Introduction to Elementary Particles (TN2811)

Theory Lecture 8

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Today's lecture

- The **Higgs boson** and symmetry breaking

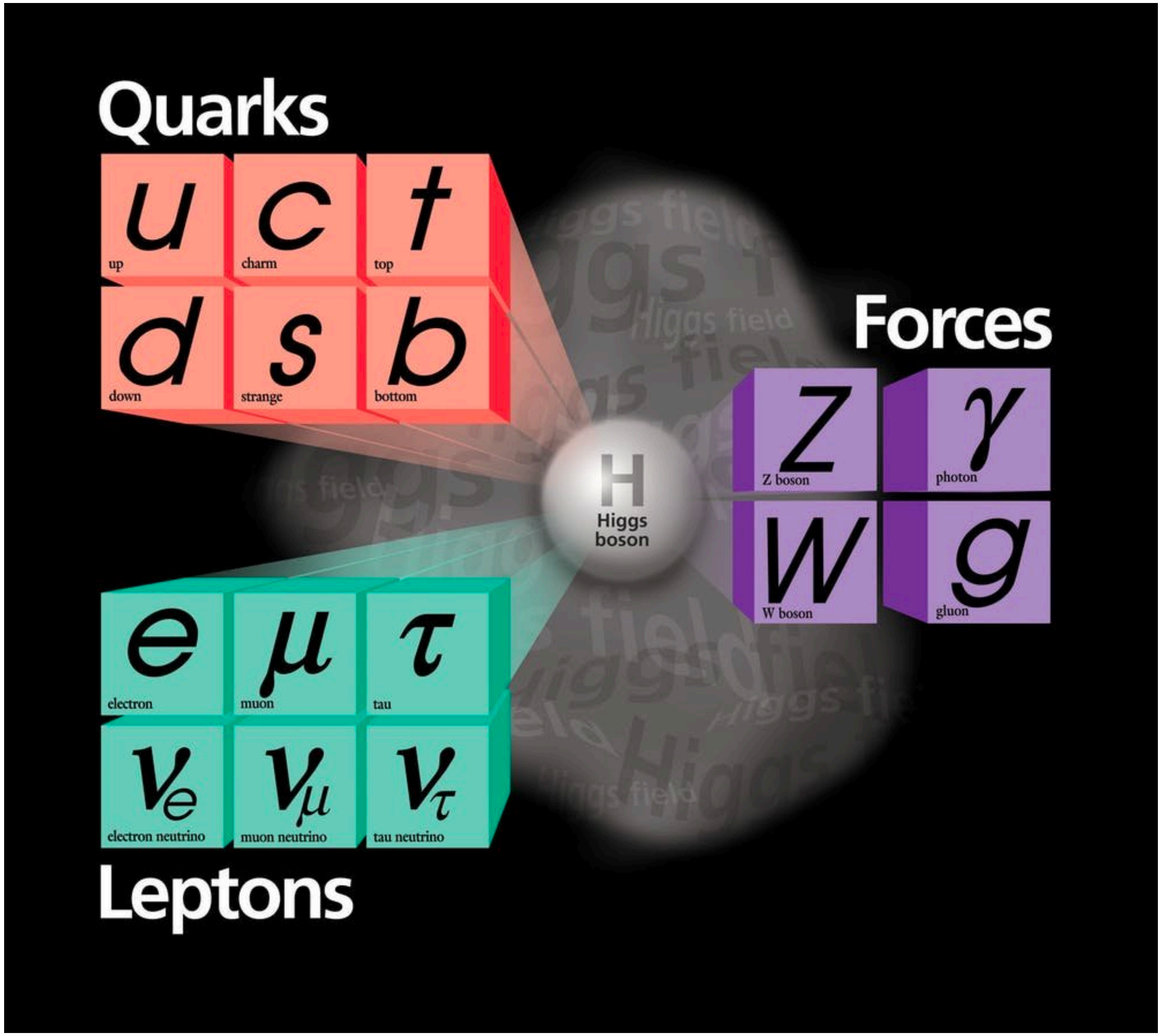
- **Collider** phenomenology and **Statistics** for particle physics

- Going **beyond the Standard Model**

- **Open discussion,** including homework problems

The Higgs boson

The Standard Model of particle physics



We are by know familiar with the different types of **matter particles** (leptons and quarks) and their interactions, mediated by the **force carrier particles**

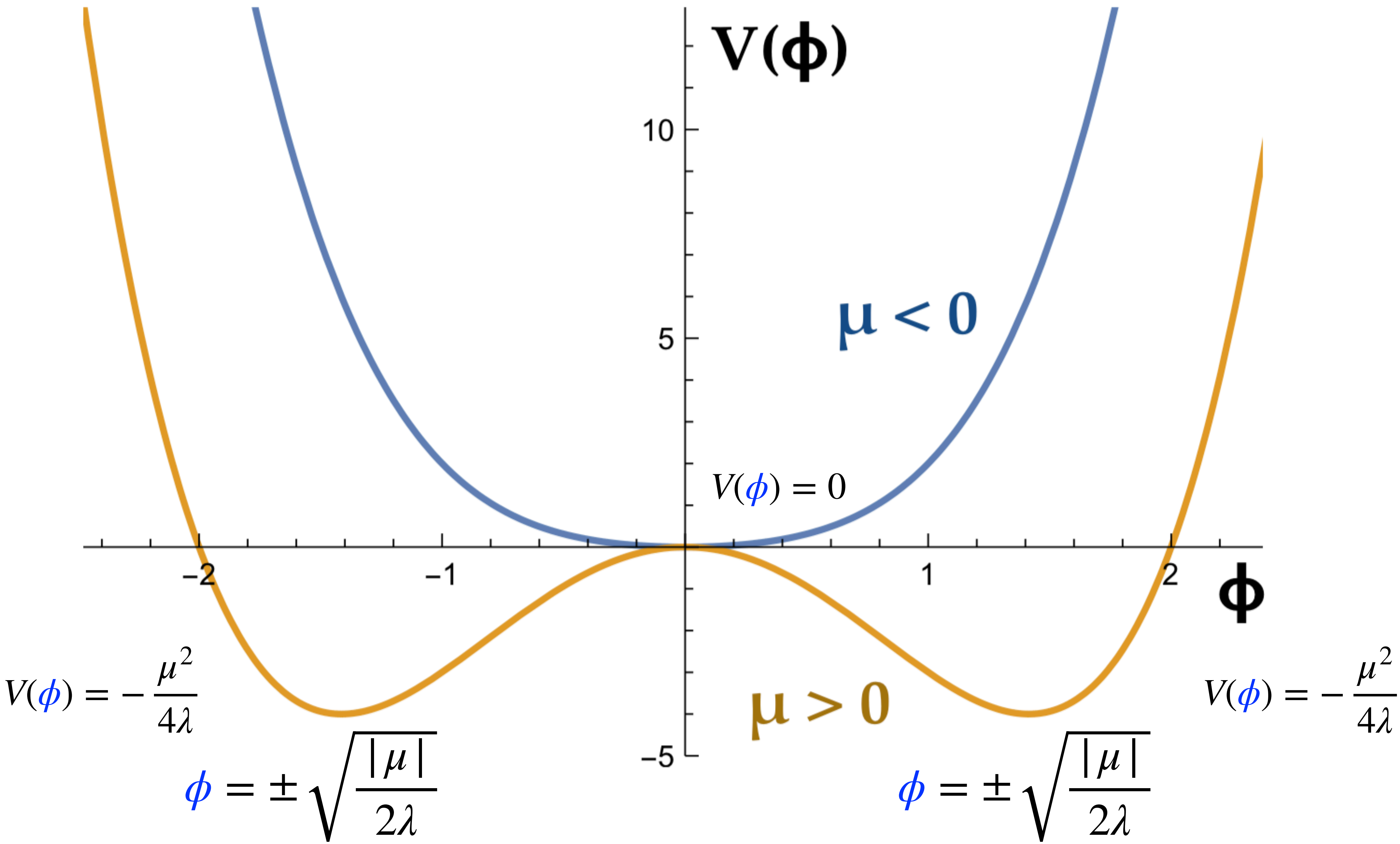
The Higgs boson

What are the defining properties of the Higgs boson?

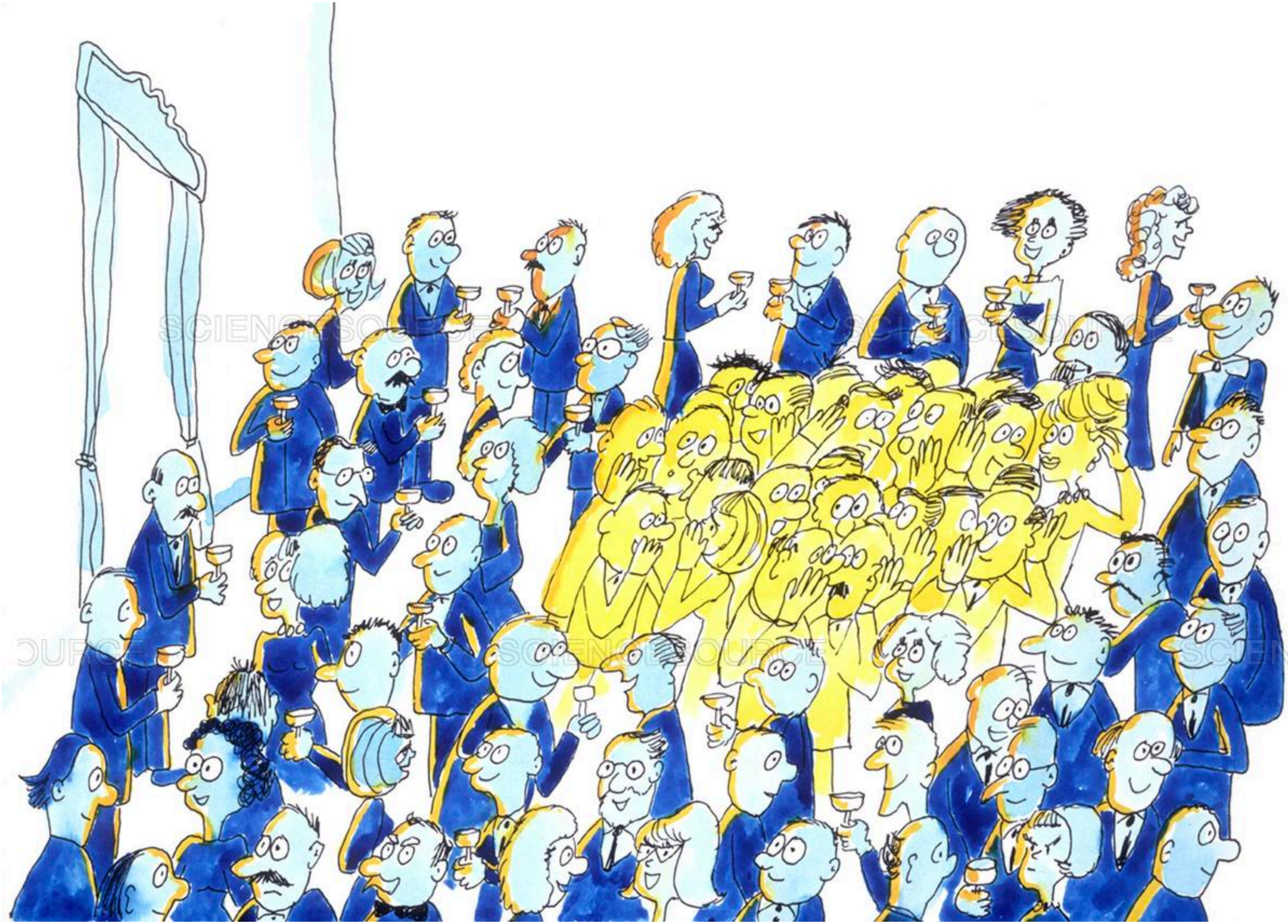
- ☑ It has spin zero: a **scalar particle** (hence the name **boson**)
- ☑ It is **elementary**, without any (known) substructure
- ☑ It interacts with **matter particles** (quarks and charged leptons) and gives them **mass**
- ☑ It is also responsible for the mass of the ***W*** and ***Z*** bosons

Without the Higgs, elementary particles would be **massless** and the Universe as we know it would be **impossible**

Higgs mechanism I



Higgs mechanism III

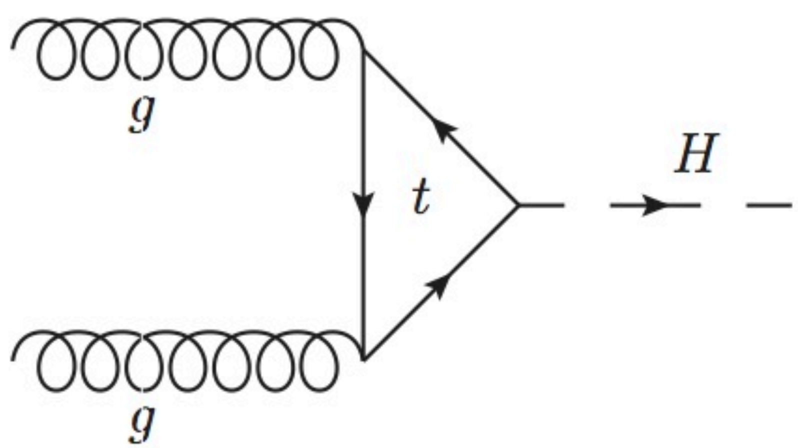


Higgs production and collider phenomenology

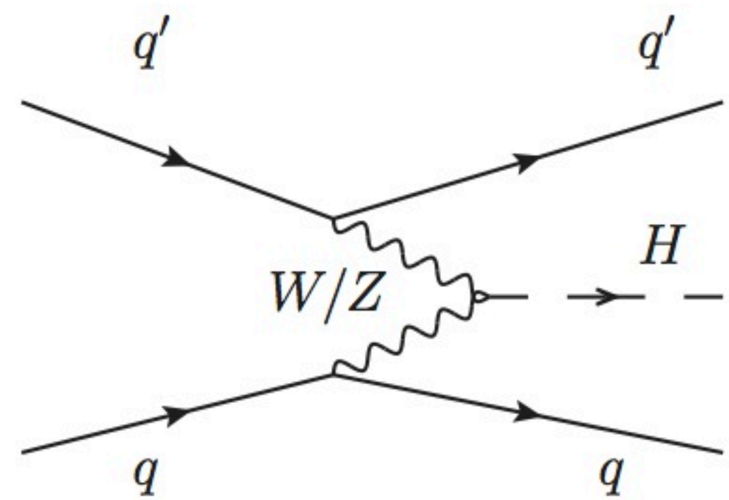
Higgs boson production

At proton-proton colliders such as the LHC, **multiple ways** to produce Higgs bosons

gluon-fusion



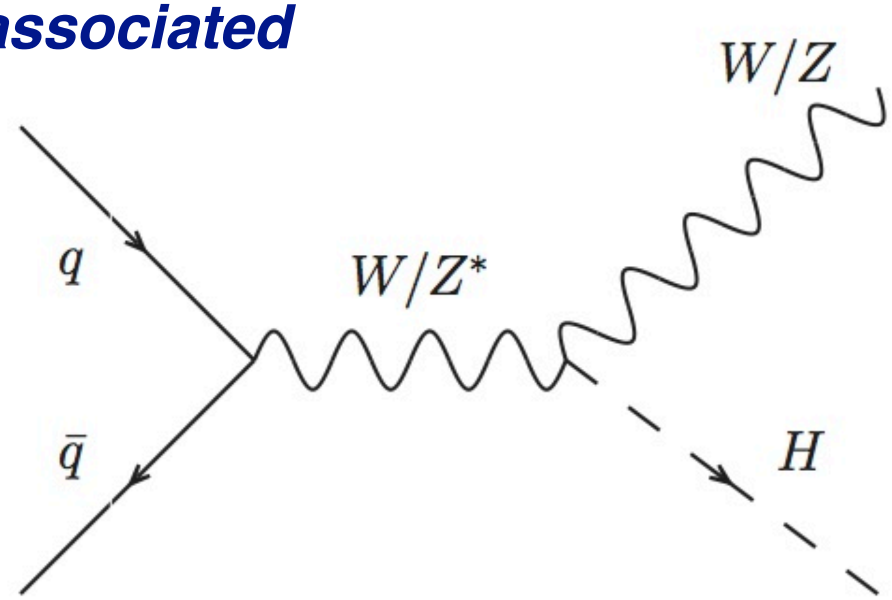
a)



b)

