Searches for double Higgs at the LHC and beyond

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Outline

Part I

- Introduction: EWSB mechanism
- The quest for the Higgs boson at the LHC
- Higgs boson: where we stand

Part II

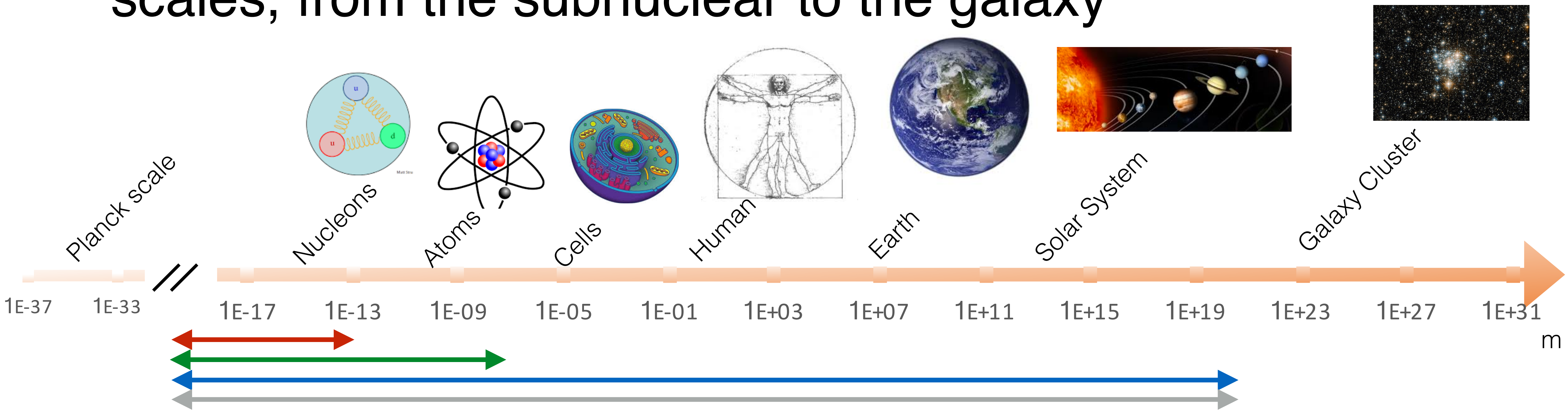
- The production of pairs of Higgs bosons
- Tools and how-to of the double-Higgs hunter
- Double-Higgs results at the LHC…
- …And beyond
- Not only double Higgs

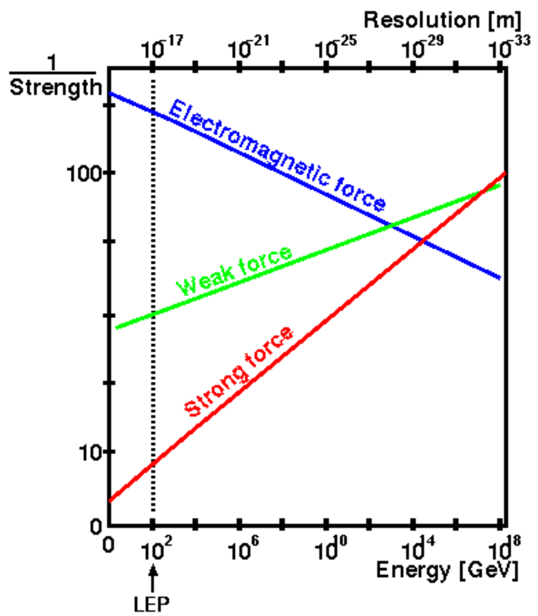
- Conclusions

The Big(gest) Picture

4 “forces”: Strong, Electromagnetism, Weak, Gravity

- These forces explain the universe on a large range of scales, from the subnuclear to the galaxy





But not much beyond galaxies and not all the way to the Planck scale

The fundamental interactions

Strong force:

- Responsible for the stability of nuclei,
- Strengths increases with distance, short range
- Confinement, Asymptotic freedom, 8 gluons, 3 quarks

Weak interaction:

- Responsible for radioactive decay
- Short range interaction, mediated by massive particles (W/Z)

Electromagnetic interaction

- Goes as $1/r^2$
- Infinite range: mediated by massless photon

Gravity

- Goes as $1/r^2$, infinite range, described by general relativity

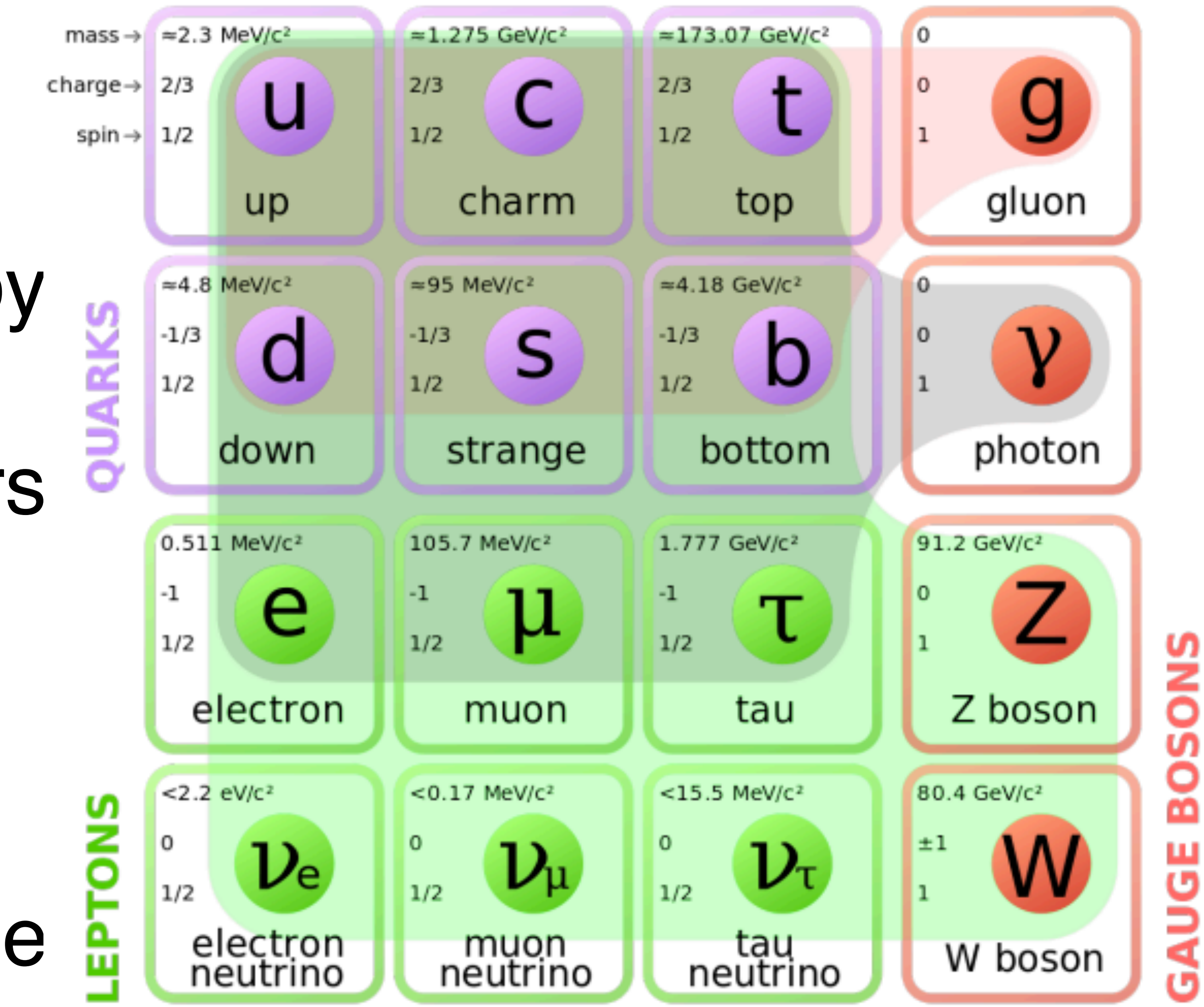
The Standard Model

The standard model is a Quantum Field Theory that explains the behaviour of the e.m+weak+strong interactions by means of interactions between particles, fields and force carriers

- electromagnetism ↔ photon, electric charge
- weak ↔ W/Z bosons, Isospin charge
- Strong ↔ gluons, colour charge

The forces acts on force-carrier bosons and on the fundamental particles:

- 3 leptons families (e,μ,τ) and 3 quarks families (u/d,s/c,t/b)



Plus the Higgs…

Symmetries

The Standard Model is a gauge theory → Invariant under some symmetry

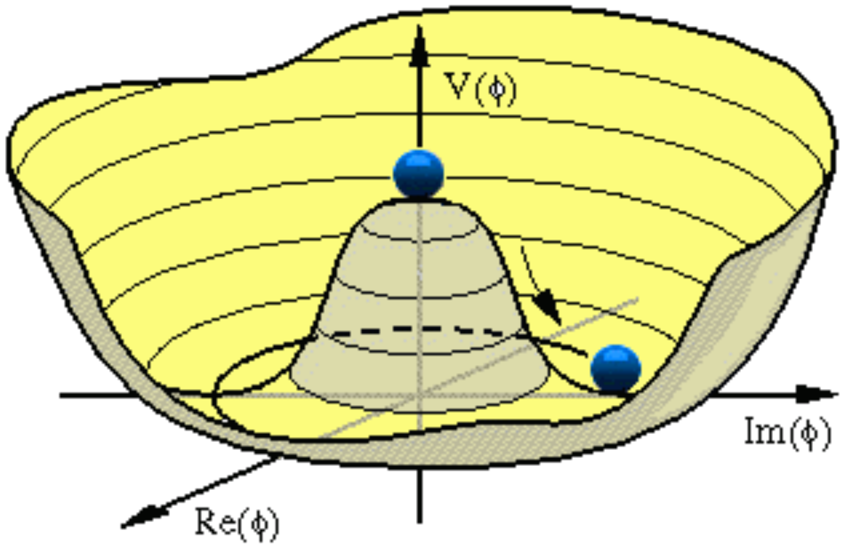
- In particular, the symmetry of the SM is $SU(3)_{colour} x SU(2)_{weakisospin} x U(1)_{hypercharge}$

Which in practice means that we know how to write a Lagrangian invariant under

- SU(3) [we need to put in 8 gluons for the strong force]
- SU(2) [we need to put in 3 “weak” bosons (W)]
- U(1) [we need to put in 1 boson]

Problem: adding a mass term breaks the gauge invariance

Spontaneous symmetry breaking



- Spontaneous electroweak symmetry breaking is the way to include mass terms in the SM Lagrangian without breaking gauge invariance
- Introduce a new scalar field H. The minimum of the H potential is not symmetric under a given symmetry (and the ground state is degenerate)
- When the system moves to the ground state the symmetry is broken.
- In the SM, this process creates new interaction terms between massive particles and the Higgs and introduce mass terms
- Bonus: in addition to W/Z it also gives mass to fermions

Higgs is the mass-giver

The Electroweak Lagrangian before EWSB:

Higgs field

$$-\frac{1}{4}W_a^{\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \overline{Q}_i i\not{D} Q_i + \overline{u}_i i\not{D} u_i + \overline{d}_i i\not{D} d_i + \overline{L}_i i\not{D} L_i + \overline{e}_i i\not{D} e_i + |D_\mu h|^2 - \lambda\left(|h|^2 - \frac{v^2}{2}\right)^2 +$$

$$-y_{u\,ij}\epsilon^{ab}\,h_b^\dagger\,\overline{Q}_{ia}u_j^c - y_{d\,ij}\,h\,\overline{Q}_i d_j^c - y_{e\,ij}\,h\,\overline{L}_i e_j^c + h.c.$$

Boson interactions

kinetic term

Yukawa term (interaction h-fermions)

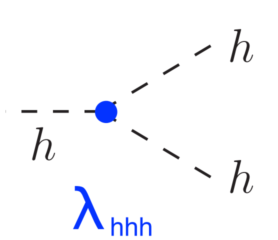
After EWSB, the Lagrangian of the SM takes its definitive shape, let's only recall:

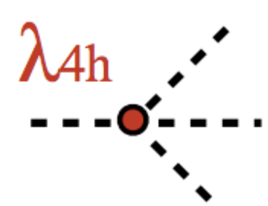
- The kinetic term, where masses appear:

$$\sum_f \overline{f}(i\not{\partial} - m_f)f - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} + m_W^2 W^+_\mu W^{-\mu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \frac{1}{2}m_H^2 H^2$$

- The Higgs sector, with the Higgs self-interaction terms:

$$-\frac{g m_H^2}{4 m_W}H^3 - \frac{g^2 m_H^2}{32 m_W^2}H^4$$





Now the SM is complete

"Easy and simple" expression which describes in detail the behaviour of weak, electromagnetic and strong interactions

Depends on 26 free parameters

- (leptons and fermions masses, CKM angles, coupling strengths, Higgs vacuum expectation value, Higgs mass + neutrinos)

The Higgs mass is a free parameter of the SM

Now the SM is complete

$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2}ig_s^2(\bar q^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar G^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac12 \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac12 \partial_\mu A_\nu \partial_\mu A_\nu - \tfrac12 \partial_\mu H \partial_\mu H - \\
\tfrac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g}H + \tfrac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac18 g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac12 g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac14 g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\
\tfrac14 g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar e^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + \\
m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar e^\lambda\gamma e^\lambda) + \tfrac23(\bar u^\lambda_j\gamma u^\lambda_j) - \tfrac13(\bar d^\lambda_j\gamma d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+ \\
\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\tfrac43 s_w^2-1-\gamma^5)u^\lambda_j) + \\
(\bar d^\lambda_j\gamma^\mu(1-\tfrac83 s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+ \\
\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \\
\tfrac{ig}{2\sqrt2}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + \\
i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+ \\
\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \\
\tfrac g2\tfrac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \tfrac g2\tfrac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \\
\bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2-\tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + \\
igc_w W^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + \\
igc_w W^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + \\
igc_w Z^0_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) + igs_w A_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) - \\
\tfrac12 gM[\bar X^+ X^+ H + \bar X^- X^- H + \tfrac{1}{c_w^2}\bar X^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar X^+ X^0\phi^+ - \\
\bar X^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-] + igMs_w[\bar X^0 X^-\phi^+ - \\
\bar X^0 X^+\phi^-] + \tfrac12 igM[\bar X^+ X^+\phi^0 - \bar X^- X^-\phi^0]
\end{gathered}
$$

"Easy and simple" expression which describes in detail the behaviour of weak, electromagnetic and strong interactions

Depends on 26 free parameters

- (leptons and fermions masses, CKM angles, coupling strengths, Higgs vacuum expectation value, Higgs mass + neutrinos)

The Higgs mass is a free parameter of the SM

With a few caveats

The SM works amazingly well

- spans over ~20 orders of magnitude
- Has been tested to incredible precision
- predicted successfully the top, W, Z masses and H existence
- Not so many free parameters (26) after all

But a few things don’t actually tick the box:

- Unification of interactions
- Metastability
- Neutrino mass hierarchy

And a big elephant in the room: gravity

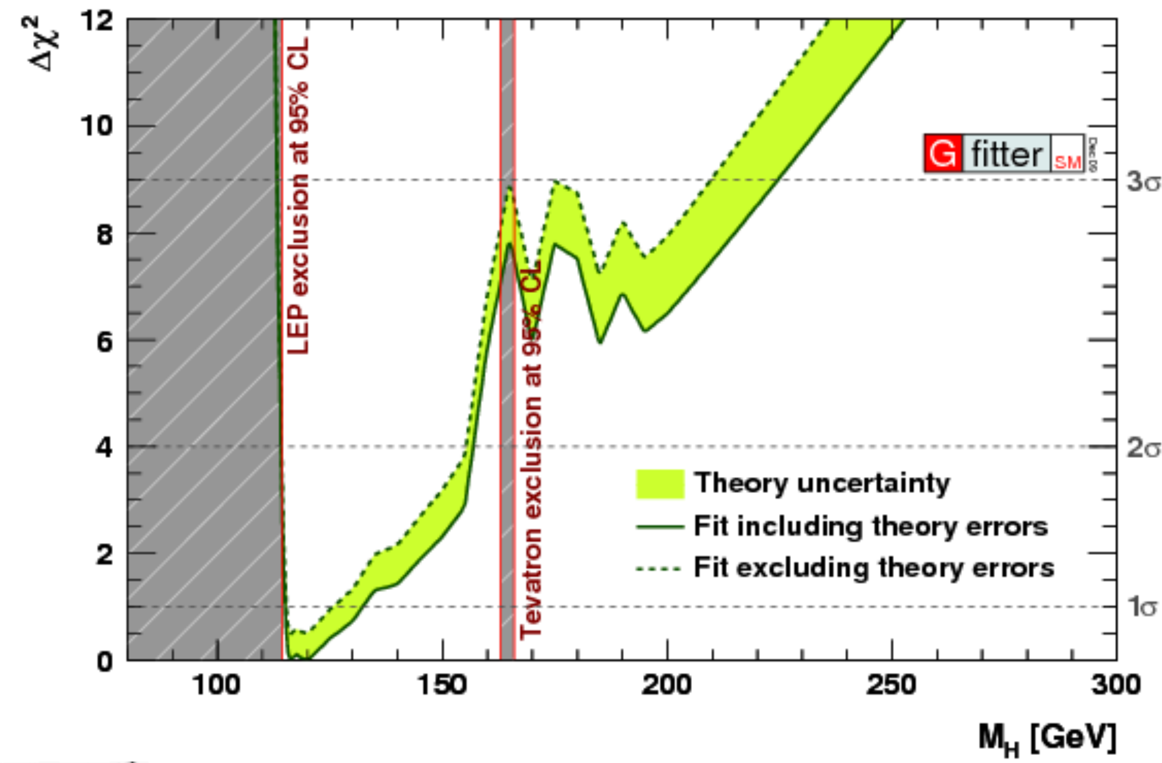
The making of a standard model

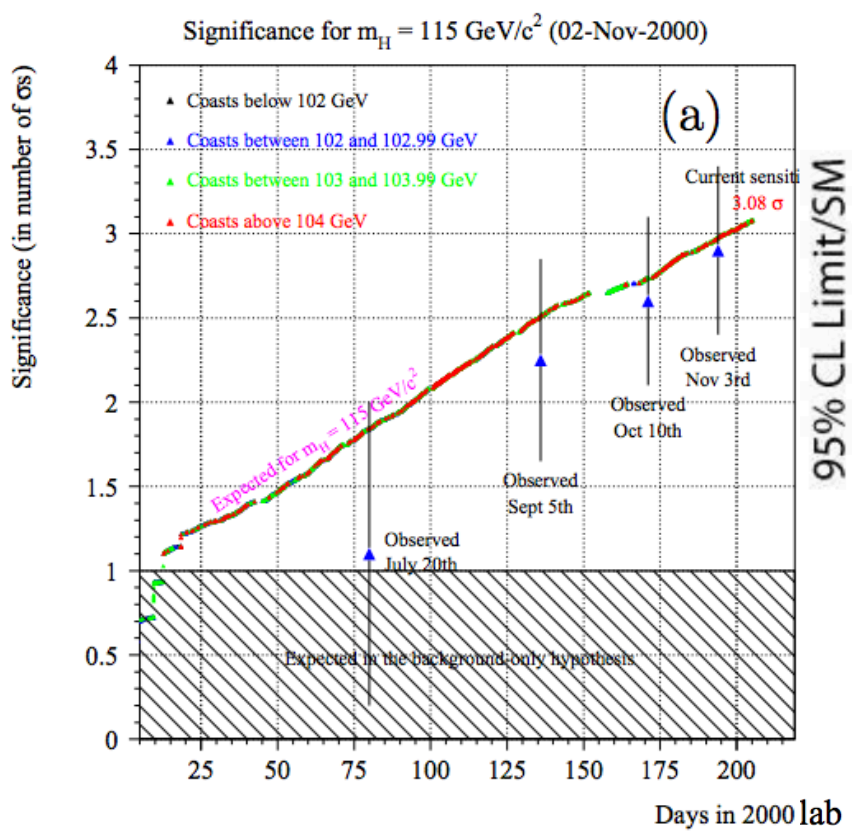
- 1954: Yang and Mills: SU(2) non-Abelian gauge theories
- 1961: Goldstone theorem. SBS bring massless scalars
- 1964: Brout-Englert-Higgs propose the Higgs boson
- 1964: Gell-Mann and Zweig theorise the “quark model”
- 1967: Weinberg, Glashow, Salam create the EW theory
- 1968: SLAC experiments confirm nucleons are composite
- 1970: Glashow, Iliopoulos, Maiani predict the charm quark
- 1983: W and Z are found at SPS
- 1989: LEP starts operations
- 1993: Superconducting Super Collider abandoned
- 1995: top quark found at Tevatron
- 2001: LEP ends operations, among fierce debate
- 2009: LHC starts operations
- 2012: Higgs discovered at the LHC

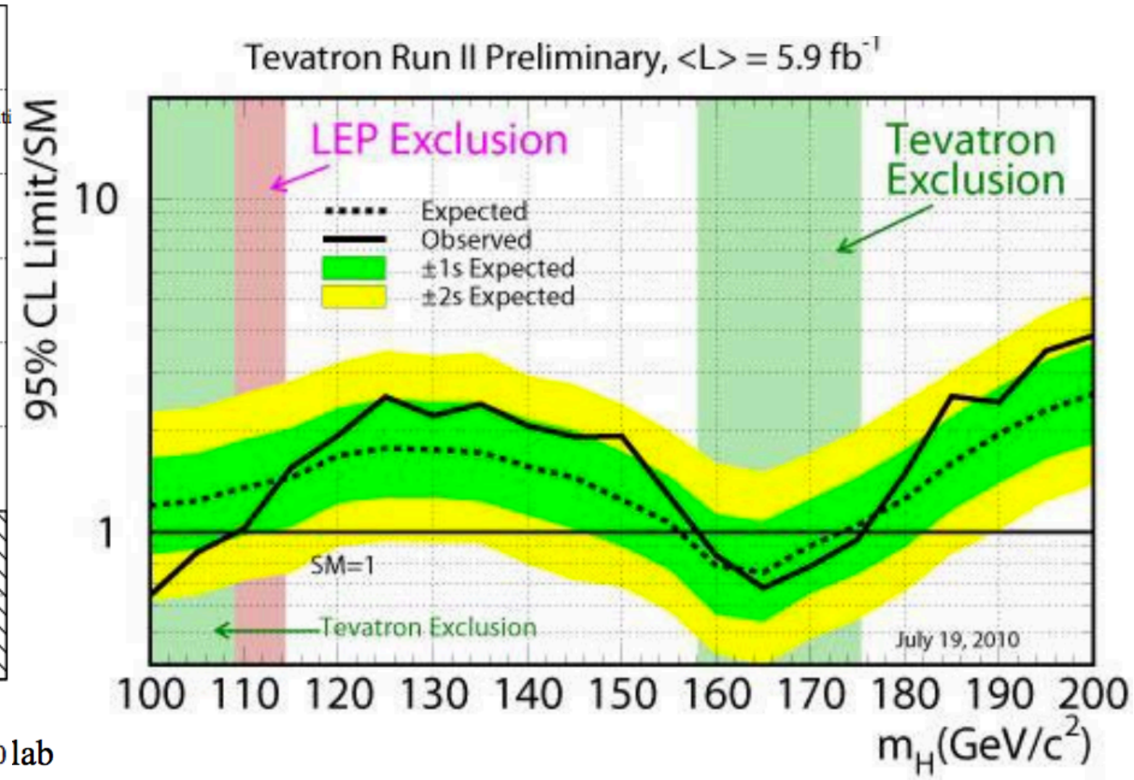
The Higgs before the LHC

Two complementary approaches to search for the Higgs boson before LHC-era

Theory side: Use high precision LEP data and our knowledge of the Standard Model to identify where is most probable that the Higgs boson lies

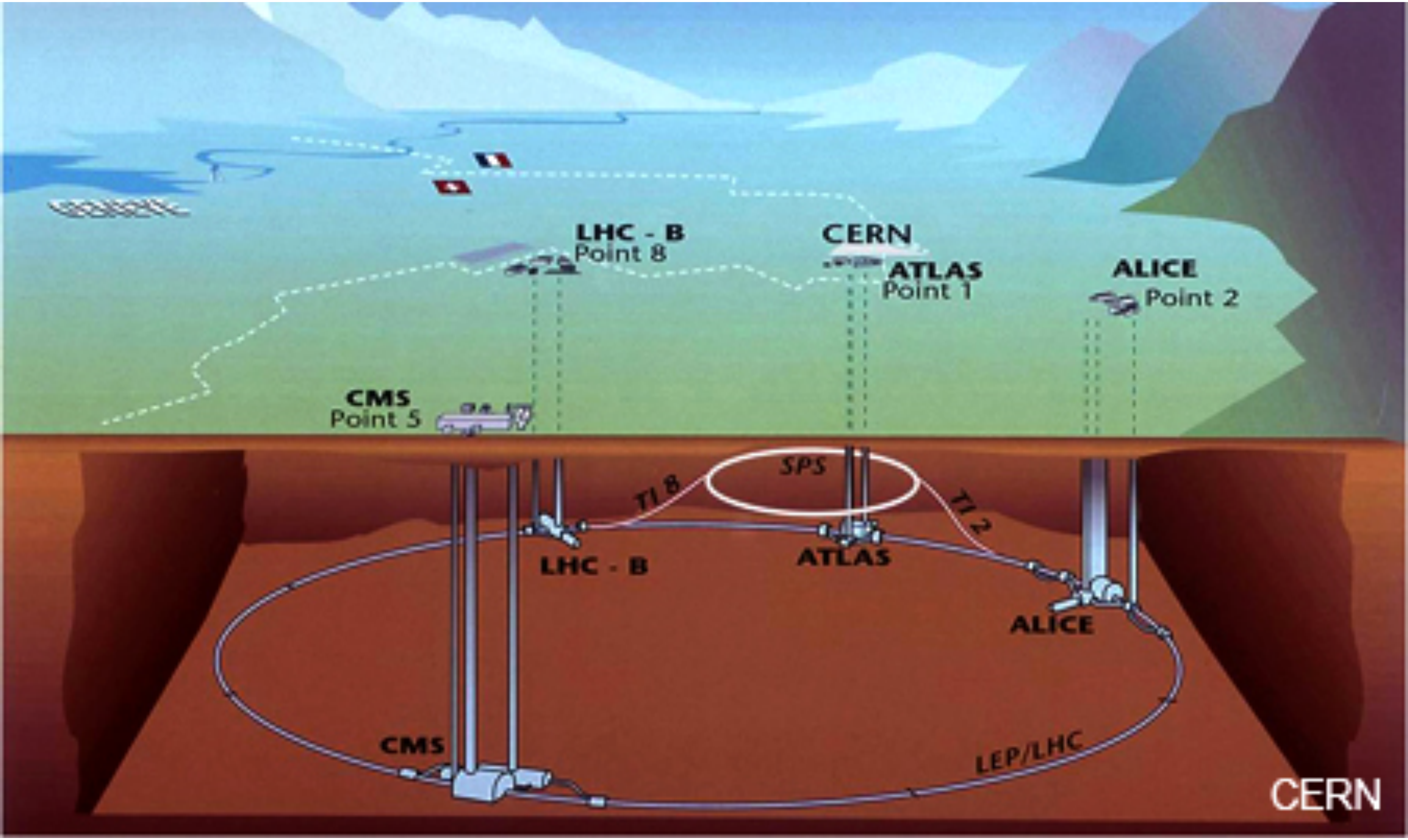






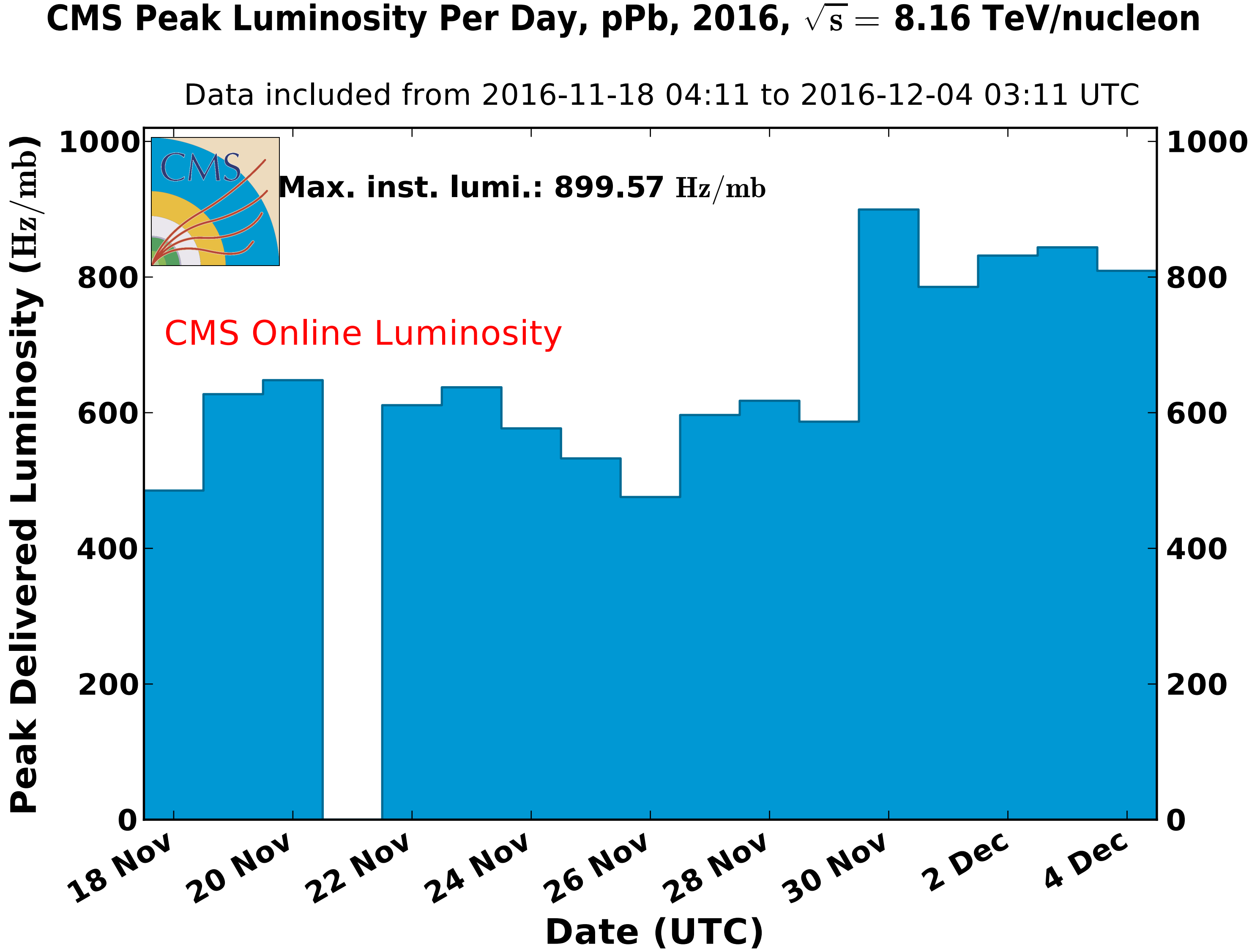
LEP and Tevatron searched for Higgs evidence, but despite tantalising hints at LEP, no discovery

The Large Hadron Collider



The Large Hadron Collider

- LHC is a very complex machine, and it is just the endpoint of a long chain of accelerators
- Operating the machine is a challenge



The Large Hadron Collider

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LAURENT THOMAS — Weasels are everywhere... — MON 21.NOV.16 0

Message ID: 960935 **Entry time:** MON 21.NOV.16 02:58:40 **Short link:** http://cmsonline.cern.ch/cms elog/960935

Author:	LAURENT THOMAS, laurent.thomas@cern.ch
Type:	CCC Update
Subject:	Weasels are everywhere...

