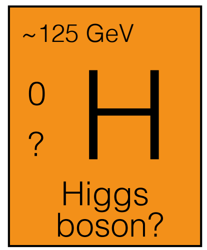
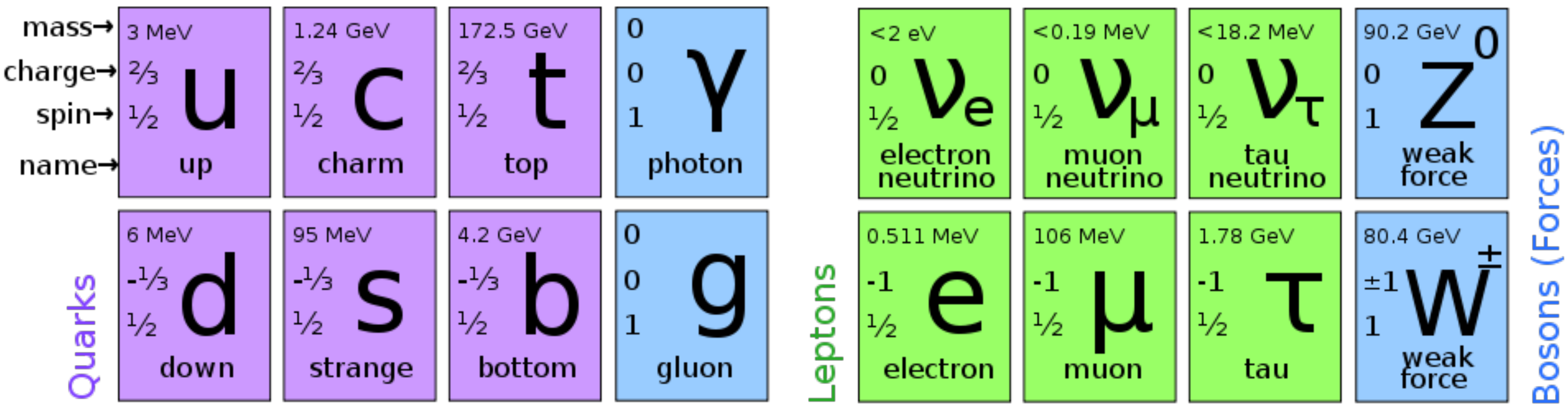
La scoperta del bosone di Higgs at LHC

P. Govoni
Università di Milano-Bicocca

the standard model of particle physics

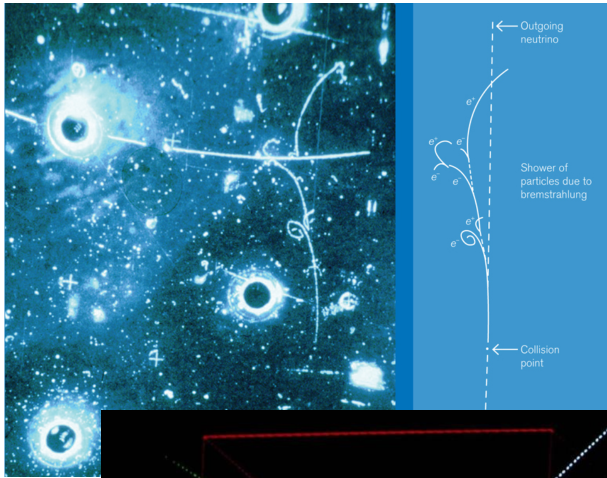
- **1954** - Yang & Mills non-abelian gauge theory
- **1961** - Sh. Glashow, SU(2)xU(1) with mass-less bosons
- **1964** - P. Higgs + Brout & Englert – Symmetry breaking
- **1967/68** - S.Weinberg / A.Salam :
- **The standard model (SM) of EWK interactions:**
  - Non-abelian gauge theory: SU(2)L x U(1)Y
  - With spontaneous symmetry breaking
- **New unequivocal predictions:**
  - A neutral massive boson (Z-boson) and its couplings
  - A massive scalar field (Higgs boson) of unpredicted mass

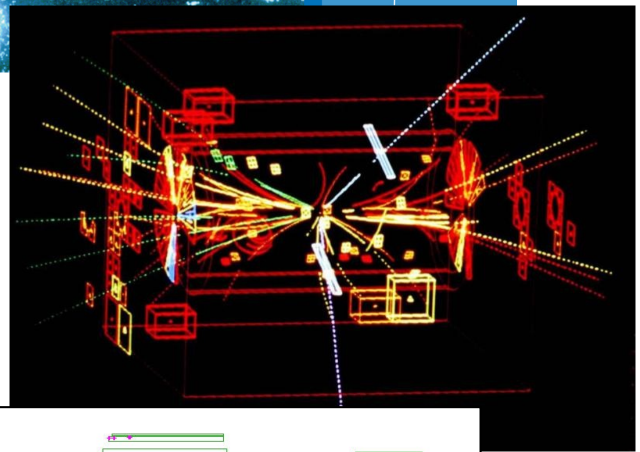


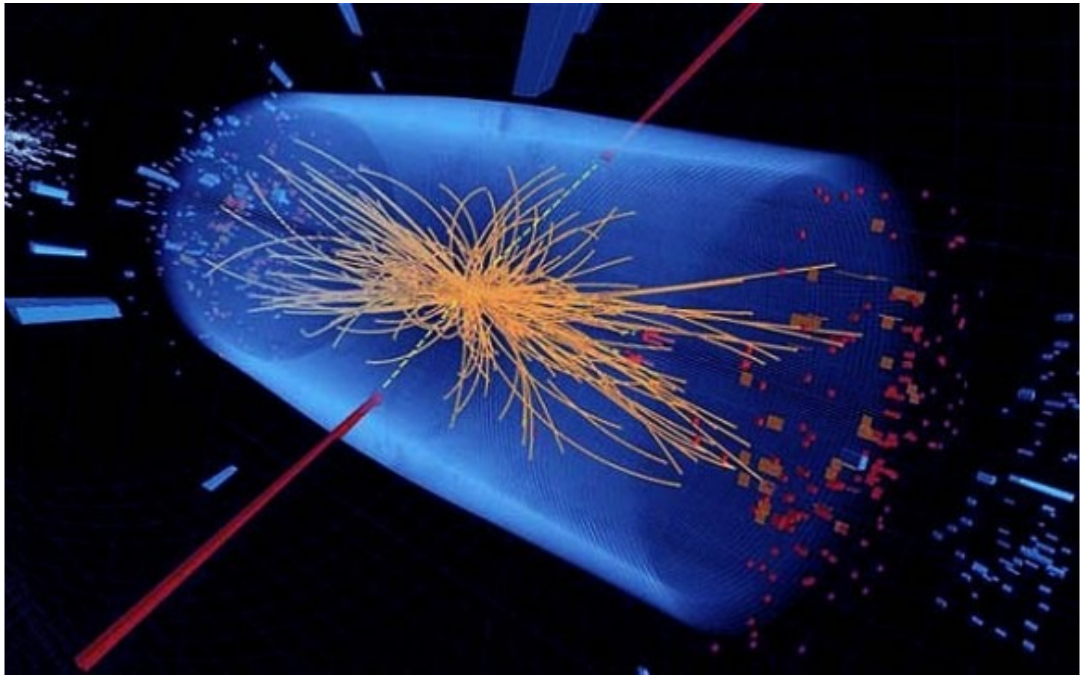


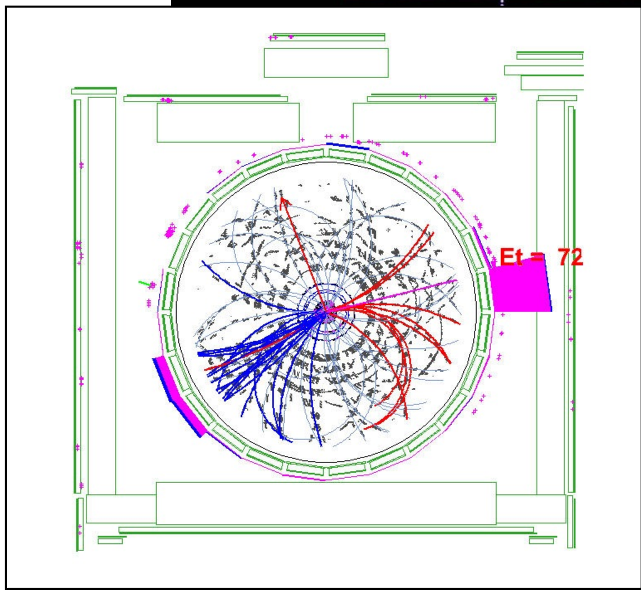
… and its measurement

- **1973** neutral currents discovery with a neutrino beam and the Gargamelle detector
- **1983** - W and Z discovery at the UA1 and UA2 experiments at CERN
- **1989-2000** - the triumph of the SM in the LEP measurements
- **1995** - top quark discovery at TeVatron
- **2012** - discovery of a Higgs-like resonance at CERN, by the CMS and ATLAS experiments









the standard model Lagrangian

Tabarelli de Fatis (Dissertori)

$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

{ $W^{\pm}, Z, \gamma$ kinetic energies and self-interactions

$$+\overline{L}\gamma^{\mu}\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)L$$
$$+\overline{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)R$$

{ lepton and quark kinetic energies and their interactions with $W^{\pm}, Z, \gamma$

$$+\left|\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)\phi\right|^{2}$$
$$-V(\phi)$$

{ $W^{\pm}, Z, \gamma$ and Higgs masses and couplings

$$-(G_1\overline{L}\phi R + G_2\overline{L}\phi_c R + h.c.)$$

{ lepton and quark masses and coupling to Higgs

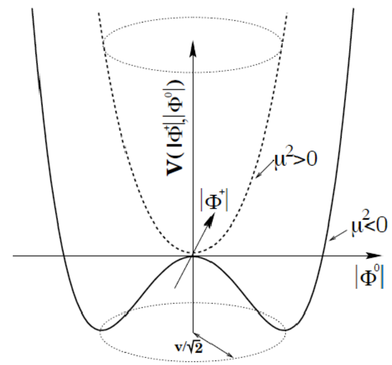
L ... left–handed fermion (l or q) doublet
R ... right–handed fermion singlet

$\mathcal{L}$ from QCD:

$$\mathcal{L} = \underbrace{\bar{q}\left(i\gamma^{\mu}\partial_{\mu} - m\right)q}_{\text{E}_{\text{kin}}(q)} - \underbrace{g\left(\bar{q}\gamma^{\mu}T_a q\right)G^a_{\mu}}_{\text{Interaction } q,\, g} - \underbrace{\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{\text{E}_{\text{kin}}(g)}$$

$\text{E}_{\text{kin}}(g)$ includes self-interaction between gluons

- the **Higgs field** provides the mechanism to give masses to particles, through the EWK symmetry breaking

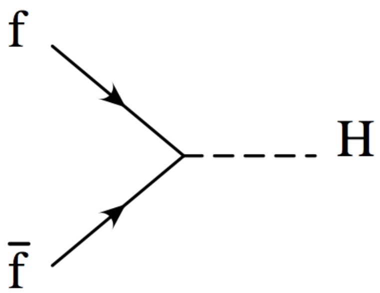


$$V(\phi) = \mu^2\phi_i^2 + \frac{\lambda}{2}\phi_i^4$$

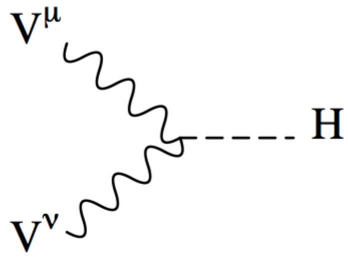
- **there is free parameters**
  - coupling constants
  - masses
- **predicts**
  - cross-sections
  - branching ratios
  - lifetimes …

the Higgs boson interactions

- extracted from the SM Lagrangian
- directly **couple with the mass** of elementary particles:

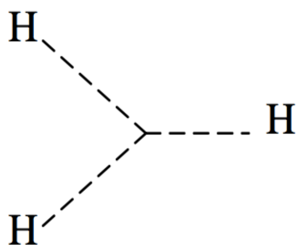


$$= -i\frac{m_f}{v}$$

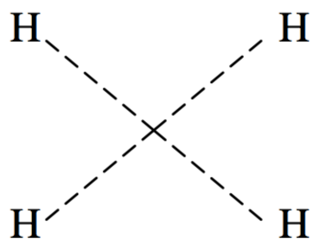


$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$

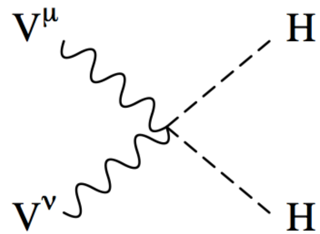
- and it is also massive, so it **couples to itself:**



$$= -3i\frac{M_H^2}{v}$$



$$= -3i\frac{M_H^2}{v^2}$$

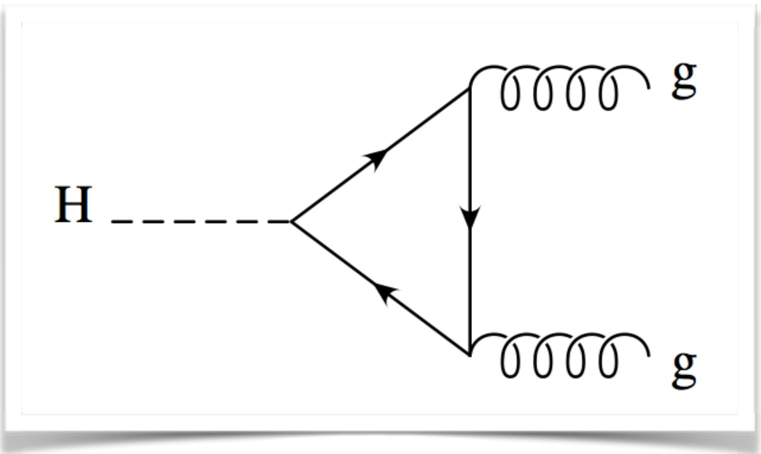


$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

L. Reina, TASI 2011: lectures on Higgs-Boson Physics

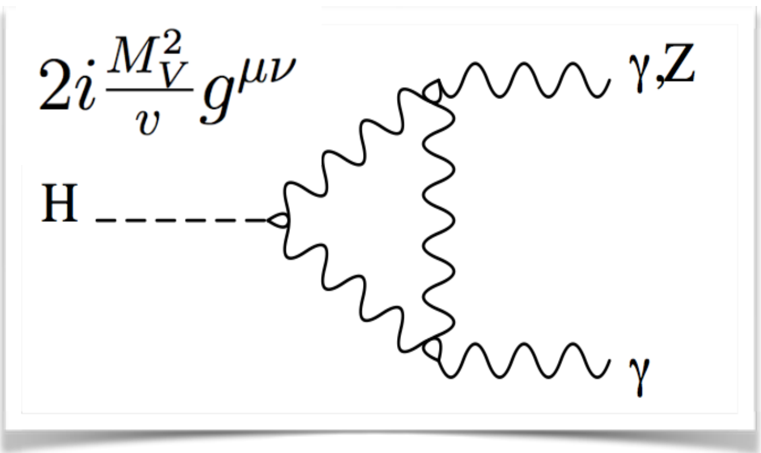
couplings to massless bosons

- do not happen at leading order
- takes place **through loops of massive particles**:

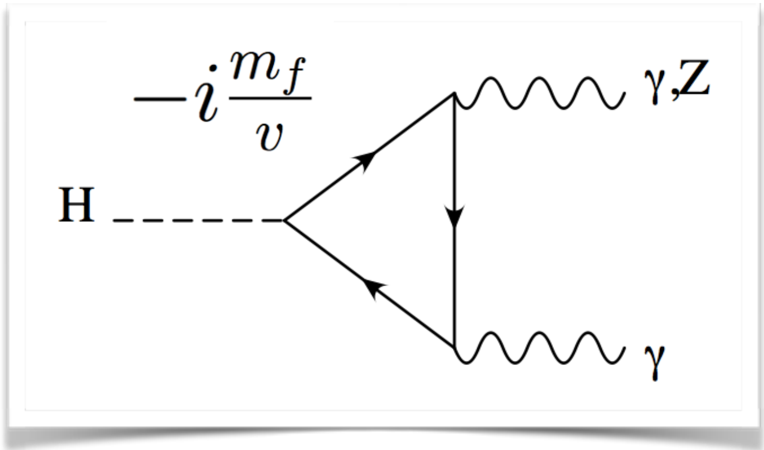


all fermions participate, but since the top quark has huge mass, it's the dominant contributor

- and sometimes with opposite effects:

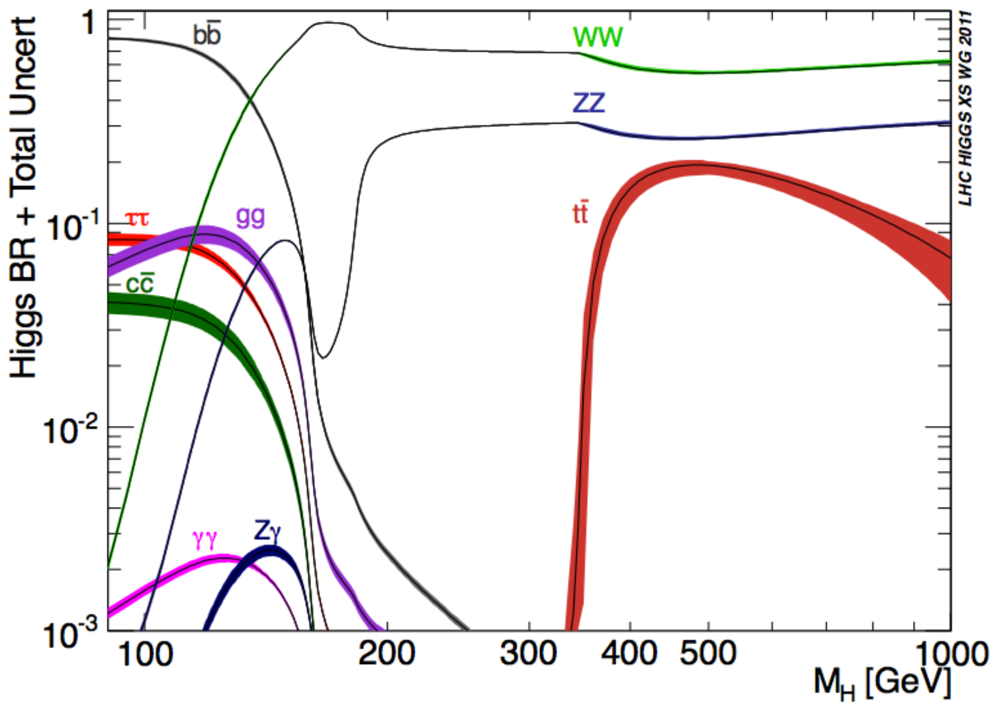


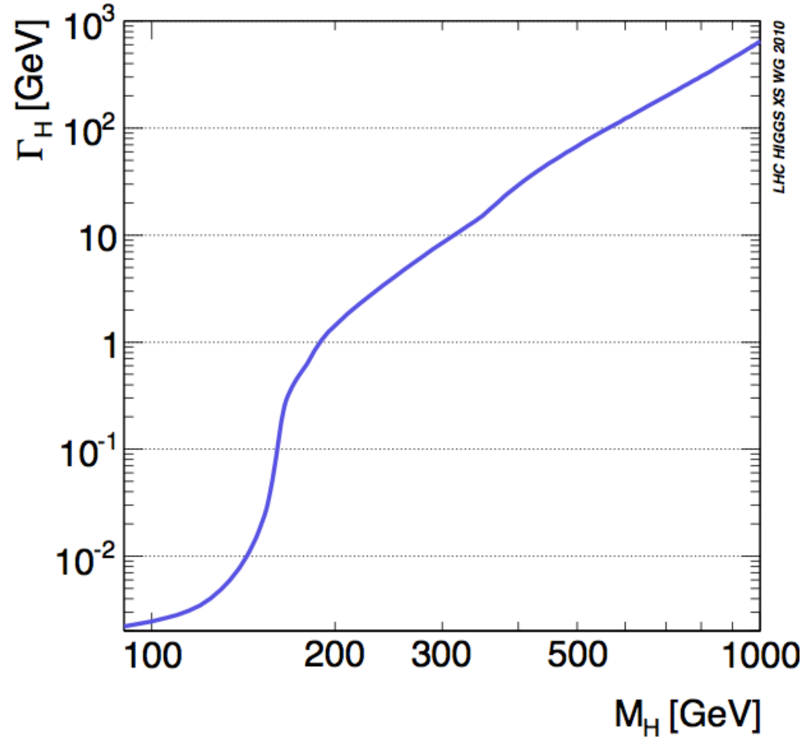
+



the SM Higgs boson properties

- for a given value of the H mass, **its properties are predicted** from the SM Lagrangian (and the other parameters of the theory)





The Higgs Hunter's vademecum

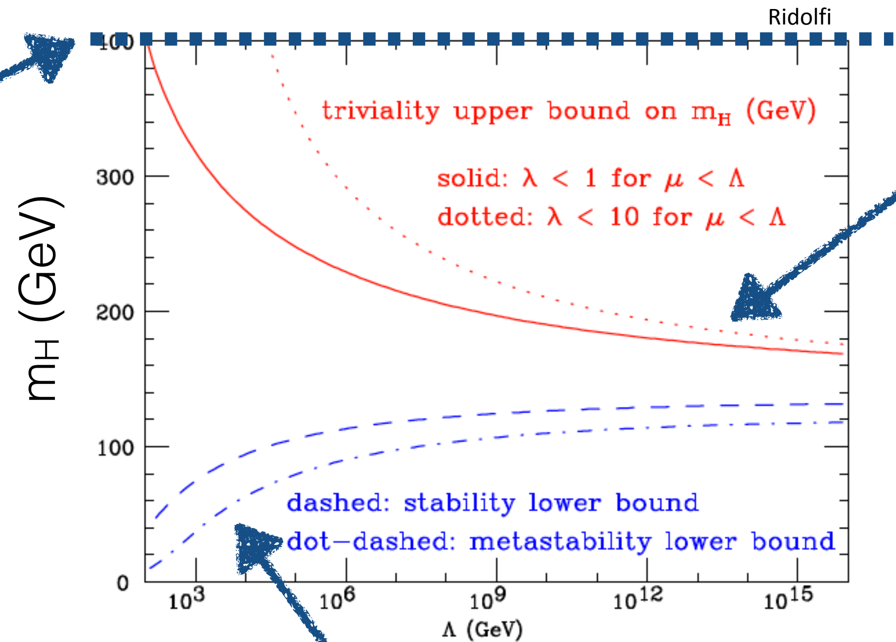
- Identify decay products
- Measure with high resolution the energy and the momentum
- Search for a (narrow) peak in the invariant mass spectrum

Higgs Cross Section Working Group TWIKI page

theoretical limits on the Higgs boson

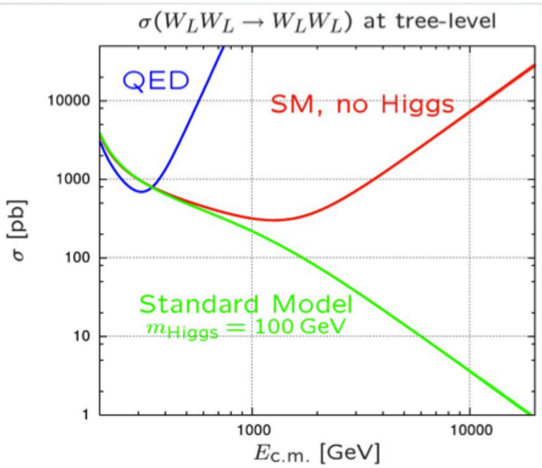
- the SM considered as an effective theory, up to a scale Λ
- the value of λ depends on the process scale
- for each value of the scale, there are theoretical bounds on m_H

stability: *guarantee the W scattering unitarity*



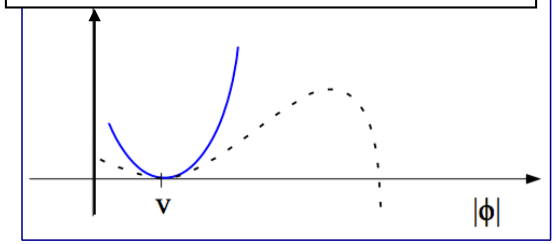
triviality: *prevent λ becoming infinite when increasing the scale*

$$\lambda(Q) = \frac{\lambda(Q_0)}{1 - \frac{3}{4\pi^2}\lambda(Q_0)\ln\left(\frac{Q^2}{Q_0^2}\right)}$$



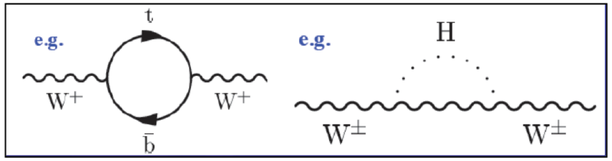
stability: *prevent the potential to decrease towards a lower minimum*

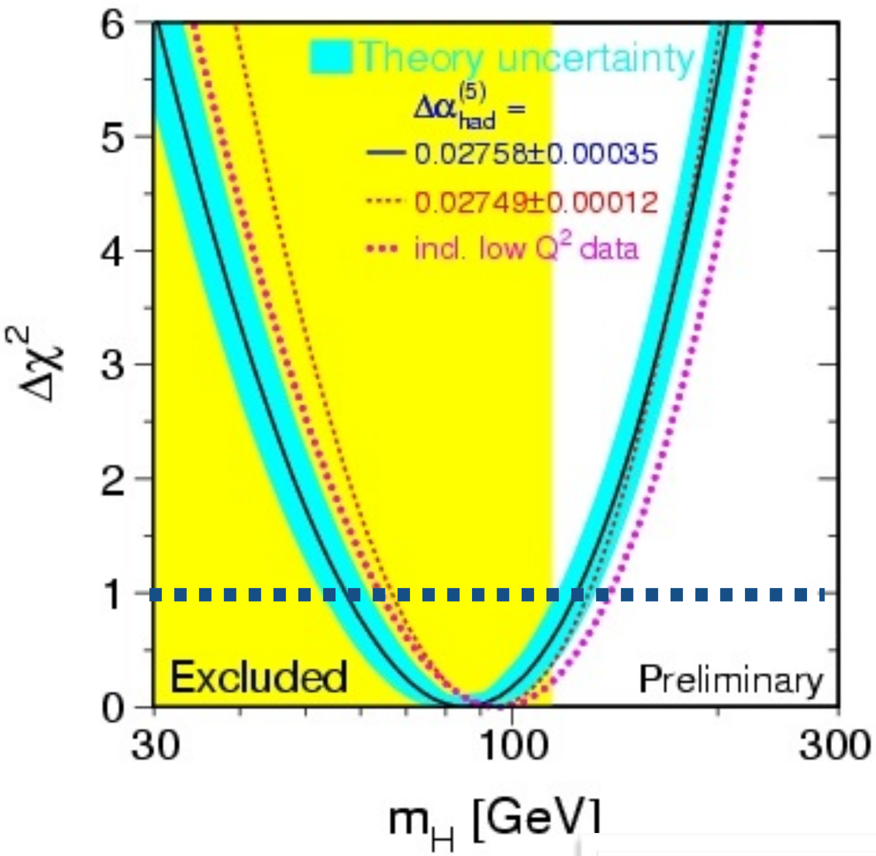
$$V(\phi) = \mu^2\phi_i^2 + \frac{\lambda}{2}\phi_i^4$$

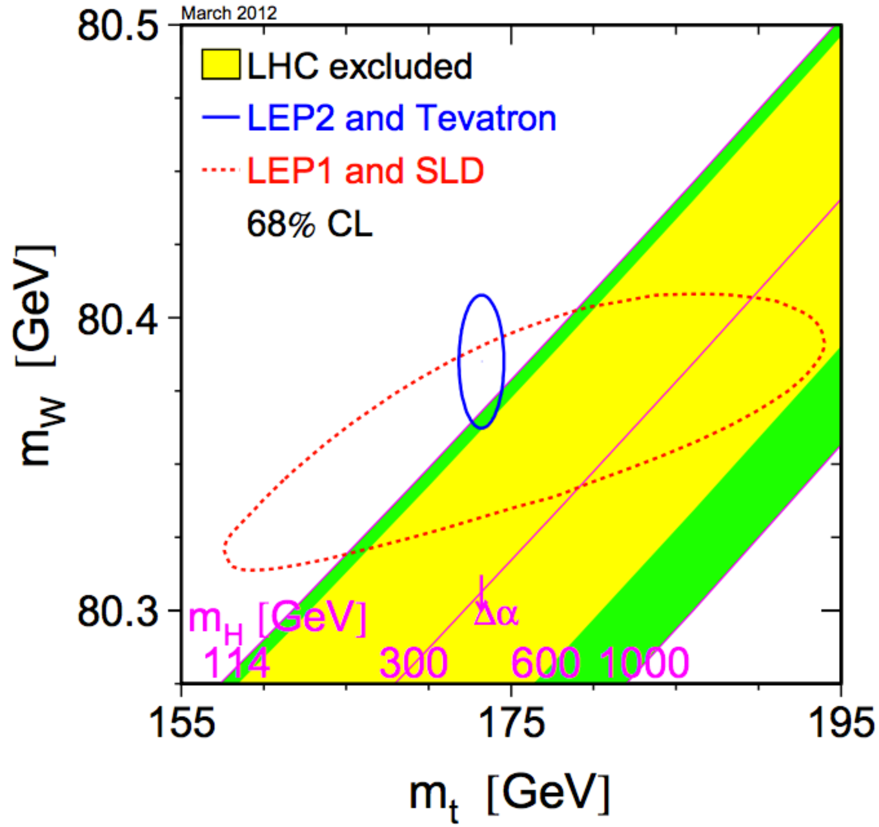


indirect measurements of the Higgs boson

- until LHC, the only way to observe the Higgs boson has been through indirect measurements, i.e. to see **its loop effects on other SM quantities**



