Higgs Boson Physics: The Past, the Present, and the Future

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TRIUMF Colloquium

14 January 2021

Outline

Introduction: Higgs Physics

The Past: what we learned in Run 1

The Present: what we learned in Run 2

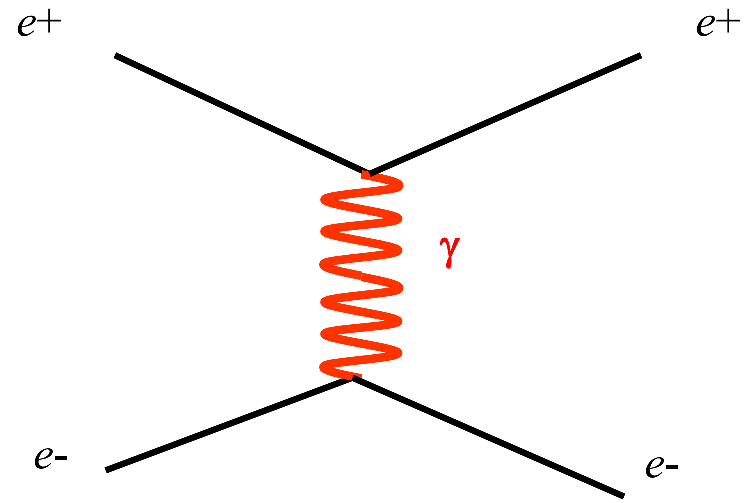
The Future: Run 3 and High Luminosity LHC

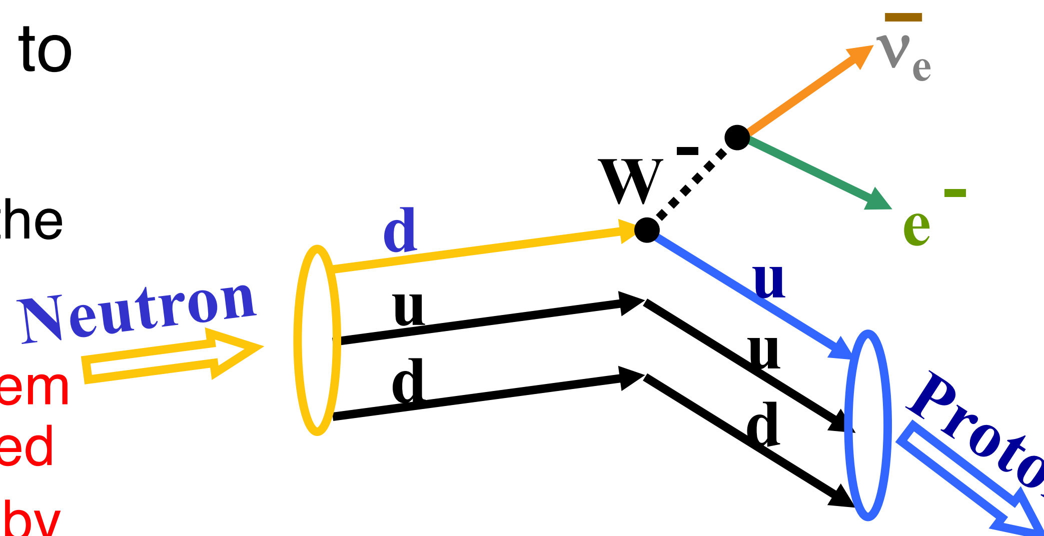
Conclusions

Higgs Boson Physics

The Electromagnetic and the Weak Forces

- A quantum theory of electromagnetism (QED) was developed at the end of the 40s
  - The force mediator is the massless photon
  - Theory is renormalizable
- The weak force appeared to require massive bosons
  - Massive mediators makes the theory non-renormalizable
  - This is the theoretical problem that Higgs* and others solved
  - Mass of W boson acquired by invoking a new scalar field



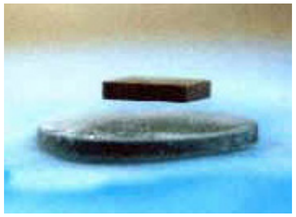


$$n \rightarrow p^+ + e^- + \nu_e$$

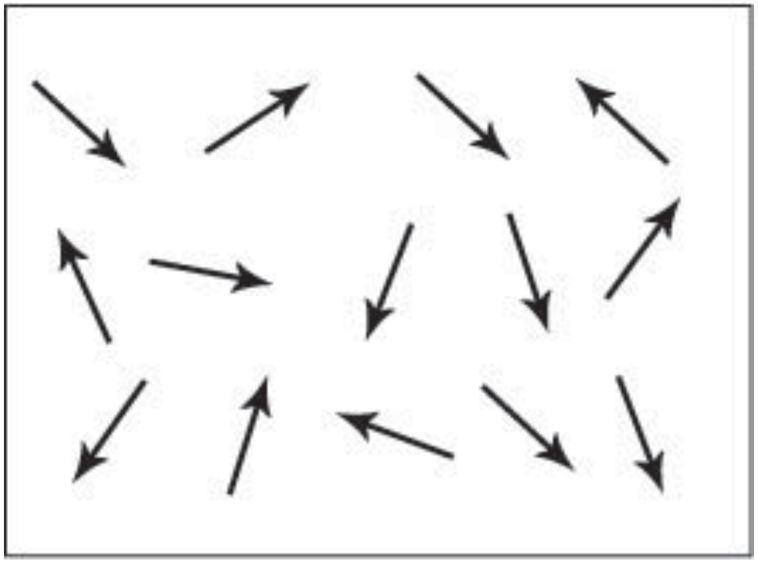
*Higgs, Brout, Englert, Kibble, Hagen, Guralnik, and also Anderson

Spontaneous Breaking of Electroweak Symmetry

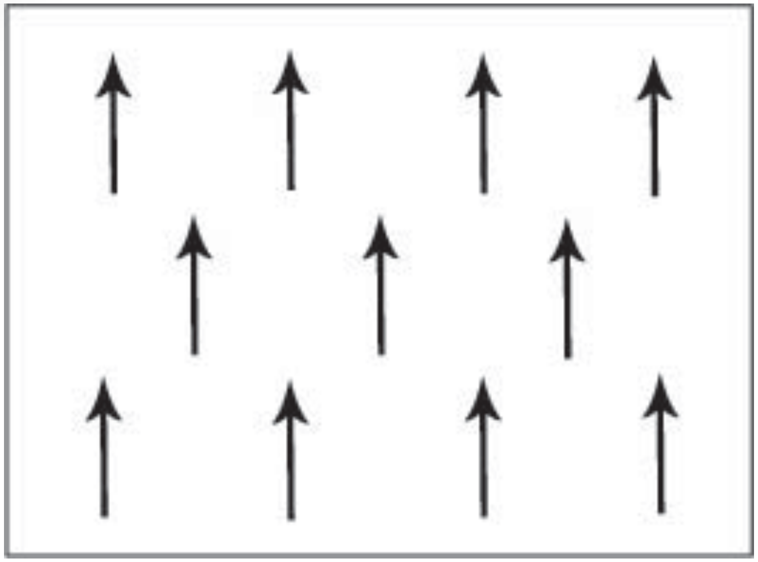
- Hypothesis: a phase transition occurred in the very early Universe: the Higgs field acquired a non-zero value
  - Similar to a phase transition in ferromagnets or a closer analogy would be the Meissner effect in superconductors



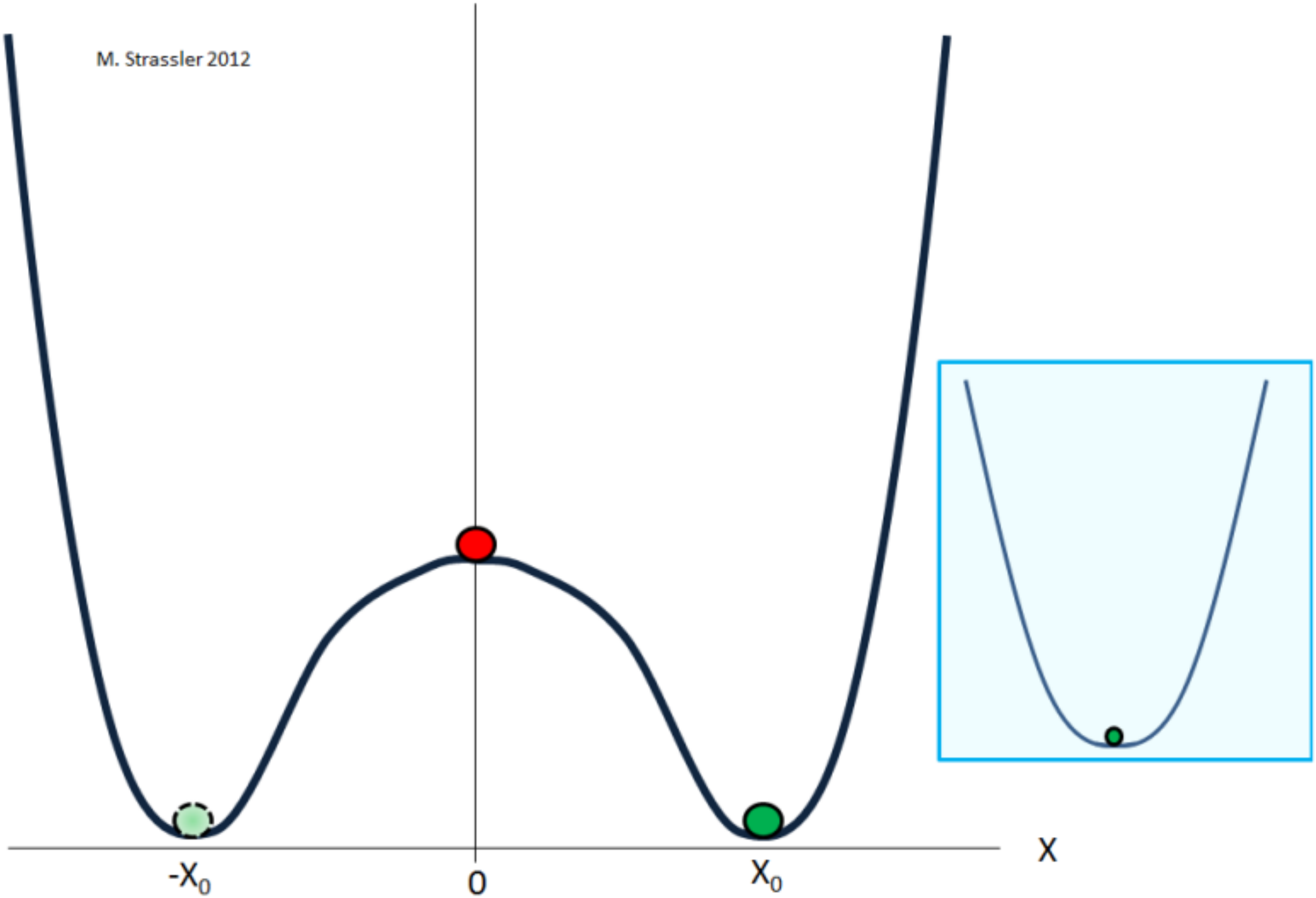
High Temperature



Low Temperature



Spontaneous Breaking of Electroweak Symmetry

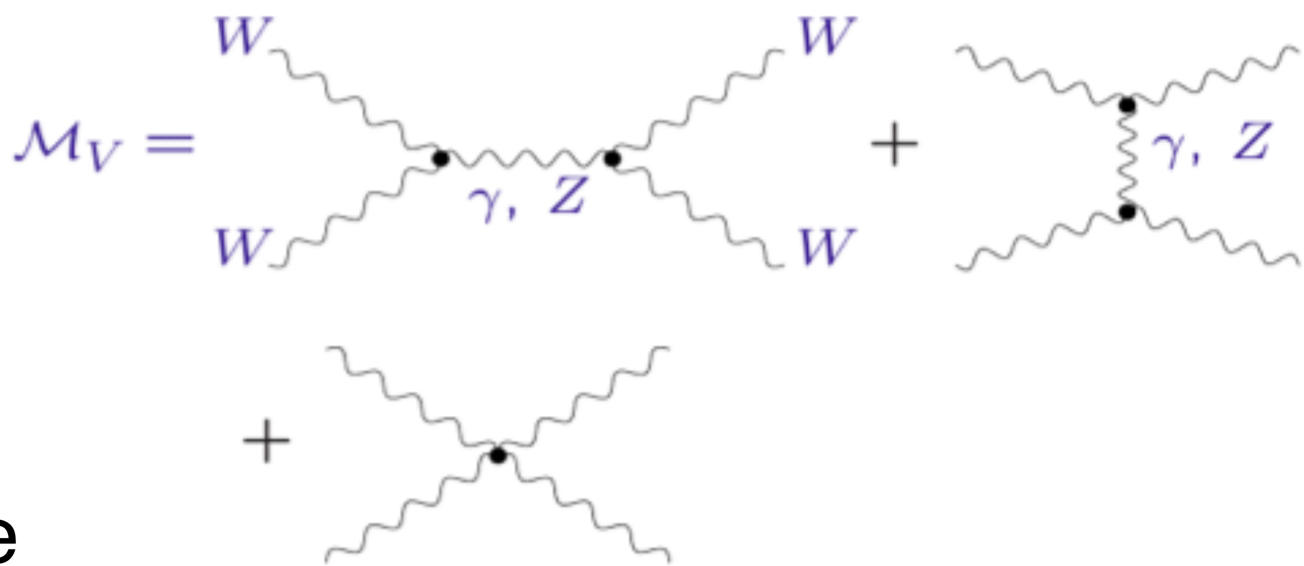


The Higgs Field

- Unlike the electromagnetic field, this field is “on” everywhere in space
  - The physical vacuum is not “empty”, it is filled with the Higgs field everywhere
- The value of the field picked by Nature determines the physics (and chemistry!) of the Universe we live in
- Fundamental particles are subject to a new kind of force and the strength of this interaction with a given particle determines its mass

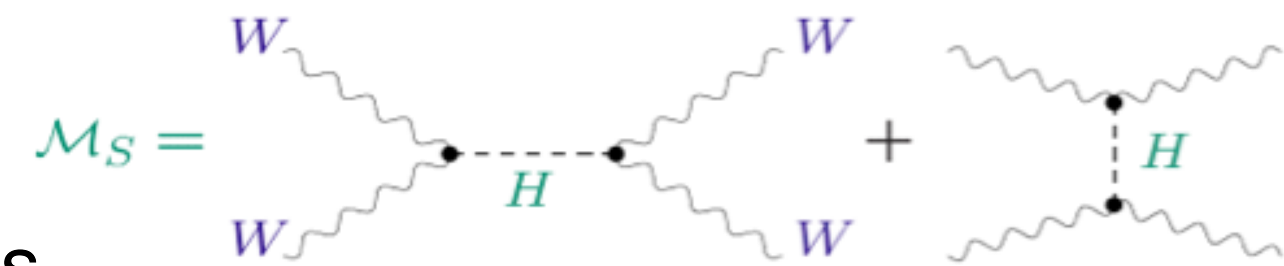
WW Scattering and the Higgs Boson

WW scattering violates unitarity above ~1 TeV



New diagrams needed to regulate the cross section

Adding diagrams with a scalar solves the problem



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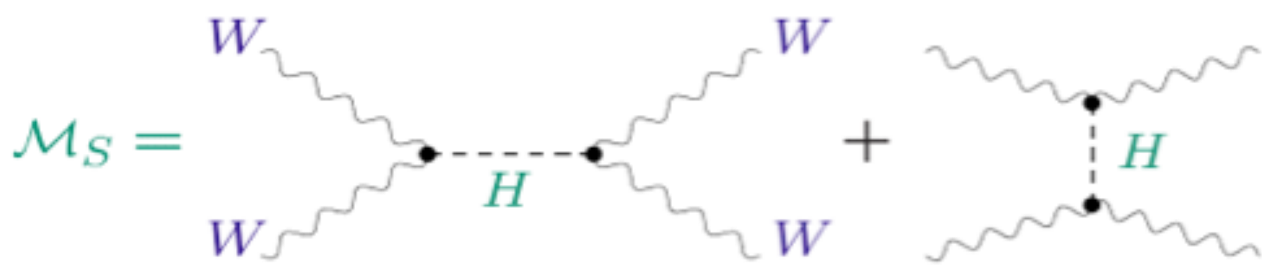
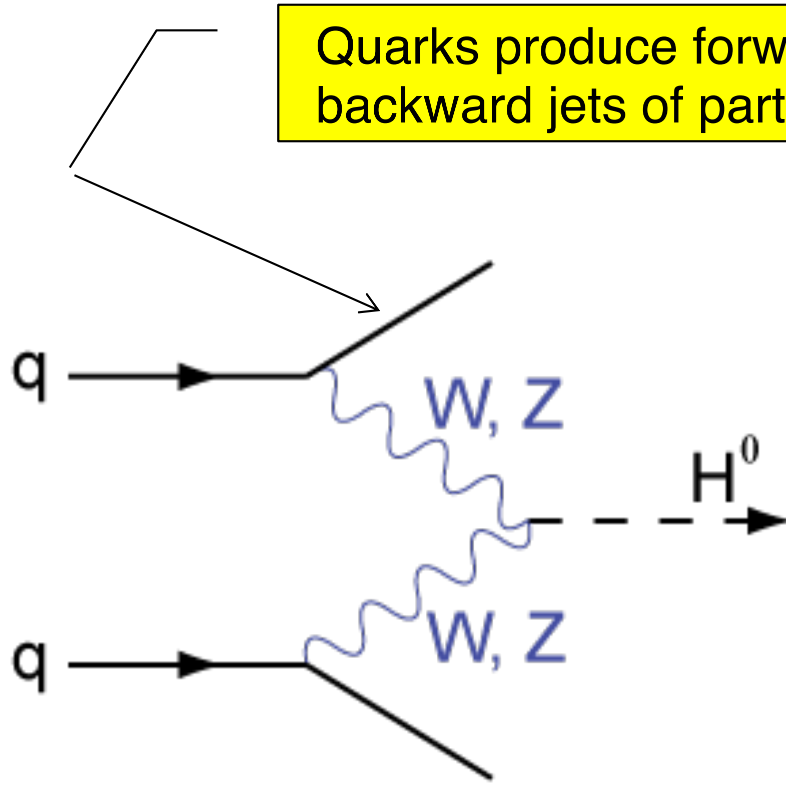


New diagrams needed to regulate the cross section

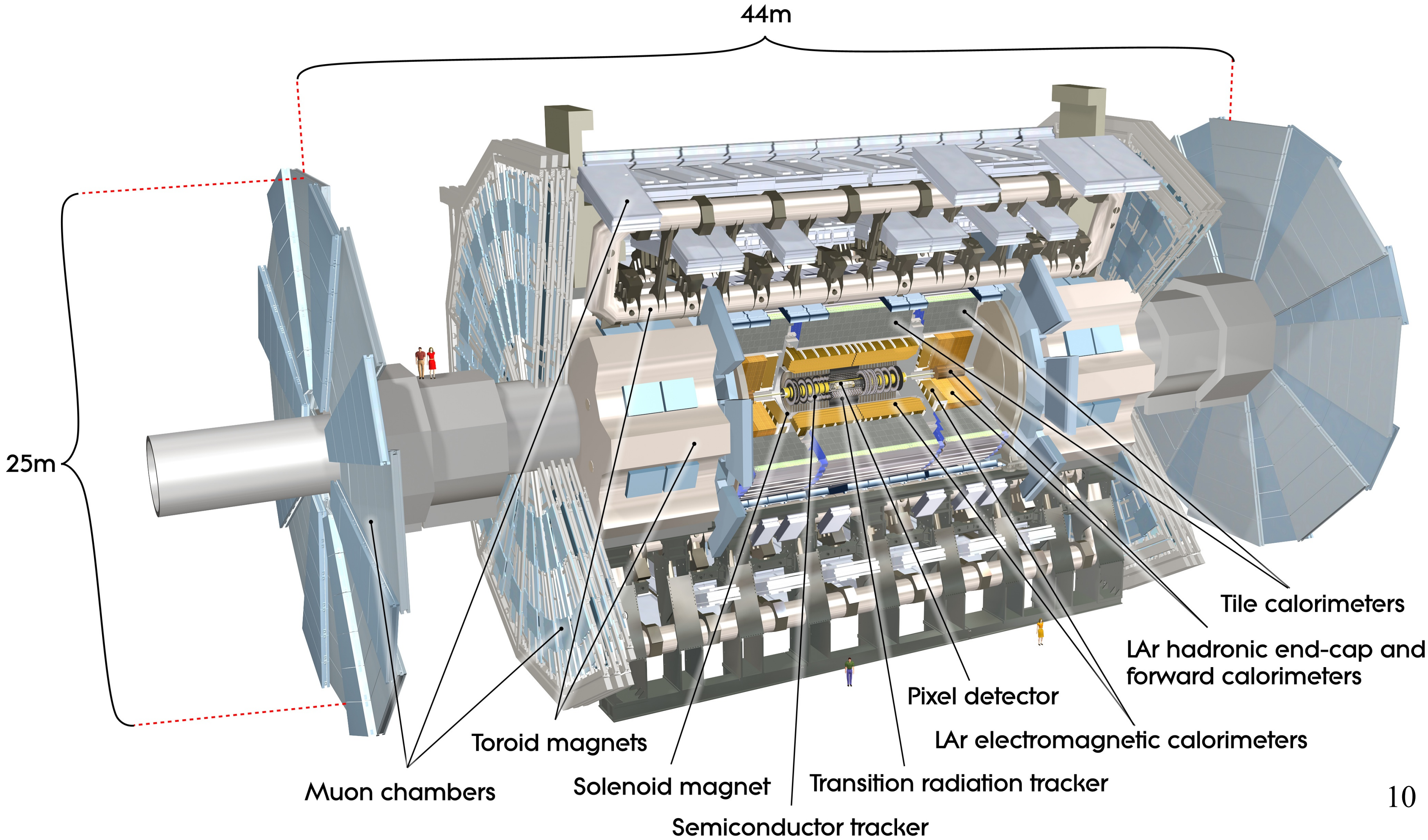
Quarks produce forward and backward jets of particles



