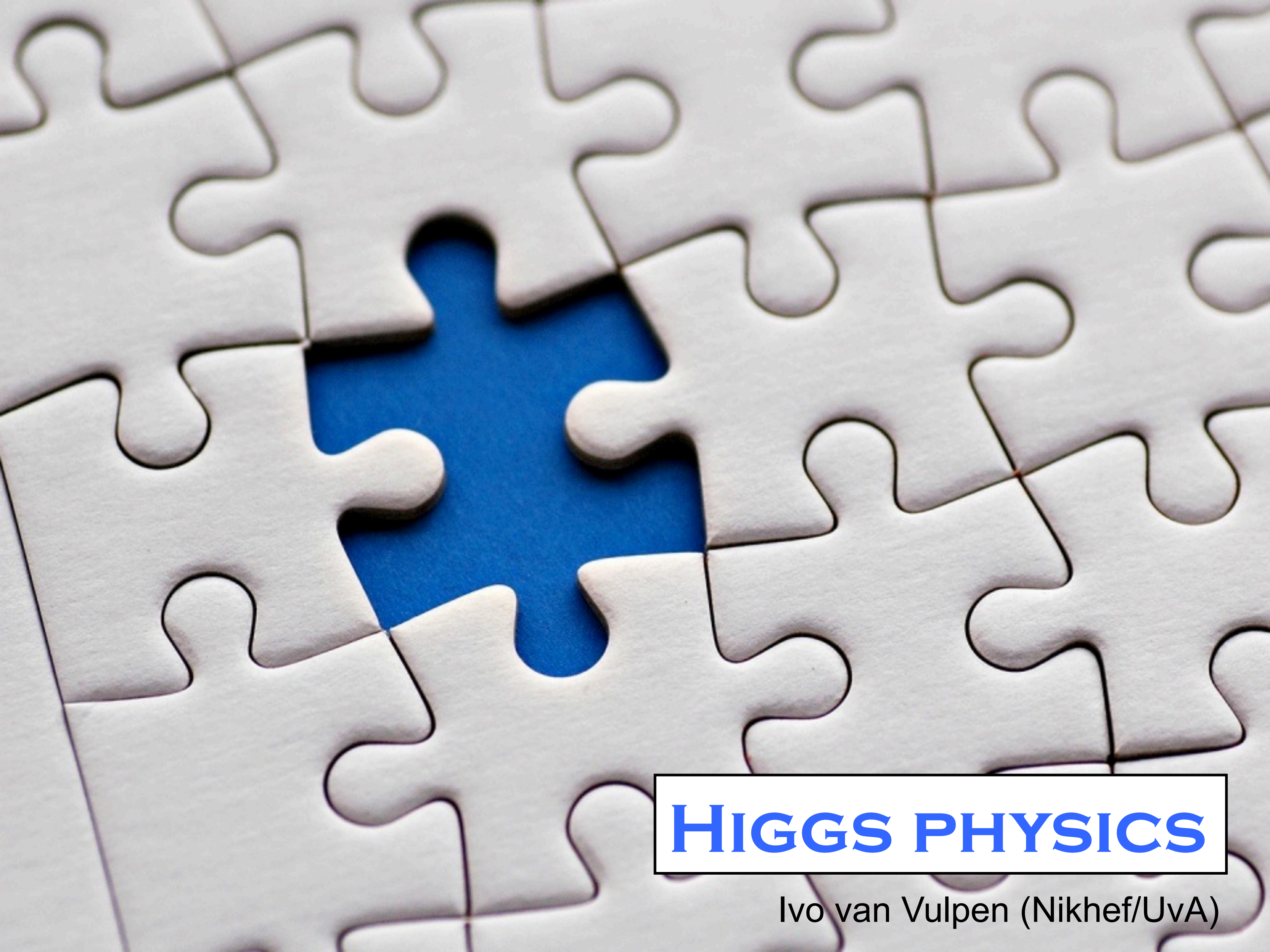
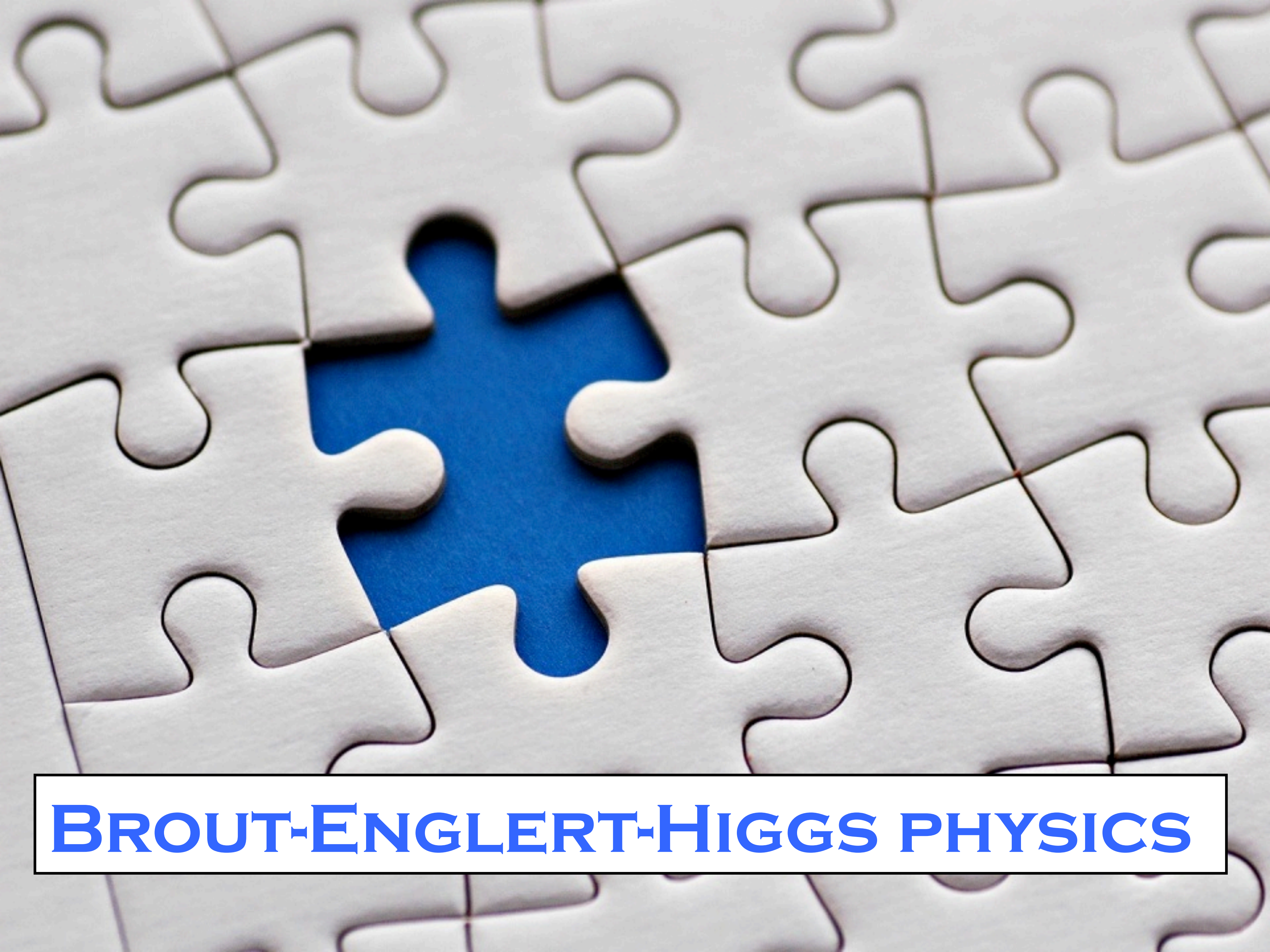


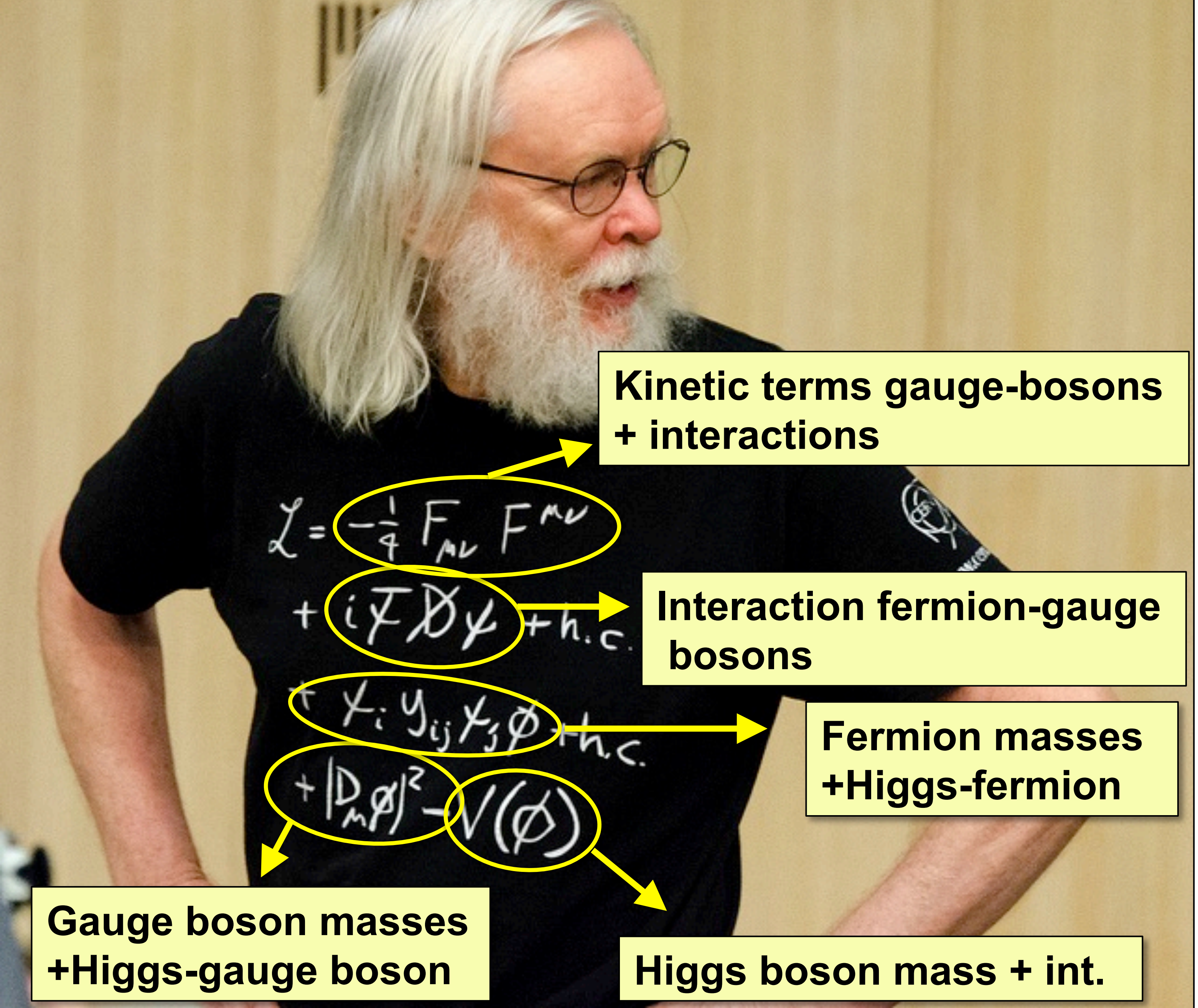
Higgs physics

Ivo van Vulpen (Nikhef/UvA)



Brout-Englert-Higgs physics

The Standard Model



Higgs in the SM

Higgs physics at the BND 2014 school

09:00-10:45 hours

Theory and role of Higgs in the SM [blackboard]

11:15-13:00 hours

Experiment + consequences/interpretations [slides]

14:30-16:15 hours

Exercises (mainly thinking/discussing)

Dag Gilbert (ATLAS) - ICHEP 2014
"Combination of the Higgs boson main property measurements using the ATLAs detector"

Dag Gilbert (CMS) – ICHEP 2014
"Combined results of the 125 GeV Higgs boson couplings using all decay channels measured by the CMS detector"

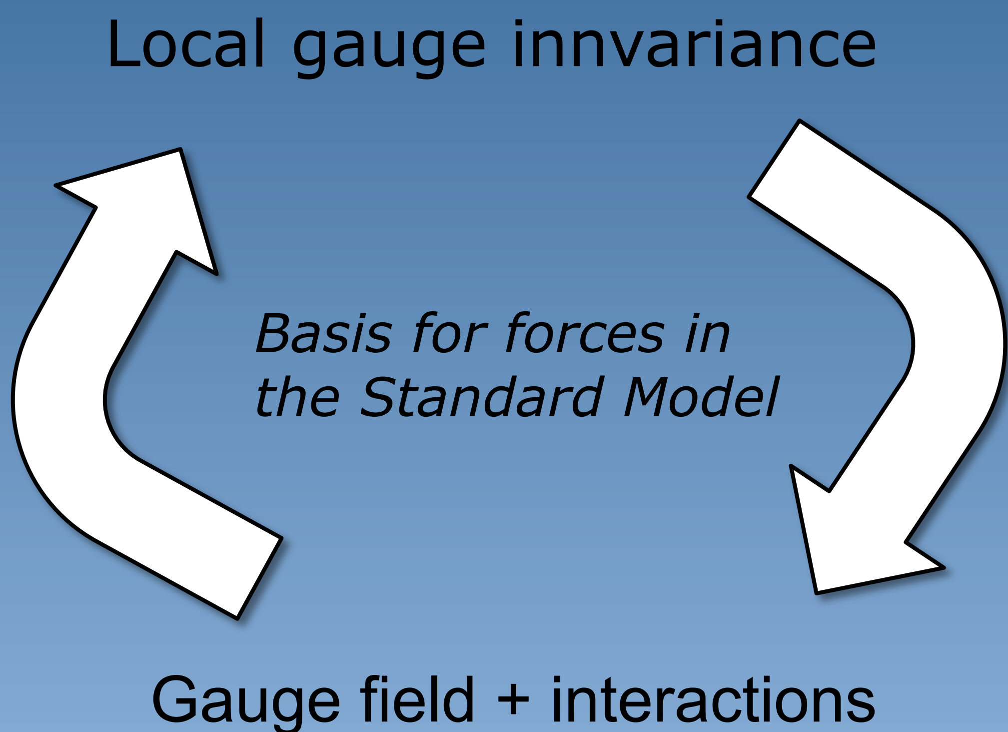
Marumi Kado (ATLAS) - ICHEP 2014
"Higgs physics in ATLAS"

Christian Veelken (CMS) - ICHEP 2014
"Search for MSSM and NMSSM Higgs bosons with the CMS detector"

Christophe Grojean (theory) - ICHEP 2014
"Physics of the Brout_Englert-Higgs boson –theory-"

+ several other parallel talks from the ICHEP meeting


the foundations


Local gauge innvariance
Basis for forces in the Standard Model
Gauge field + interactions

What symmetries define the Standard Model

$$\mathrm{U(1)_Y \otimes SU(2)_L \otimes SU(3)_C}$$

Rotations in hypercharge space

Rotations in colour space

Rotations in weak iso-spin space

QED:	$U(1)_Y$ → 1 d.o.f	**γ**	*Spin-1 particles*
Weak force:	$SU(2)_L$ → 3 d.o.f	**W^+, W^- en Z^0**	
Strong force:	$SU(3)_C$ → 8 d.o.f	**8 gluons**	

What is missing in our Standard Model ?

Good things:

- ‘understand’ origin of forces
- Excellent agreement data
- Connection EM / Weak force

Not-so-good things:

- No massive gauge bosons ($W^{\pm}$,Z)
- No massive fermions (all particles)
- Vector boson scattering diverges

↓

Solved by the Higgs mechanism

Theory

Reality

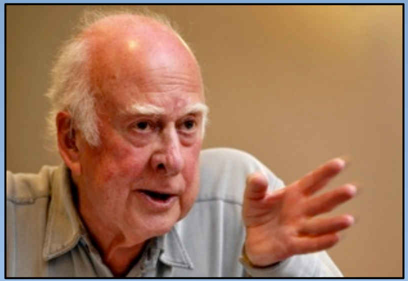
The Standard Model

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

+ Higgs boson

$\neq$

Particles have ***no*** *ma*




BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

- September 1964 -

The Higgs mechanism

Particles ***do*** *have mass*

Higgs field in tha vacuum

"If I'm right there shold be a new particle: ***the Higgs boson****"*

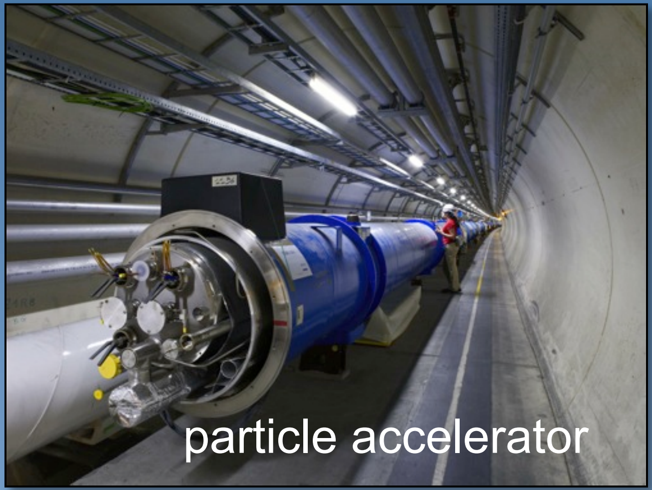
Higgs production & decay at the LHC

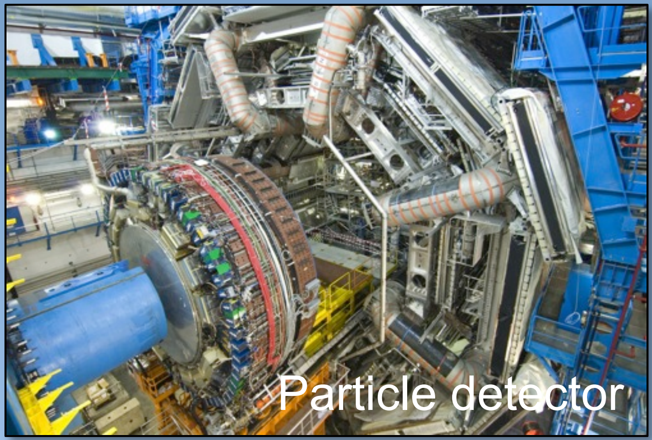
“There are electromagnetic waves around us that contain voices and images”

“There is a Higgs field that allows particle to acquire a mass.”

antenna

radio

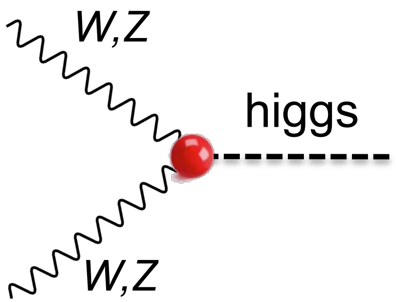




Production of the Higgs boson

Gauge bosons

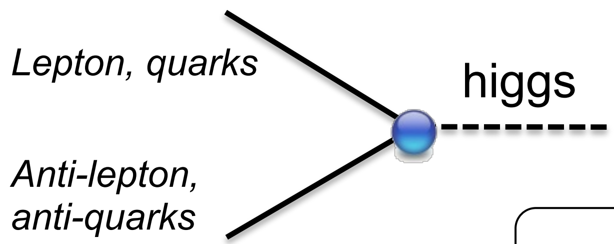
Massive gauge boson ?
… then the Higgs couples to it



$$\propto m_V^2$$

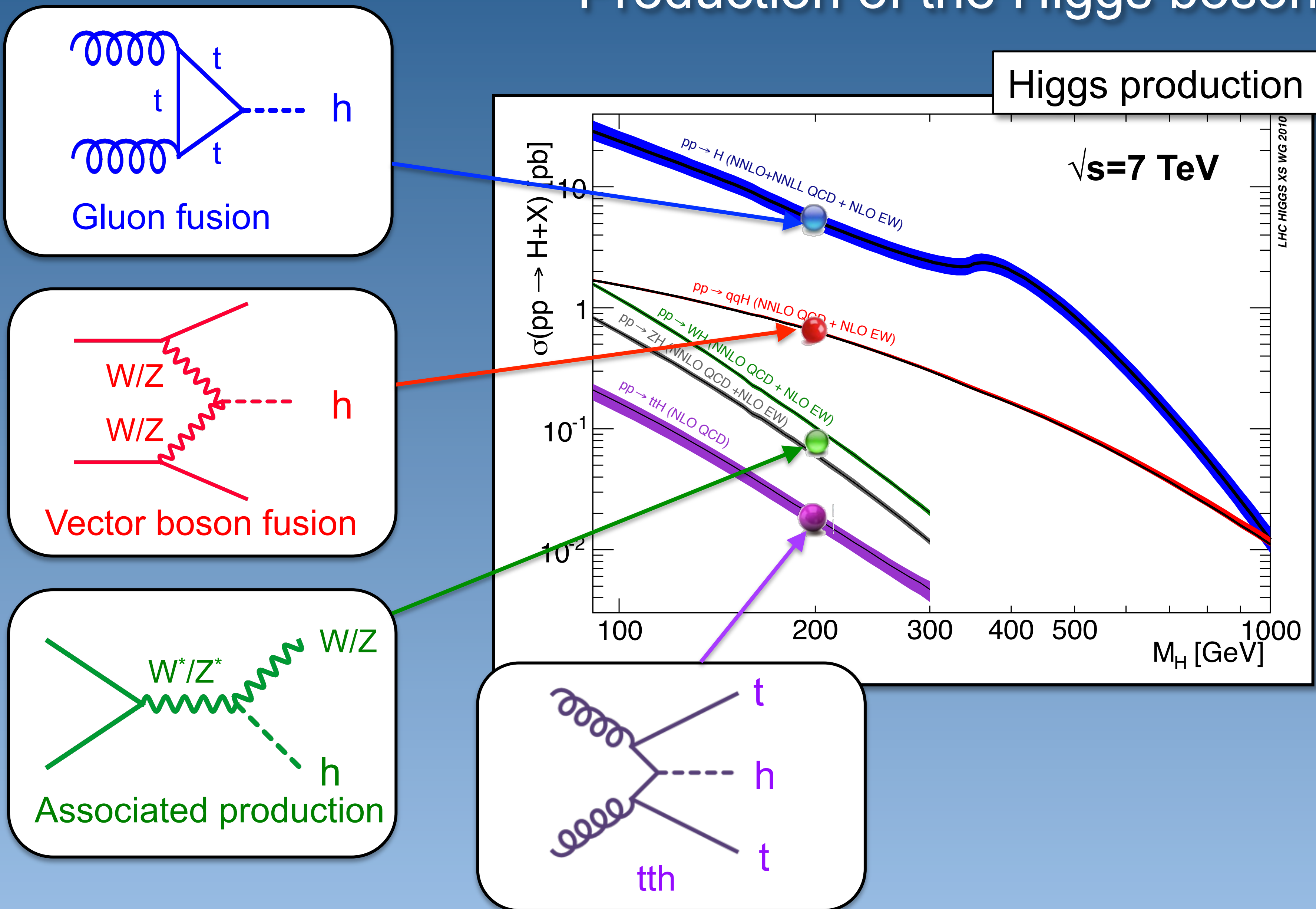
Fermions

Massive fermion ?
… then the Higgs couples to it



$$\propto m_f^2$$

Production of the Higgs boson



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR3

How many Higgs bosons have been produced at the LHC run-1

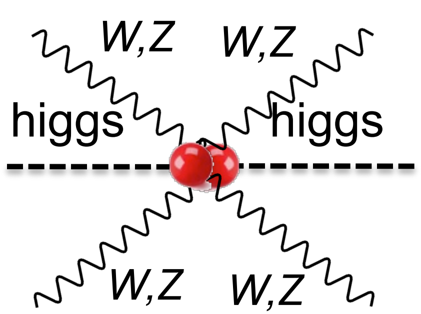
m_h = 125 GeV: ~ 500k

Higgs branching fractions

Decay of the Higgs boson

Gauge boson

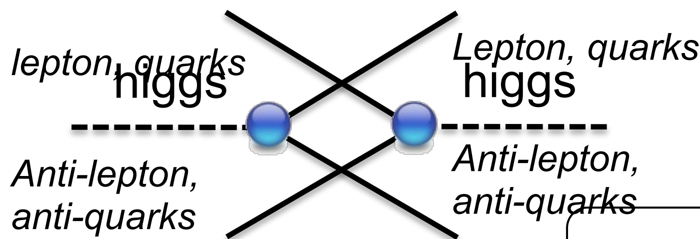
Massive gauge boson ?
… then the Higgs couples to it



$$\propto m_V^2$$

Fermion

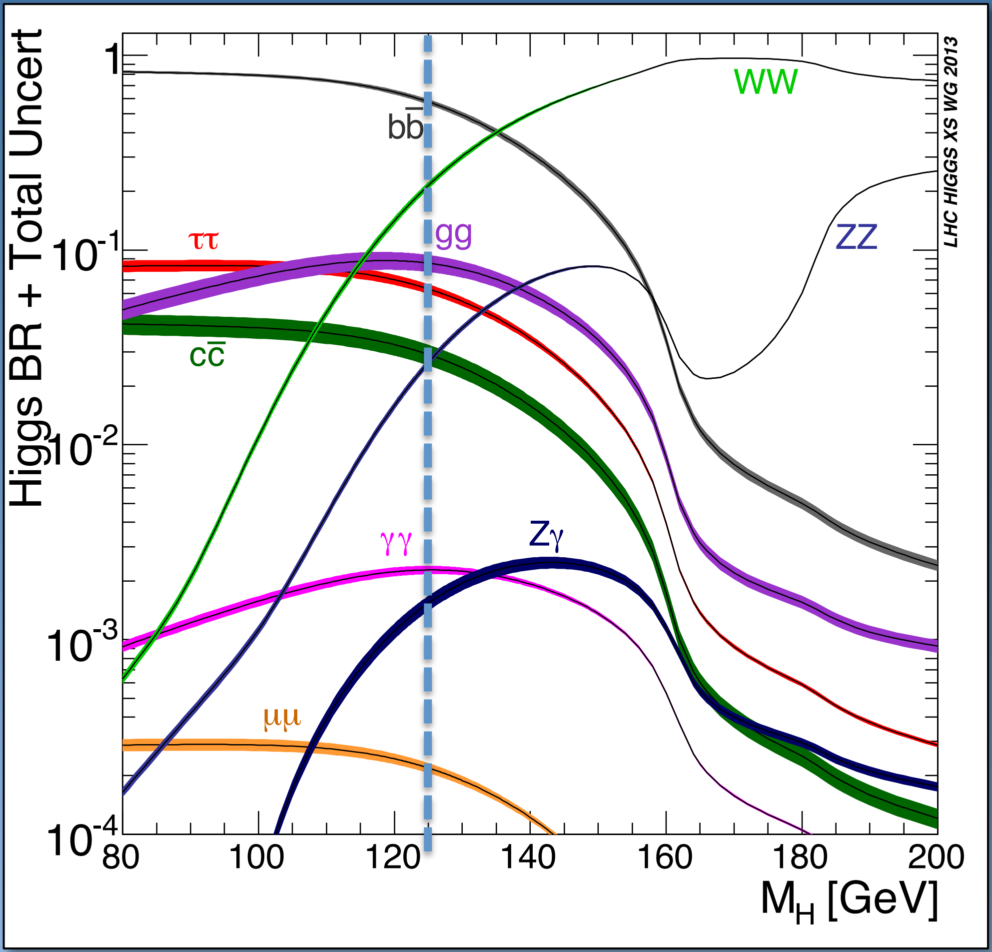
Massive fermion ?
… then the Higgs couples to it



$$\propto m_f^2$$

Higgs boson production
Higgs boson decay

Higgs branching fractions



m_h = 125 GeV

Br(h→bb) = 57.7 %

Br(h→WW) = 21.5 %

Br(h→ττ) = 6.32 %

Br(h→ZZ) = 2.64 %

Br(h→γγ) = 0.23 %

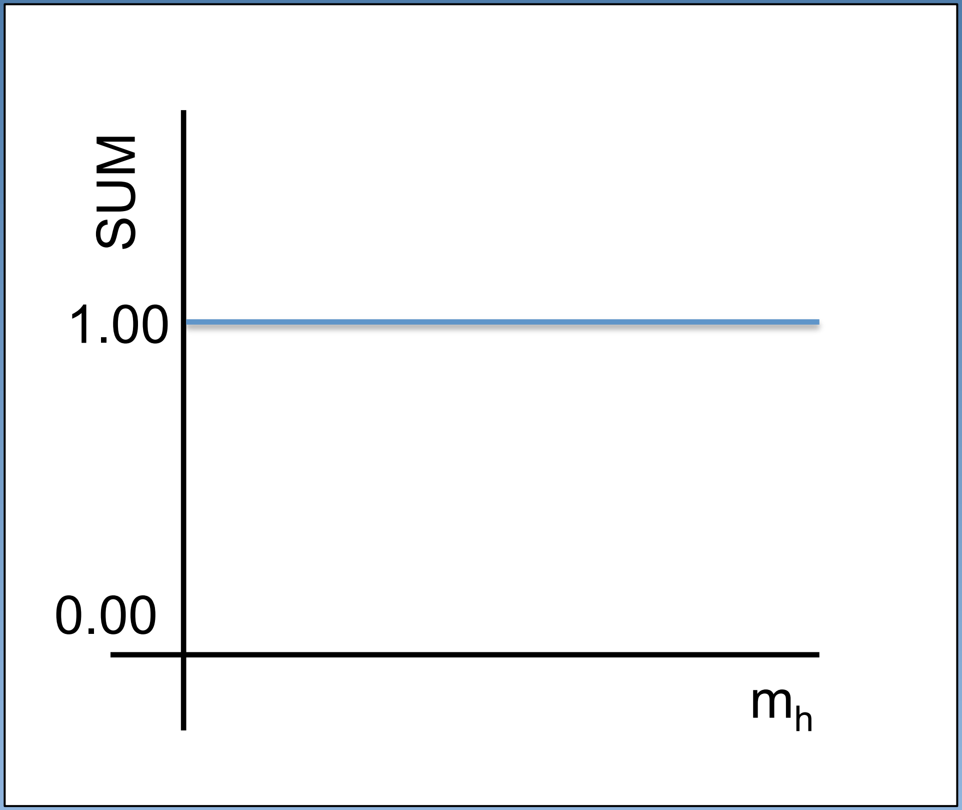
Br(h→Zγ) = 0.15 %

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR3

KABBALAH

Trivialities in the Higgs sector

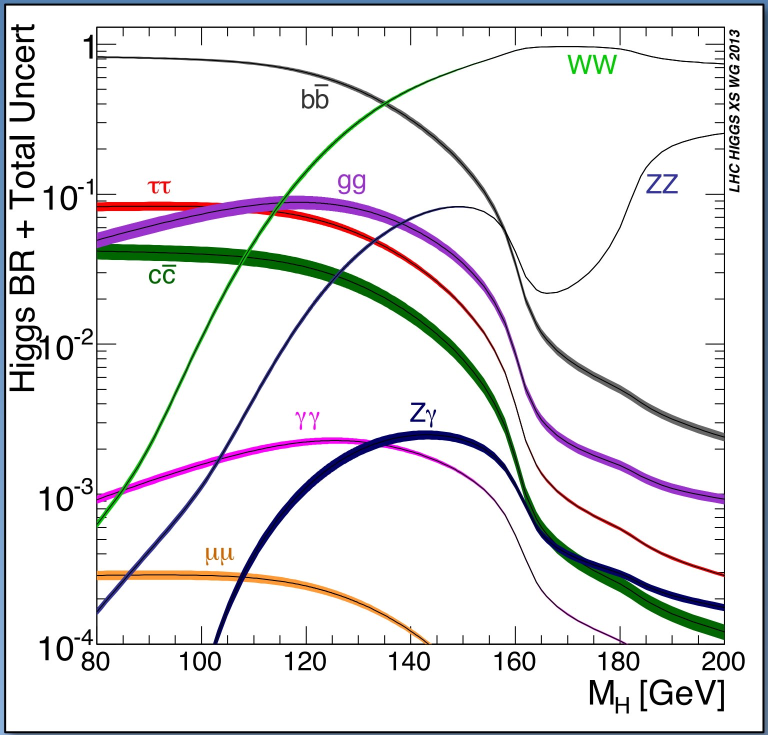
$$\text{SUM} = \sum_i BR_{h\to i}(m_h)$$

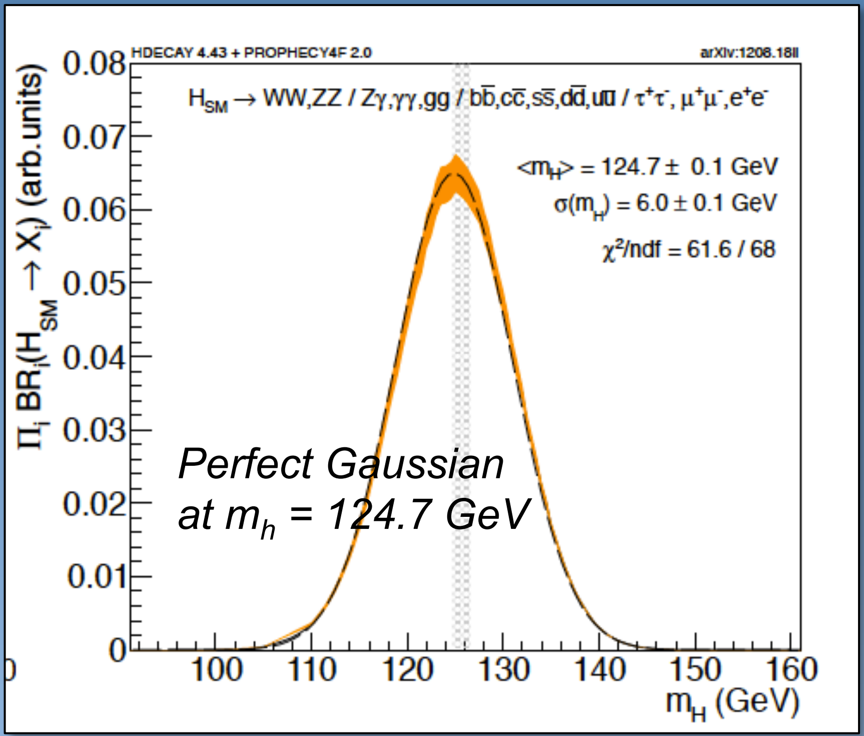


A perfect straight line at 1.00

Kabbalah in the Higgs sector

$$\text{PROD} = \prod_i BR_{h\to i}(m_h)$$





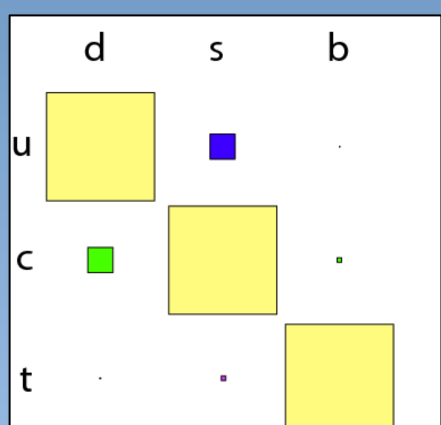
So ? m_h=125 GeV gives access to largest variety of decay channels

Kabbalah in the Standard Model

Quark mixing

$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\textit{CKM-matrix}} \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

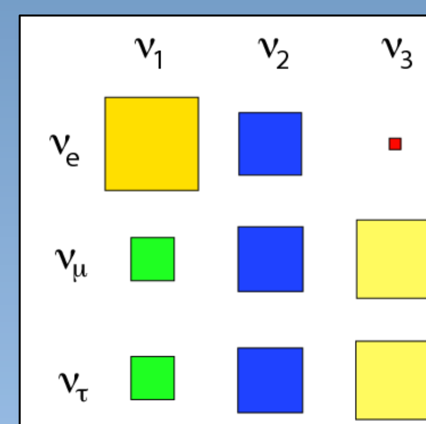
CKM-matrix



Neutrino mixing

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\textit{PMNS-matrix}} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

PMNS-matrix



Kabbalah in the Standard Model

Quark mixing

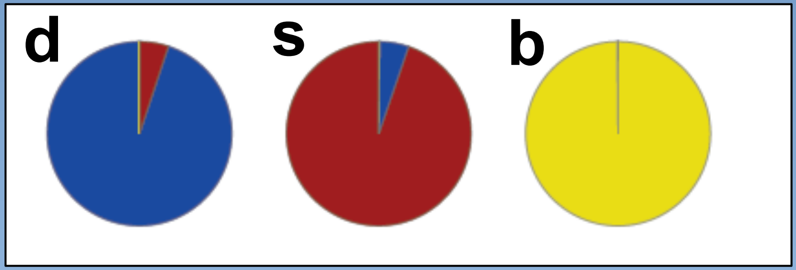
$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

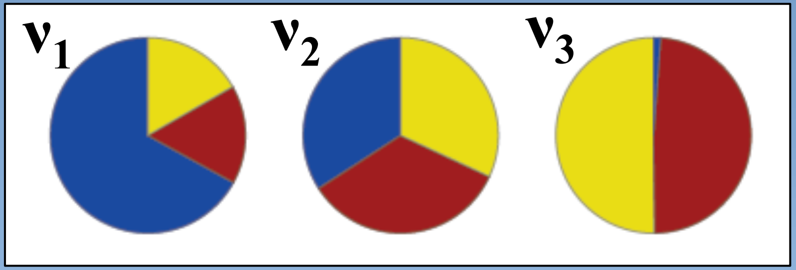
CKM-matrix

Neutrino mixing

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

PMNS-matrix





Completely different hierarchy, good parametrisations ➔ origin unknown!

