The Higgs boson

Teraschool PhD introductory school, DESY, 21 april 2015, Ivo van Vulpen

Higgs physics and data-analysis exercises

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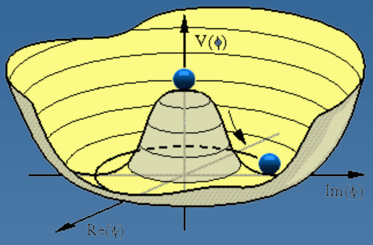
particle Physics, programming, Higgs

Researcher at Nikhef, Amsterdam
ATLAS (top & Higgs physics)

Lecture 1: Higgs physics intro



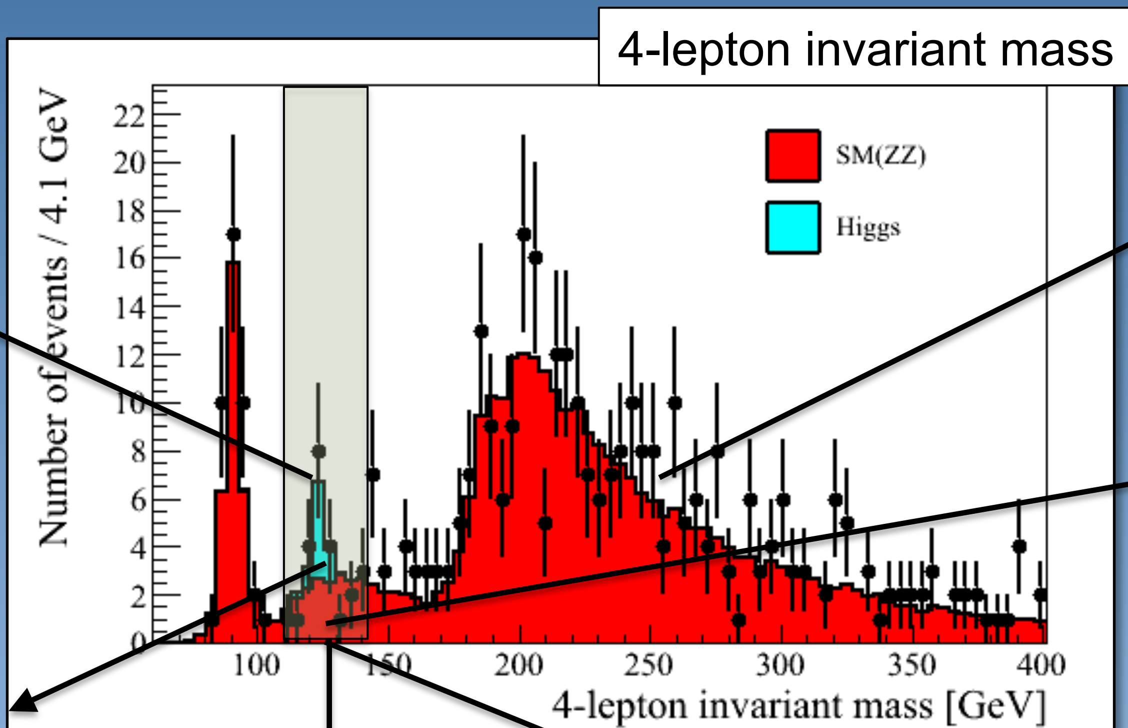
Theory:

- *Electroweak symmetry breaking in the Standard Model*
- *massive gauge bosons, fermions & extra scalar*

Experiment:

- *Higgs boson production & decay at the LHC*
- *discovery and current research*
- *open questions, problems and future research*

Lecture 2: hands-on data analysis



Cross-section measurement

Excluding Higgs masses

Test statistic & Toy-MC

Significance optimization

Mass measurement

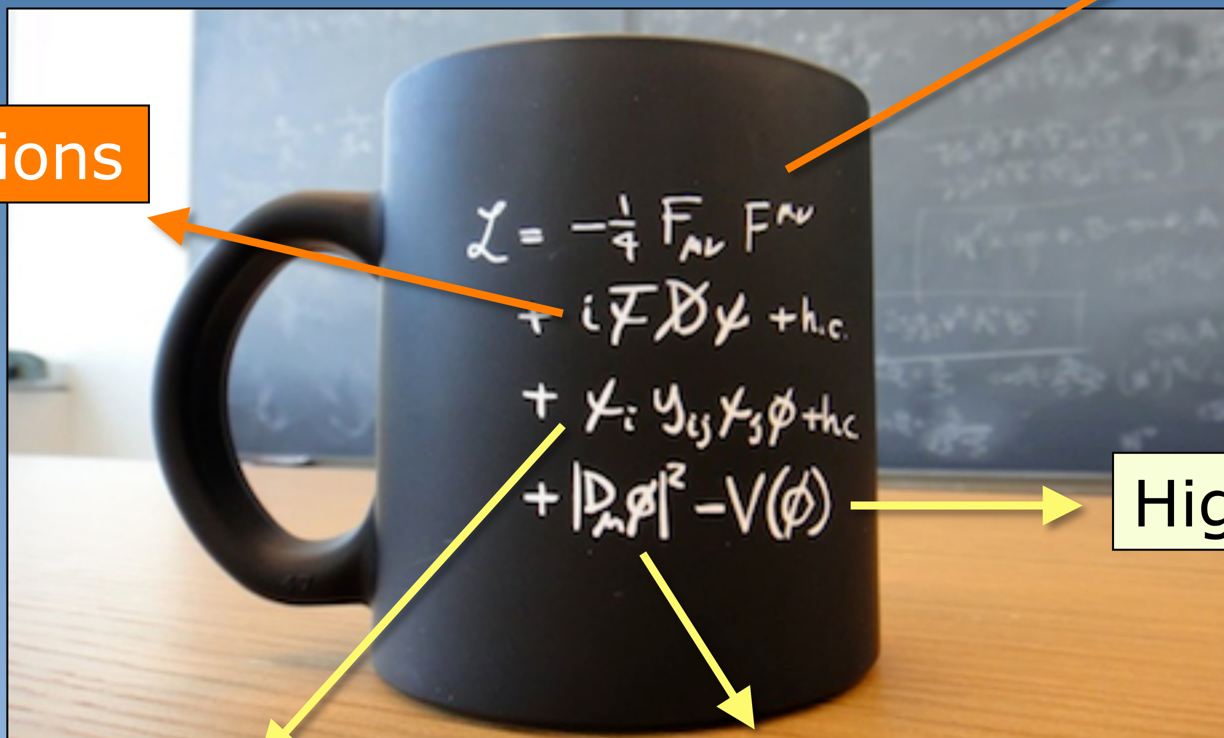
Data-driven background estimate (likelihood fit)

Higgs boson theory

Lagrangian of the Standard Model

Gauge fields

Interactions



Higgs particle

Fermion masses

Gauge boson masses

‘reading’ Lagrangians

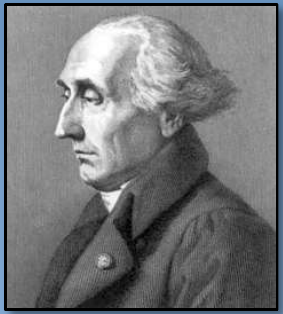
Lagrange formalism

Lagrangian

$$\mathcal{L} = \mathrm{T(kinetic)} - \mathrm{V(potential)}$$

Euler Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0$$



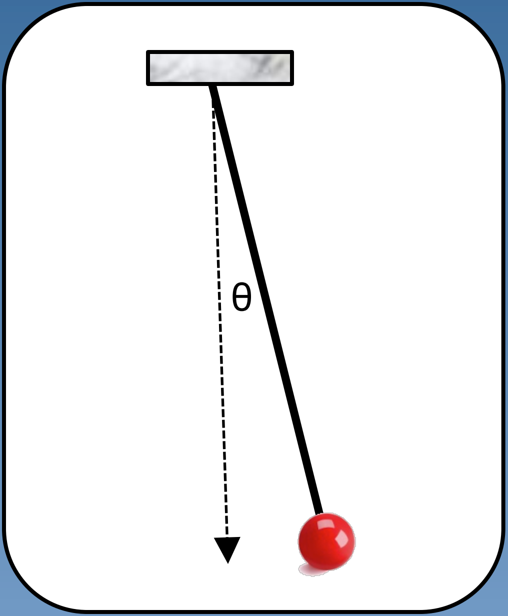
equation of motion

Classical mechanics

pendulum

$$E_{kin} = \frac{1}{2} m \left(l \dot{\theta} \right)^2$$

$$E_{pot} = -mgl\cos(\theta)$$



Euler-Lagrange

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = 0$$

Equation of motion

$$\ddot{\theta} + \frac{g}{l}\sin(\theta) = 0$$

Small angles θ<<1:

$$\ddot{\theta} = -\frac{g}{l}\theta \longrightarrow \theta(t) = \theta_0 \cos\left(\sqrt{\frac{g}{l}}t\right)$$

$$T = 2\pi\sqrt{\frac{l}{g}}$$

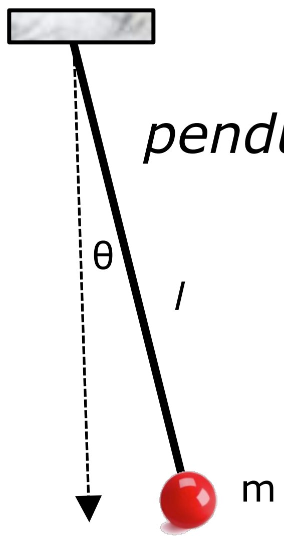
All angles:

$$T = 2\pi\sqrt{\frac{l}{g}} \sum_{n=0}^{\infty} \left[\left(\frac{(2n)!}{(2^n n!)^2} \right)^2 \sin^{2n}\left(\frac{\theta_0}{2} \right) \right]$$

Tricky: friction, coupled pendula, spring, rotating system, …

Equation of motion for elementary particles

pendulum



$$L = \frac{1}{2} m (l\dot{\theta})^2 + mgl\cos(\theta)$$

$$\ddot{\theta} + \frac{g}{l}\sin(\theta) = 0$$

electron

$$\mathcal{L}_{\mathrm{fermion}} = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi\,.$$

$$\left(i\gamma_\mu\partial^\mu - m\right)\psi = 0$$

Dirac equation

General structure of a Lagrangiaan

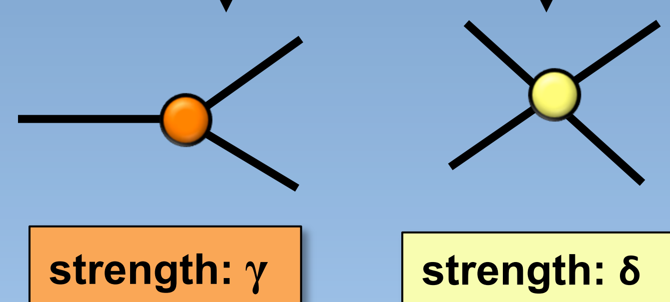
kinetic energy

mass term

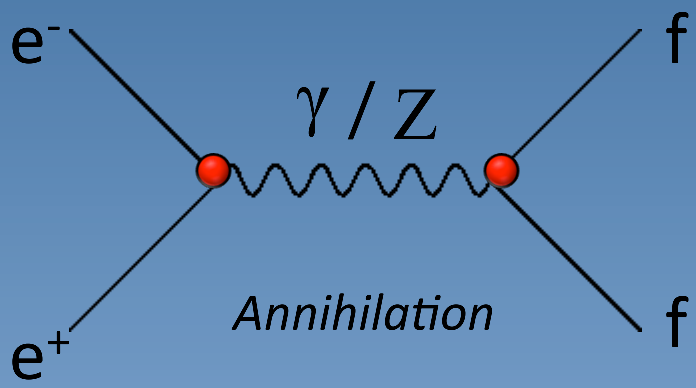
interactions

$$\mathcal{L} = \underbrace{(\partial_\mu\phi)^2}_{\text{kinetic term}} + \underbrace{C}_{\text{constant}} + \underbrace{\alpha\phi}_{?} + \underbrace{\beta\phi^2}_{\text{mass term}} + \underbrace{\gamma\phi^3}_{\text{3-point int.}} + \underbrace{\delta\phi^4}_{\text{4-point int.}} + \dots$$

No impact on the equation of motion



Cross-sections and interactions



$$\frac{d\sigma}{d\Omega}\Big|_{CM} = \underbrace{\frac{1}{64\pi^2}\frac{p_f}{p_i}}_{\text{kinematics}}\underbrace{\left|M^2\right|}_{\text{physics}}$$

kinematics

physics

Photon

$$i\mathcal{L}_{int}^{\mathrm{QED}} = -ie\bar{\psi}_f\gamma_\mu Q\psi_f A^\mu$$

Coupling strength: Q

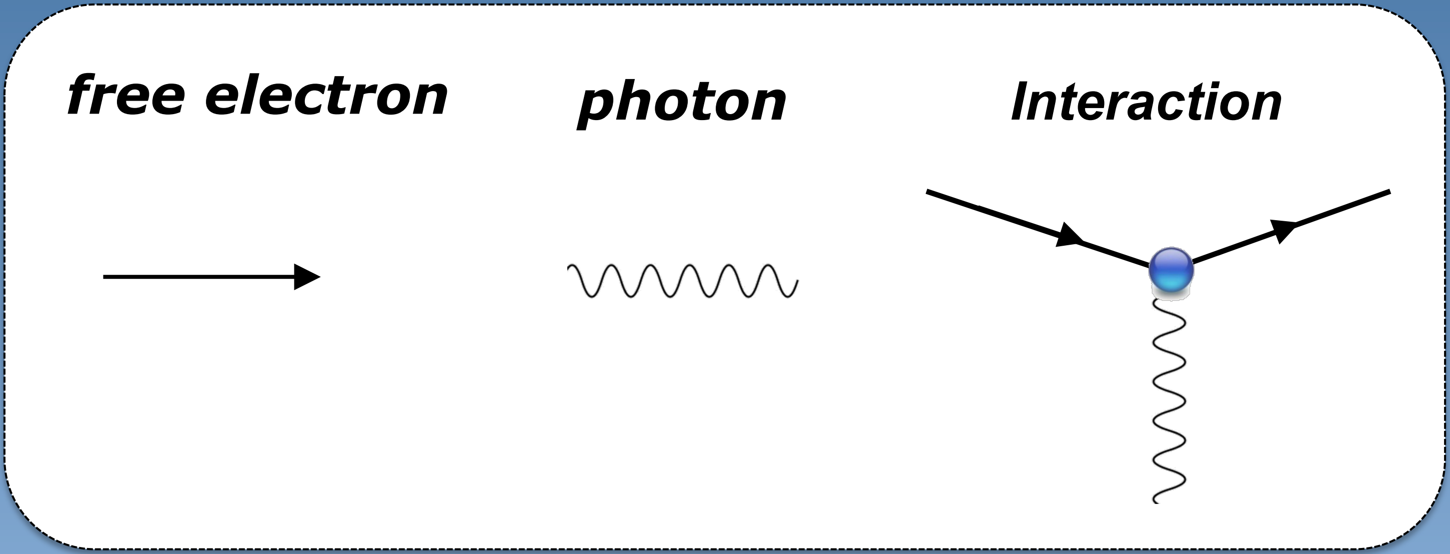
Z-boson

$$i\mathcal{L}_{int}^{\mathrm{NC}} = -i\frac{g}{\cos\theta_w}\bar{\psi}_f\gamma_\mu\left[\left(\frac{1-\gamma_5}{2}\right)T_3 - \sin^2\theta_w Q\right]\psi_f Z^\mu$$

Coupling strength: mix of iso-spin & hypercharge

Quantum Electro Dynamics

$$L_{QED} = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - e\bar{\psi}\gamma_{\mu}A^{\mu}\psi$$



(local) gauge invariance

The origin of fources in the SM

Local gauge invariance

Schrödinger equation:

$$H\Psi(\vec{r}) = \left(-\frac{\hbar^2}{2m}\vec{\nabla}^2 + V(\vec{r})\right)\Psi(\vec{r}) = E\Psi(\vec{r})$$

Symmetric under **global** phase (α):

$$\Psi(\vec{r}) \rightarrow \Psi'(\vec{r}) = e^{i\alpha}\Psi(\vec{r})$$

Not symmetric under **local** phase (α(r)):

$$\Psi(\vec{r}) \rightarrow \Psi'(\vec{r}) = e^{i\alpha(\vec{r})}\Psi(\vec{r})$$

U(1) symmetry: rotation

It is possible to keep physics invariant under this local gauge transformation

Local gauge invariance

Schrödinger equation:

$$H\Psi(\vec{r}) = \left(-\frac{\hbar^2}{2m}\vec{\nabla}^2 + V(\vec{r})\right)\Psi(\vec{r}) = E\Psi(\vec{r})$$

solution

Covariant derivative:

$$\vec{\nabla} \rightarrow \vec{\nabla} - i\vec{A}(\vec{r})$$

new vector field

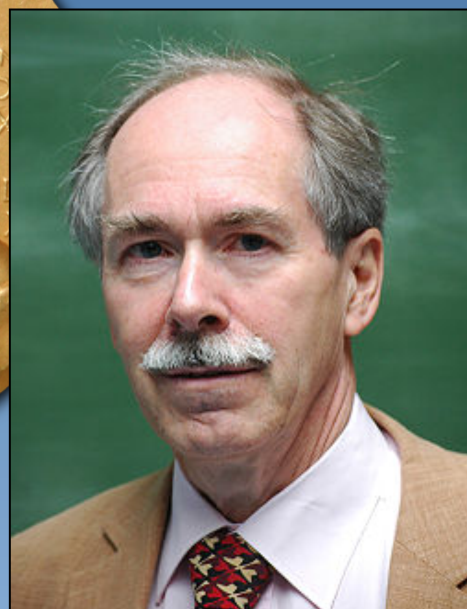
vector field special properties

$$\vec{A}(\vec{r}) \rightarrow \vec{A}(\vec{r}) + \vec{\nabla}\alpha(\vec{r})$$

$$\left[-\frac{\hbar^2}{2m}\left(\vec{\nabla} - i\vec{A}(\vec{r})\right)^2 + V(\vec{r})\right]\Psi(\vec{r}) = E\Psi(\vec{r})$$

Local gauge invariance: why ?

Why demand such a high degree of symmetry ?



Gerard 't Hooft

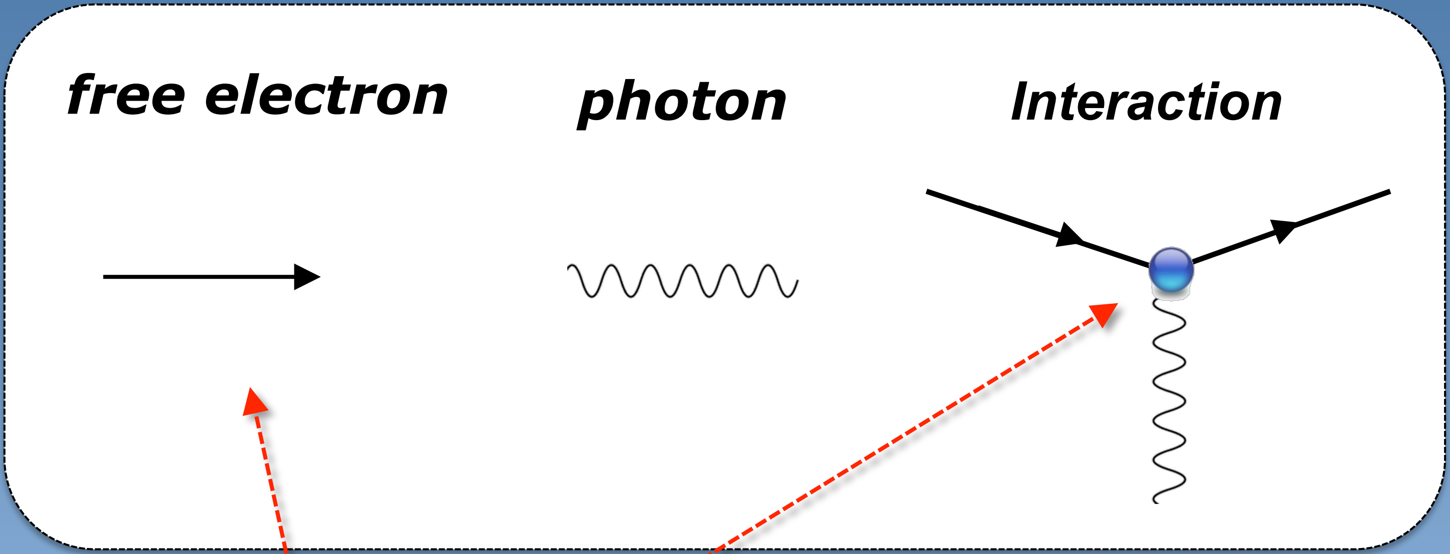
Martinus Veltman

Necessary to keep the Standard Model 'well behaved'

You 'automatically' get gauge fields and interactions

QED: local U(1) gauge invariance

$$L_{QED} = \quad i\bar{\psi}\gamma_\mu \partial^\mu \psi \quad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad -e\bar{\psi}\gamma_\mu A^\mu \psi$$



$$L_{QED} = i\bar{\psi}\gamma_\mu(\partial_\mu - ieA_\mu)\psi$$
$$= i\bar{\psi}\gamma_\mu D_\mu \psi$$

Linked to $U(1)_Q$ invariance:

$$\psi(\vec{r}) \rightarrow e^{iQ\alpha(\vec{r})}\psi(\vec{r})$$

Symmetry-basis of the Standard Model

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

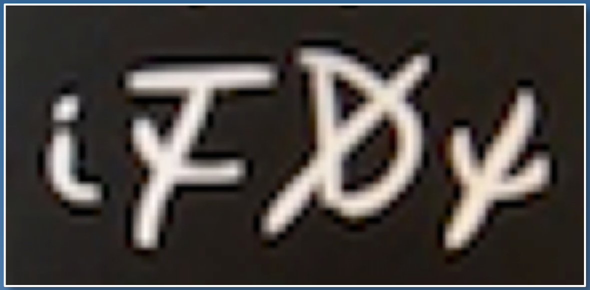
Rotations in hypercharge space

Rotations in weak iso-spin space

Rotations in colour space

QED	$U(1)_Y$ → 1 d.o.f → 1 gauge boson	}	**γ, W^+, W^-, Z^0**
Weak force	$SU(2)_L$ → 3 d.o.f → 2 gauge bosons	}	
Strong force	$SU(3)_C$ → 8 d.o.f → 8 gauge bosons		**8 gluons**

Electroweak theory



Covariante derivative

$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{1}{2}YB_\mu$$

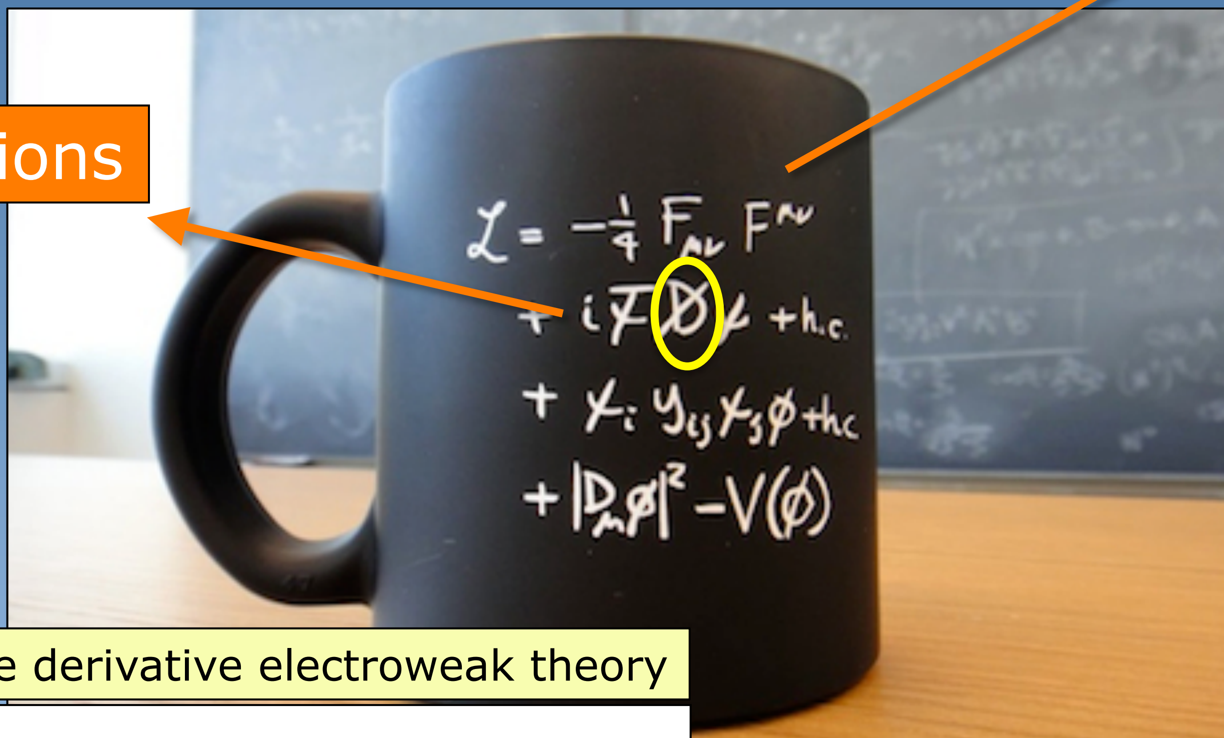
Rotations in weak iso-spin space
$SU(2)_L$: 3 gauge fields: W_1, W_2, W_3

Rotations in hypercharge space
$U(1)_Y$: 1 gauge field: B

Lagrangian of the Standard Model

Gauge fields

Interactions

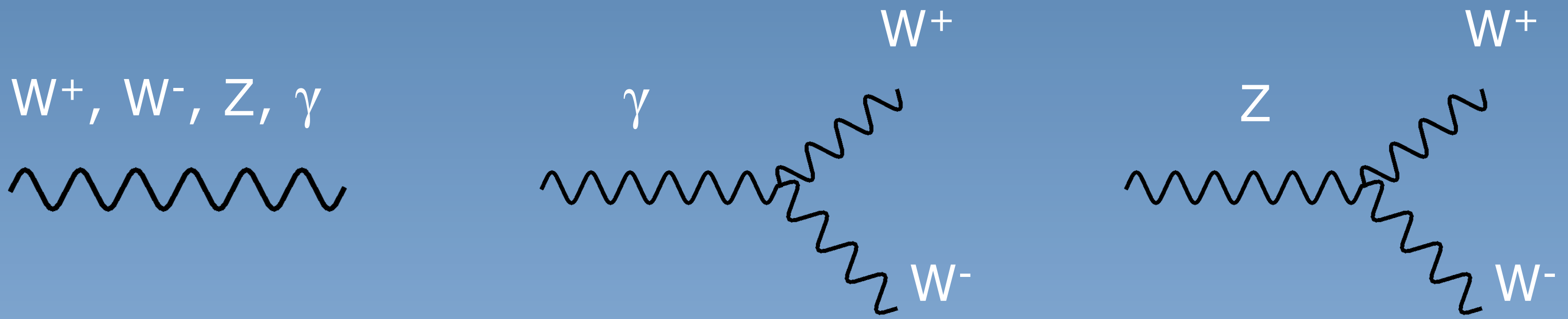


Covariante derivative electroweak theory

$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau} \cdot \vec{W}_\mu + ig'\frac{1}{2}Y B_\mu$$

Self-coupling gauge fields: prediction

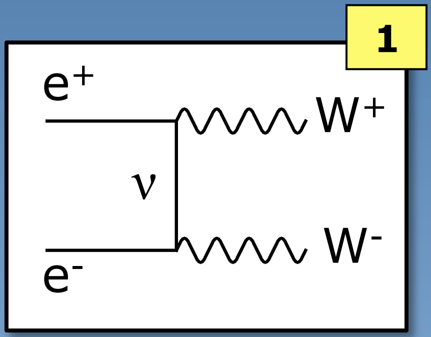
Rotations in SU(2) do not commute → self interaction gauge fields

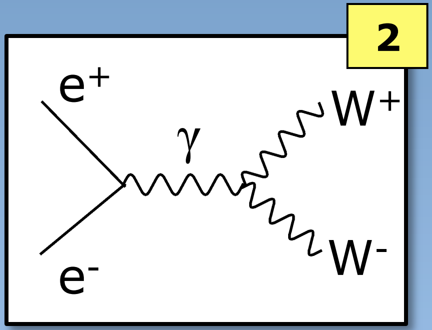


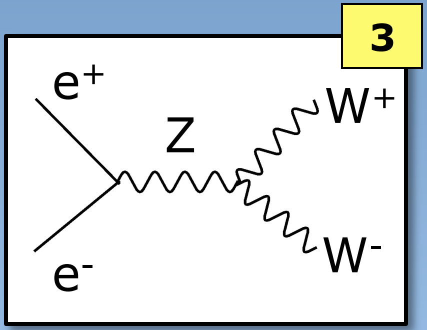
boson propagator *self-coupling* *self-coupling*