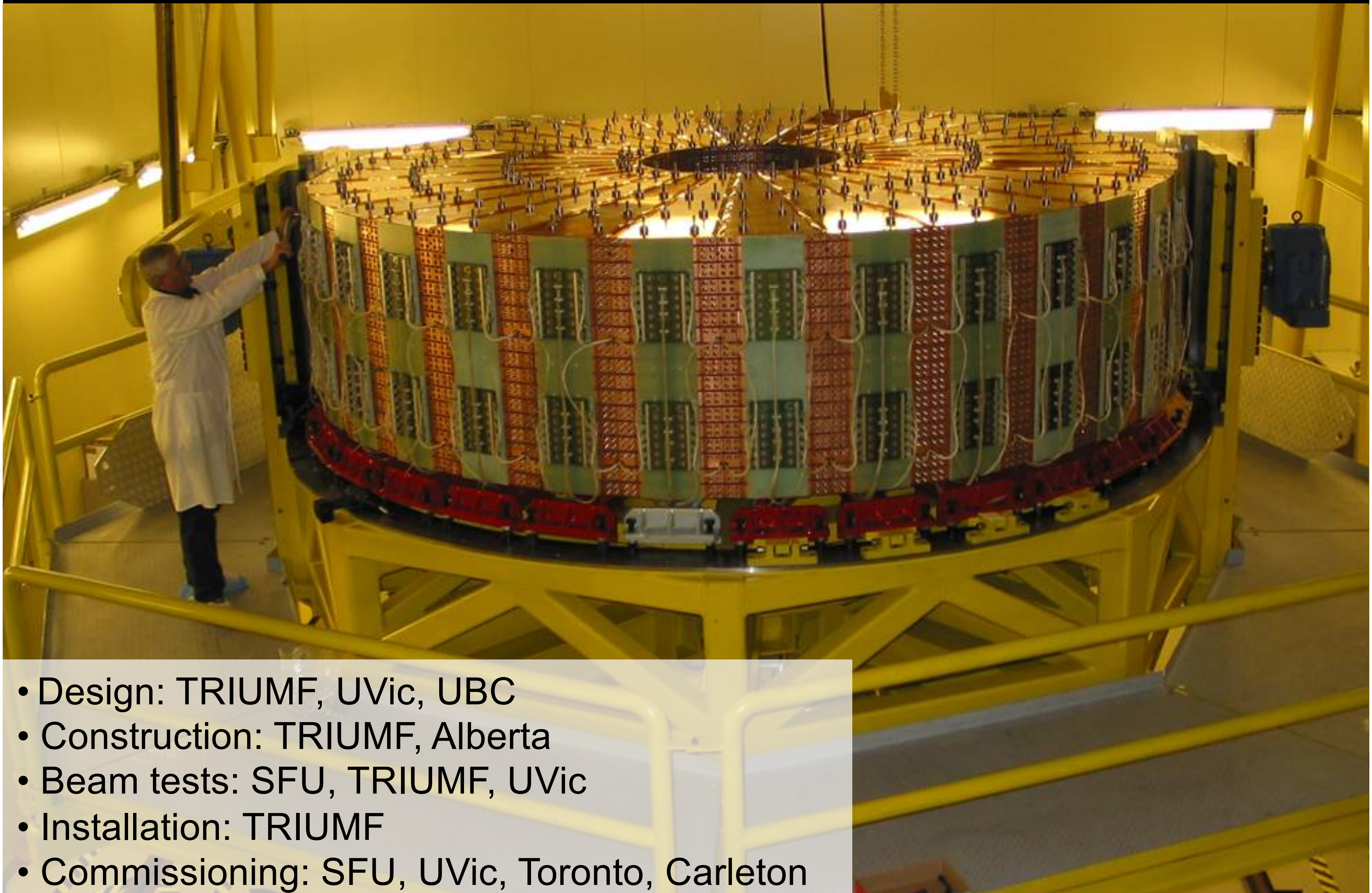
Adding Higgs diagrams solves the problem

ATLAS Detector

Designed to find or exclude the SM Higgs over a mass range up to 1 TeV



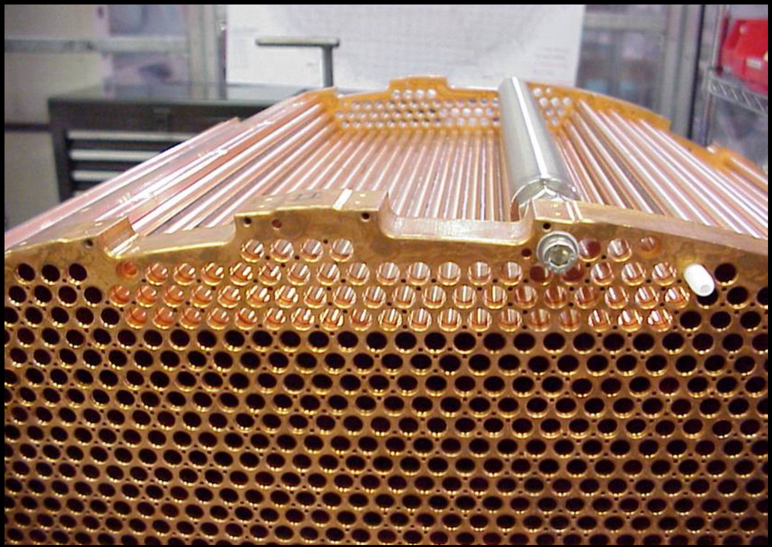
Endcap Calorimeter



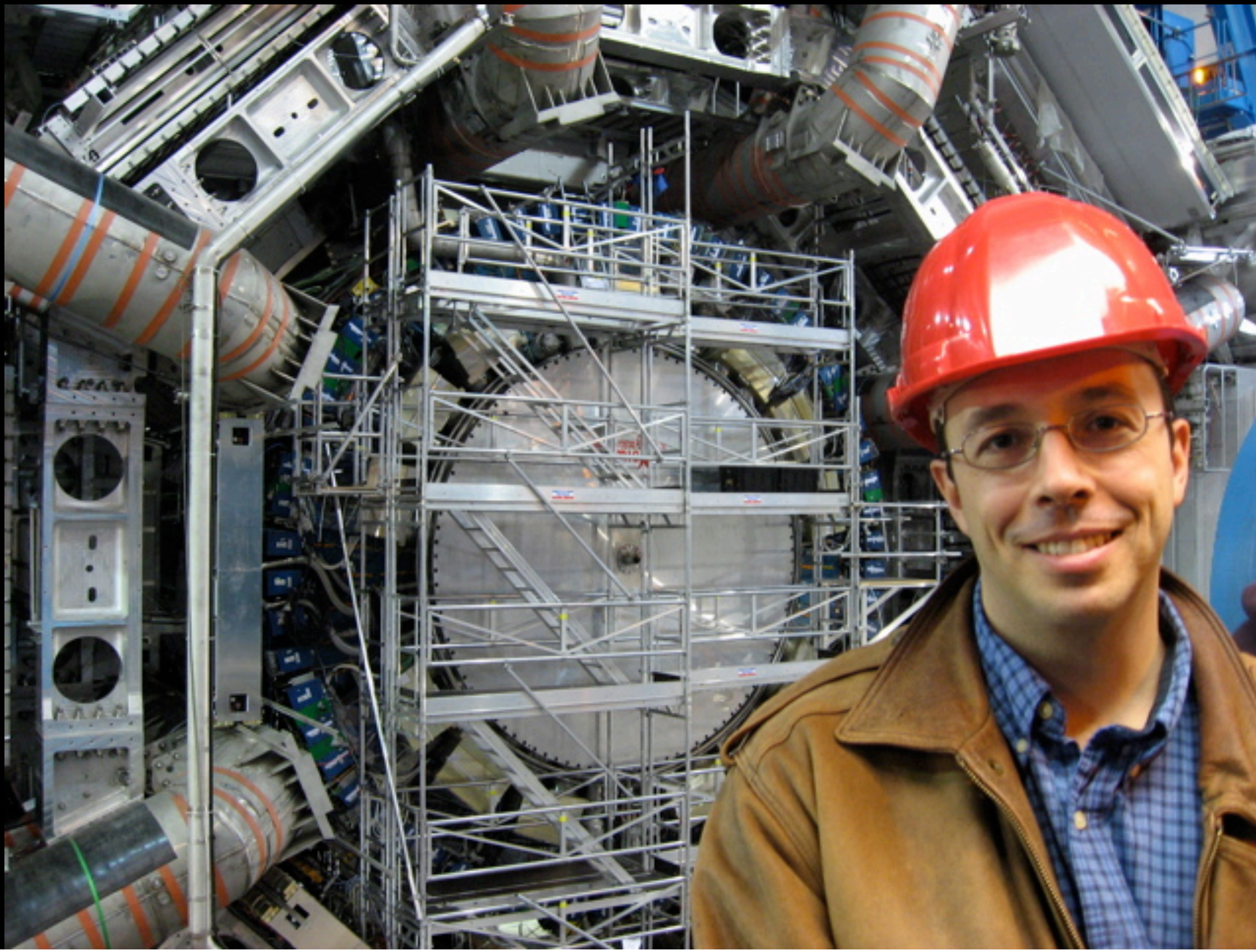
- Design: TRIUMF, UVic, UBC
- Construction: TRIUMF, Alberta
- Beam tests: SFU, TRIUMF, UVic
- Installation: TRIUMF
- Commissioning: SFU, UVic, Toronto, Carleton

Forward Calorimeter

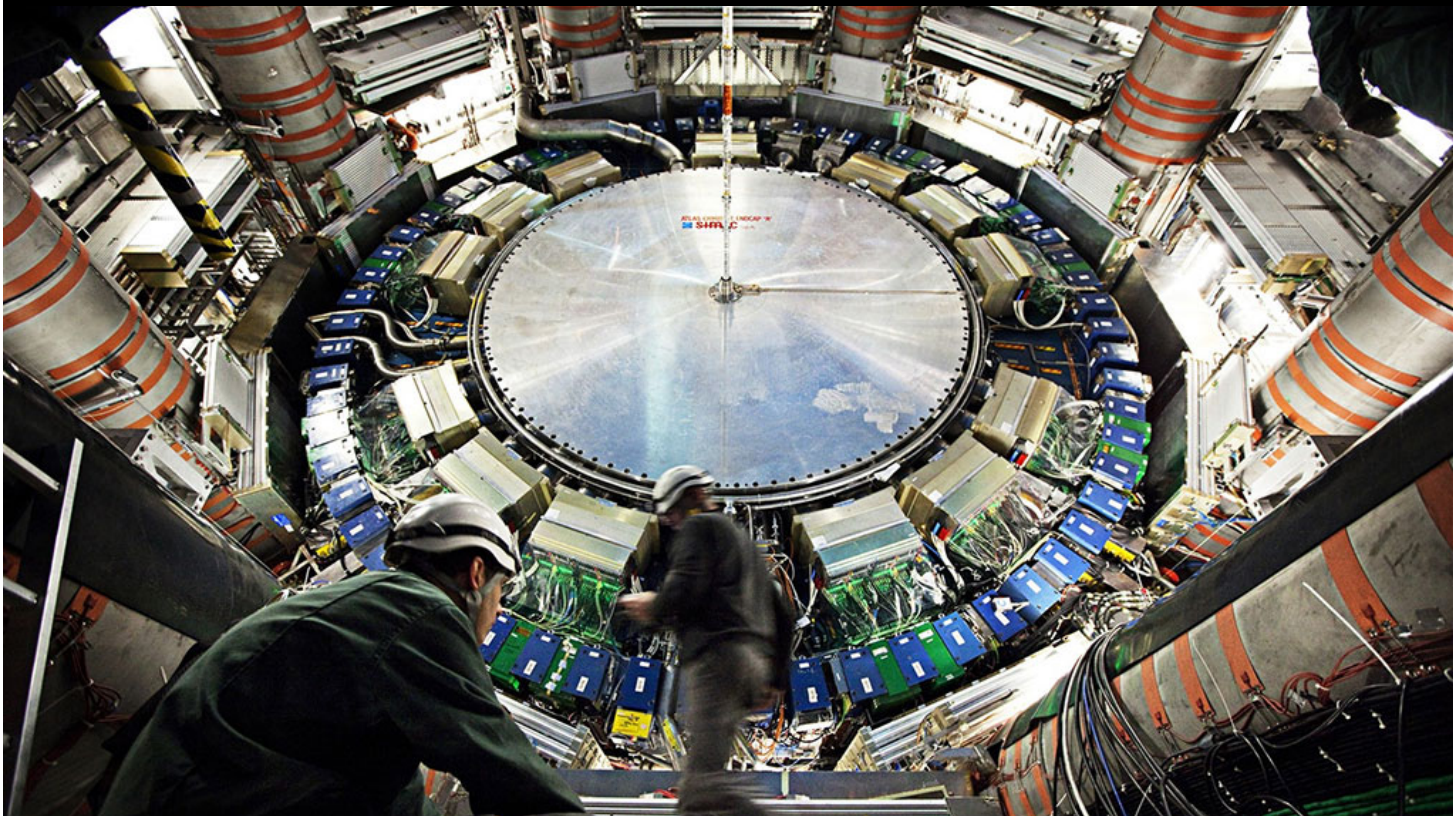
Design, Construction, Beam tests,
Installation & Commissioning:
Carleton, Toronto

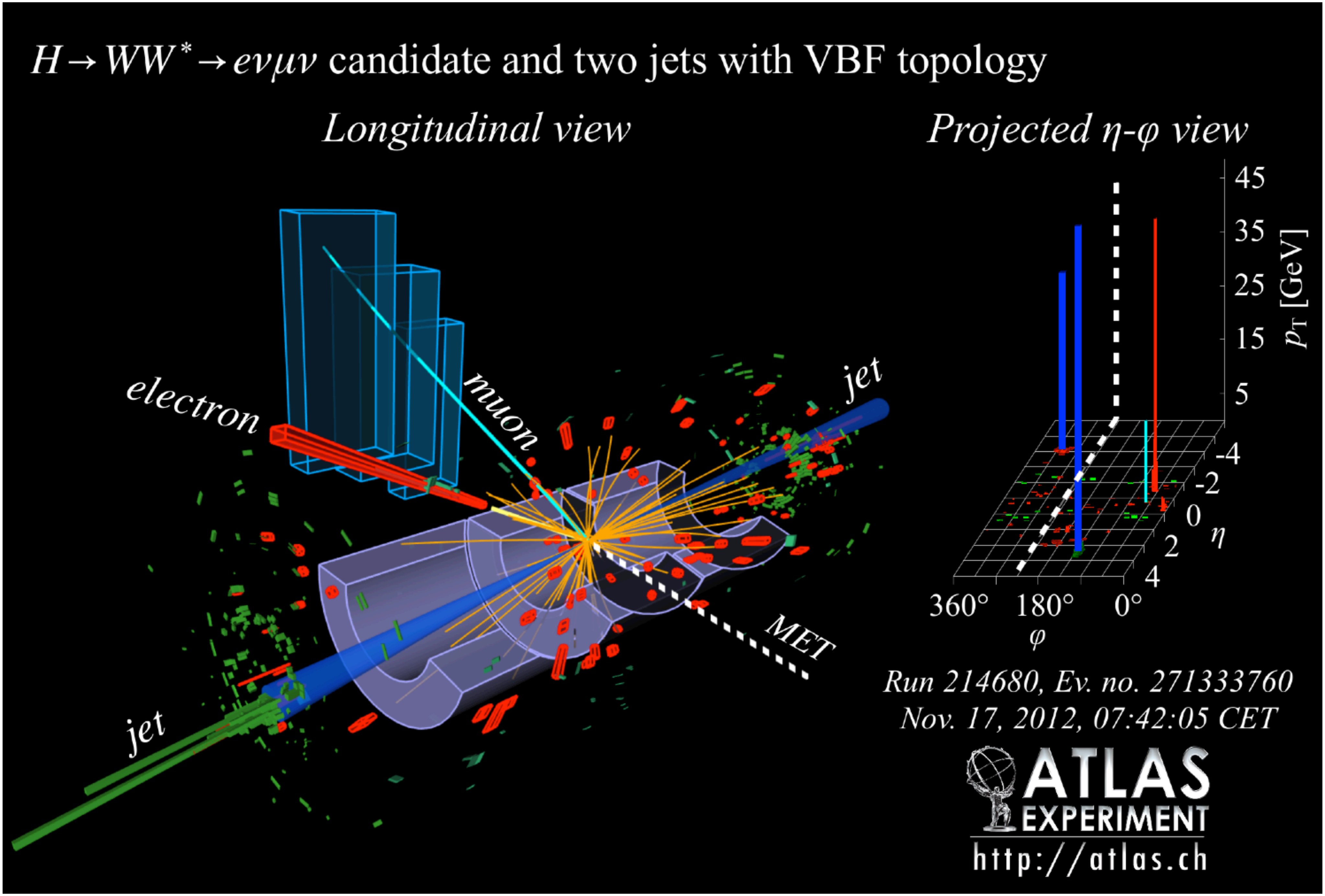


ATLAS Detector with Calorimeter



ATLAS Detector with Calorimeter




$H \to WW^* \to e\nu\mu\nu$ candidate and two jets with VBF topology
Longitudinal view
Projected η-φ view
electron
muon
jet
jet
MET
45
35
25
15
5
p_T [GeV]
-4
-2
0
2
4
η
360°
180°
0°
φ
Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET
ATLAS
EXPERIMENT
http://atlas.ch

The Standard Model

Some important dates

1967:

"A Model of Leptons" (Weinberg)

1971-73:

Renormalizability of theory, Quantum Chromodynamics asymptotic freedom

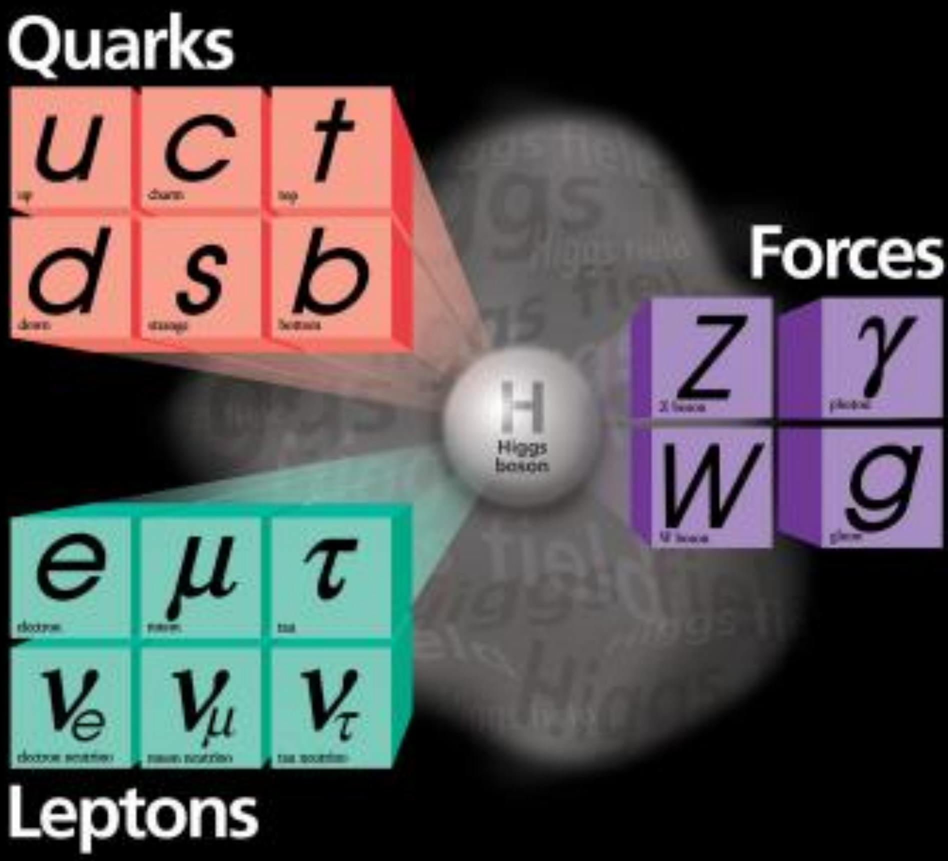
Mid-70s:

Discovery of 3rd generation fermions

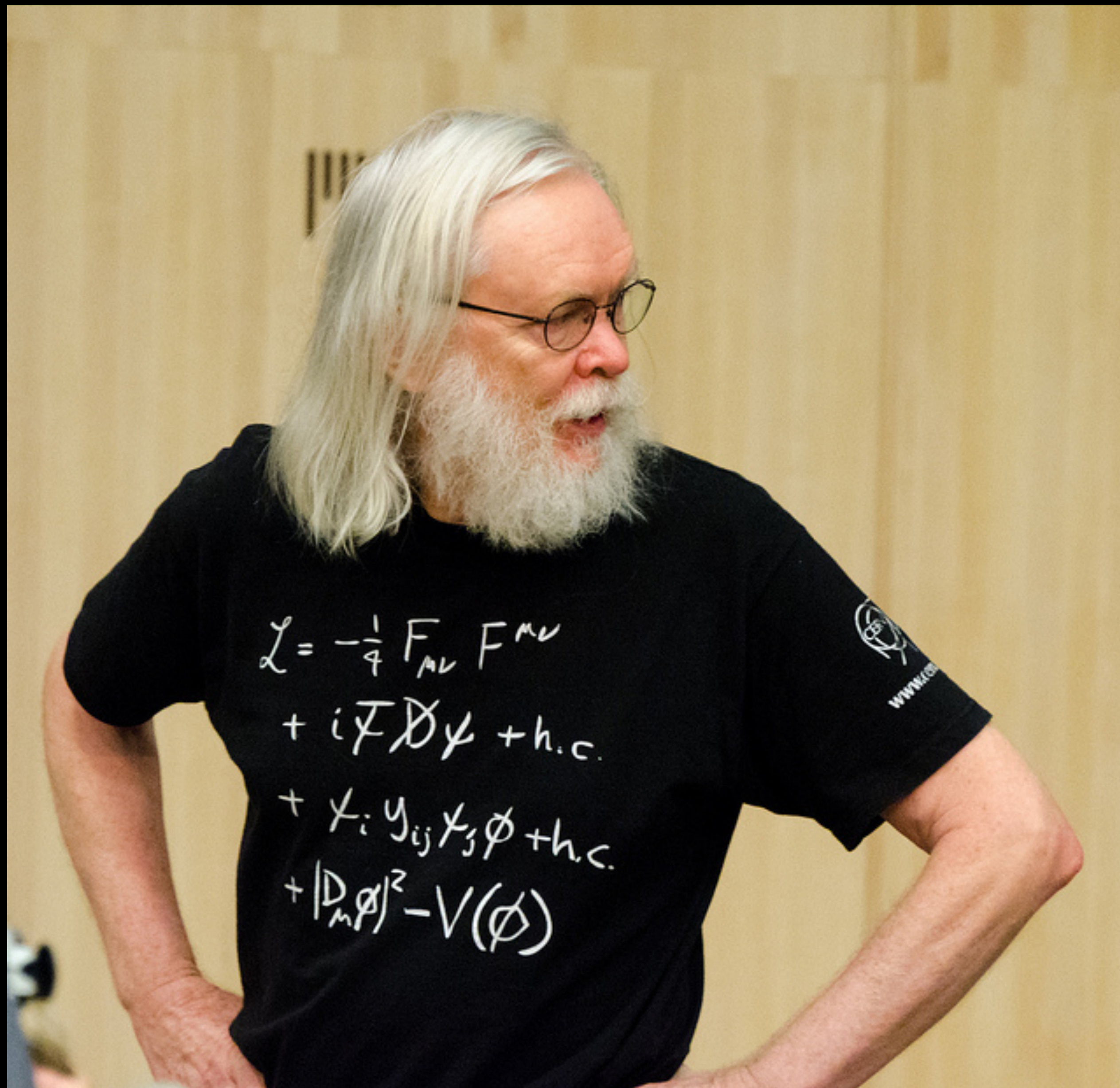
1995:

Top quark discovery, completed the third fermion generation*

Until 2012 we were still missing a key Ingredient of the model: a scalar boson

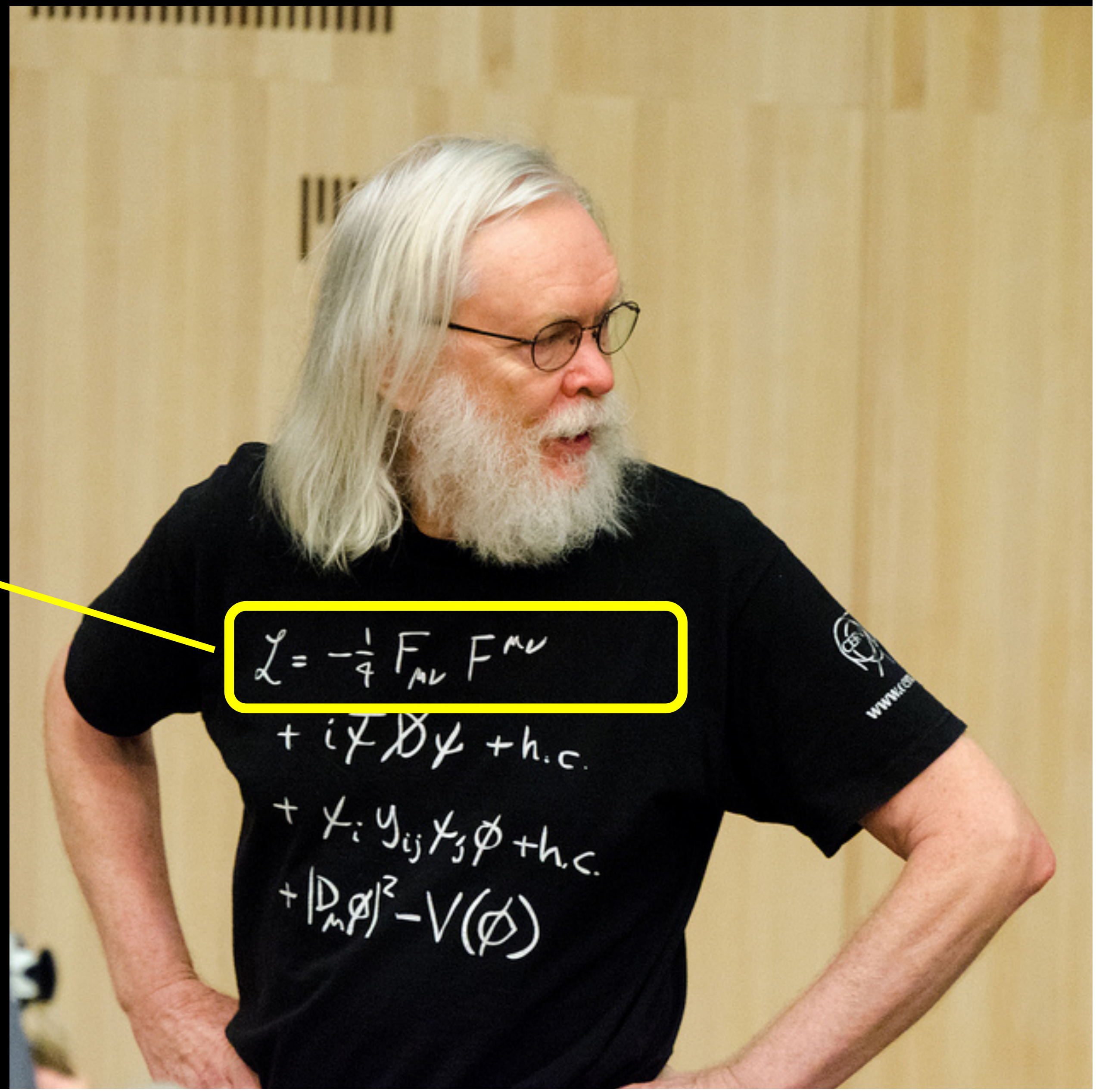


The Standard Model Lagrangian



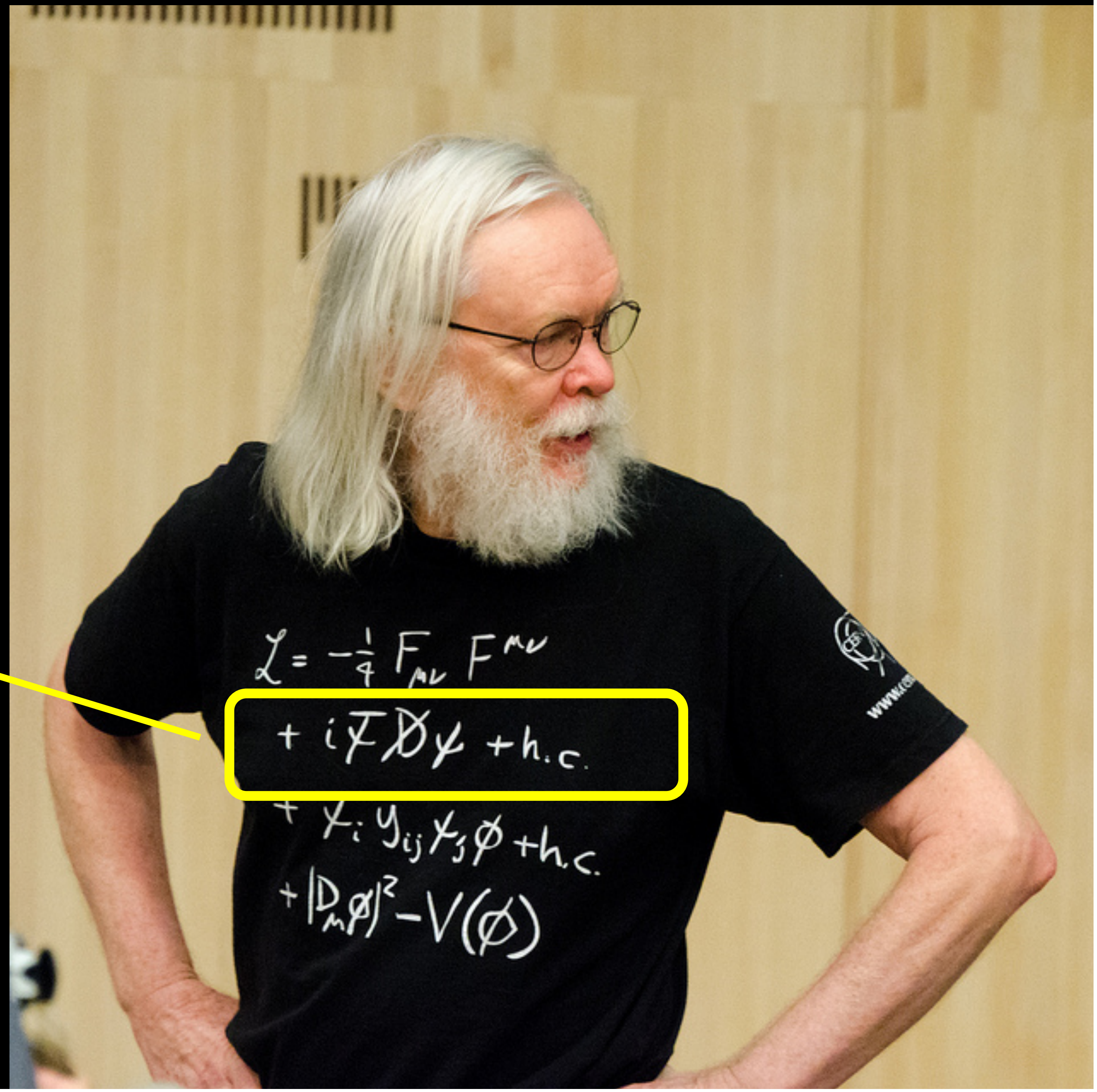
The Standard Model on a T-Shirt

Kinetic term for gauge bosons



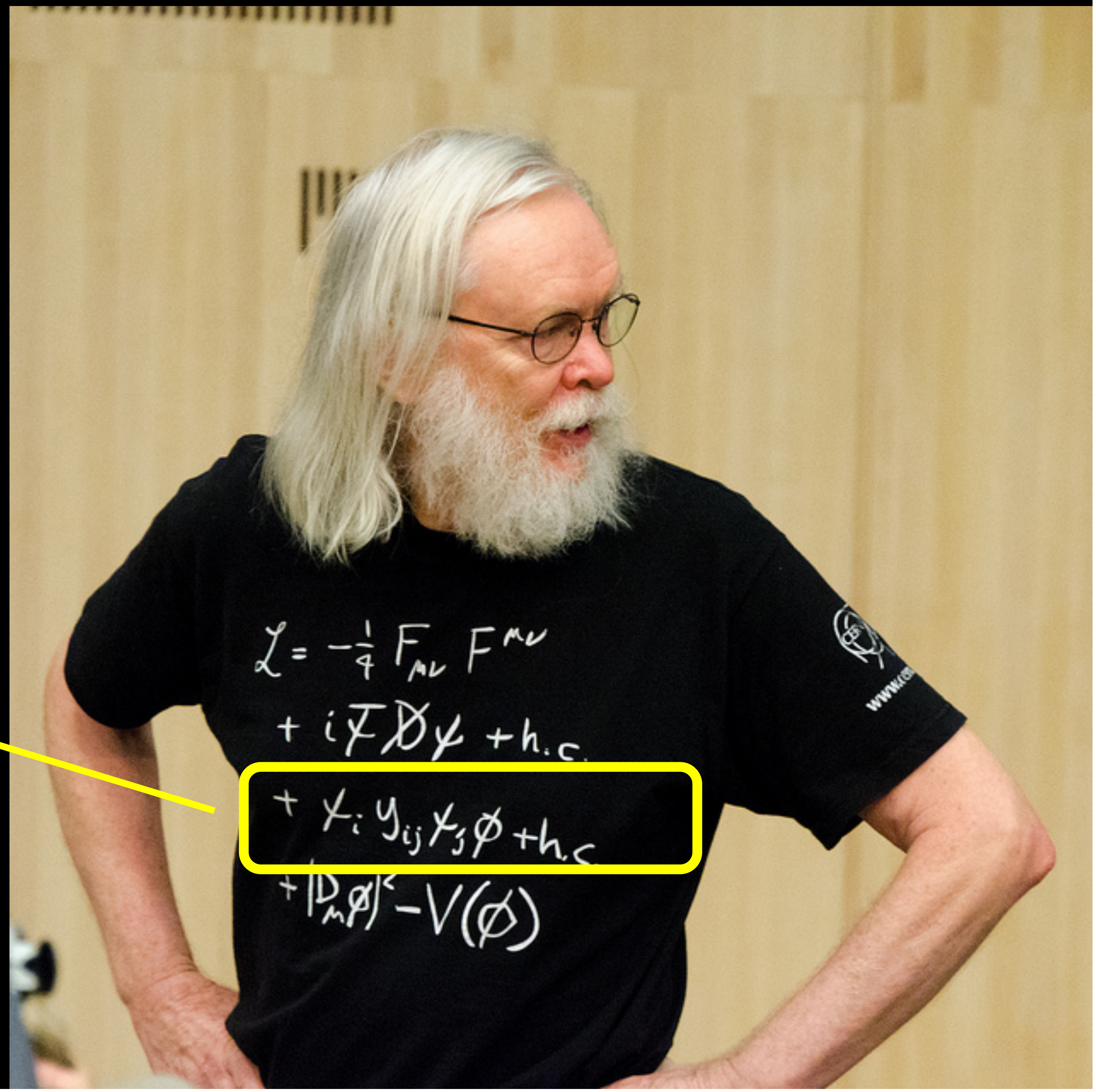
The Standard Model on a T-Shirt

Kinetic term for fermions



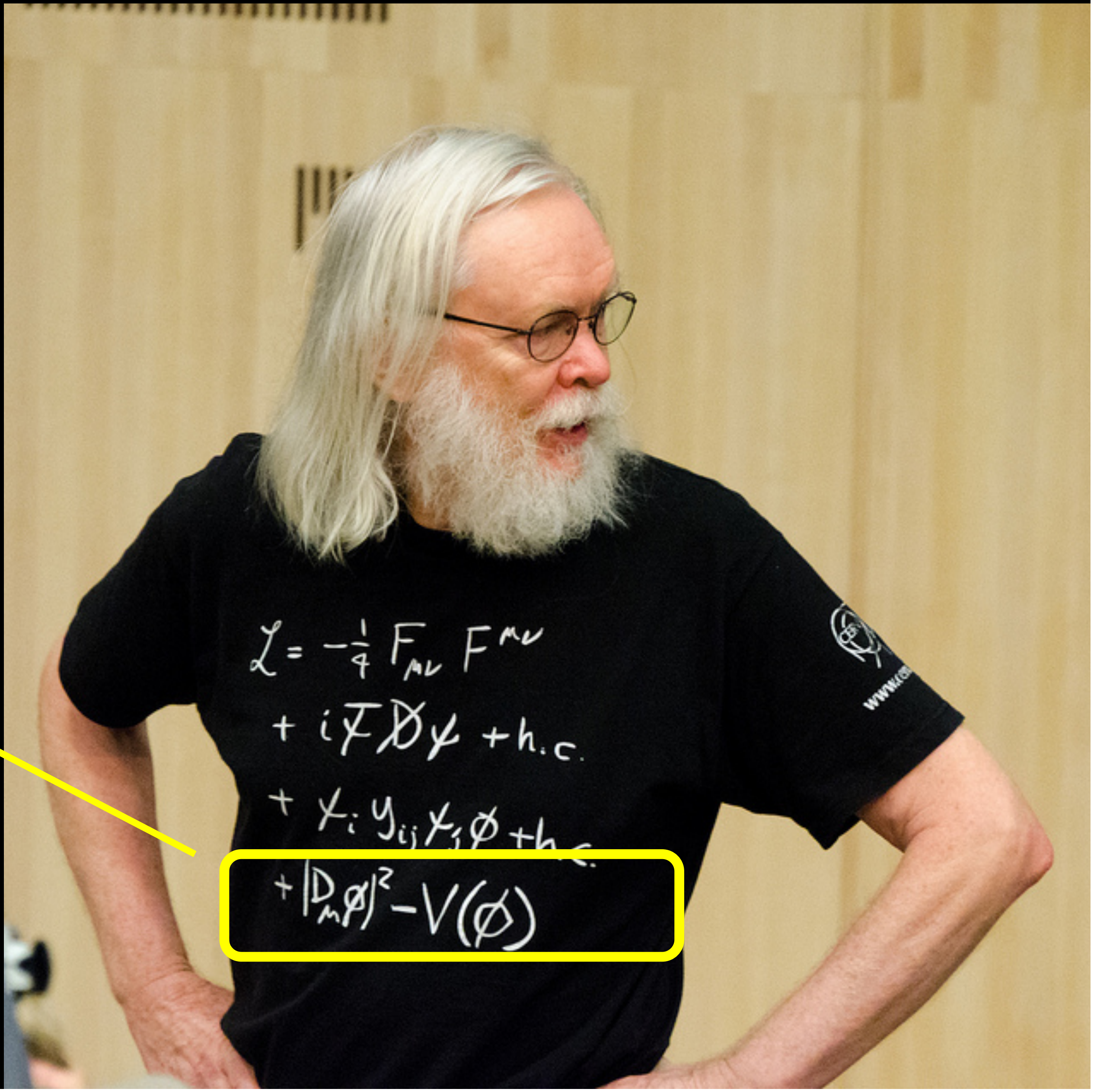
The Standard Model on a T-Shirt

Interaction of the Higgs with fermions, fermion mass terms



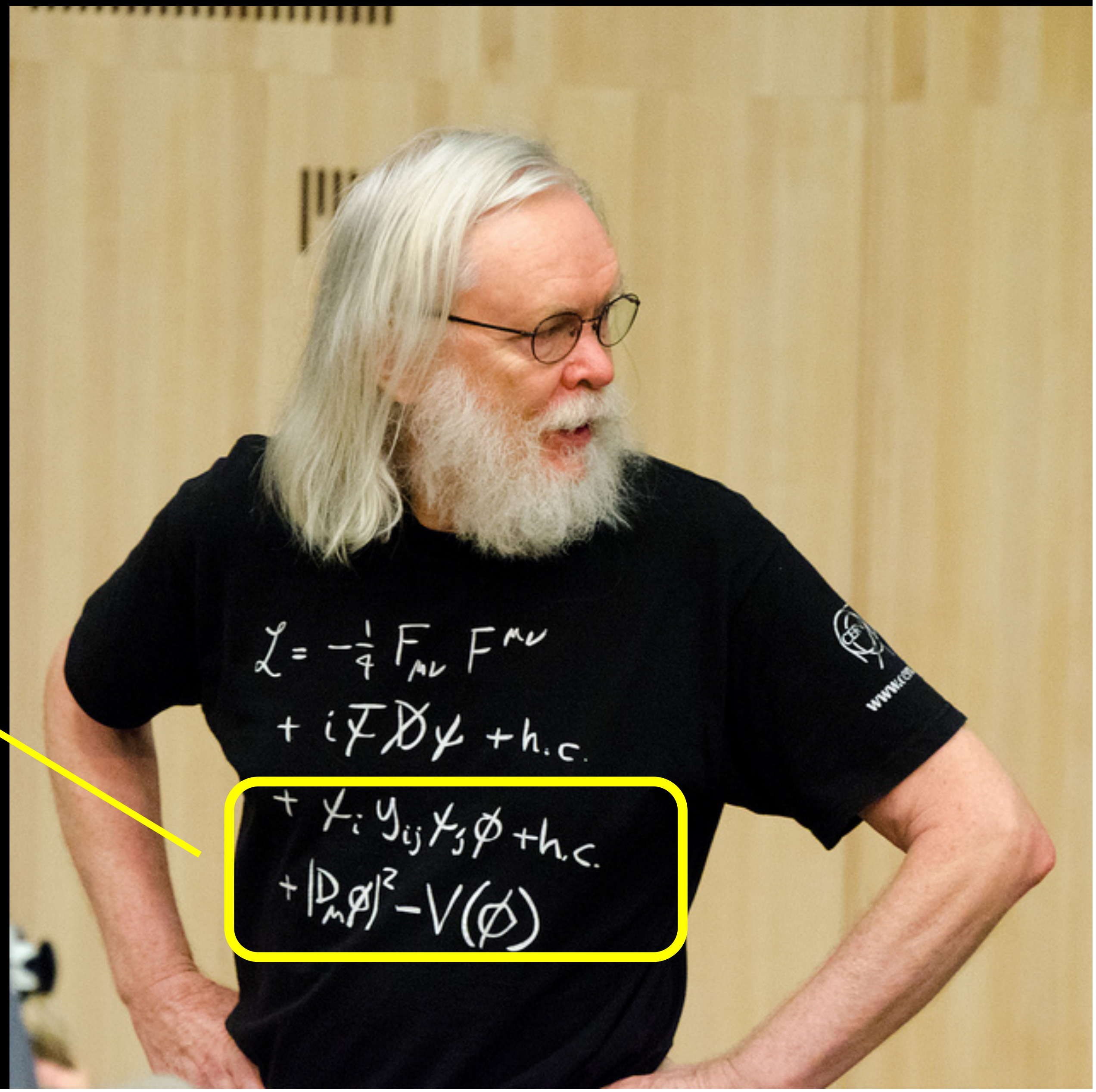
The Standard Model on a T-Shirt

Interactions of the Higgs with weak gauge bosons (and itself), weak boson mass terms



The Standard Model on a T-Shirt

Do these terms really describe Nature?

