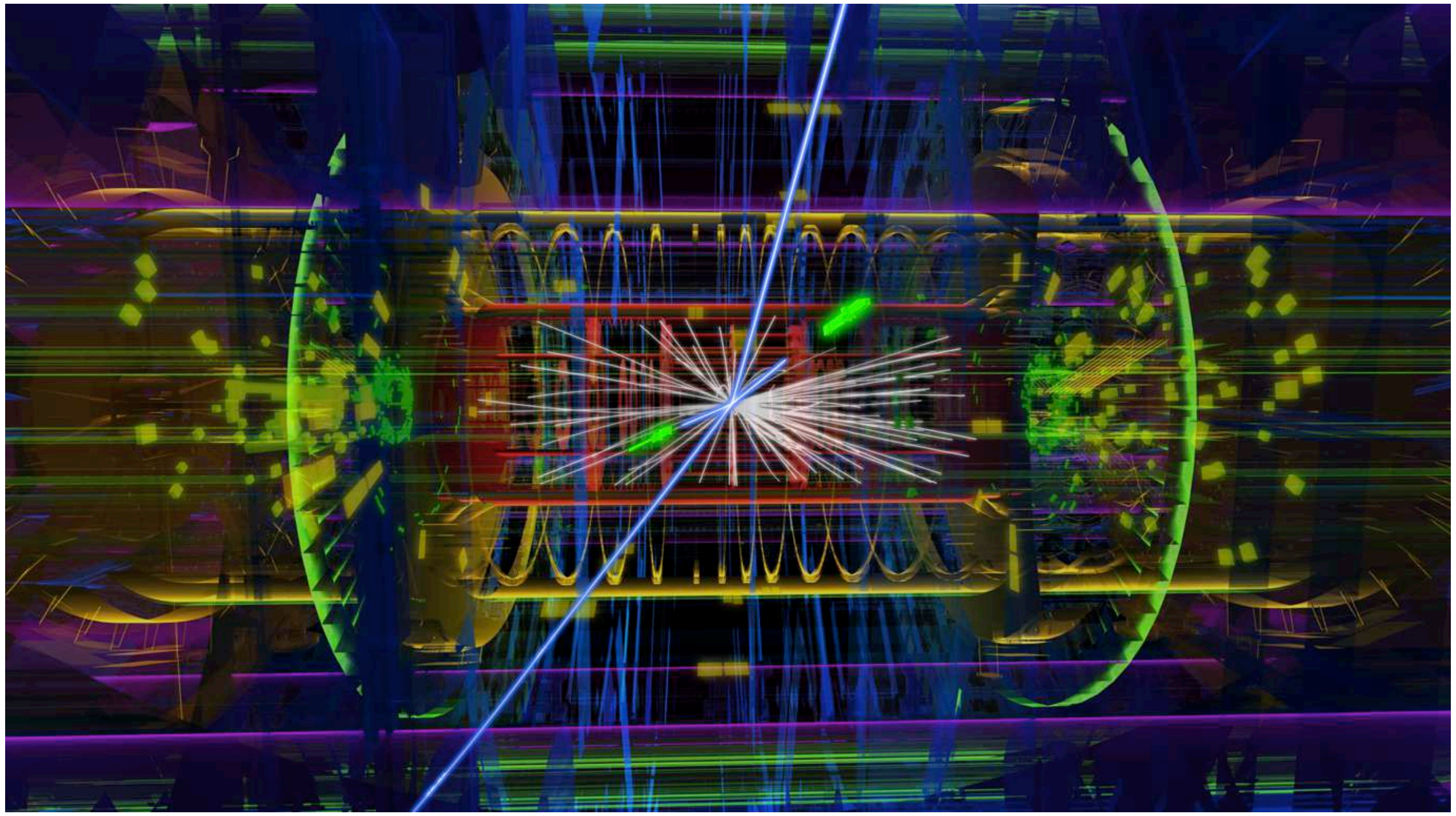
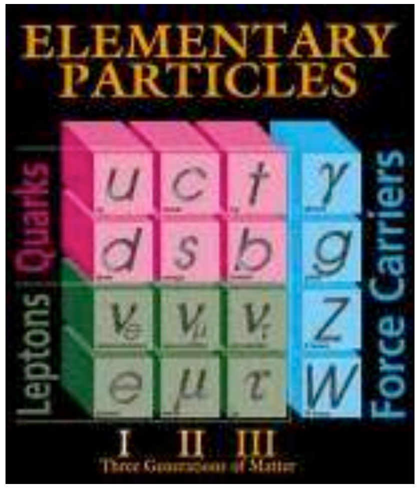
Precision Studies of the Higgs



Giulia Zanderighi
CERN & University of Oxford

Saturday Morning Lectures
Oxford, 7th February 2015

Status of particle physics



- Standard Model (SM): successful theory of strong (QCD), weak and electromagnetic (EW) elementary interactions

- Yet, no fundamental theory:
  theoretical issues + unexplained phenomena (e.g. gravity, matter anti-matter asymmetry, dark matter, dark energy, ...)

- The LHC is designed to

  ☑ unravel EW symmetry breaking (test origin of mass through the Higgs mechanism)

  ☐ find physics beyond the SM (still to be done)

BUT

Do we know what this really means?

What is the problem with particles having a mass?

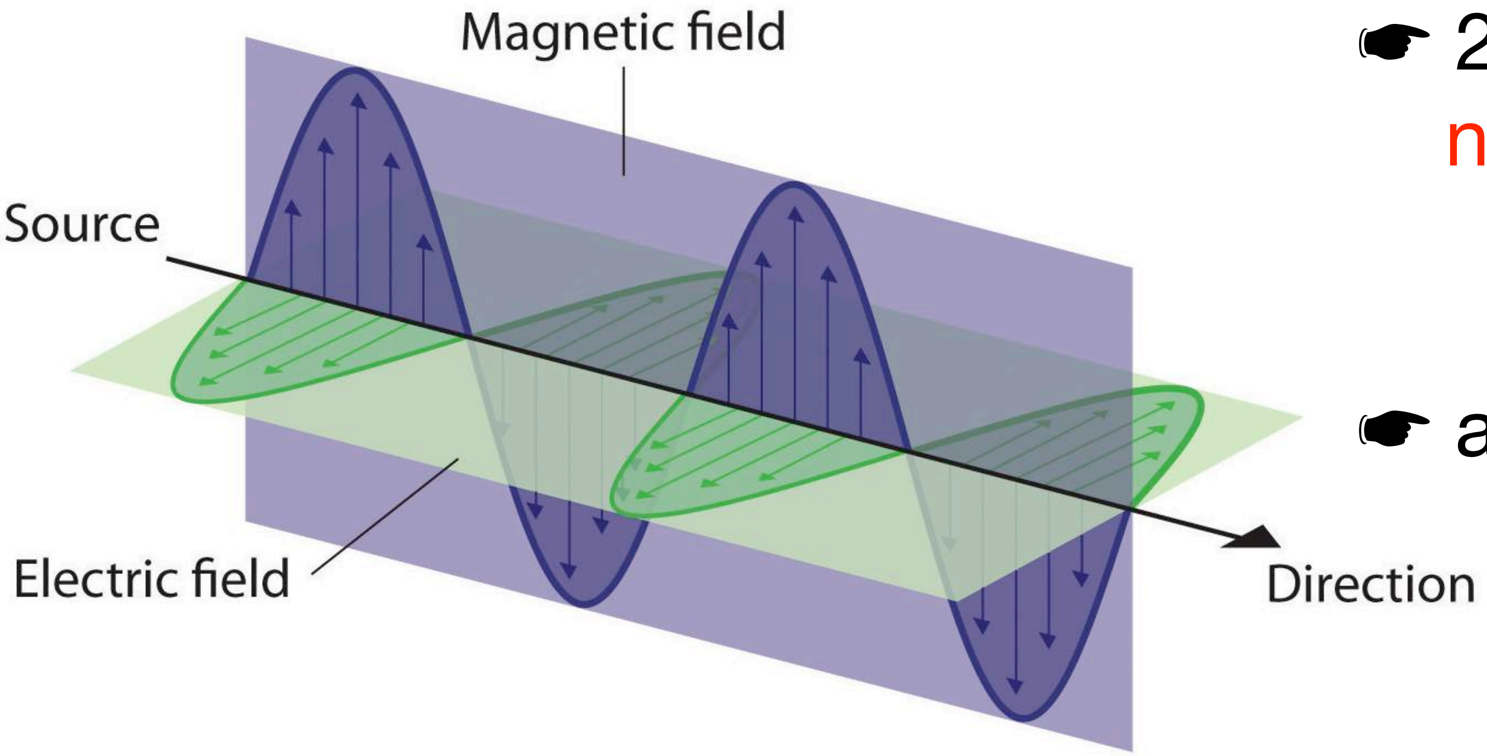
What is the Higgs mechanism & how does it solve the problem?

Why should there be New Physics at the TeV scale?

Step back

Duality in quantum field theory: wave ⇔ particle

electromagnetic wave ⇔ photon

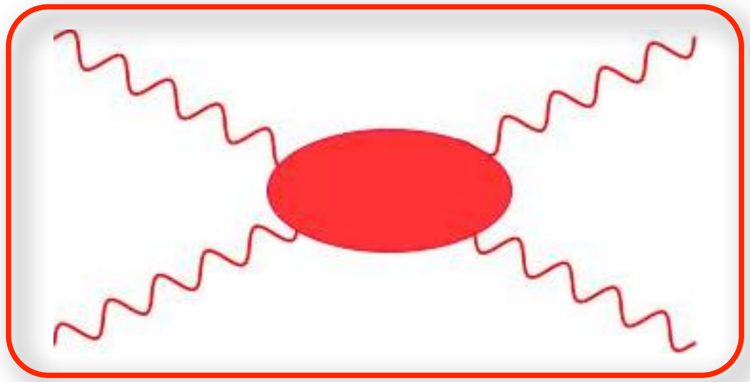


☛ 2 transverse polarisations,
no longitudinal polarisation

☛ an empirical but crucial fact

Gauge symmetry

If a 3rd longitudinal polarization existed



⇒ scattering probability grows with energy

Violation of unitarity (probability > 1) ⇒ field theory breaks down

Gauge symmetry

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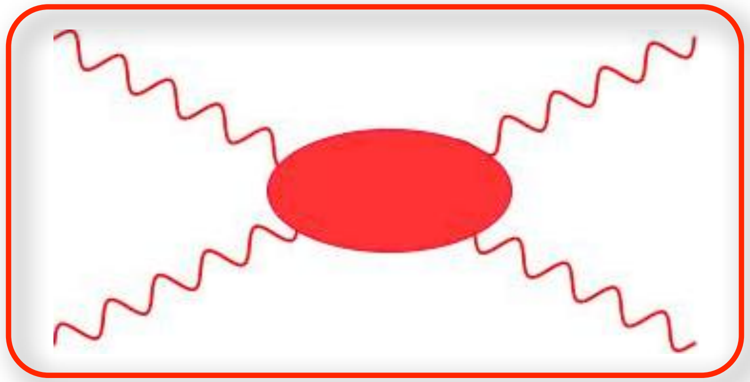
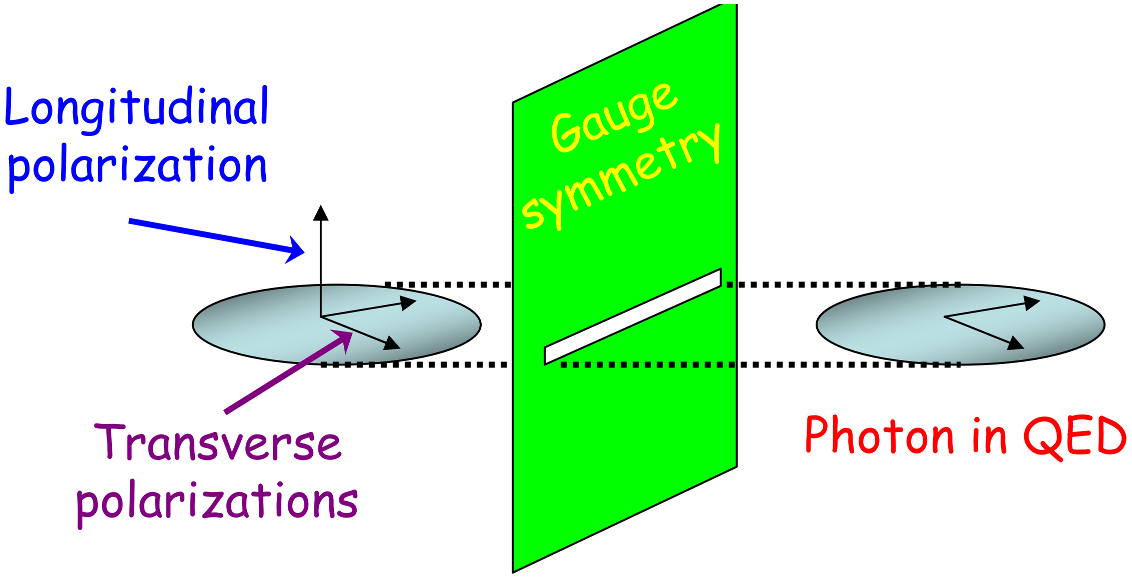


⇒ scattering probability grows with energy

Violation of unitarity (probability > 1) ⇒ field theory breaks down

In QED:

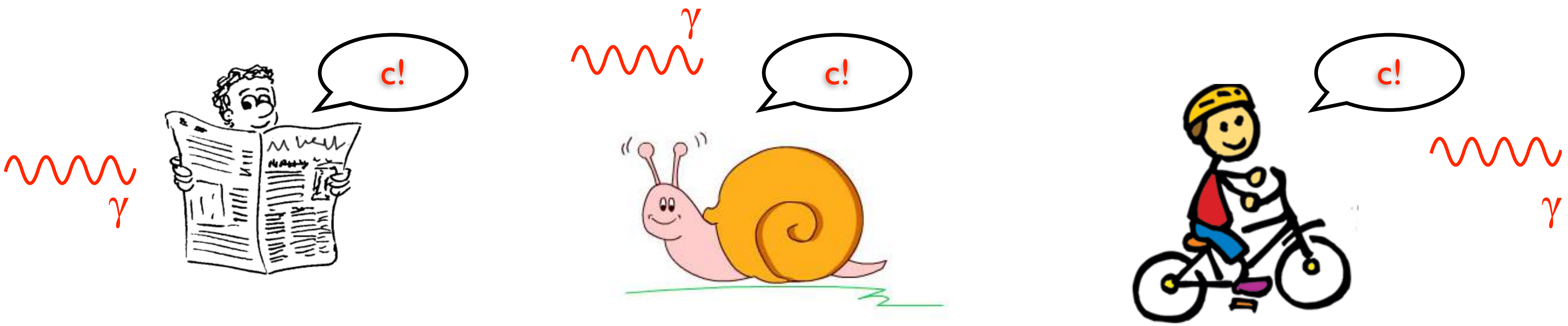
3rd polarization does not exist ↔ gauge symmetry