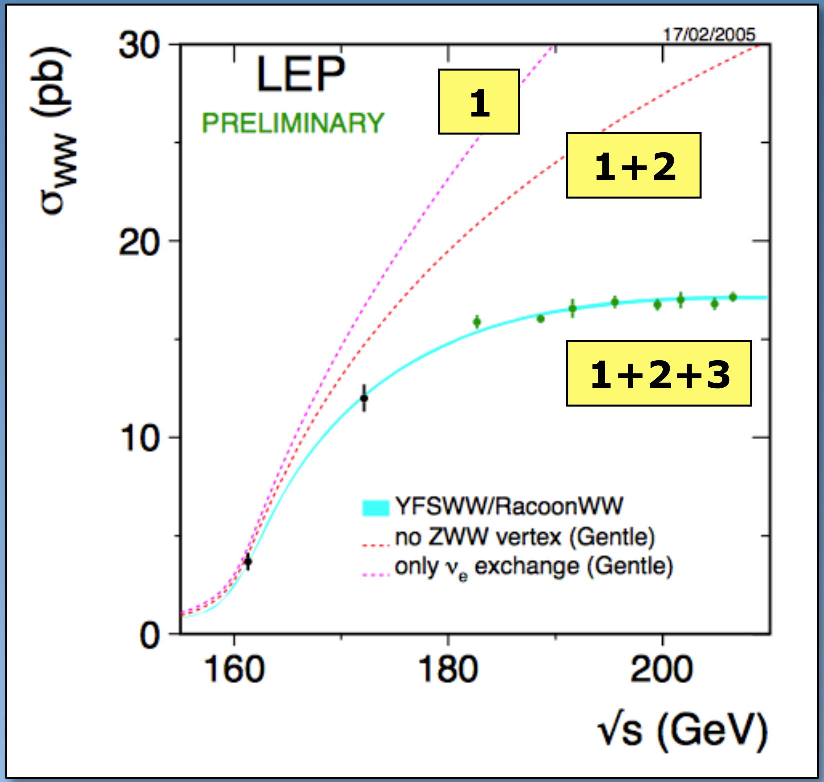
Self-coupling gauge fields: measurement

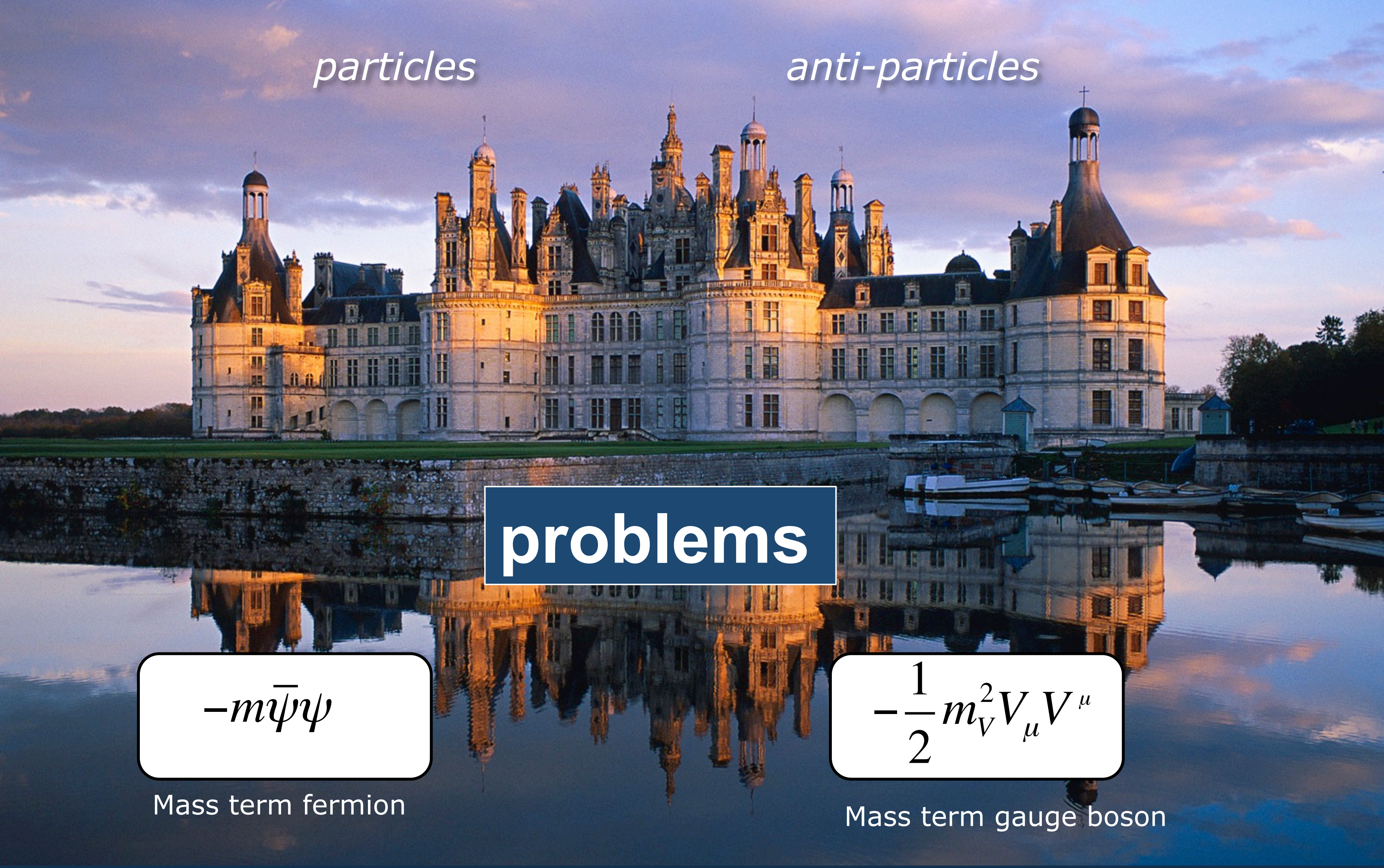
Measurement of $e^+e^- \rightarrow W^+W^-$ cross-section at LEP accelerator











Standard Model does ***not*** allow for massive gauge bosons or fermions

Higgs in the SM

Symmetry breaking

Adding a new field φ to the model

$L_{tot} = L_{old} +$

extra

$$\mathcal{L}_{\phi} = \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi)$$
$$= \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

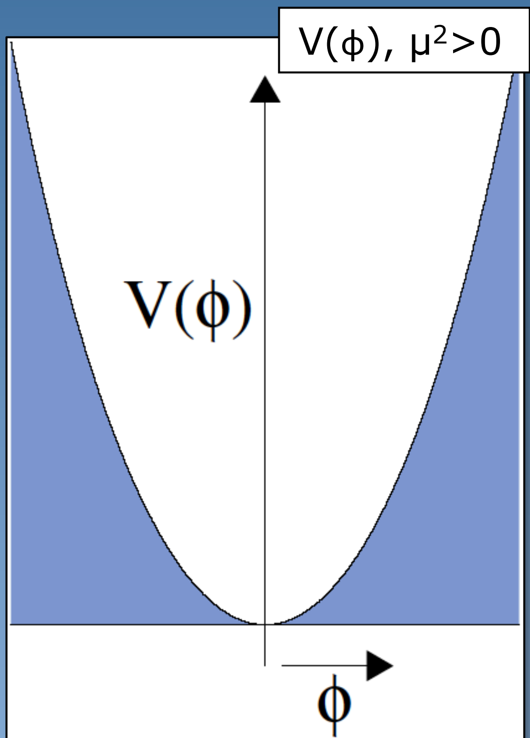
Current theory

kinetic energy

potential energy

Note:
- potential symmetric under $\phi \rightarrow -\phi$
- Two possibilities $V(\phi)$: $\mu^2>0$ and $\mu^2<0$
- Particle content interpretation ? Look at excitations around vacuum

Option 1: $\mu^2>0$



Particle content:

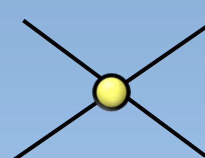
- Minimum at $\phi=0$ → excitations in ϕ

extra

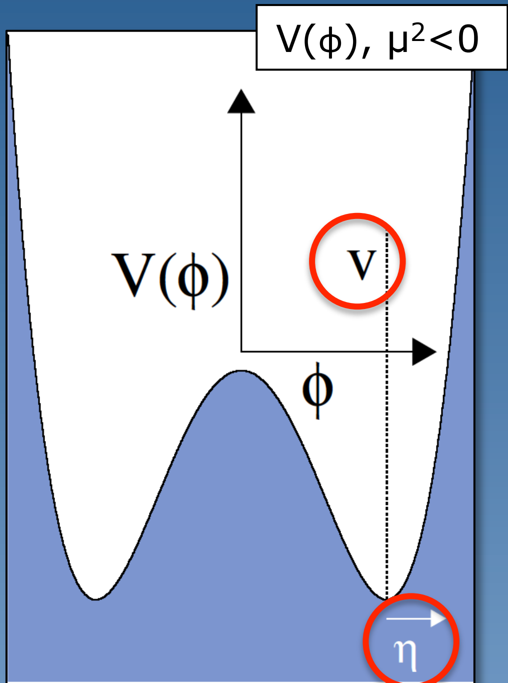
$$
\begin{aligned}
\mathcal{L}_{\phi} &= \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) \\
&= \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4
\end{aligned}
$$

massive particle
$m_\phi = \mu$

self-interaction



Option 2: $\mu^2<0$



Particle content of the model:

- Minimum at $\phi = \phi_0 = v = \sqrt{-\frac{\mu^2}{\lambda}}$ → excitations in η
- Potential is symmetric in ϕ, but not in η

$$\mathcal{L}_{\phi} = \frac{1}{2}(\partial_\mu \phi)^2 - \mathrm{V}(\phi)$$
$$= \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4$$

extra

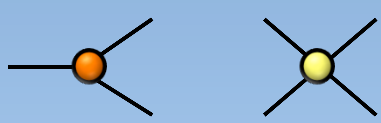
rewrite in terms of η=ϕ-v

constant

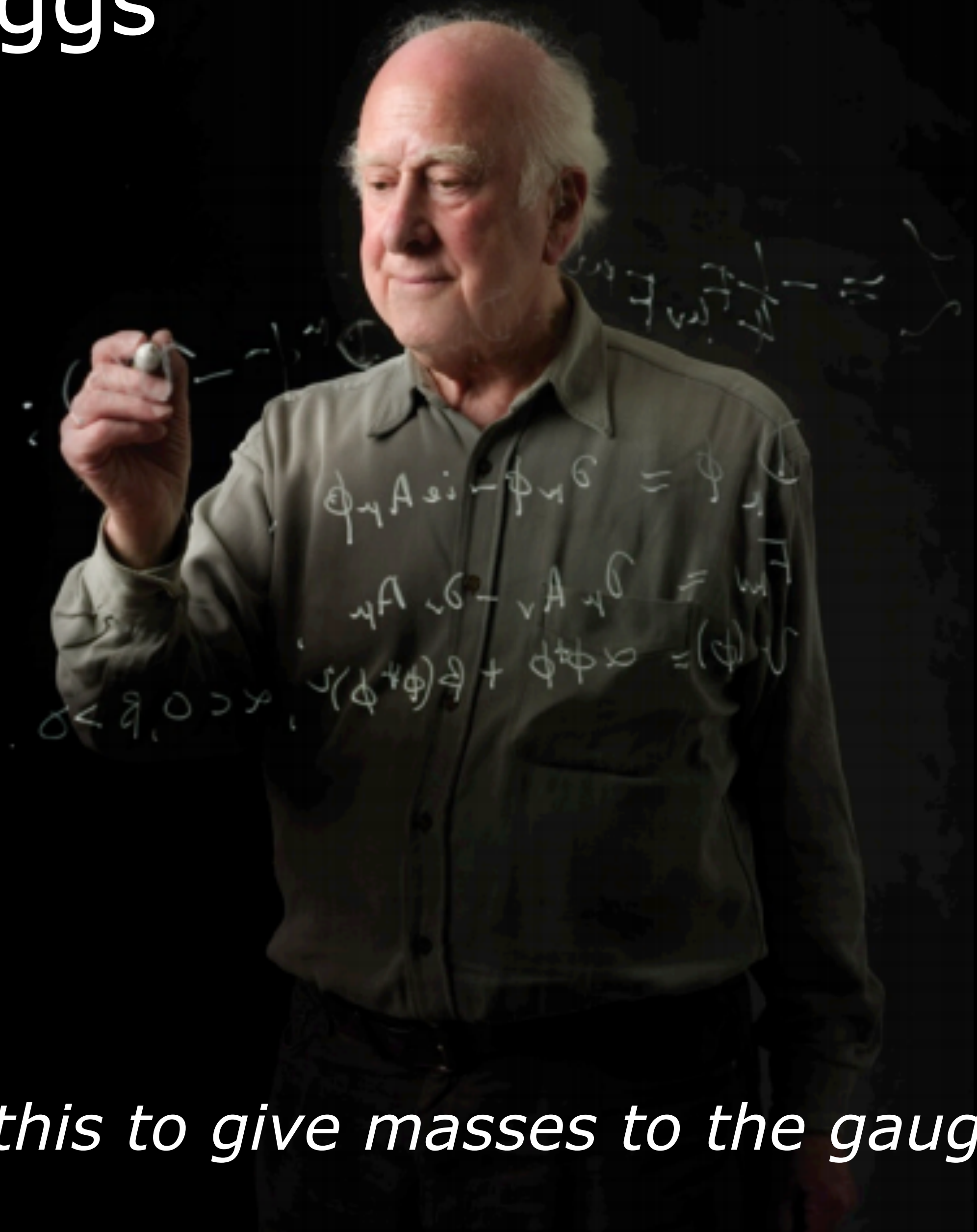
$$\mathcal{L}(\eta) = \frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \lambda v^2 \eta^2 - \lambda v \eta^3 - \frac{1}{4}\lambda\eta^4 - \frac{1}{4}\lambda v^4$$

massive particle
$m_\eta = \sqrt{(-\mu^2)}$

self-interactions

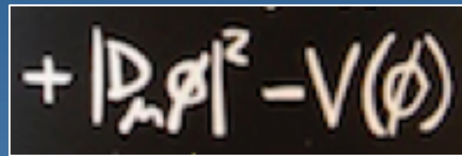


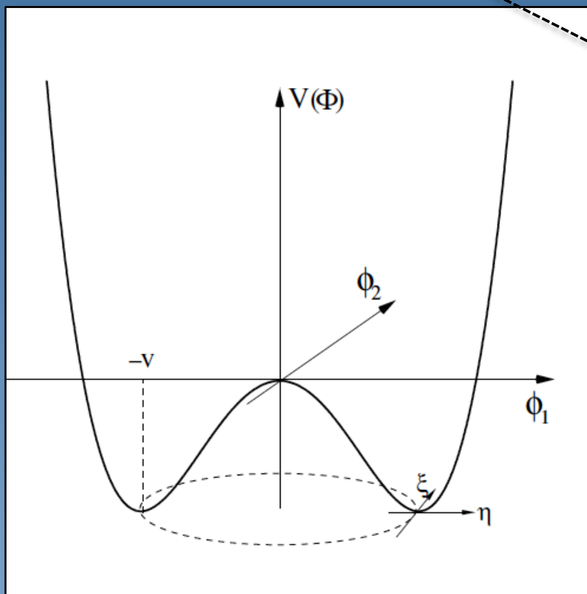
Peter Higgs



“I can use this to give masses to the gauge bosons”

Adding a complex field to Standard Model





Basic 'object' in SM, like (neutrino electron)

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \qquad \phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$$\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi^\dagger \phi)$$

massive scalar + self-int.

Terms ~ $(v+h)^2 X^2$, with $X = W_1, W_2, W_3, B$

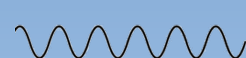
$$+|D_\mu \phi|^2 - V(\phi)$$

$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{1}{2}YB_\mu$$

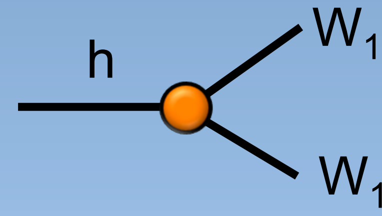
$$\phi = (v + h)$$

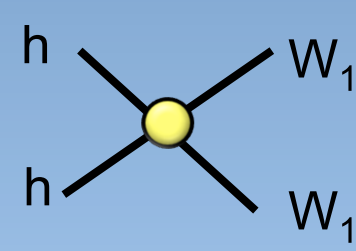
Terms W_1 boson = $(v+h)^2 W_1^2$

$$= v^2W_1^2 \quad + \quad 2vhW_1^2 \quad + \quad h^2W_1^2$$



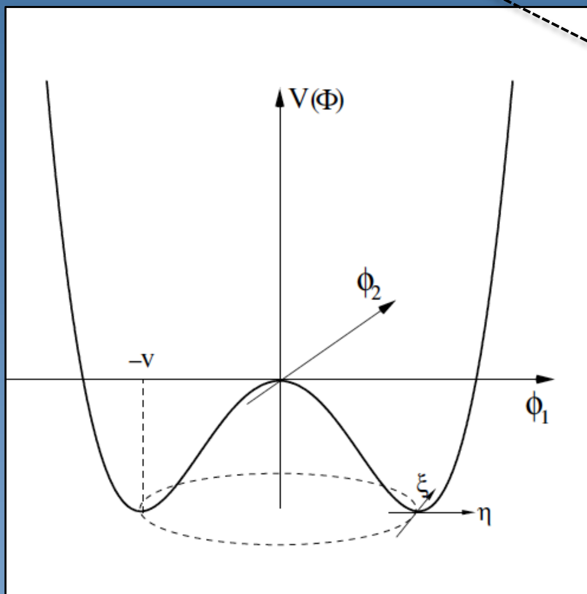
Mass term W_1 boson





Adding a complex field to Standard Model

$$+|D_\mu \phi|^2 - V(\phi)$$



Basic 'object' in SM, like (neutrino electron)

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$$\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi^\dagger \phi)$$

massive scalar + self-int.

Terms ~ $(v+h)^2X^2$, with X = W_1, W_2, W_3, B

Part associated to gauge boson masses ($\sim v^2X^2$):

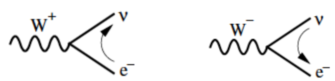
$$(D^\mu \phi)^\dagger (D_\mu \phi) = \frac{1}{8} v^2 \left[g^2 (W_1^2 + W_2^2) + (-gW_3 + g' Y_{\phi_0} B_\mu)^2 \right]$$

Problem: - W_1 and W_2 not charge eigenstates
- W_3 and B not mass eigenstates

Solution: use other basis to span rotations in $SU(2)_L x U(1)_Y$ space

Part of Lagrangian with ~ αvV²

$$(D^\mu\phi)^\dagger(D_\mu\phi) = \frac{1}{8}v^2\left[g^2(W_1^2+W_2^2)+(-gW_3+g'Y_{\phi_0}B_\mu)^2\right]$$



$$W^\pm = \frac{1}{\sqrt{2}}(W_1 \mp iW_2)$$

electroweak mixing

$$\frac{1}{\sqrt{g^2+g'^2}}(g'W_3+gB_\mu) = A_\mu \quad \text{photon}(\gamma)$$

$$\frac{1}{\sqrt{g^2+g'^2}}(gW_3-g'B_\mu) = Z_\mu \quad \text{Z-boson (Z)}$$

$$(D^\mu\phi)^\dagger(D_\mu\phi) = \frac{1}{8}v^2[g^2(W^+)^2+g^2(W^-)^2+(g^2+g'^2)Z_\mu^2+0\cdot A_\mu^2]$$

$$M_{W^+} = M_{W^-} = \frac{1}{2}vg$$

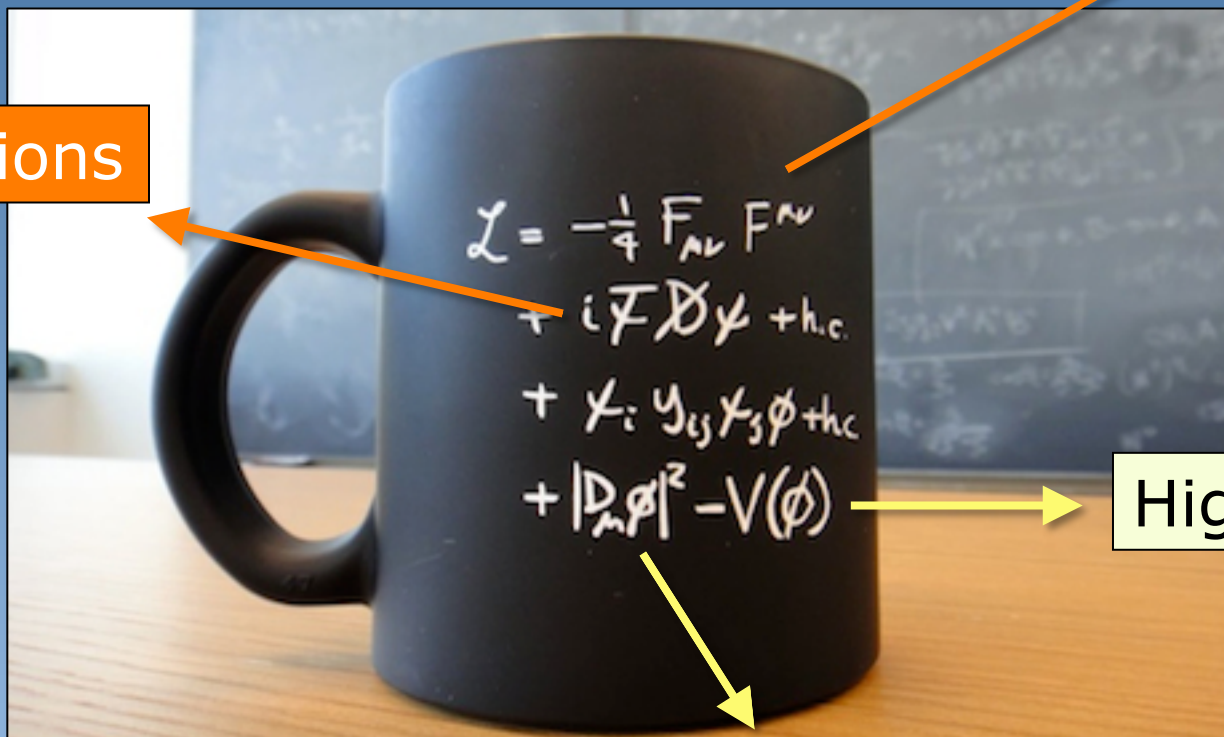
$$M_\gamma = 0.$$

$$M_Z = \frac{1}{2}v\sqrt{(g^2+g'^2)}$$

Lagrangian of the Standard Model

Gauge fields

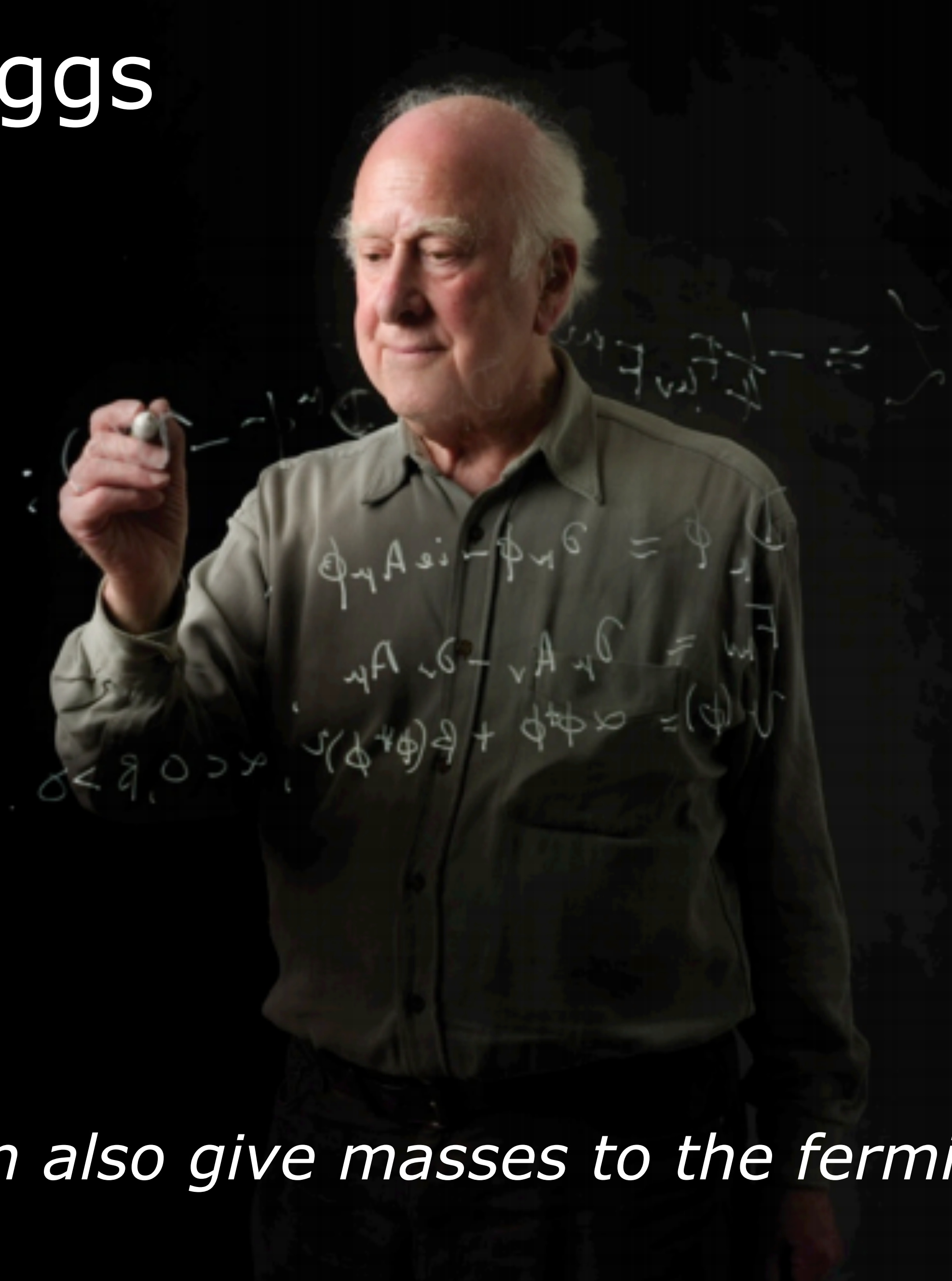
Interactions



Higgs particle

Gauge boson masses

Peter Higgs



"I can also give masses to the fermions"

Fermion masses

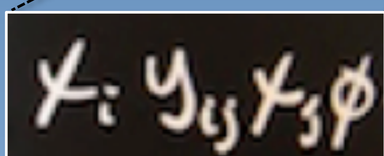
$$L_{QED} = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\bar{\psi}\psi$$

***Not** local gauge invariant*

$$-m[\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L]$$

$$L_{QED} = i\bar{\psi}\gamma_{\mu}\partial^{\mu}\psi - m\bar{\psi}\phi\psi$$

local gauge invariant



$$-m\bar{\psi}(v + h)\psi$$

Fermion mass-term

Interaction fermion-Higgs

$$\mathcal{L}_e = -\underbrace{\frac{\lambda_e v}{\sqrt{2}}\bar{e}e}_{\text{electron mass term}} - \underbrace{\frac{\lambda_e}{\sqrt{2}}h\bar{e}e}_{\text{electron-higgs interaction}}$$

$$m_e = \frac{\lambda_e v}{\sqrt{2}} \qquad \frac{\lambda_e}{\sqrt{2}} \propto m_e$$

Lagrangian of the Standard Model

Gauge fields

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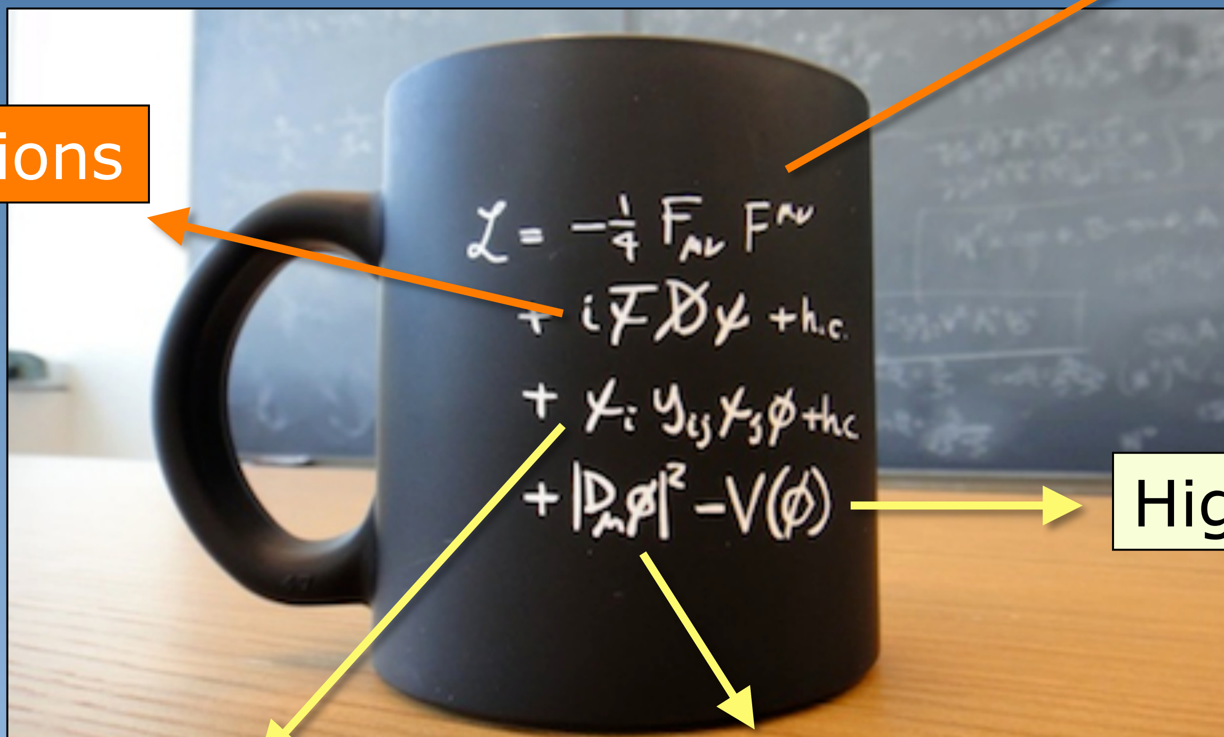