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From LHC logbook:
"Latest on the fault in P2: a weasel (again!) caused an arc (and subsequent earth fault) at the incoming
connection of the SVC filter."
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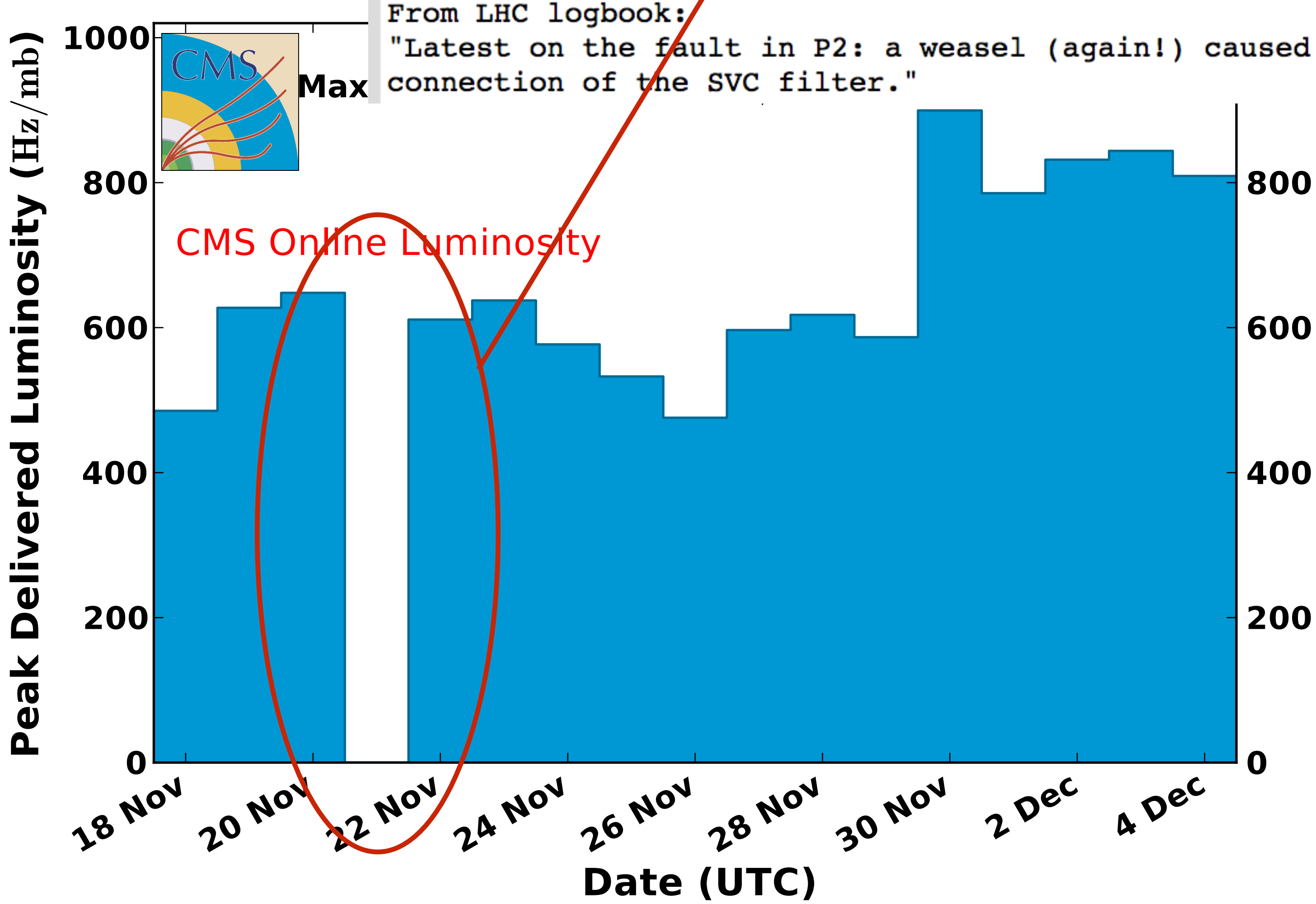
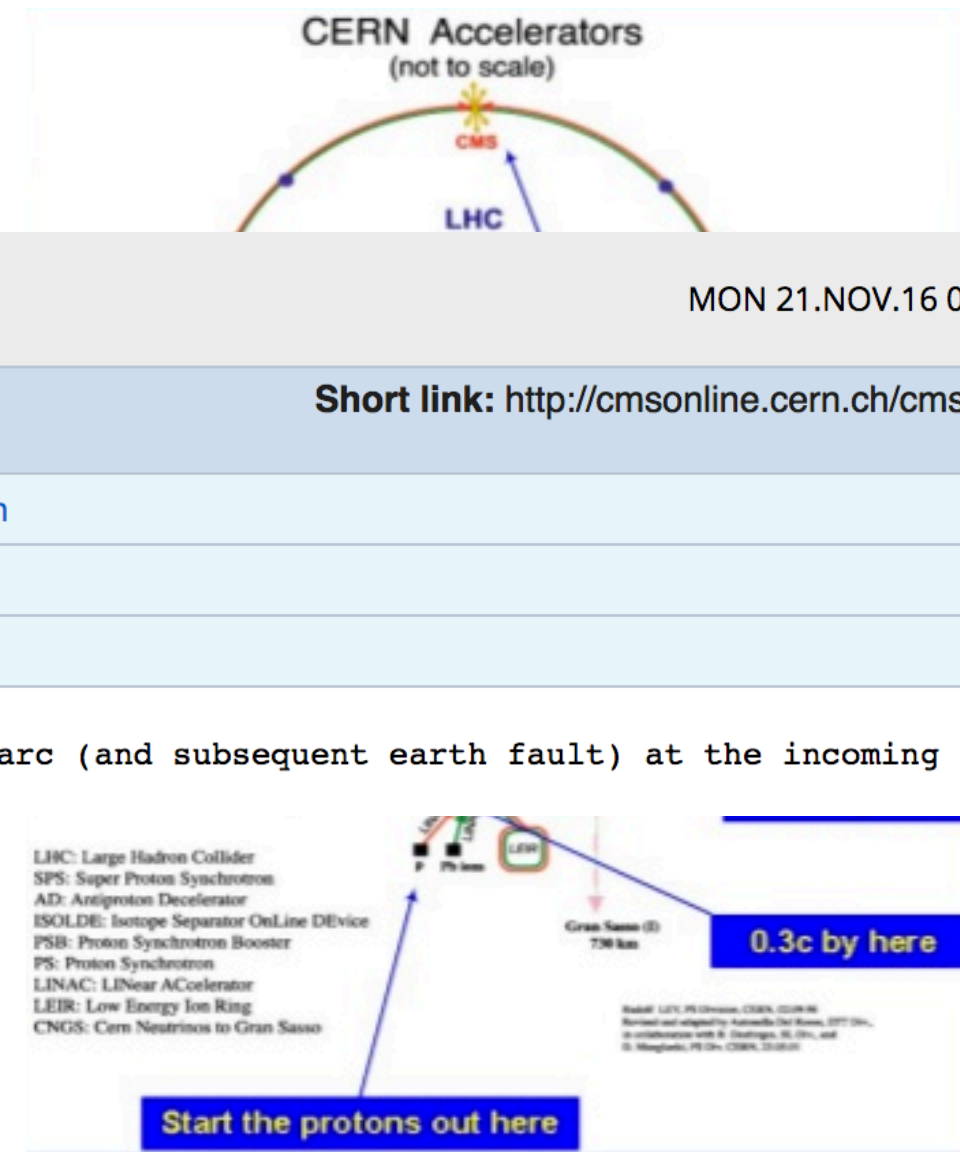
CMS Peak Lumin

Data incluc

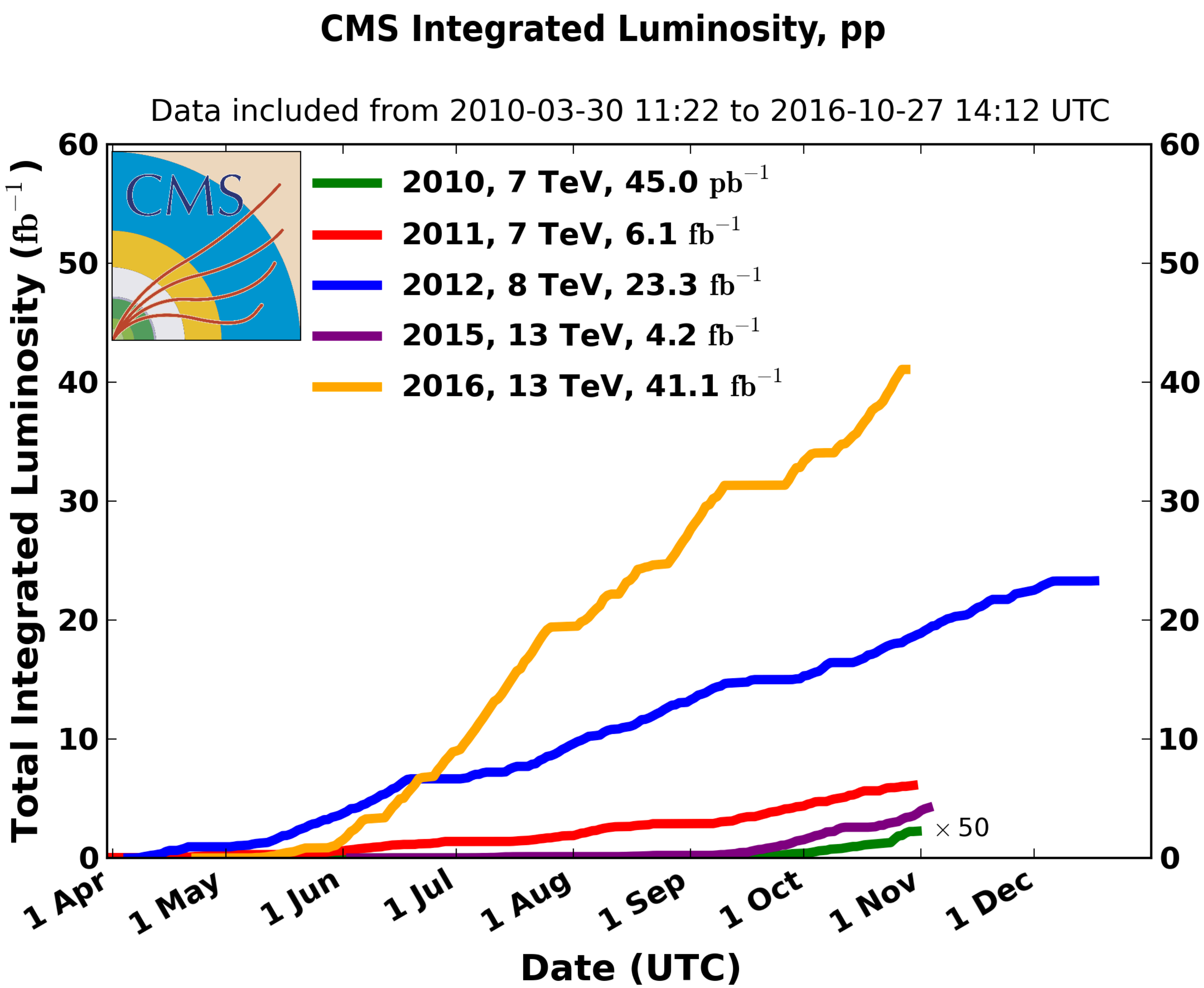




Upgrades of the LHC

Every year LHC performances improve

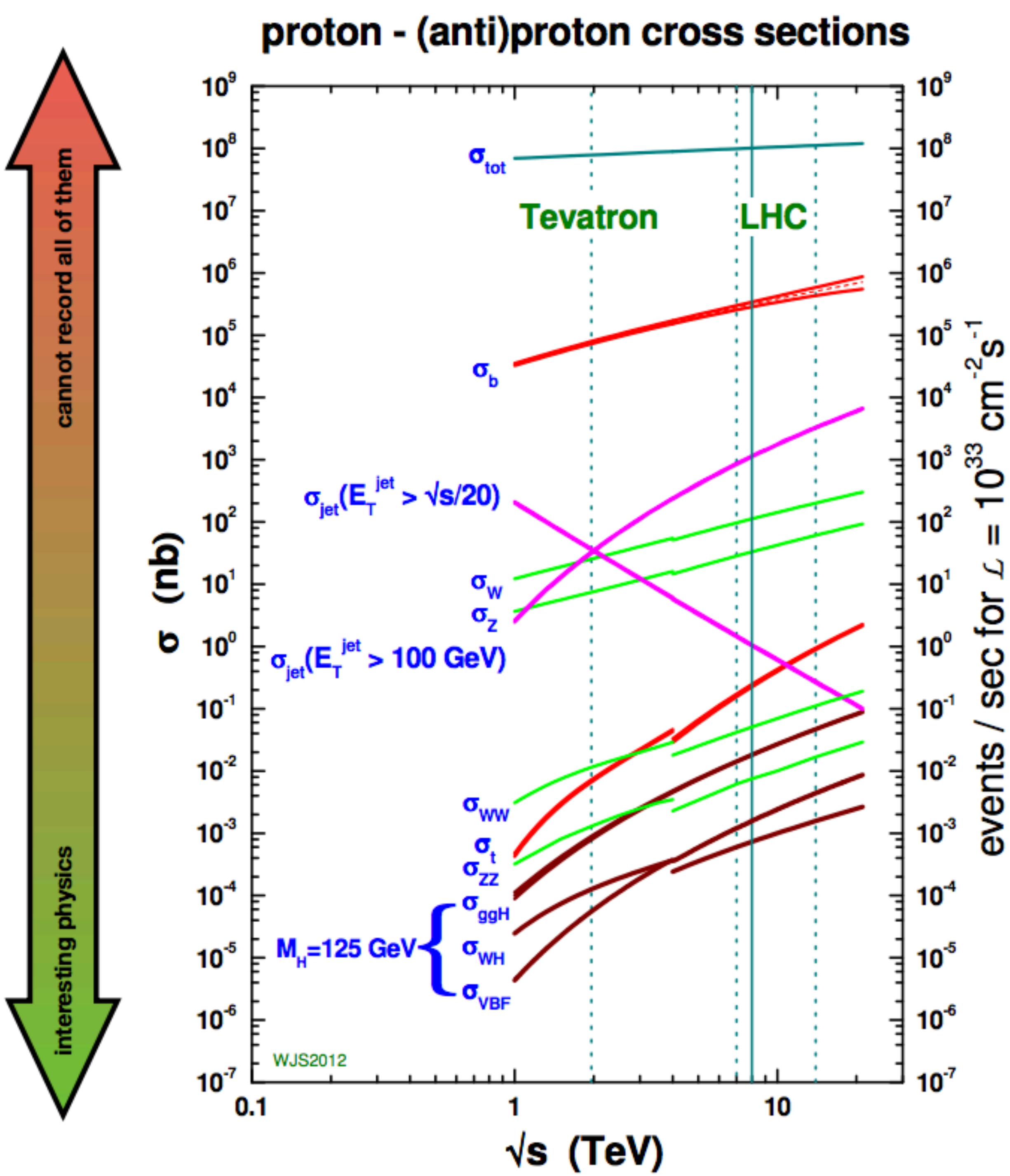
- More luminosity, more events, more Higgses (and more chances for new physics)



But also:

- More particles to reconstruct
- More pile-up
- Need to change triggers, specifications
- A lot of work goes into preparing every year of data taking

Triggers



The rate of collisions for LHC is ~40MHz

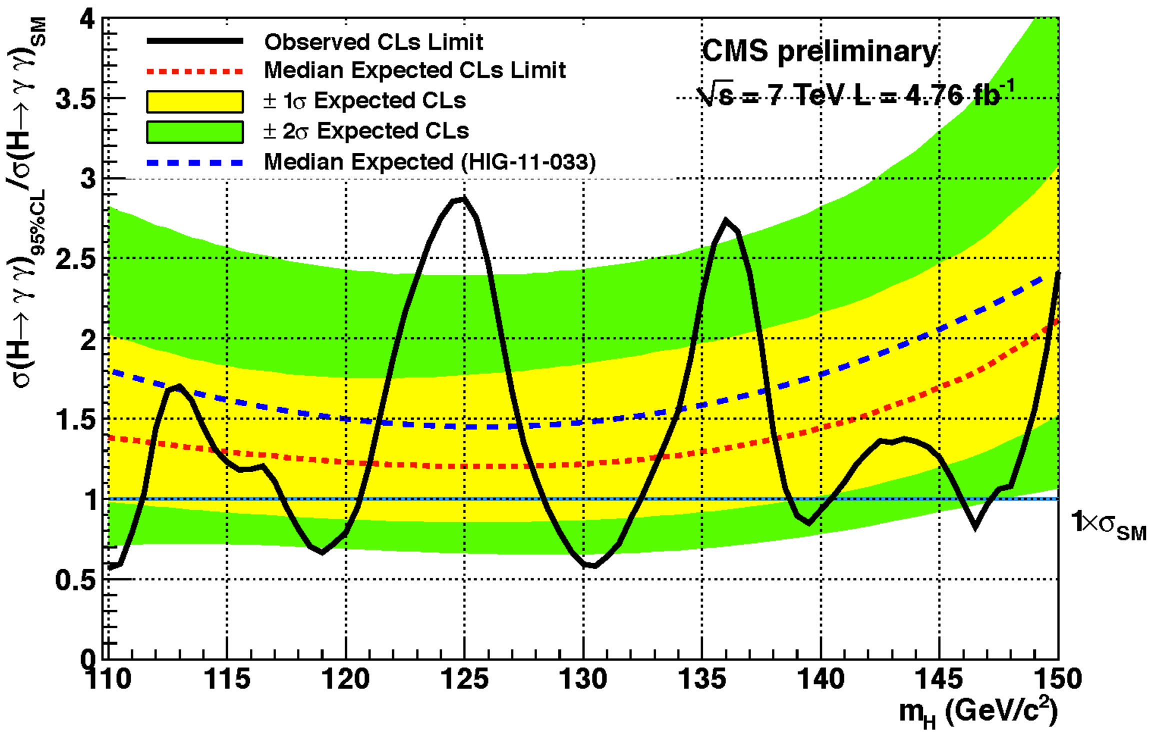
It is impossible to record all of them, CMS can afford ~1KHz

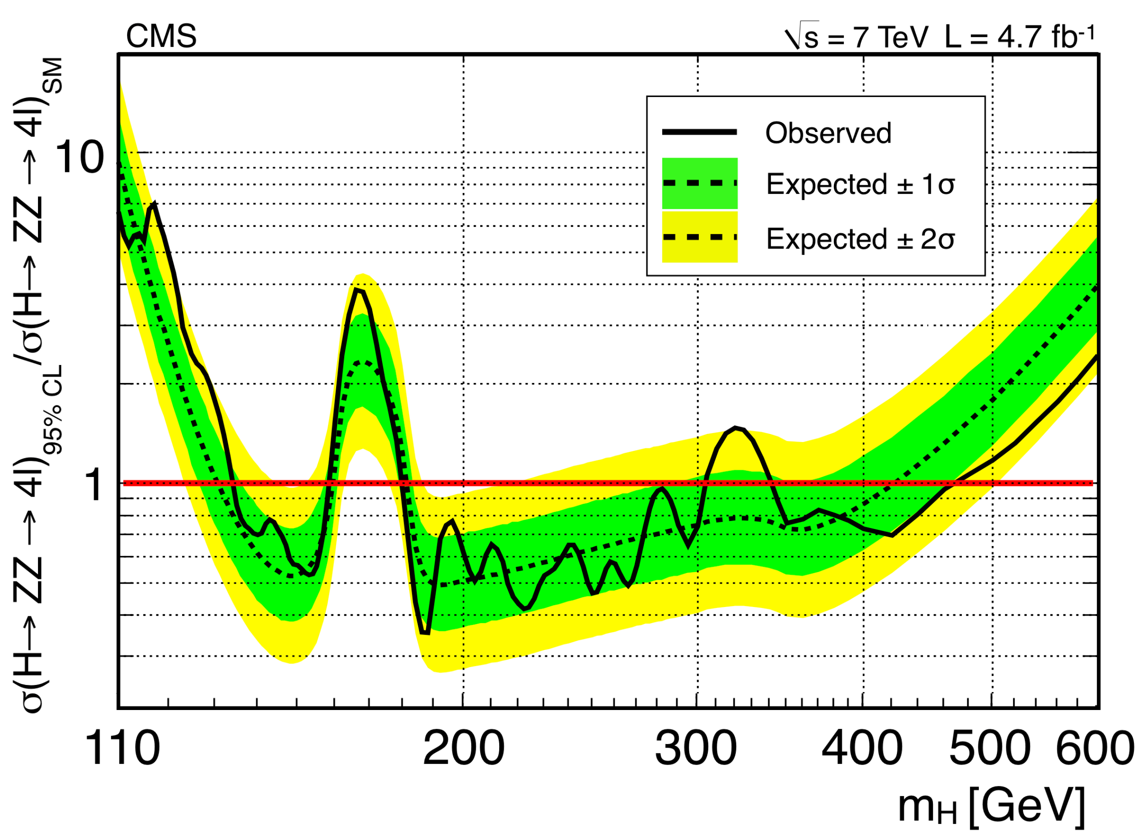
A trigger is a system to discard "not interesting" events by flagging only those that have some signal-like feature, at the very basic level

For double Higgs we search events triggered by:

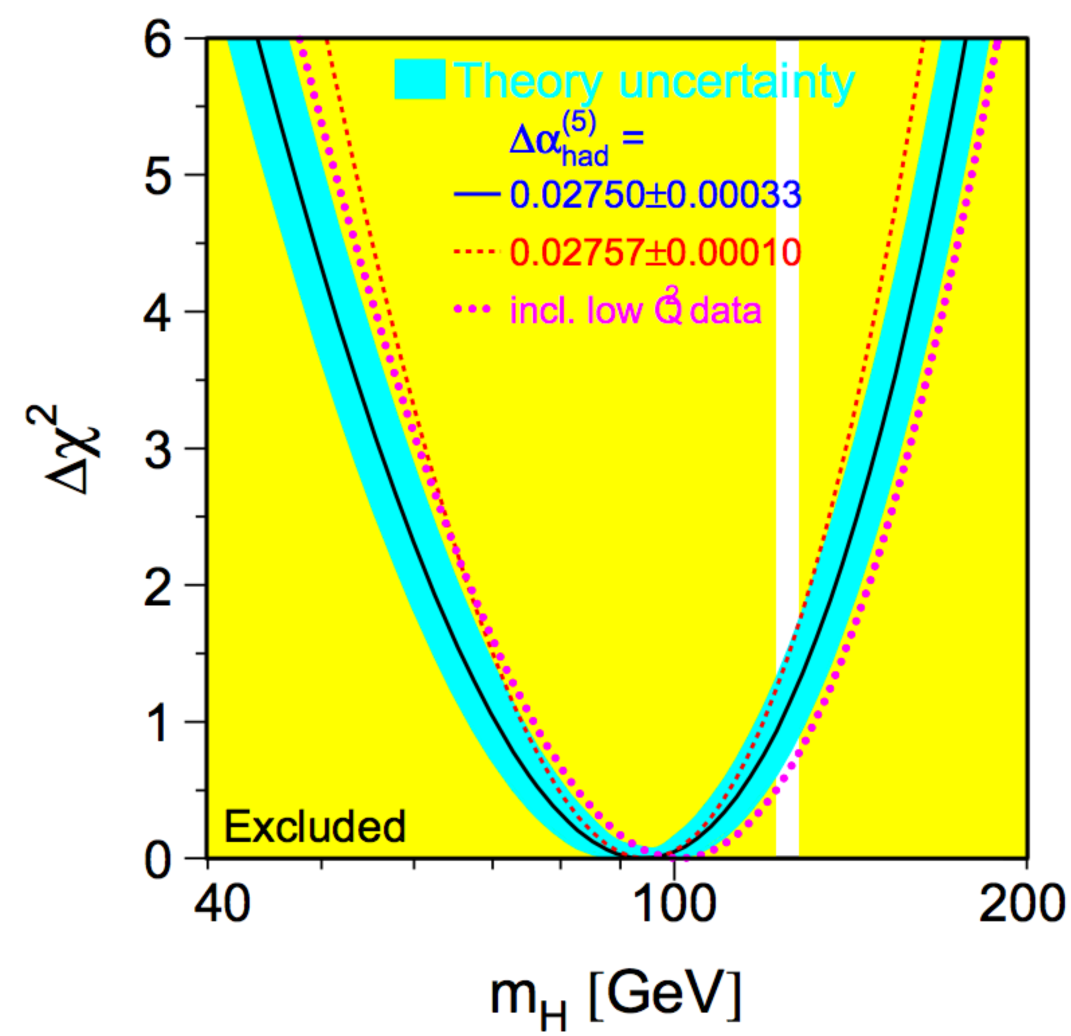
- e/μ (pT>~20GeV),τ (pT>35GeV)
- b jets or high pT jets
- photons

After the first run

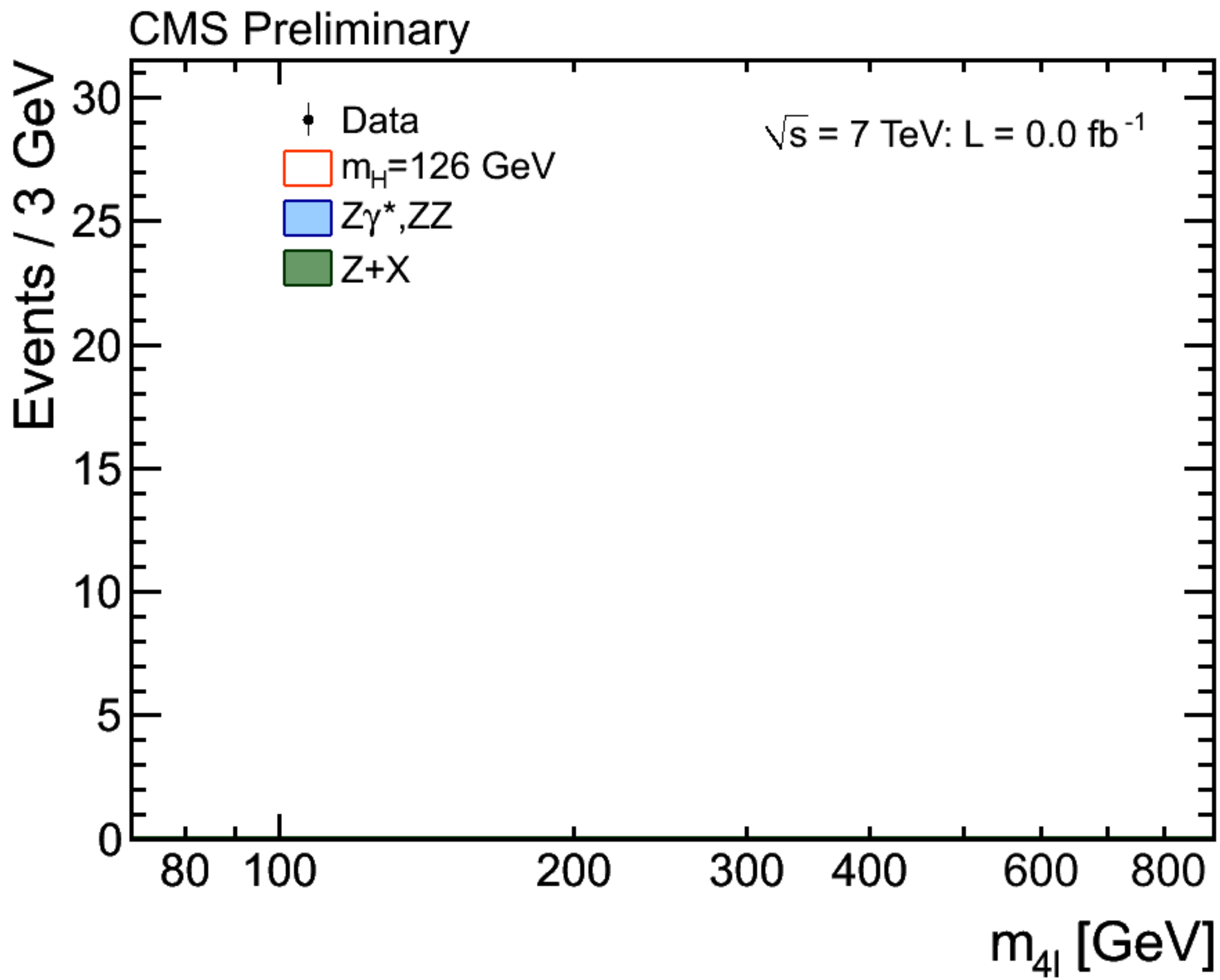




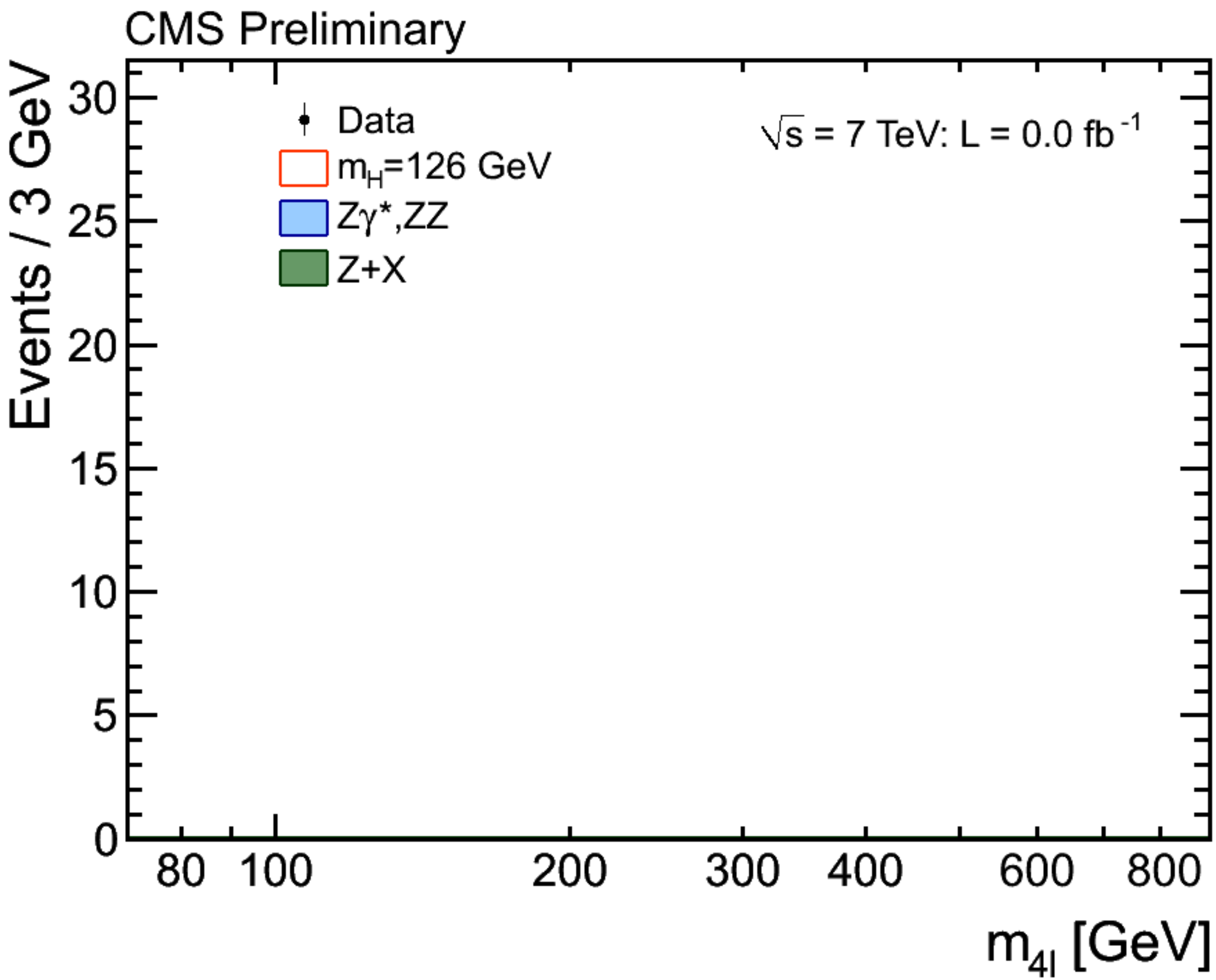
Results after the first 2 years of LHC data taking left a very narrow region available for the Higgs existence



