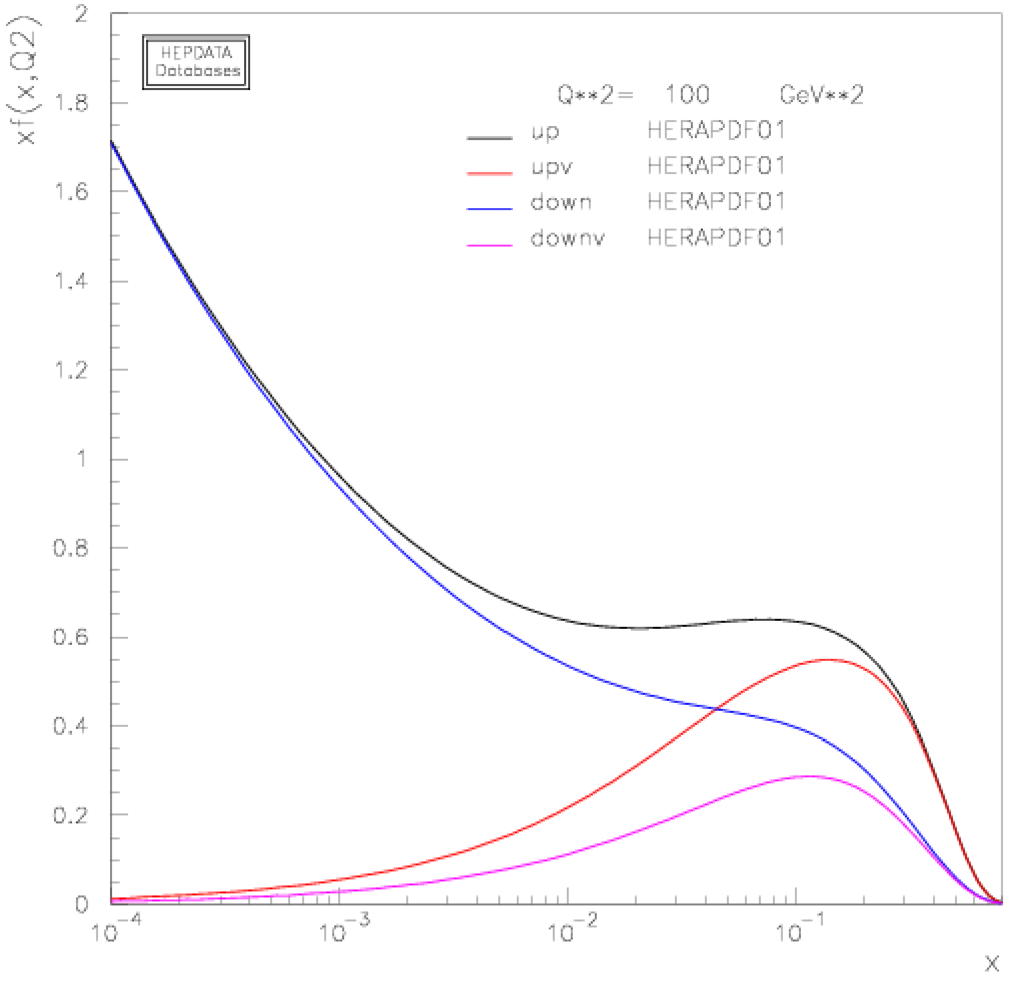
Total cross section (pp)

Parton density functions of partons 1 and 2;
x: fraction of proton momentum;
μ: momentum exchange

Partonic cross section

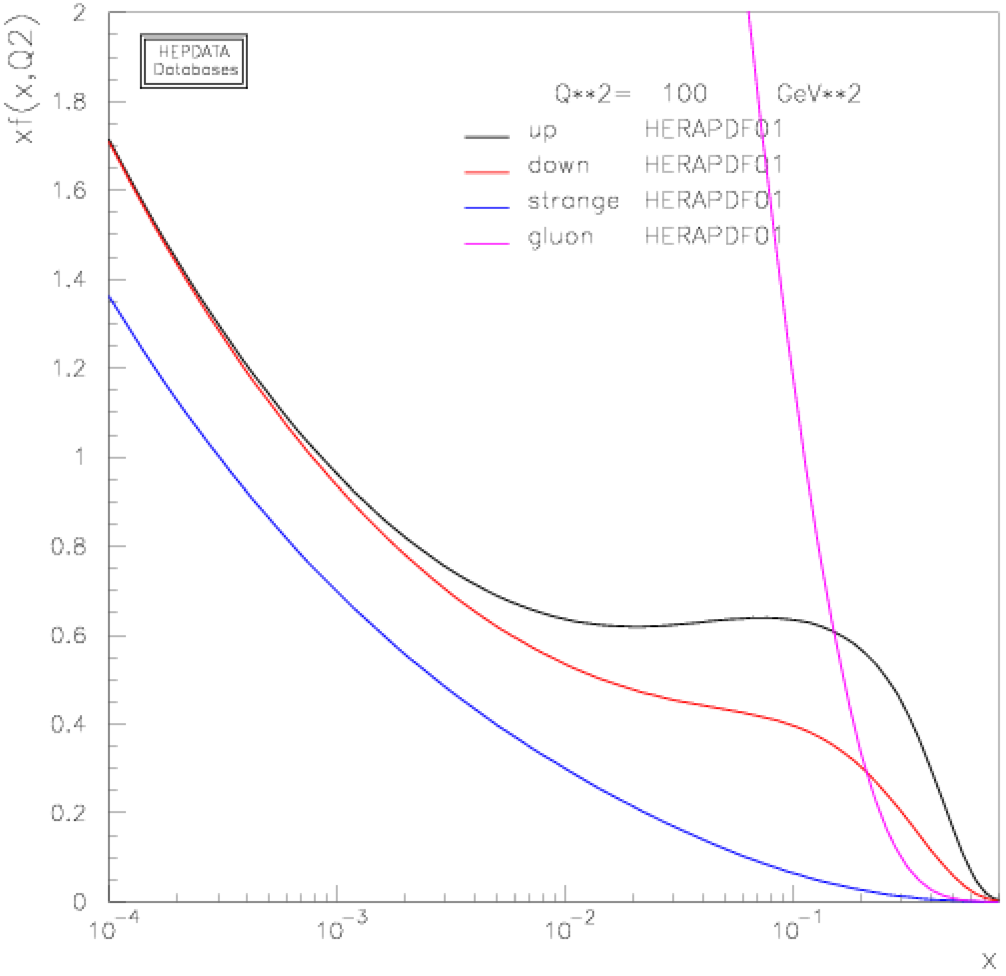
From https://gsalam.web.cern.ch/gsalam/repository/talks/2009-Bautzen-lecture2.pdf