Gauge symmetry crucial to keep theory sensible at high energy

Gauge filter and masses

From relativity: the speed of light is the same in all frames



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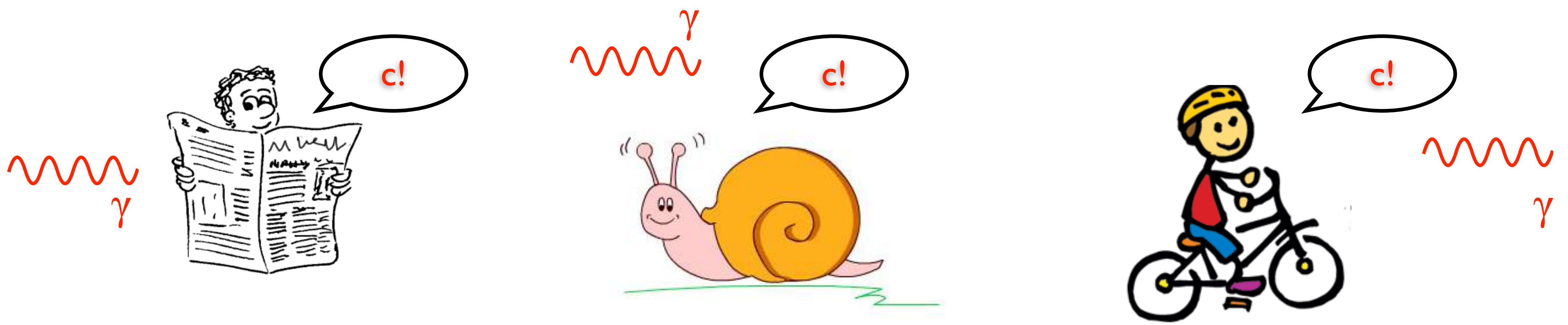
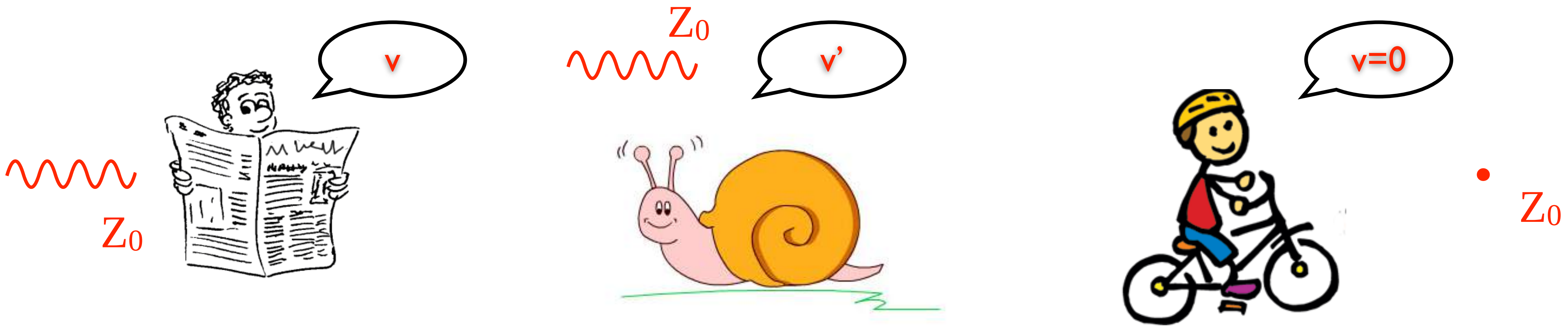


For massive particle can choose a frame where the particle is at rest



In that frame, the distinction between transverse and longitudinal polarizations breaks rotational invariance

Gauge trick does not work with massive particles

EW symmetry breaking

Sp$\bar{p}$S (1983-1985) p$\bar{p}$ collider at CERN, Geneva, running at E_{beam} = 450 GeV

LEP-II (1990-2001) e^+e^- collider at CERN, Geneva, running at E = 91.2 ➠ 206 GeV

Z/W interactions are described by a EW gauge theory
But Z/W masses break EW symmetry ⇒ theory breaks down at high E

gauge symmetry ↔ massless states ↔ sensible field theory

At what energy does this happen?

E > 1 TeV

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E >1 TeV

That's why the LHC was designed to investigate

- the mechanisms of mass generation
- how to keep the theory sensible at higher energy

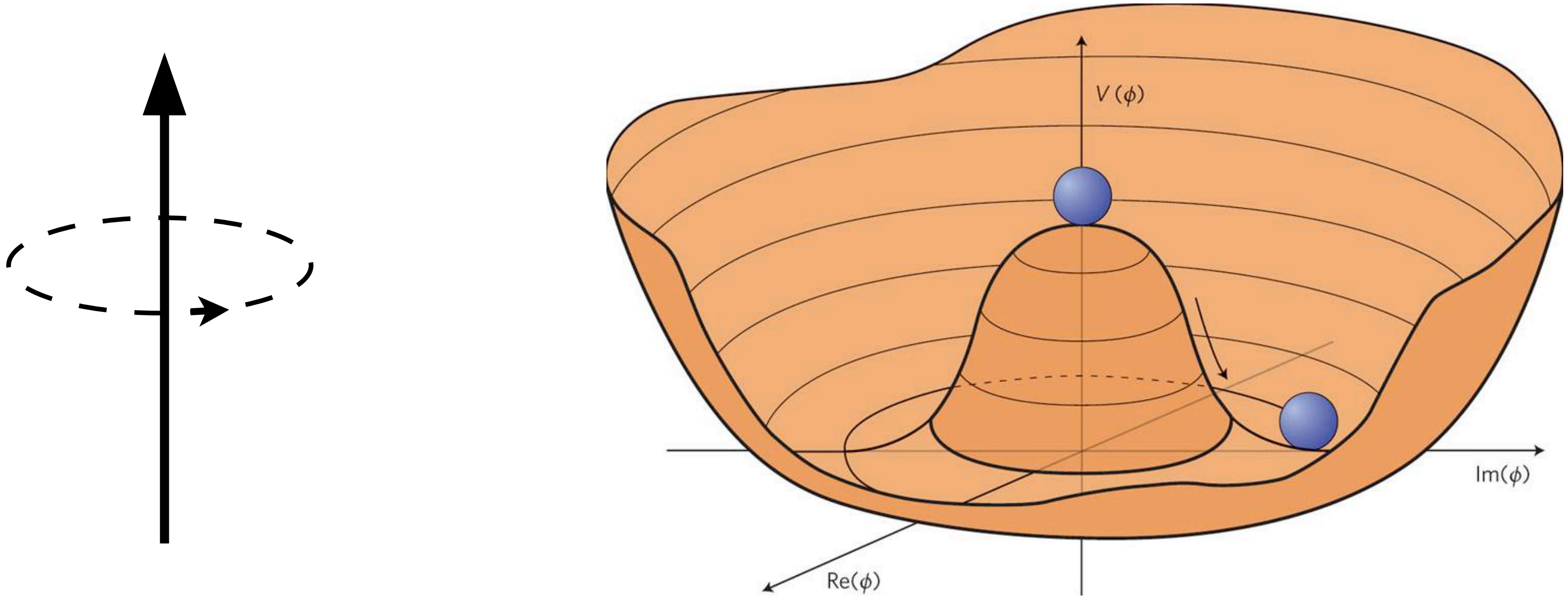
Spontaneous symmetry breaking

<u>Most popular solution:</u>

Higgs mechanism, i.e. EW symmetry spontaneously broken

<u>Spontaneous symmetry breaking (SSB):</u> symmetry of equations but not of solutions

What does this mean ?



configuration breaks rotational invariance, laws do not

Spontaneous symmetry breaking

With SSB relations implied by the exact symmetry can be modified

e.g. laws invariant under $d \leftrightarrow u$ with solutions $m_d = m_u$

but also solutions with $m_d > m_u$ are possible

as long as $m_d < m_u$ also exists

Spontaneous symmetry breaking

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but also solutions with $m_d > m_u$ are possible

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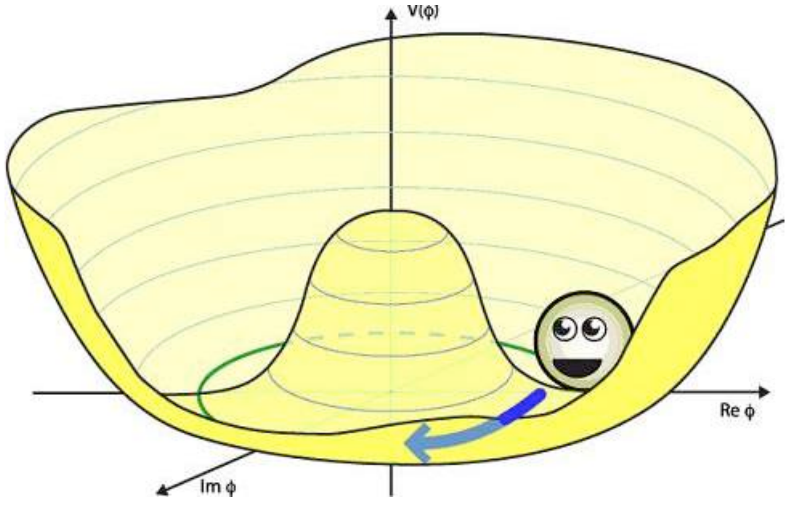
Typical of SSB is degeneracy of solutions.
Quantum interpretation: zero energy excitation, i.e. massless particle

Goldstone ’61



Problem: in Nature there is *no* massless Goldstone boson

EW symmetry breaking

Higgs mechanism

with gauge interactions, zero-energy excitation absorbed by the gauge field ⇒ massive gauge particles and no Goldstone boson

Brout, Englert, Higgs ’64; Weinberg and Salam ’67

EW symmetry breaking

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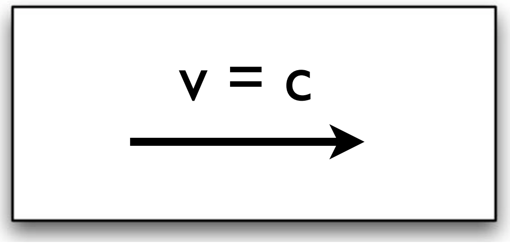
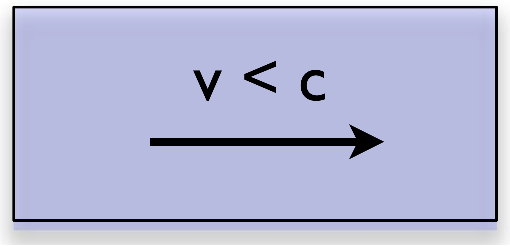
Higgs field

continuum medium pervading the whole universe. Particles interacting undergo a slow-down just as particles propagating in any medium do