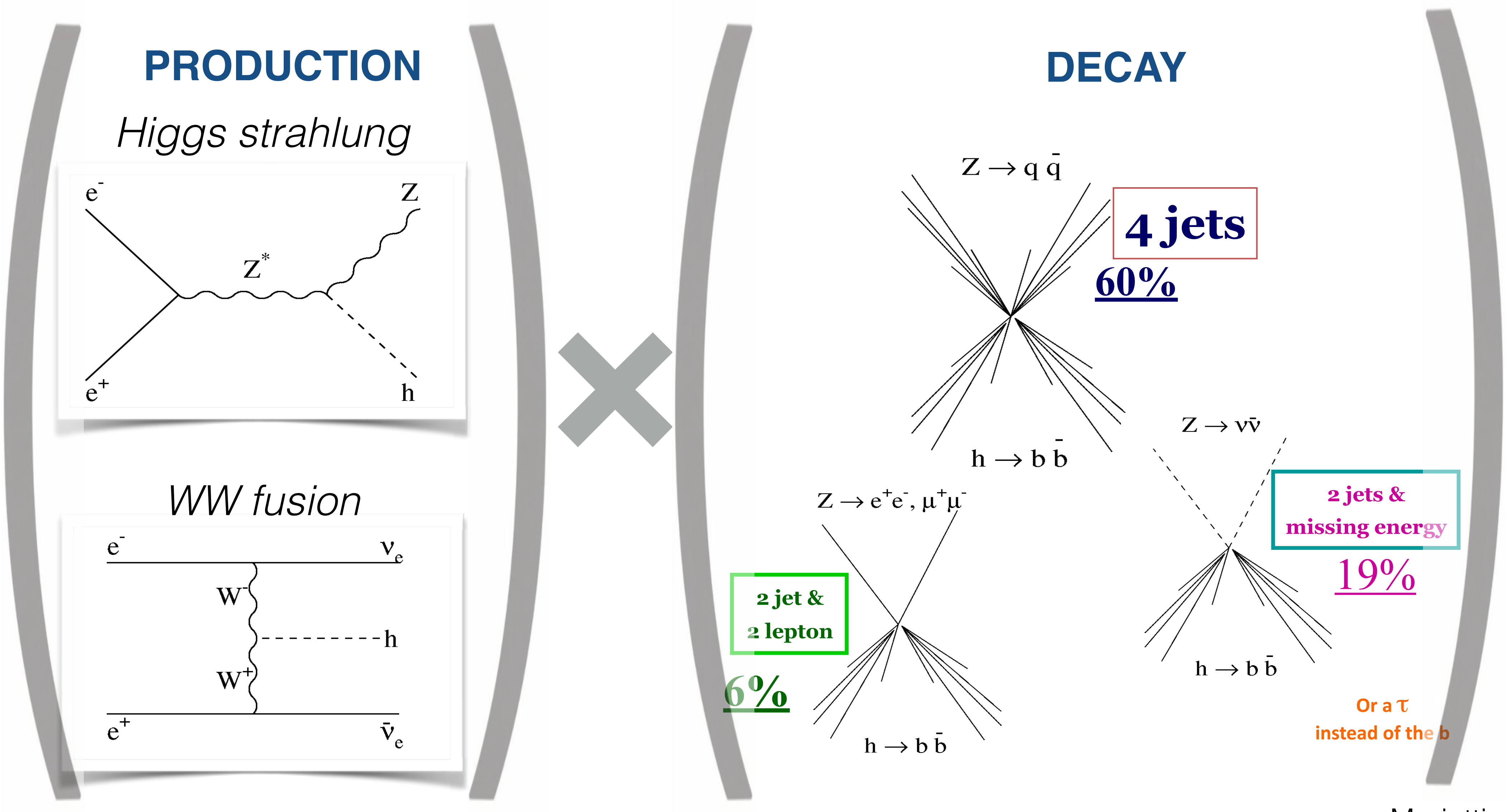




$m_H = 94^{+29}_{-24}$ GeV

direct searches at LEP

- the energy to produce a Higgs boson with m_H ~ 100 GeV becomes available at LEP2
- e^+e^- collider that run up to 209 GeV of energy in its centre of mass



Mariotti

the measurement

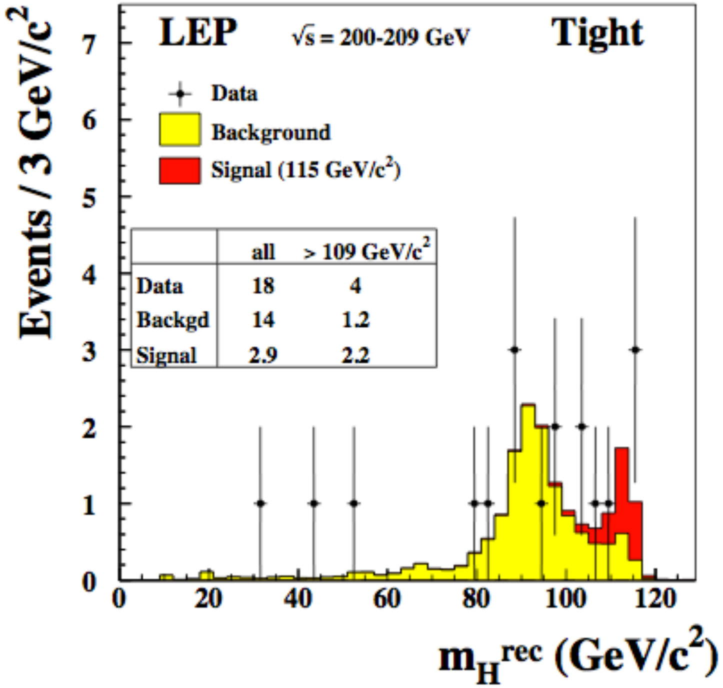
- reconstruct the **decay products invariant mass** and compare to the simulation forecasts
- need a **measure of the compatibility** of data to the B-only or S+B hypotheses

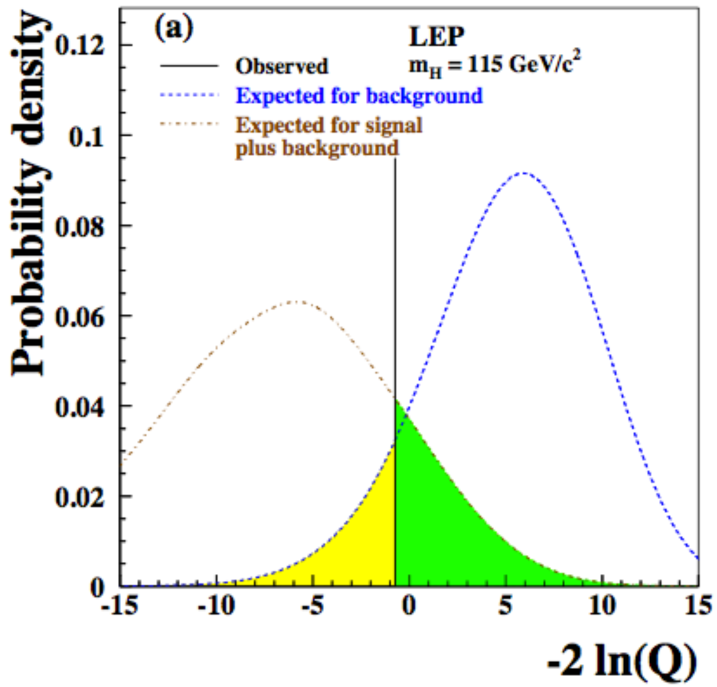
$$\mathcal{L}(H_1) = \prod_{a=1}^{N_{ch}} \mathcal{P}_{\text{Poisson}}(n_a, s_a + b_a) \prod_{j=1}^{n_a} \frac{s_a \mathcal{S}_a(\vec{x_j}) + b_a \mathcal{B}_a(\vec{x_j})}{s_a + b_a}$$

$$\mathcal{L}(H_0) = \prod_{a=1}^{N_{ch}} \mathcal{P}_{\text{Poisson}}(n_a, b_a) \prod_{j=1}^{n_a} \mathcal{B}_a(\vec{x_j}) .$$

- likelihood ratio:

$$\lambda = -2 \ln Q \, , \text{ with } Q = \frac{\mathcal{L}(H_1)}{\mathcal{L}(H_0)}$$

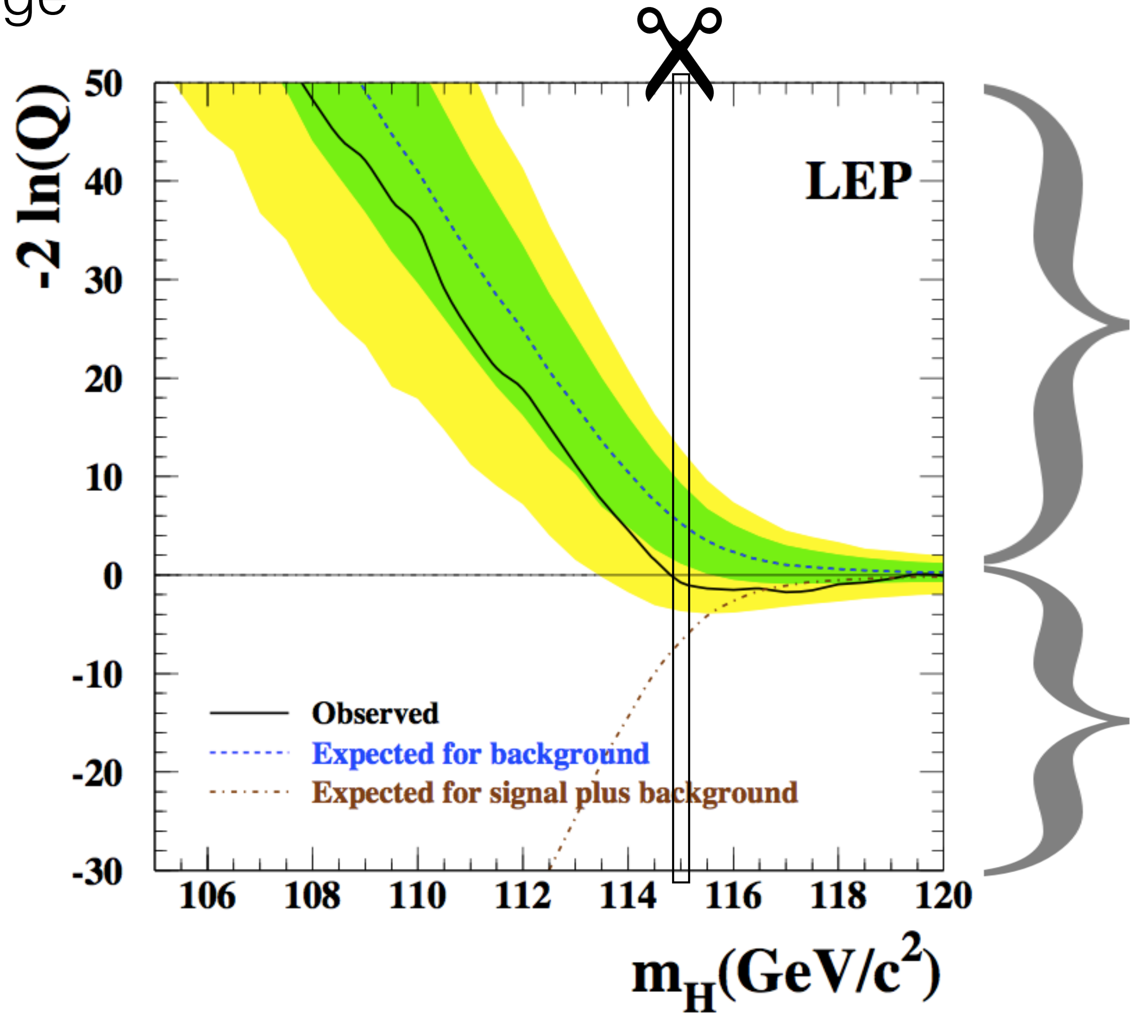




A. Read, Modified frequentist analysis of search results (the CLs method)

the exclusion limit

- the comparison is performed for several masses, along the LEP2 sensitivity range



background *likelihood for B-only is larger than the S+B one*

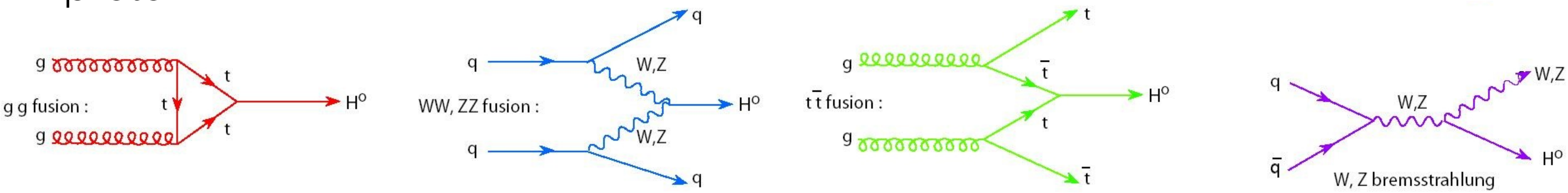
signal + background

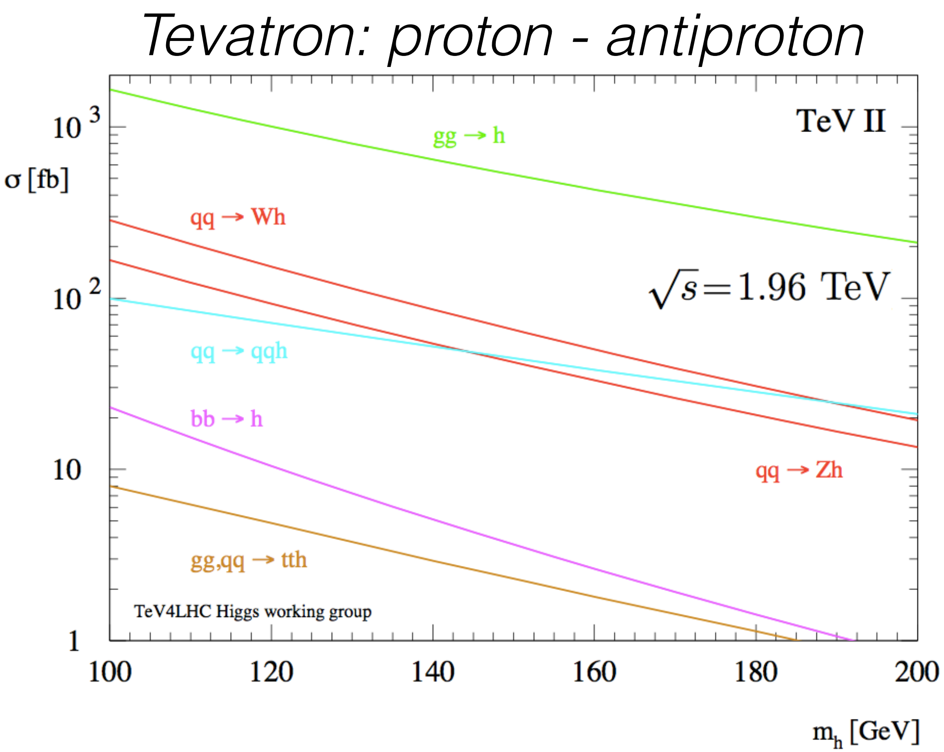
- the Higgs boson is excluded at 95% confidence level in the low mass range

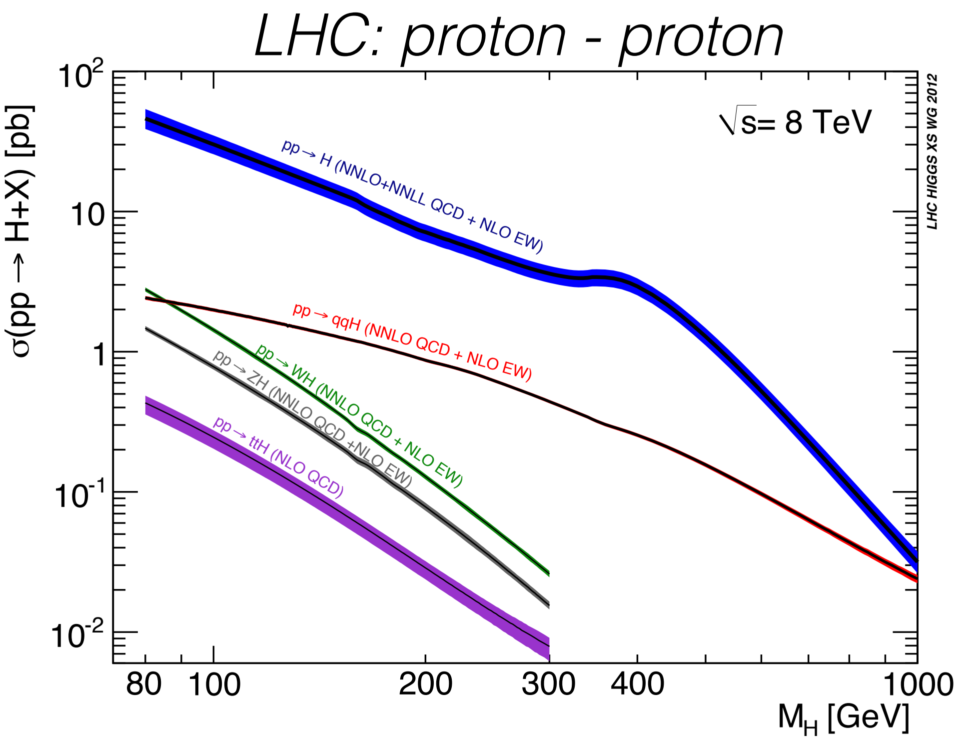
m_H > 114.4 GeV (expected 115.3 GeV)

Higgs boson production at hadron colliders

- the beams are not made of elementary particles
- the actual **scattering happens between quarks and gluons**
- the total cross-section is modulated by the parton density functions of the proton





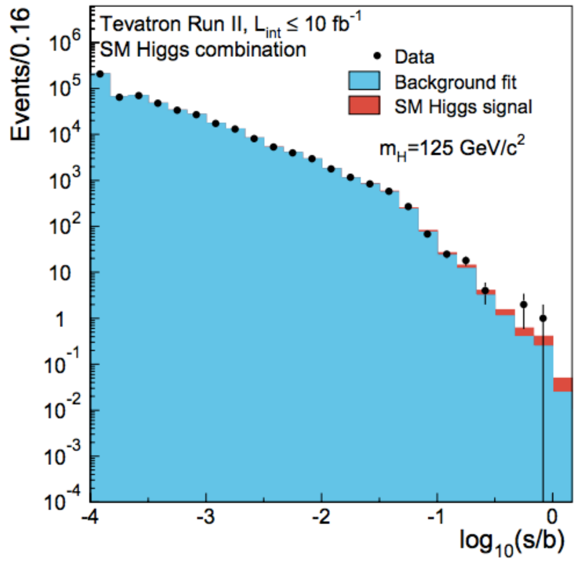


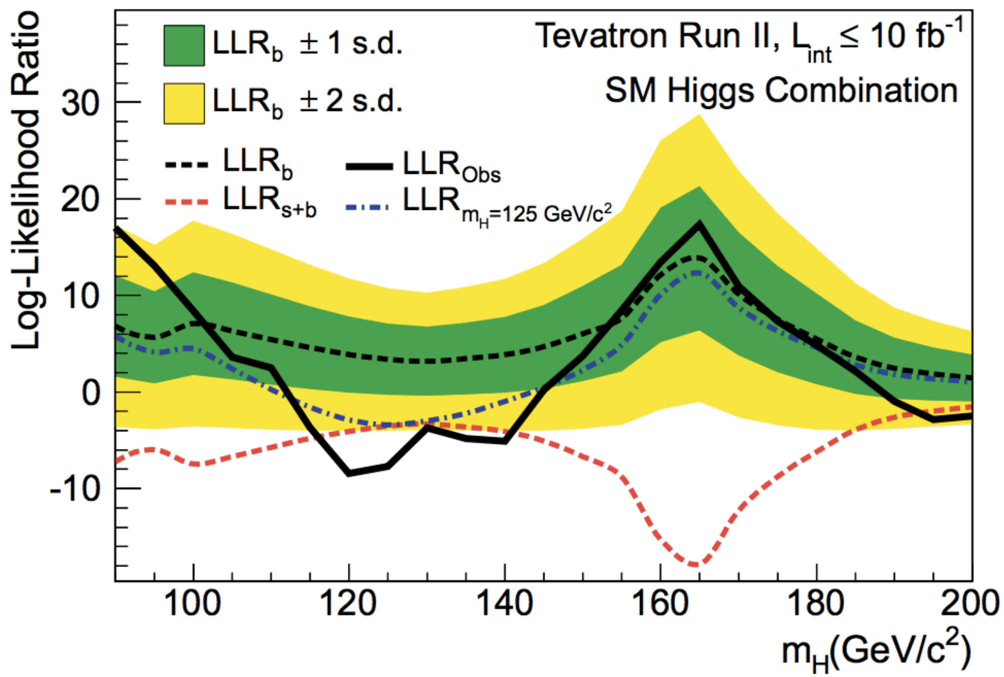
Higgs boson exclusion at Tevatron

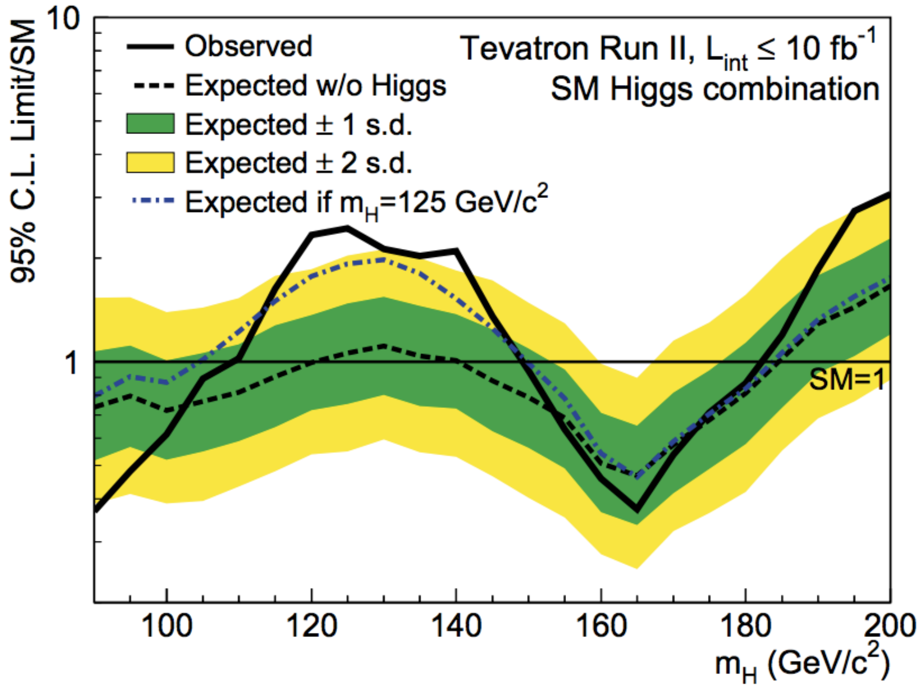
- **grand combination** of several channels and two experiments
- define **signal intensity**:

$$\mu = \frac{\sigma_{\text{signal}}}{\sigma_{\text{SM}}}$$

- plot μ for which the experiment has an exclusion power of 95% CL







the Large Hadron Collider

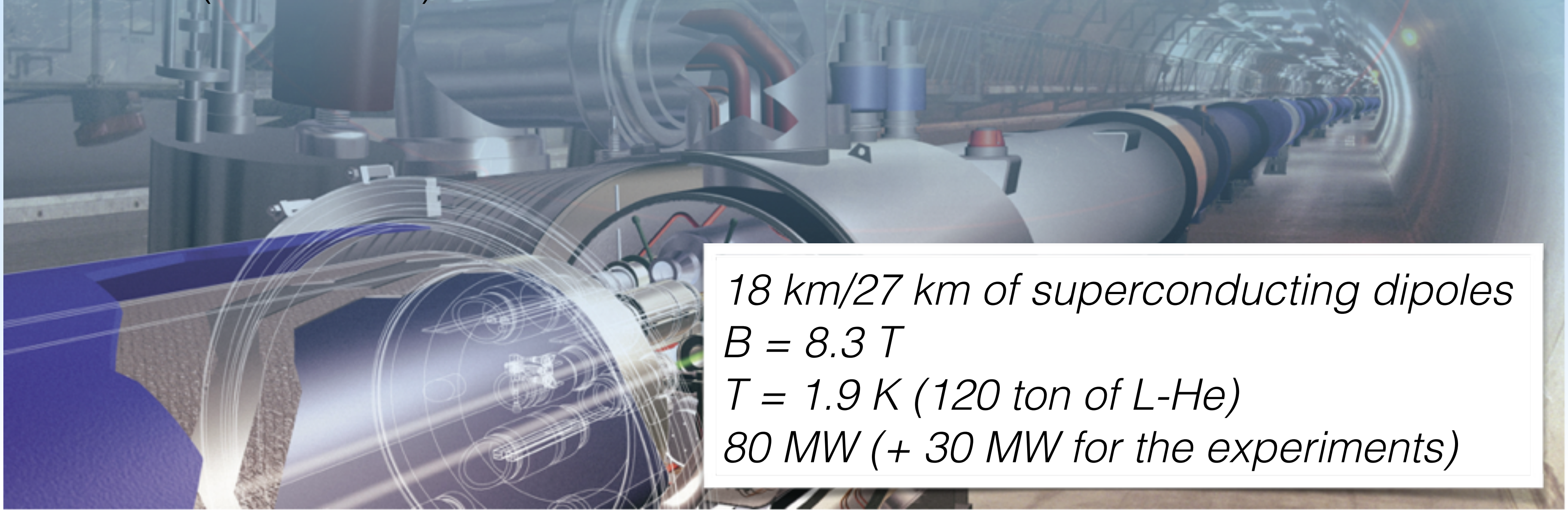
Primary objectives:

- Search for the SM Higgs boson up to 1 TeV
  - characterise it, if found
- Search for phenomena beyond the standard model
  - New gauge bosons, ‘new physics’ at the 1 TeV scale
  - Dark matter candidate

Centre of mass energy:

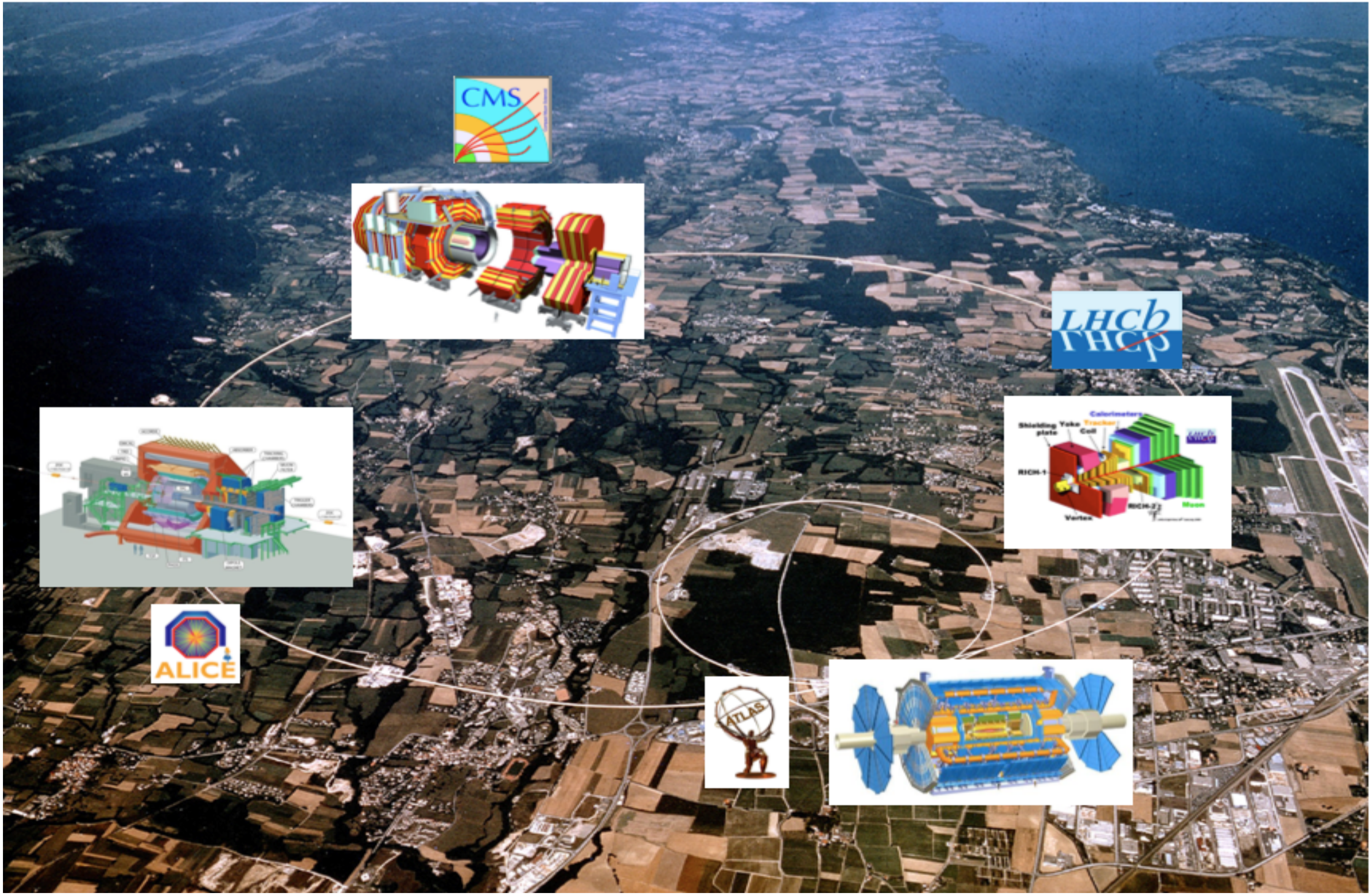
- 7-8 TeV (2010-2012)
- 13 TeV (2015-2018)