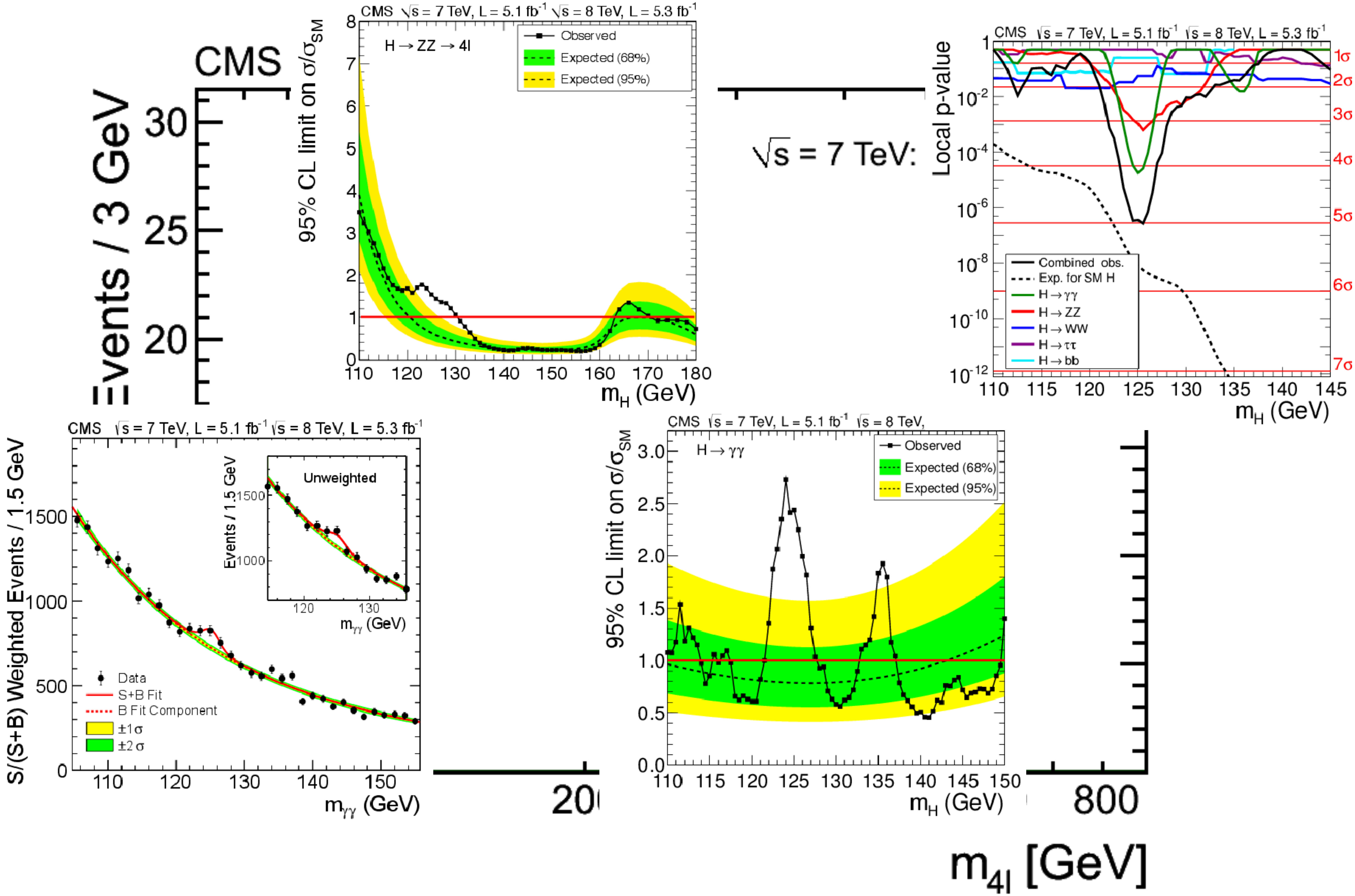
The discovery



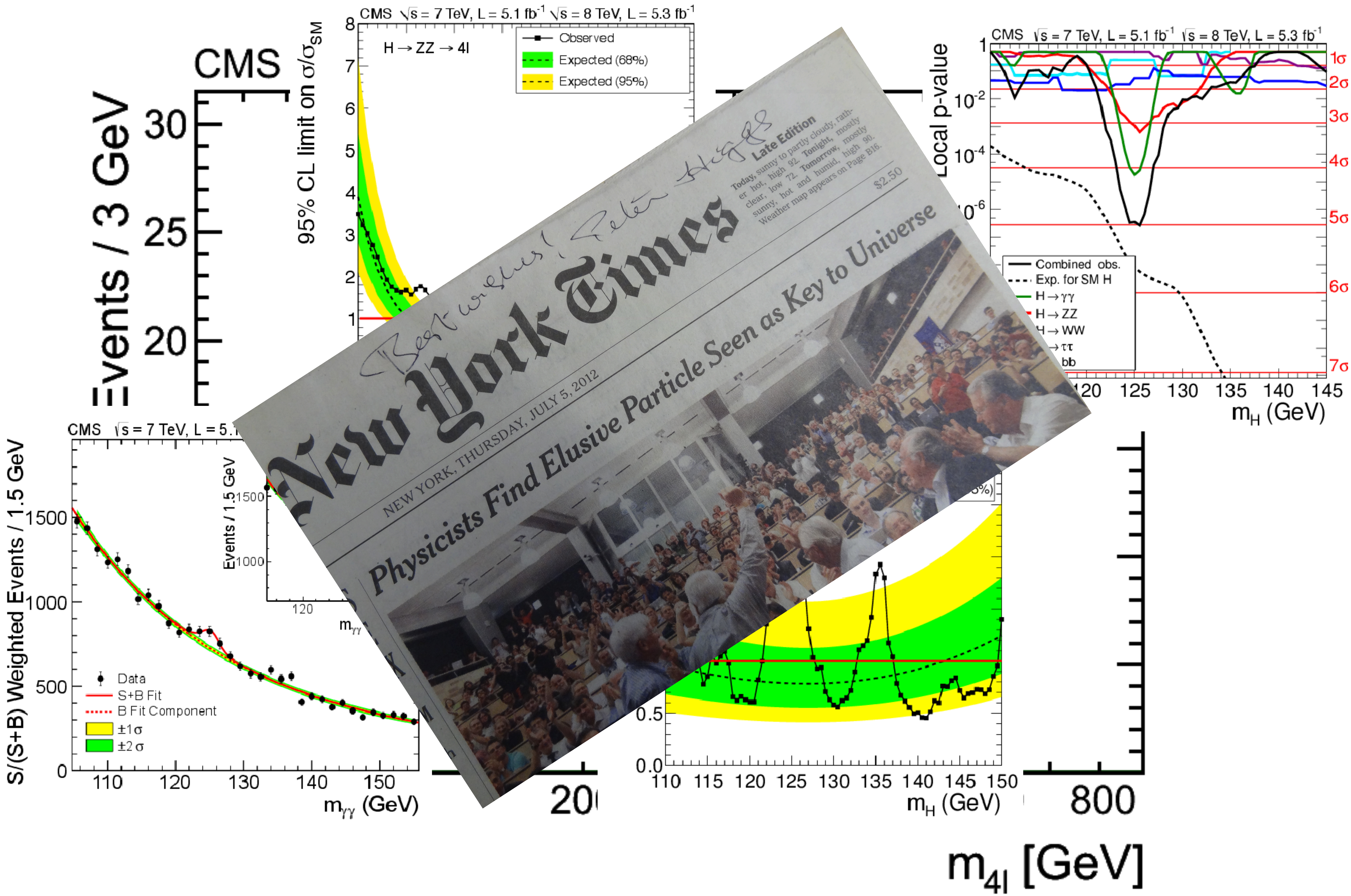
The discovery



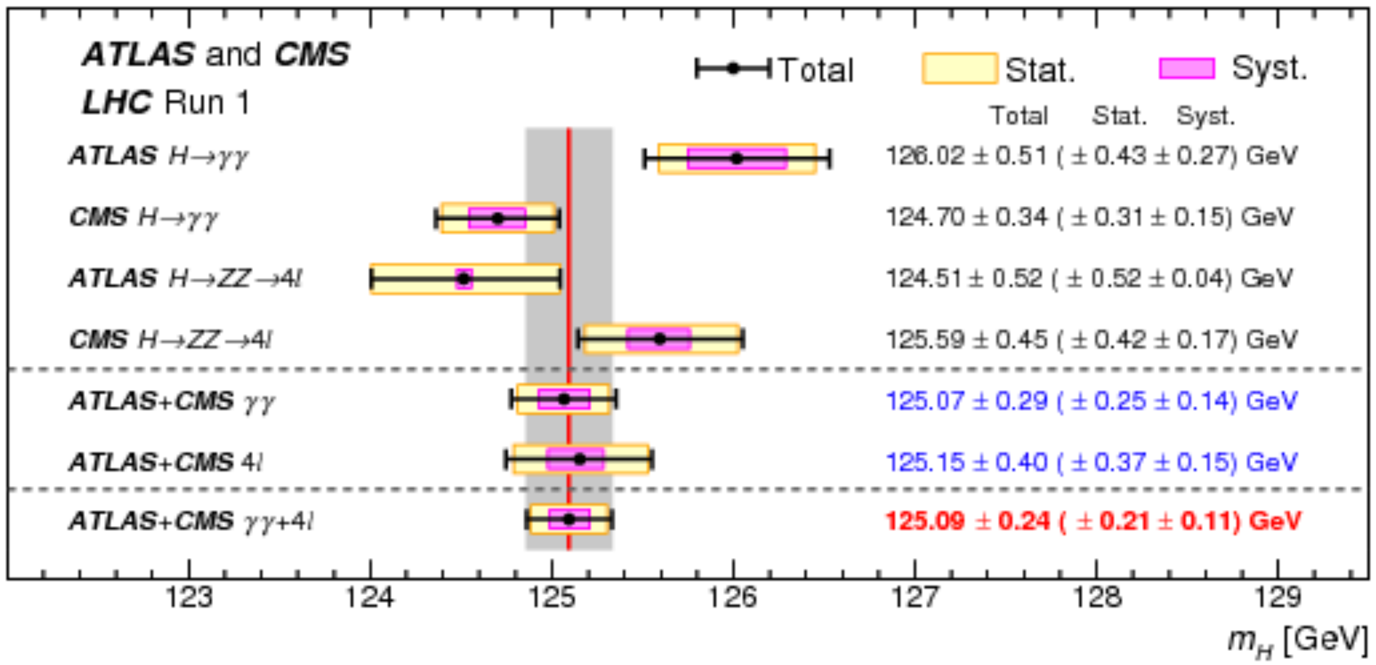
The discovery

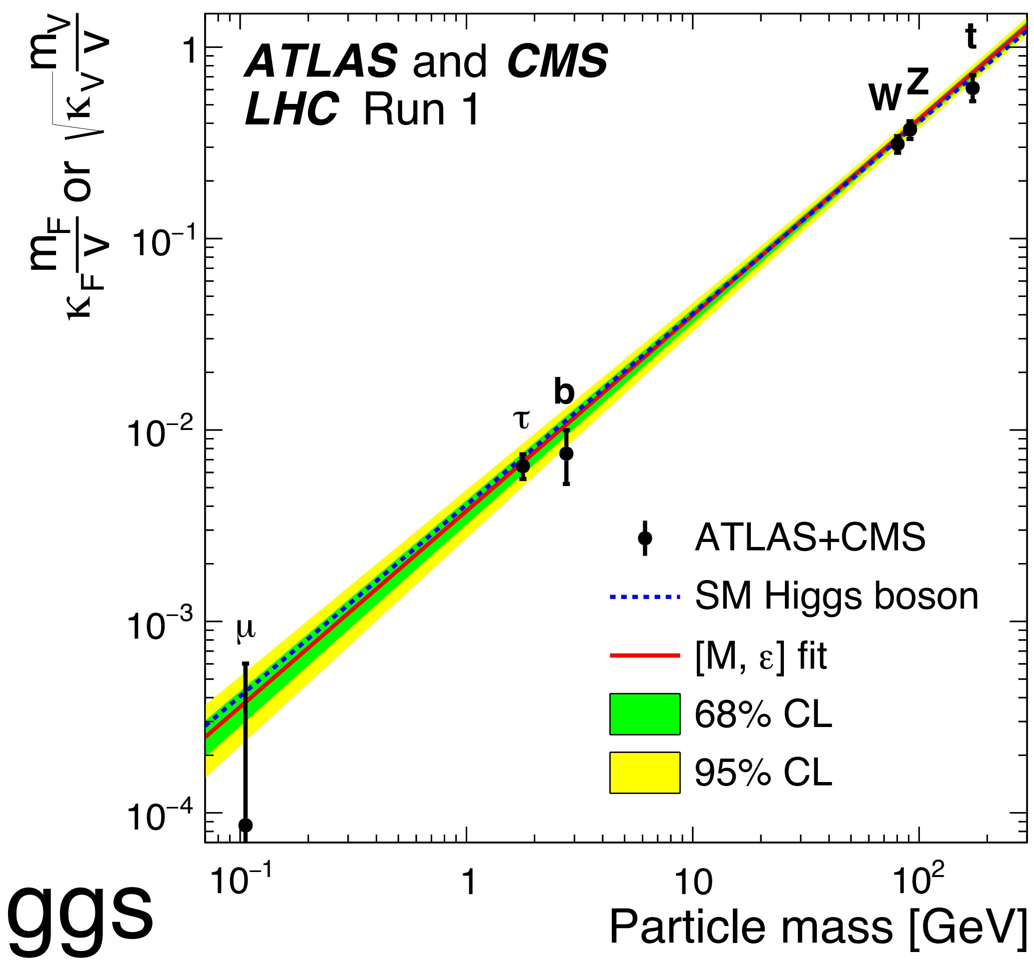


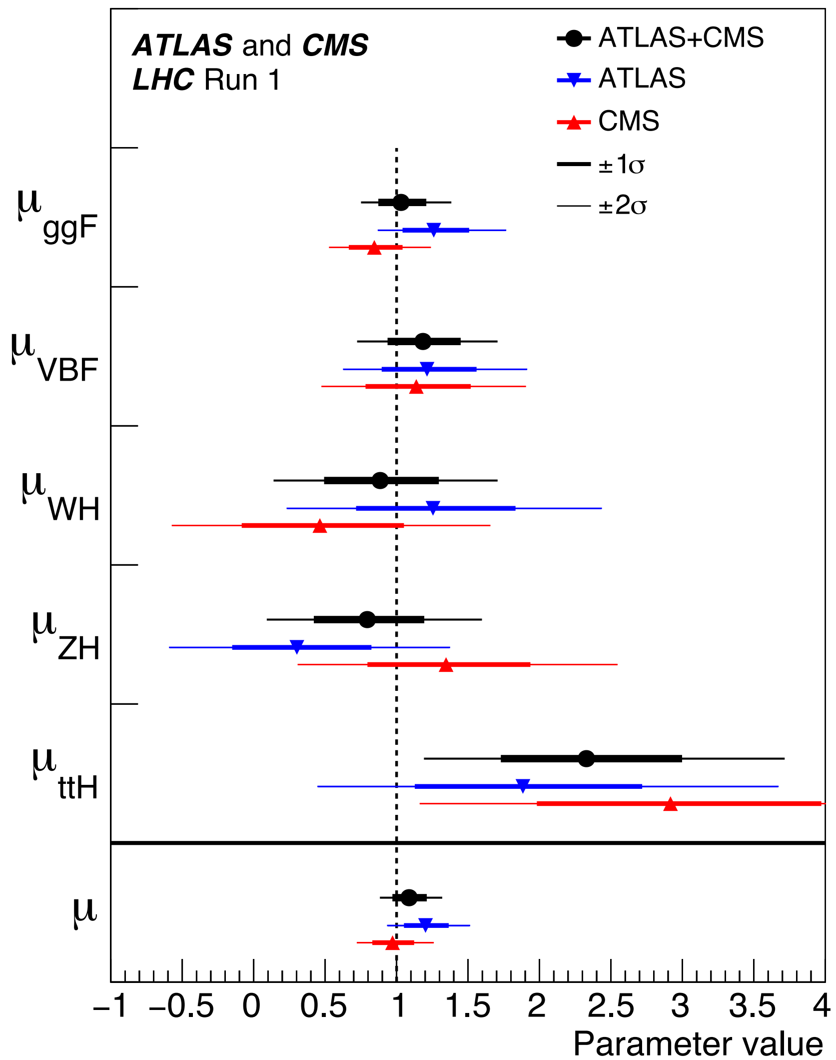
The discovery



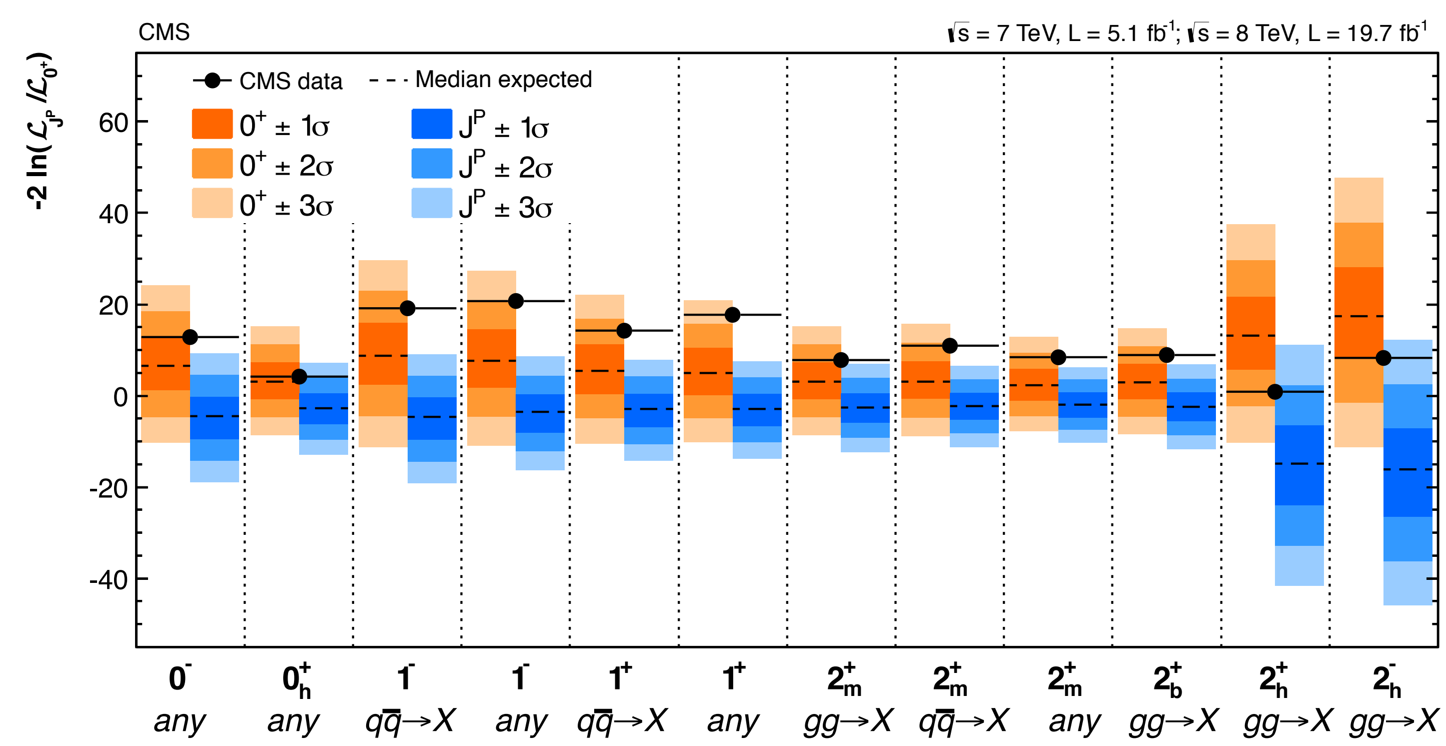
Higgs results: spin and couplings



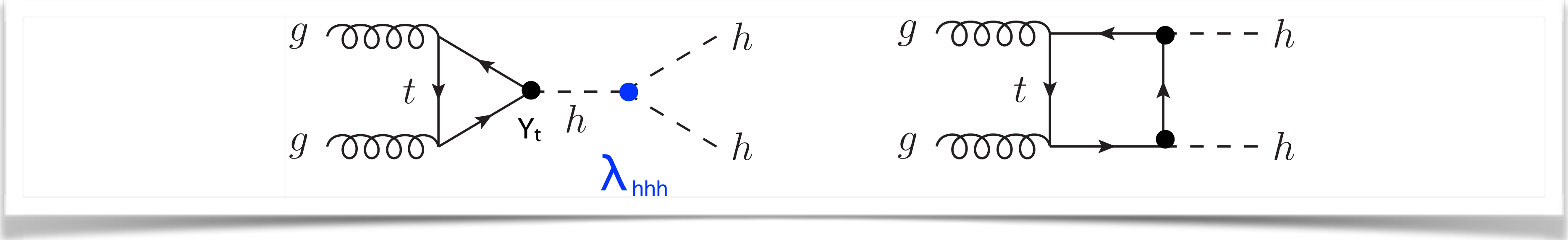




It really is the SM Higgs

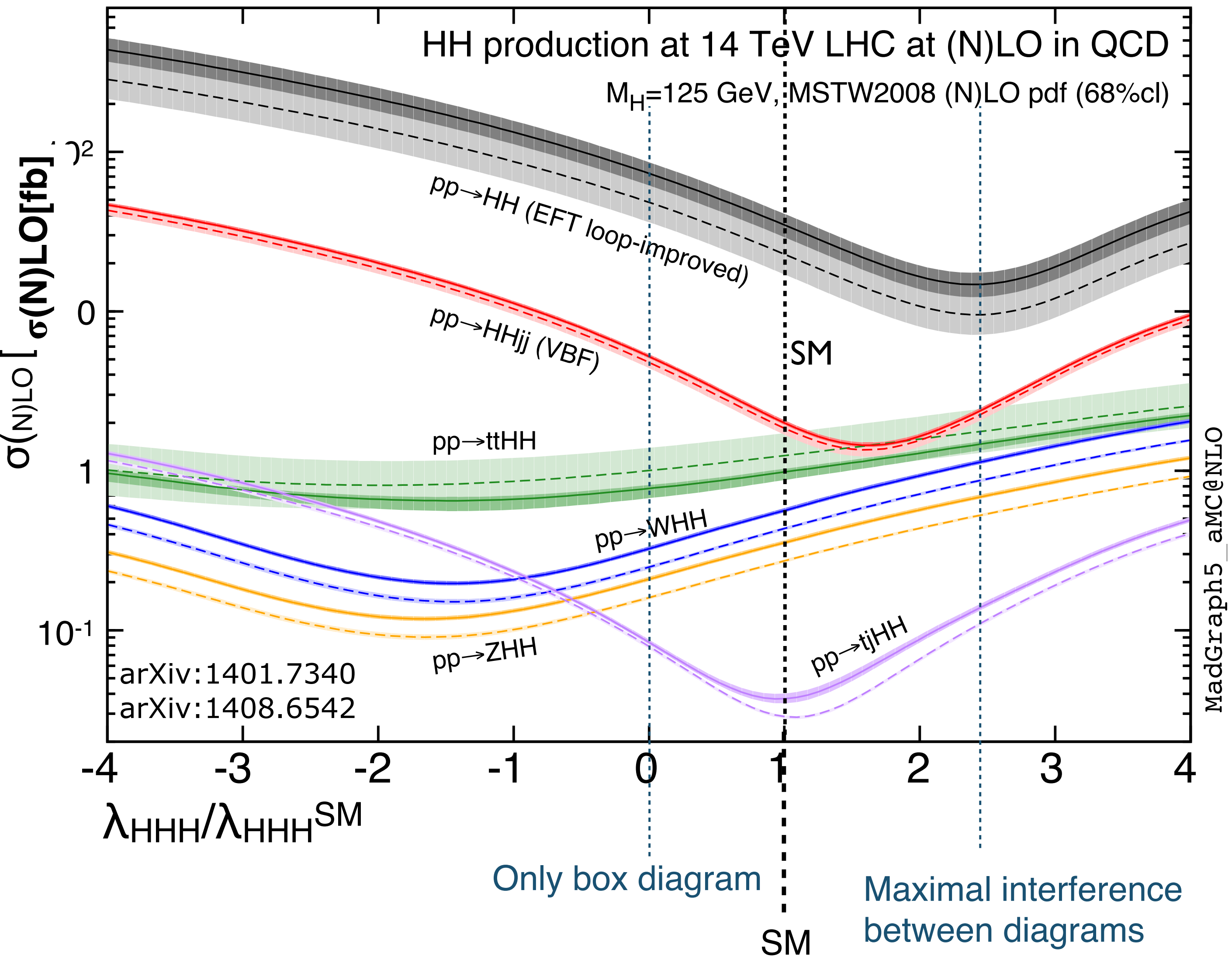


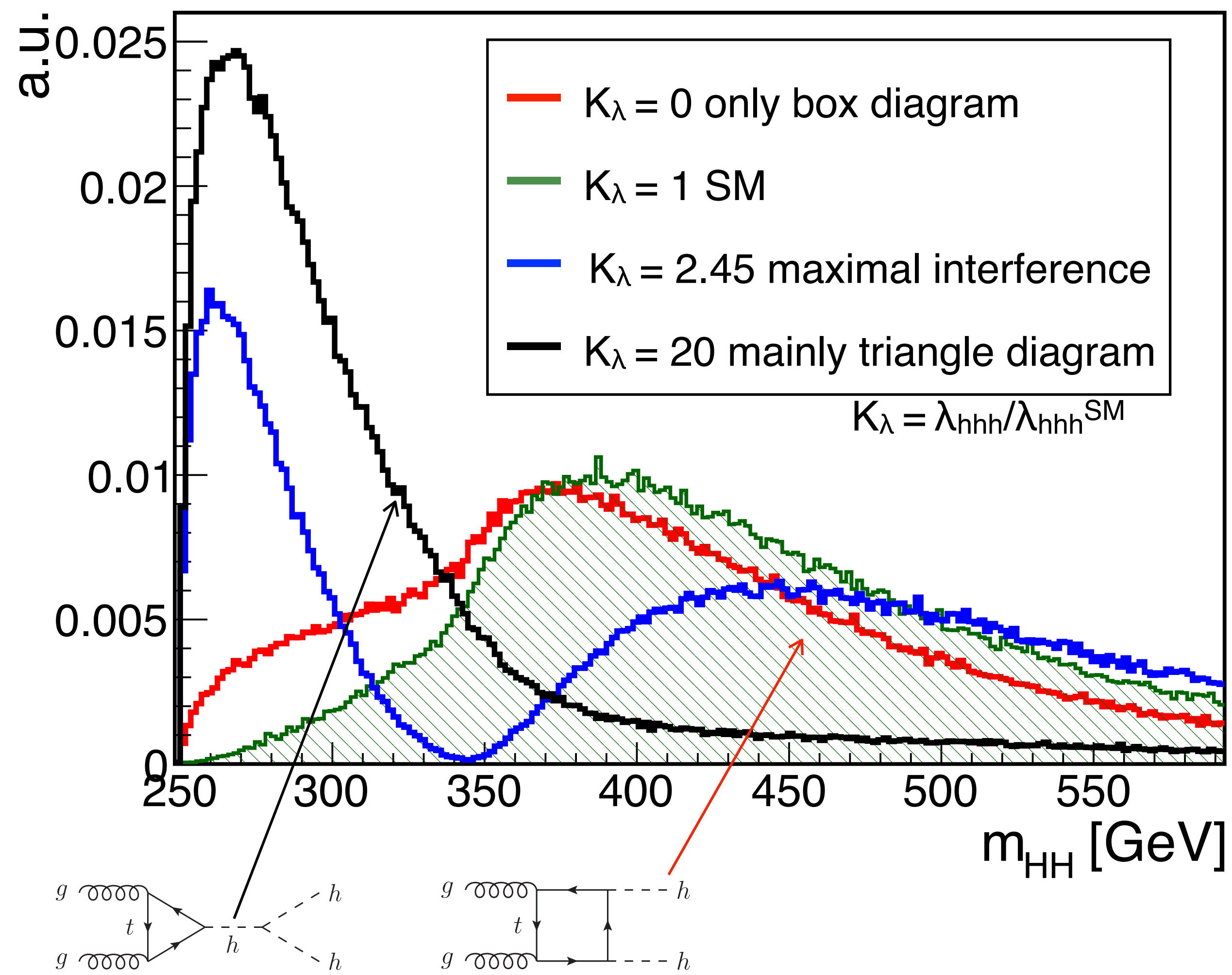
Higgs trilinear coupling



$\sigma^{SM}_{hh}(13TeV) = 33.45fb^{+4.3\%}_{-6.0\%}$(scale unc.) ±3.1%(PDF+$\alpha_S$ unc)

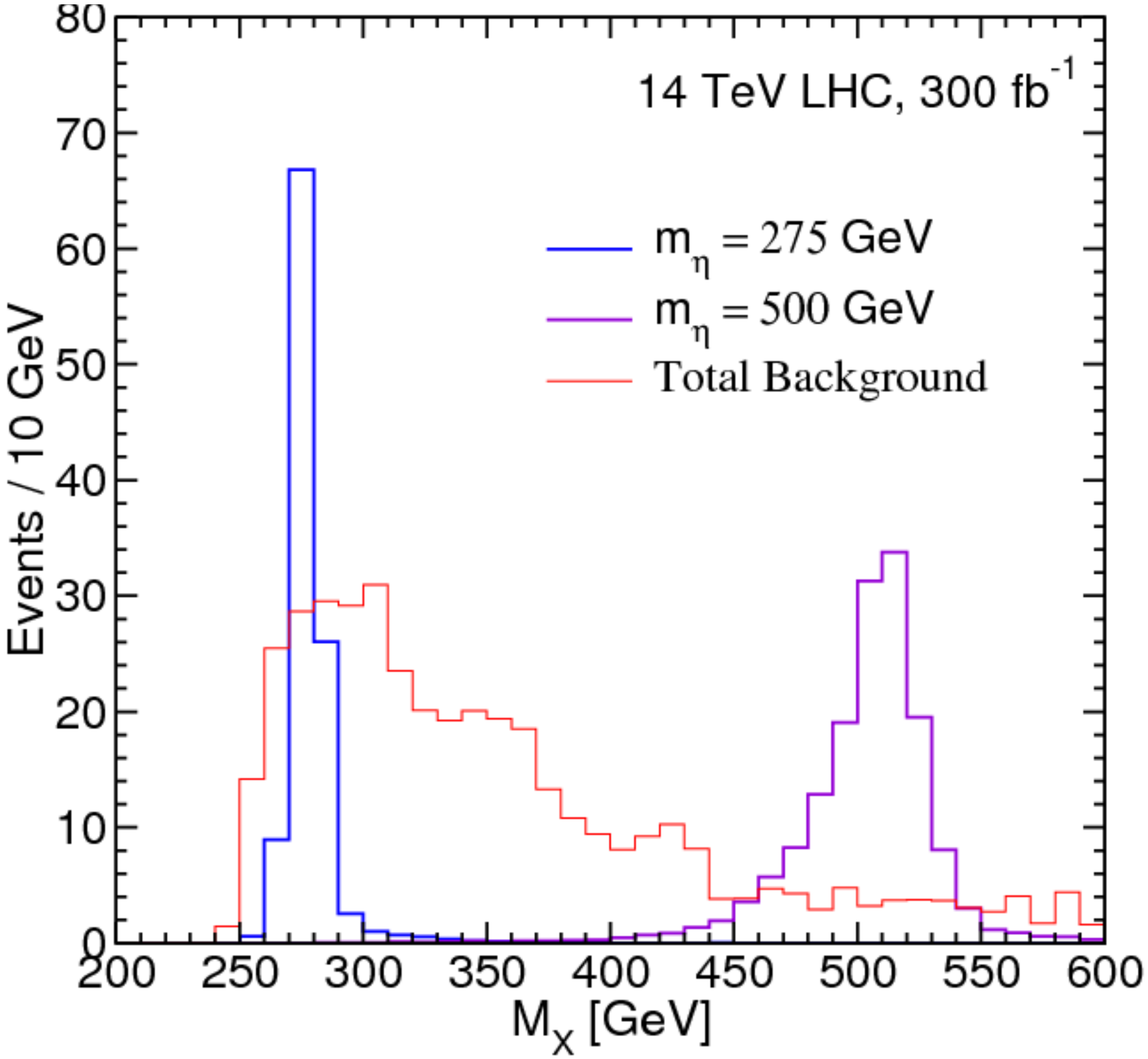
About 1/1000 smaller then single H production





The value of λ_{hhh} affects both the production cross-section and the hh kinematics