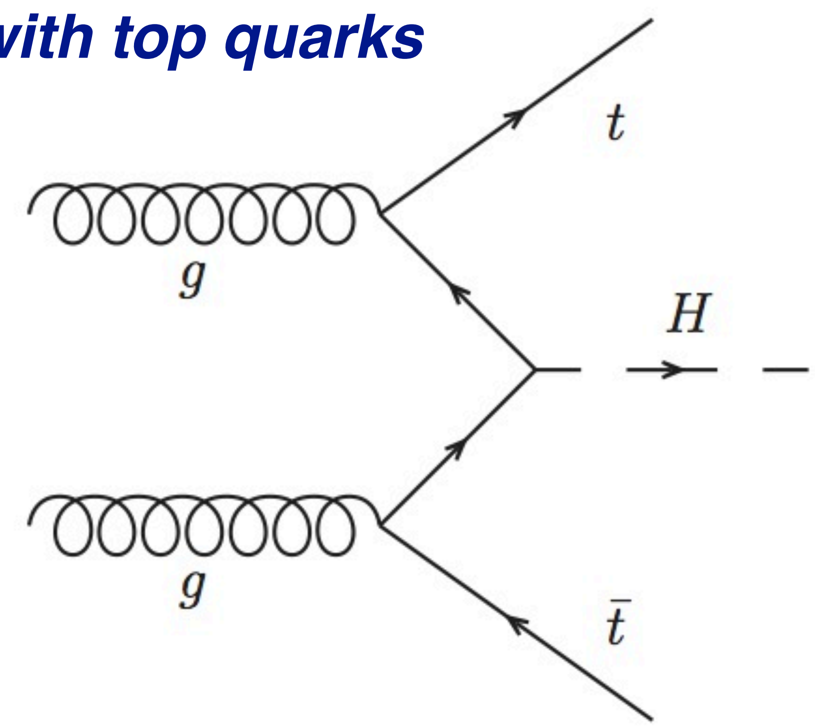
Weak boson fusion

W/Z associated



c)

with top quarks

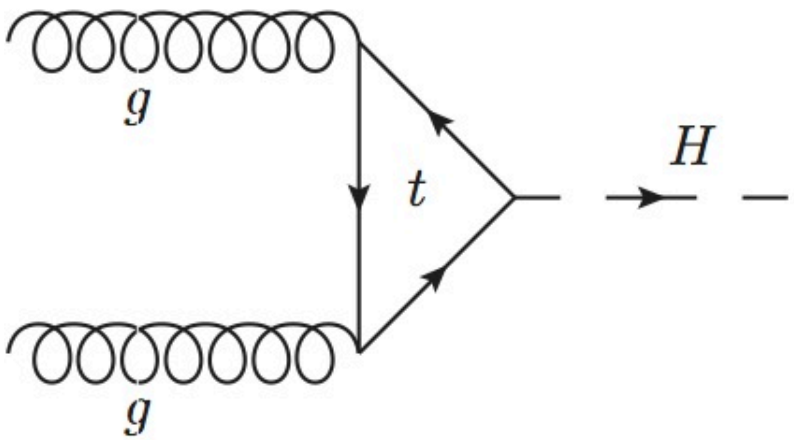


d)

Higgs boson production

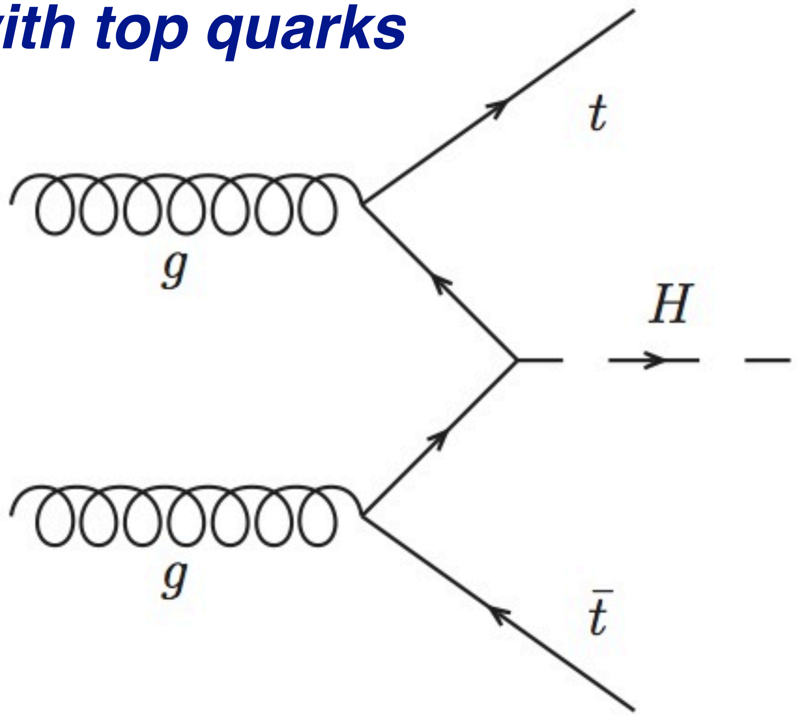
Which processes are **more likely** to happen? Strength of Higgs boson coupling to a particle is **proportional to the particle mass**

gluon-fusion



a)

with top quarks



c)

d)

Higgs boson production

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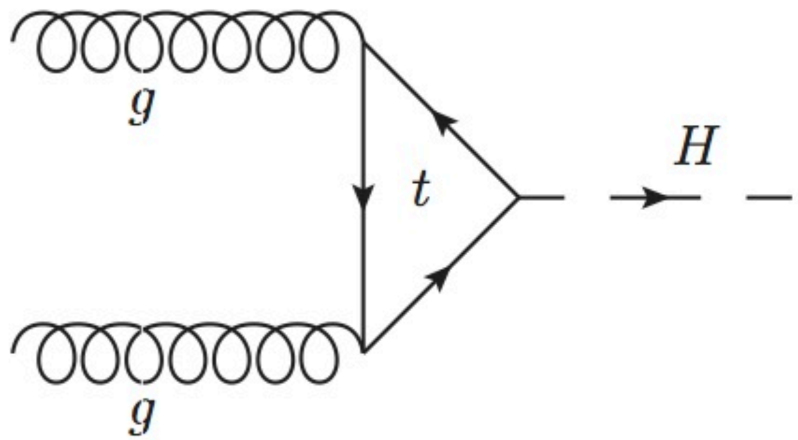
gluon-fusion



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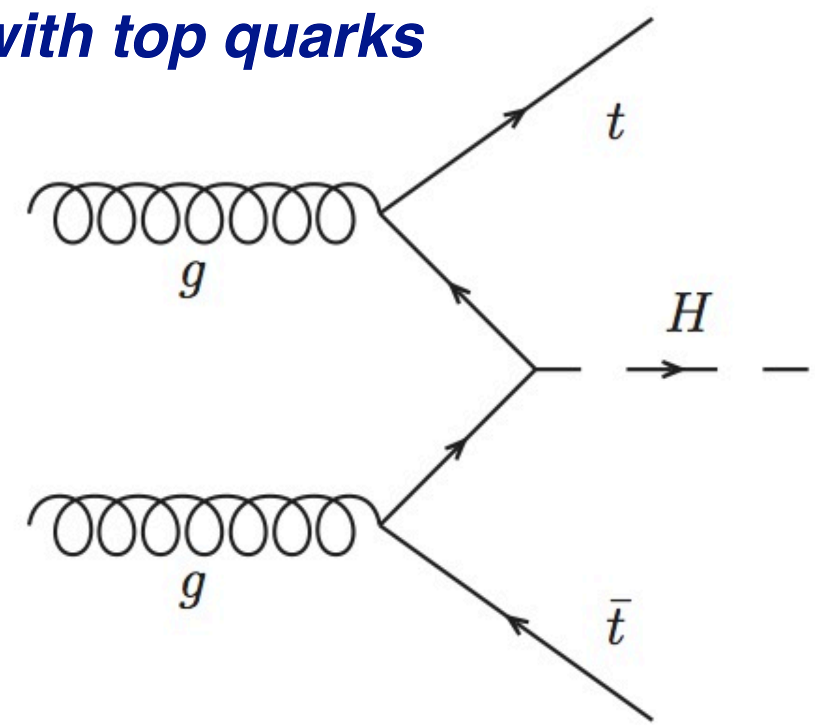
>

with top quarks



Same coupling between Higgs and top quarks …

But in one case one needs to produce **in addition a top quark pair** which requires a lot of extra energy

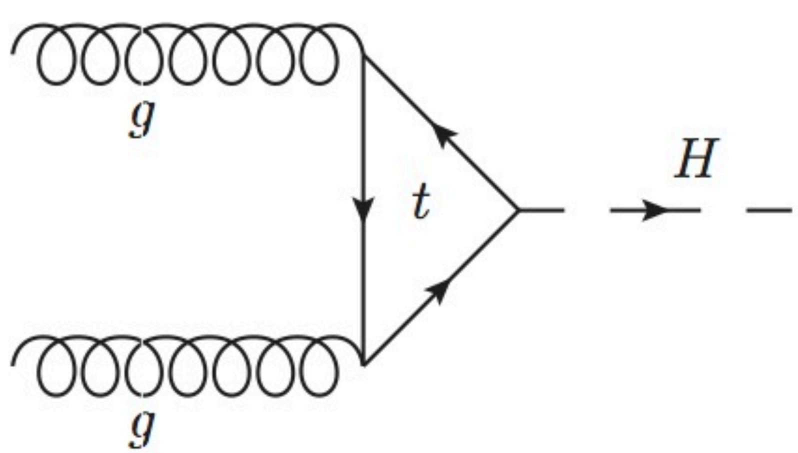
c)

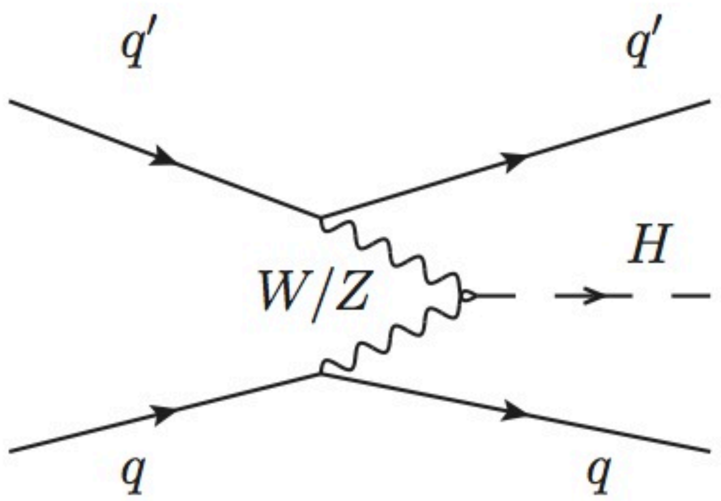
d)

Higgs boson production

Which processes are **more likely** to happen? Strength of Higgs boson coupling to a particle is **proportional to the particle mass**

gluon-fusion



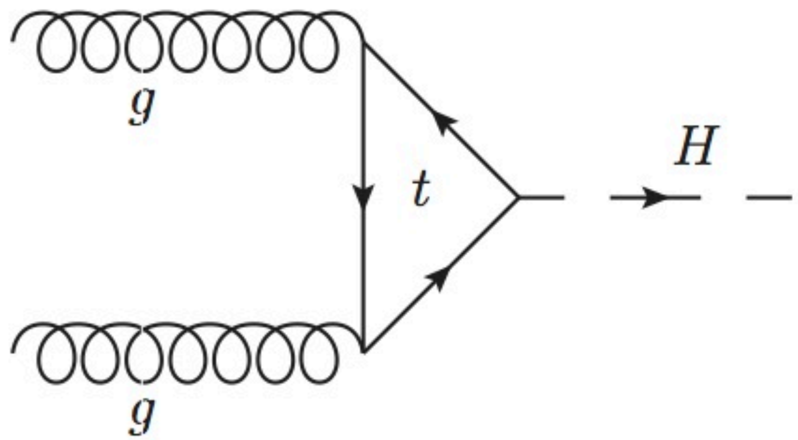


Weak boson fusion

Higgs boson production

Which processes are **more likely** to happen? Strength of Higgs boson coupling to a particle is **proportional to the particle mass**

gluon-fusion



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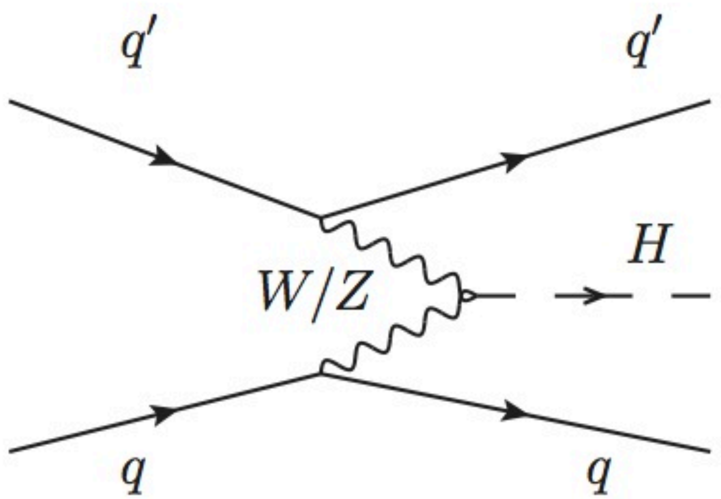
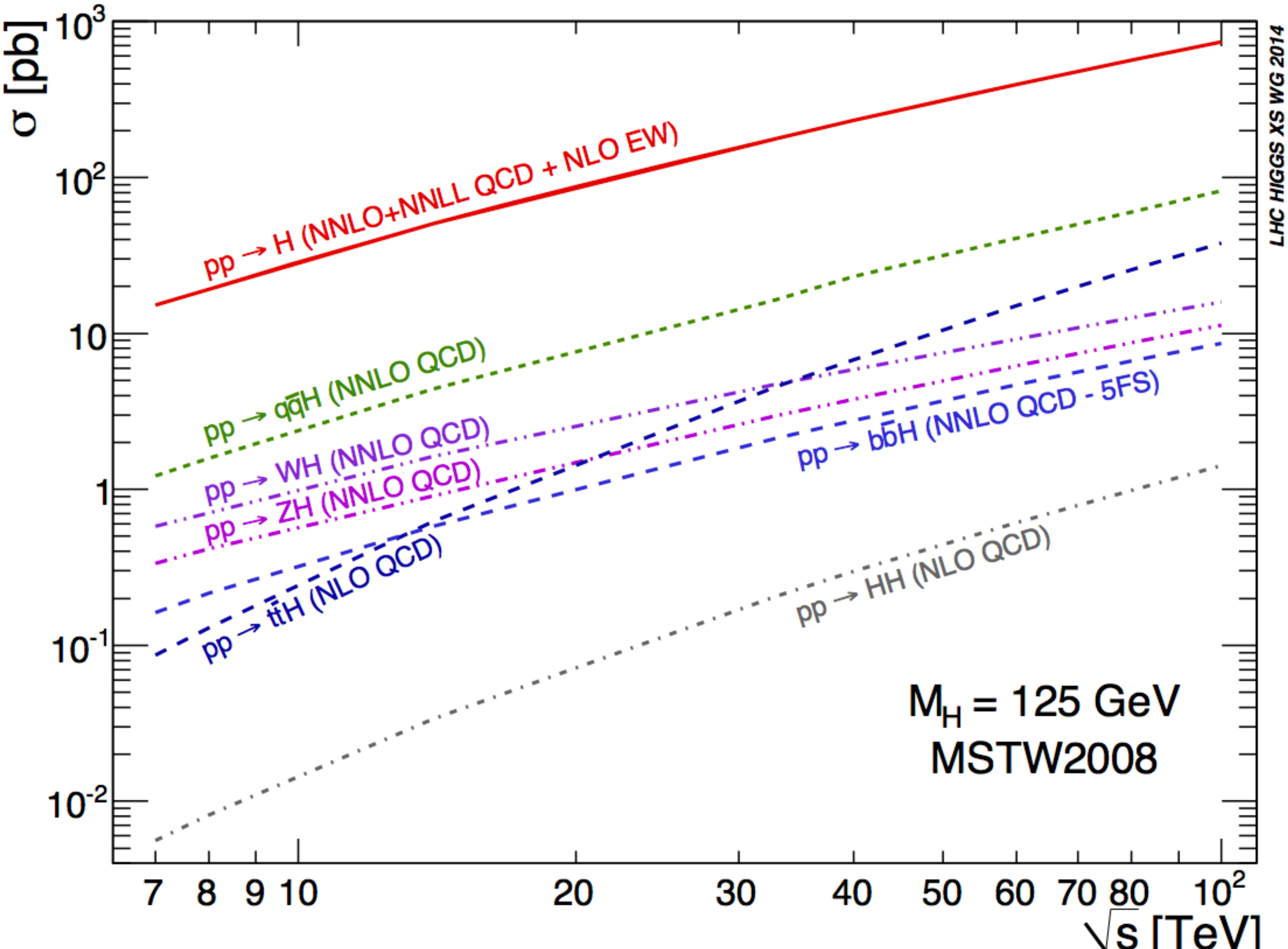


