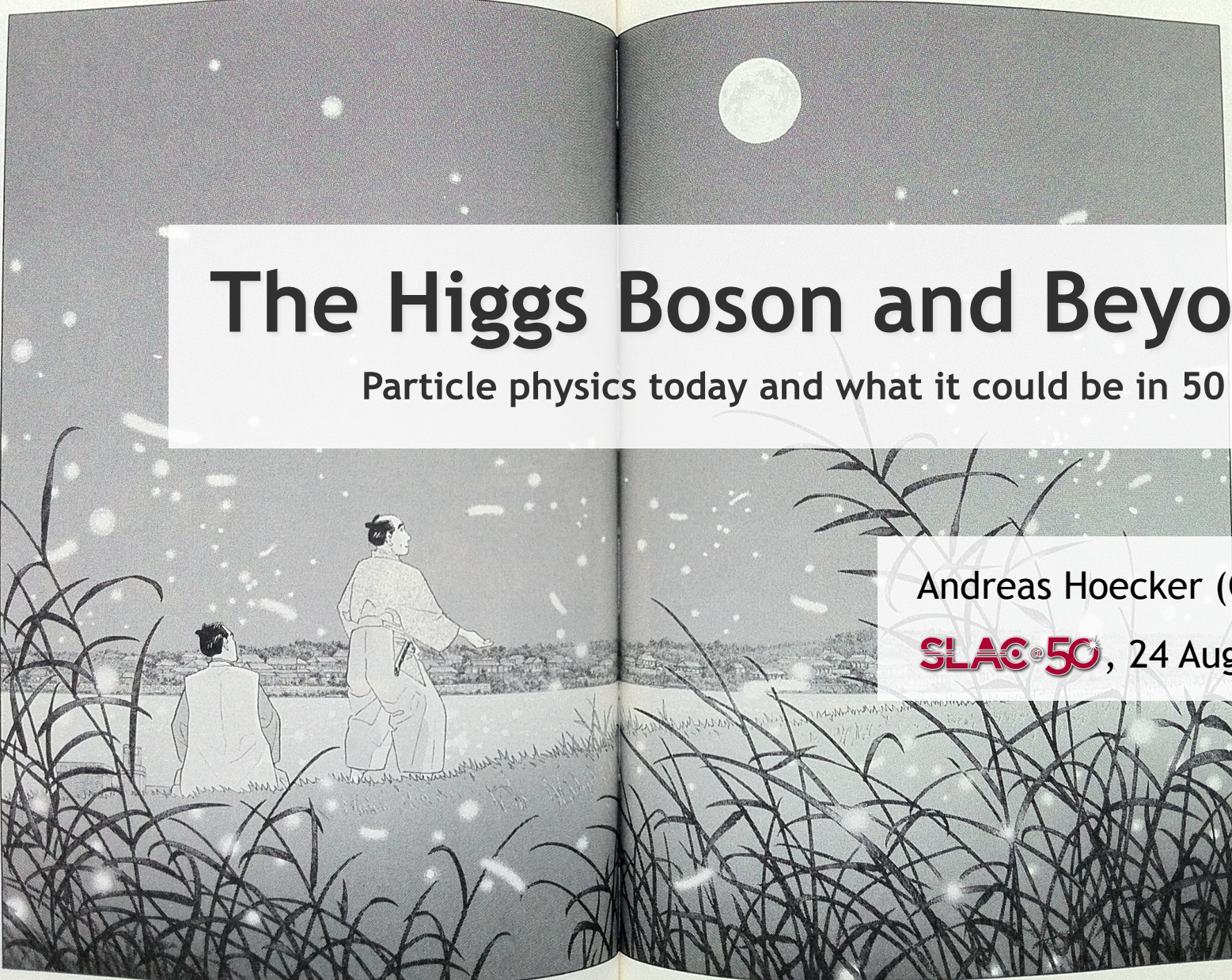




The Higgs Boson and Beyond

Particle physics today and what it could be in 50 years

Andreas Hoecker (CERN)

SLAC@50, 24 Aug 2012

*"It's all made of a handful
of particles and forces"*

*"Through its relation with
cosmology the study of
particles and forces is also
a journey back in time"*

Jiro Taniguchi, Furari, © Casterman (2012)



*"Can we truly grasp the magnitude of
everything that has unfolded in the
natural universe between those first
momentary particles and the present
day?"*

Brian Watson in The Salem News (Aug 16, 2012)

**Mankind's search for the smallest unit of
matter, its different forms, and the
forces acting is much, much older than
*particle physics***

***Particle physics* is a term naming the
search for the ultimate laws of Nature**

*Everyday life, and
particle physics, are
described by the
Standard Model (SM)*

Jiro Taniguchi, Furari, © Casterman (2012)



**The SM is *the* legacy of 20th century
particle physics**

- *It unifies quantum mechanics, special relativity and field theory*
- *It describes ~ all laboratory data*

**Is the SM the theory of everything?
Or rather of *almost* everything? Or ...**

Year
when
energy
reached
in labs

~2010

~1970

~1900

$L_{\text{gravitation}} \sim 10^{-35} \text{ m}$

$L_{\text{weak}} \sim 10^{-18} \text{ m}$

$L_{\text{strong}} \sim 10^{-15} \text{ m}$

$L_{\text{atomic}} \sim 10^{-10} \text{ m}$

10^{19} GeV

10^{16} GeV

10^{14} GeV

10 TeV

1 TeV

100 GeV

10 GeV

1 GeV

100 MeV

10 MeV

1 MeV

100 keV

10 keV

1 keV

100 eV

10 eV

1 eV

100 meV

10 meV

0

Planck scale (M_{Pl})

GUT ?

ν_R ?

LHC reach

New Physics ?

t, Z, W, H, EWSB

ψ, b, Y, B

$\tau, c, n, p, \rho, \phi$

μ, s, π, QCD

$u, d, \text{nuclear binding } E$

e

core of Sun

atomic binding E

ν 's

$\downarrow ?$

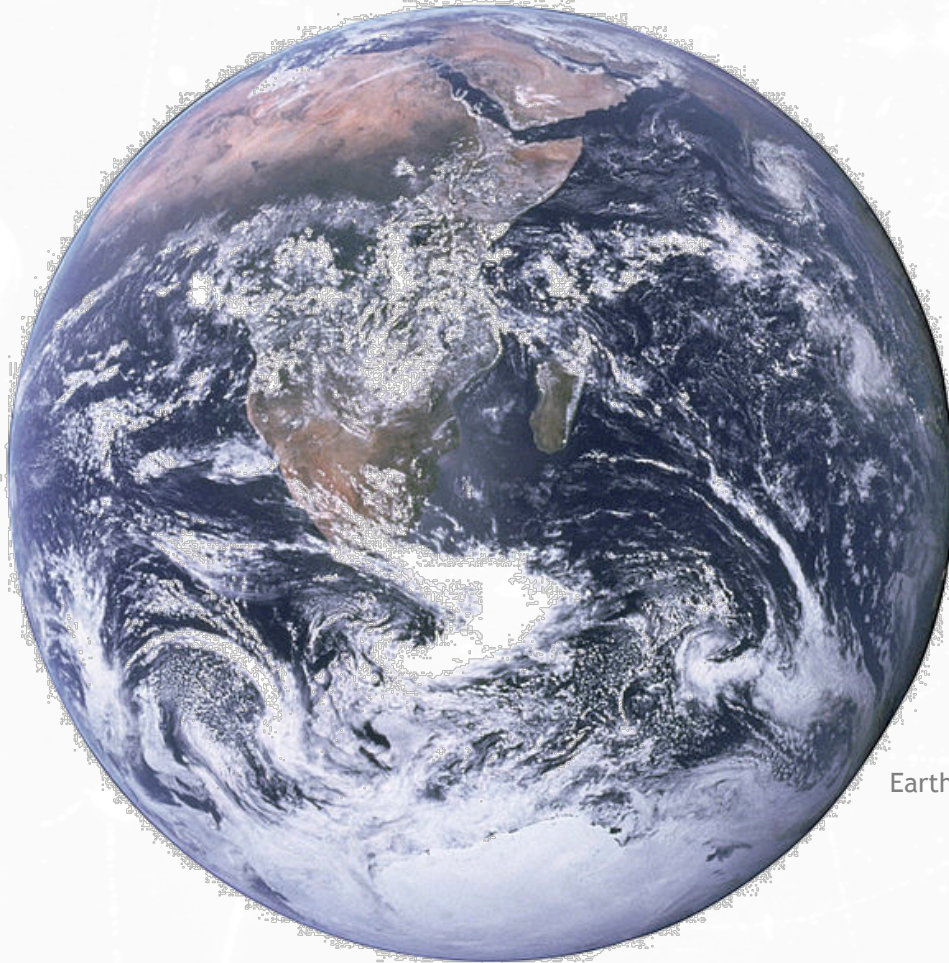
γ, g

...probing
attometer
scales

A 1 TeV-frequency microscope looks at really, really tiny objects...

Nanoscience

Particle physics today
(TeV scale)



Earth



Siphonaptera (flea)

The Standard Model

The SM consists of **24 elementary matter particles** and **3 forces** with total of 26 parameters

Fermions

Matter particles

Organised in 3 families

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

6 Leptons

$$\ell$$

6 Quarks

$$q$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Bosons

Force quanta

Distinguishing 3 forces

Photon

$$\gamma$$

3 weak bosons

$$W^\pm$$

$$Z^0$$

8 Gluons

$$8 \times g$$

Electro-magnetic force

Weak force

Strong force

Higgs boson

$$H^0$$

*Breaks electroweak symmetry
Generates boson and fermion masses*

The Standard Model

Elementary particle physics is successfully described by **local gauge theories**

A problem: local gauge symmetry requires **massless spin-1 “gauge” (=force) boson**

This has been well verified for QED, with a massless photon (= infinite range)

However, the **W, Z bosons are massive** (= finite range $\sim 10^{-15}$ cm)

Only way to break gauge symmetry consistently is to **spontaneously break the symmetry of the vacuum:**

$$M_{Z,W} \neq 0 \quad \Leftrightarrow \quad \langle 0 | \phi | 0 \rangle = v \neq 0 \quad [\text{non-zero vacuum expectation value}]$$

ϕ is a complex doublet field with non-zero vacuum expectation value.

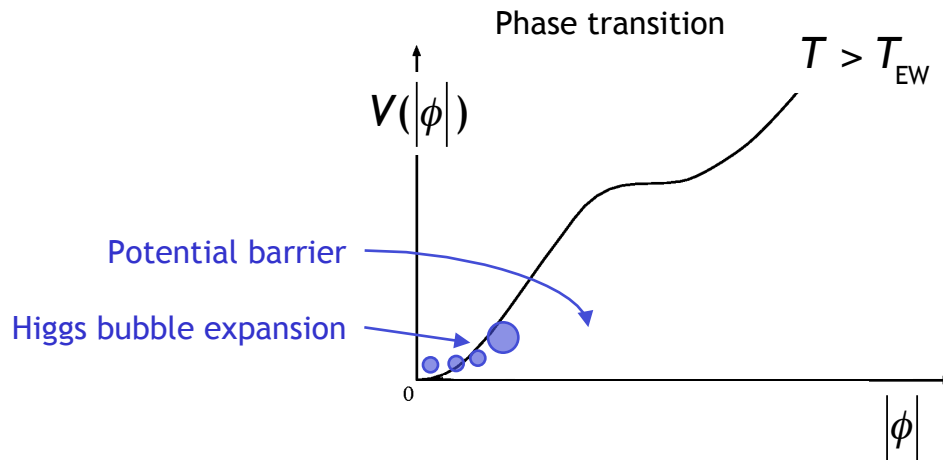
3 d.o.fs become Z, $W^\pm$ masses, remaining d.o.f is **massive scalar Higgs boson**

This is known as the **“Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism”**

The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

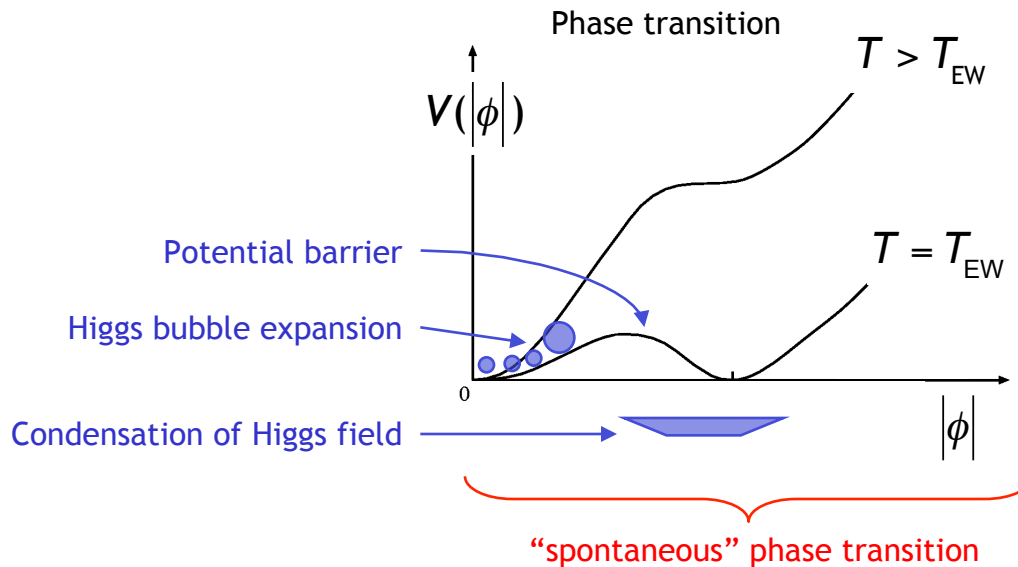
The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ (10^{-10} s after big bang) led to $|\phi_{min}| > 0$



The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
 A phase transition at $\sim T_{EW}$ (10^{-10} s after big bang) led to $|\phi_{min}| > 0$



Higgs potential:
$$V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

Simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems.

Carries the seeds for new physics ...

The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

A **Higgs field** displaces ground
state breaking gauge symmetry

It fills all space time (but w/o
orientation as spin=0)

Particles interact with the Higgs
field and reduce their velocity.
They acquire a mass proportional
to interaction strength

→ Action of the Higgs field
creates a ***vacuum viscosity***

Higgs quantum liquid in broken phase

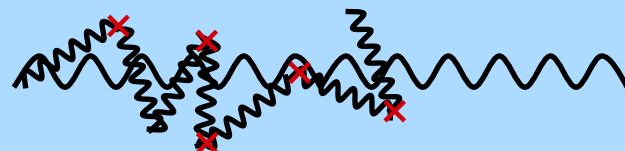
Gravity



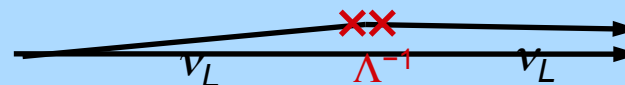
Photon



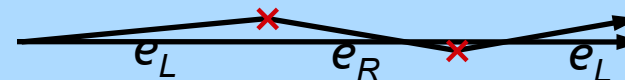
Weak boson



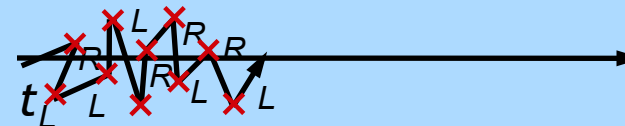
Neutrinos



Electrons



Top quark



H. Murayama

Massive particles
interacting with the
condensed Higgs field

*... like fireflies in the
night sky of Ochiai*



The Higgs boson – last of the particles ?

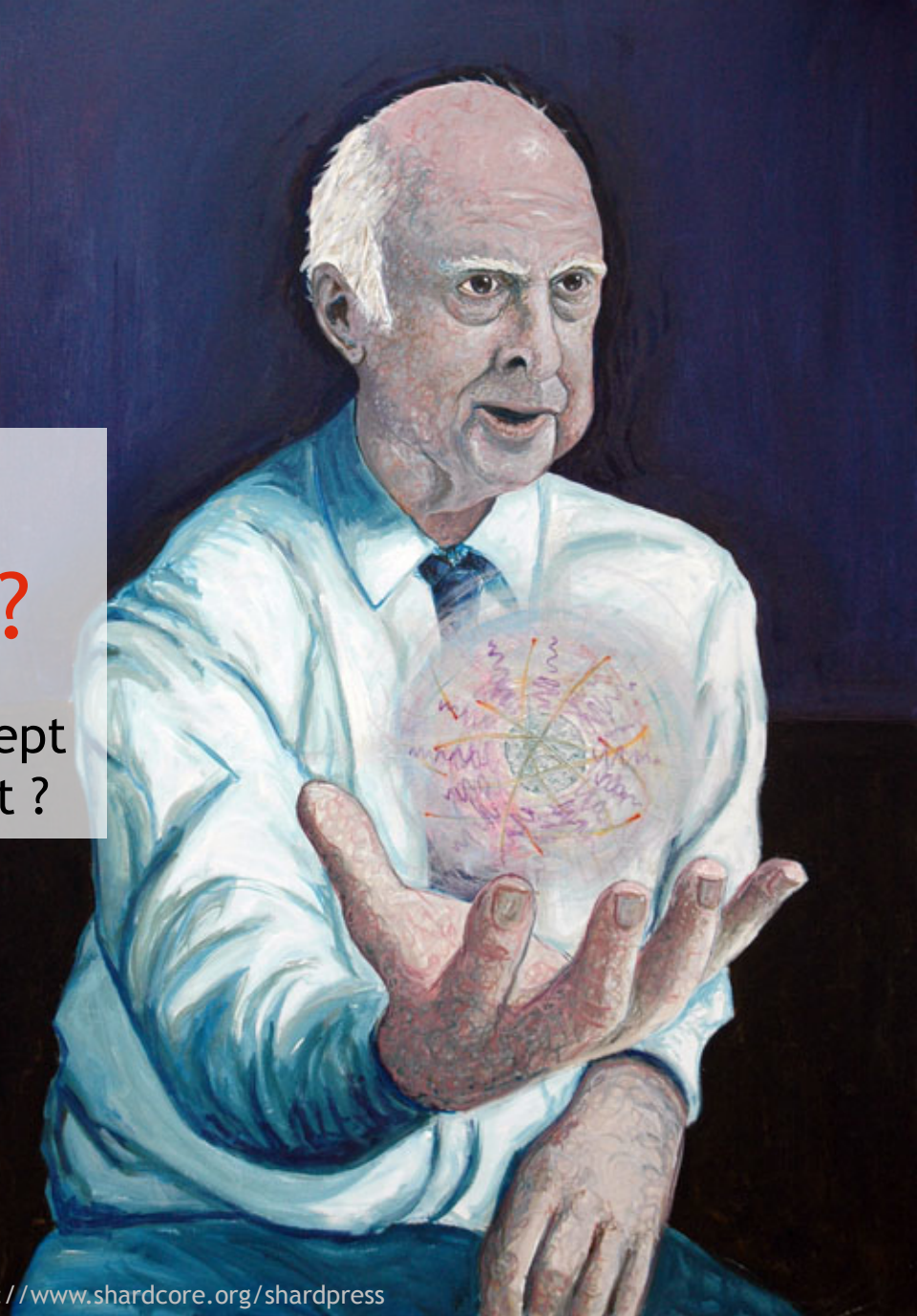
The SM predicts all its properties, except
for its mass. What was known about it ?

Full references for mechanism:

F. Englert and R. Brout, PRL 13 (1964) 321.
P.W. Higgs, PRL 13 (1964) 508.
G. Guralnik, C. Hagen, and T.W.B. Kibble, PRL 13 (1964) 585.