Approved in 1994
First collisions in 2009

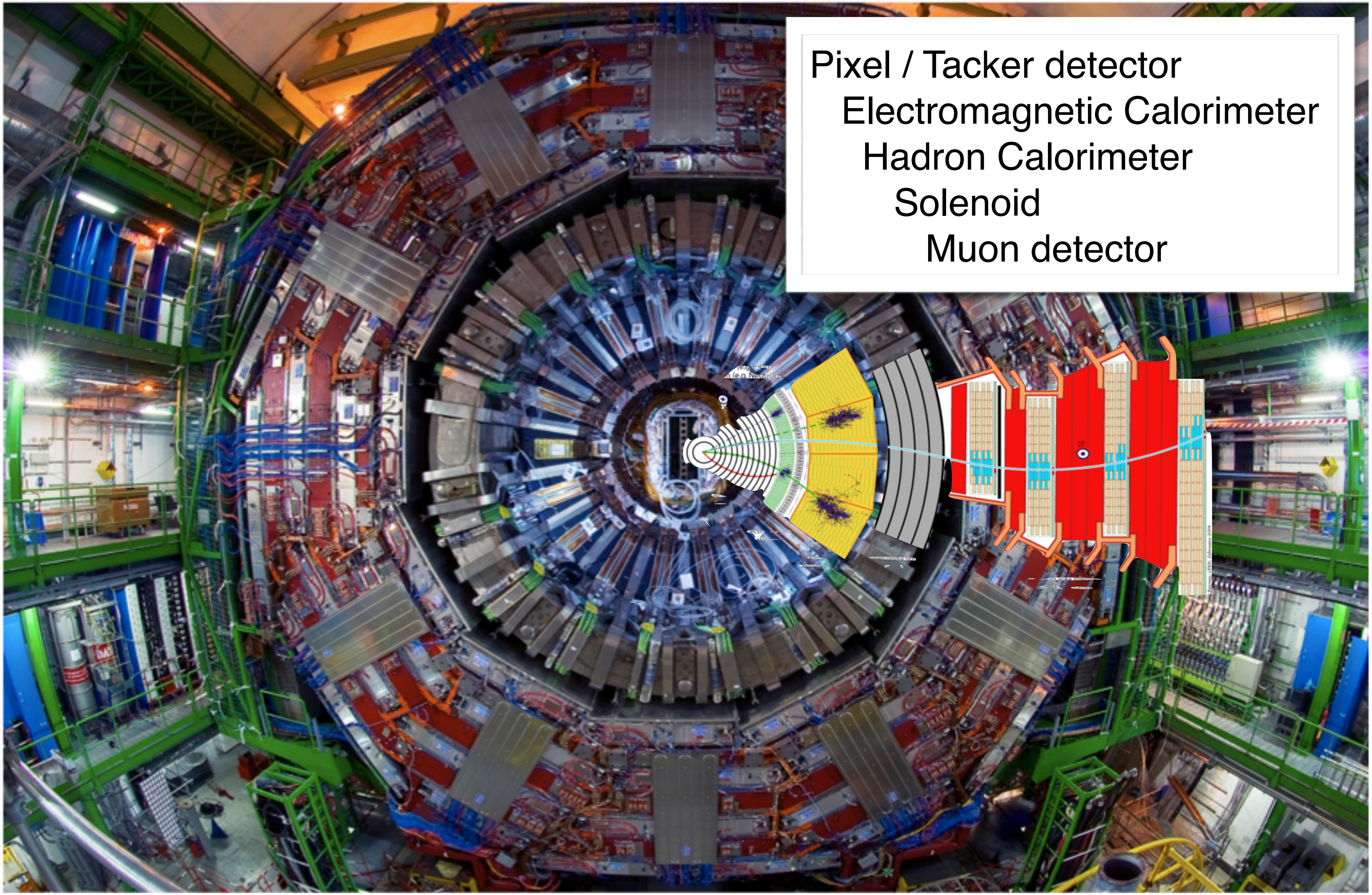


18 km/27 km of superconducting dipoles
B = 8.3 T
T = 1.9 K (120 ton of L-He)
80 MW (+ 30 MW for the experiments)

The LHC detectors

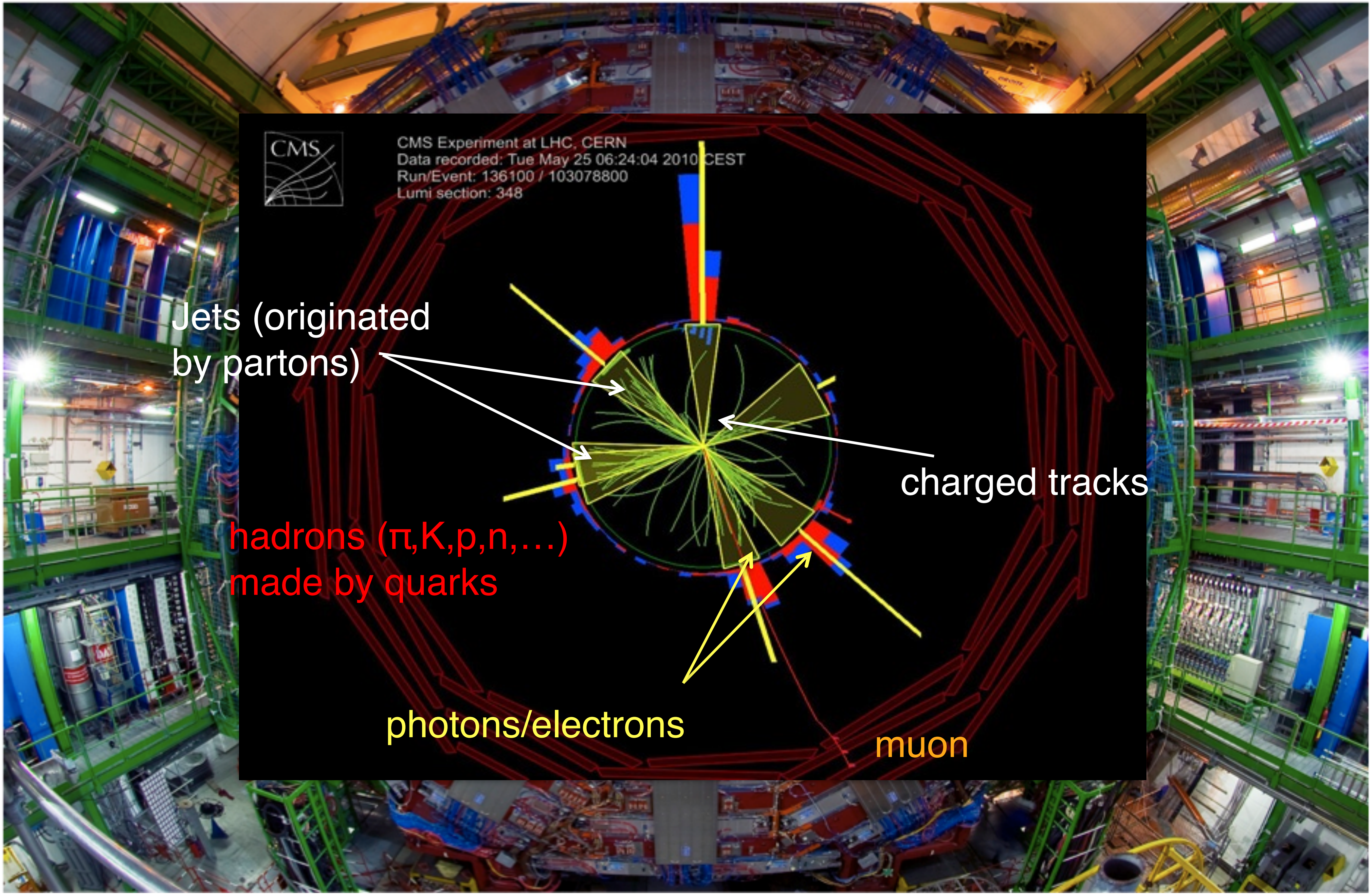


The Compact Muon Solenoid



The Compact Muon Solenoid

Tabarelli de Fatis

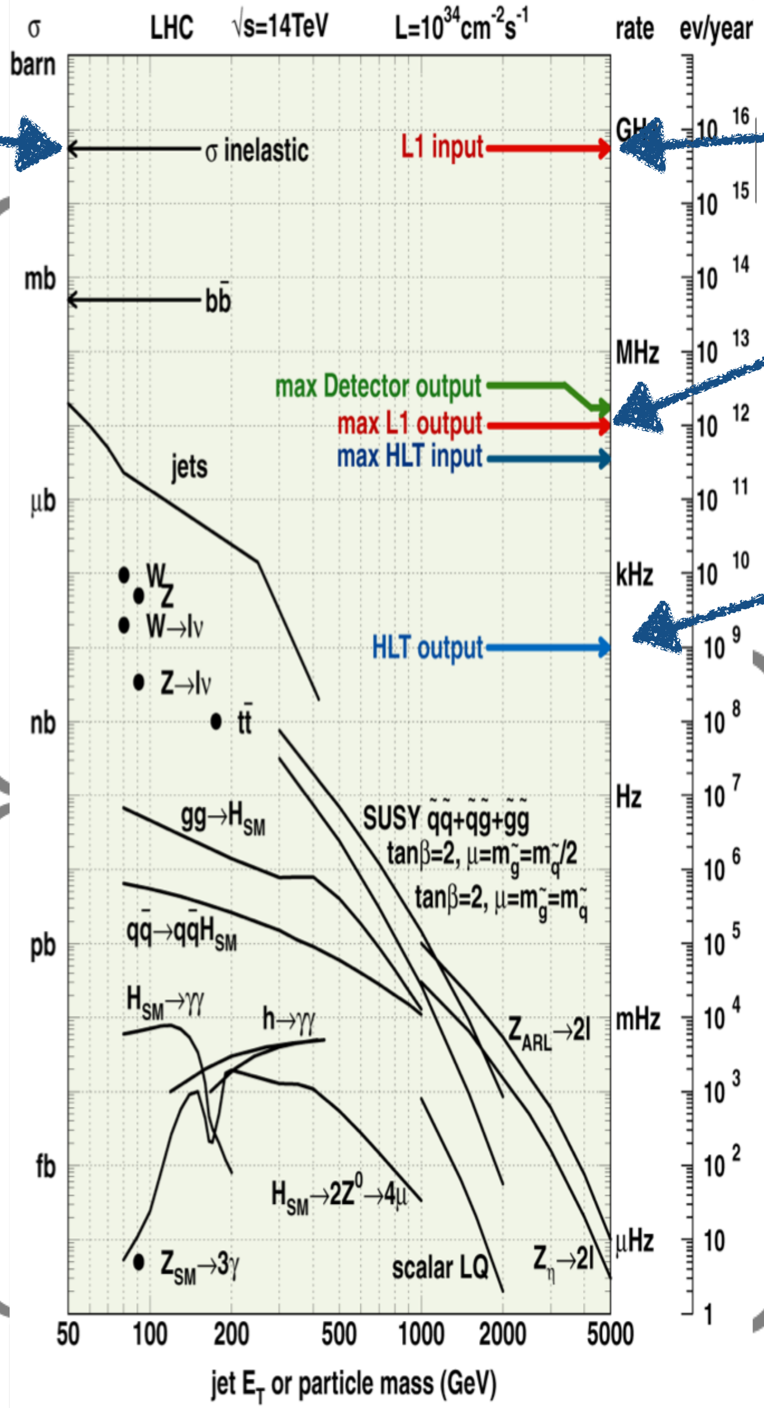


experimental challenges: the event selection

total LHC production cross-section

backgrounds
heavy quarks and vector bosons production

signal
Higgs decay products



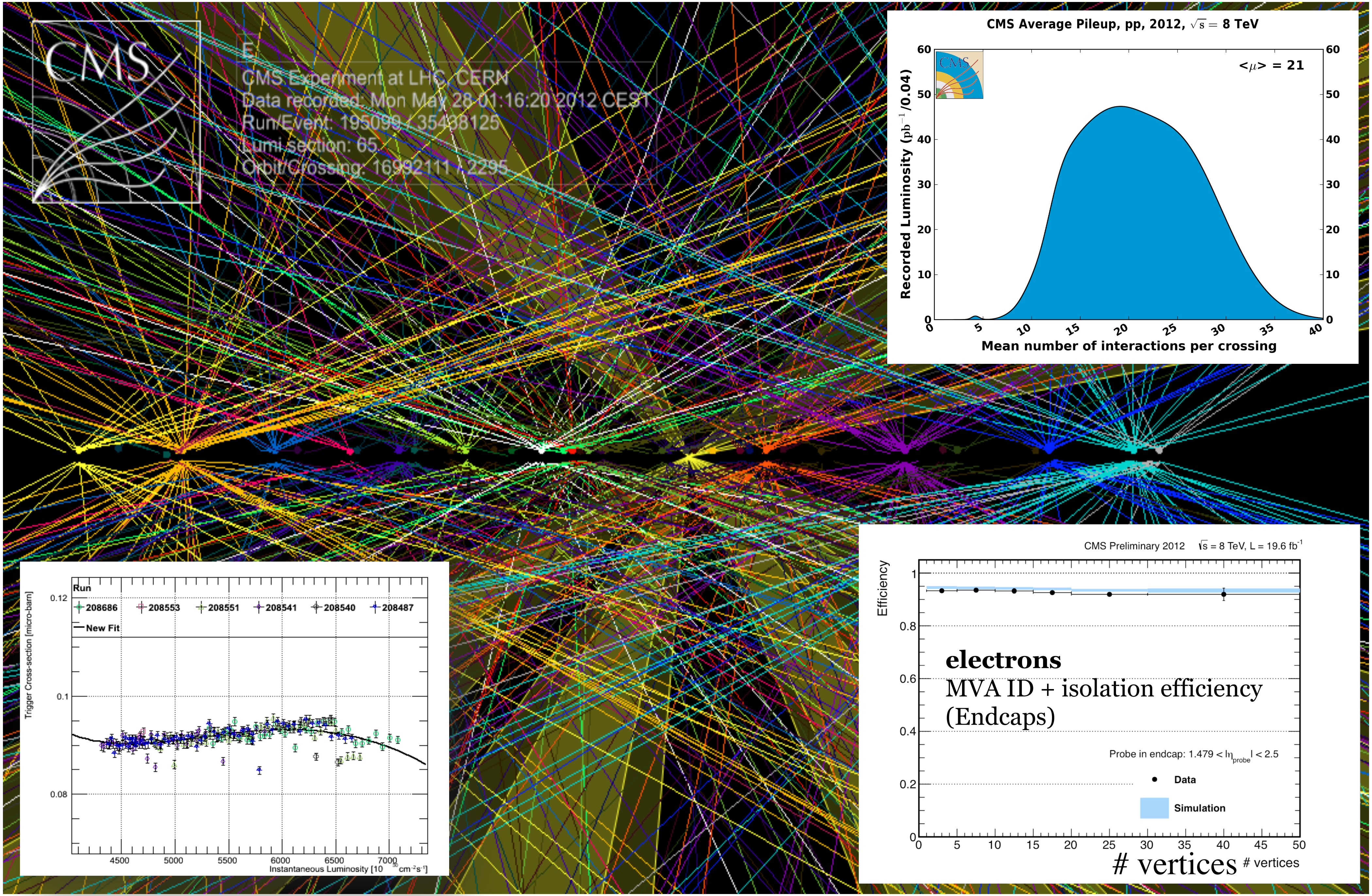
total event rate

L1 trigger
discard immediately events with no relevant info

HLT trigger
discard events with no relevant physics topology

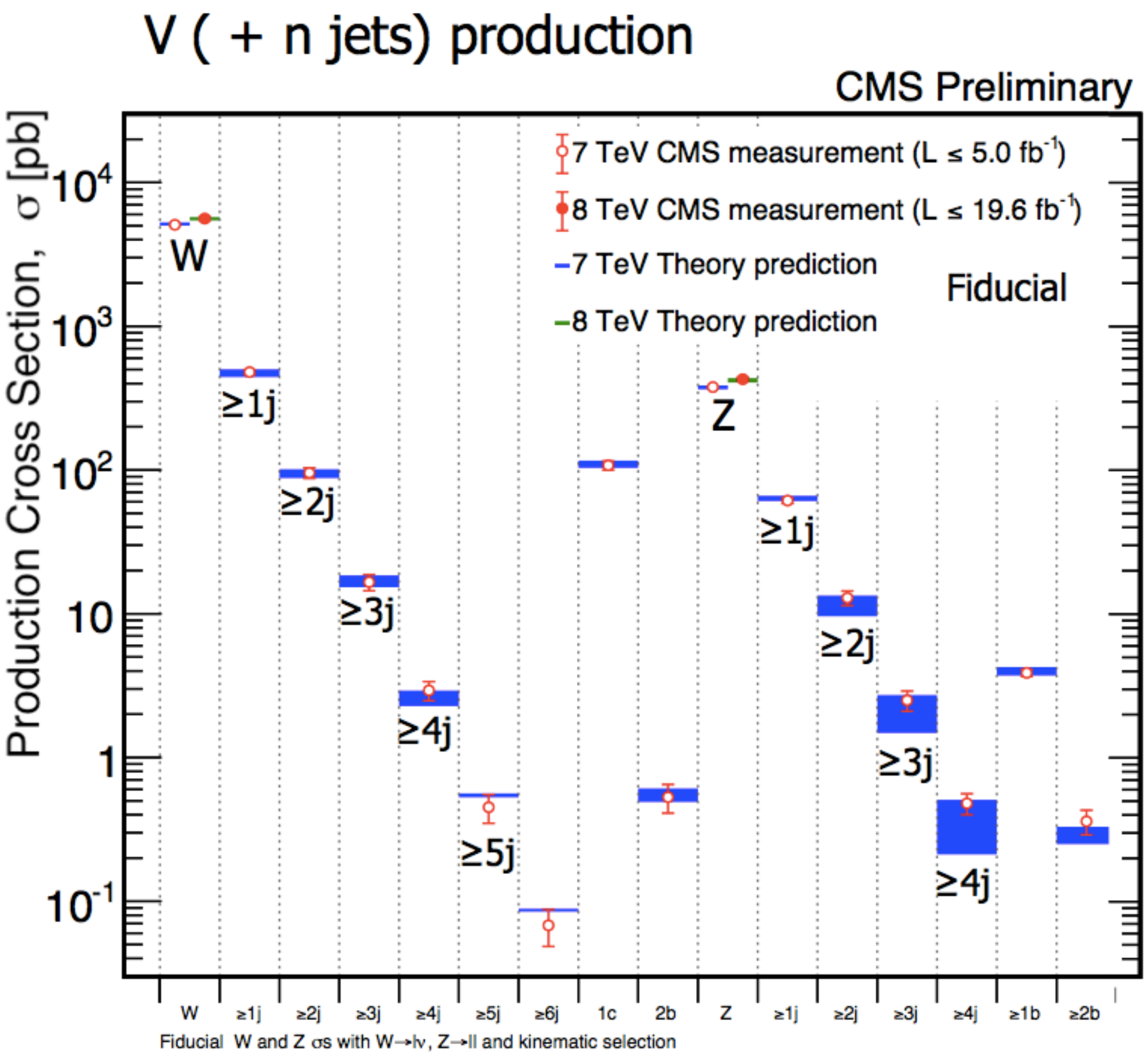
offline
all what survives the HLT gets saved for data analysis

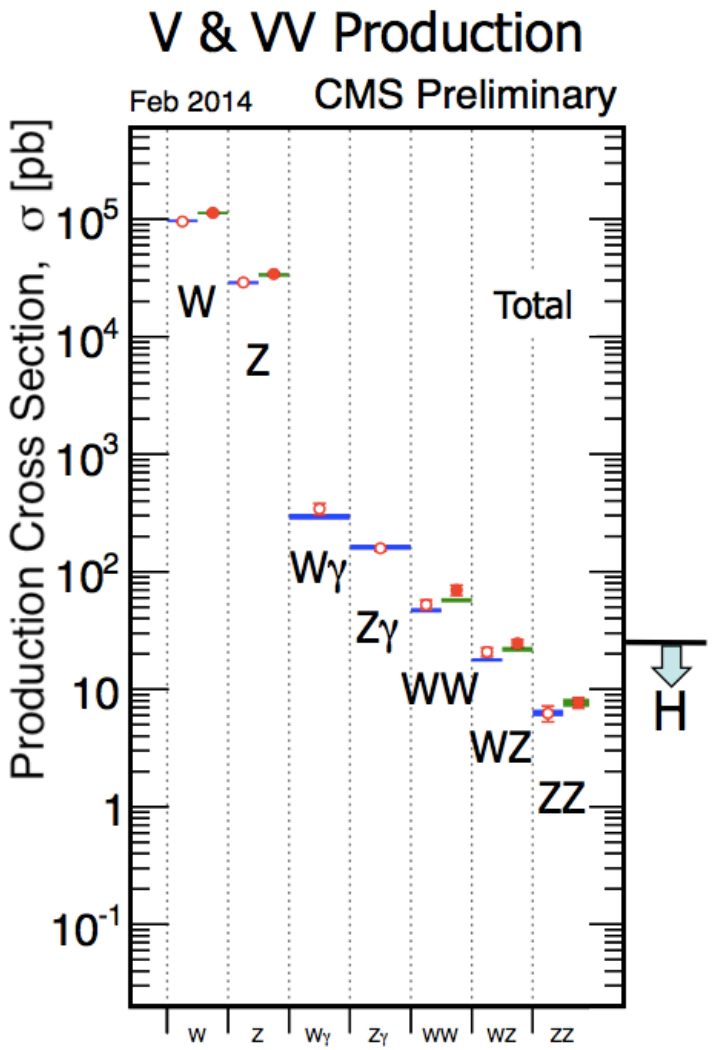
experimental challenges: the pile-up



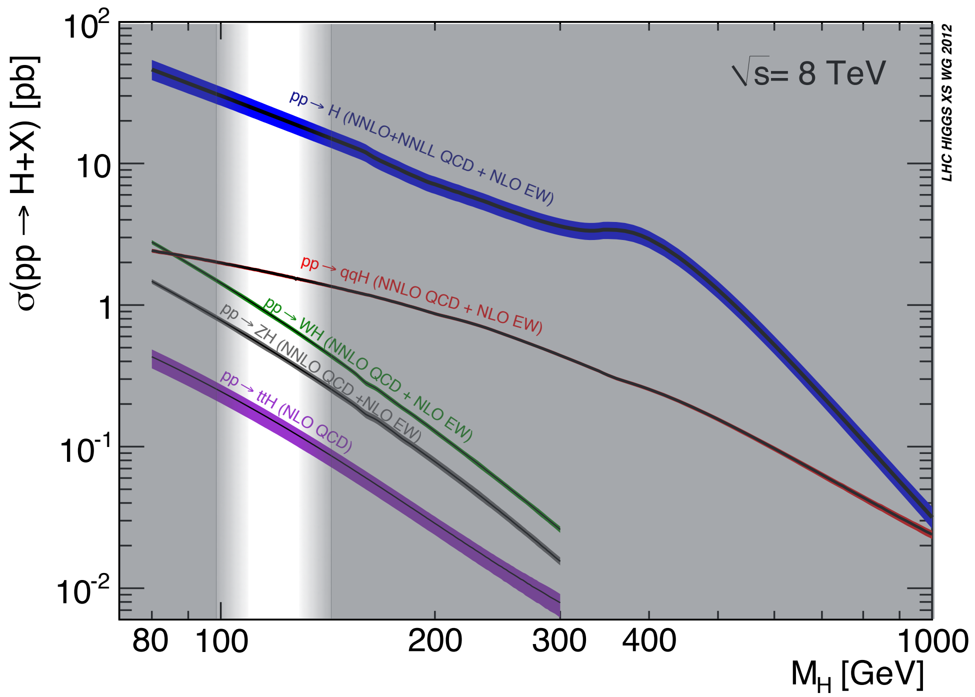
understanding the backgrounds

- **production cross section measurements**, corrected for leptonic branching fractions
- All theoretical expectations calculated at NLO or higher
- similar results obtained by the ATLAS experiment

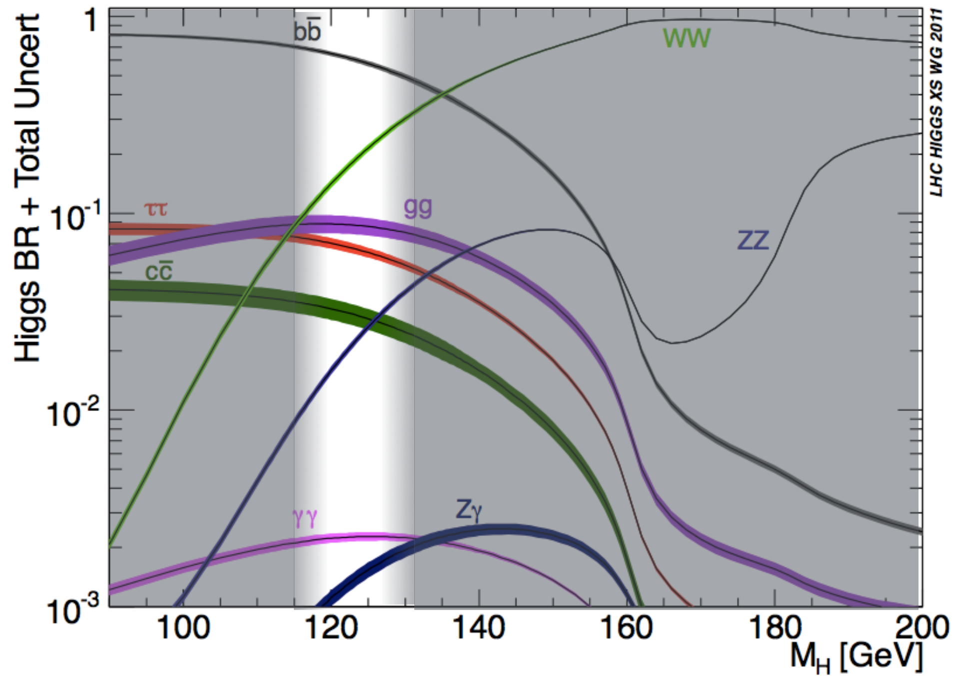




main Higgs boson search channels



×



	untagged	VBF	VH	ttH
H-> gamgam				
H-> ZZ				
H->WW				
H-> bb				
H-> tau tau				

de Roeck

the main characteristics

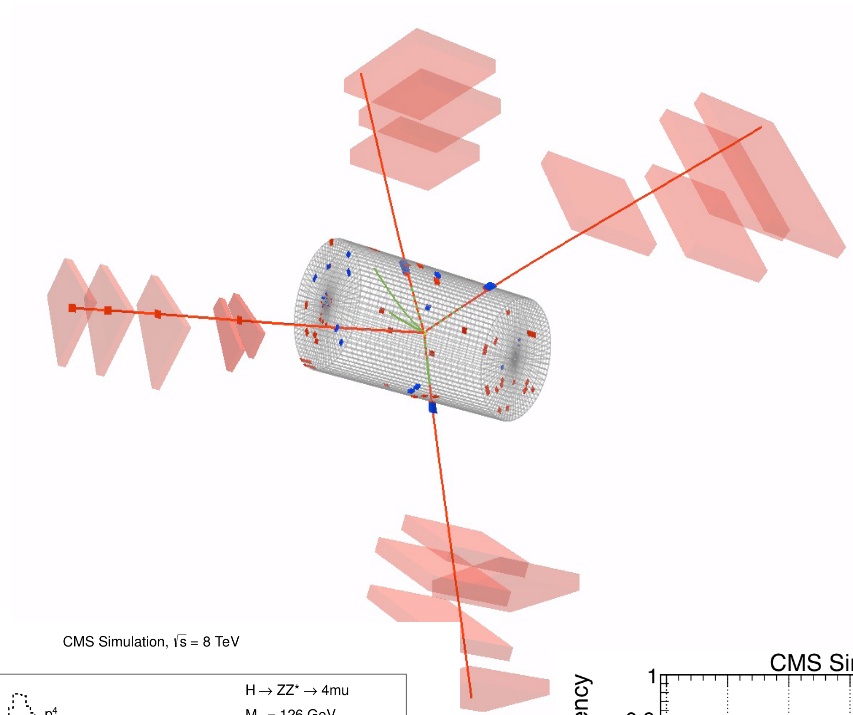
- the decay branching ratio determines **the range in m_H** where a channel is significant
- the final state objects determine **the resolution of the m_H reconstruction**

$$m_H = \sqrt{E_H^2 - \vec{p}_H^{\,2}} = \sqrt{\sum E_i^2 - \sum \vec{p}_i^{\,2}}$$

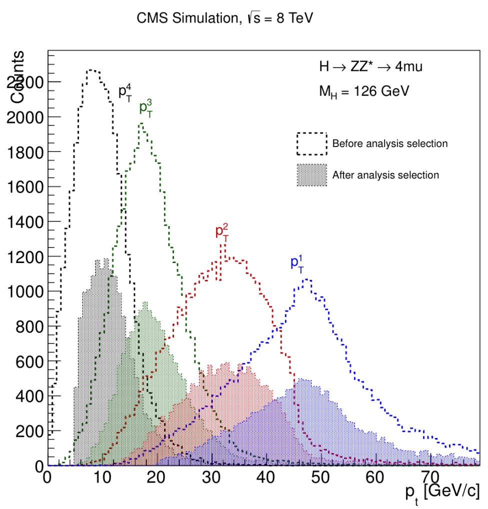
Channel	m_H range (GeV/c^2)	Data used 7+8 TeV (fb^{-1})	m_H resolution
H -> γγ	110-150	5.1+19.6	1-2%
H -> tautau	110-145	4.9+19.6	15%
H -> bb	110-135	5.0+19.0	10%
H -> WW -> lnulnu	110-600	4.9+19.5	20%
H -> ZZ -> 4l	110-1000	5.1+19.6	1-2%