Weak boson fusion

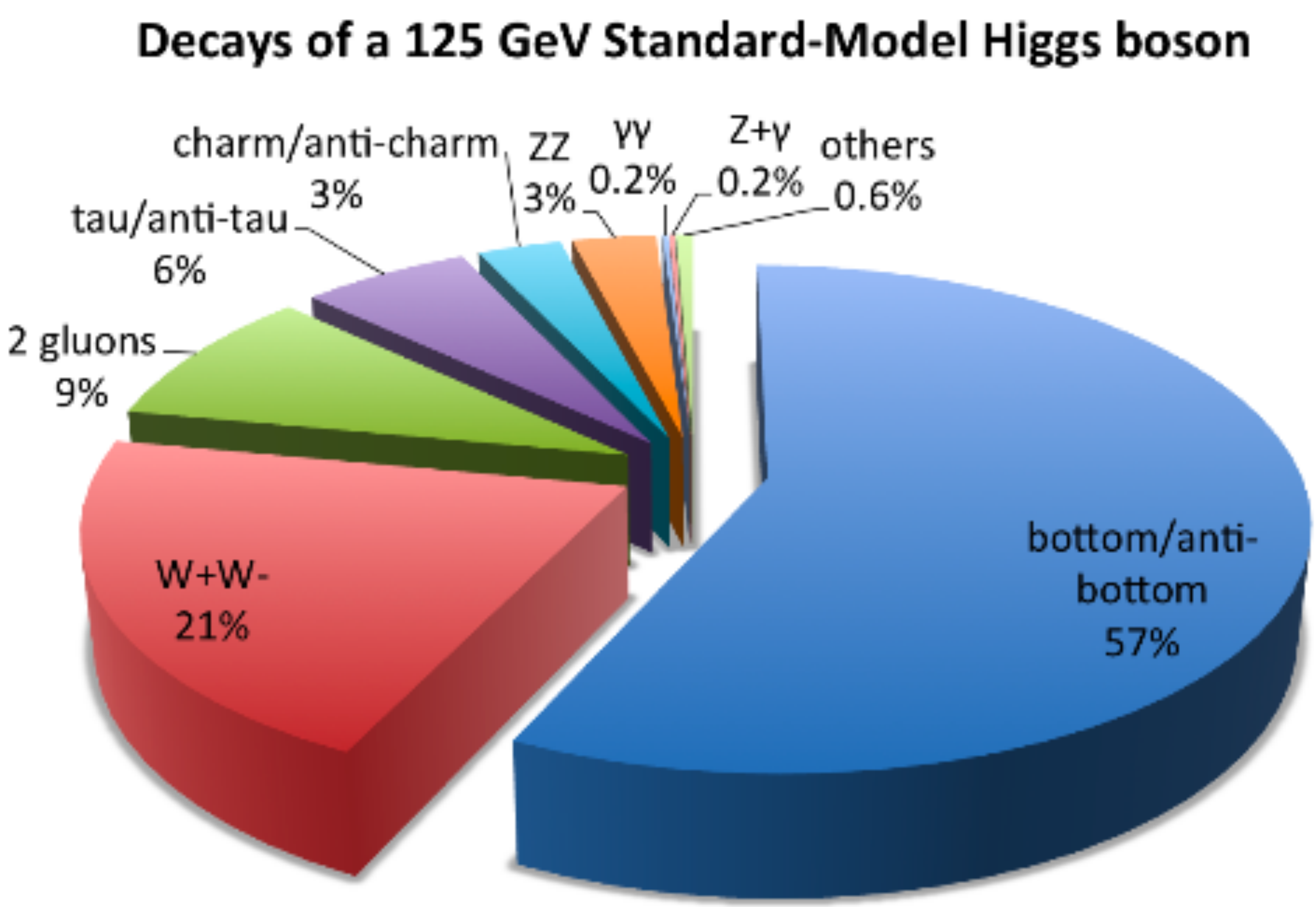
The **top quark mass**, 173 GeV, is l**arger than the weak boson masses**, 80 GeV and 91 GeV, therefore the Higgs coupling to tops is larger and the gluon-fusion process is more likely to happen

Higgs boson production



Higgs boson decays

Once produced, the Higgs boson **decays almost instantaneously**



The define a **branching ratio BR** as the likelihood that a particle **decays to a given final state**, normalised to all possible final states

Higgs boson decays

Once produced, the Higgs boson **decays almost instantaneously**

$$BR(h \to b\bar{b}) = 0.57$$

$$BR(h \to W^+W^-) = 0.21$$

$$BR(h \to \tau^+\tau^-) = 0.21$$

$$BR(h \to \gamma\gamma) = 0.003$$

$$BR(h \to ZZ) = 0.03$$

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Higgs boson decays

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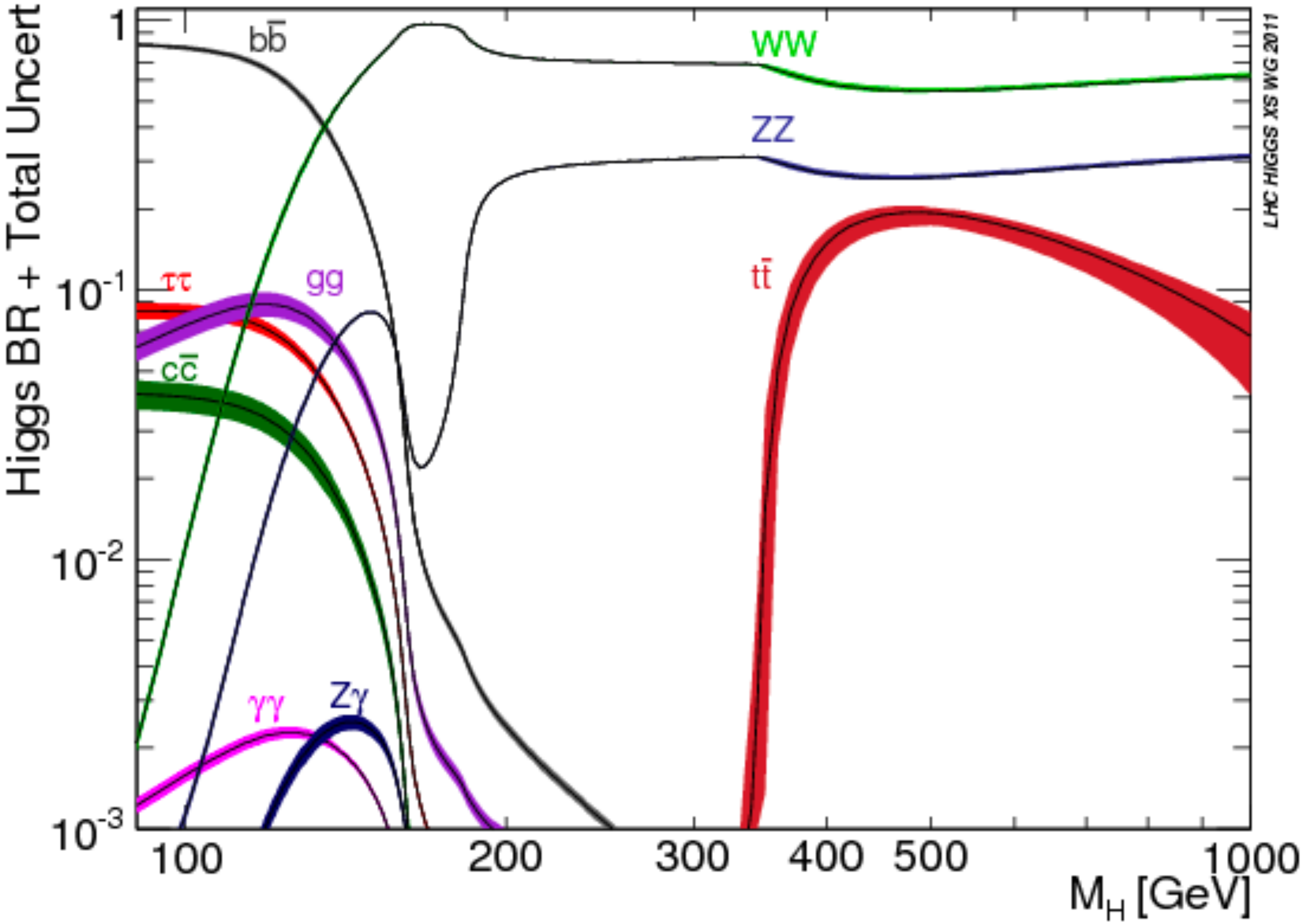
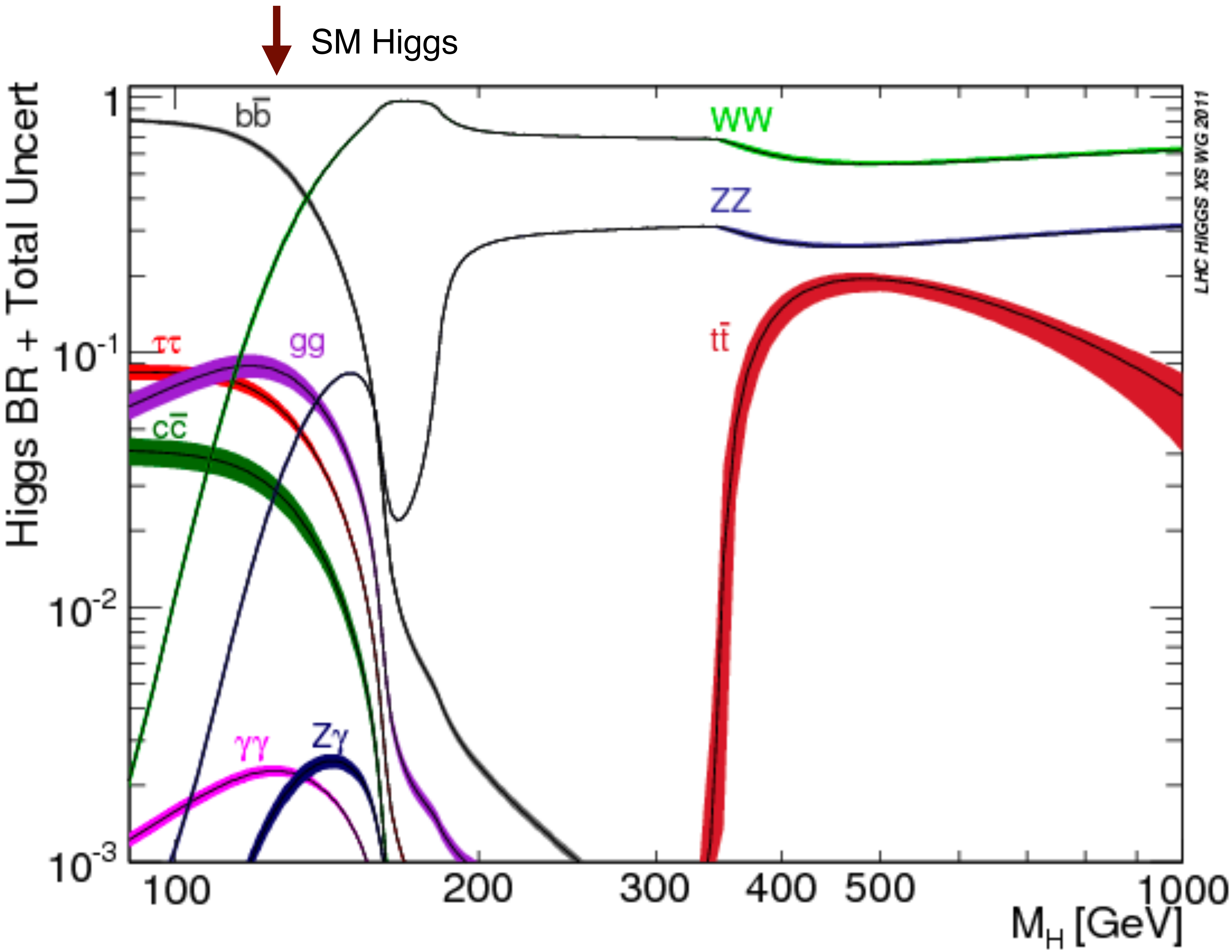
The Higgs tends to decay more into particles to which **it couples more strongly** (so with higher mass), but there is also a suppression factor if the decay products **have similar or bigger mass** than the Higgs