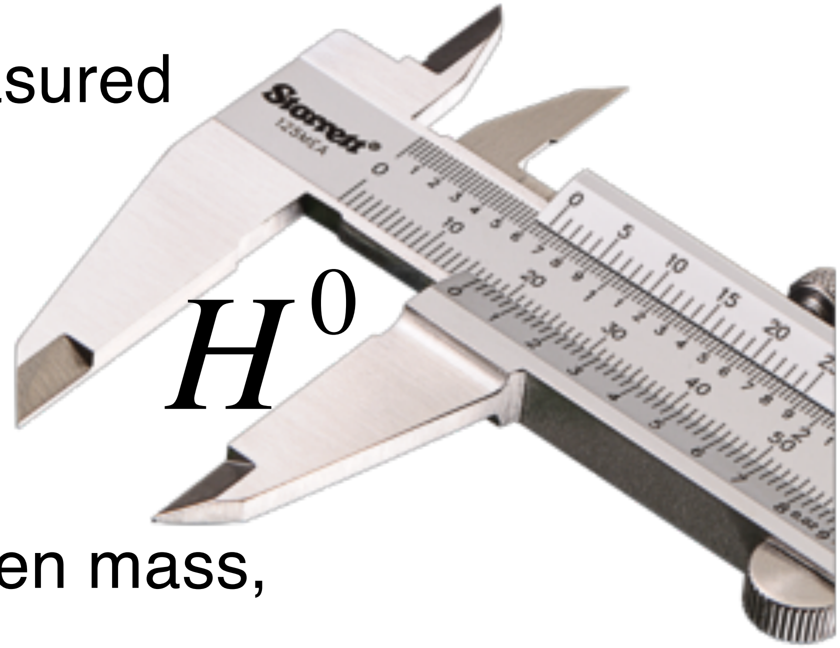


Testing the Theory…

- How do we go about testing that there is such a thing as a Higgs field that interacts with massive particles?
  - We need to produce excitations of that field i.e. produce the Higgs bosons and measure how they interact with massive particles
- Producing Higgs bosons and demonstrating that what you observe is indeed a Higgs boson is very difficult…
  - The Higgs boson is very heavy, need a lot of energy
  - The Higgs boson is produced very rarely. And, only a small fraction of those produced can be identified as likely Higgs candidates: need many, many collisions
    - Roughly 1 Higgs in every 10,000,000,000 collisions
    - And we typically look for rare decays of the Higgs…

Properties of SM Higgs boson

- Mass: not predicted must be measured

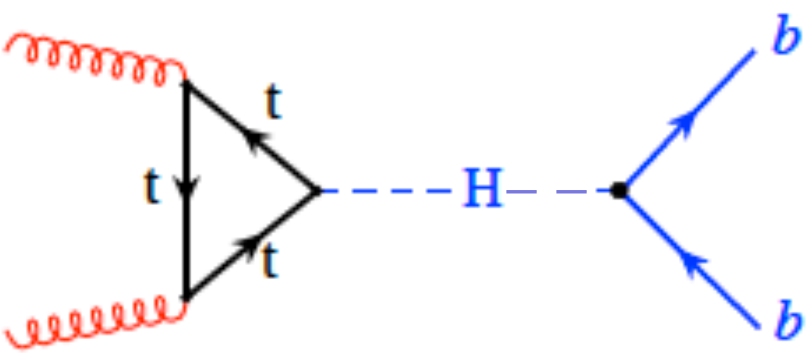


- Electric charge: 0 (easy!)

- Spin: 0

- Coupling to SM particles: at a given mass, predicted for all particles

  – Can be extracted from production and decay rates

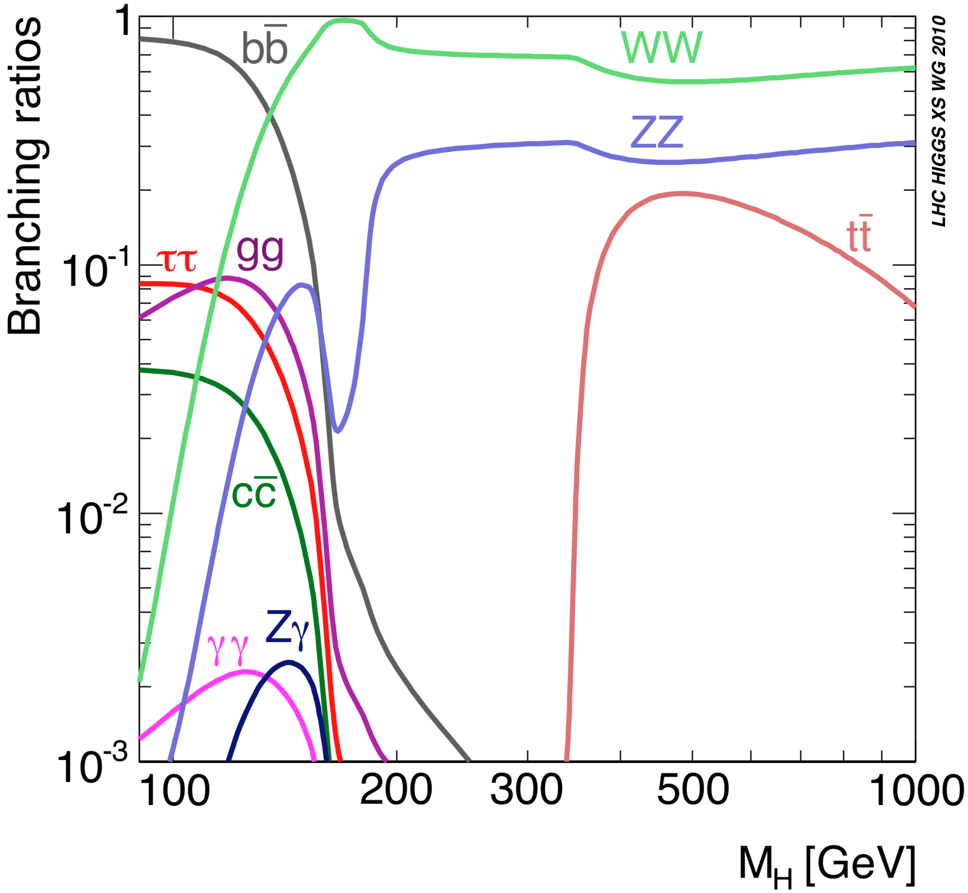


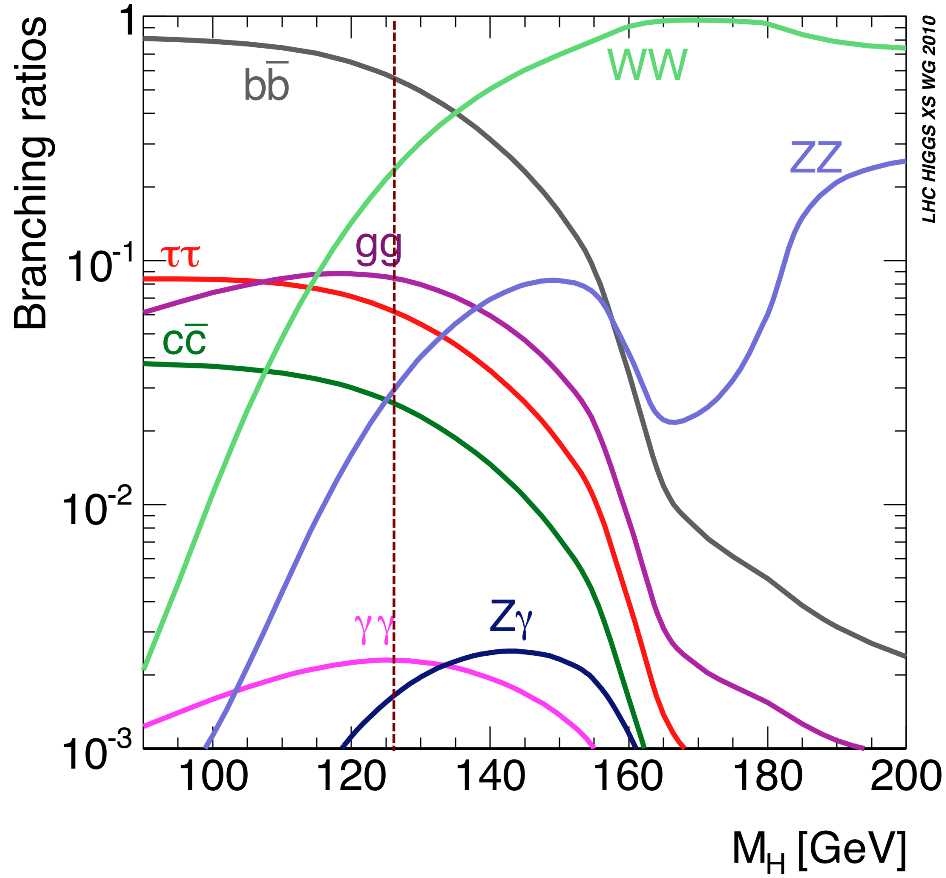
The observed rate of the process on the left depend on the Higgs's coupling to both top quarks and bottom quarks

Higgs Decays

- Standard Model is a very predictive theory with respect to the Higgs boson once we measure the Higgs mass

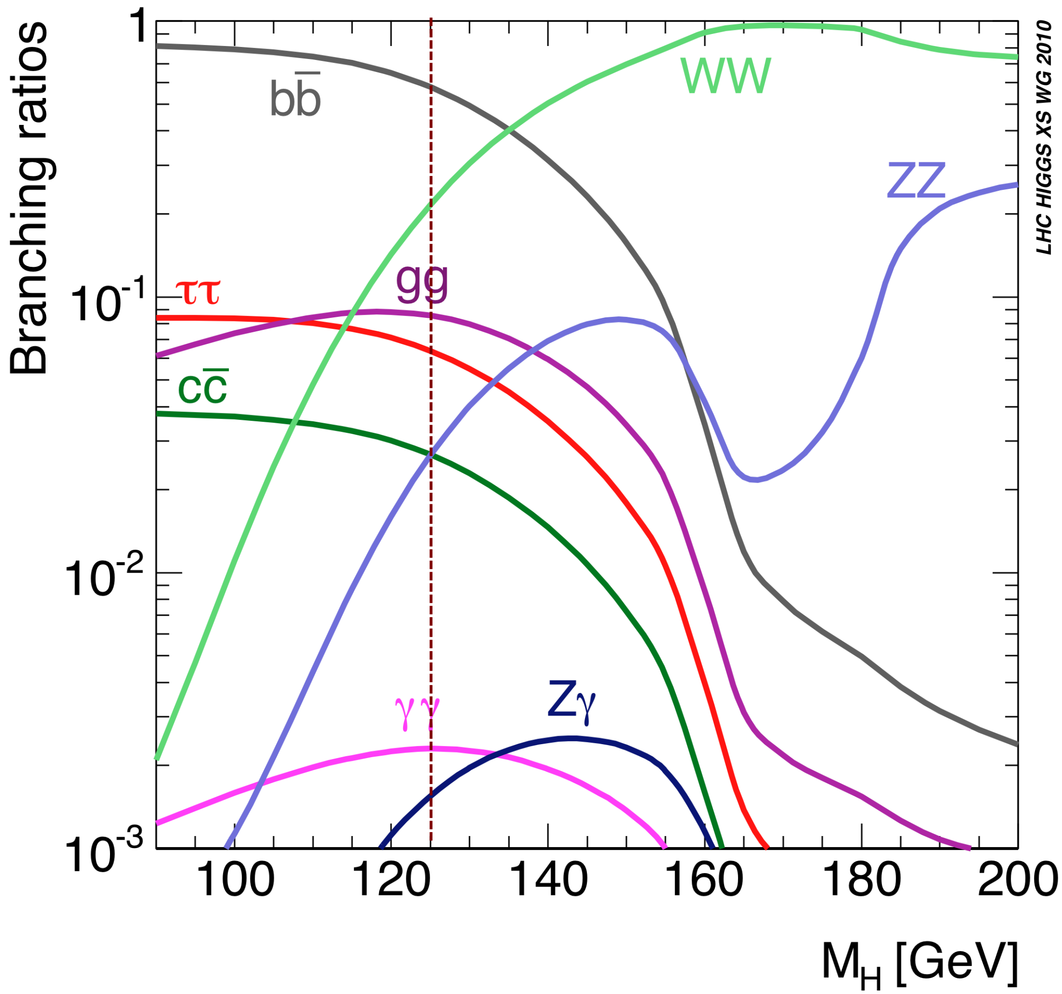
$$M_H^2 = 2v^2 \lambda$$





Higgs Decays

- At m_H = 125 GeV, many decay channels can be studied



SM Decay Modes
(M_H = 125.1 GeV)

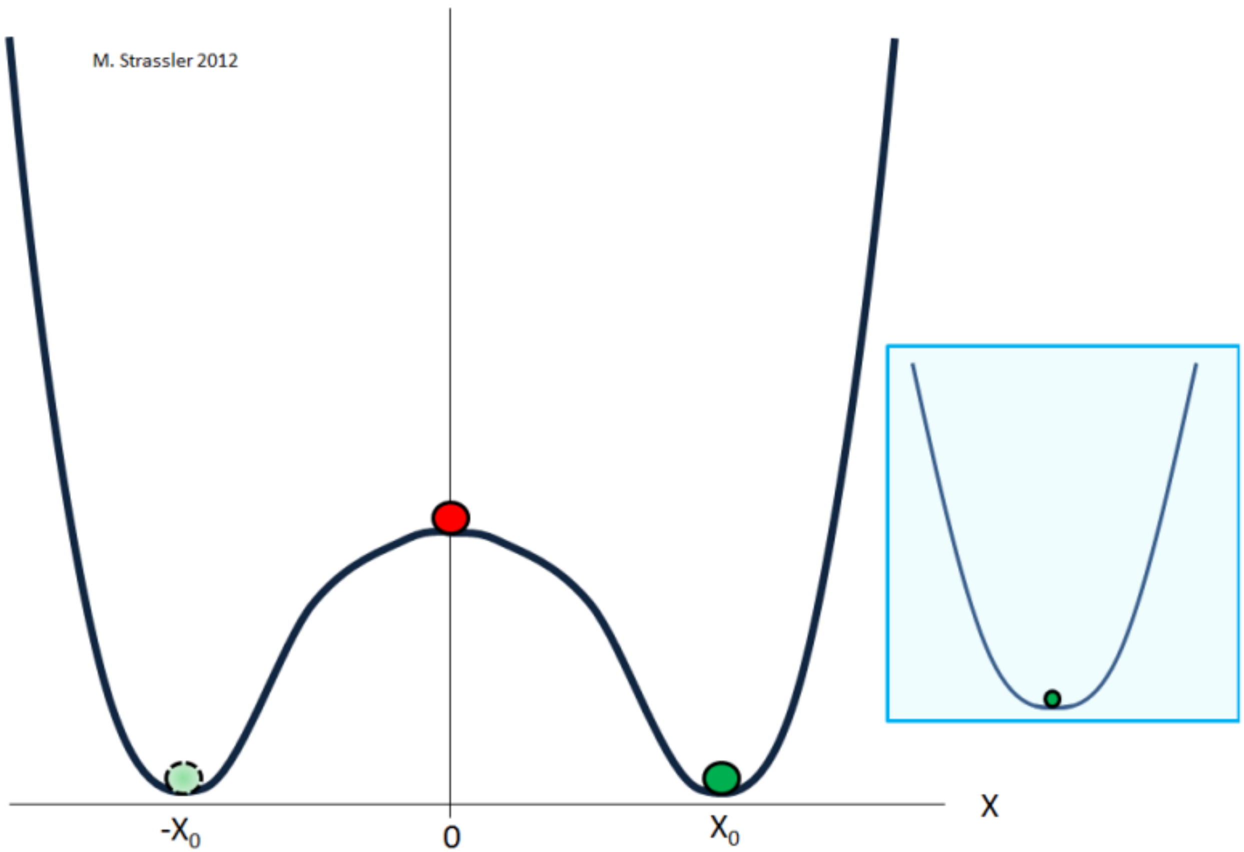
Decay Process	Decay Fraction
bb	0.58
WW	0.22
$\tau\tau$	0.06
ZZ	0.027
$\gamma\gamma$	0.0023
$Z\gamma$	0.0016
$\mu\mu$	0.0002

Higgs Decays

- Standard Model is a very predictive theory with respect to the Higgs boson: the only unknown parameter is the Higgs mass

$$M_H^2 = 2v^2 \lambda$$

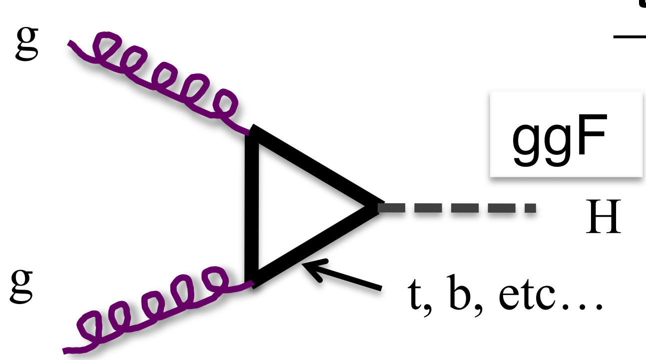
$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

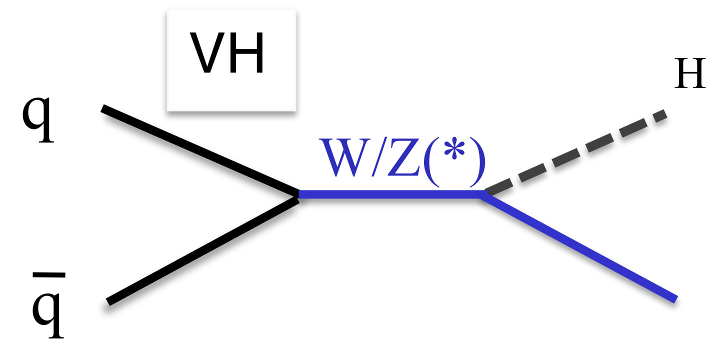


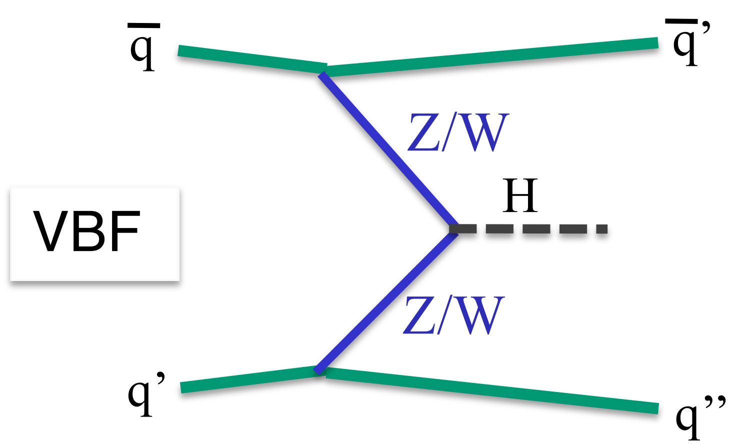
Higgs Production

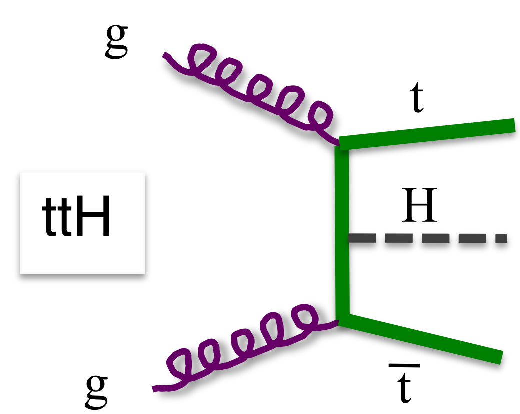
Cross sections for m_H=125 GeV:

	process	8 TeV	13 TeV
ggF	gluon-gluon fusion	19 pb	44 pb
VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
ttH	associated production	0.13 pb	0.51 pb





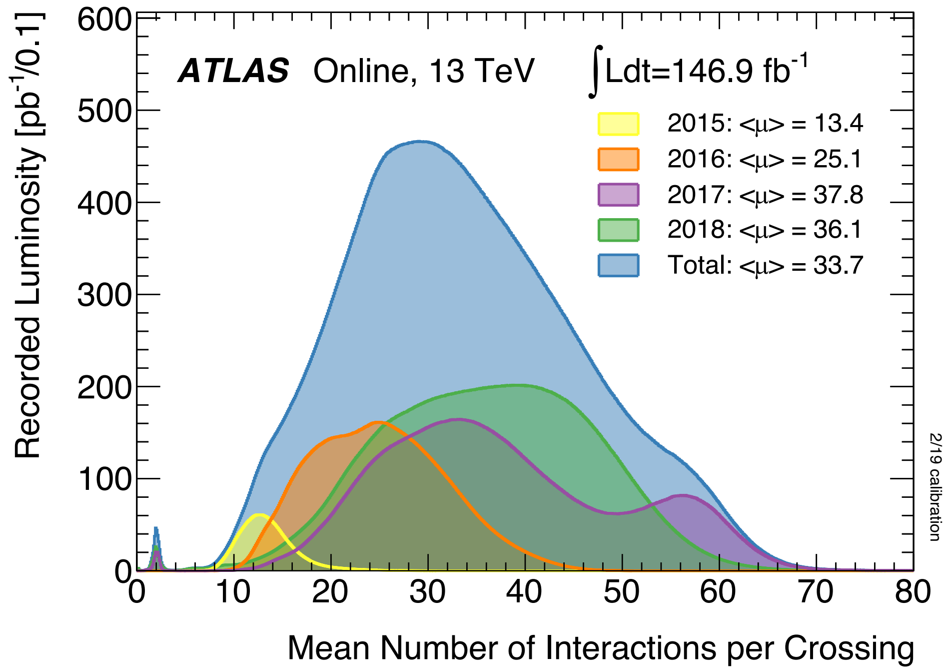


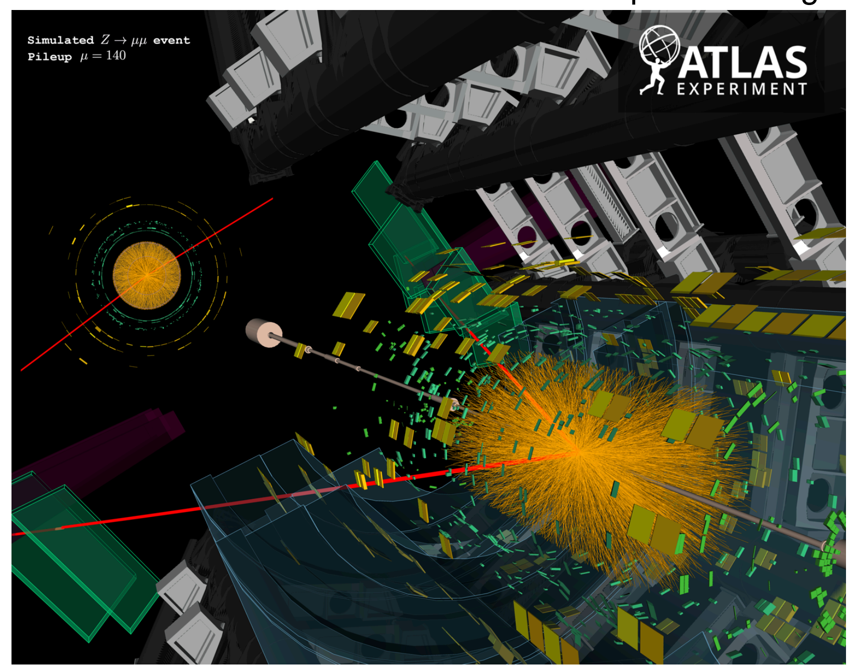


LHC Datasets

Proton-proton datasets:

- Run 1 ~25 fb^{-1} at 7 and 8 TeV
- Run 2 ~140 fb^{-1} at 13 TeV
  - Large, high quality dataset yielding very impressive results
- Run 3 expected to yield ~170-190 fb^{-1} with CM energy to be determined
  - Next 8 years: Run 2 dataset will be combined with Run 3 data for most measurements
- HL-LHC expected to yield 3000 fb^{-1} at 14 TeV: a ~20-fold increase over current dataset
  - A Higgs factory that will produce close to 200M Higgs bosons
  - Challenging collision environment: up to 200 interactions per bunch crossing

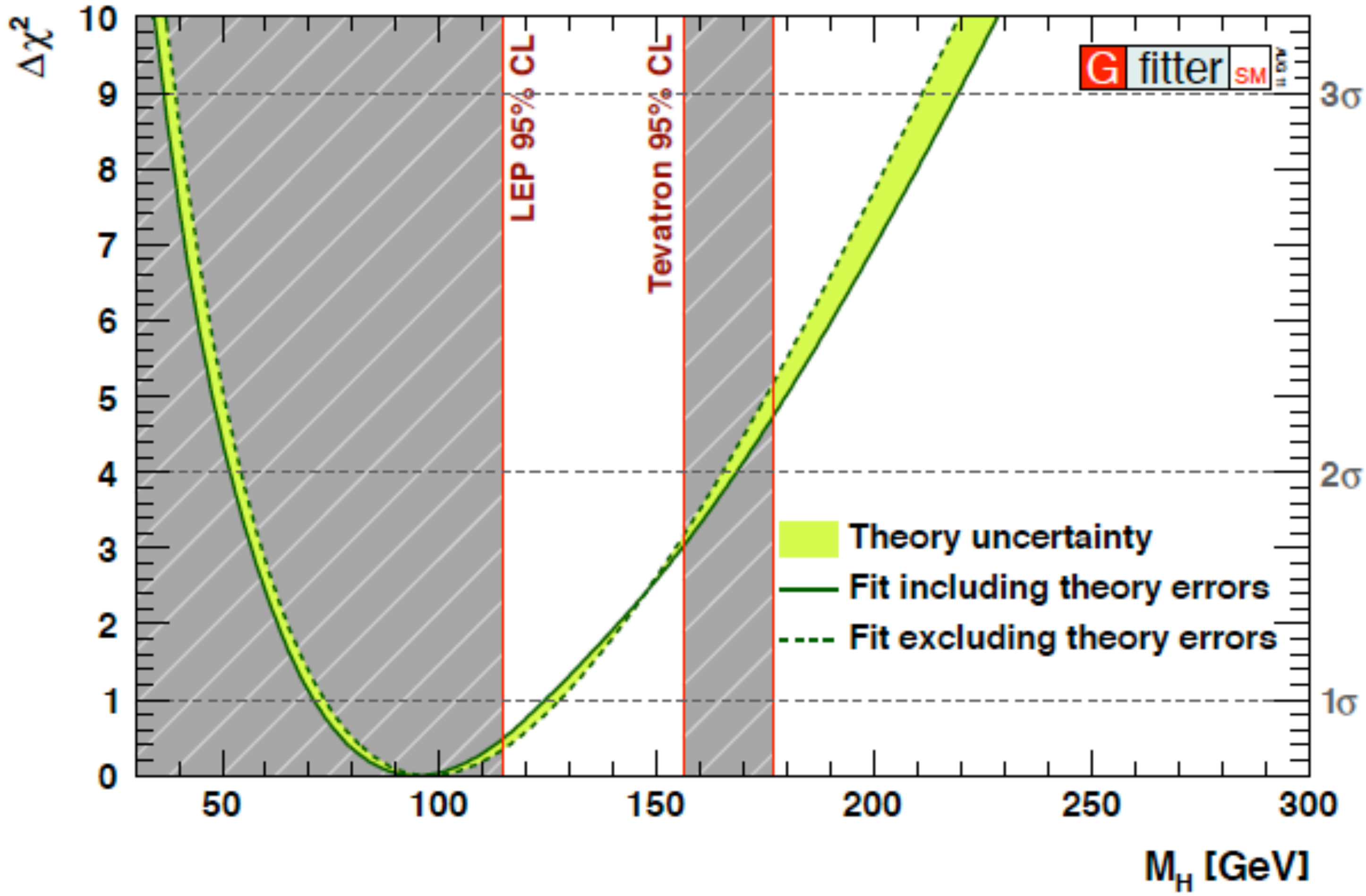




The Past

Before LHC: where to expect the Higgs?

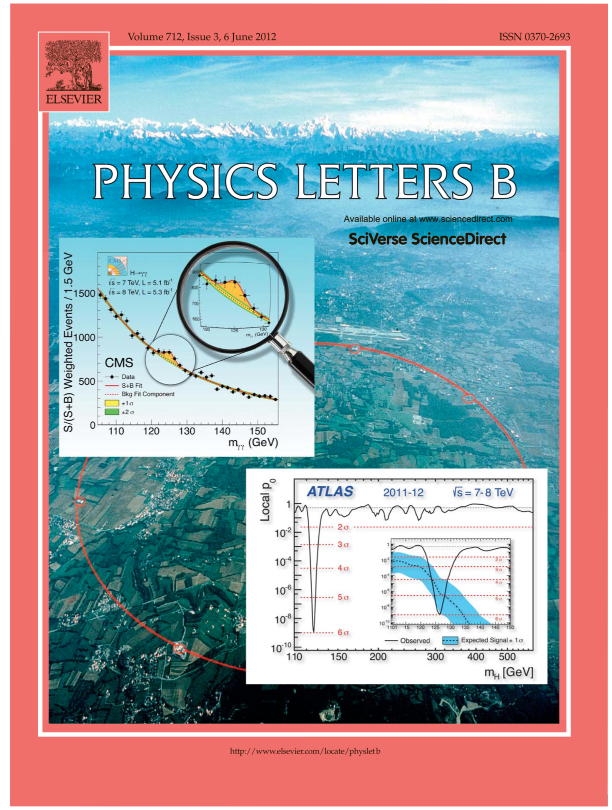
- Fits to Standard Model data favoured a "light" Higgs Boson
- After 2010, at 95% CL, a 40 GeV window was left for the SM Higgs



Discovery

•In April of 2012, the LHC started to produce collisions at a centre of mass of 8 TeV. The 7 TeV run showed some hints of a signal consistent with the SM Higgs boson

•On July 4th of 2012, both ATLAS and CMS announced that they had discovered a new particle consistent with what was expected in the SM. Two papers were then submitted at the end of July



•The ATLAS paper was titled:

"Observation of a New Particle in the Search for the Standard Model Higgs Boson"

Run 1, after Discovery

- The LHC delivered 4 times the data used for the discovery by the end of 2012. Results using the full dataset presented in March 2013 prompted CERN to declare that the new particle was “a” Higgs boson
- This was followed by two key ATLAS papers on the couplings and the spin of the discovered particle

Physics Letters B 726 (2013) 88–119

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

Physics Letters B 726 (2013) 120–144

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

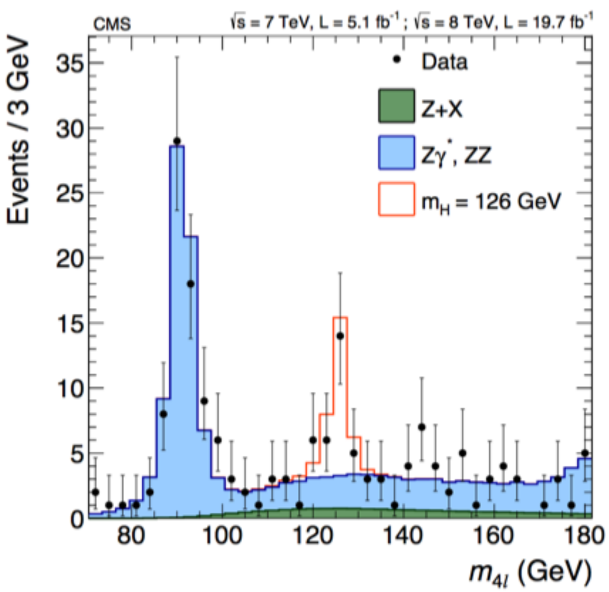
ELSEVIER

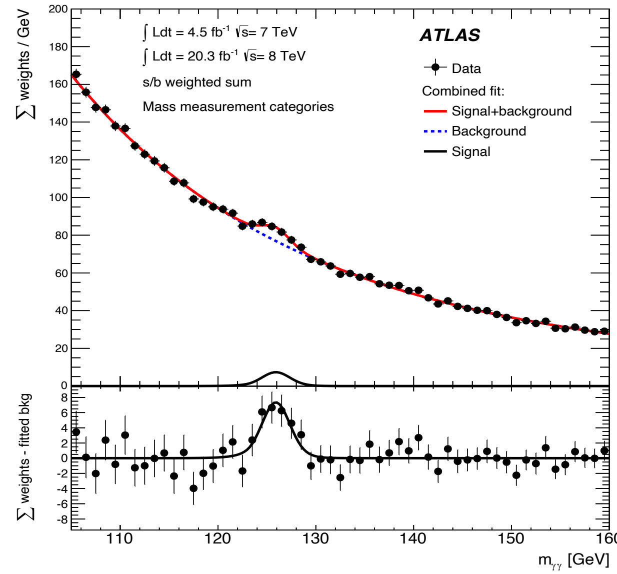
Evidence for the spin-0 nature of the Higgs boson using ATLAS data ☆

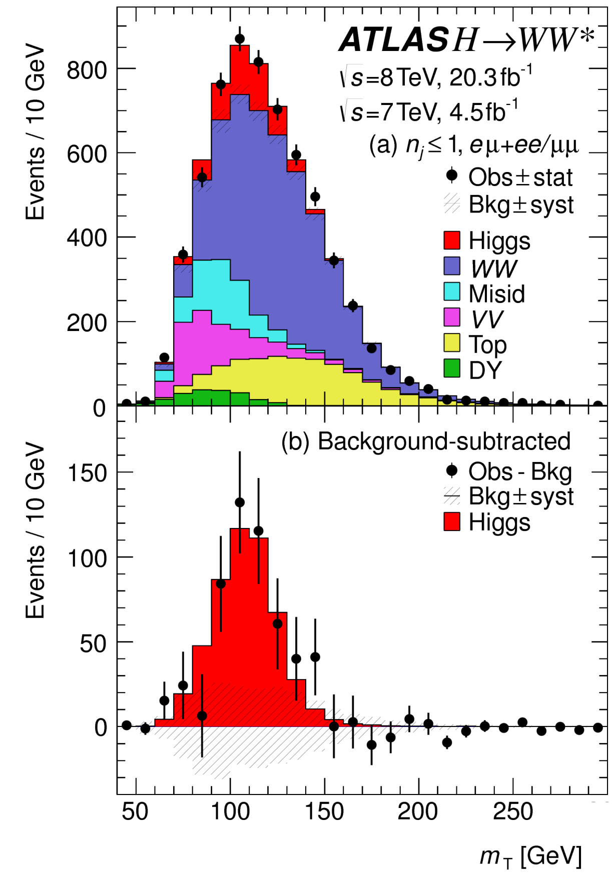
ATLAS Collaboration *

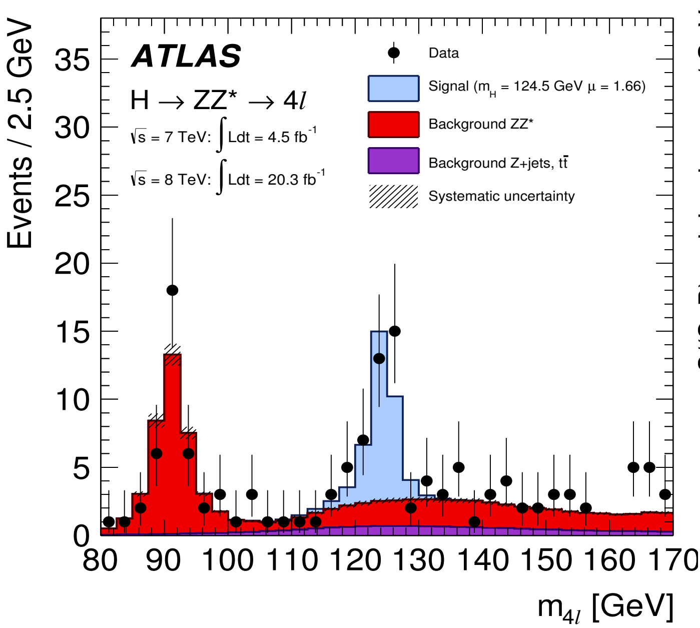
2013 Nobel Prize in physics

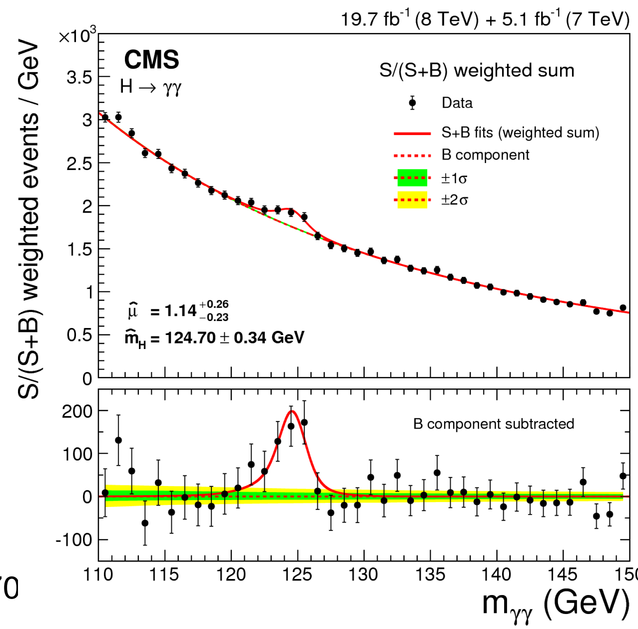
Run 1: 5σ Observation In Decays to Bosons

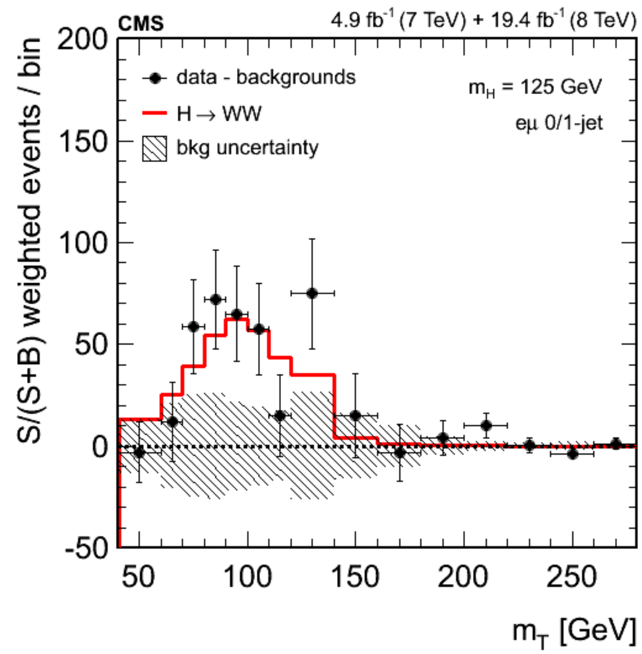












Higgs Boson in PDG

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

GAUGE AND HIGGS BOSONS

γ $I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-35}$ e
Mean life τ = Stable

g or gluon $I(J^{P}) = 0(1^{-})$

Mass $m = 0$ [a]
SU(3) color octet

W $J = 1$

Charge $= \pm 1$ e
Mass $m = 80.385 \pm 0.015$ GeV
$m_Z - m_W = 10.4 \pm 1.6$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.085 \pm 0.042$ GeV
$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$
$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$
$\langle N_{p} \rangle = 0.92 \pm 0.14$
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

$$H^0$$

Z $J = 1$

Charge $= 0$
Mass $m = 91.1876 \pm 0.0021$ GeV [d]
Full width $\Gamma = 2.4952 \pm 0.0023$ GeV
$\Gamma(\ell^+\ell^-) = 83.984 \pm 0.086$ MeV [b]
$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]
$\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV
$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.0009 \pm 0.0028$
$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 1.0019 \pm 0.0032$ [f]

Higgs Bosons — H^0 and $H^\pm$

H^0 Mass $m = 125.9 \pm 0.4$ GeV

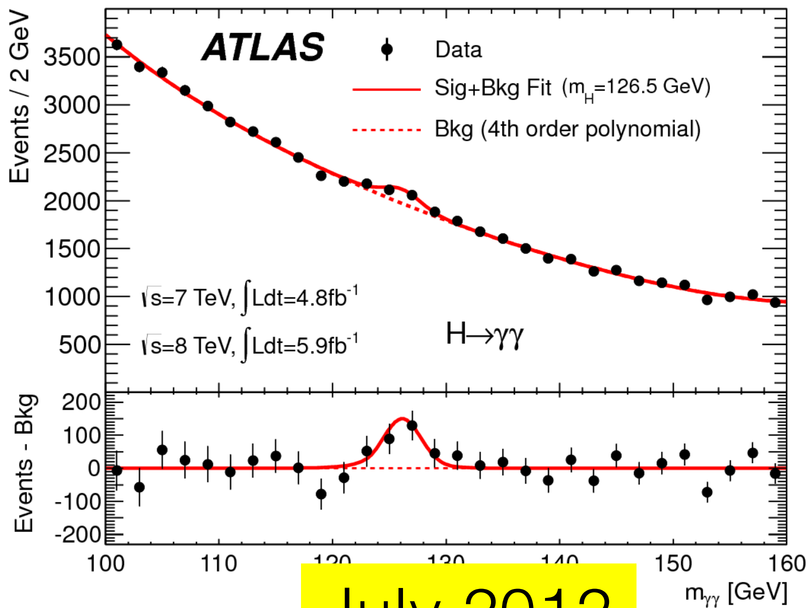
H^0 signal strengths in different channels [n]

Combined Final States $= 1.07 \pm 0.26$ (S = 1.4)
WW^* Final State $= 0.88 \pm 0.33$ (S = 1.1)
ZZ^* Final State $= 0.89^{+0.30}_{-0.25}$
$\gamma\gamma$ Final State $= 1.65 \pm 0.33$
$b\bar{b}$ Final State $= 0.5^{+0.8}_{-0.7}$
$\tau^+\tau^-$ Final State $= 0.1 \pm 0.7$