PDF, valence vs sea



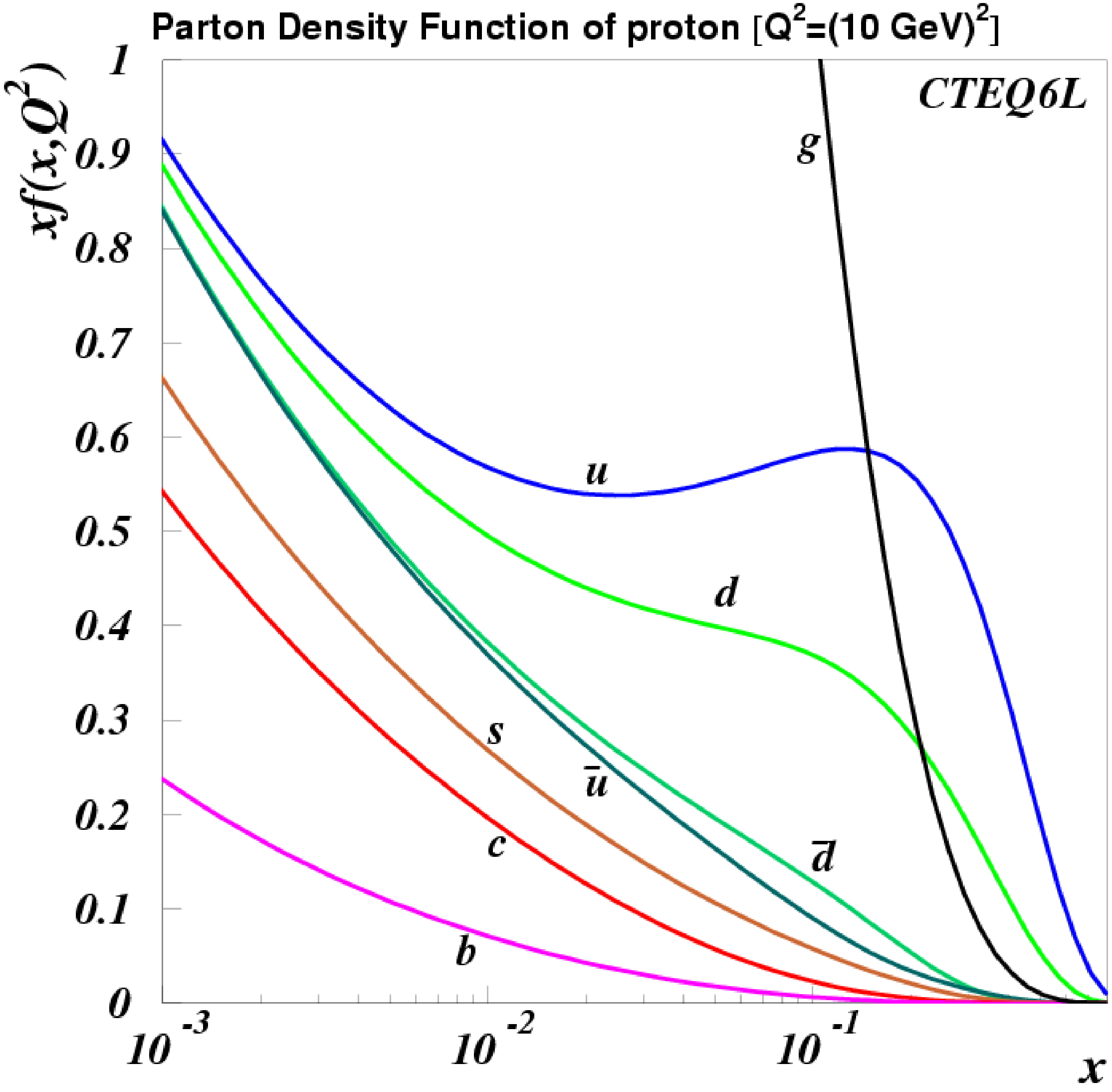
Online calculator: http://hepdata.cedar.ac.uk/pdf/pdf3.html

PDF, quarks vs gluon



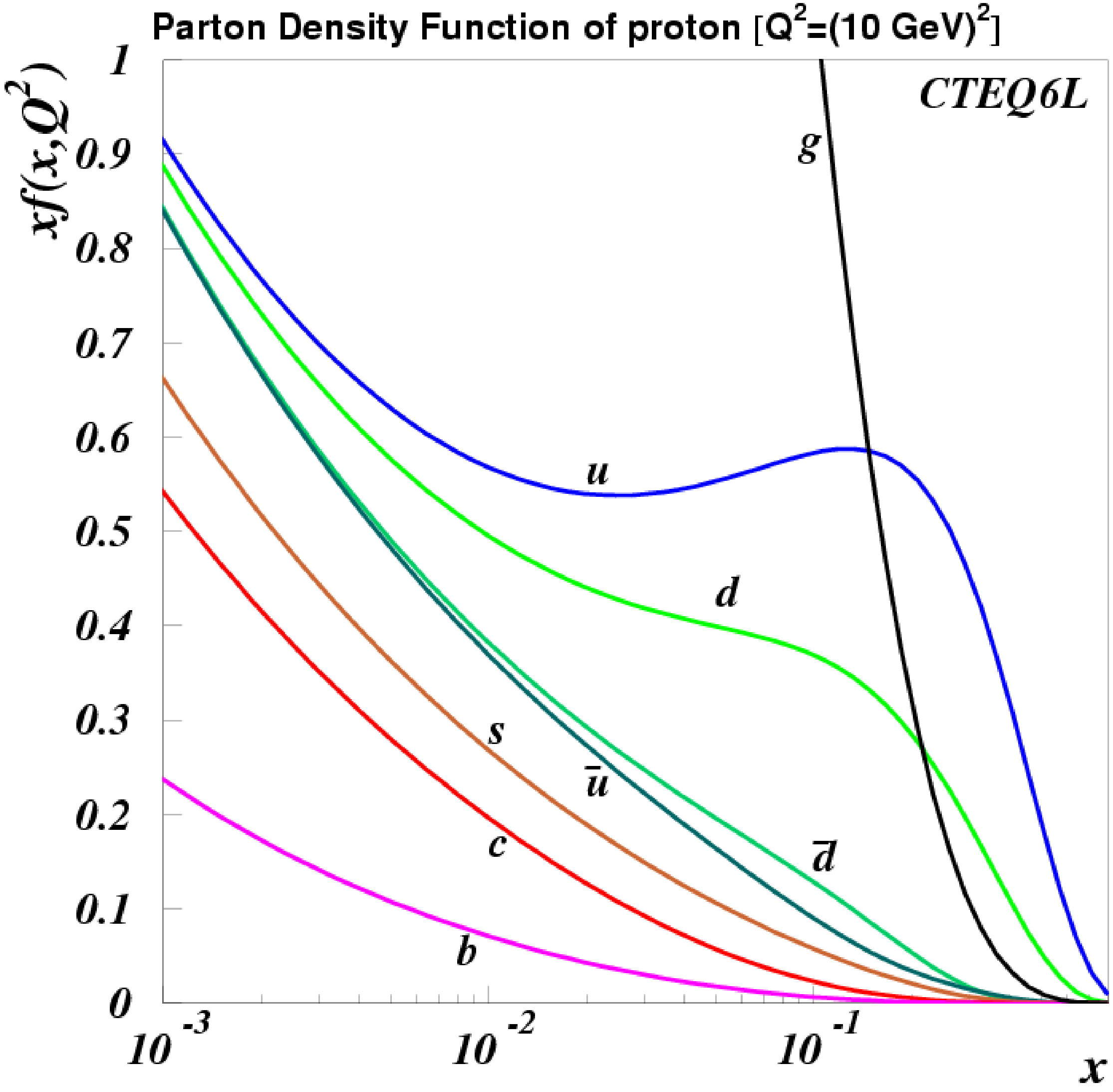
Online calculator: http://hepdata.cedar.ac.uk/pdf/pdf3.html