Higgs boson decays

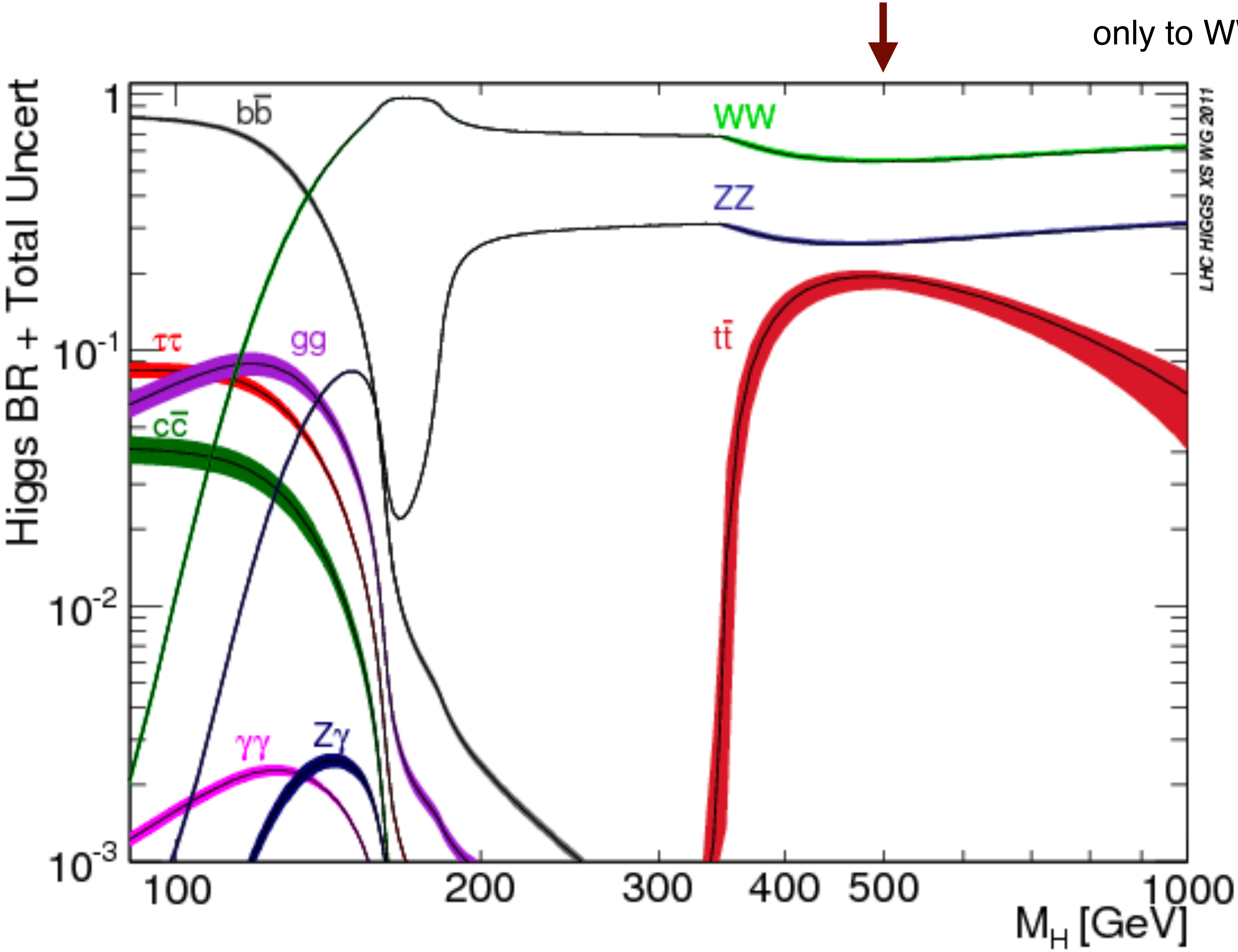


Higgs boson decays



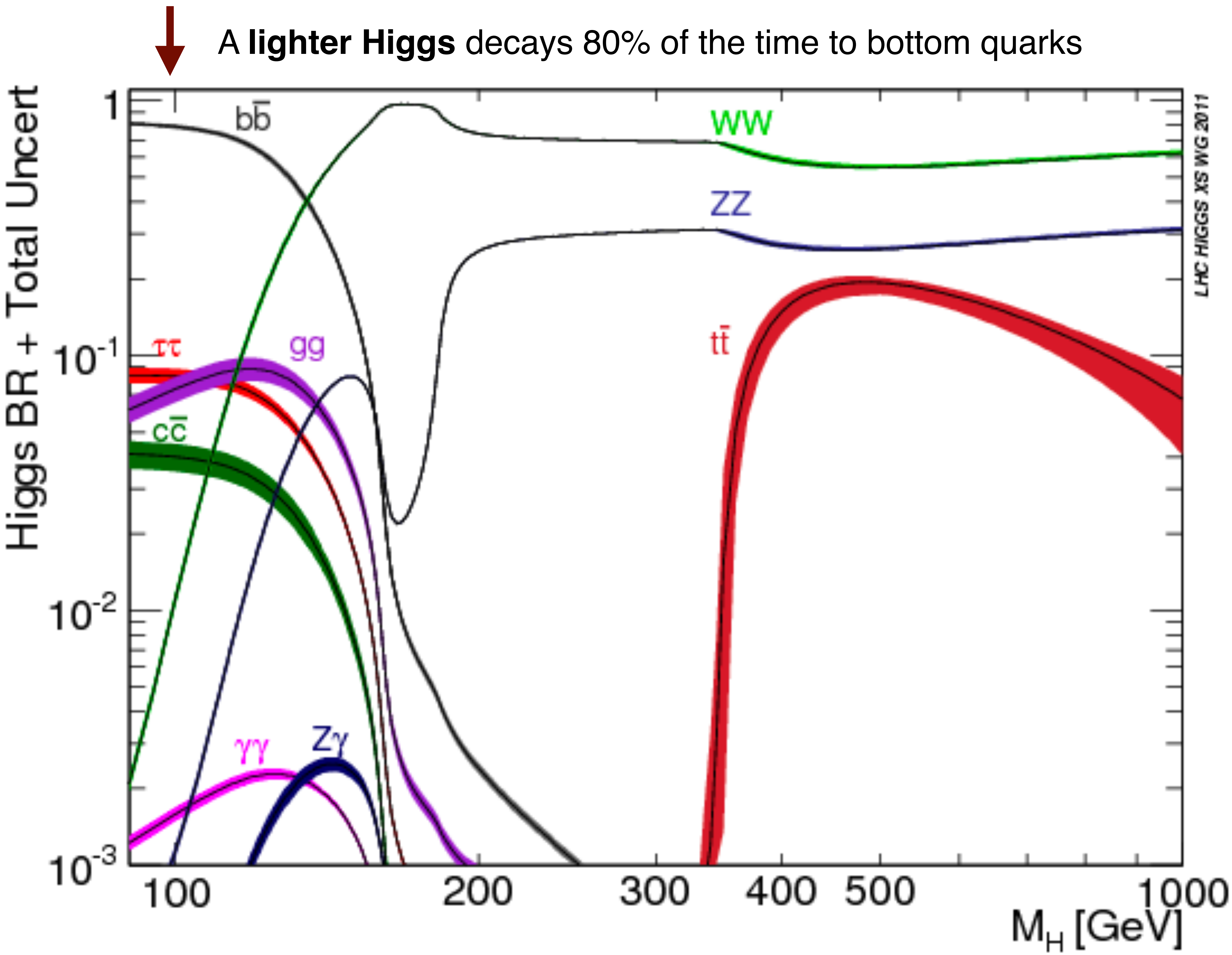
Higgs boson decays

A heavy Higgs decays only to WW, ZZ, tt



Higgs boson decays

A **lighter Higgs** decays 80% of the time to bottom quarks



From cross-sections to event rates

The **interaction cross-section σ** measures how likely a given scattering reaction is to take place. It is a kind of **effective collision area** and the units are cm^{-2}

The number of Higgs bosons produced at the LHC will be

$$N_h = \mathscr{L}_{\rm int} \times \sigma(pp \to h + X) \times BR(h \to Y)$$

where the **integrated luminosity** measures how many protons are available for scattering in a given period of time

For elementary particles, the **barn** is a more suitable unit for cross-sections

$$1\,\mathrm{b} = 10^{-24}\,\mathrm{cm}^2$$

$$1\,\mathrm{pb} = 10^{-36}\,\mathrm{cm}^2$$ (picobarn)

$$1\,\mathrm{fb} = 10^{-39}\,\mathrm{cm}^2$$ (femtobarn)

Counting Higgs bosons

exercise

Up to 2018, the LHC has accumulated ***L = 150 fb*** of luminosity

Compute the number of Higgs bosons produced in *i) gluon fusion* and *ii) associated production with a W,* and in each case in the *i) diphoton* and *ii) bottom-antibottom* final states

$$\sigma(pp \to gg \to h) = 50\,\mathrm{pb} \qquad BR(h \to b\bar{b}) = 0.57$$

$$\sigma(pp \to hW) = 1.4\,\mathrm{pb} \qquad BR(h \to \gamma\gamma) = 0.003$$

Counting Higgs bosons

exercise

Gluon-fusion production + bottom-antibottom decay

$$N_h = \mathscr{L}_{\rm int} \times \sigma(pp \to h + X) \times BR(h \to Y)$$

$$N_h = 150\,\mathrm{fb}^{-1} \times 50\,\mathrm{pb} \times 0.57 = 4.3 \times 10^6$$

Counting Higgs bosons

exercise

Gluon-fusion production + bottom-antibottom decay

$$N_h = \mathscr{L}_{\rm int} \times \sigma(pp \to h + X) \times BR(h \to Y)$$

$$N_h = 150\,{\rm fb}^{-1} \times 50\,{\rm pb} \times 0.57 = 4.3 \times 10^6$$

Gluon-fusion production + diphoton decay

$$N_h = \mathscr{L}_{\rm int} \times \sigma(pp \to h + X) \times BR(h \to Y)$$

$$N_h = 150\,{\rm fb}^{-1} \times 50\,{\rm pb} \times 0.003 = 2.3 \times 10^4$$

Counting Higgs bosons

exercise

Associated production with W boson + bottom-antibottom decay

$$N_h = \mathscr{L}_{\rm int} \times \sigma(pp \to h + X) \times BR(h \to Y)$$

$$N_h = 150\,{\rm fb}^{-1} \times 1.4\,{\rm pb} \times 0.57 = 1.2 \times 10^5$$

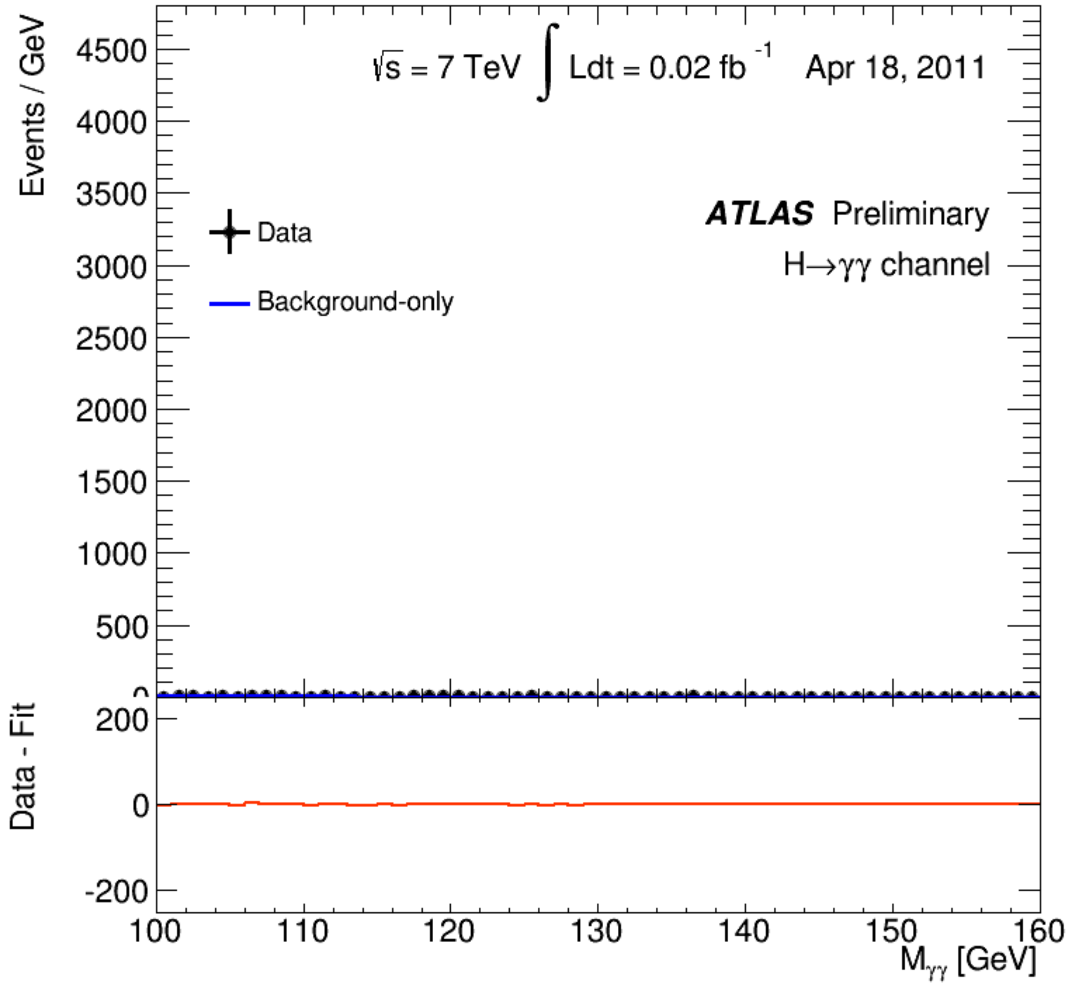
Associated production with W boson + diphoton decay

$$N_h = \mathscr{L}_{\rm int} \times \sigma(pp \to h + X) \times BR(h \to Y)$$

$$N_h = 150\,{\rm fb}^{-1} \times 1.4\,{\rm pb} \times 0.003 = 630$$

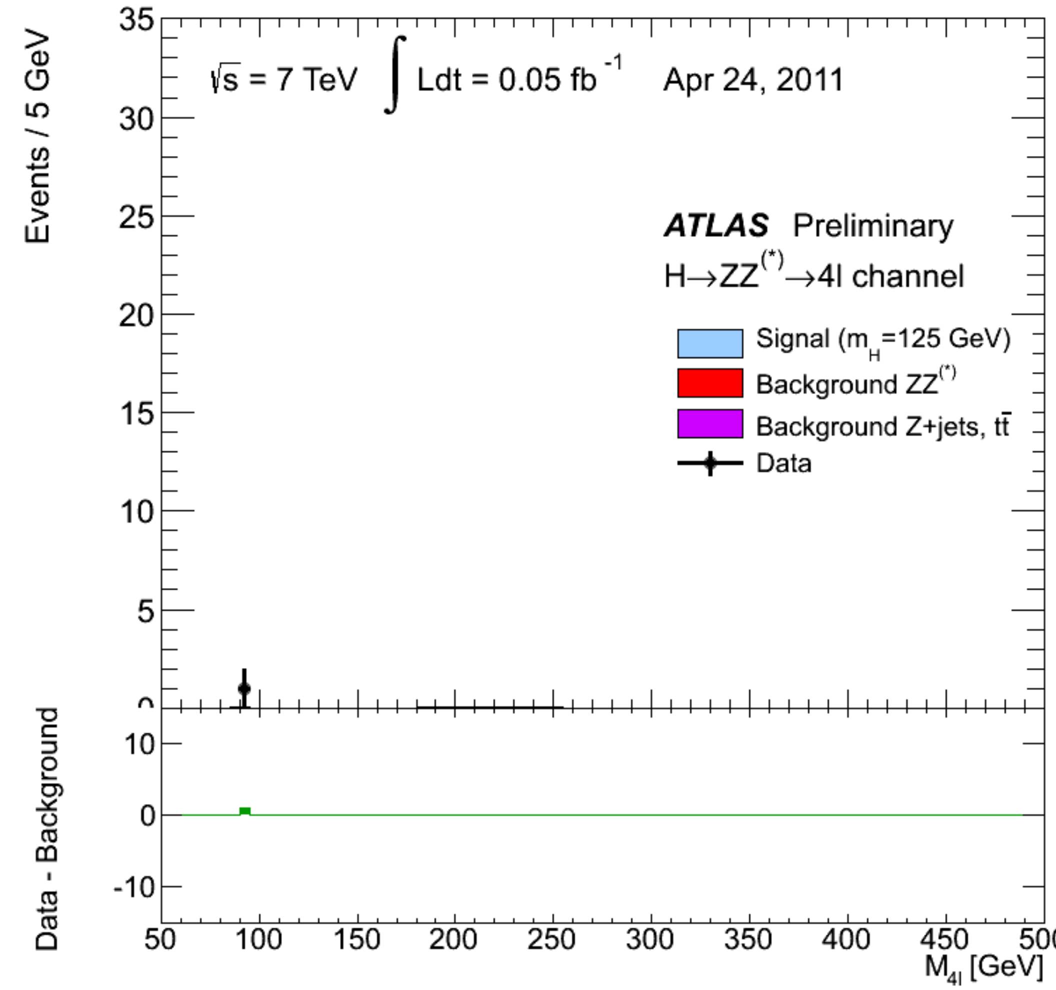
Discovery?