Higgs particle

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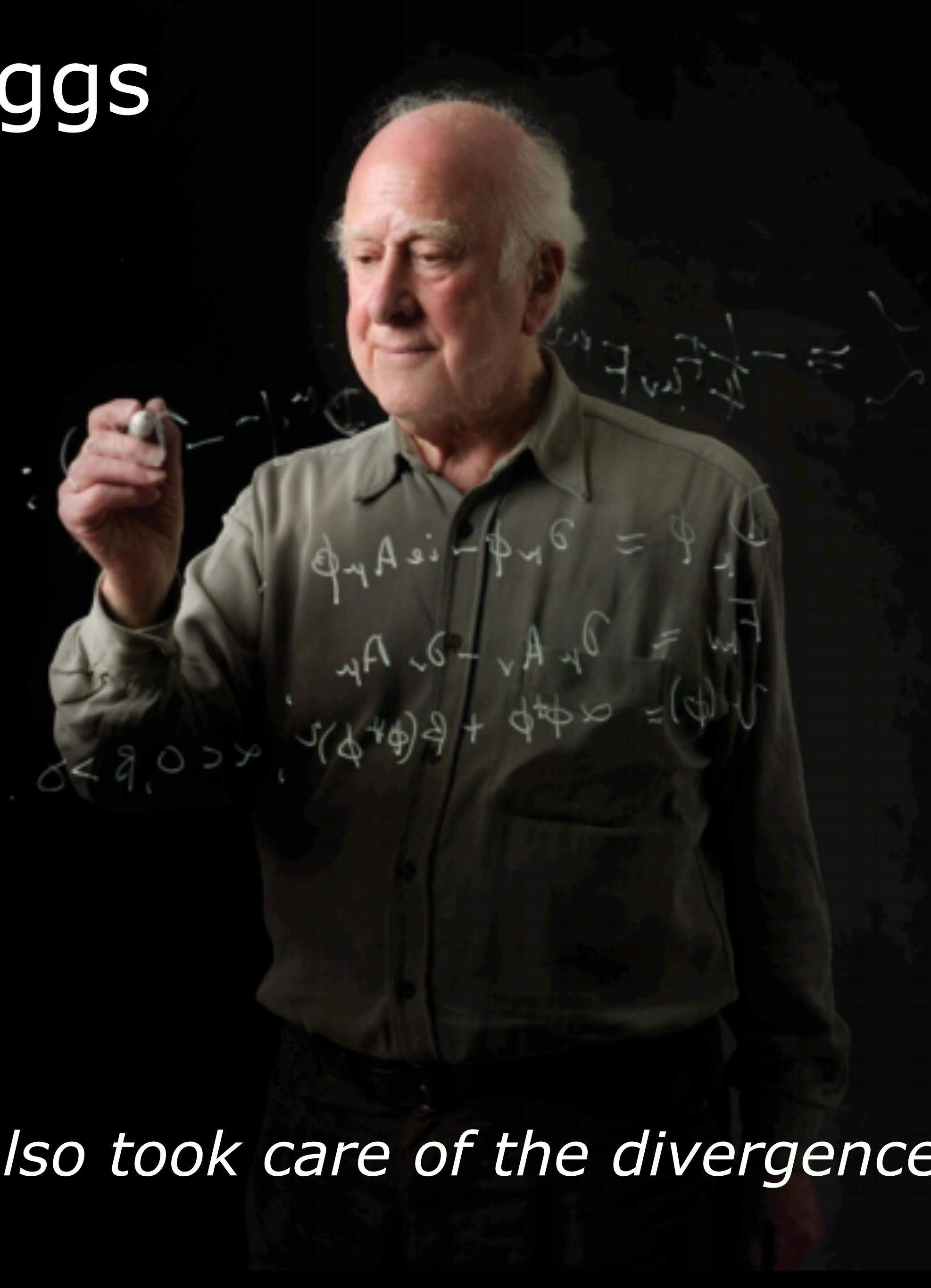
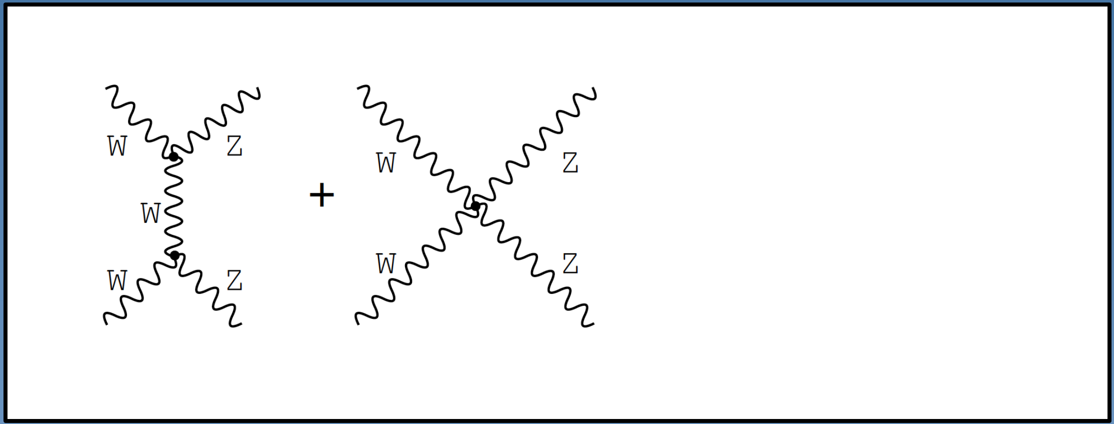
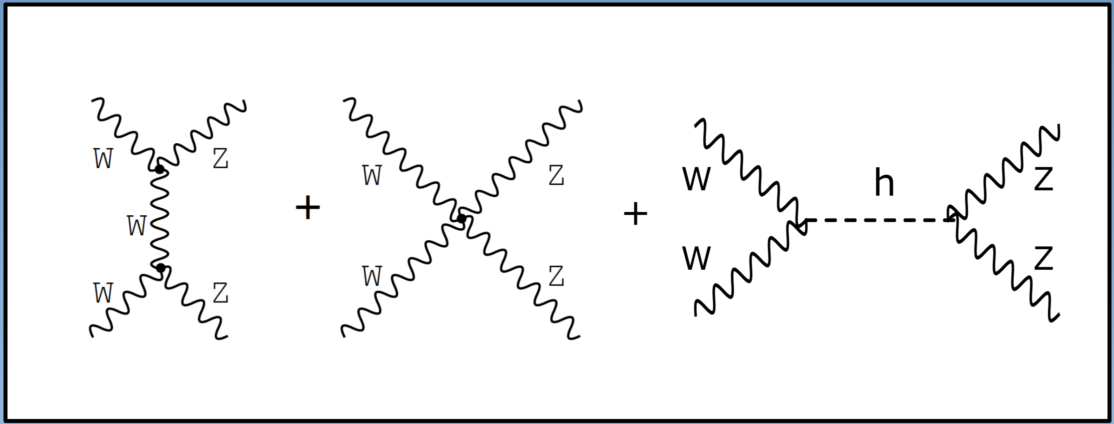


" I also took care of the divergences"

Higgs boson regulates vector boson scattering



$$M^2 \propto E^2$$



$$M^2 \propto \text{constant}$$

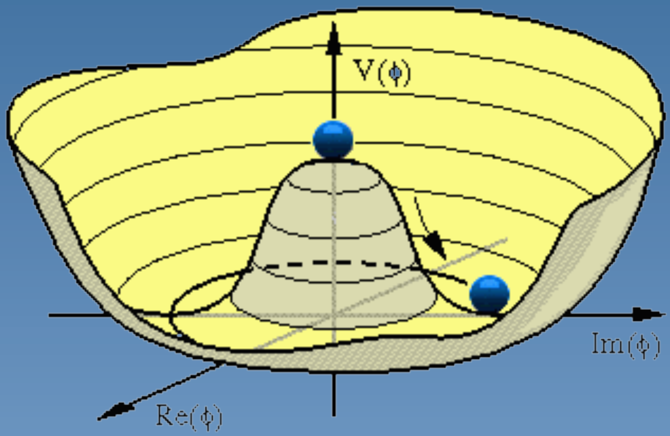
Higgs mechanims

Summary

The Higgs mechanism

You have:

An $SU(2)_L xU(1)_Y$ local gauge invariant theory



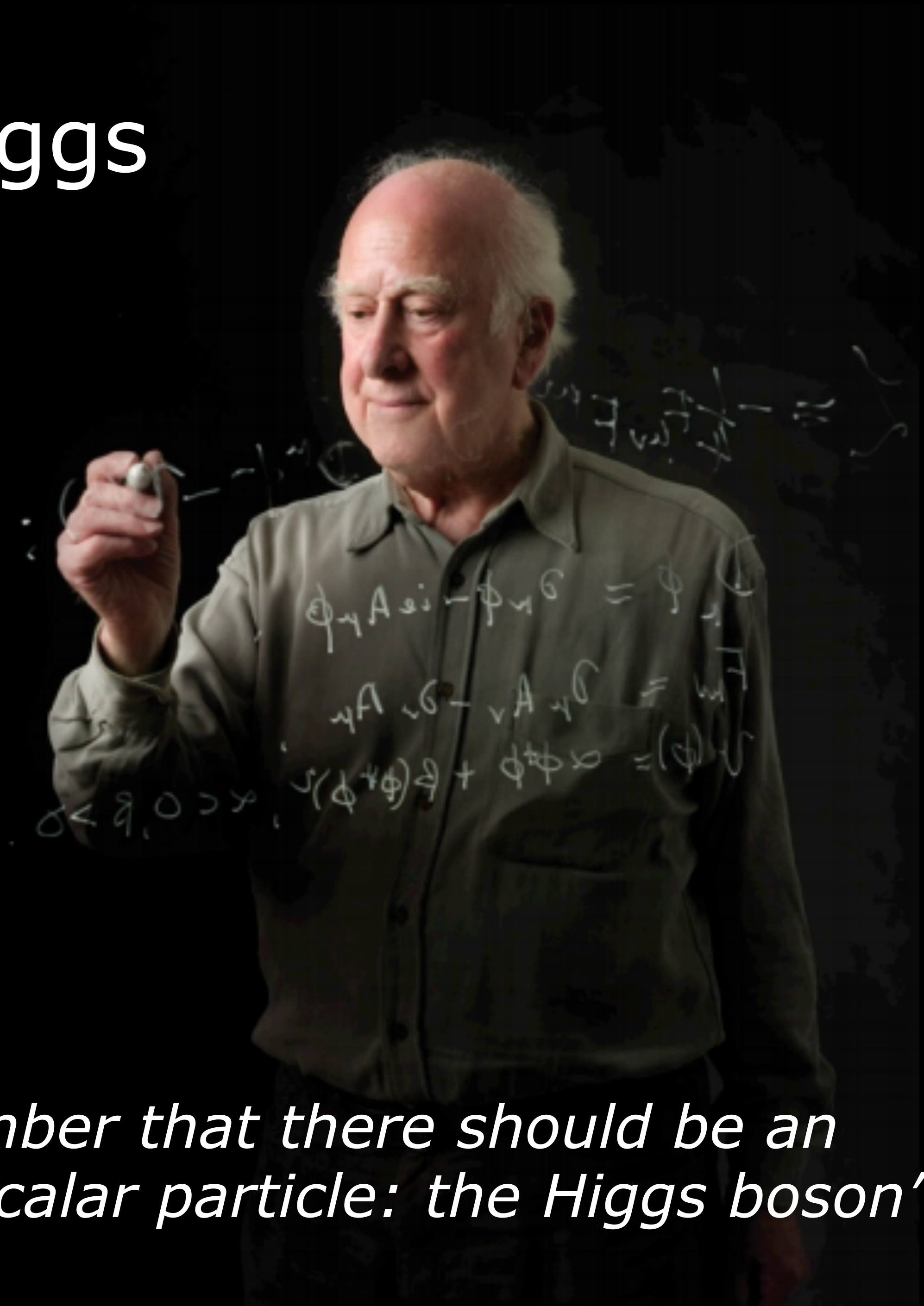
You put in:

- Extra $SU(2)_L$ doublet ϕ_{Higgs} with Y=+1
- Mexican hat potential $V(\phi)$

You get out:

1) Masses for the gauge bosons
   → automatic coupling between gauge bosons and Higgs boson
2) Masses for the fermions
   → automatic coupling between the fermions and the Higgs boson
3) Renormalizable Standard Model
4) Scalar particle: the Higgs boson

Peter Higgs



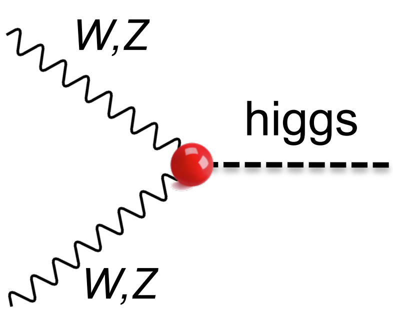
“Remember that there should be an extra scalar particle: the Higgs boson”

Higgs production & decay at the LHC

Production of the Higgs boson

Gauge bosons

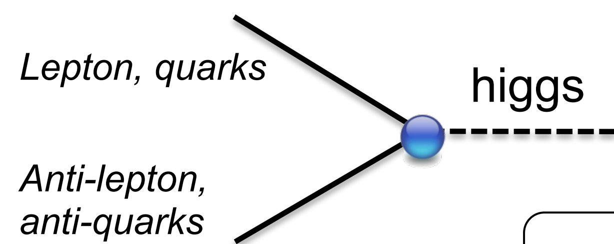
Massive gauge boson ?
… then the Higgs couples to it



$\propto m_V^2$

Fermions

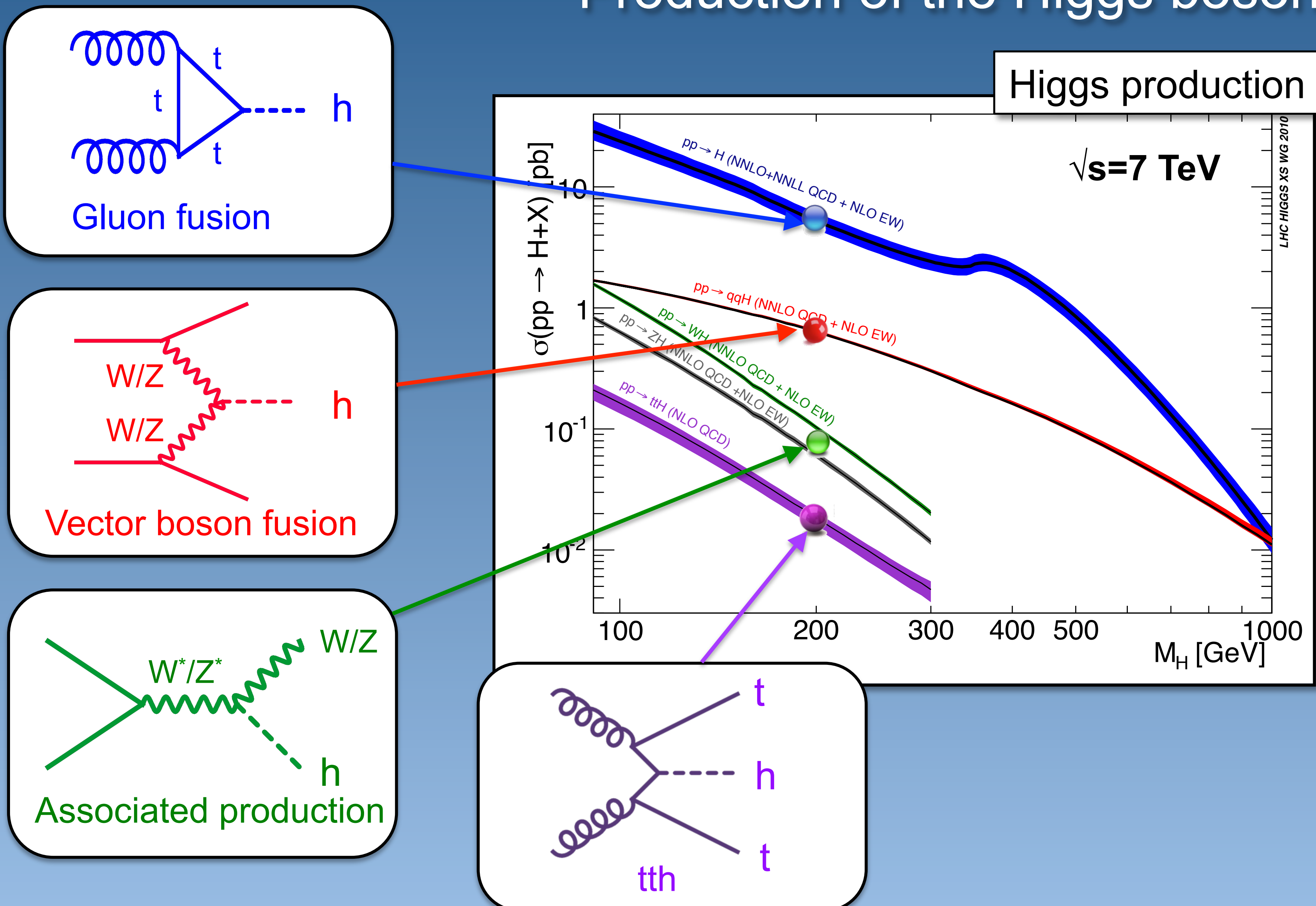
Massive fermion ?
… then the Higgs couples to it



$\propto m_f^2$

For a specific mass, all Higgs boson's properties (like couplings) are fixed

Production of the Higgs boson



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

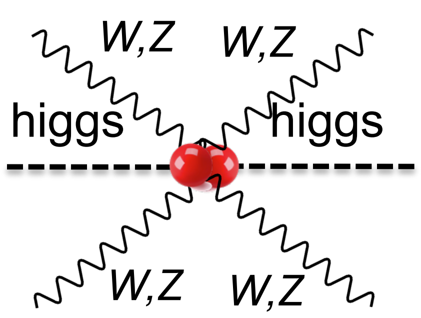
How many Higgs bosons have been produced at the LHC run-1

m_h = 125 GeV: ~ 500k

Decay of the Higgs boson

Gauge boson

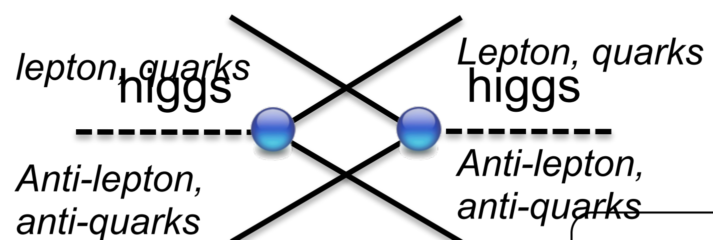
Massive gauge boson ?
… then the Higgs couples to it



$$\propto m_V^2$$

Fermion

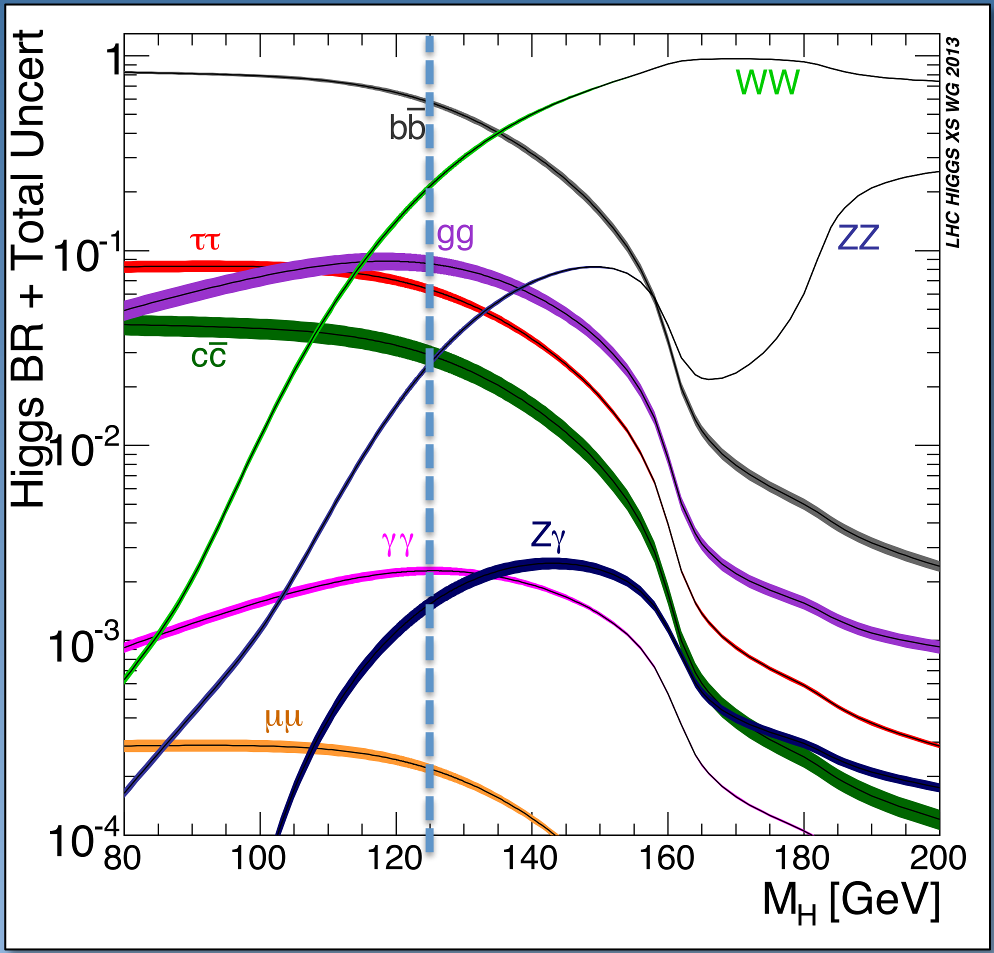
Massive fermion ?
… then the Higgs couples to it



$$\propto m_f^2$$

Higgs boson decay
Higgs boson production

Higgs branching fractions



m_h = 125 GeV

Br(h→bb) = 57.7 %

Br(h→WW) = 21.5 %

Br(h→ττ) = 6.32 %

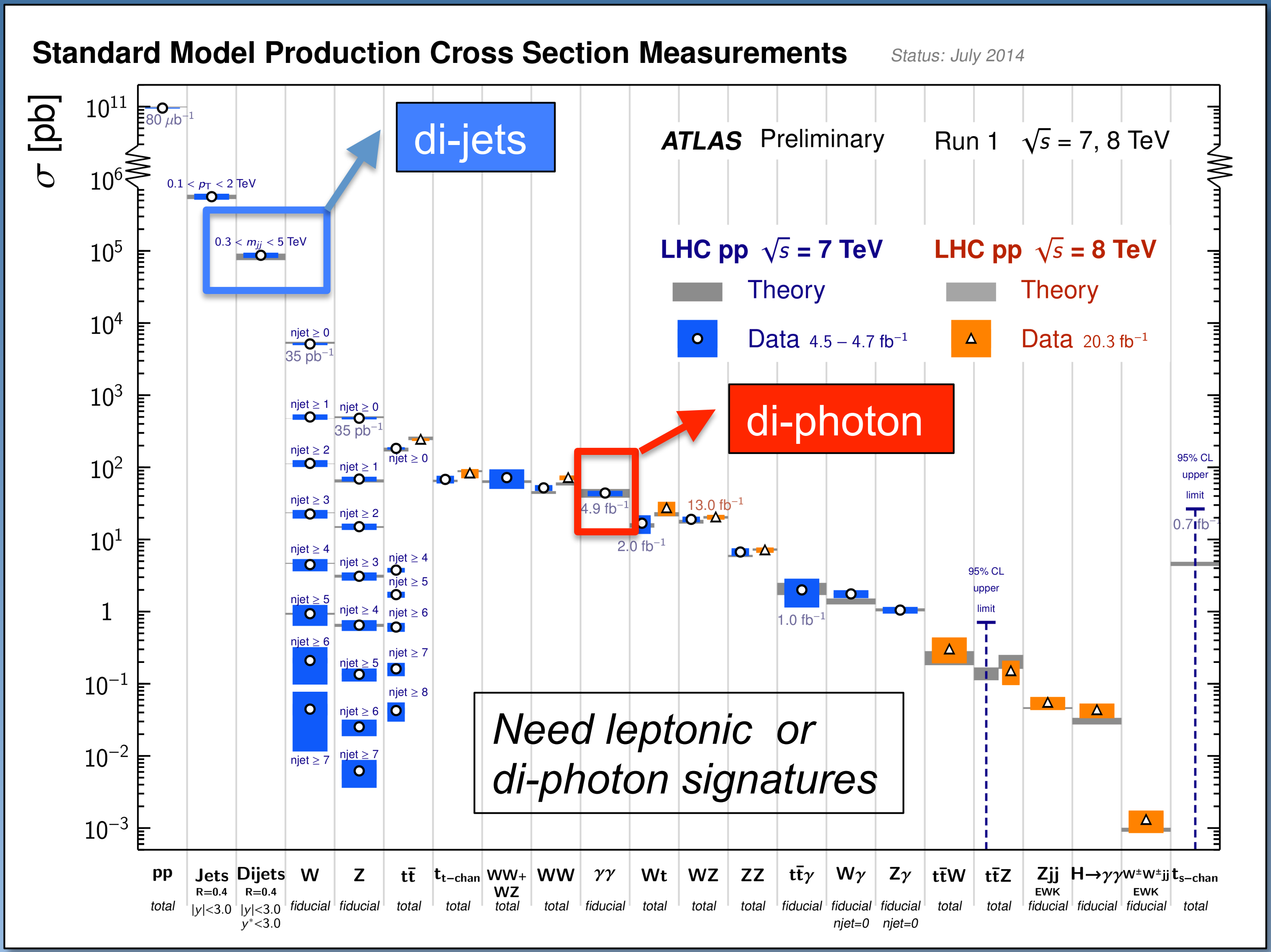
Br(h→ZZ) = 2.64 %

Br(h→γγ) = 0.23 %

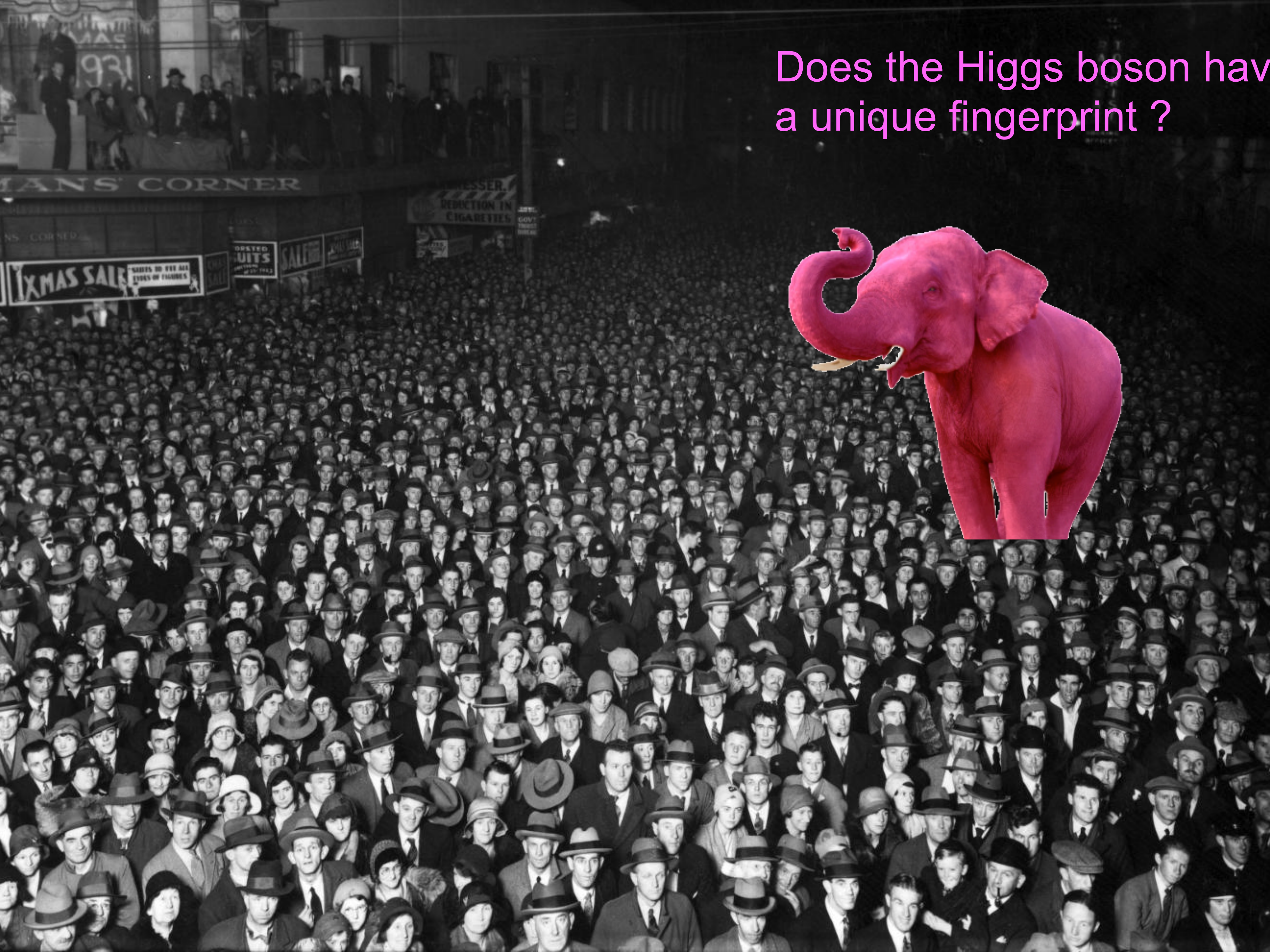
Br(h→Zγ) = 0.15 %

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

Standard Model cross-sections at the LHC

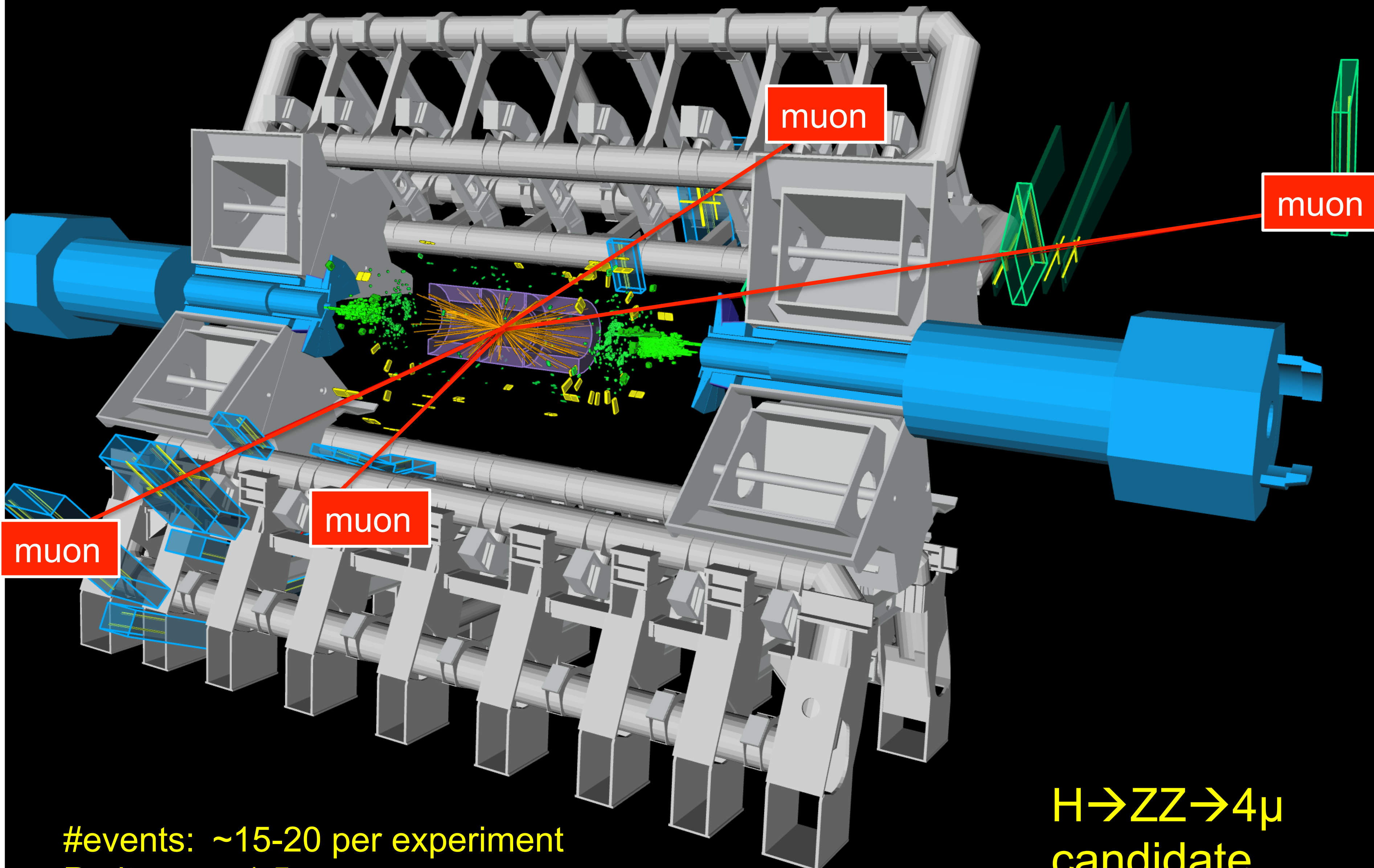



discovery


Does the Higgs boson hav
a unique fingerprint ?
ANS' CORNER
XMAS SALE
REDUCTION IN
CIGARETTES
SUITS


Liu Bolin
Or is it hidden in the background?