W boson production in $p\bar{p}$ and pp



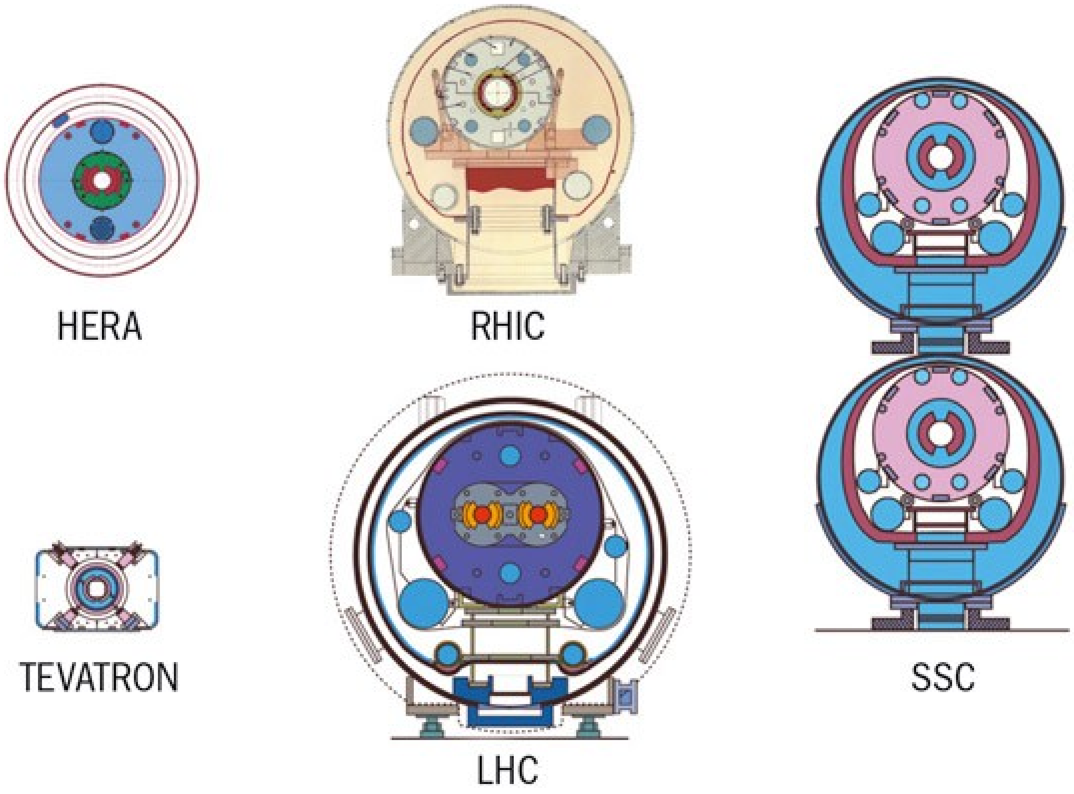
- To create a W boson (M~80 GeV) the main process is $q\bar{q}'\rightarrow W$
- $Sp\bar{p}S$: s=(540 GeV)^2 ⇒ the u,d,$\bar{u}$,$\bar{d}$ quarks with x>0.15 are able to contribute; also $\bar{u}$,$\bar{d}$ can be valence
- In a pp collider, at the same s: the $\bar{u}$,$\bar{d}$ quarks come only from the sea
- LHC 2010-2011: s=(7 TeV)^2 ⇒ u,d,$\bar{u}$,$\bar{d}$ quarks with x>0.01
- The larger the c.o.m. E, the larger the fraction that can contribute

H boson production



- To create a H boson (M~125 GeV) the main process is gg→H
- No distinction from gluon PDF between $p\bar{p}$ and pp collisions
- The gluon PDF is very small with respect to u,d quarks at large x
- Gluon-initiated processes not advantageous when looking for a heavy particle at low c.o.m. E (large x is selected); but they are dominant if the x needed for the process is below a few %
- No reason to collide $p\bar{p}$; easier to get large luminosity with pp

2-in-1 design at LHC

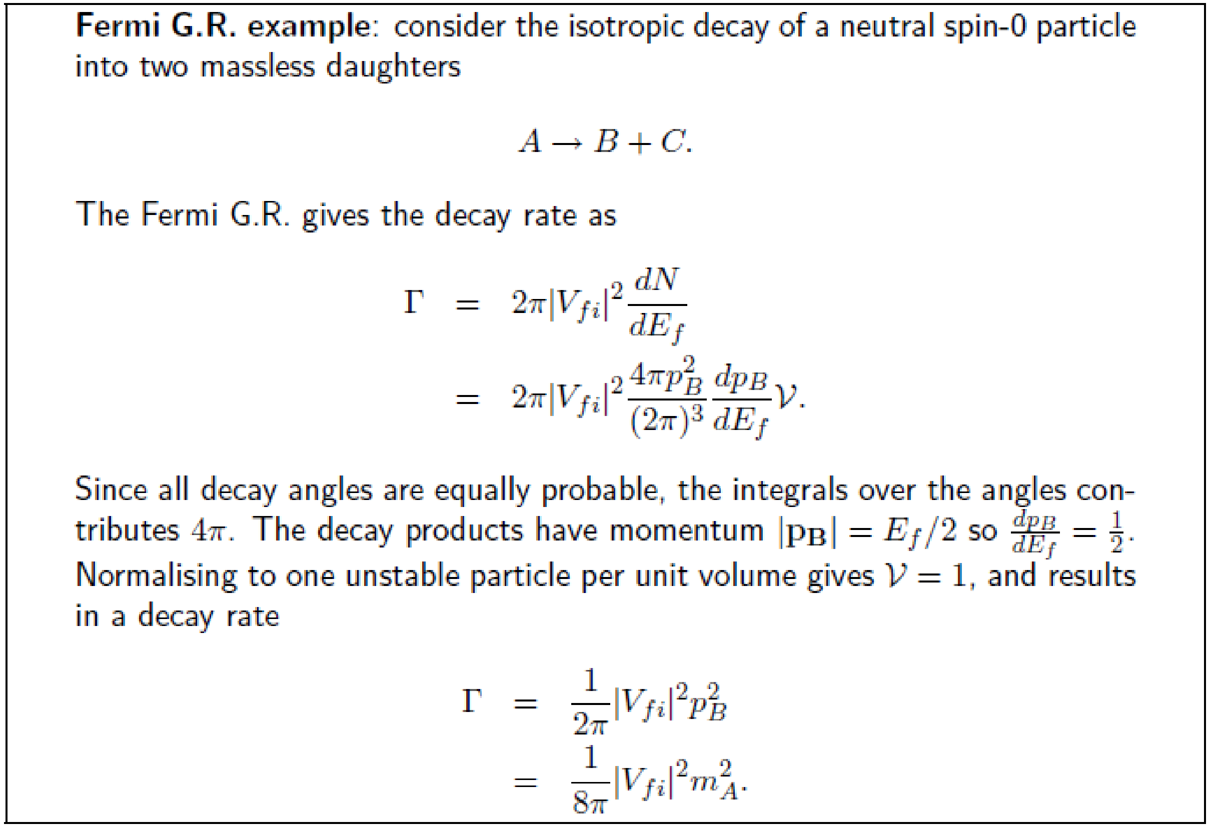


From http://cerncourier.com/cws/article/cern/47504

When you collide particles of opposite charge, you can use the same magnetic field for both beams.
For pp, you need two beam pipes.