Higgs Decays into Two Photons

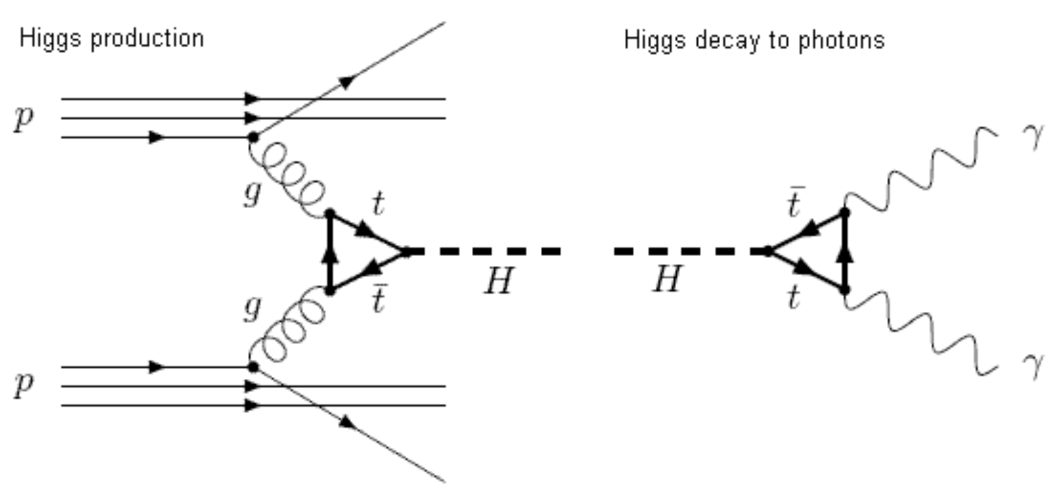


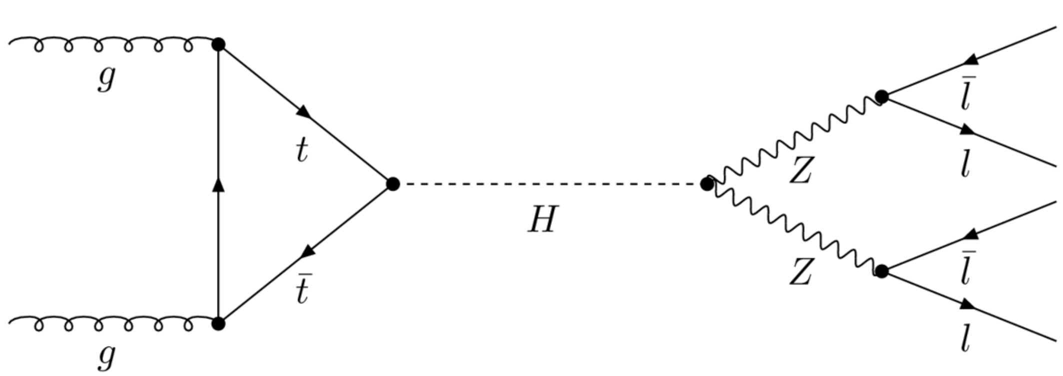
Mass of Photon Pair

Higgs Decays into Four Leptons



Invariant Mass of Four Leptons





Discovery?

A measurement of a production cross-section based on ***N_h* events** will have associated a **statistical uncertainty** given by

$$\frac{\delta_{\rm stat}\sigma}{\sigma} = \frac{1}{\sqrt{N_h}}$$

For example, for Higgs+*W* production in the diphoton final state:

$$N_h = 150\,{\rm fb}^{-1} \times 1.4\,{\rm pb} \times 0.003 = 630$$

$$\frac{\delta_{\rm stat}\sigma}{\sigma} = 0.04$$

has associated a **statistical uncertainty** of around 4%

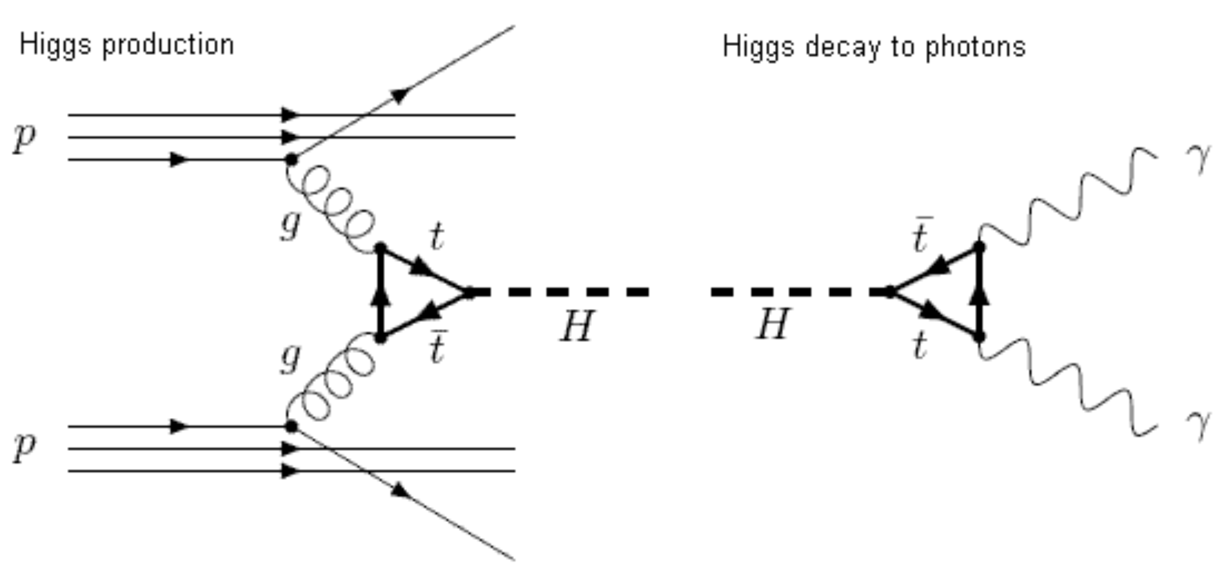
Discovery?

In particle physics, we claim to have **evidence** of a new phenomenon (particle, interaction, …) when its **statistical significance** reaches **3-sigma**

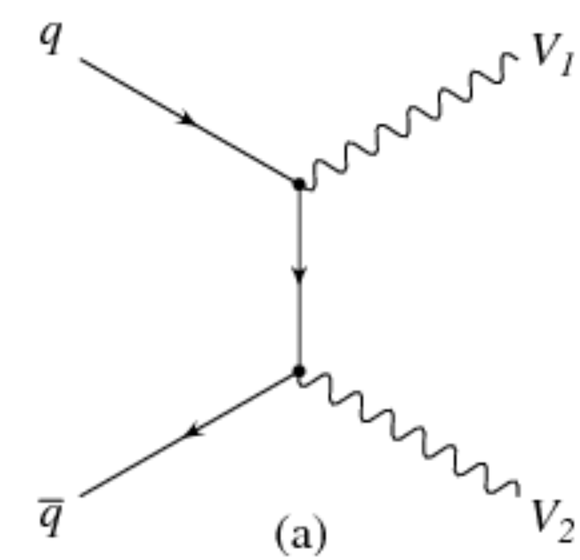
$$\frac{N_S}{\sqrt{N_B}} \geq 3$$

where $\boldsymbol{N_s}$ is the number of signal events and $\boldsymbol{N_s}$ the number of background events

Signal



Background



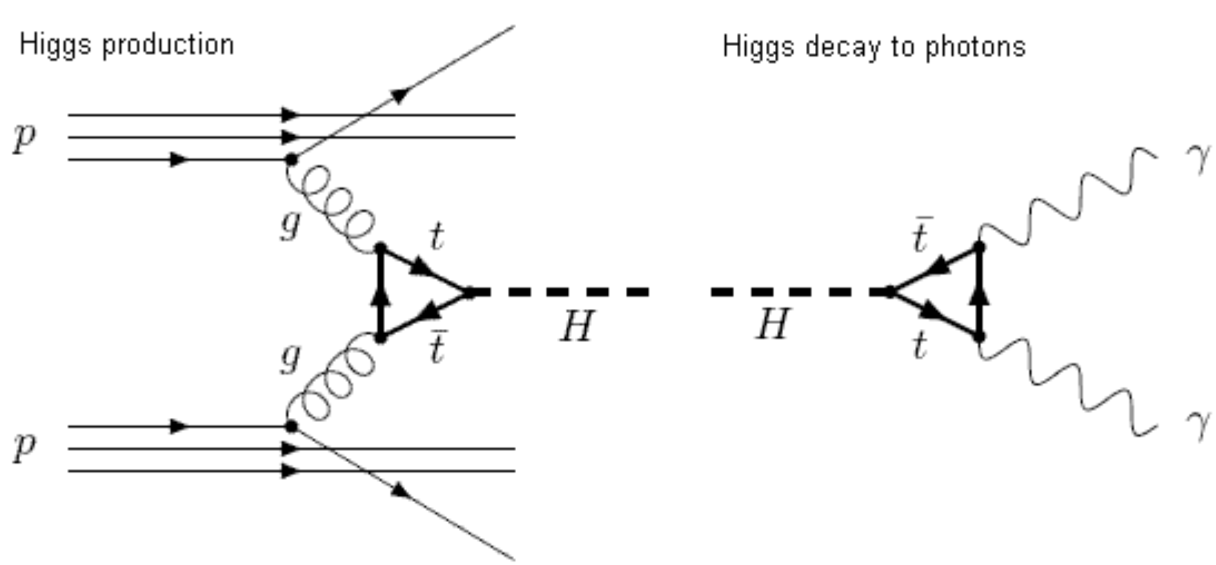
Discovery?

In particle physics, we claim to have **discovery** of a new phenomenon (particle, interaction, …) when its **statistical significance** reaches **5-sigma**

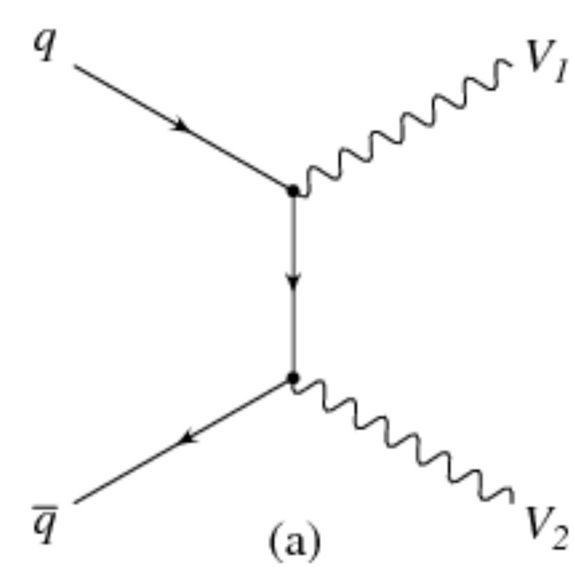
$$\frac{N_S}{\sqrt{N_B}} \geq 5$$

where $\boldsymbol{N_s}$ is the number of signal events and $\boldsymbol{N_s}$ the number of background events

Signal



Background



Statistical significance

Why the statistical significance of a **signal process** is defined this way?

$$N_S$$

average number of signal events

$$N_B$$

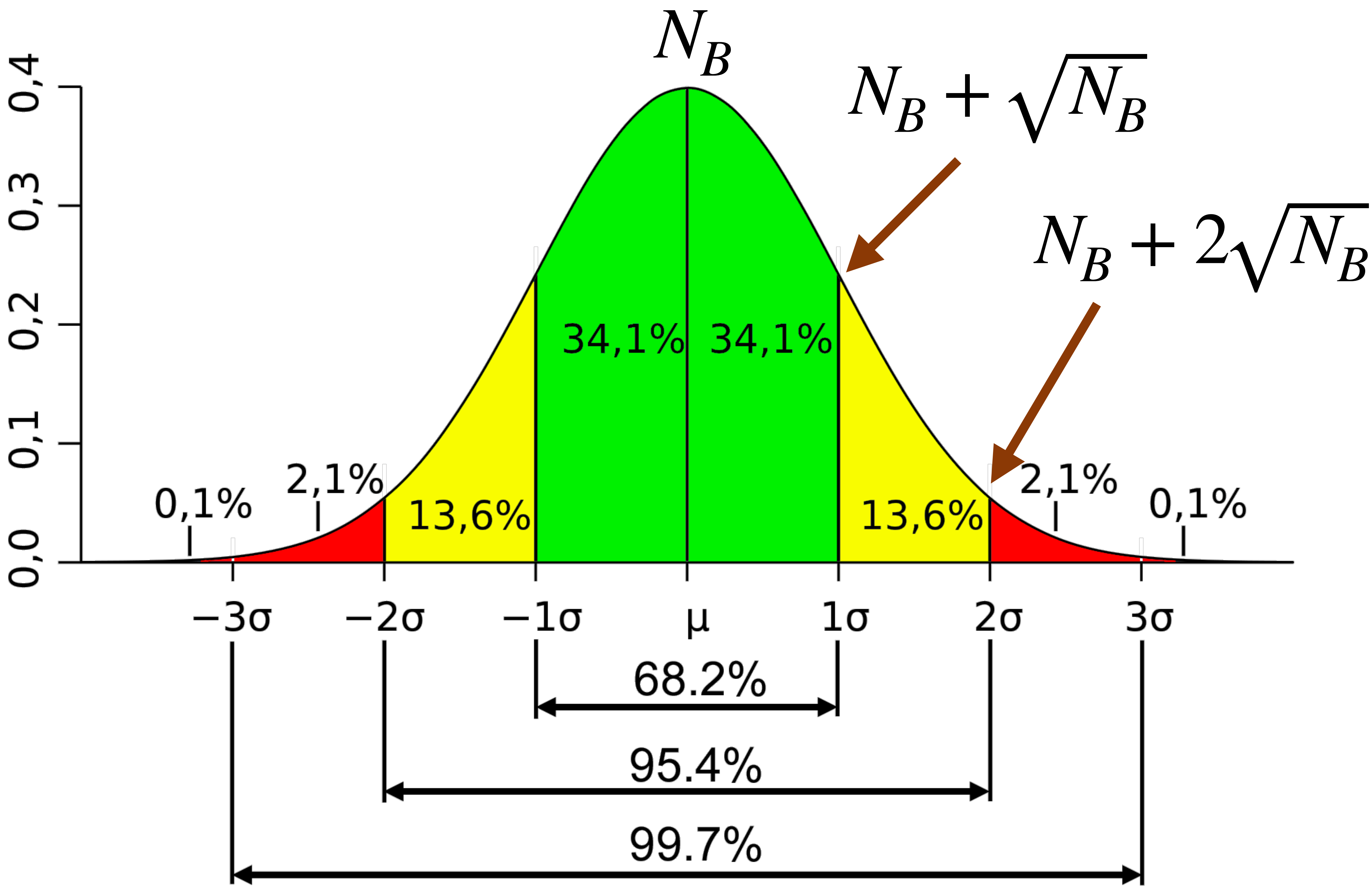
average number of background events

$$N_B + \sqrt{N_B}$$

upper statistical fluctuation in the number of background events, with probability 16%

the number of background events observed is **Gaussianly distributed** and fluctuates around the mean N_B with **variance** $N_B^{1/2}$