HH Studies: Resonant



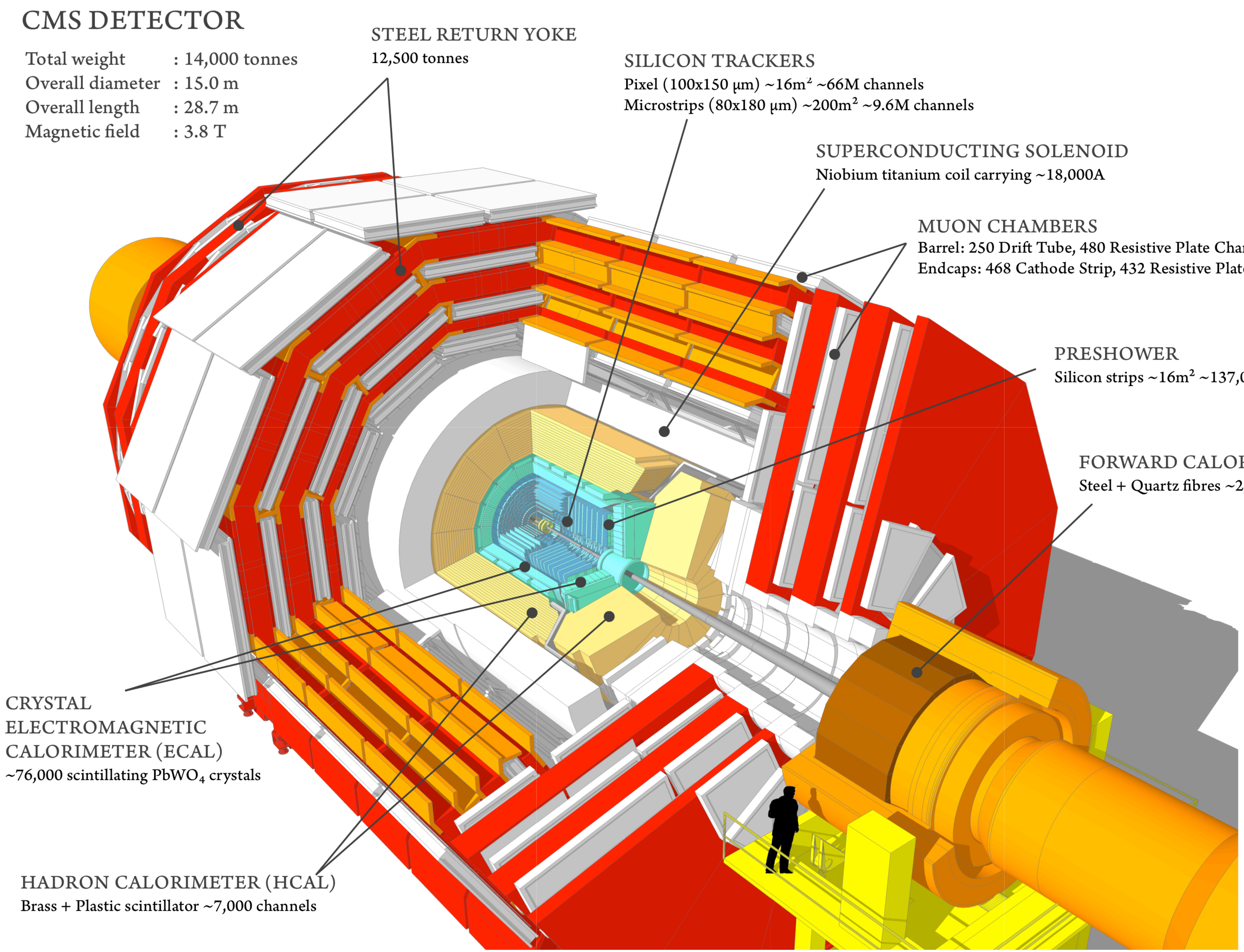
Non-resonant production is a SM process, but there are interesting things to probe in HH

In general, Higgs couples to massive particles. We can think of a particle with $M_X > 2M_H$ that inside the SM only couples with the Higgs

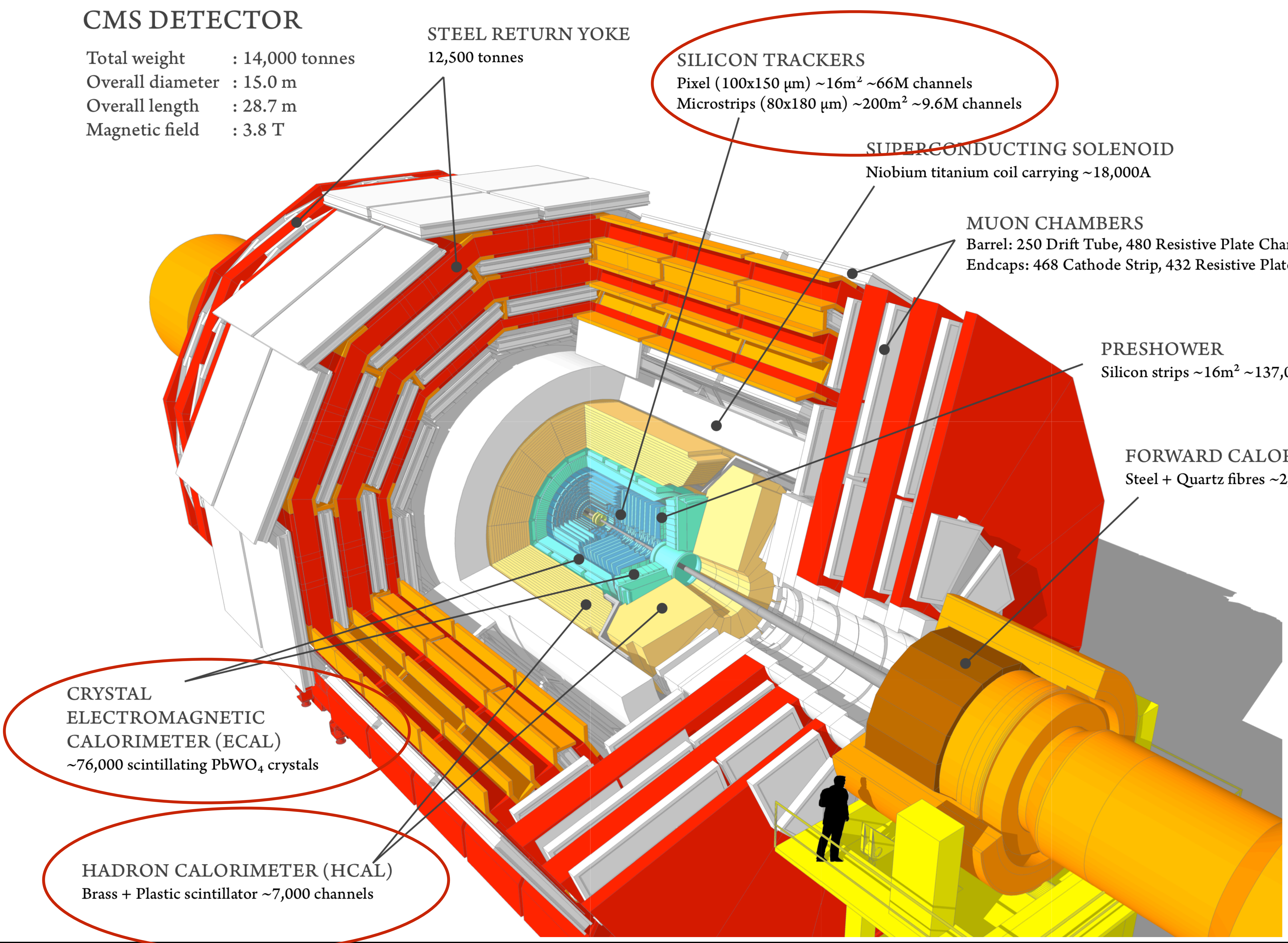
Such a particle would only be visible through its HH decay, and would appear as a resonance (peak) in the double Higgs invariant mass spectra

Several theoretical model available for such a particle (SUSY, extra dimesions…)

The CMS detector

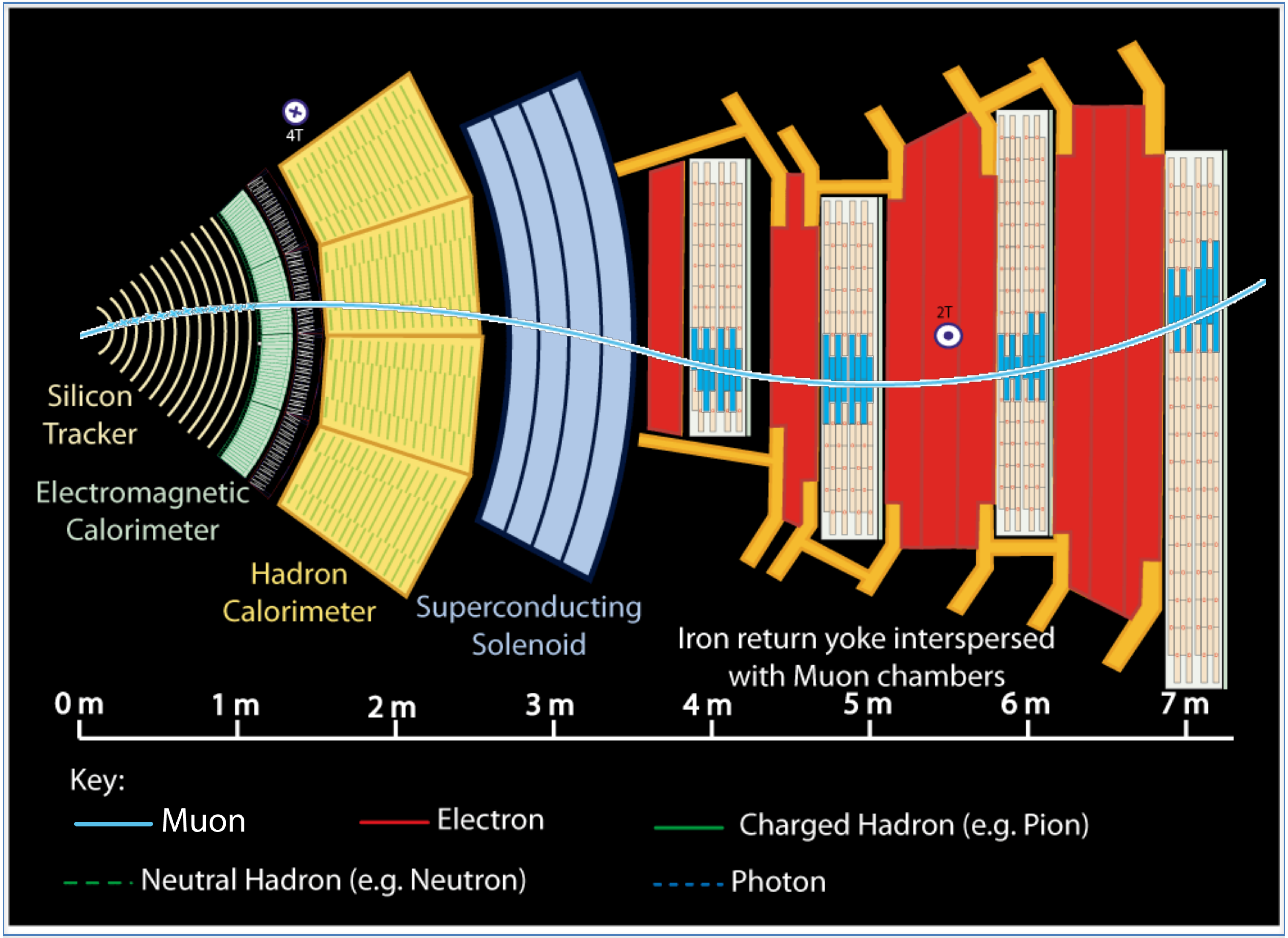


The CMS detector



How CMS detects particles

How CMS detects particles



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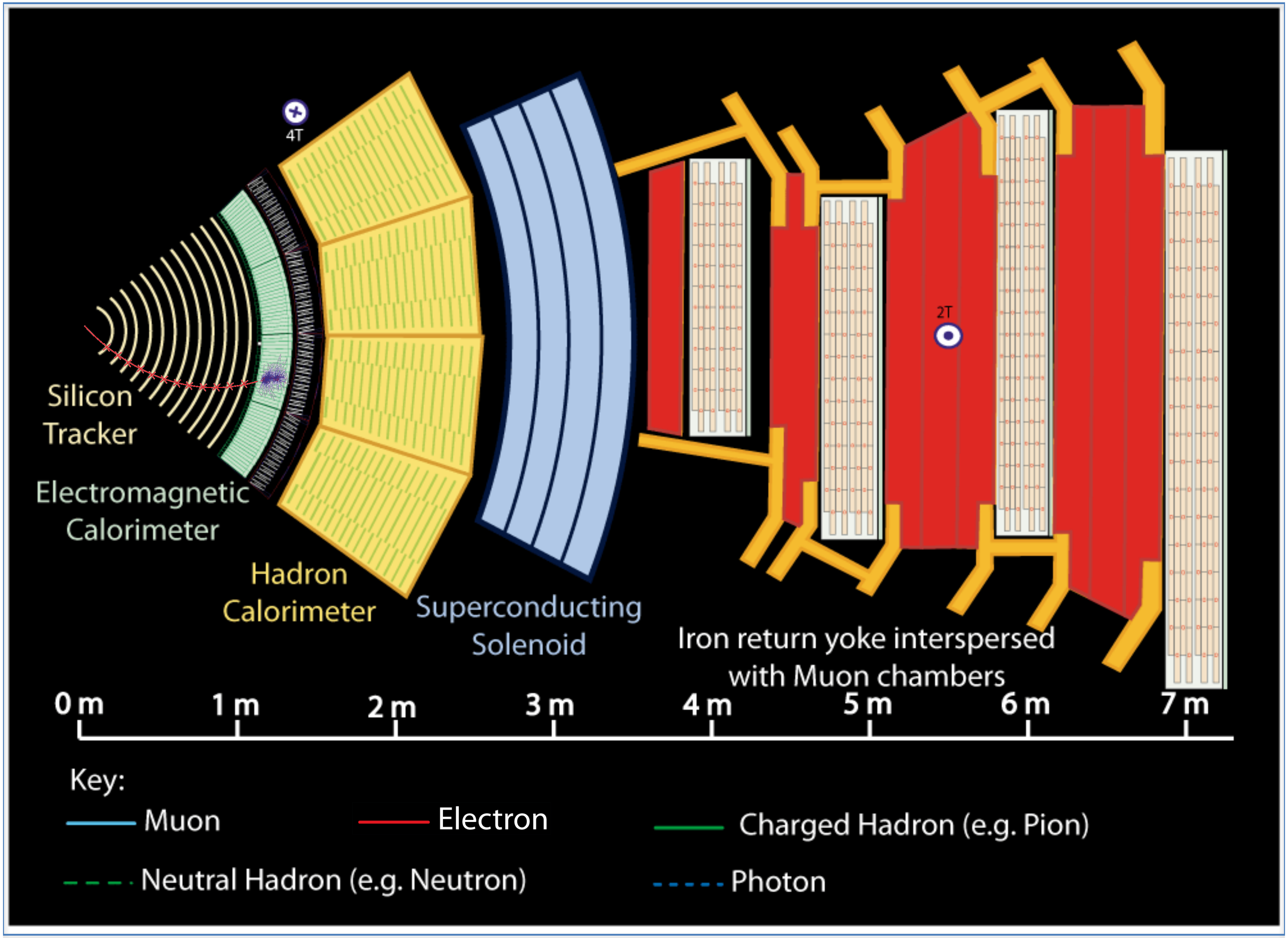
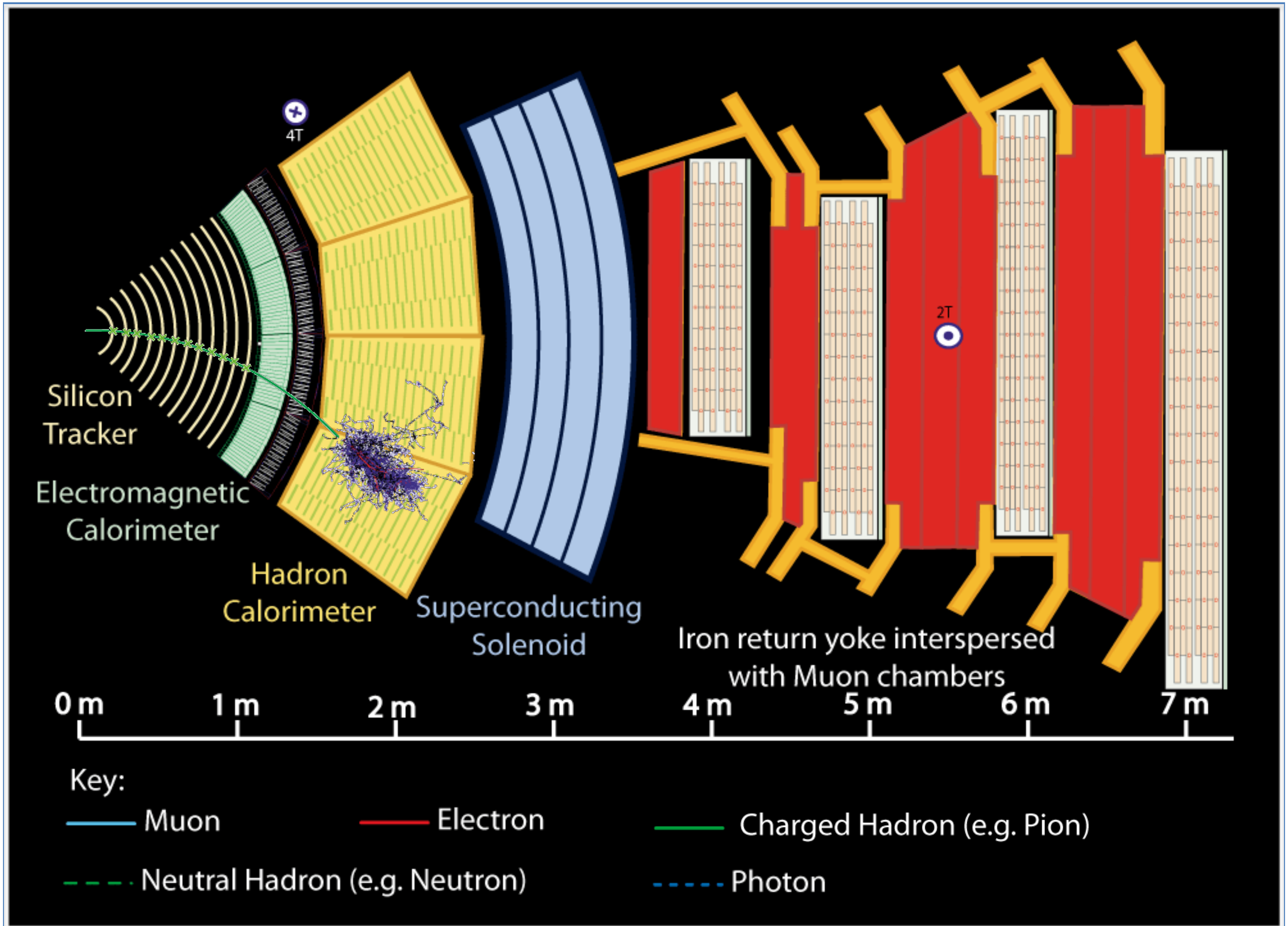
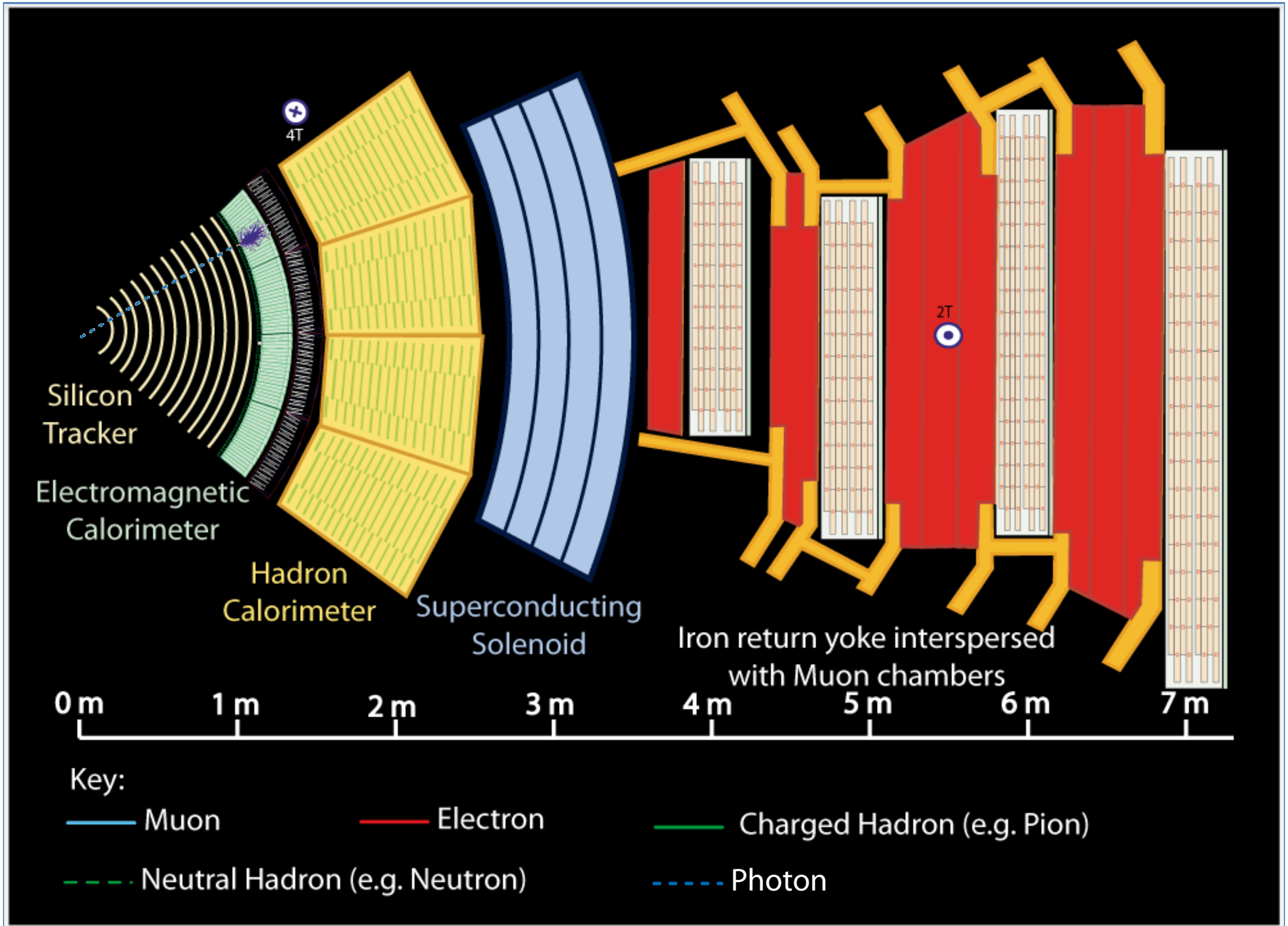


How CMS detects particles

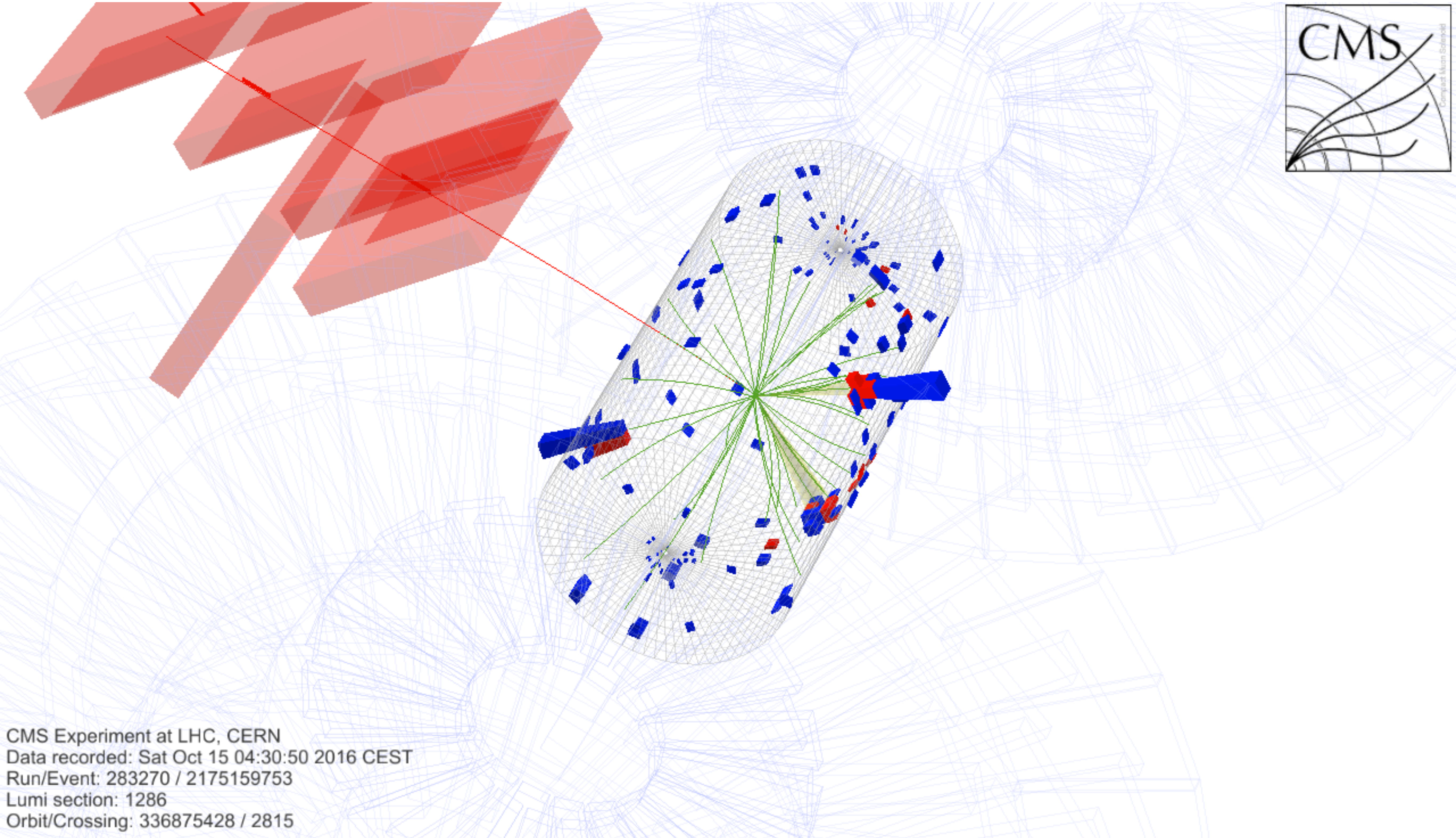


How CMS detects particles

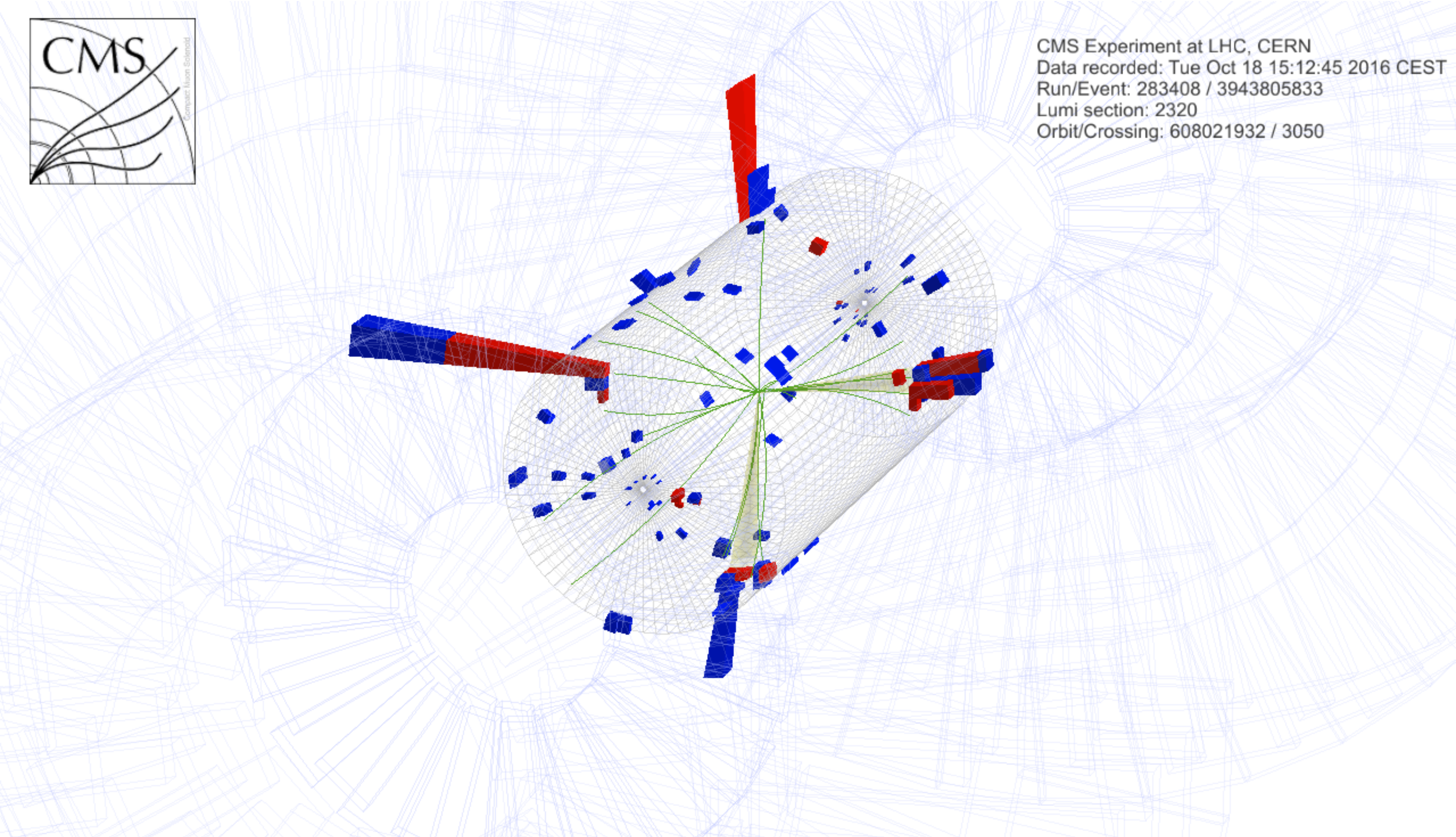


hh→bb$\tau\tau$ events

hh→bbττ events



hh→bbττ events



CMS searches

4 different searches performed in CMS presented today:

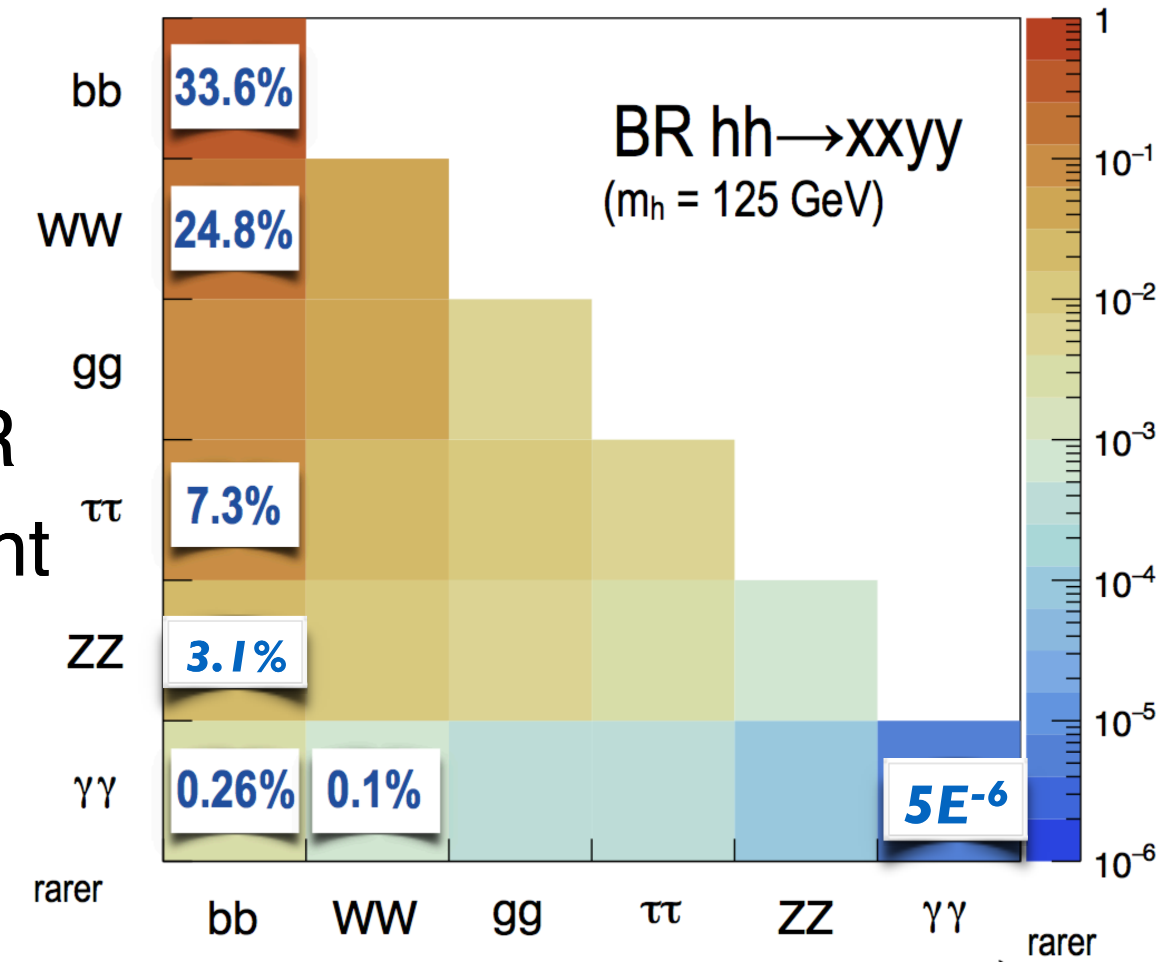
- bbbb, bbWW, bb$\tau\tau$, bb$\gamma\gamma$

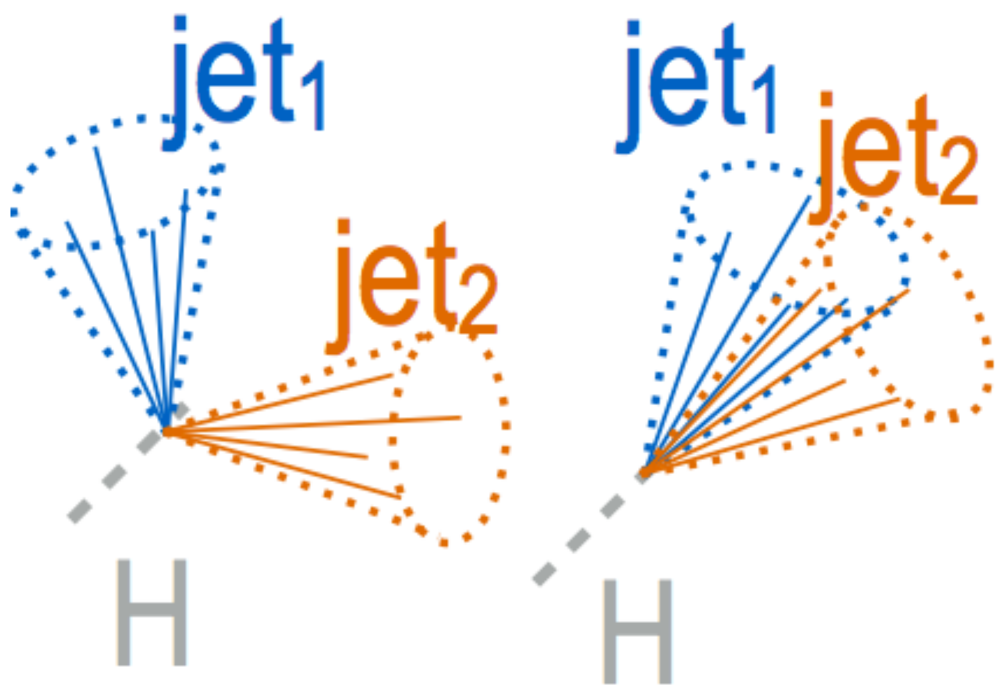
At least one h→bb to have large enough BR

Rare processes, low σ, complex environment

B-tagging algorithm to identify b-jets from jet constituents

At high m_H→boosted regime→merged jets





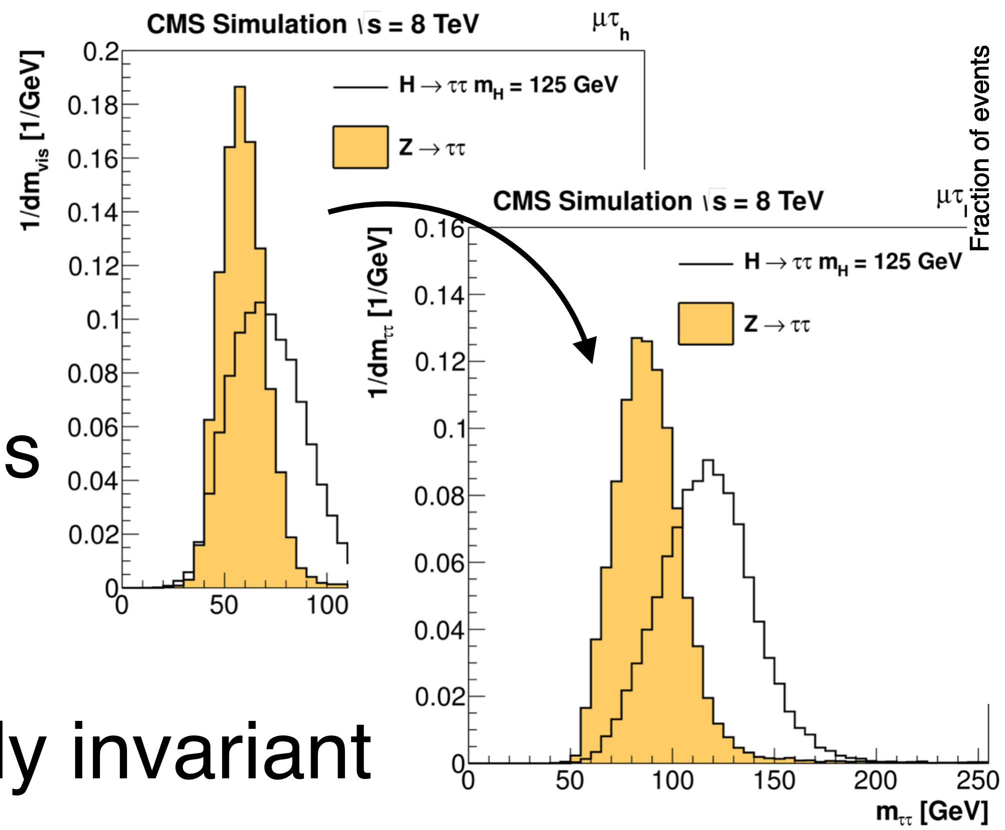
Trade-off between BR and contamination, complementarity among channels

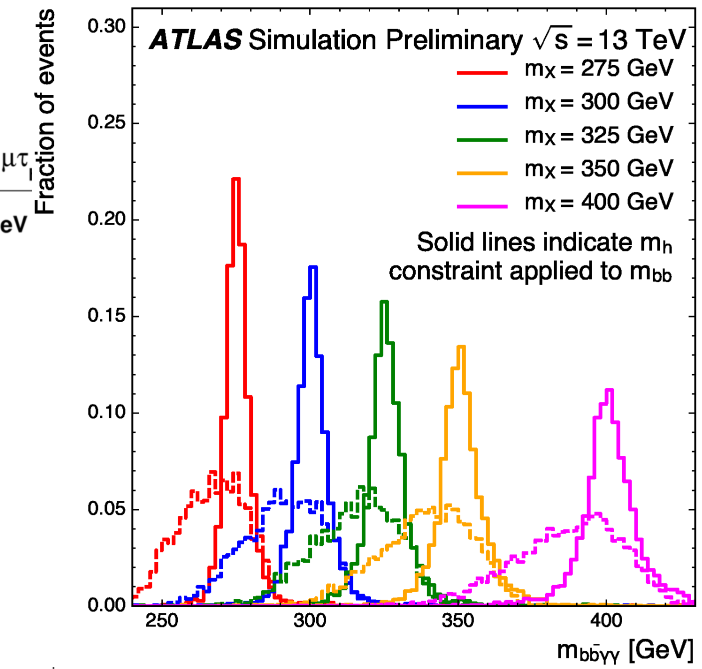
- bbbb: highest BR, high QCD/$t\bar{t}$ contamination
- bbWW: high BR, large irreducible $t\bar{t}$ background
- bb$\tau\tau$: relatively low background and BR
- bb$\gamma\gamma$: high purity, very low BR

Experimental challenges

Difficult event reconstruction

- Limited resolution on bjet invariant mass
  → regression / mH rescale
- Missing energy in $\tau\tau$ searches
  → likelihood methods



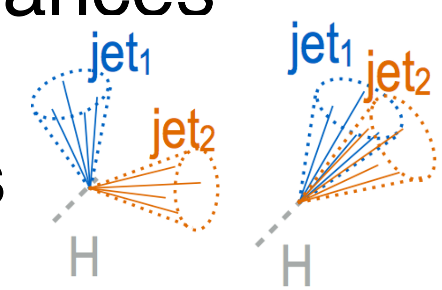


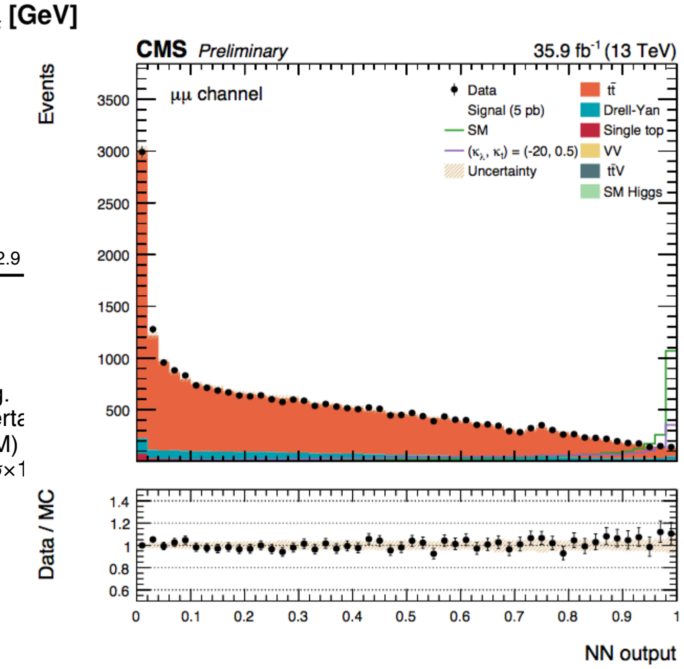
Looking for signal using 4-body invariant mass

- Improve resolution with kinematic fit

b-jets from high mass resonances overlap

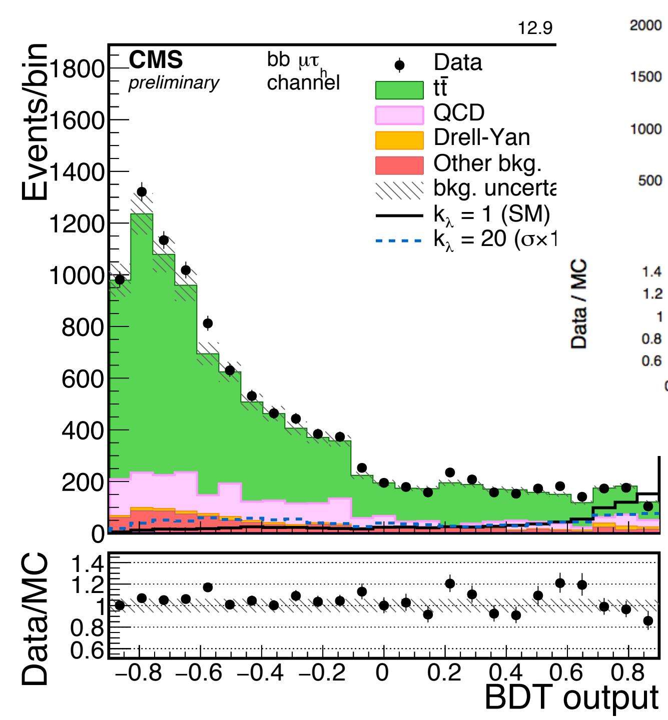
- jet substructure techniques



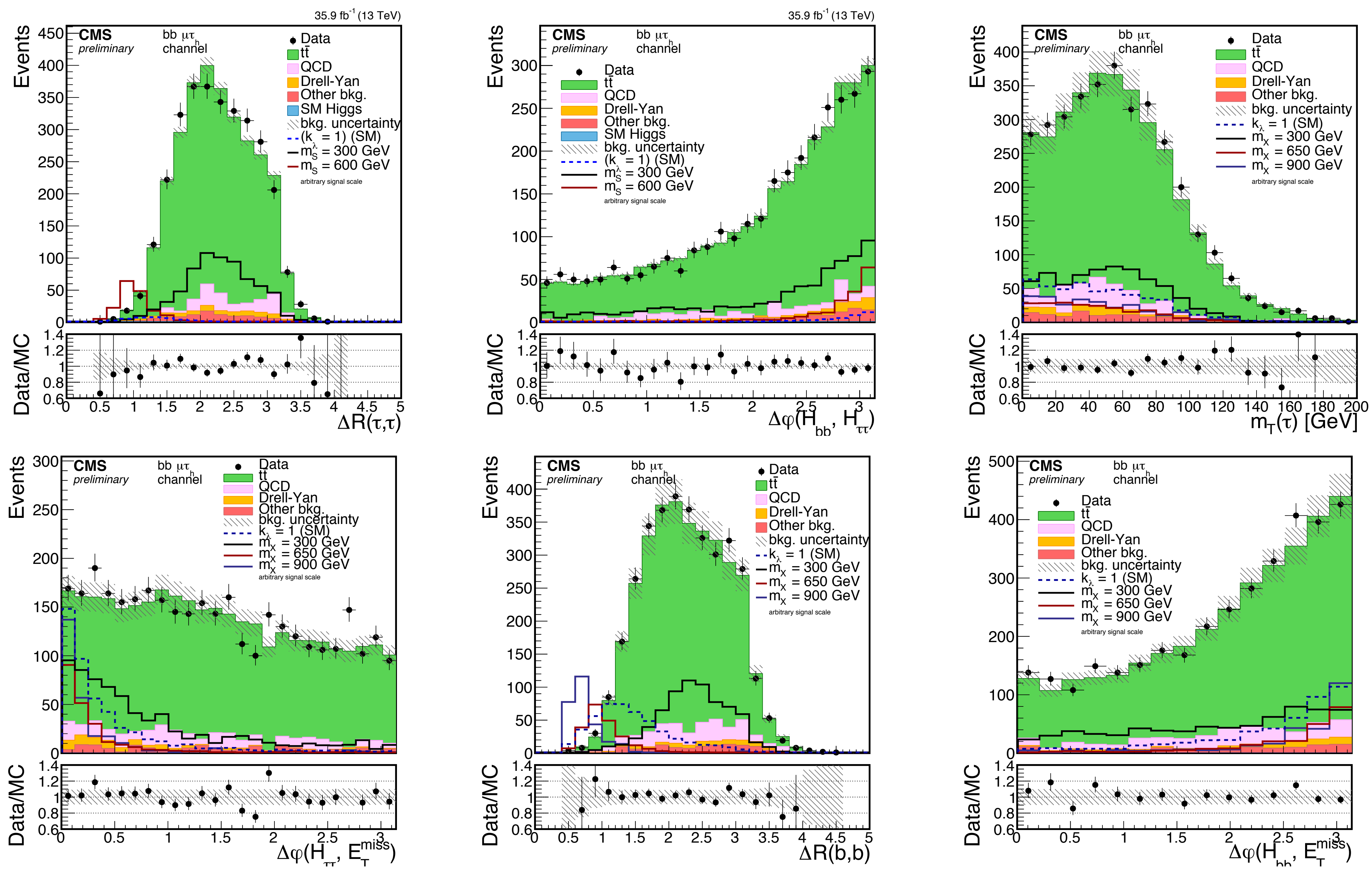


Small signals with large backgrounds

- MVA methods to separate from overwhelming backgrounds

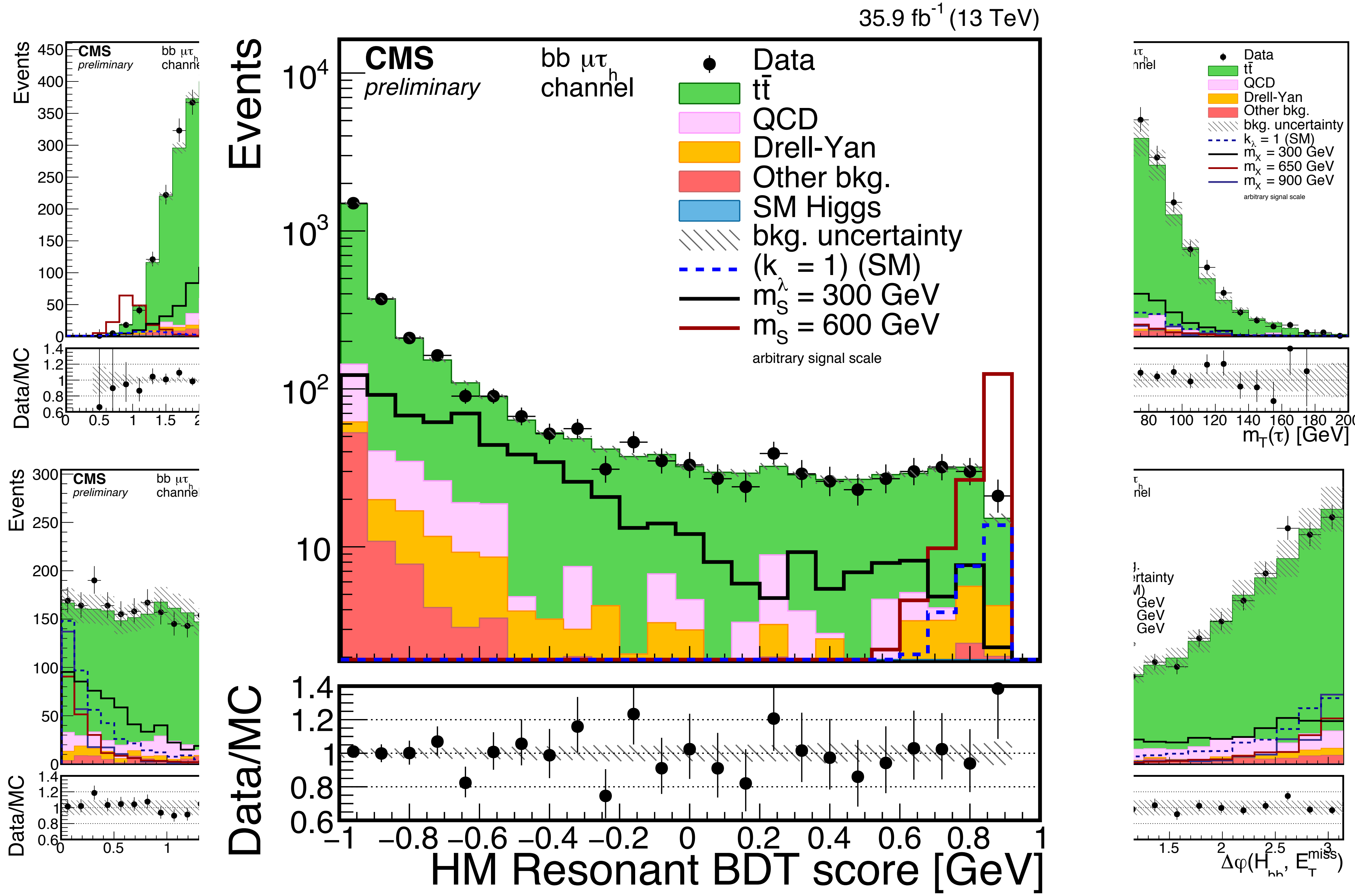


hh→bbττ: BDT and categorization



Goal: use information from the event to separate signal from background
Build a list of variables for which background and signal have different distribution, and compute a probability for each event

hh→bbττ: BDT and categorization



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hh→bbττ

Intermediate BR, fully reconstructed final state

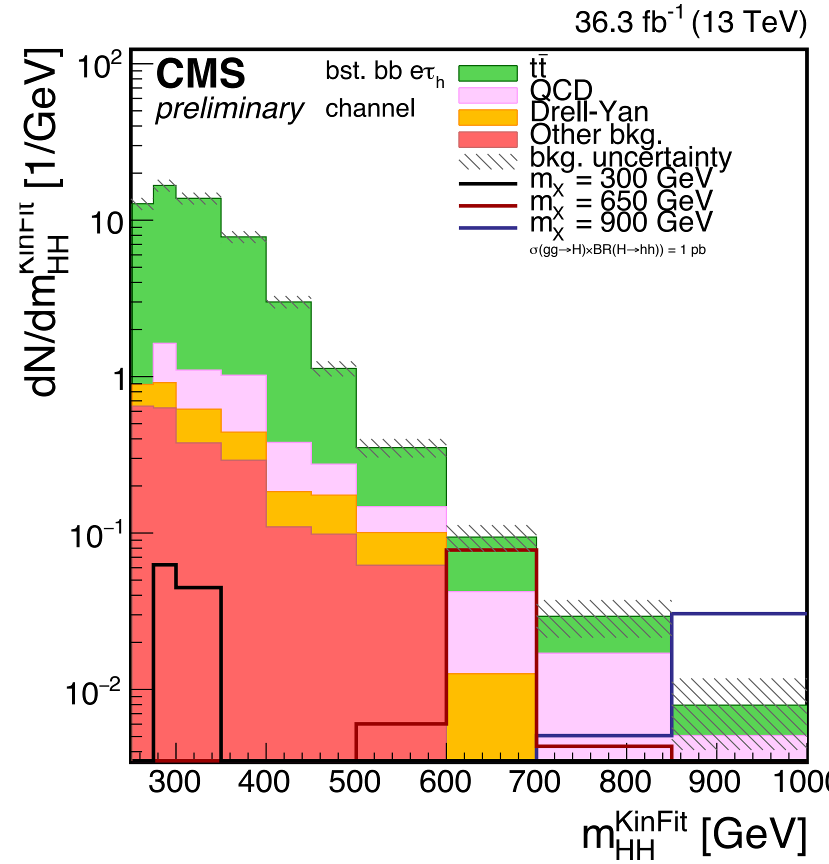
1τ_H+1 isolated leptons (e, μ, τ_H)+2 bjets final state

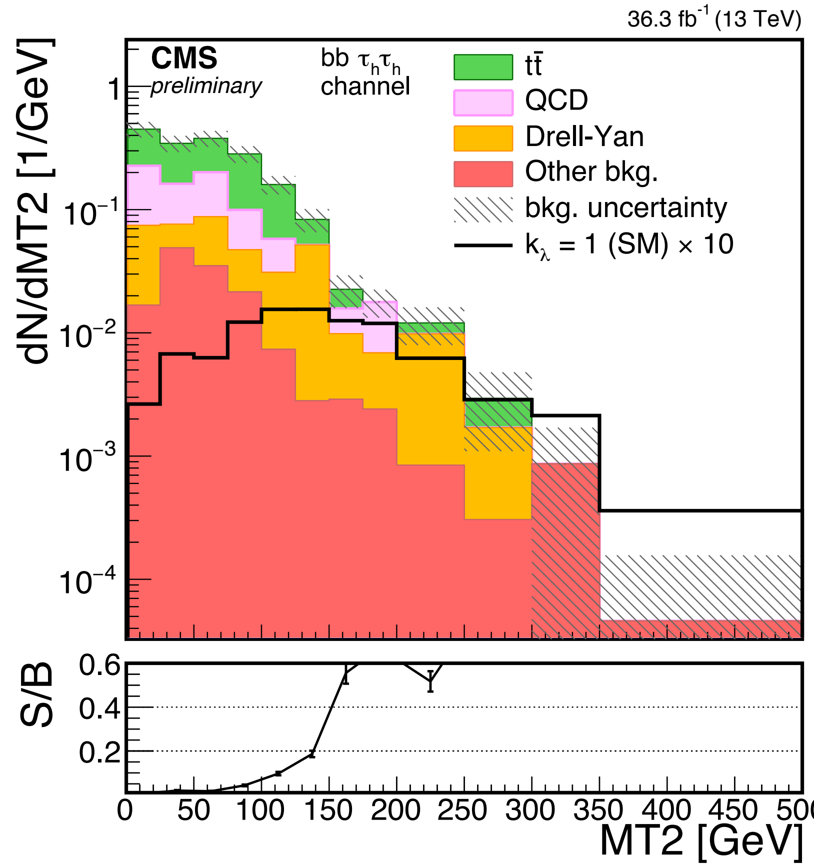
3 final states: eτ_H, $\mu\tau_H$, $\tau_H\tau_H$

Main backgrounds: $t\bar{t}$ (from MC), QCD multijet (from data in control regions)

BDT to separate signal and background events

3 categories: 1bjet, 2bjet, boosted b-jets category





Resonant search:

- Limit extraction on kinematic fit of the 4-body invariant mass;

Non-resonant analysis:

- stransverse mass as final variable

$$m_{T2} \equiv \min_{p_{T1}+p_{T2}=p_T^{\tau\tau}} \left\{ \max\left[m_T\left(m_{b1}, p_T^{b1}, m_{vis}^{\tau1}, p_{T1}\right), m_T\left(m_{b2}, p_T^{b2}, m_{vis}^{\tau2}, p_{T2}\right) \right] \right\}$$

hh→bbττ

Intermediate BR, fully reconstructed final state

$1\tau_H$+1 isolated leptons (e, μ, τ_H)+2 bjets final state

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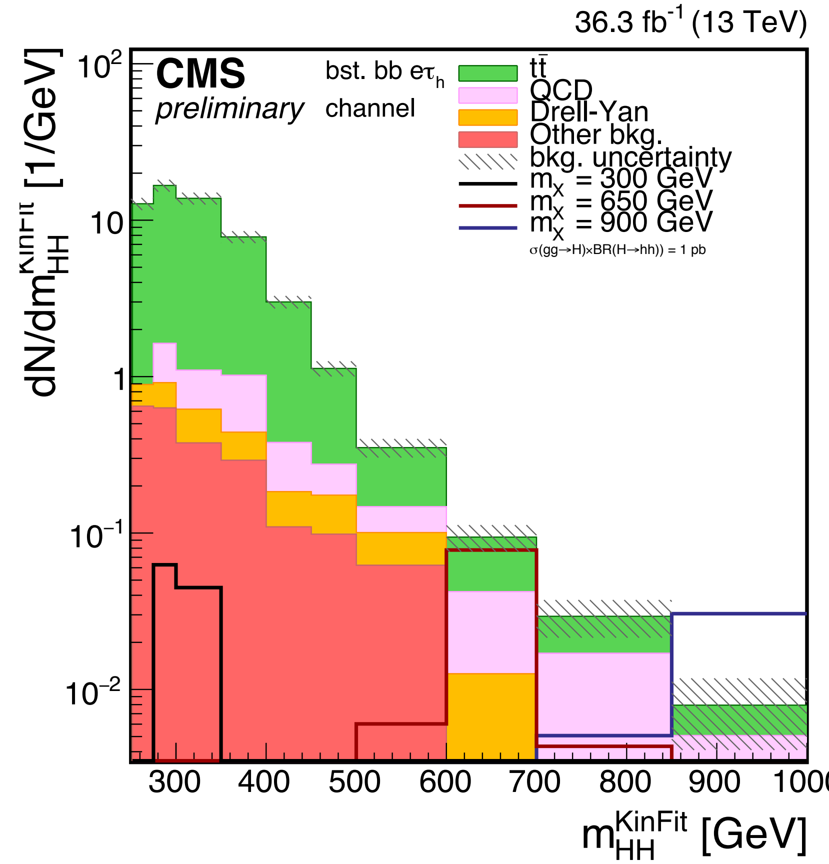