Decay width

- The more decay channels are accessible, the faster a particle will decay
- $\Gamma = \hbar/\tau$ (short $\tau \Rightarrow$ large Γ)
- $\Gamma \propto |\text{amplitude}|^2 \cdot$(phase space volume)
- So even if the coupling is large (amplitude is large), decay rate can be small if there is little phase space available (e.g., $m_A \sim m_B + m_C$)



Fermi G.R. example: consider the isotropic decay of a neutral spin-0 particle into two massless daughters

$$A \to B + C.$$

The Fermi G.R. gives the decay rate as

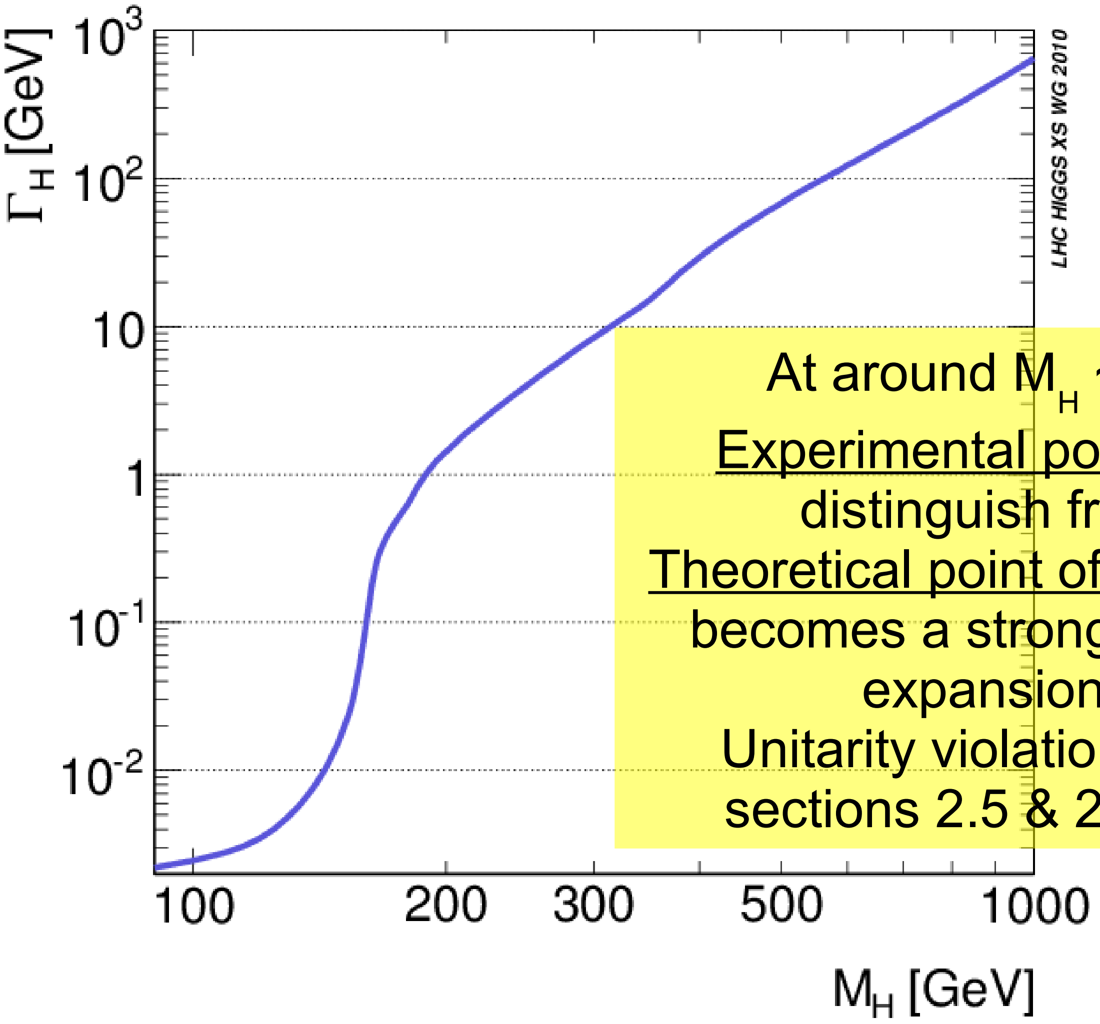
$$\begin{aligned} \Gamma &= 2\pi |V_{fi}|^2 \frac{dN}{dE_f} \\ &= 2\pi |V_{fi}|^2 \frac{4\pi p_B^2}{(2\pi)^3} \frac{dp_B}{dE_f} \mathcal{V}. \end{aligned}$$

Since all decay angles are equally probable, the integrals over the angles contributes 4π. The decay products have momentum $|\mathbf{p_B}| = E_f/2$ so $\frac{dp_B}{dE_f} = \frac{1}{2}$. Normalising to one unstable particle per unit volume gives $\mathcal{V} = 1$, and results in a decay rate

$$\begin{aligned} \Gamma &= \frac{1}{2\pi} |V_{fi}|^2 p_B^2 \\ &= \frac{1}{8\pi} |V_{fi}|^2 m_A^2. \end{aligned}$$