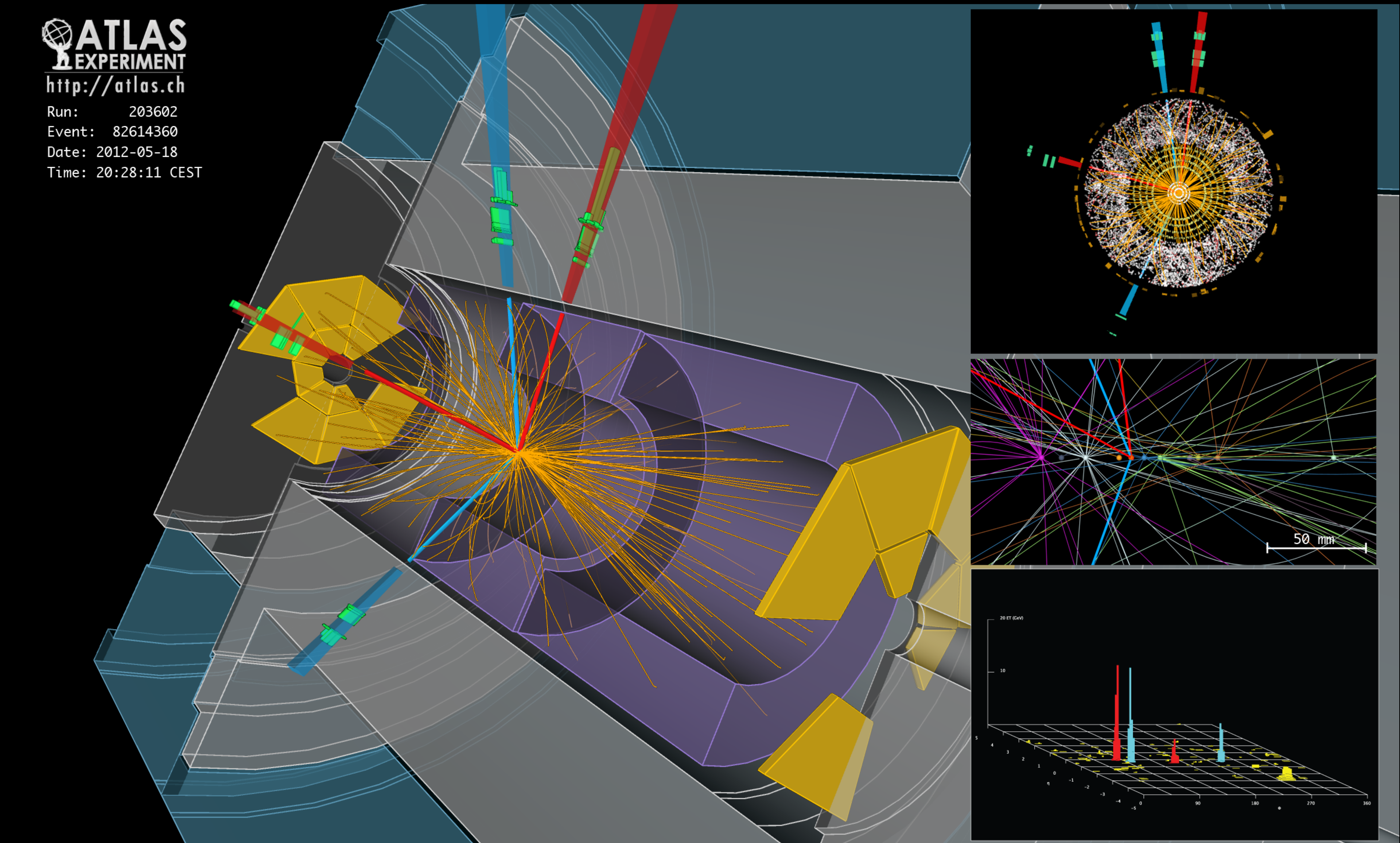

起重臂下严禁站人
ZL50
北京01
厂内 5301



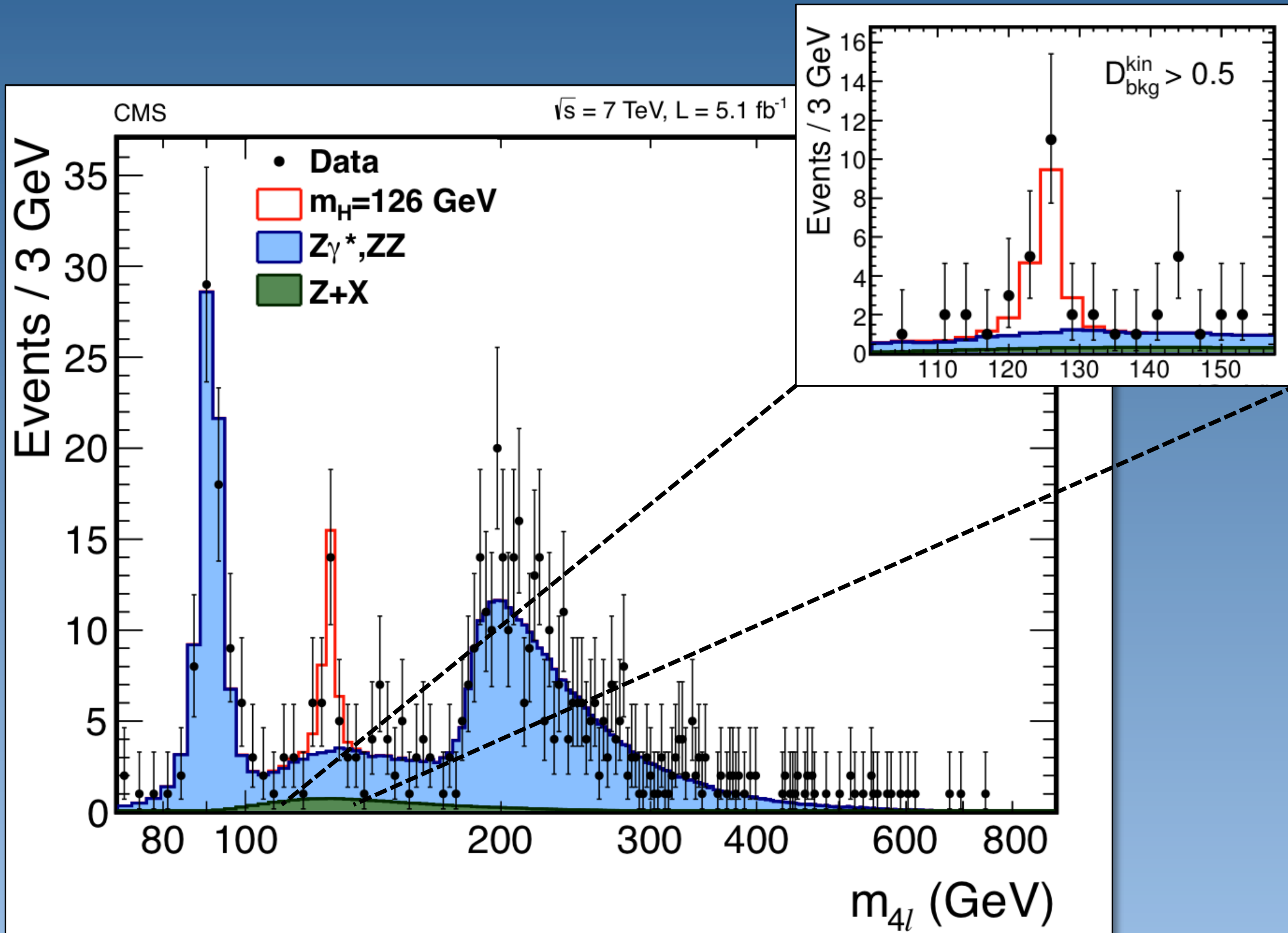
H→ZZ→4μ candidate

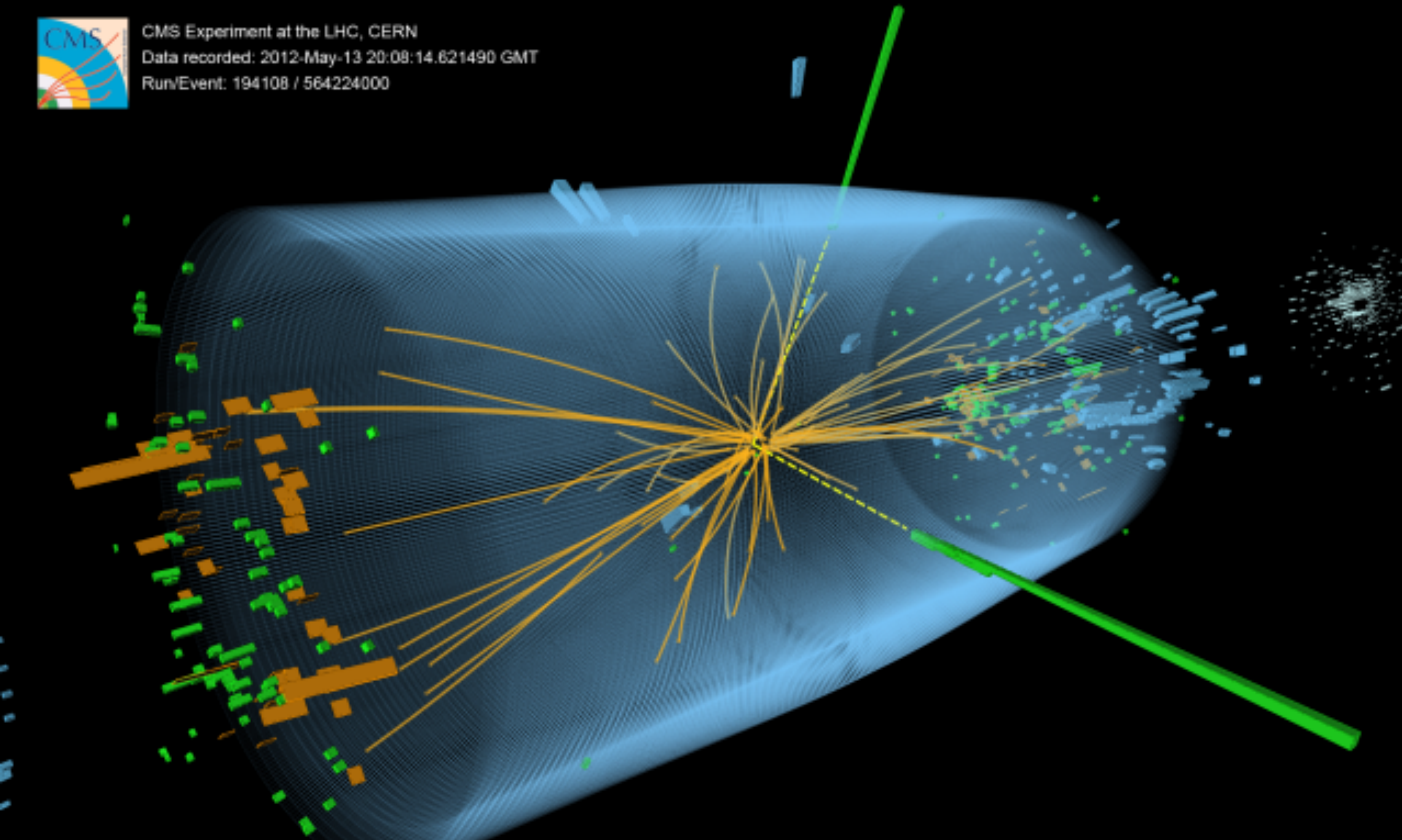
#events: ~15-20 per experiment
Purity: ~ 1.5

Another 4-lepton candidate



4 lepton invariant mass



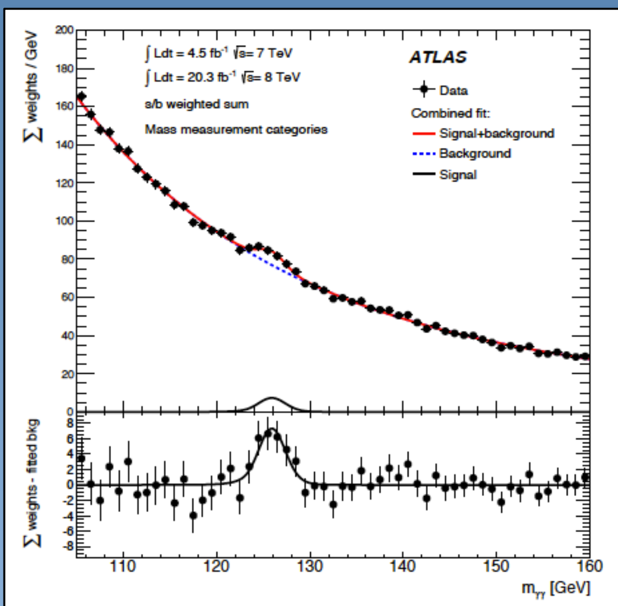


#events: ~ 500 per experiment
Purity: ~ 2%-60%

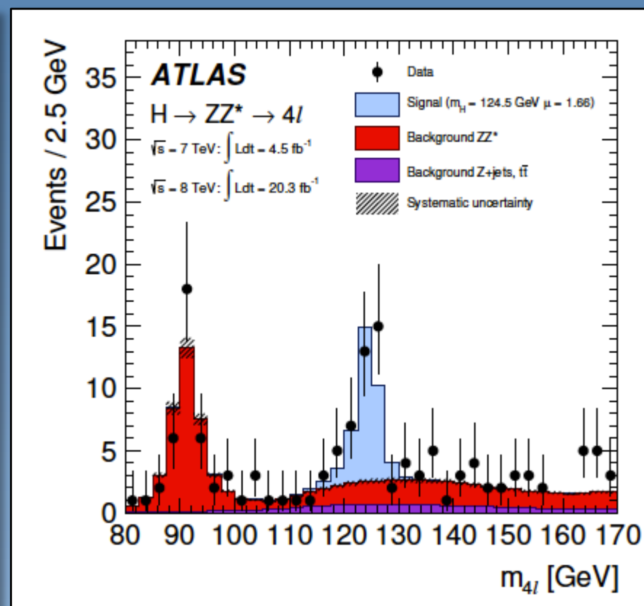
$H \rightarrow \gamma\gamma$ candidate

Discovery channels

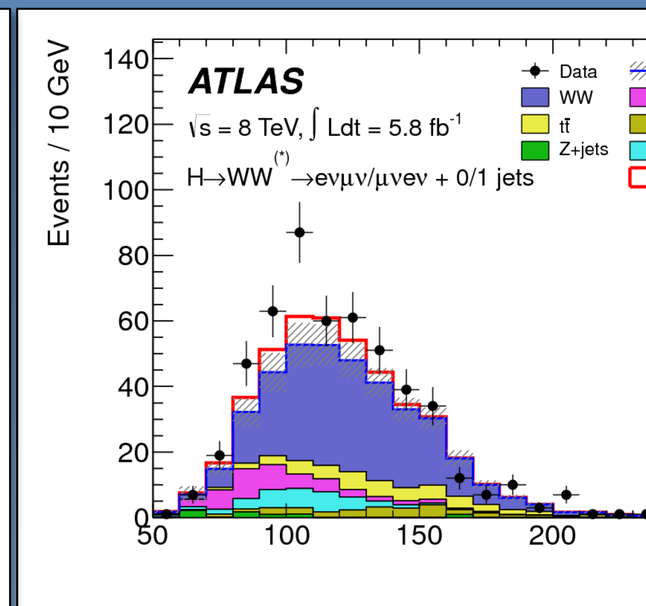
h→γγ



h→ZZ→4 leptonen



h→WW$^{(*)}$→lυlυ

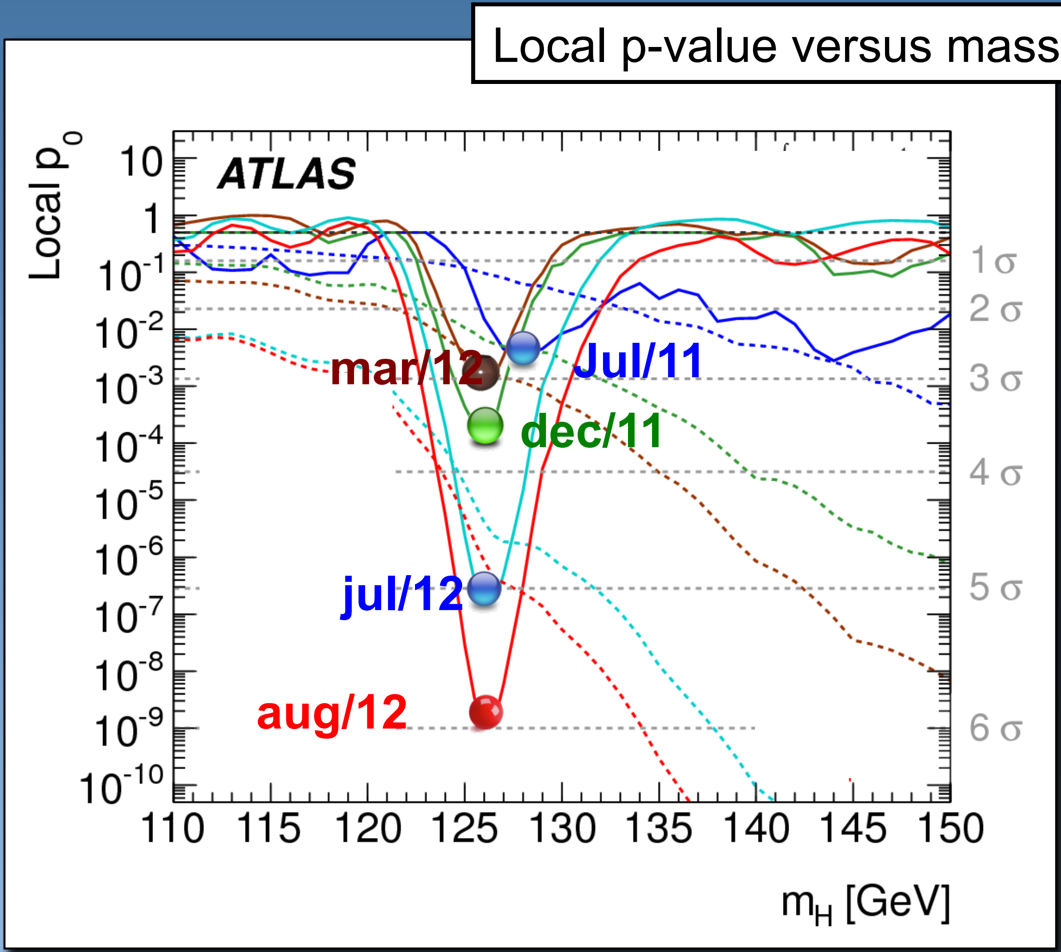


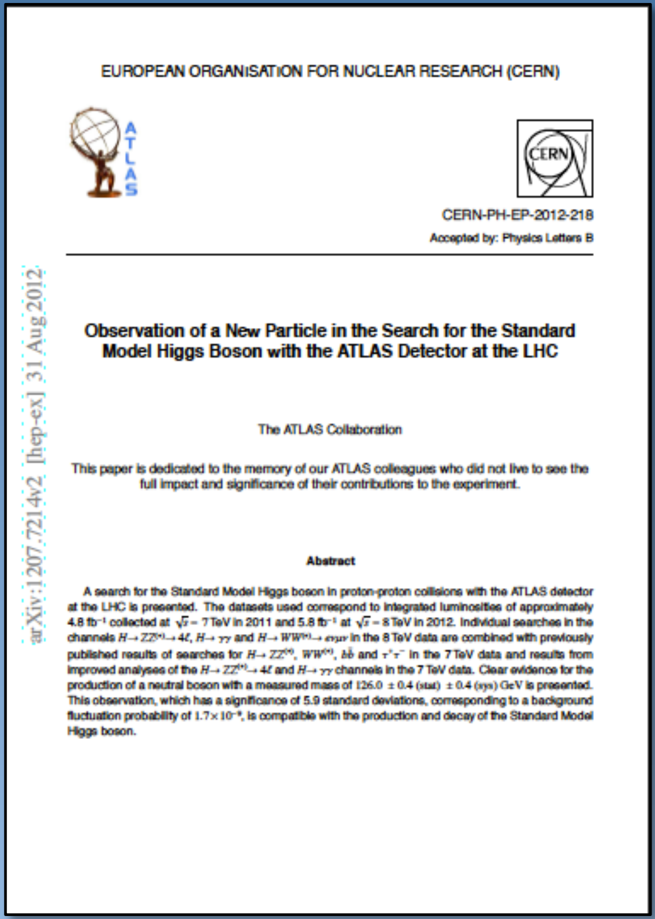
Invariant mass

statistics

We’ll do this in the exercise session

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.

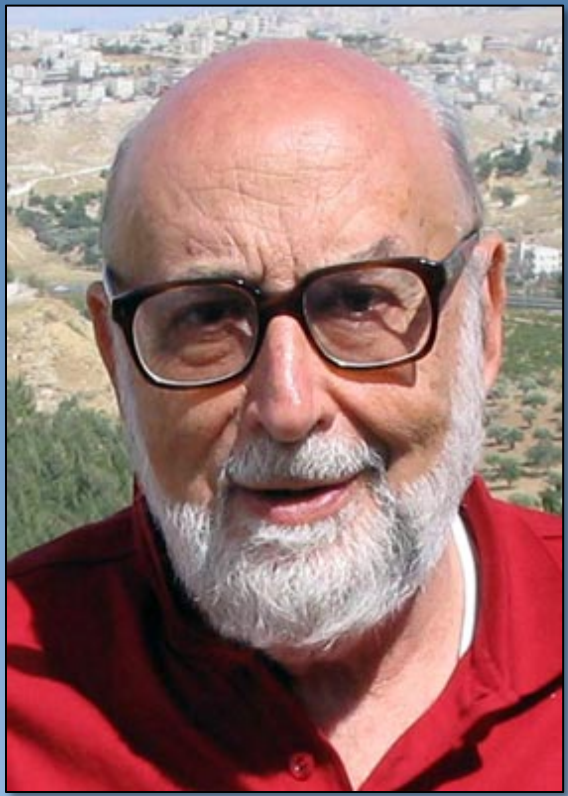
Abstract

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.

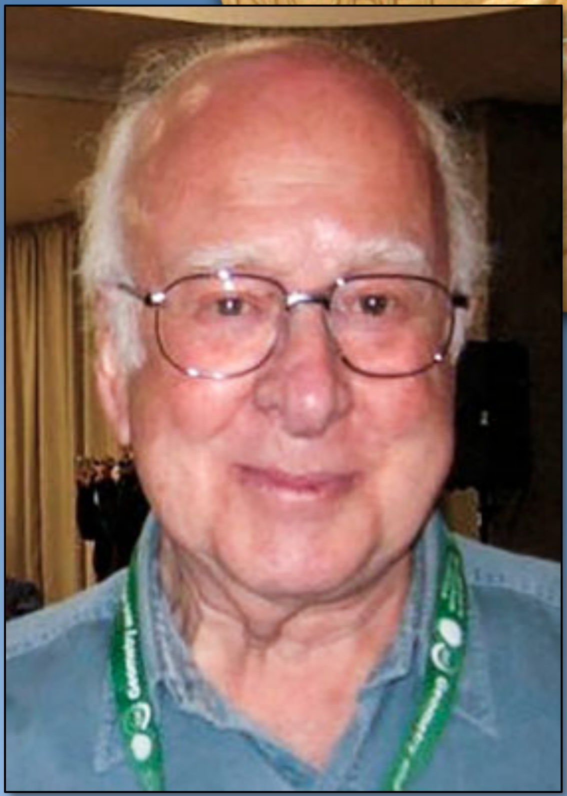
Physics is forever

Nobelprize Physics 2013

“There is a Higgs field in the vacuum”