More Kabbalah in the Standard Model

Yoshio Koide formula:

$$\frac{m_e + m_\mu + m_\tau}{\left(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau}\right)^2} \approx \frac{2}{3}$$

= 0.666659(10)

Top-quark Yukawa coupling:

$$\lambda_t = \frac{\sqrt{2} m_t}{v} \approx 1.00$$

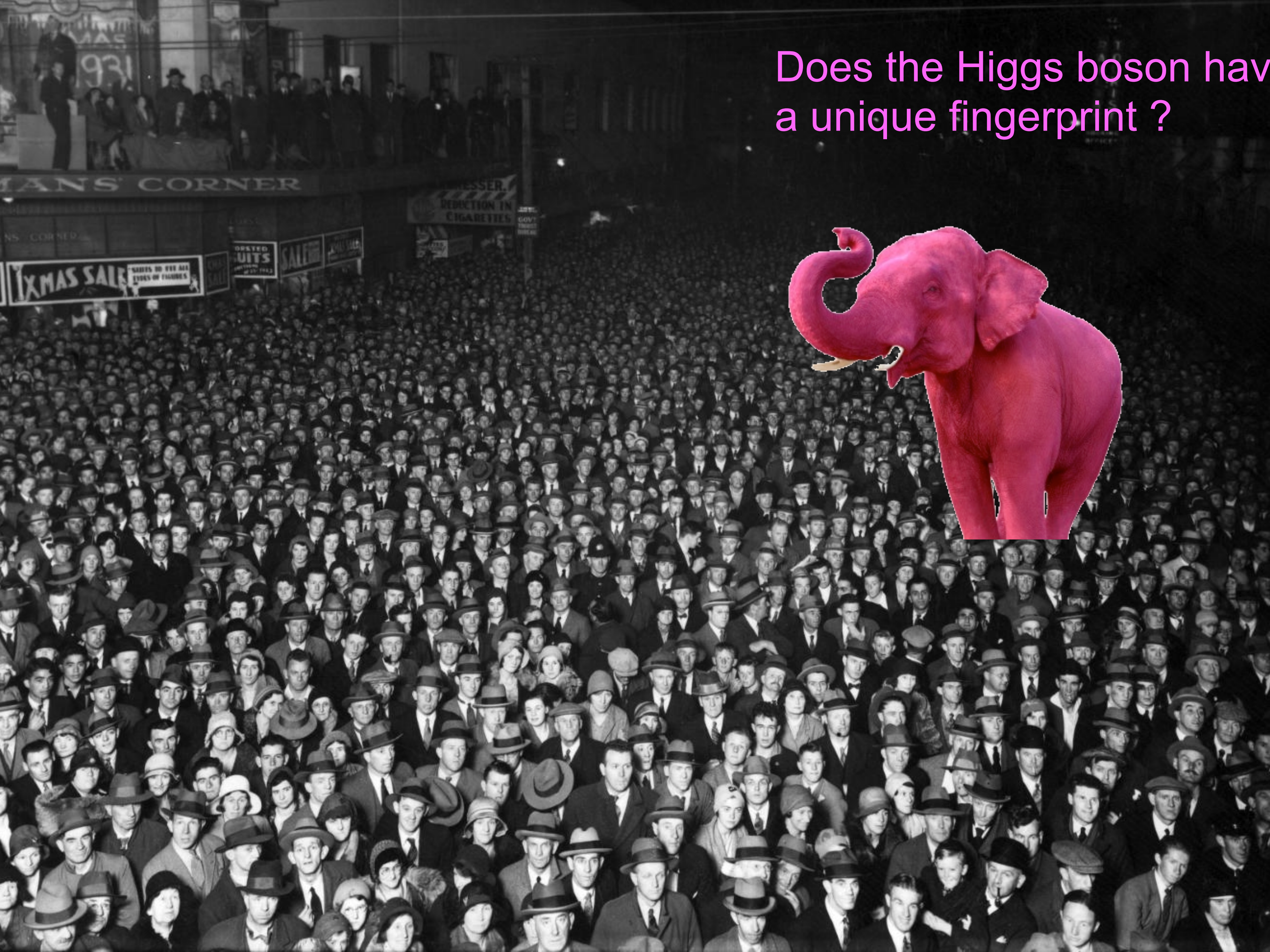
= 0.9956

$$v = \frac{1}{\sqrt{\sqrt{2} G_F}} = 246.22 \qquad m_t = 173.34$$


discovery

… The real work

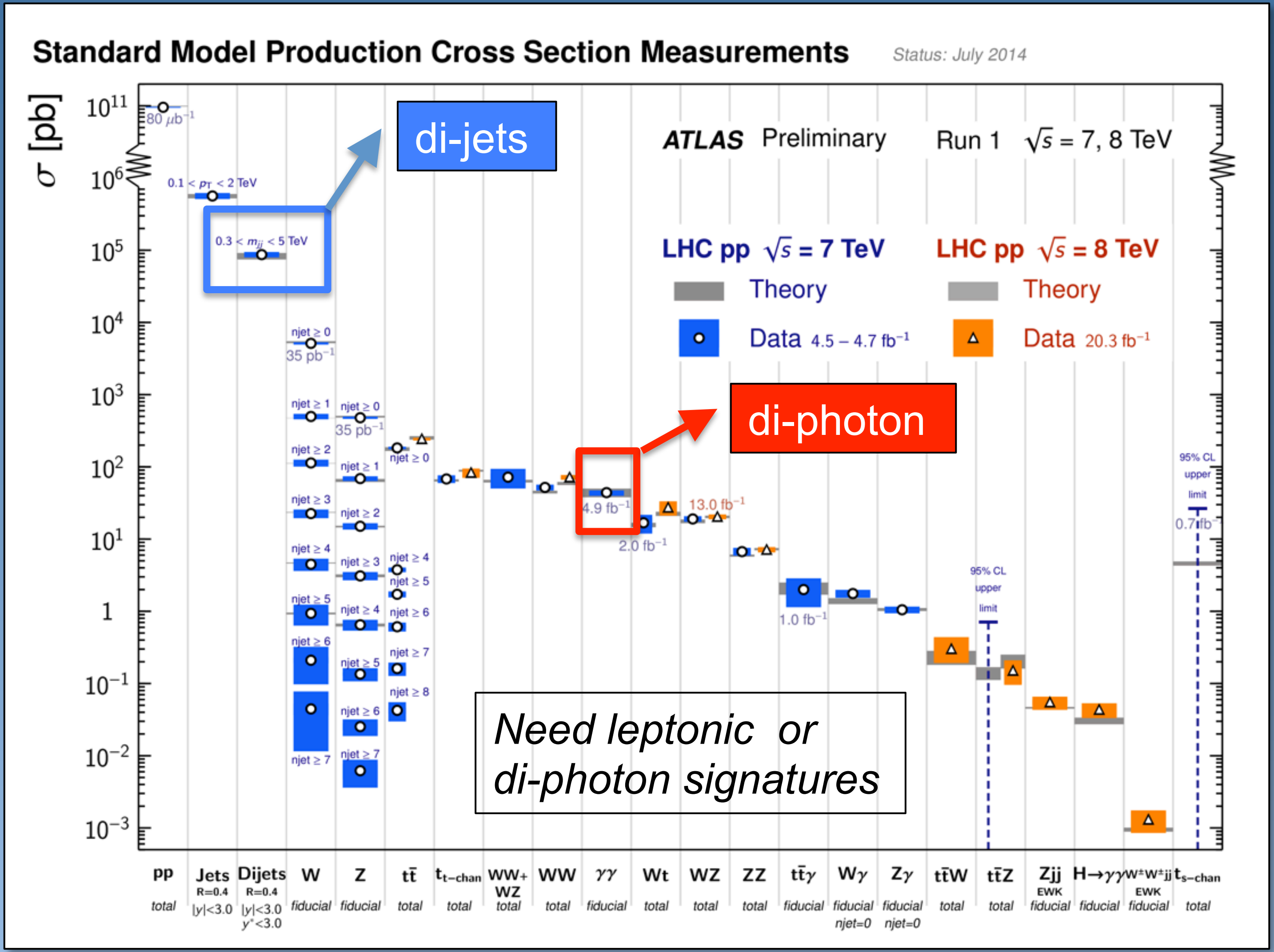
Does the Higgs boson hav
a unique fingerprint ?

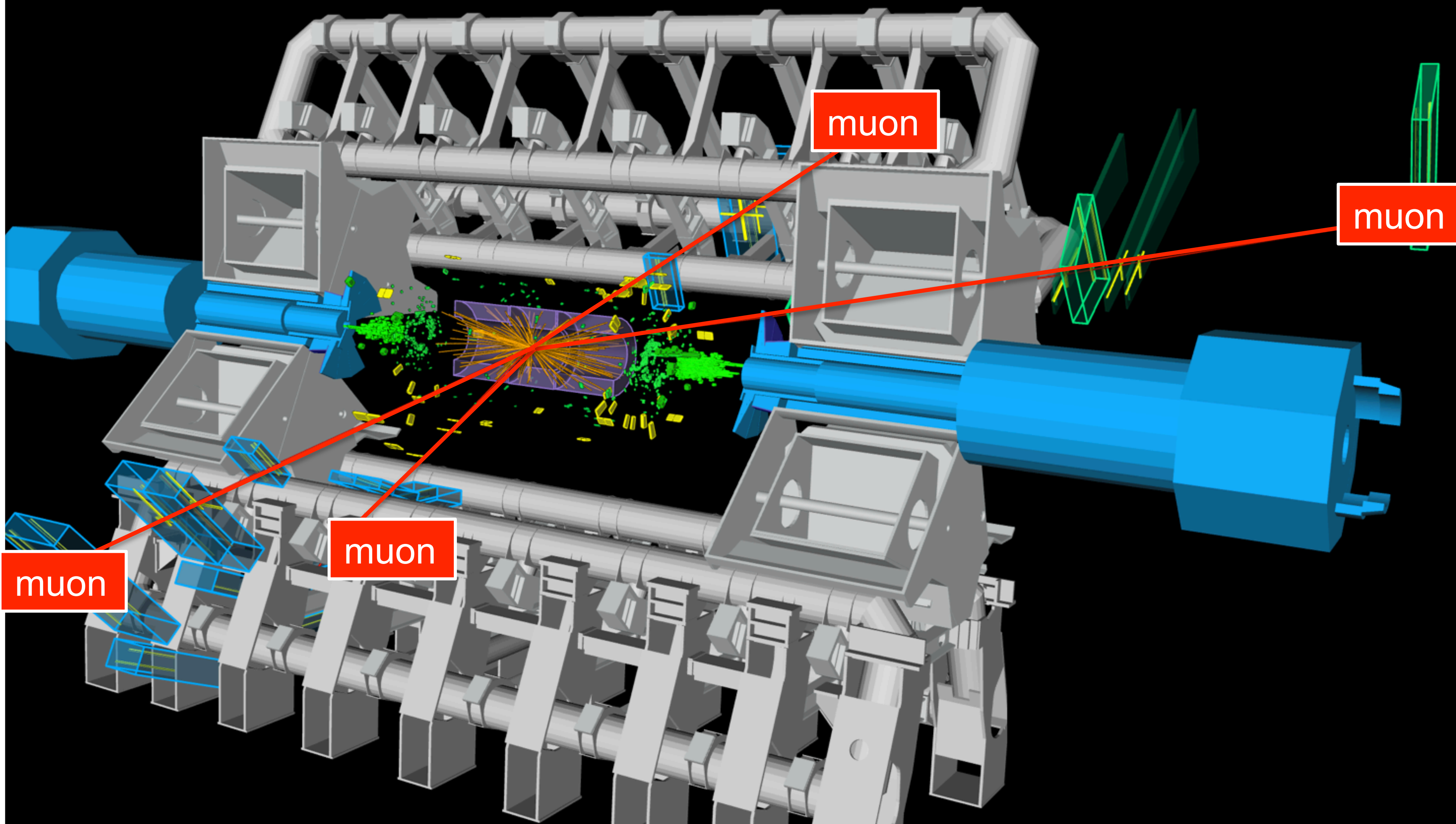



Liu Bolin
Or is it hidden in the background?

Liu Bolin

Standard Model cross-sections at the LHC

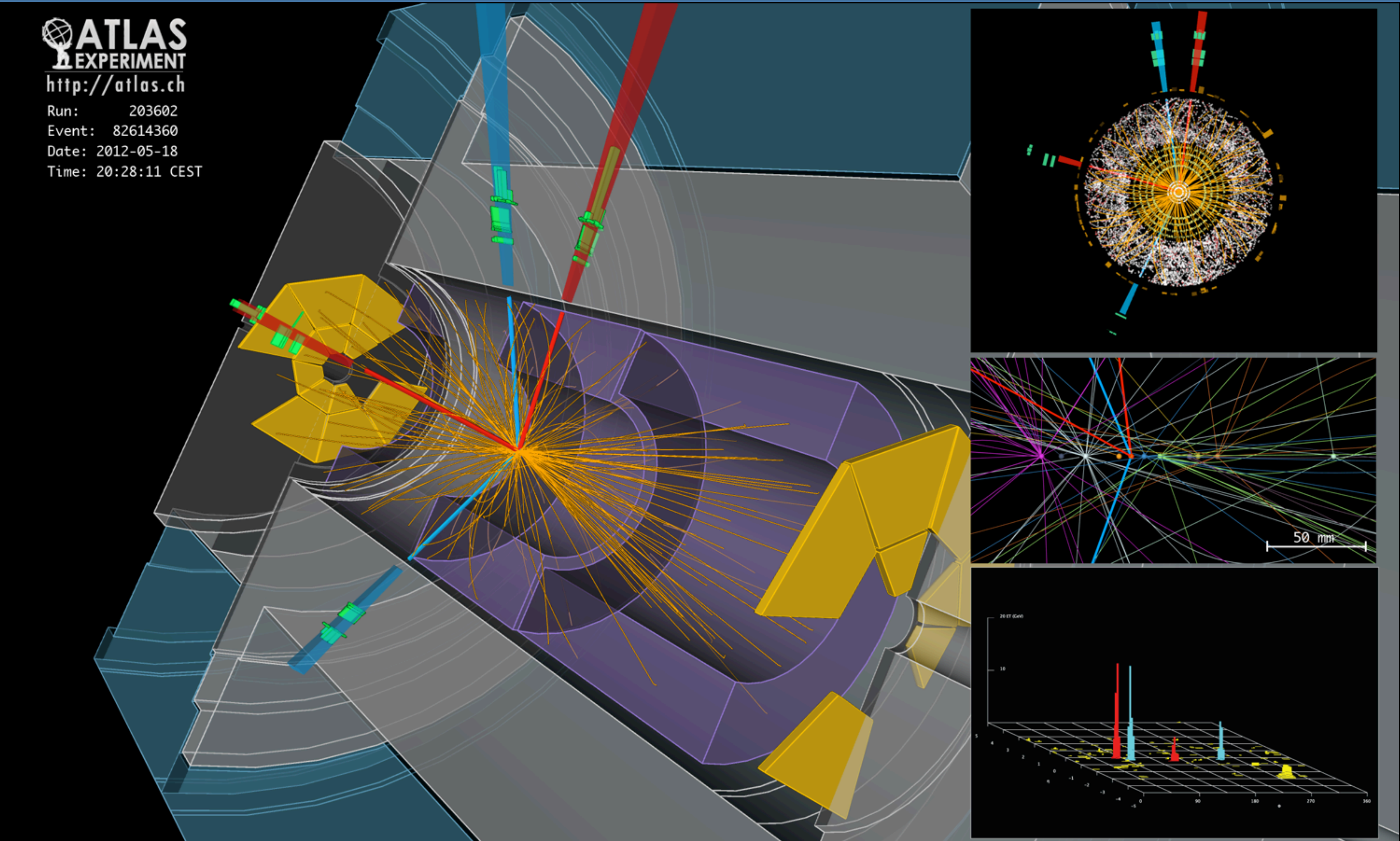


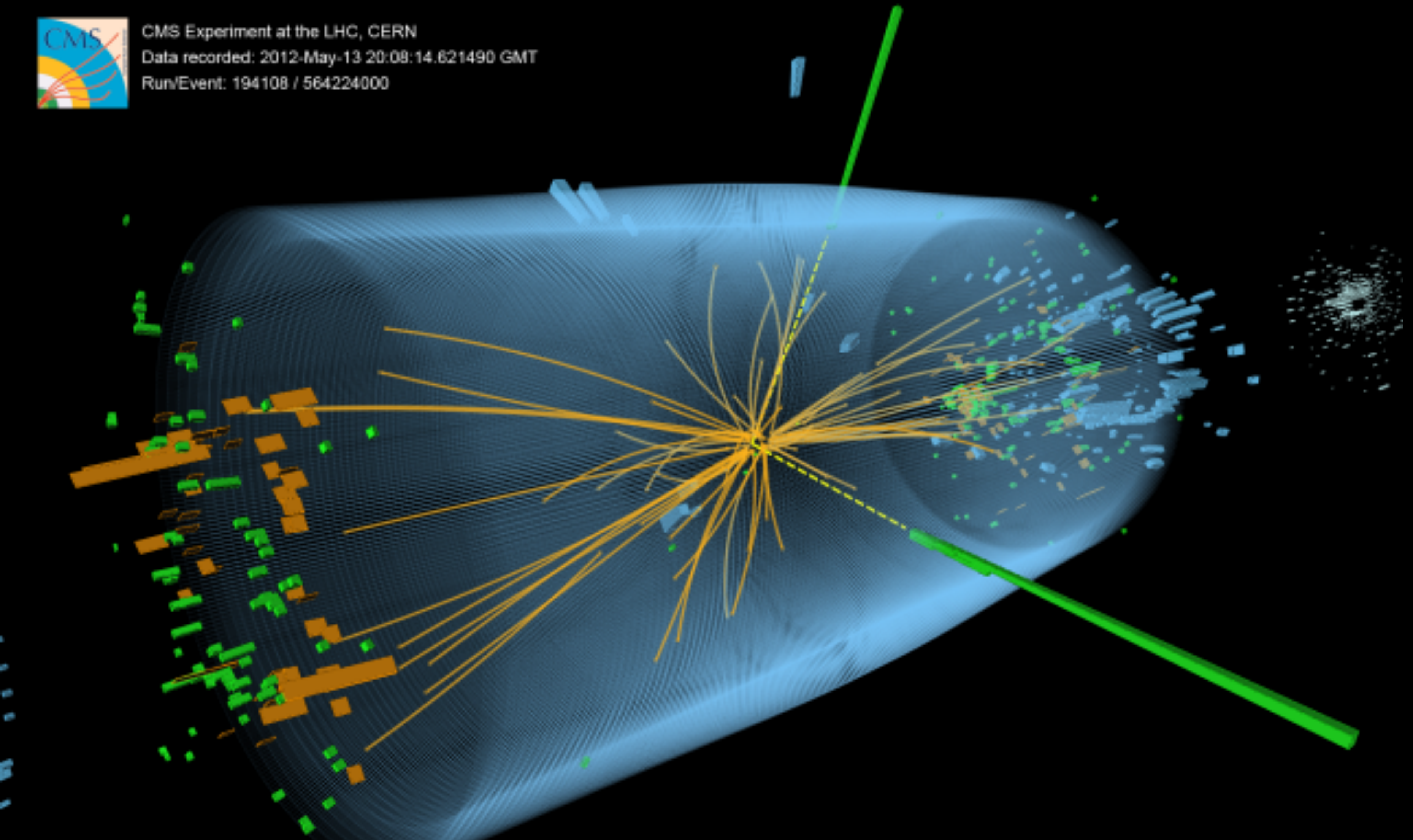


H→ZZ→4μ candidate

#events: ~15-20 per experiment
Purity: ~ 1.5

Another 4-lepton candidate



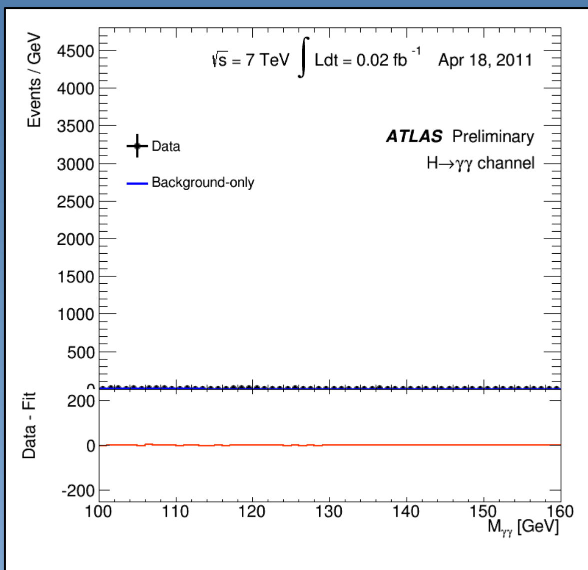


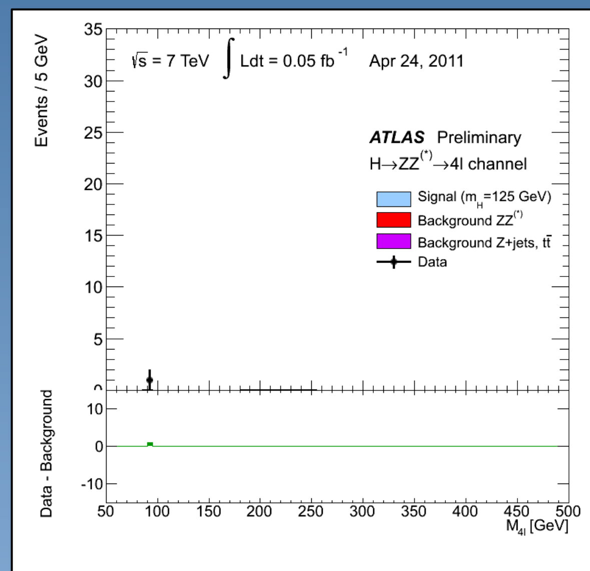
#events: ~ 500 per experiment
Purity: ~ 2%-60%

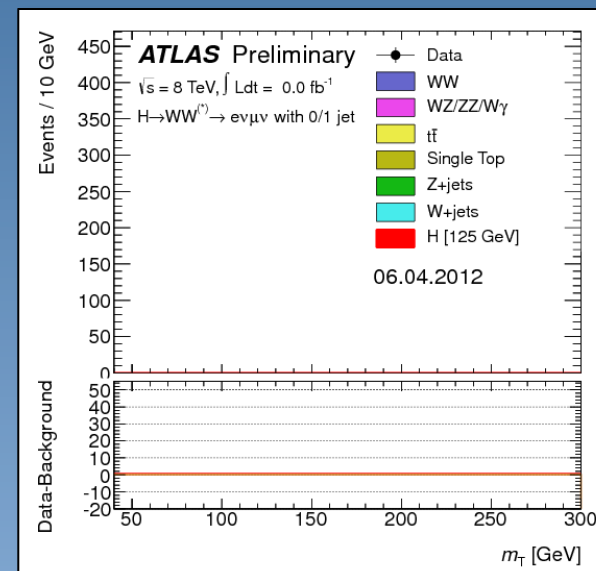
$H \rightarrow \gamma\gamma$ candidate

Animation of the discovery

test







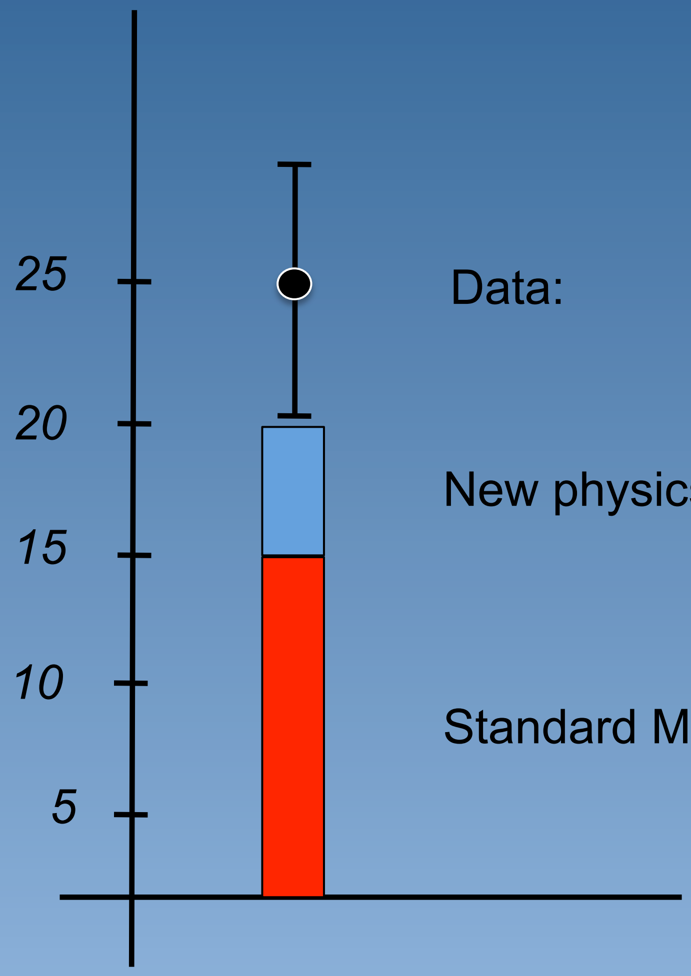
h→γγ

h→ZZ→4l

h→WW→lνlν


statistics

What is significance ?



Data: $N_{data} = 25$

New physics: $N_{sig} = 5$

Standard Model: $N_{bgr} = 15$

Significance: probability to measure N events (or more) under the background-only hypothesis

Observed significance in our example:

$$\int_{25}^{\infty} \text{Poisson}(N \mid 15)\, dN = 0.0112 \quad \leftarrow \textit{p-value}$$

$$= 2.28 \text{ sigma} \quad \leftarrow \textit{significance}$$

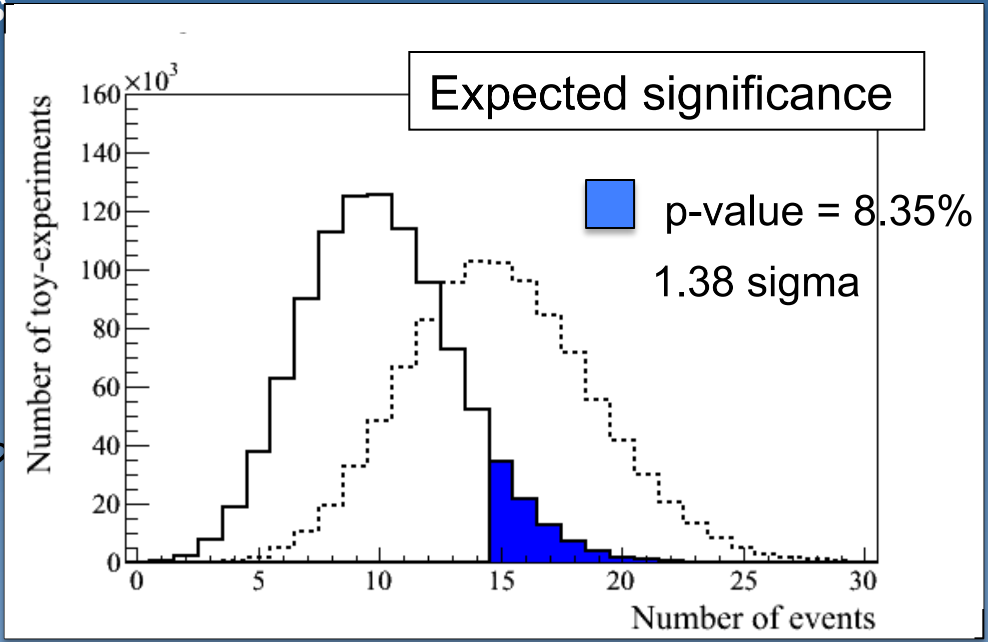
discovery if p-value < 2.87×10^{-7}

→ 39 events

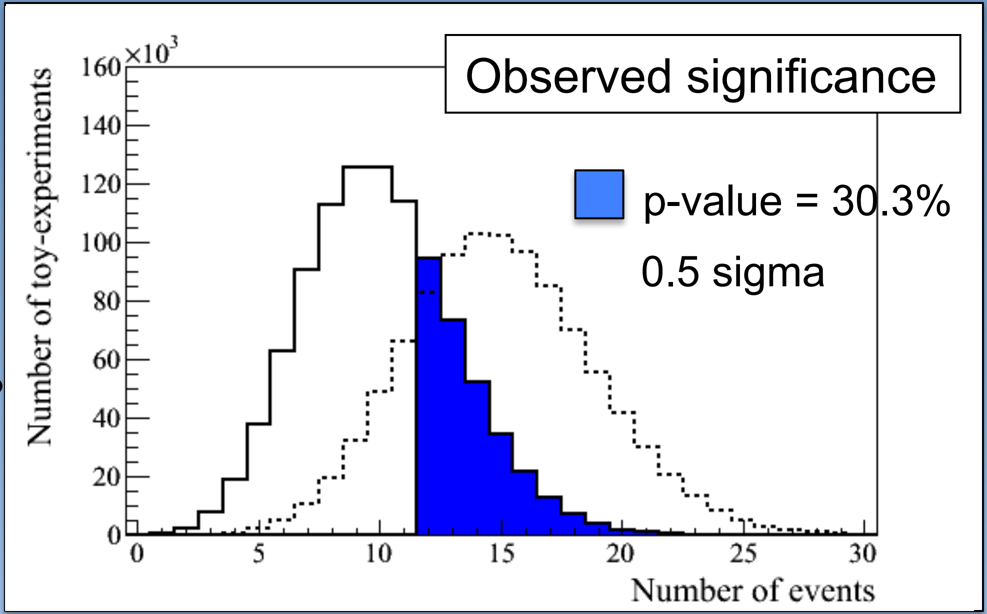
Discovery-aimed: p-value and significance

incompatibiliy with SM-only hypothesis

SM	10
Higgs	5
Data	12



1) *What is the* ***expected*** *significance ?*



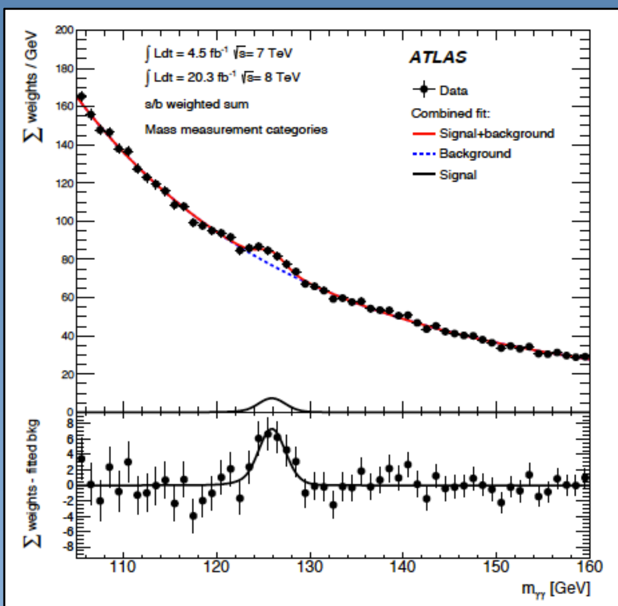
2) *What is the* ***observed*** *significance ?*

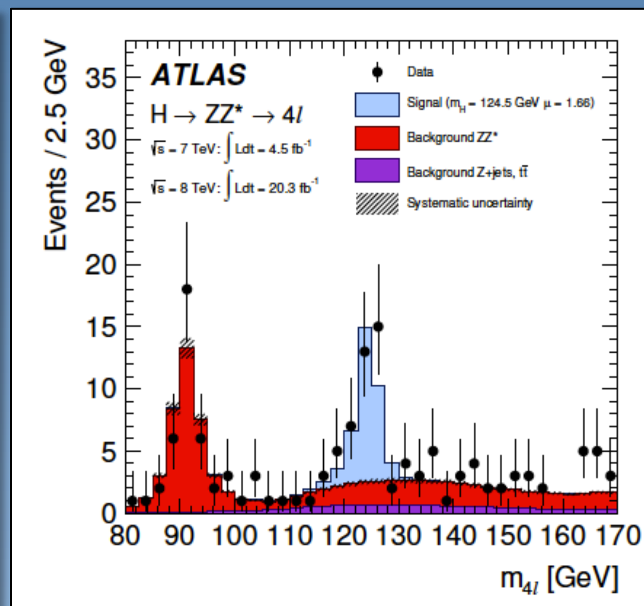
Discovery channels

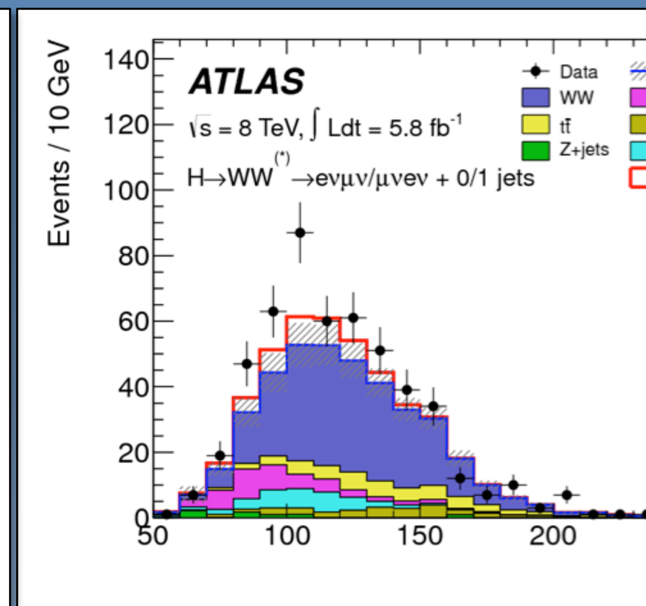
$h \rightarrow \gamma\gamma$

$h \rightarrow ZZ \rightarrow 4$ leptonen

$h \rightarrow WW^{(*)} \rightarrow l\upsilon l\upsilon$

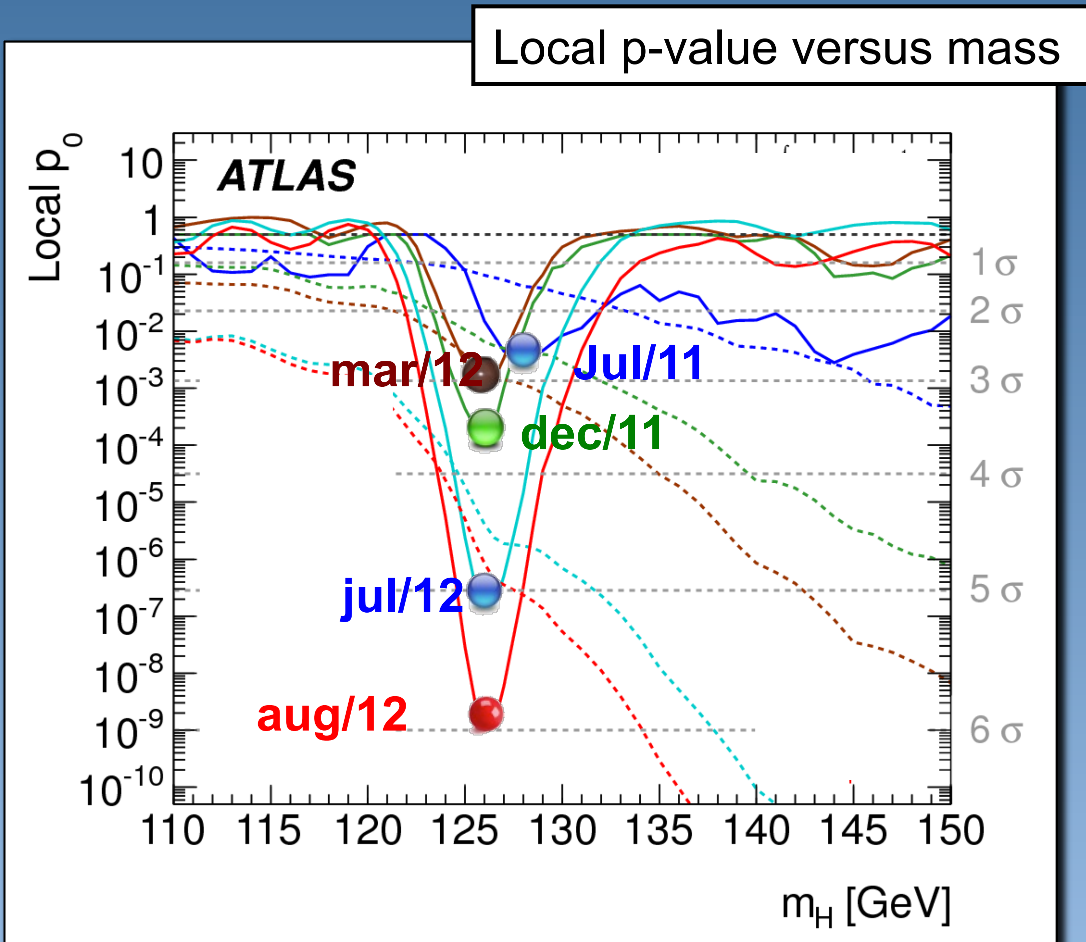






Invariant mass

A textbook discovery in slow-motion



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2012-218
Accepted by: Physics Letters B