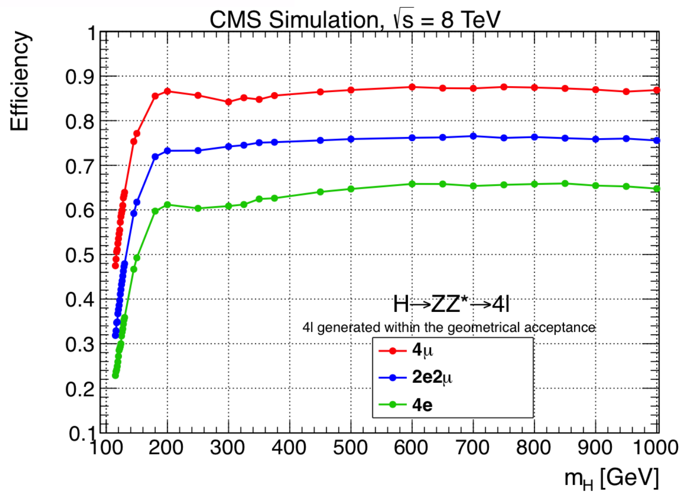
the H → ZZ → 4ℓ decay

- The “golden” channel – **Narrow peak over a locally flat continuum**
- Very high mass resolution and S/B >> 1
- Very low rates (σ x β ~ 0.8 fb at 125 GeV)

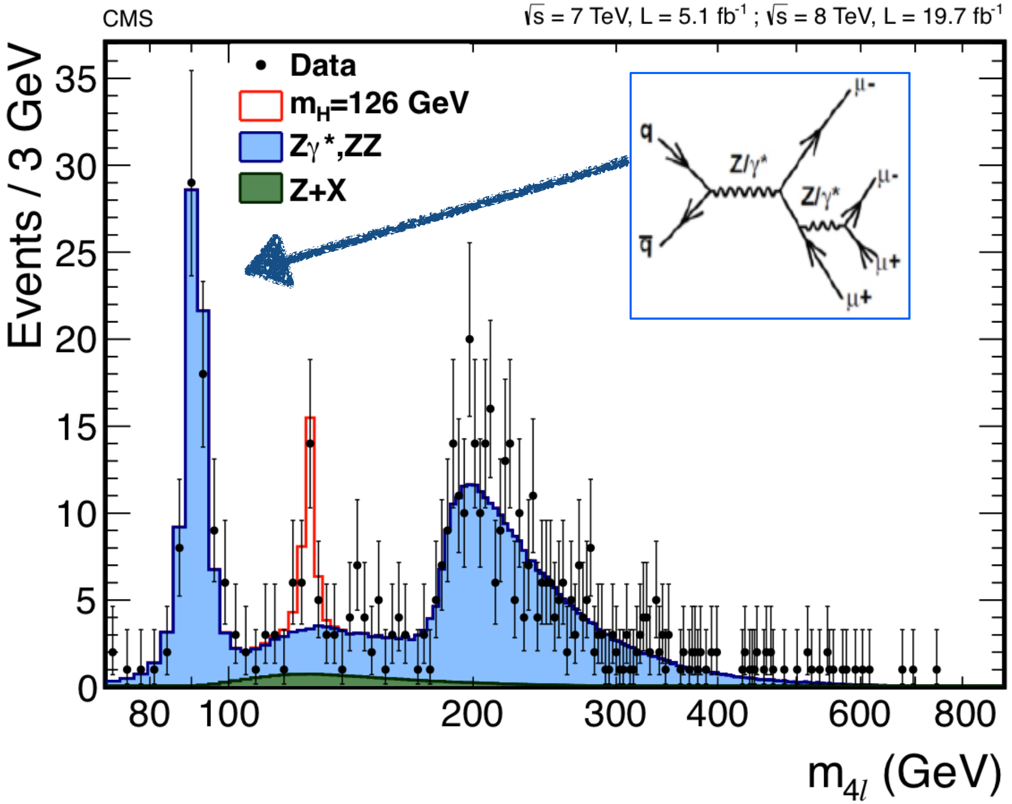


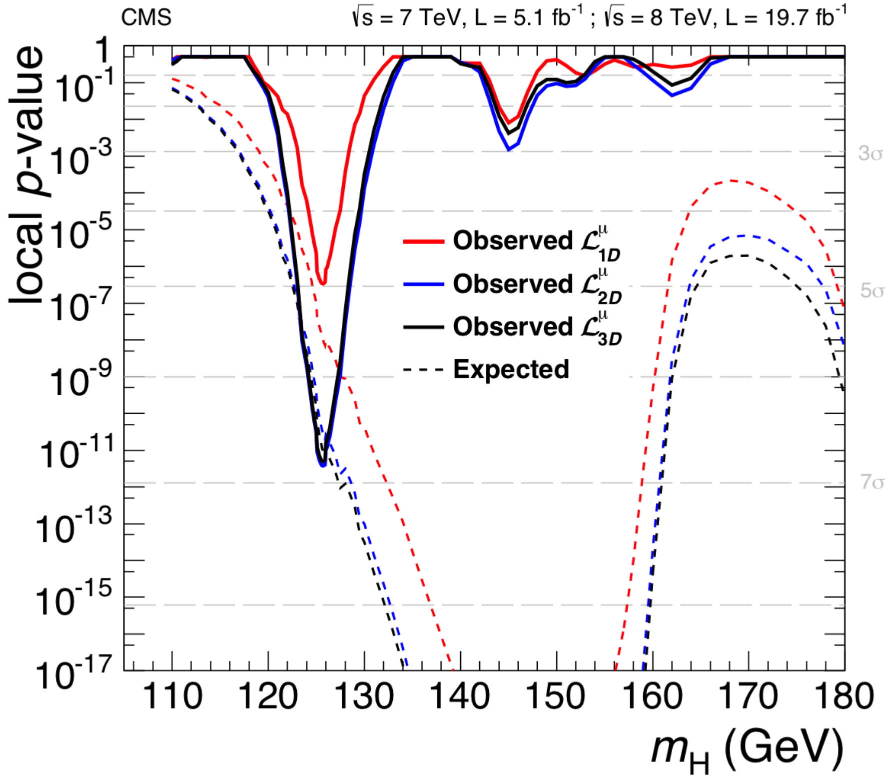
- **4 isolated leptons** from a common primary vertex
- Precision on lepton (E,P) & highest possible ε_{lepton} down to lowest p_T
- Maintain the reducible background well below the ZZ* continuum
- **discriminating variables**:
    - $m_{4\ell}$
    - Kinematic Discriminant (e.g. m_{Z1}, m_{Z2}, 5 angles from decay chain)





the observation





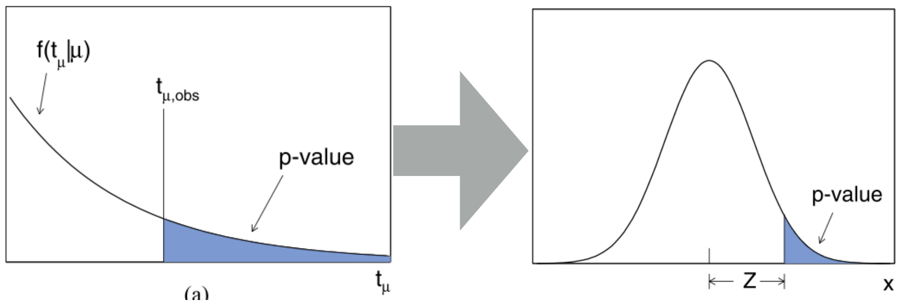
Significance: 6.8σ

σ/σ_{SM} =

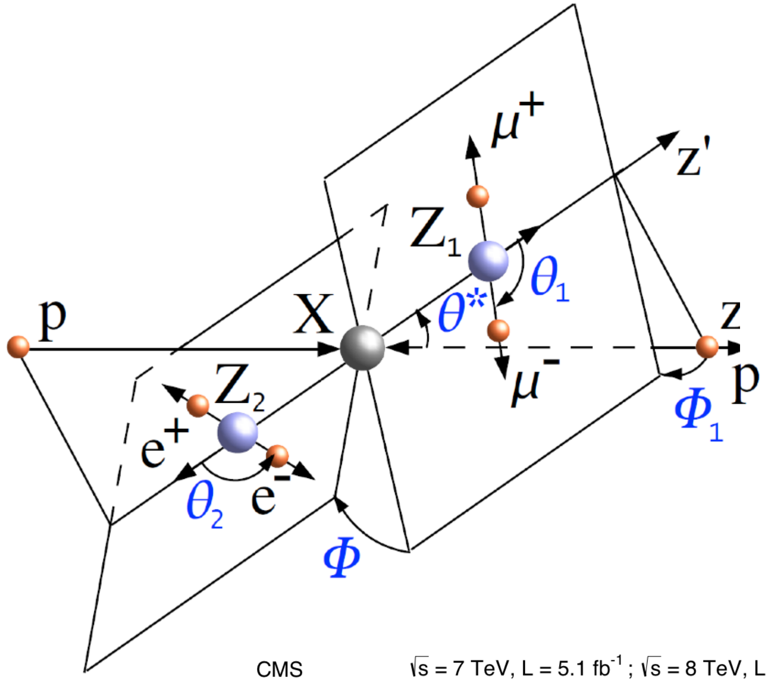
$0.93^{+0.26}_{-0.23}$ (stat.) $^{+0.13}_{-0.09}$ (syst.)

p-value

probability for the background-only hypothesis to fluctuate up to the observation

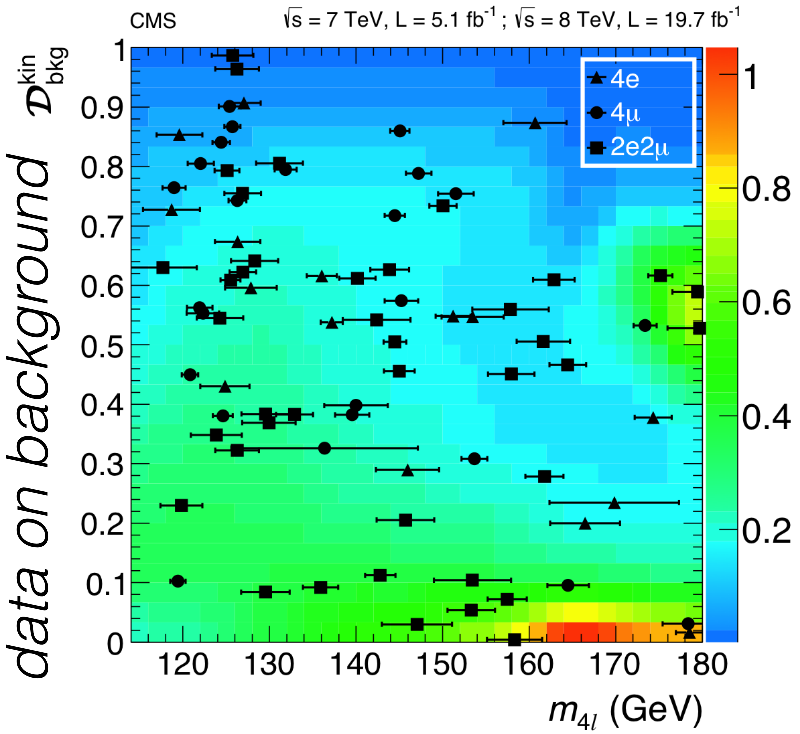


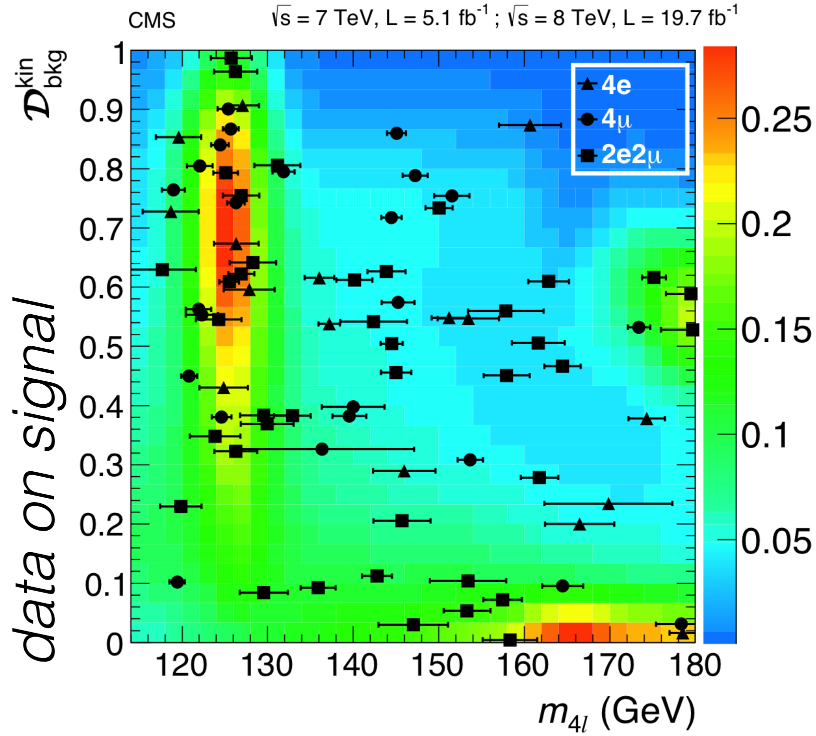
the signal discrimination



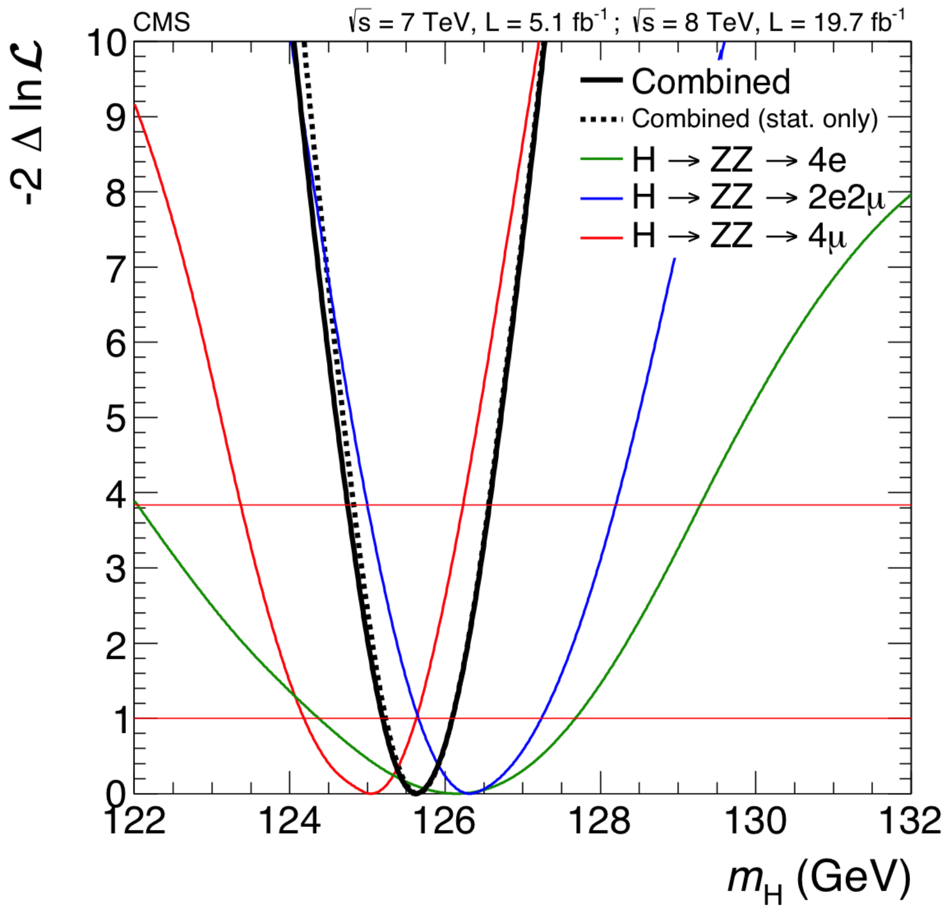
Matrix Element Likelihood Analysis:
uses kinematic inputs to build a kinematic discriminant (K_D) for signal to background discrimination using $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

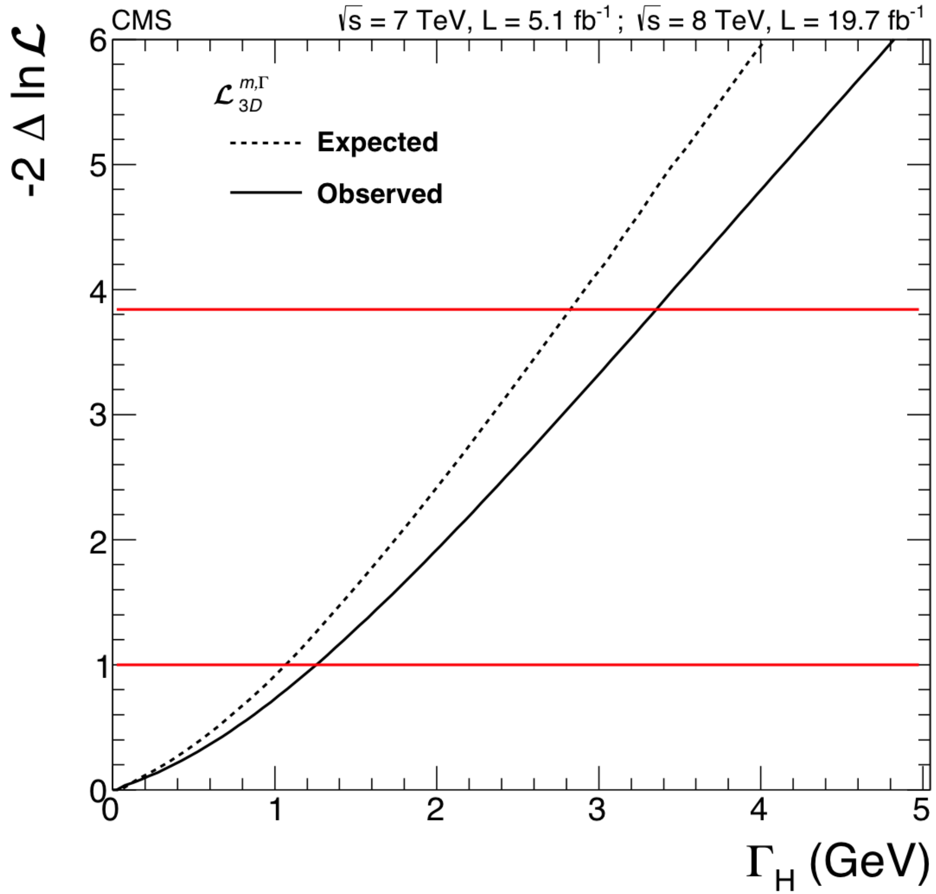
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$





first measurements on the resonance





m_H= 125.6 ± 0.4 (stat.) ± 0.2 (syst.) GeV

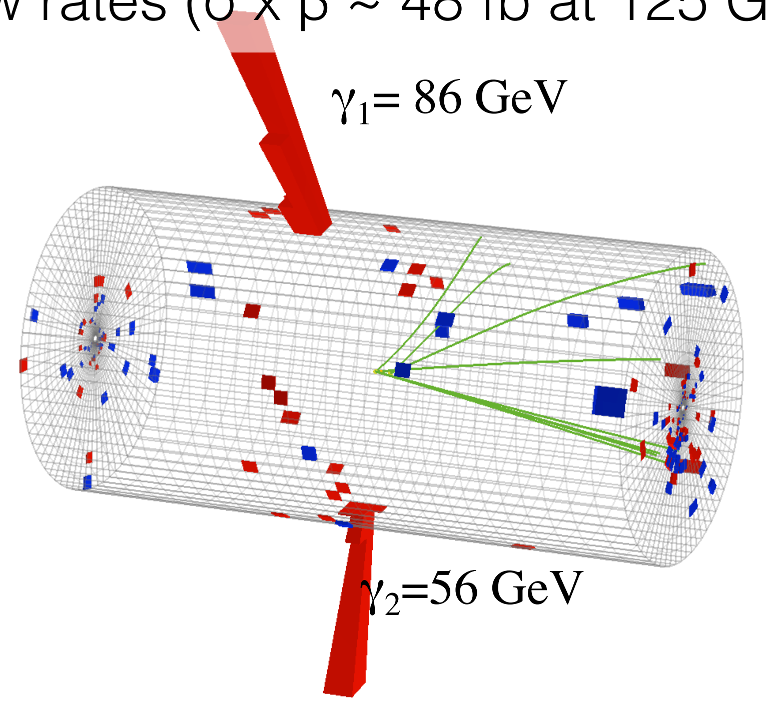
Γ_H<= 3.4 GeV at a 95% CL

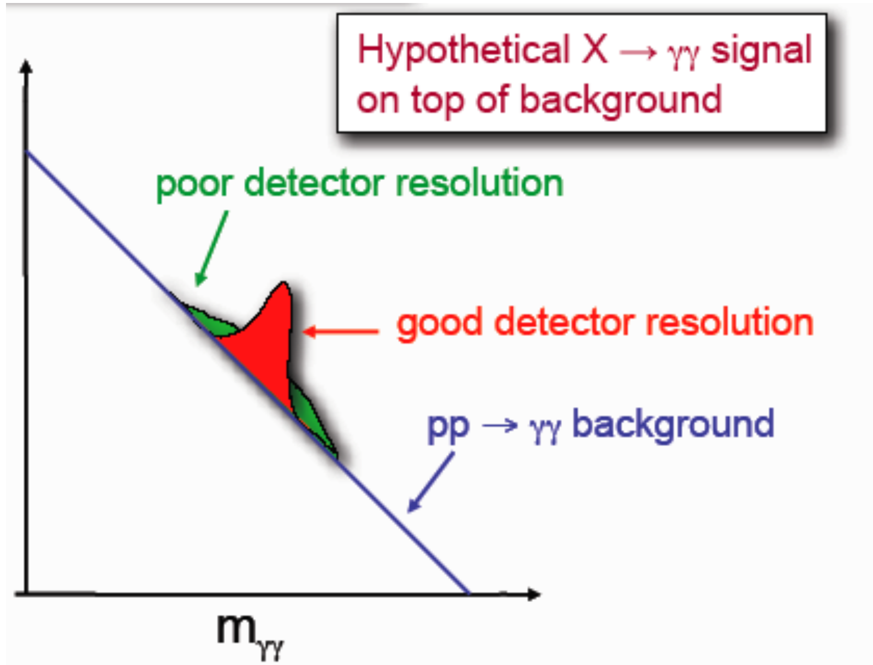
***NB** expected ~ 4 MeV!*

H → γγ

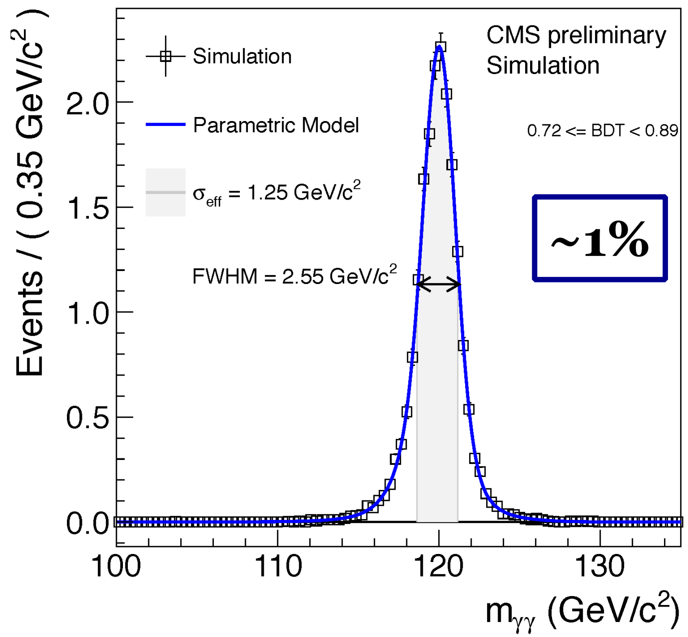
Mariotti

- high mass resolution, but S/B < 1
- low rates (σ x β ~ 48 fb at 125 GeV)





Signature: 2 energetic, isolated γ, in a narrow mass peak on top of a steeply falling spectrum

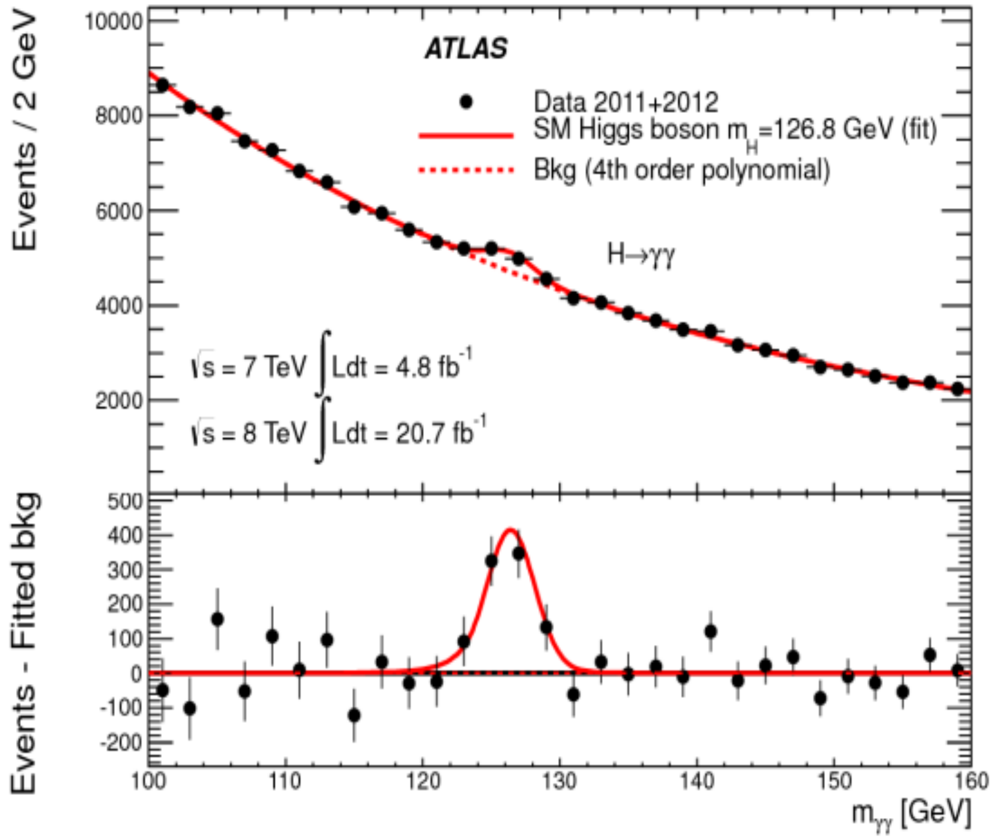


Relevant aspects:

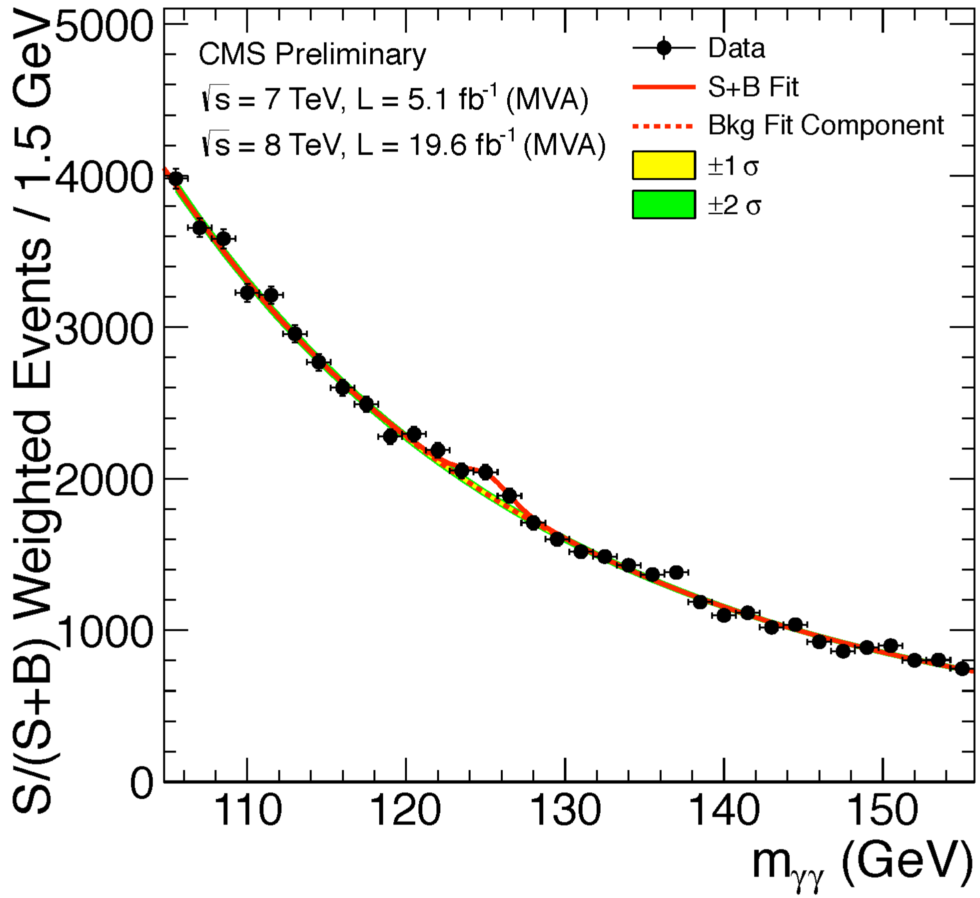
- Photon identification/ background rejection
- Di-photon mass spectrum
- Background estimation
- Primary vertex determination (pile-up!)