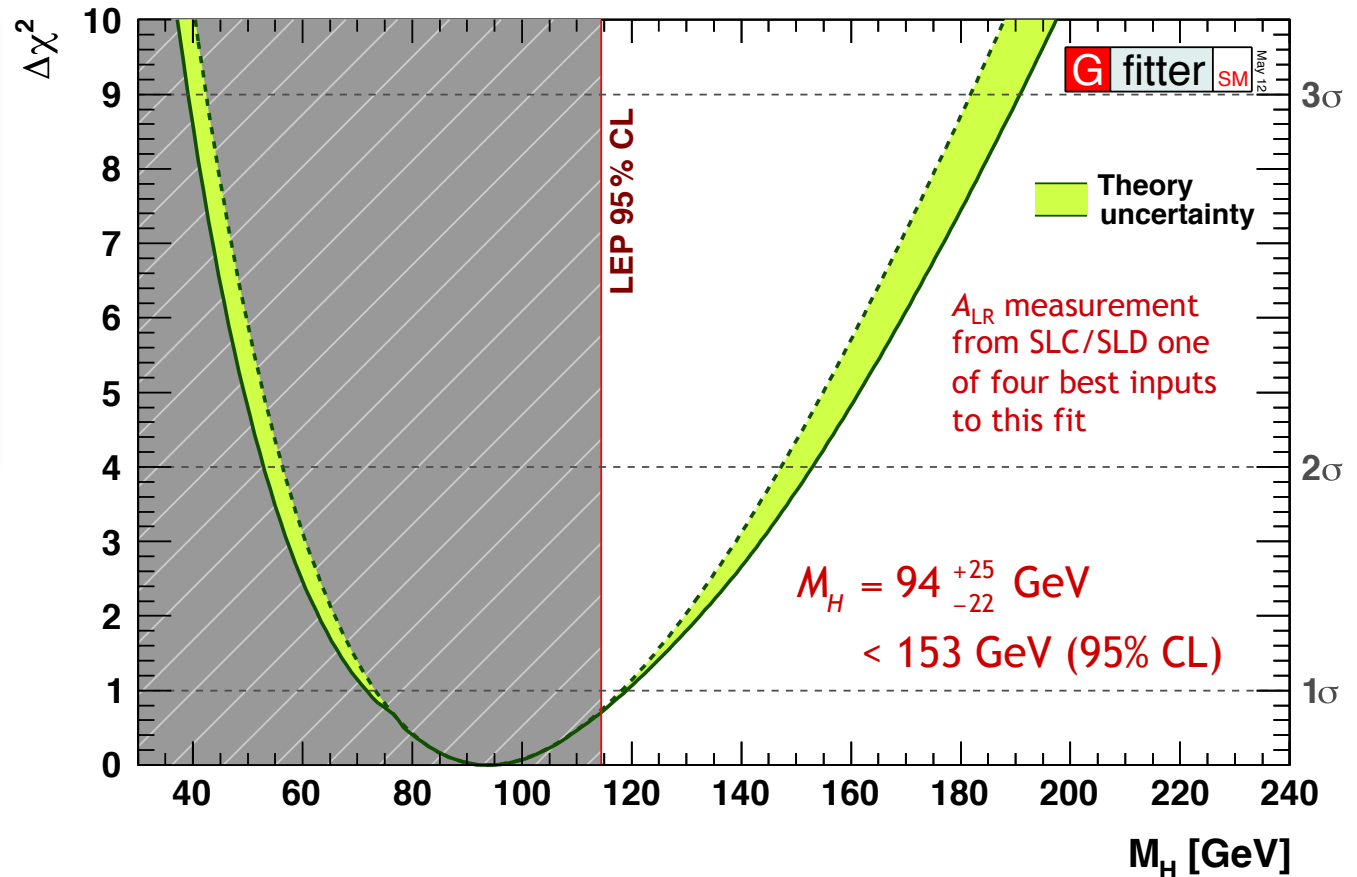
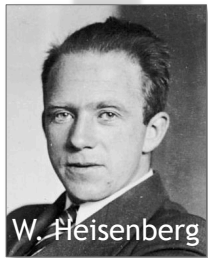
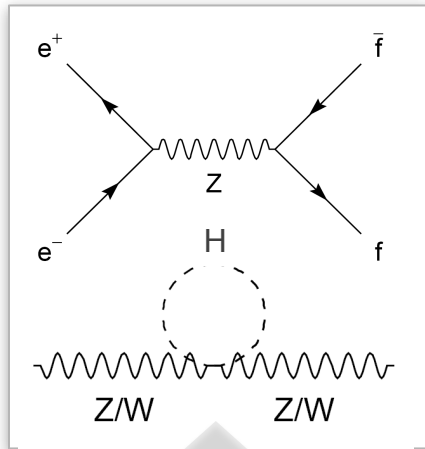
It is also of note that Landau and Ginzburg had proposed a field giving the photon a mass in a superconductor, the mathematics of which is identical to the “Higgs mechanism” and predates it by several years.

<http://www.shardcore.org/shardpress>



Constraints from global electroweak fit

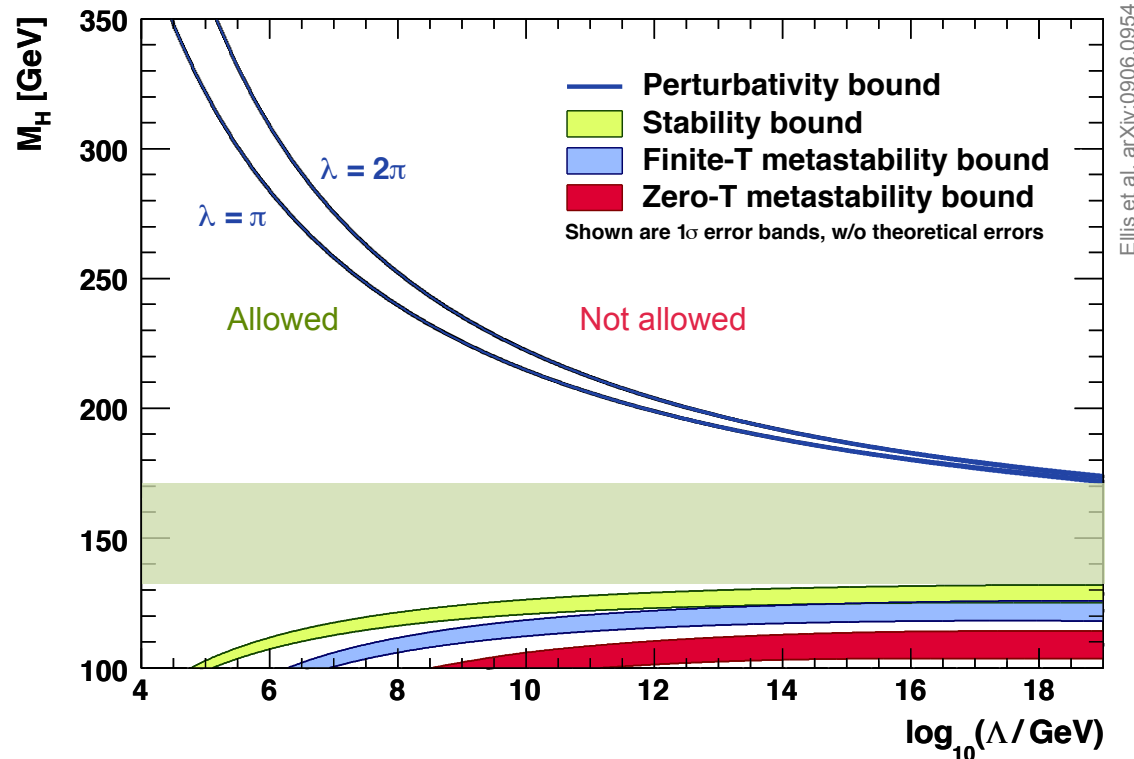
Global fit of all EW precision measurements to SM prediction constrains M_H



<http://gitter.desy.de>

The Higgs boson should not be too light, and not too heavy...

Perturbativity and (meta)stability bounds versus the SM cut-off scale Λ



The SM Higgs must steer a narrow course between two disastrous situations if the SM is to survive up to the Planck scale $M_P \sim 2 \times 10^{18}$ GeV



Global Effort → Global Success

Results today only possible due to extraordinary performance of accelerators – experiments – Grid computing

Observation of a new particle consistent with a Higgs Boson (but which one...?)

Historic Milestone but only the beginning

Global Implications for the future



ps

LEP/LIBRARY

CERN LIBRARIES, GENEVA



LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

Duration of projects /planning stability:
First LHC workshop 1984 !

Global Effort → Global Success

Results today only possible due to
extraordinary performance of
accelerators – experiments – Grid computing

Observation of a new particle consistent with
a Higgs Boson (but which one...?)

Historic Milestone but only the beginning



Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine



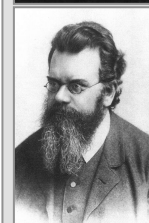
Lawrence

Particles accelerators:

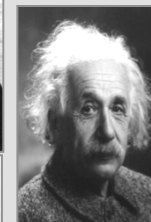
- Look deeper into matter (size $\sim 1/E$)
("powerful microscopes")
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)



de Broglie



Einstein

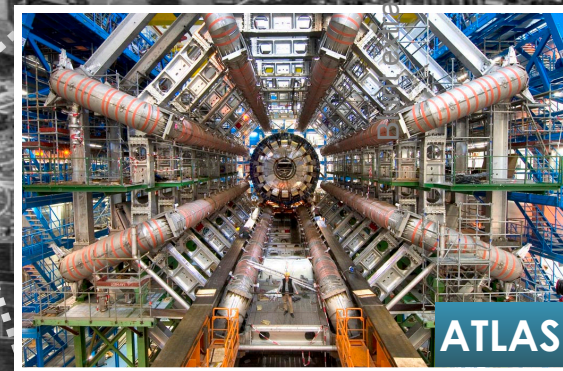
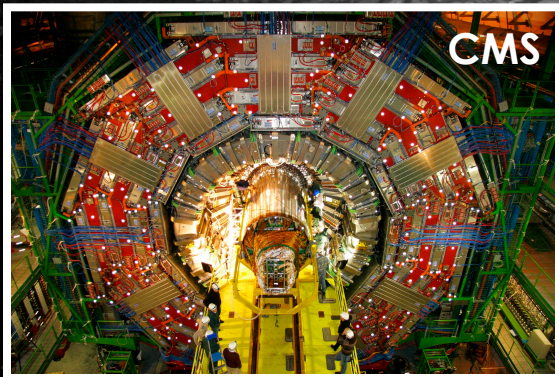


Boltzmann

An aerial photograph of the CERN facility in Switzerland, showing the extensive LHC ring. The ring is a large, circular structure that spans across a vast, patchwork landscape of fields and forests. The text "LHC ring at CERN: 27 km circumference" is overlaid on the image. The landscape is a mix of green fields and brown patches, with some buildings and roads visible. The sky is a deep blue, and the overall scene is a high-angle view from above.

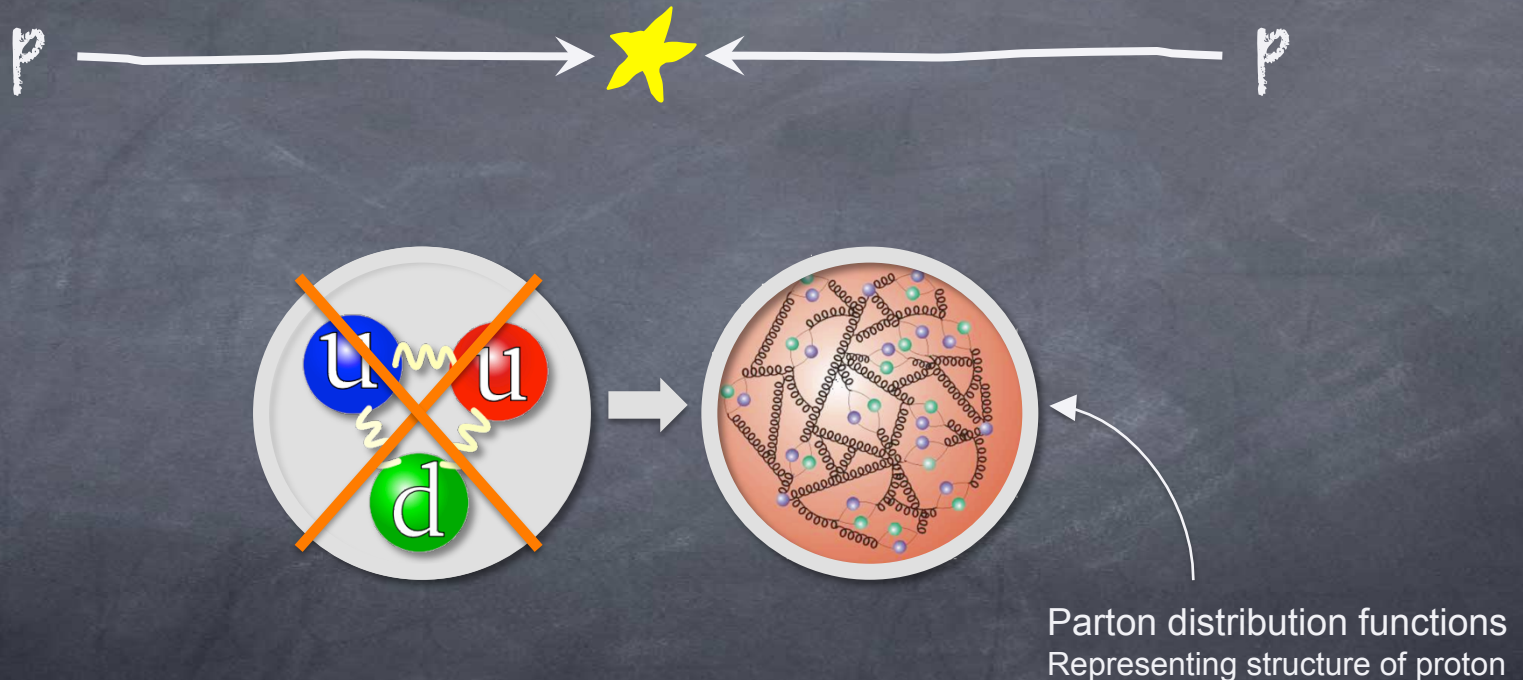
**LHC ring at CERN:
27 km circumference**

**So far:
7/8 TeV proton–proton collisions
2.76 TeV Pb–Pb collisions**



Higgs boson searches at the LHC

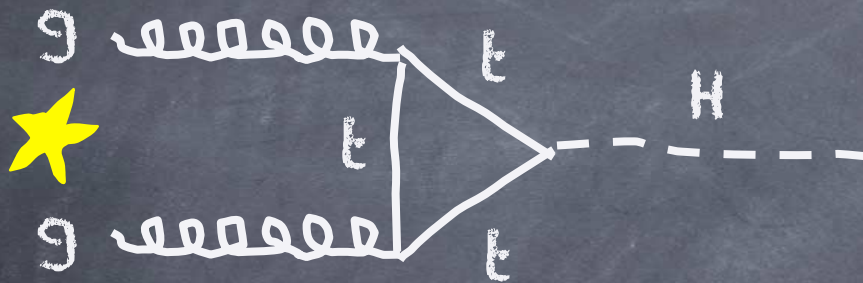
Higgs production and decay probabilities predicted vs. Higgs mass by SM



Higgs boson searches at the LHC

Higgs production and decay probabilities predicted vs. Higgs mass by SM

At the LHC, the Higgs boson is produced dominantly from gluon fusion via top loop



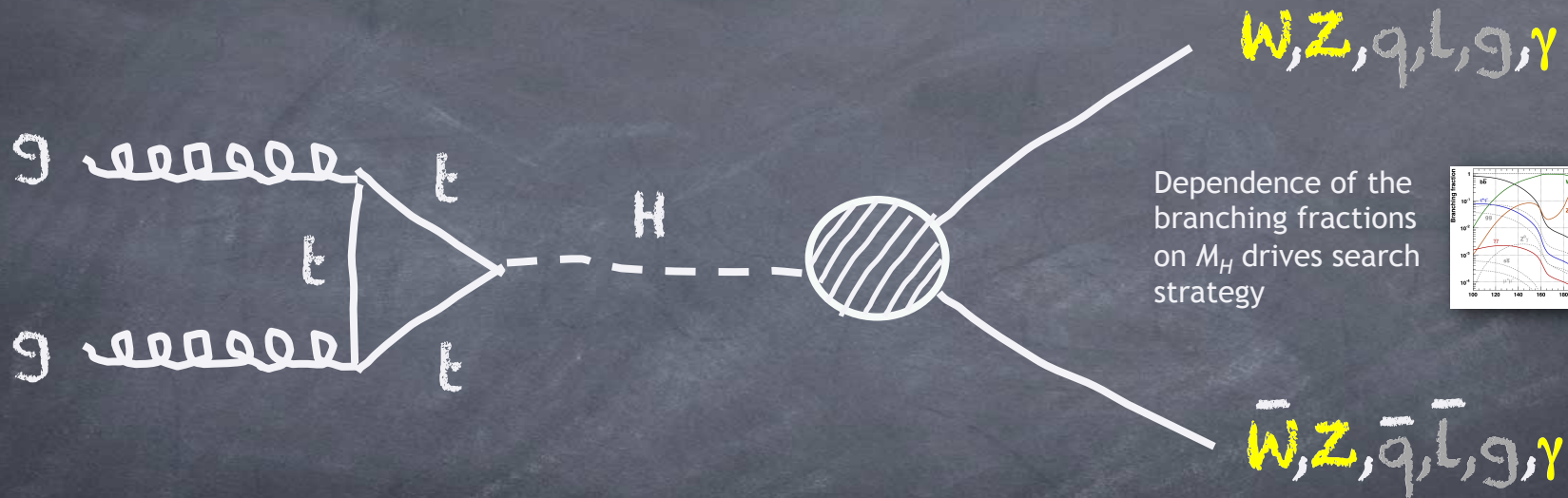
Total production of
~210 thousand Higgs
bosons of 125 GeV in
2011 and 2012 in each
ATLAS and CMS (by 07/2012)