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

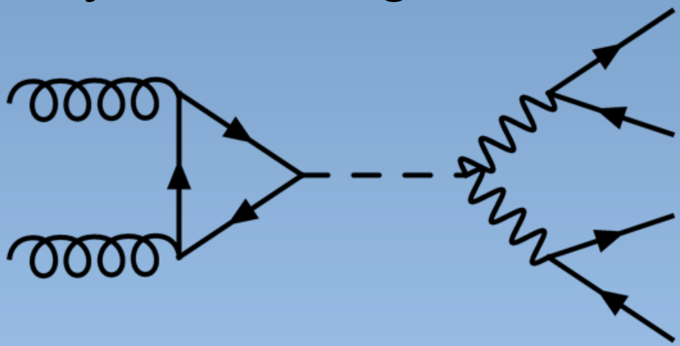
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

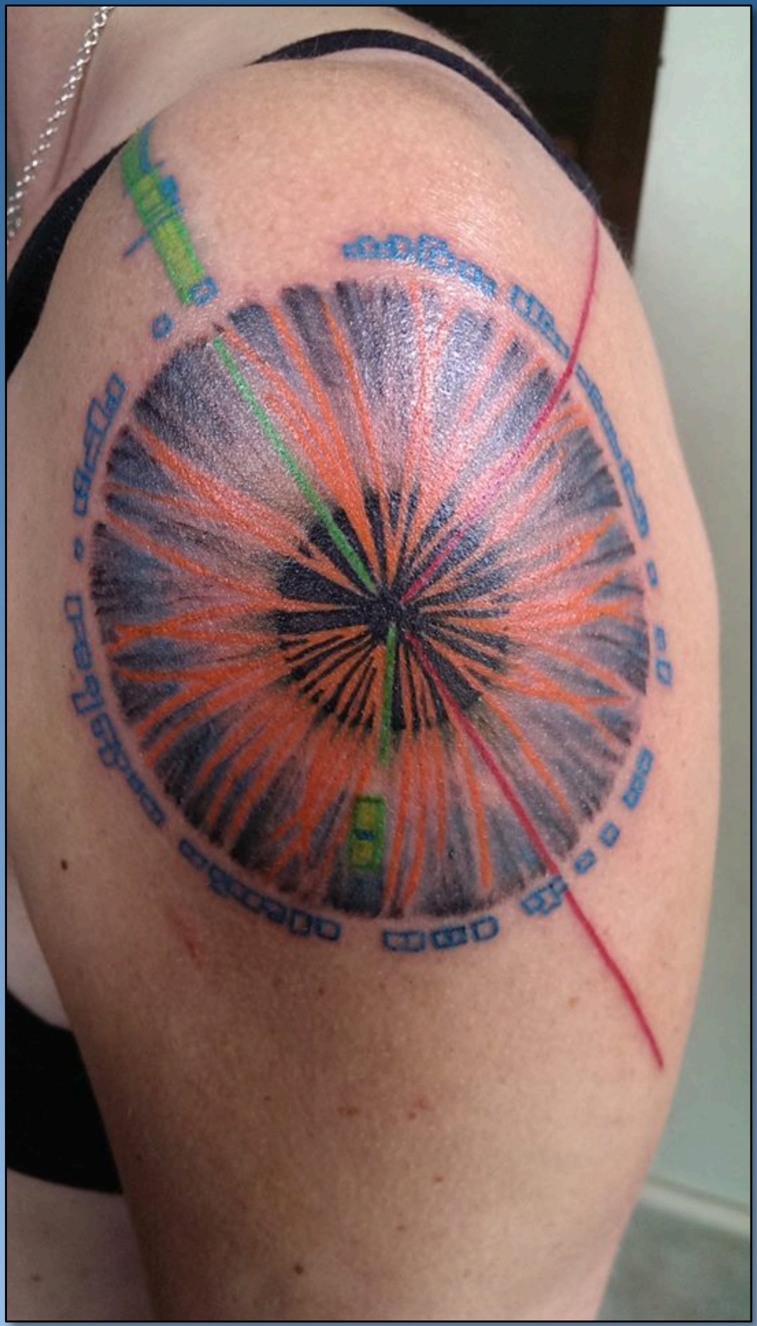
Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s}$ = 7 TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}$ = 8 TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,(\text{stat}) \pm 0.4\,(\text{sys})$ GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Nice moments as a scientist

Feynman diagram

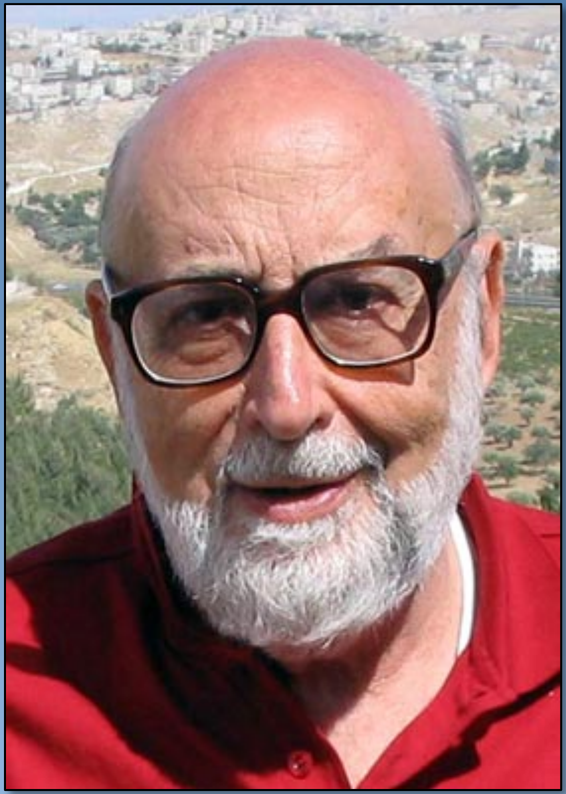




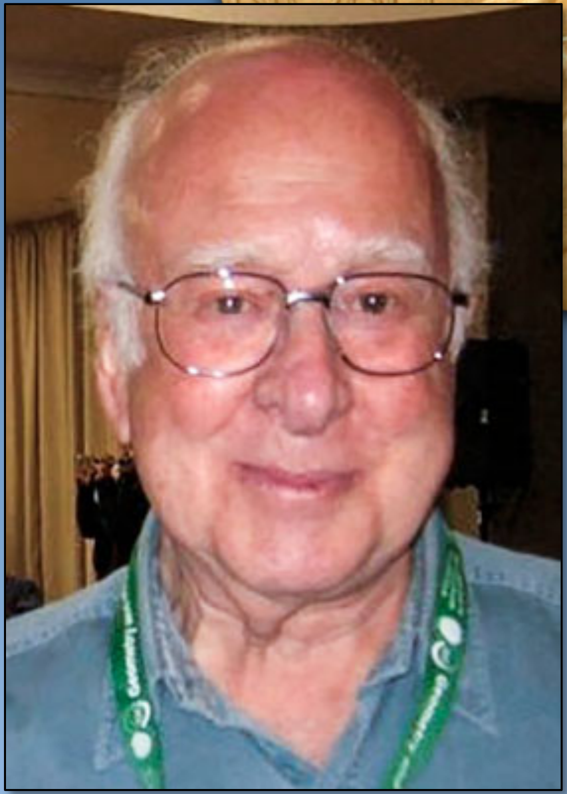
July 4th 2012: party time !!

Nobelprize Physics 2013

“There is a Higgs field in the vacuum”

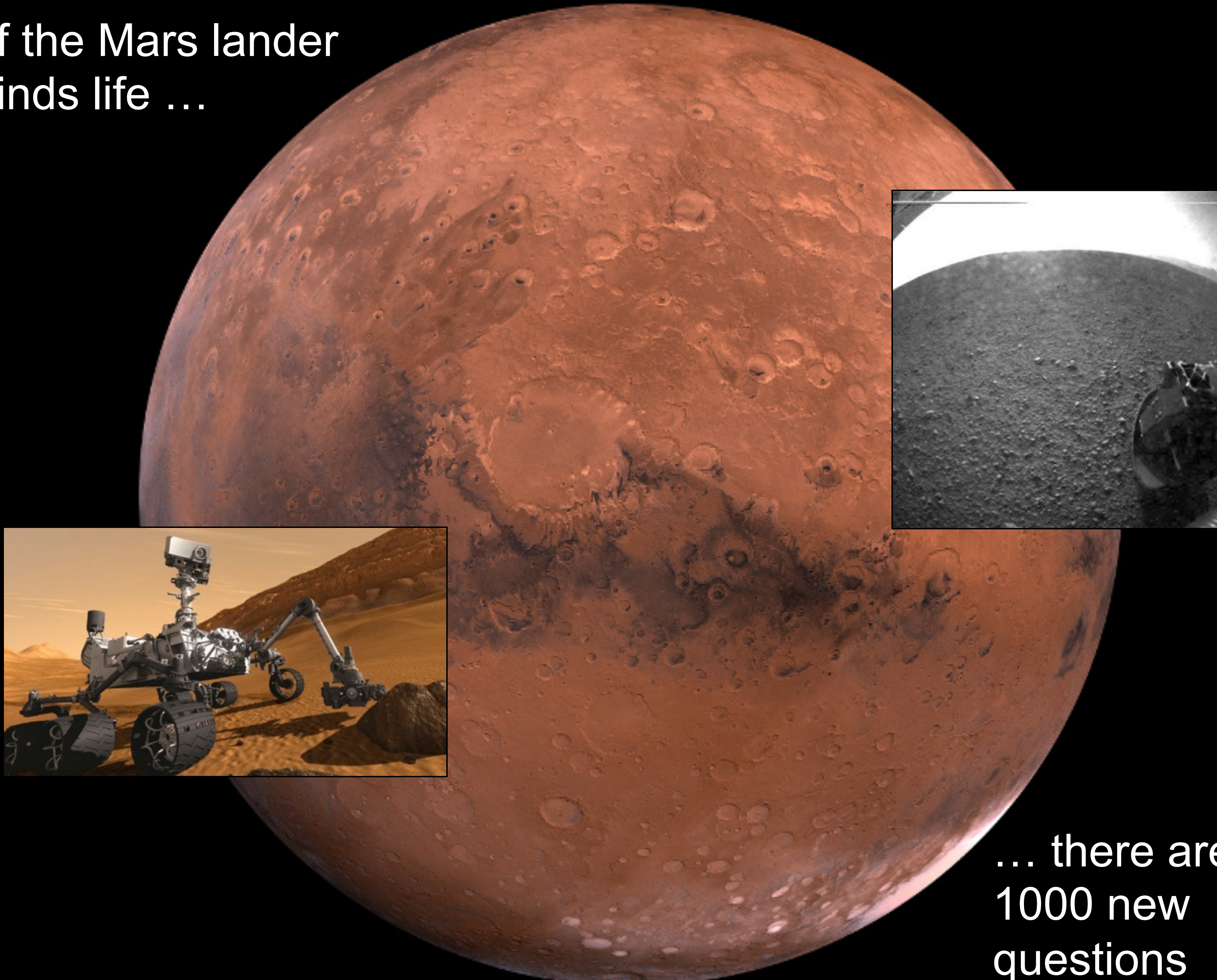


François Englert



Peter Higgs

If the Mars lander finds life …



… there are a 1000 new questions

Problems

The problems with the Higgs mechanism

The Higgs solves many problems:

- Massive gauge bosons
- Massive fermions
- WW scattering, CKM matrix, EW unification, …

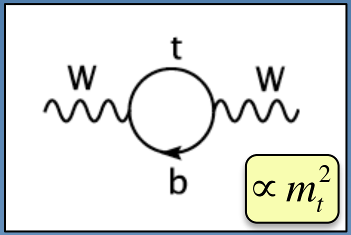
The Higgs also creates problems:

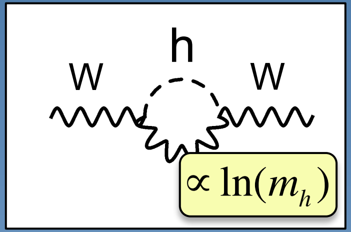
- Hierarchy problem
- Vacuum energy contribution
- Why so simple ?

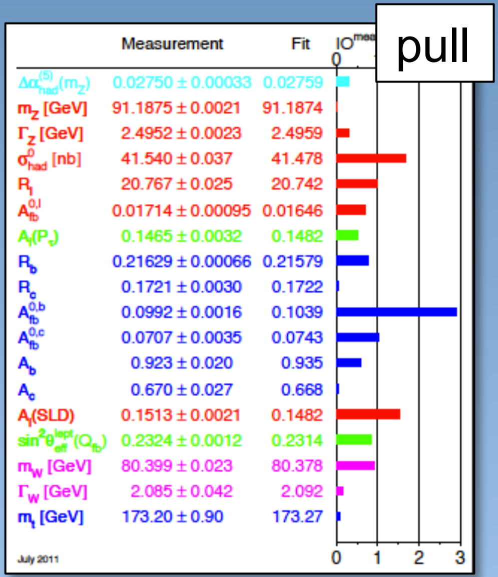
Problem 1: the hierarchy problem

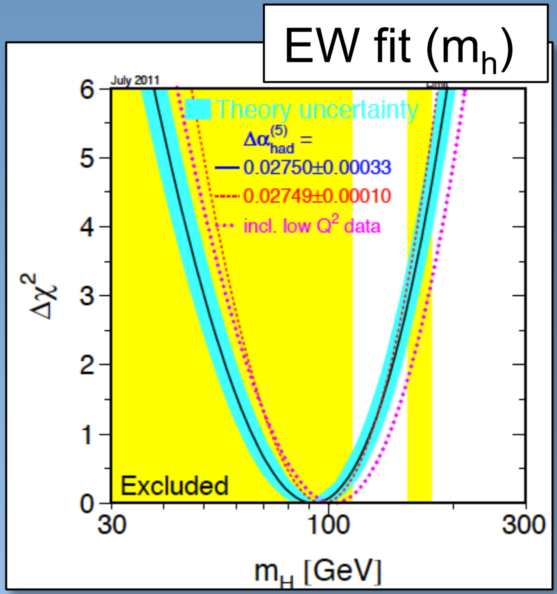
Radiative corrections from the Higgs boson explode

Radiative corrections:
- EW precision measurements
- predicting top mass







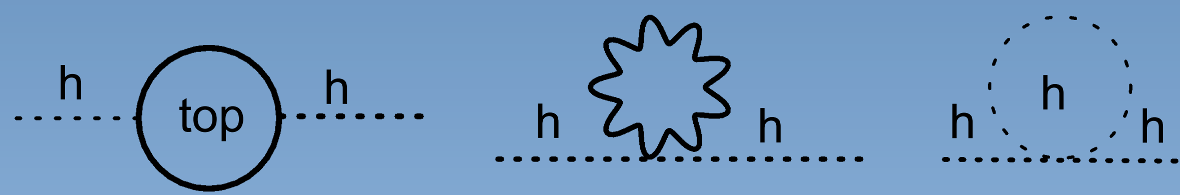


Problem 1: the hierarchy problem

Radiative corrections from the Higgs boson explode

$$m_h = m_h^{\text{bare}} + \Delta m_h^{\text{ferm.}} + \Delta m_h^{\text{gauge}} + \Delta m_h^{\text{Higgs}} + \ldots$$

correction

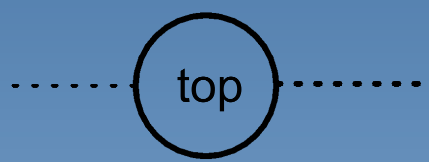


$$\left(\Delta m_h^2\right)^{top} \propto \lambda_t^2 \Lambda^2 \qquad \left(\Delta m_h^2\right)^{W,Z} \propto \Lambda^2 \qquad \left(\Delta m_h^2\right)^{h} \propto \Lambda^2$$

This is not stable and corrections grow: $\Lambda = 10^{16}$ GeV ?

Problem 1: the hierarchy problem (solution?)

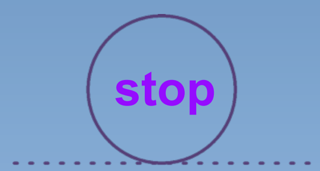
$m_h = m_0 + \Delta m_h$



fermions

$$\Delta m_H^2 \sim \frac{|\lambda_f|^2}{16\pi^2}\left(-2\Lambda^2 + 6m_f^2 \ln\frac{\Lambda}{m_f} + \ldots\right)$$

Supersymmetry can cancel the quadratic divergences



scalars

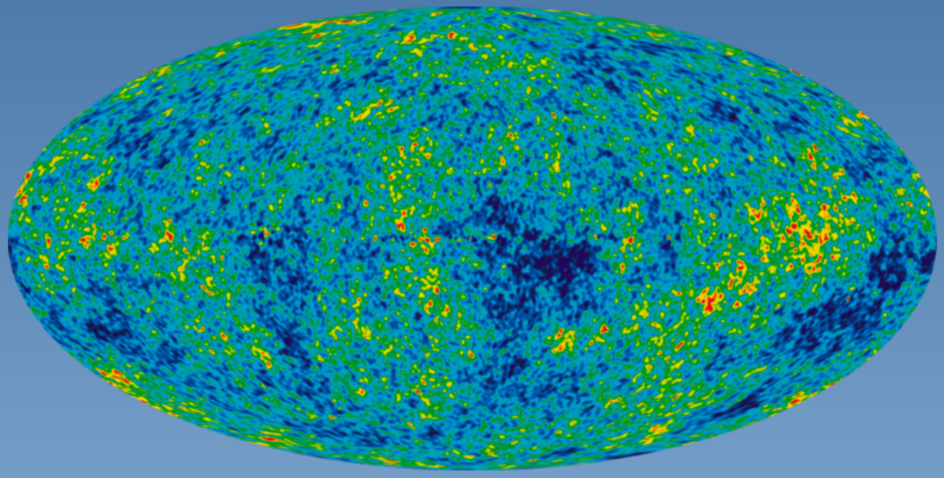
$$\Delta m_H^2 \sim \frac{\lambda_s}{16\pi^2}\left(\Lambda^2 + 2m_f^2 \ln\frac{\Lambda}{m_s} + \ldots\right)$$

… but we do not know if SUSY exists.

Problem 2

"If the Higgs field exists then the universe should be the size of a football"

Contribution of the Higgs to the vacuum energy



Prediction

$$\rho_{Higgs}^{vac} \sim 10^{+8}\,\mathrm{GeV}^4$$

Measurement

$$\Omega_\Lambda = 10^{-46}\,\mathrm{GeV}^4$$

Factor 10^{54} wrong: one of the 'small' problems in cosmology

Questions regarding the Higgs boson

Is the Higgs boson exactly that of the SM – couplings ?

Is the Higgs boson exactly that of the SM – spin, parity, … ?

Is it elementary or composite ?

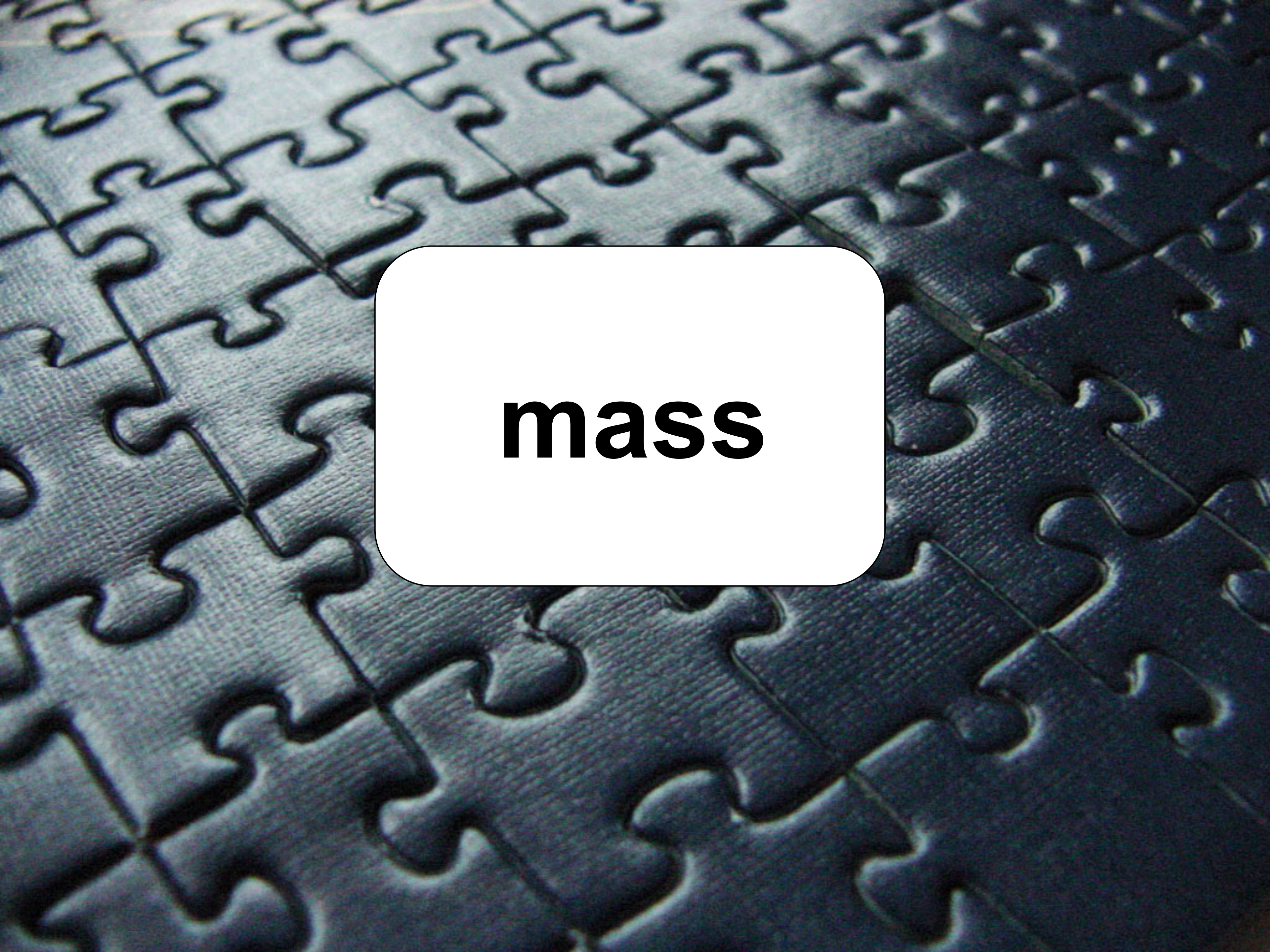
Are there more Higgs bosons (singlets, SUSY, …) ?

What explains the mass hierarchy ?

Is it possible that Higgs field is linked to inflation ?

…

Each of the new models will change the Higgs boson’s properties



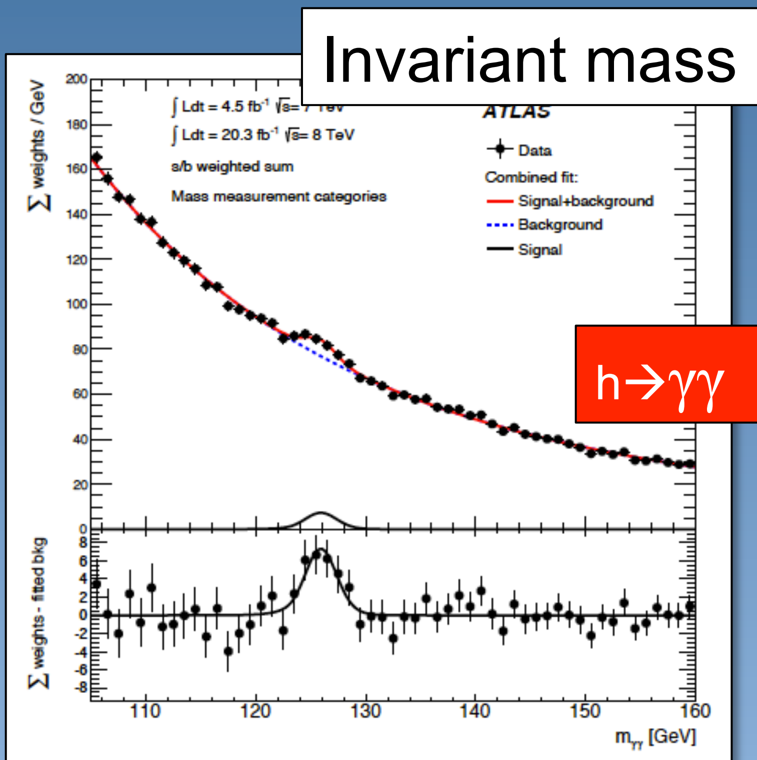
mass

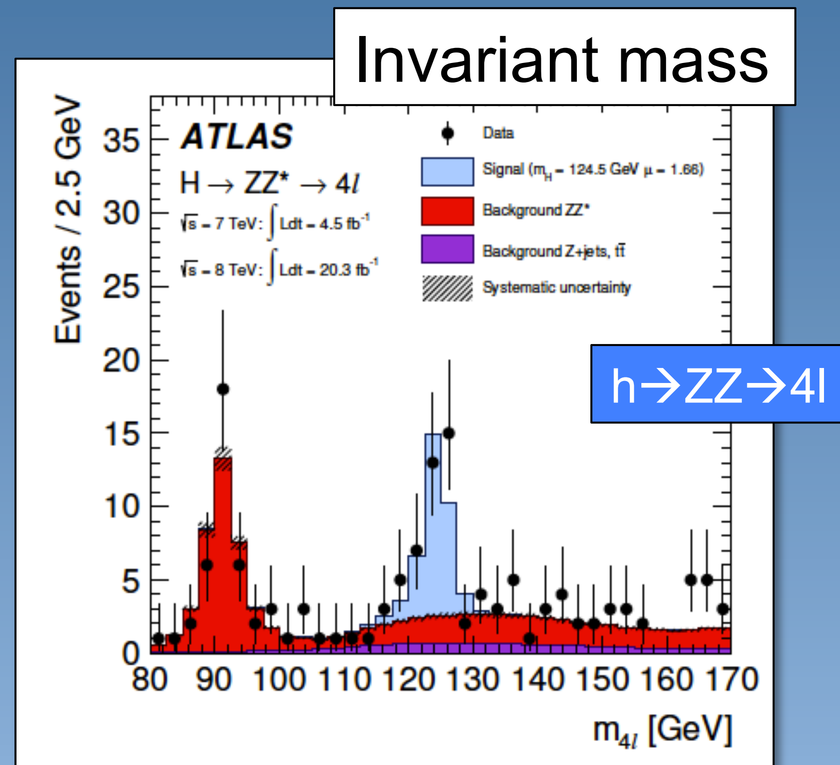
Why measure the mass to high precision ?

Branching ratio's depend on the mass of the Higgs boson

		Δm	$\Delta \Gamma/\Gamma_{125}$
m_h = 123.7 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.34%	-1%	-11%
m_h = 124.0 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.41%		
m_h = 124.5 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.52%	0.4%	-4.5%
m_h = 125.0 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.64%	0.0%	0.0%
m_h = 125.5 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.76%	0.4%	+4.5%
m_h = 126.0 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.89%		
m_h = 126.3 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.97%	+1%	+12%

Mass of the newly disovered particle





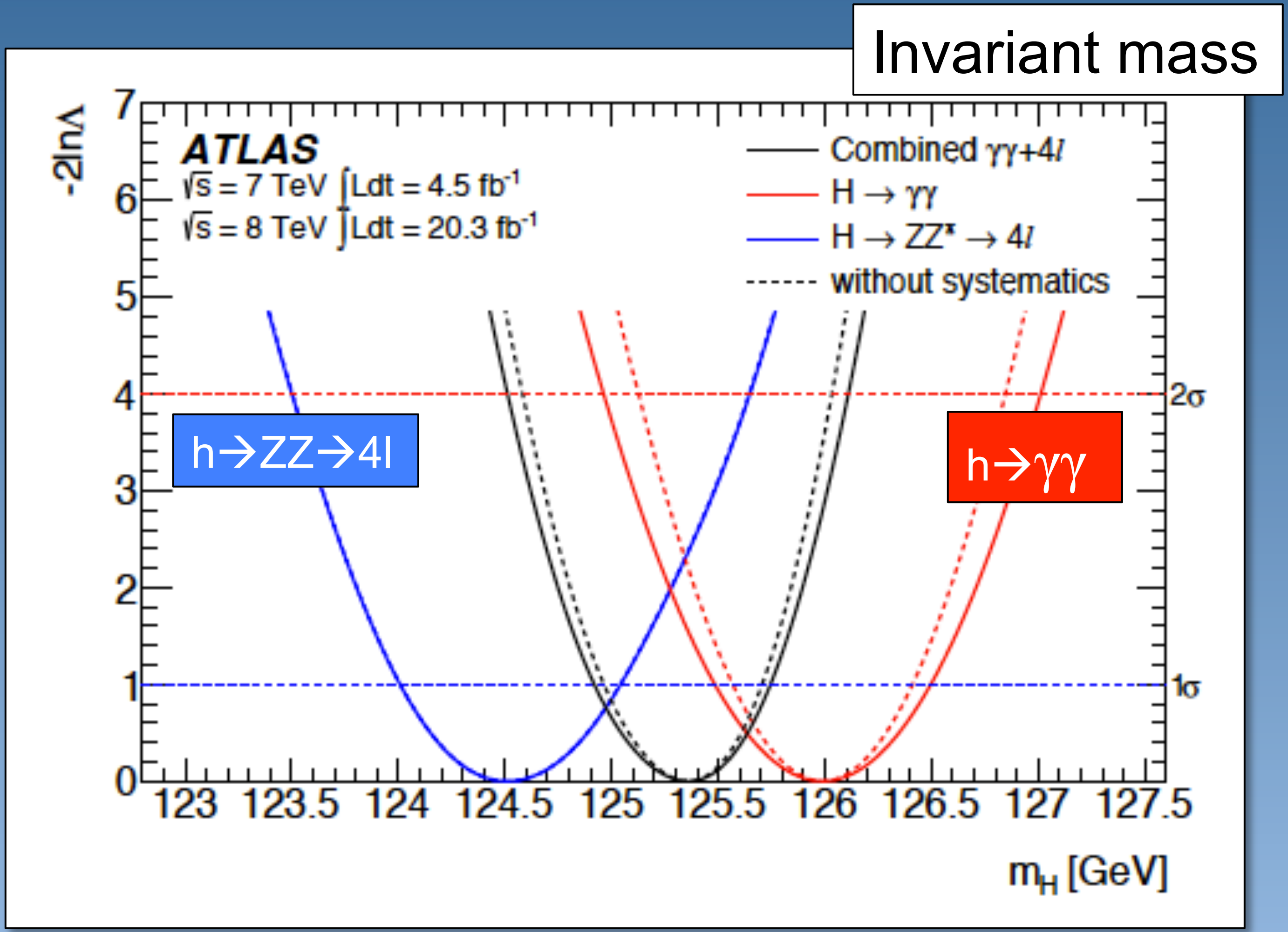
m_h = 125 .98 ± 0.42 (stat) ± 0.28(syst) GeV

m_h = 125 .98 ± 0.50 GeV

m_h = 124 .51 ± 0.52 (stat) ± 0.06(syst) GeV

m_h = 125 .98 ± 0.52 GeV

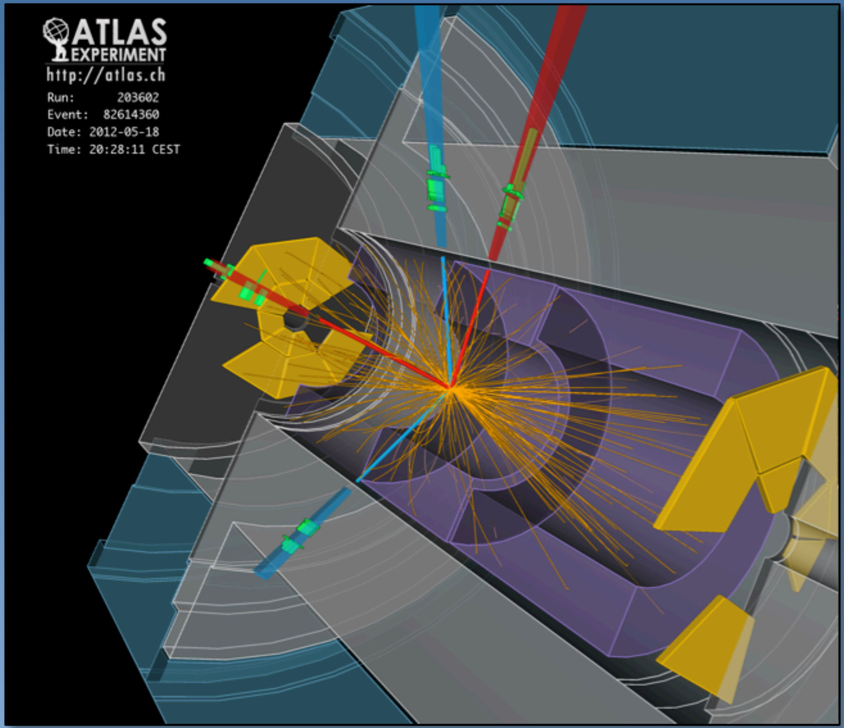
Mass combination in ATLAS

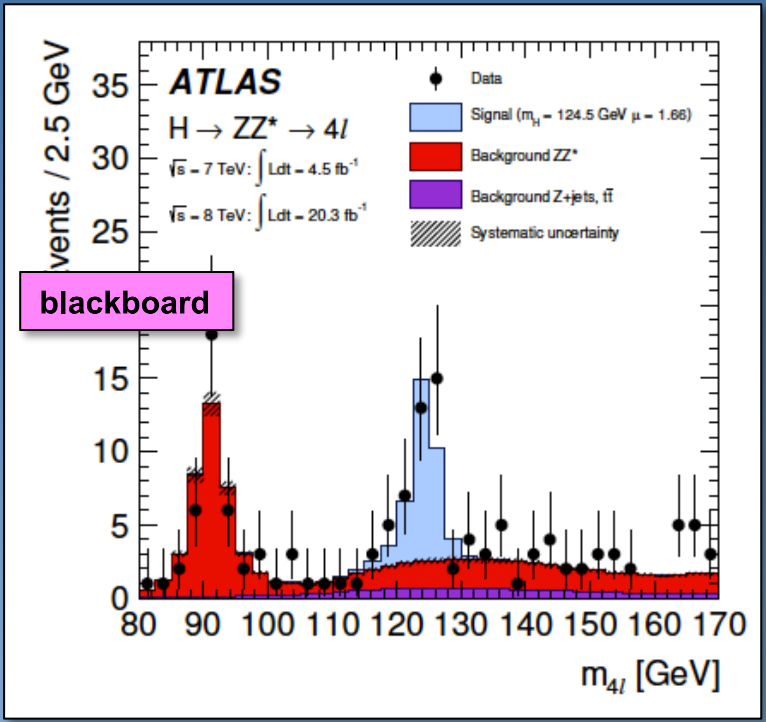


m_h = 124 .36 ± 0.41

Δm_h = 1.47 ± 0.72 GeV
1.98 sigma

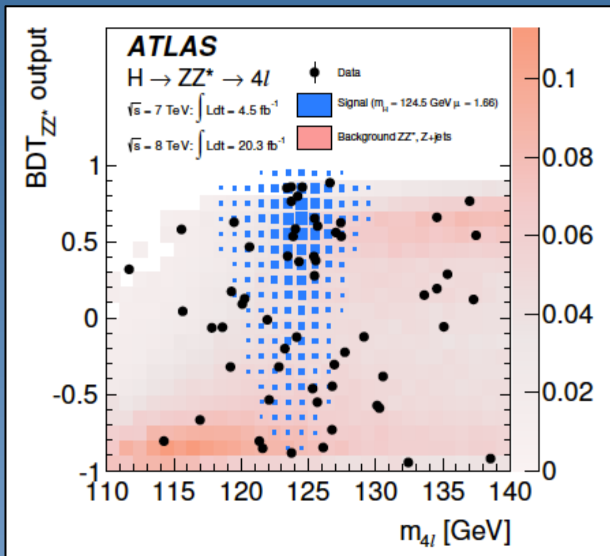
Mass measurement in the 4-lepton channel

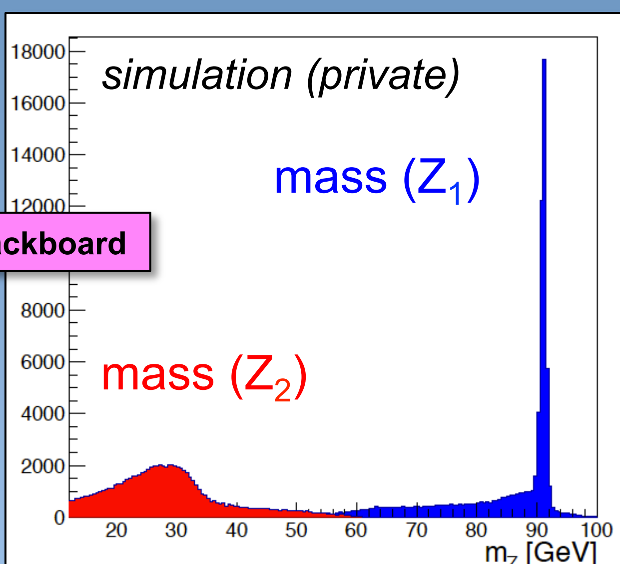




Small number of events:	26.5 expected (37 observed), 4 categories
Clean signature:	S/B ~2 in mass region 120-130 GeV
Excellent mass resolution:	1.6 (2.2) GeV in the 4μ (4e) channel
Backgrounds:	ZZ*, Z+jets, tt