The mass distribution

ATLAS



CMS

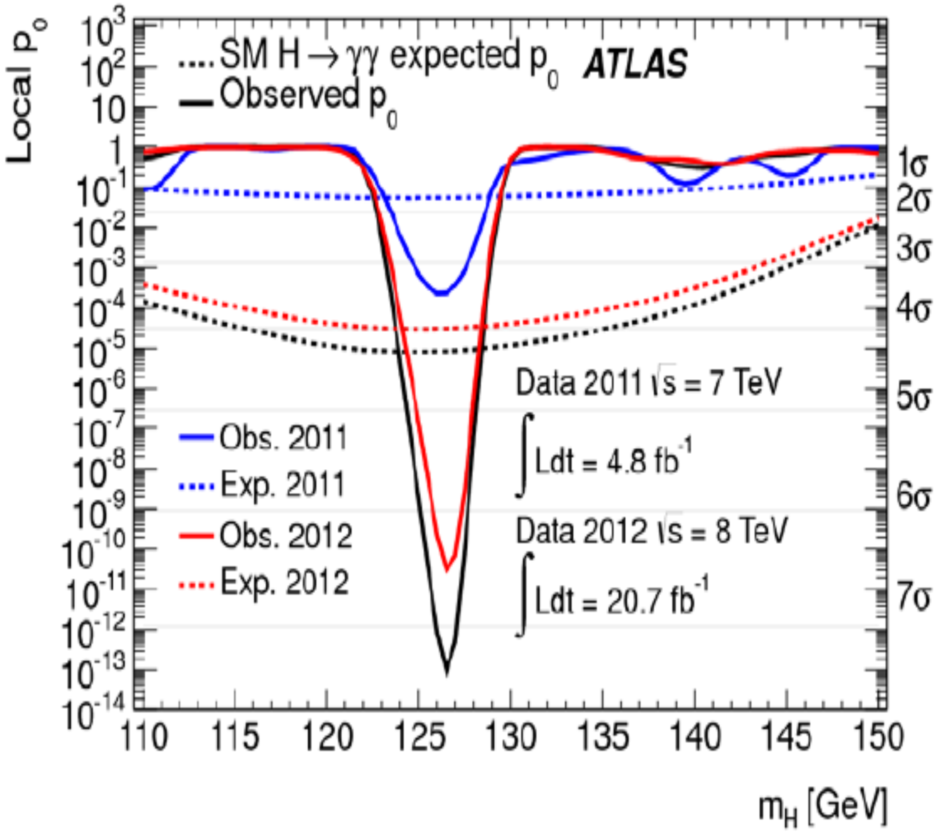


High level analysis very similar between ATLAS and CMS:

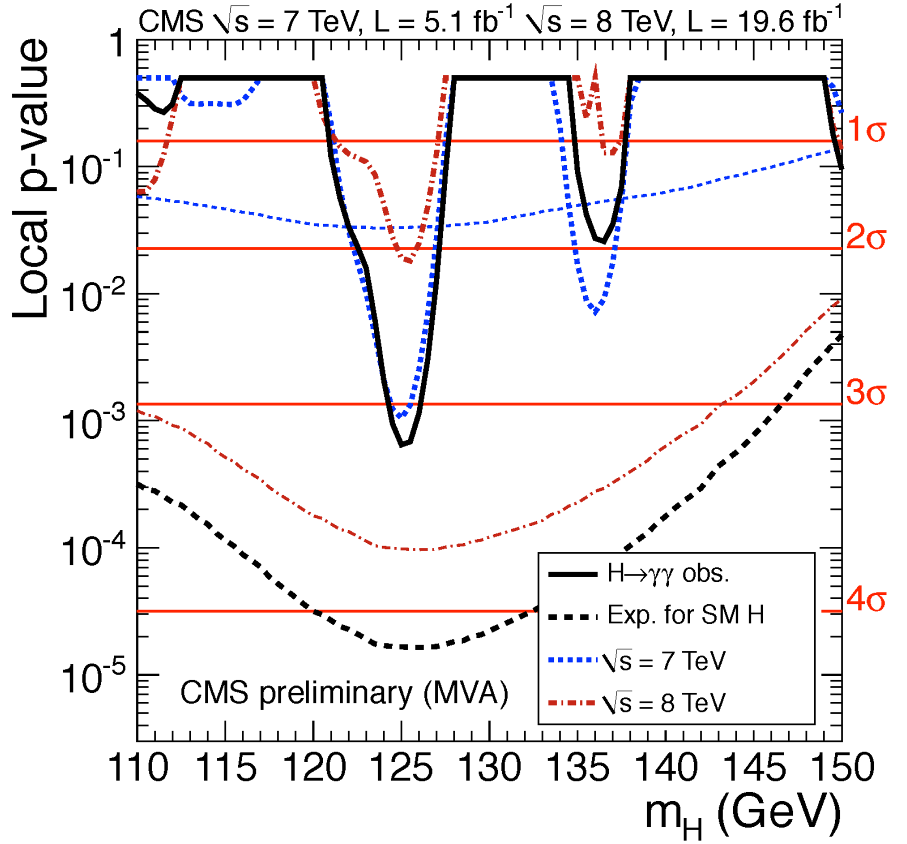
- categorisation by S/B, resolution and pT (ATLAS w/ cuts, CMS w/ a BDT)
- Similar di-jet categories with O(70%) purity
- Mass fit with polynomial background (to minimise the bias on the signal)

Compatibility with the background-only hypothesis

ATLAS



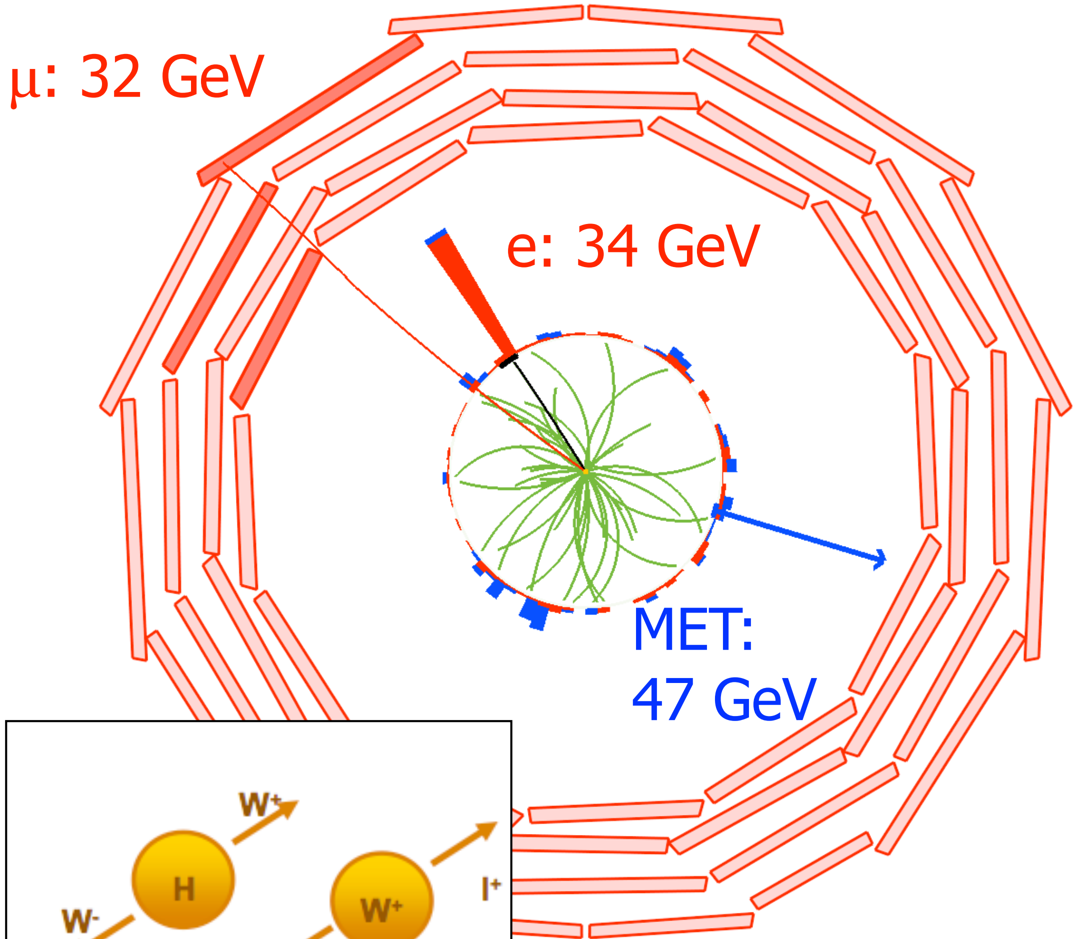
CMS

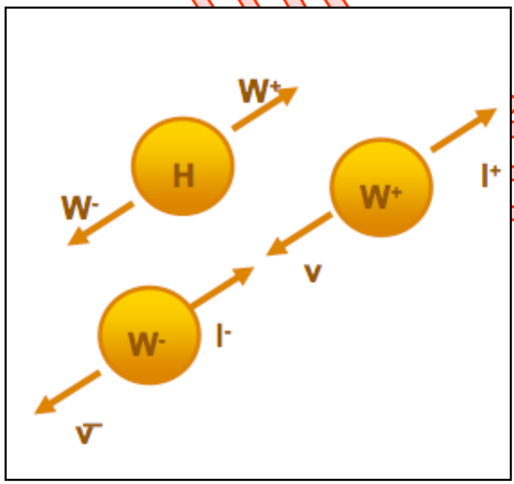


	ATLAS	CMS
m	126.8 ± 0.2 (stat) ± 0.7 (sys)	125.4 ± 0.5 (stat) ± 0.6 (sys)
significance	7.4σ (4.3σ expected)	3.2σ (4.2σ expected)
signal strength	1.57 ± 0.24 (stat) ±0.22 (sys)	0.78 ± 0.27

the H → WW → 2l 2v decay

- large rate (σ x β ~ 200 fb at 125 GeV)
- poor mass resolution





Analysis features

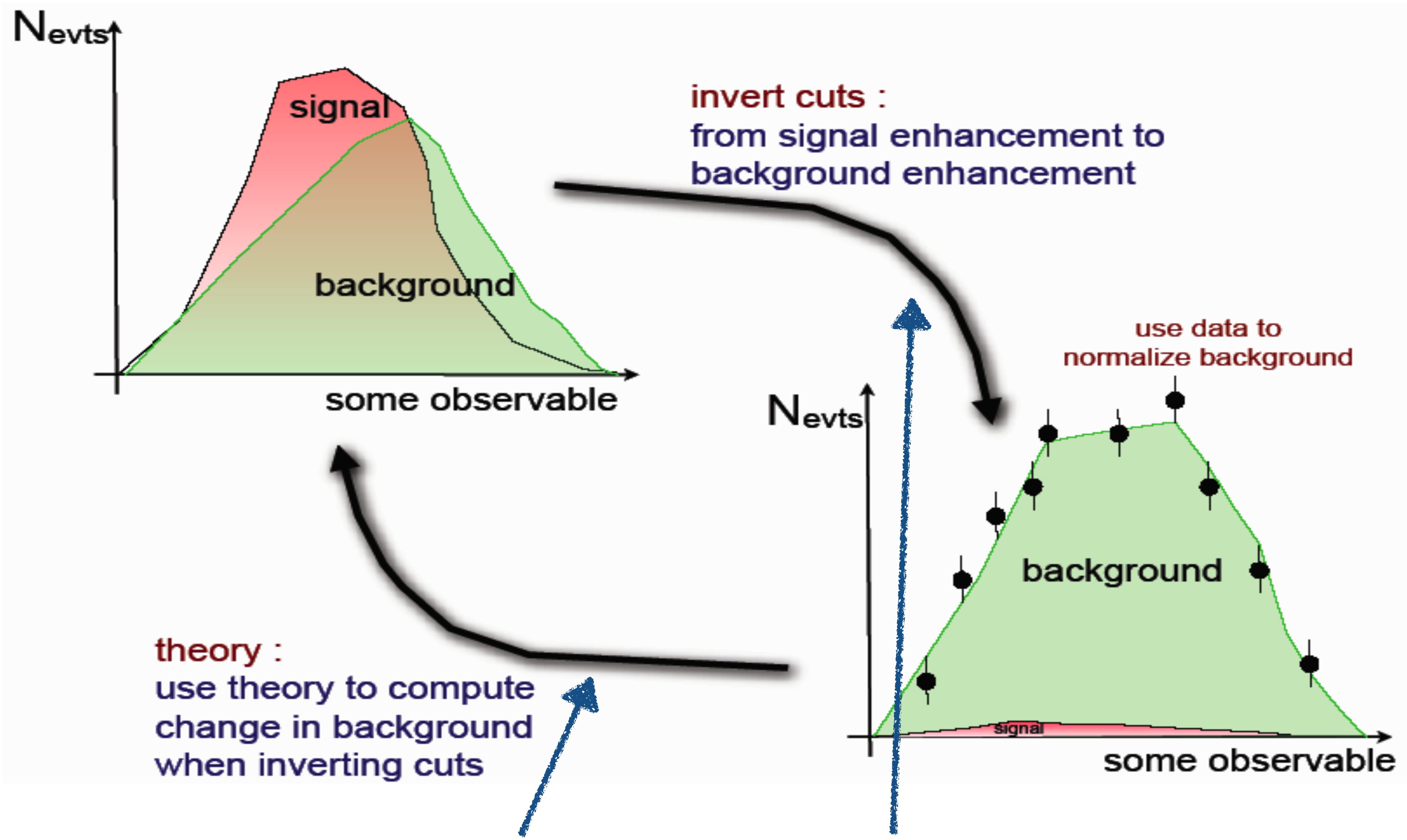
- Two opposite charge leptons (e, μ)
- Two neutrinos = missing transverse energy (MET)
- No Higgs mass peak
- Counting & 2D shape analyses
- Enhance sensitivity by subdividing into (0,1,2) jets categories

Challenges

- Understand backgrounds: WW, W+jets, top, Z+jets
- determined from control regions

Scalar decay and V-A structure of W decay lead to a small opening angle between leptons

The measure of the background



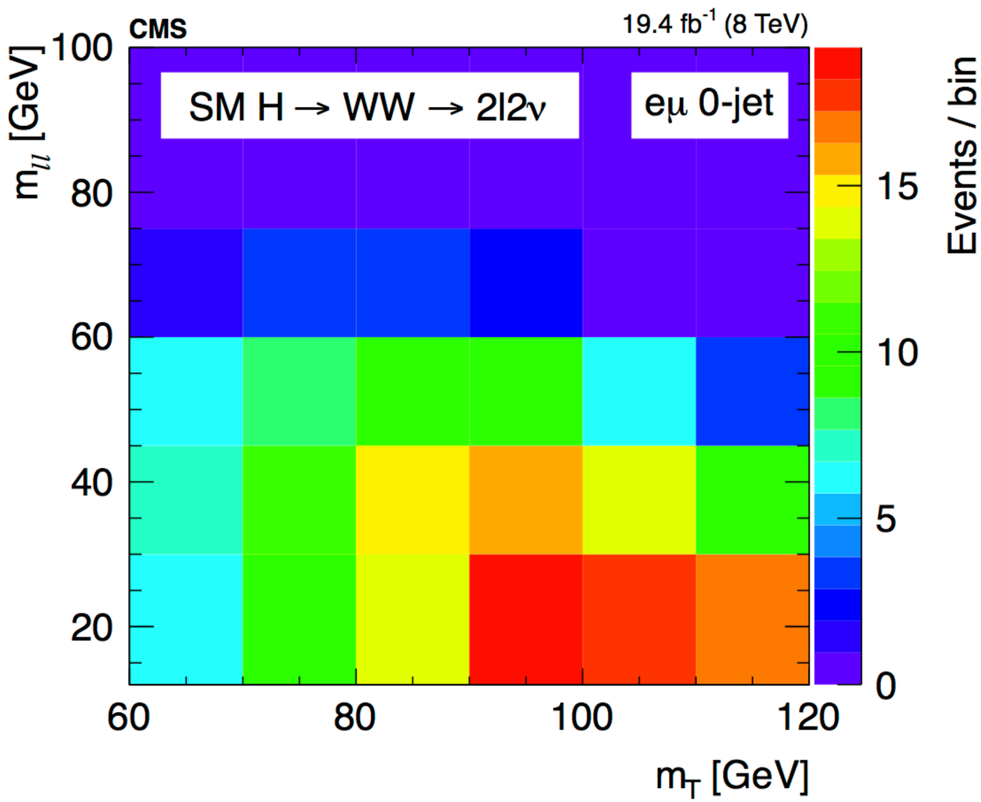
Theoretical uncertainties (diff. distr. + pdf +scale+…)

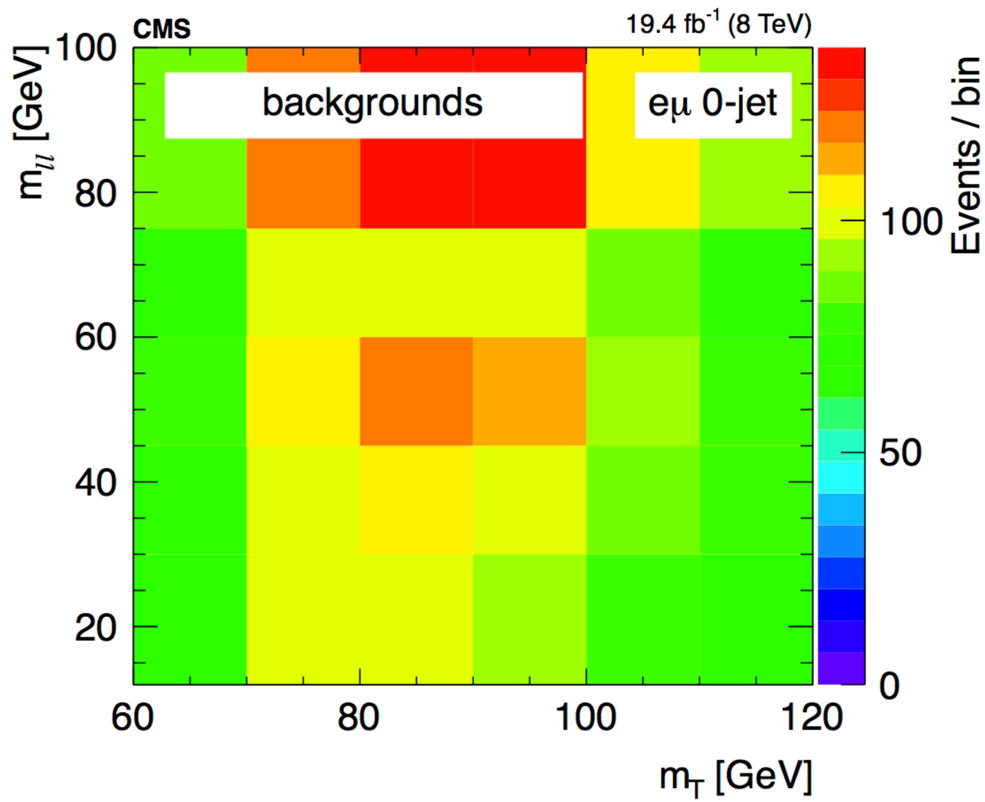
experimental uncertainties (like isolation, pt etc…)

Mariotti

the analysis strategy

- Analysis on the full data set for WW+0 jets and +1 jets categories
- Use a cut based analysis for same flavour lepton events and **2D m_T-$m_{\ell\ell}$ analysis** for different flavour events

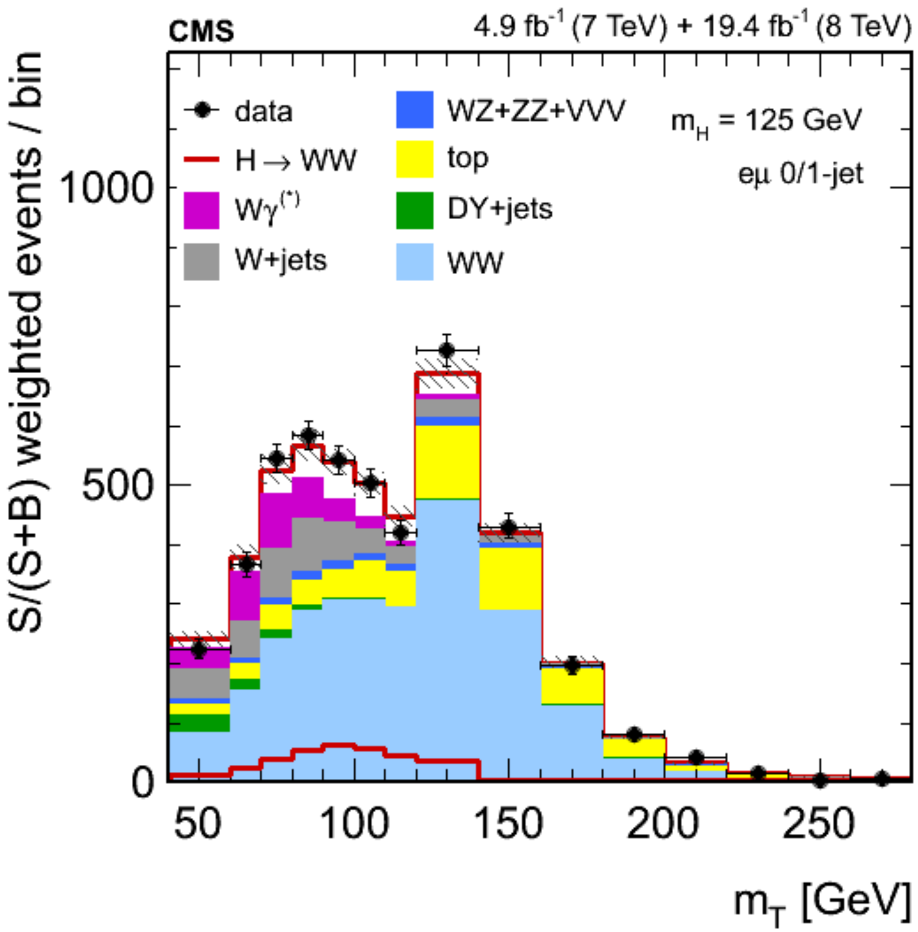


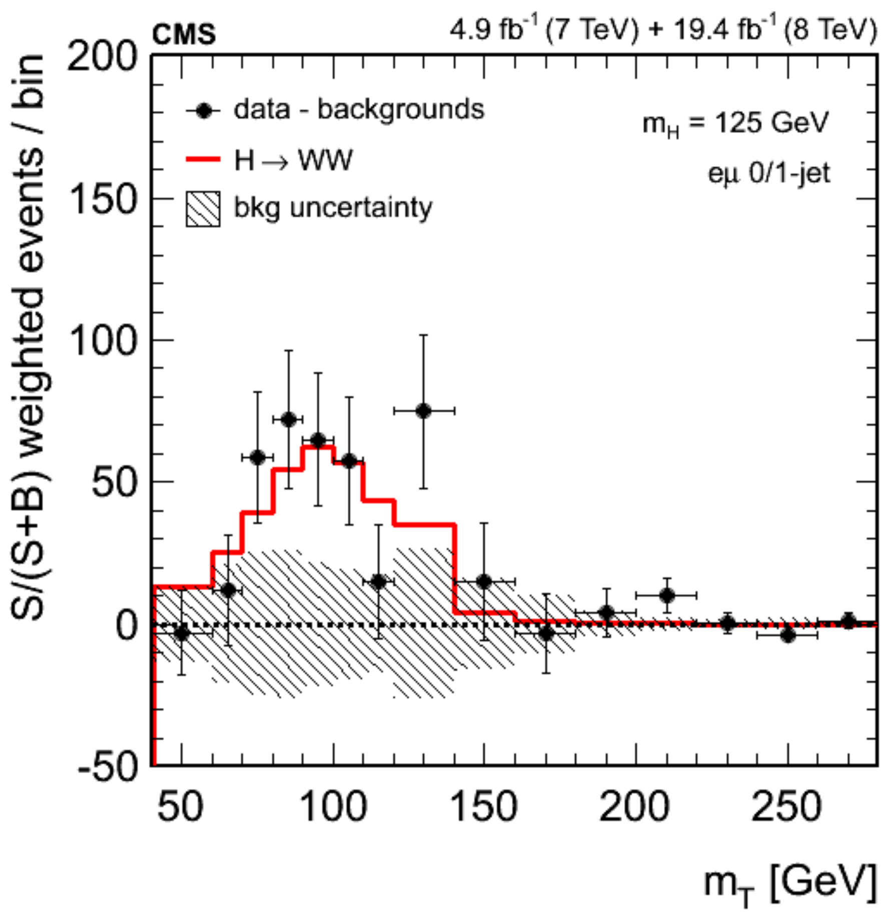


final state	cut-based approach	shape-based approach
DF 0-jet	counting	2D $m_{\ell\ell}$-m_T
SF 0-jet	counting	counting
DF 1-jet	counting	2D $m_{\ell\ell}$-m_T
SF 1-jet	counting	counting

the invariant mass spectra

Events with 0- and 1-jet and different flavour leptons (7+8 TeV Data)



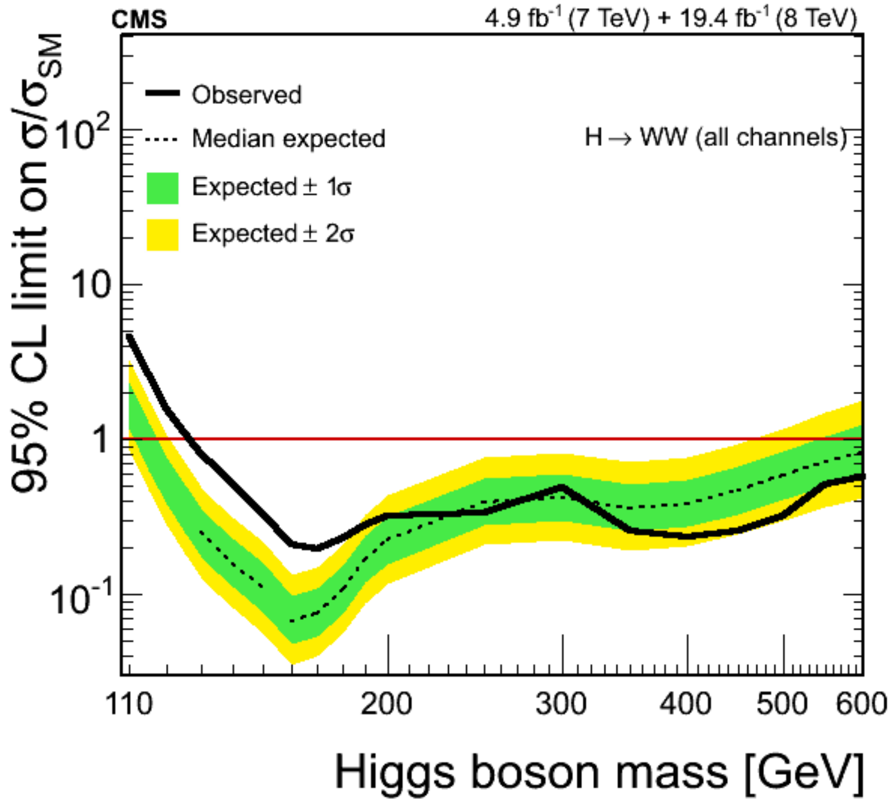


$$M_T = \sqrt{2p_T^{\ell\ell} E_T^{miss} \cos(\Delta\phi_{\ell\ell} - E_T^{miss})}$$