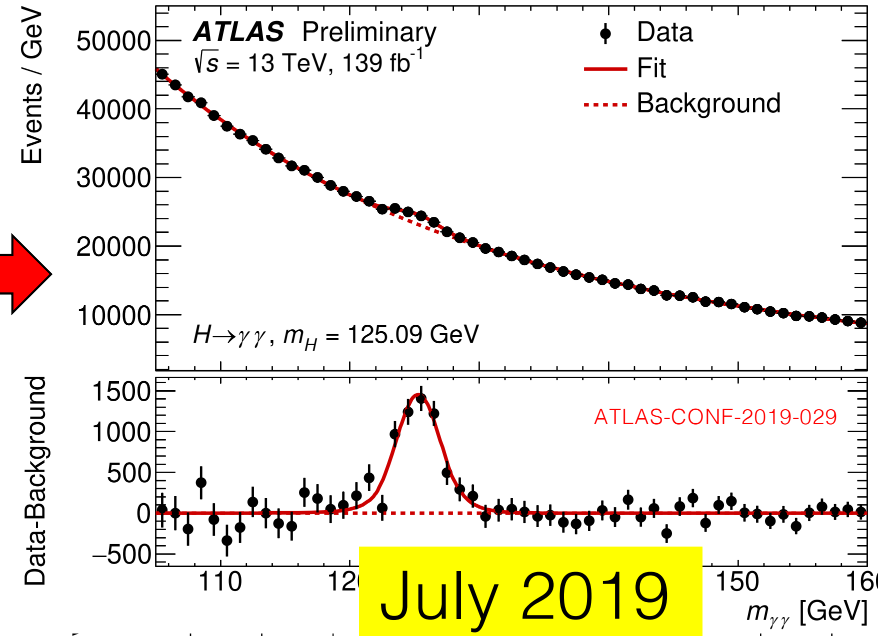
The Present

The Higgs Boson: then and now

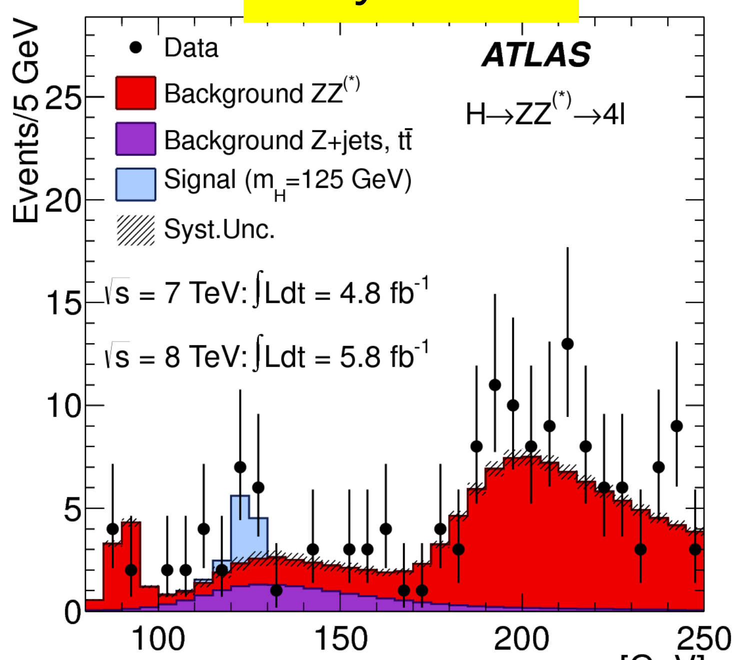
Full Run-2



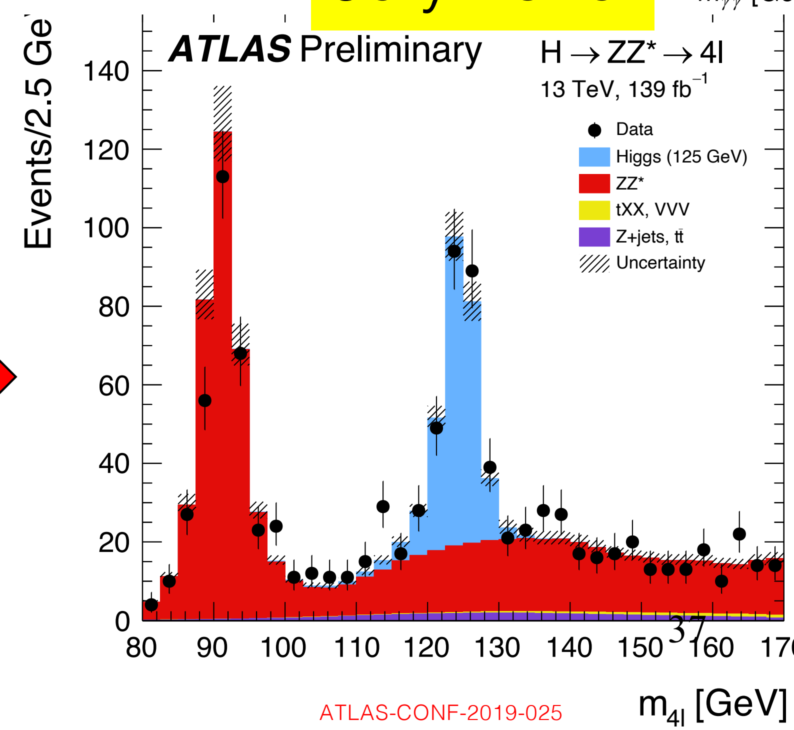
July 2012



July 2019



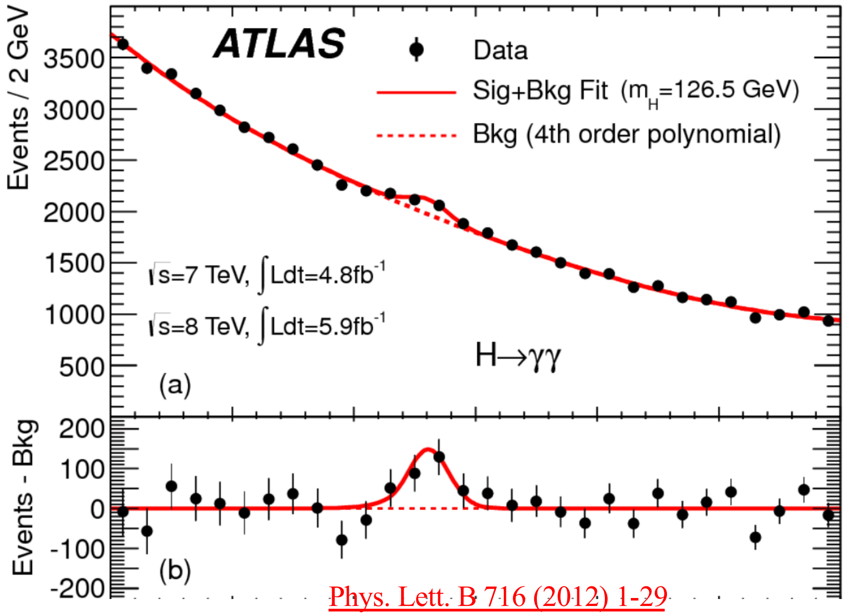
Phys. Lett. B 716 (2012) 1-29



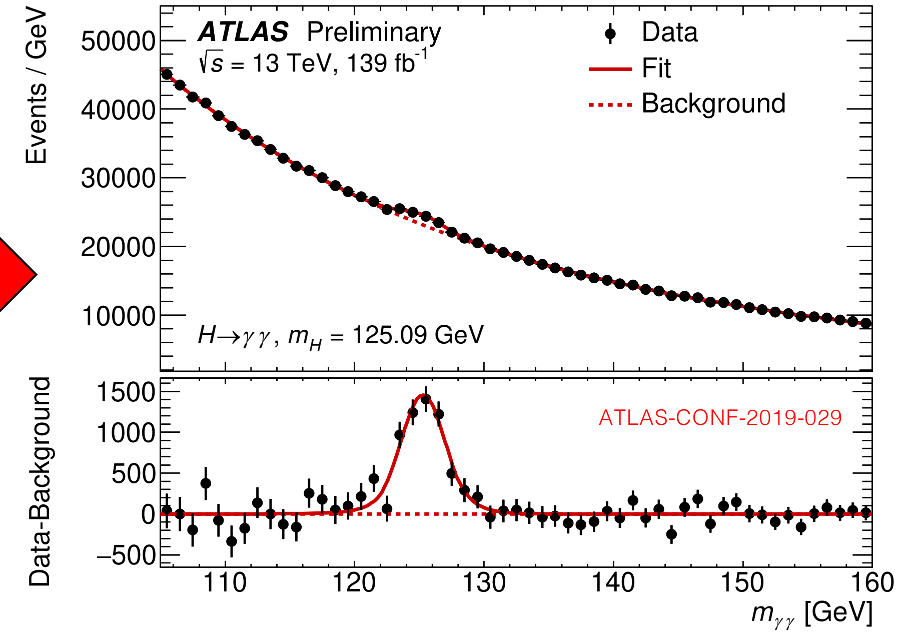
ATLAS-CONF-2019-025

The Higgs Boson: then and now

Full Run-2



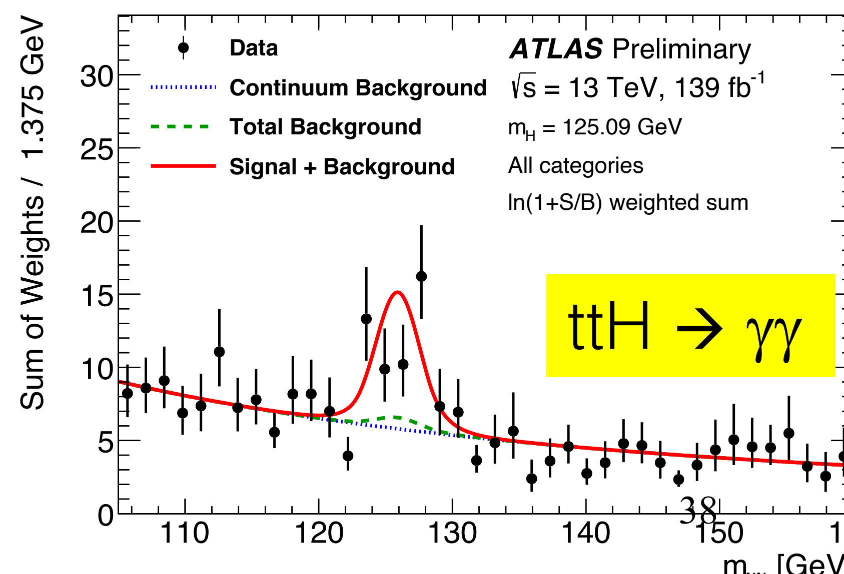
July 2012



July 2019

Observation of H → γγ in rare ttH production channel in 2019

ATLAS-CONF-2019-004



ttH → γγ

Main Production and Decays

Analyses performed by ATLAS targeting specific production and decay modes:

	WW	ZZ	$\gamma\gamma$	bb	$\tau\tau$	$\mu\mu$
ggH	X	X	X		X	X
VBF	X	X	X	X	X	X
WH	X	X	X	X	X	X
ZH	X	X	X	X	X	X
ttH	X	X	X	X	X	X

As of 2020, all the production and decay modes above except $\mu\mu$ have been observed with a significance above 5 standard deviations

The observed rates consistent with Standard Model predictions

Higgs Boson Physics: where we are now

- Large sample of ~8M Higgs bosons (per experiment) produced in Run 2 allows for precision tests of the Higgs sector of the SM:

Channel	Produced	Selected	Mass resolution
$H \to \gamma\gamma$	18,200	6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$ 210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$ 5,880	20%
$H \to \tau\tau$	490,000	2,380	15%
$H \to bb$	4,480,000	9,240	10%

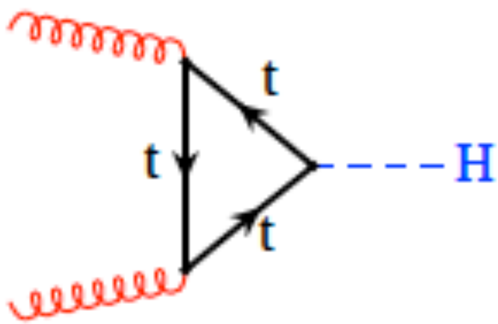
Major progress in last few years:

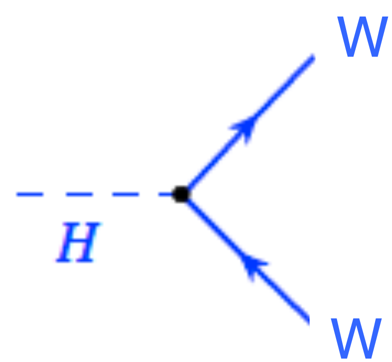
- Observation of H→bb decay
- Observation of ttH production
- Evidence of H→$\mu\mu$ decay

At the end of Run 2:

- Mass measurement precision ~0.1%
- All major production and decay modes have been observed. Other targets for future runs:
  - $Z\gamma$, $\mu\mu$ decay modes
  - tH production mode (if SM, very difficult…)

Couplings Framework





μ^i_p μ^j_{BR}

•Signal strength "μ" reflects the ratio of observed rates to predicted rates

•"κ framework": use all measurements of signal strength parameters (μ^i_p, μ^j_{BR}) to extract modifiers to the SM couplings:

•Decay: $\Gamma_i = \kappa_i^2\ \Gamma_i^{SM}$

•Production: $\sigma_i = \kappa_i^2\ \sigma_i^{SM}$

•Width: $\Gamma_H = \Sigma_i\,\kappa_i^2\ \Gamma_i^{SM}$

Assumptions:
- Only one Higgs
- SM production and decay kinematics
  - Tensor structure is that of SM
  - 0+ scalar
- Narrow resonance

Where we are now, before start of Run 3

The 125 GeV Higgs boson has been shown to be very compatible with the Standard Model:

- Recent ATLAS and CMS combined signal strengths:

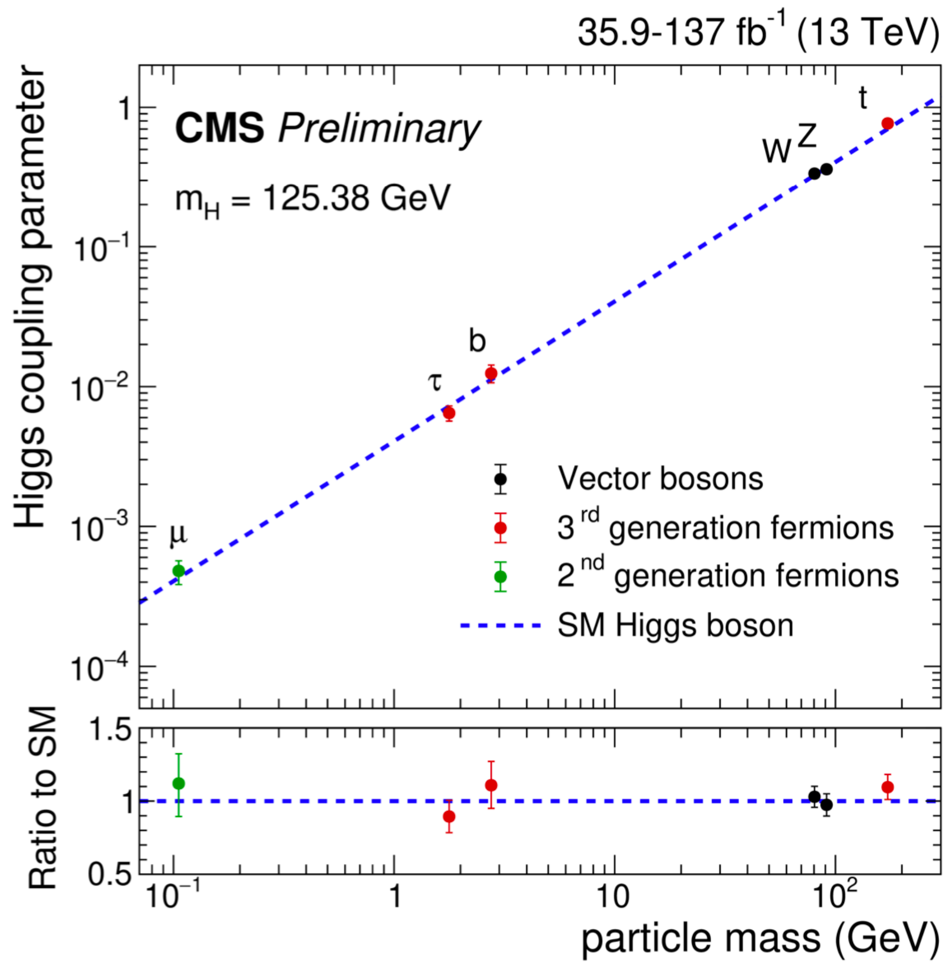
ATLAS-CONF-2019-037 $$\mu = 1.06 \pm 0.07$$

CMS-PAS-HIG-19-005 $$\mu = 1.02^{+0.07}_{-0.06}$$

- Yukawa couplings observed for top, bottom, and tau fermions with non-universal pattern predicted by the SM

Parameter	Result
κ_Z	1.02 ± 0.06
κ_W	1.05 ± 0.06
κ_b	$0.98\ ^{+\ 0.14}_{-\ 0.13}$
κ_t	$0.96\ \pm 0.08$
κ_τ	$1.06\ ^{+\ 0.15}_{-\ 0.14}$
κ_μ	$1.12\ ^{+\ 0.26}_{-\ 0.32}$

CMS-PAS-HIG-19-006

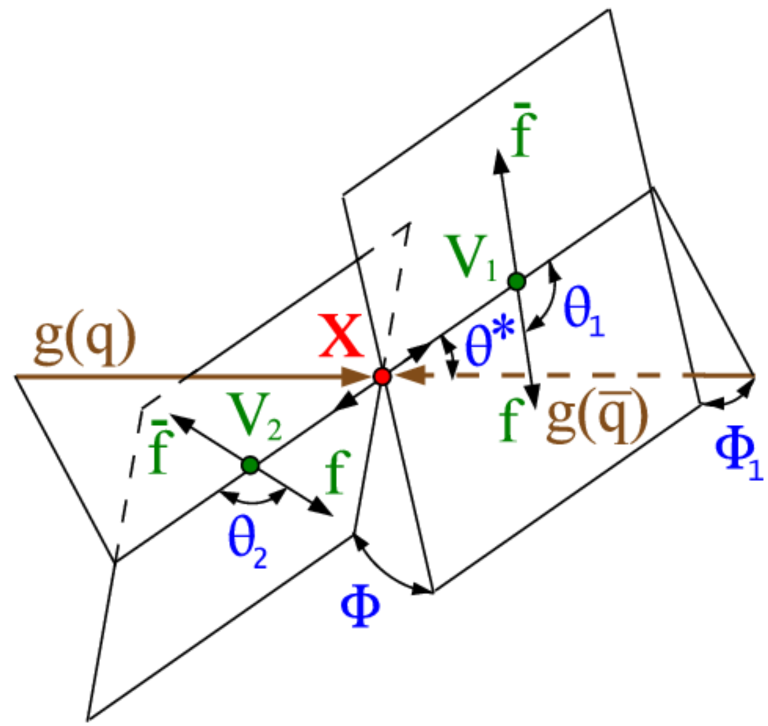


Where we are now, before start of Run 3

- Spin 0 confirmed during Run 1 with pure CP-odd state easily excluded in H→ZZ

- No hints yet of CP-odd coupling component to SM fermions
    - analyses using ttH production by ATLAS and CMS exclude pure CP-odd top coupling at more than 3σ C.L
    - Analysis excludes pure CP-odd τ coupling at more than 3σ C.L.

ZZ: full kinematic information available for spin/CP determination



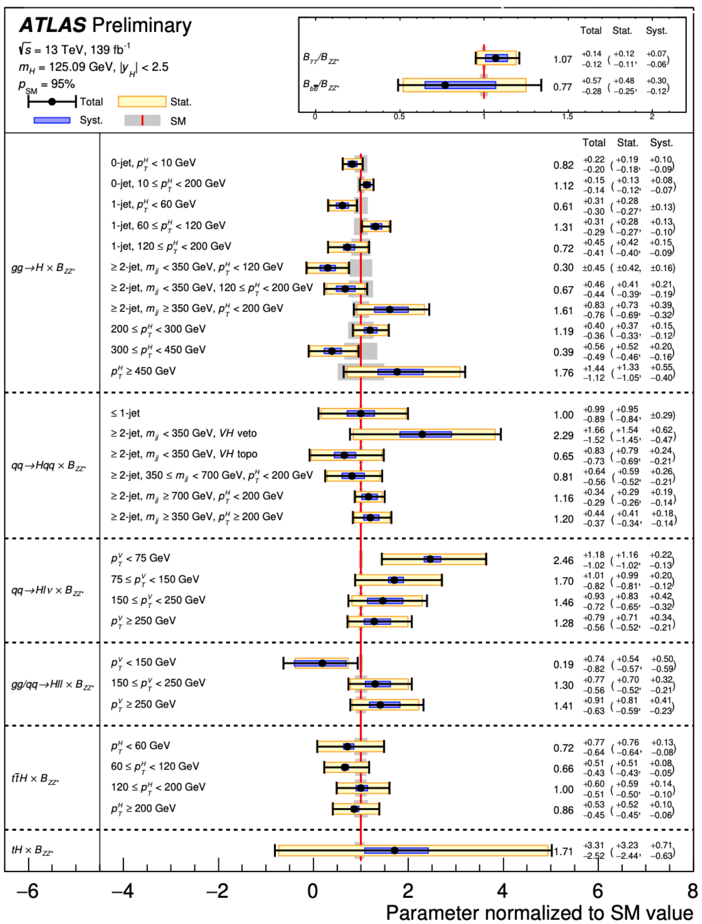
ATLAS-CONF-2020-052

Where we are now: comprehensive kinematic studies

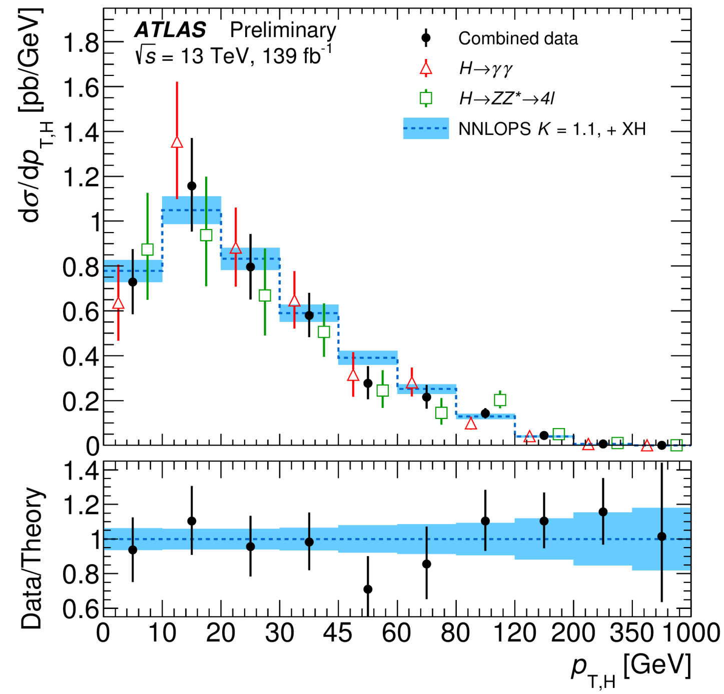
After observation, vast programme of kinematic measurements was launched

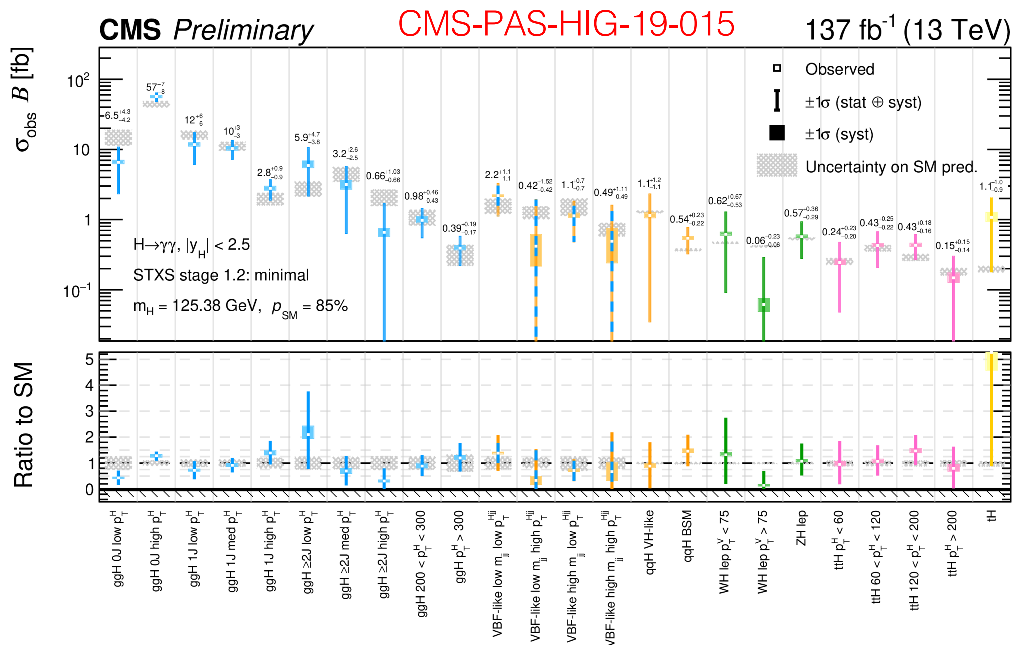
- Differential cross sections
- Measurements by production mode in various kinematic regions (STXS)