Mass measurement in the 4-lepton channel

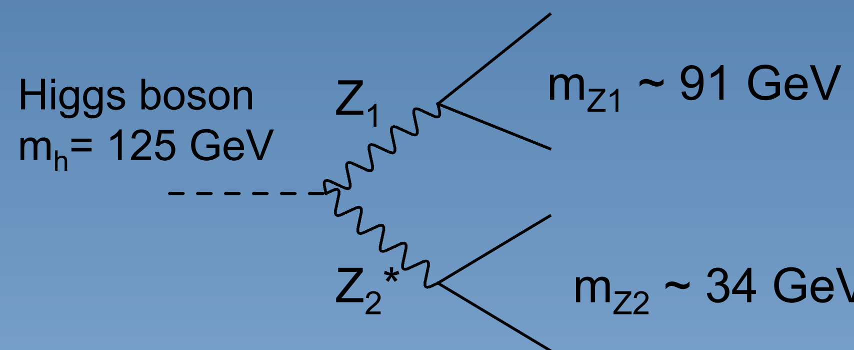




blackboard

Extra signal/background separation:

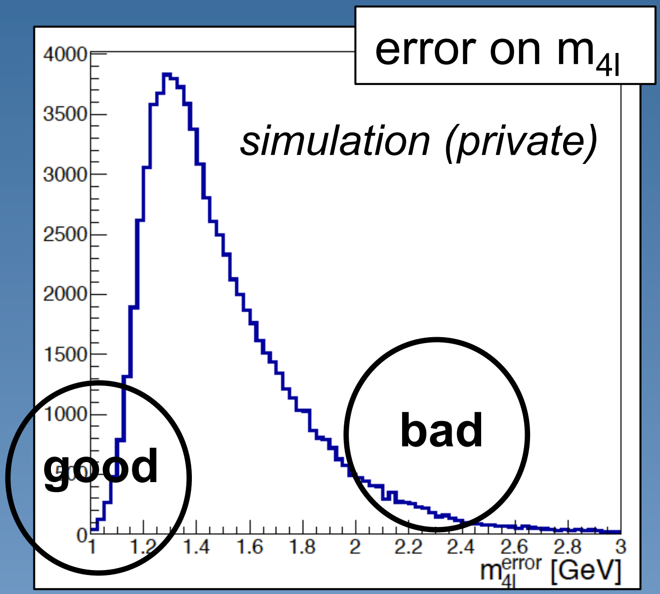
BDT output based on kinematic information



Z-mass constraint:

- One Z boson is preferably off-shell
- Fix mass to M_Z (91.18 GeV) for the on-shell Z when computing m_{4l}

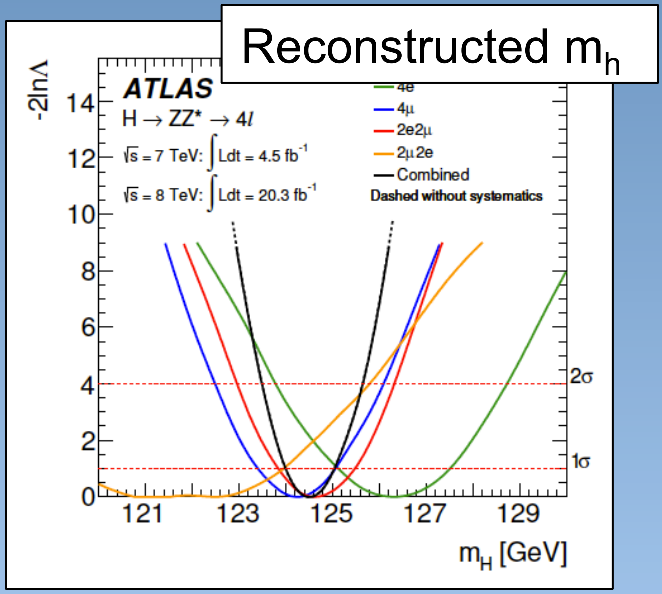
Mass measurement in the 4-lepton channel



Per event error distribution

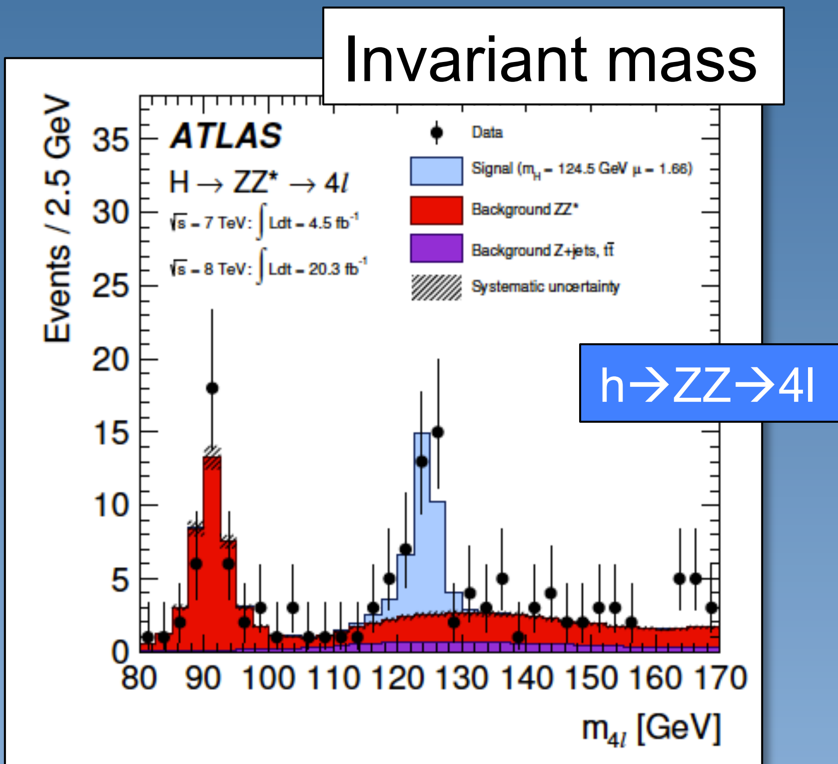
- Neglected for now in ATLAS **blackboard**

- Wait for Antonio Castelli's thesis



Consistency between channels

Mass measurement in the 4-lepton channel



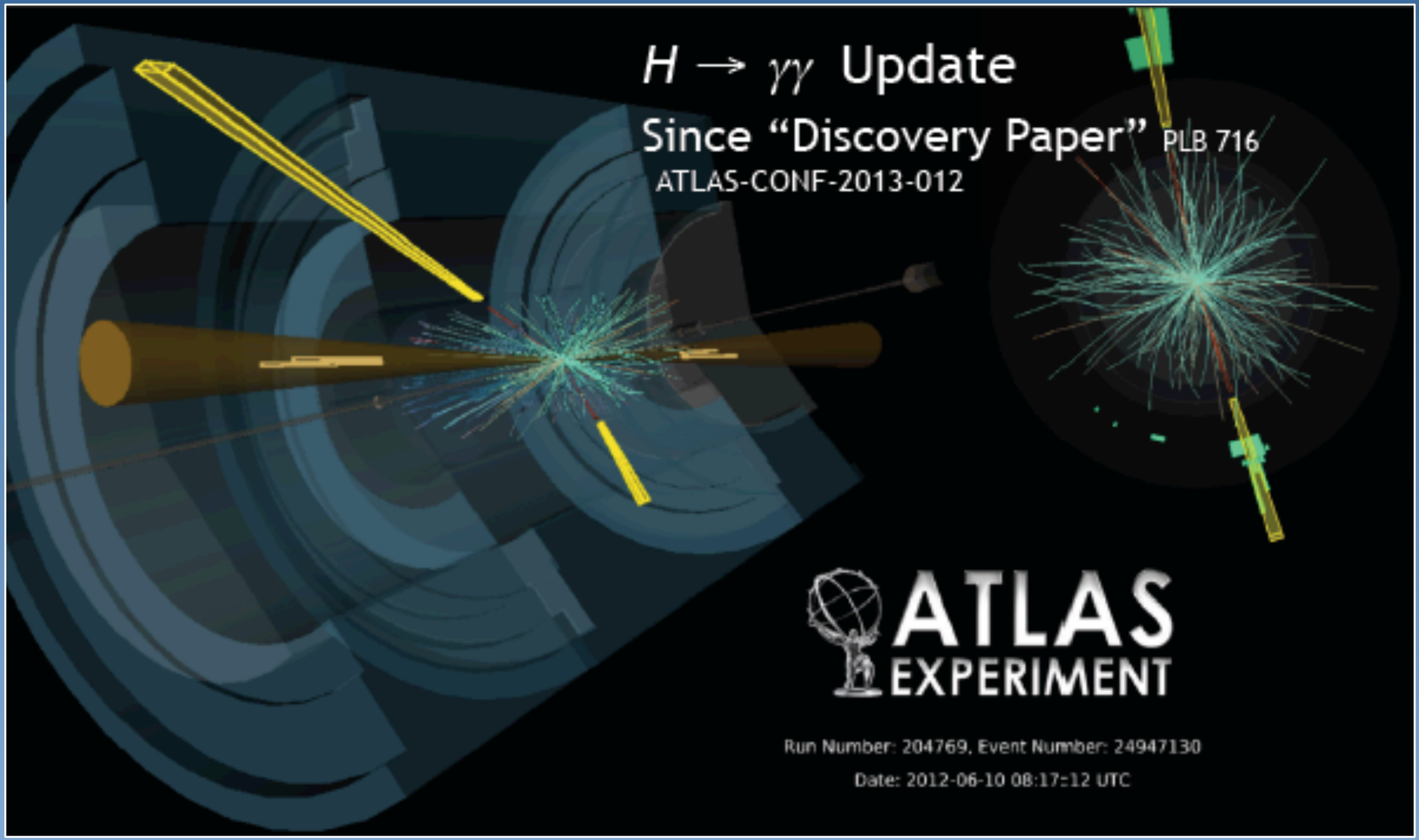
ATLAS experiment

m_h = 124 .51 ± 0.52 GeV

$$\mu = 1.66^{+0.45}_{+0.38}$$

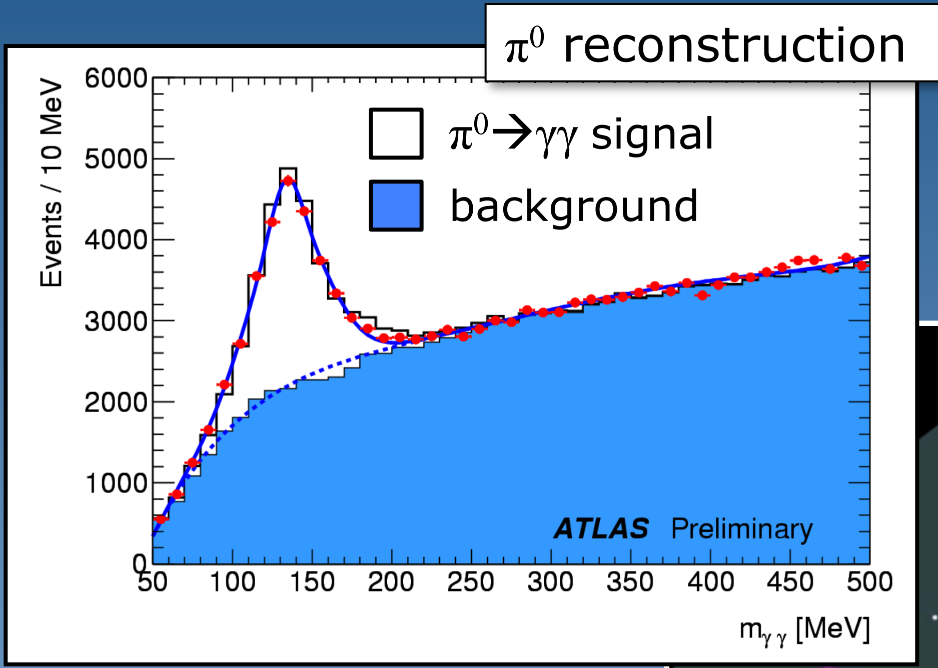
More events than expected and excellent mass measurement

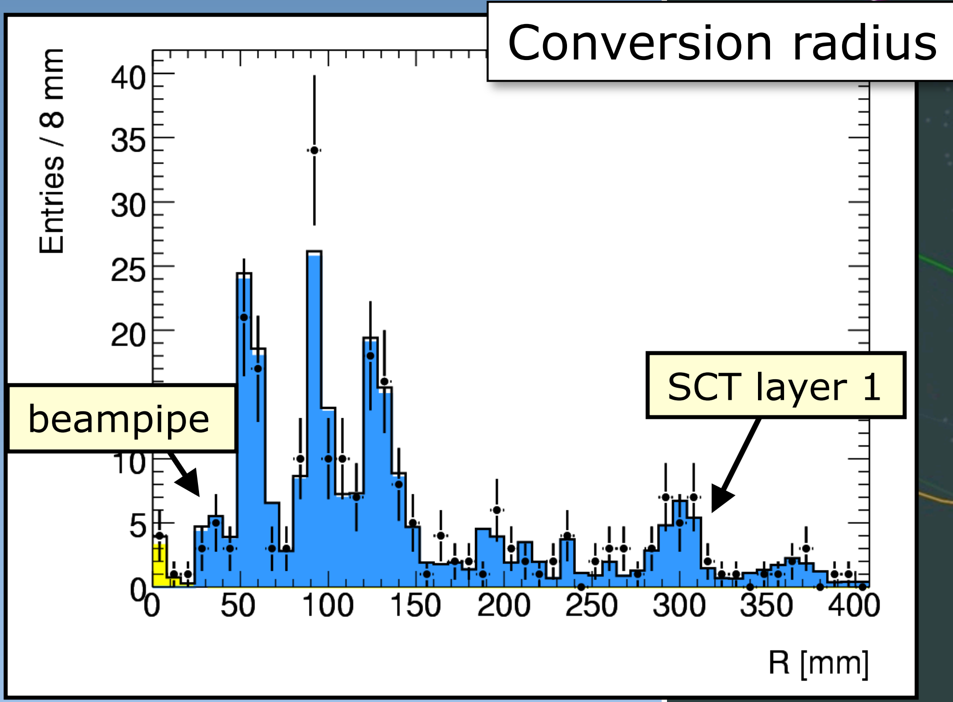
Difficulties in the 2-photon channel



Many topologies:	450 events in 10 categories
	S/B from 0.02 – 0.60
Excellent mass resolution:	1.2-2.4 GeV (1.7 GeV on average)
Backgrounds:	$\gamma\gamma$, γj, jj

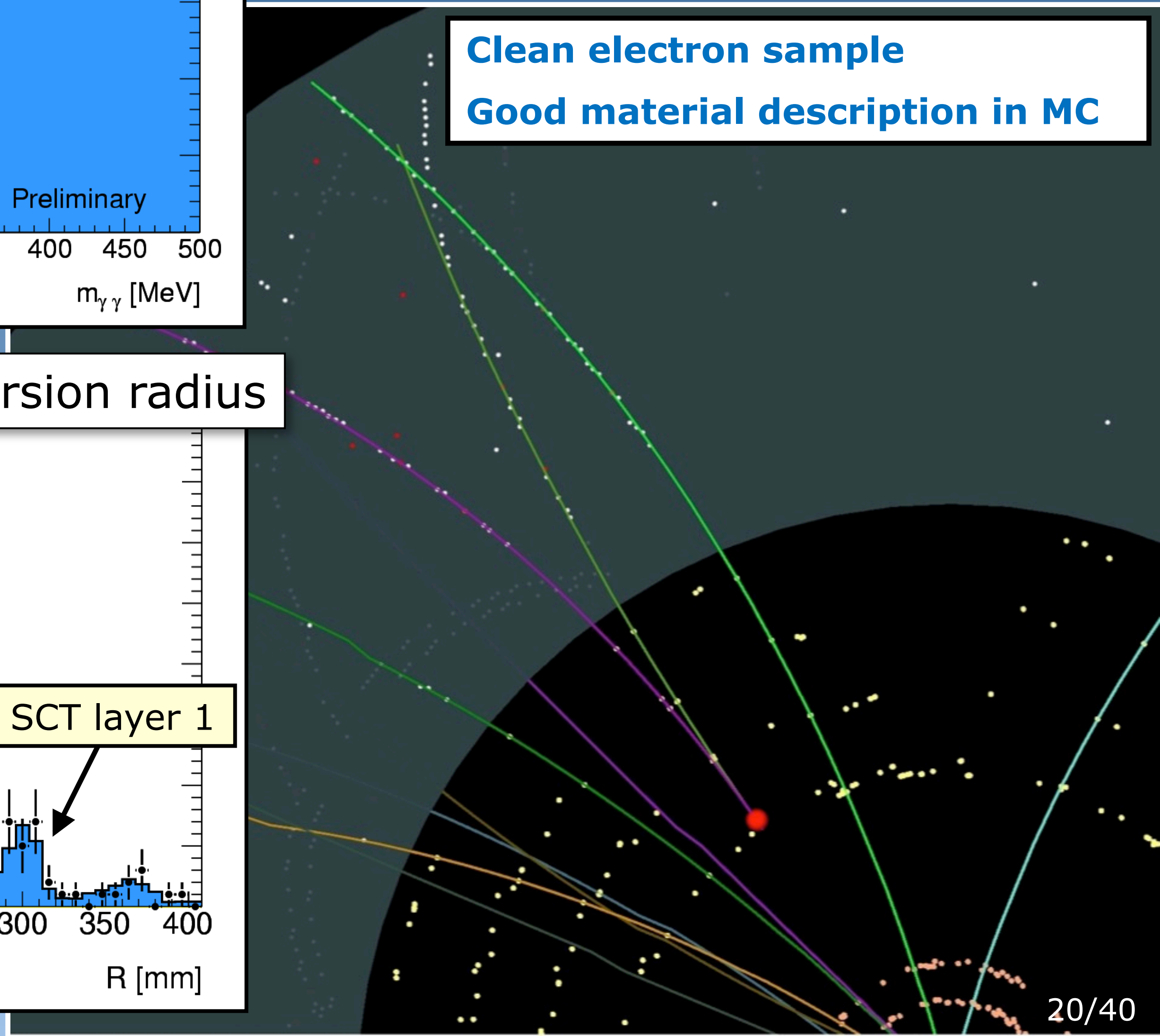
Photon conversions





Clean electron sample

Good material description in MC



2-photon channel

10 different categories:

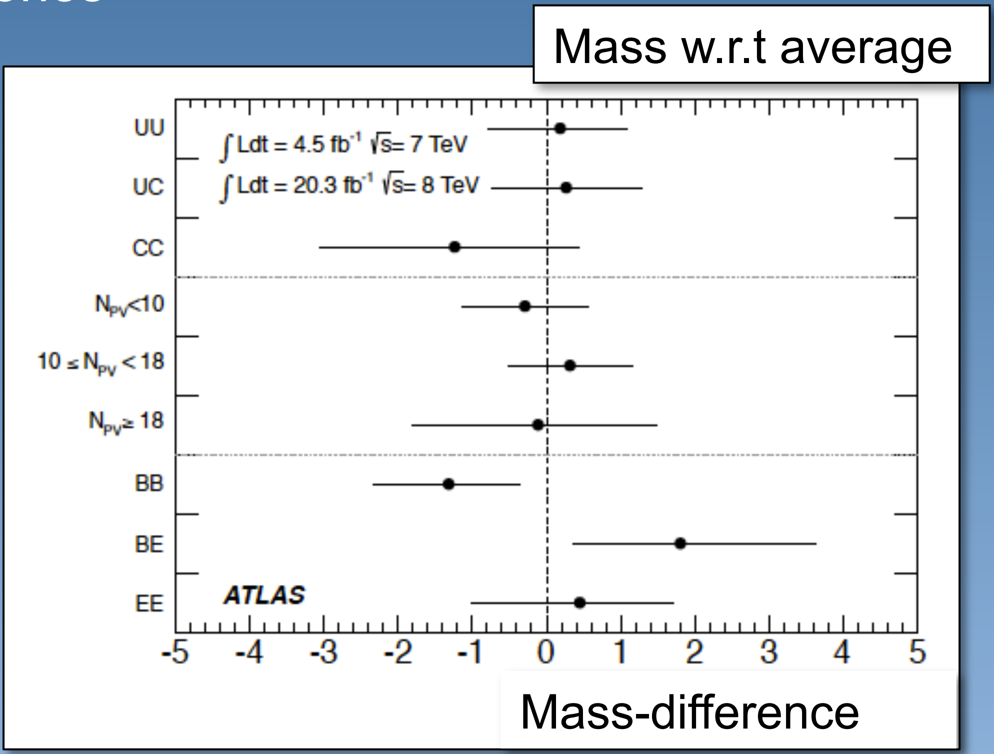
Category	n_{sig}	FWHM [GeV]	σ_{eff} [GeV]	b in $\pm\sigma_{eff90}$	s/b [%]	$s/\sqrt{b}$
			$\sqrt{s}$=8 TeV			
Inclusive	402.	3.69	1.67	10670	3.39	3.50
Unconv. central low p_{Tt}	59.3	3.13	1.35	801	6.66	1.88
Unconv. central high p_{Tt}	7.1	2.81	1.21	26.0	24.6	1.26
Unconv. rest low p_{Tt}	96.2	3.49	1.53	2624	3.30	1.69
Unconv. rest high p_{Tt}	10.4	3.11	1.36	93.9	9.95	0.96
Unconv. transition	26.0	4.24	1.86	910	2.57	0.78
Conv. central low p_{Tt}	37.2	3.47	1.52	589	5.69	1.38
Conv. central high p_{Tt}	4.5	3.07	1.35	20.9	19.4	0.88
Conv. rest low p_{Tt}	107.2	4.23	1.88	3834	2.52	1.56
Conv. rest high p_{Tt}	11.9	3.71	1.64	144.2	7.44	0.89
Conv. transition	42.1	5.31	2.41	1977	1.92	0.85

20% improvement statistical uncertainty by treating categories independently

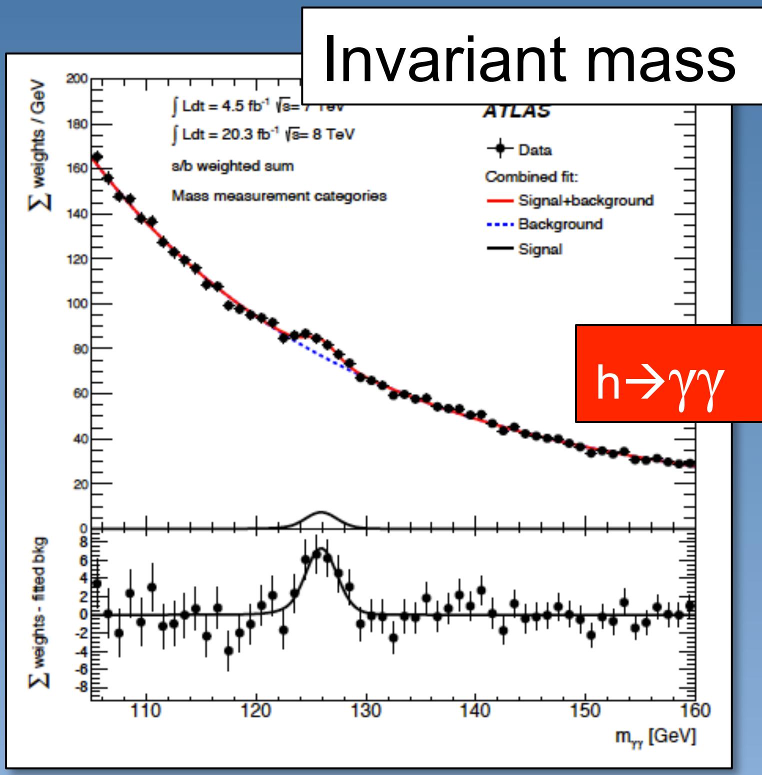
Systematics in 2-photon channel

Masses in each of these categories

Category	n_{sig}
Inclusive	402.
Unconv. central low p_{Tt}	59.3
Unconv. central high p_{Tt}	7.1
Unconv. rest low p_{Tt}	96.2
Unconv. rest high p_{Tt}	10.4
Unconv. transition	26.0
Conv. central low p_{Tt}	37.2
Conv. central high p_{Tt}	4.5
Conv. rest low p_{Tt}	107.2
Conv. rest high p_{Tt}	11.9
Conv. transition	42.1



Mass measurement in the 2-photon channel



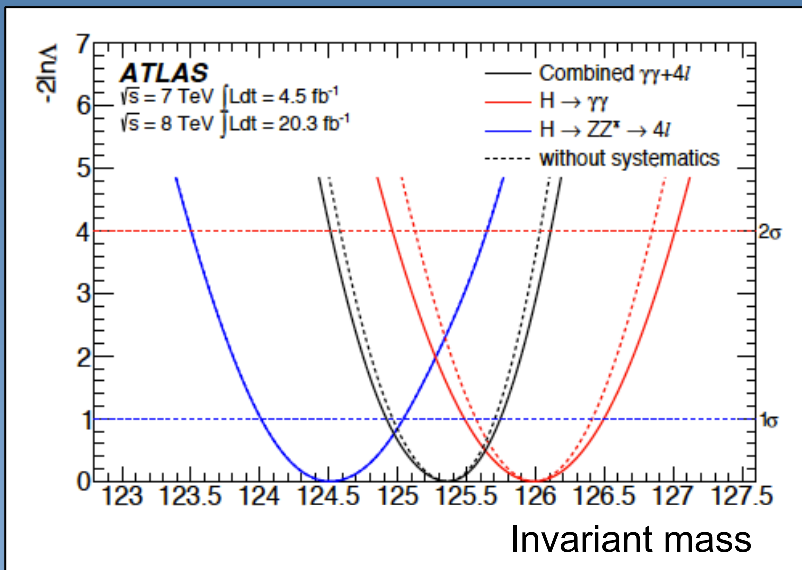
ATLAS experiment

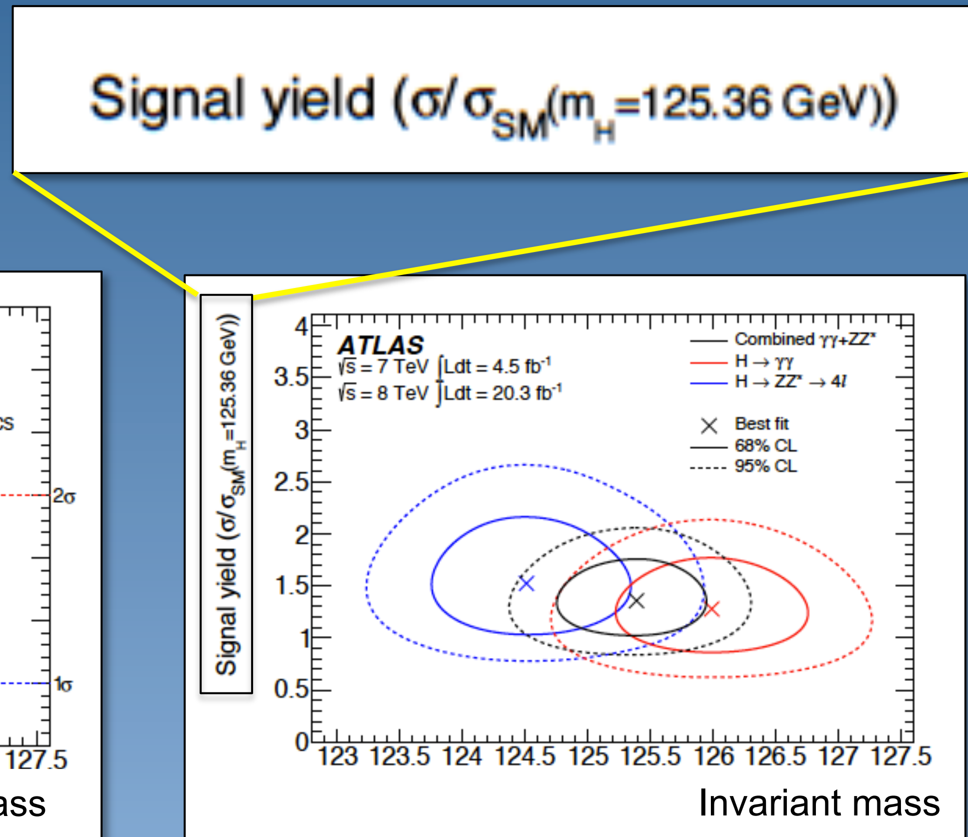
m_h = 125 .98 ± 0.50 GeV

$$\mu = 1.29 \pm 0.30$$

More events than expected and good mass measurement

Combined mass measurement



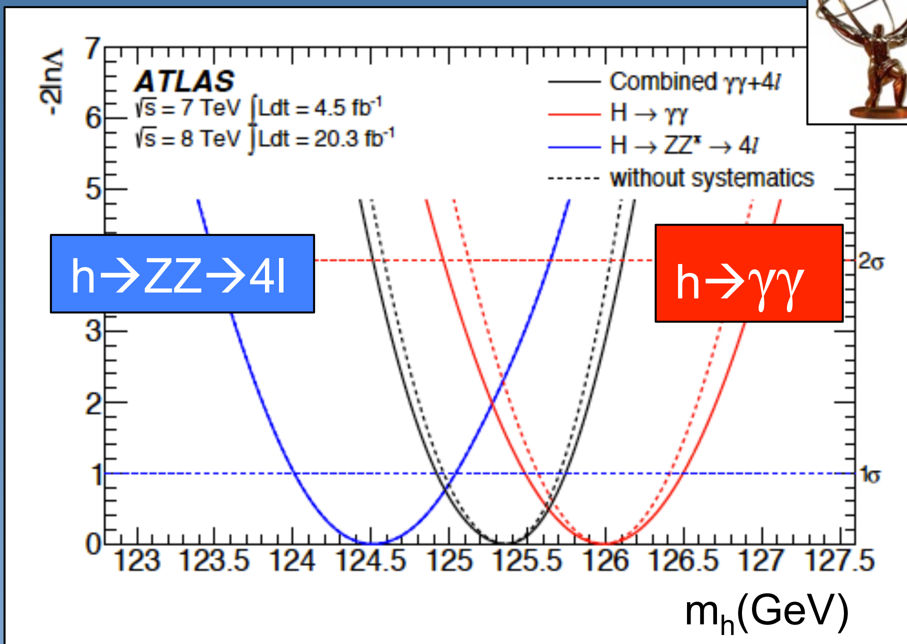


m_h = 124 .36 ± 0.37 (stat) ± 0.18(syst) GeV

m_h = 124 .36 ± 0.41

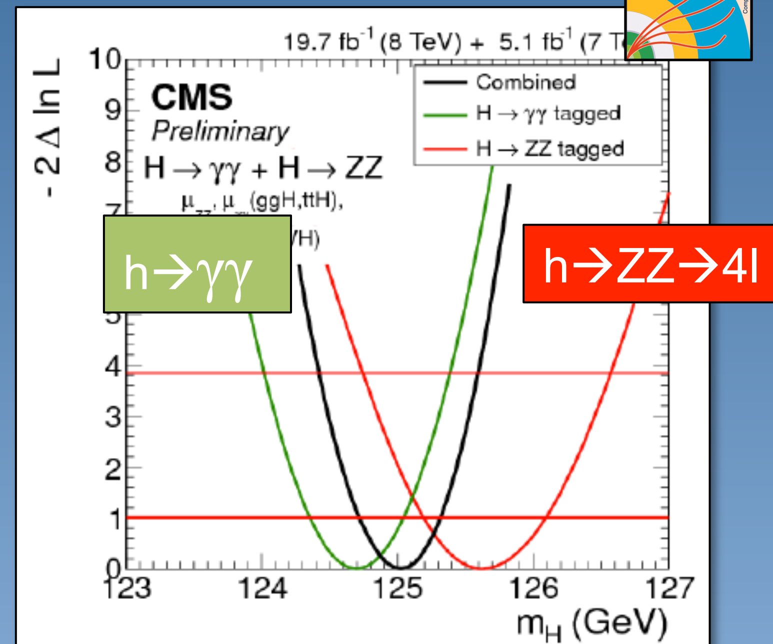
Combined mass measurement

ATLAS experiment

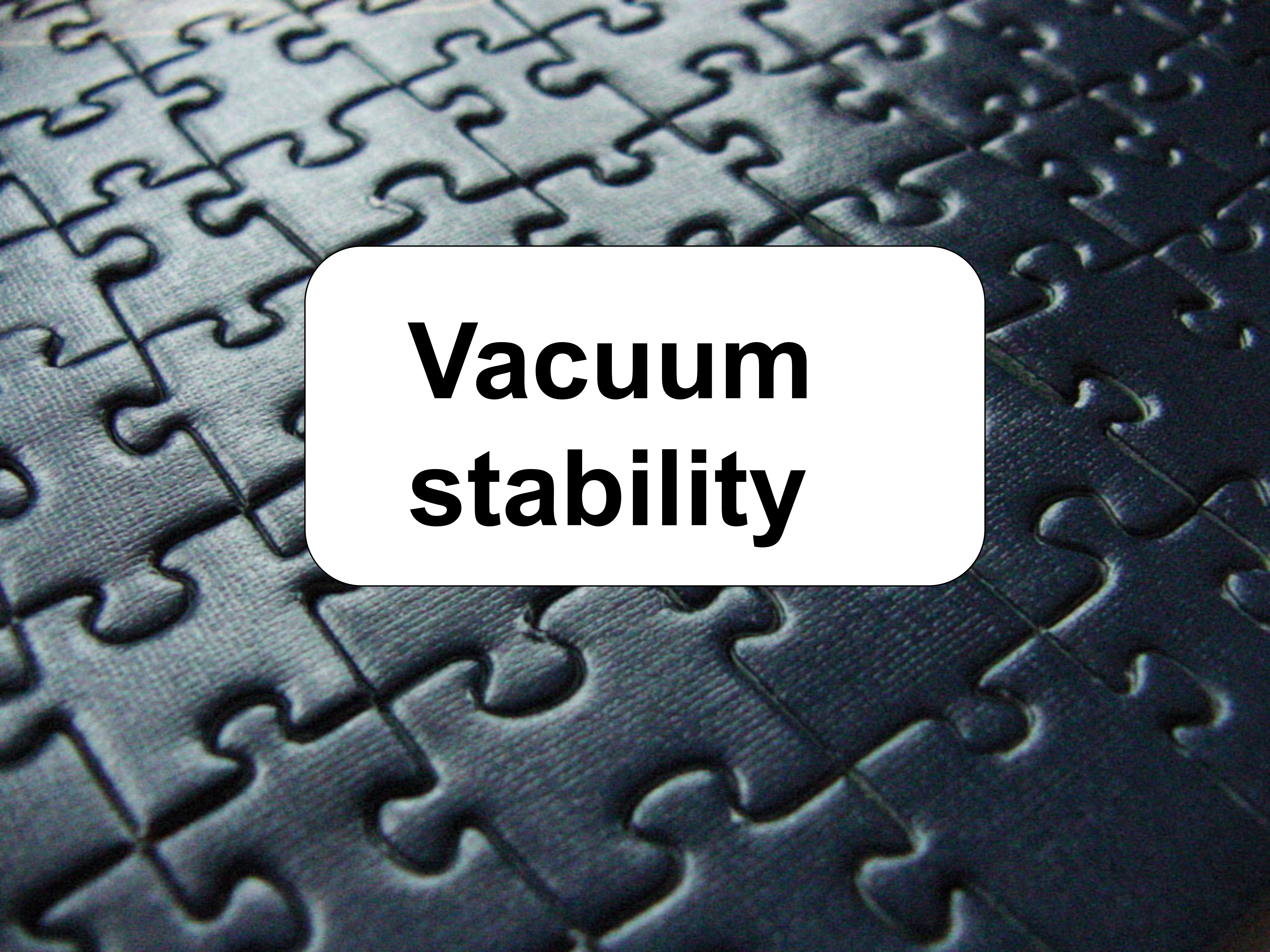


$$m_h = 125.36 \pm 0.37(stat) \pm 0.18(syst)$$

CMS experiment



$$m_h = 125.03 \,^{+0.26}_{-0.27}(stat)\,^{+0.13}_{-0.15}(syst)$$


Vacuum
stability

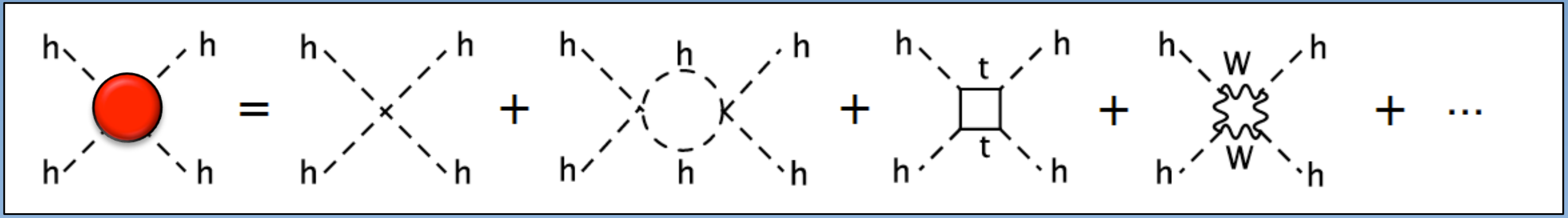
Theoretical implications of particular Higgs mass

$$\frac{d\lambda}{dt} = \beta_\lambda, \text{ with } t = \ln(Q^2)$$

Relates strength λ(Λ) with that at λ(v)