Statistical significance



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average number of background events

$$N_B + \sqrt{N_B}$$

upper statistical fluctuation in the number of background events, with probability **16%**

$$N_B + 2\sqrt{N_B}$$

upper statistical fluctuation in the number of background events, with probability **2.5%**

$$N_B + 3\sqrt{N_B}$$

upper statistical fluctuation in the number of background events, with probability **0.1%**

Statistical significance

In particle physics, we claim to have **discovery** of a new phenomenon (particle, interaction, …) when its **statistical significance** reaches **5-sigma**

$$\frac{N_S}{\sqrt{N_B}} \geq 5$$

where $\boldsymbol{N_s}$ is the number of signal events and $\boldsymbol{N_s}$ the number of background events

The **"5-sigma" criterion** requires that the number of signal events is larger than the statistical fluctuations of the number of background events that can happen **once every 3.5 million times!**

Beyond the Standard Model

Open questions in particle physics

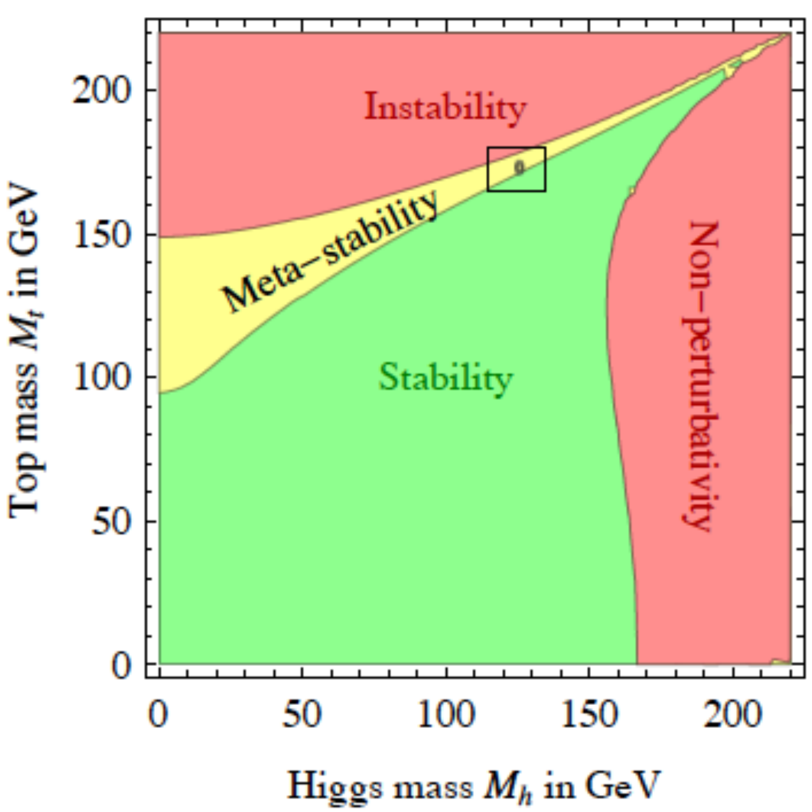
The Higgs boson

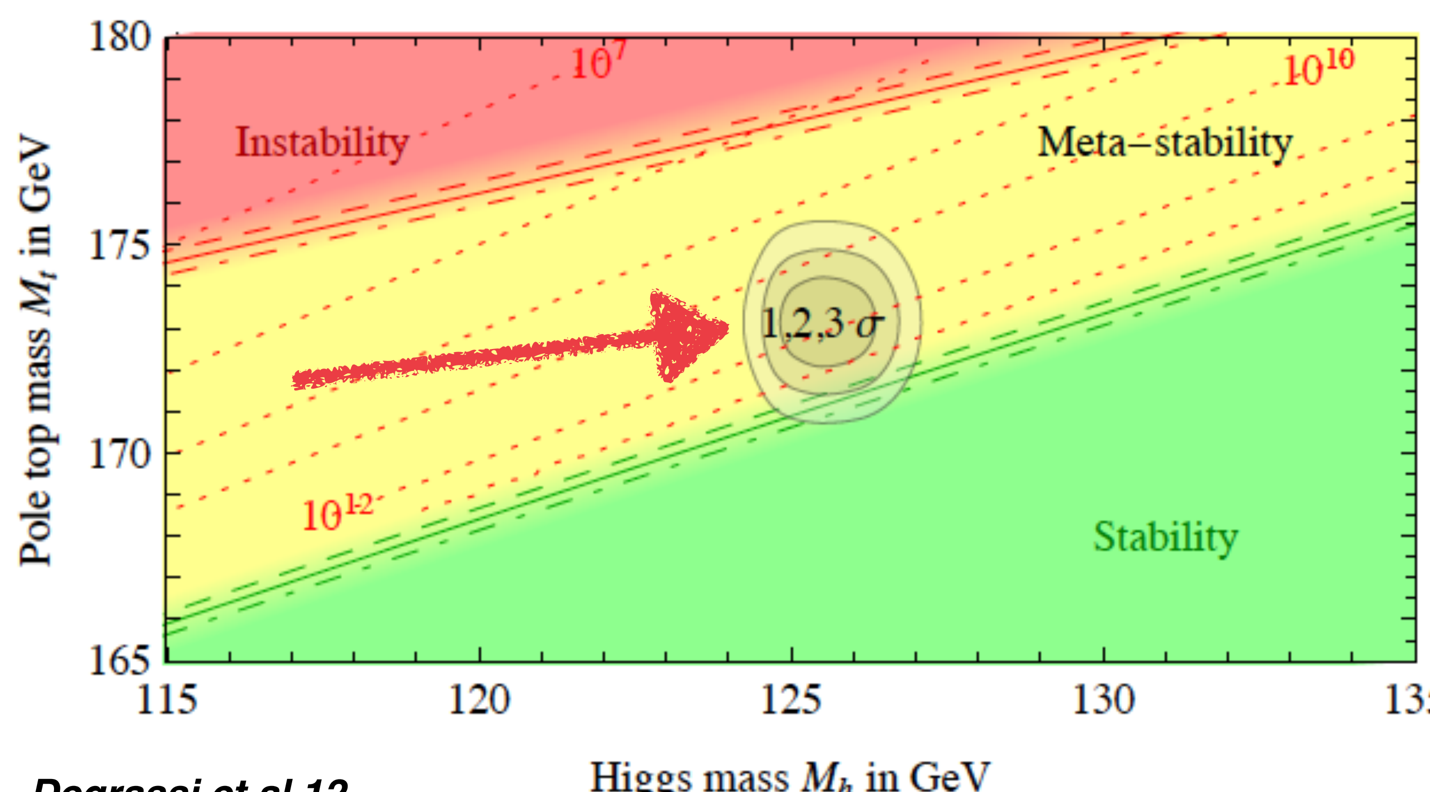
- Huge gap between **weak** and **Plank scales?**
- **Compositeness**? Non-minimal Higgs sector?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?

- 10^{19} **GeV** (Planck scale)

What defines the value of the weak scale? Why so different from Planck scale?

- **125 GeV** (Higgs mass)
- 1 GeV (Proton mass)





Degrassi et al 12

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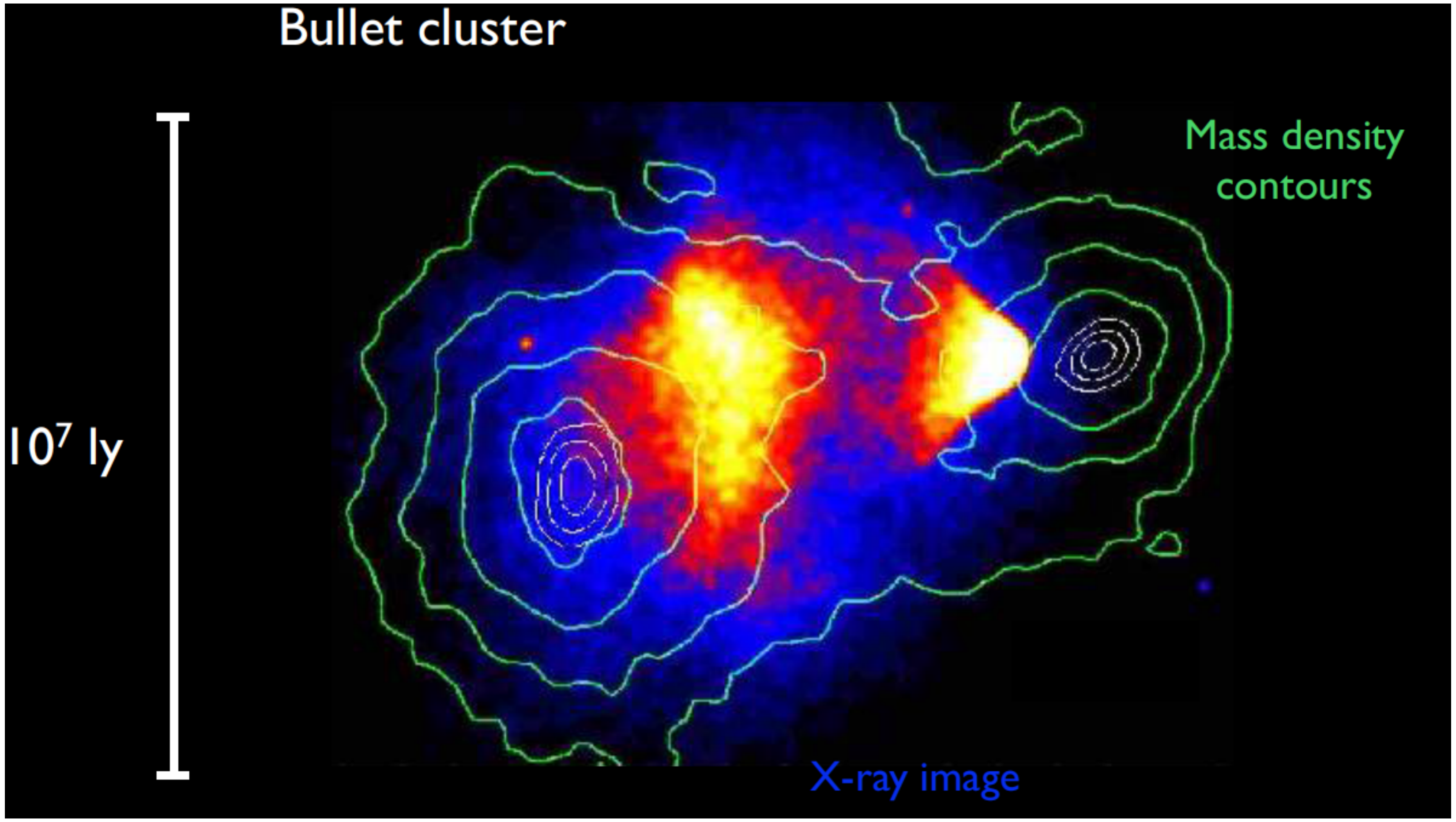
Dark matter

- **Weakly interacting massive particles**? Neutrinos? Ultralight particles (axions)?
- **Interactions** with SM particles? Self-interactions?
- **Structure** of the Dark Sector?



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Quarks and leptons

- Why **3 families?** Origin of **masses, mixings**?
- Origin of **Matter-Antimatter asymmetry?**
- Are **neutrinos Majorana or Dirac**? CP violation in the lepton sector?