Higgs production cross section decreases with Higgs mass

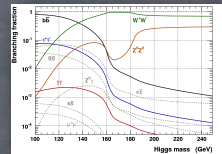
Higgs boson searches at the LHC

Higgs production and decay probabilities predicted vs. Higgs mass by SM

At the LHC, the Higgs boson is produced dominantly via gluon fusion through top



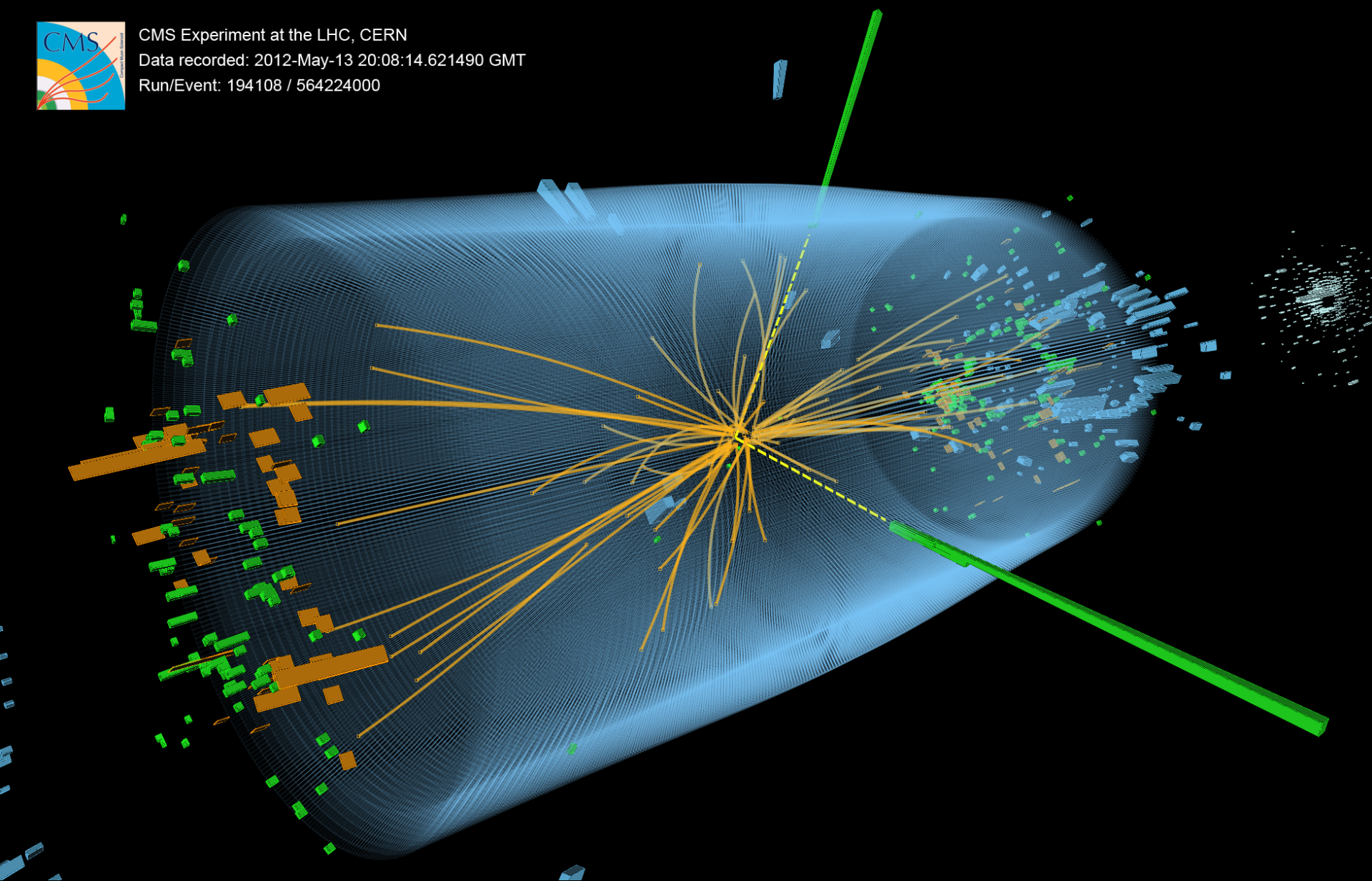
Dependence of the branching fractions on M_H drives search strategy



Higgs decays: Higgs couples to mass $\rightarrow$ stronger coupling to heavier particles
Coupling to massless particles (photons, gluons) through *heavy virtual particles*



CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



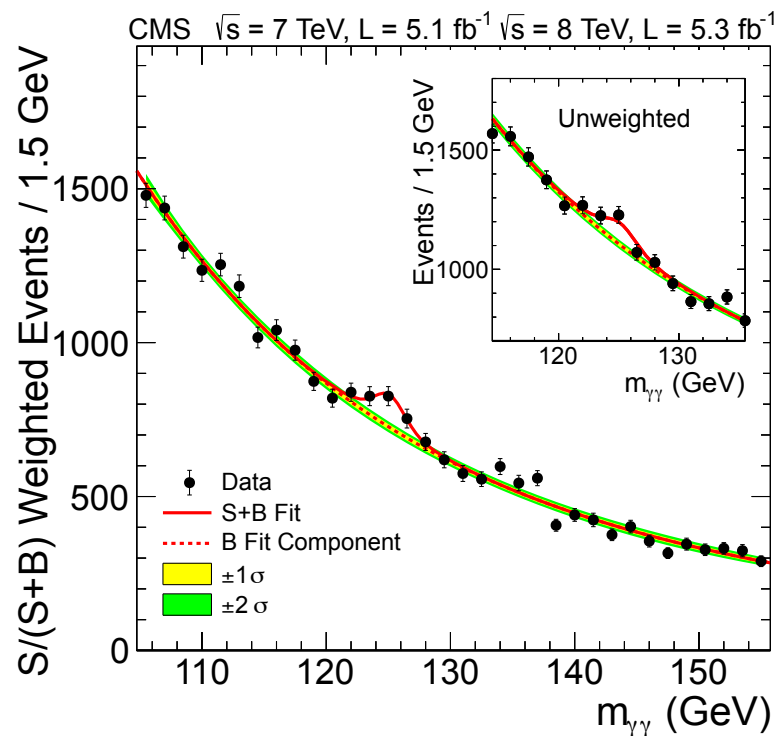
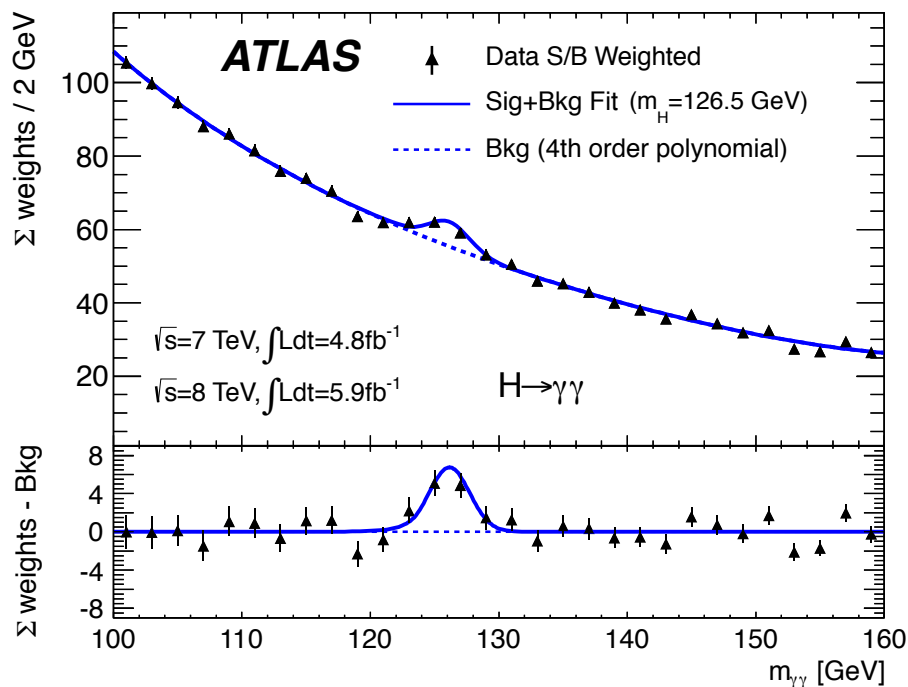
$H \rightarrow \gamma\gamma$ candidate event (CMS) — note: background dominated sample

$$H \rightarrow \gamma\gamma$$

Clean discovery channels for Higgs, allowing precise mass determination

ATLAS arXiv:1207.7214, CMS arXiv:1207.7235, both submitted on Aug 1st, 2012 to PLB

Benefit from excellent energy resolution and photon identification capabilities of ATLAS/CMS



Both experiments classify events according to resolution and topology in ML fit

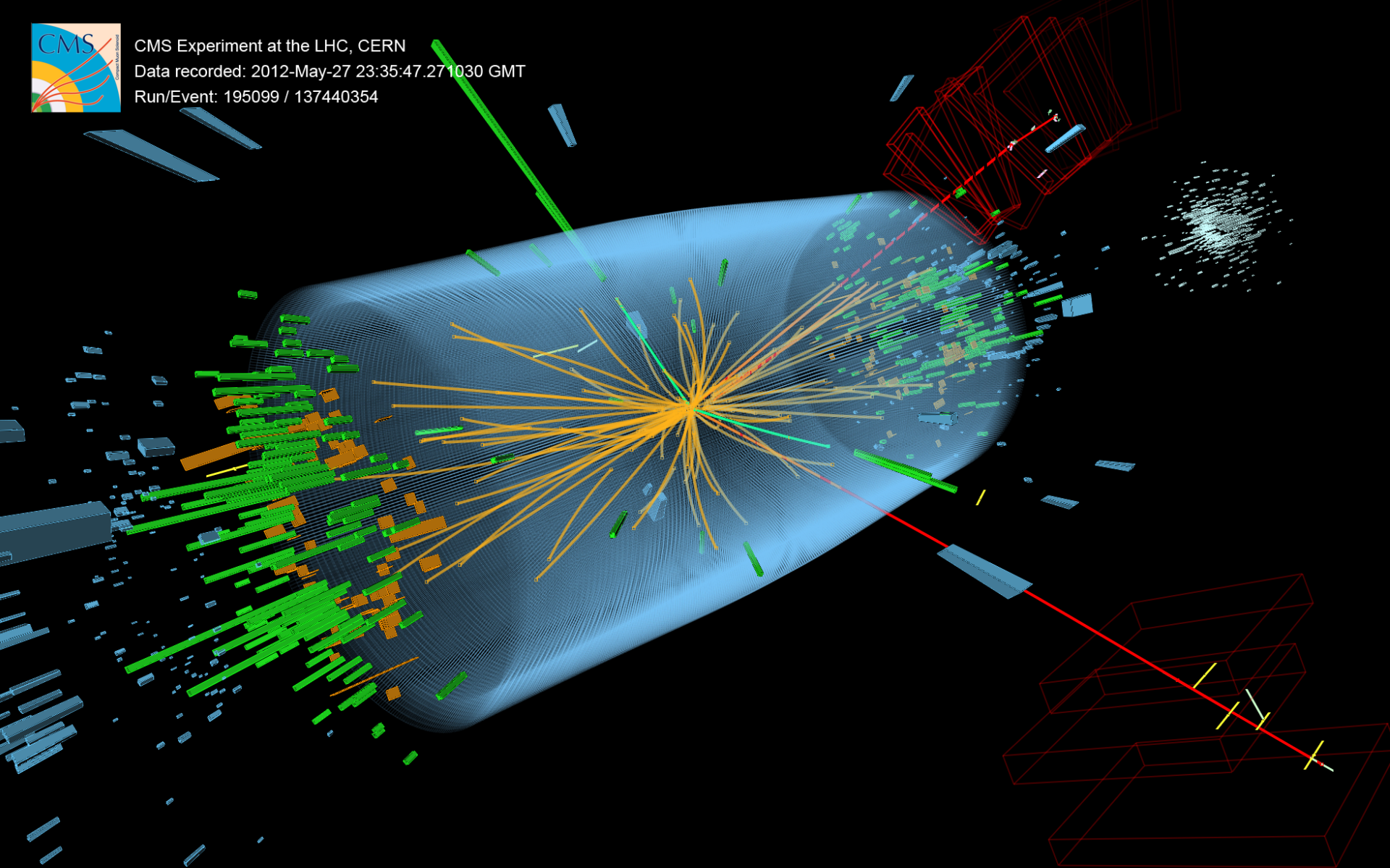
Maximum excess of 4.5σ (4.1σ) seen by ATLAS (CMS) at 126.5 (125) GeV



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354



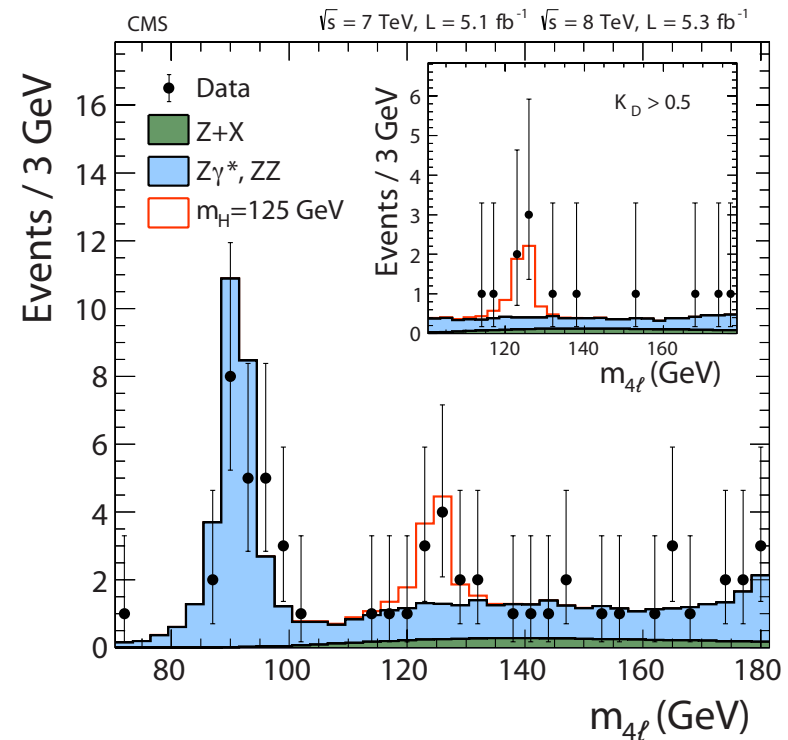
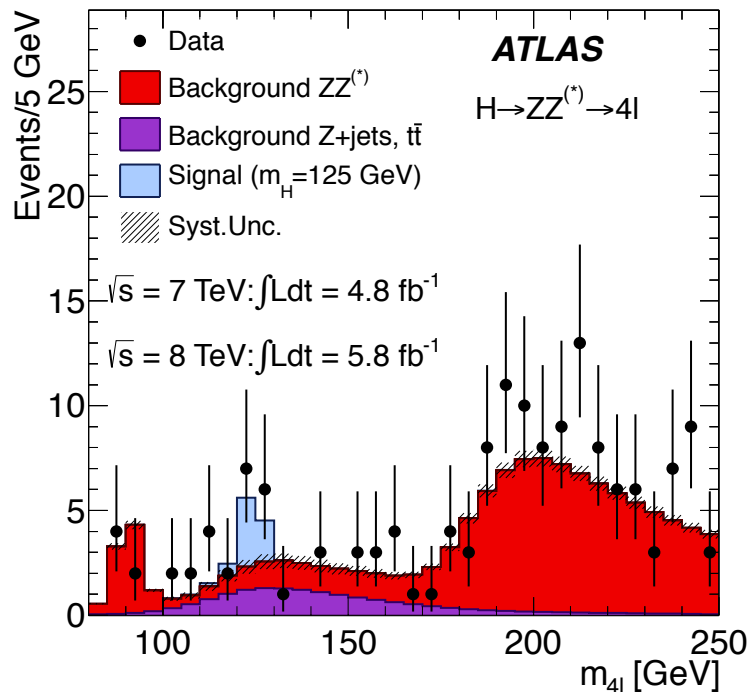
$H \rightarrow 2e2\mu$ candidate event (CMS)

$$H \rightarrow ZZ^{(*)} \rightarrow 2(e, \mu) + 2(e, \mu)$$

Clean discovery channels for Higgs, allowing precise mass determination

ATLAS arXiv:1207.7214, CMS arXiv:1207.7235, both submitted on Aug 1st, 2012 to PLB

Benefit from excellent energy/momentum resolution and identification capabilities at ATLAS/CMS



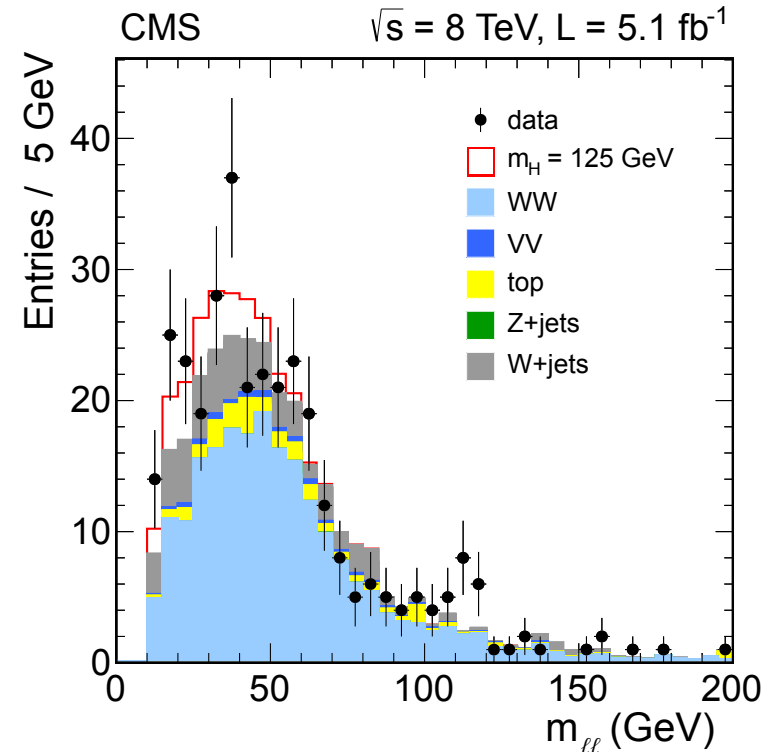
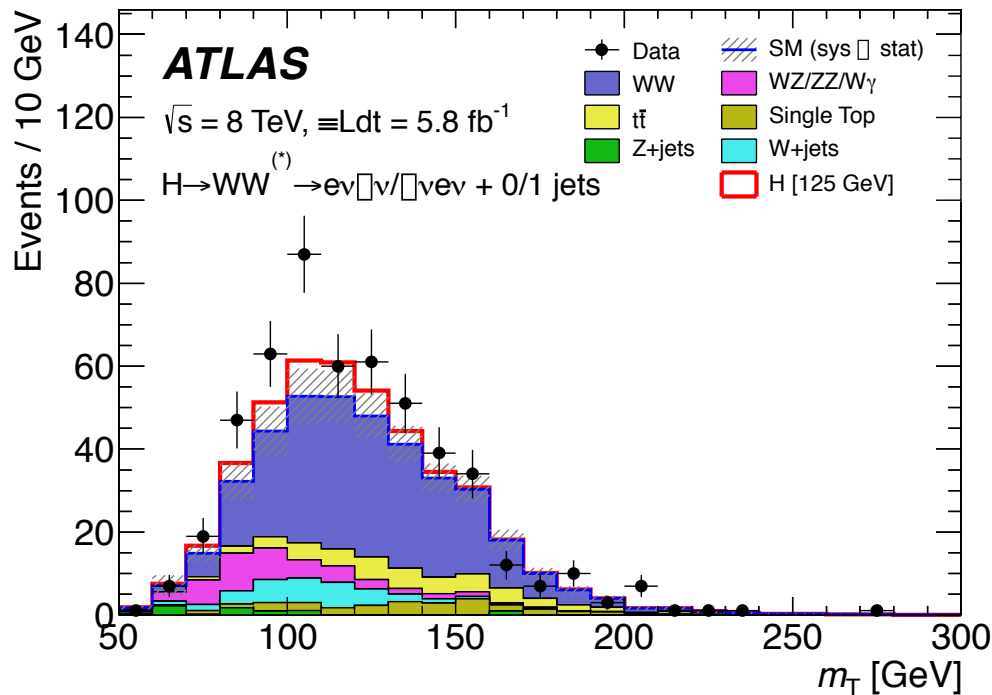
Order one S/B ratio. Maximum excess of 3.6σ (3.2σ) seen by ATLAS (CMS) at 125 (125.6) GeV

$$H \rightarrow WW^{(*)} \rightarrow 2(e, \mu) + 2\nu$$

Not clean, but abundant (competitive at 125 GeV) – little mass sensitivity

ATLAS arXiv:1207.7214, CMS arXiv:1207.7235, both submitted on Aug 1st, 2012 to PLB

Signal selection: reconstruct transverse Higgs mass, exploit W polarisation (leptons emitted in same dir.)