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - 24 y_t^4 + \frac{3}{8} g'^4 + \frac{3}{4} g'^2 g^2 + \frac{9}{8} g^4 - \lambda(3g'^2 + 9g^2 - 24 y_t^2) + \ldots$$

blackboard



2 regimes: $\lambda >> g, g', y_t$ and $\lambda << g, g', y_t$

triviality

vacuum stability

Triviality

regime where $\lambda \gg g, g', y_t$ → upper bound on m_h

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - 24y_t^4 + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - \lambda(3g'^2 + 9g^2 - 24y_t^2) + \ldots$$

$$\frac{d\lambda}{dt} = \frac{3}{4\pi^2}\lambda^2 \quad \Rightarrow \quad \lambda(\Lambda) = \frac{\lambda(v)}{1 - \frac{3\lambda(v)}{4\pi^2}\ln\left(\frac{\Lambda^2}{v^2}\right)}$$

If Λ grows, also λ(Λ) grows. For every λ(v) there is a Λ, Landau pole, for which λ(Λ) = ∞

$$\Lambda = v e^{2\pi^2 / 3\lambda(v)}$$

Consequenses:

If you want λ to be finite (or <1) up to some scale Λ, then this puts a maximum value for λ(v), or m_h

$$m_h = \sqrt{-2\lambda(v) v^2}$$

$$m_h < \sqrt{\frac{8\pi^2 v^2}{3\ln\left(\frac{\Lambda^2}{v^2}\right)}}$$

Vacuum stability

regime where $\lambda \ll g, g', y_t$ → lower bound on m_h

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - 24 y_t^4 + \frac{3}{8} g'^4 + \frac{3}{4} g'^2 g^2 + \frac{9}{8} g^4 - \lambda(3g'^2 + 9g^2 - 24 y_t^2) + \dots$$

$$\frac{d\lambda}{dt} = -\frac{3}{4\pi^2} y_t^4 \quad \Rightarrow \quad \lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^4 \ln\left(\frac{\Lambda^2}{v^2}\right)$$

If Λ grows, λ(Λ) gets smaller

… and eventually becomes negative

blackboard

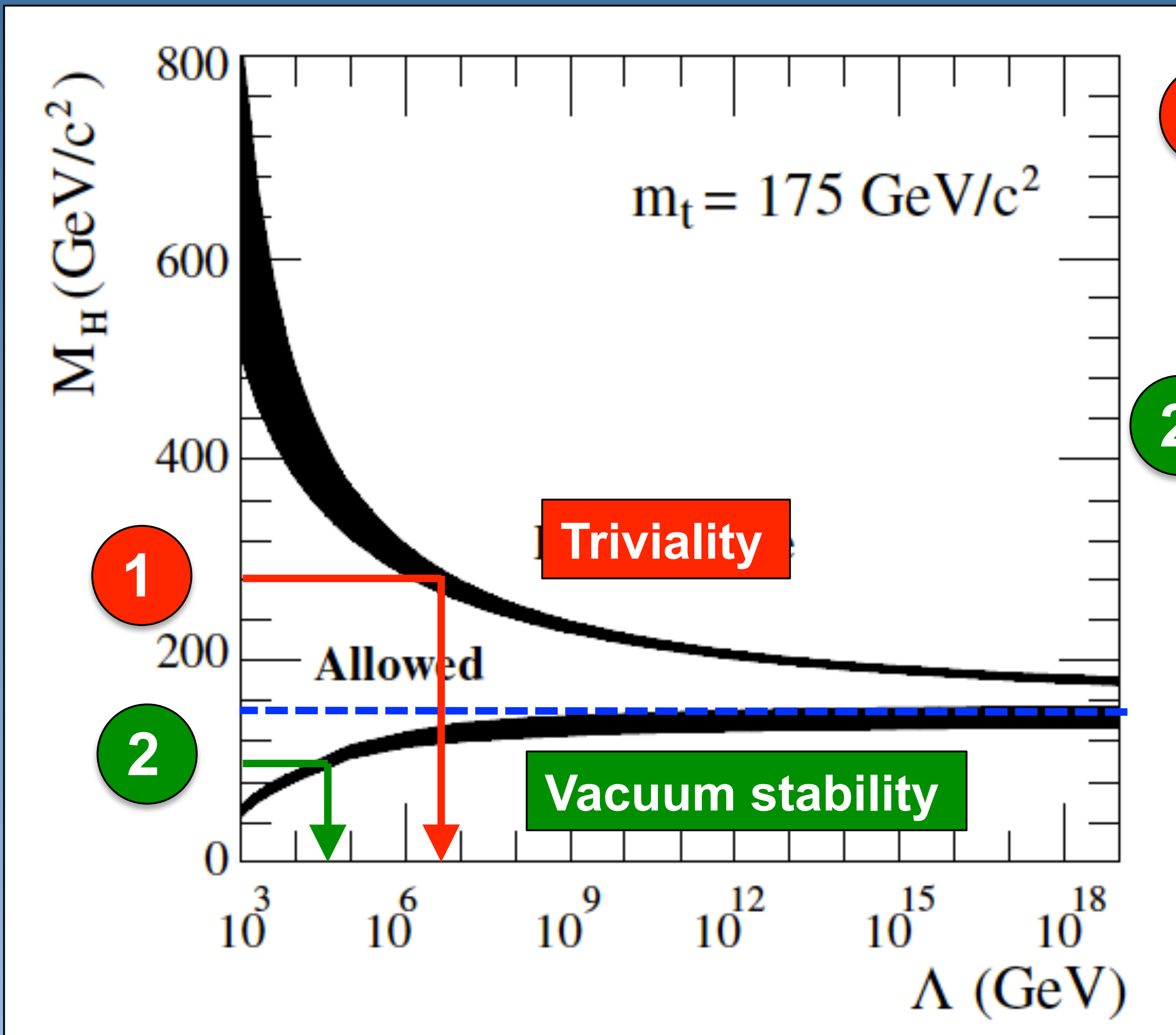
Consequences:

If you want λ to remain positive up to some scale Λ, then this puts a minimum value for λ(v).

This means a lower limit on m_h as $m_h = \sqrt{-2\lambda(v) v^2}$

$$m_h > \sqrt{\frac{3v^2}{2\pi^2} y_t^4 \ln\left(\frac{\Lambda^2}{v^2}\right)}$$

Theoretical limits on the Higgs boson mass

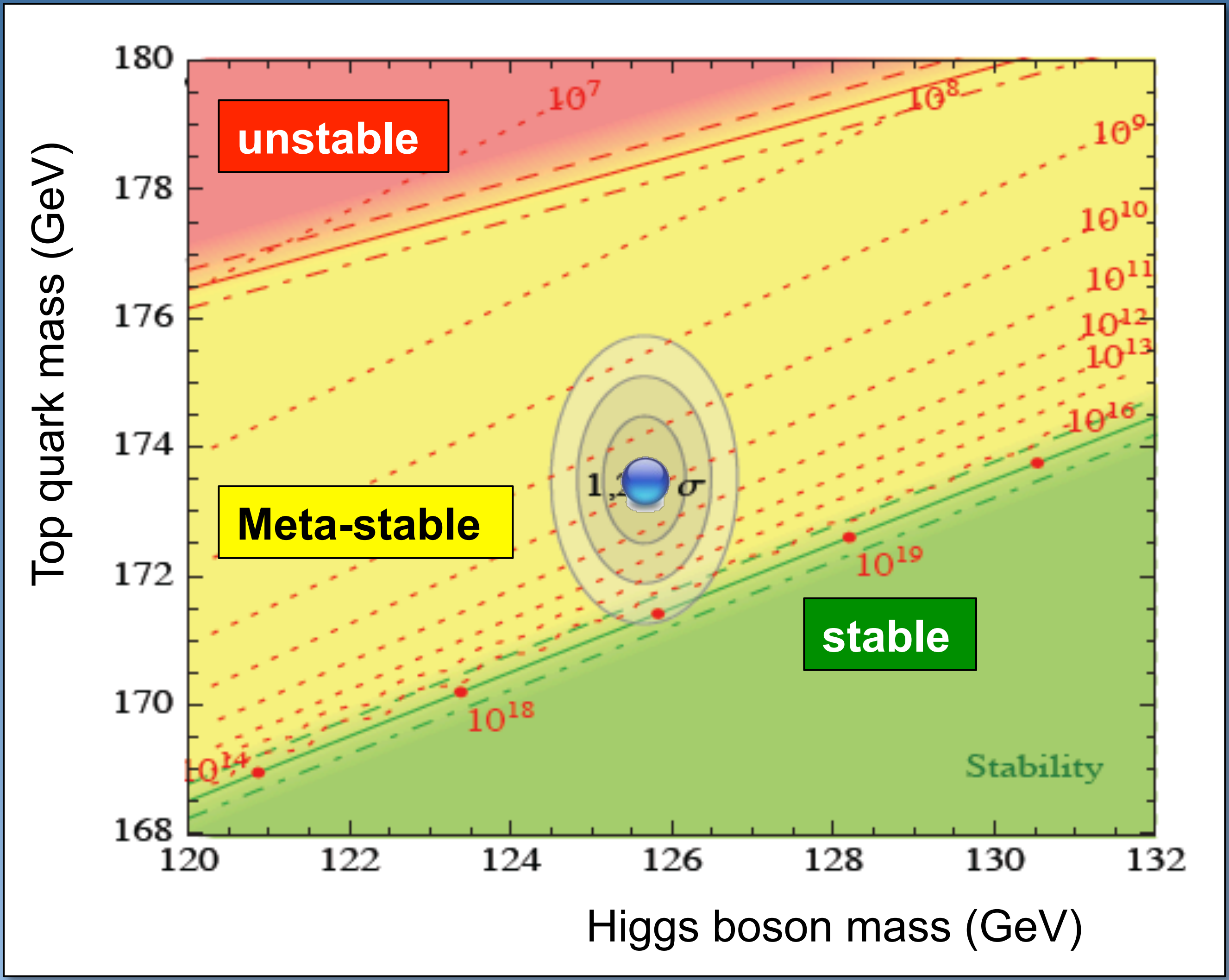


1 Heavy Higgs boson
→ new physics
before M_{planck}

2 Light Higgs boson
→ new physics
before M_{planck}

LHC data

Stability of the vacuum

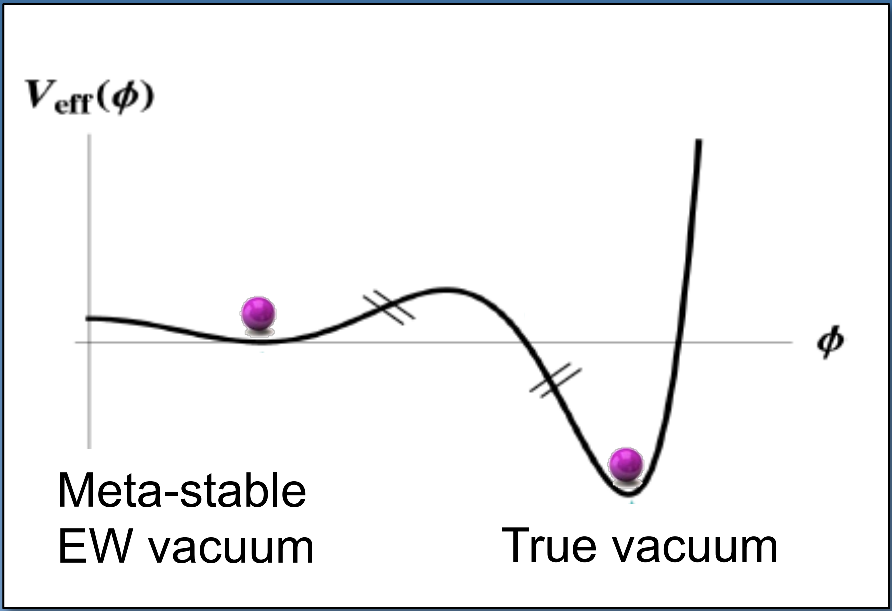


Branchia ICHEP

Stability of the vacuum: meta-stability

New physics at the Planck scale:
2 higher dimensional operators

$$V(\phi) \;=\; \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

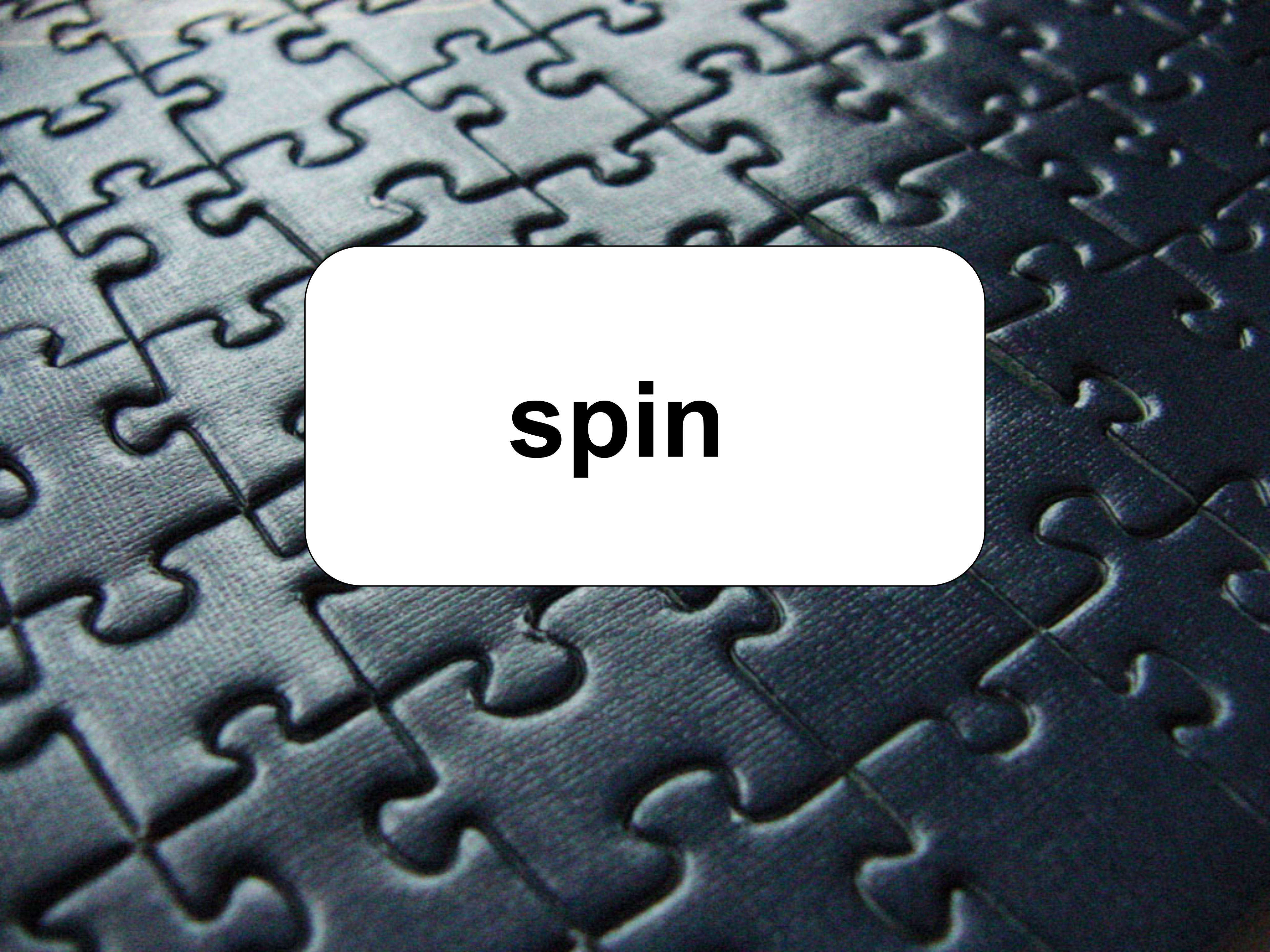


Tunneling time:
EW to true vacuum

$$\Gamma = \frac{1}{\tau} = T_U^3 \, \frac{S[\phi_b]^2}{4\pi^2} \left| \frac{\det'\left[-\partial^2 + V''(\phi_b)\right]}{\det\left[-\partial^2 + V''(v)\right]} \right|^{-1/2} e^{-S[\phi_b]}$$

Lifetime of the universe

Branchia ICHEP



spin

Higgs quantum numbers: spin and parity

Parity = +

Charge conjugation = +

Scalar spin=0

J^{PC}

Differences in each of these parameters lead to different event topologies

- Production angle for different production meachanisms
- Decay angles and event topologies for decay channels

Different scenario's for new particle X

2 vector bosons

scenario	production mode	X→VV decay	
0^+_m	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs scalar boson
0^+_h	$gg \to X$	$g_2^{(0)} \neq 0$	scalar higher-dim. op.
0^-	$gg \to X$	$g_4^{(0)} \neq 0$	pseudo-scalar
1^+	$q\bar{q} \to X$	$b_2 \neq 0$	exotic pseudo-vector
1^-	$q\bar{q} \to X$	$b_1 \neq 0$	exotic vector
2^+_m	$g_1^{(2)} \neq 0$	$g_1^{(2)} = g_5^{(2)} \neq 0$	RS graviton min. coupl.
2^+_h	$g_4^{(2)} \neq 0$	$g_4^{(2)} \neq 0$	tensor higher-dim. op.
2^-_h	$g_8^{(2)} \neq 0$	$g_8^{(2)} \neq 0$	"pseudo-tensor"

Structure of the matrix element

Write out most generic form of the matrix element. Can also contain CP-information

Spin 0 (qq production)

$$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2 \, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} \, q_1^\alpha q_2^\beta \right) \tilde{f}^{*(2),\mu\nu})$$

scalar pseudo-scalar

Spin 1 (qq production)

$$A(X \to V_1 V_2) = b_1 \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta$$

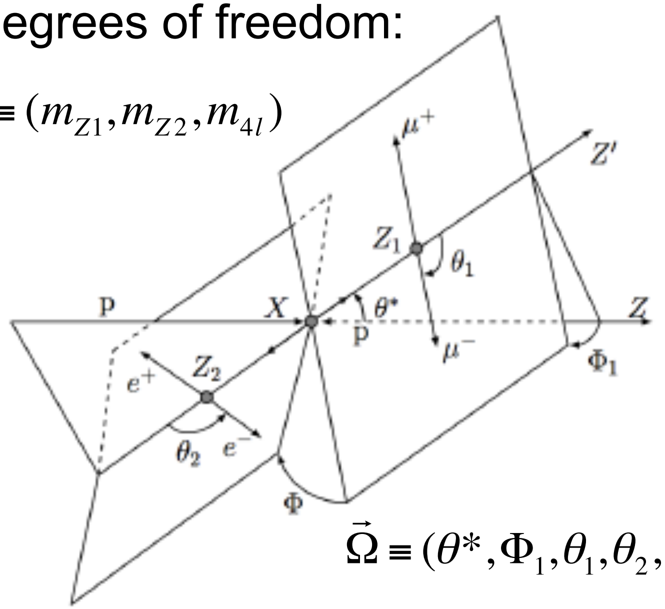
Spin 2 (gg and qq production)

$$\begin{aligned} A(X \to V_1 V_2) = \Lambda^{-1} \Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) \\ & + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\ & + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Big] \end{aligned}$$

4 lepton final state

8 degrees of freedom:

$$\vec{M} \equiv (m_{Z1}, m_{Z2}, m_{4l})$$



$$\vec{\Omega} \equiv (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$$

ϕ_1*: angle defined between the decay plane of the leading lepton pair and a plane defined by the vector of the Z_1 in the four lepton rest frame and the direction of the parton following the positive z-axis*

θ^* *production angle of the Z_1 defined in the 4 lepton rest frame*

Analysis strategy:

Build an 8-dimensional likelihood and fit for the anomalous couplings

CMS

Analysis strategy:

Train BDT on two hypotheses. Use likelihood ratio to test compatibilities

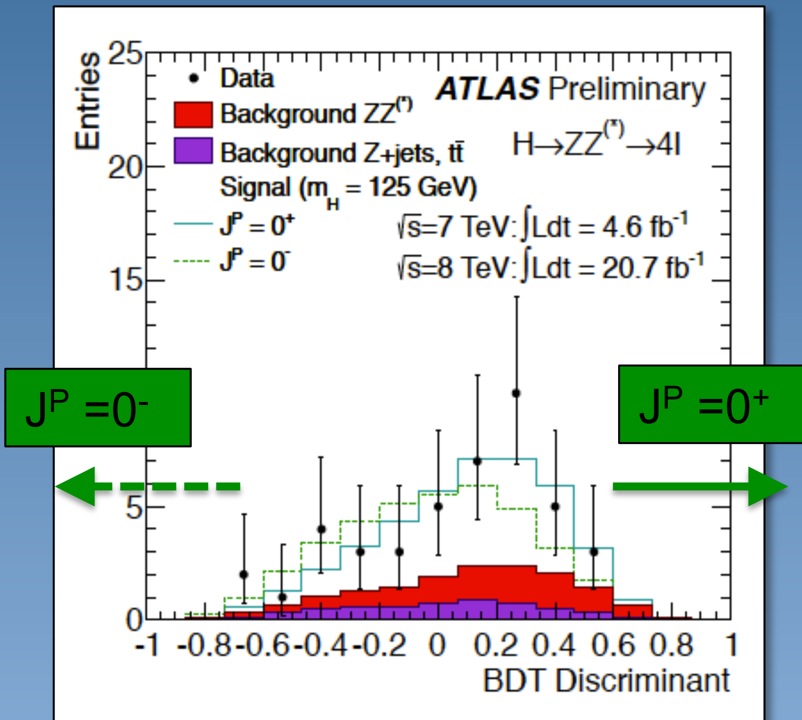
ATLAS

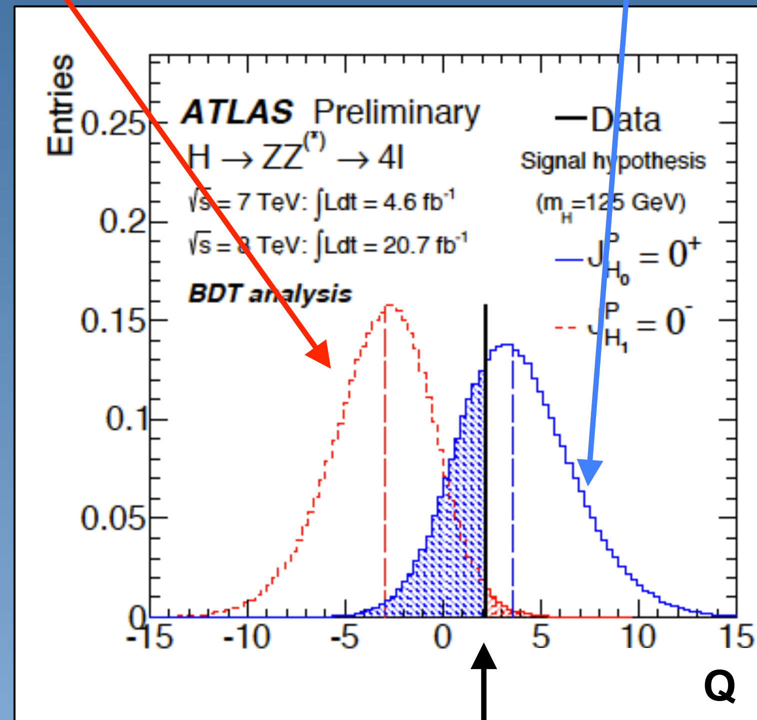
J^P in ZZ→4l

testing a 0^- hypothesis

distribution for Q for 100.000 0^- experiments

distribution for Q for 100.000 0^+ experiments





DATA

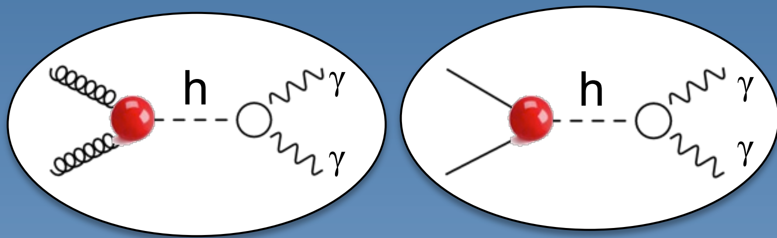
Small probability to originate from the 0^- hypothesis:

→ we exclude 0- hypothesis at 97.8% Confidence level

J^P: 2-photon channel

testing a spin-2 hypothesis

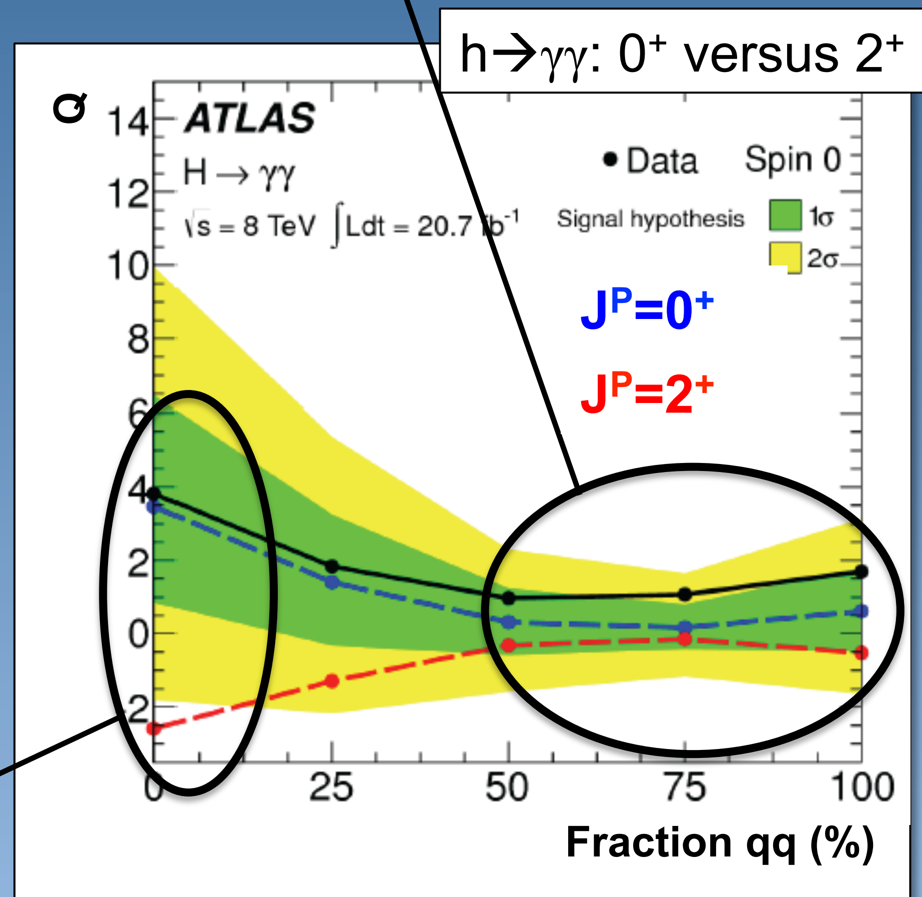
gluon-induced *quark-induced*



$$f_{qq} = \frac{\sigma(qq \to H)}{\sigma(qq \to H) + \sigma(gg \to H)}$$

dependence on production mode

Almost identical

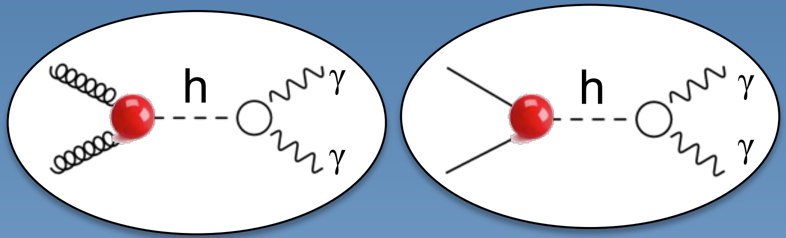


'clear' separation

CL_S	0.007	0.054	0.260	0.337	0.124

J^P: 2-photon channel

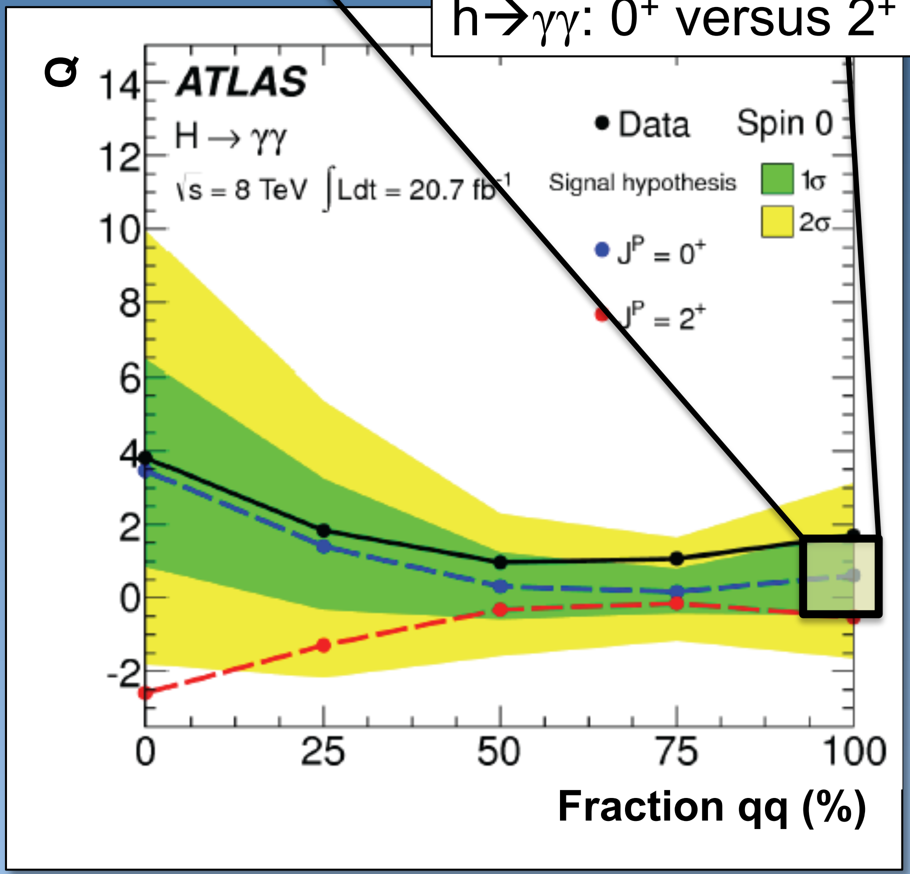
gluon-induced *quark-induced*



Stay critical

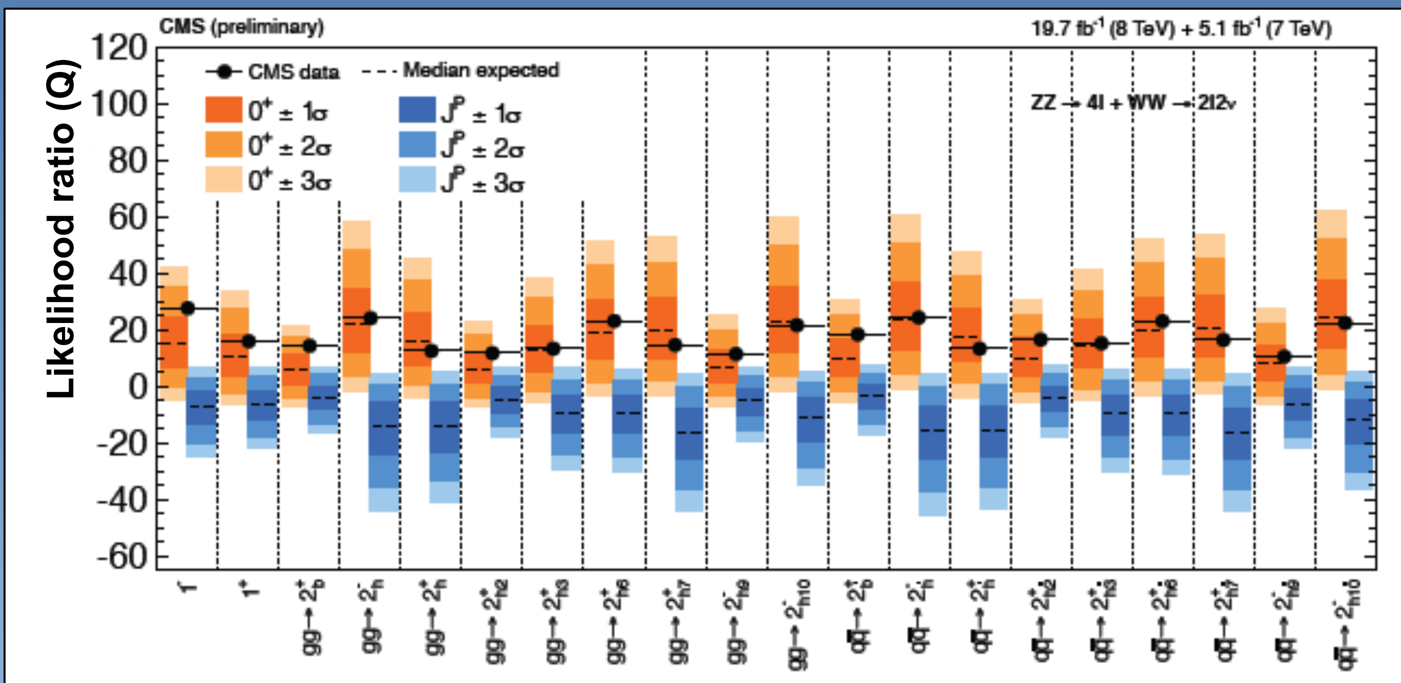
How can 2 spin-½ particles produce a spin-2 particle ?