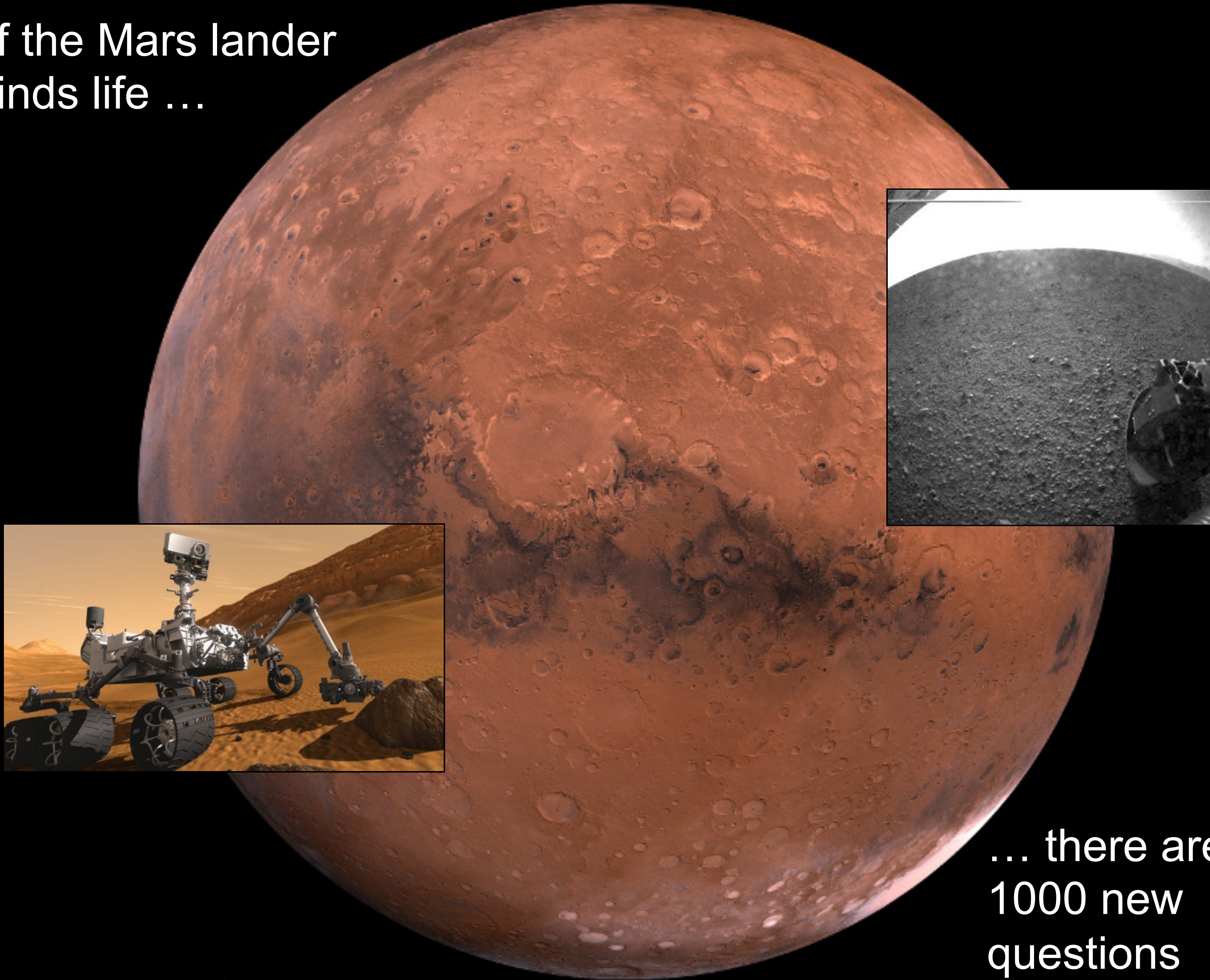


François Englert



Peter Higgs

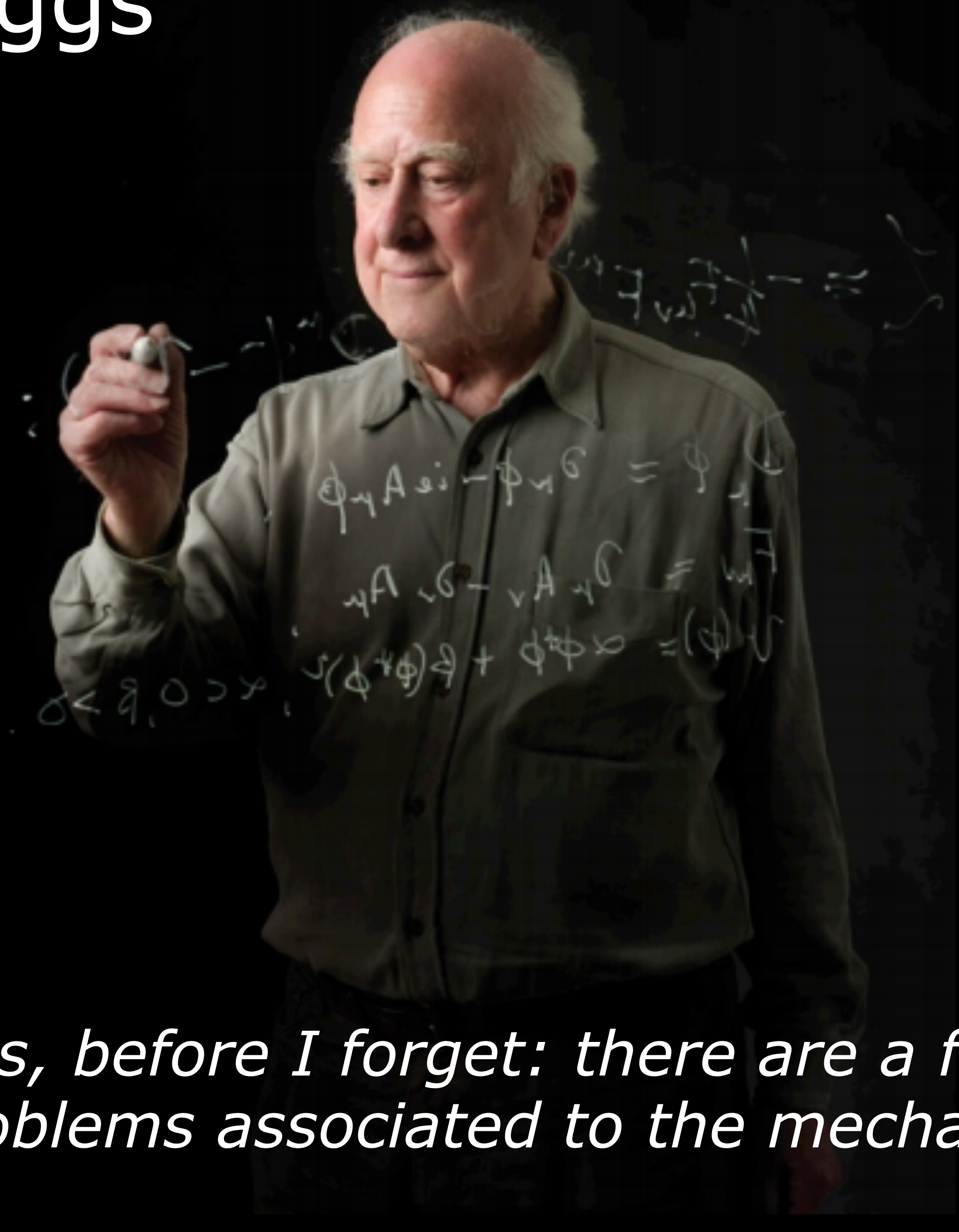
If the Mars lander finds life …



… there are a 1000 new questions

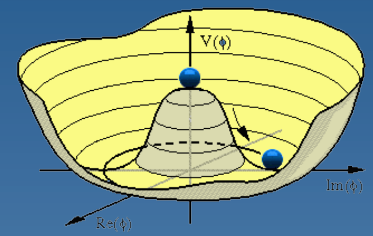
Problems

Peter Higgs

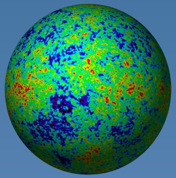


" Ah yes, before I forget: there are a few tiny problems associated to the mechanism"

Problems with the Higgs boson



1) Contribution Higgs field to vacuum energy

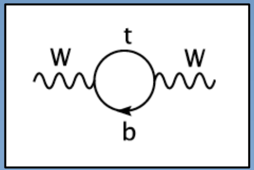
 

Prediction (SM): 1

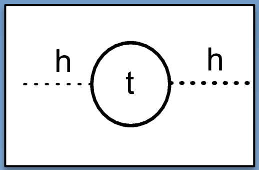
Measurement (CMB): 0.00000000000000000000000000000000000000000000000000000001

So, how come the universe is bigger than a soccer ball ?

2) Quantum corrections to effective boson masses



Z/W boson:
< 1 %



Higgs boson:
> 10000000000000 %

3) More fundamental questions

- What sets particle masses ? M_{top} ~ 1000000 x m_e ~ 1000000 x 1000000 x m_{ν}
- Higgs potential stable at high energies ? Only 1 Higgs boson ?

Questions regarding the Higgs boson

Is it the SM Higgs boson – couplings, spin, partity, … ?

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

What explains the mass hierarchy ?

Is it possible that Higgs field is linked to inflation ?

Each new idea changes the Higgs boson's properties

Higgs results are public

ATLAS experiment

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

CMS experiment

http://cms.web.cern.ch/org/cms-higgs-results

mass

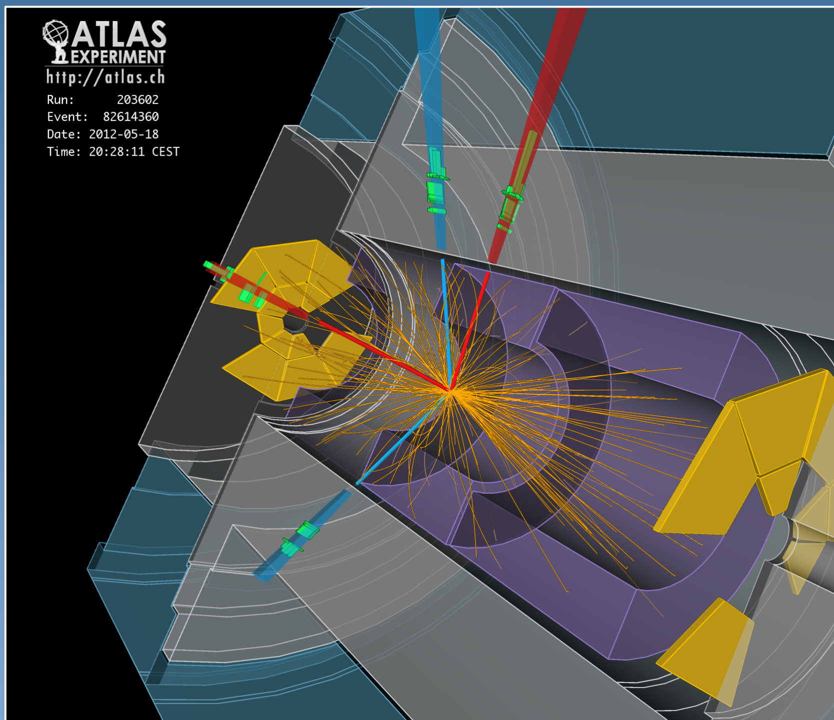
Why would you want to measure the Higgs mass to high accuracy ?

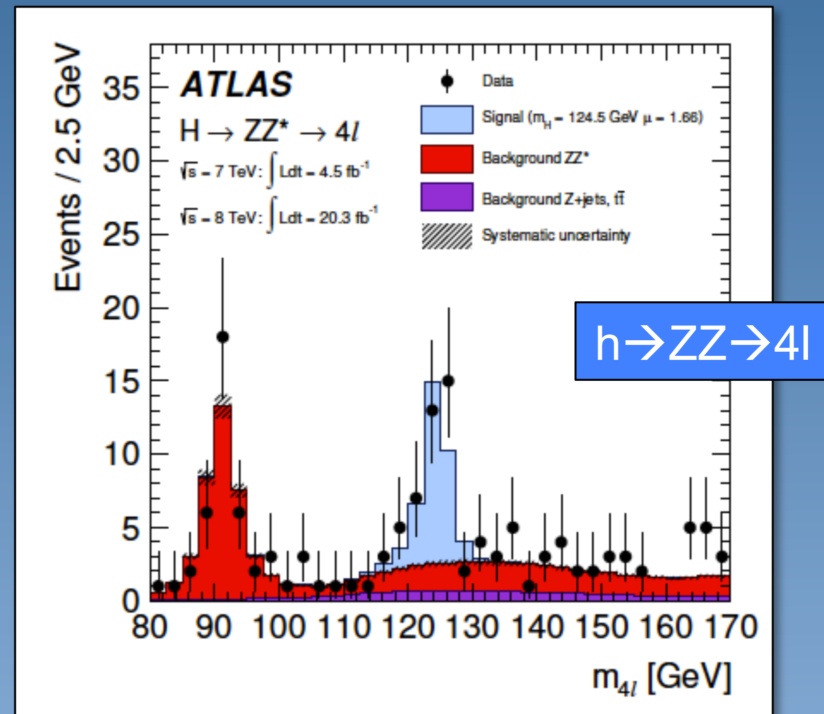
Why measure the mass to high precision ?

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

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

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

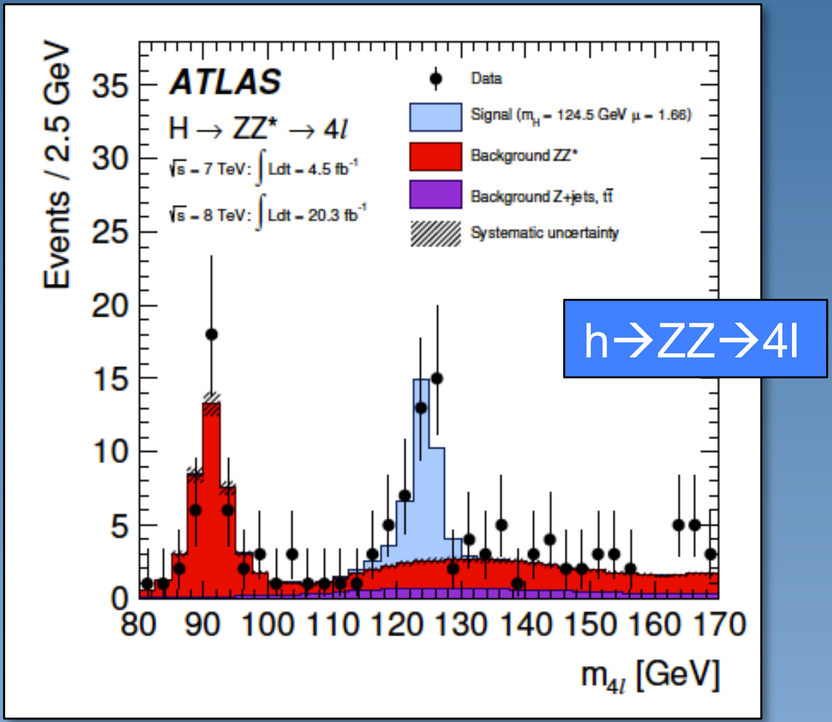
Mass measurement in the 4-lepton channel

Mass and signal strength
4-lepton channel

m_h = 124 .51 ± 0.52 GeV

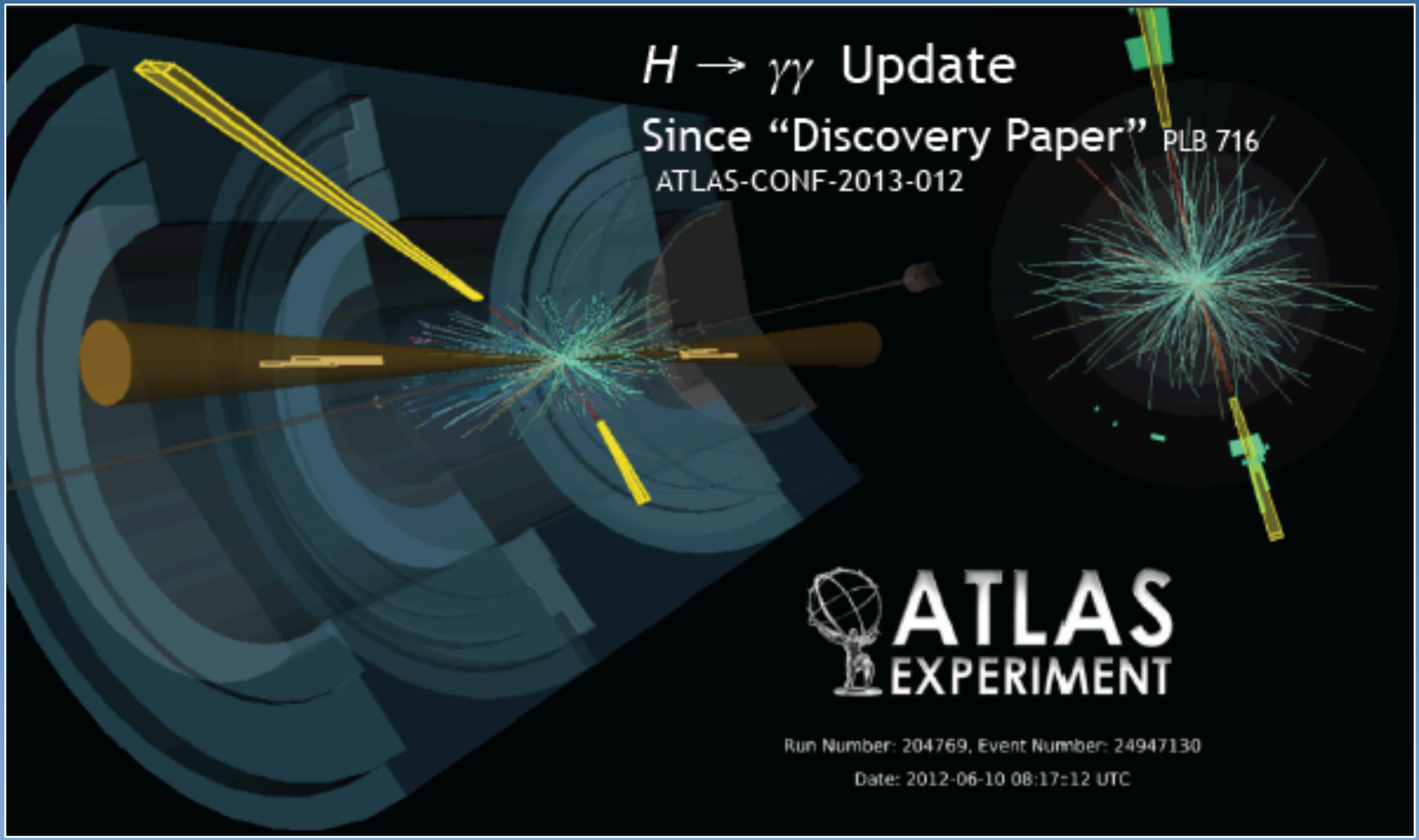
$$\mu = 1.66^{+0.45}_{+0.38}$$

cross-section w.r.t SM



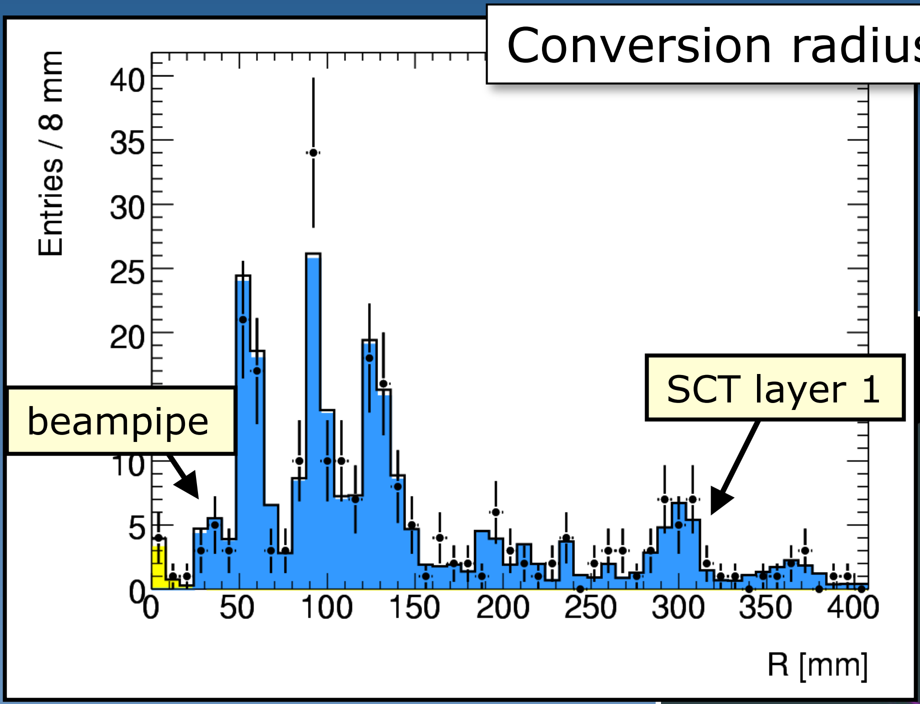
Excellent mass measurement, more events than expected

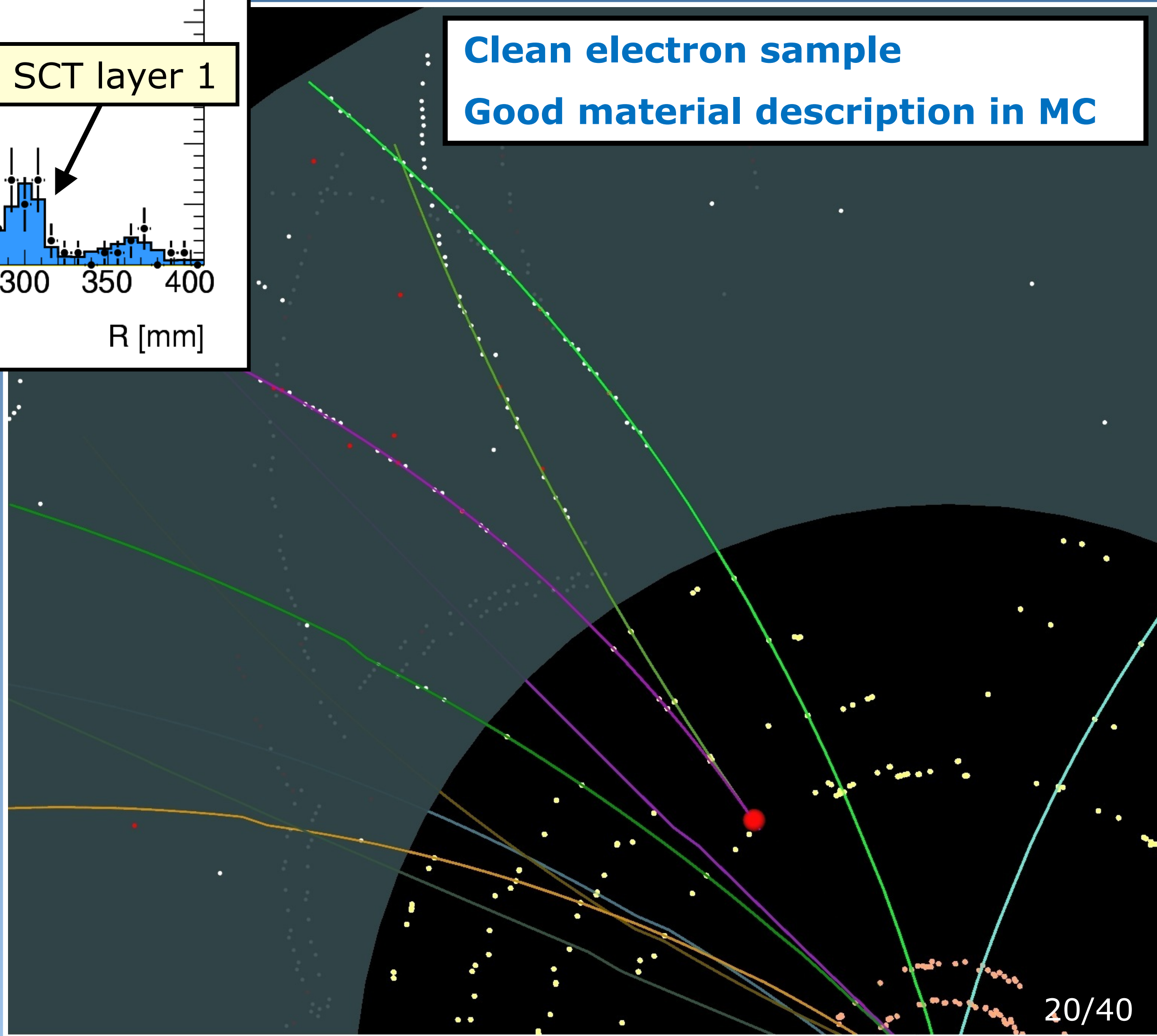
Difficulties in the 2-photon channel



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:	γγ, γj, jj

Photon conversions

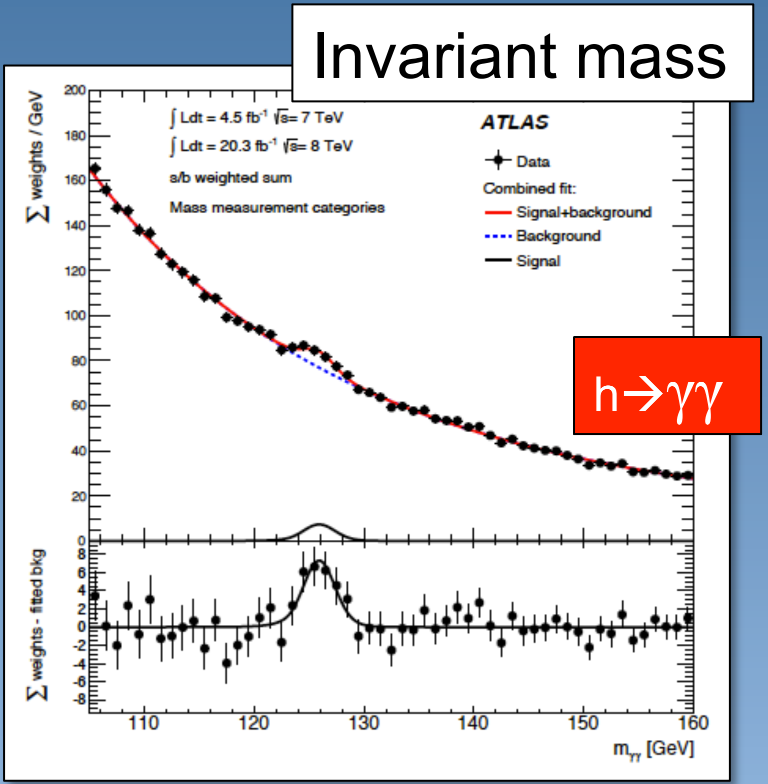




Event categories in 2-photon channel

Event 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



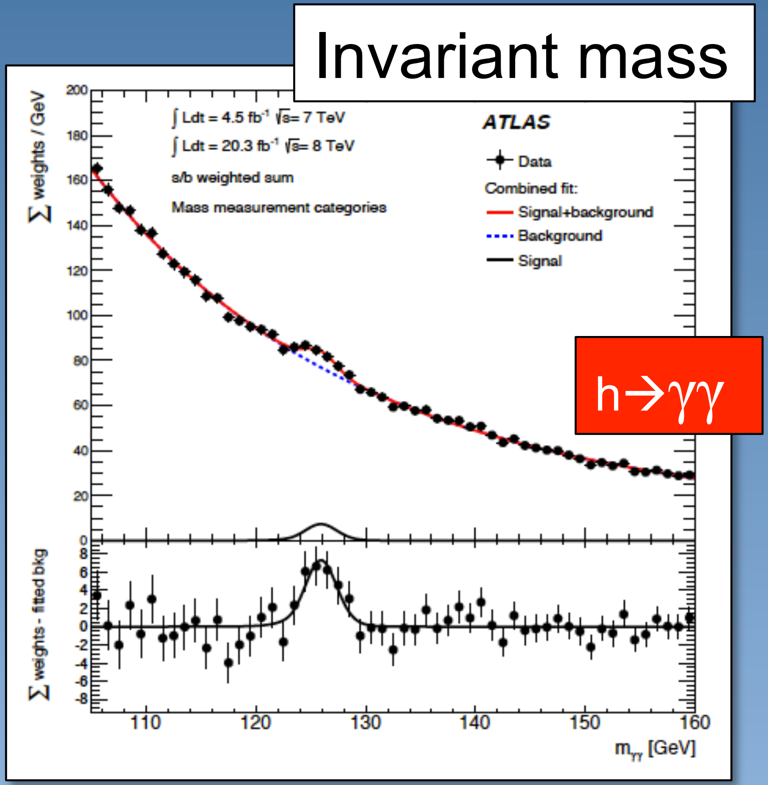
Event categories in 2-photon channel

Mass and signal strength
2-photon channel

m_h = 125 .98 ± 0.50 GeV

$$\mu = 1.29 \pm 0.30$$

cross-section w.r.t SM

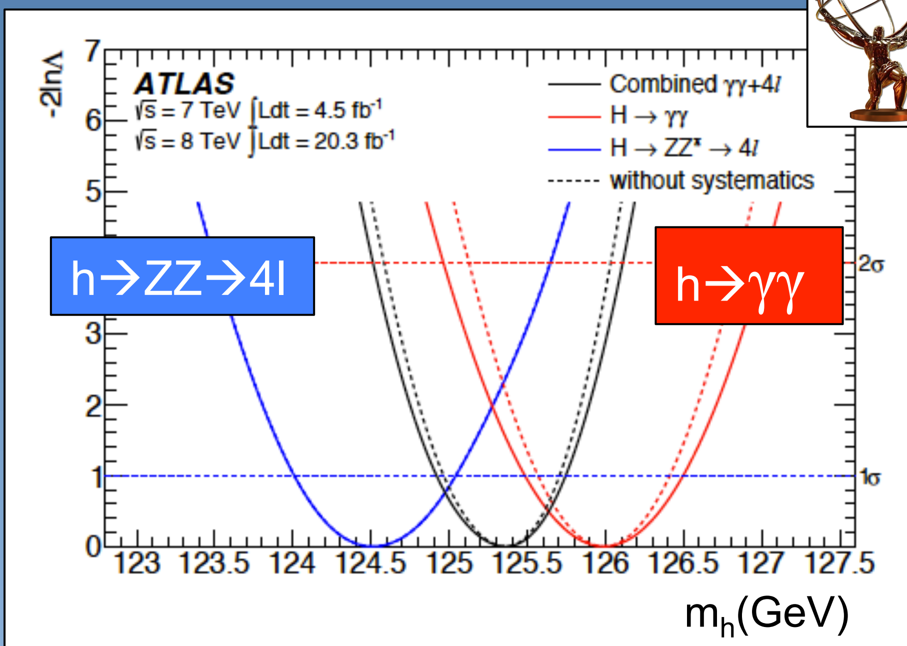


Nice mass measurement, more events than expected

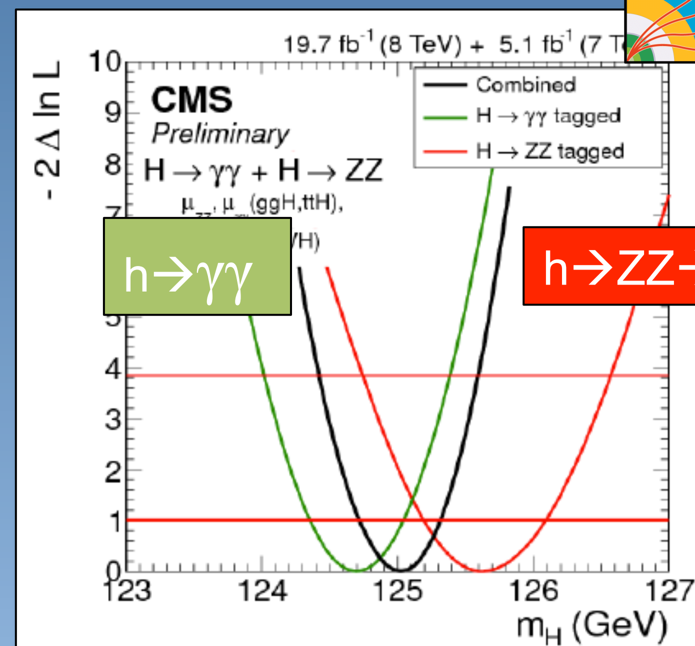
Mass differences ?