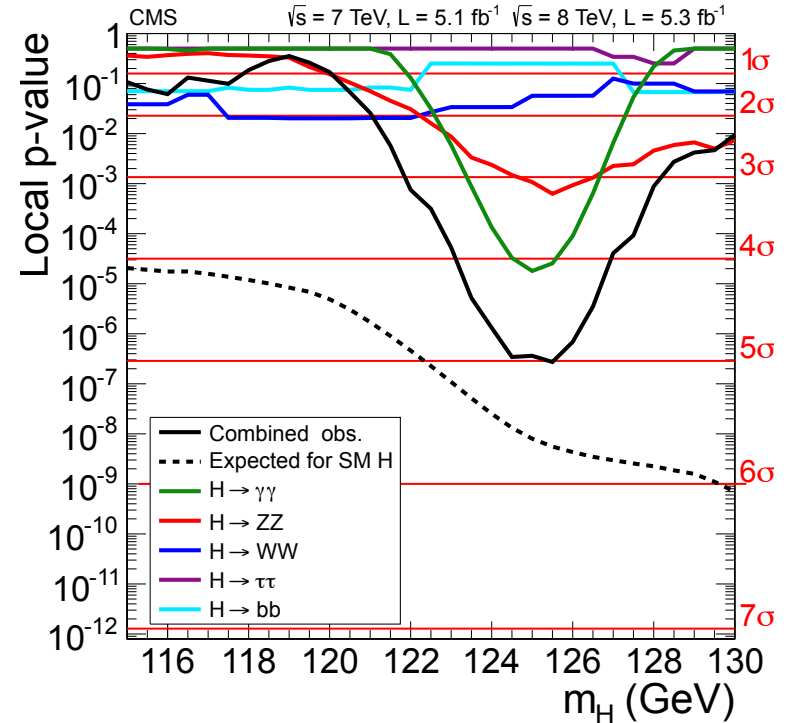
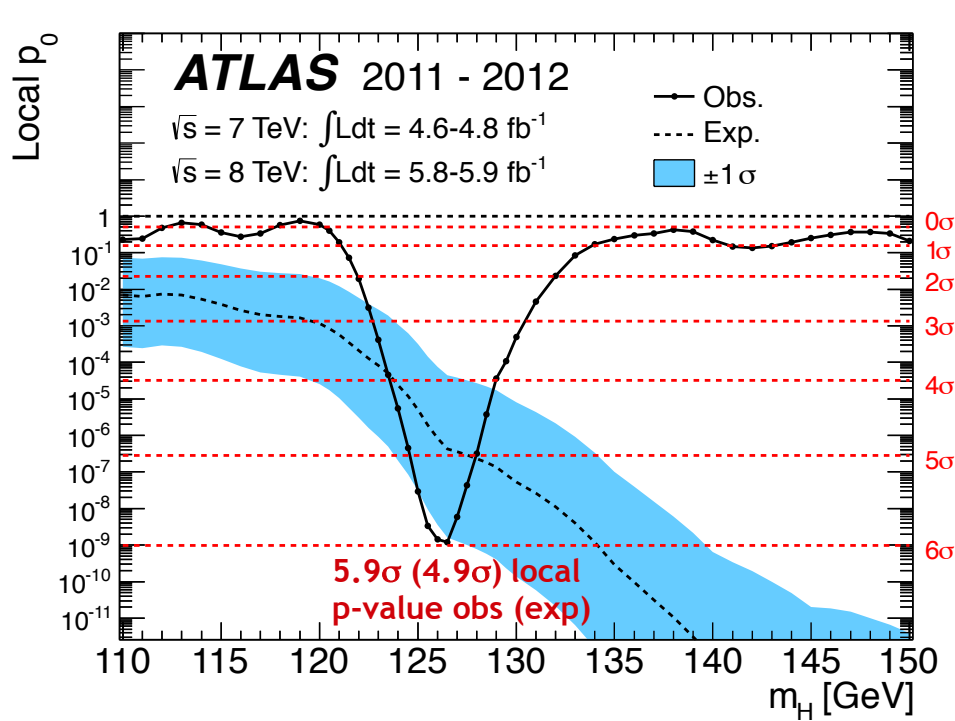
Some excess seen by both experiments: 2.8σ (1.6σ) for ATLAS (CMS) at $\sim 125 \text{ GeV}$

Combining all the channels

Discovery significance

ATLAS arXiv:1207.7214, CMS arXiv:1207.7235, both submitted on Aug 1st, 2012 to PLB

All results [$\gamma\gamma$, ZZ , WW , $\tau\tau$, bb] combined. Left: ATLAS right: CMS — low mass region shown only



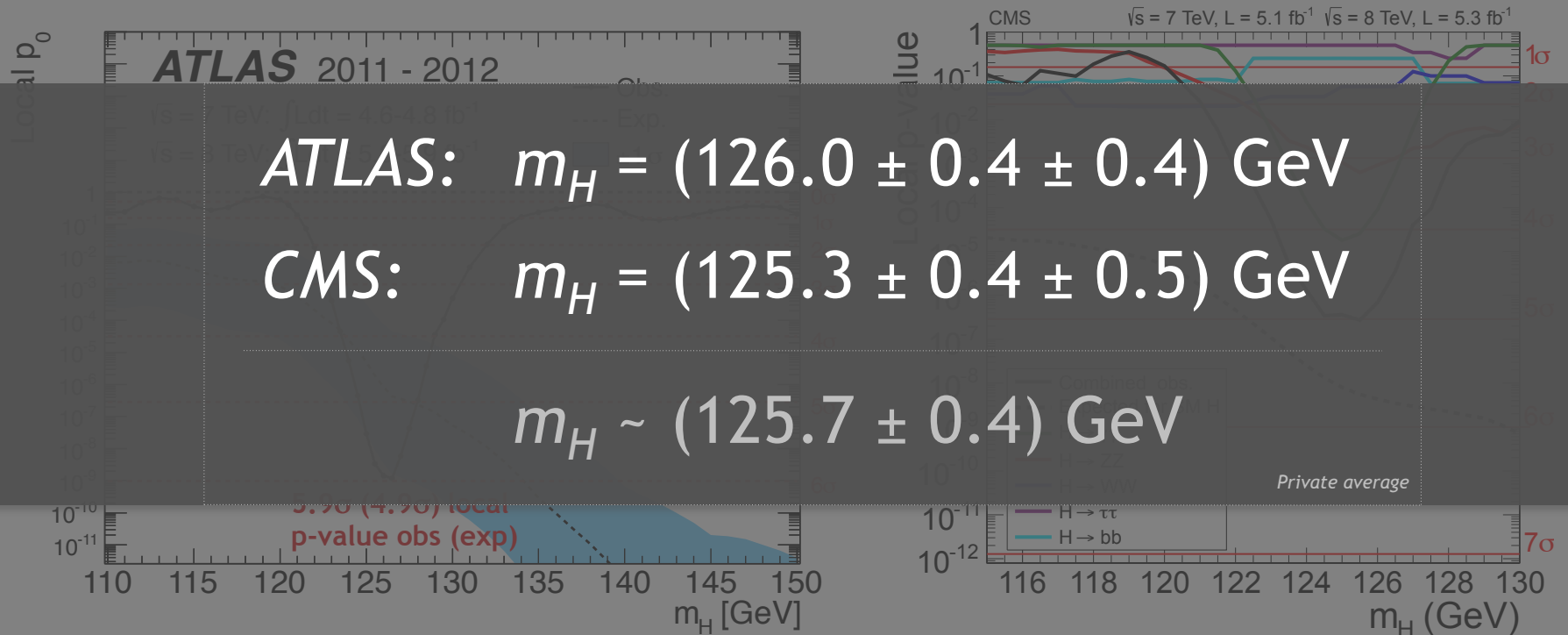
ATLAS (CMS) sees 5.9 σ (5.0 σ) excess at mass of 126.5 (125.3) GeV, $\delta(\text{mass}) \sim 0.6$ GeV

Combining all the channels

Discovery significance

ATLAS arXiv:1207.7214, CMS arXiv:1207.7235, both submitted on Aug 1st, 2012 to PLB

All results [$\gamma\gamma$, ZZ , WW , $\tau\tau$, bb] combined. Left: ATLAS right: CMS — low mass region shown only



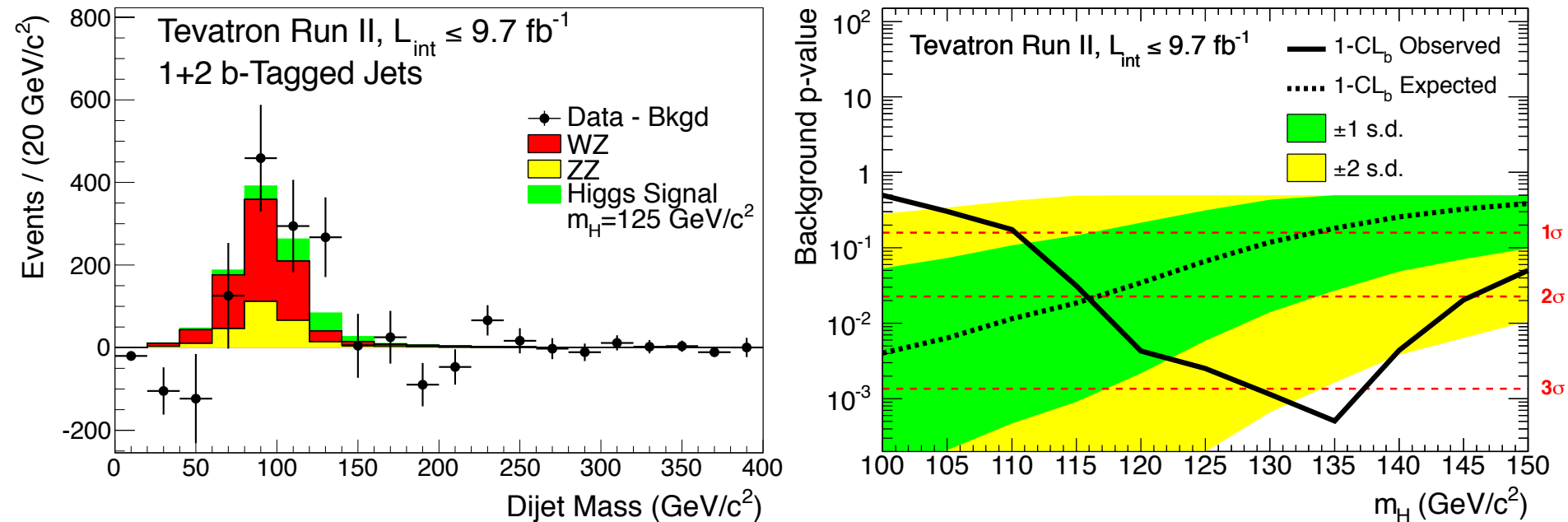
ATLAS (CMS) sees 5.9 σ (5.0 σ) excess at mass of 126.5 (125.3) GeV, $\delta(\text{mass}) \sim 0.6 \text{ GeV}$

Tevatron publishing final Higgs search results

Evidence for excess in $H \rightarrow bb$ produced in association with Z/W

CDF & D0, arXiv:1207.6436

Channels depends on good jet energy reconstruction. Harder at LHC due to increased background

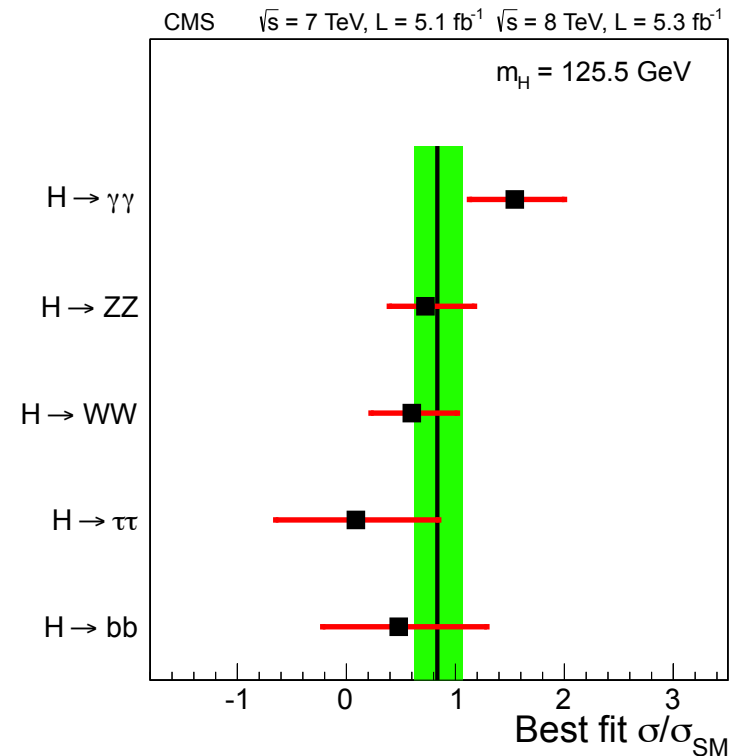
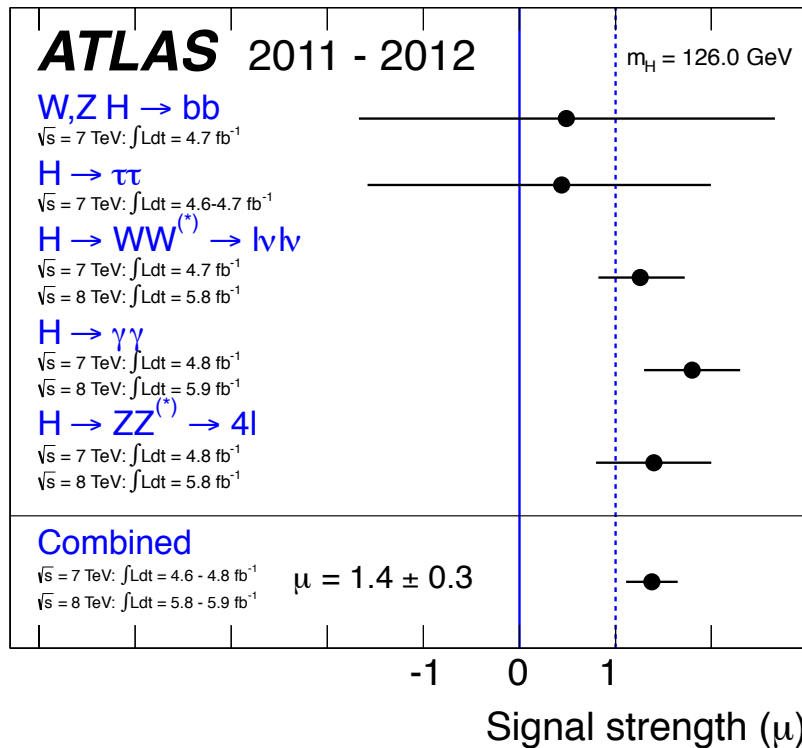


Maximum local excess of 3.1σ at 135 GeV ($\sim 1\sigma$ expected) but coarse mass resolution

Is it the Higgs boson with $J^{PC} = 0^{++}$ and SM couplings ?

Individual channel strength wrt. SM expectation seen by ATLAS and CMS

ATLAS arXiv:1207.7214, CMS arXiv:1207.7235, both submitted on Aug 1st, 2012 to PLB



$H \rightarrow \gamma\gamma$ channel a bit strong, overall agreement with SM within large uncertainties

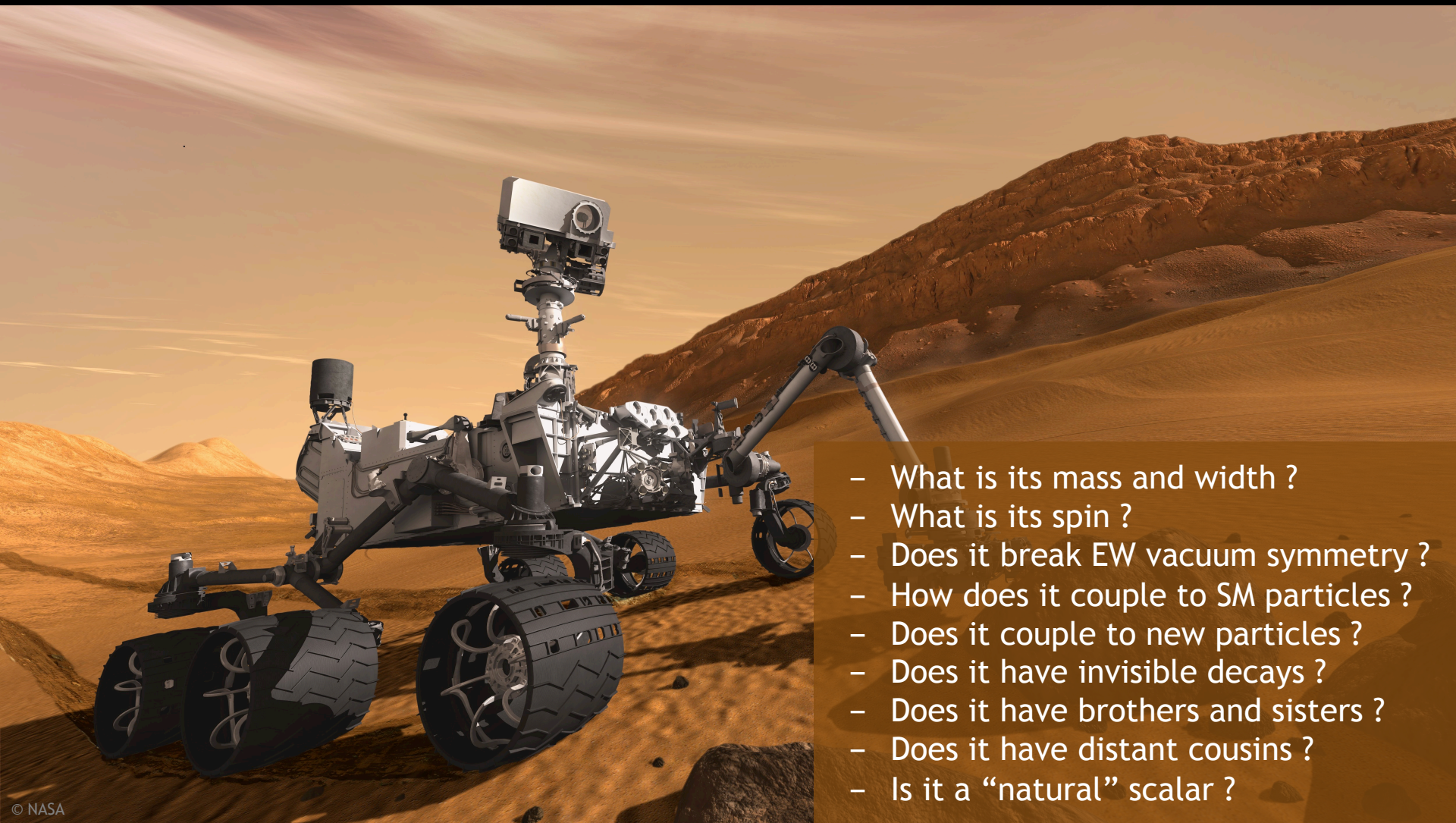
Is it the Higgs boson with $J^{PC} = 0^{++}$ and SM couplings ?