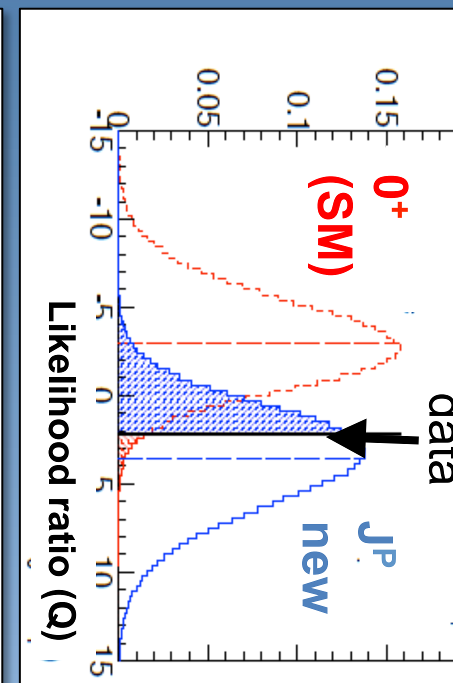
h→γγ: 0^+ versus 2^+



J^P: combination ZZ, WW and $\gamma\gamma$ channel

Sensitivity CMS experiment for alternative J^P hypotheses:





J=1,2: all models are excluded at more that 99.9% CL (WW+ZZ)

J^P: combination ZZ, WW and $\gamma\gamma$ channel

Exclusion levels for different scenario's:

$J^P = 2^+$: excluded at > 99.9% CL independent of f_{qq} (WW+ZZ+$\gamma\gamma$)

$J^P = 0^-$: excluded at > 97.8% CL (ZZ)

$J^P = 1^-$: excluded at > 99.73% CL (WW+ZZ)

$J^P = 1^+$: excluded at > 99.97% CL (WW+ZZ)

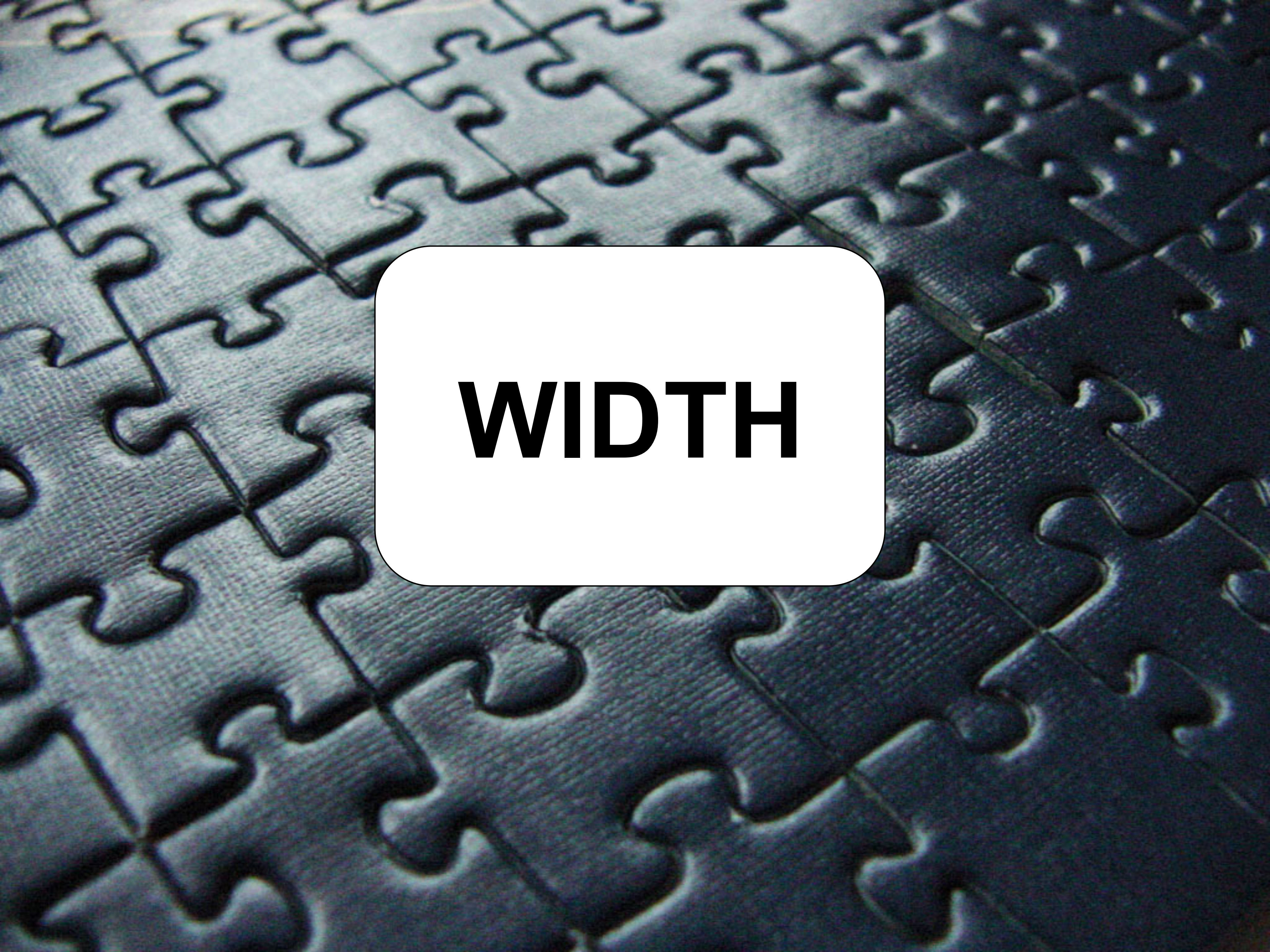
ATLAS

spin-1 excluded at ≥99.9% CL (WW+ZZ) and $\gamma\gamma$ observation (5.70σ)

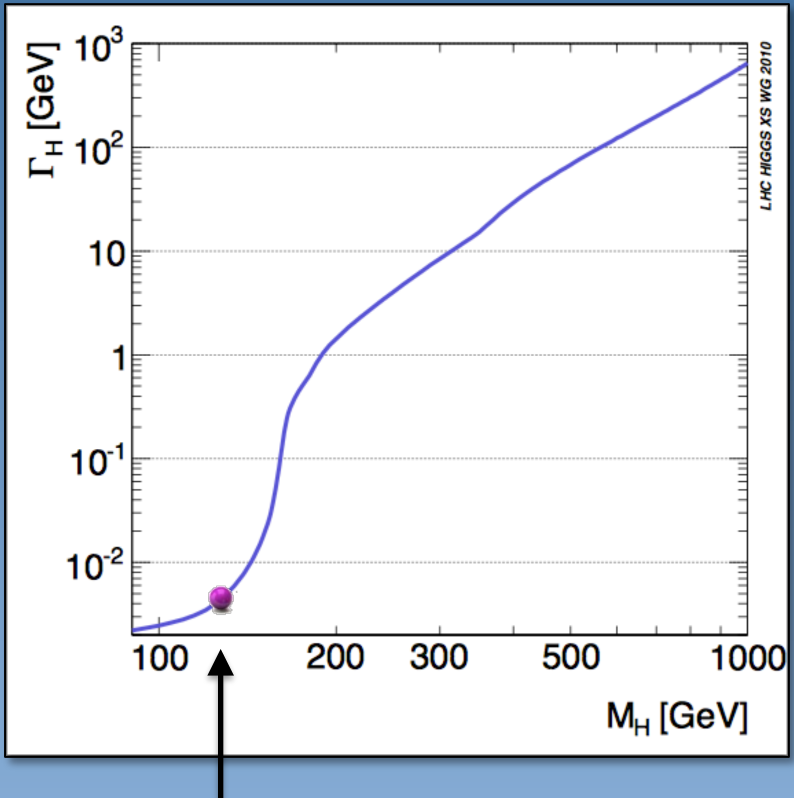
spin-2 excluded at ≥99.9% CL (WW+ZZ)

CMS

The quantum numbers of the Higgs boson seems to as predicted by the Standard Model: a spin-0 particle with positive parity


WIDTH

The width of the Higgs boson: Γ_H



m_h=125 GeV

Higgs boson:

Γ_H = 4.07 MeV

Gauge bosons:

Γ_Z = 2.495 GeV

Γ_W = 2.085 GeV

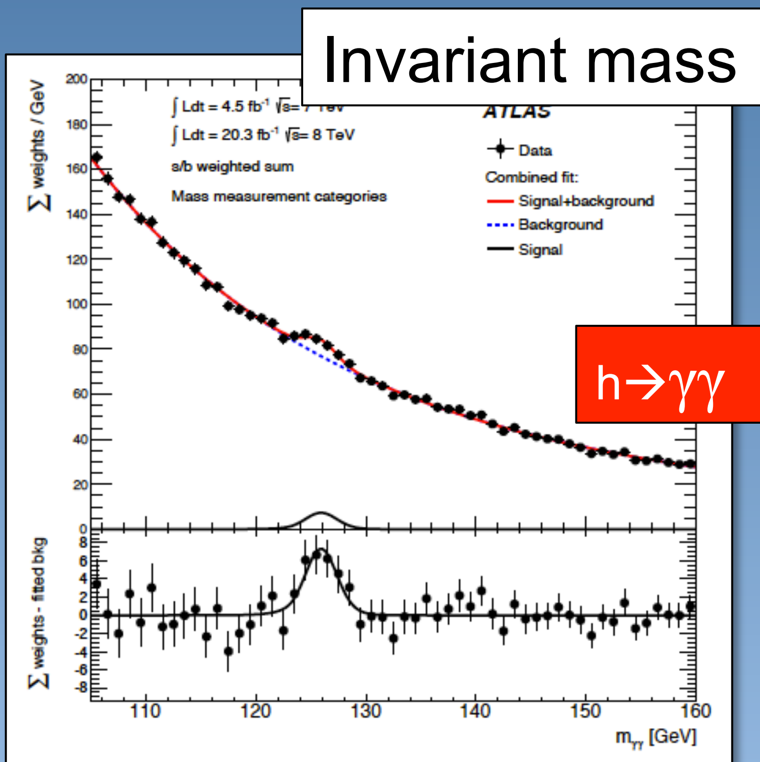
Importance of the width:

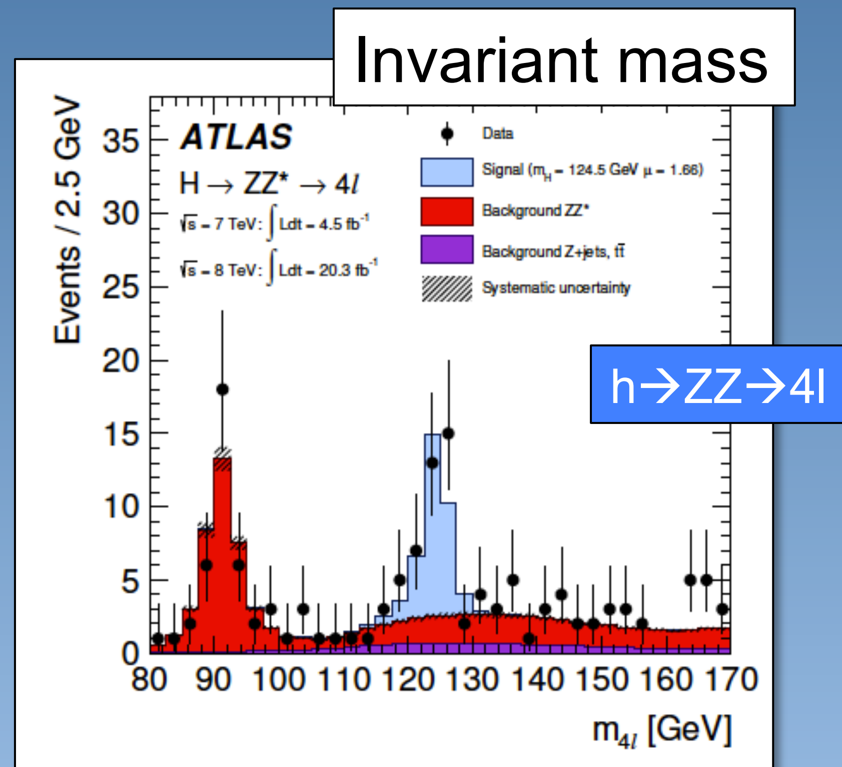
- BR into non-SM particles
- Invisible decays
- Couplings different to SM

Estimate of Γ_H: direct

Mass distribution brings sensitivity to width of the Higgs boson

$$\sigma_{tot} = \sqrt{\sigma_{resol.}^2 + \Gamma_H^2} \longrightarrow \textit{resolution} \sim 400 \times \Gamma_H$$



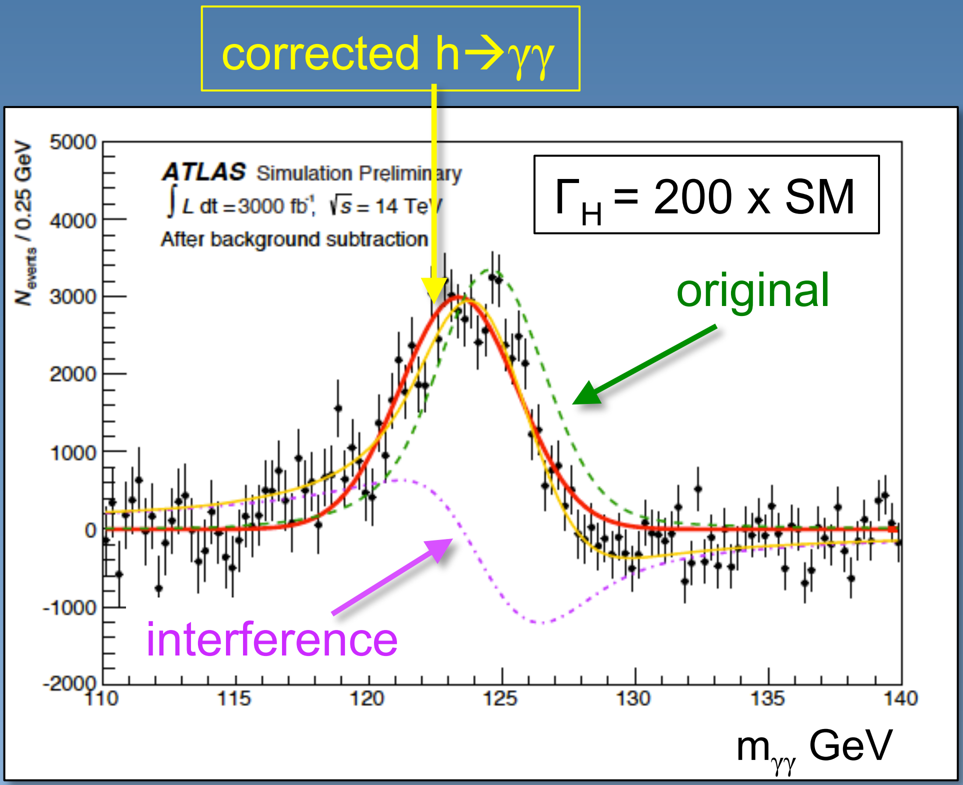


Γ_{4l}<2.6 (3.5) GeV

$\Gamma_{\gamma\gamma}$<5.0 (6.2) GeV

Estimate of Γ_H: subtle

Interference between the h→γγ and the γγ continuum (gg→γγ box diagram) induces a mass shift in the di-photon mass.



Look for:

- Difference between $m_{\gamma\gamma}$ and m_{ZZ}
- Mass shift only at low P_T

Ultimate sensitivity: L=3000 fb^{-1} → Γ_H=200 MeV (50 x Standard Model Γ_H)

Measurement of the off-shell signal strength

&

constraints on the Higgs boson width

Estimate of Γ_H: off-shell couplings

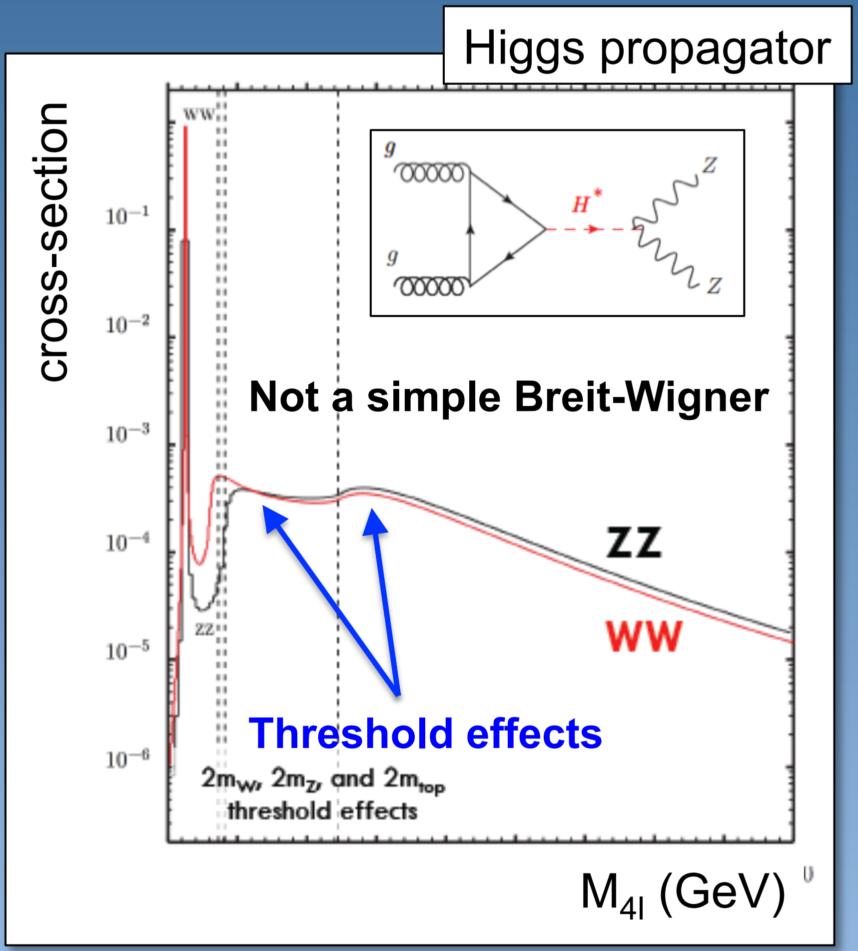
Higgs propagator

$$\frac{d\sigma_{gg\to h\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggh}g^2_{hZZ}}{\left(m^2_{ZZ}-m^2_h\right)^2+m^2_h\Gamma^2_h}$$

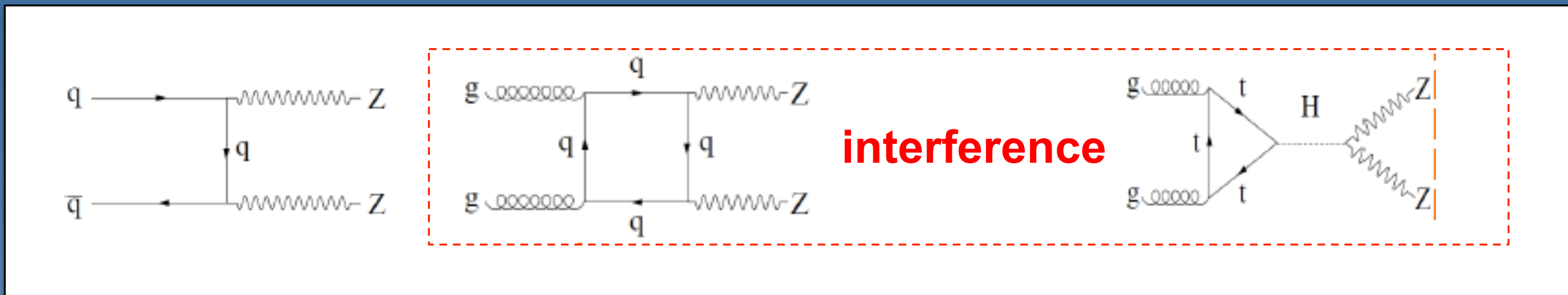
m_{ZZ}~m_h $$\sigma^{on-shell}_{g\to h\to ZZ} \sim \frac{g^2_{ggh}g^2_{hZZ}}{m_h\Gamma_h}$$

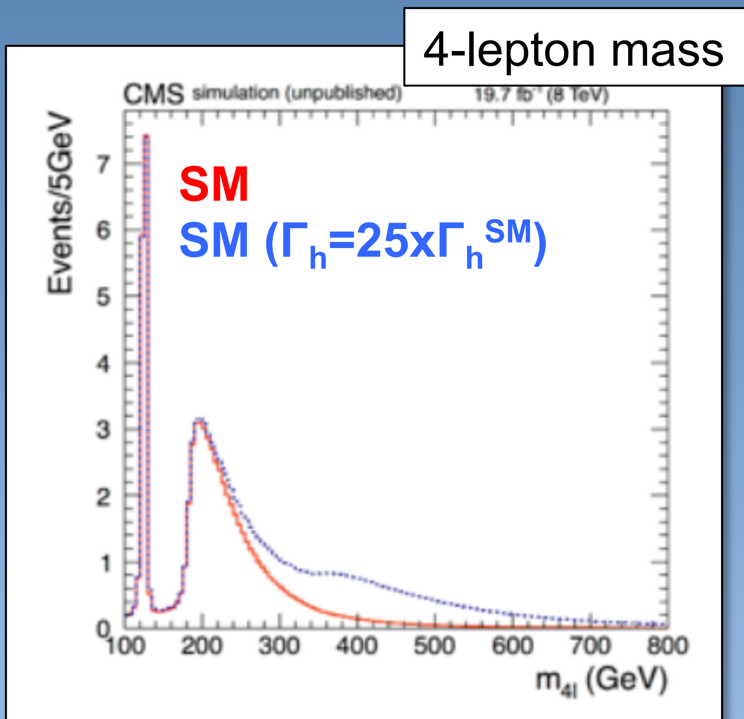
m_{ZZ}>>m_h $$\sigma^{off-shell}_{g\to h\to ZZ} \sim \frac{g^2_{ggh}g^2_{hZZ}}{\left(2m_Z\right)^2}$$

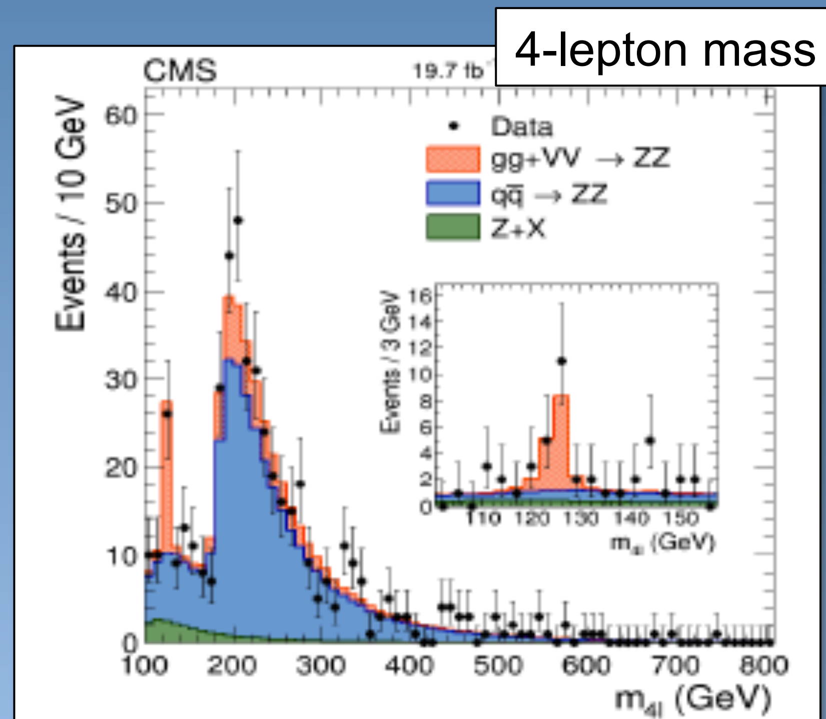
$$\frac{\sigma^{off-shell}_{g\to h\to ZZ}}{\sigma^{on-shell}_{g\to h\to ZZ}} \sim \Gamma_h$$



Estimate of Γ_H: off-shell couplings

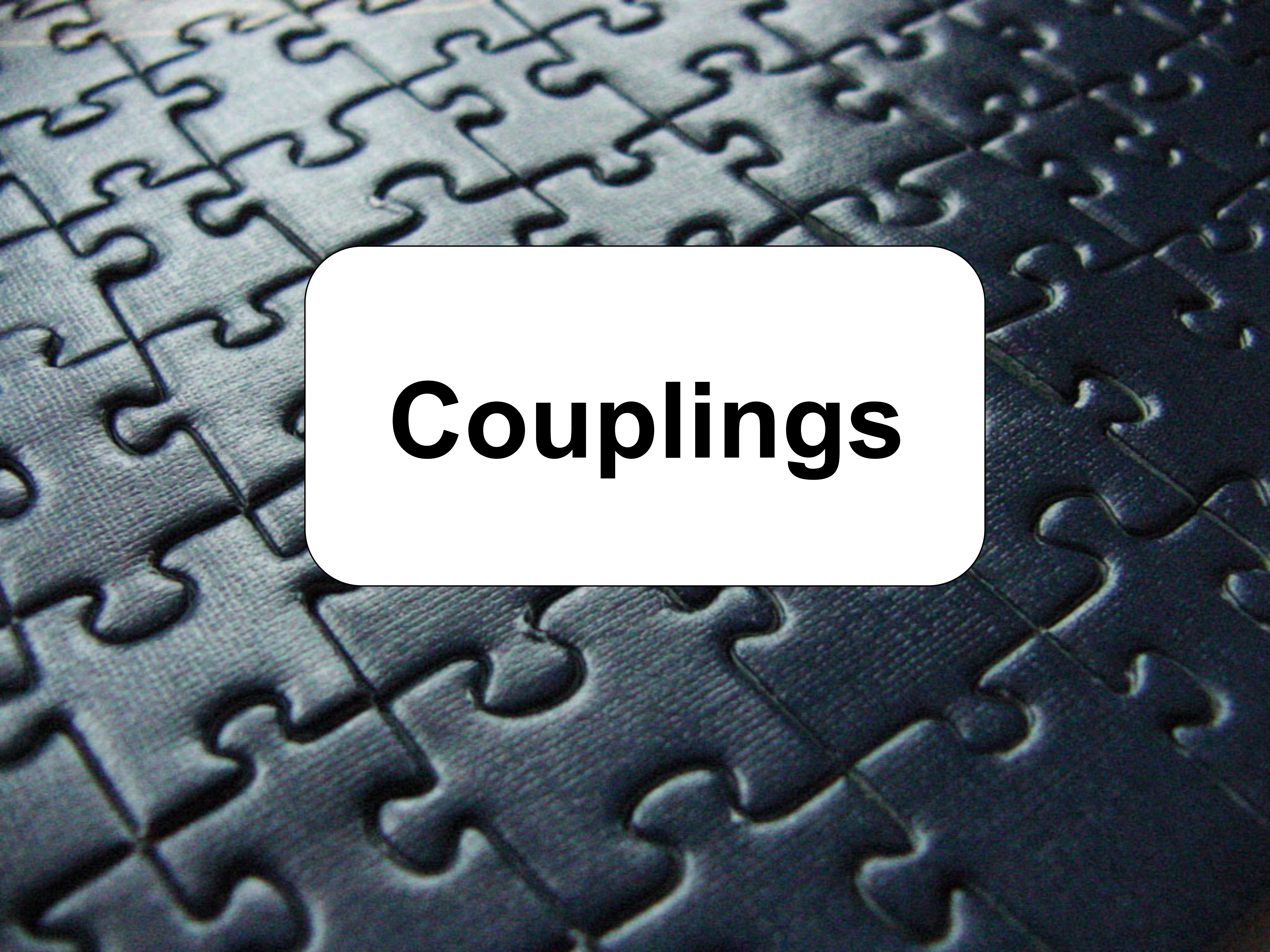






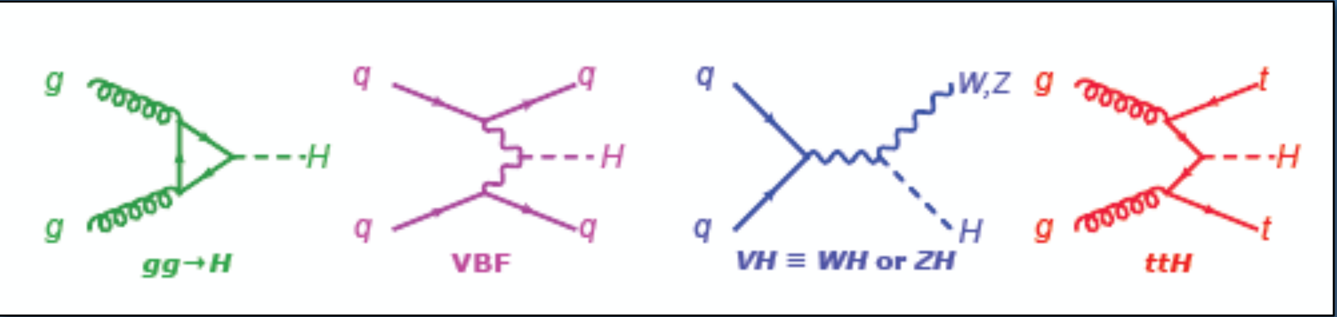
$\Gamma_h = 1.8^{+7.7}_{-1.8}$ MeV

$\Gamma_h < 22$ MeV at 95% CL



Couplings

Higgs production and decay

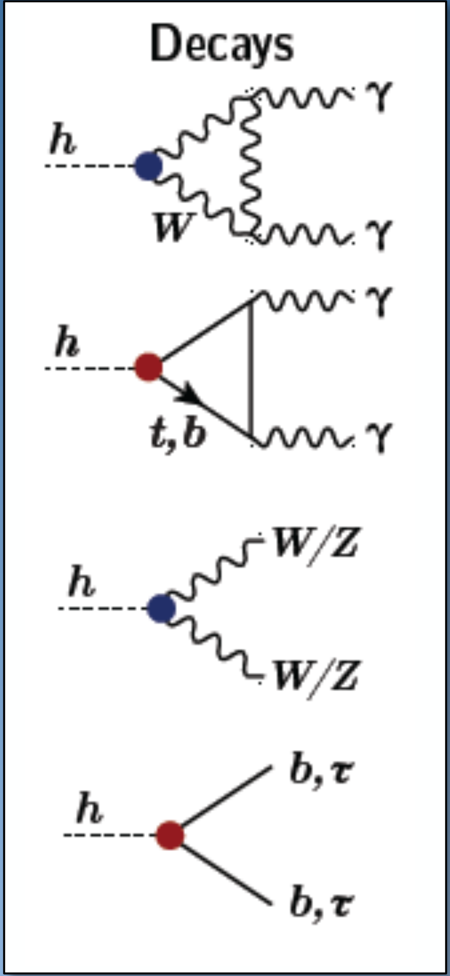


Is the Higgs boson behaving as it should:

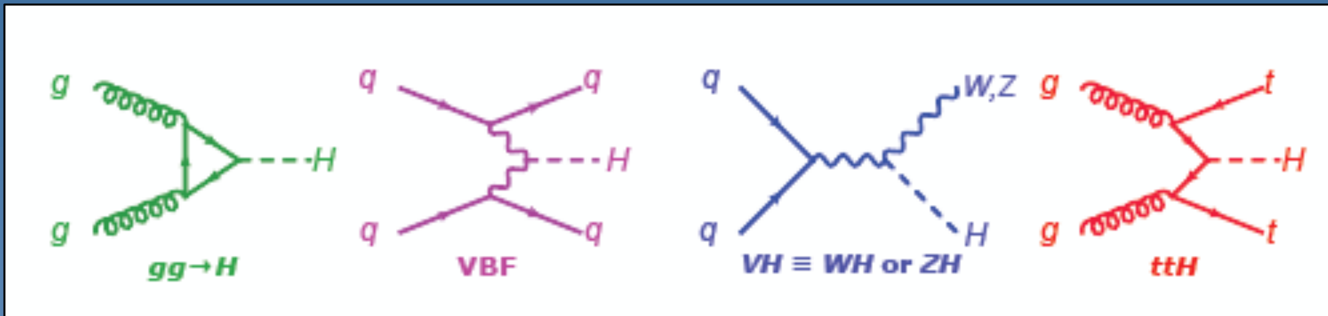
- do we see all production modes ?
- de we see all decay possibilities ?
- are they all in agreement with predictions ?

Note: rate differences wrt SM expressed as μ (ratio)

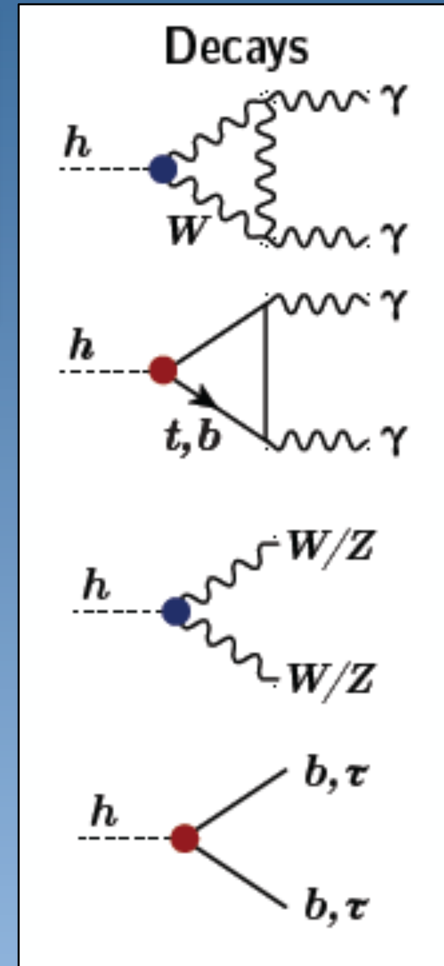
$$\mu = \frac{\sigma^{observed}}{\sigma^{SM}}$$



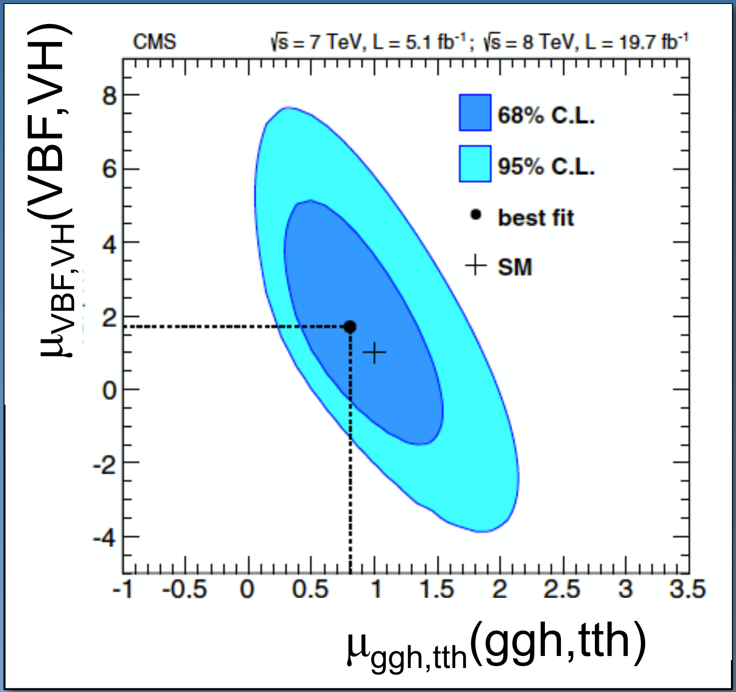
Higgs production and decay



Decay tag	incl.(ggH)	VBF tag	VH tag	ttH tag
H→ZZ	✔	✔		
H→γγ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
H→ττ	✔	✔	✔	✔
H→bb		✓	✔	✔
H→Zγ	✓	✓		
H→μμ	✓	✓		
H→inv.		✓	✓	



Disentangle production modes



$$\mu = 1.45^{+0.89}_{-0.62}$$

40-60% uncertainty

$$\mu = 0.83^{+0.31}_{-0.25}$$

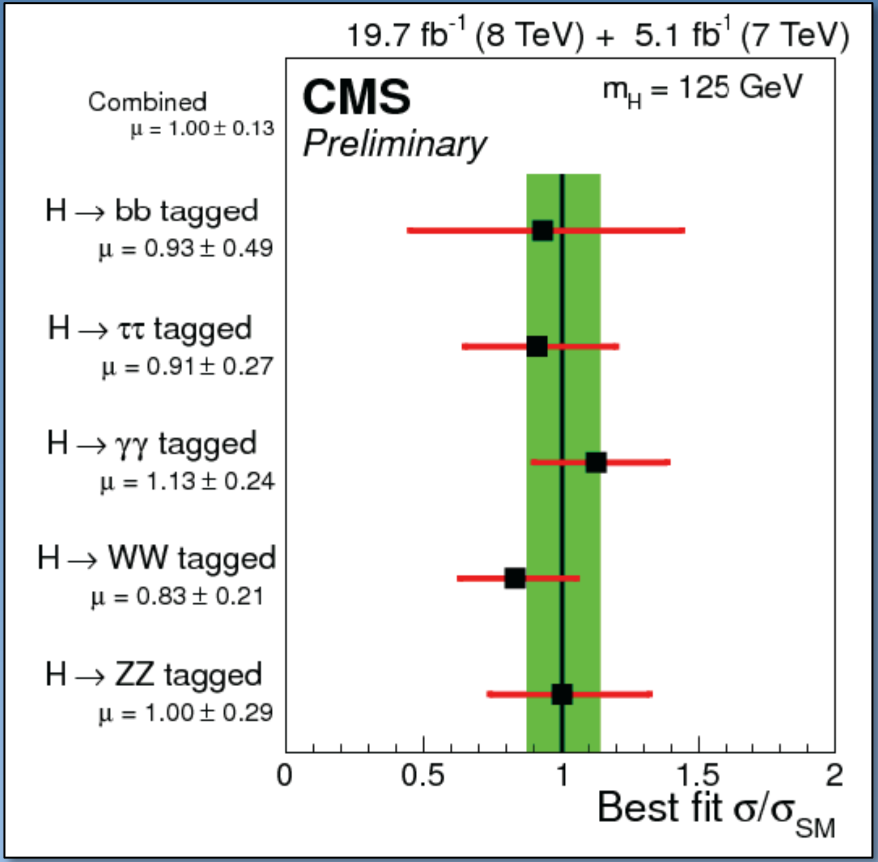
25-30% uncertainty

Exploit differences in topology (jets)

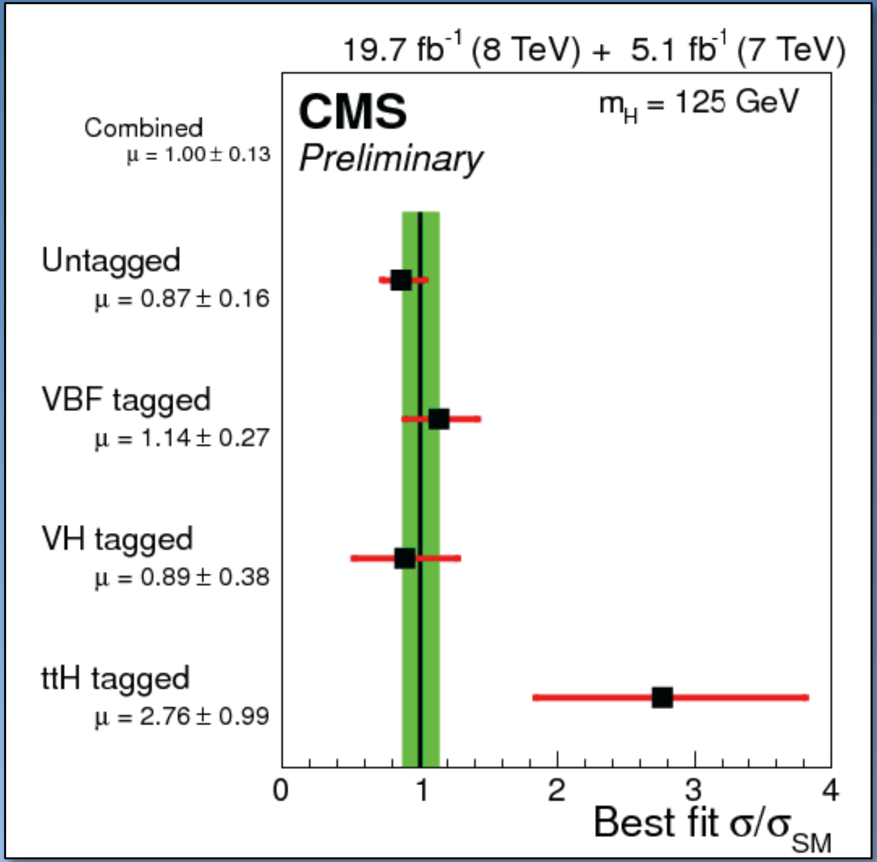
Decay tag	incl.(ggH)	VBF tag	VH tag	ttH tag
H→ZZ	✔	✔		
H→γγ	✔	✔	✔	✔