Mass difference between ZZ and γγ final state

ATLAS experiment



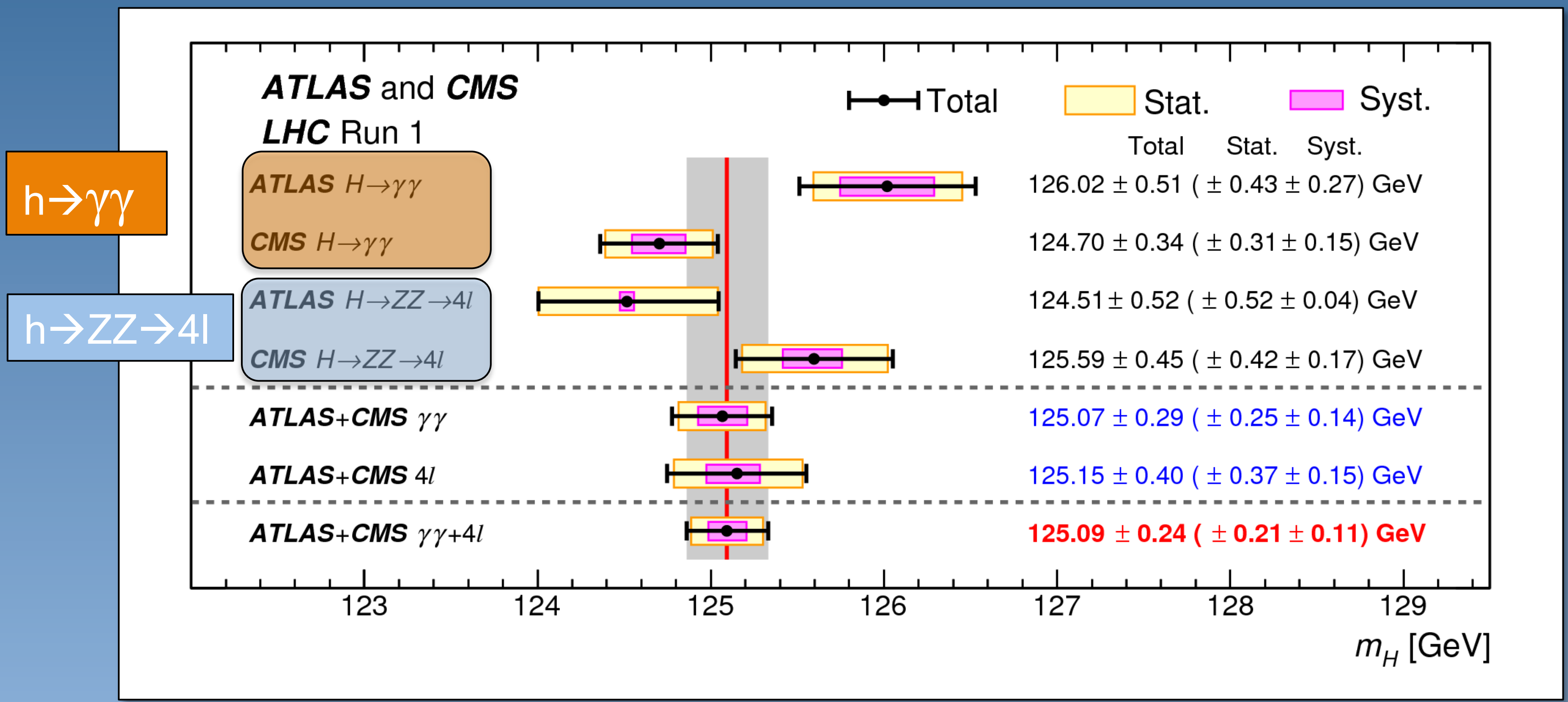
CMS experiment



Δm_h = 1.47 ± 0.72 GeV
1.98 sigma

ATLAS & CMS combination

ATLAS + CMS combined mass measurement



$$m_h = 125.09 \pm 0.21(stat) \pm 0.11(syst)$$

Vacuum stability

How does the Higgs potential change at high energy ?

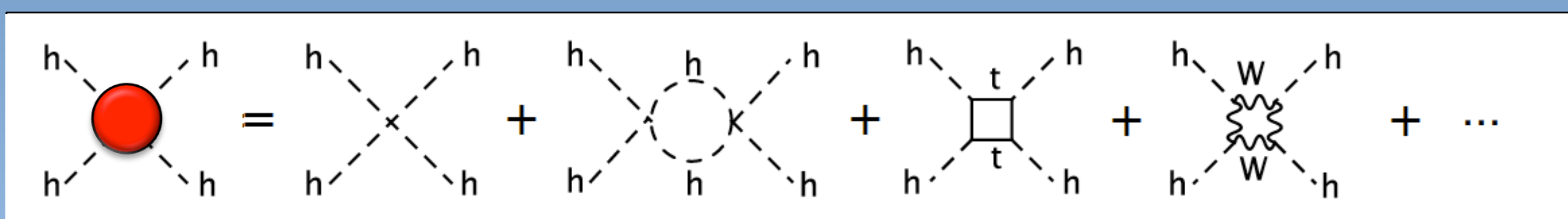
Theoretical implications of particular Higgs mass

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

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

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

effective λ



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

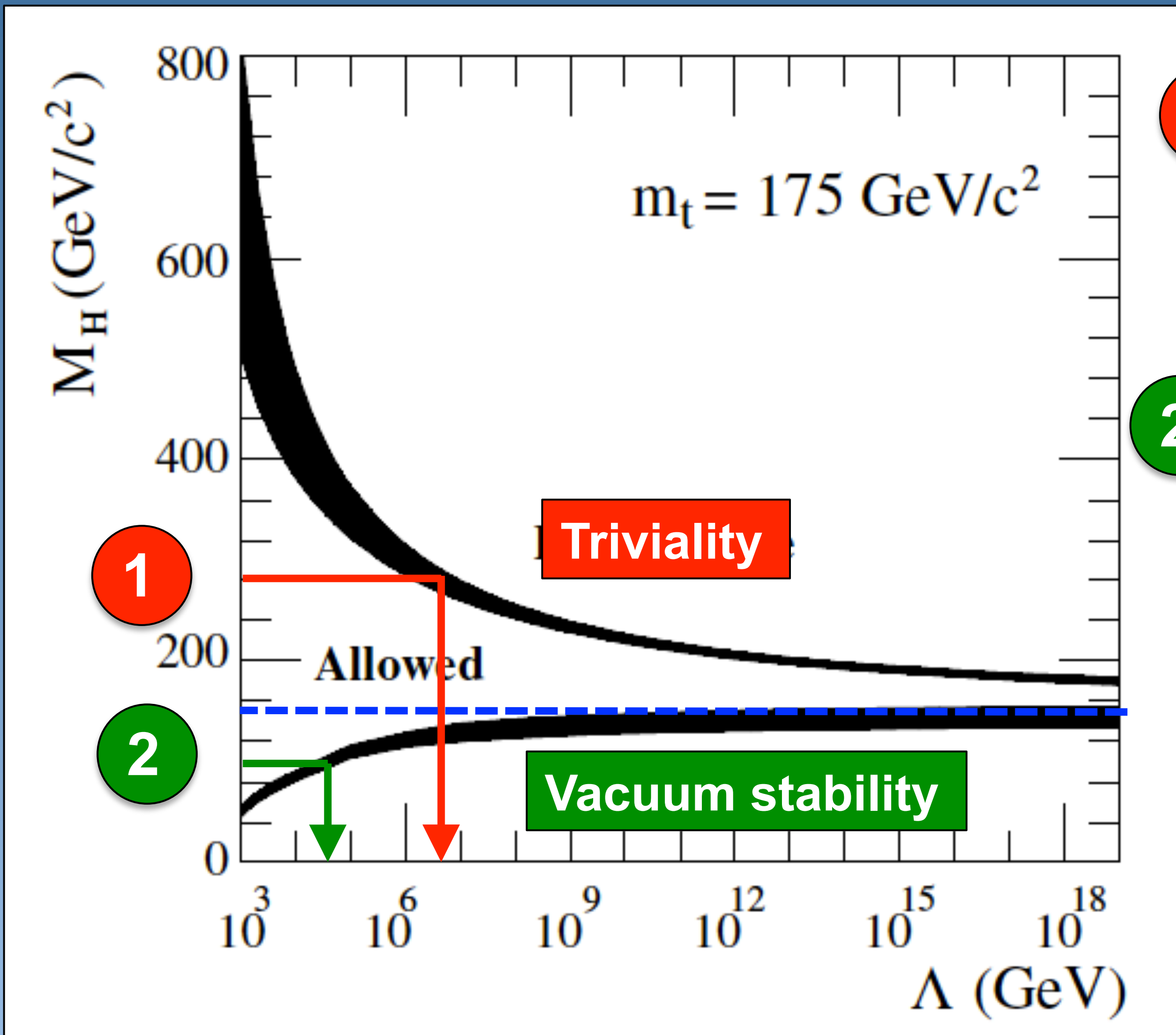
triviality **vacuum stability**

Vacuum stability

$$\frac{d\lambda}{dt} = -\frac{3}{4\pi^2} y_t^4$$

Λ gets smaller at higher energy
… and eventually becomes negative

Theoretical limits on the Higgs boson mass

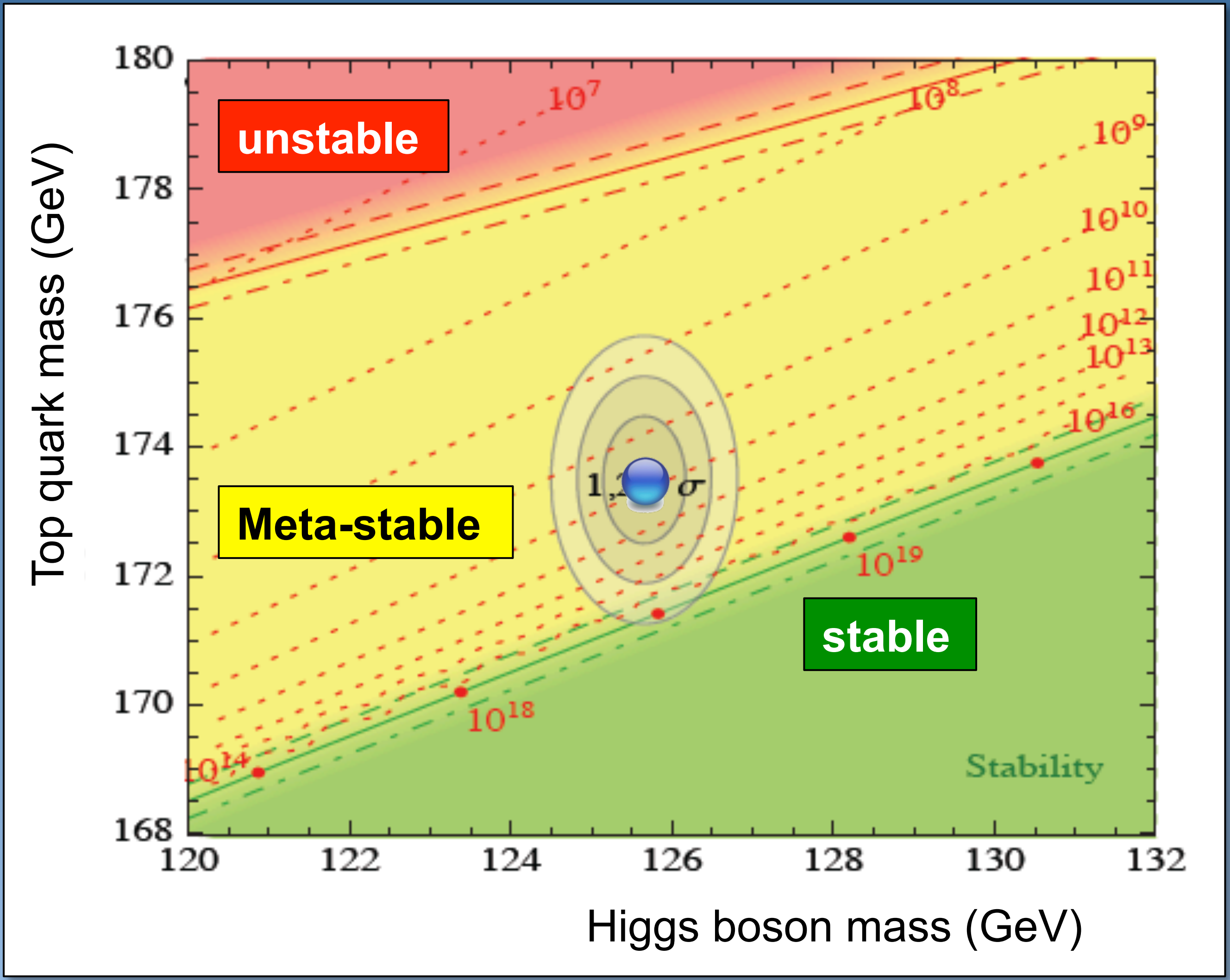


1 Heavy Higgs boson → new physics before M_{planck}

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

LHC data

Stability of the vacuum



Branchia ICHEP

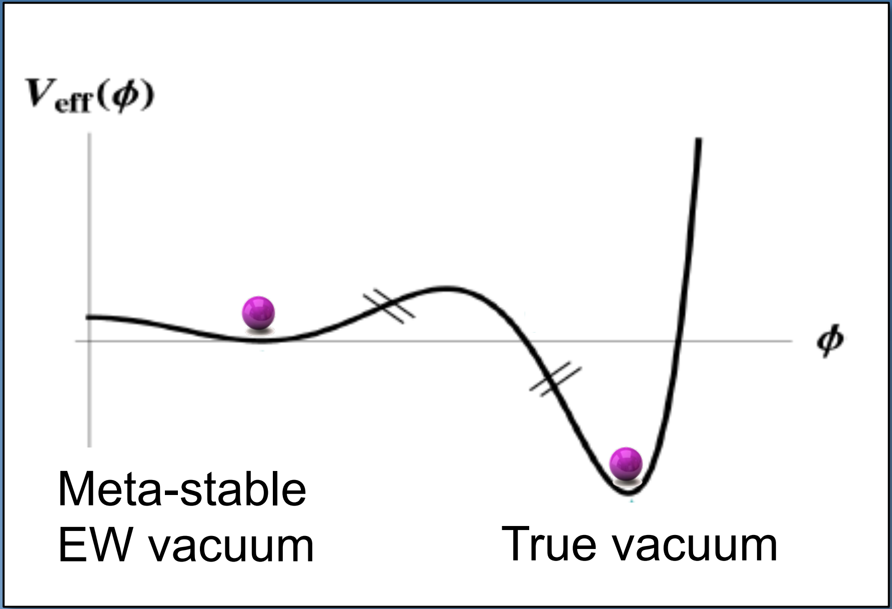
Stability of the vacuum: meta-stability

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 to true vacuum

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

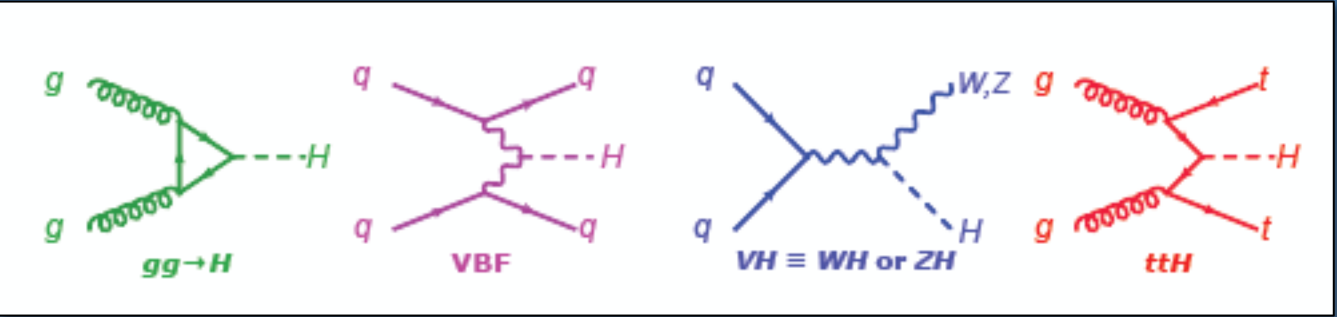


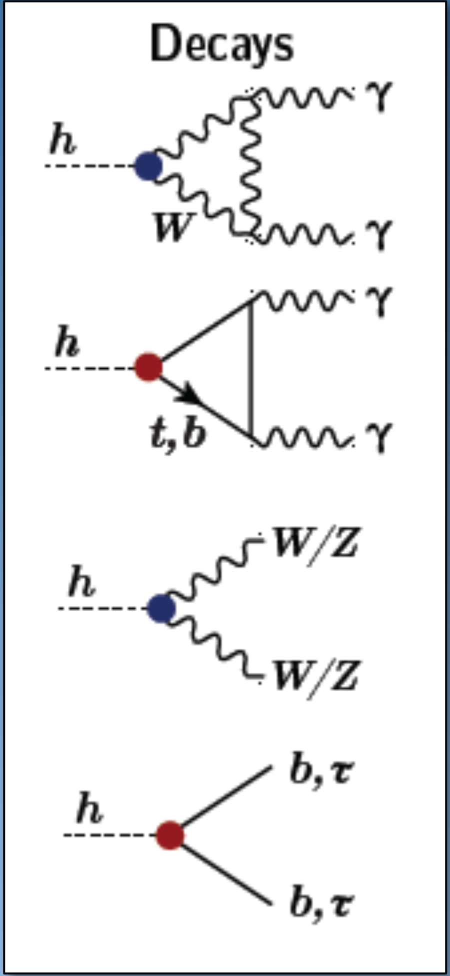
Not before these guys become World Champion

Couplings

Does the Higgs boson couple
to particle as SM dictates ?

Higgs production and decay



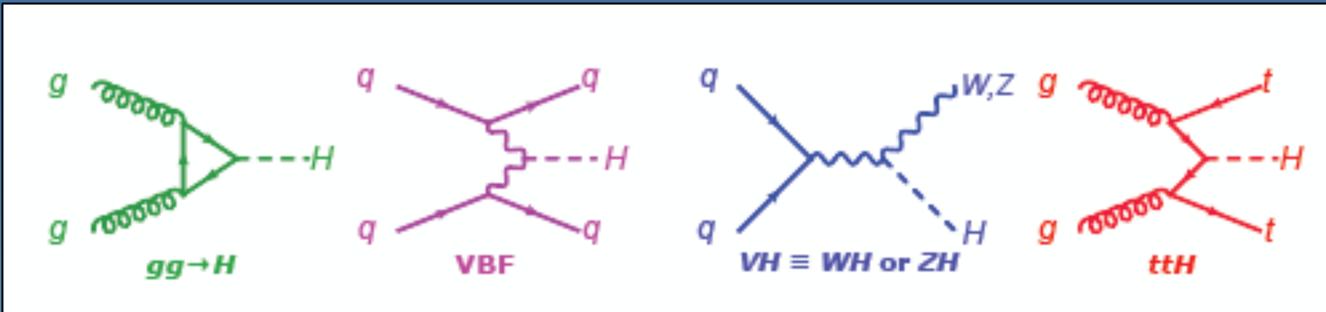


All production and decay modes ?
In agreement with prediction ?

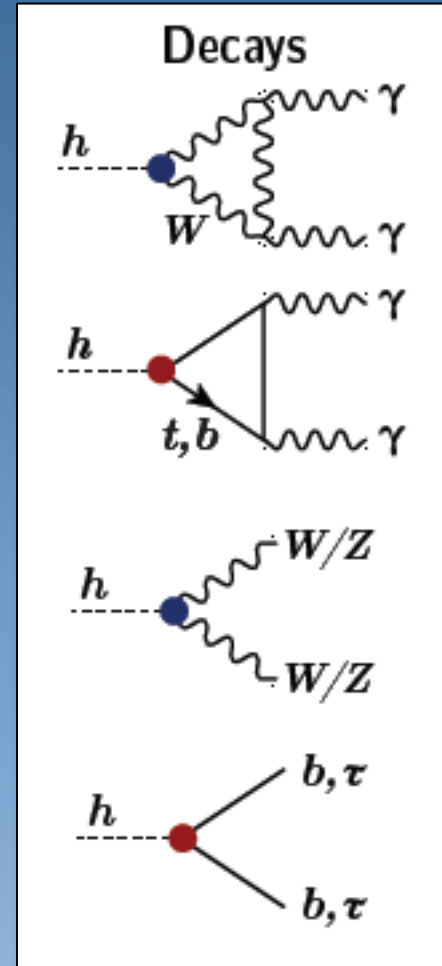
Rate differences expressed as: $\mu = \frac{\sigma^{observed}}{\sigma^{SM}}$

Note: characteristics SM Higgs boson are **fixed** once mass is known

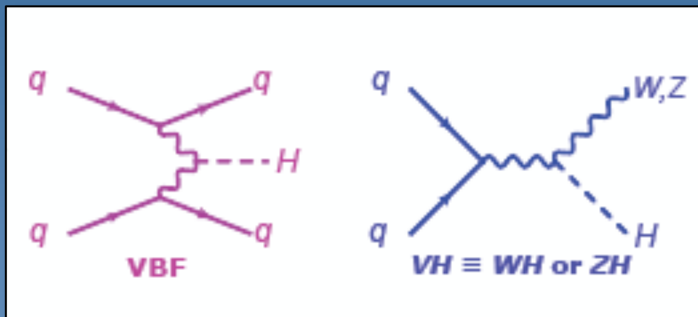
Higgs production and decay



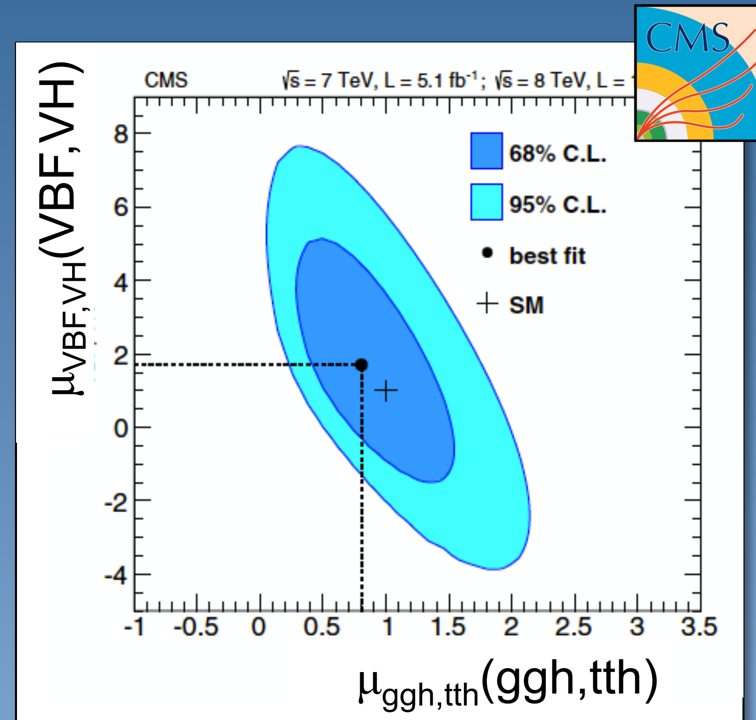
Decay tag	incl.(ggH)	VBF tag	VH tag	ttH tag
H→ZZ	✔	✔		
H→γγ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
H→ττ	✔	✔	✔	✔
H→bb		✓	✔	✔
H→Zγ	✓	✓		
H→μμ	✓	✓		
H→inv.		✓	✓	



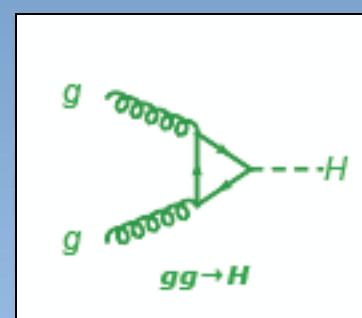
Disentangle production modes



40-60% uncertainty



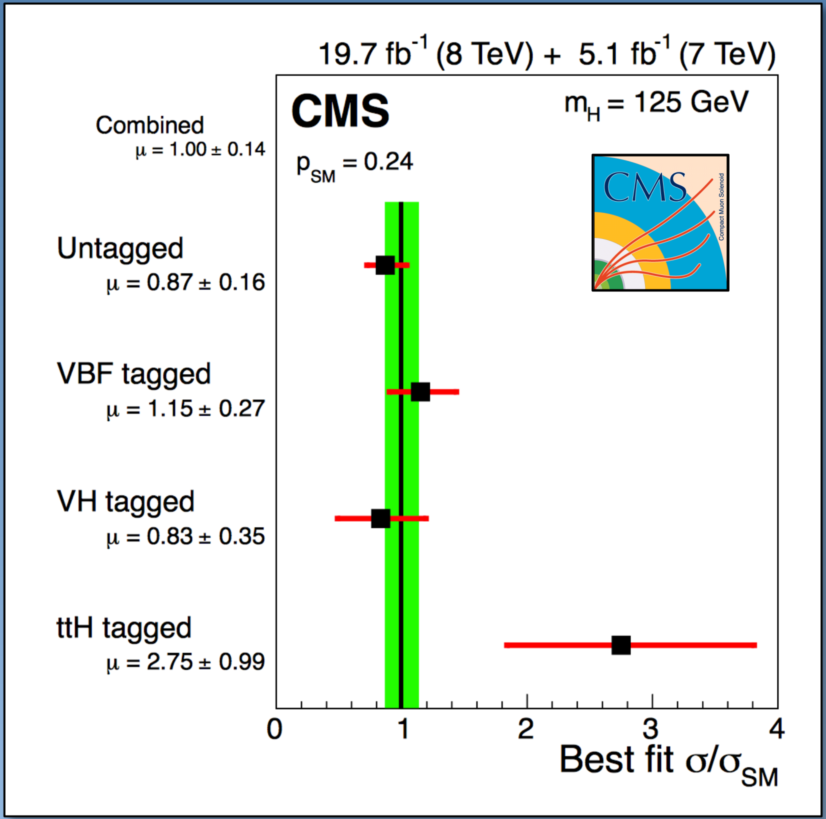
Exploit differences in topology (jets)



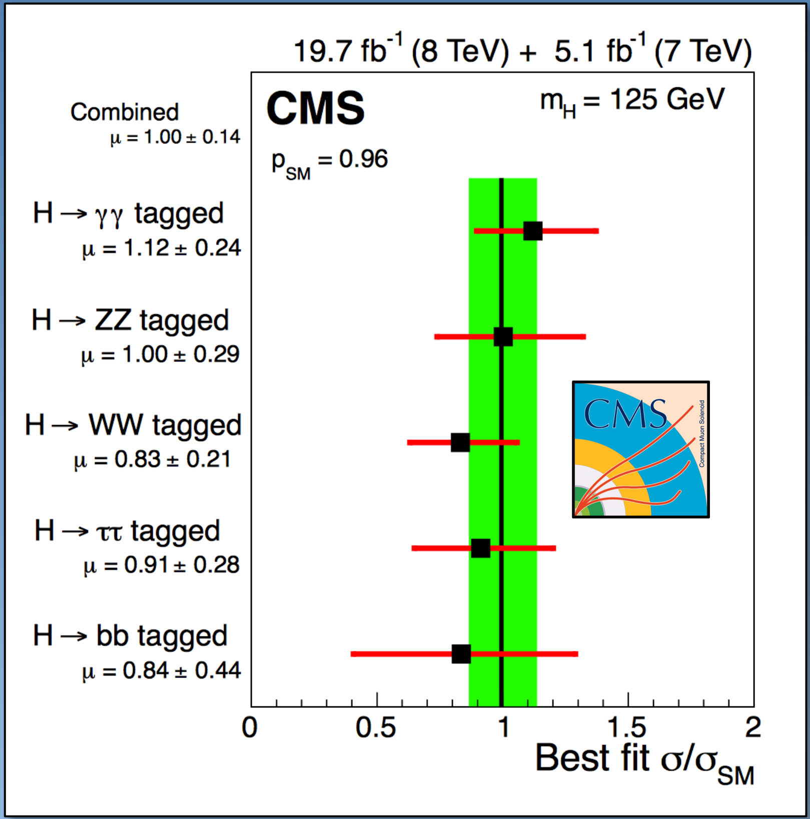
25-30% uncertainty

Rate measurement summary CMS experiment

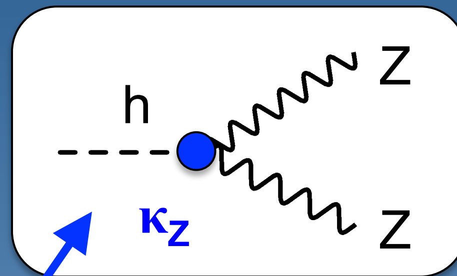
production modes

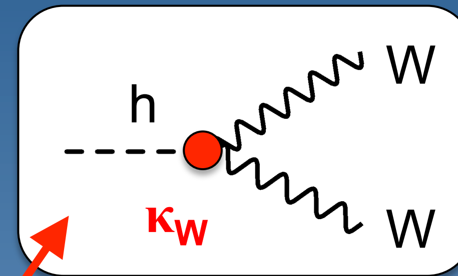


decay modes



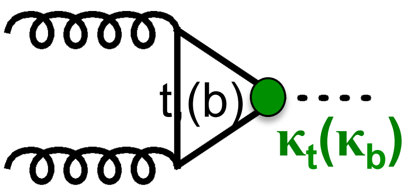
Effective Lagrangian



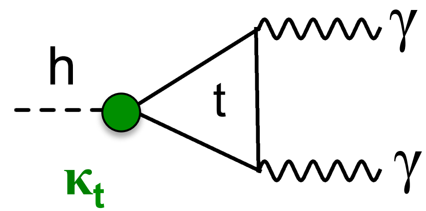


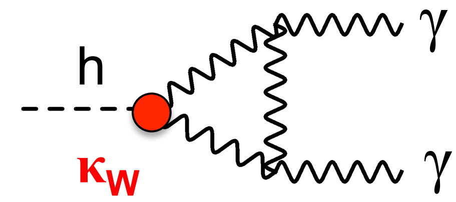
Use scale factors κ to parametrise deviations from SM ($\kappa=1$):

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



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





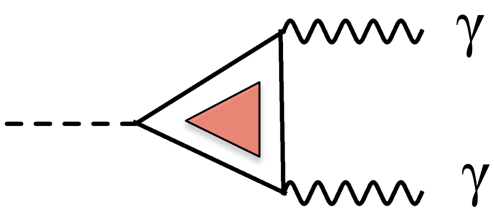
$$\kappa_\gamma^2 \propto 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$

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

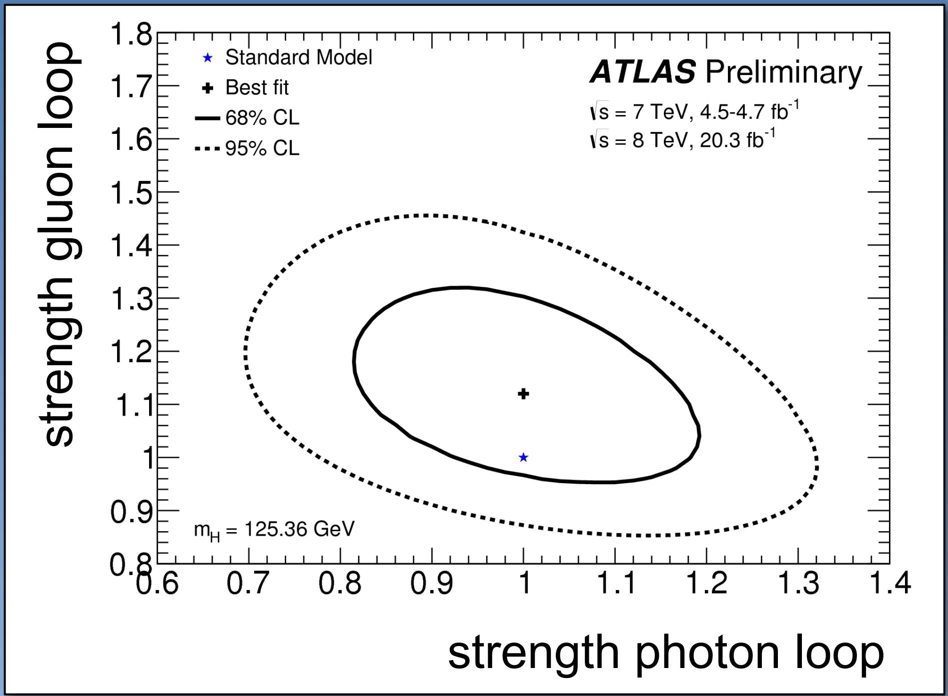
Rates and relations are modified if non-SM particles enter in the loops

Evidence for new particles in loops ?