slow down ⇒ inertia ⇒ mass



vacuum

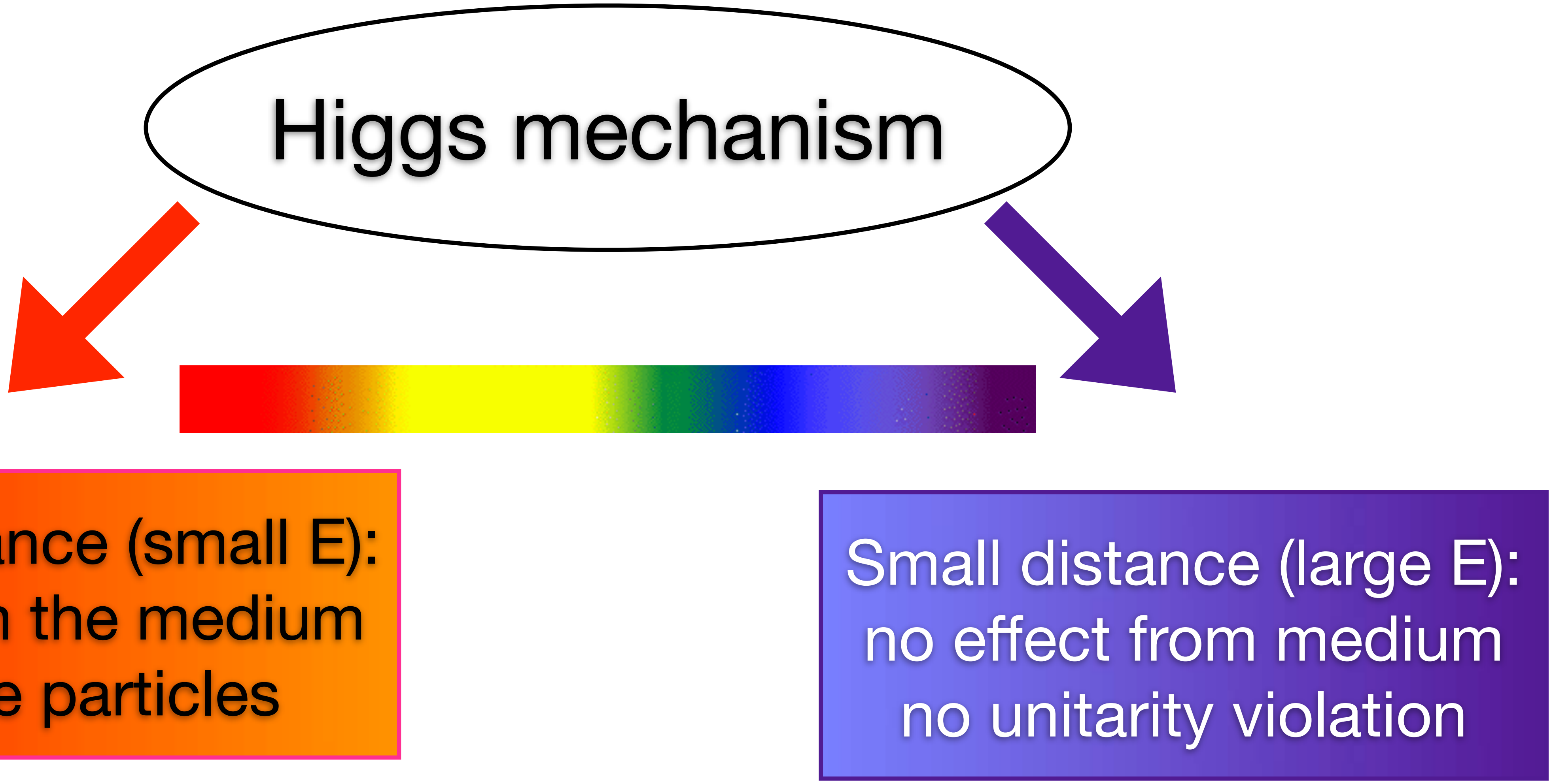


Higgs filled vacuum

EW symmetry breaking

The problem was → massless particles ↔ gauge invariance

The problem was → massive particles ↔ unitarity violation



Higgs mechanism

Large distance (small E):
effect from the medium
massive particles

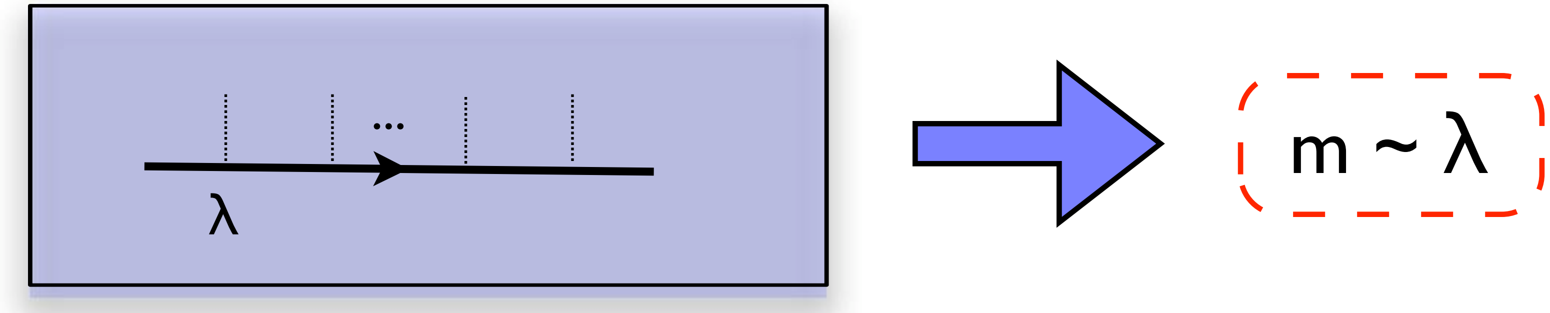
Small distance (large E):
no effect from medium
no unitarity violation

NB: EW charge distribution carries no electric charge ⇒ photon remains massless even after EWSB

Higgs mechanism in EW

- If the Higgs field exists, then quanta of the field must exist too ⇒ Higgs boson

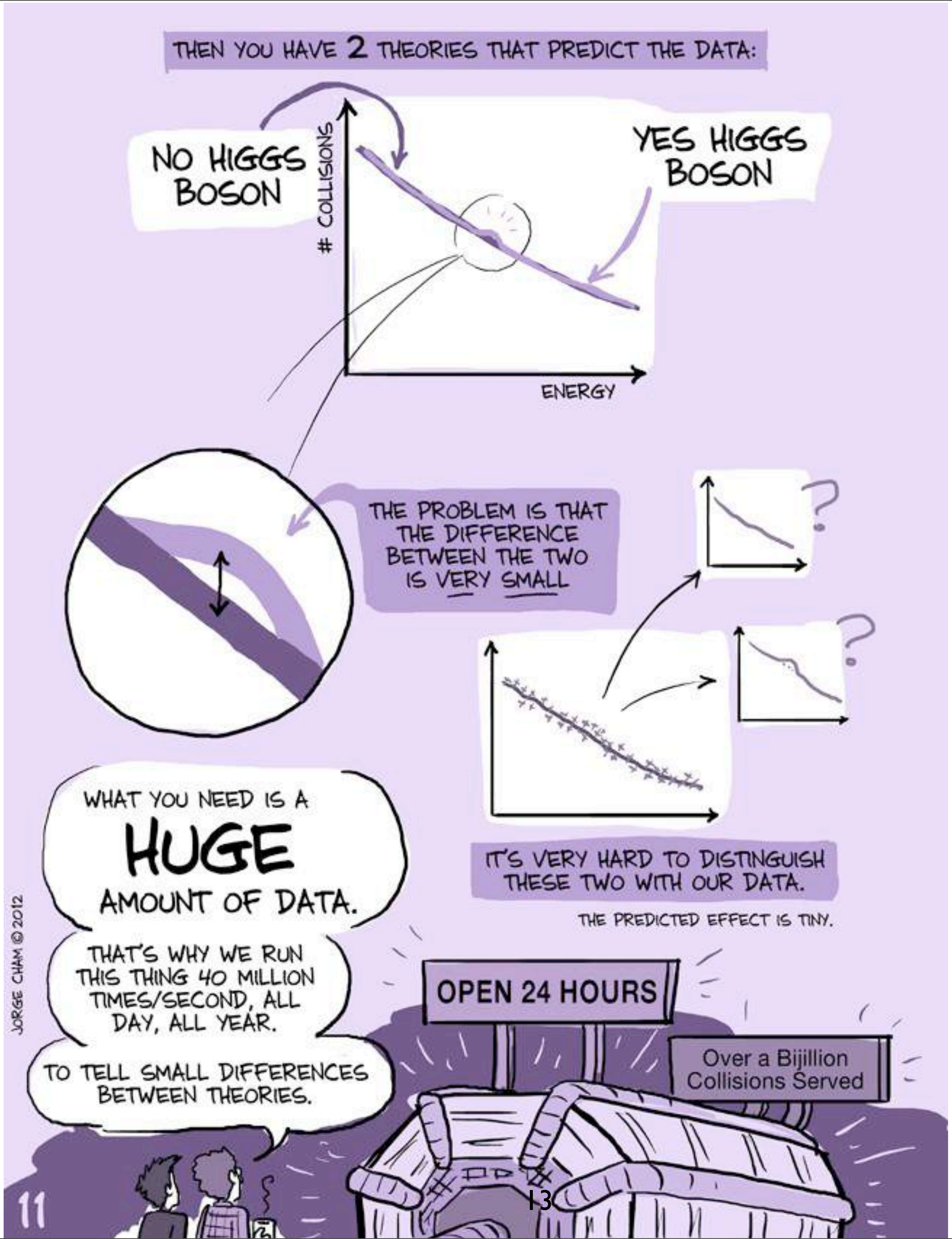
- Coupling of a particle to Higgs is proportional to the particle's mass



Higgs filled vacuum

- The Higgs boson will have a mass too ... because the Higgs slows itself down as it propagates in the (Higgs) vacuum

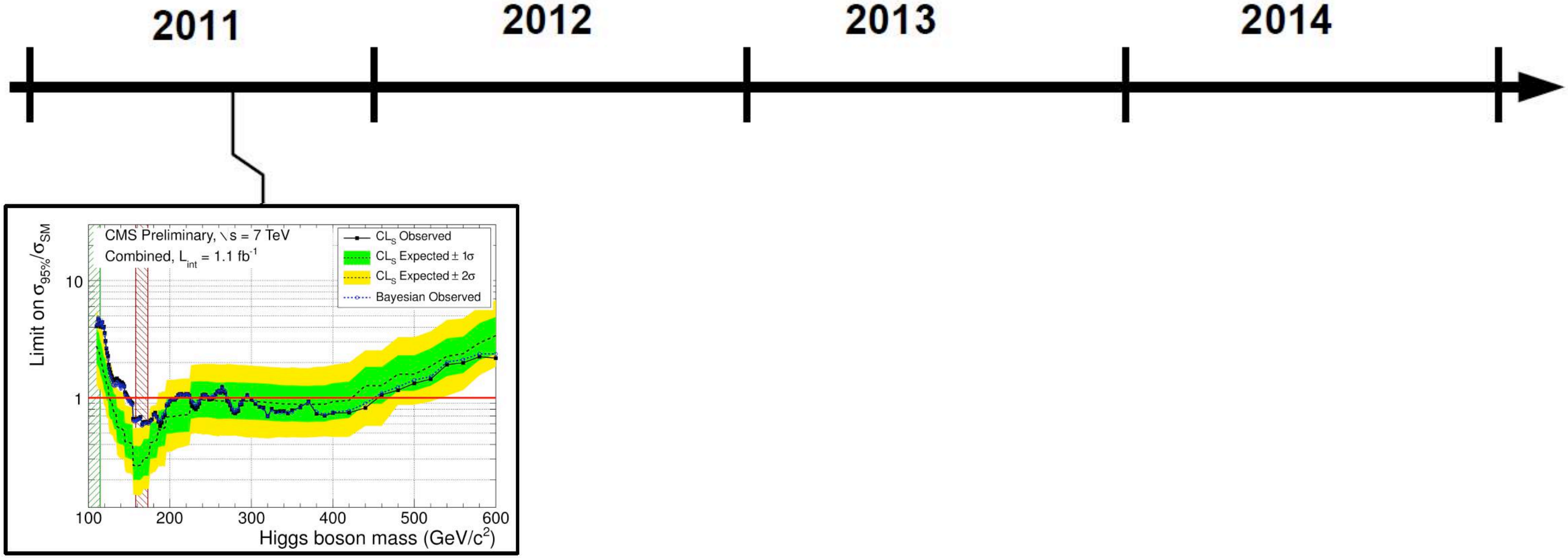
- In the SM the Higgs mass is a free parameter, but once its value is determined everything else (couplings/masses) is fixed



Before the discovery

A brief history

First combined exclusion limits



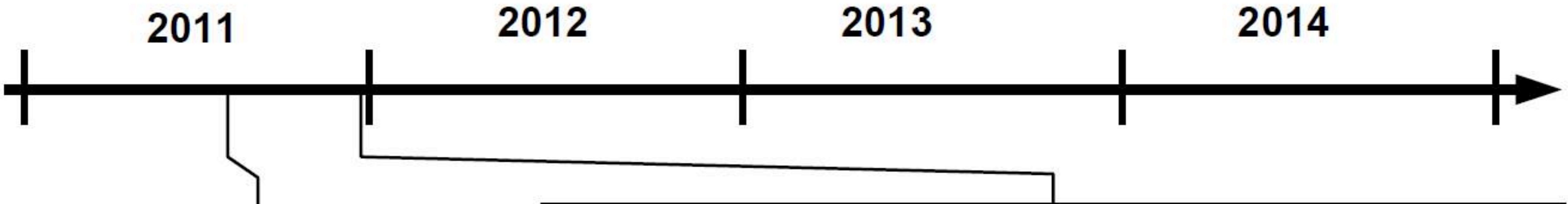
First 1fb^{-1} (7TeV):

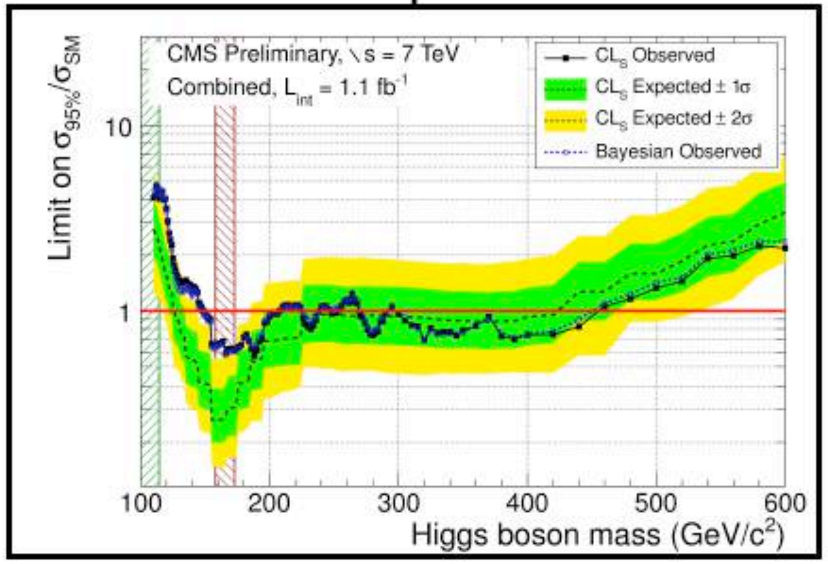
no Higgs boson between 160 and 500GeV

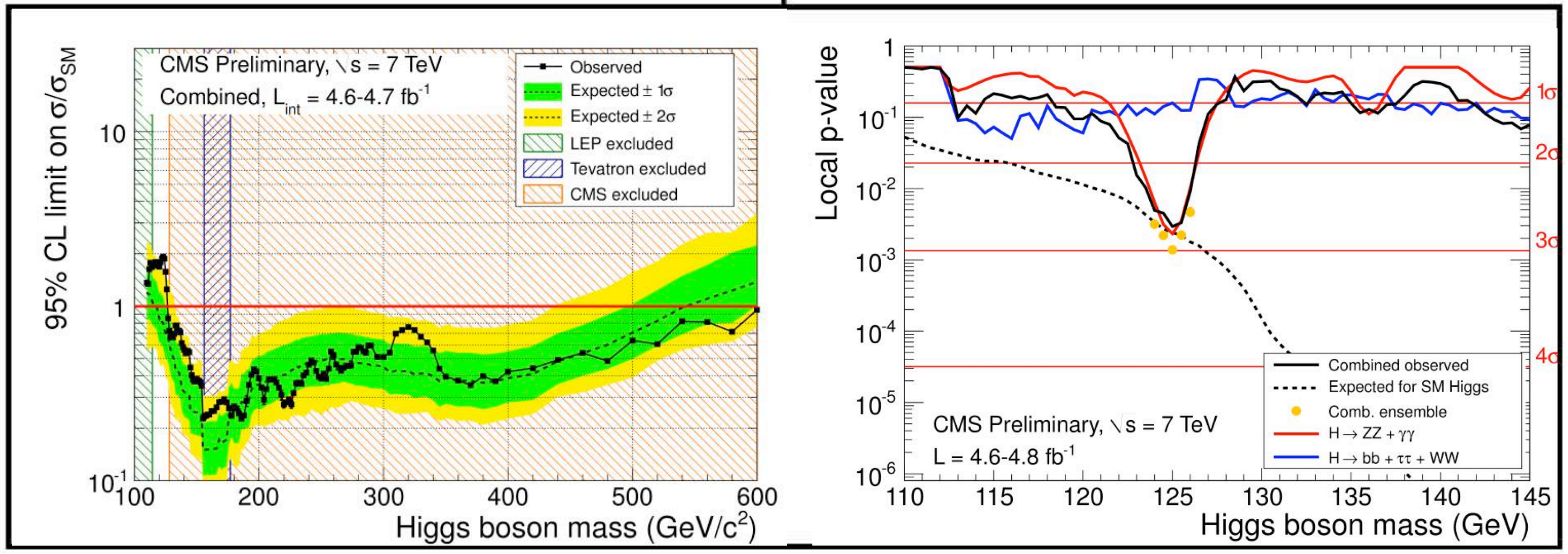
EPS-HEP '11
Lepton-Photon '11

A brief history

First hints







First 5fb^{-1} (7TeV):