Rate measurement summary CMS experiment

decay modes

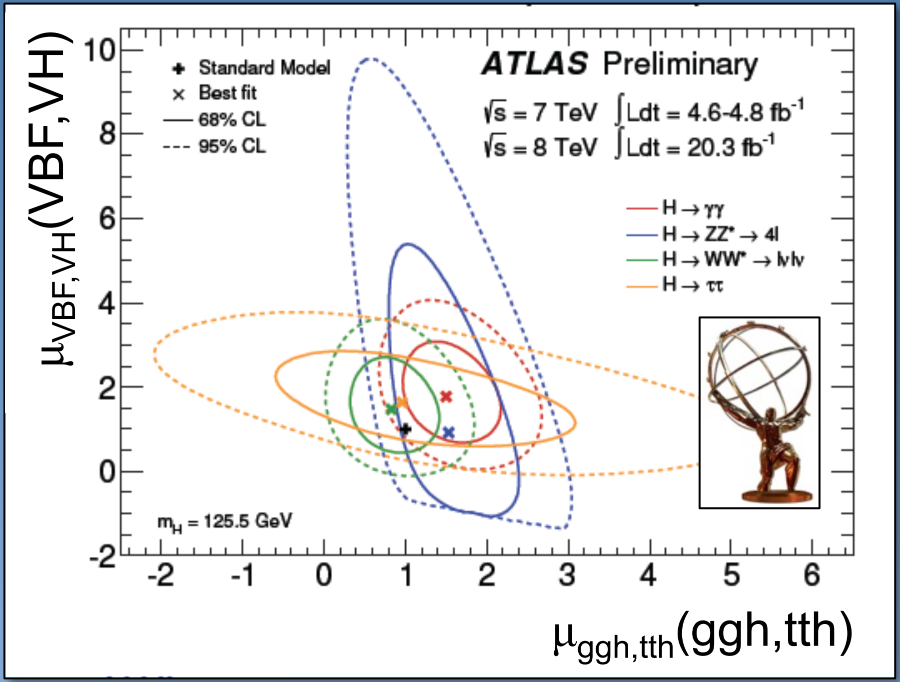


production modes

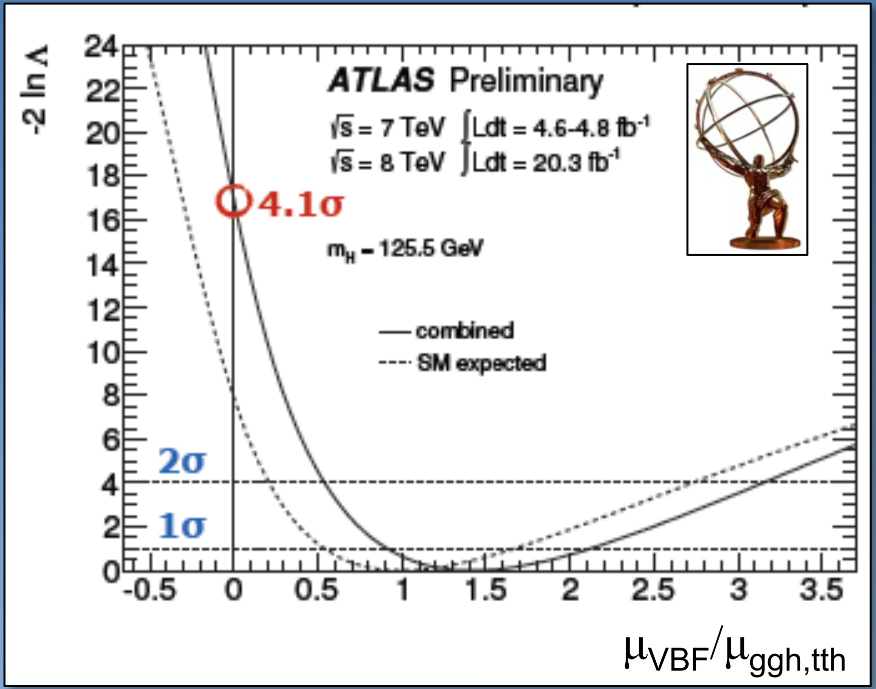


Proof of vector boson fusion

Production rate per production mode



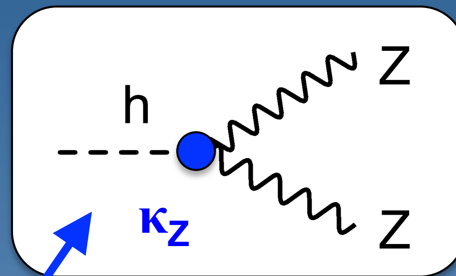
Is there proof for VBF production

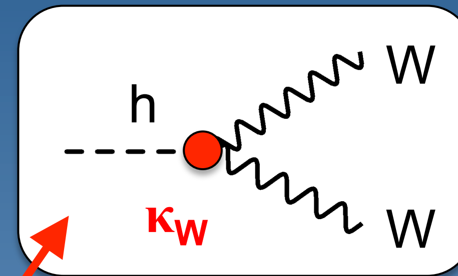


Evidence at 4.1 σ for VBF production

ATLAS	CMS
$\mu = 1.4^{+0.5+0.4}_{-0.4-0.3}$	$\mu = 1.25^{+0.63}_{-0.45}$

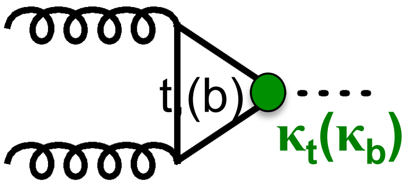
Effective Lagrangian



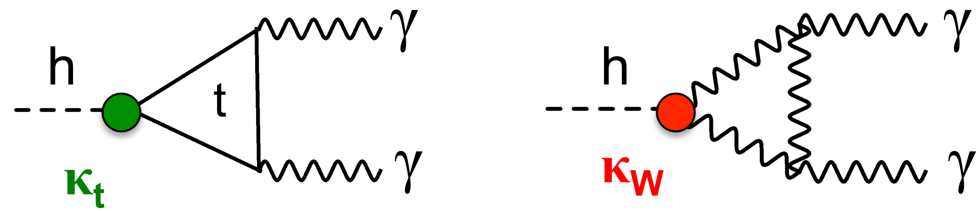


Use scale factors κ to parametrise deviations from SM (κ=1):

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$



$$\kappa_g^2 \propto 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$$



$$\kappa_\gamma^2 \propto 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
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Rates and relations are modified if non-SM particles enter in the loops

Parametrize production/decay processes:

Standard Model (narrow width approx):

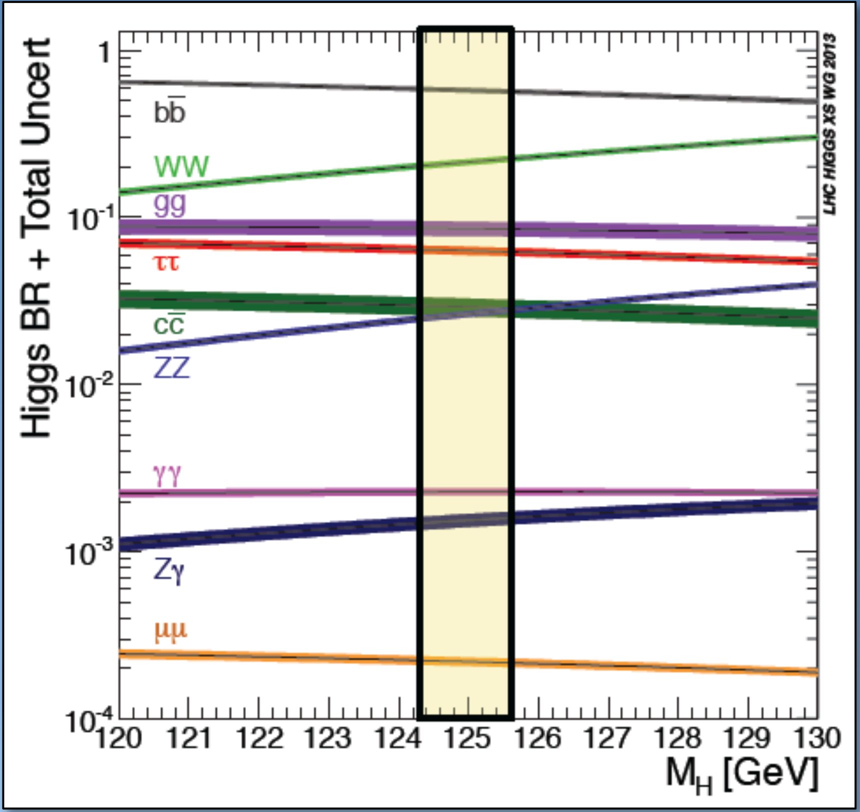
$$\sigma(gg \to h) \times Br(h \to \gamma\gamma) = \frac{\sigma_{ggF}\Gamma(h \to \gamma\gamma)}{\Gamma_H}$$

General:

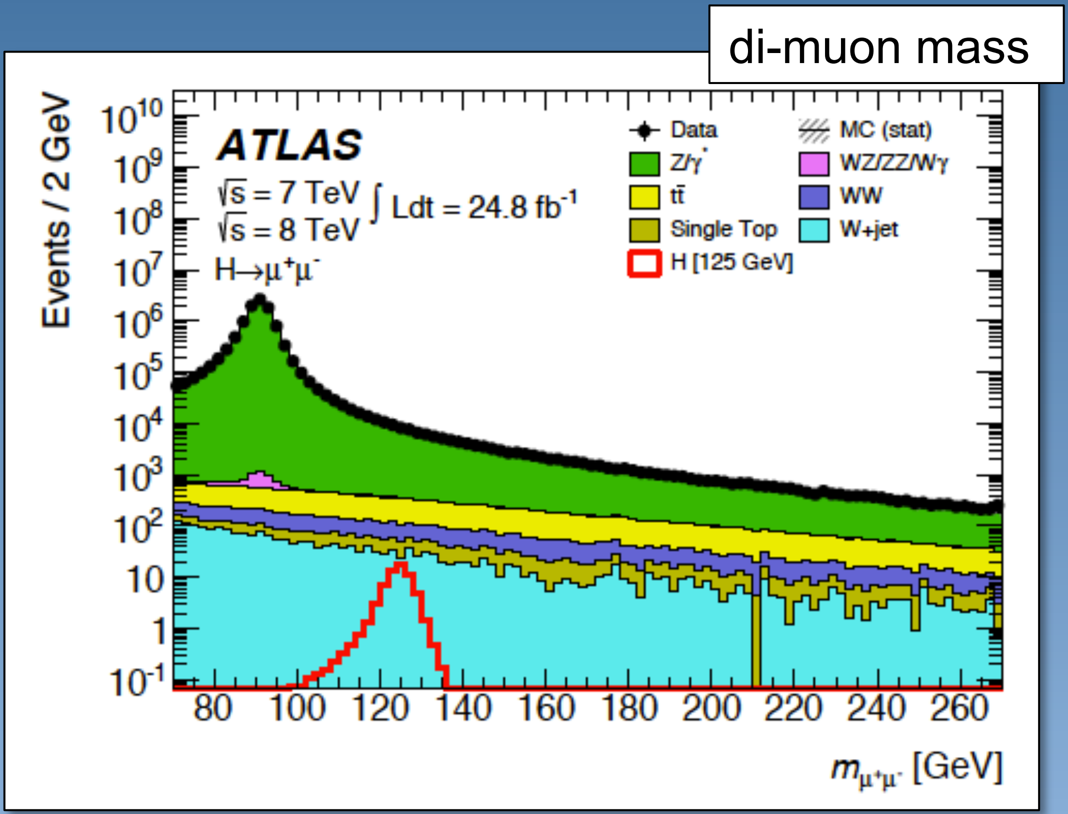
$$SM \times \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

m_h=125 GeV

bb	57.7%	$\Gamma_{b\bar{b}} / \Gamma_{b\bar{b}}^{SM} = \kappa_b^2$
WW	21.5%	$\Gamma_{WW*} / \Gamma_{WW*}^{SM} = \kappa_W^2$
ττ	6.32%	$\Gamma_{\tau\tau} / \Gamma_{\tau\tau}^{SM} = \kappa_\tau^2$
ZZ	2.64%	$\Gamma_{ZZ*} / \Gamma_{ZZ*}^{SM} = \kappa_Z^2$
cc	2.91%	$\Gamma_{c\bar{c}} / \Gamma_{c\bar{c}}^{SM} = \kappa_c^2$
μμ	0.02%	$\Gamma_{\mu\mu} / \Gamma_{\mu\mu}^{SM} = \kappa_\mu^2$



Difficult does not mean we do not try: h→μμ



$\Gamma(h \rightarrow \mu\mu) = 0.02\%$

Enormous Drell-Yan background

How do you summarize such a negative result ?

Set a limit on $\mu_S = \Gamma(h \rightarrow \mu\mu)/\Gamma^{SM}(h \rightarrow \mu\mu)$

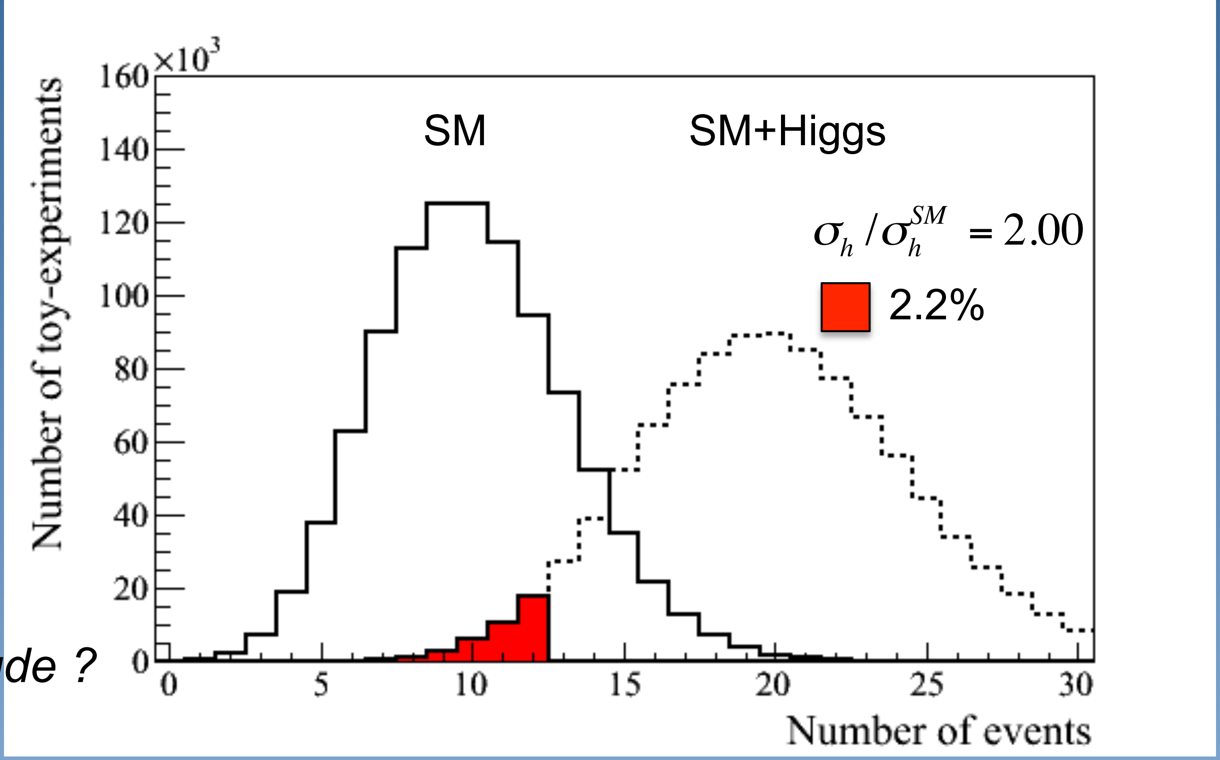
When / how do you exclude a signal

Standard Model

SM	10
Higgs	5
Data	12

Can we exclude the SM+Higgs hypothesis ?

What σ_h/σ_h^{SM} can we exclude ?



When / how do you exclude a signal

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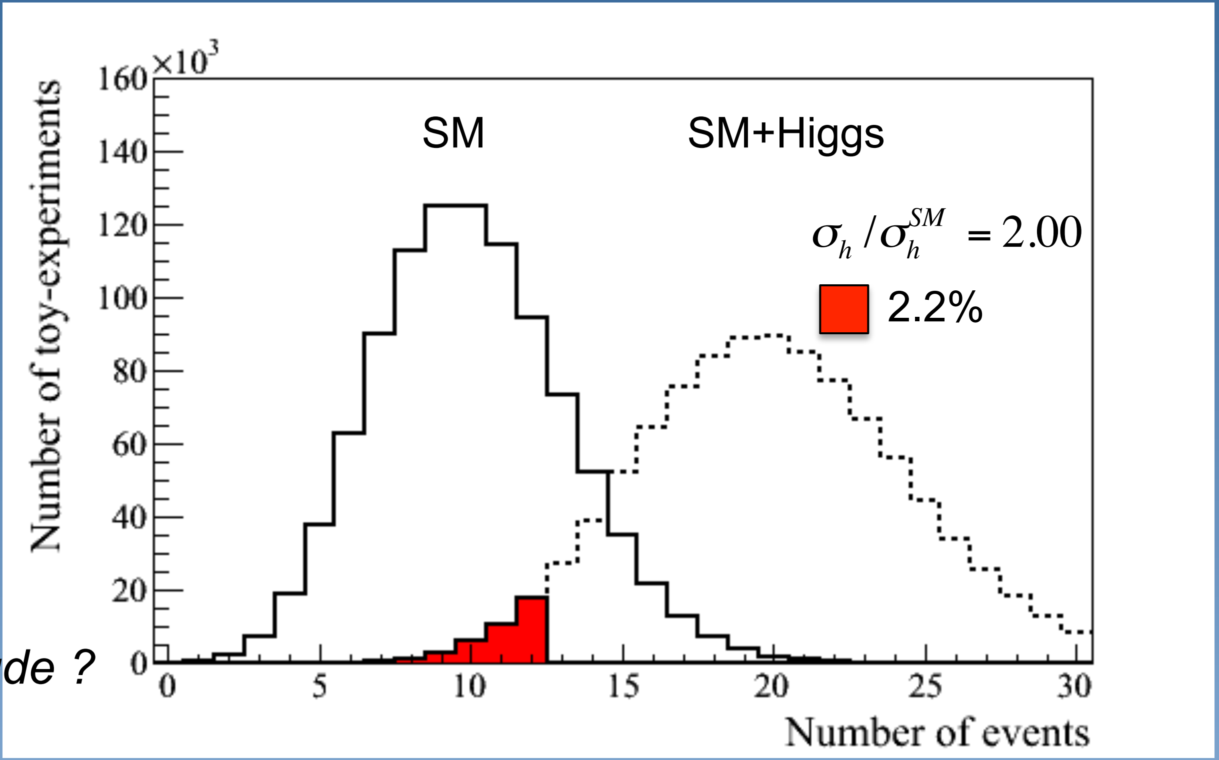


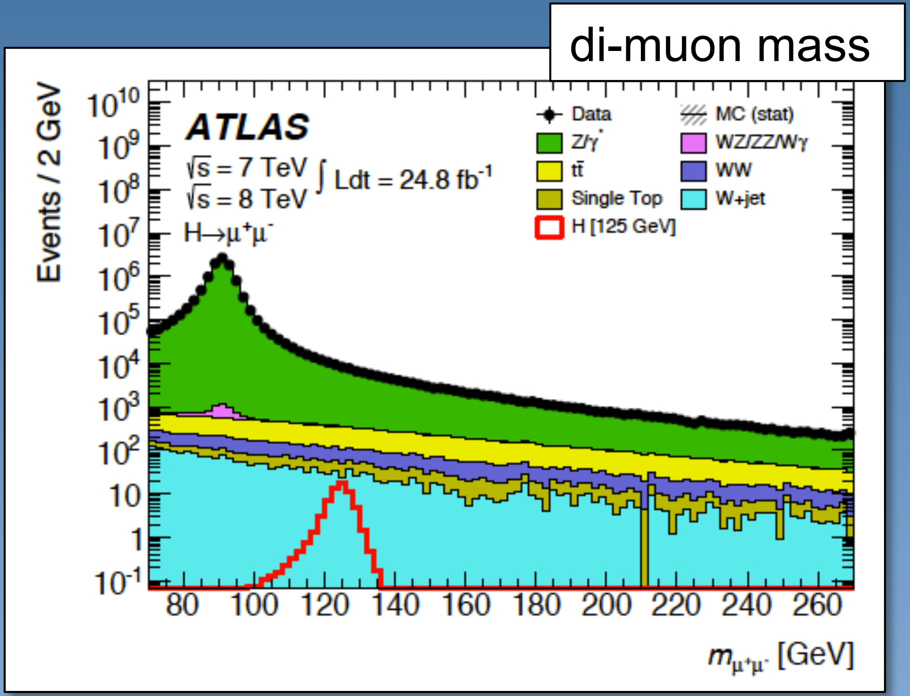
σ/σ_{SM}	SM	# data	SM+Higgs	
1.0	10	12	15.0	18.5 %
1.5	10	12	17.5	6.8%
2.0	10	12	20.0	2.2%

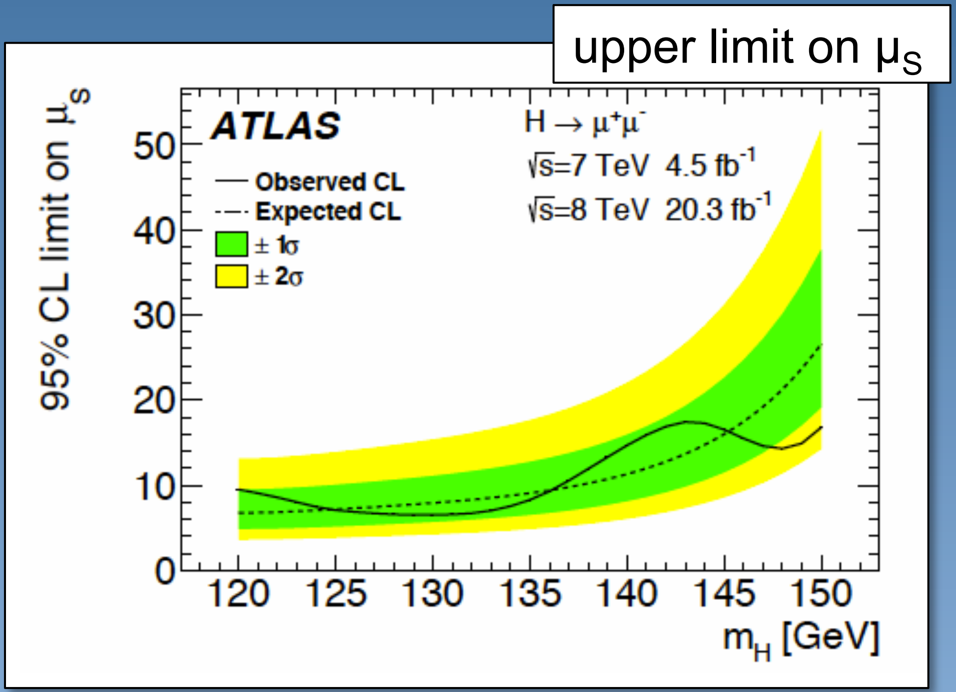
excluded

Expected exclusion ? Use mean SM instead of Ndata

Observed excluded cross-section, σ_h/σ_h^{SM} , = 1.64

Difficult does not mean we do not try: h→μμ





$\mu_S < 7$

Parametrize production/decay processes:

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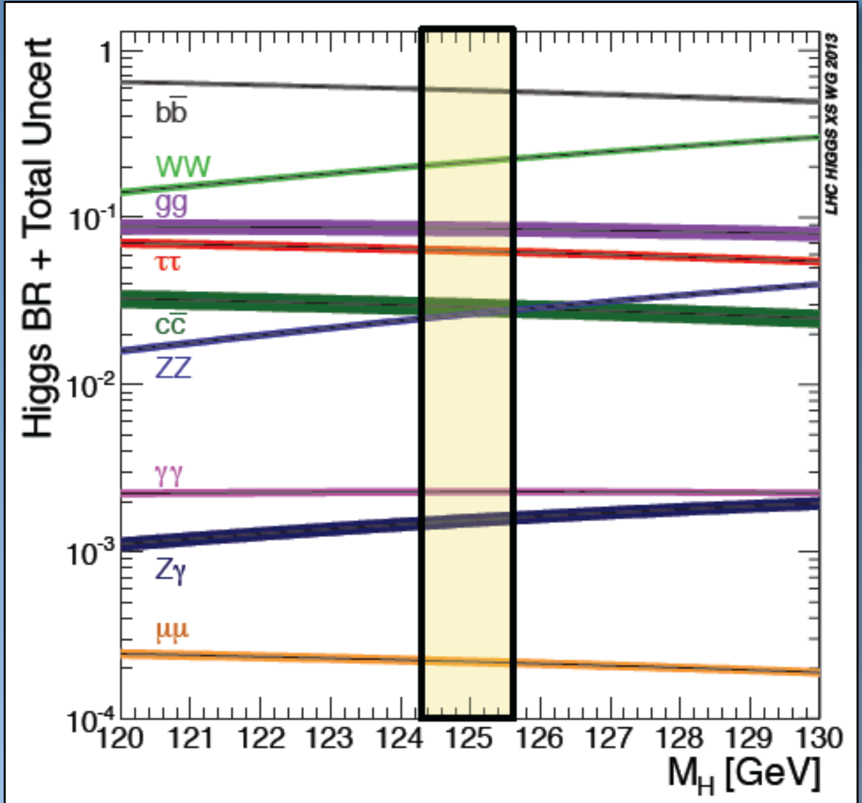
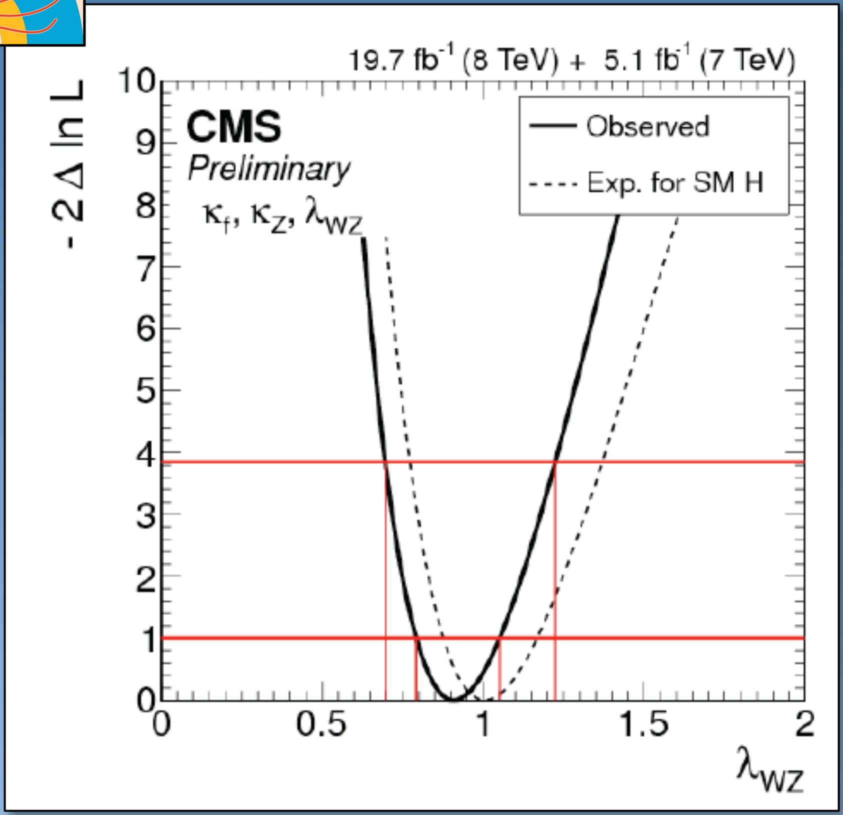


Vector boson couplings: W versus Z



custodial symmetry

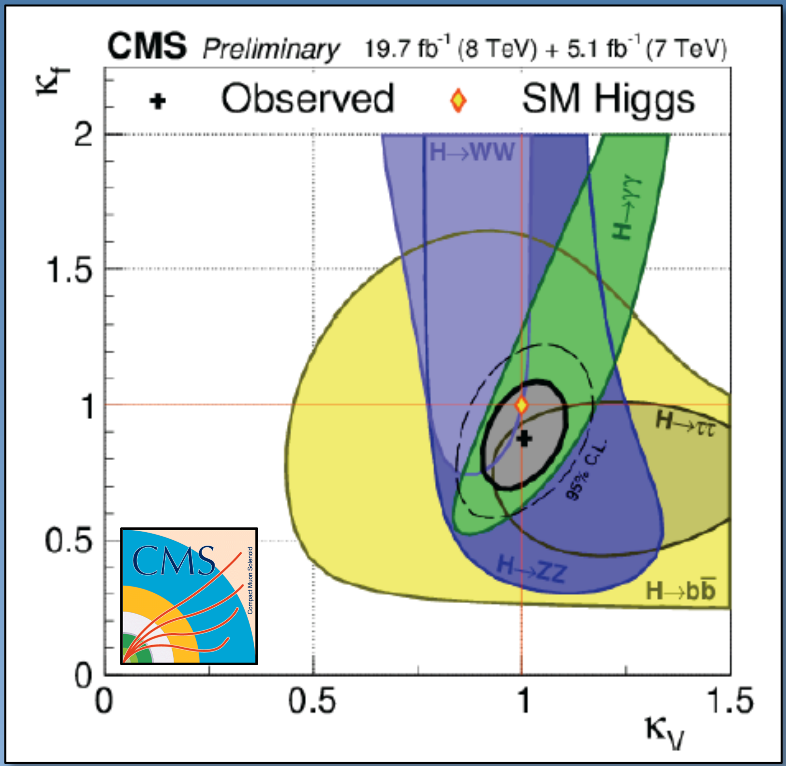
Already tested in high precision measurements at LEP and Tevatron

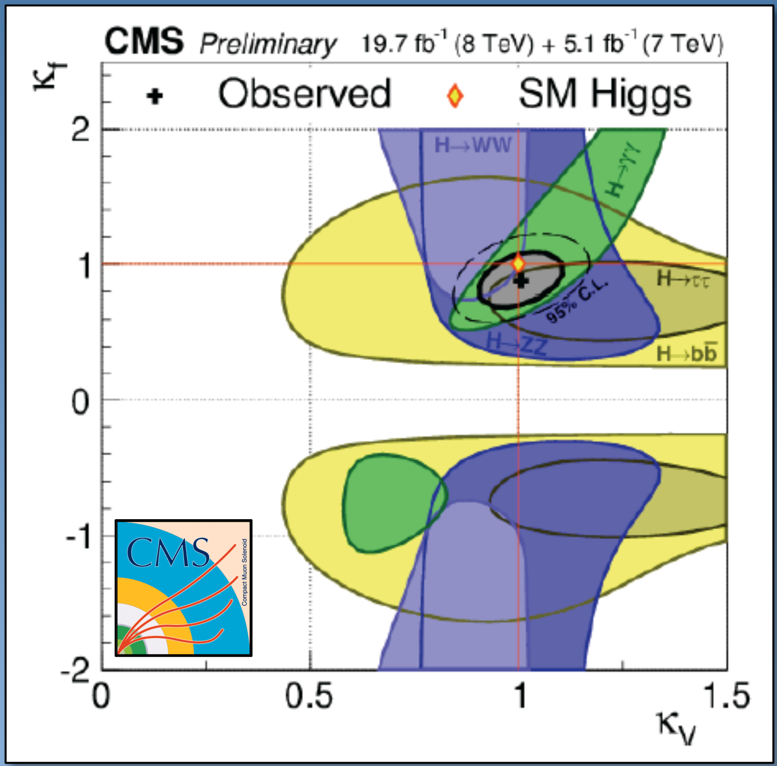
$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$$

→ Treat W and Z as similar (V)

$$\kappa_W = \kappa_Z \equiv \kappa_V$$

κ_V versus κ_F → vector bosons versus fermions



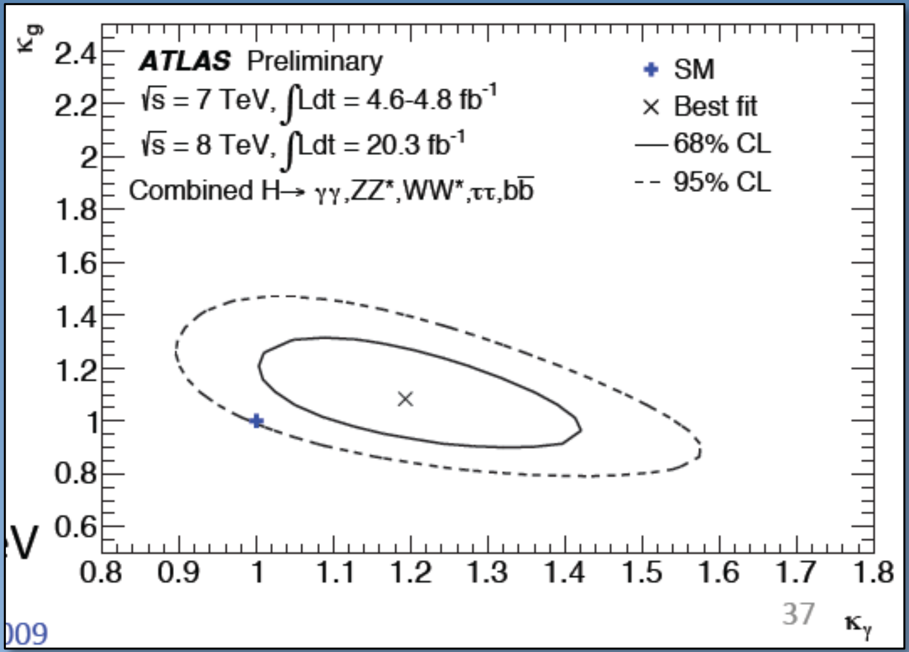


- Consistent with Standard Model
- Opposite sign κ_f still possible

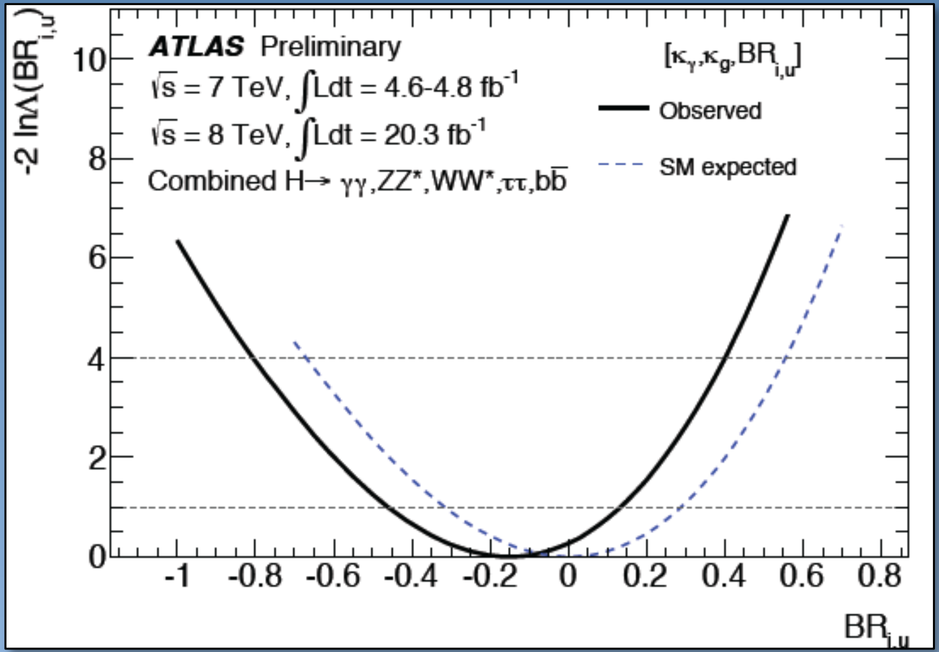
Testing loops

New physics will enter in the loops

κ_γ and κ_g top (and W) loops



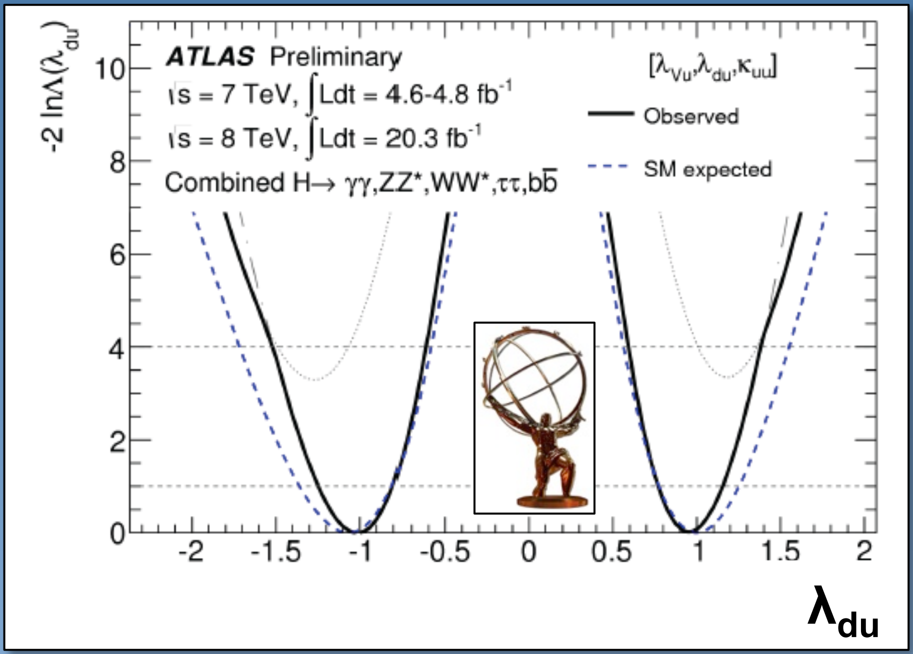
Interpretation in invisible width



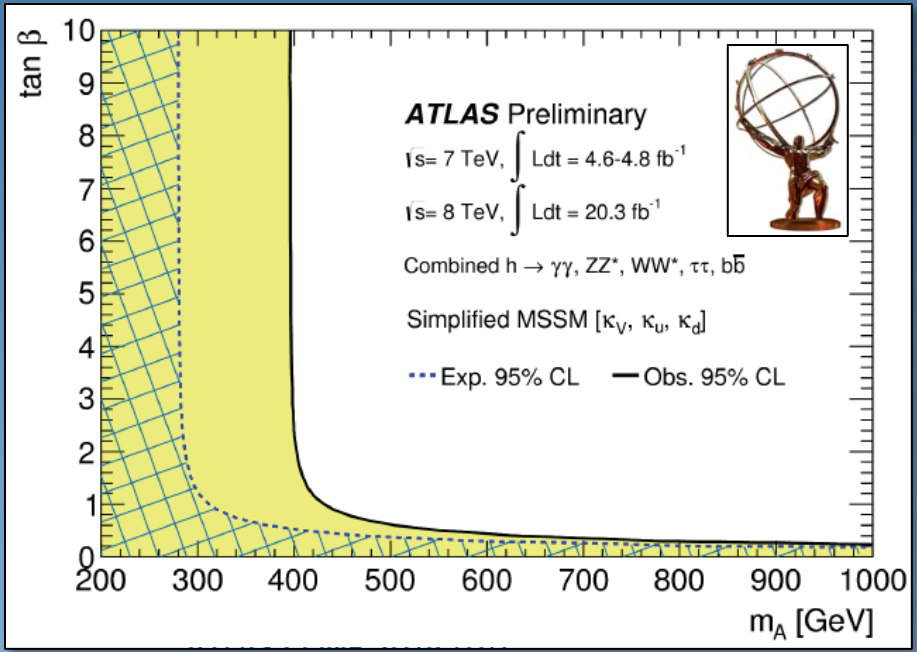
$BR_{inv} < 41\% \rightarrow \Gamma_{inv} < 7.9$ MeV

