Particle Physics after the Higgs discovery: what's next?

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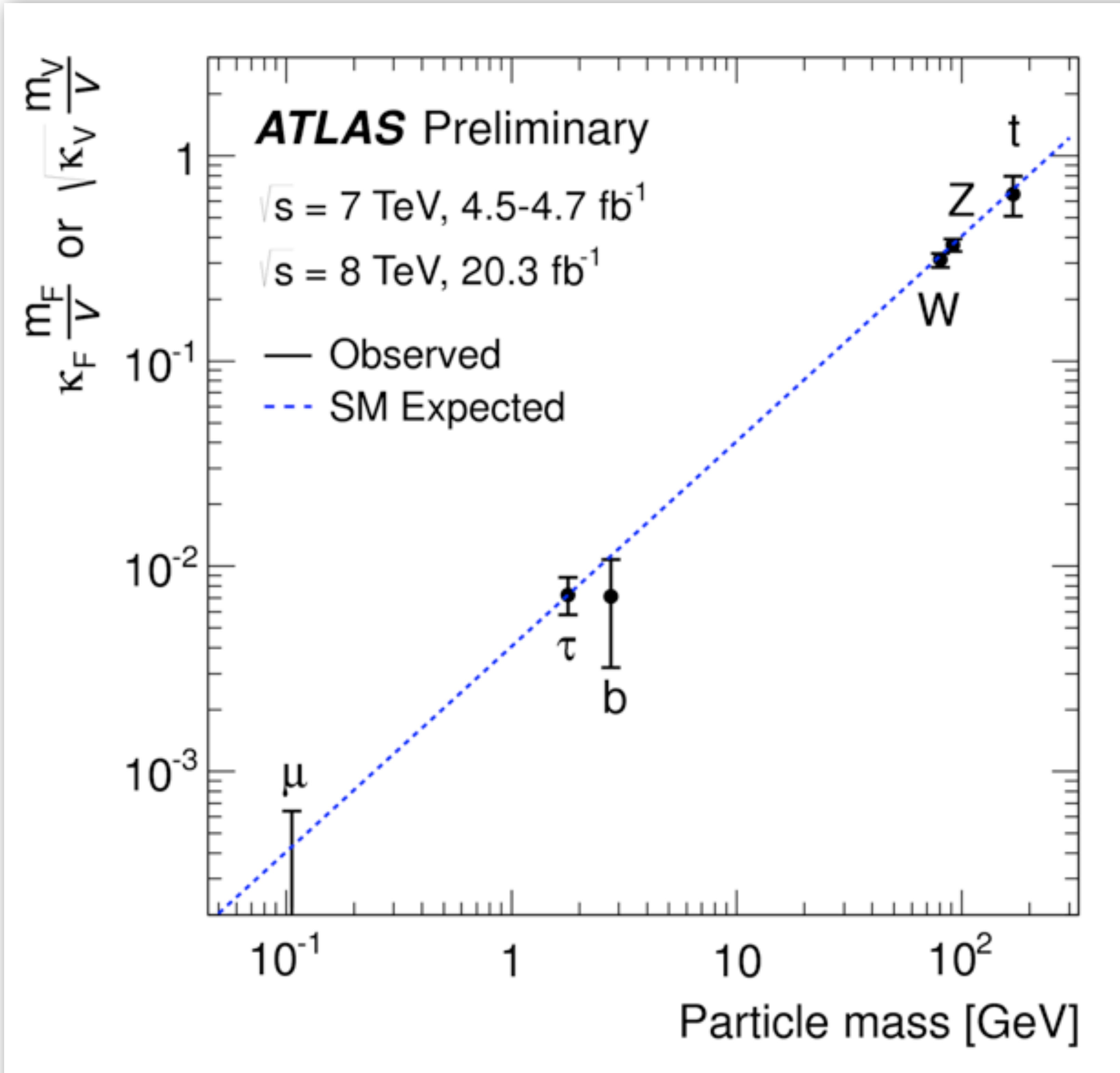
Introduzione

- Con la scoperta dell'Higgs, il Modello Standard e' completo.
- Il MS potrebbe non essere l'ultima parola, e molti fatti, sperimentali e teorici, lo confermano. Ma ancora non abbiamo una nuova teoria che indichi, in modo univoco, la strada per le prossime scoperte.
- Il prossimo futuro avra' come tema dominante la ricerca, diretta o indiretta, di anomalie rispetto alle predizioni del MS, che permettano di discernere fra i vari modelli "BSM" (beyond the Standard Model), per isolare il piu' promettente candidato al ruolo del prossimo MS
- Al momento, non esiste tuttavia alcun esperimento o misura, all'LHC o altrove, in corso o progettabile, che possa garantire una nuova scoperta.
- Dopo 30 anni dedicati alla verifica del MS, guidati dalle sue previsioni, la fisica sperimentale e' tornata al suo ruolo primordiale di pura esplorazione
- Se le risposte non sono garantite, esiste comunque una serie di domande ben poste che orientano i nostri studi .....

Run 1 of the LHC determined, with a precision of ±20%, that the Higgs boson gives a mass to SM particles



Note on "the mass of the Universe"

- proton's mass arises from QCD dynamics, not from the mass of its constituent quarks. Half of it is kinetic energy of the tightly bound relativisitic quarks, the other half is binding energy ($M=Ec^2$, E=K+U, virial theorem....)

- the mass of particles composing Dark Matter does not need to arise from the coupling with the Higgs. E.g. in Supersymmetry models it could mostly come from the breaking of supersymmetry, nothing to do with the Higgs or EWSB

Open Higgs issues for run 2 and beyond

1. *This limited precision,* due to low statistics, *is not sufficient to probe most possible scenarios alternative to the SM:* ***will the SM withstand more accurate tests?***

   Example: BR[$H \to \mu\tau$] = (0.89 ± 0.40)% reported by CMS, needs more statistics to confirm (In the SM should be 0)

2. *The Higgs mechanism has only been tested on a fraction of the SM particles,* due to low statistics: ***do the other particles (e.g. muon, charm, etc) interact with the Higgs as predicted by the SM?***

   Example: more than 300 fb^{-1} required to establish $H \to \mu\mu$ at 5σ

3. *Neutrino masses are not a SM ingredient:* ***how do neutrinos acquire their mass?***

4. ***Are there more Higgs bosons?***

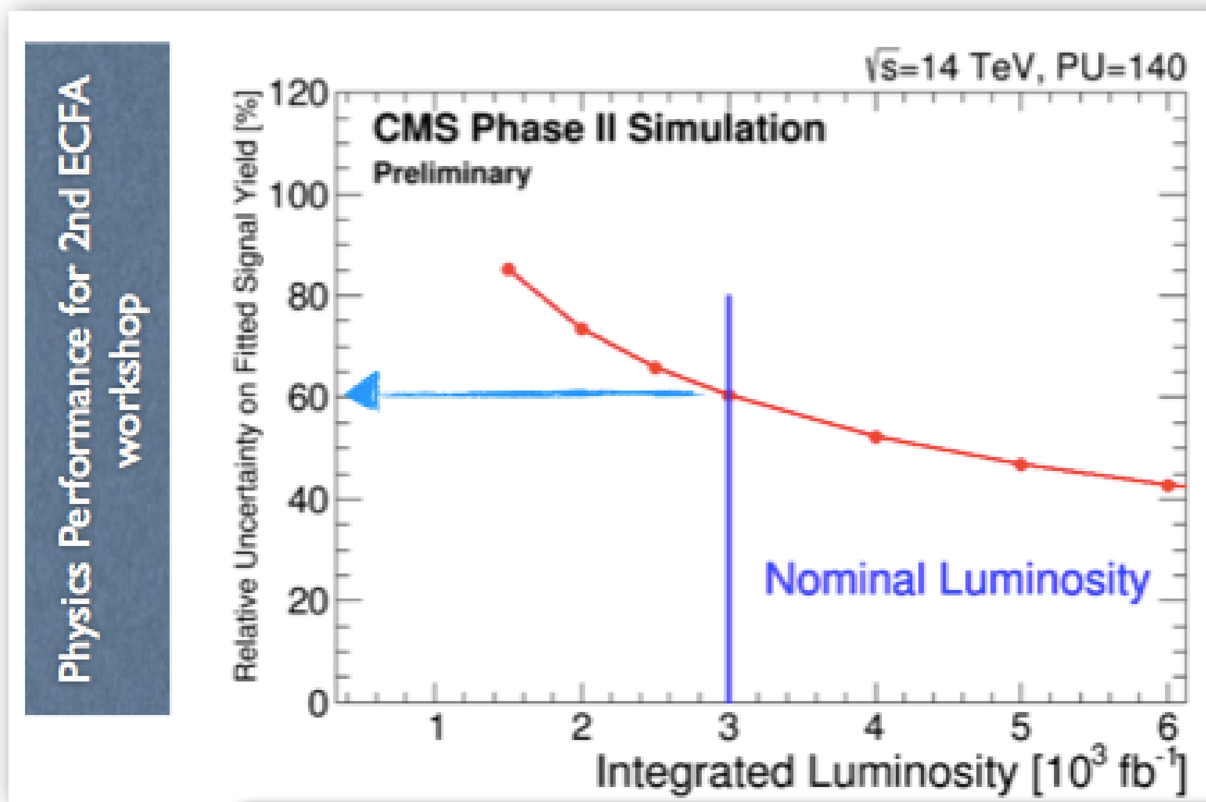
   Most theories beyond the SM have more Higgs bosons

5. What gives mass to the Higgs ??

Obvious question, with a trivial answer in the SM: the Higgs gives mass to itself!