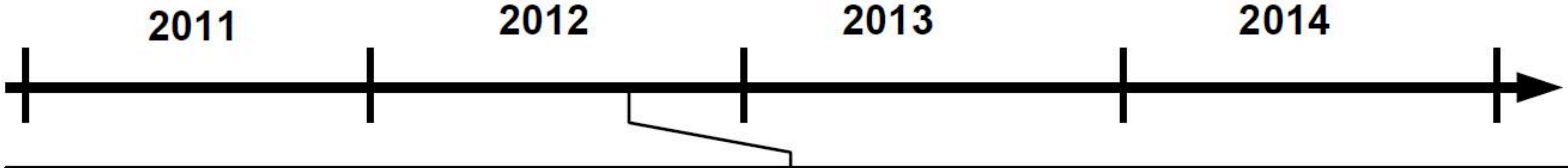
SM Higgs boson excluded for 127 < m_H < 600GeV

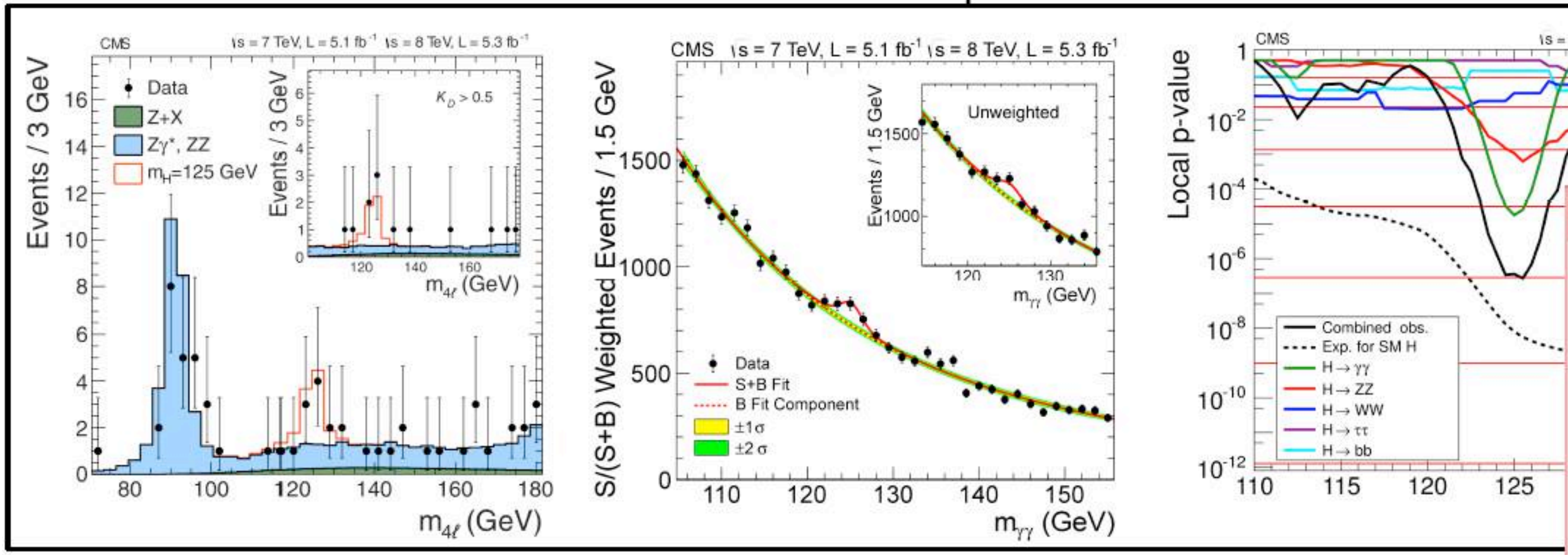
Excess (local significance 2.8σ) for m_H~125GeV

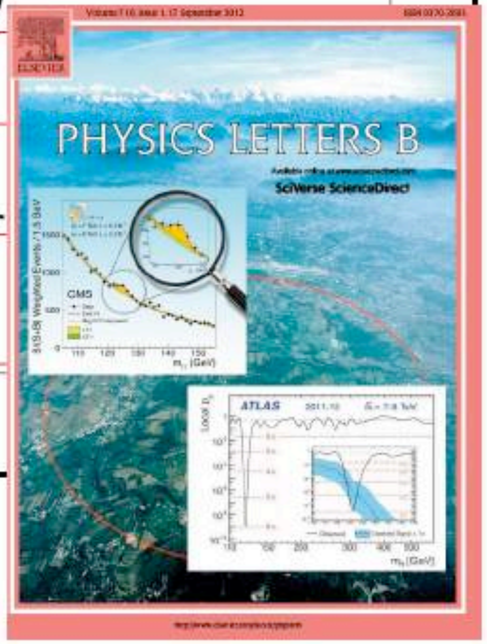
CMS/ATLAS Higgs Jamboree
Moriond 2012

A brief history

Evidence of a new boson



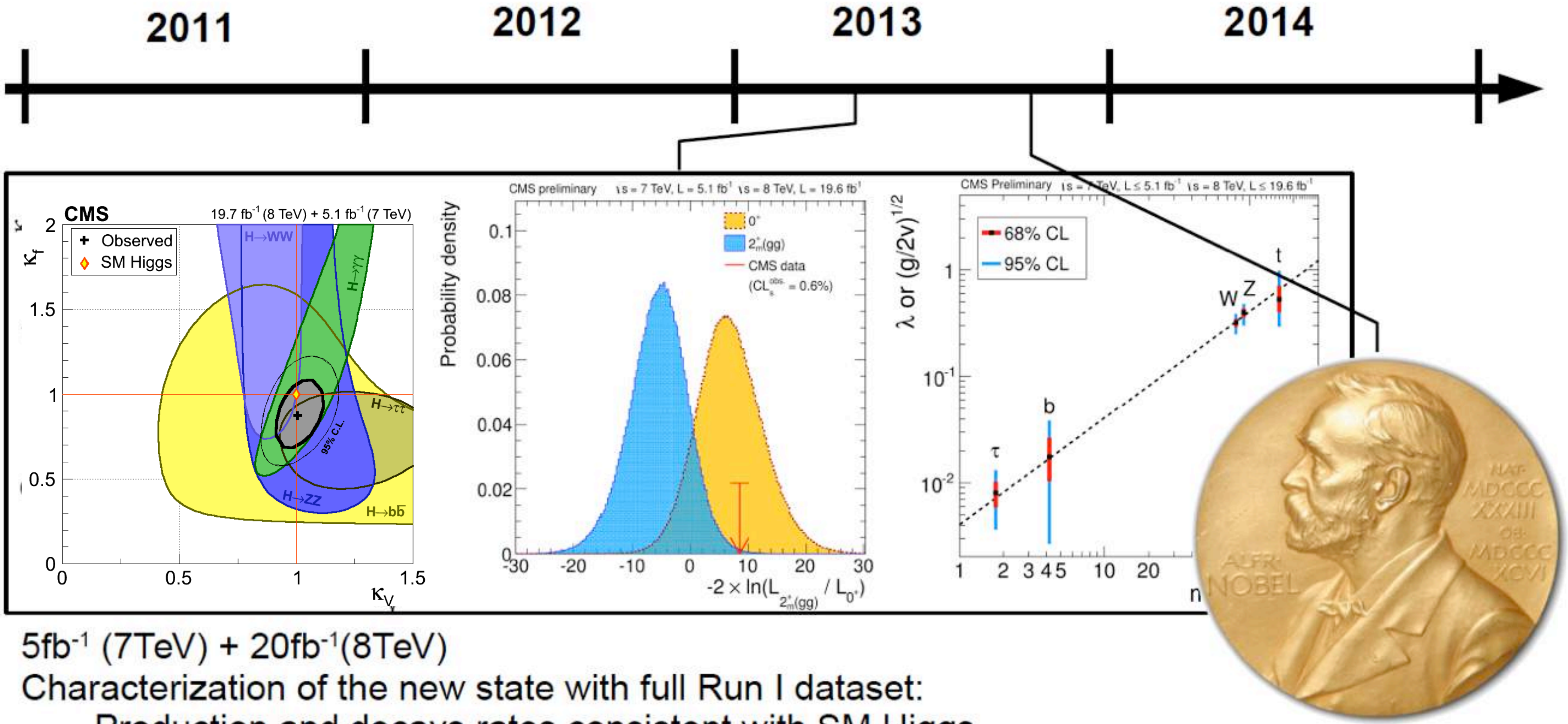




5 fb^{-1} (7TeV) + 5 fb^{-1} (8TeV)
4th July 2012: CMS and ATLAS announce Evidence for a new boson.

A brief history

Identification of the Higgs boson



5fb^{-1} (7TeV) + 20fb^{-1}(8TeV)

Characterization of the new state with full Run I dataset:

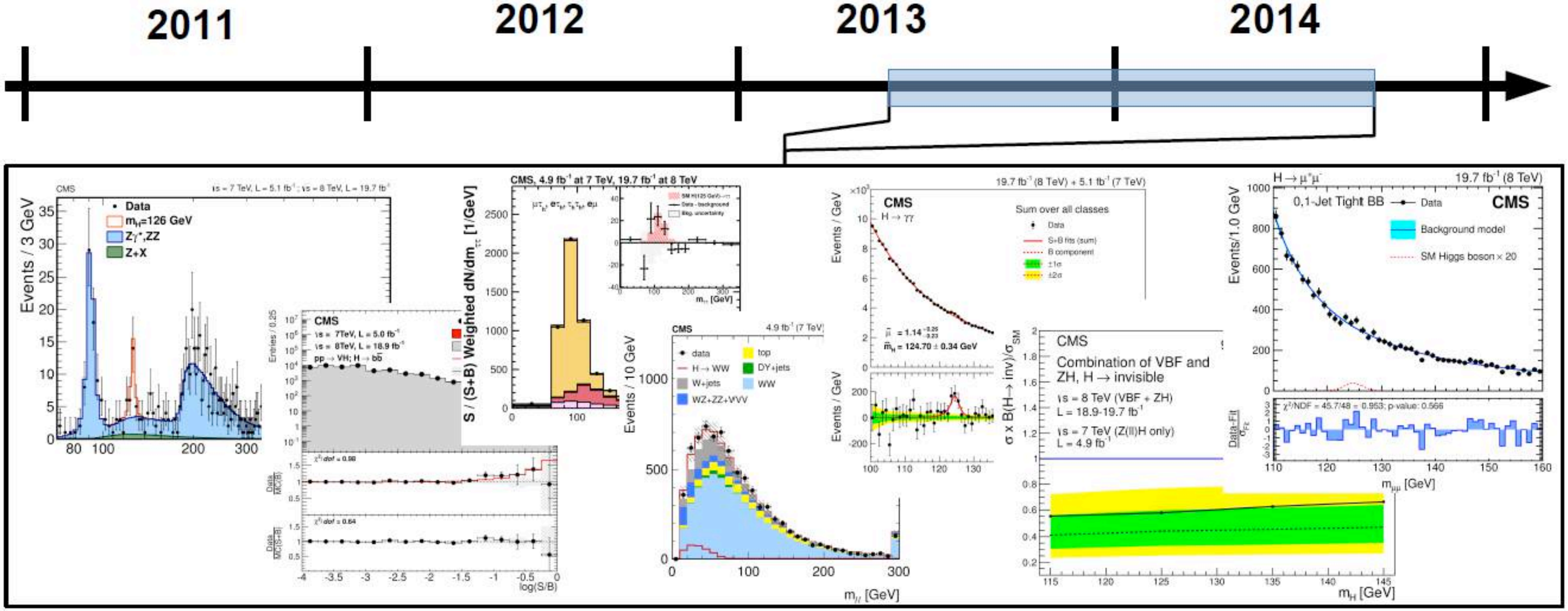
Production and decays rates consistent with SM Higgs

0^+ spin parity favoured by data.

8th October 2013: Nobel Prize for Physics awarded to prof. Higgs and Englert.

A brief history

The Run I legacy



$5fb^{-1}$ (7TeV) + $20fb^{-1}$(8TeV)

Final results on Run I full dataset published 1-2 years after the discovery of the new boson.

Ultimate precision for this dataset attained.

Preliminary combined analysis of all channels presented in July 2014.

A brief history

2012-2014 remarkably intense and exciting years for particle physics

The hierarchy problem

- the Higgs mass receives corrections from vacuum fluctuations

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- the size of the correction should be proportional to the maximum allowed energy M_{Planck} , M_{GUT}, . . .

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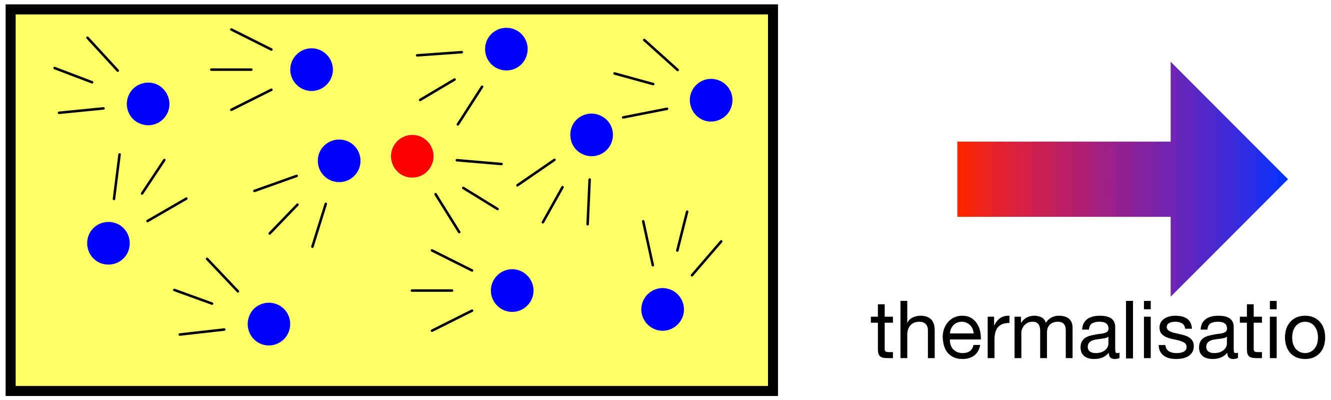
The hierarchy problem

- the Higgs mass receives corrections from vacuum fluctuations
- the size of the correction should be proportional to the maximum allowed energy M_{Planck} , M_{GUT}, . . .
- $M_H \ll M_{\text{Planck}}$ requires fine-tuning up to 17 digits or New Physics!