Individual channel strength wrt. SM expectation seen by ATLAS and CMS

Michael Peskin, in theoretical summary talk at HiggsHunting (July 2012):

SM strength (i.e., ‘large’) Higgs coupling to WW , ZZ is
“prima facie evidence that the particle is a CP even spin 0 state from a field with a vacuum expectation value that breaks $SU(2) \times U(1)$ ”

A new era in particle physics has begun: the exploration of planet Higgs

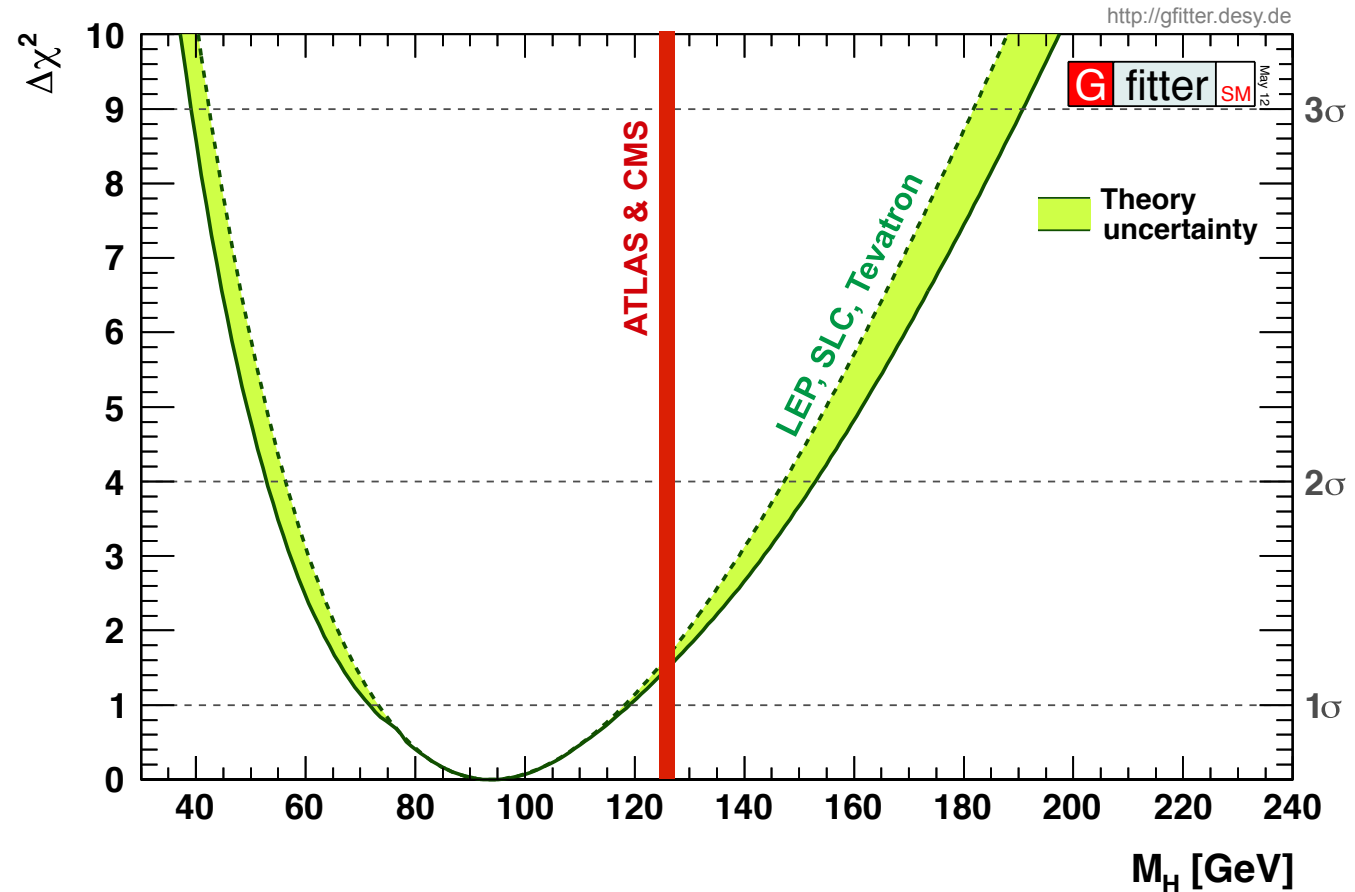
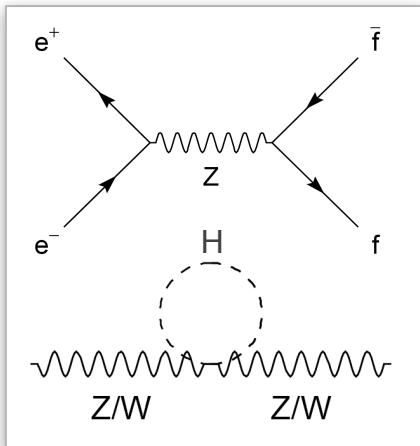


- What is its mass and width ?
- What is its spin ?
- Does it break EW vacuum symmetry ?
- How does it couple to SM particles ?
- Does it couple to new particles ?
- Does it have invisible decays ?
- Does it have brothers and sisters ?
- Does it have distant cousins ?
- Is it a “natural” scalar ?

What can we conclude from this discovery

Recall: light Higgs was predicted from SM fit to precision measurements

Discovery of light Higgs boson is a *huge success* of the Standard Model



What can we conclude from this discovery

Is the electroweak vacuum stable or metastable (if SM holds) ?

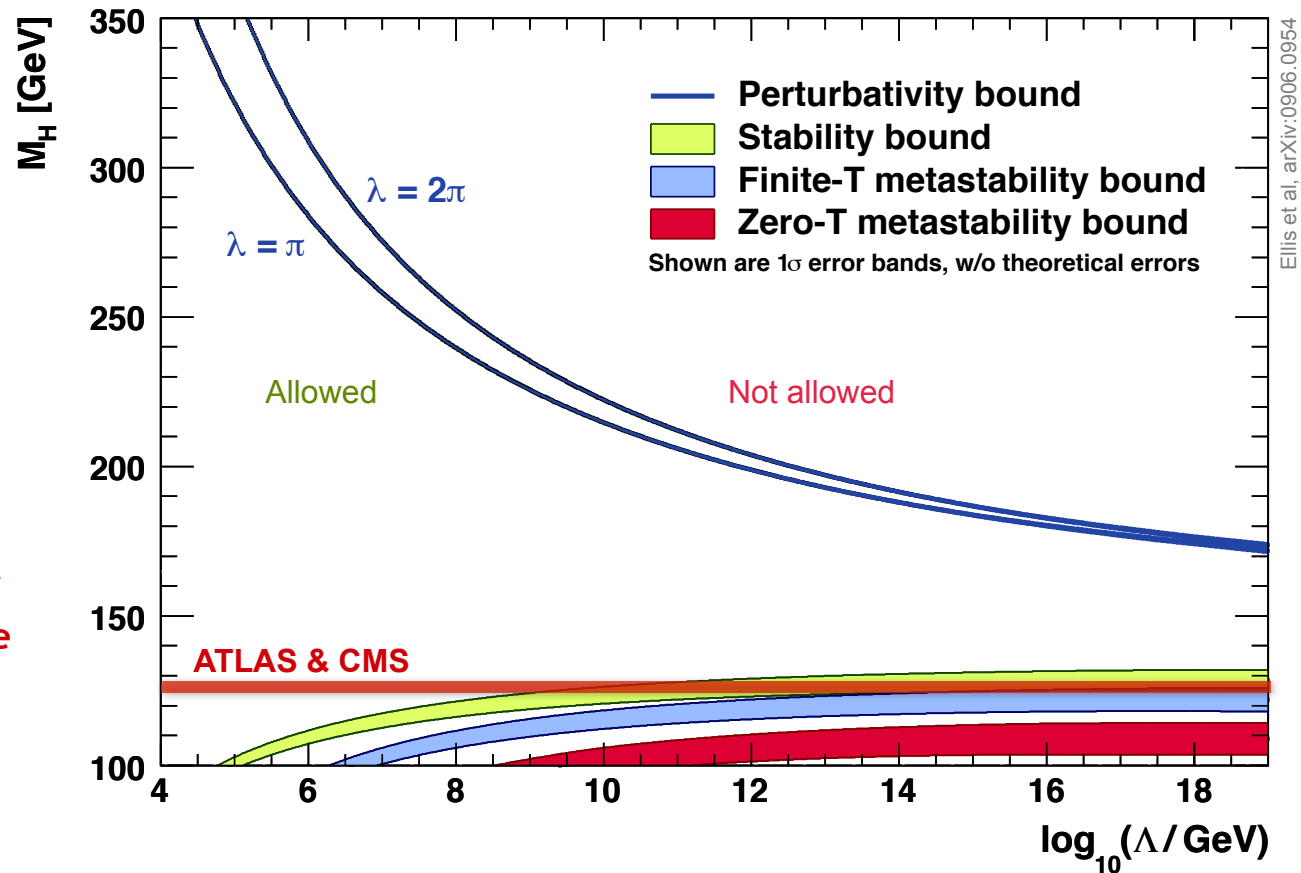
Barely stable ?

But: prediction of the stability bound suffers from theoretical uncertainties ...

Newest full NNLO result moves up stability bound at Planck mass by +0.8 GeV and reduces uncertainty

→ **barely stable or metastable, but certainly the Higgs self coupling would become very weak at M_{Pl}**

Degrassi et al, arXiv:1205.6497



100 years after the discovery of cosmic rays...

The discovery of the Higgs boson completes the Standard Model

Jiro Taniguchi, Furari, © Casterman (2012)



It is a triumph for the imagination and rigour of the human mind

It is a triumph for the greatest experimental undertaking ever:

Frontier of accelerator & detector technologies

Global data sharing, analysis & collaboration

The Standard Model
holds tight

Let us go through a
few more examples

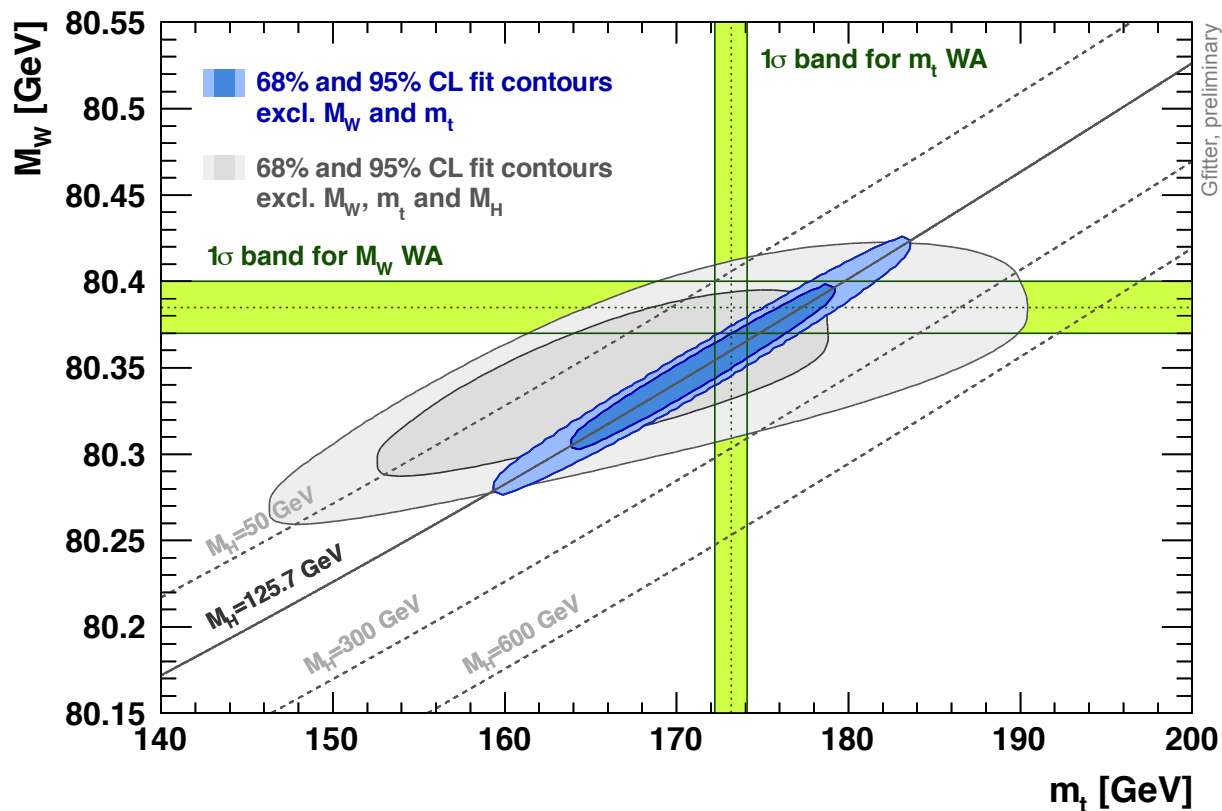
Jiro Taniguchi, Furari, © Casterman (2012)



The Standard Model holds tight

Electroweak unification has been verified at, below and above the Z-boson scale

Measured W vs. top mass compared to EW prediction



Gauge sector of SM at tree level is given by 3 free parameters, e.g.: α , M_Z , G_F

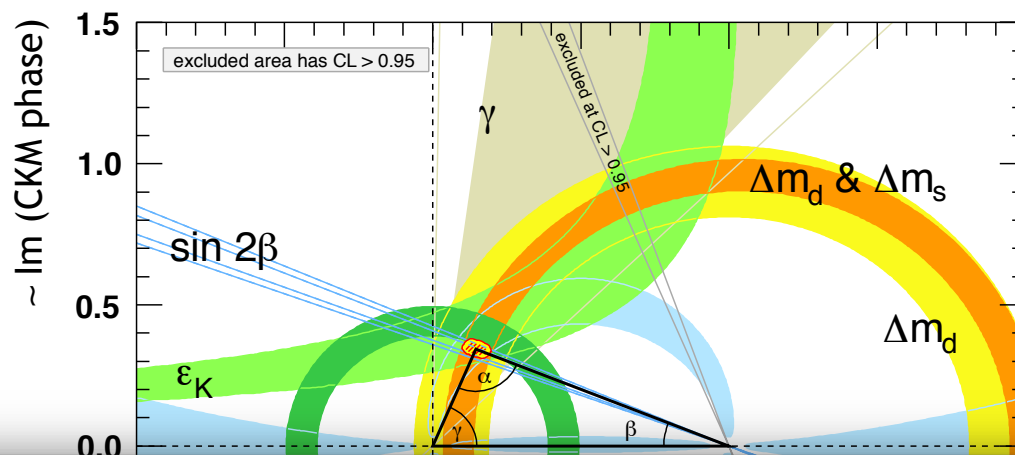
→ M_W predicted

Radiative corrections introduce quark mass dependence

Crucial contribution from SLC/SLD to this unification evidence

The Standard Model holds tight

All observations of CP violation are described by a single phase in the CKM matrix

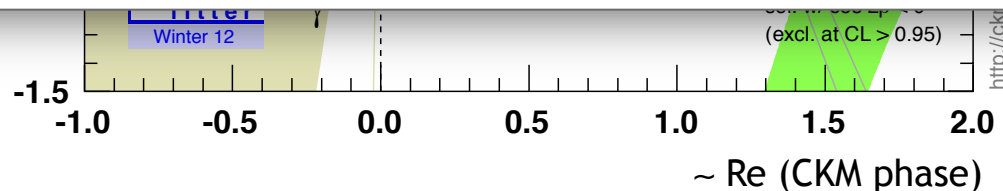


All CKM-phase sensitive measurements agree

[So far, agreement with SM also in the B_s system (LHC)]

Nobel prize for Kobayashi-Maskawa in 2008

Successful programme that relied on the strong vision and leadership of SLAC to build and exploit PEP-II and BABAR



The Standard Model holds tight

This is wonderful because:

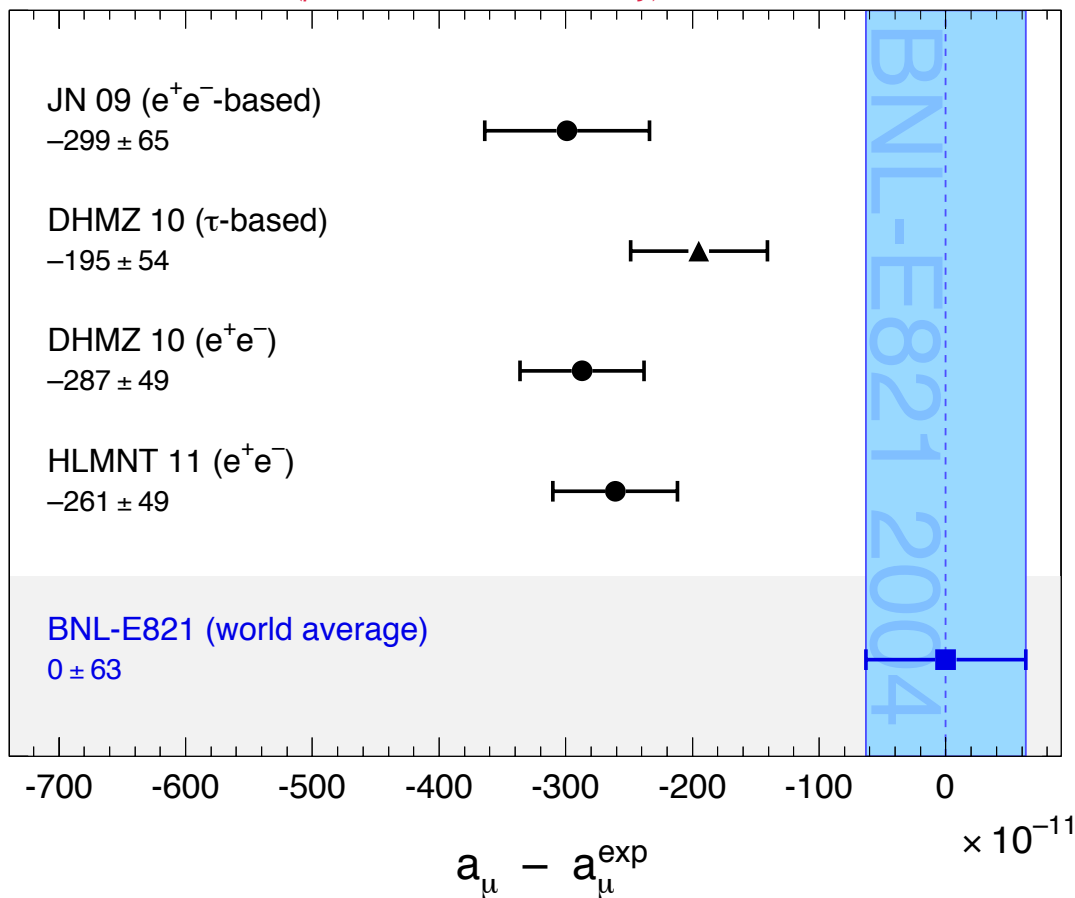
- we quantitatively understand what we see
- we can exploit this understanding to look for deviations

Does the Standard Model hold tight ?

The electron and muon magnetic moments have been verified at ppm level...