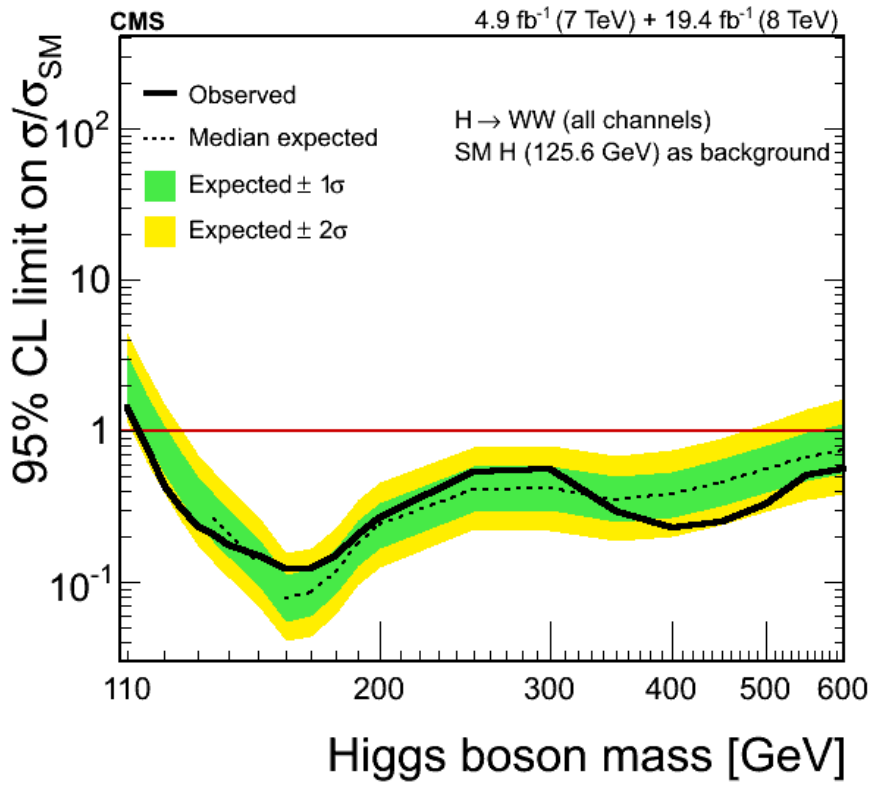
A significant excess is observed…

the exclusion limits

Standard Analysis



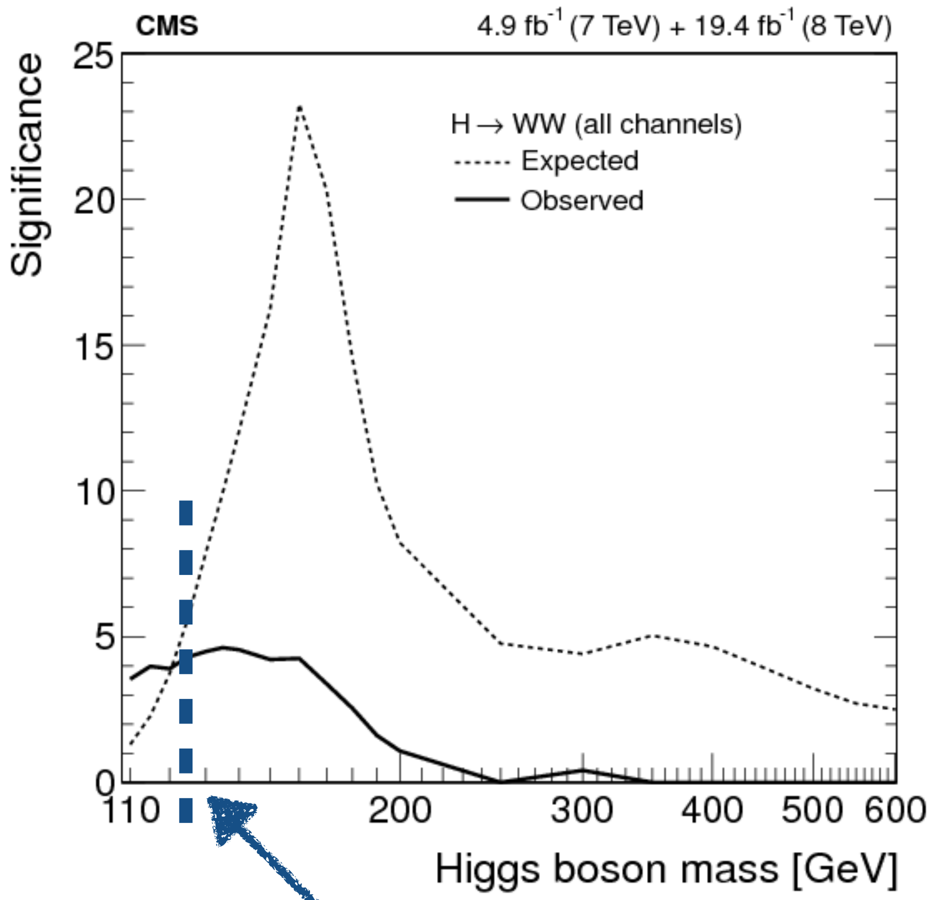
Using m_H = 125 GeV as a background

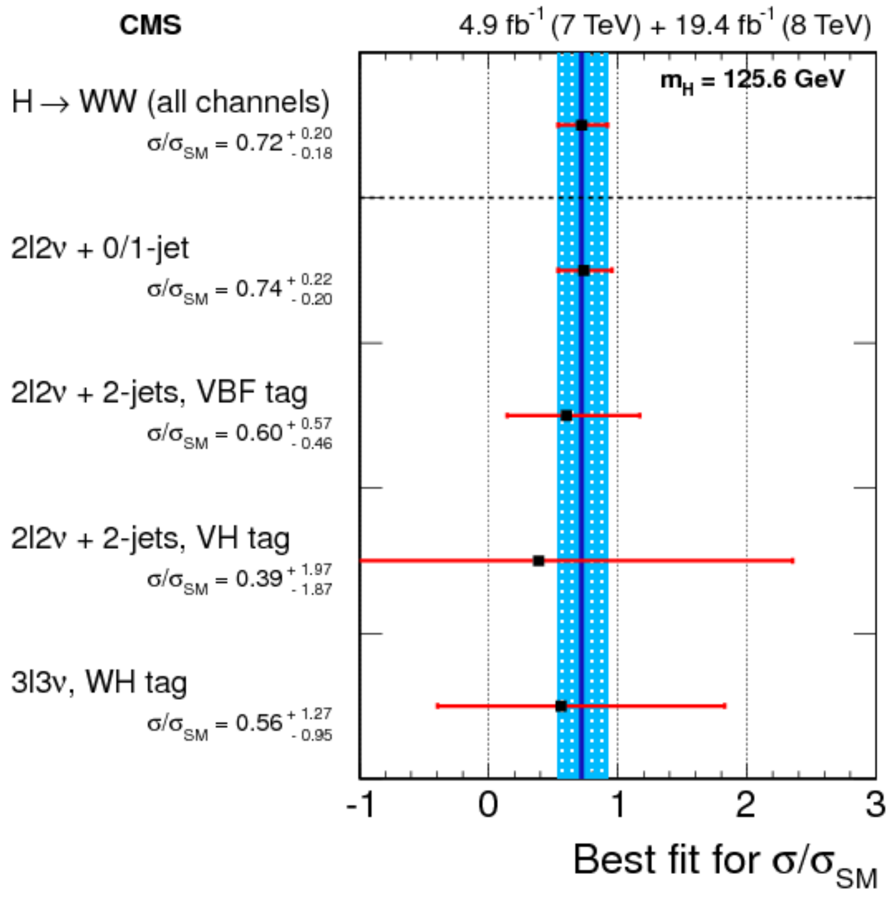


- Exclusion at 95% CL in the mass range 128-600 GeV
- **Large excess** in the low mass region
- **When including m_H = 125 GeV as part of the background**, no significant excess is seen over the entire mass range

the signal strength measurement

- **several channels are combined** to get the final result
- **compare the signal strength** values in the various sub-channels



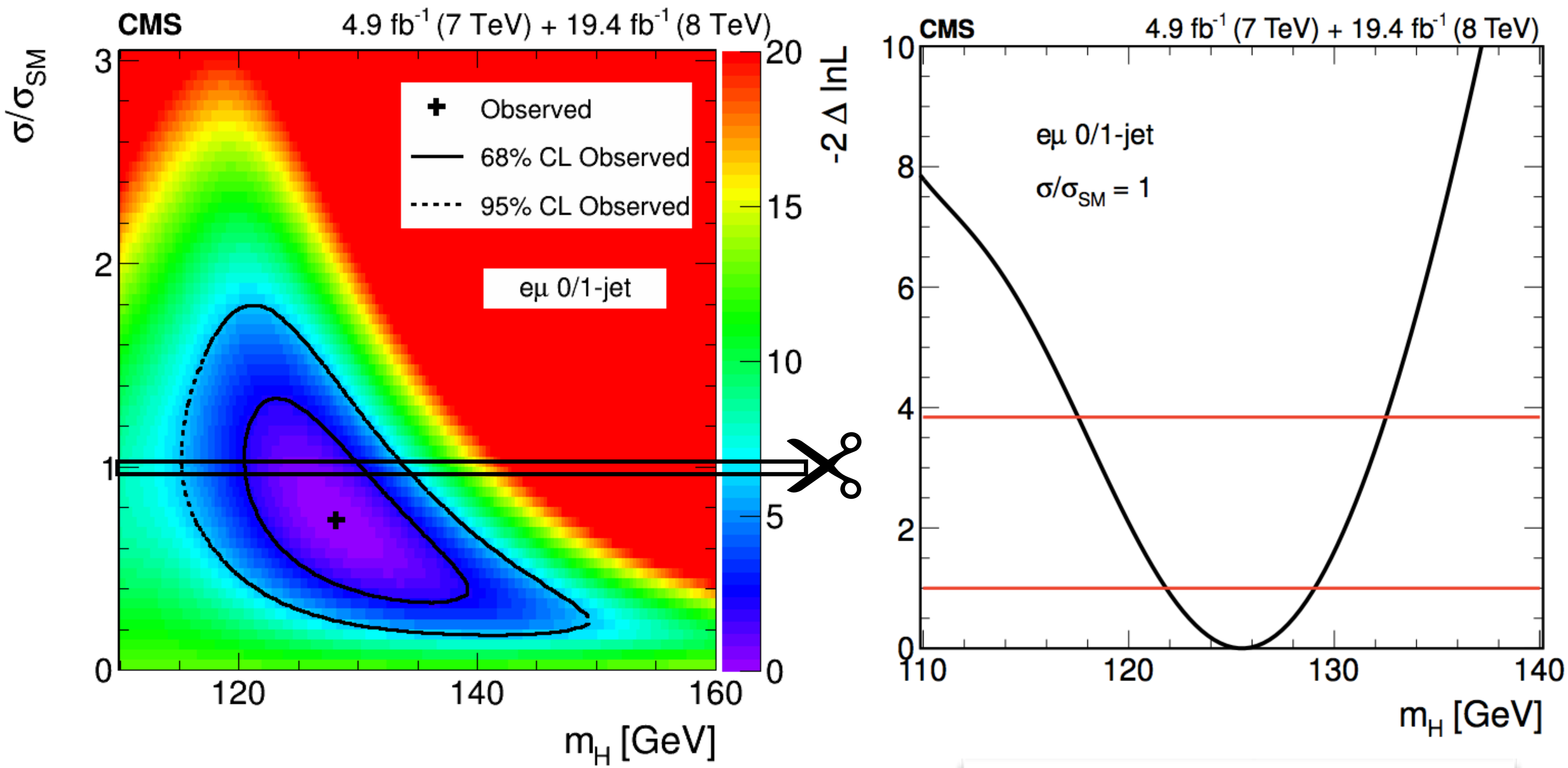


A 4.0σ (5.1σ) observed (expected) significance at $m_H \sim 125$ GeV

$\sigma/\sigma_{SM} = 0.72 \pm 0.20$

the invariant mass measurement

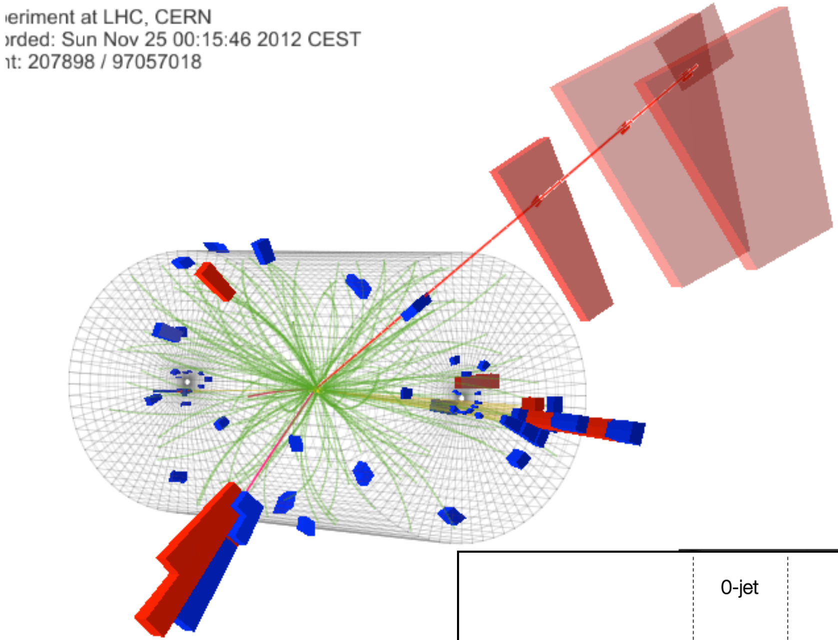
- **reconstruct m_H** by boosting in the (approximate) reference system of the Higgs boson
- **minimise the signal likelihood** with respect to m_H and μ

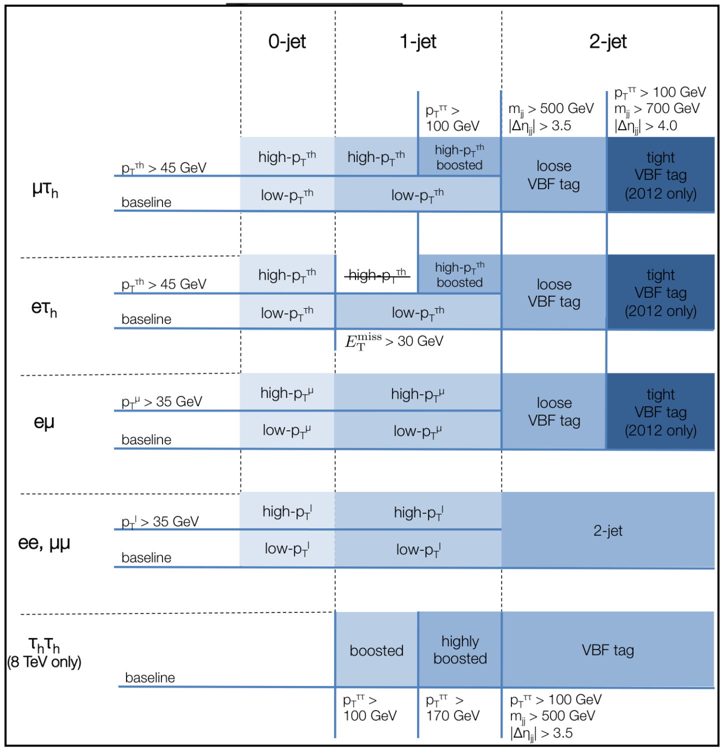


$m_H = 125.5^{+3.6}_{-3.8}$ GeV

the H →ττ decay

- Large rates and medium mass resolution





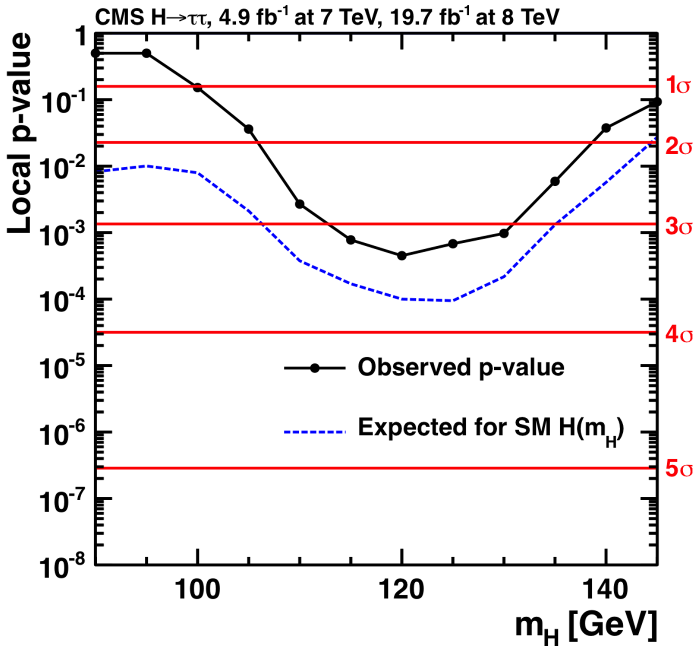
Analysis

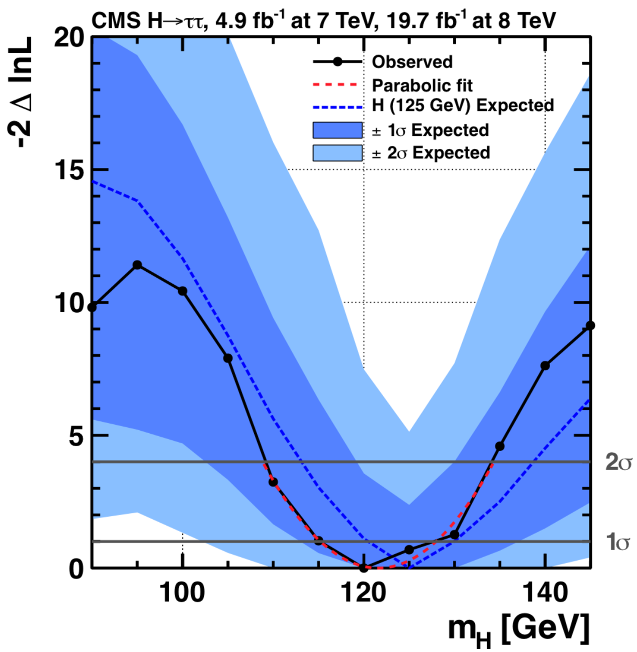
- Tau decays to e, μ, τ_{had} used to reconstruct tau leptons
- Reconstruct the ττ invariant mass
- Use many categories to increase the sensitivity

Analysis challenges

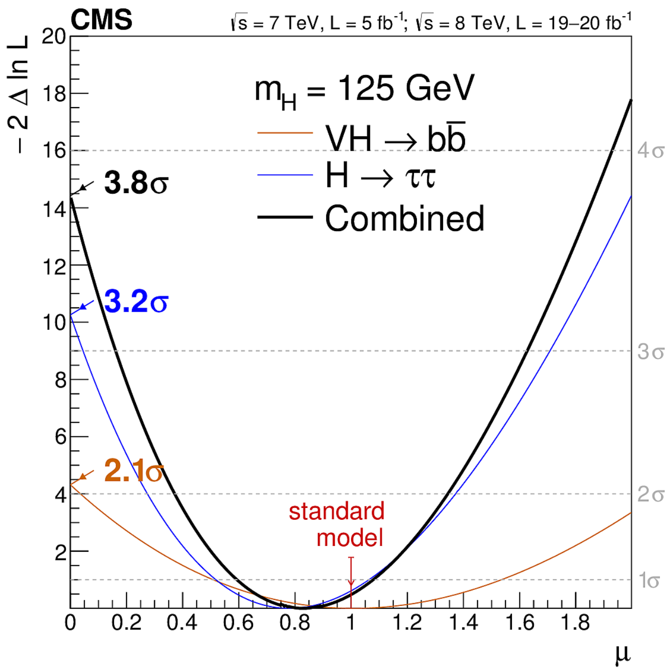
- separate the Higgs peak from the Drell-Yan decay
- reduce as much as possible the invariant mass resolution

the results



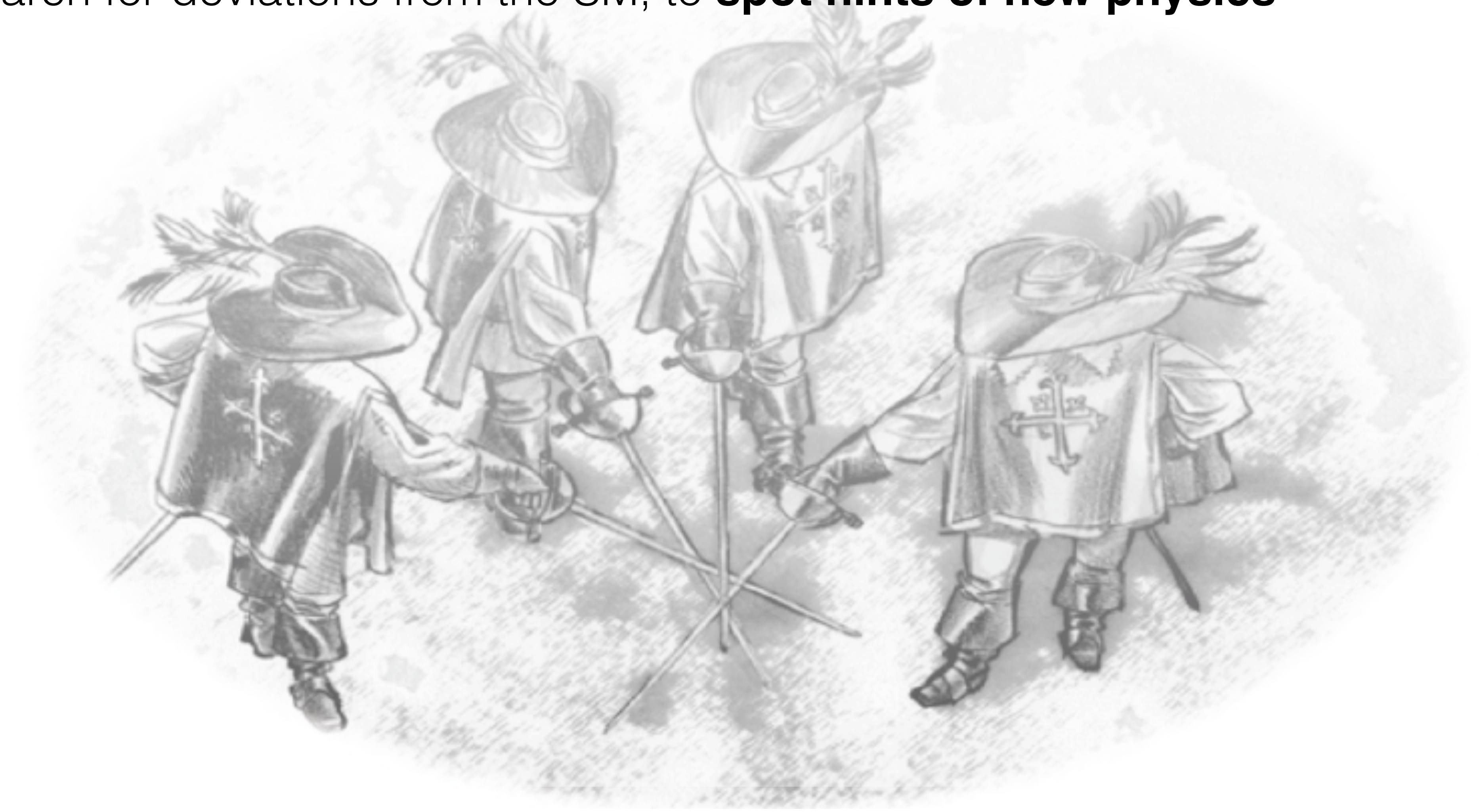


more than 3σ significance



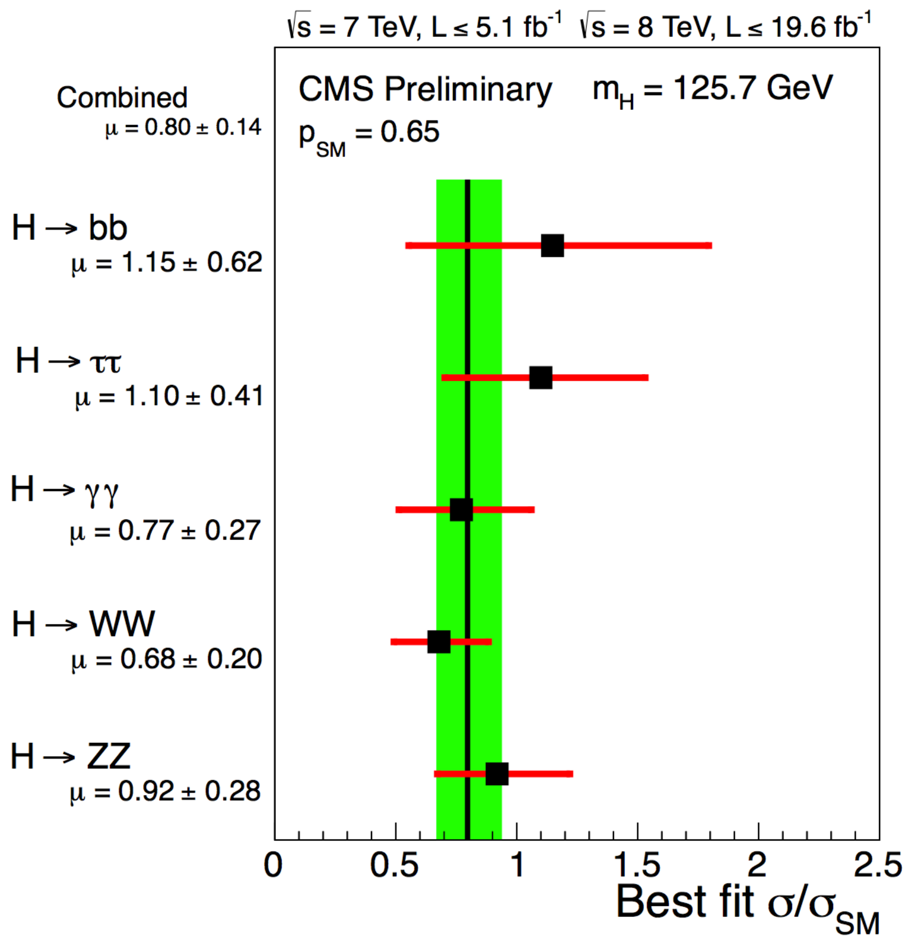
the ττ and bb channels are combined to determine the ***compatibility with the standard model fermionic sector***

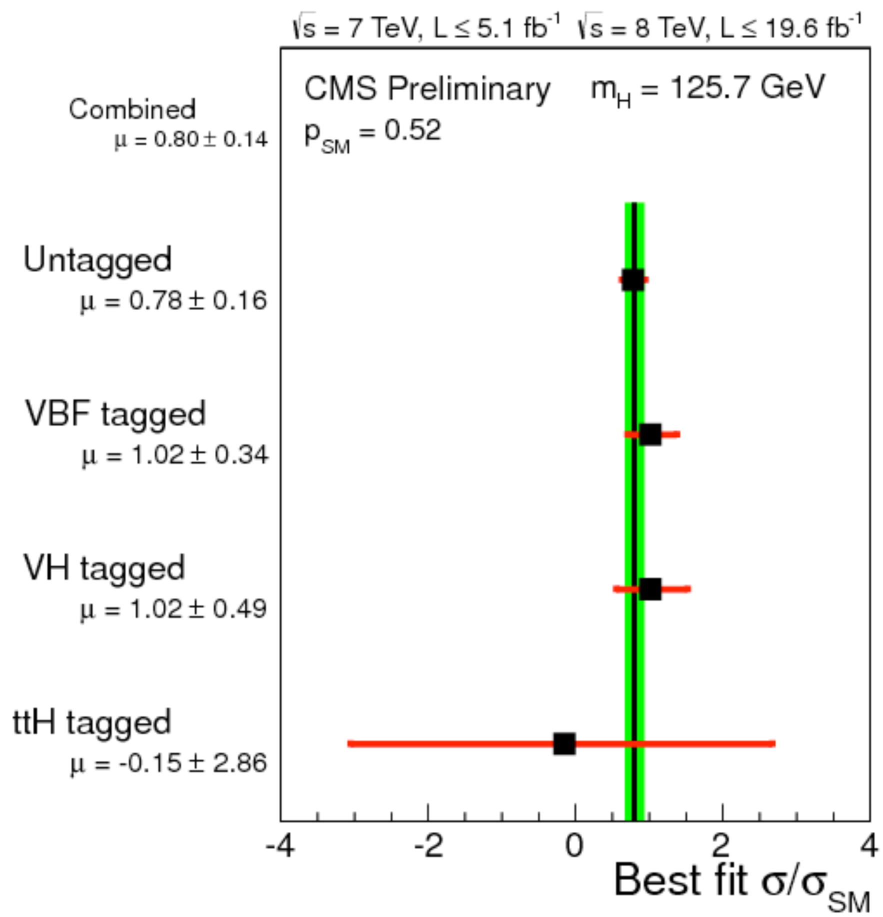
- combining all the channels = **fully insert the new found resonance in the standard model** and perform global fits
  - properly correlate expected yields and uncertainties
- **exploit at best** the power of the experiment
- search for deviations from the SM, to **spot hints of new physics**



the signal strength

- not enough data to fit everything, but one can look at the result with different perspectives
- choose different parameterizations and compare the results