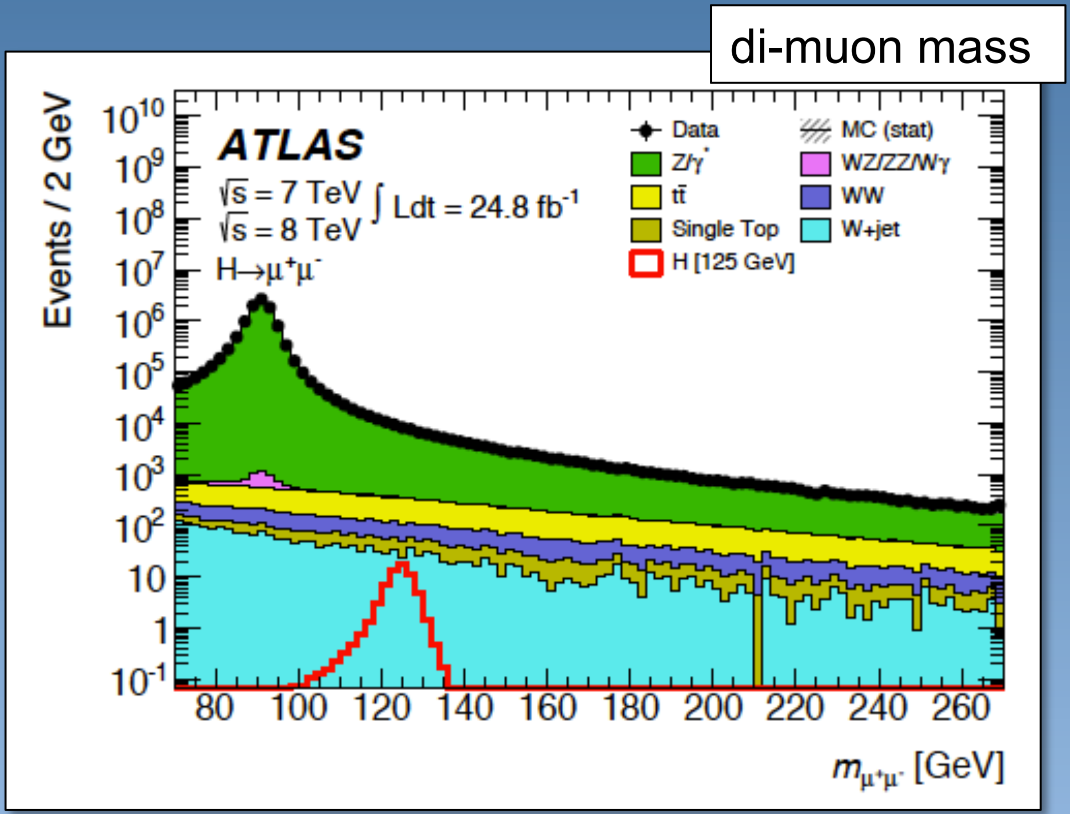
New particles can enter loop



SUSY particles, …



Because it's difficult doesn't mean wont try: h→μμ

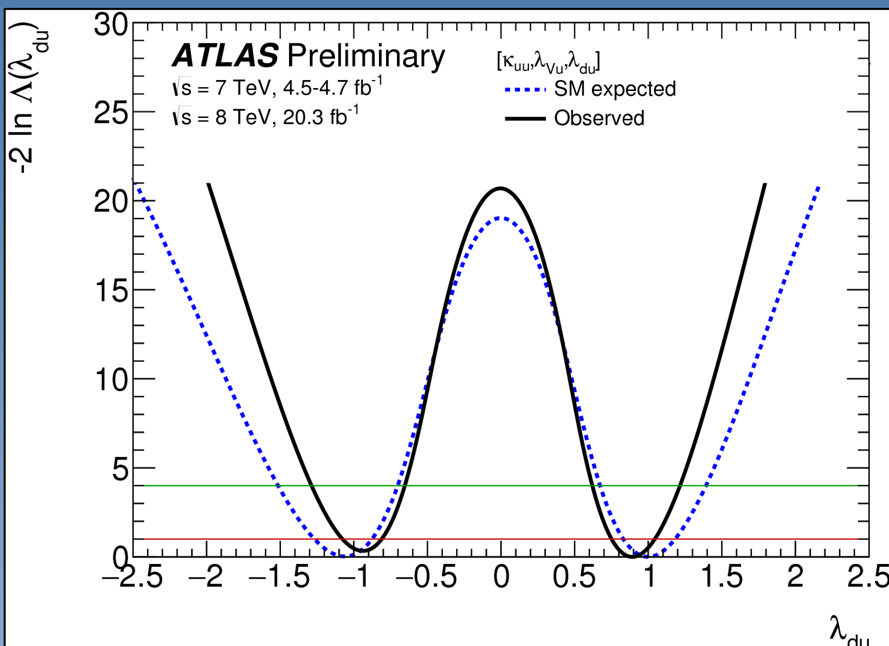


Γ(h→μμ) = 0.02%

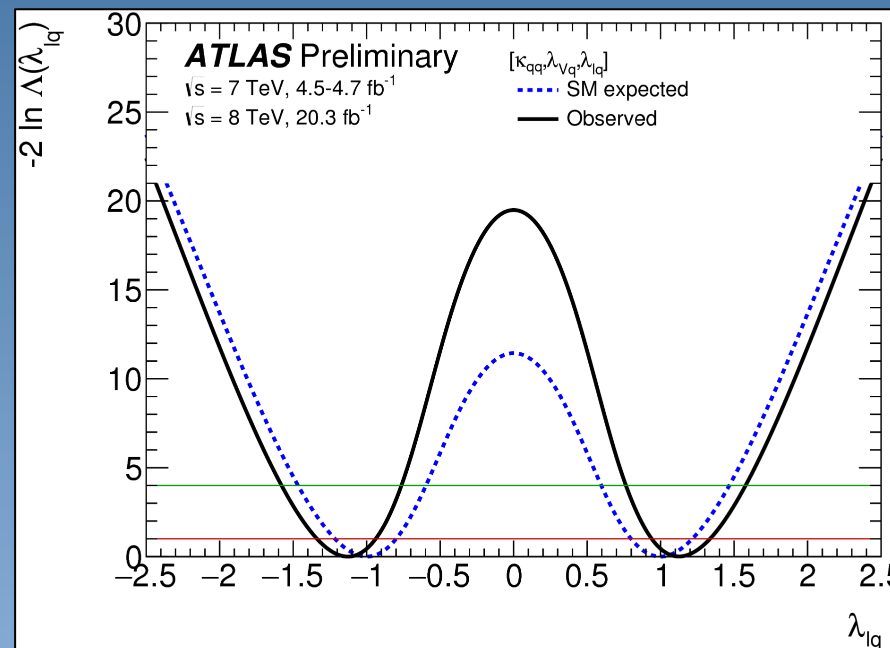
Enormous Drell-Yan background

Coupling ratio's

up-type versus down type quarks



leptons versus quarks



interpretation

What do these couplings mean ?

2 Higgs doublet models (general)

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

5 Higgs bosons

Several models predict that there are more Higgs bosons

Properties of lightest (SM-like) Higgs boson are different from SM one

2-Higgs doublet models (general)

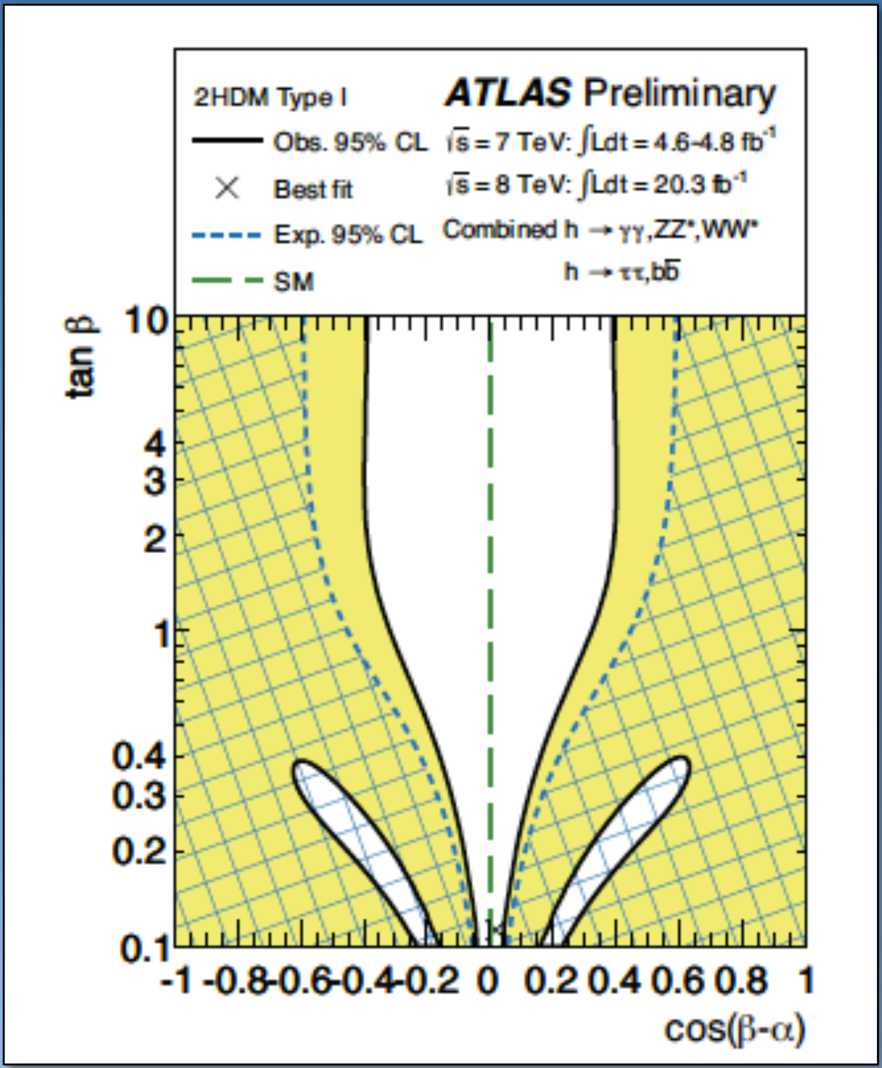
Differences in couplings in 2HDM's

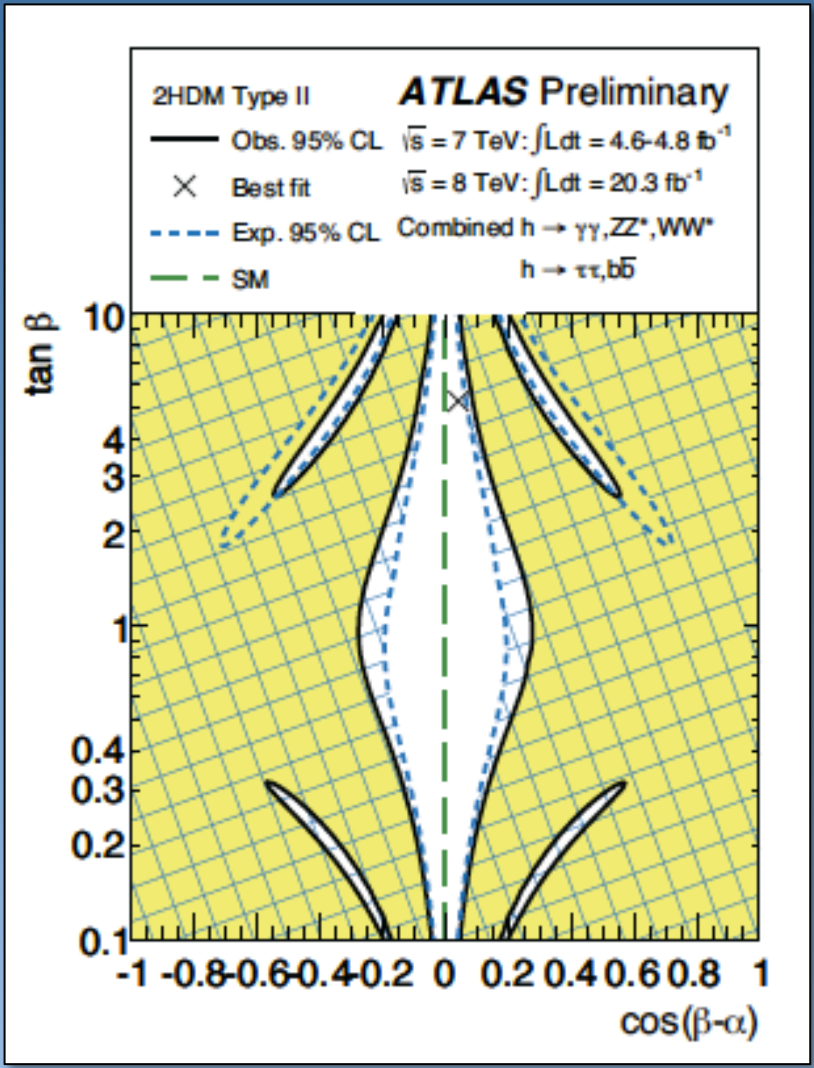
Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$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

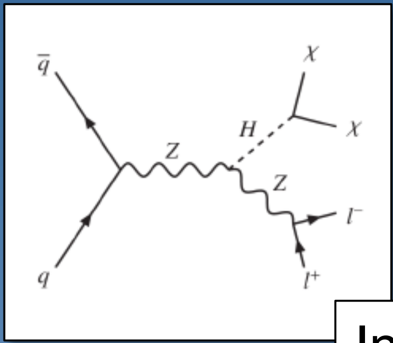
TYPE II: MSSM-like:
- 1 doublet for up-type
- 1 doublet for down-type

2-Higgs doublet models (general)



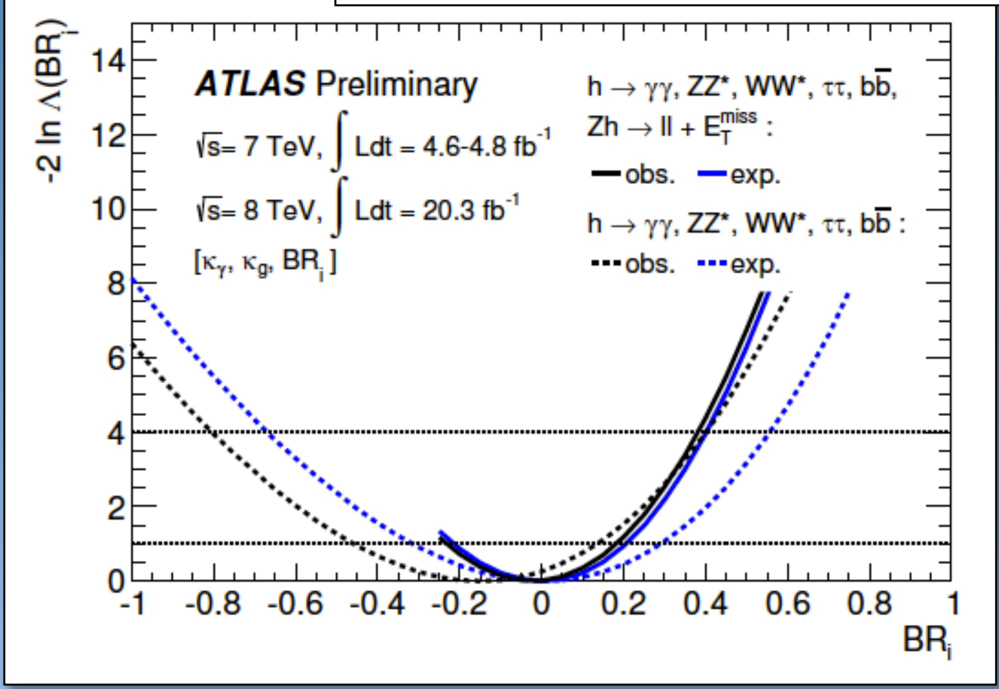


Invisible decays & portal to dark matter

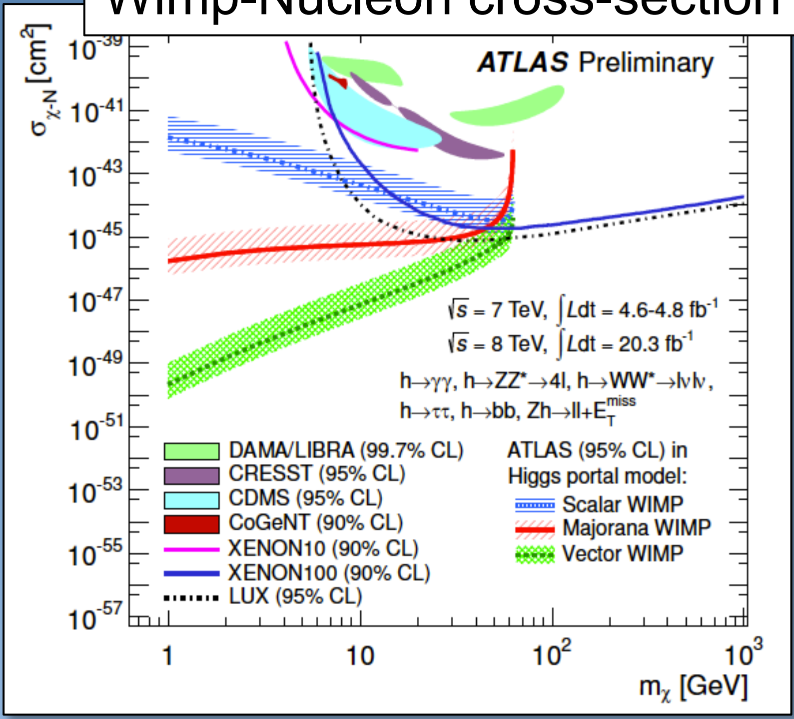


Higgs couples to WIMP

Invisible branching fraction



Wimp-Nucleon cross-section



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

spin

Is the Higgs boson a scalar particle ?

Parity = +

Charge conjugation = +

spin=0

J^{PC}

Higgs quantum numbers

scenario	*mode*	*physics model*
0_m^+	$gg \to X$	SM Higgs scalar boson
0_h^+	$gg \to X$	scalar higher-dim. op.
0^-	$gg \to X$	pseudo-scalar
1^+	$q\bar{q} \to X$	exotic pseudo-vector
1^-	$q\bar{q} \to X$	exotic vector
2_m^+	$g_1^{(2)} \neq 0$	RS graviton min. coupl.
2_h^+	$g_4^{(2)} \neq 0$	tensor higher-dim. op.
2_h^-	$g_8^{(2)} \neq 0$	"pseudo-tensor"

Event topology for different J^{PC} scenario's

Spin 0 (qq production)

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

Spin 1 (qq production)

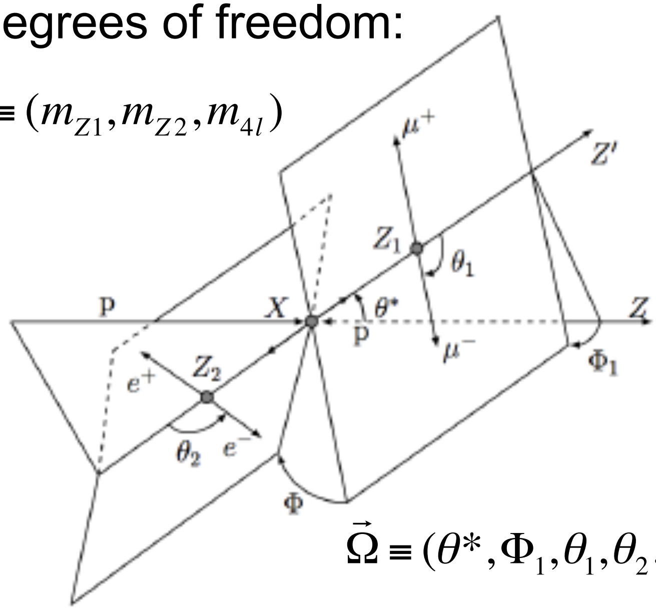
$$A(X \to V_1 V_2) = b_1 \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta$$

Spin 2 (qq and gg production)

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

8 degrees of freedom:

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



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

4 lepton final state

Analysis strategy:

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

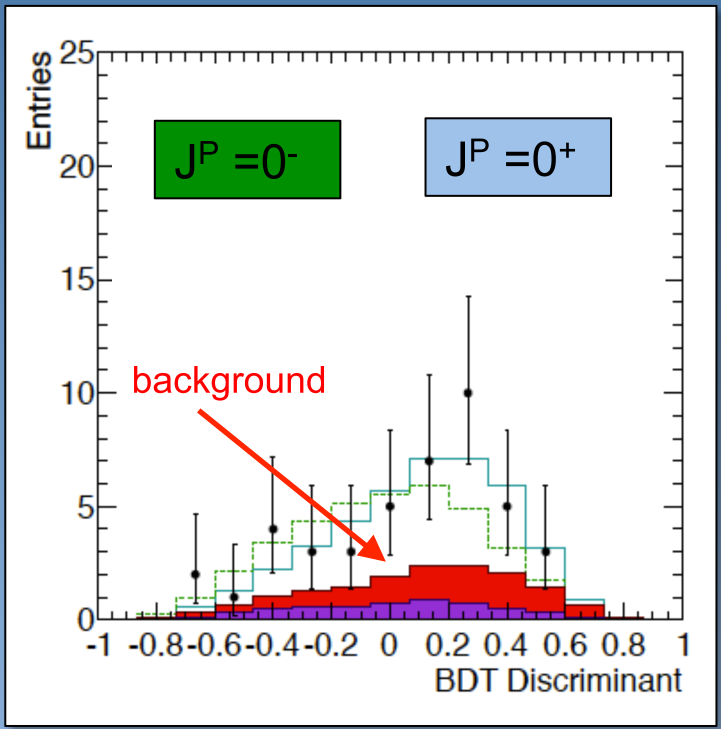
CMS

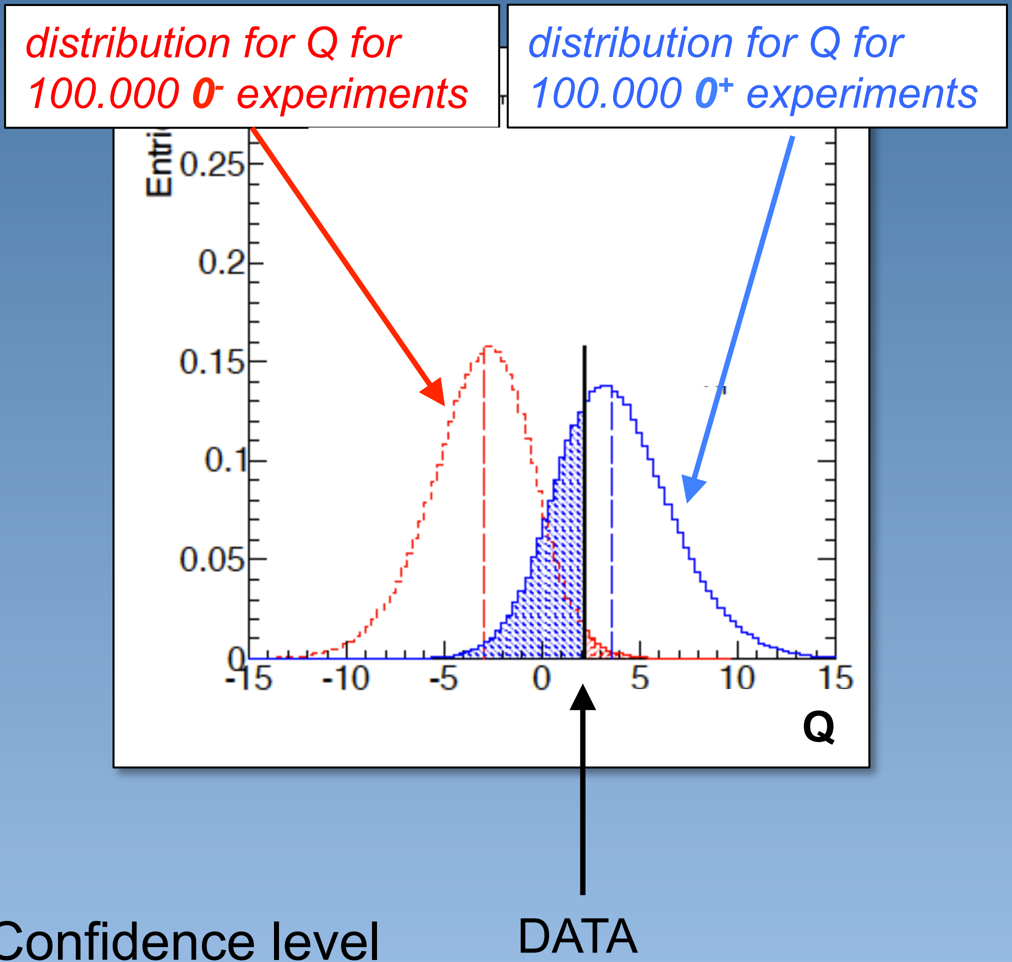
Analysis strategy:

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

ATLAS

Testing a 0^+ *versus a* 0^- *hypothesis*



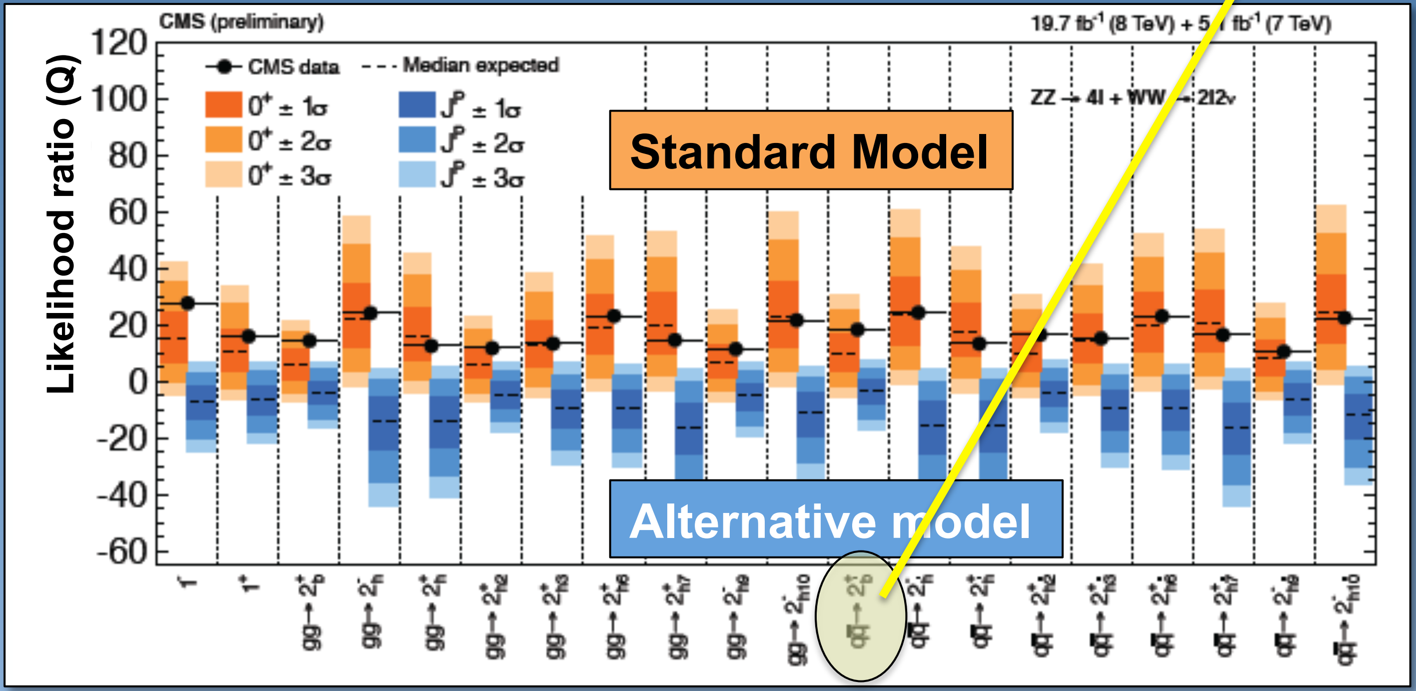


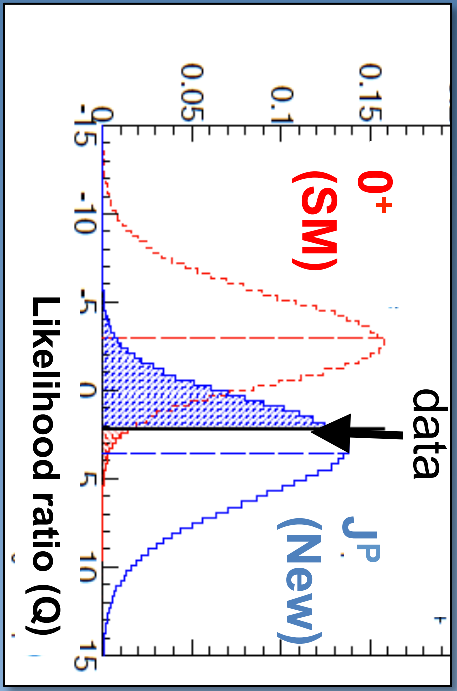
Exclude 0- hypothesis at 97.8% Confidence level

It is a spin-0 particle

How can 2 spin-1/2 particles form a spin-2 object ?