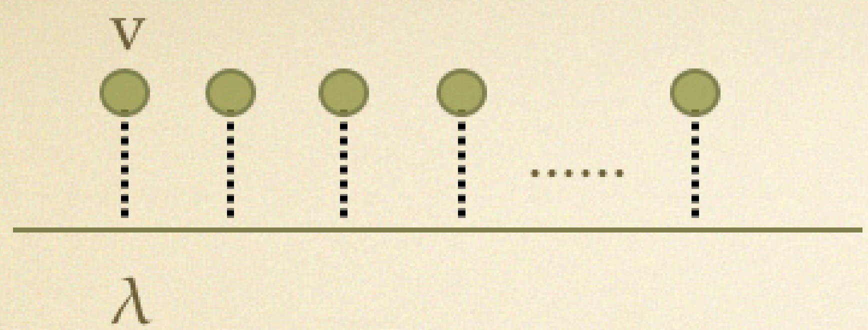
But less trivial answers can arise in beyond-the-SM scenarios

Testing how the Higgs interacts with itself (*this is how we probe the origin of the Higgs mass*) will require the full High Luminosity programme, and possibly more



The measurement of Higgs self-interactions has broad implications on issues such as the nature of the EW phase transition during the Big Bang

Dalla mia lezione dell'anno scorso:



$m \propto \lambda\, v$

The number "v" is a universal property of the Higgs field background. The quantity "λ" is characteristic of the particle moving in the Higgs field. Particles which have large λ will have large mass, with $m \propto \lambda\, v$

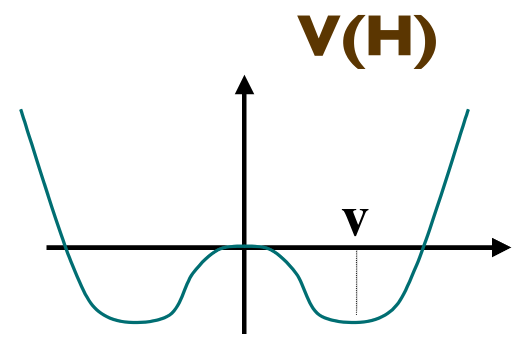
Now the question of "why does a given particle has mass **m**" is replaced by the question "why does a given particle couple with the Higgs field with strength $\lambda \propto m \,/\, v$"

However at least now we have a model to understand **how** particles acquire a mass.

Higgs selfcouplings

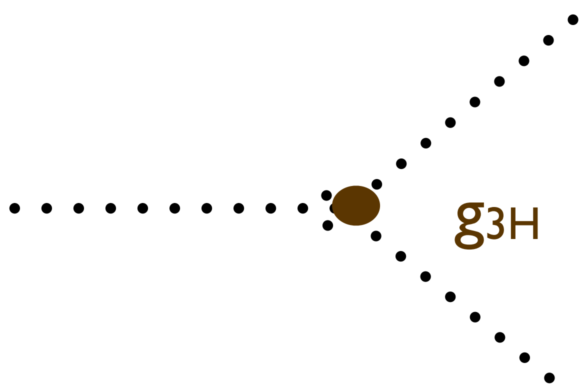
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

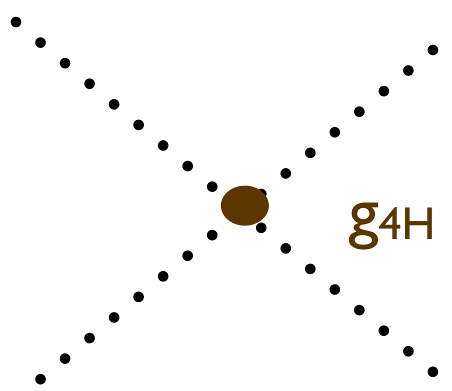


$$\frac{\partial V_{SM}(H)}{\partial H}\Big|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}\Big|_{H=v} \quad \Rightarrow \quad \begin{aligned} \mu &= m_H \\ \lambda &= \frac{m_H^2}{2v^2} \end{aligned}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of m_H



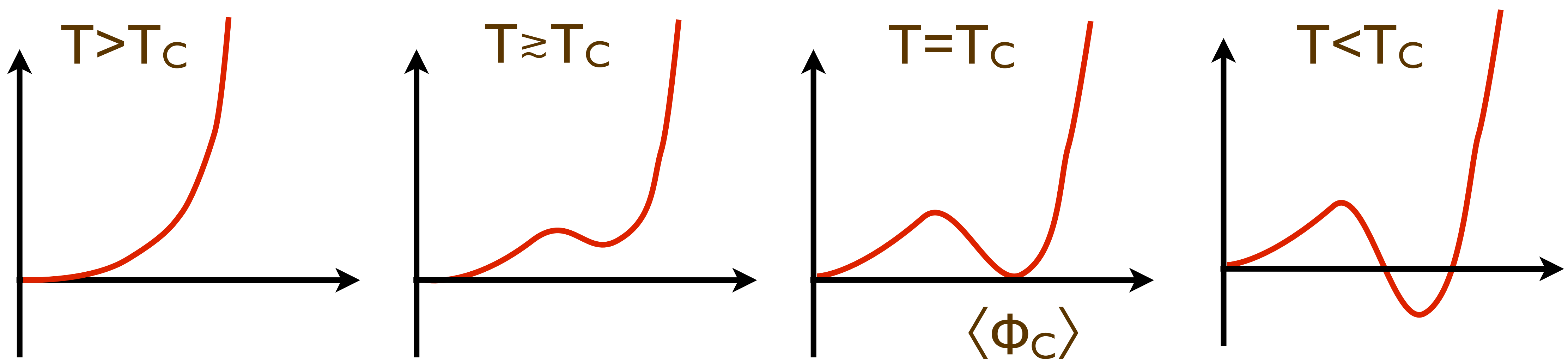
$g_{3H} \Rightarrow 6\lambda v = \frac{3m_H^2}{v}$ ~O(m_{top})



$g_{4H} \Rightarrow 6\lambda = \frac{3m_H^2}{v^2}$ ~O(1)

Testing these relations is therefore an important test of the SM nature of the Higgs mechanism

The cosmological evolution of the Higgs potential: what's the nature of the EW phase transition?



Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV ⇒ new physics, coupling to the Higgs and effective at scales O(TeV), must modify the Higgs potential to make this possible

Why is it difficult to study the Higgs ?

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we "bang" on the Higgs background we can stimulate "Higgs waves", i.e. what we call the Higgs boson ...

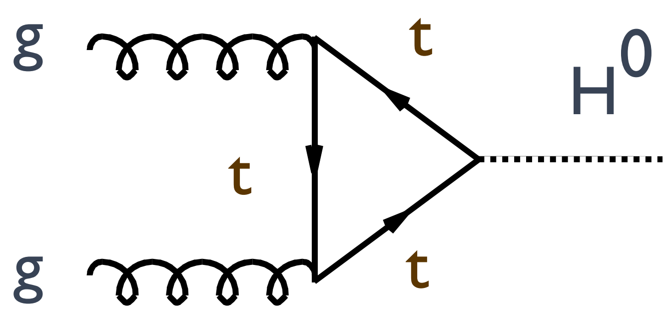
This requires not just energy (enough to create the H), but a large-mass probe (the H couples to mass, not to energy!)

Thus we typically need not just the energy required to produce the H, but also the energy required to produce the heavy particles that will stimulate its emission ...

$\Longrightarrow$ low rates, complex final states, large backgrounds, ...

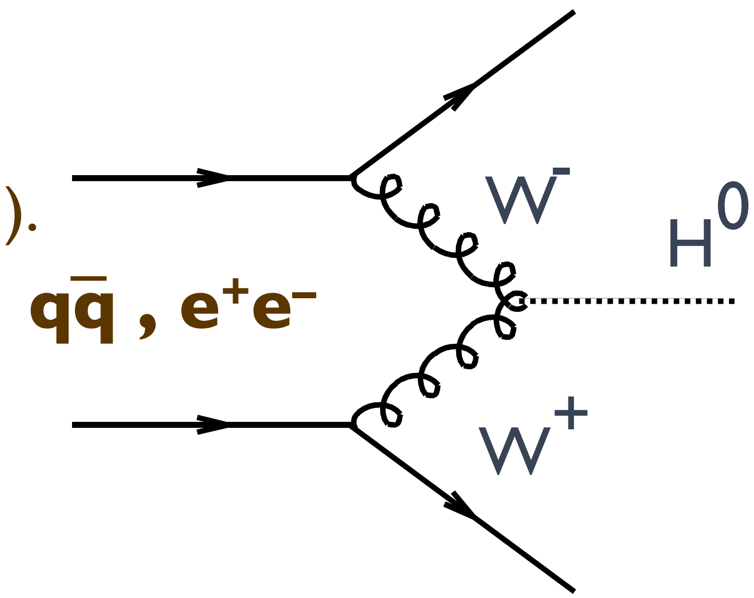
* Higgs particles are thus a bit like phonons ...