ATLAS-CONF-2020-027



ATLAS-CONF-2020-026

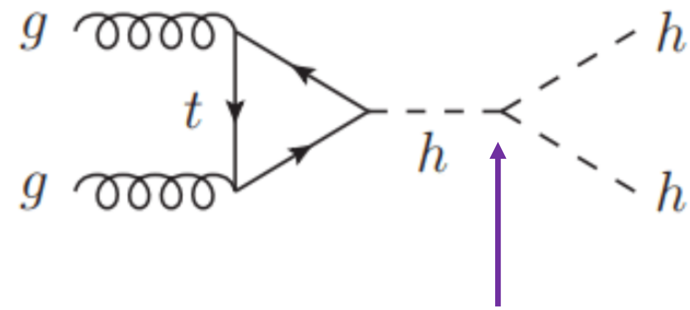




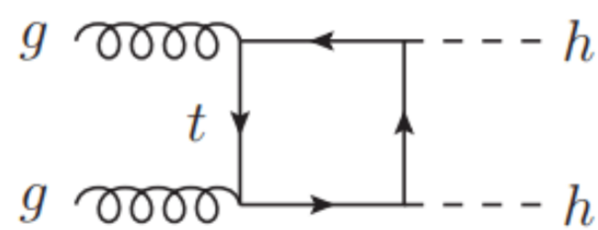
Where we are now: towards the self-coupling

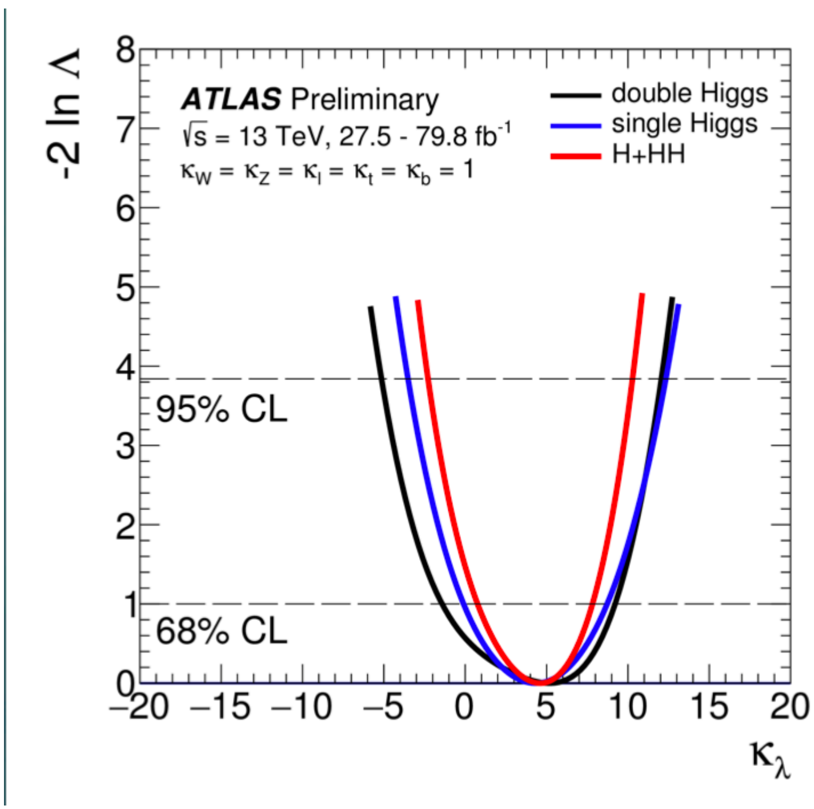
Making progress towards testing the shape of the Higgs potential through the Higgs self-coupling (λ_3)

Sensitivity to SM coupling will require HL-LHC but much progress can be made in coming years (more later…)



$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$



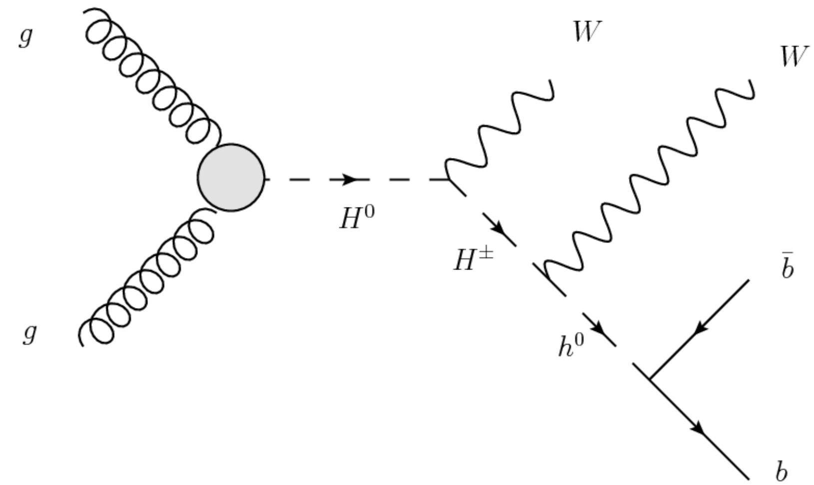


Model	$\kappa_{\lambda\,-1\sigma}^{\;+1\sigma}$	κ_λ [95% CL]	
κ_λ-only	$4.6^{+3.2}_{-3.8}$	$[-2.3, 10.3]$	obs.
	$1.0^{+7.3}_{-3.8}$	$[-5.1, 11.2]$	exp.
Generic	$5.5^{+3.5}_{-5.2}$	$[-3.7, 11.5]$	obs.
	$1.0^{+7.6}_{-4.5}$	$[-6.2, 11.6]$	exp.

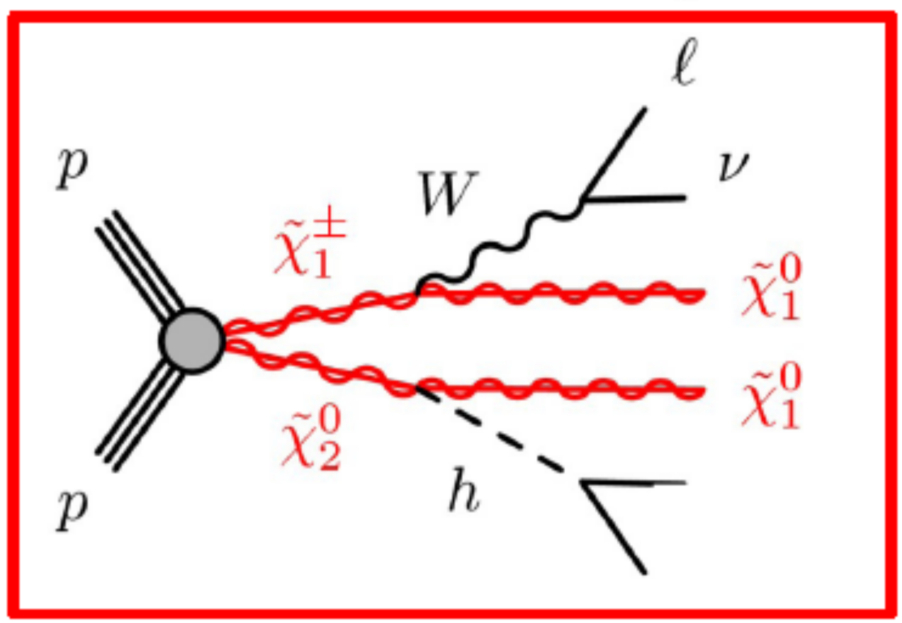
ATLAS-CONF-2019-049

BSM Higgs Physics

Different strategies to look for physics beyond the SM in the Higgs sector



- Search for other Higgs bosons
  - Extensive search program looking for new scalars in many final states
- Search for exotic decays of the 125 Higgs
  - Rich phenomenology that includes invisible decays, displaced decays
- Use the 125 GeV Higgs as a tool to find new physics
  - Higgs in decays
  - Use measurements to constrain BSM scenarios



BSM Higgs Searches

A non-exhaustive list…

Neutral Heavy Higgs to Fermions	H/A→(b)ττ (LL,LH,HH)
	H/A→(b)μμ
	H/A→(b)bb
	H/A→tt
Neutral Heavy Higgs to Bosons	H→γγ
	H→ZZ→4l
	H→ZZ→llνν
	H→ZZ→llqq
	H→ZZ→ννqq
	H→WW→lνlν
	H→WW→lνqq
Neutral Heavy Higgs to Bosons, including light Higgs	(H→)hh→γγbb
	(H→)hh→4b
	(H→)hh→bbττ
	(H→)hh→VVγγ→4jγγ,
	(H→)hh→WWγγ→lνqqγγ
	A→Zh→llττ (LL,LH,HH)
	A→Zh→(ll/νν)bb

Heavy and light Charged Higgs	H+→τν+jets
	H+→tb (resolved)
	H+→tb s-chan (had, L+j
	H+→τν+lep(s)
	H+→μν
	H+→cs
	H+→cb
	- AW
	H+→Wh (WH, WA)
	H+→Wγ
	H+→tb (boosted)
	H+→WZ→tb (lνqq, qqll)
	H++
LFV / FCNC / rare decays	H→τμ, τe
	H→eμ
	H→J/ψγ, Υγ
	H→ZJ/ψ, ZΥ
	H→φγ
	t→cH (various

Exotics decays with MET, Dark-sector Inspired	mono H (→γγ+MET)
	mono H (→bb+MET)
	mono H (→4l+MET)
	H→γγdark
	ZH→(ll)INV
	VBF H→INV
	VH→(jj)INV
	ttH→INV (various
	ggF H→INV (monojet).
Exotics decays with no MET, Dark-sector / NMSSM Inspired	H→ZdarkZ(dark)→4l
	h→2a→μμμμ
	h→Za→llμμ
	a→μμ
	h→2a→4γ(multiphoton)
	h→2a→bbμμ
	h→2a→bbττ
	(bb)a→(bb)ττ→(bb)eμ
	h→2a→4τ
	H+→aW

BSM Higgs Searches

A non-exhaustive list… Many of the searches below were performed in Run 1

Neutral Heavy Higgs to Fermions	H/A→(b)ττ (LL,LH,HH)
	H/A→(b)μμ
	H/A→(b)bb
	H/A→tt
Neutral Heavy Higgs to Bosons	H→γγ
	H→ZZ-
	H→ZZ-
	H→ZZ-
	H→ZZ-
	H→WW
	H→WW
Neutral Heavy Higgs to Bosons, including light Higgs	(H→)hh→γγbb
	(H→)hh→4b
	(H→)hh→bbττ
	(H→)hh→VVγγ→4jγγ,
	(H→)hh→WWγγ→lνqqγγ
	A→Zh→llττ (LL,LH,HH)
	A→Zh→(ll/νν)bb

	H+→τν+jets
	H+→tb (resolved)
	H+→tb s-chan (had, L+j
	H++
LFV / FCNC / rare decays	H→τμ, τe
	H→eμ
	H→J/ψγ, Υγ
	H→ZJ/ψ, ZΥ
	H→ϕγ
	t→cH (various

Exotics	mono H (→γγ+MET)
	mono H (→bb+MET)
	mono H (→4l+MET)
	H→γdark
	(ll)INV
	H→INV
	(jj)INV
	INV (various
	H→INV (monojet).
Exotics decays with no MET, Dark-sector / NMSSM Inspired	darkZ(dark)→4l
	a→μμμμ
	h→Za→llμμ
	a→μμ
	h→2a→4γ(multiphoton)
	h→2a→bbμμ
	h→2a→bbττ
	(bb)a→(bb)ττ→(bb)eμ
	h→2a→4τ
	H+→aW

Executive Summary:
No significant excess yet…

Preliminary Conclusions

- The properties of the Higgs boson we have found are consistent with SM predictions (within current uncertainties)
    - The SM is a very good effective theory that is consistent with observations at high energy colliders so far
- But
    - The SM is incomplete and faces theoretical problems when we extend it to very high energies
    - SM makes many predictions and is therefore easy to falsify: deviations from the SM may yet appear with more precise measurements

- The road ahead:
    - Continue the characterization program of the discovered Higgs boson
    - Search for Higgs boson physics beyond the Standard Model

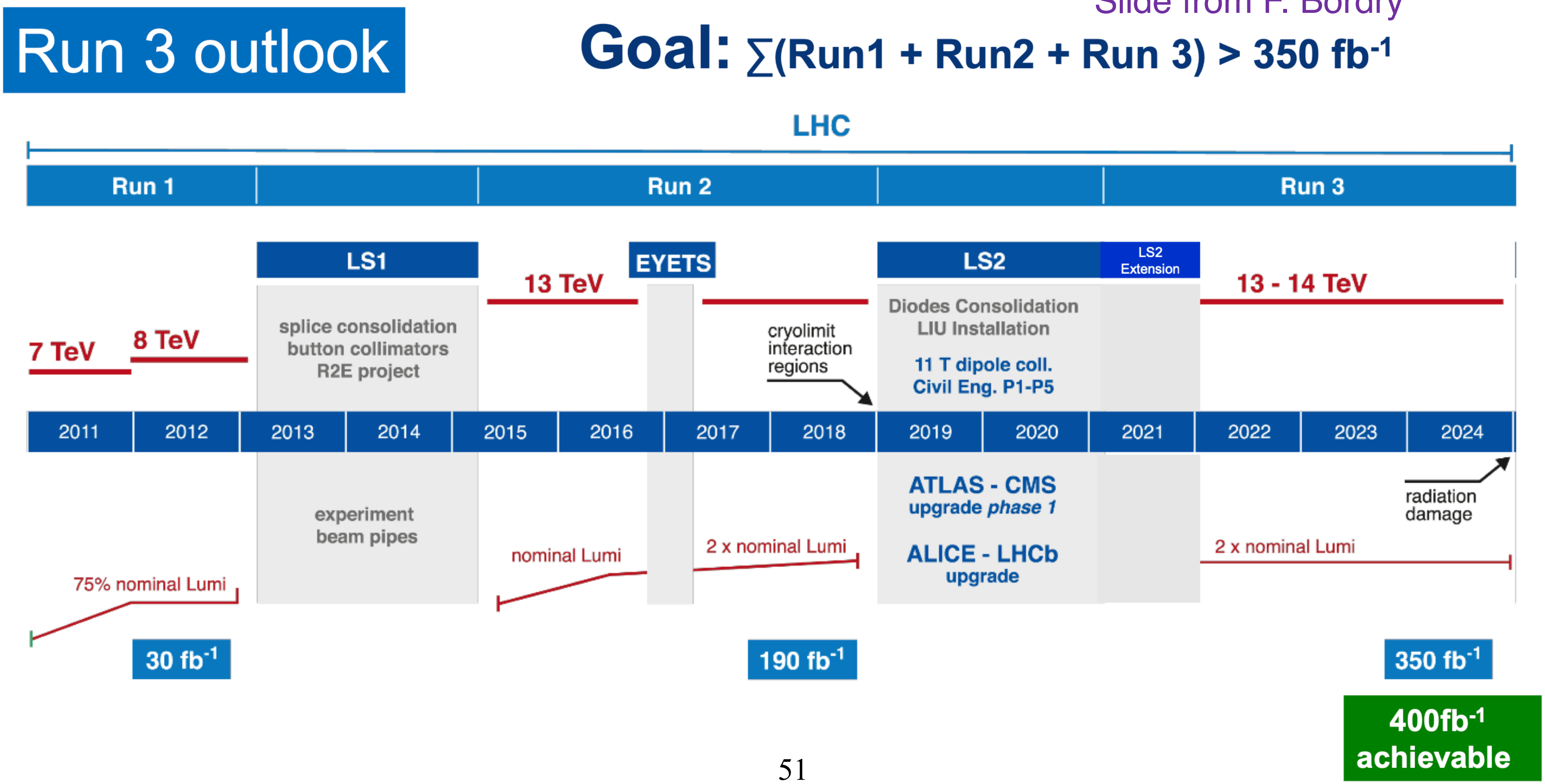
The Future

Run 3 Schedule

Start of Run 3 has been delayed due to the pandemic

- A 3-year Run
- Plan to run at 2 times nominal luminosity

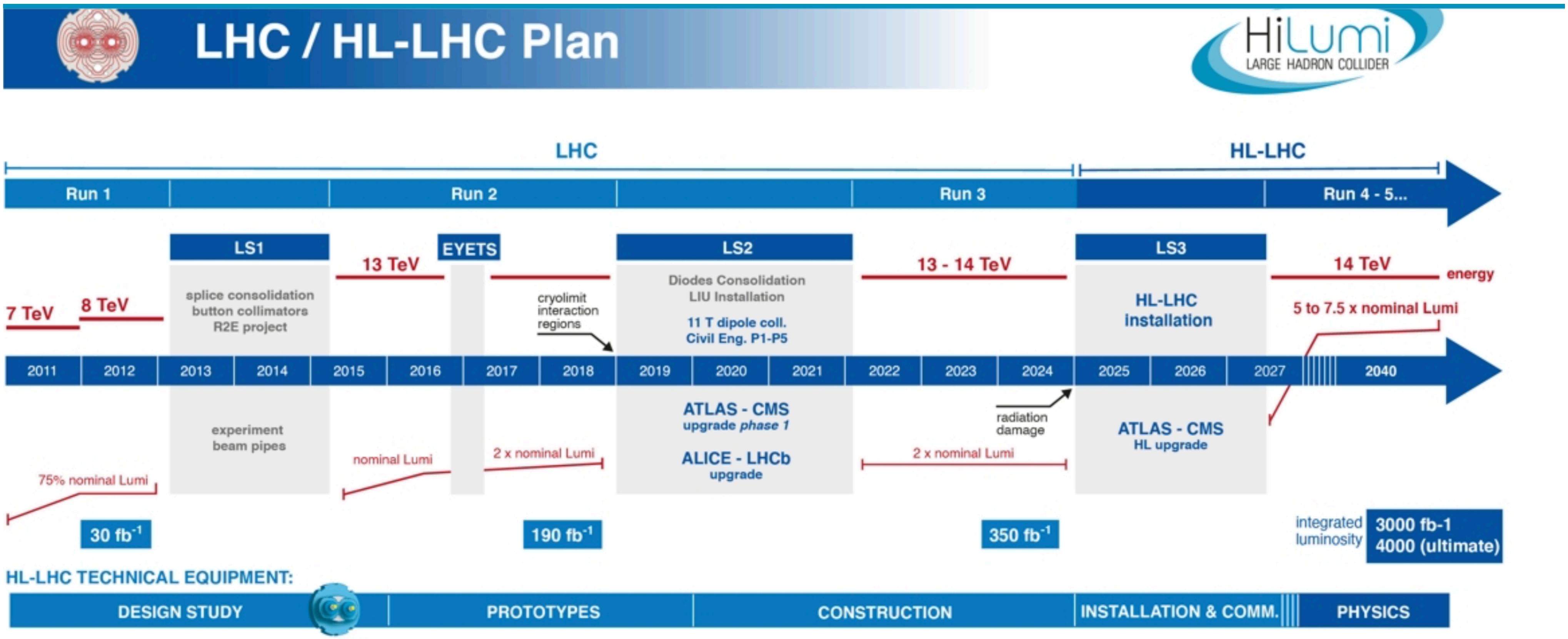
Slide from F. Bordry



HL-LHC Schedule

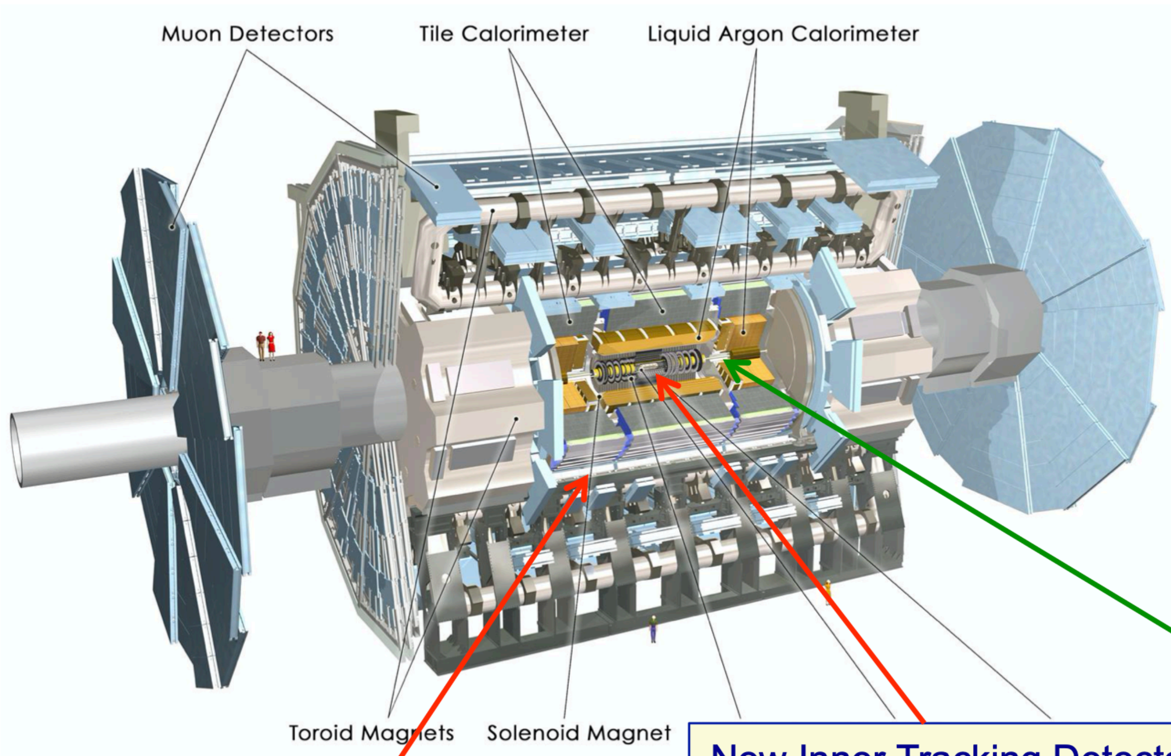
Start of HL-LHC planned for 2027, physics ~2028

- Run at nominal energy of 14 TeV
- Plan to run at 5-7.5 times nominal luminosity



ATLAS Phase-II Upgrade

From K. Jakobs



Upgraded Trigger and Data Acquisition System:

- L0: 1 MHz
- Improved High-Level Trigger

Electronics Upgrade :

- LAr Calorimeter
- Tile Calorimeter
- Muon system

New Inner Tracking Detector (all silicon tracker, up to $|\eta| = 4$)

New muon chambers in the inner barrel region

High granularity timing detector (forward region)
Approved by CERN Research Board (16th Sept.)