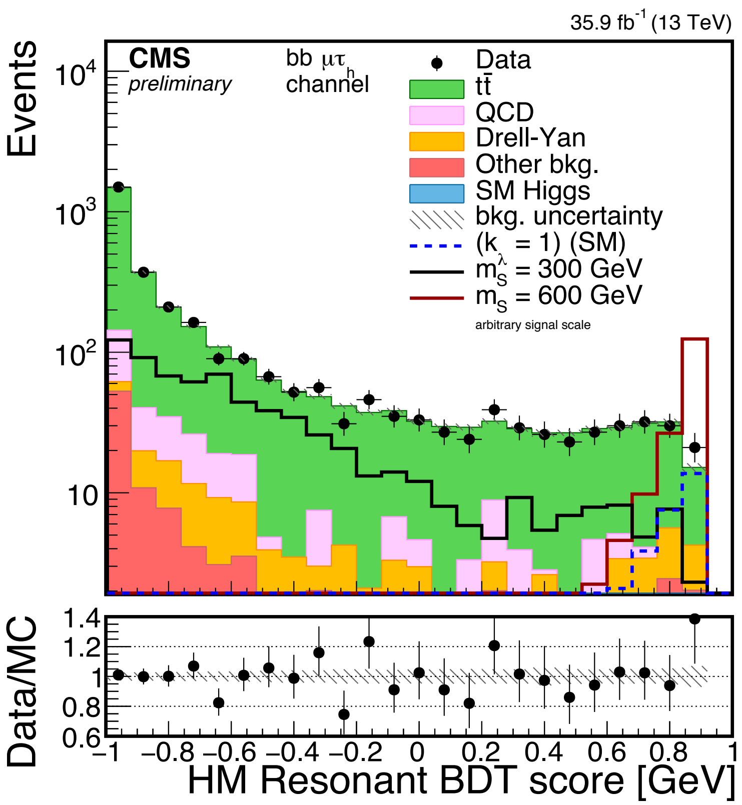

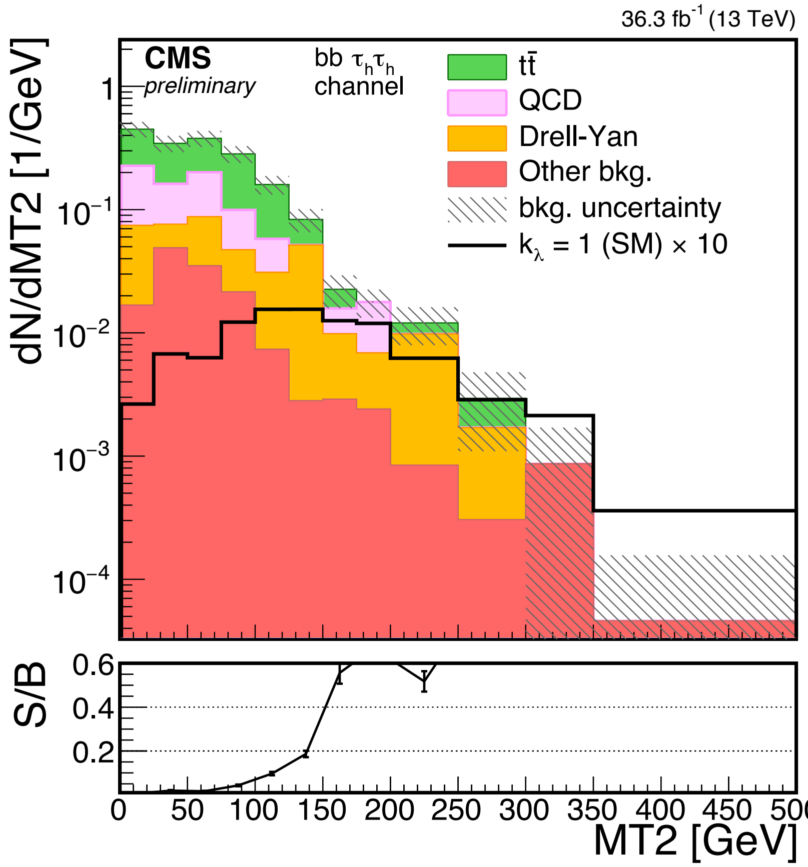

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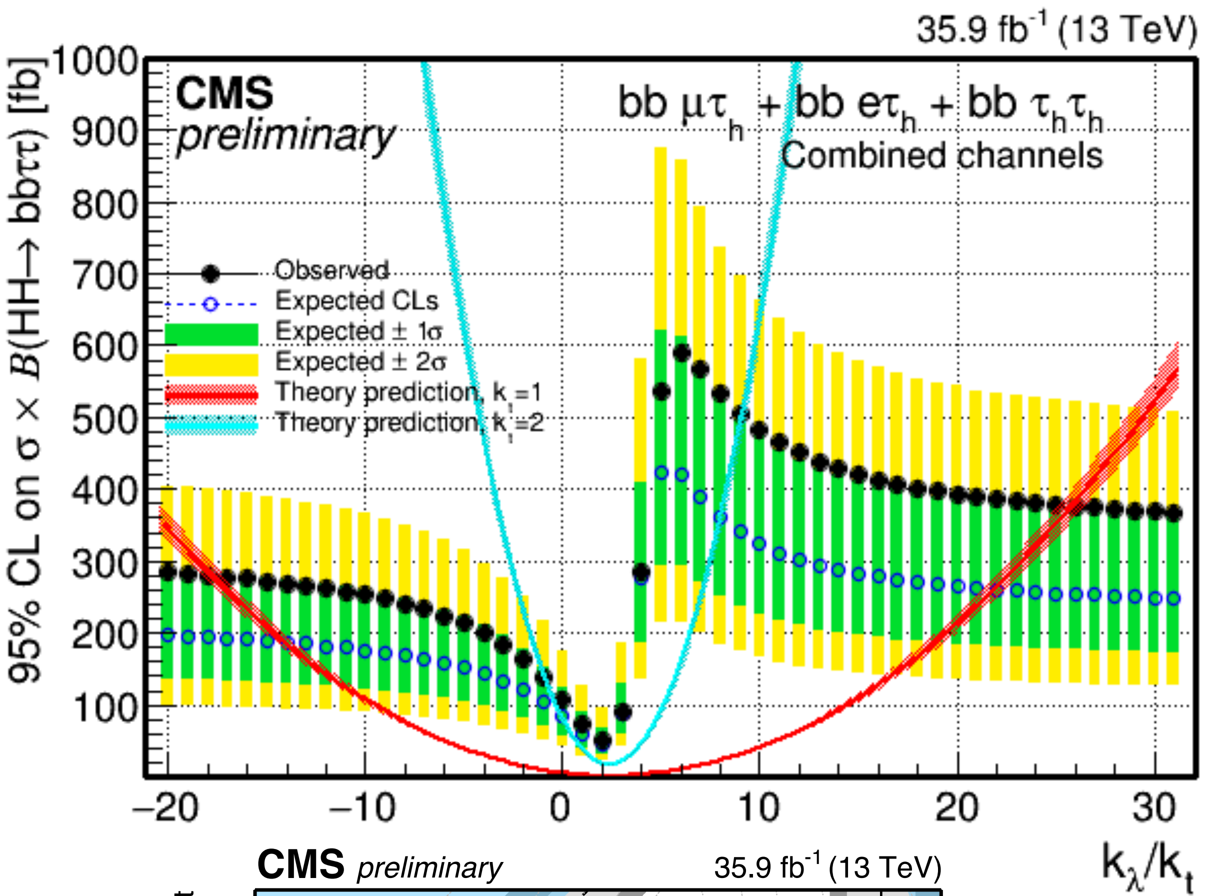
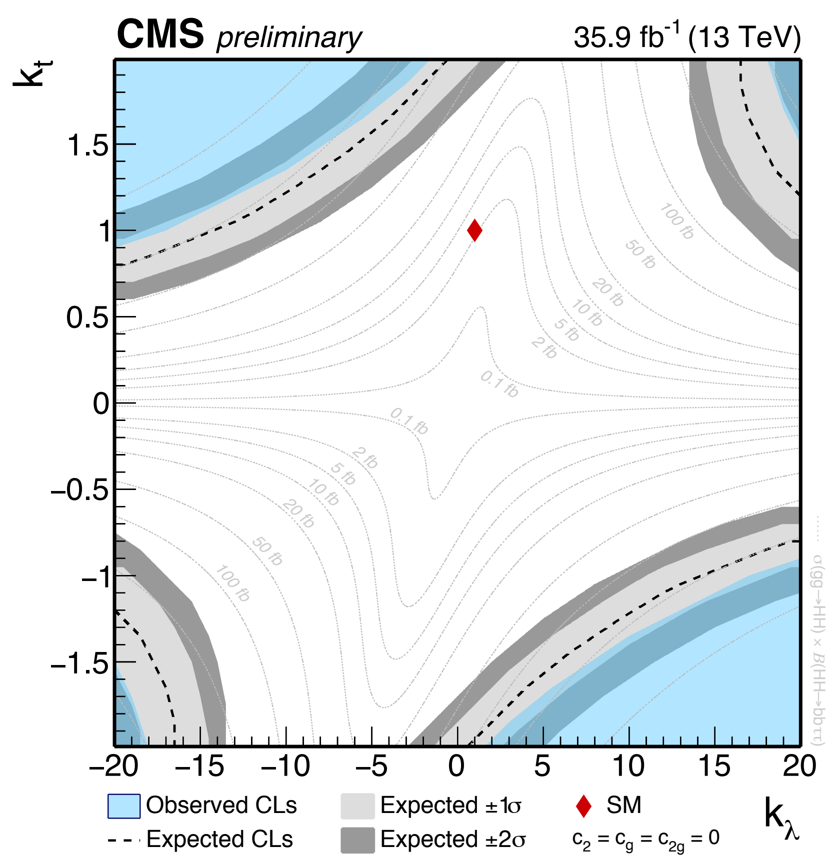
hh→bbττ: results

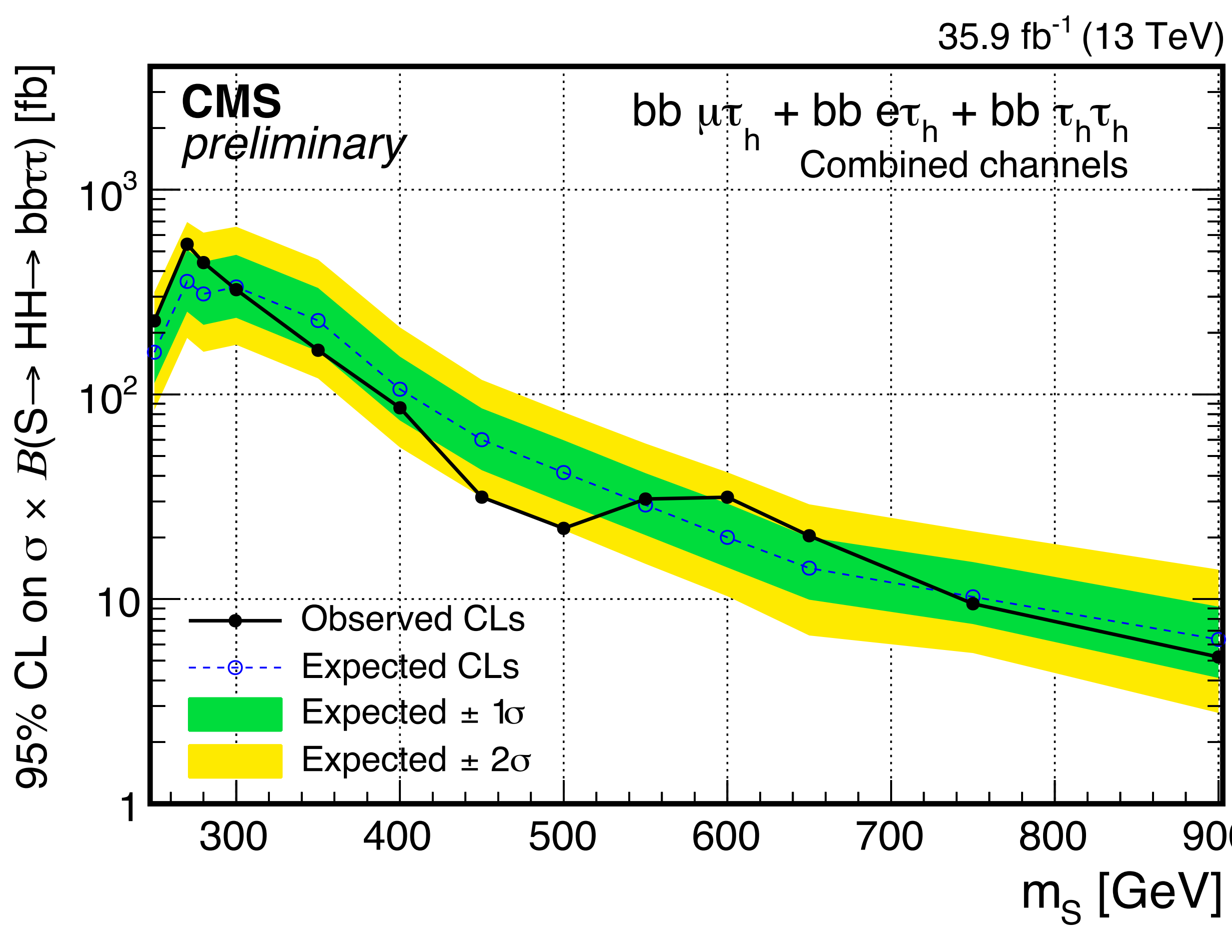




Final limit on resonant production is ~25 times the Standard Model

Sensitive to the sign of k_t

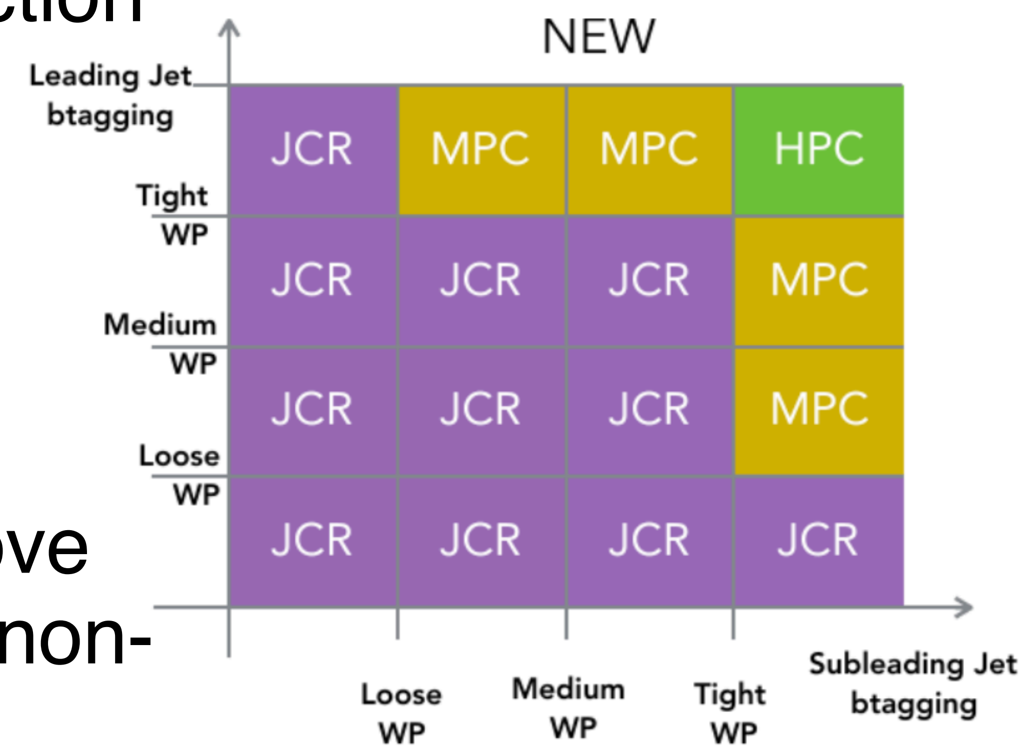
No peak visible in resonant production

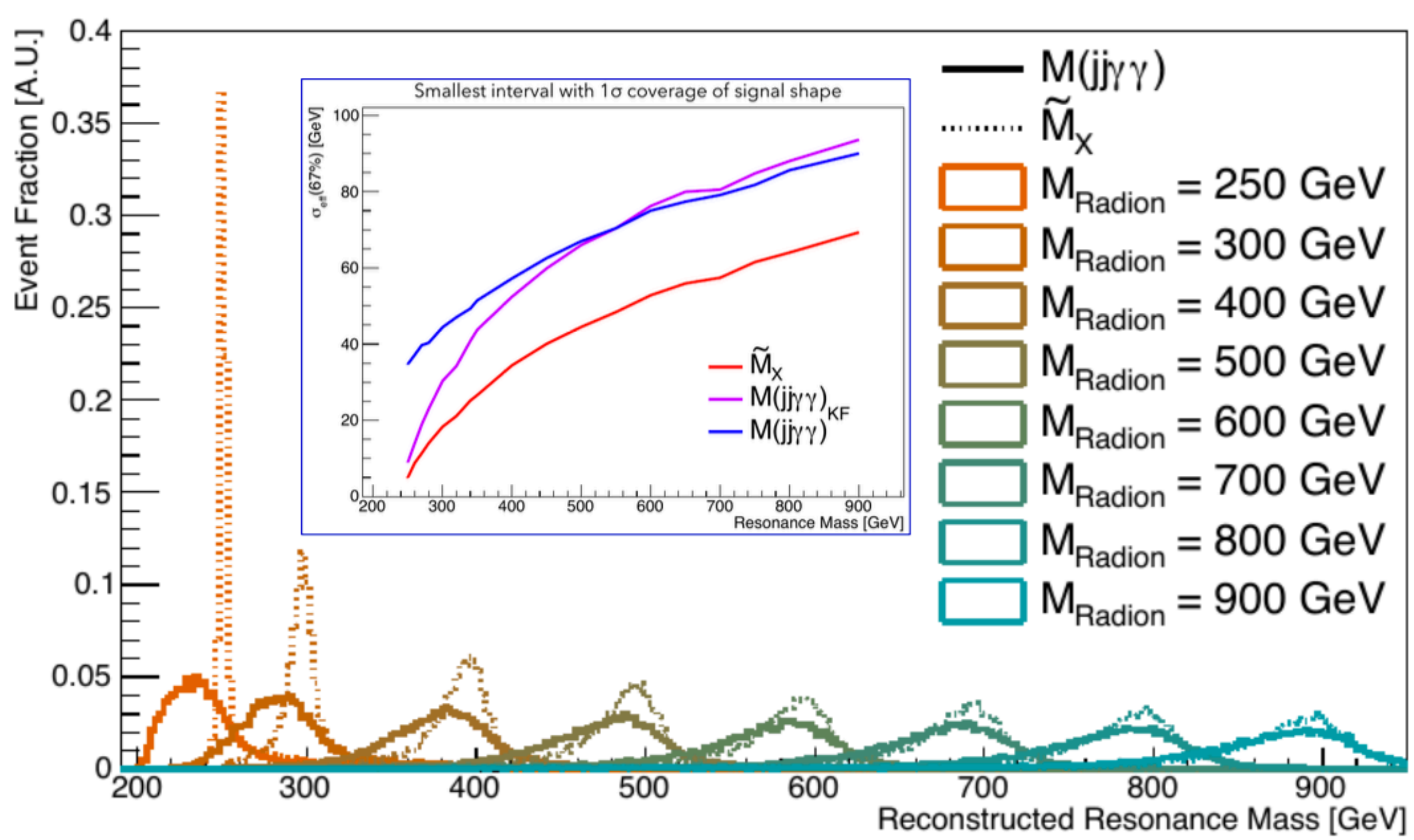


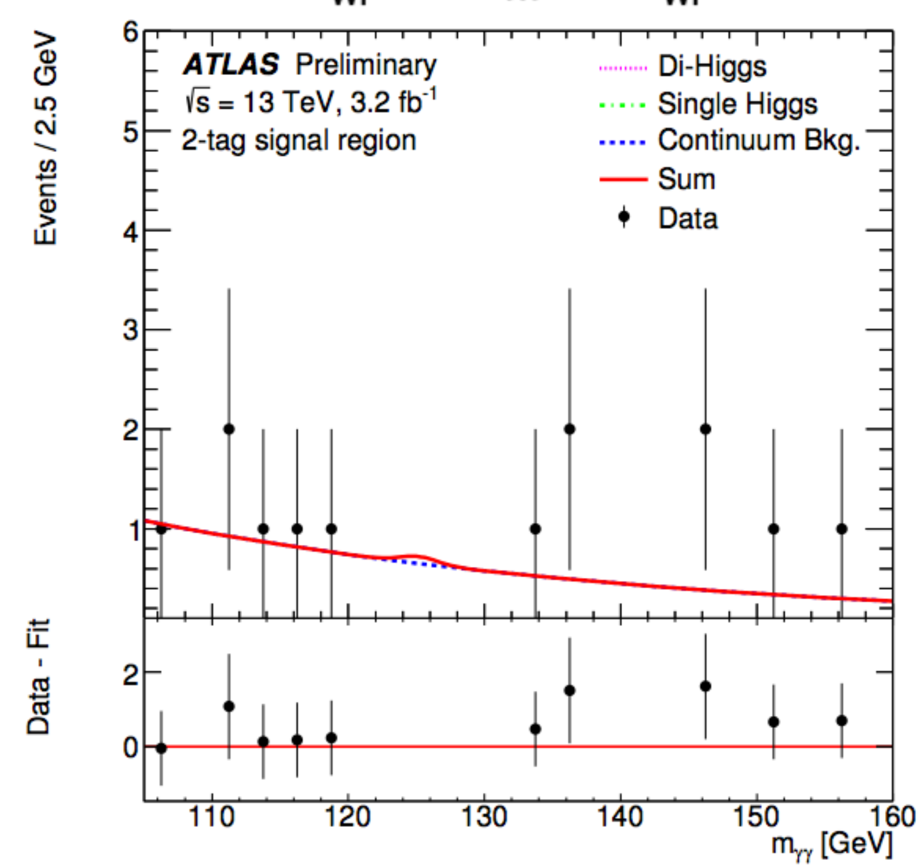
hh→bbγγ

Most sensitive channel for non-resonant production

- Di-photon trigger + 2 b-jets in the event
- MVA to select events, as in SM H→γγ
- 2 b-tag categories (low/high purity)
- Background from fit to the data
- 2D fit on the reconstructed H_1,H_2 masses
- Effective mass $M_X = M_{jj\gamma\gamma} - M_{jj} + 125$ GeV to remove background (resonant) or categorise events (non-resonant)

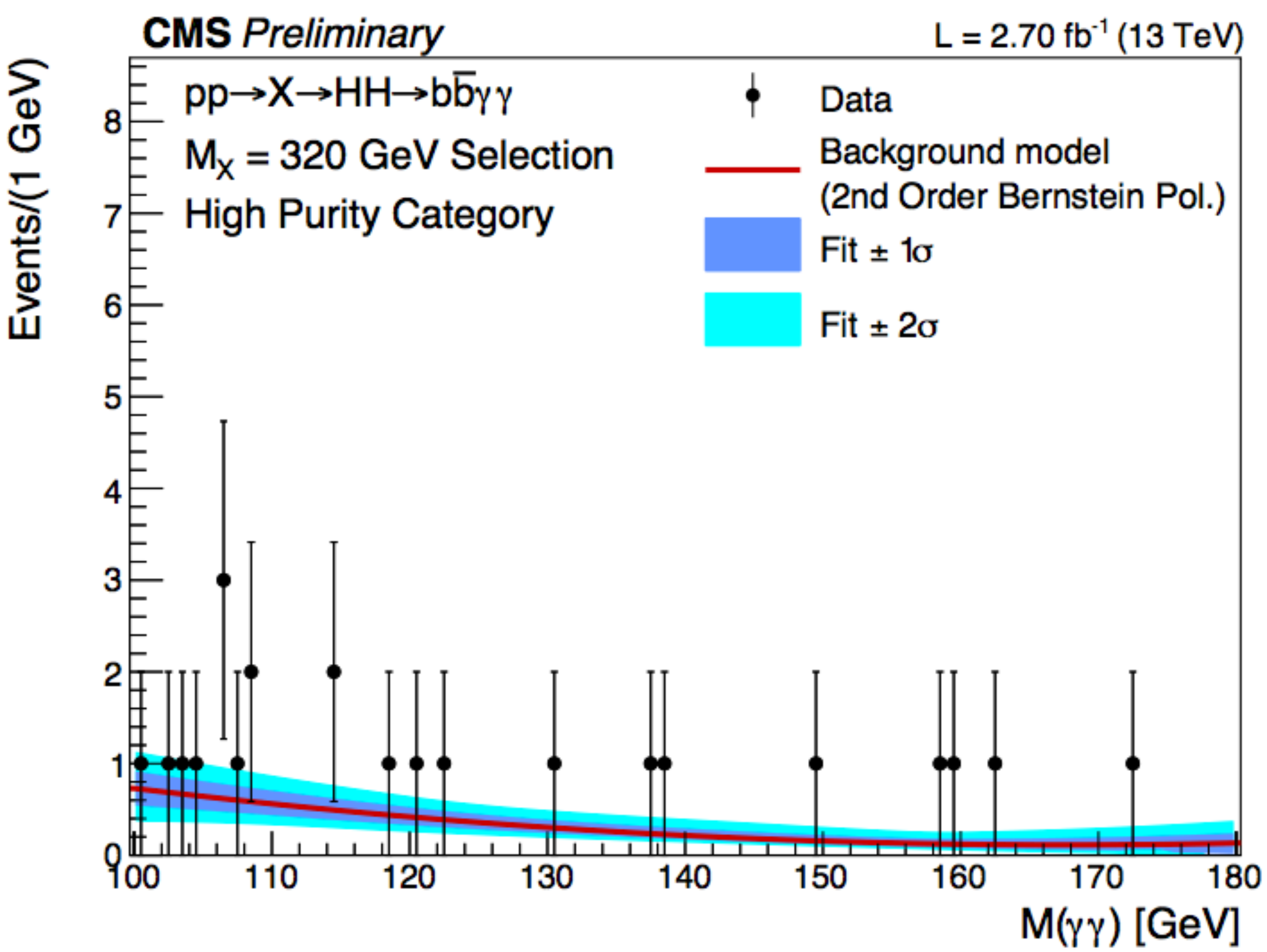


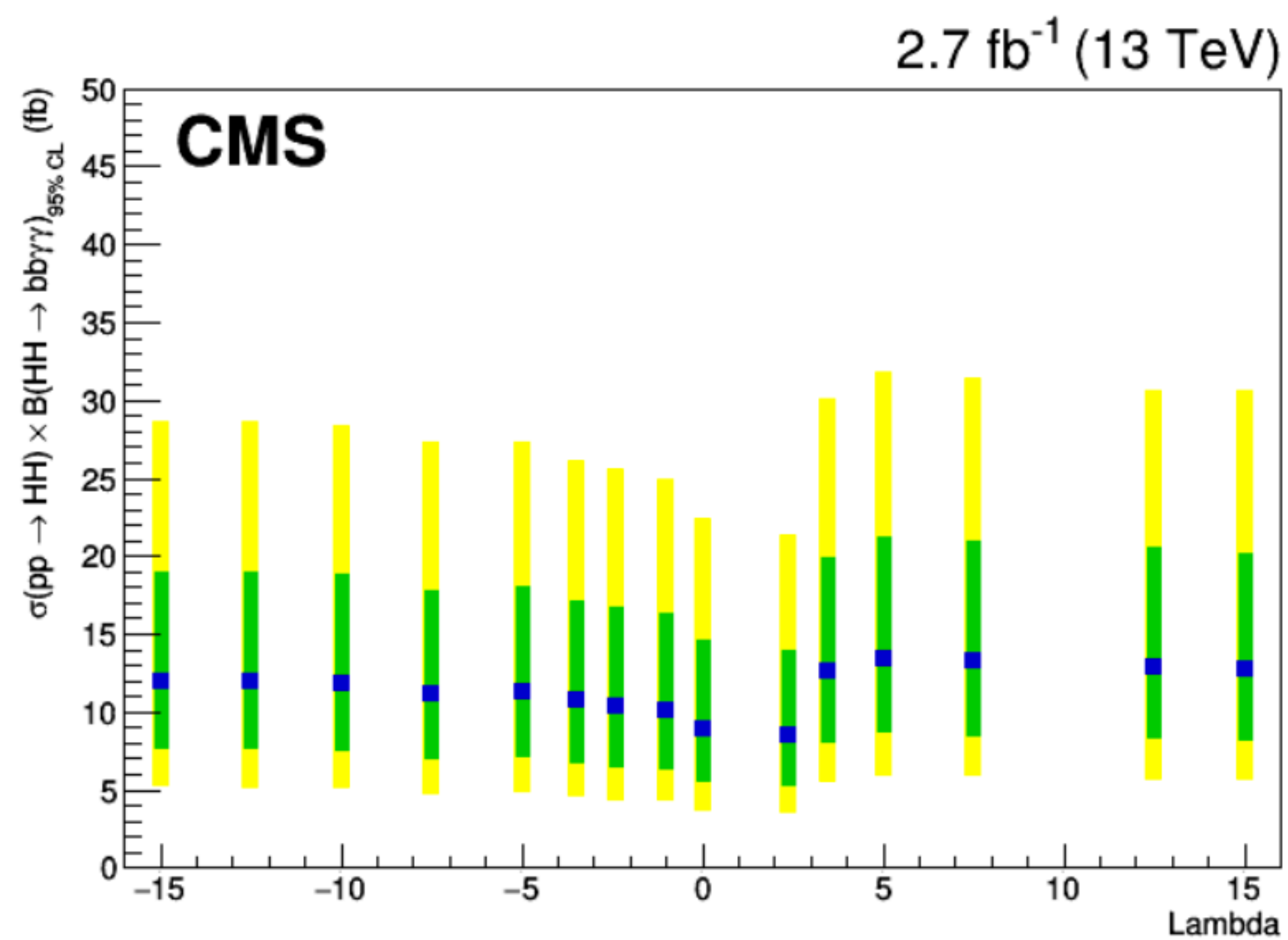




hh→bbγγ results

With 2015 (limited) statistics of 2.7fb^{-1}: sensitivity at the level of 91xSM
Like all HH analyses, this is statistics dominated
The precision of the background estimation is limited as well by the statistics
2016 data is ~36fb^{-1}, the sensitivity is ~15-20xSM level (not public yet)





HH→bbWW

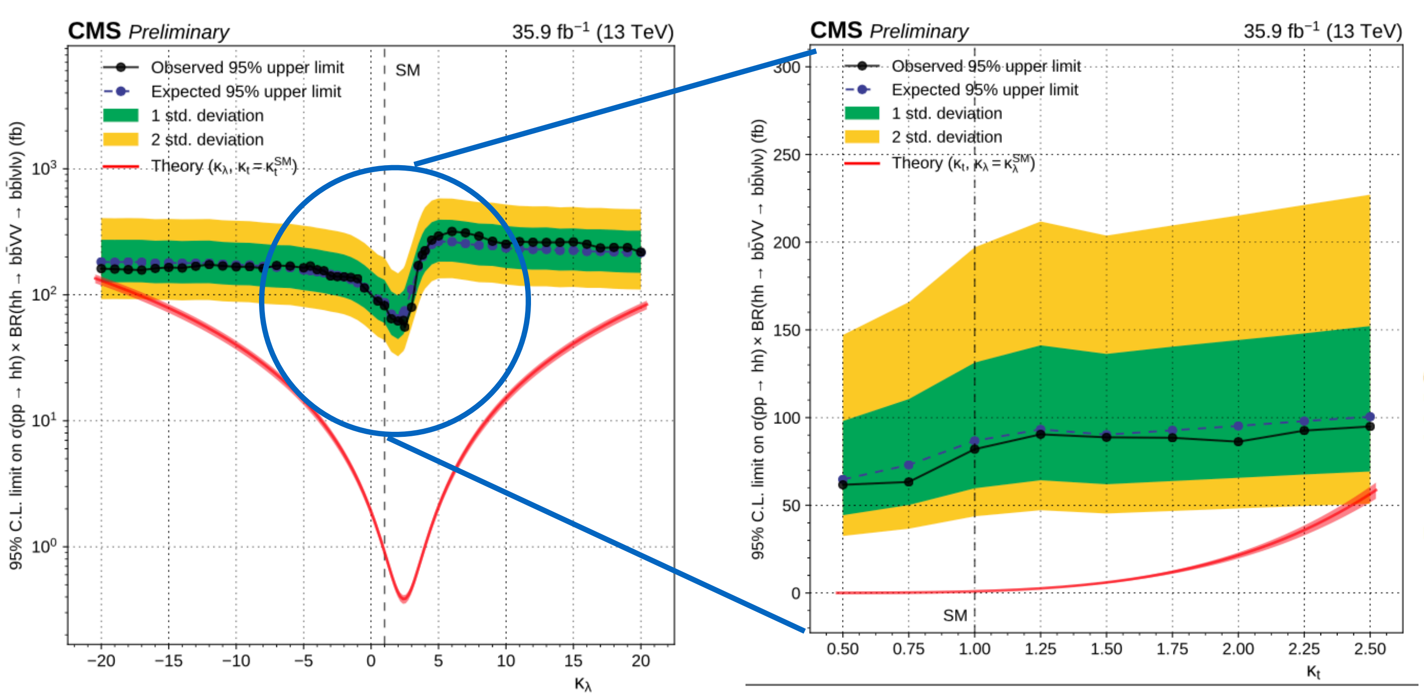
Search for hh→bbWW→bb2l2v, BR~2%, huge irreducible tt background

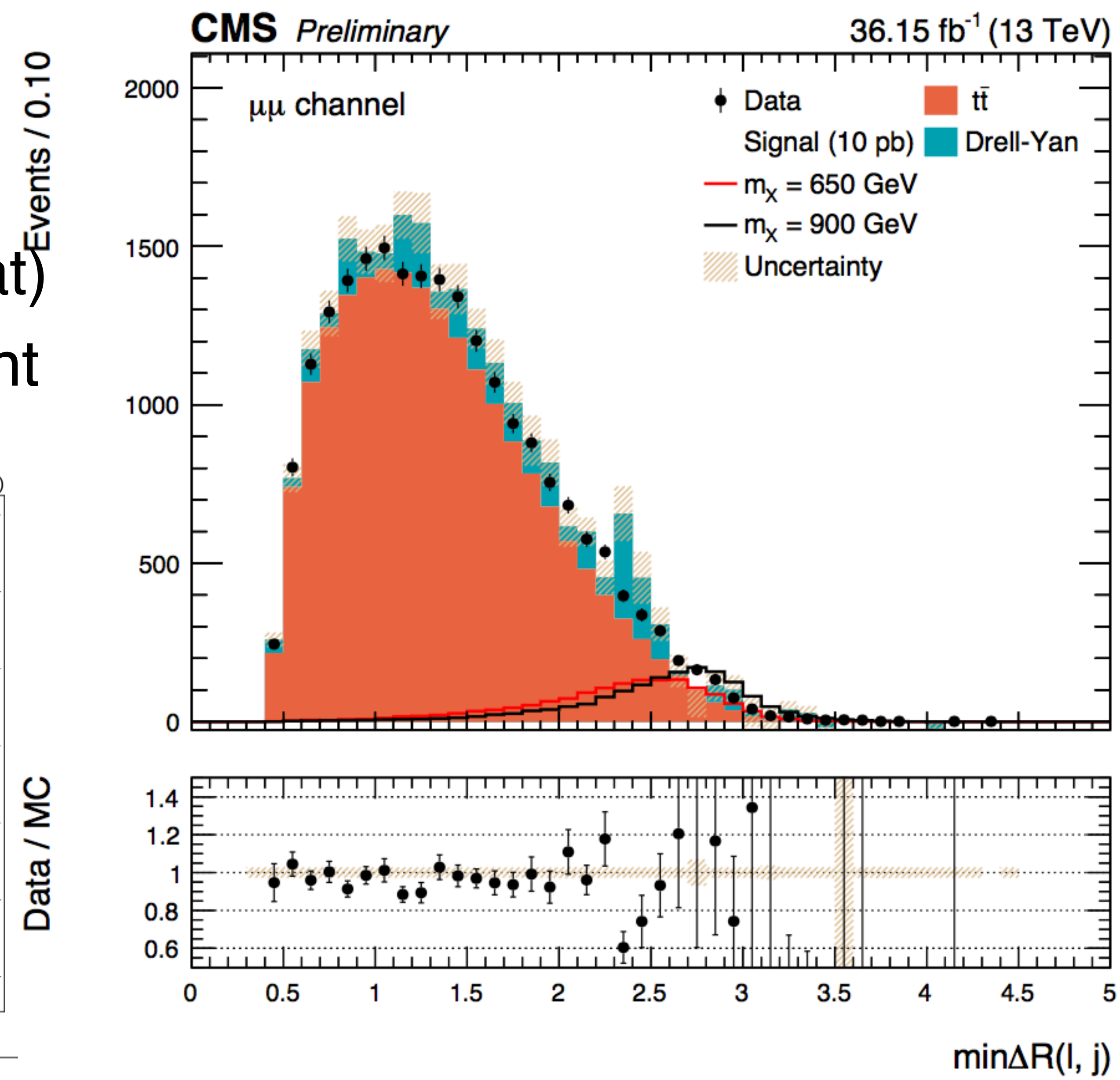
- ATLAS is planning the fully hadronic channel
- Select events with 2 OS leptons (SM H→WW ID) +2 medium b-tag jets
- Reject pairs in the Z peak
- BDTs to remove the background
- Mjj side bands to check the background
- 2D fit in (M_{bb},BDT)