κ_{up} versus κ_{down} → down versus up type fermions

down versus up type fermions

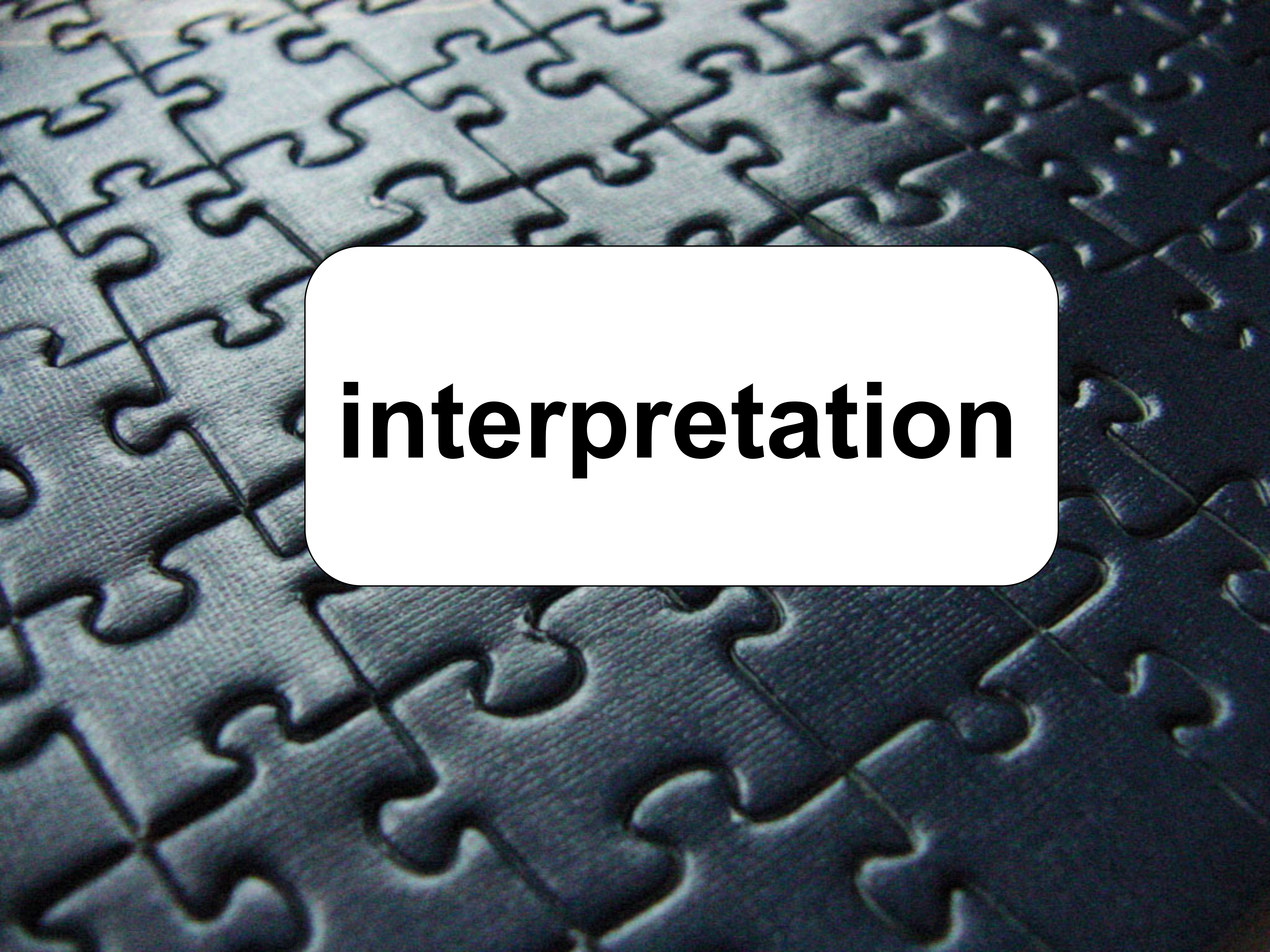


Interpretation in MSSM



$$\lambda_{ud} = \frac{\kappa_{up}}{\kappa_{down}} = \frac{\kappa_t}{(\kappa_b, \kappa_\tau)}$$

Different New Physics models, like MSSM predict deviations from SM expectation


interpretation

Supersymmetry: MSSM

MSSM

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

2 scalars:	h,H
1 pseudo-scalar:	A
2 charged:	H^+,H^-

blackboard

reduced # parameters

$\tan\beta \quad m_A$

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{H,h}^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4\left(m_Z m_A \cos(2\beta)\right)^2}\right]$$

Example of a 2-Higgs-doublet-model
Couplings different than those in SM
Extra Higgs bosons

2-Higgs doublet models (general)

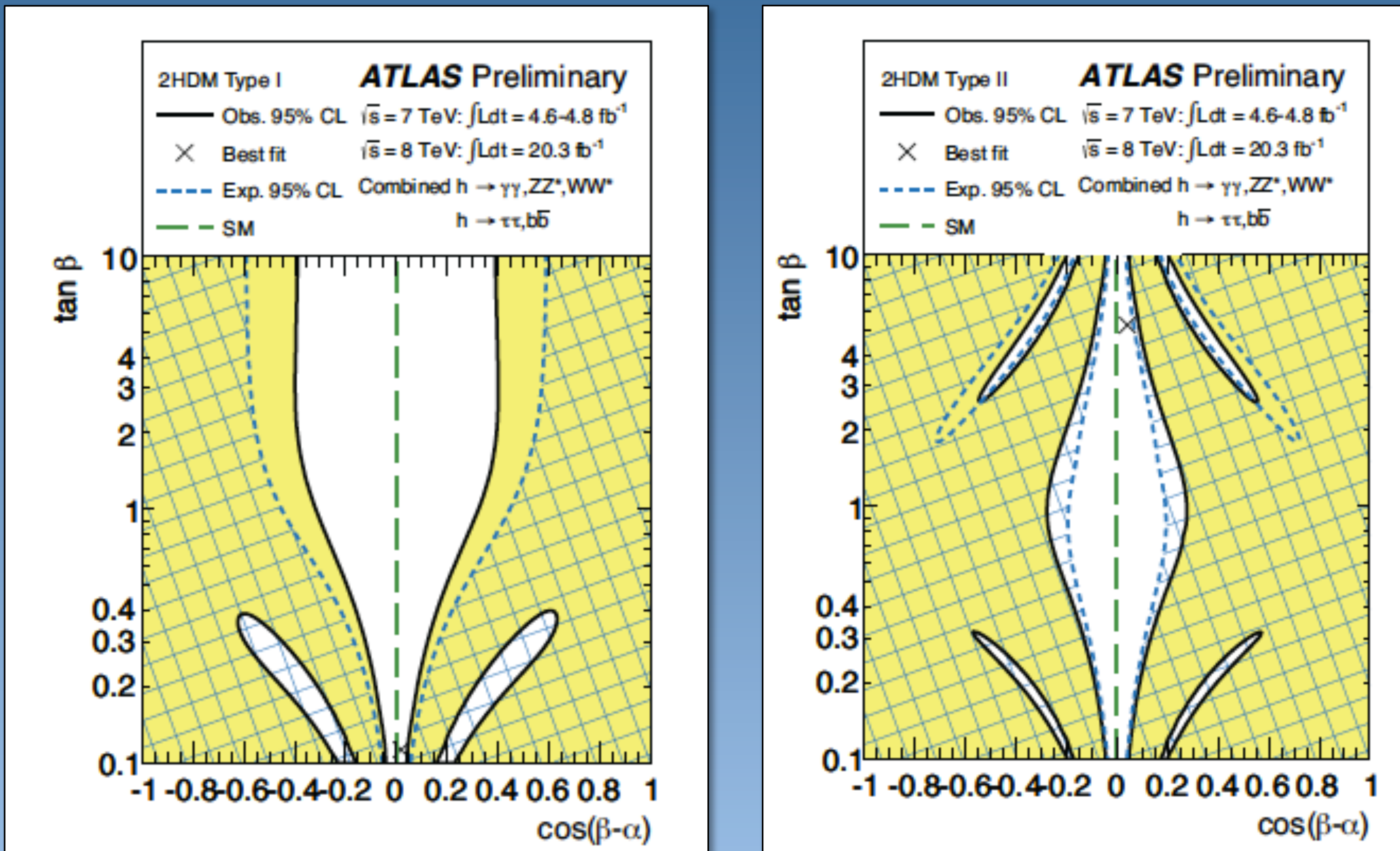
Differences in couplings in 2HDM's

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

TYPE I:
- 1 doublet for vector bosons (fermiophobic)
- 1 doublet for fermions

TYPE II: MSSM-like:
- 1 doublet for up-type
- 1 doublet for down-type

2-Higgs doublet models (general)



MSSM and NMSSM

MSSM

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

2 scalars:	h,H
1 pseudo-scalar:	A
2 charged:	H^+,H^-

Difficult to reach m_h=125 GeV

NMSSM

EW singlet

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \quad S$$

2 scalars:	h_1, h_2, h_3
1 pseudo-scalar:	a_1,a_2
2 charged:	H^+,H^-

Less radiative constraints
Mixing S and H_u results in SM-like couplings

Additional electroweak singlet

Extra singlet will mix with h → 2 CP-even Higgs bosons

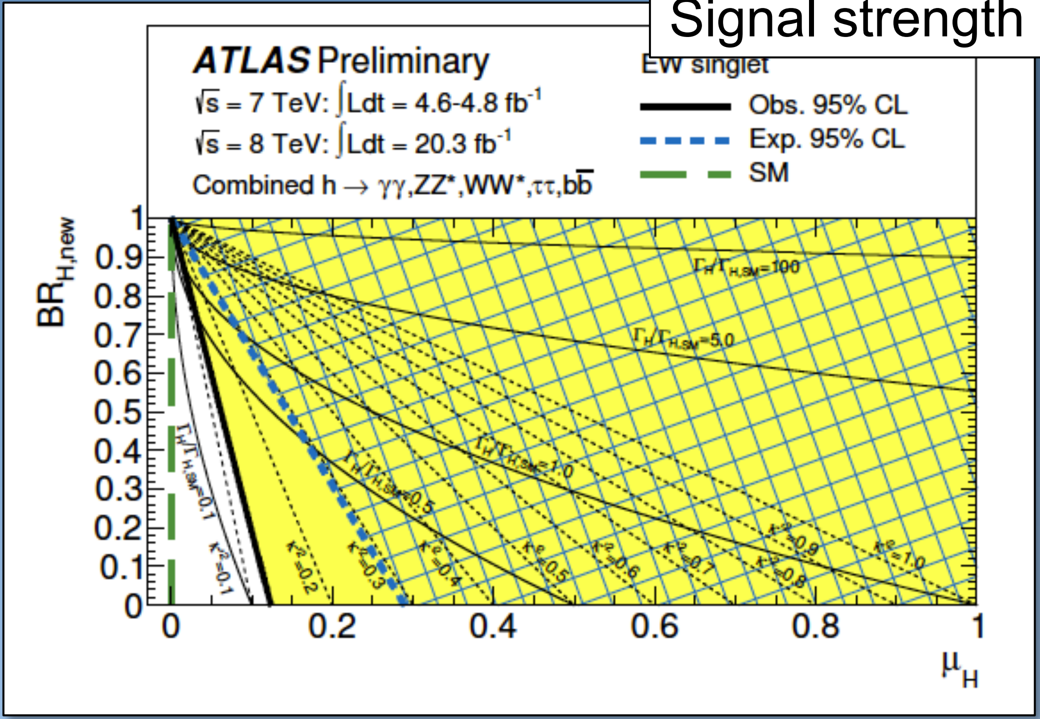
h (strength κ) and H (strength κ'). Note: $\kappa^2 + \kappa'^2 = 1$

Signal strength:

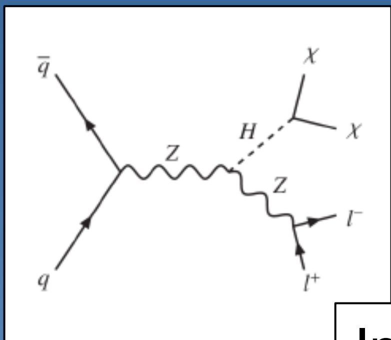
$$\mu_h = \frac{\sigma_h \times BR_h}{(\sigma_h \times BR_h)_{SM}} = \kappa^2$$

$$\mu_H = \frac{\sigma_H \times BR_H}{(\sigma_H \times BR_H)_{SM}} = \kappa'^2 (1 - BR_{H,new})$$

Signal strength

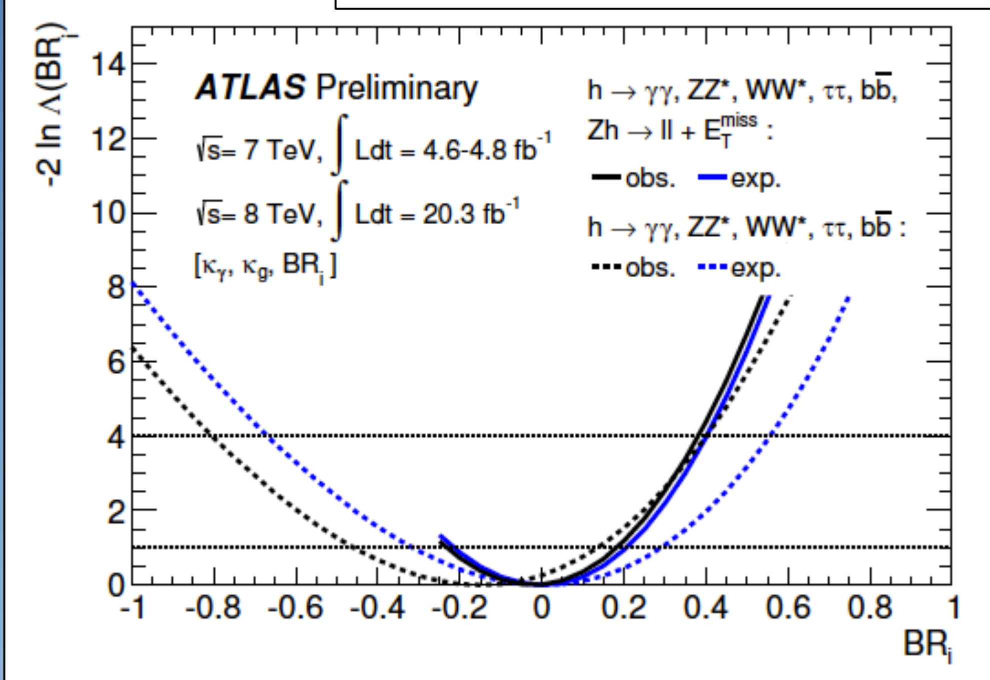


Invisible decays & portal to dark matter

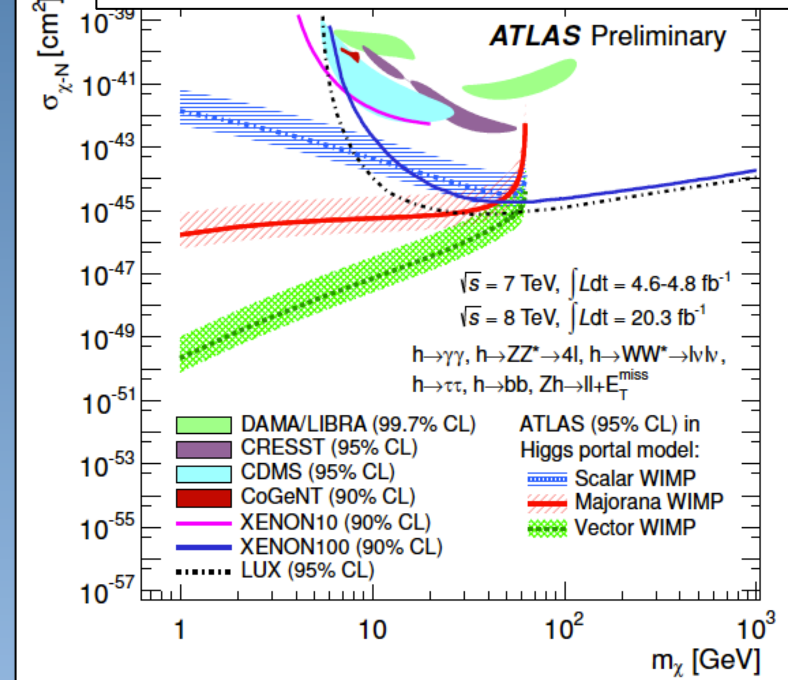


Higgs couples to WIMP

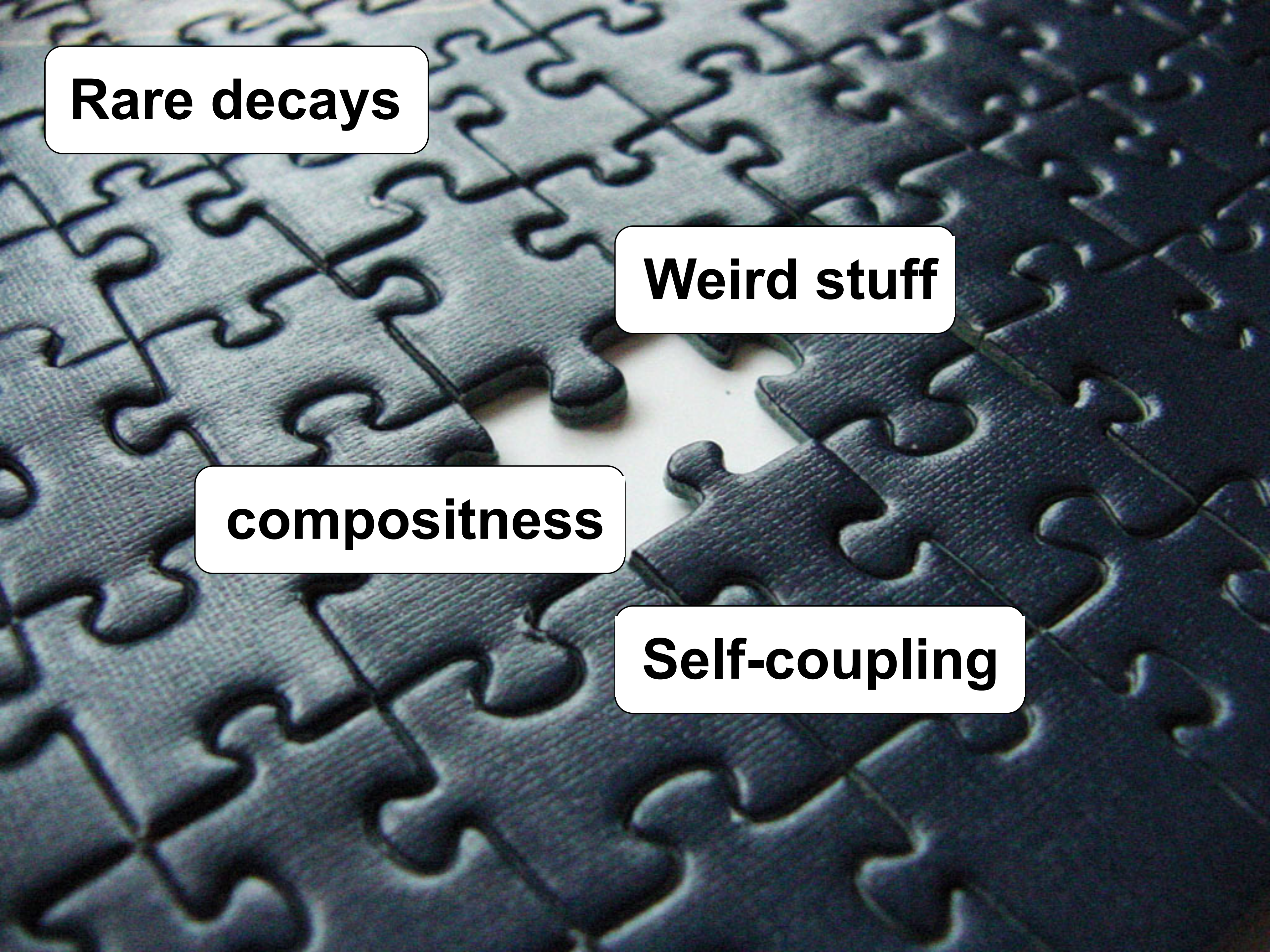
Invisible branching fraction



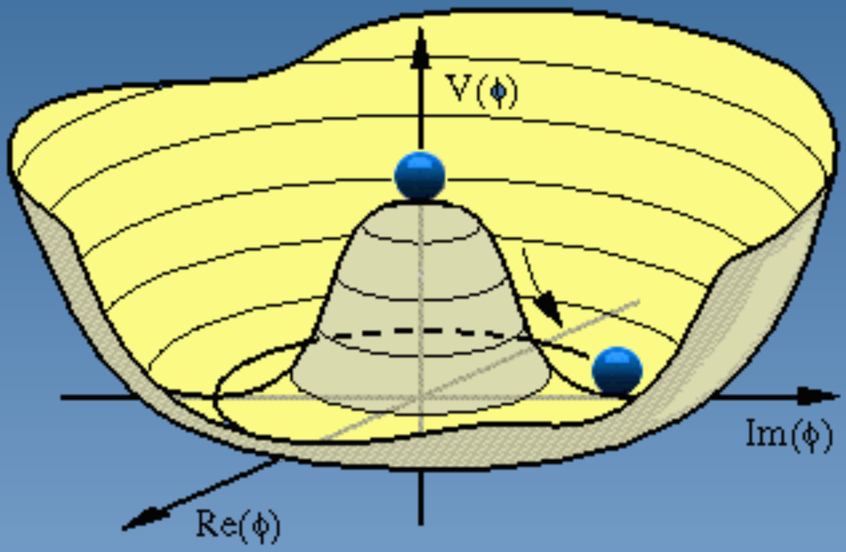
Wimp-Nucleon cross-section



$Br_{invisibl3} < 37\%$ at 95% CL


Rare decays
Weird stuff
compositness
Self-coupling

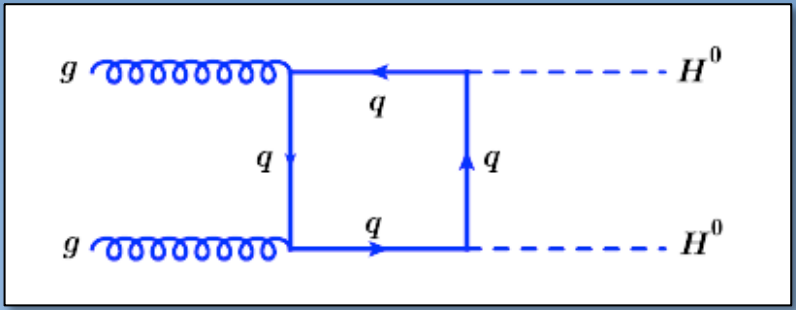
Higgs self-coupling

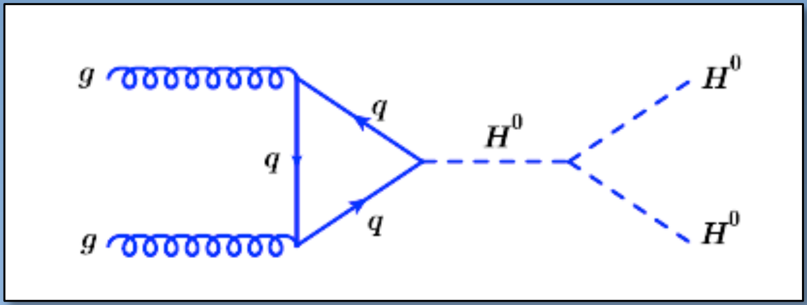


Higgs self-couplings

$$\lambda_{3H} = \frac{3m_H^2}{v}, \qquad \lambda_{4H} = \frac{3m_H^2}{v^2}.$$

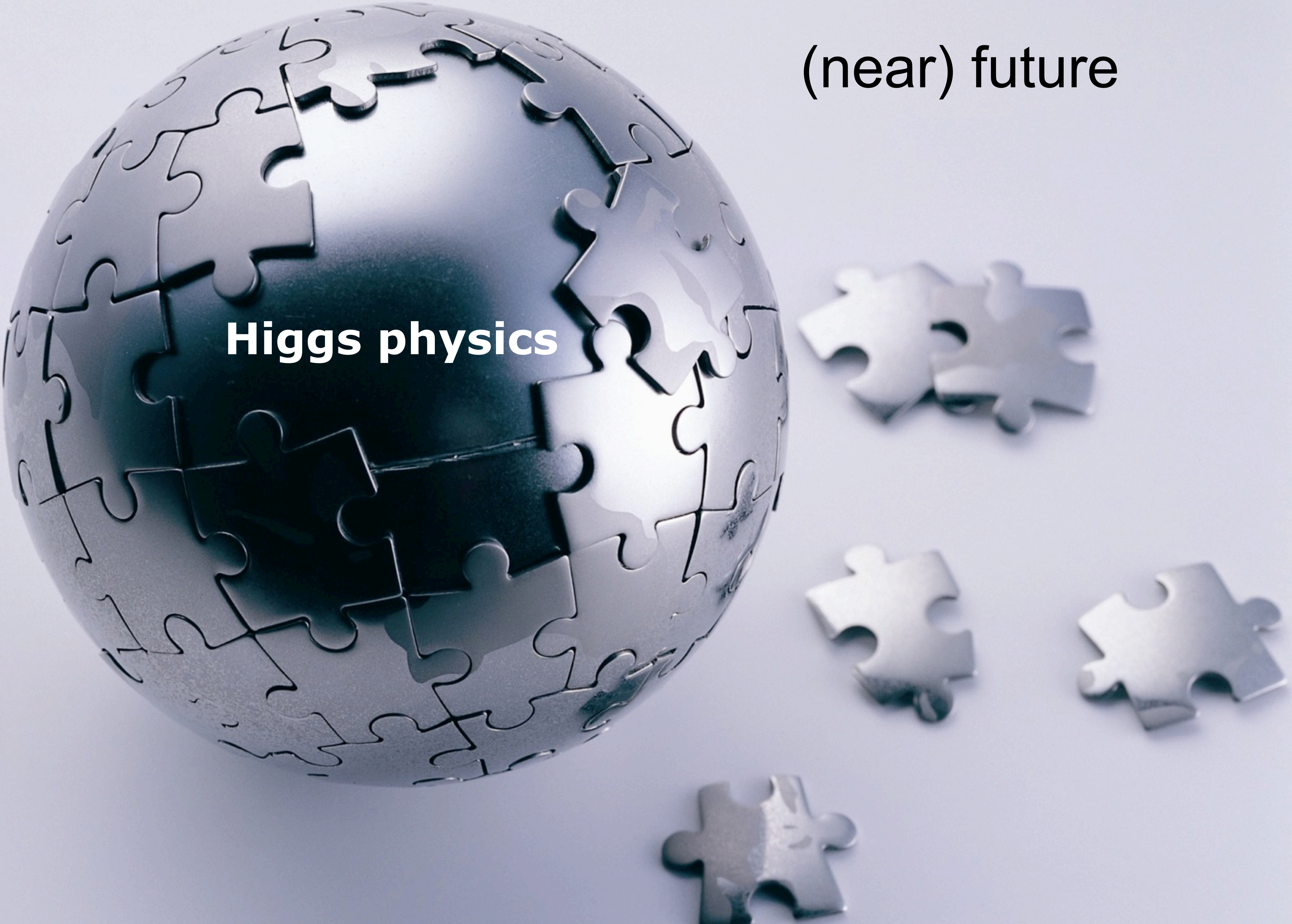
Blackboard: how is this possible (with Γ_h=4 MeV)





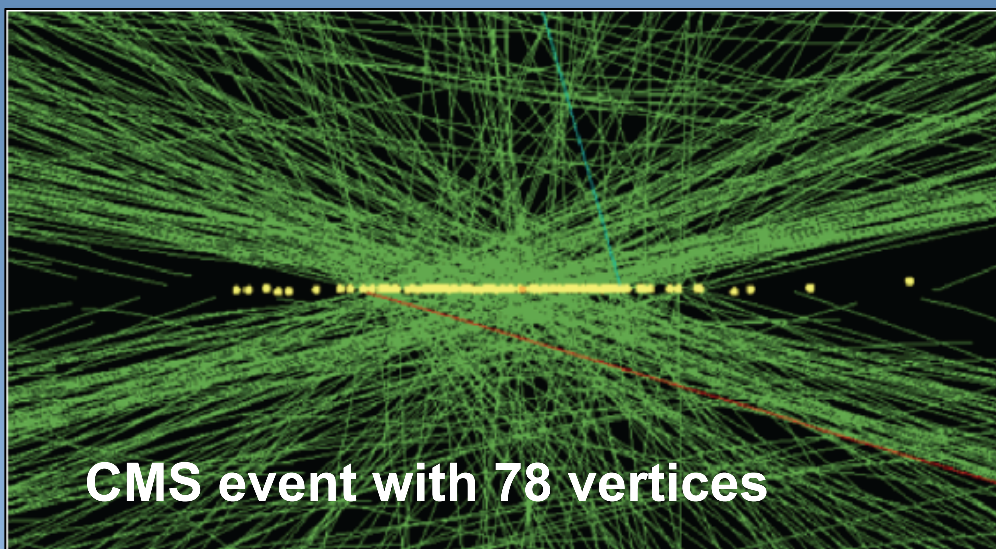
Very difficult to reach sensitivity (bbγγ ?). Also large negative interference.

(near) future



Future LHC operation

Energy: 14 TeV
Luminosity 3000 fb^{-1}


CMS event with 78 vertices

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi

2013/14 Prepare LHC for design *E* & lumi **LS1**

Collect ~30 fb^{-1} per year at 13/14 TeV

2018 Phase-1 upgrade ultimate lumi **LS2**

Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year

~2022 Phase-2 upgrade to HL-LHC **LS3**

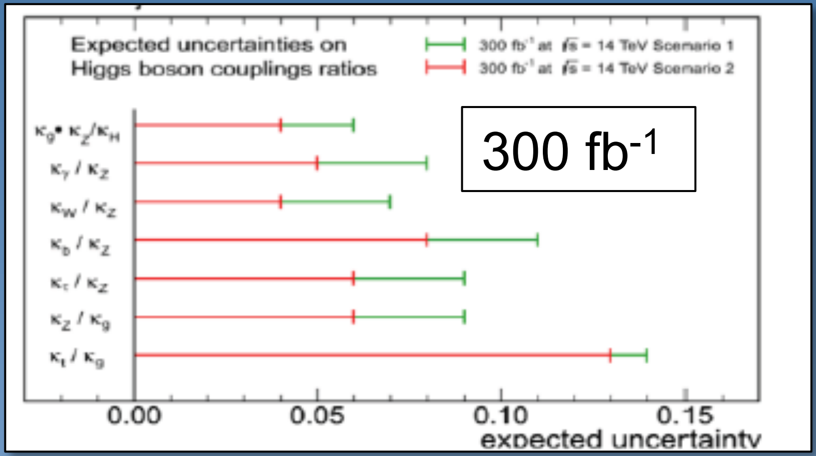
~300 fb^{-1} per year, run up to > 3 ab^{-1} collected

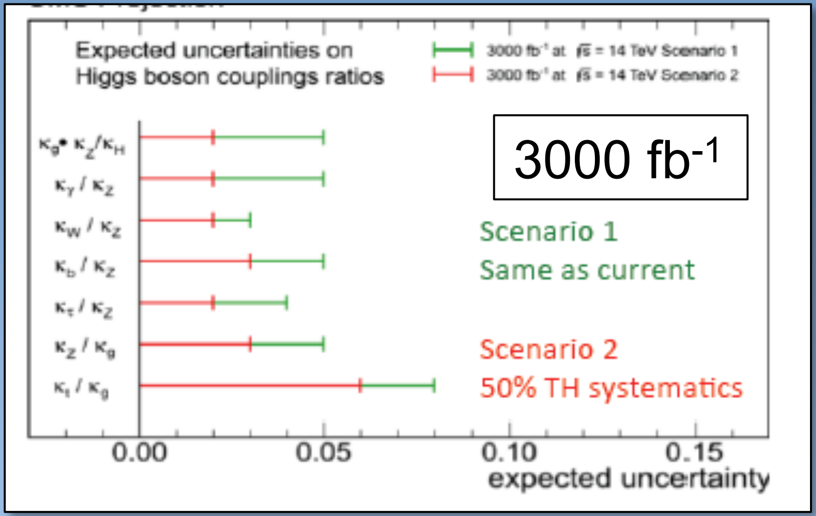
~2030

Coupling limits projection (CMS)

statistics (systematics)

statistics (systematics)
+ 50% theory error





Bit further future

e^+e^- (ILC) $\sqrt{s}$ = 250, 500, 1000 GeV L = few x 10^{34}

e^+e^- (CLIC) $\sqrt{s}$ = 500, 1500, 3000 GeV L = few x 10^{34}

pp (CERN) $\sqrt{s}$=100 TeV
e^+e^- (CERN) $\sqrt{s}$=250 GeV

ultimate machine ? muon collider

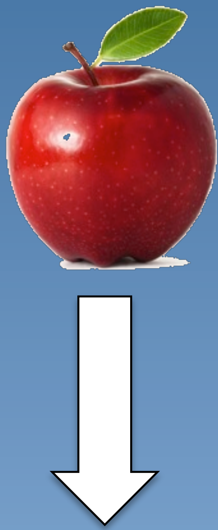
Conclusions:

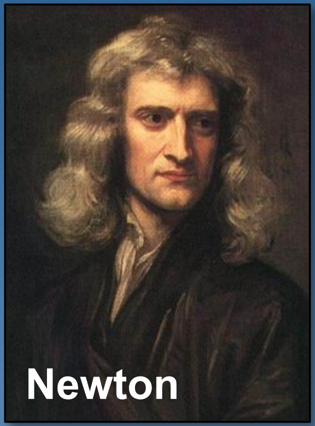
Vacuum is filled with the Higgs field

Feels, smells, tastes like SM Higgs

Big questions still open

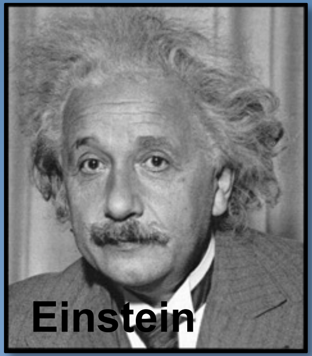
Waarom valt een appel naar beneden ?





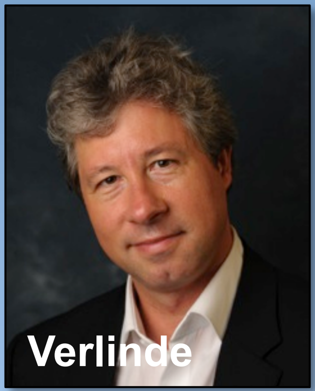
massa's trekken elkaar aan

$$F = G_N \frac{m_1 m_2}{r^2}$$



ruimte-tijd is gekromd

$$G_{\mu\upsilon} + \Lambda g_{\mu\upsilon} = \frac{8\pi G_N}{c^4} T_{\mu\upsilon}$$



Entropie (informatie)