Analogy with thermal fluctuations

t = 0



thermalisation

At large t expect to have

$$E_{\color{red}\bullet} \sim E_{\color{blue}\bullet}$$

While the observation is

$$E_{\color{red}\bullet} \sim 10^{-17} E_{\color{blue}\bullet}$$

While there is no inconsistency, it just seems hard to believe!

Explanations for gauge hierarchy

- ☛ In the analogy: natural explanation could be that red does not really interact with blue because the interaction is screened

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Explanations for gauge hierarchy

- ☛ In the analogy: natural explanation could be that red does not really interact with blue because the interaction is screened

- ☛ In the Higgs case: similarly, the interaction could be screened by new forces/particles

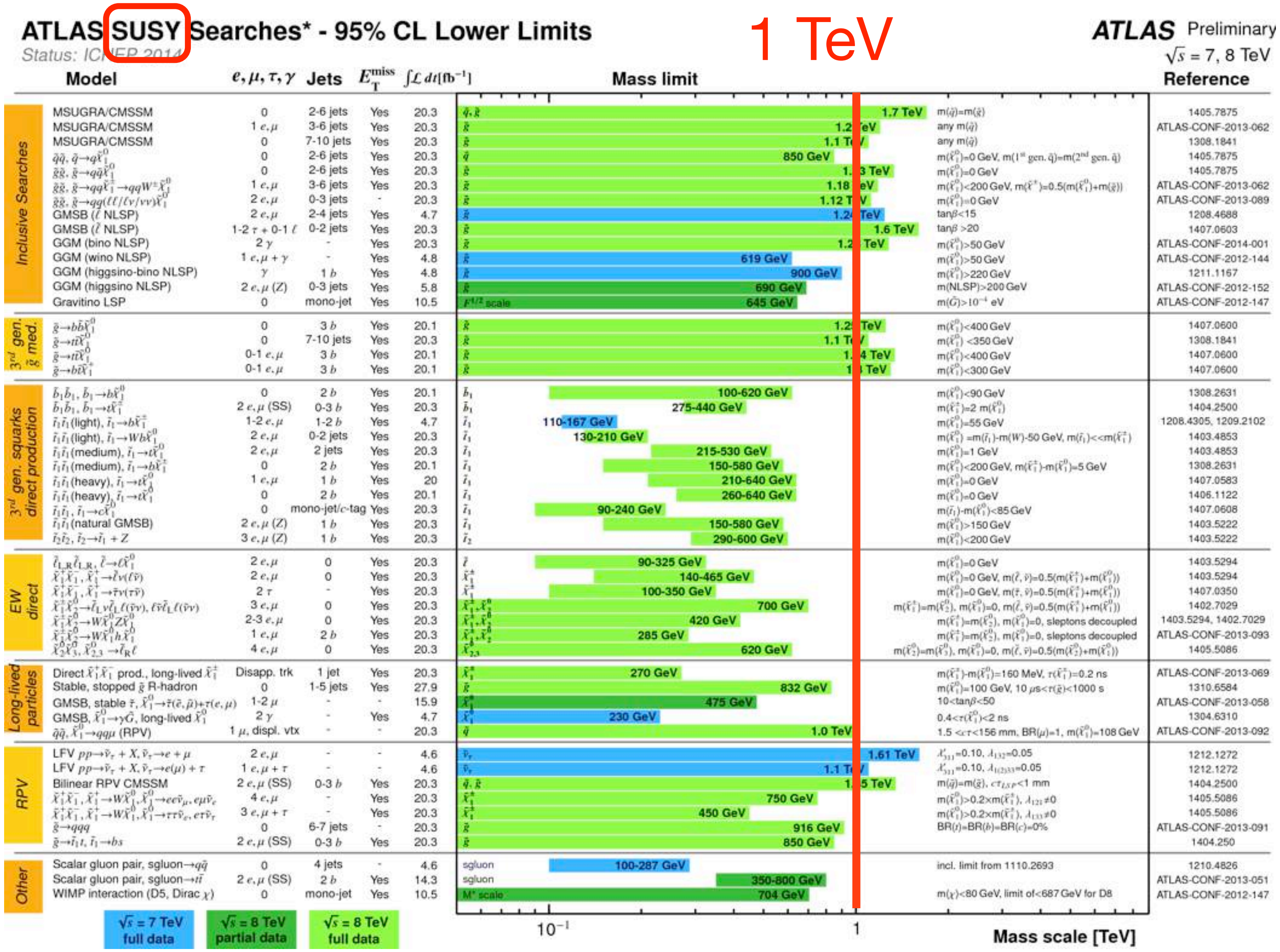
A variety of possible explanations exist to protect the Higgs mass from having a sensitivity to high-energy scales

(supersymmetry, technicolour, Randall-Sundrum warped space, pseudo-Goldstone Higgs, Little Higgs, ...)

Currently these are all speculations. Only experimental data can discriminate between the predictions of various models

Status of New Physics searches

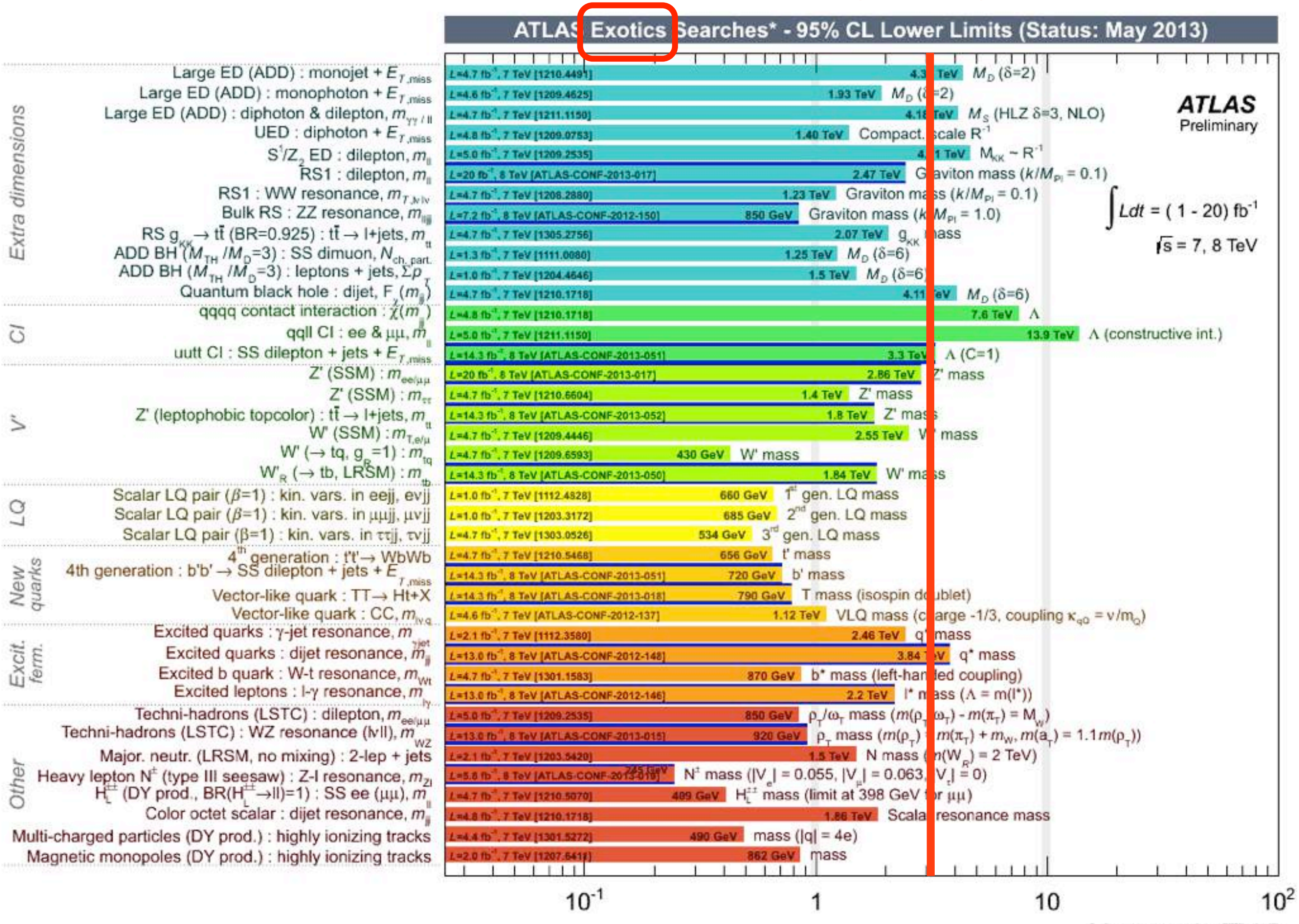
Unfortunately, direct searches are so far not successful



Status of New Physics searches

Unfortunately, direct searches are so far not successful

few TeV



*Only a selection of the available mass limits on new states or phenomena shown

Future direction

- Run II at almost twice the energy will allow us to push the reach of these direct searches considerably
- Yet, the possibility must be taken into account, that no new state is produced directly (simply because the energy is not enough)
- Indirect searches and precision tests more prominent in Run II
- the Higgs sector in particular will undergo scrupulous precision tests (remember: given the Higgs mass everything is predicted in the SM, so everything can and must be tested)
- Precision tests require both accurate measurements and precise theoretical predictions

Precision through Perturbation

At the LHC, QCD and electroweak (EW) interactions are weak. We can compute perturbative expansions in the (small) coupling. Higher-order terms will improve predictions. Different expansions:

fixed order

$\frac{\sigma}{\sigma_0} = 1$	LO
$+ c_1\alpha$	NLO
$+ c_2\alpha^2$	NNLO
$+ \ldots$	

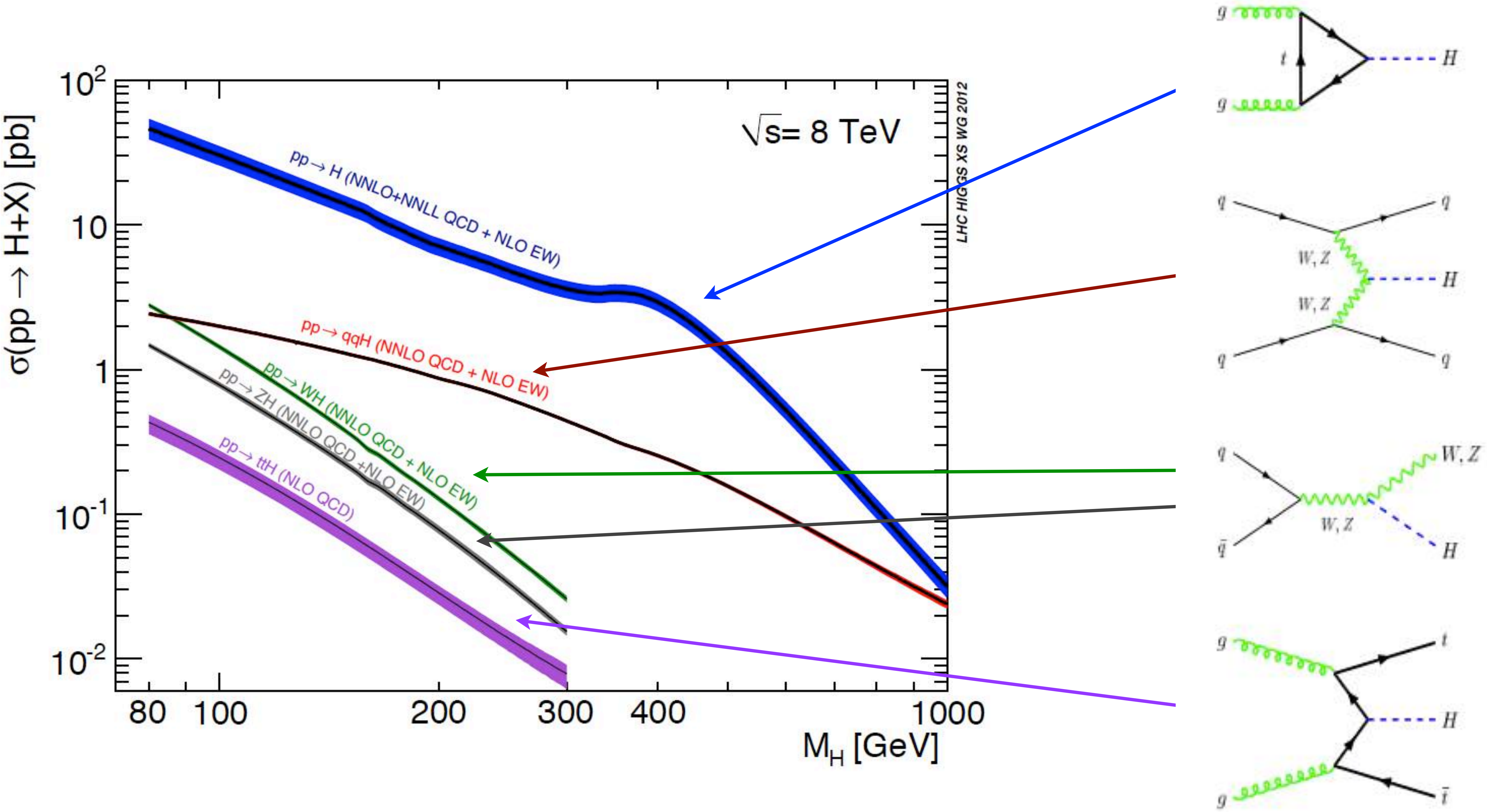
all order (L = some large logarithm)

$\ln\frac{\sigma}{\sigma_0} = \alpha^n L^{n+1}$	LL
$+ \alpha^n L^n$	NLL
$+ \alpha^n L^{n-1}$	NNLL
$+ \ldots$	

QCD: α ~ 0.1 expect NLO to be O(10%) correction, NNLO O(1%) ...

EW: α ~ 0.01 expect NLO to be O(1%) correction, ...