Status: summer 2011 (*published results shown only*)

Hoecker, Marciano, PDG 2011

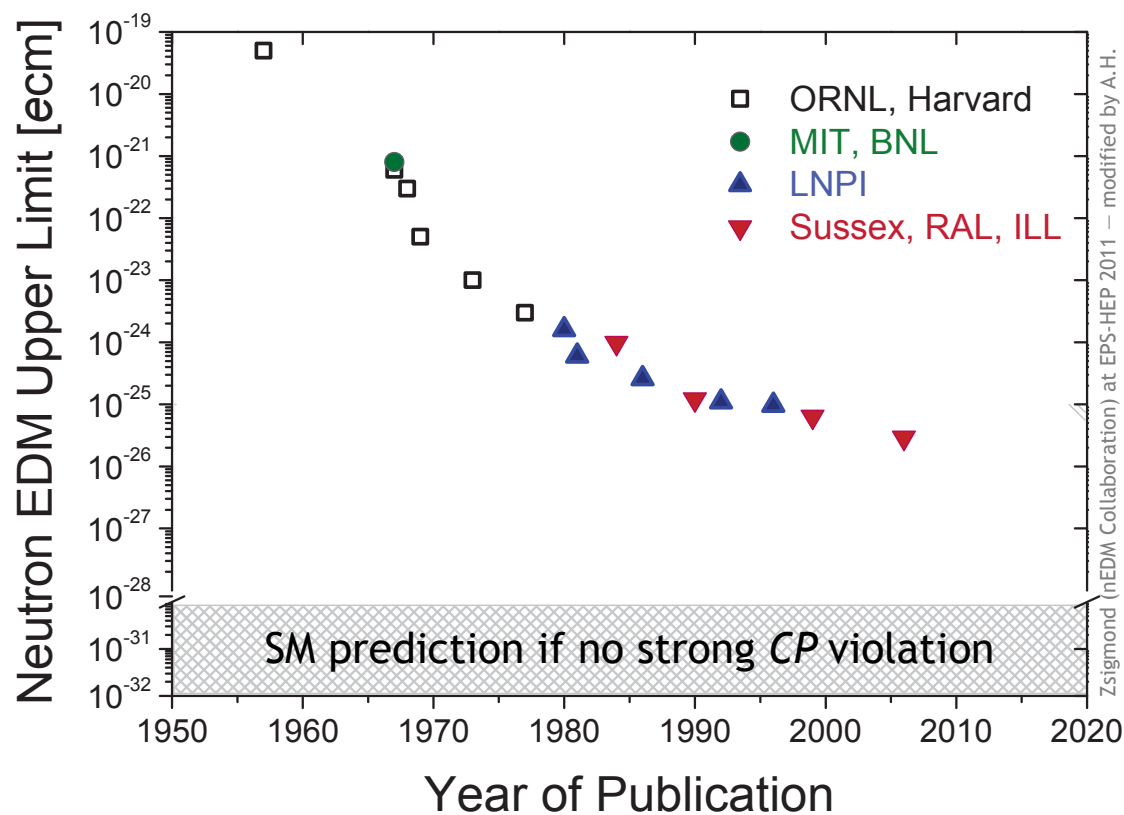


The muon anomalous magnetic moment may deviate from the SM prediction (not conclusive): it would be stronger than expected

Does the Standard Model hold tight ?

Electric dipole moments are tiny — but why for neutrons ?
→ “strong *CP* problem”

Neutron EDM upper limits versus time. Current best limit: $|d_n| < 2.9 \times 10^{-26}$ ecm



Sussex-RAL-ILL,
PRL 97, 131801 (2006)

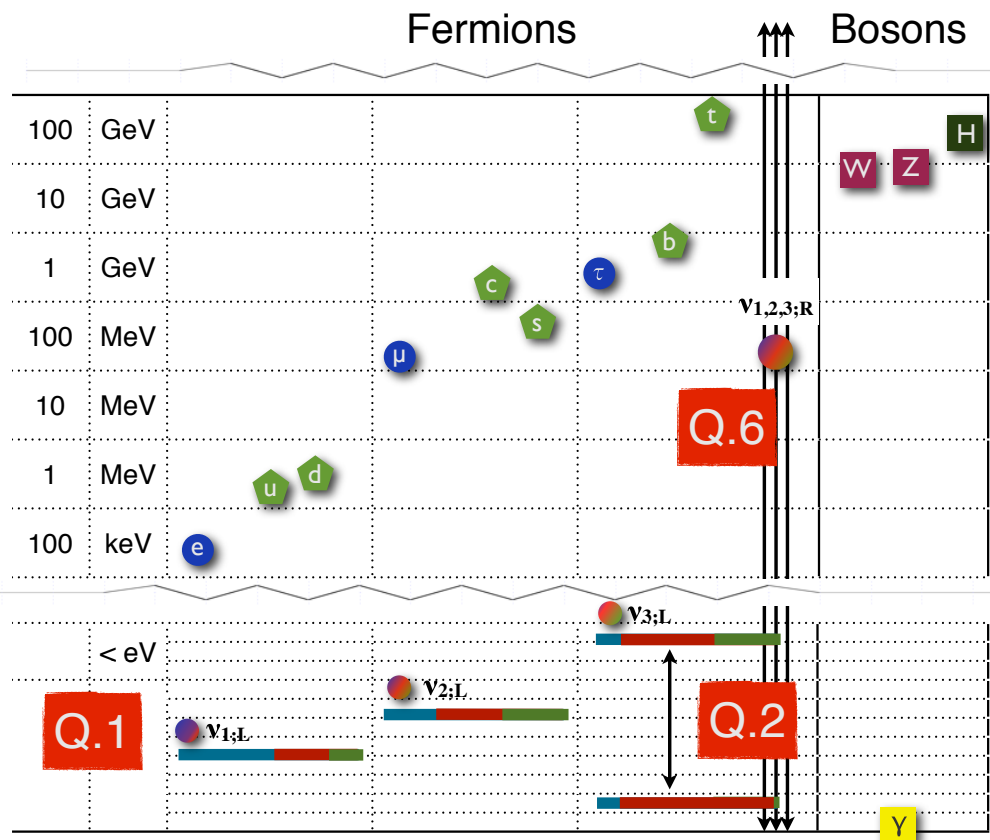
Is a new symmetry (*Peccei-Quinn*) responsible for this ?

Its manifestation would be a new particle, the *axion*, which could also be responsible for the cold dark matter

Does the Standard Model hold tight ?

The neutrino revolution: massive neutrinos are likely beyond the SM phenomena

Dramatic progress in neutrino physics – fundamental tasks/questions still open



- Q1: Absolute mass scale of neutrinos
- Q2: Normal or inverted mass hierarchy
- Q3: CP violation in neutrino oscillations
- Q4: Unitarity of neutrino mixing matrix
- Q5: Neutrinoless double beta decay
- Q6: Existence of "sterile neutrino(s)"

Dufour-Wark, arXiv:1207.3983

Does the Standard
Model hold tight ?

Can we conclude that
the Standard Model is
the theory of matter
and force ?

Jiro Taniguchi, Furari, © Casterman (2012)



The SM cannot be the final theory, because ...

Higgs is only fundamental scalar

neither matter, nor force,
- all known scalars are composite states

Huge mass hierarchy between matter particles

Gauge hierarchy / scalar SM sector is unstable

Dark matter and dark energy

Grand unification of the forces

Causally connected observable universe

Matter-antimatter asymmetry in universe

Strong CP problem

Massive neutrinos

Gravitation

The SM cannot be the final theory, because ...

The Higgs potential ($\mu < 0$, $\lambda \geq 0$: *physics or just mathematics?*) exemplifies our success with description but lack of understanding

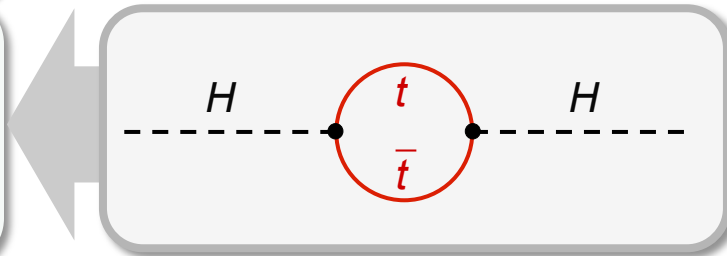
$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

Higgs boson mass term

$$\delta m_H^2 \sim |\delta \mu_H^2| \propto \Lambda_{\text{cut-off}}^2$$

“Hierarchy problem”

→ new physics at ~TeV



The SM cannot be the final theory, because ...

The Higgs potential ($\mu < 0$, $\lambda \geq 0$: *physics or just mathematics*?) exemplifies our success with description but lack of understanding

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

Is this the right potential?

If the Higgs field fills all space-time, is it related to inflation and dark energy?

Higgs boson mass term

$$\delta m_H^2 \sim |\delta \mu_H^2| \propto \Lambda_{\text{cut-off}}^2$$

“Hierarchy problem”

→ new physics at ~TeV

Higgs self coupling

$$\lambda_{\text{SM}} = G_F m_H^2 / \sqrt{2} \sim 0.13$$

EW vacuum may be meta-stable

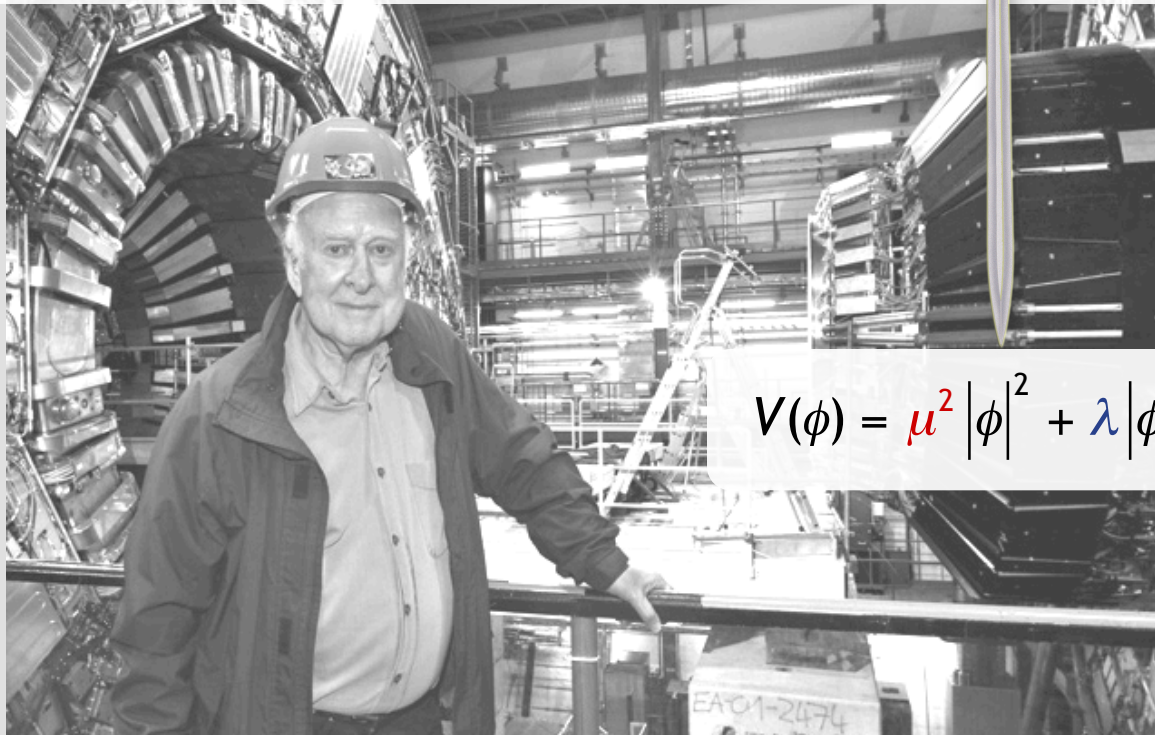
Higgs–fermion couplings

“SM flavour problem”:
large mass hierarchy
between fermion families

G. Isidori at HiggsHunting 2012

Through the missing protection of the scalar potential to high-scale physics (no symmetry for $m_H = 0$!), the Higgs boson is considered a “*portal to new physics*”

Higgs discovery puts these questions into spotlight



$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

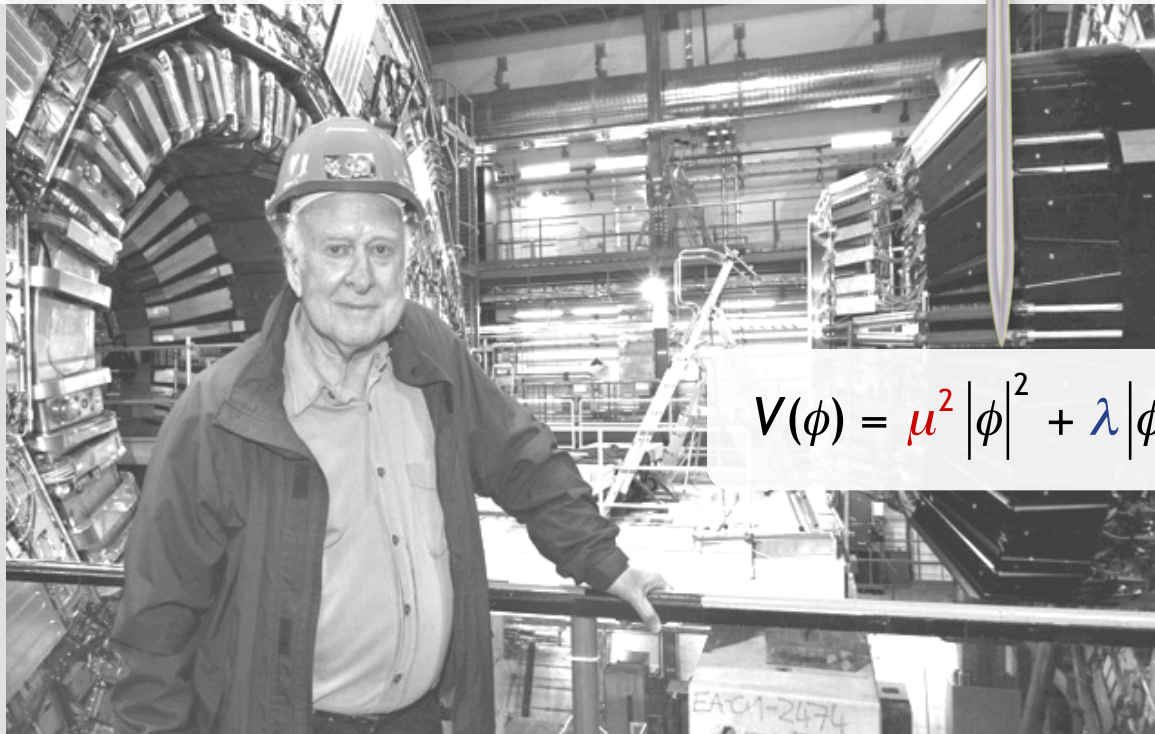
P. Higgs at CMS

Proposed solutions to hierarchy problem

- **Weakly coupled:** Supersymmetry, ...
- **Strongly coupled:** Little Higgs, Composite Higgs, ...

Different manifestations of similar scenarios. Many models also provide dark matter candidates

Higgs discovery puts these questions into spotlight

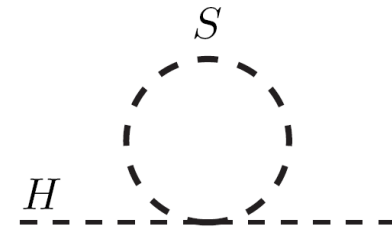
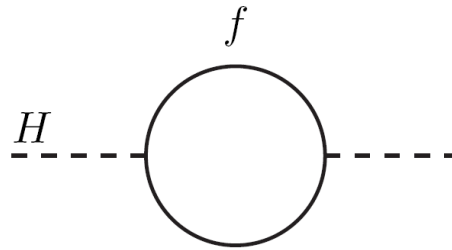


$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

P. Higgs at CMS

Does a symmetry between fermions and bosons regularise the Higgs radiative corrections ?

Fermion loop



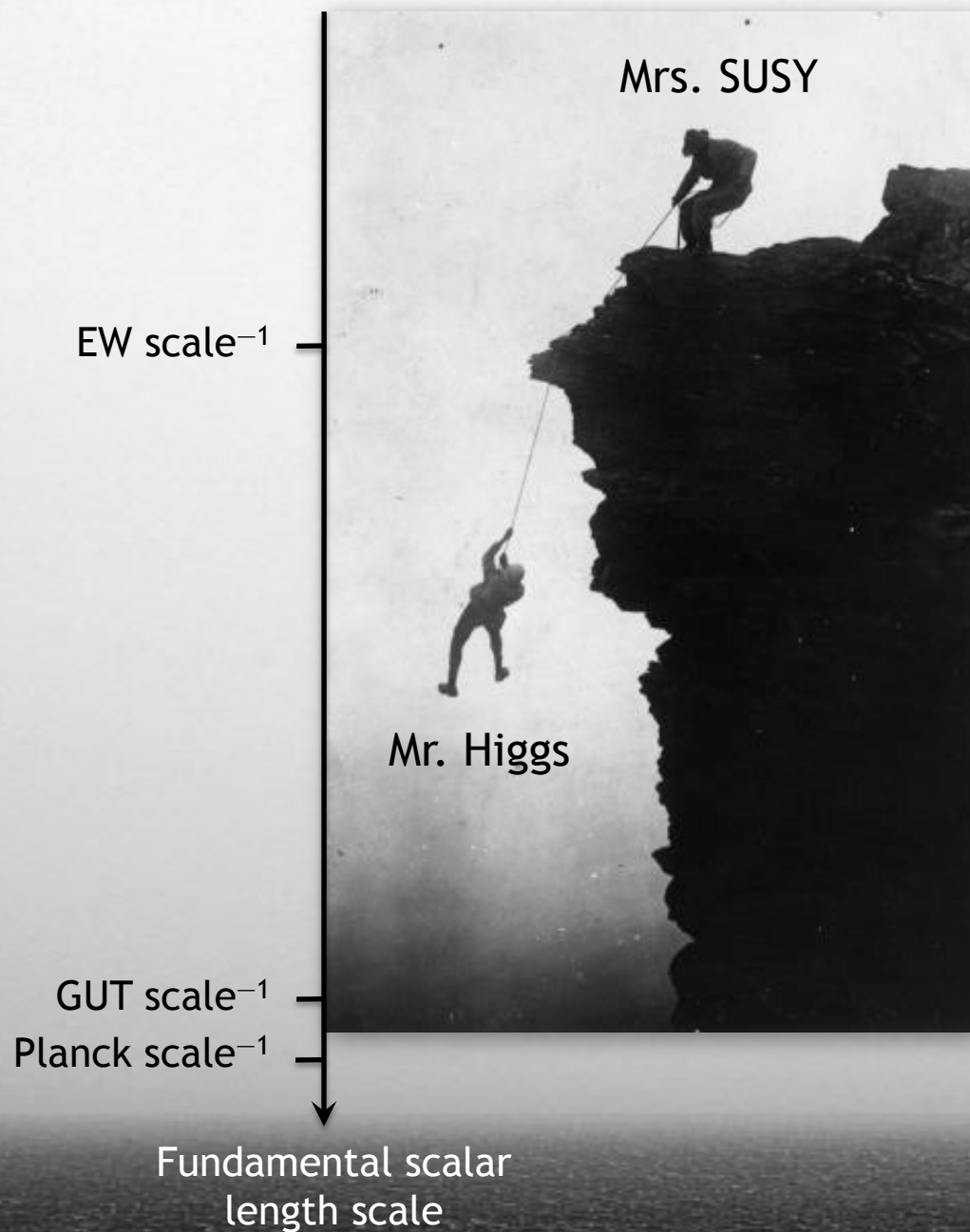
Boson loop

(weak-scale) Supersymmetry (SUSY)