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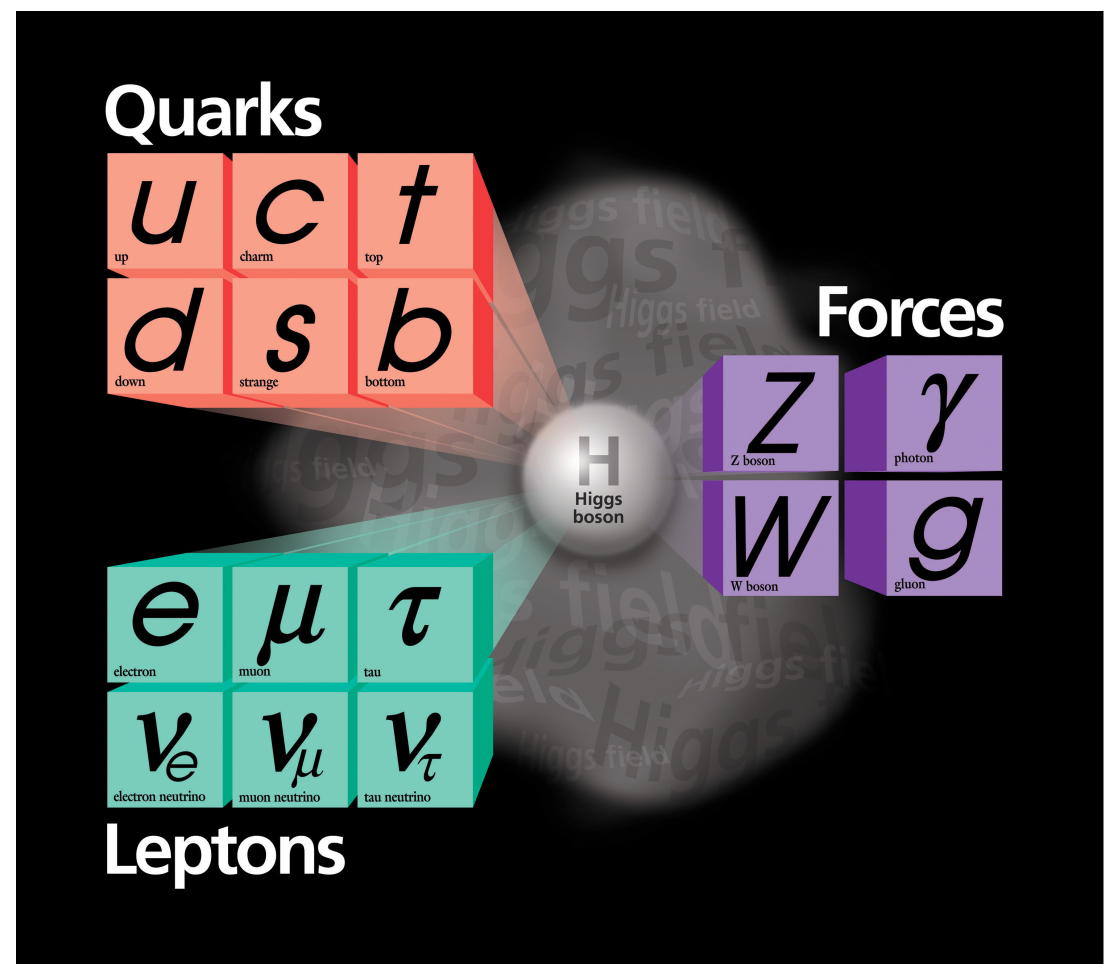
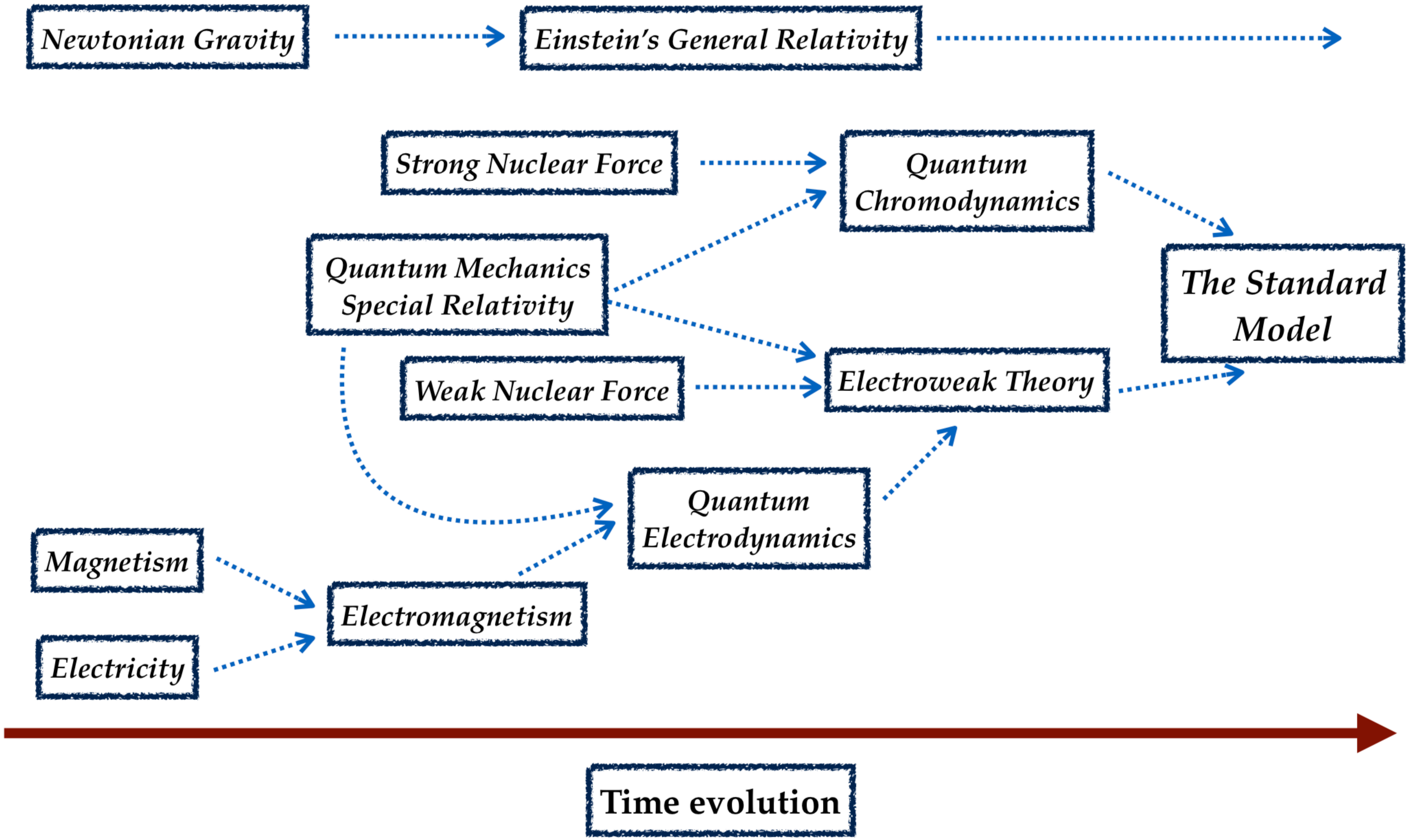
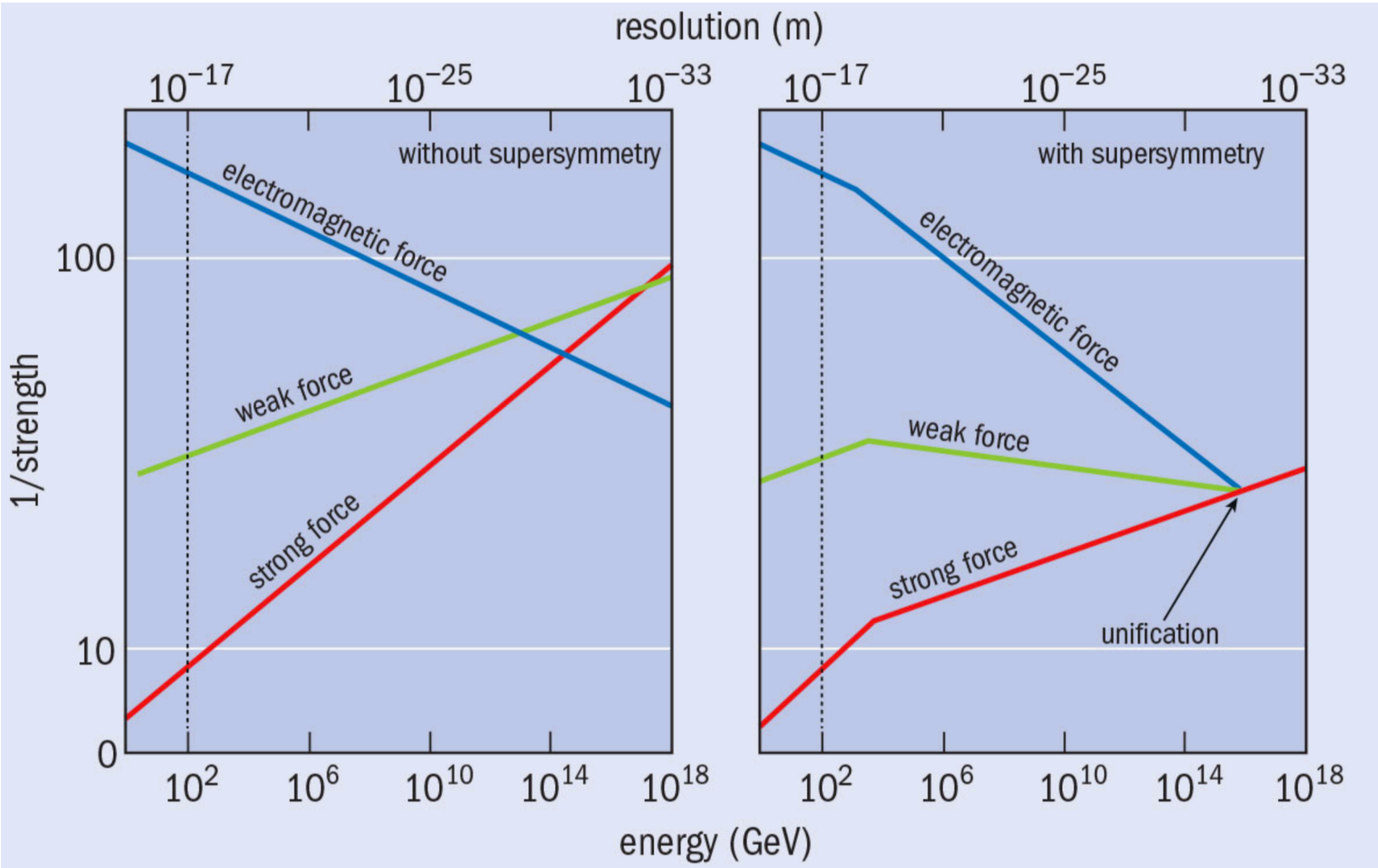


Beyond the Standard Model



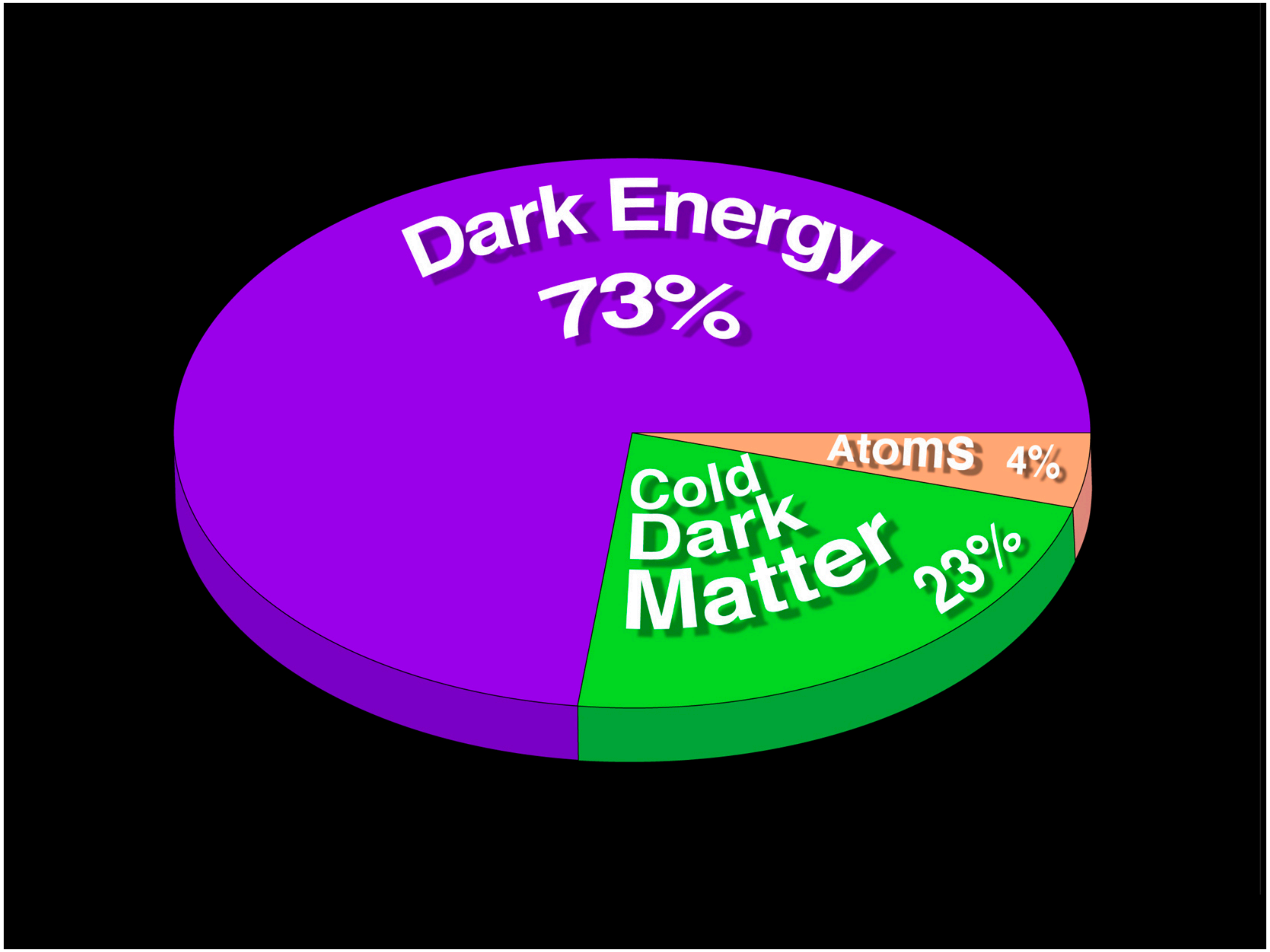
Unification of forces?

Some theories predict that strong, weak, and electromagnetic forces **unify at high energies**



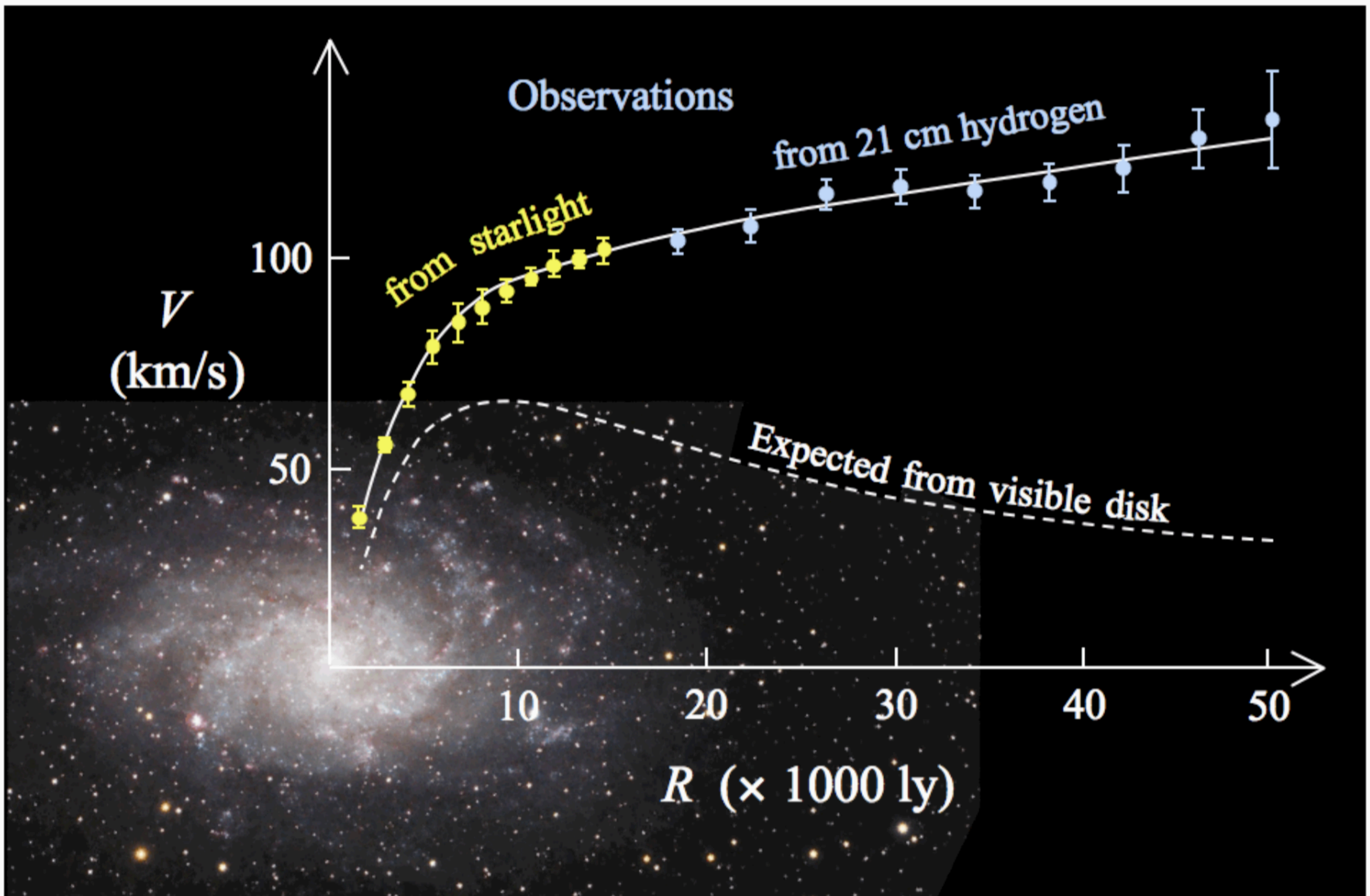
The dark universe

Most of the energy/matter in the **Universe is dark** (does not emit radiation): can only obtain indirect evidence for their existence. ``*Normal" matter* is **only 4% of the total energy budget**!