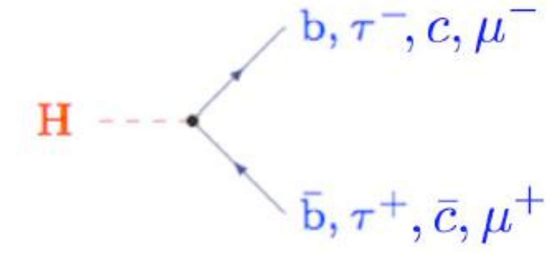
Higgs production at the LHC

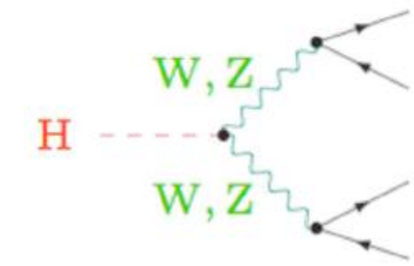


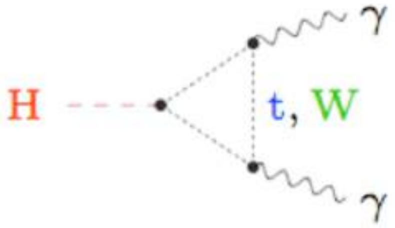
Higgs decay modes

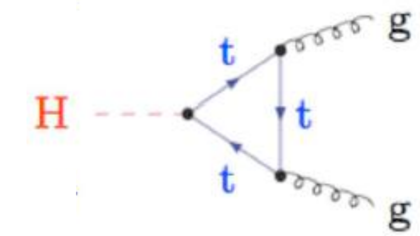
i.e. what is actually seen in detectors

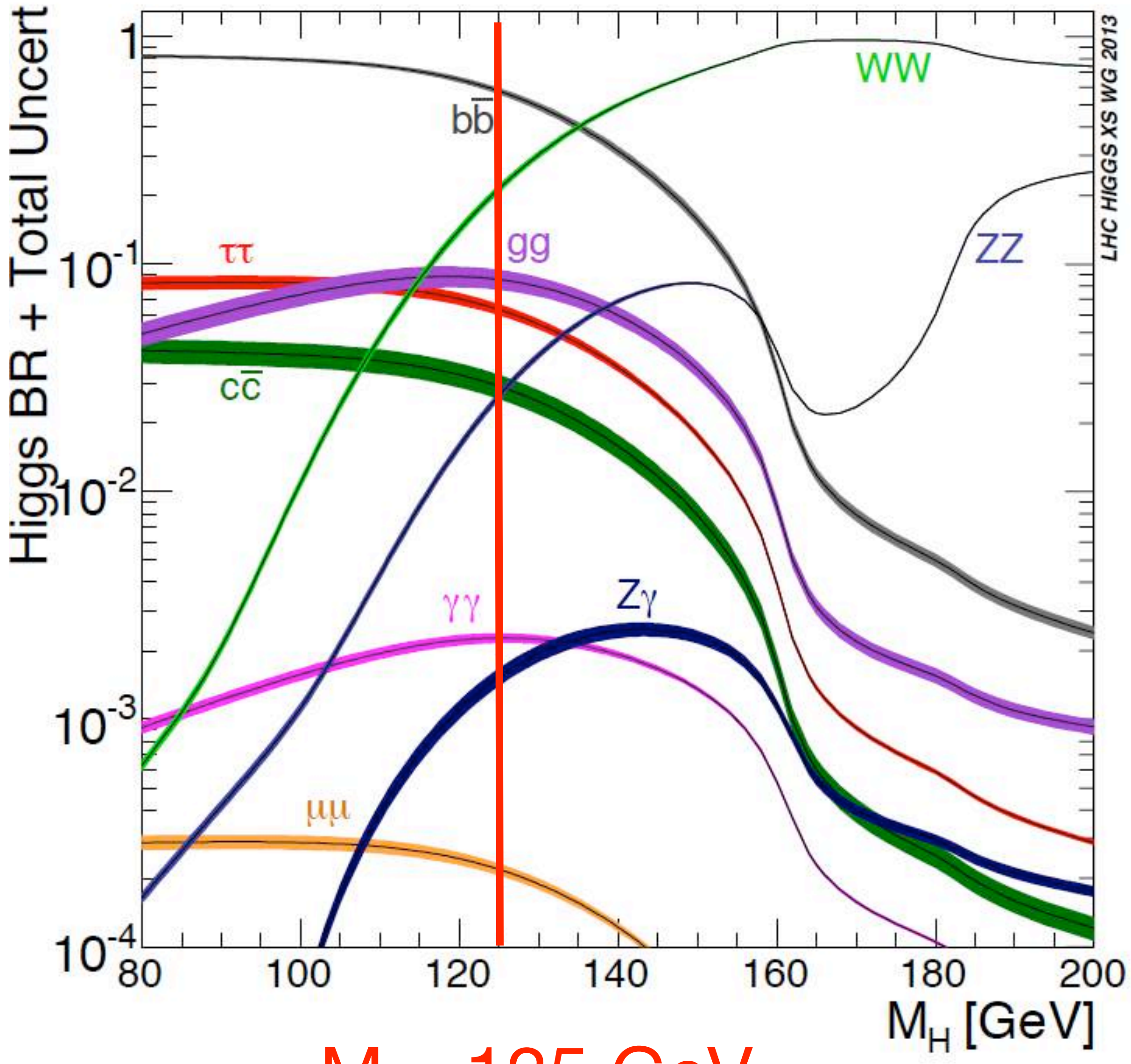
Higgs decays very very quickly.... fortunately, its mass lies in a sweet spot (M_H ~125 GeV) where many decay modes are available







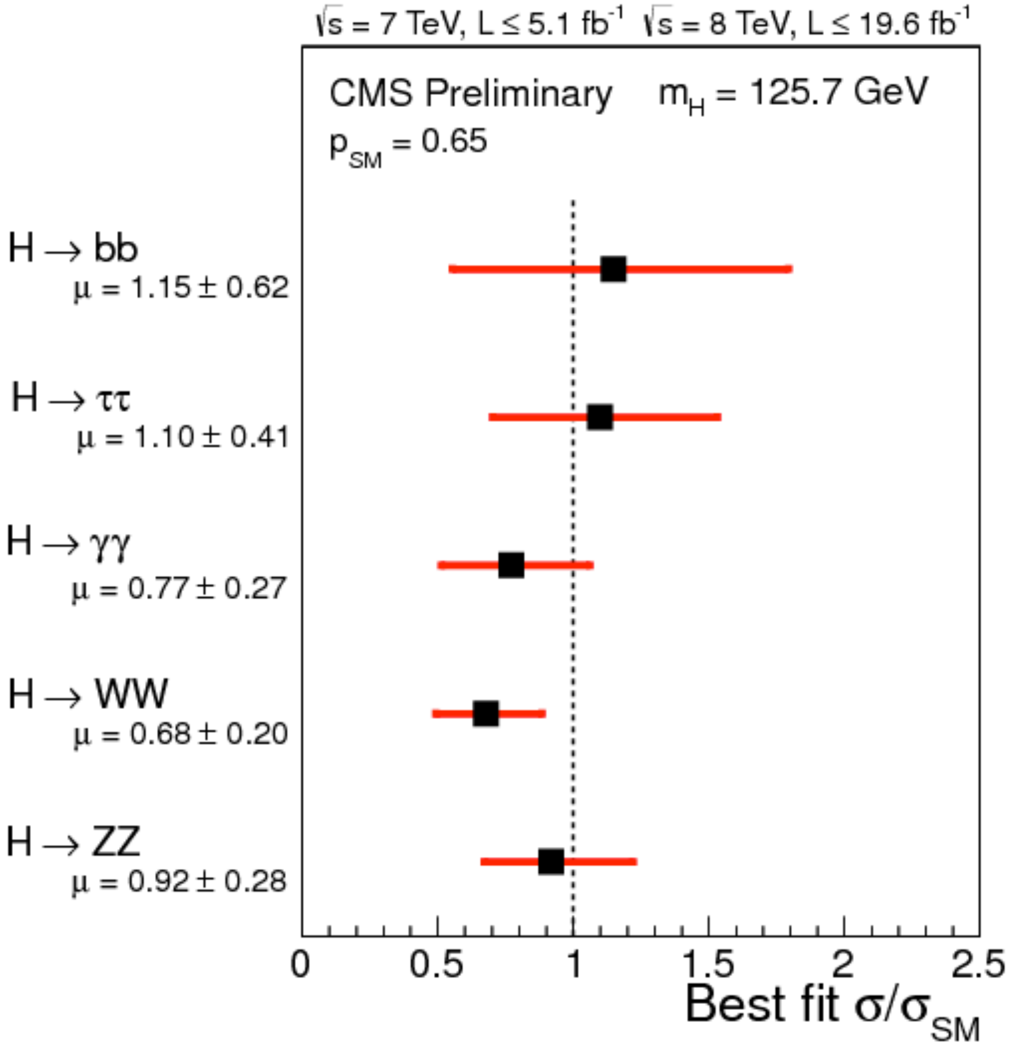


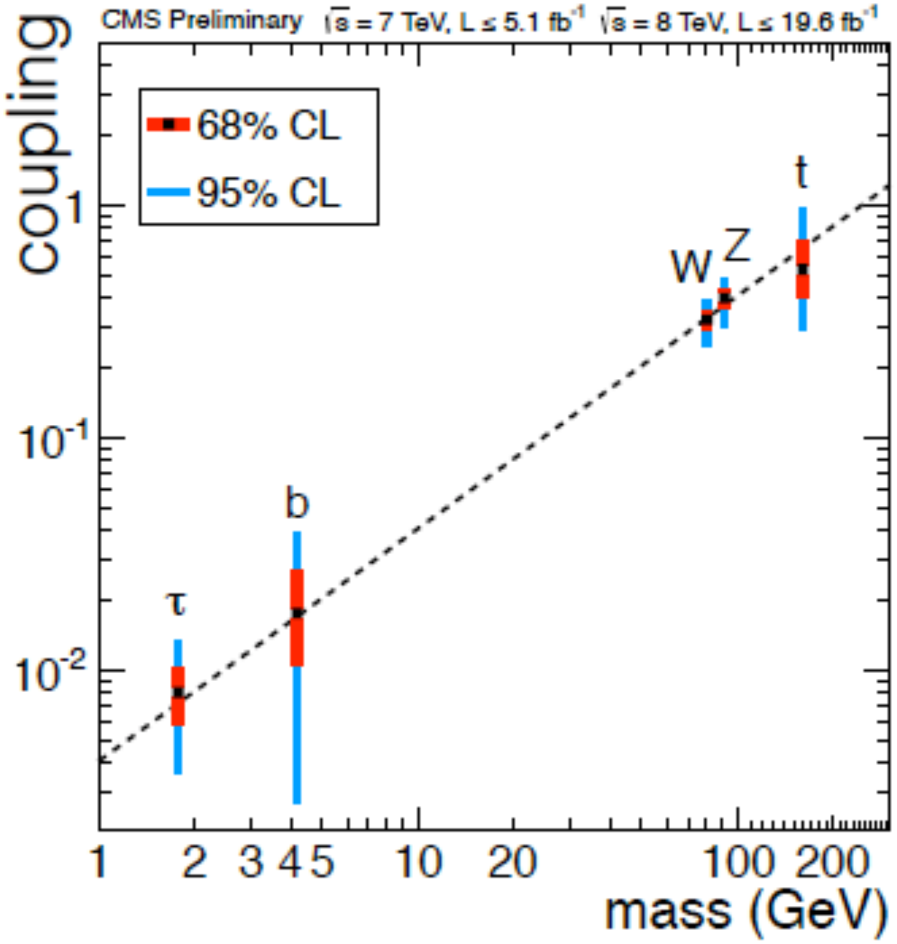


M_H=125 GeV

Status of Higgs measurements

Precision Higgs phenomenology (based on full 7 and 8 TeV data) shows so far no departure from a plain SM Higgs boson pattern



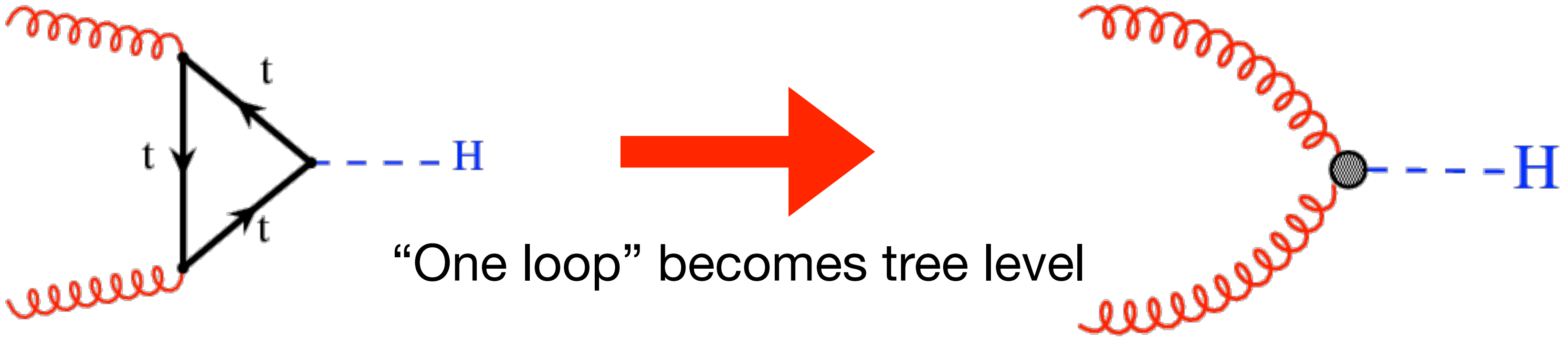


Run II at the LHC about to start: focus will be on accurate Higgs measurements using high-precision theory

Inclusive Higgs production

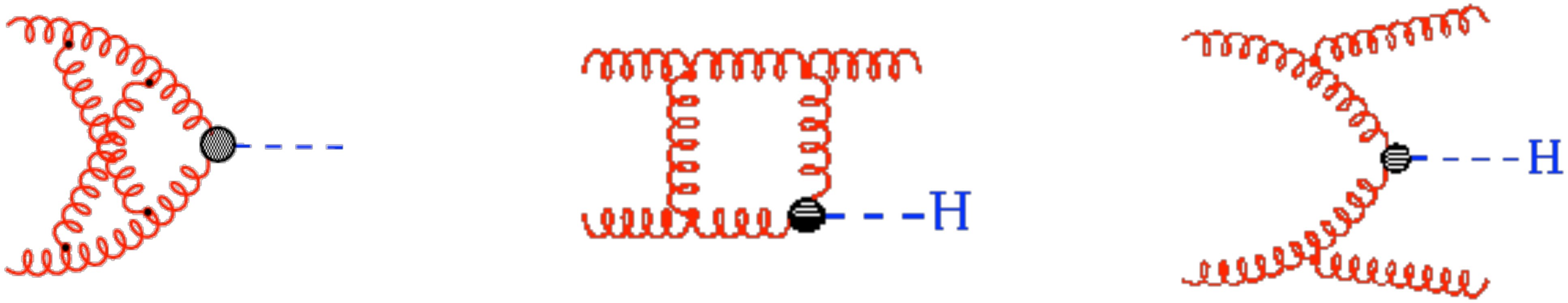
<u>One example:</u> the simplest (and dominant) Higgs production mechanism via gluon-gluon fusion (no decays).
How well do we know this cross-section?