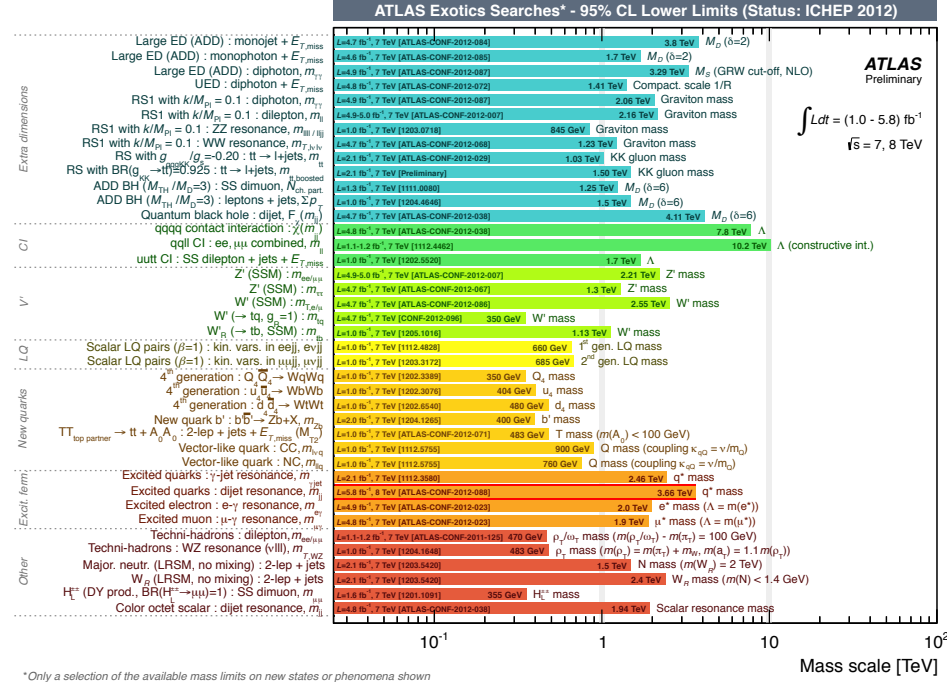
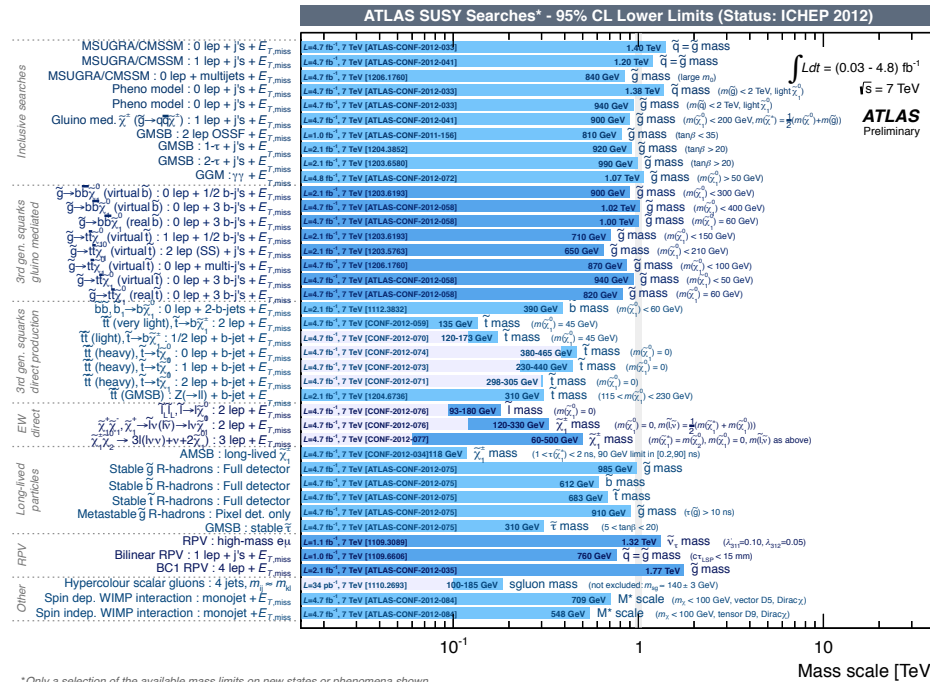
P. Higgs at CMS

The scalar precipice



Broad search spectrum at ATLAS and CMS

So far unsuccessful new physics searches (beyond Higgs)



Mass reach of searches for SUSY (left) and other new phenomena (right) (here: ATLAS)

Broad search spectrum at ATLAS and CMS

The LHC is pushing the limits on new phenomena



F. Le Diberder © CERN 2012

The next 50 years ...

(remember particle physics 50 years ago ?)

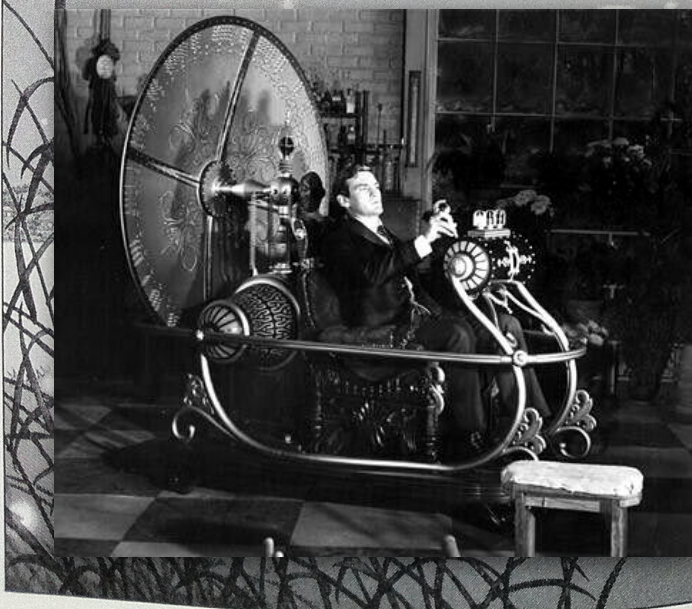
The energy frontier

The intensity frontier

The cosmic frontier (→ JF, RO)

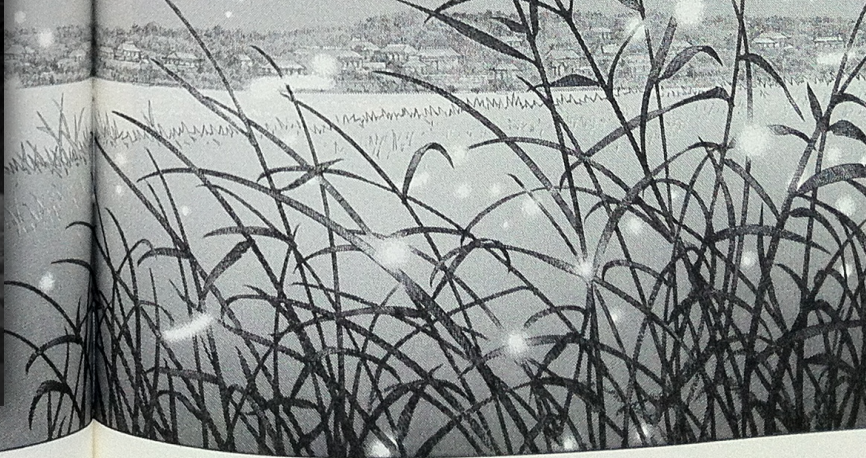
Other areas

Jiro Taniguchi, Furari, © Casterman (2012)



I will be brief on:

- The strong connection of particle physics with astrophysics and cosmology → Jonathan Feng & Rene Ong
- Introduction to future accelerators → Frank Zimmermann



The next 50 years' particle physics research programs depend on LHC results

By now, a new Higgs-like particle has been discovered and **we are entering a new era of particle physics**

[More can be expected; let us assume here scenarios after accumulating more than 3 ab^{-1} of data at the HL-LHC at ~ 2030 ($\sim 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, up to 140 interactions per crossing)]

The high-energy frontier



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The high-energy frontier

Options ($\rightarrow$ see talk by F. Zimmermann)

HE-LHC

[pp up to 33 TeV,
new magnets, reuse
infrastructure]

ILC (H-Factory)

[e^+e^- at 0.5-1 TeV,
mature technology,
new infrastructure]

CLIC

[e^+e^- up to 4 TeV,
new technology,
new infrastructure]

VLHC

[pp up to 175 TeV,
new everything]

LEP-3 (H-Factory)

[e^+e^- at 0.25 TeV,
new accelerator,
reuse infrastructure]

Muon Collider

[$\mu^+\mu^-$ up to 4 TeV,
new everything]

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The high-energy frontier

A remark is in order: CLIC & muon collider are here representatives for new accelerator technologies.

Powerful alternatives, actively developed at SLAC, could become multi-TeV high-gradient accelerators using, eg, plasma wakefield acceleration. See talk by Tor Raubenheimer (SLAC) at EPS-HEP 2011 $\rightarrow$ F. Zimmermann

If the physics case is given (see later), all acceleration techniques will be on the table

reuse infrastructure]

CLIC

[e^+e^- up to 4 TeV,
new technology,
new infrastructure]

Muon Collider

[$\mu^+\mu^-$ up to 4 TeV,
new everything]

Scenario 1) TeV-scale new particles are found at LHC

The high-energy frontier

Options (→ see talk by F. Zimmermann)

HE-LHC

[pp up to 33 TeV,
new magnets, reuse
infrastructure]

M-LHC

[pp up to 175 TeV,
new everything]

ILC

[e^+e^- at 0.5-1 TeV,
mature technology,
new infrastructure]

LEP-3

[e^+e^- at 0.25 TeV,
new accelerator,
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CLIC

[e^+e^- up to 4 TeV,
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Muon Collider

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Scenario 1) TeV-scale new particles are found at LHC

Scenario 2) Higgs boson is SM and remains only new phenomenon seen at LHC

The high-energy frontier

Options (→ see talk by F. Zimmermann)

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Scenario 1) TeV-scale new particles are found at LHC

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Scenario 3) As 2), but new physics from “intensity and precision frontier”

The high-energy frontier

Options (→ see talk by F. Zimmermann)

HE-LHC

[pp up to 33 TeV,
new magnets, reuse
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VLHC

[pp up to 175 TeV,
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CLIC

[e^+e^- up to 4 TeV,
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Scenario 1) TeV-scale new particles are found at LHC

Scenario 2) Higgs boson is SM and remains only new phenomenon seen at LHC

Scenario 3) As 2), but new physics from “intensity and precision frontier”

The high-energy frontier

In either scenario, in 50 years, we should have built, operated and exploited a new e^+e^- collider

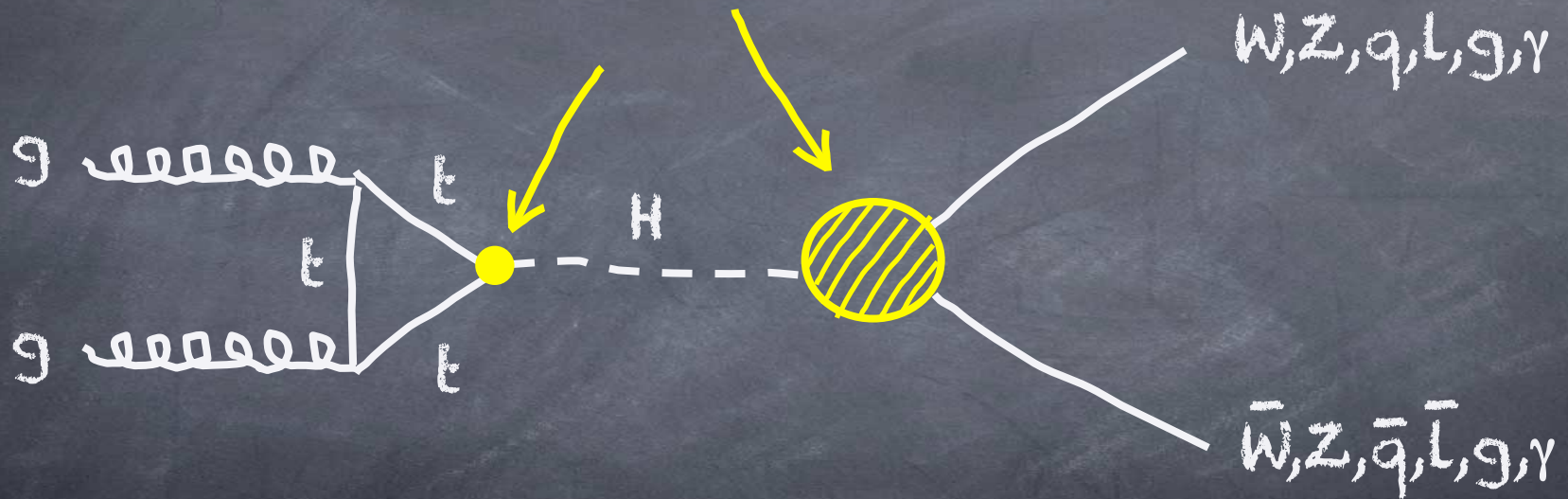
(and we might be operating CLIC and/or a HE-LHC, while a multi-TeV muon collider and large scale multi-GV/m gradient acceleration is technologically mature)

What will this (and the LHC) have taught us ?

Higgs physics – *in 50 years...*

Higgs properties will have been precisely measured at linear collider

- Higgs couplings will be known to a few % (LC, LHC: ratios > 5%; needs theory improvement)

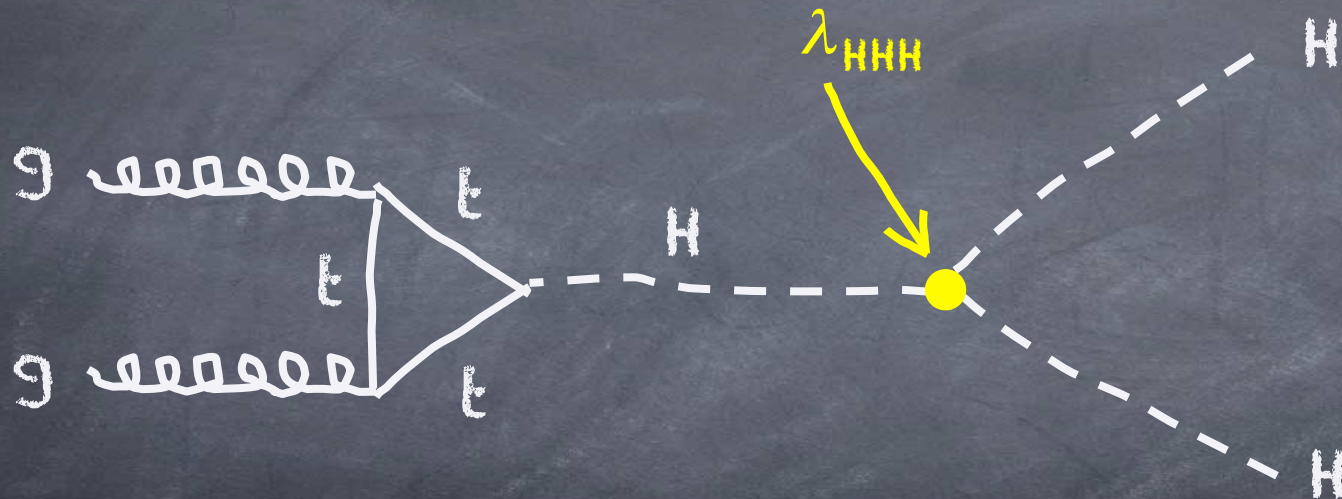


→ New heavy particles may couple to the Higgs and modify the couplings

Higgs physics – *in 50 years...*

Higgs properties will have been precisely measured at linear collider

- The trilinear Higgs self-coupling will have been measured (~20%)



→ Teaching us about the form of the Higgs potential

The hierarchy problem – *in 50 years...*

We will have “some” answer to one of the primary shortcomings of the SM

- If new particles were discovered at the TeV scale, they will have been studied in detail by a TeV scale linear collider. Energy scales up to 10 TeV may already have been covered by the HE-LHC.
- We will have understood if the Higgs is fundamental, regularised by new weak couplings (e.g., SUSY), or rather a composite, e.g., a witness of a new strongly interacting TeV scale symmetry

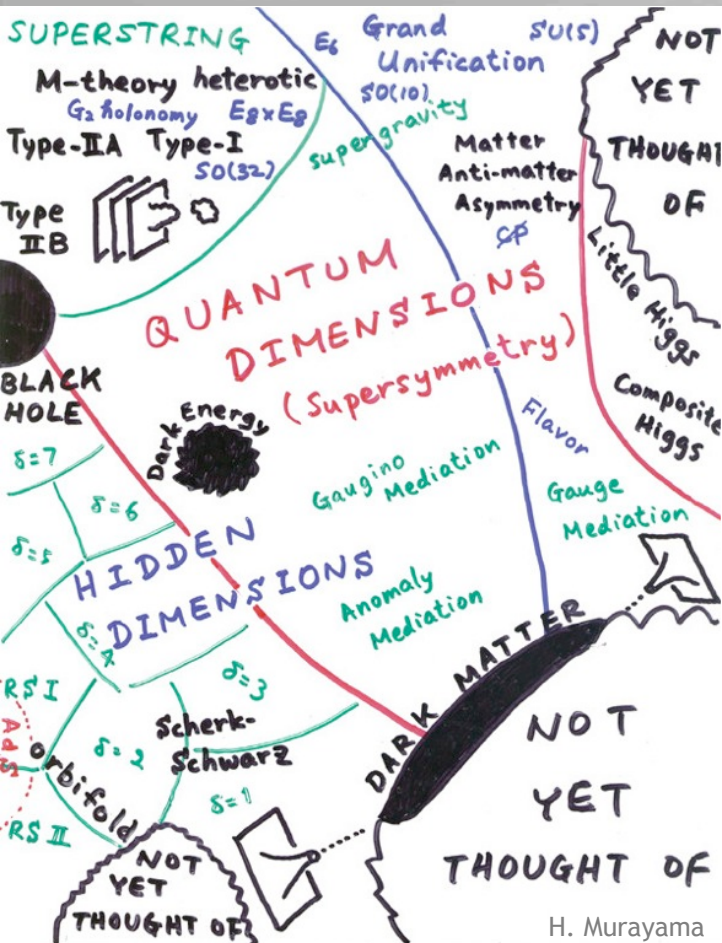
→ *a revolution to our perception of matter and force*

-
- If no new physics is discovered, the hierarchy problem may be reality and naturalness as scientific criterion has to be questioned

→ *a revolution of thinking physics and possibly a hint to a statistical choice of the universe's parameters ?*

Beyond the Standard Model physics – *in 50 years...*

Tightly related to the hierarchy problem, to dark matter and to unification



If new particles were discovered and measured ...

- Their nature will have been determined

SUSY, new strong interactions with heavy partners of known SM particles, extra space dimensions, new vector-like matter states, ..., or combinations of these

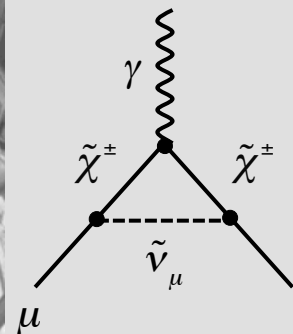
- Dark matter candidates may have been found, and if, their relic abundance precisely determined, possibly fully solving the dark matter puzzle
- New *CP*-violating interactions would impact our understanding of baryogenesis
- Likely the new physics will have taught us about physics at energy scales far above any accelerators

Modified force evolution may enable grand gauge unification

By exploiting contributions from radiative corrections, precision measurements, in line with accurate theoretical predictions, can be used to probe physics at higher energy scales than the masses of the particles directly involved in the experimental reactions.