http://www-pnp.physics.ox.ac.uk/~barra/teaching/resonances.pdf

Higgs width vs mass



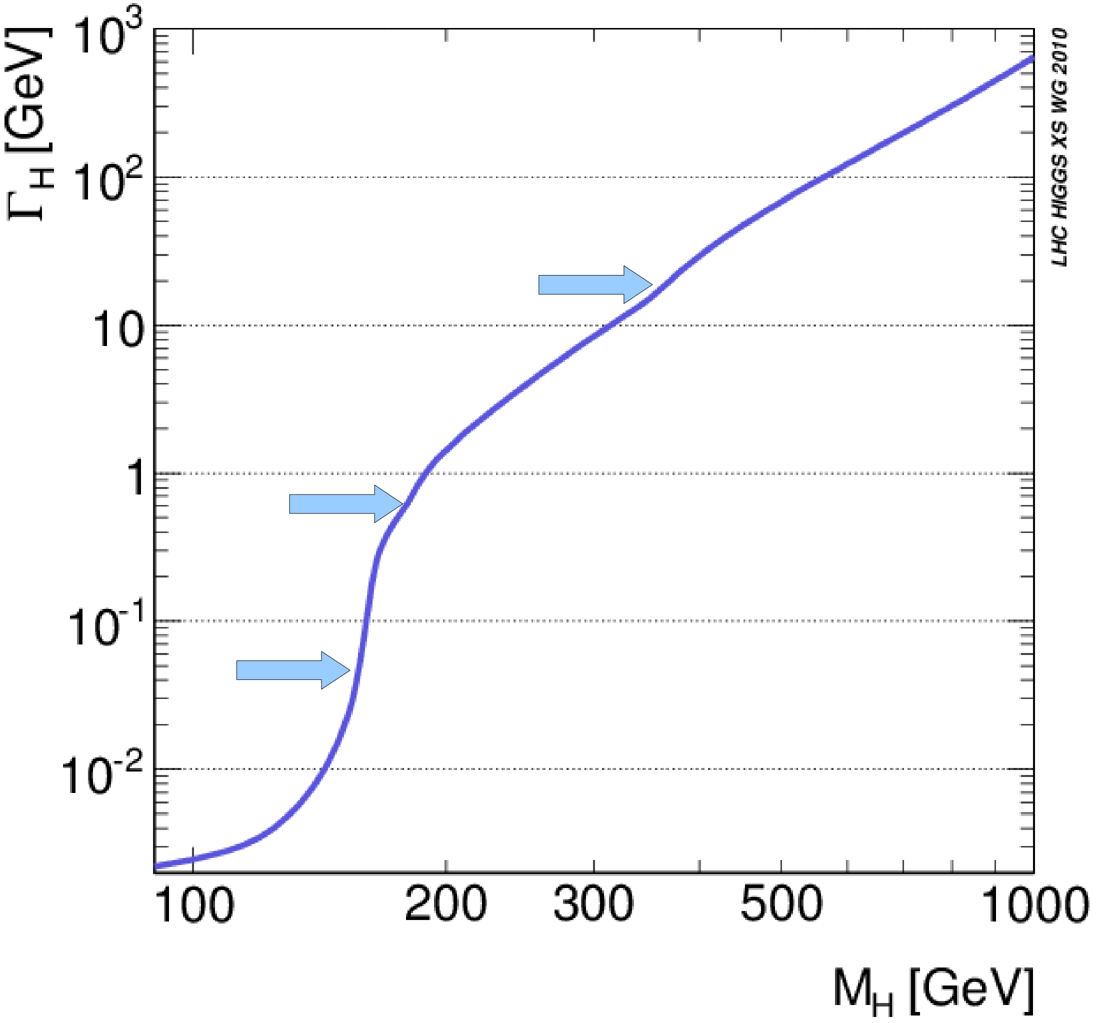
At around M_H ~ 1 TeV, **$\Gamma_H \sim M_H$**

Experimental point of view: hard to distinguish from continuum.

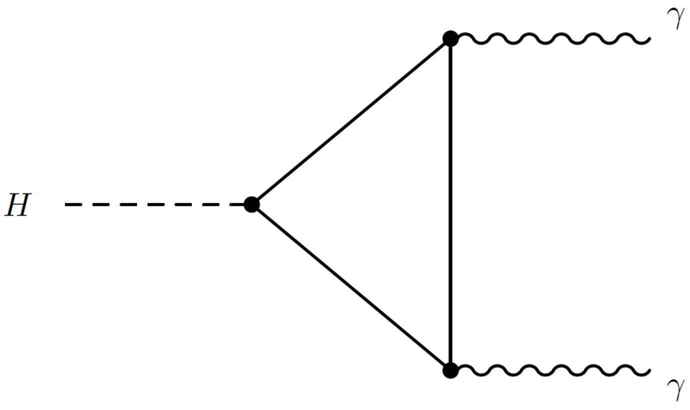
Theoretical point of view: self-interaction becomes a strong force, perturbative expansion impossible.

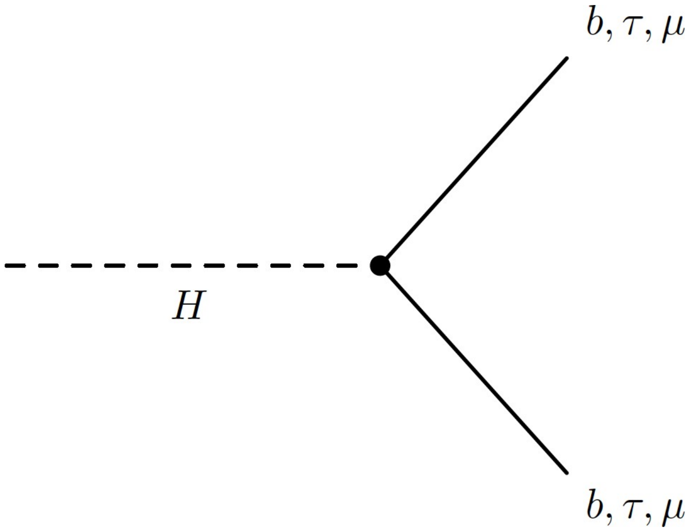
Unitarity violation at O(1 TeV), see sections 2.5 & 2.6 of Gunion et al.