Most calculations based on the large m_t-limit effective theory:



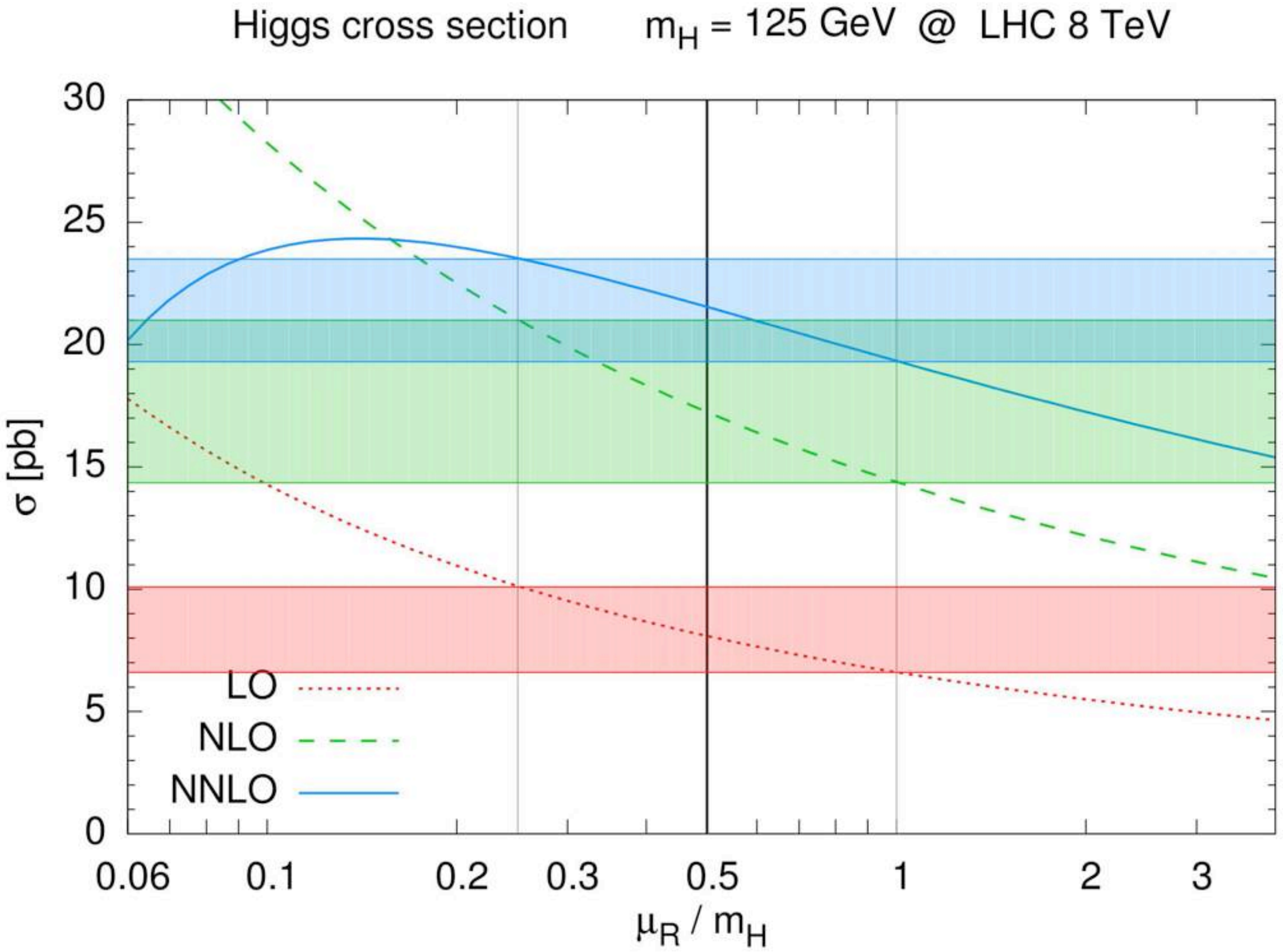
“One loop” becomes tree level

In this limit, NNLO corrections known for many years:



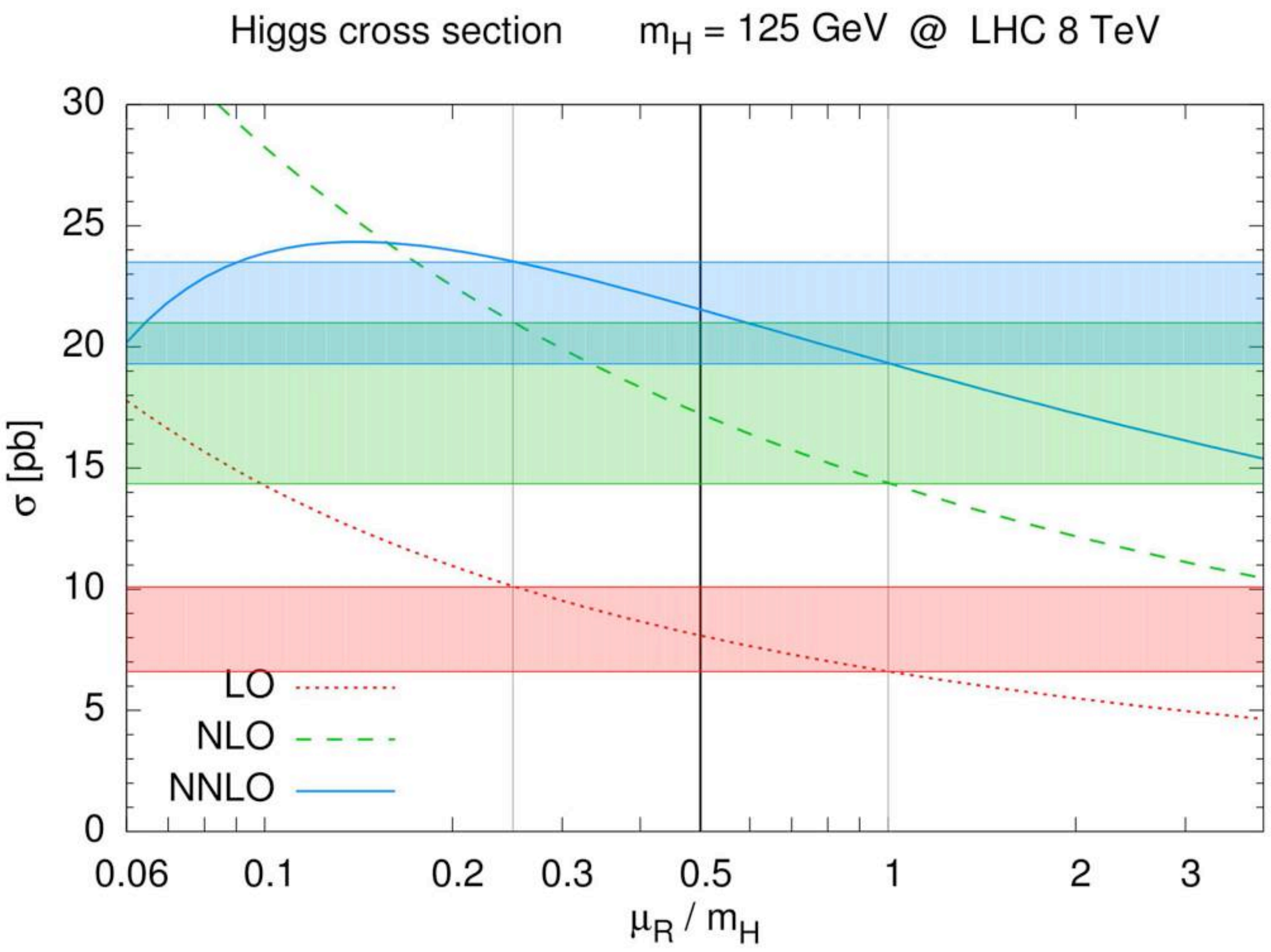
Kilgore, Harlander ’02; Anastasiou, Melnikov ’02

Inclusive Higgs production



- perturbative series for gg → H converges very slowly
- renormalization scale variation (commonly used to estimate theory uncertainty) underestimates the shift to the next order

Inclusive Higgs production

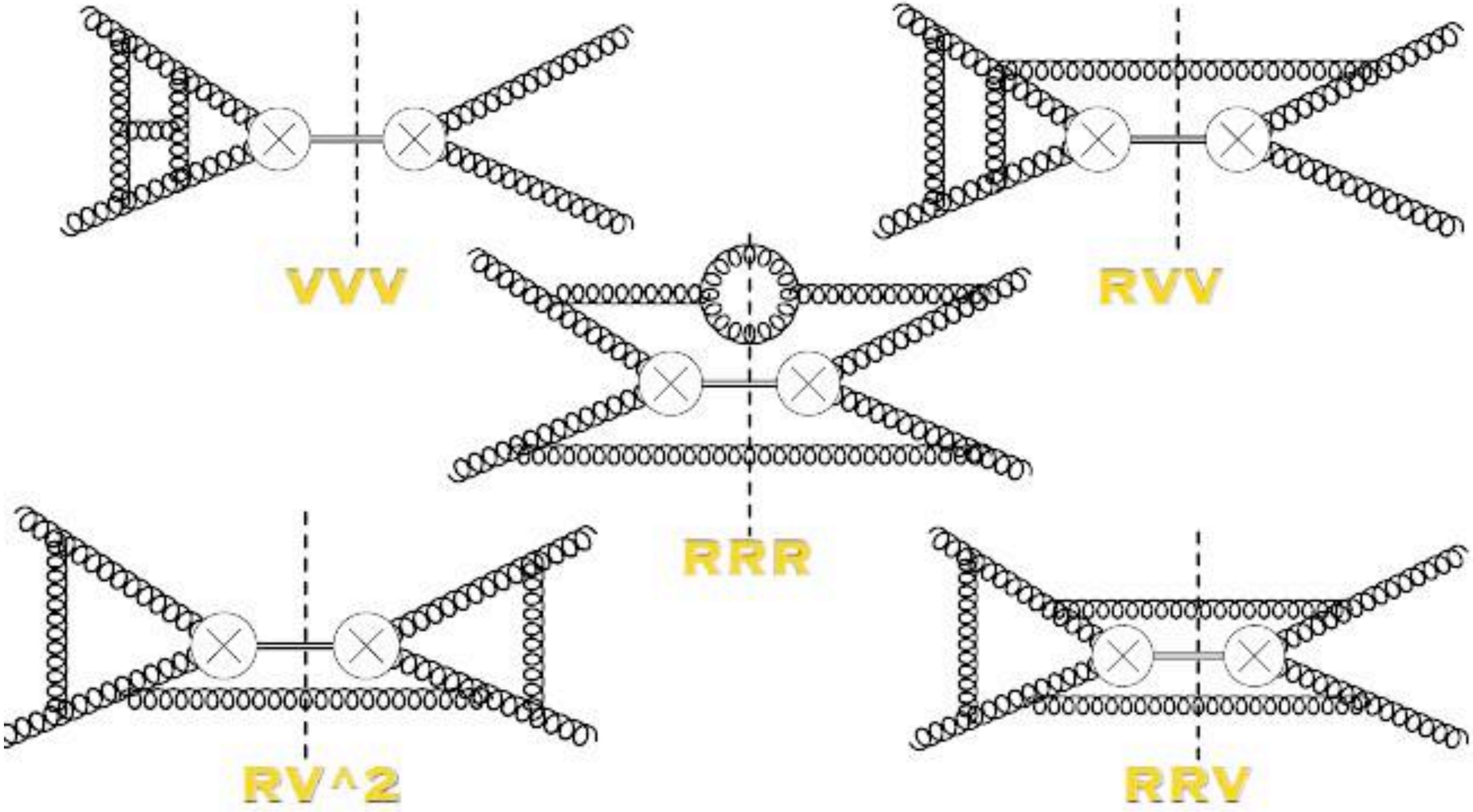


Two ways to go:

- try to compute higher orders approximately (resummations)
- try to compute exact N^{3}LO i.e. O(α_s^3) correction. Is it that difficult?