Wise research decisions will have allowed to exploit a huge physics potential that complements the high-energy frontier

The intensity frontier



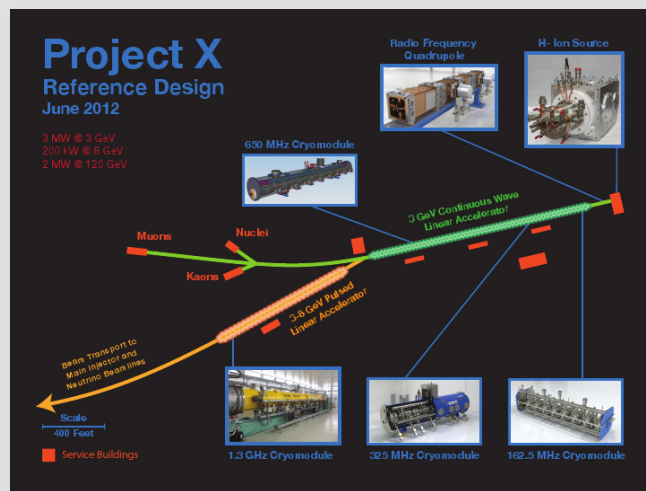
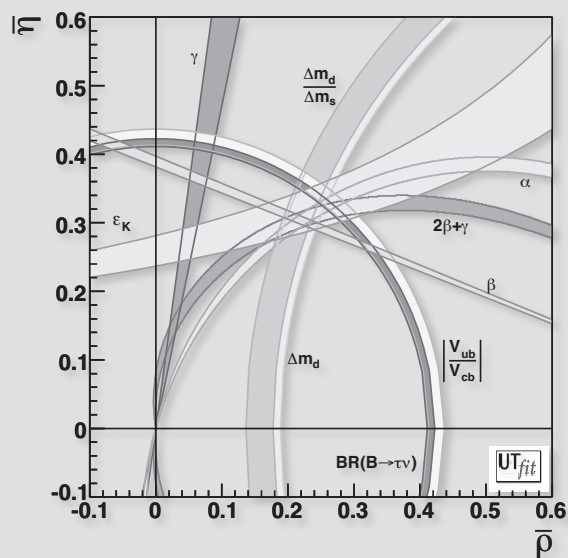
New techniques for the measurement of EDMs of the neutron, electron and muon will have improved the current sensitivity by three orders of magnitude

The LHC and new “Super B factories” led to sub-% CPV & rare decay measurements

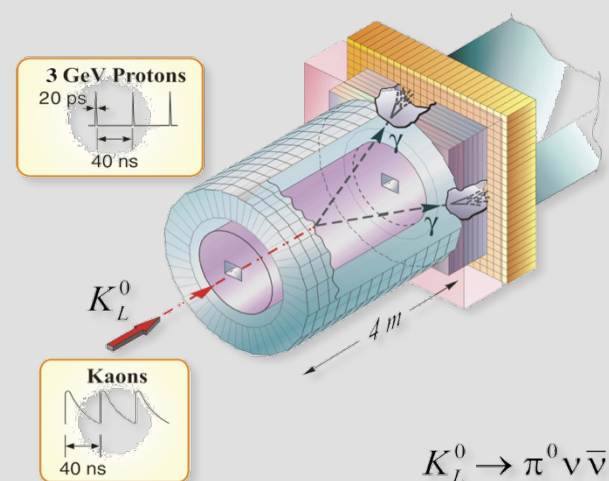
High-intensity proton drivers (> 5 MW proton source) will increase K and μ production rates for rare decay experiments (CLFV to 10^{-19} , observation of $K_L \rightarrow \pi^0 \nu \bar{\nu}$, etc)

The LC (also in Giga-Z mode) will have greatly improved the precision of EW sector

The intensity frontier



3 MW of total beam power to 3 GeV program and
2 MW to a neutrino production target at 60-120 GeV



$$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$$

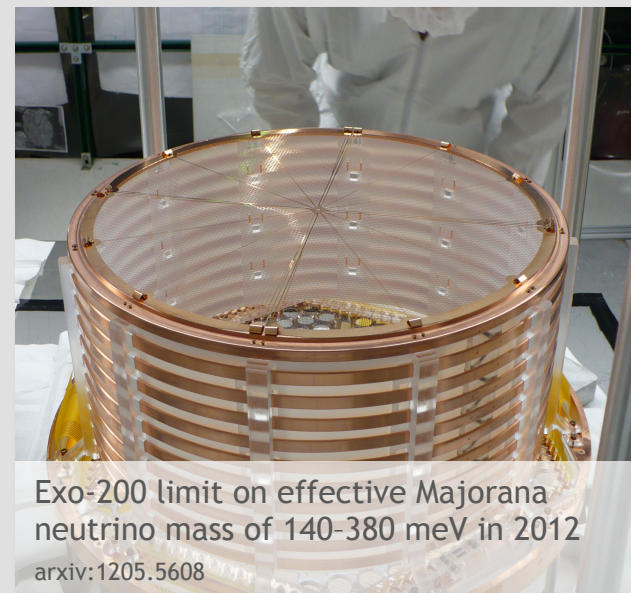
Combination of long & short baseline and reactor neutrino experiments will have established the neutrino mass hierarchy, precision angle measurements and hints on leptonic CPV. A neutrino factory is the logical next step – already done ?

Ton-scale neutrinoless double beta experiments have explored the nature of neutrinos down to masses of meV (are neutrinos their own antiparticles ?)

Direct electron neutrino mass measurements obtained sensitivities to meV

The intensity frontier / neutrino properties

Project-X
neutrino
beam
lines



EXO-200
detector

Exo-200 limit on effective Majorana
neutrino mass of 140-380 meV in 2012

arxiv:1205.5608

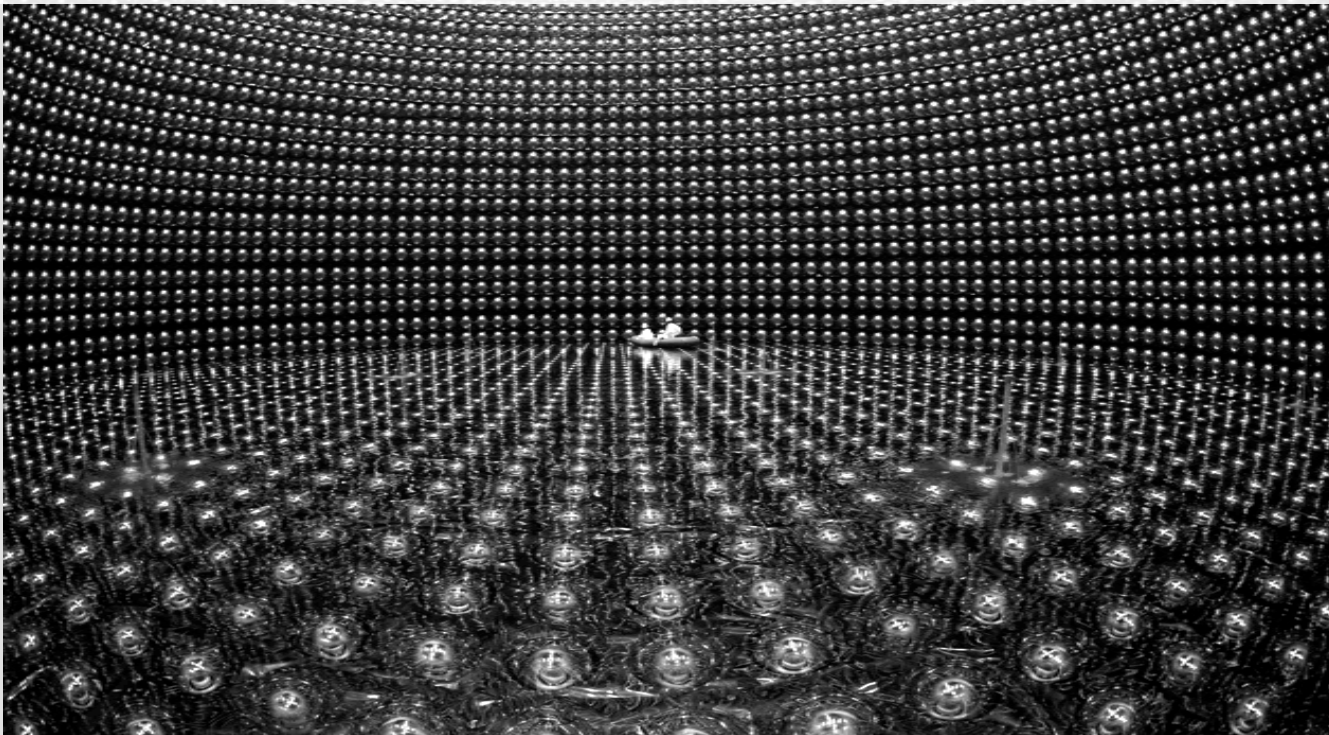
Mega-ton neutrino detectors will have achieved a proton lifetime sensitivity of $>10^{36}$ y (SK: $\sim 2 \times 10^{34}$ y), impacting our understanding of GUT & baryogenesis

Axion experiments will have covered the CDM mass range $1 \mu\text{eV} \sim 1 \text{ meV}$

Ground and space-based DM experiments may have detected dark matter reactions in complementarity to accelerator-based searches $\rightarrow$ Jonathan Feng

Protons, axions, dark matter

Super-K
detector

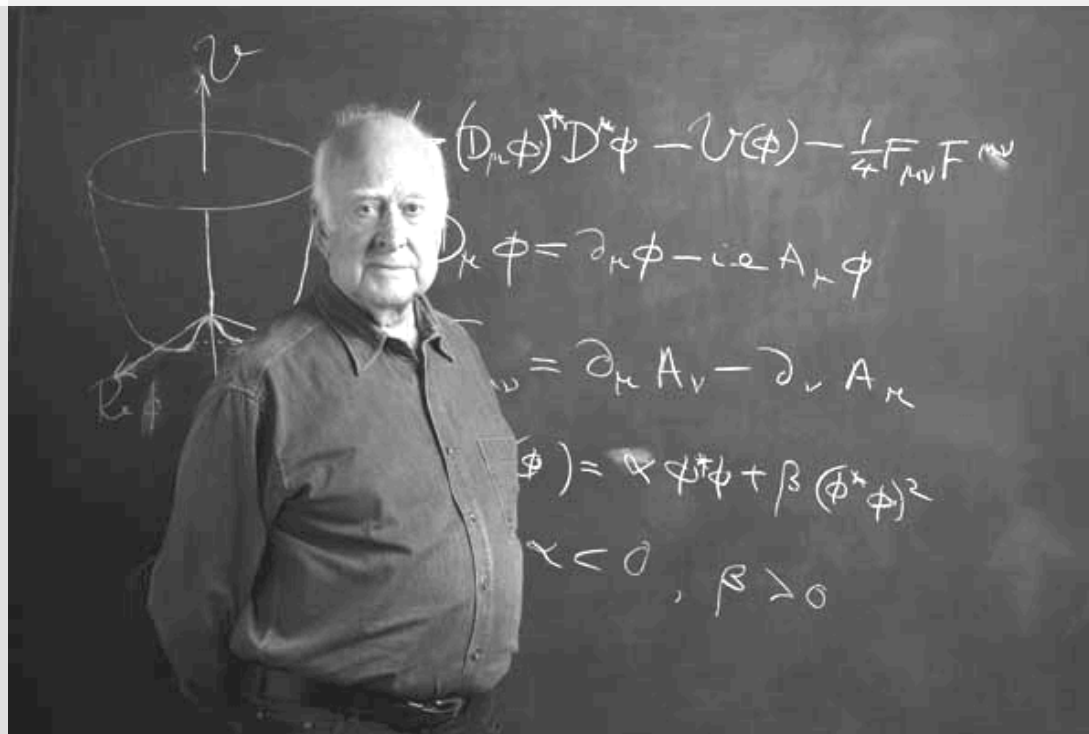


The last 40 years we have seen a profusion of theoretical ideas motivated by the shortcomings of the SM, cosmological observations, and Planck-scale physics

Experiment is behind, but critically needed to understand the choices nature took

The next 50 years shall be the age of experiment and theoretical truth

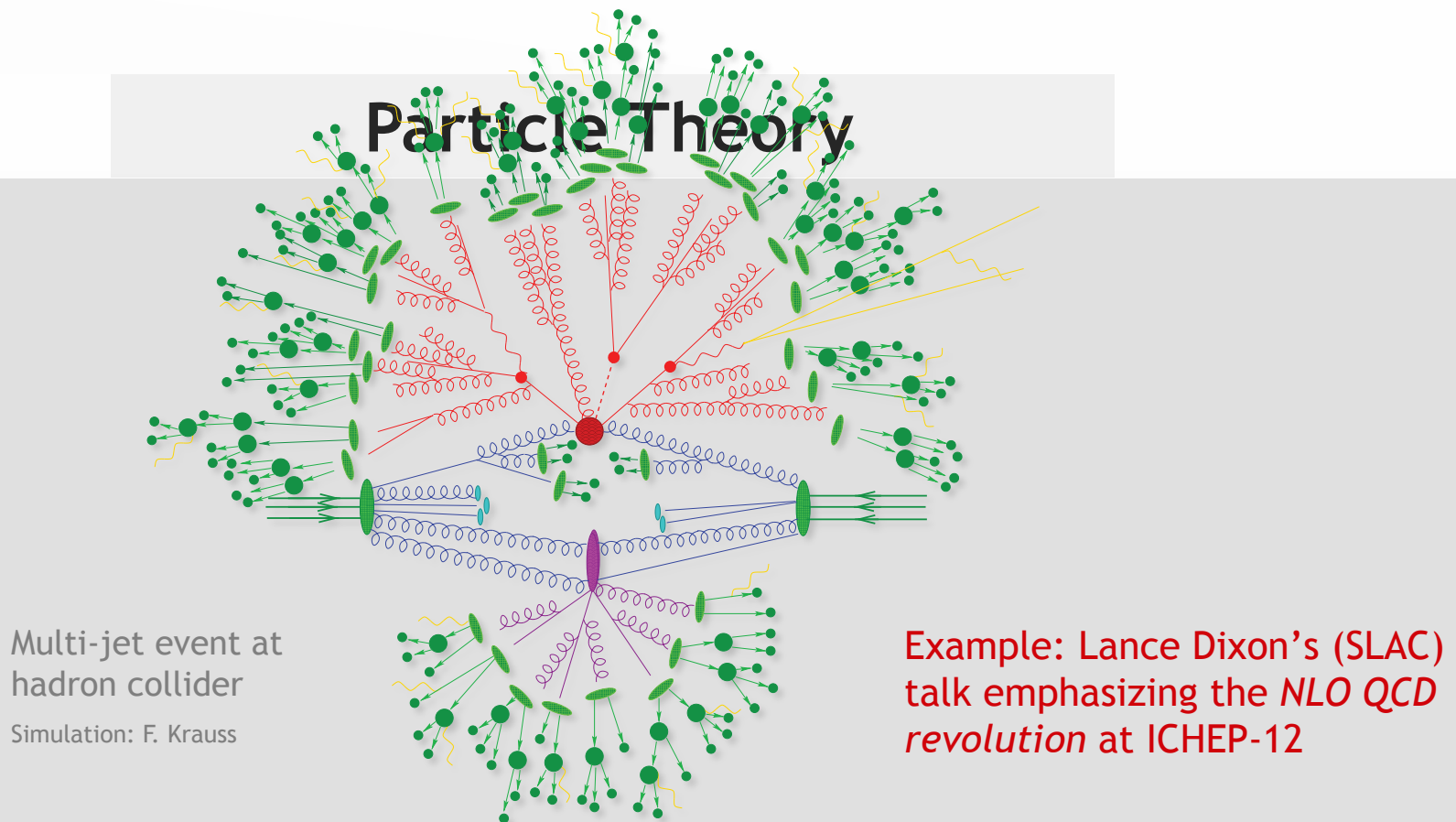
Particle Theory



But particle theory is more than model building; it is also hard calculus and programming on which the interpretation of data crucially relies

Similar to experiment: it requires large-scale resources and organisation

Theoretical revolutions are perhaps even less predictable than experimental ones. It is clear, however, that SLAC must remain a world-leading theoretical centre !



Particles Physics Relies on Accelerators

Each new accelerator project pushed the limits of technology and organisation,
and ended enriching our understanding of what we are made of

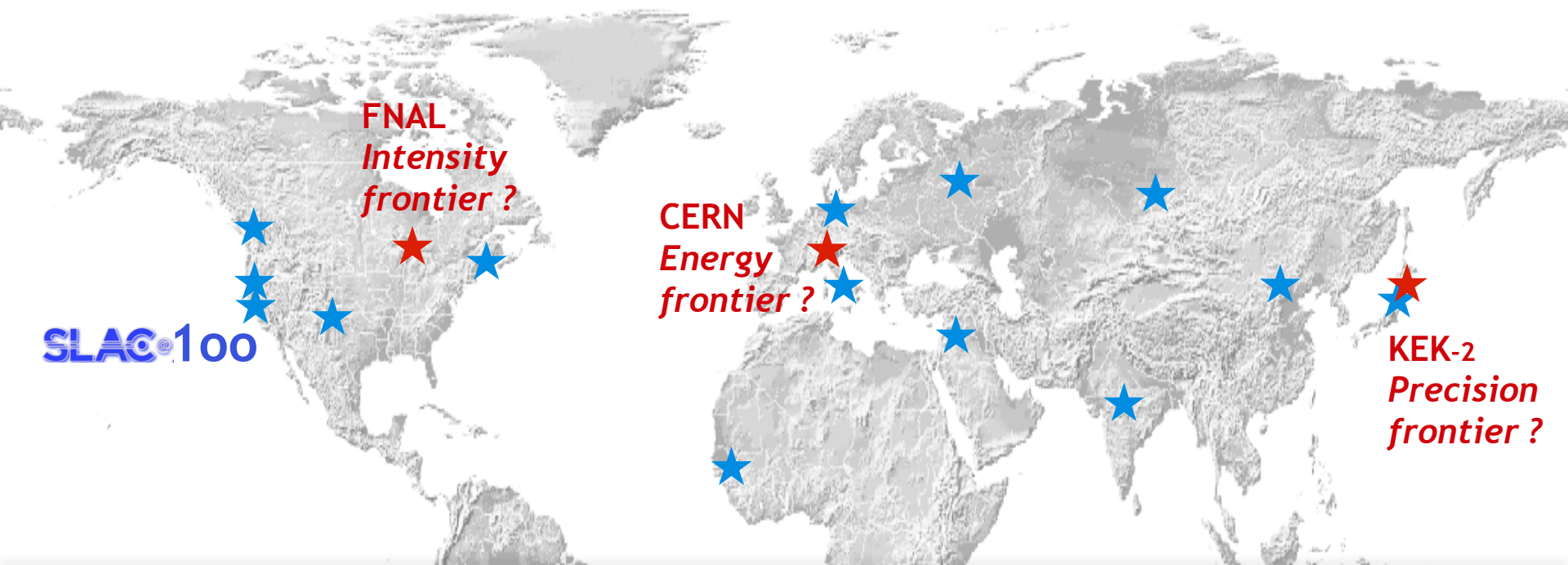
It is the price of knowledge — there is no other way



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The Landscape of Particle Physics Labs in 2062 ?

Extremely challenging experimental programmes require **global organisation**

Several successful examples of global head organisations already (ICFA, ILC-GDE, IDS-NF,...) —
Also in communication: interactions.org, and also the wonderful SLAC/FNAL symmetry-magazine !

Global Labs in different world regions host the very large facilities

Strong and versatile national labs with technological leadership coordinate
R&D for new machines and detectors (e.g., FACET at SLAC) [map of labs not to trust!]

The next 50 years ...

Looking back to what we've learned during the last 50 years, if we continue our path of globalising our strengths while keeping fruitful competition and the individual's creativity vivacious, we will keep up the pace to unravel Nature's deepest mysteries

In 50 years from now a new particle physics will have emerged with new symmetries, new particles, new interactions that have extended the SM to a far more complete theory.

SLAC will look back and enjoy its strong fingerprints in the making of it !



*Congratulations
SLAC!*

I am indebted to Michel Davier, François Le Diberder and Michael Peskin for their help during the preparation of this talk.

My deepest thanks go to SLAC for giving me the opportunity to talk about our field at this extraordinaire anniversary during these extraordinary times for all particle physicists.

I thank my LHC colleagues for their dedication and work to make this scientific endeavour a success.