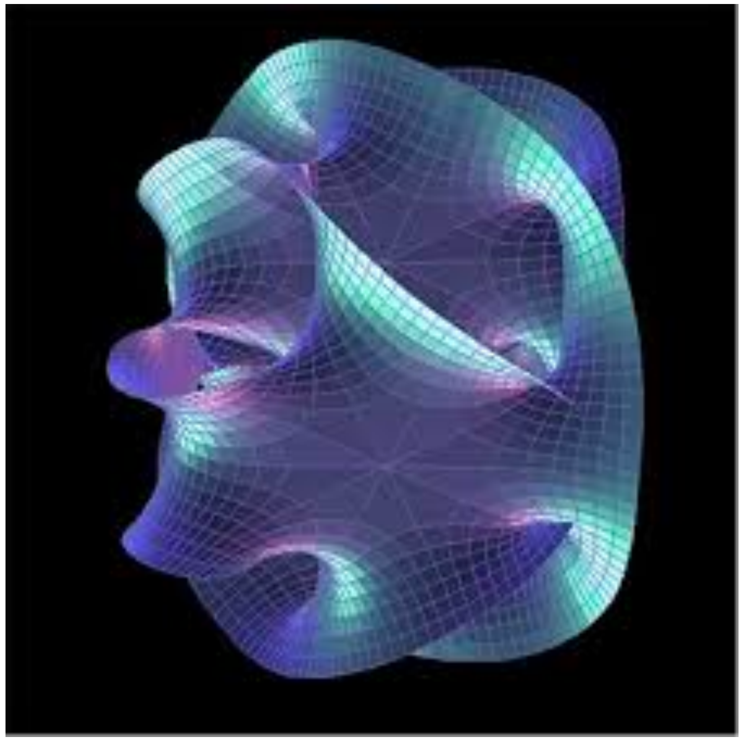


The dark universe

Indirect evidence for dark matter provided by the **galactic rotation curves** from which one can infer that the **total galactic mass** is much bigger than the visible mass

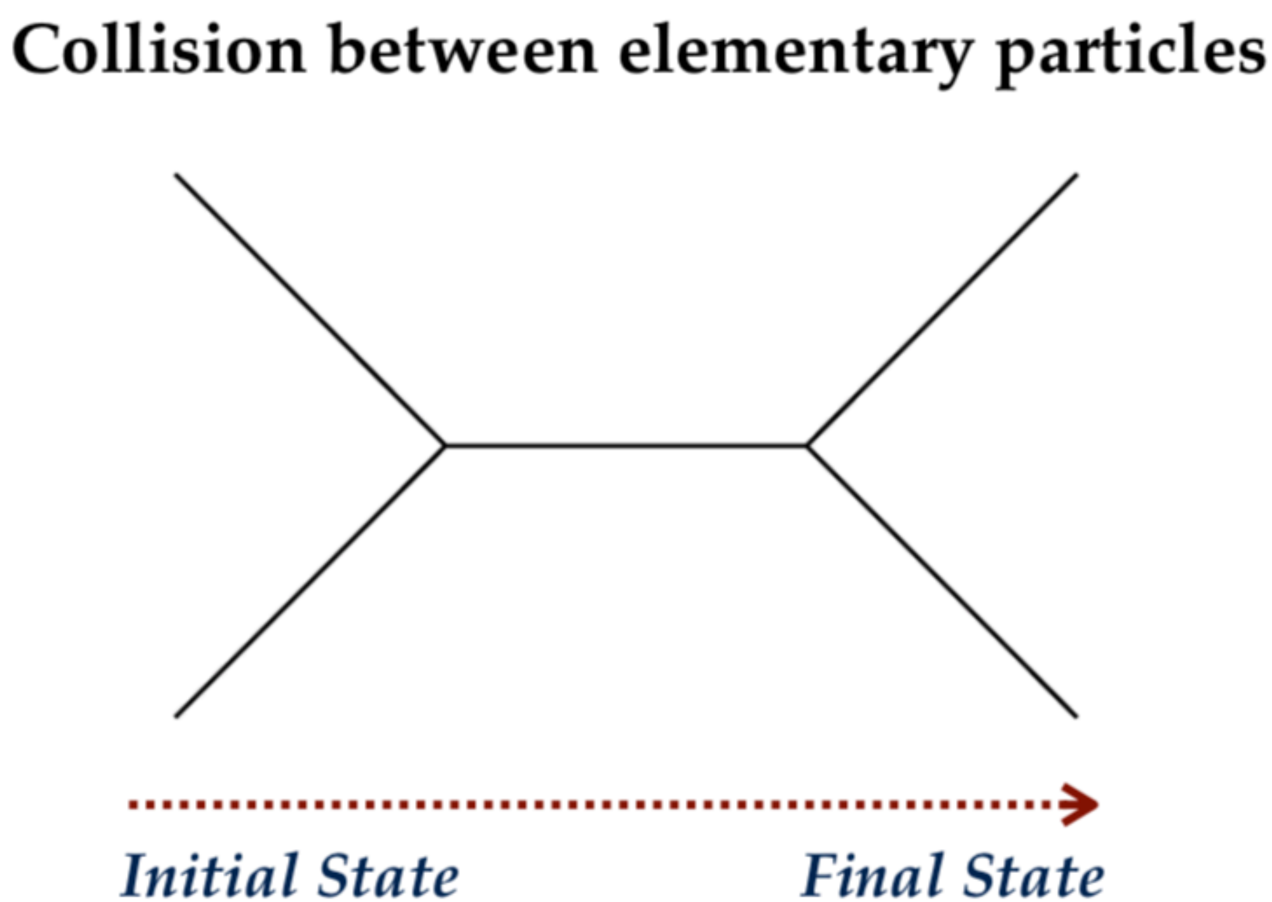


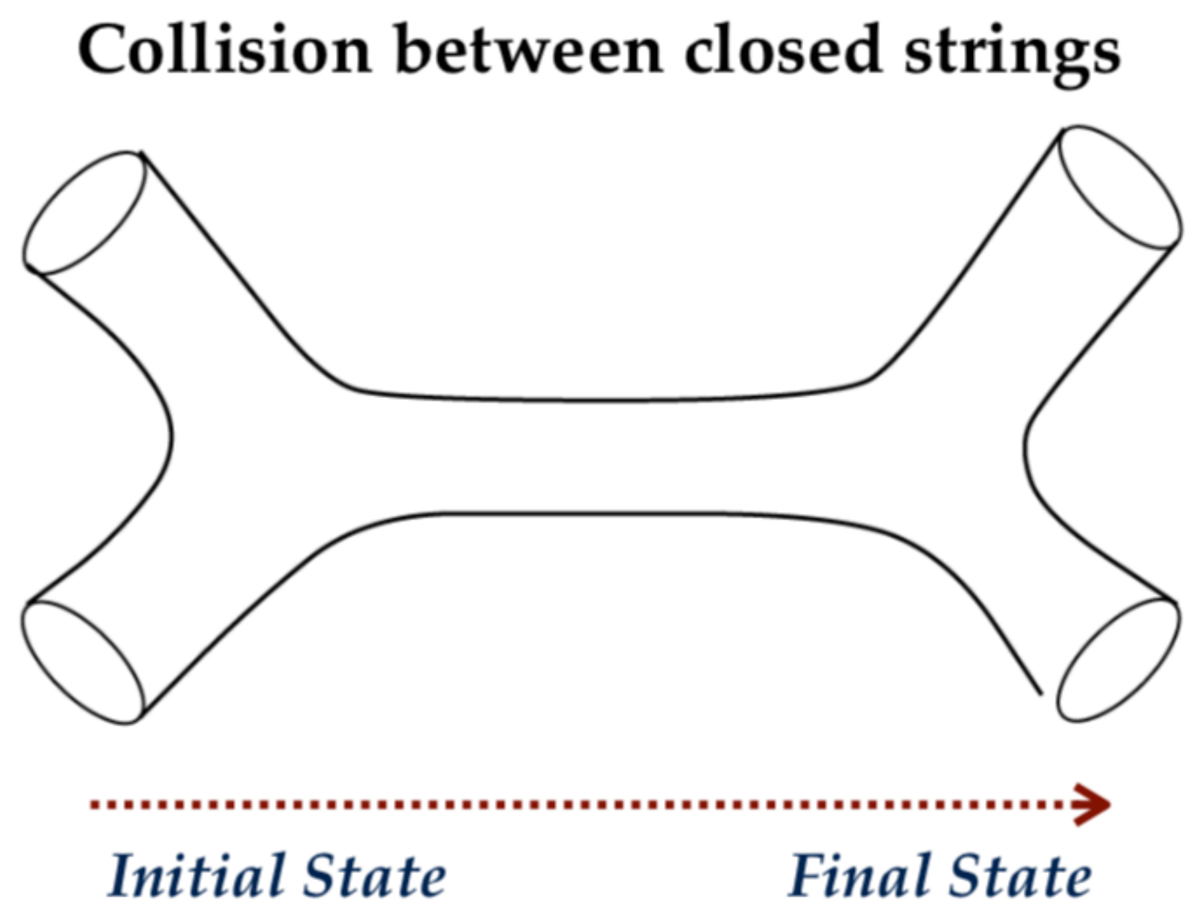
Quantum gravity



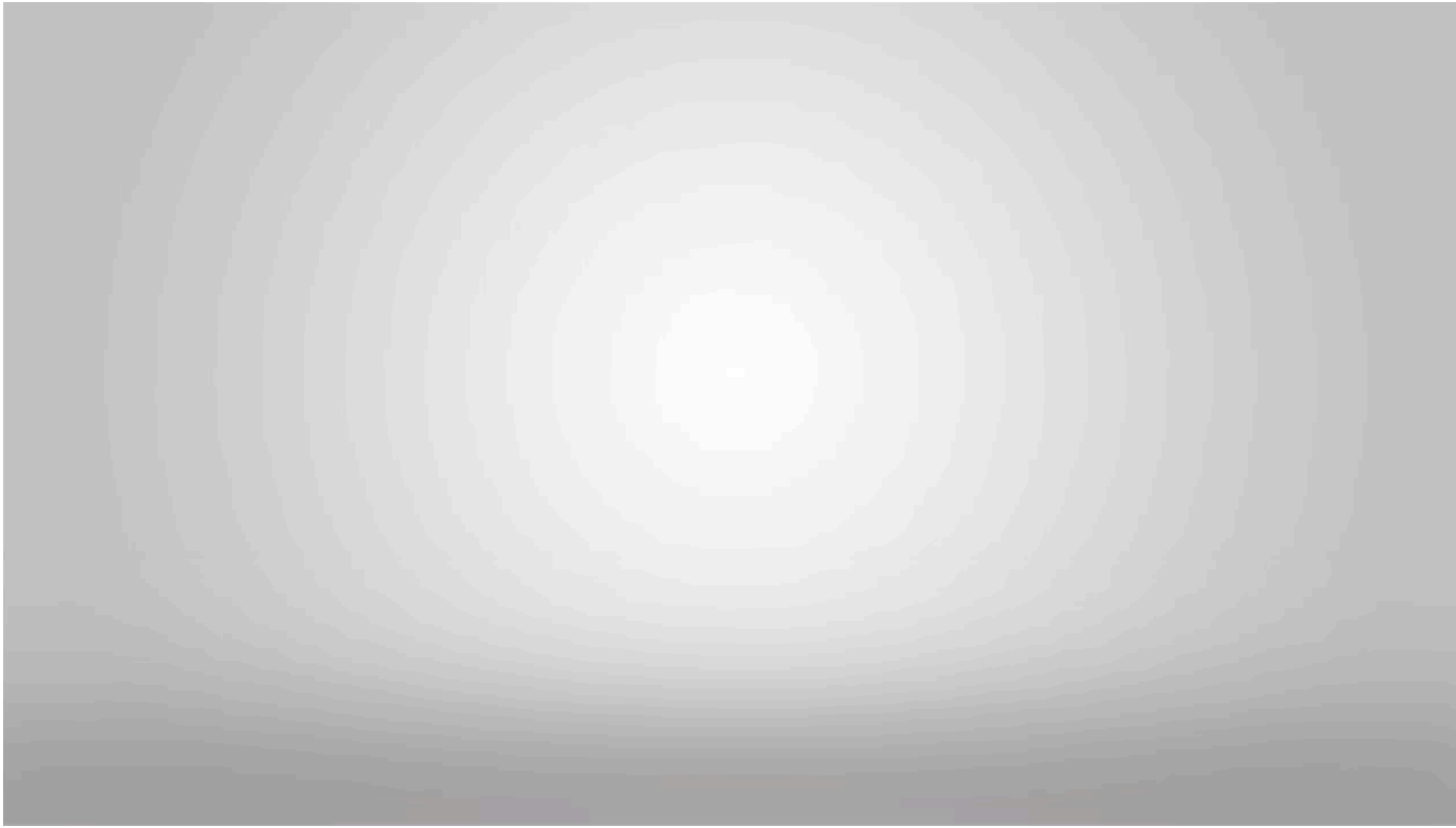
Applying **quantum mechanics** to **Einstein's general relativity** returns physically inconsistent results

Many theories attempt to quantise gravity, such as **string theory,** so far unsuccessfully



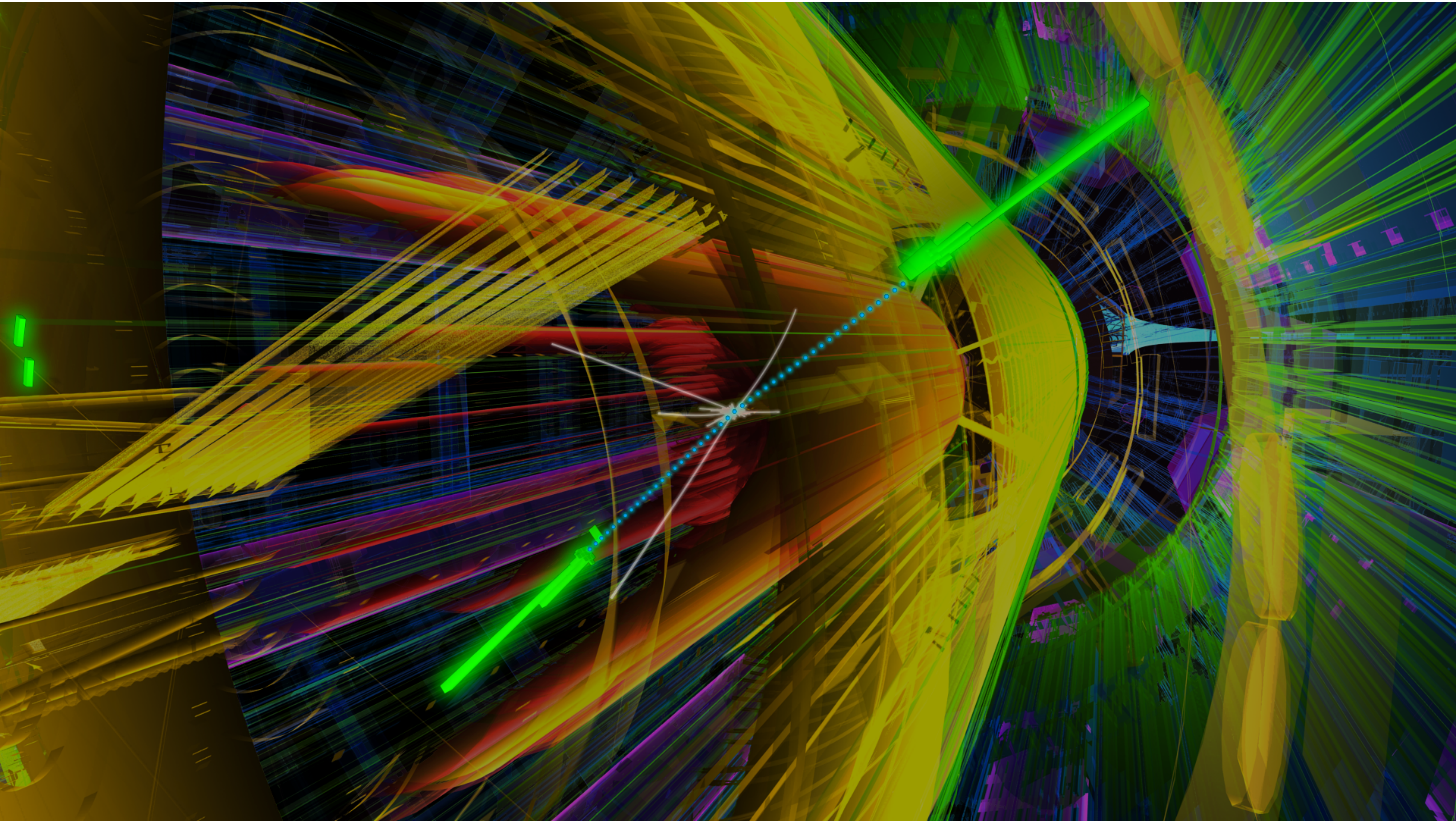


String theory in a nutshell



https://www.youtube.com/watch?v=iTTa9YcTe1k

These are exciting times for particle physics!



Stay tuned for new discoveries!