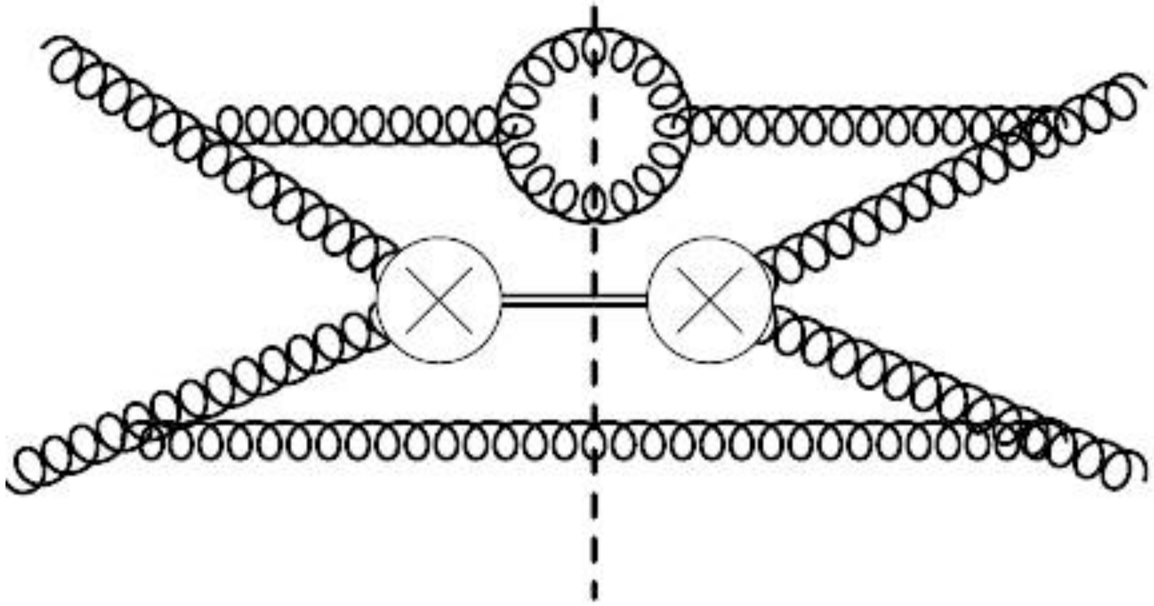
Facts about N^{3}LO

- O(100000) interference diagrams (1000 at NNLO)



Facts about N^{3}LO

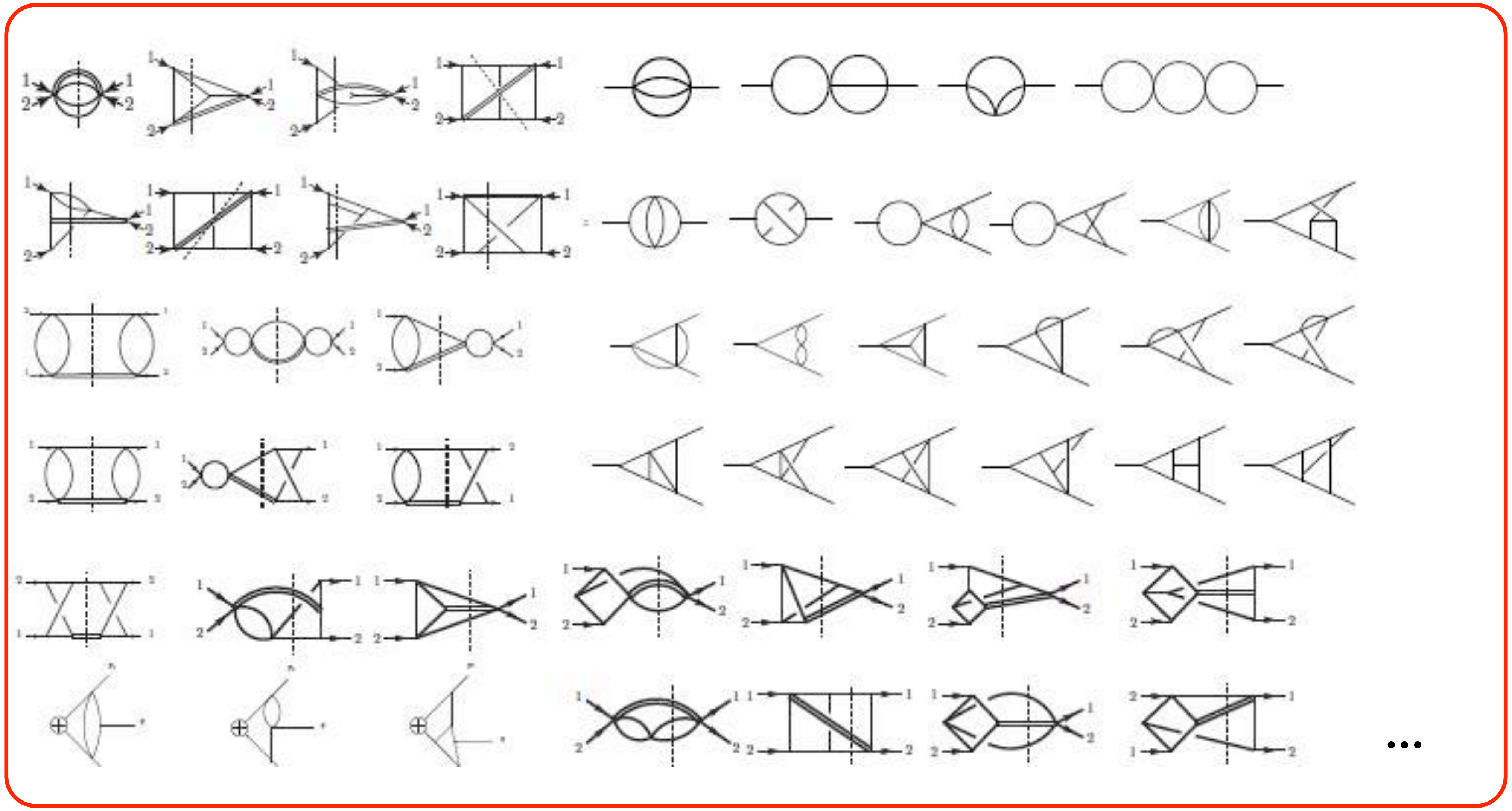
- O(100000) interference diagrams (1000 at NNLO)
- 68273802 loop and phase space integrals (47000 at NNLO)



+ 68273801 integrals

Facts about N^3LO

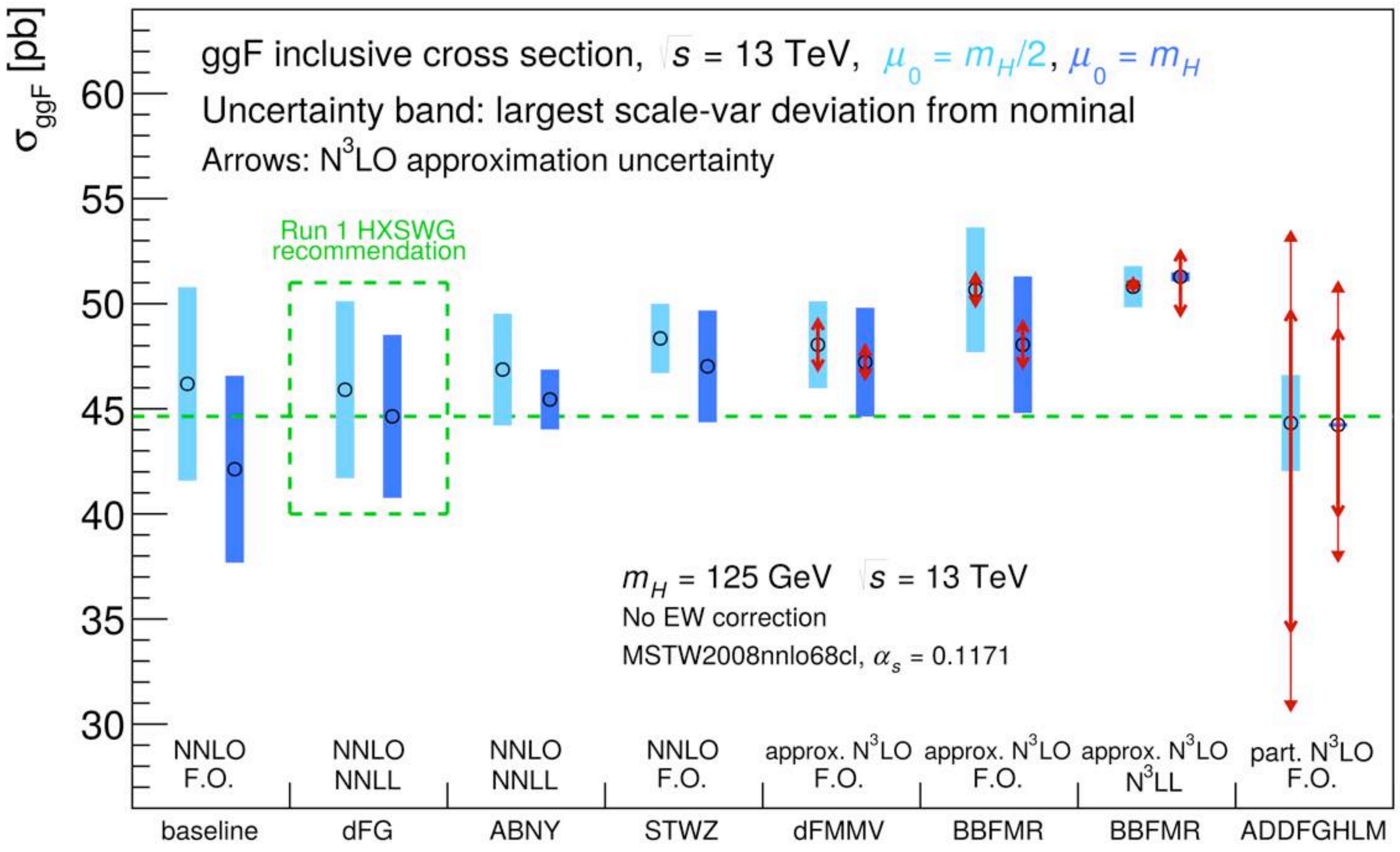
- O(100000) interference diagrams (1000 at NNLO)
- 68273802 loop and phase space integrals (47000 at NNLO)
- about 1000 master integrals (26 at NNLO)



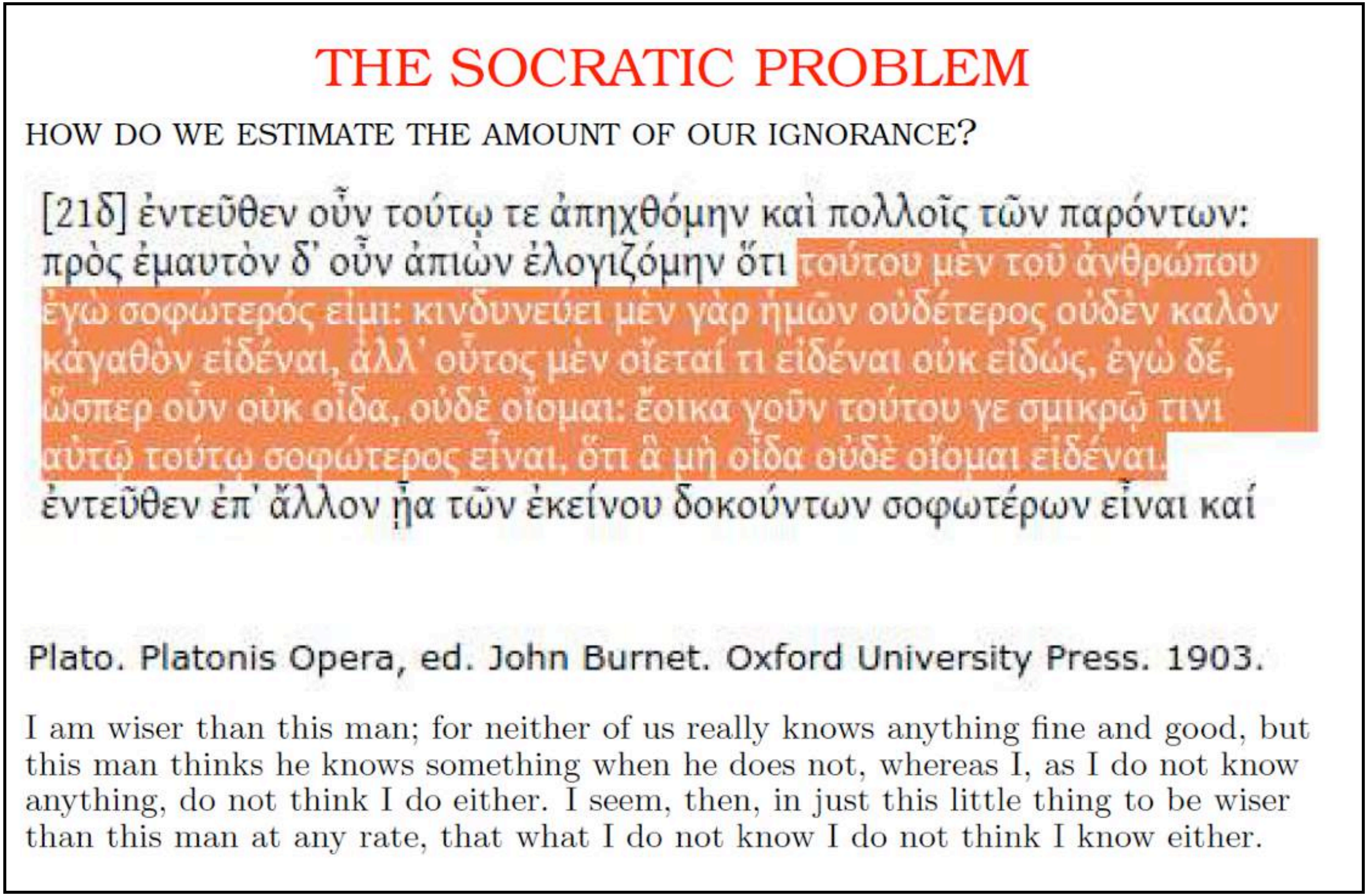
Approximate N^{3}LO

Approximate N^{3}LO from different groups (possibly including higher order logarithmic terms) together with their uncertainty

approx N^{3}LO from Anastasiou et al ’14



What is the most reasonable approximation based on our current knowledge? Central value and size of uncertainty hotly debated!



THE SOCRATIC PROBLEM

HOW DO WE ESTIMATE THE AMOUNT OF OUR IGNORANCE?

[21δ] ἐντεῦθεν οὖν τούτῳ τε ἀπηχθόμην καὶ πολλοῖς τῶν παρόντων: πρὸς ἐμαυτὸν δ' οὖν ἀπιὼν ἐλογιζόμην ὅτι τούτου μὲν τοῦ ἀνθρώπου ἐγὼ σοφώτερός εἰμι: κινδυνεύει μὲν γὰρ ἡμῶν οὐδέτερος οὐδὲν καλὸν κἀγαθὸν εἰδέναι, ἀλλ' οὗτος μὲν οἴεταί τι εἰδέναι οὐκ εἰδώς, ἐγὼ δέ, ὥσπερ οὖν οὐκ οἶδα, οὐδὲ οἴομαι: ἔοικα γοῦν τούτου γε σμικρῷ τινι αὐτῷ τούτῳ σοφώτερος εἶναι, ὅτι ἃ μὴ οἶδα οὐδὲ οἴομαι εἰδέναι. ἐντεῦθεν ἐπ' ἄλλον ᾖα τῶν ἐκείνου δοκούντων σοφωτέρων εἶναι καί

Plato. Platonis Opera, ed. John Burnet. Oxford University Press. 1903.

I am wiser than this man; for neither of us really knows anything fine and good, but this man thinks he knows something when he does not, whereas I, as I do not know anything, do not think I do either. I seem, then, in just this little thing to be wiser than this man at any rate, that what I do not know I do not think I know either.

talk given by S. Forte at the 8th Workshop of the Higgs Cross Section Working Group, 22nd Jan. '15

Conclusions

- Fantastic data available and expected from LHC (restarts operation for three years this summer)
- Higgs discovery was a true milestone for particle physics, but also leaves many questions open (hierarchy problem, naturalness, ...)
- Run II will focus on precision studies: what does the future hold?