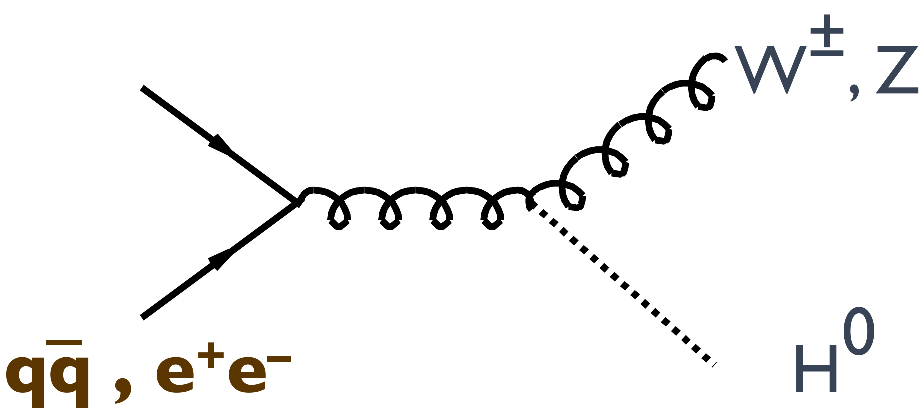
Four main production mechanisms



Gluon-gluon fusion (NNLO):
- Largest rate for all m(H).
- Proportional to the top Yukawa coupling, y_t
- gg initial state

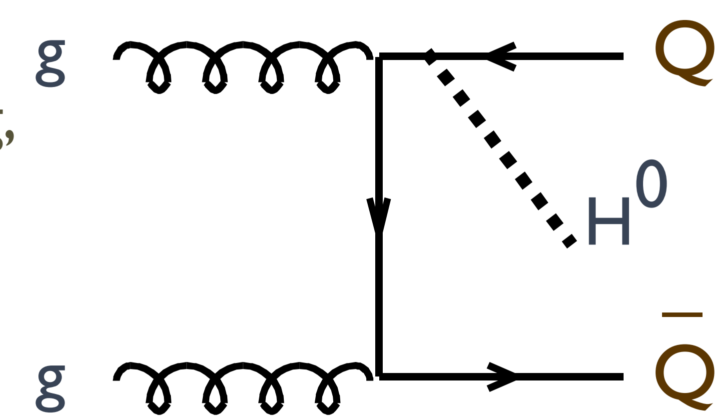
Vector-boson (W or Z) fusion (NLO):
- Second largest, and increasing rate at large m(H).
- Proportional to the Higgs EW charge
- mostly ud initial state



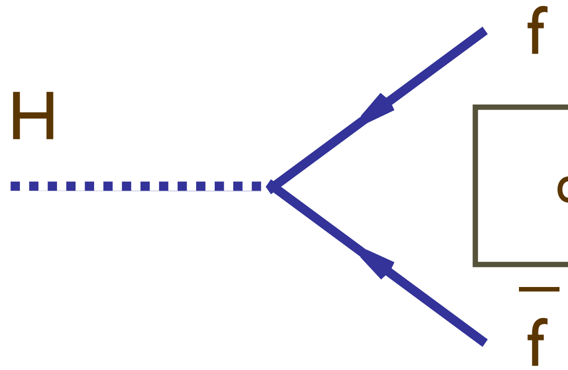


W(Z)-strahlung (NNLO):
- Same couplings as in VB fusion
- Different partonic luminosity

ttH/bbH associate production (NLO):
- Proportional to the heavy quark Yukawa coupling, y_Q, dominated by ttH
- Same partonic luminosity as in gg-fusion, except for different x-range

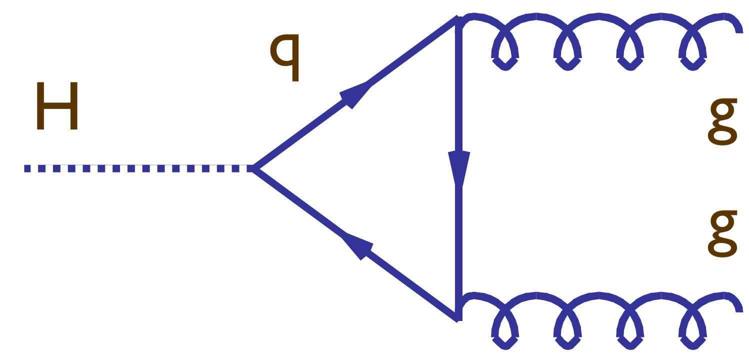


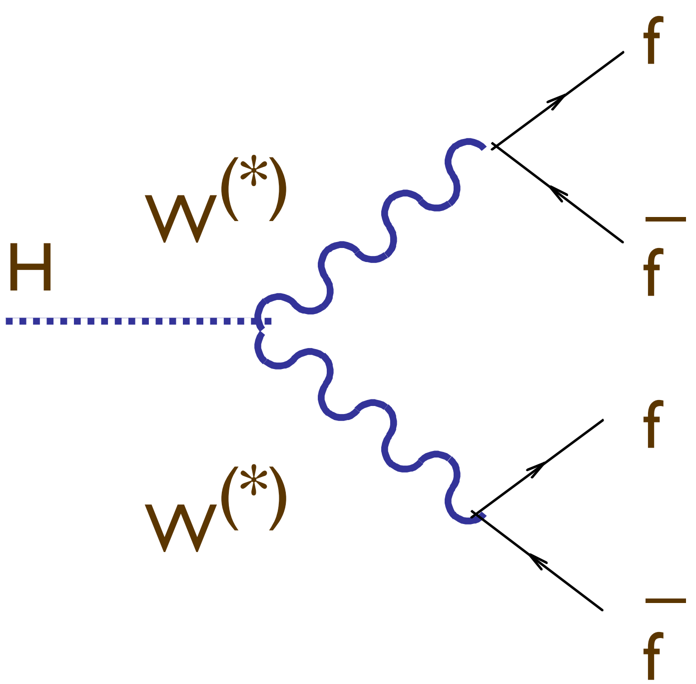
Higgs decays



$\propto m_f^2$ (evaluated at m_H, including QCD running effects)

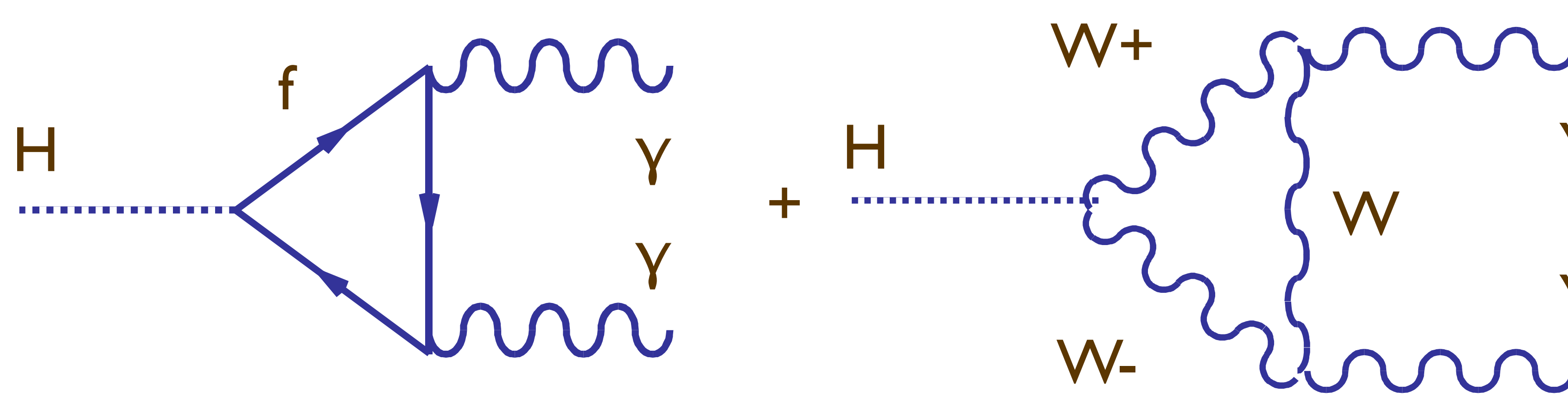
$\propto m_f^2$ (dominated by top-quark loops)