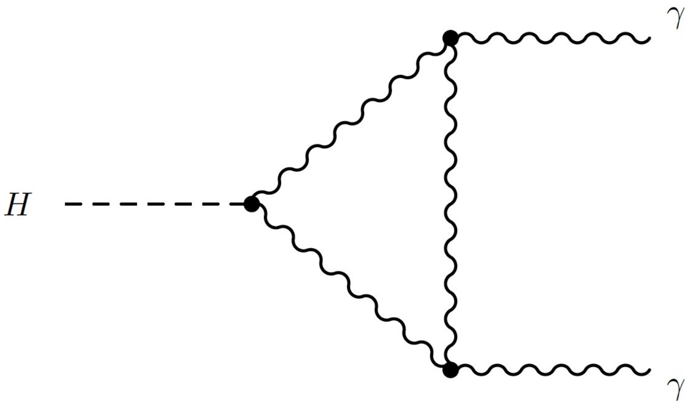
Quiz: explain the changes of slope

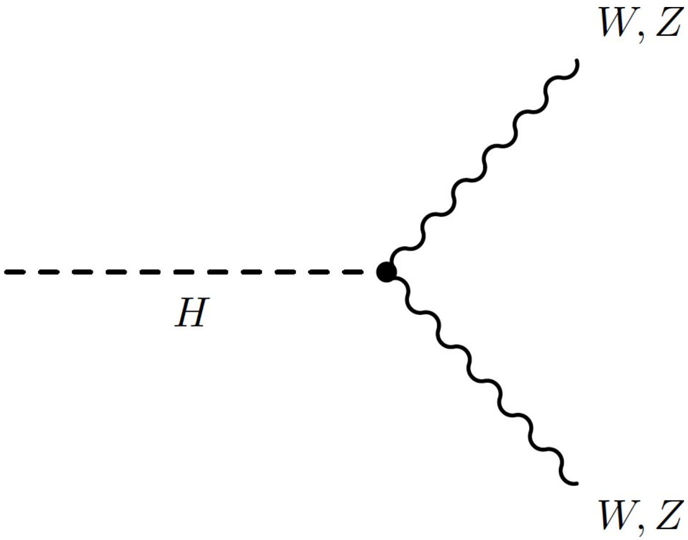


Higgs decays







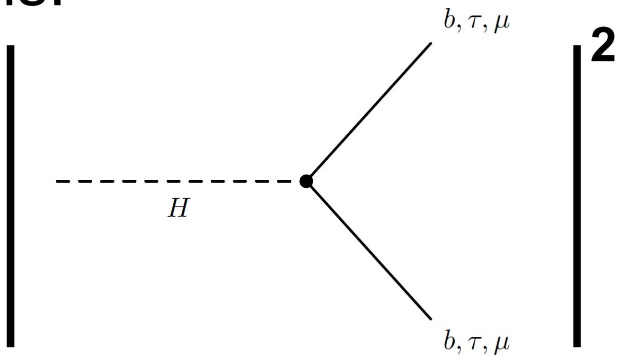


Relationship between coupling and branching ratio

The *branching ratio* of final state X_i is BR ≡ $\Gamma(H\to X_i)/\Gamma(H\to \text{anything})$; theorists obtain it by calculating $\Gamma(H\to X_i)$, $\forall$ i; experimentalists use the derived formula BR = #(events $H\to X_i$) / #(events H→anything).

Higgs decays into fermions:

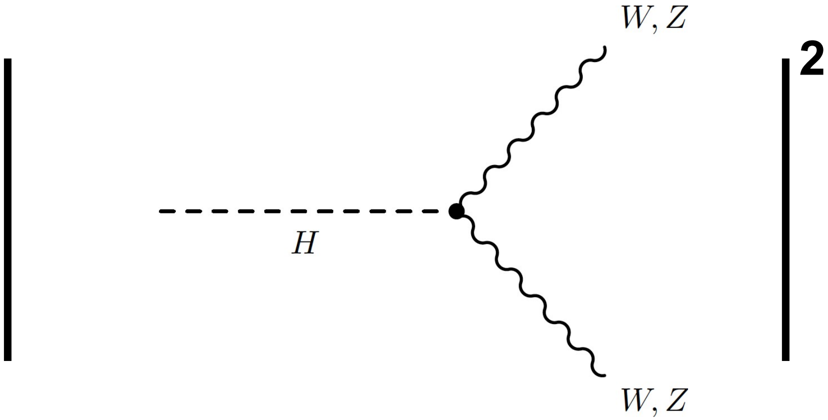
$\boldsymbol{\Gamma(H\to f\bar{f})\propto}$



The heavier the fermion, the larger the BR.

Higgs decay into W, Z

$\Gamma(H\rightarrow VV)\propto$

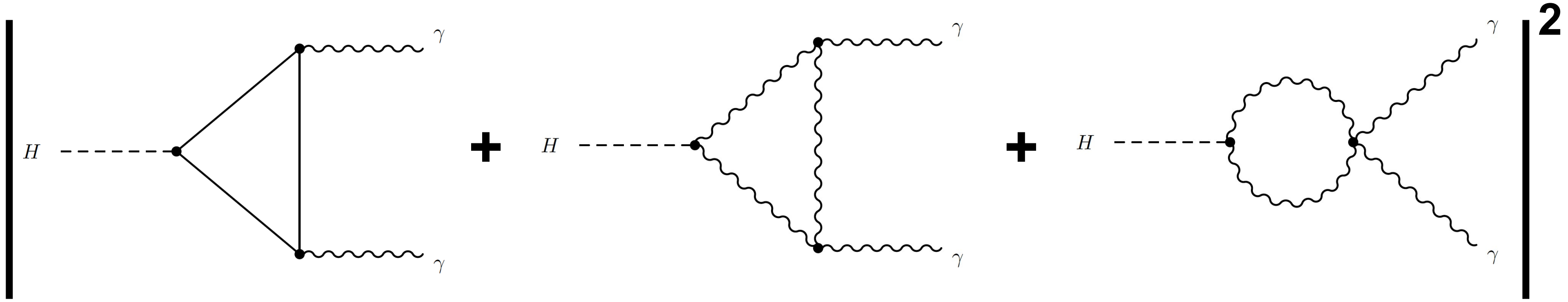


Proportional to g^2 (and g'^2)

Quiz: for m_H = 125 GeV (< 2 m_W and < 2 m_Z), is this decay allowed?
And what about $H\rightarrow t\bar{t}$?