Run 3: some considerations

- Last 8 years: enormous progress
  - Large increases in integrated luminosity vs time
  - LHC collision energy increase
  - Major improvements in performance and analysis techniques
- Next 8 years: analysis of Run 2 and Run 3 data
  - ~2-2.5 increase in integrated luminosity
  - Modest increase in energy
  - Significant progress possible on many fronts

Run 3: challenges and opportunities

- Systematic uncertainties are becoming more dominant for many results

		th.	stat.	syst.	bbb
CMS H tautau (μ)	$0.85^{+0.12}_{-0.11}$	$^{+0.08}_{-0.07}$	$^{+0.06}_{-0.06}$	$^{+0.07}_{-0.06}$	$^{+0.04}_{-0.03}$

- ATLAS H bb (μ) $1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$
- ATLAS VBF (σ) $0.85 \pm 0.10\ (\text{stat.})\ ^{+0.08}_{-0.07}\ (\text{exp syst.})\ ^{+0.13}_{-0.10}\ (\text{sig. theo.})\ ^{+0.07}_{-0.06}\ (\text{bkg. theo.})$ pb
- CMS global μ fit: $1.02 \pm 0.04(\text{th}) \pm 0.04(\text{exp}) \pm 0.04(\text{stat})$

- Need to reduce systematics (Theory, Modelling, PDFs), and improve our treatment of systematics

HL-LHC Higgs Physics

Physics potential of the HL-LHC recently re-appraised and documented in a series of Yellow Reports

Yellow reports were submitted to the European Strategy Group at the end of 2018

Higgs Yellow Report:

CERN-LPCC-2018-04

- A huge effort: 400 authors, 340 pages

Can't do justice to the work in this document: I encourage you to take a look and see the full extent and promise of HL-LHC Higgs physics

FERMILAB-PUB-19-074-PPD-T

CERN-LPCC-2018-04
February 4, 2019

Higgs Physics at the HL-LHC and HE-LHC

Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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This document was prepared by [HL-LHC and HE-LHC Collaborations] using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

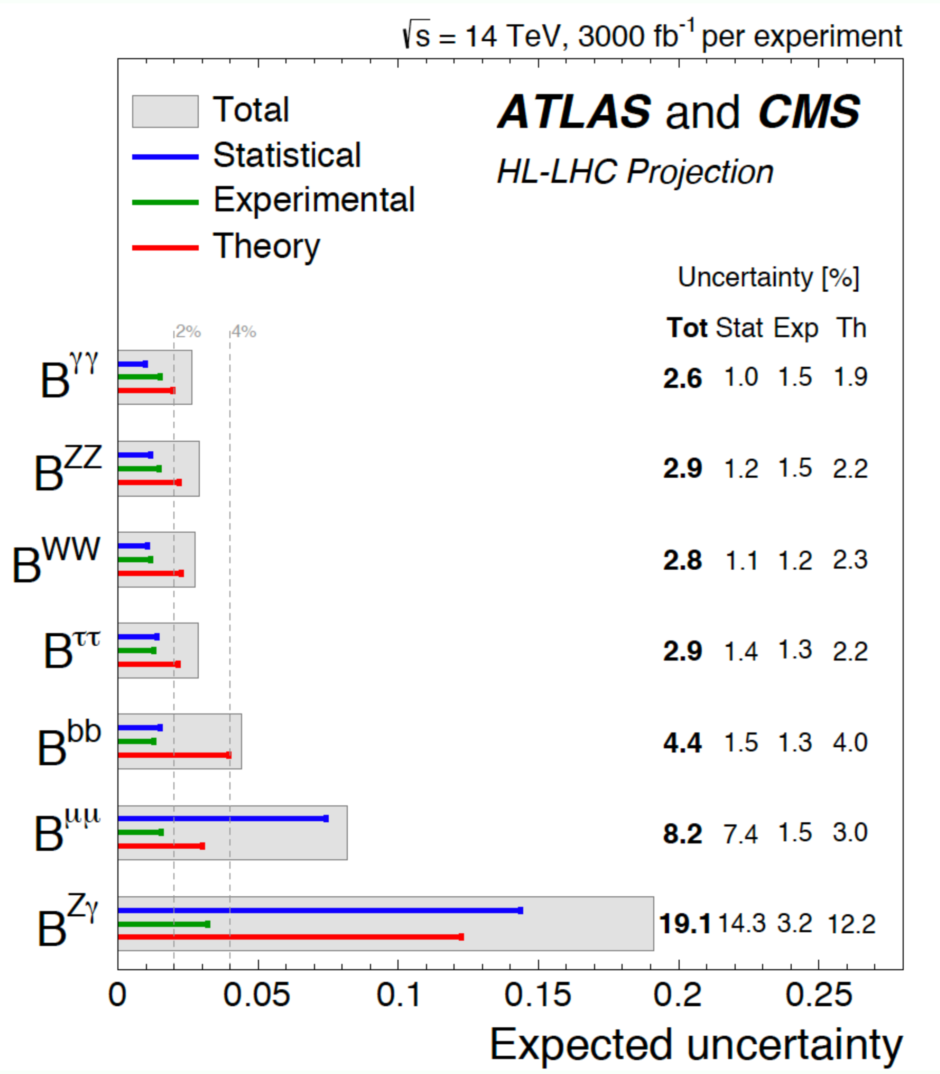
HL-LHC Higgs Physics

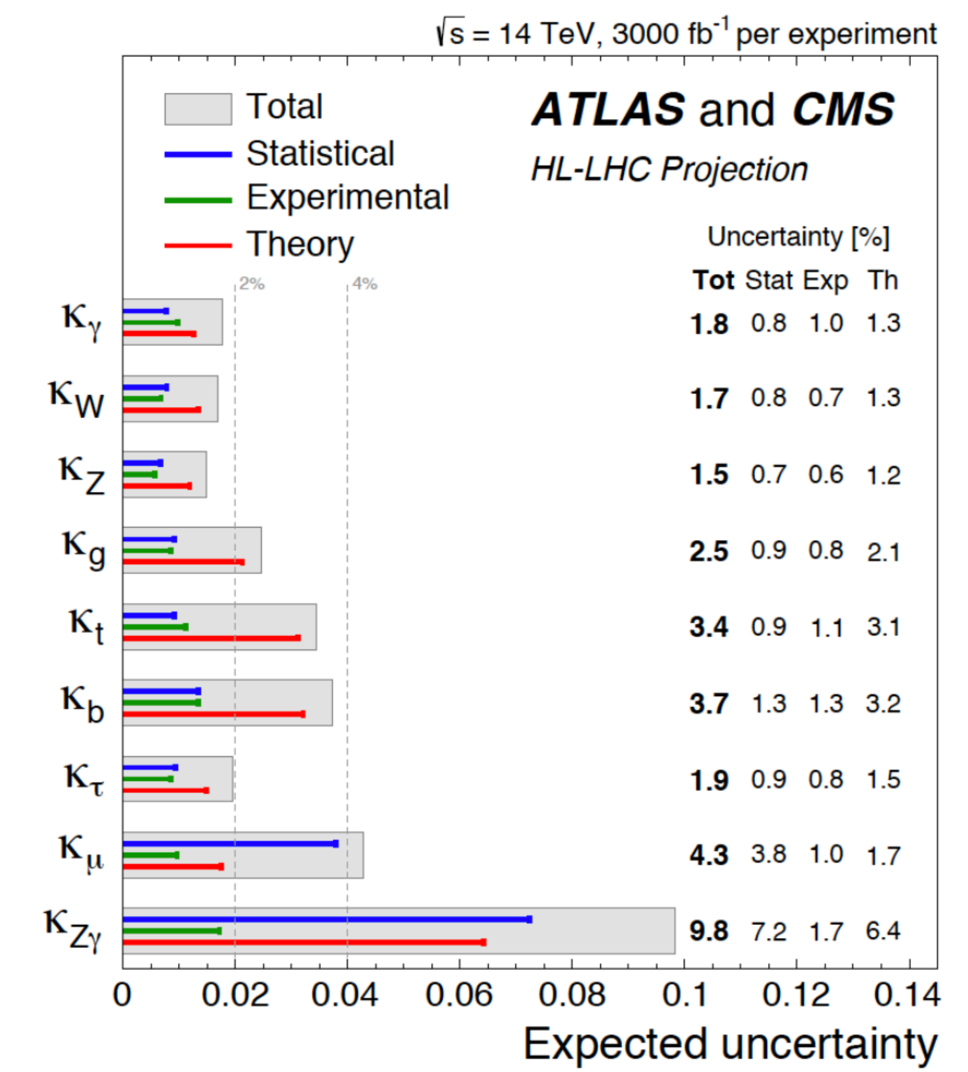
Two uncertainty scenarios were considered for the projections:

- S1 - Conservative, based on the current Run2 systematic uncertainties (including theory)
- S2 - Ultimate, based on estimates of ultimate performance for experimental uncertainties, and applying a factor of 1/2 for theoretical uncertainties

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

HL-LHC: Branching Ratios and Cross Sections

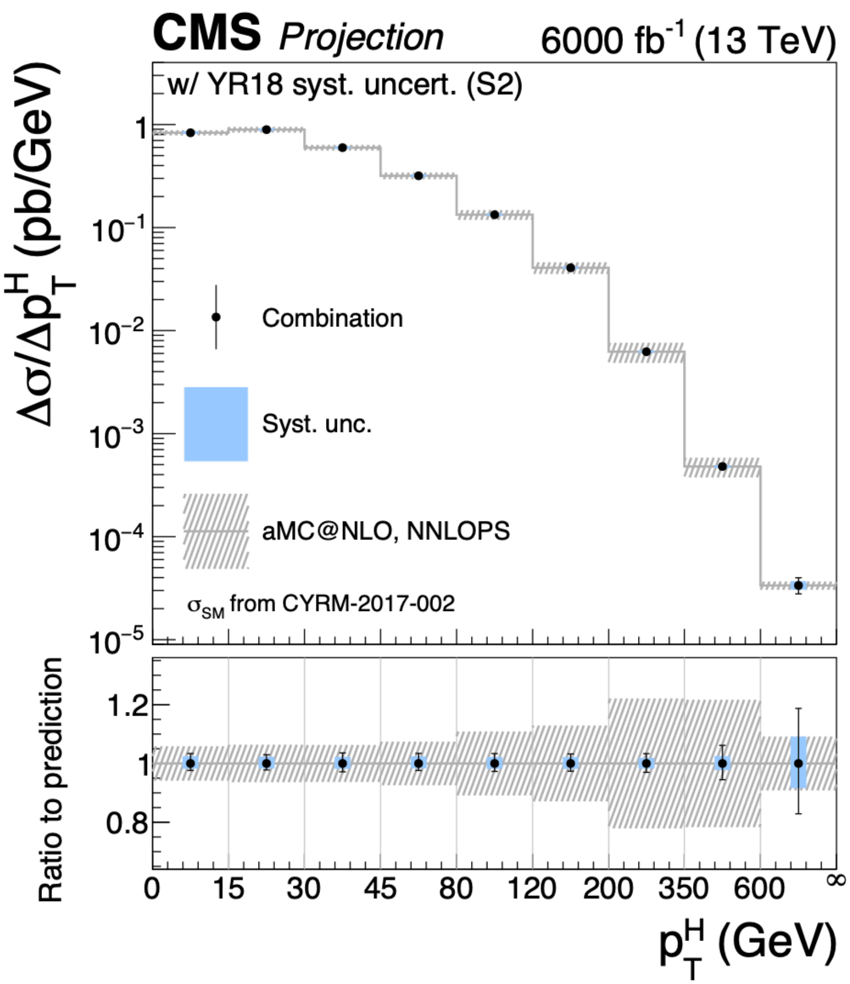


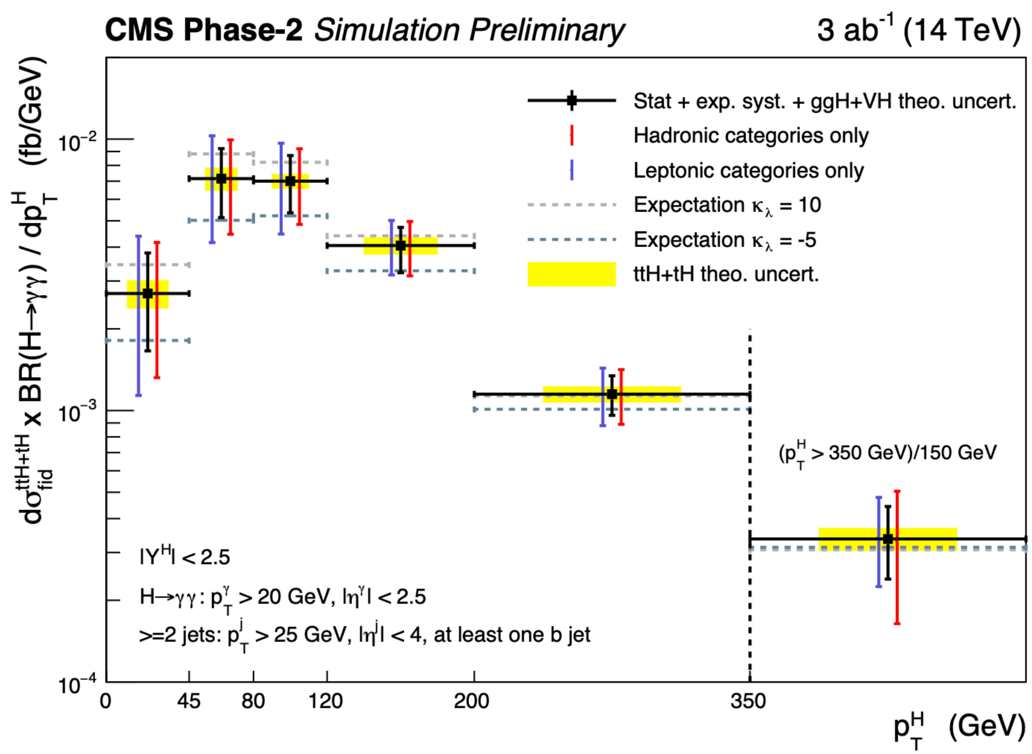


Combination of ATLAS and CMS for systematic uncertainty scenario 2

- Theory uncertainty remains the largest component for most measurements

HL-LHC: Differential Cross Sections





CMS-PAS-FTR-18-020

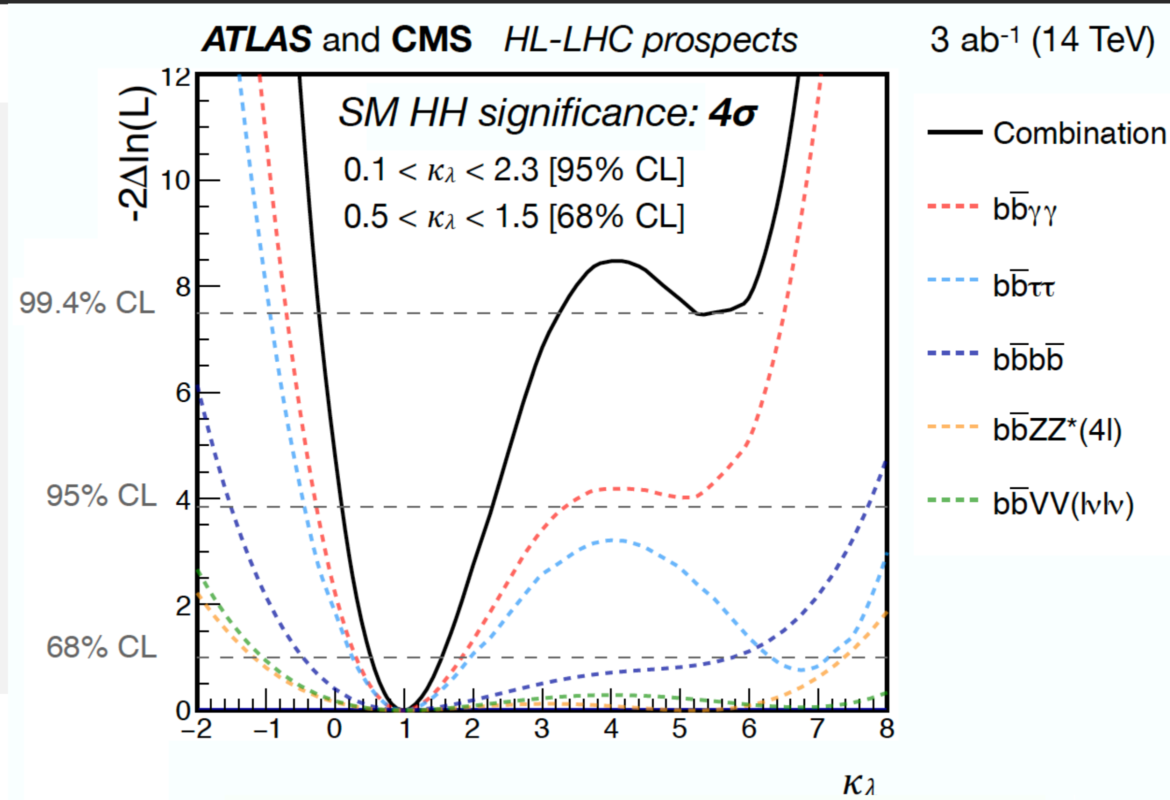
Left plot: results for CMS for systematic uncertainty scenario 2

- Theory uncertainty dominates in all bins except p_T > 600 GeV

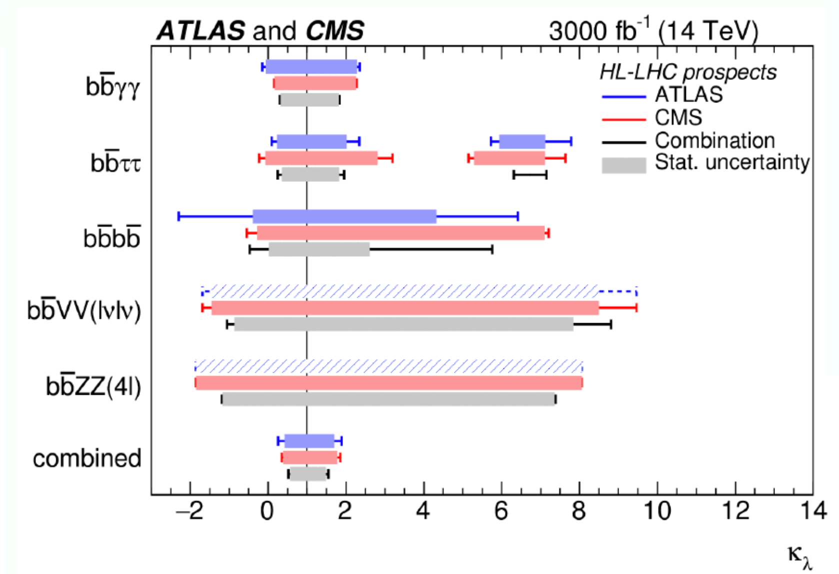
Right plot: p_T^H distribution for ttH production using the H→γγ decay

HL-LHC: Higgs Self-Coupling

- Significance of HH signal at the 4σ level (both exp.)
- Uncertainty on κ_λ of 50%
    - 2nd minimum excluded at > 99% CL
- Note that HH observation analysis and κ_λ analysis require different optimizations



	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



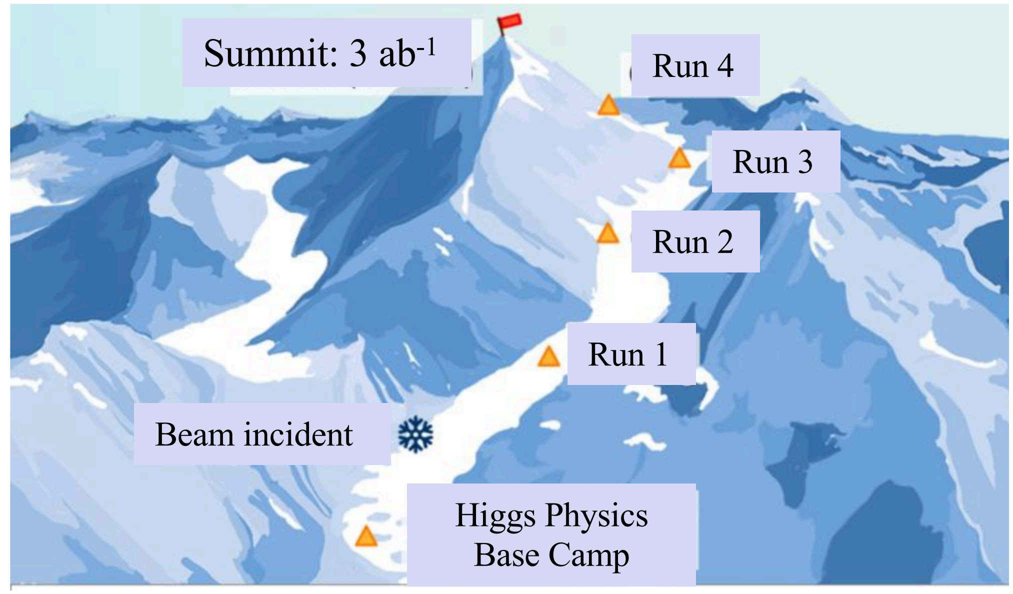
Some Concluding Thoughts

After Run 2, there is still a long way to go before we reach the summit

Slower dataset doubling time and the fact that systematics are already larger than statistical uncertainties in many analyses means that we will need to work hard and innovate:

- True for both experimental and theory communities

- Studies in Higgs HL-LHC Yellow Report imply that we will need major advances in theory to reach the "summit" i.e. exploit the full potential of HL-LHC



Unclear if/when new machines will provide results competitive with most LHC results:

- This challenging work that will be done in coming years could have a very, very long shelf life – worth the effort!

Summary

- The theory that describes fundamental particles and forces (the Standard Model) predicted the existence of a new particle: the Higgs boson
- More than 40 years after it was postulated, the particle was finally observed in July 2012 by two scientific collaborations at CERN
- The field associated with this particle gives mass to all massive particles. This field is “on” everywhere. It fills the physical vacuum
- This discovery has important implications on cosmology and our understanding of the very early Universe
- 8 years after the discovery, we have entered the era of “precision Higgs physics”. Up until now, the Standard Model describes the data very well
- In the years to come, we will increase the size of our dataset by more than a factor of 10. The Standard Model will face much more stringent tests

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