At the moment not large sensitivity, mostly due to the small BR

about 90xSM (down from ~400 with 2015 stat)

Other searches with bbZZ under development





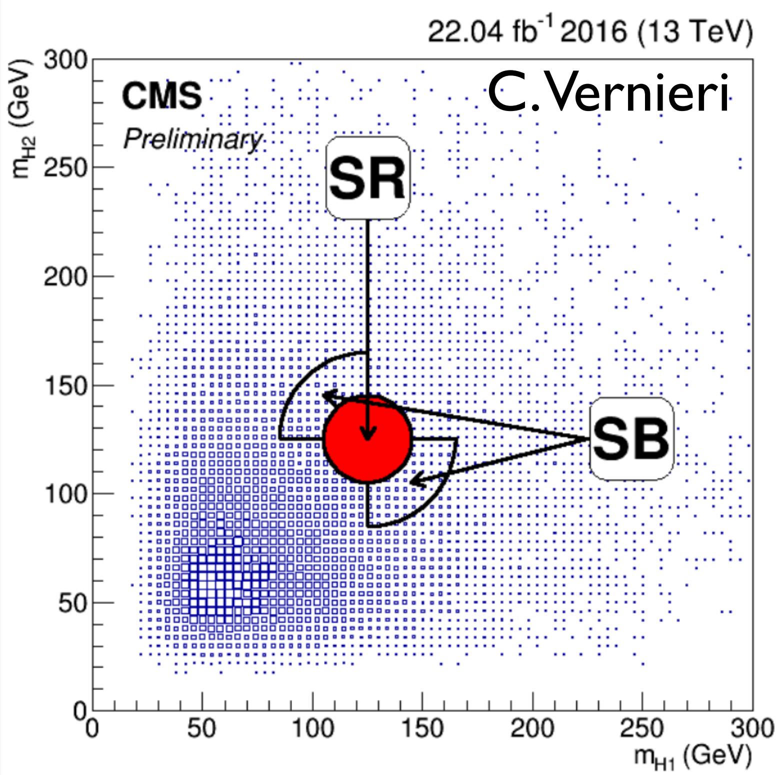
hh→bbbb

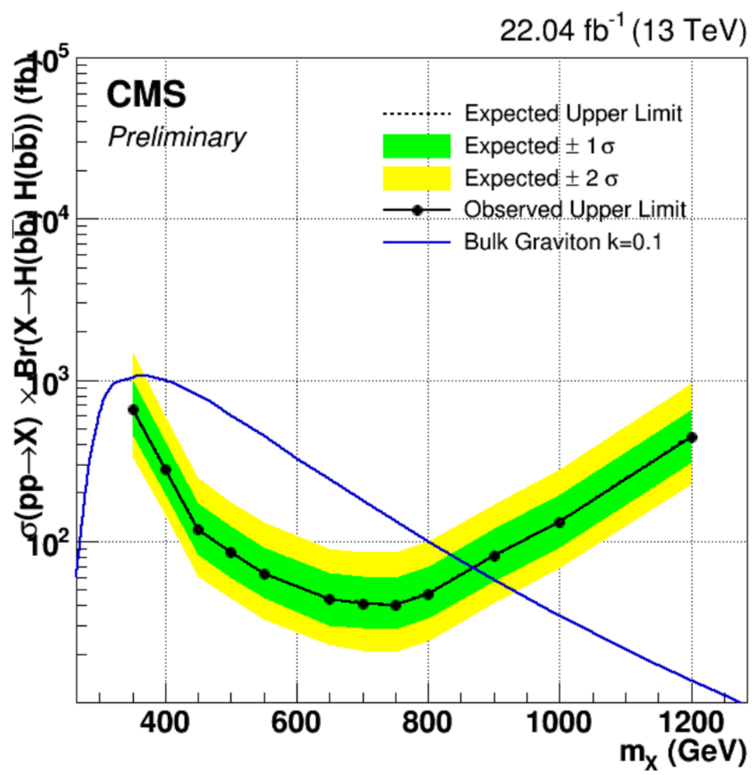
- Most sensitive resonant channel (both for CMS and ATLAS)
- Different strategies for resonant/non-resonant
- CMS 3-4 b-tag at trigger level, ≥4 b-tag in the event
- ATLAS overperforming CMS (for now) thanks to trigger system

Resonant analysis:

Low Mass (m_H<400) and High Mass (400<m_H<1200) studied separately

Background shape estimation from data





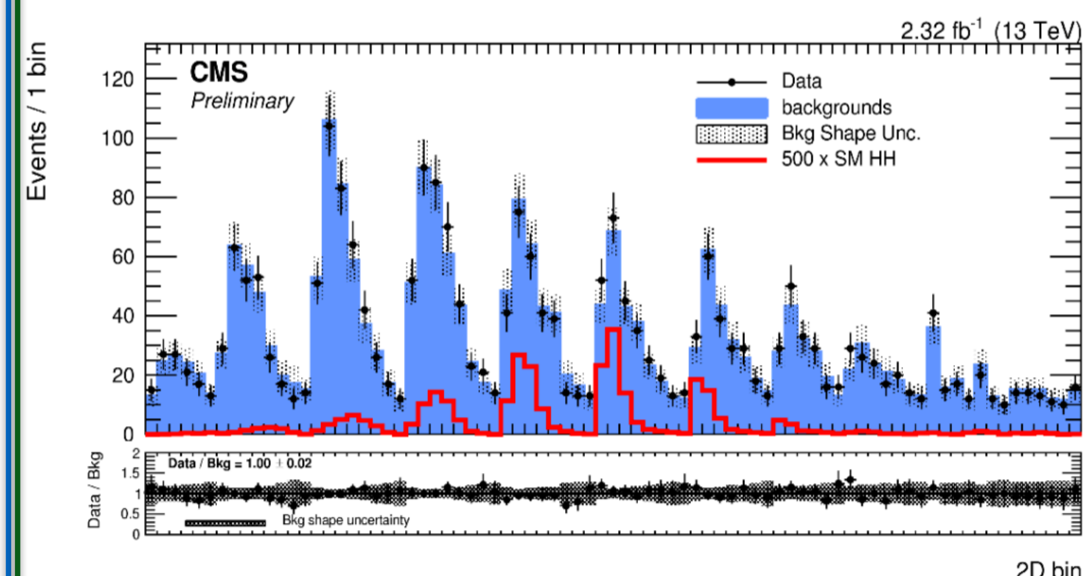
Non-Resonant analysis:

Final limit:

CMS: 342xSM (with 2.7fb^{-1})

ATLAS: 109xSM (with 3.2fb^{-1})

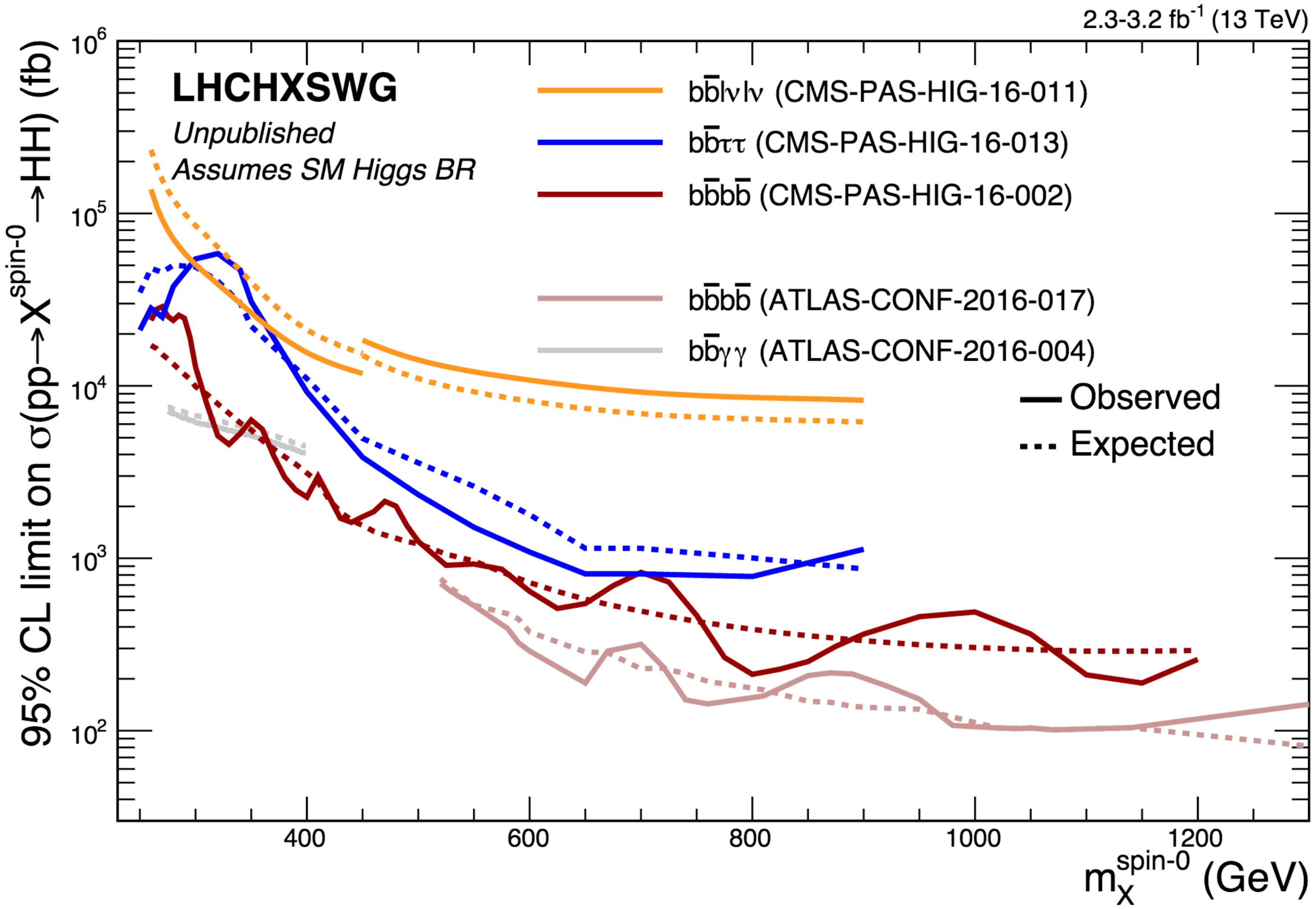
29xSM (with 13.3fb^{-1})



Summary and combination

channel	luminosity	limit exp. (obs)
bbbb	13.3fb^{-1}	29(38)
bbWW	35.9fb^{-1}	91(96)
bb$\tau\tau$	35.9fb^{-1}	25(28)
bb$\gamma\gamma$	35.9fb^{-1}	~20

lumi analysed @ 13TeV, obs(exp) non-resonant limitXSM



bbbb, bb$\tau\tau$, bb$\gamma\gamma$ all have similar sensitivities

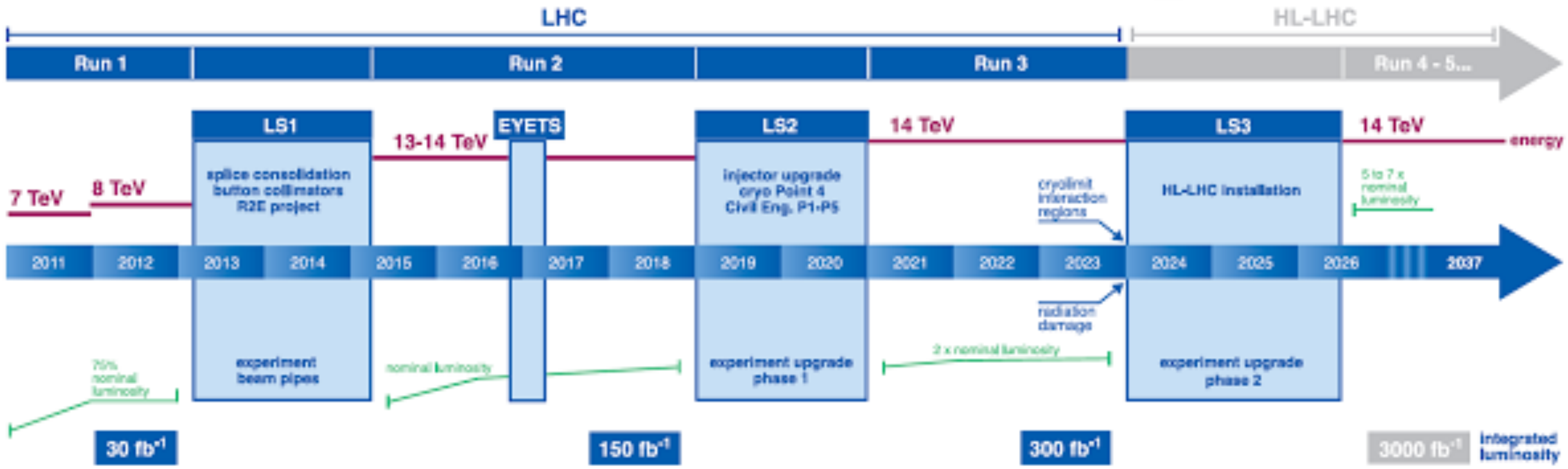
Combining those channels together effectively amounts to increase x3-5 the available statistics and further improve sensitivity

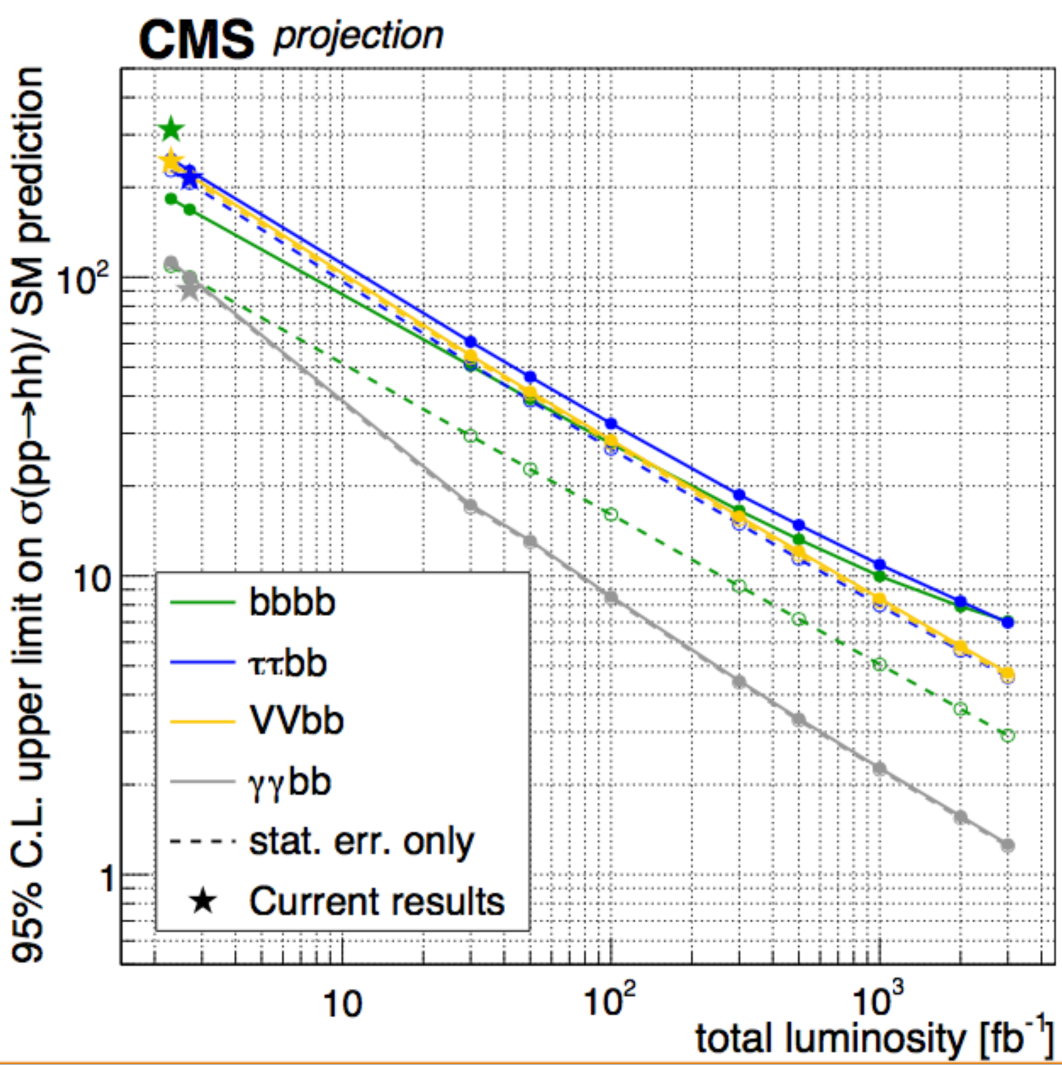
Planned once all 2016 data have been analysed

More channels are preparing results as well

Future

HH analyses are clearly a topic for HL-LHC



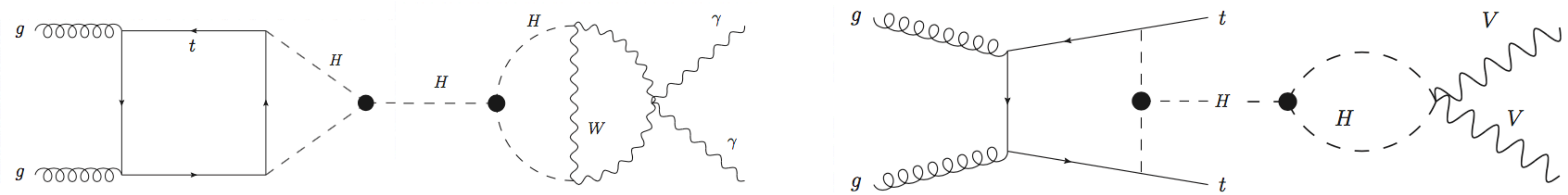


Current projections, based on limited statistics.

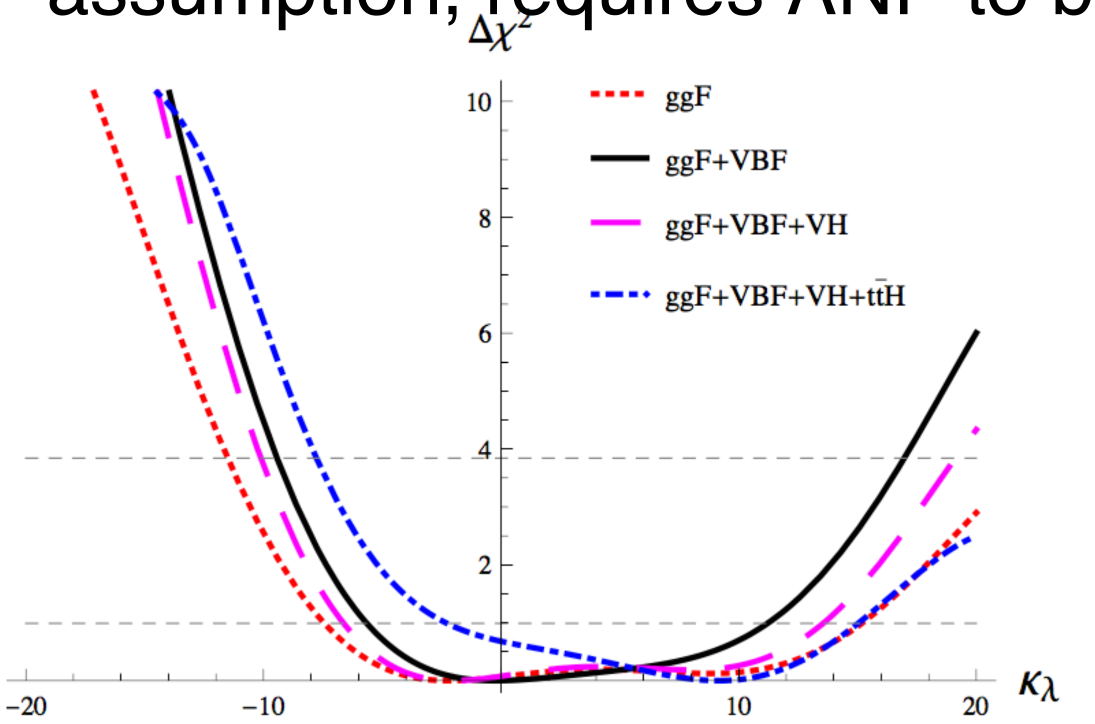
Underestimate the possible performances, mostly because larger statistics will improve the background estimation, and does not include all the 2016 improvements.

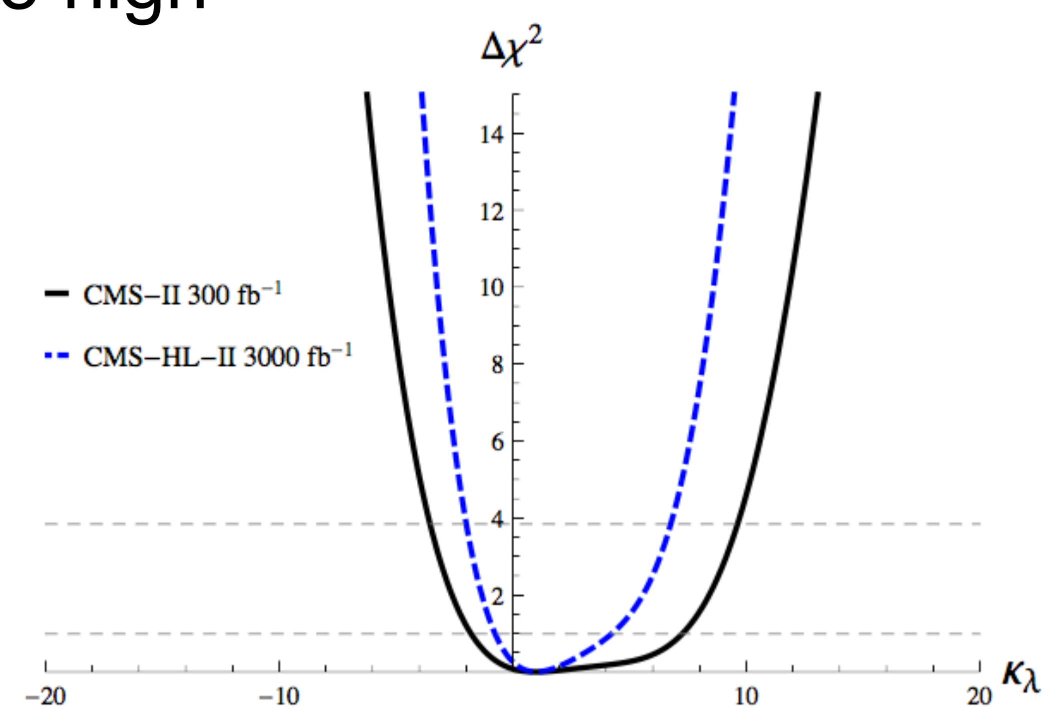
We will over perform

Trilinear coupling from single Higgs



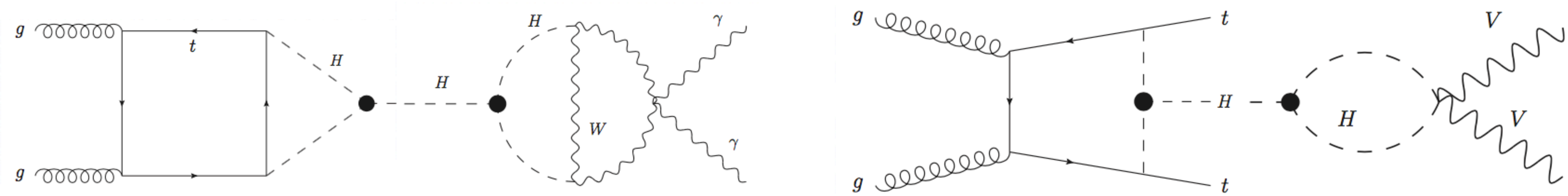
Assumption: NP only manifest itself via an anomalous trilinear coupling, while all other couplings are unchanged (or modifications are negligible)
Several discussions are ongoing to decide if it is a reasonable assumption, requires ΛNP to be not too high





Quick projection: results are competitive with what is obtained from double Higgs production.

Trilinear coupling from single Higgs



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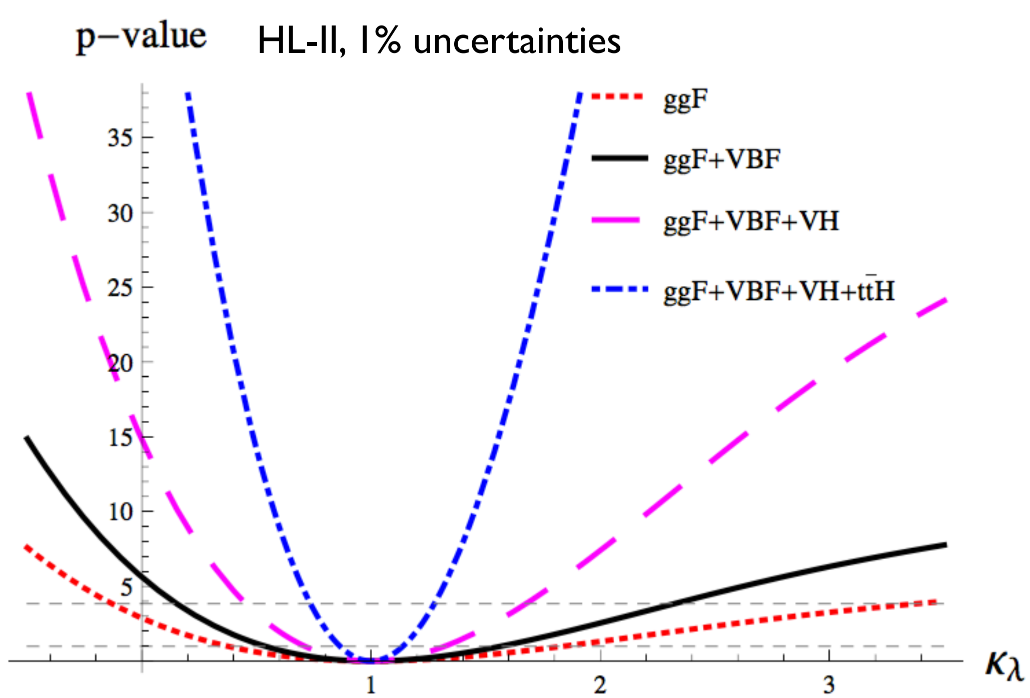
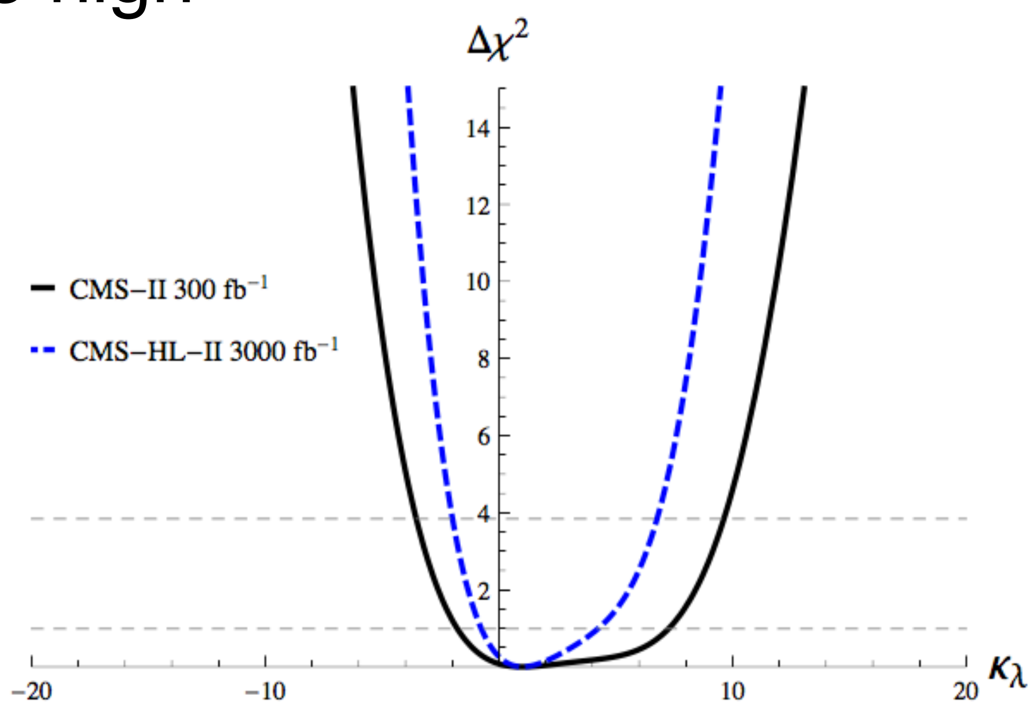




Quick projection: results are competitive with what is obtained from double Higgs production. ttH production is the main driver of the sensitivity

Conclusions

After 60 years, since the discovery of the Higgs boson the Standard Model can be considered complete

The EWSB is the crucial feature of the theory, and the measurement of the trilinear coupling is important to test it and understand whether it works as predicted by the theory

- The double Higgs production is the best tool we have to perform such studies.