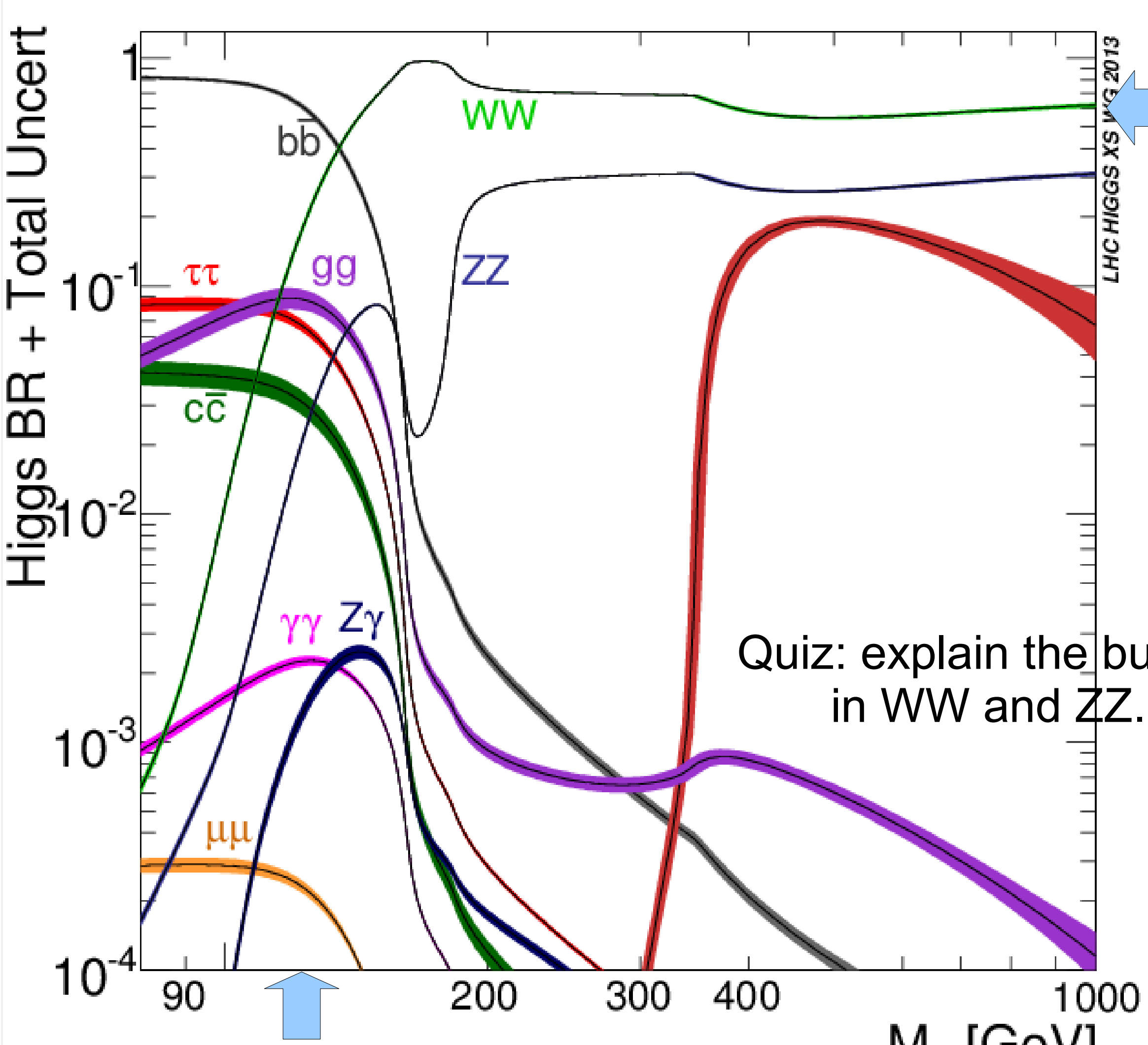
A more complicated case

$\Gamma(H\to\gamma\gamma)\propto$



- Both the top and the V(=W,Z) couplings contribute
- Fermion loops and boson loops have amplitudes of opposite sign → destructive interference in SM
- This BR is small (but luckily not negligible) for a combination of this fact and of the large masses implied in the loops, that reduce the probability

Branching ratios vs mass

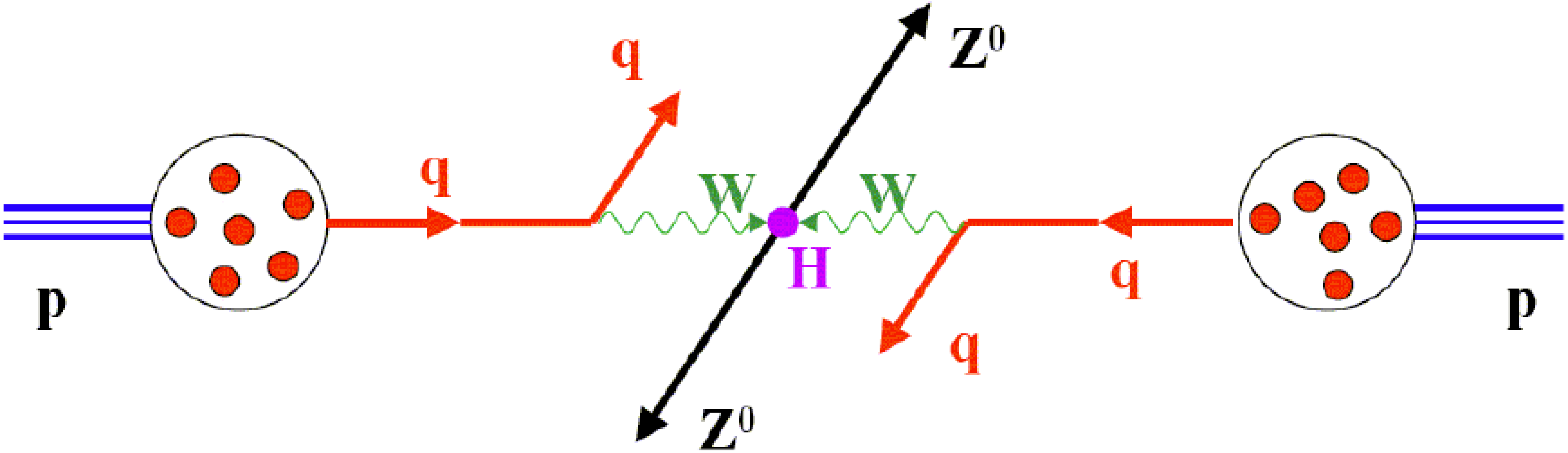


125 GeV

At high mass, WW channel dominates; the very clean ZZ channel is a relatively strong signal too

Quiz: explain the bumps and depressions in WW and ZZ. Hints: as usual...

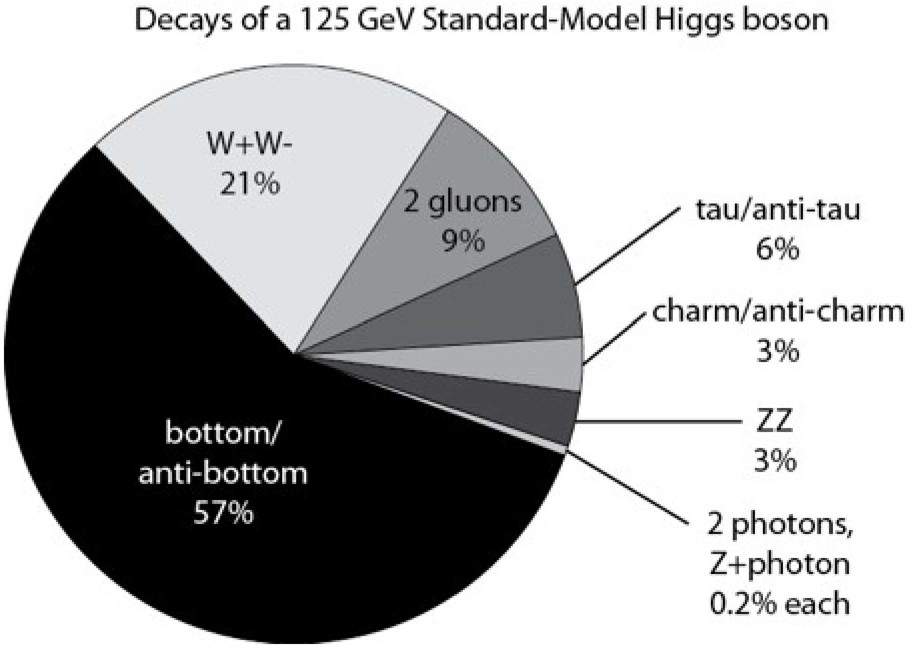
Accelerator and dectector choices



Ensure sensitivity up to M_H ~ 1 TeV (approximate unitarity bound):