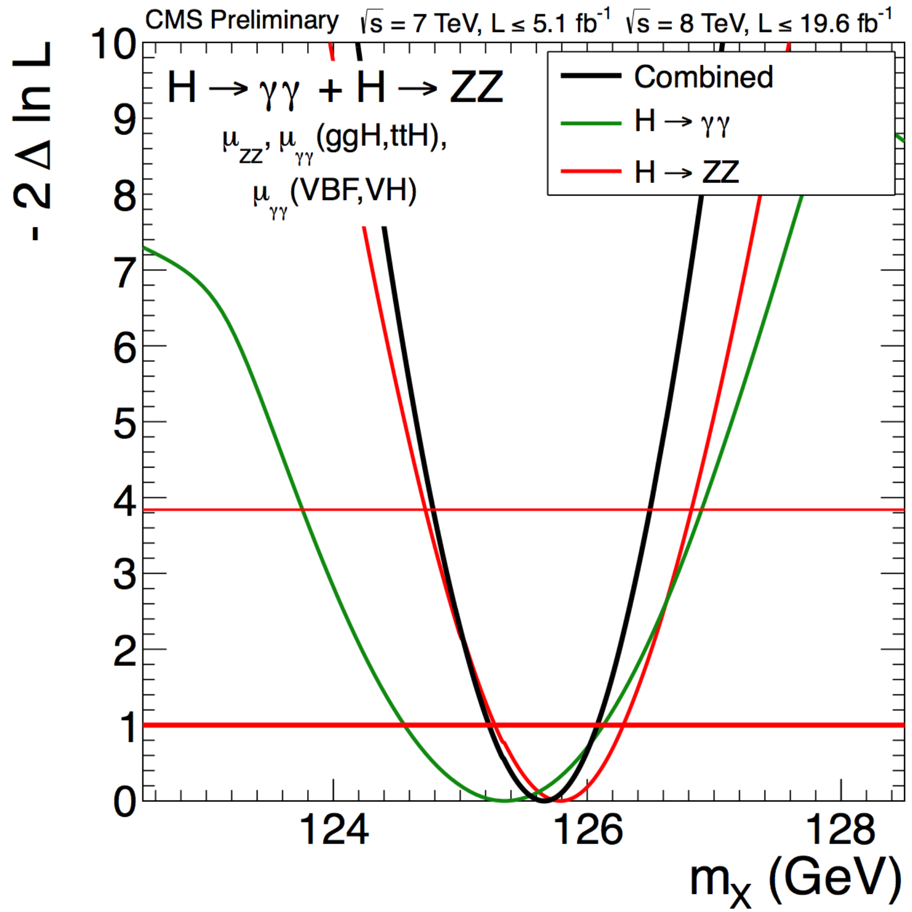


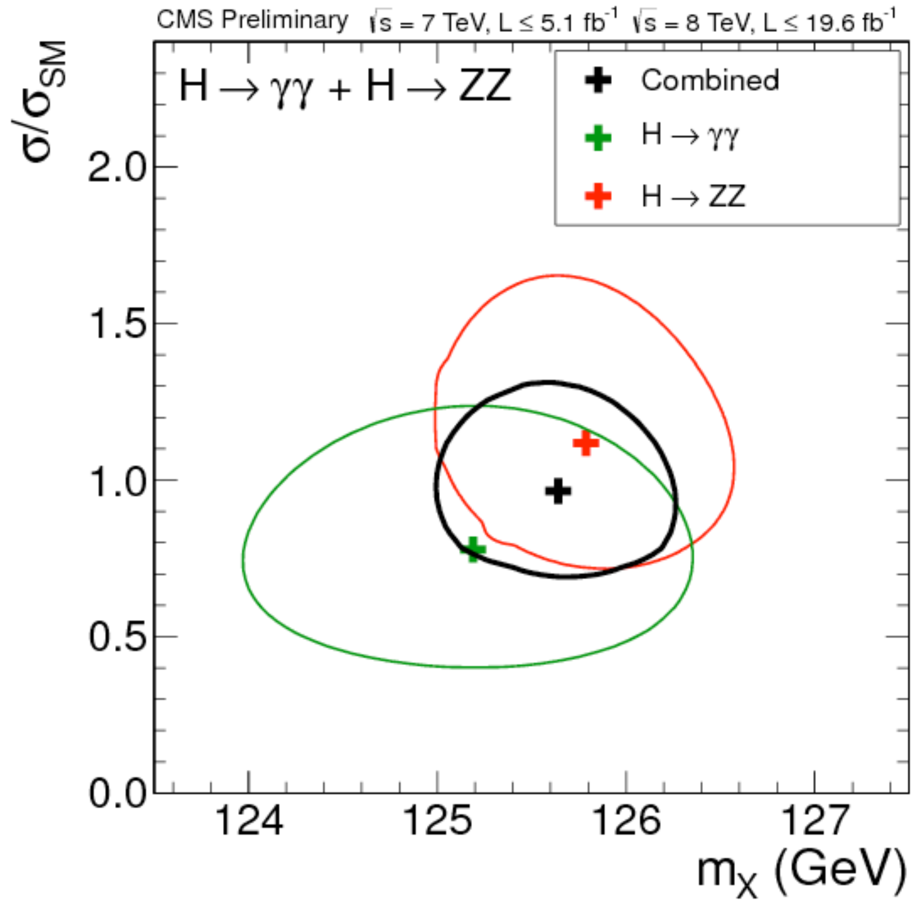
Combined signal strength: $\mu=0.80\pm0.14$

the invariant mass

$H \to ZZ \to 4l$: $m_H = 125.8 \pm 0.5$ (stat.) ± 0.2 (syst.) GeV

$H \to \gamma\gamma$: $m_H = 125.4 \pm 0.5$ (stat.) ± 0.6 (syst.) GeV



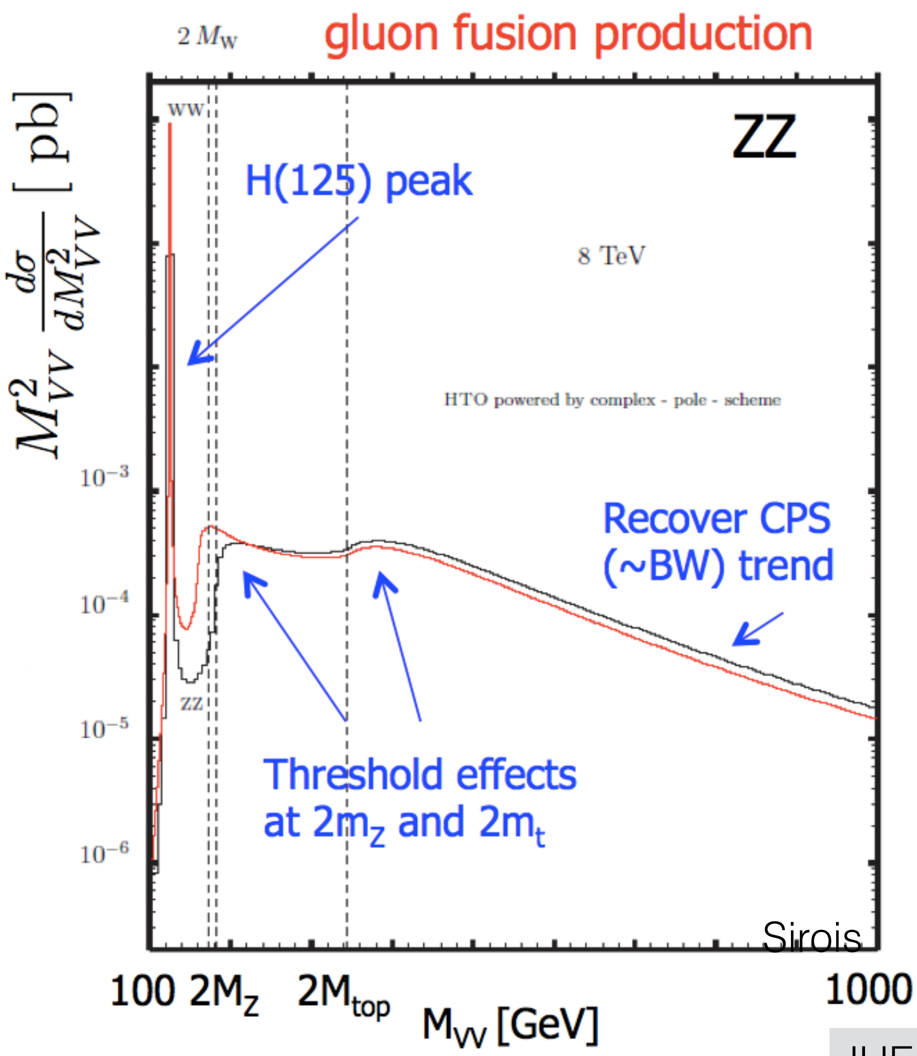


$m_H = 125.7 \pm 0.3^{(stat)} \pm 0.3^{(syst)}$ GeV

$= 125.7 \pm 0.4$ GeV

the resonance width

- direct measurement of resonance width **limited by experimental precision**
- **indirect use of the "propagator"** in a model-dependent analysis
  - exploit relative intensity of the on- and off-peak signal, taking interference with irreducible background into account (H → 4ℓ channel)



$$\frac{d\sigma_{pp\to H\to ZZ}}{dM^2_{4l}} \propto \frac{g^2_{Hgg}\, g^2_{HZZ}}{(M^2_{4l} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

under the peak:

$$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

modify the couplings:

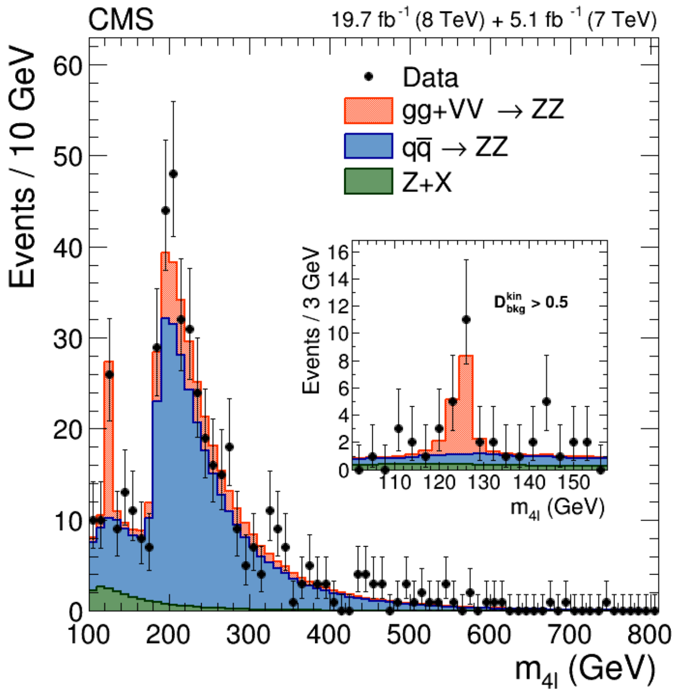
$$\begin{cases} g = \xi g_{\mathrm{SM}} \\ \Gamma_H = \xi^4 \Gamma_{\mathrm{H,SM}} \end{cases}$$

off-peak the cross-section changes: from the ratio one gets ξ and therefore Γ

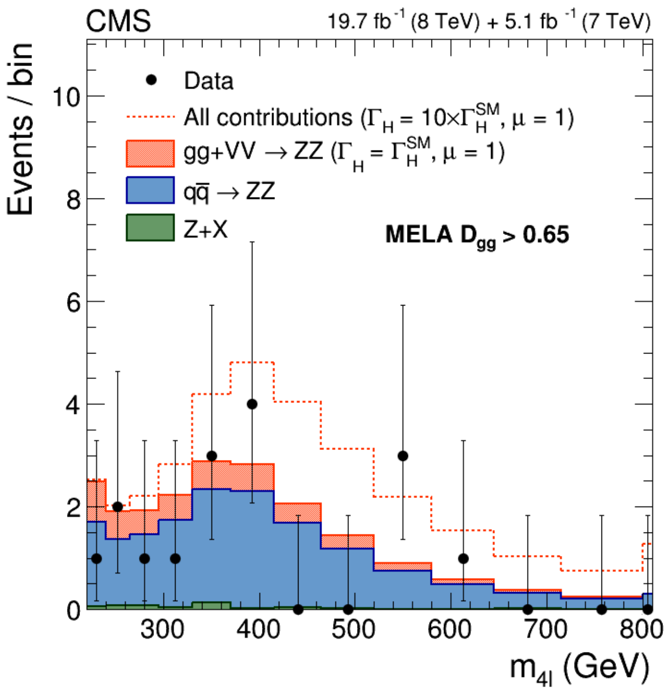
JHEP 08 (2012) 116, JHEP 1404 (2014) 060, PRD 88 (2013) 054024 arXiv:1405.3455

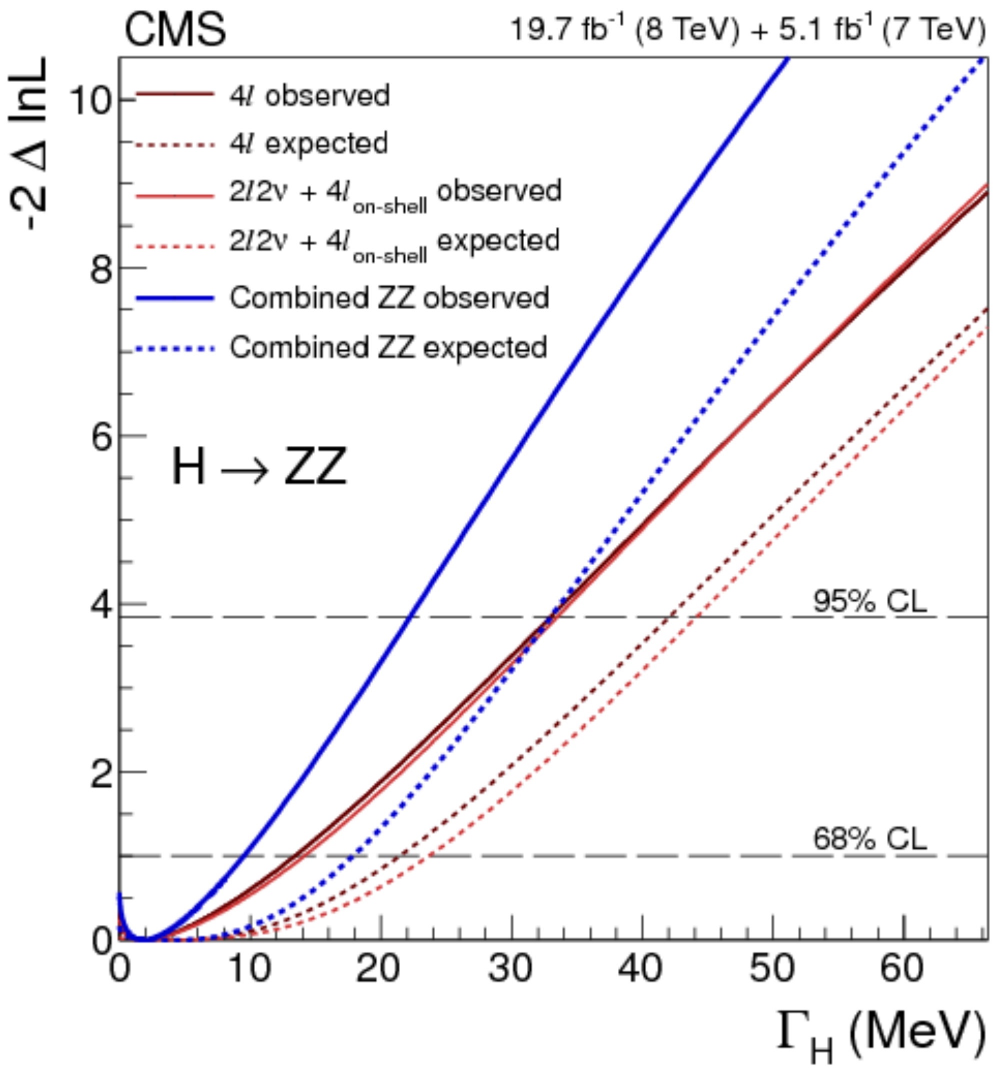
the astonishing result

under the peak



far from the peak



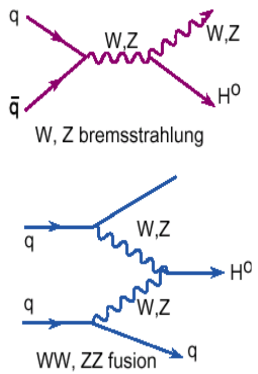


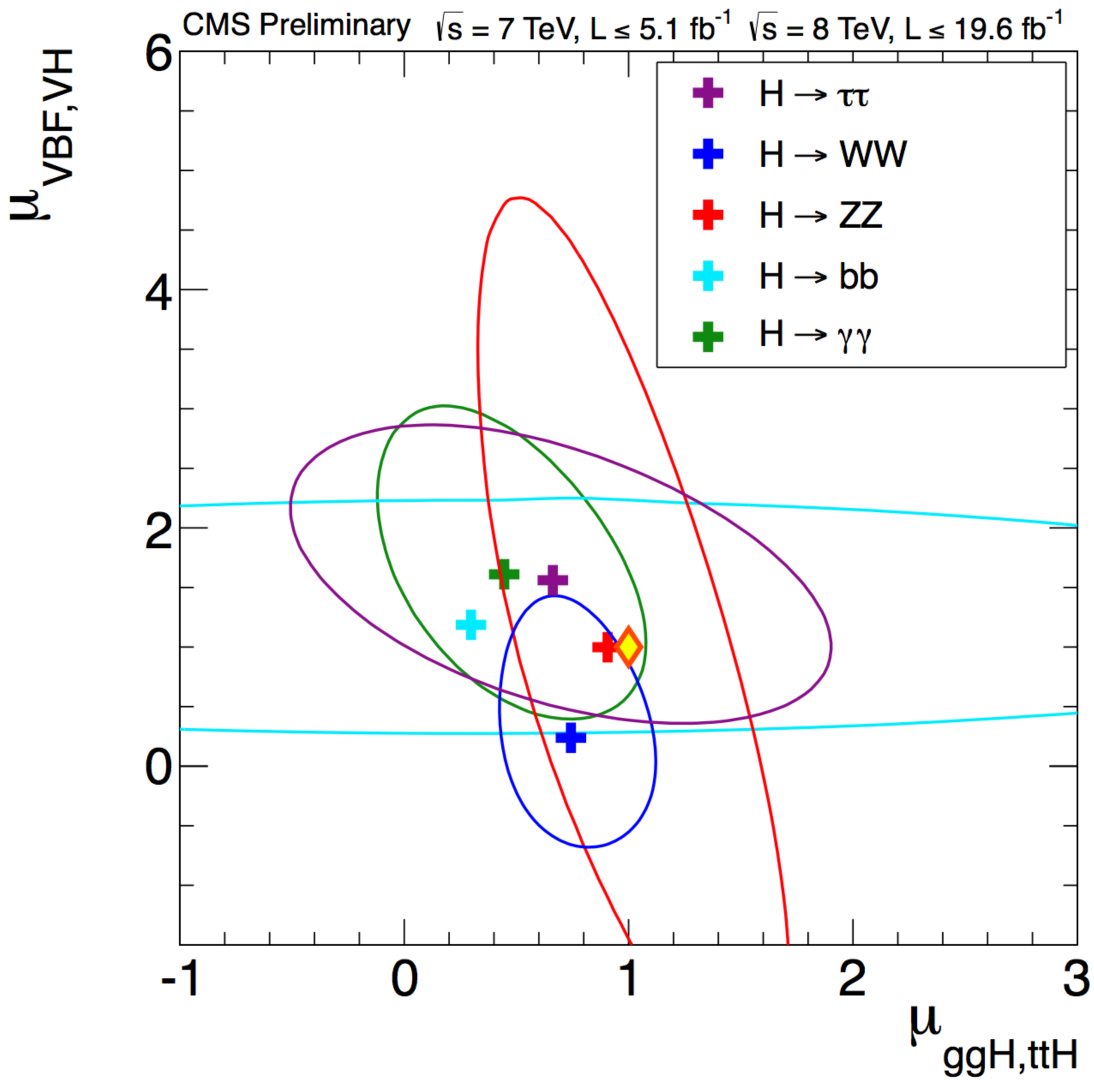
ΓH < 22 MeV at a 95% CL

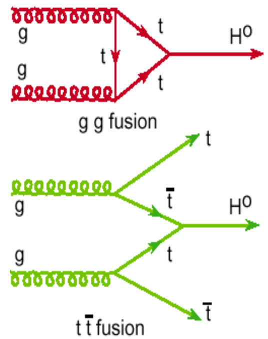
5.4 times the SM value

2D view: **test production modes** in the various decay modes

Vector Boson Couplings





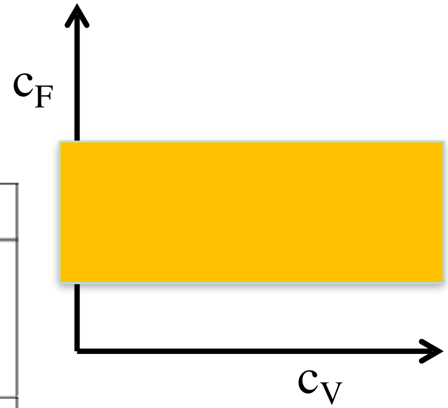


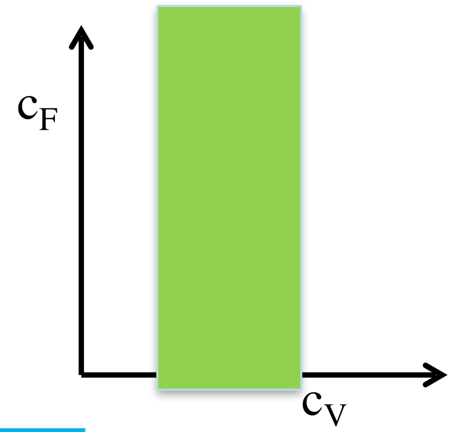
Fermion Couplings

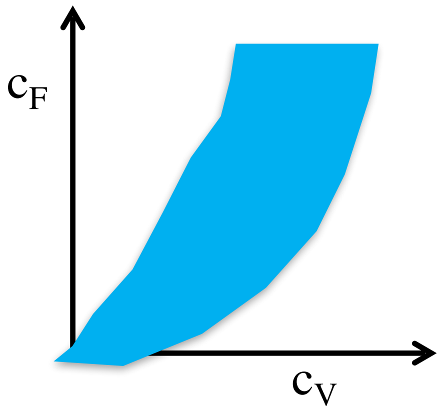
Is it a SM Higgs boson?

Test of compatibility w.r.t SM predictions by introducing two parameters **(c_V, c_F)** modifying the coupling to vector bosons and fermions respectively

Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4 / C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^4 / C_F^2$



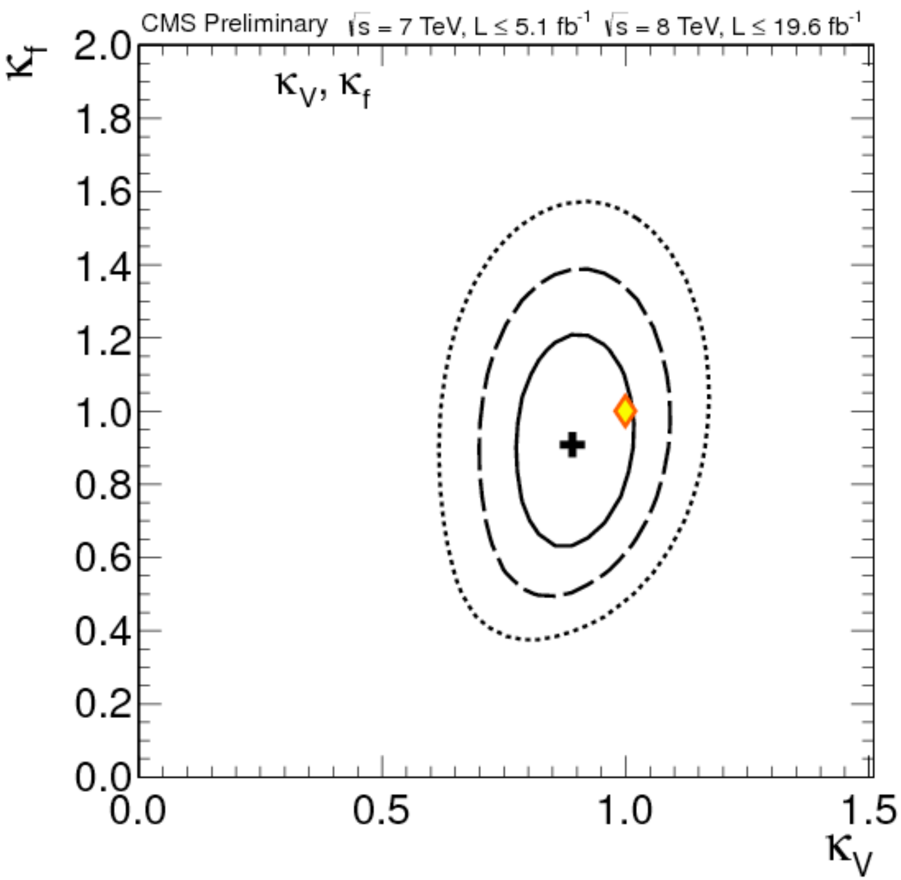




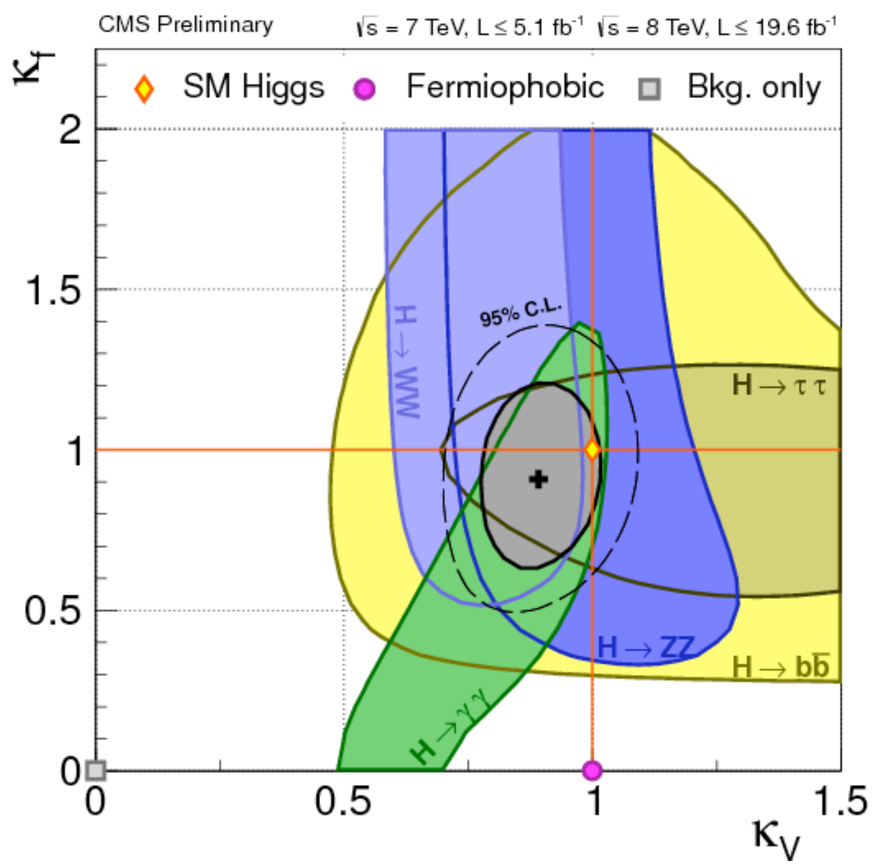
Mariotti

couplings to fermions and bosons

global result



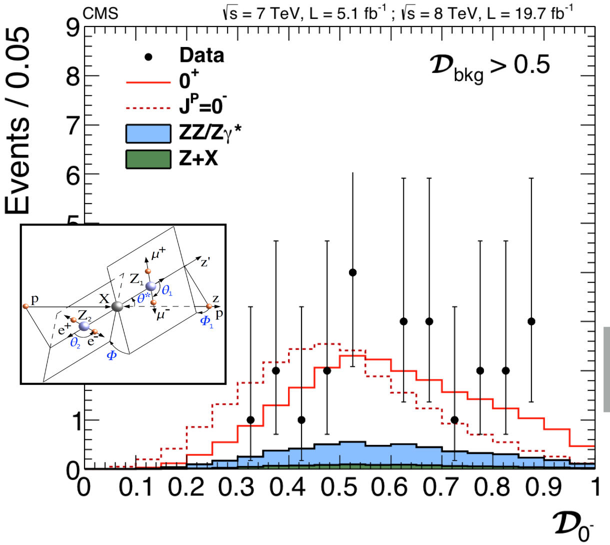
the single decay channels

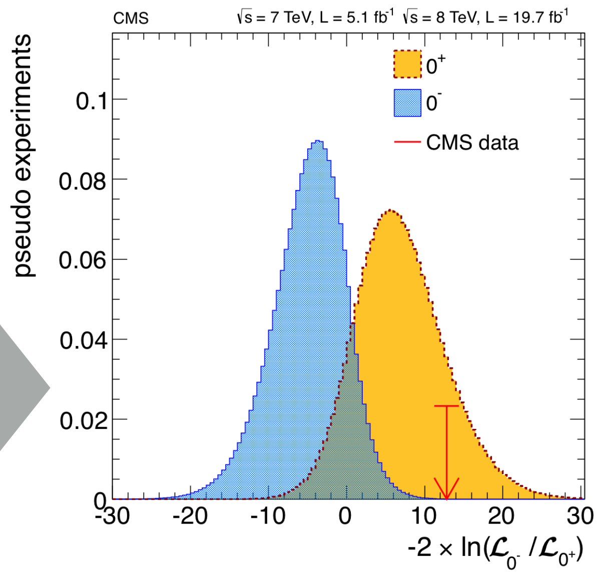


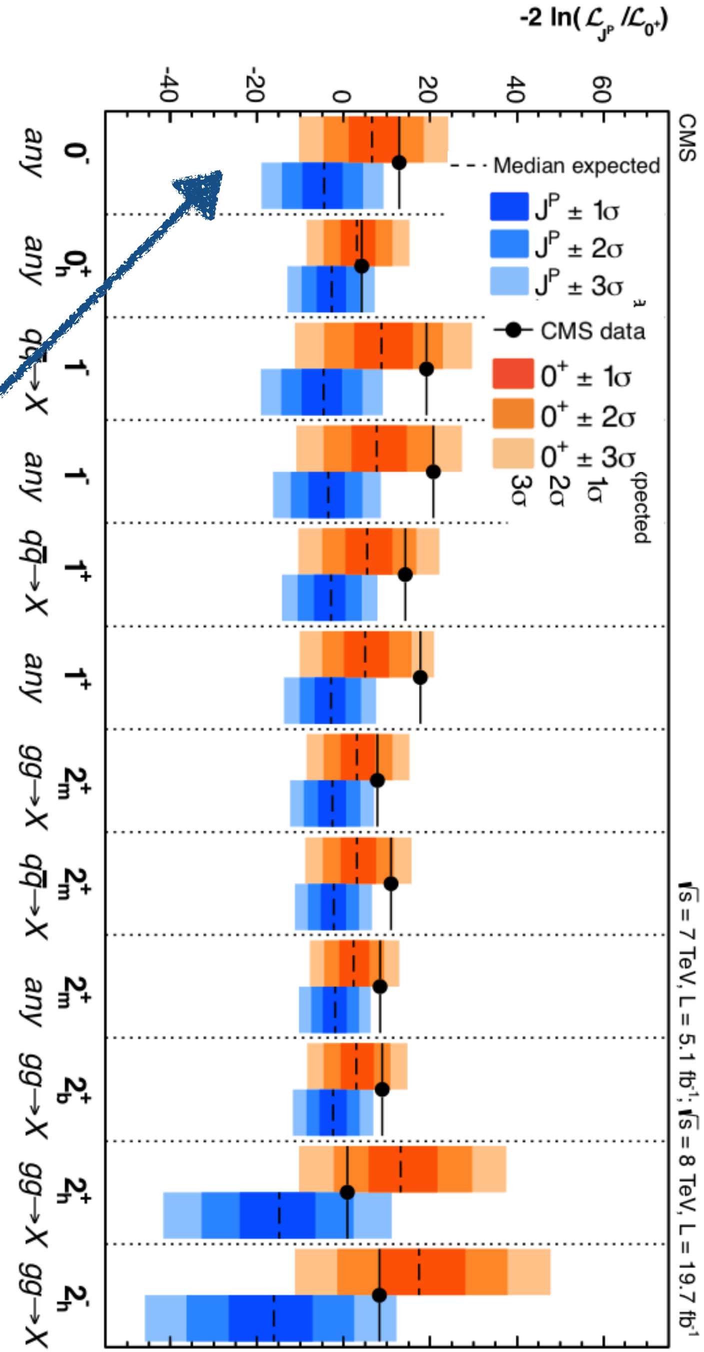
Results within 1σ of the Standard Model prediction