Sensitivity CMS experiment for alternative J^P hypotheses:





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

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)

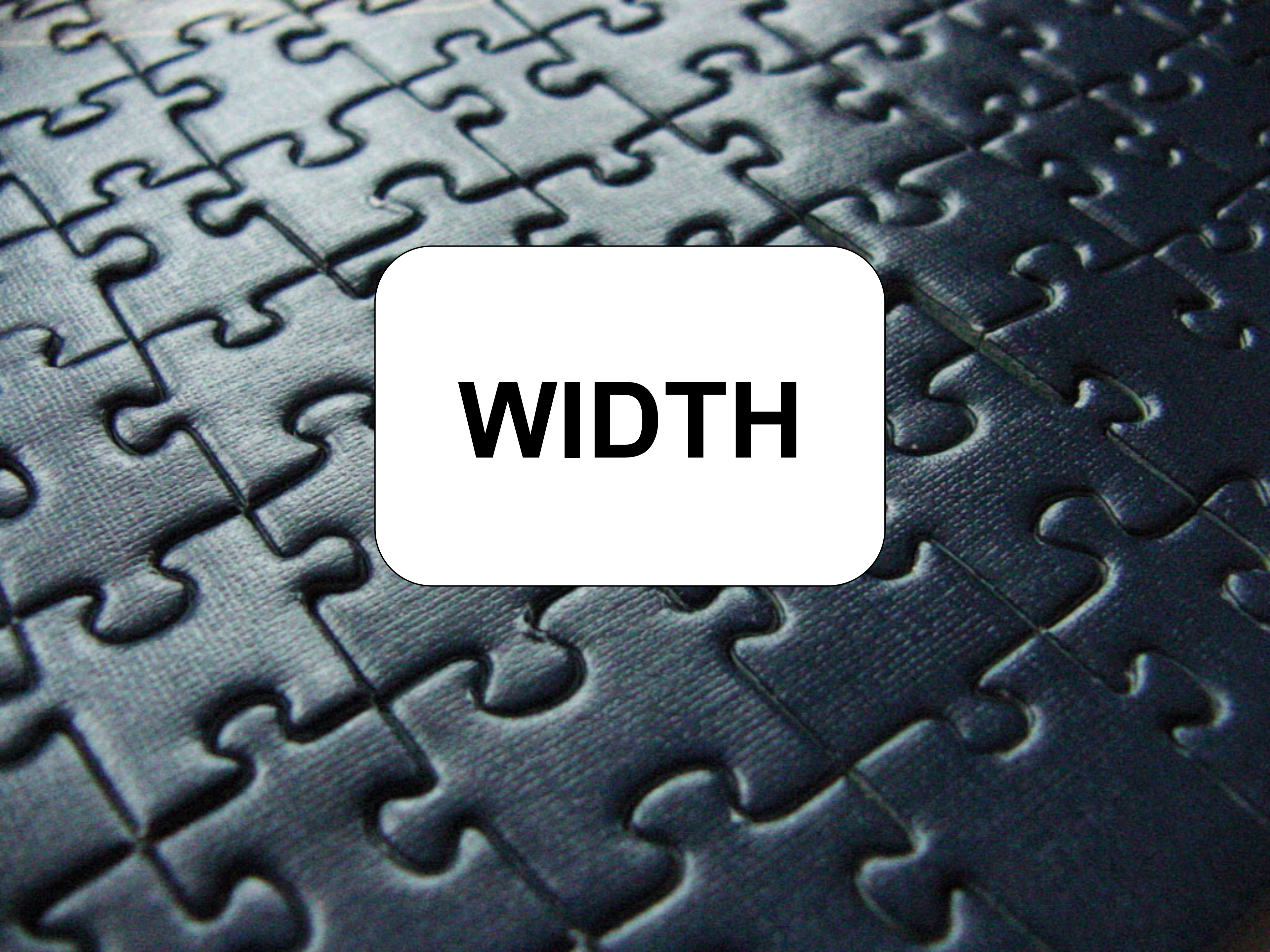
ATLAS

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

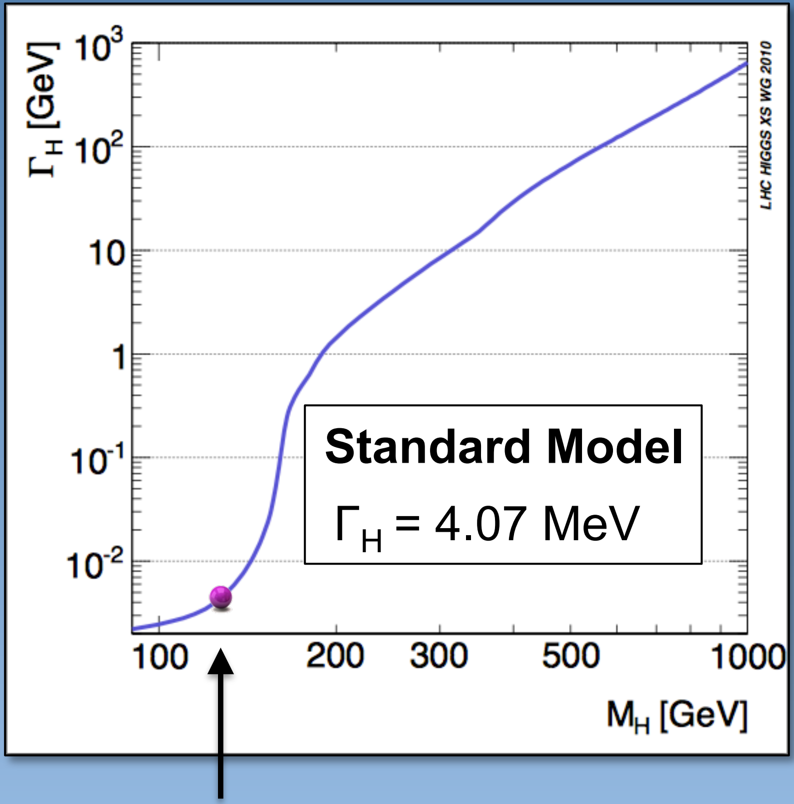
spin-2 excluded at ≥99.9% CL (WW+ZZ)

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

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

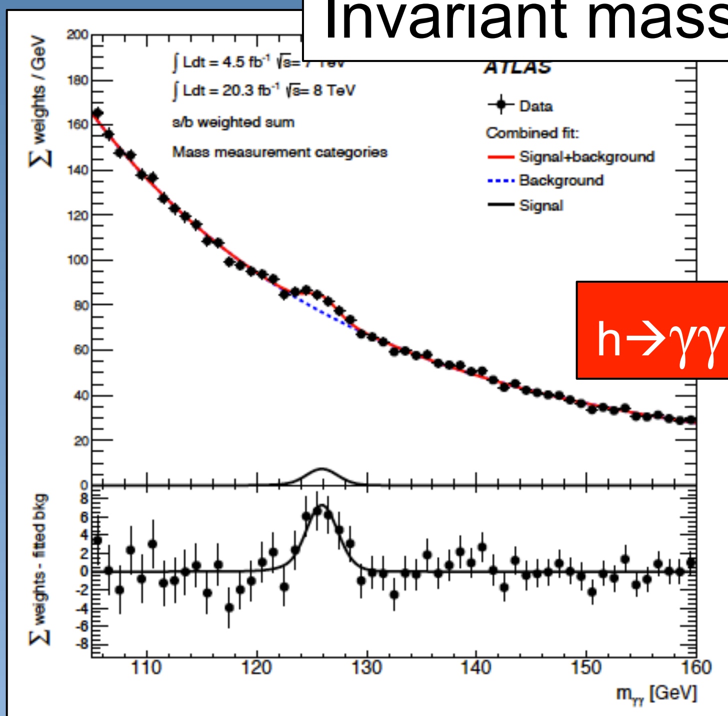
Estimate of Γ_H: direct

Mass distribution brings sensitivity to width of the Higgs boson

$$\sigma_{tot} = \sqrt{\sigma^2_{resol.} + \Gamma^2_H}$$ → *resolution ~ 400 x Γ_H*

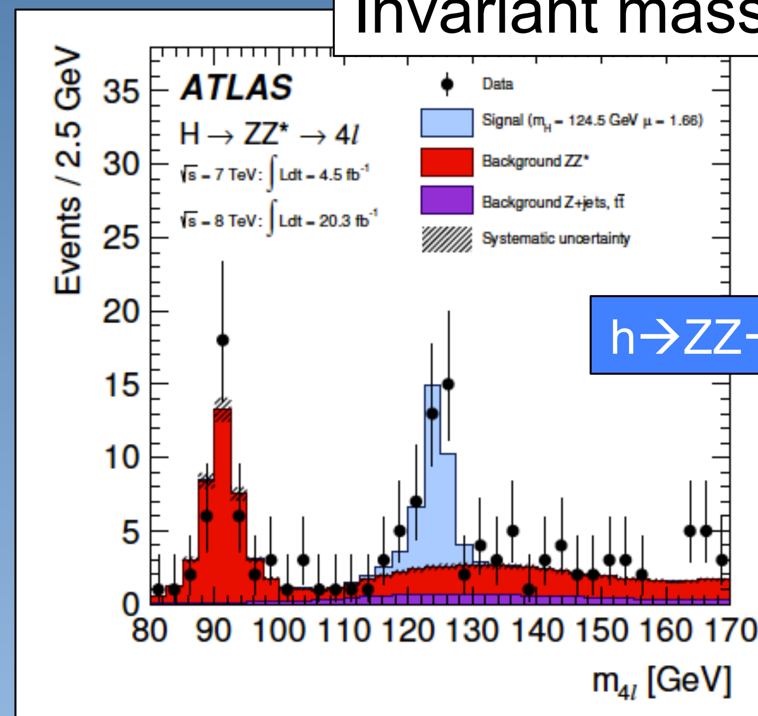
Invariant mass

h→γγ



Invariant mass

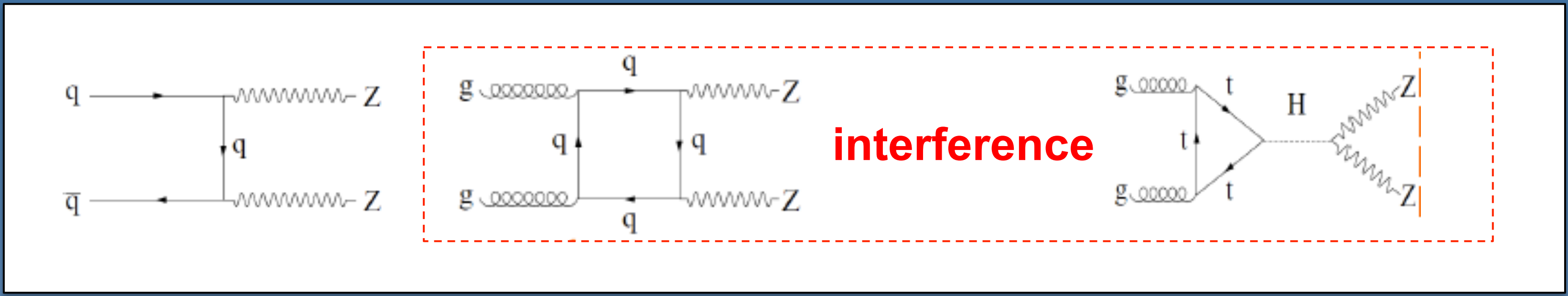
h→ZZ→4l



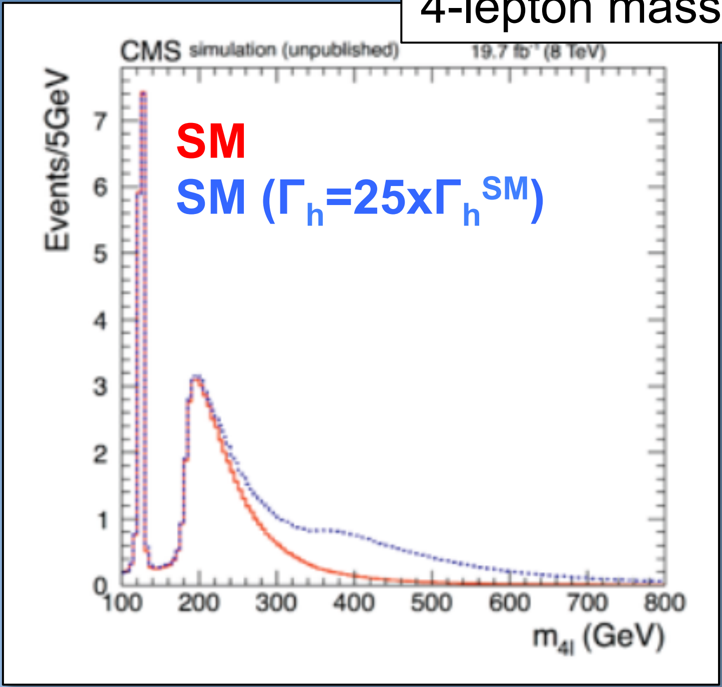
Γ_{4l}<2.6 (3.5) GeV

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

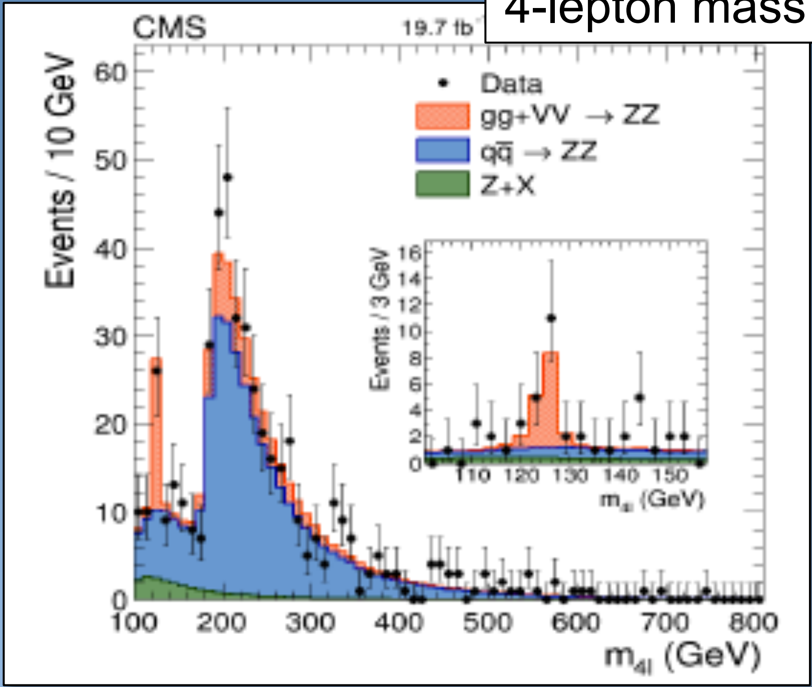
Estimate of Γ_H: off-shell couplings



4-lepton mass



4-lepton mass

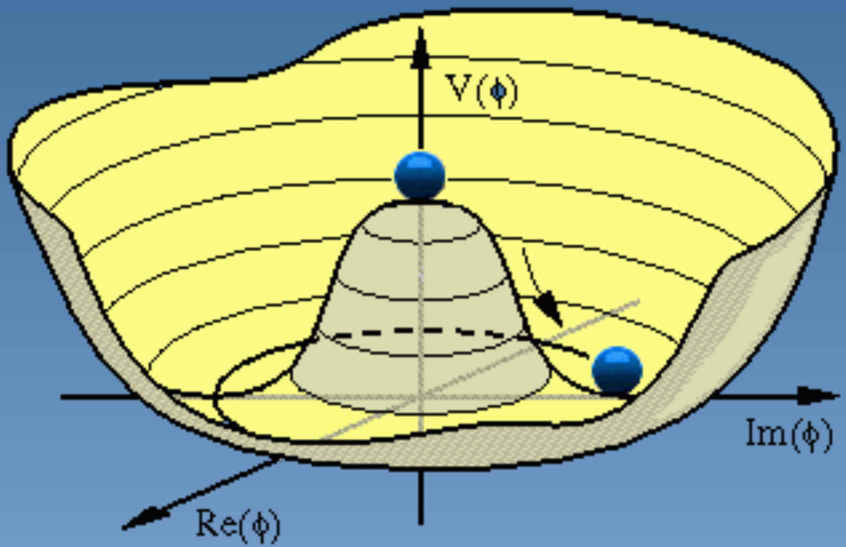


$\Gamma_h = 1.8^{+7.7}_{-1.8}$ MeV

$\Gamma_h < 22$ MeV at 95% CL


rare decays
weird stuff
compositness
self-coupling
Extra Higgs bosons

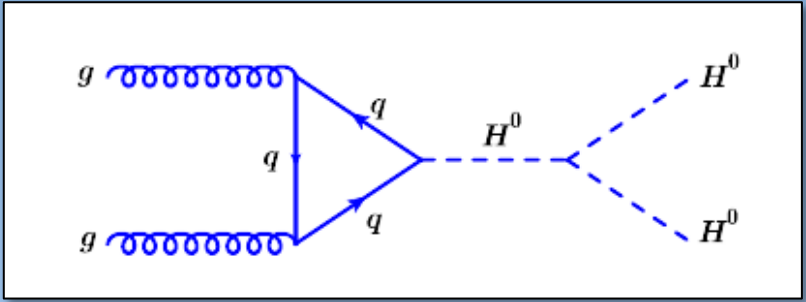
Higgs self-coupling



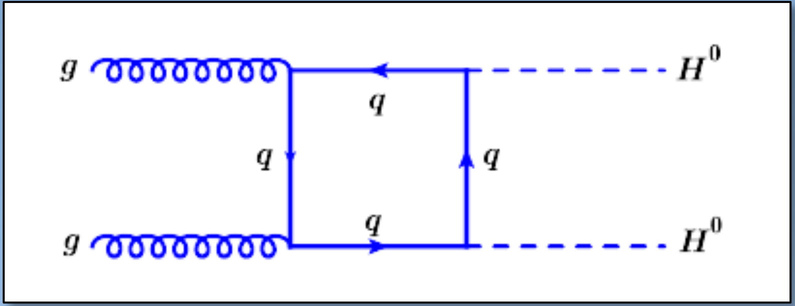
Higgs self-couplings

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

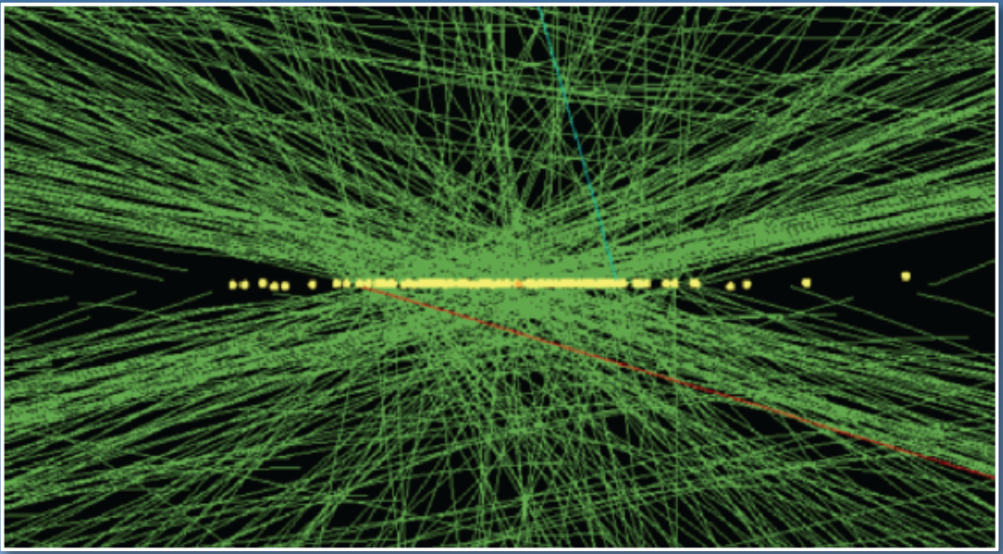
signal



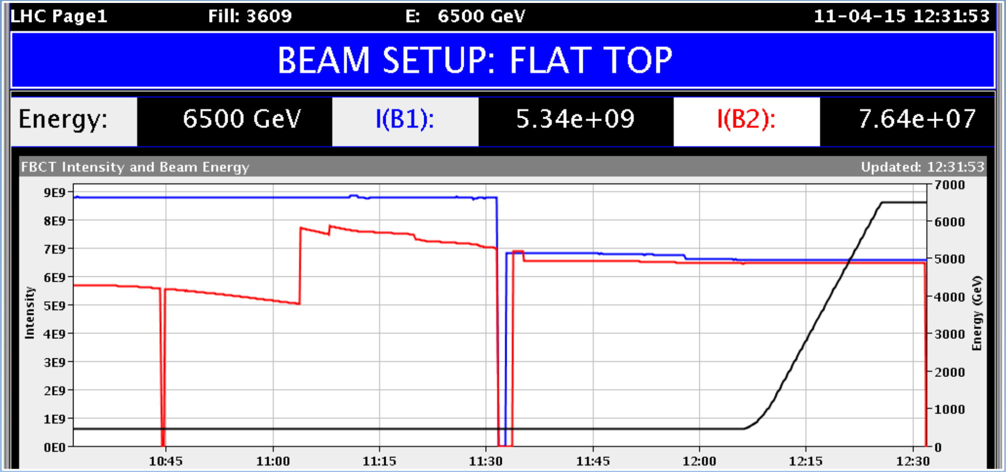
'background'



Future LHC operation



CMS event with 78 vertices



LHC back in business

Longer future: muon collider

EP Seminar

SPEAKER: Prof. Carlo Rubbia (GSSI-INFN (IT))

TITLE: **A complete demonstrator of a muon cooled Higgs factory**

DATE: Tue 14/04/2015 16:00

PLACE: Main Auditorium

ABSTRACT

In analogy with the discovery of the W and Z with hadrons and the subsequent study of the Z resonance in the pure s-state with LEP, the recent discovery of the Higgs particle of 125 GeV has revised the interest in the so-called second generation Higgs factory. However the direct production of the H^0 scalar resonance in the s-state has a remarkably small narrow width, since $\Delta E/E < 4$ MeV / 125 GeV = 3.2 x 10^{-5}. We describe here a $\mu^+\mu^-$ collider at a modest energy of 62.5 GeV and the adequate cooled muon intensity of about 6 x 10^{12} muons of each sign, a repetition rate of 15-50 p/s and $L \approx 10^{32}$ cm^{-2} s^{-1}, corresponding to about 10'000 H^0 for each detector x year. Its partial widths can be studied with remarkable accuracies. With the help of the decay frequency of the polarized $\mu \rightarrow e$ nu nu decay electrons, the H^0 mass itself can also be measured to about ±100 keV, i.e. $\Delta m/m \approx 10^{-6}$.

The next modest step, prior to but adequate for the subsequent H^0 physics programme, could be the practical realization of an appropriate *muon cooling demonstrator*. Starting from a conventional pion beam, the required longitudinal and transverse emittances are achieved with a cascade of two unconventional but very small muon rings of few meters radius. Low momentum muons of about 250 MeV/c, initially with $\Delta p/p \approx 0.1$, are cooled in a first ring, extracted and ionization cooled to about 70 MeV/c, and cooled ultimately in a second small ring up to a longitudinal momentum spread of 0.7 MeV/c r.m.s. The operation of the demonstrators may be initially explored and fully demonstrated with the help of a modest muon beam already available in a number of different accelerators.

The additional but relatively conventional components necessary to realize the facility with the appropriate muon current and luminosity should then be constructed only after this *initial cooling experiment* has been successfully demonstrated. The ultimate $\mu^+\mu^-$ collider for a Higgs Factory may be situated within the existing CERN site or elsewhere.

Organised by: Rolf Heuer, Livio Mapelli..
Tea and Coffee will be served at 15h30

Colloquium Alain Blondel (University of Geneva) 17-04-2015

Friday 17 April, 11:00h, at Nikhef in H331

Speaker: Prof. Alain Blondel (University of Geneva)

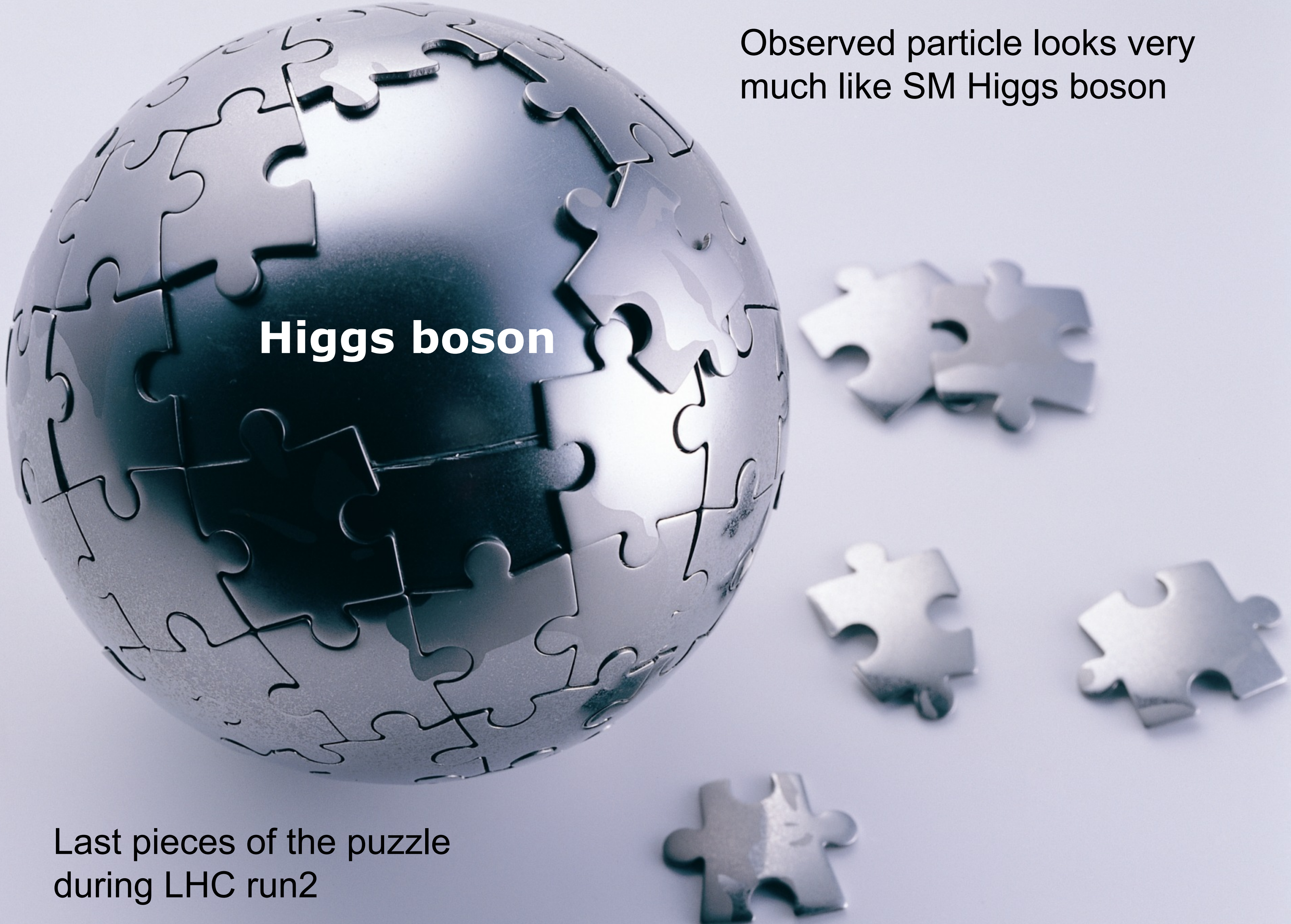
Title: "Higgs Factories"

Abstract:
With the discovery of the Higgs boson the question arises of the means of investigation of this unique spin zero particle, as well as possibly using it as portal to discovery of the solution to some of the burning questions of particle physics today.
The present and future 'Higgs Factory' accelerators: HL-LHC, linear e+e- colliders, circular colliders (CEPC/FCC-ee), muon collider, and finally the 100 TeV FCC-hh will be reviewed. It will be shown that the most powerful combination is the Future Circular Collider complex under study at CERN, hosting in a first step a high luminosity, 90-350 GeV circular e+e- collider, with the ultimate goal of hosting a 100 TeV pp collider.

14 April 2015 CERN colloquium

17 April 2015 Nikhef colloquium

Observed particle looks very
much like SM Higgs boson



Last pieces of the puzzle
during LHC run2

BACKUP

Systematics … how can we improve this ?