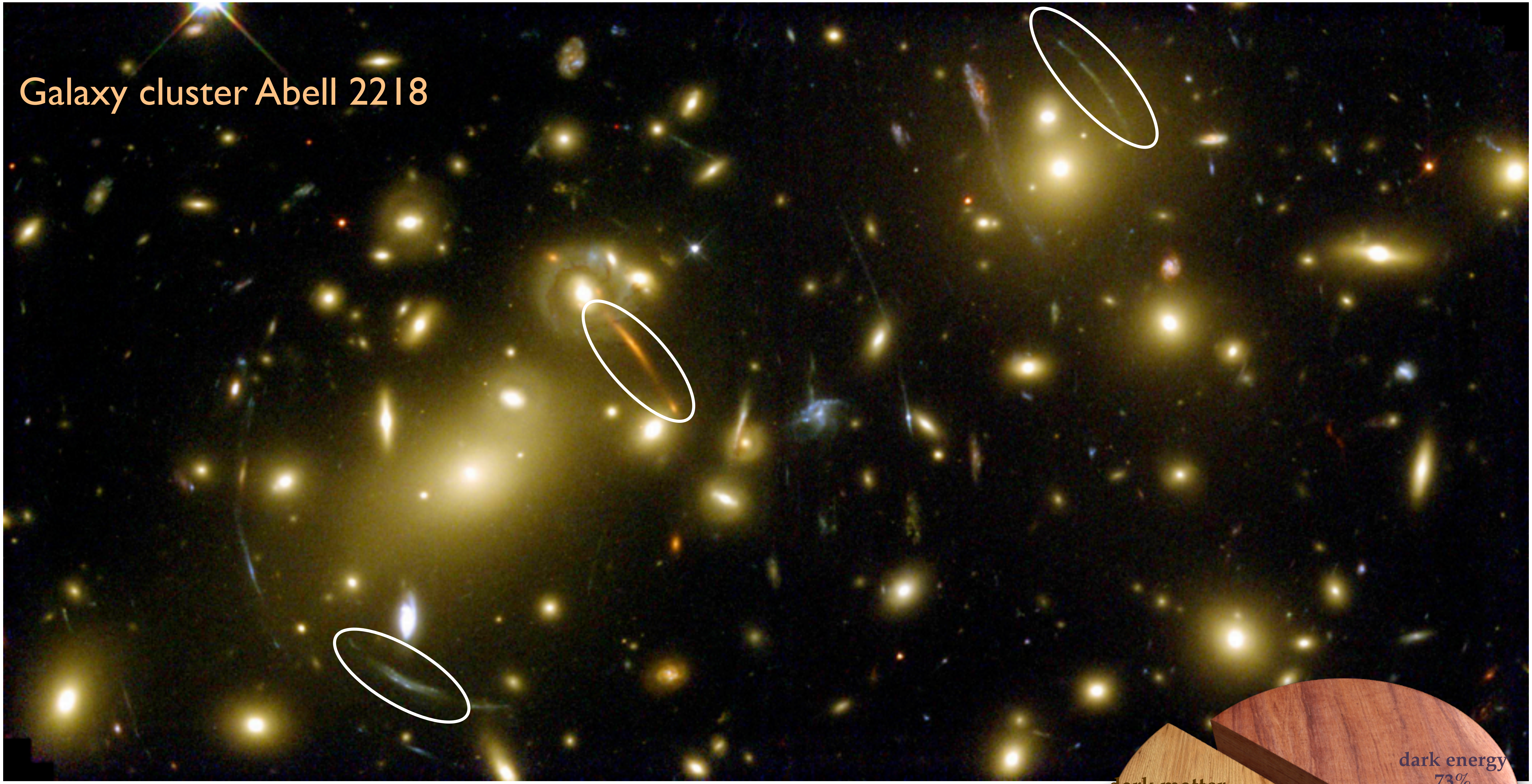


$\propto \alpha_W$ (sharp thereshold at m_H=2m_W , but large BR even down to 125 GeV). Similar processes with W↔Z.

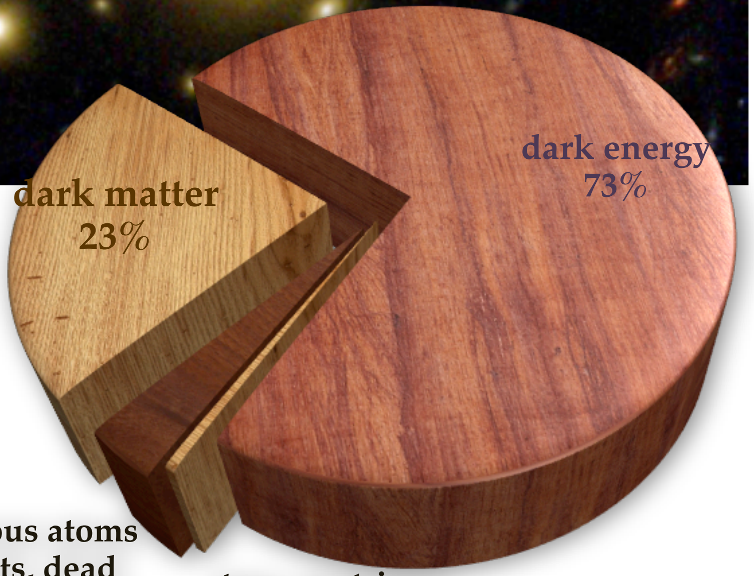
Dominated by the EW couplings, only minor contribution from top loop m ⇒ correlated to H→WW



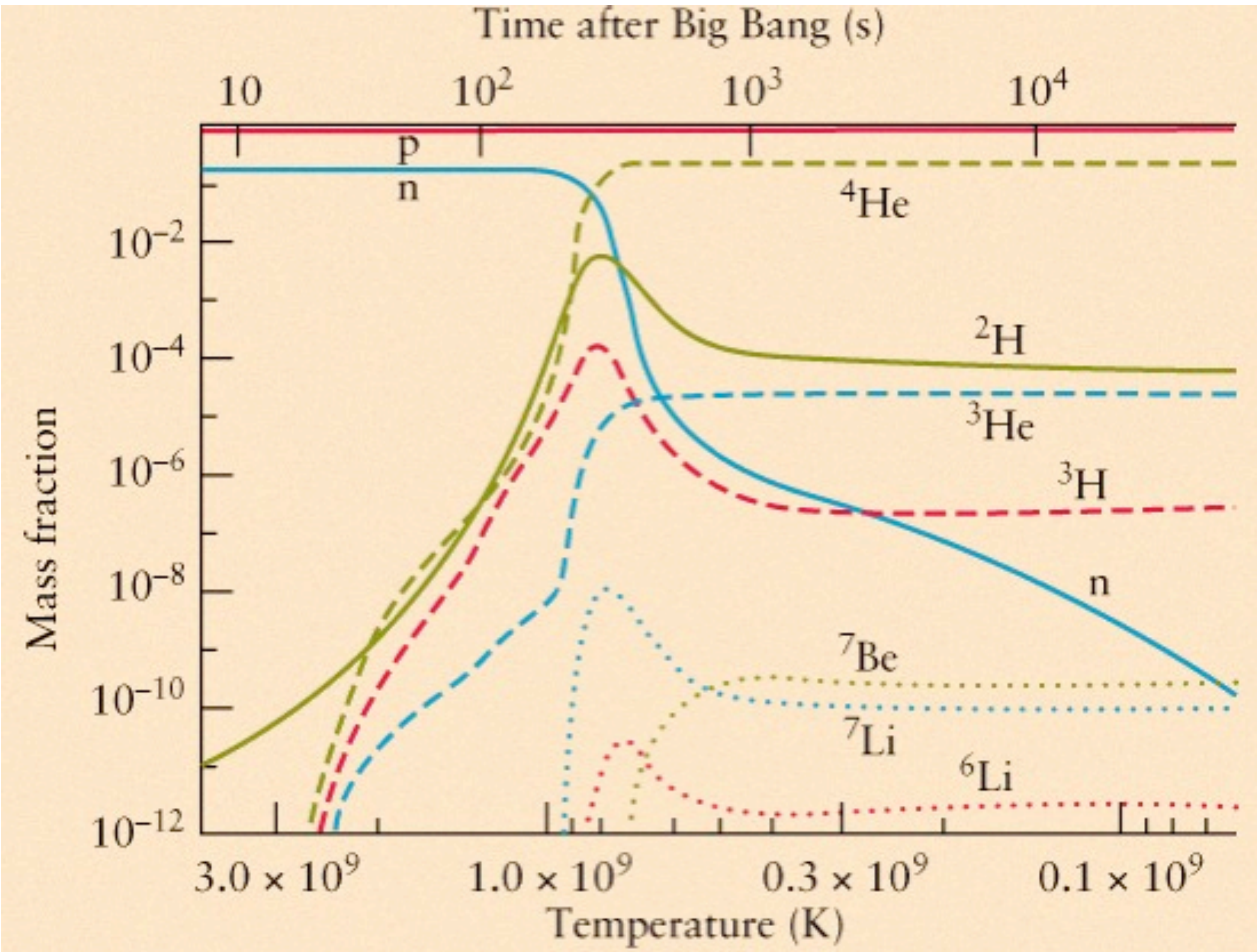
What is Dark Matter?