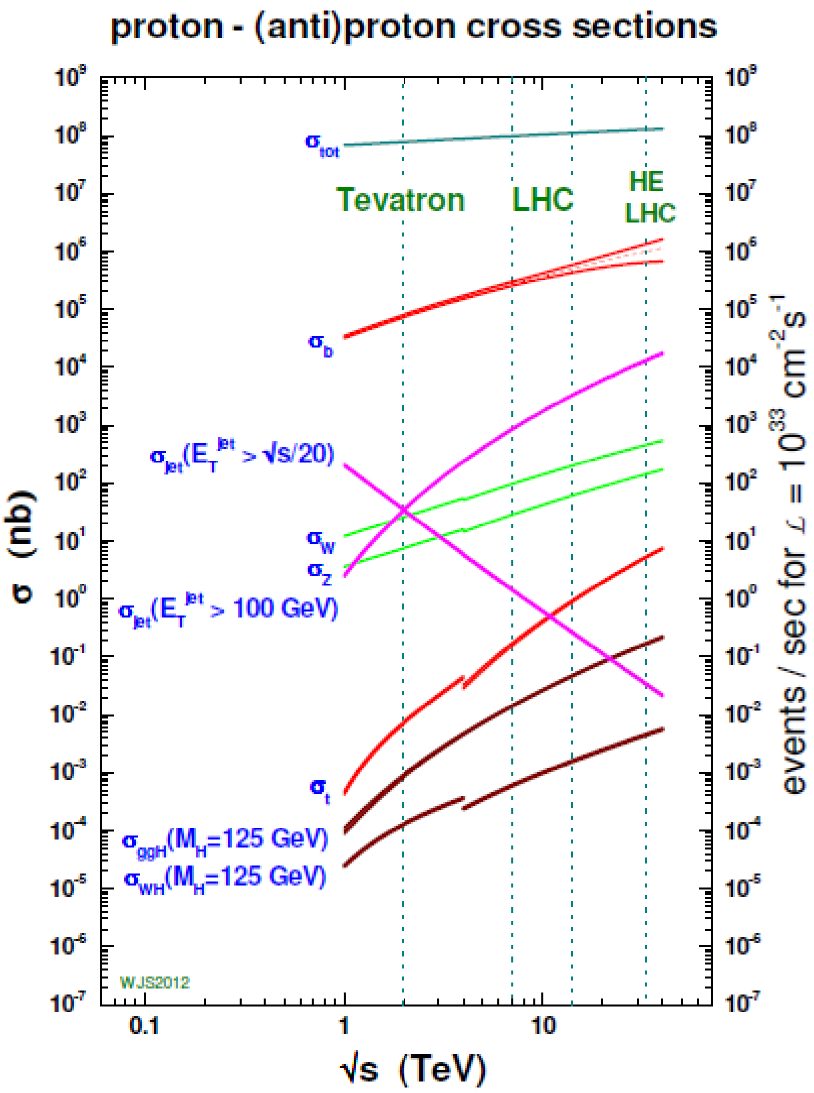
- Detectors must be sensitive to Higgs decays up to ~ 500 GeV W and Z decays up to ~250 GeV precise momentum measurement up to that scale detector with large magnetic field and large radius
- Large probability of finding a parton, in the proton, able to radiate a particle (e.g., a W) of ~ 500 GeV parton momentum of O(1 TeV) the proton beams must have multi-TeV energy

Branching ratios @ 125 GeV



Cocktail of several channels, where the most abundant (bb) is very tough at LHC, and the cleanest ones (ZZ→4l and γγ) are small but not negligible

Backgrounds

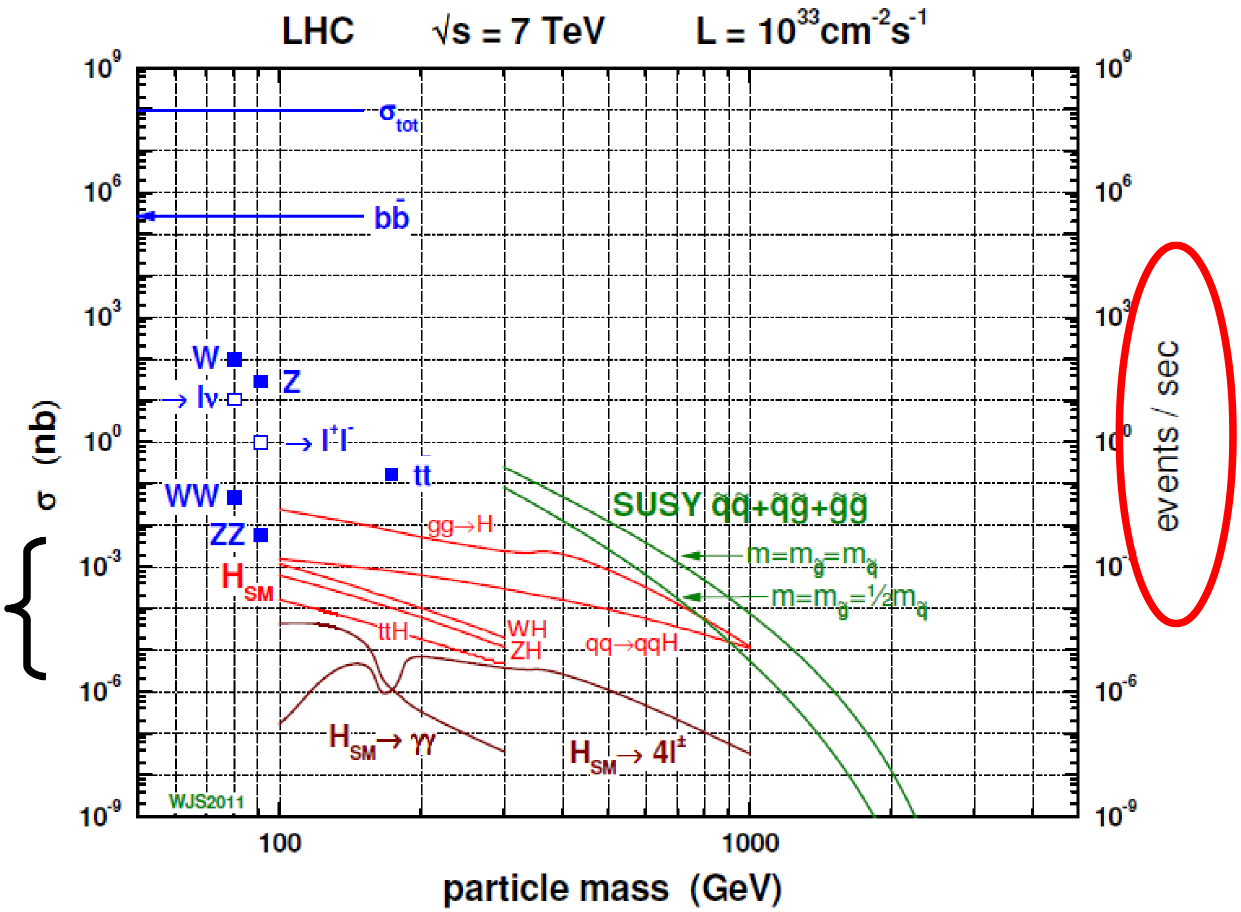


Channel gg→H→$b\bar{b}$ is the most abundant signal process (best cross section times best BR @ 125 GeV); but continuum gg→$b\bar{b}$ background from QCD is 7 orders of magnitude larger.

Quiz: why is there a discontinuity in some of these curves? And why not in all?

Backgrounds

H→ZZ→4l is rare @125 GeV, but continuum ZZ is rare too



This is what matters when developing a *trigger* algorithm (discussed later)

This is an old plot; rates are much higher now: larger luminosity (10^{34} cm^{-2}s^{-1}); larger energy (13 TeV) → more particles; larger pile-up (i.e., simultaneous pp collisions)

Summary

- The discovery or exclusion, and then the study of the Higgs boson, were a well-defined experimental goal of the LHC and guided its design, as well as the design of the multi-purpose experiments ATLAS and CMS
- To be able to discover or exclude the full range of realistic mass values imposed some very challenging choices for the accelerator and the detector
- Next: I will review the main Higgs analyses at the LHC, channel by channel

Questions?