Higgs boson spin and parity

- **The spin-parity of the Higgs boson** candidate can be can be tested in di-boson decay channels or via associated production
- the presence of the **H →γγ decay** excludes the spin = 1 hypothesis
- in general, **hypothesis testing** is performed:



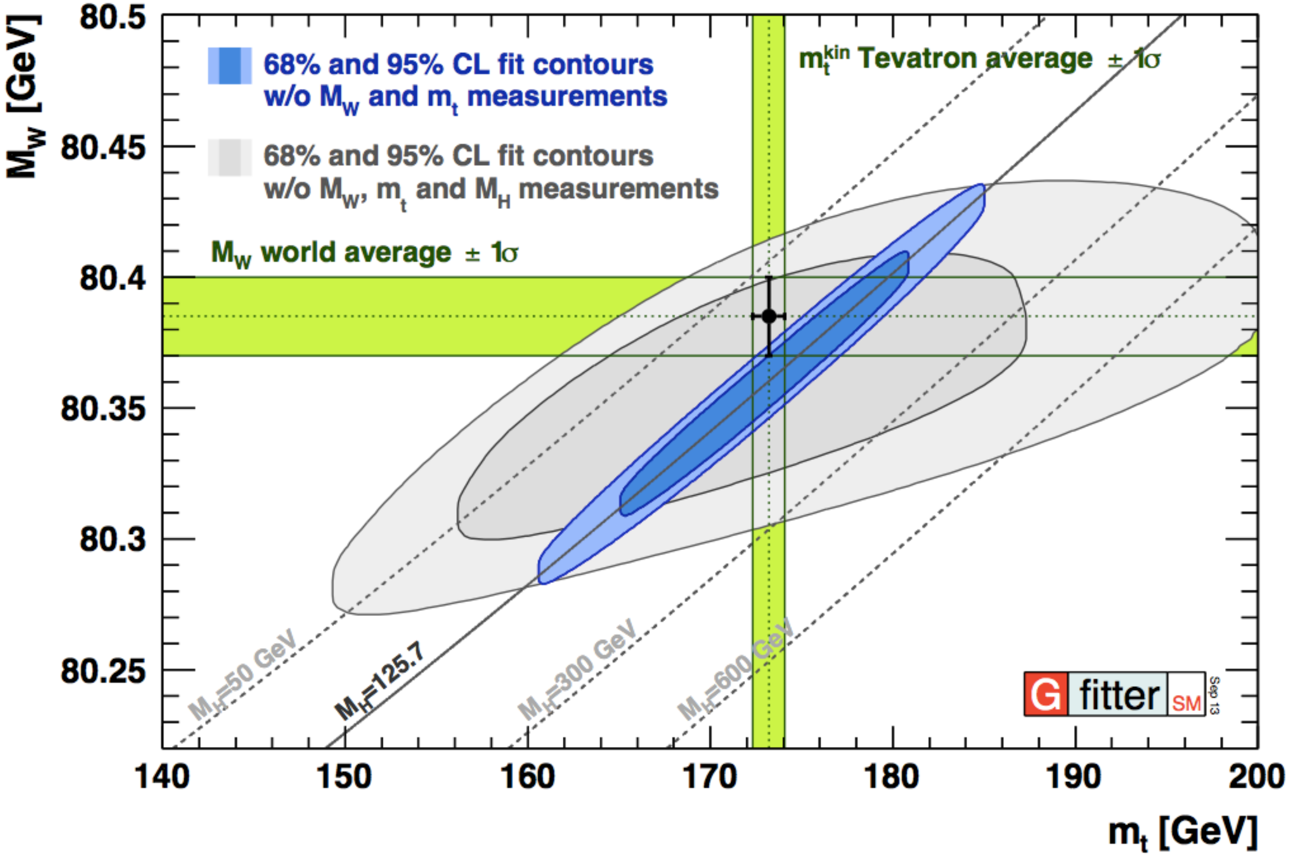




- the procedure is applied to **several alternative hypotheses**

where do we stand?

- **Higgs boson discovery** is now firmly established at $m_H \sim 125$ GeV
- Couplings to fermions and to weak bosons **consistent with the minimal scalar sector required** for the BEH mechanism
- **Custodial symmetry** verified (~ 15% precision) and the **existence of a boson with non-universal family couplings** established
- Provides **unitarization of the theory!** (at least partially – additional or different structure still possible but postponed)

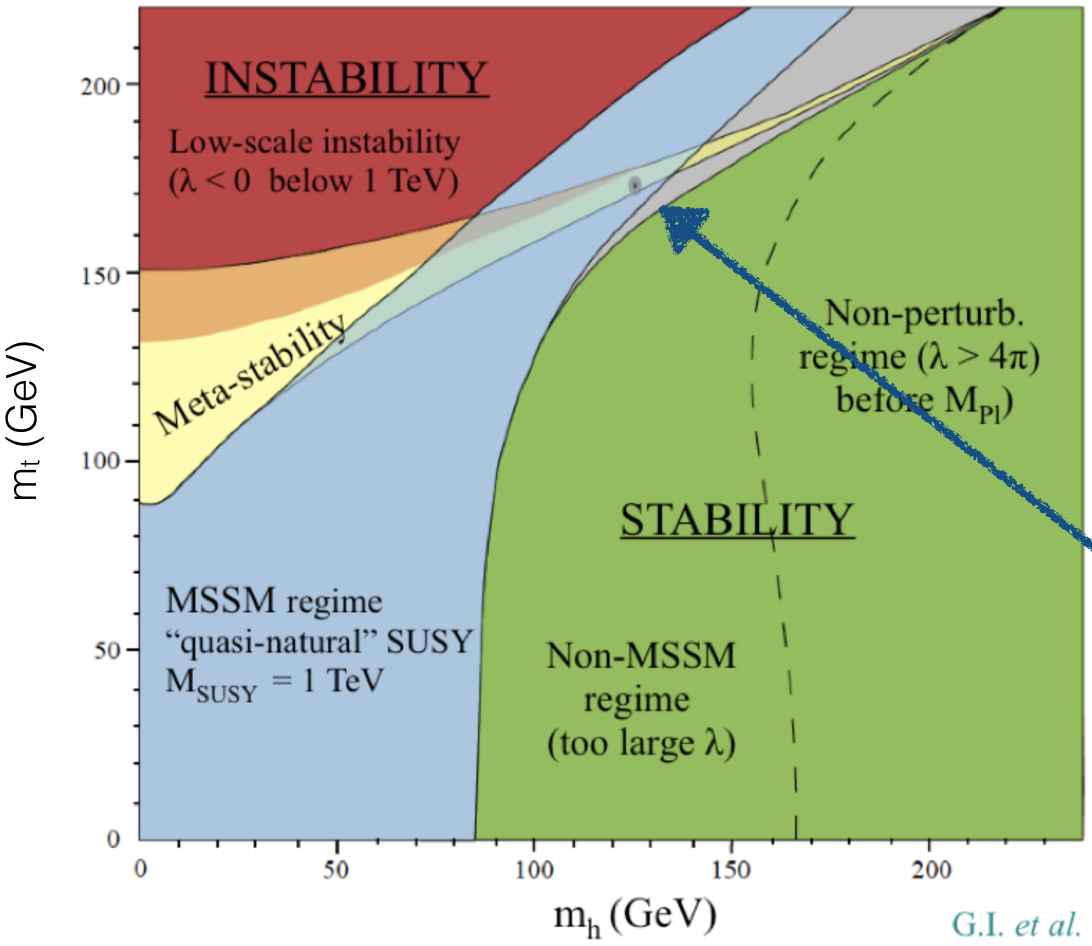


SM-like Higgs at ~125.7 GeV is compatible with global EWK data at 1.3σ

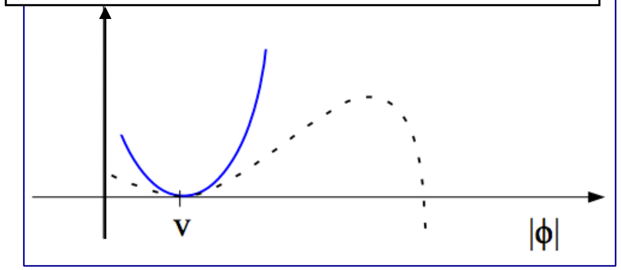
Sirois

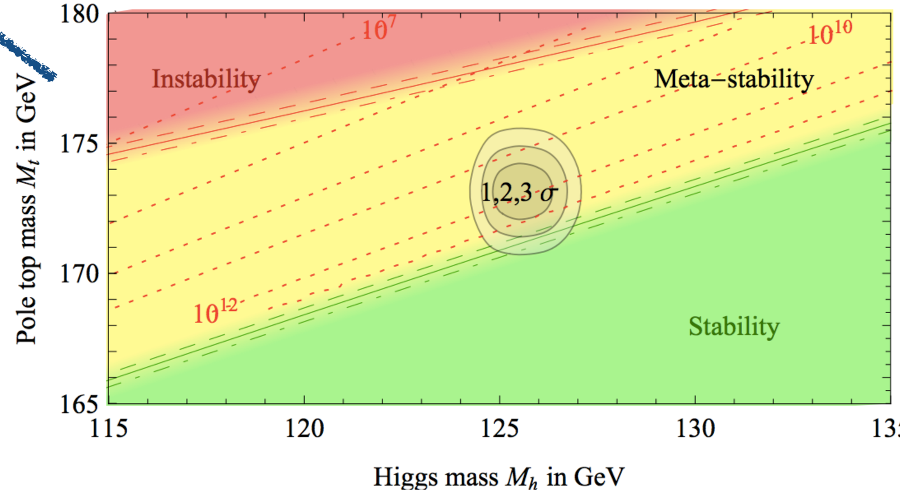
what about the Higgs potential?

- Assuming validity of the SM up to the Planck scale, **the faith of the Universe depends on the precise values of m_t and m_H !**
- The Higgs quartic coupling λ (quasi-)vanishes at Planck scale



$$V(\phi) = \mu^2 \phi_i^2 + \frac{\lambda}{2} \phi_i^4$$

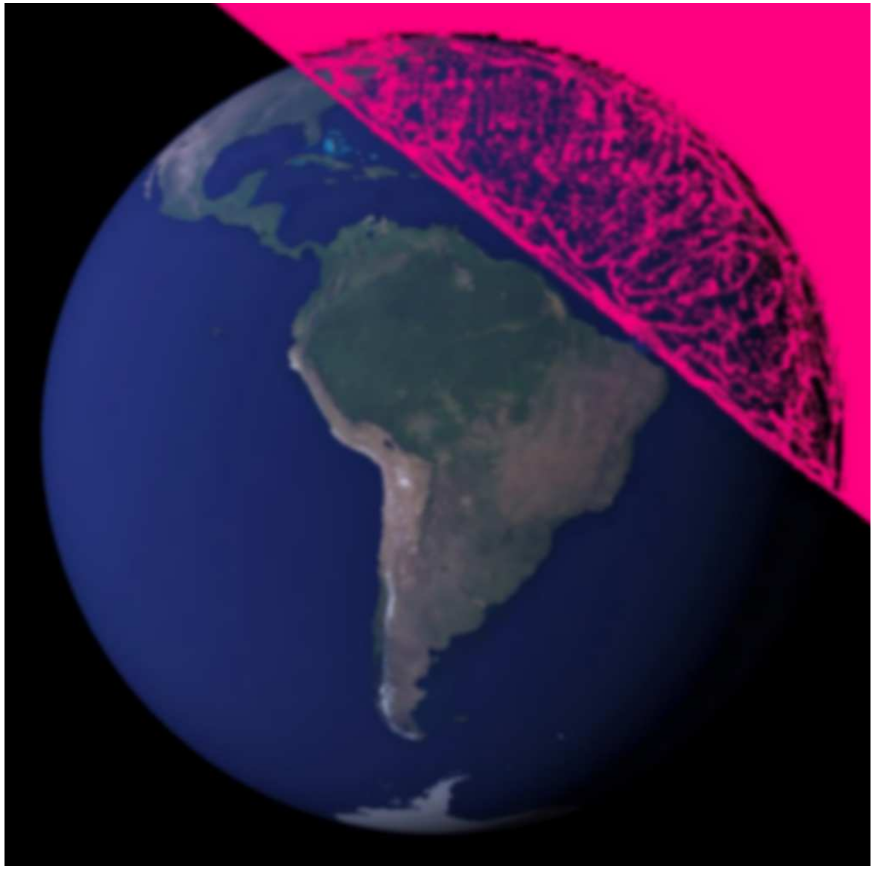




If our vacuum is only a local minimum of the potential, at some point **quantum tunnelling towards the true minimum** will happen.

The process was studied by Coleman and is 'similar' to boiling of water (quantum field theory is formally similar to thermal field theory for matter...)

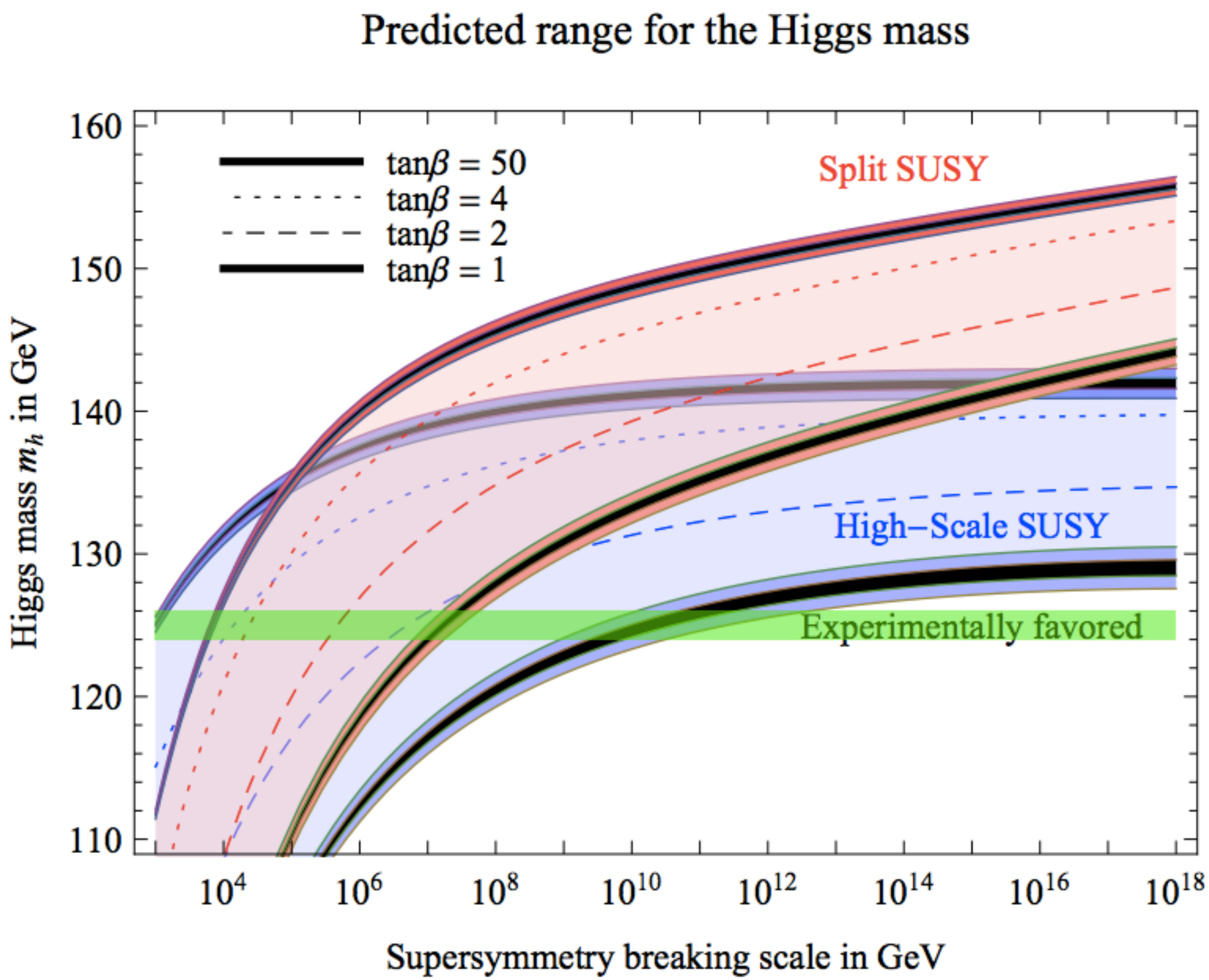
A bubble of negative-energy true vacuum can appear anywhere and anytime and start expanding at the speed of light.

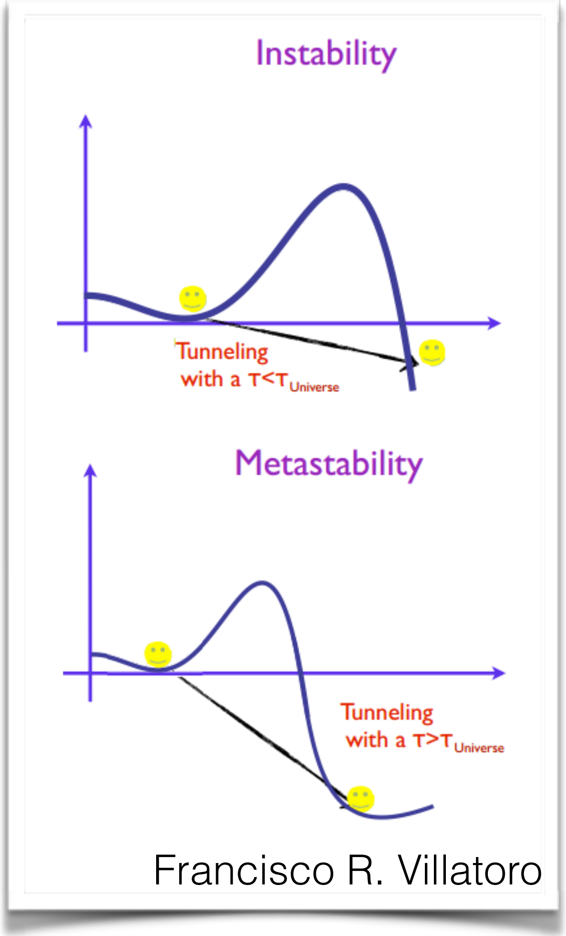


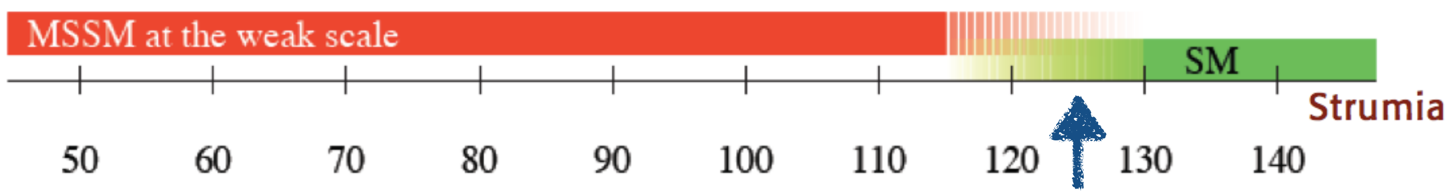
The probability density of vacuum decay is $dp/dV\,dt = e^{-S}/R^4$, suppressed by the action S of the classical field configuration $h(r)$ that interpolates vacua

$h(\infty) =$ unstable vacuum $\qquad h(0) \approx$ other side of the potential barrier

and yet we are alive

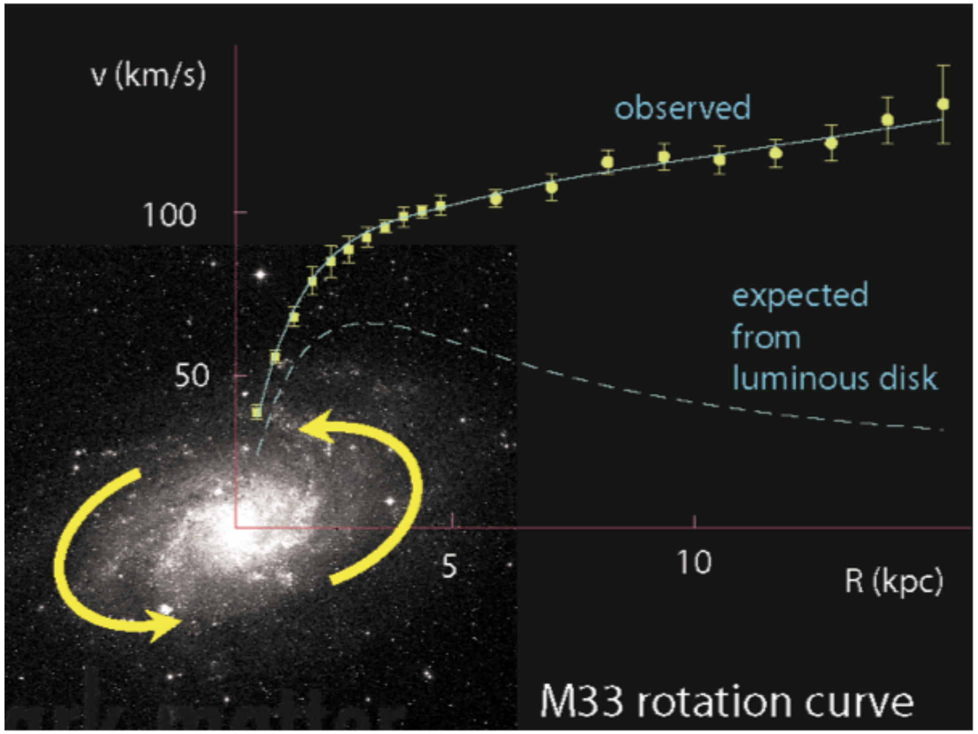




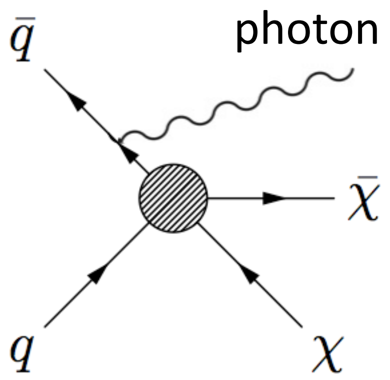


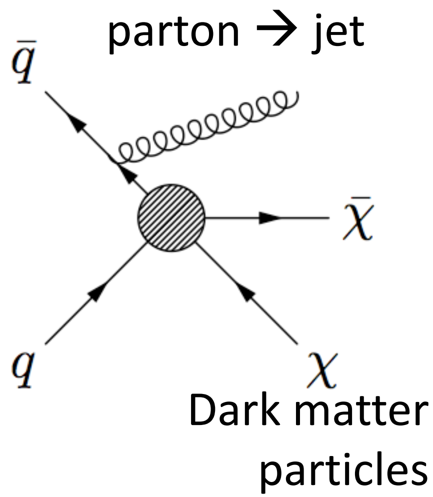
the standard model is not enough

- E.g. **dark matter**:
  - An experimental evidence that there is more than the standard model
  - Astrophysical evidence from rotation curves, gravitational lensing, bullet clusters
  - Six times more abundant than ordinary matter
  - ¼ of the total energy budget of the Universe



- Particle candidates proposed in several models
- Detection at LHC:
  - Jet of hadrons or photon
  - Missing energy (Dark matter footprint)

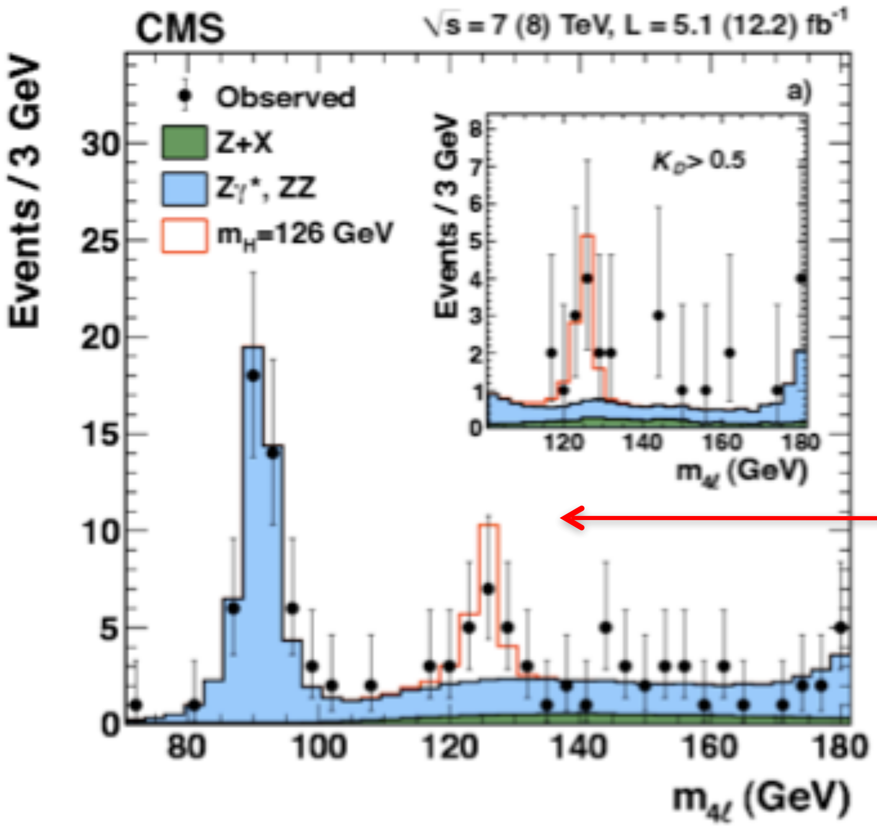




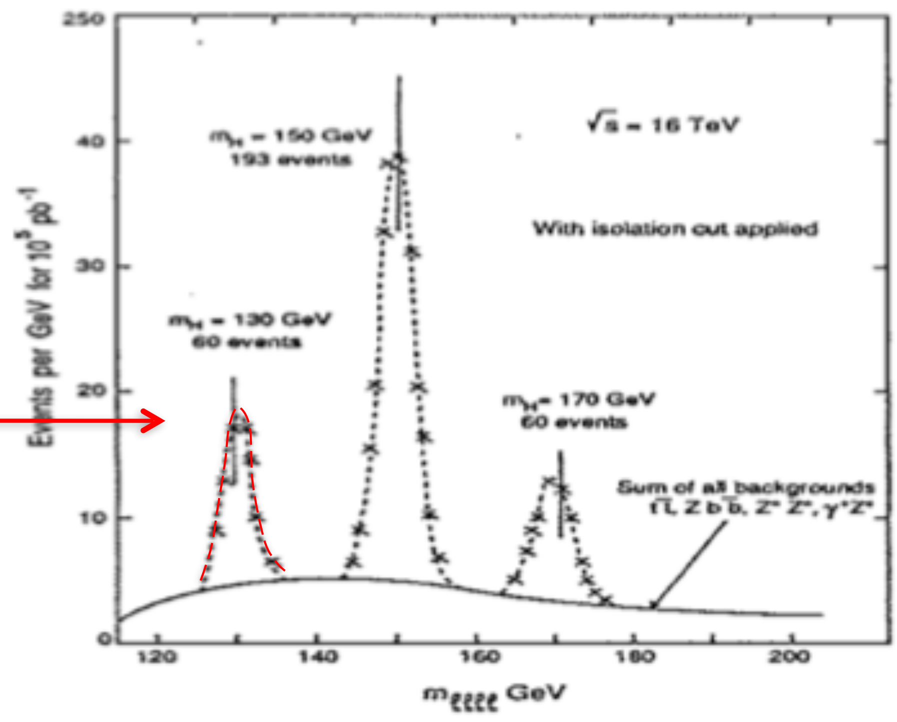
Tabarelli de Fatis

restrospective view

- Comparison between H→ZZ* results and projections from the first LHC Workshop in 1990



Simulation for three mass hypotheses



7 - 8 TeV, ~25 fb^{-1}

Significance ~7 σ

16 TeV, 100 fb^{-1}

Significance ~6 σ

Even better than anticipated

conclusions

- the resonance discovered at the LHC run 1 is **consistent with the properties expected from the standard model Higgs boson**

- **deviations from the SM** might be observable with the LHC or high luminosity LHC precision

- the capacity to discover new physics critically depends on the **experimental and theoretical modelling** of the SM processes