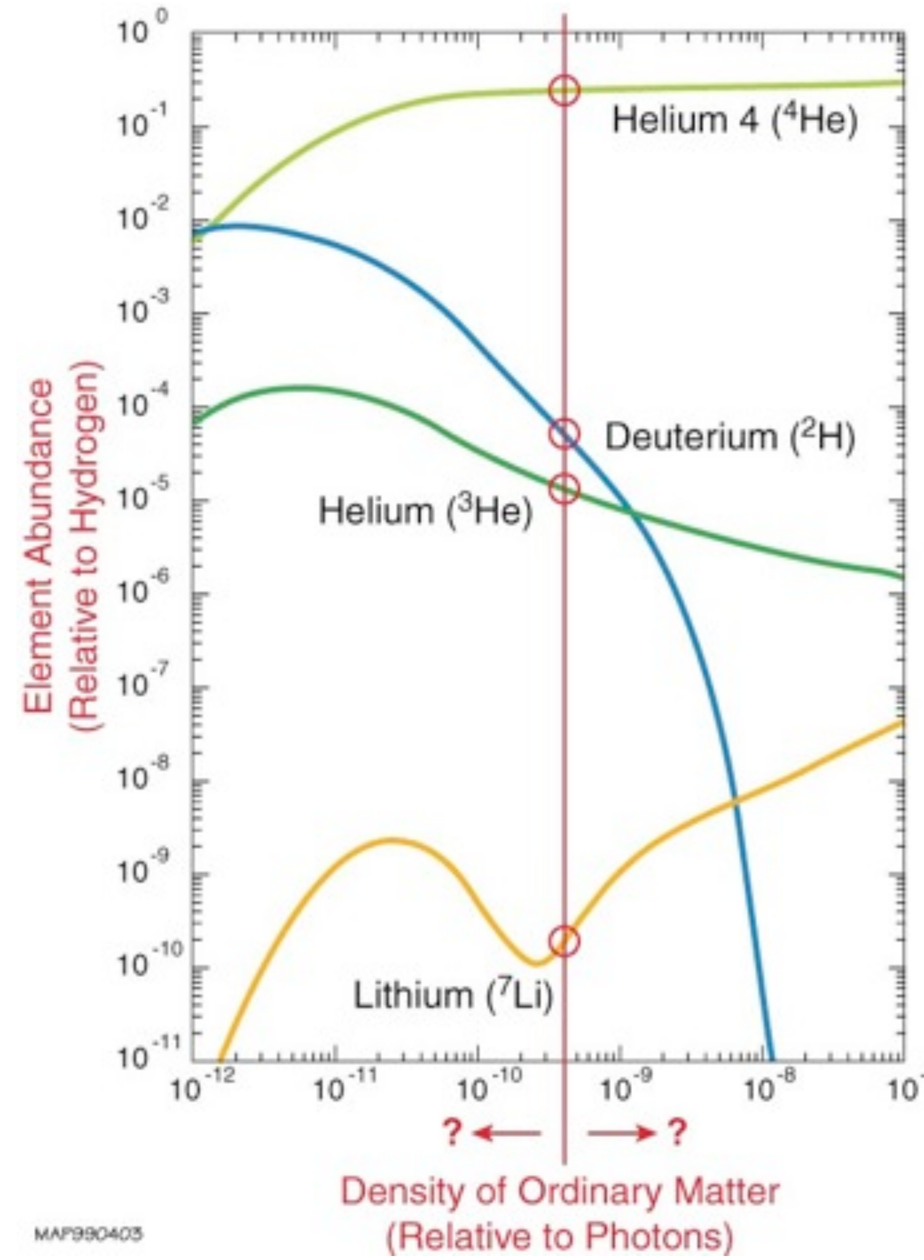


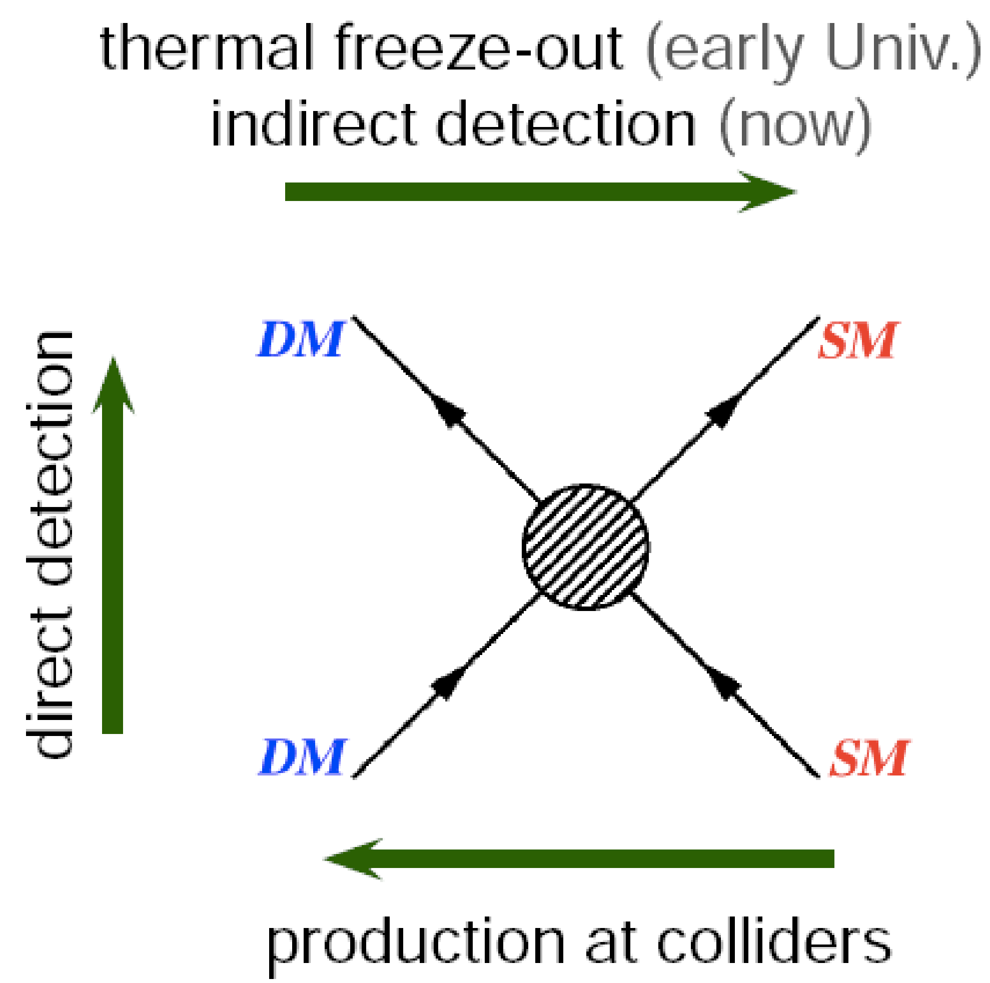
The modeling of Dark Matter has become more and more articulate. From a single source (WIMP, axion, neutrino, ...) to the possibility of dark hidden worlds



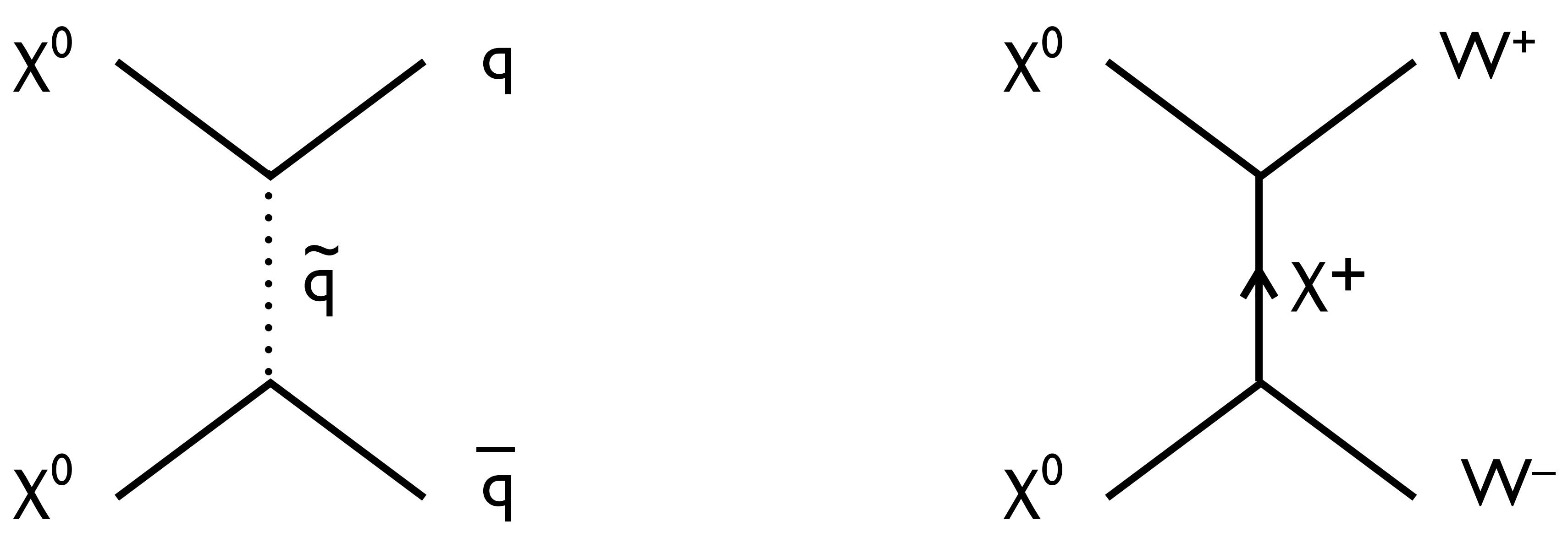
perche' la materia oscura non puo' essere fatta di materia ordinaria?



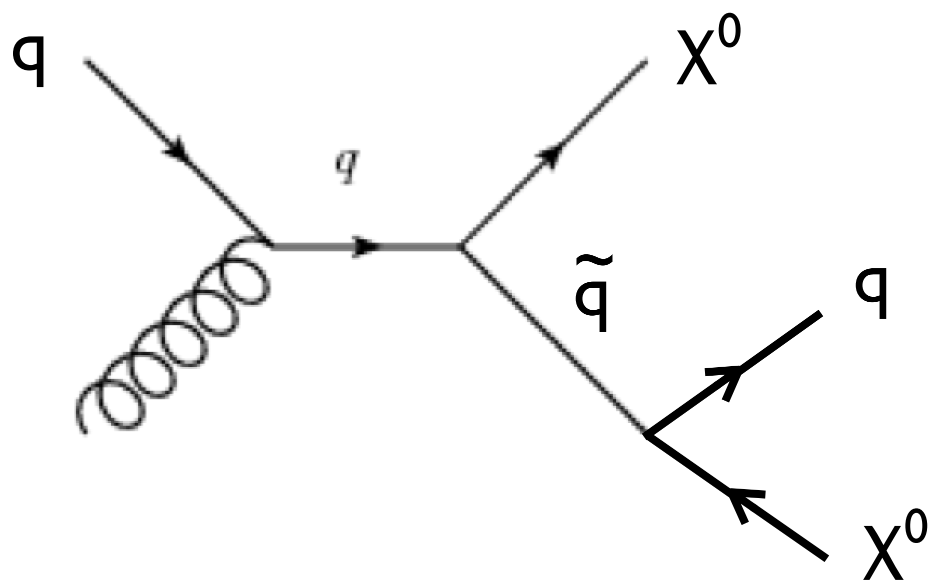


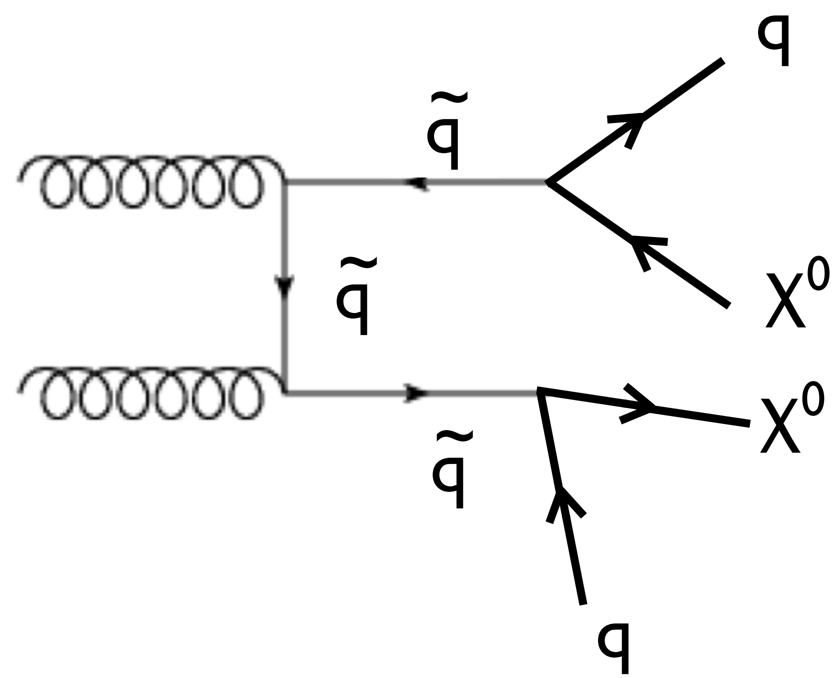

thermal freeze-out (early Univ.)
indirect detection (now)
direct detection
DM
SM
DM
SM
production at colliders

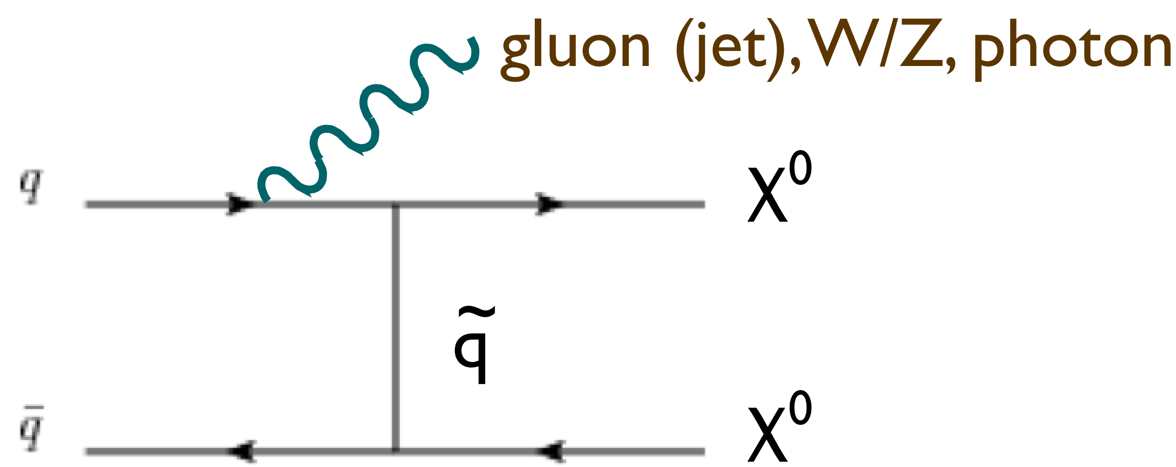
For example:


χ0
q
q̃
χ0
q̄
χ0
W+
χ+
χ0
W−

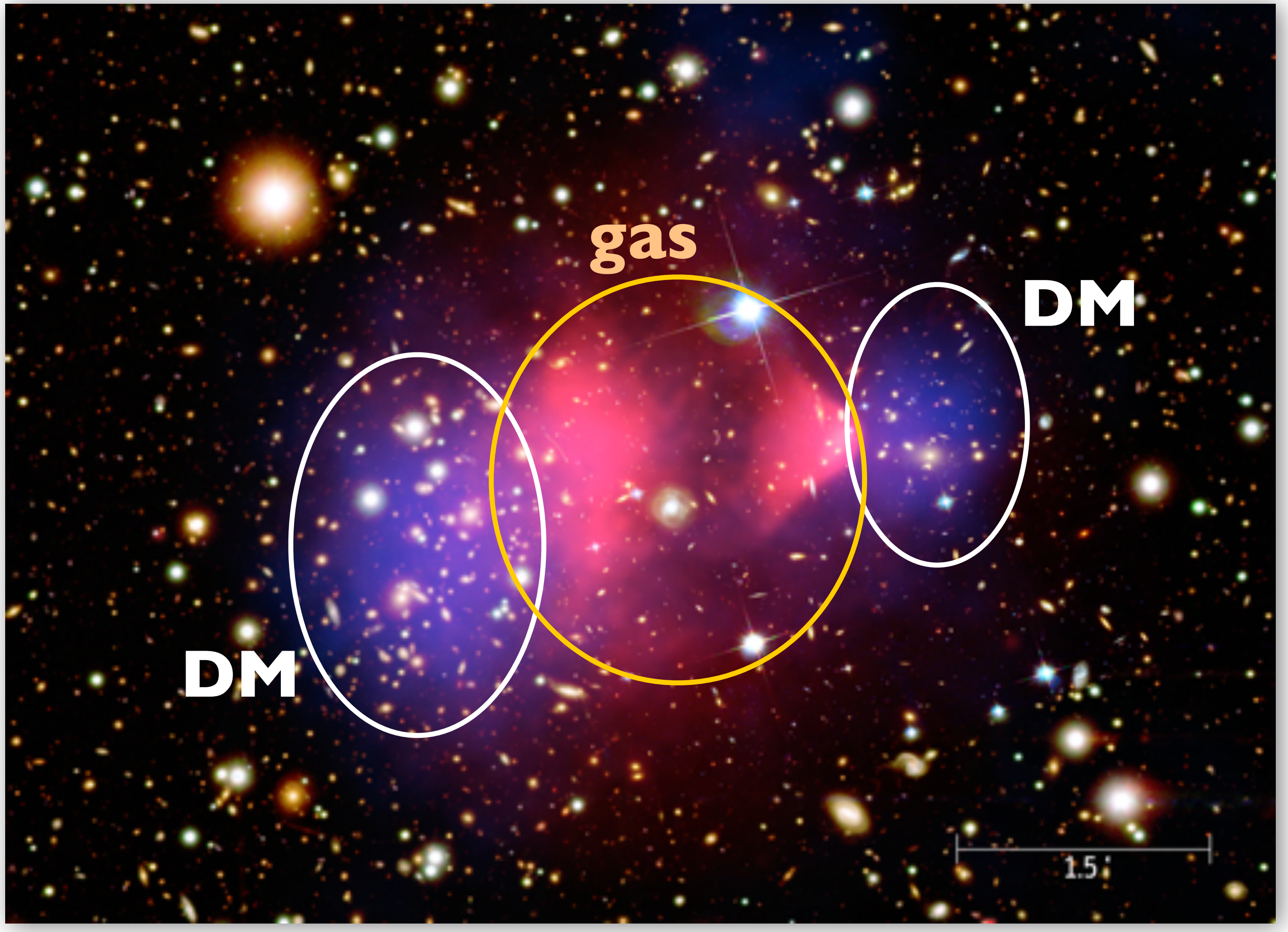
At the LHC

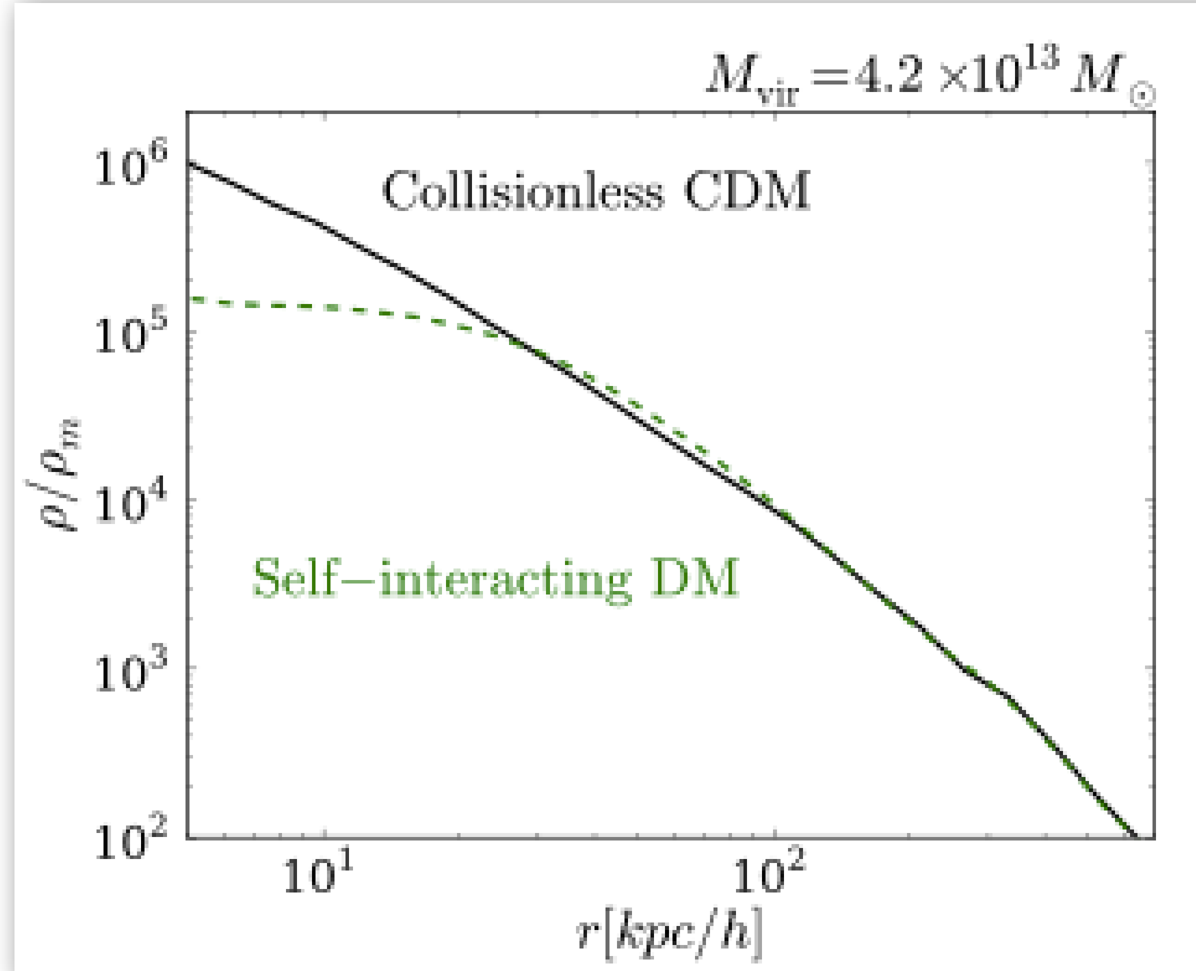






Evidence building up for self-interacting DM





$\sigma \sim 1 cm^2 (m_X/g) \sim 2 \times 10^{-24} cm^2 (m_X/GeV)$

For a WIMP: $\sigma \sim 10^{-38} cm^2 (m_X/100 GeV)$

Growing interest in models with rich sectors of "dark" particles, coupled to the SM ones via weakly interacting "portals"

6. Can the Higgs be the portal between the visible and the hidden world?

Plausible BSM theories of this type exist. They may also

- solve the hierarchy problem in a *natural* way
- connect the mechanisms that create the matter-over-antimatter asymmetry in the Universe, with those generating Dark Matter
- explain why there are similar amounts of visible and dark matter in the Universe

The opportunities for testing and discovering such scenarios at the LHC are being studied

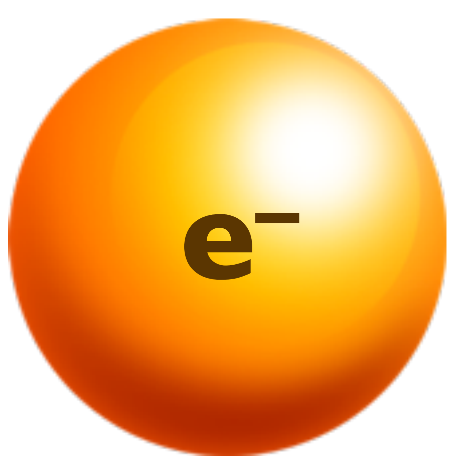
The search for Dark Matter particles at the LHC continues, independently of these scenarios, and remains one of the key goals of future runs ....

Milestones of the XX century

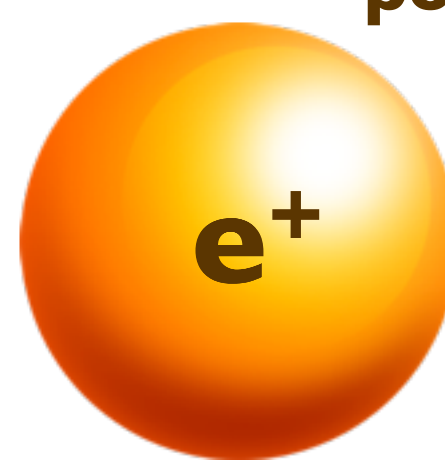
Special relativity from space-time symmetry
+
quantum mechanics

foremost consequence of the two:

the electron is not alone !



positron

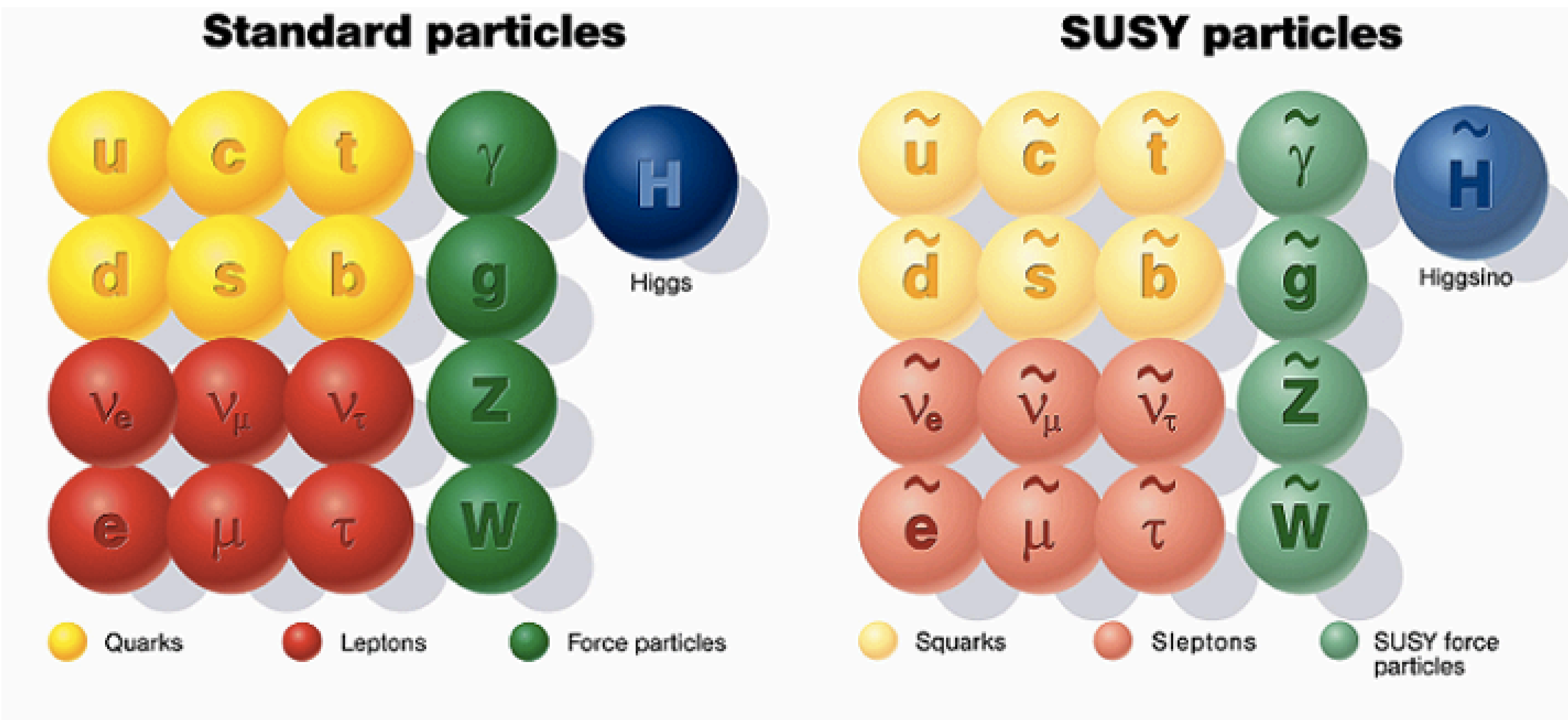


this is generalized to all other fundamental particles: *(except the photon and the Z)* ***they all have an antiparticle !!***

Supersymmetry: an additional possible symmetry of the space-time

... in fact, the largest possible symmetry of the space-time as we know it ....

foremost consequence: each SM particle has a "supersymmetric partner"



Is Supersymmetry (*SUSY*) really an underlying symmetry of our world ?

Fundamental implications:

- the discovery of a single Susy particle implies the existence of all others!!
- several SUSY particles and interactions directly address, and could solve, open issues of particle physics:
  - breaking of EW symmetry, triggering the Higgs mechanism
  - origin of DM
  - origin of matter/antimatter asymmetry
  - “hierarchy problem”
  - relation between gravity and the “other” forces (strong and electroweak)
  - unification of all forces (GUT), and a framework to understand neutrino masses

Most other BSM theories address one or more of these issues.

None has the same intrinsic “simplicity” (builds on the basic concept of space-time symmetries), with the most extensive range of conceptual and practical implications

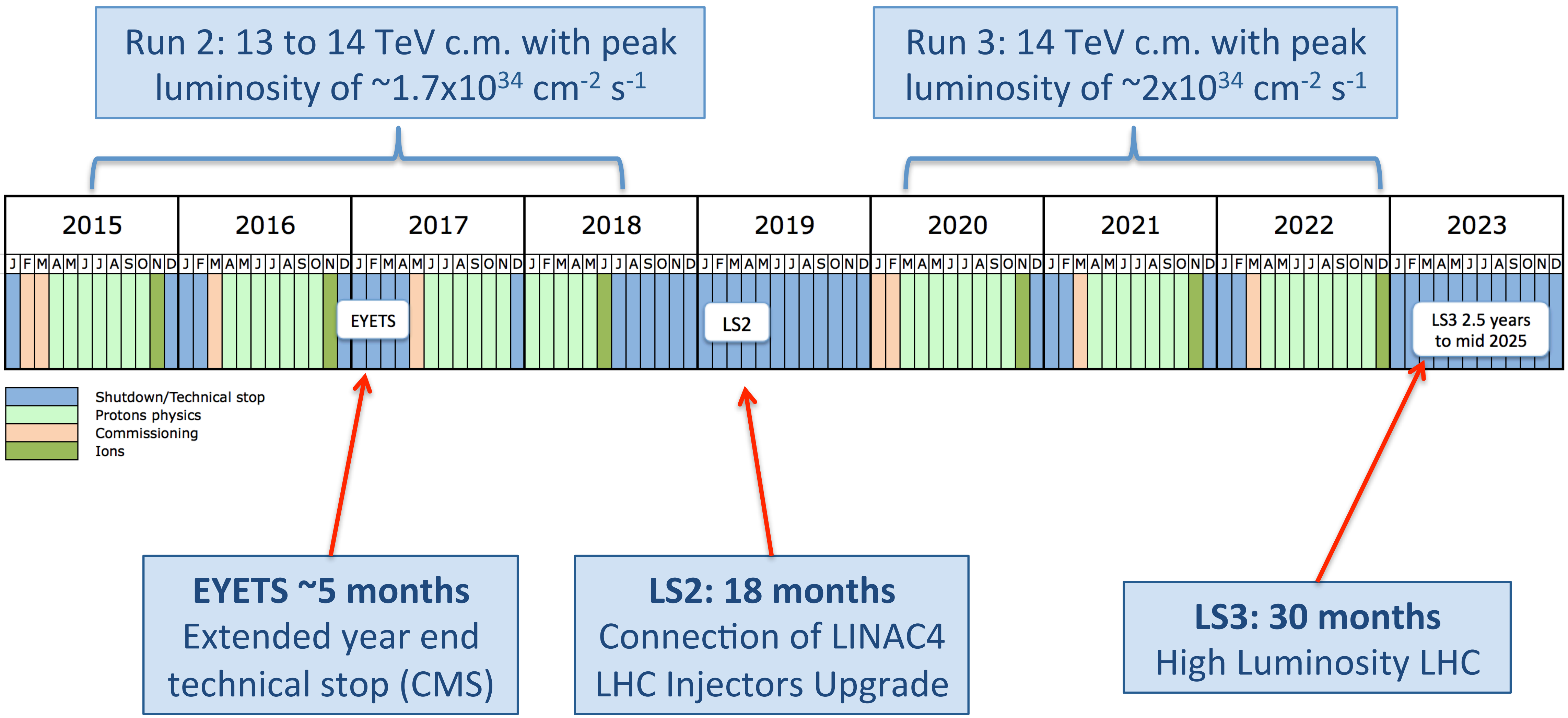
altre questioni sempre aperte ....

- Esistono altre forze?
- Quarks e leptoni: sono elementari o composti?
- Esistono altre dimensioni?
- Che relazione esiste fra la gravita’ e le altre forze?
- Le particelle sono elementari, o stringhe?
- ....

The directions

- Direct exploration of physics at the weak scale
    - High-energy colliders (e^+e^-, *pp*, *ep*; linear/circular; muons?)
- Quarks: flavour physics, EDM's
- Neutrinos: CP violation, mass hierarchy and absolute scale, majorana nature
- Charged leptons: flavour violation, g–2, EDMs
- Axions, axion-like's (ALPs), dark photons, ...

Il futuro prossimo dell'LHC



..... seguito da 10 anni (2025-2035) di ulteriore presa dati, per raccogliere alla fine una quantita' di dati oltre 100 volte maggiore di quanto disponibile oggi

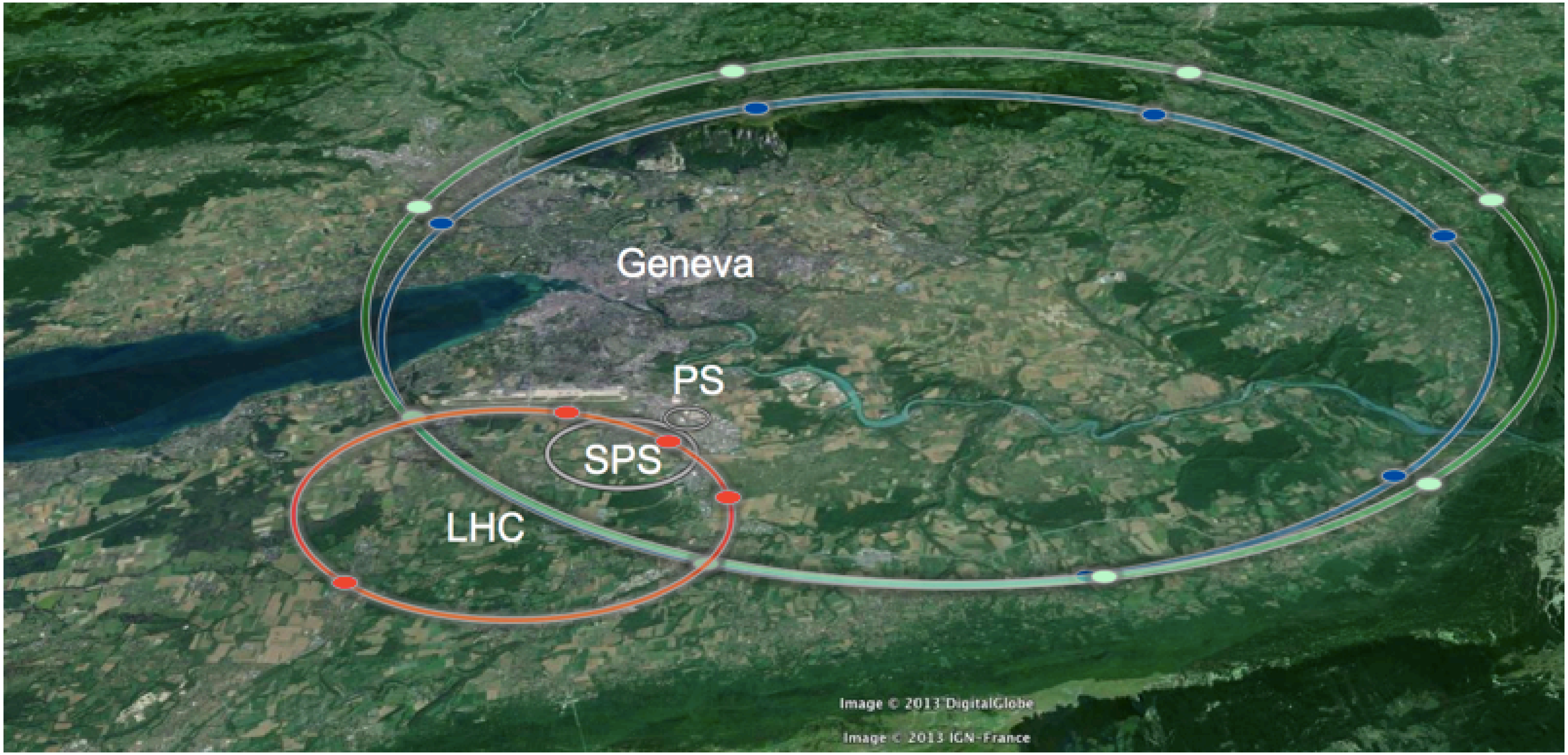
remark:

there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which will guarantee an answer to any of the questions above

$\Rightarrow$

- target broad and well justified scenarios
- consider the potential of given facilities to provide conclusive answers to relevant (*and answerable!*) questions
- weigh the value of knowledge that will be acquired, no matter what, by a given facility (*the value of "measurements"*)

Design study for Future Circular Colliders



FCC-hh	FCC-ee	FCC-eh
pp @100 TeV	e^+e^- @ $\sqrt{S}$ = 91, 160, 240, 350 GeV	$e^{\pm}$(50-175 GeV)-p(50 TeV)