The current non-resonant results are showing performances beyond most expectations, and the physics program is well on track to reach the SM sensitivities

- Even neglecting upcoming upgrades to the detectors

BACKUP

Room for improvements

Upgrades are being developed in the non-resonant analysis:

- BDT tuning and reduced mass MX = M(4j)–M(jj_{H1})–M(jj_{H2})+250 GeV
- ATLAS can benefit from 2 b-tag online ev. selection, analysis optimised for several years

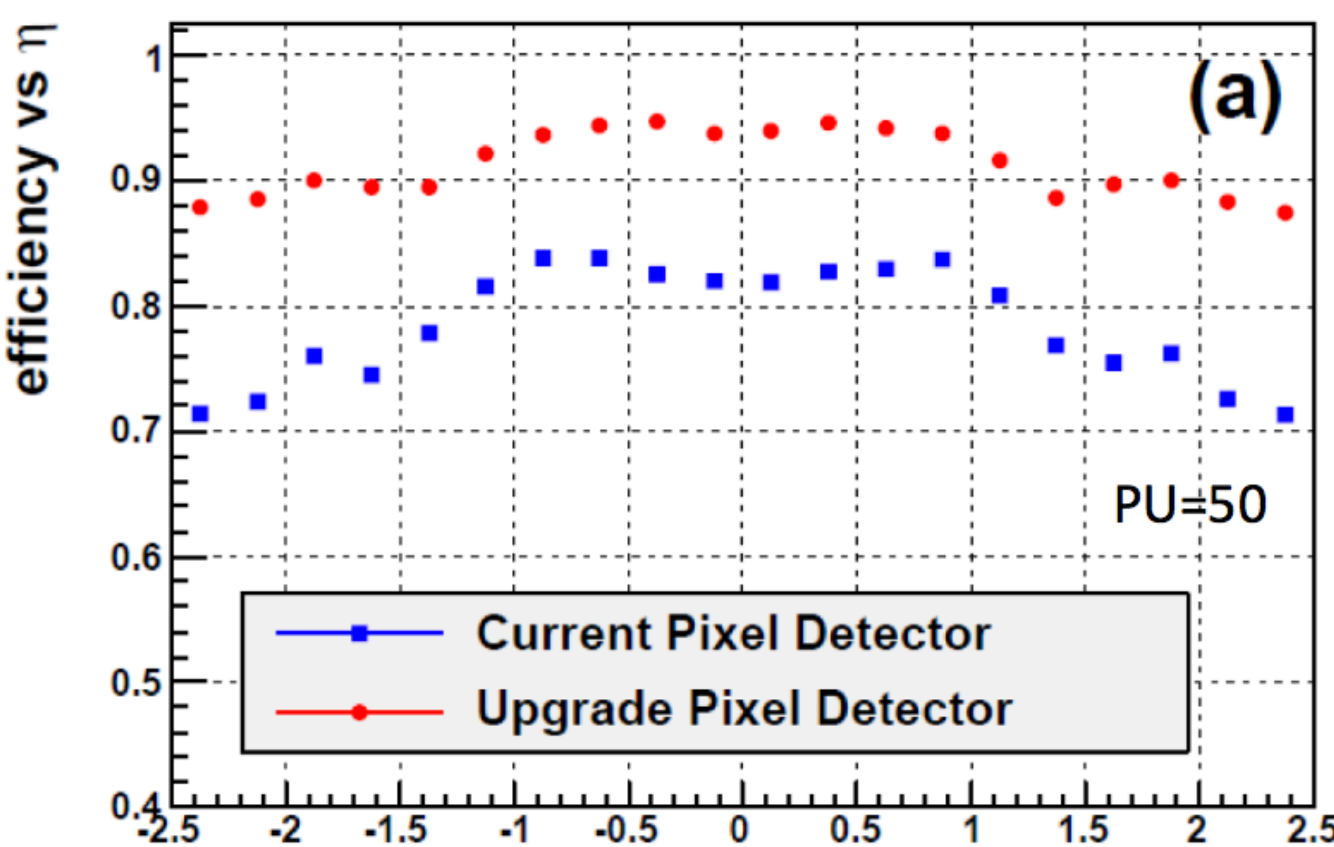
But the most important update to cover the gap will be the pixel upgrade: ATLAS got a factor 2-4 boost from their upgrade. We will get:

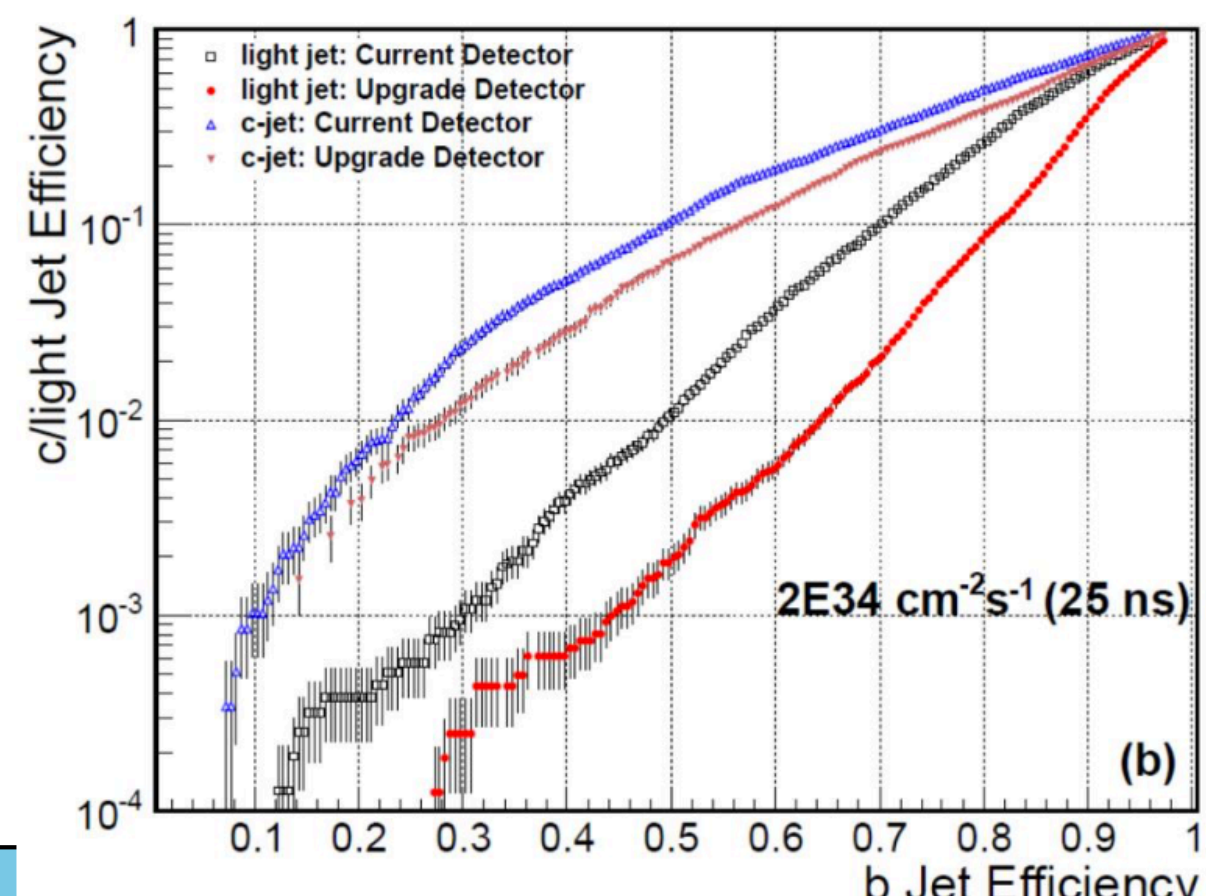
- Higher tracking efficiency
- >10% improvement in b-tagging (for each b-jets)

2017 trigger: general request is HT increase at L1, need to assess the impact on bbbb

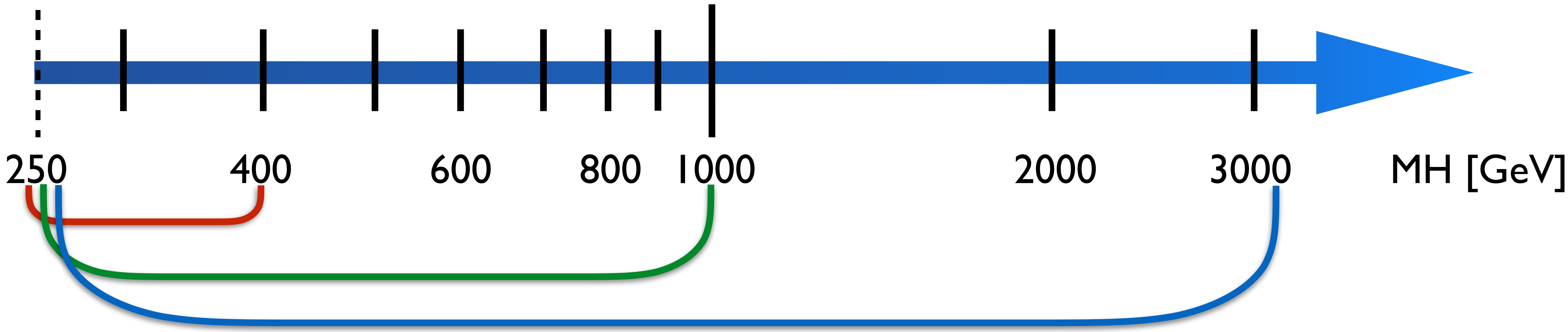
After EYETS: How to fully exploit new pixels capabilities? Any contribution is welcome

Summary: CMS can cover the gap with ATLAS, but a lot of work to do!





HH Studies: Resonant



MSSM/2HDM: Additional Higgs doublet→CP-even scalar H.

- We can probe the low m_A/low tanβ region where BR(H→h(125)h(125)) is sizeable.

Singlet model: Additional Higgs singlet with an extra scalar H.

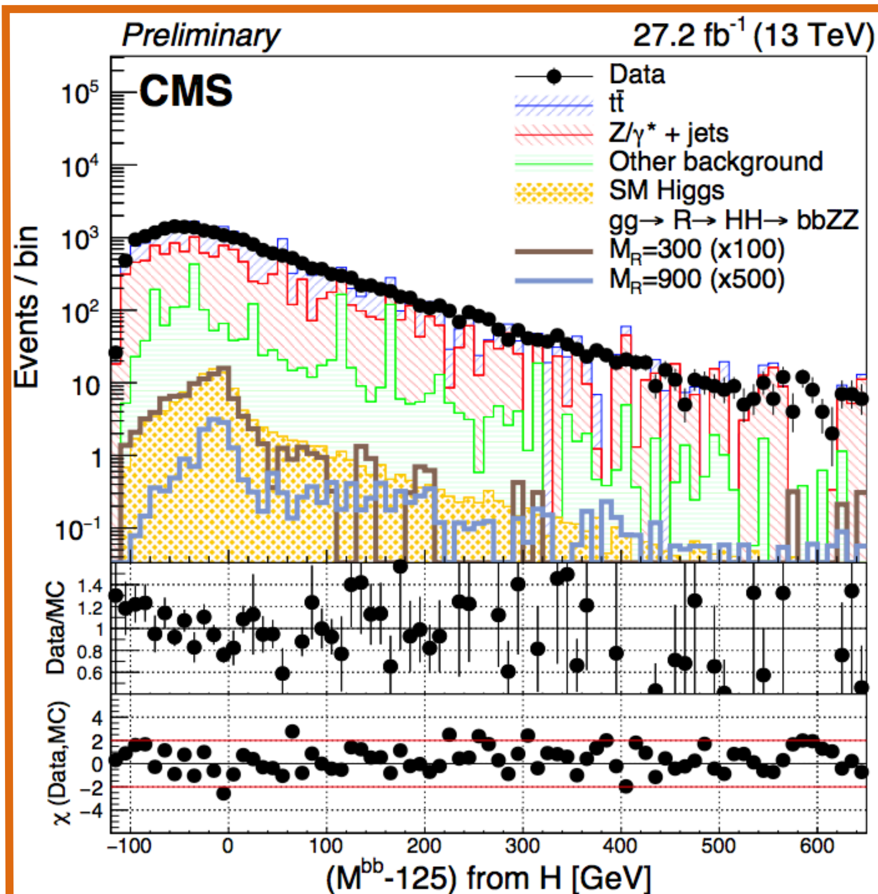
- Sizeable BR beyond $2 \times m_{top}$, non negligible width at high m_H.

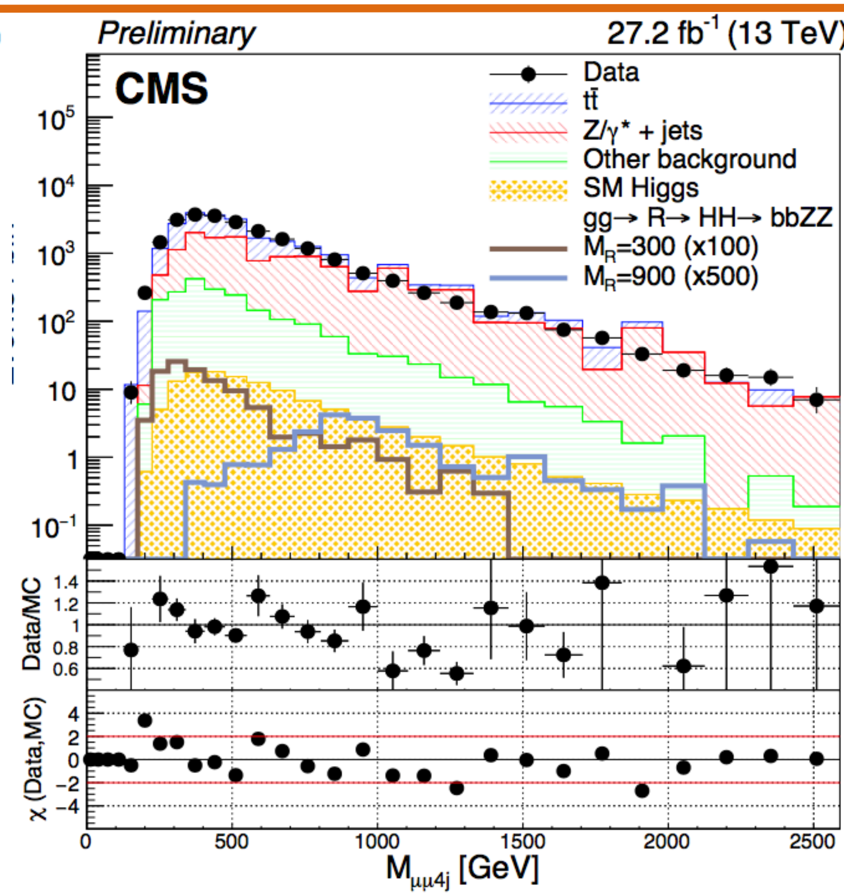
Warped Extra Dimensions:
spin-2 (KK-graviton) and spin-0 (radion) resonances.

- Different phenomenology if SM particles are allowed (bulk RS) or not (RSI model) in the extra dimensional bulk

HH→bbZZ and γγγγ

New entries in 2017! Only entering for resonant searches for now.



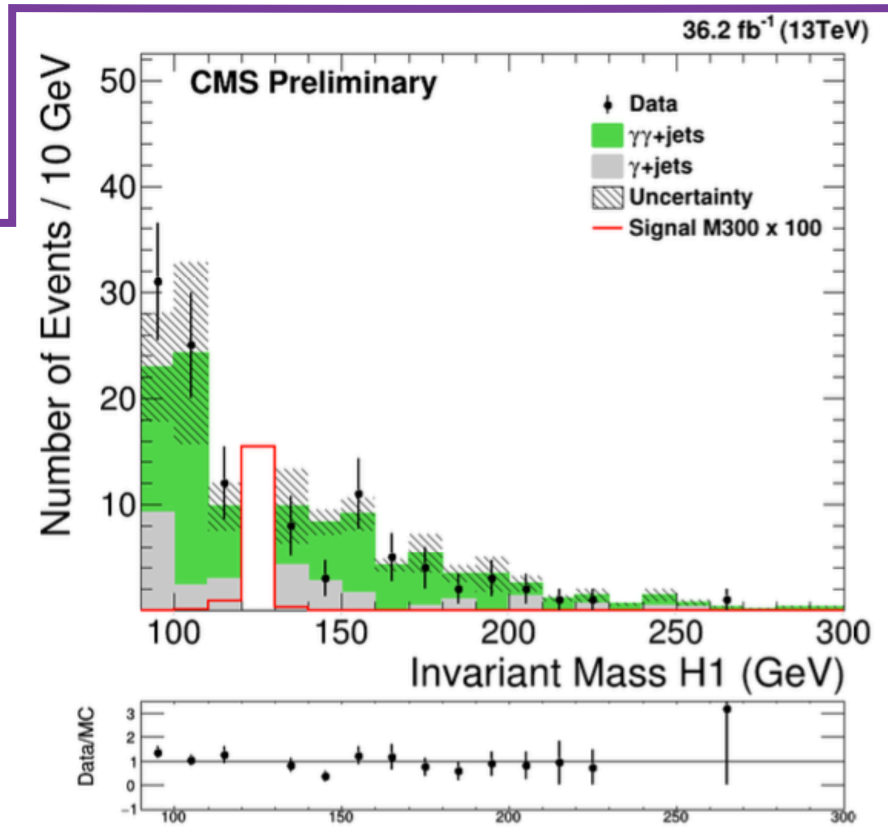


HH→bbZZ→bb2l2j BR=0.15%

- Can use a lot of kinematic handles/recoils
- but a lot of jet combinatorial as well
- Analysis not finalised yet
- Good data/(private)MC agreement

HH→γγγγ

- Inheriting from SM H→γγ, basically same strategy with loosen photon-ID
- Impressive resolution, almost 0 BR
- No estimate about sensitivity yet, but very few events in the signal region



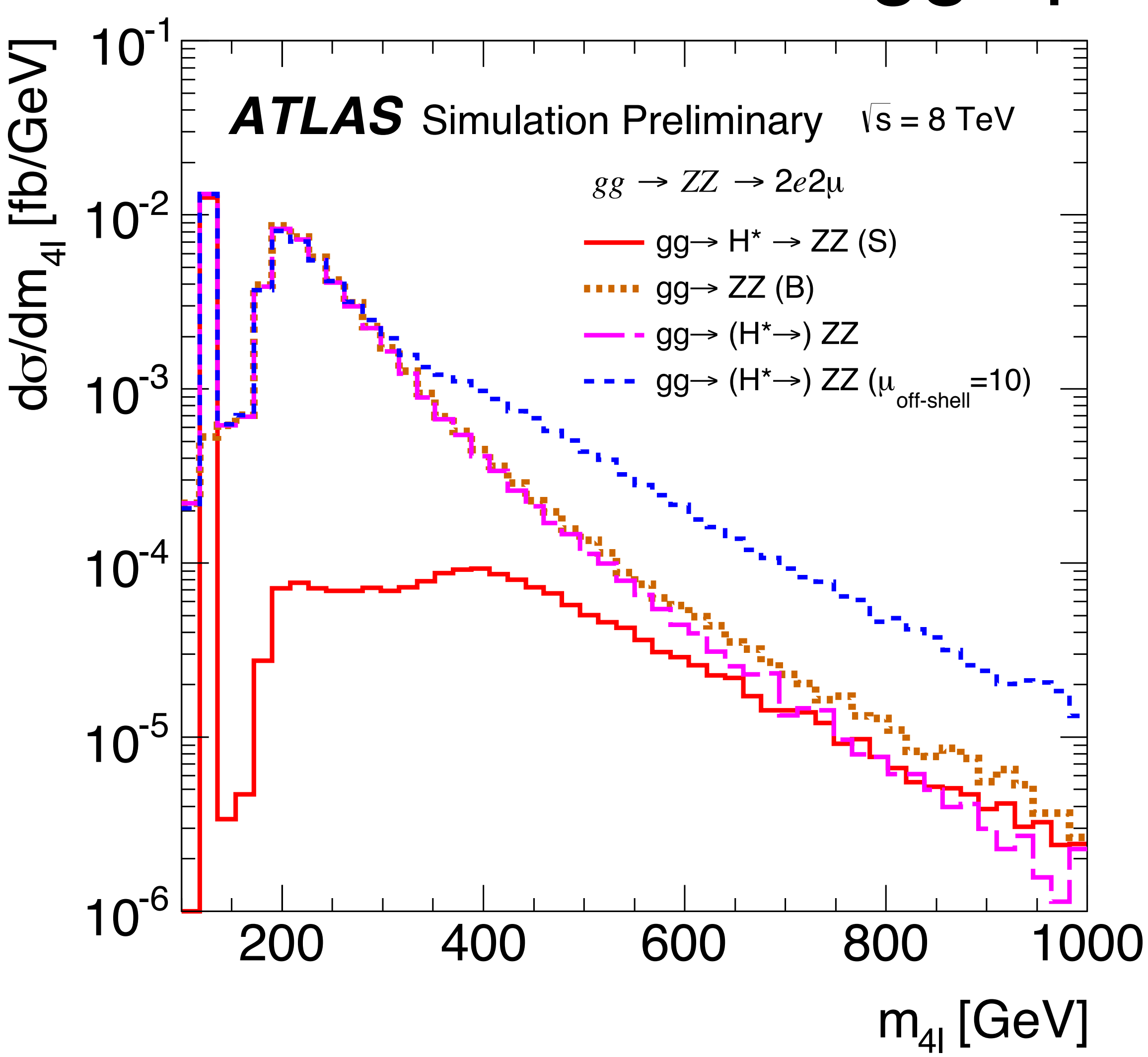
Width off-shell

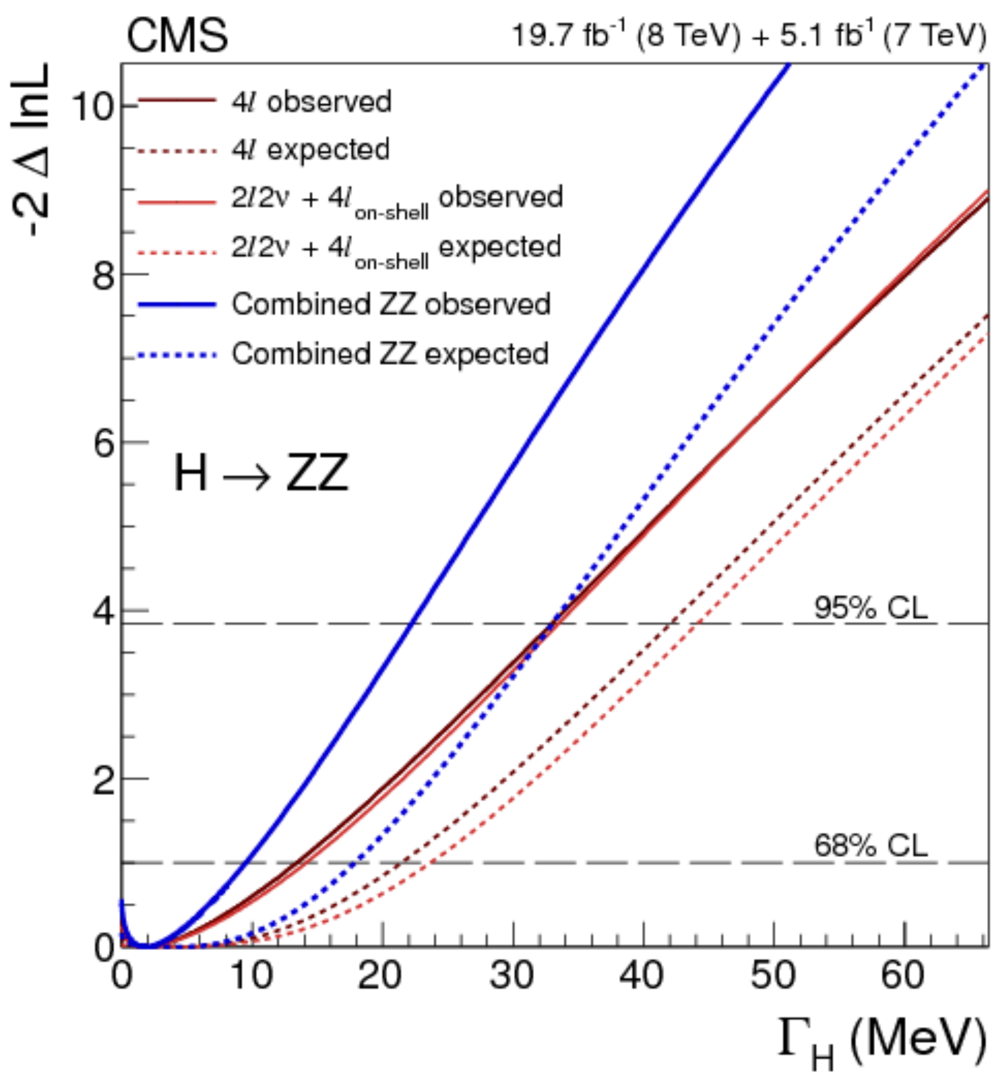
The Higgs boson, like all unstable resonances, can be produced off-shell

This was a feature that was exploited to measure the Higgs decay width

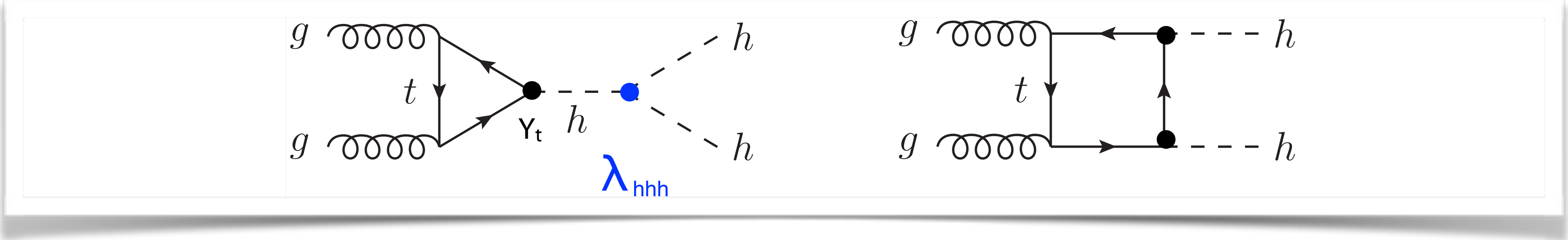
Technique developed in Turin

Crucial for double Higgs production as well





HH Studies: BSM

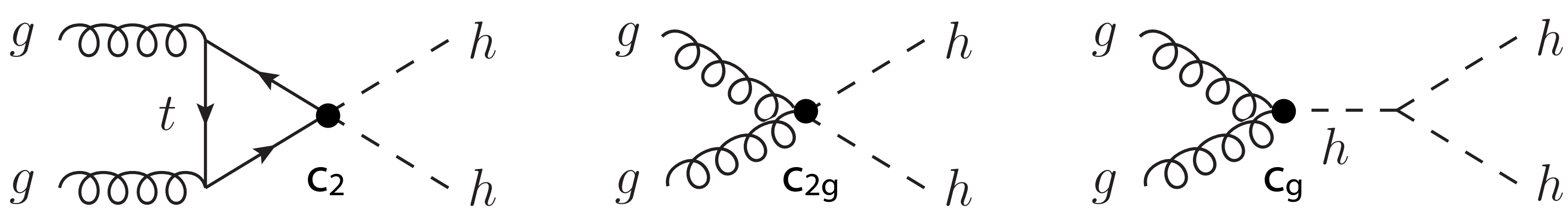


$\sigma^{SM}_{hh}(13\,\text{TeV}) = 33.45\,\text{fb}^{+4.3\%}_{-6.0\%}$(scale unc.) $\pm 3.1\%$(PDF+α_S unc)[1]

The non-resonant double Higgs production is the principal way to extract the Higgs trilinear coupling (λ_{hhh}). Even if in Run2 we will not have full sensitivity to "measure" λ_{hhh}

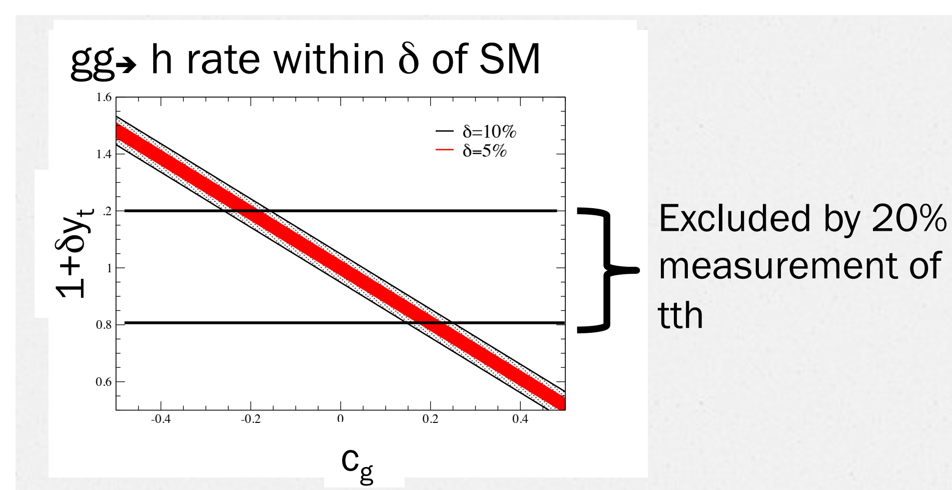
→ The BSM physics can be modelled in EFT adding dim-6 operators[2] to the SM Lagrangian, and the physics can be described with 5 parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

- Non SM Yukawa and λ_{hhh} couplings
- New diagrams and couplings in the game



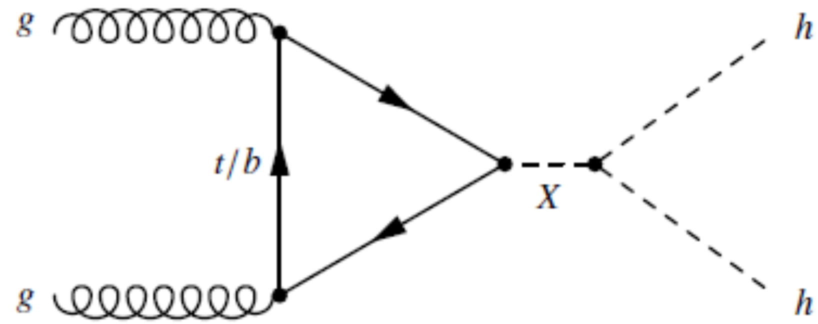
To be noted :

in a linear EFT $c_g = c_{2g}$ and $c_2 = -(3m_t/2v)y_t$



[1] LHCHSWG Yellow Report 4
[2] *Phys. Rev.* **D91** (2015), no. 11, 115008

Projections for resonant : bbbb



Typical BSM spin-0 production diagram

Projection of the sensitivity to the resonant HH production at 3 ab^{-1} expected to be collected during the HL-LHC program. The projections are based on 13 TeV analysis performed with data collected in 2015. The 95% CL expected limits are provided for different spin-0 resonances masses assuming: preliminary analysis from 2015; Scenario 2 - reduced systematic uncertainties taking advantage of a larger data sample and upgraded detector; no systematic uncertainties. For each resonant mass the value of the mass scale $\Lambda_R = \sqrt{6}\exp[-kl]\overline{M}_{Pl}$ excluded at 95% CL is also provided.

m_X (TeV)	Median expected limits on σ (fb)			$\sigma_R(\Lambda_R = 1\,\text{TeV})$ (fb)	Λ_R (TeV) excluded
	2.3 fb^{-1}	ECFA16 S2+	Stat. Only		
0.3	2990	46	41	7130	13
0.7	129.4	7.3	3.4	584	8.9
1.0	81.5	4.4	2.4	190	6.6

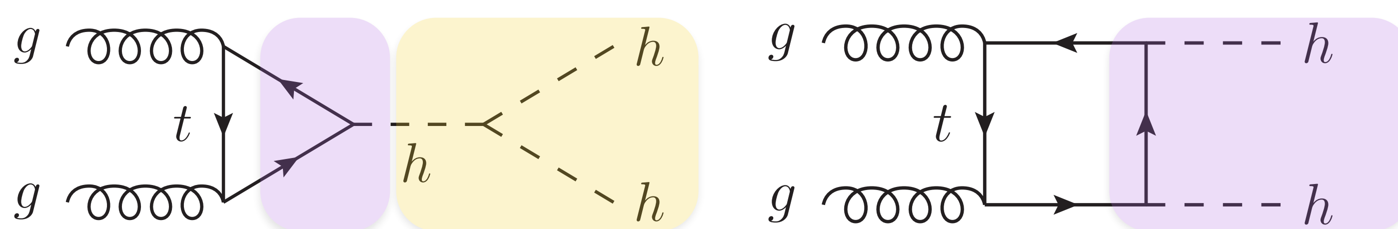
- **CMS-PAS-HIG-16-002**: gg → X → HH → bbbb

gg→hh parametrization

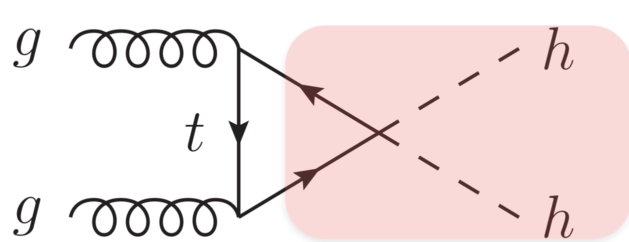
The relevant lagrangian terms of gg→HH production in D=6 EFT

$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H + c_6\right)h^3 + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a$$
$$- \left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \text{h.c.}\right] - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \text{h.c.}\right]$$

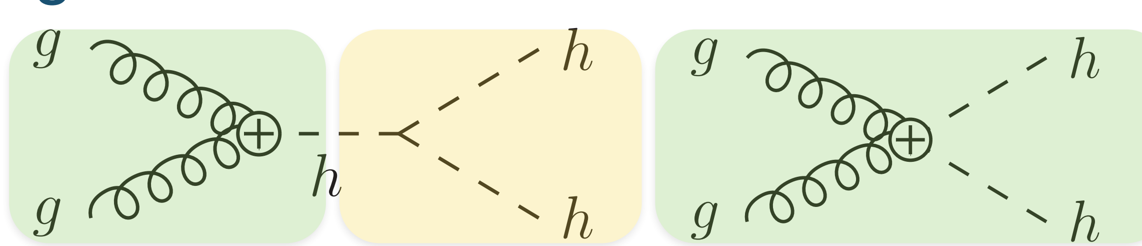
arXiv:1410.3471



SM diagrams



ttHH non-linear interaction



Higgs-gluon contact interactions

An EFT implementation for hh

The double Higgs production cross section can be written as a function of the 5 EFT parameters: λ_{hhh}, y_t, c_2, c_{2g}, c_g

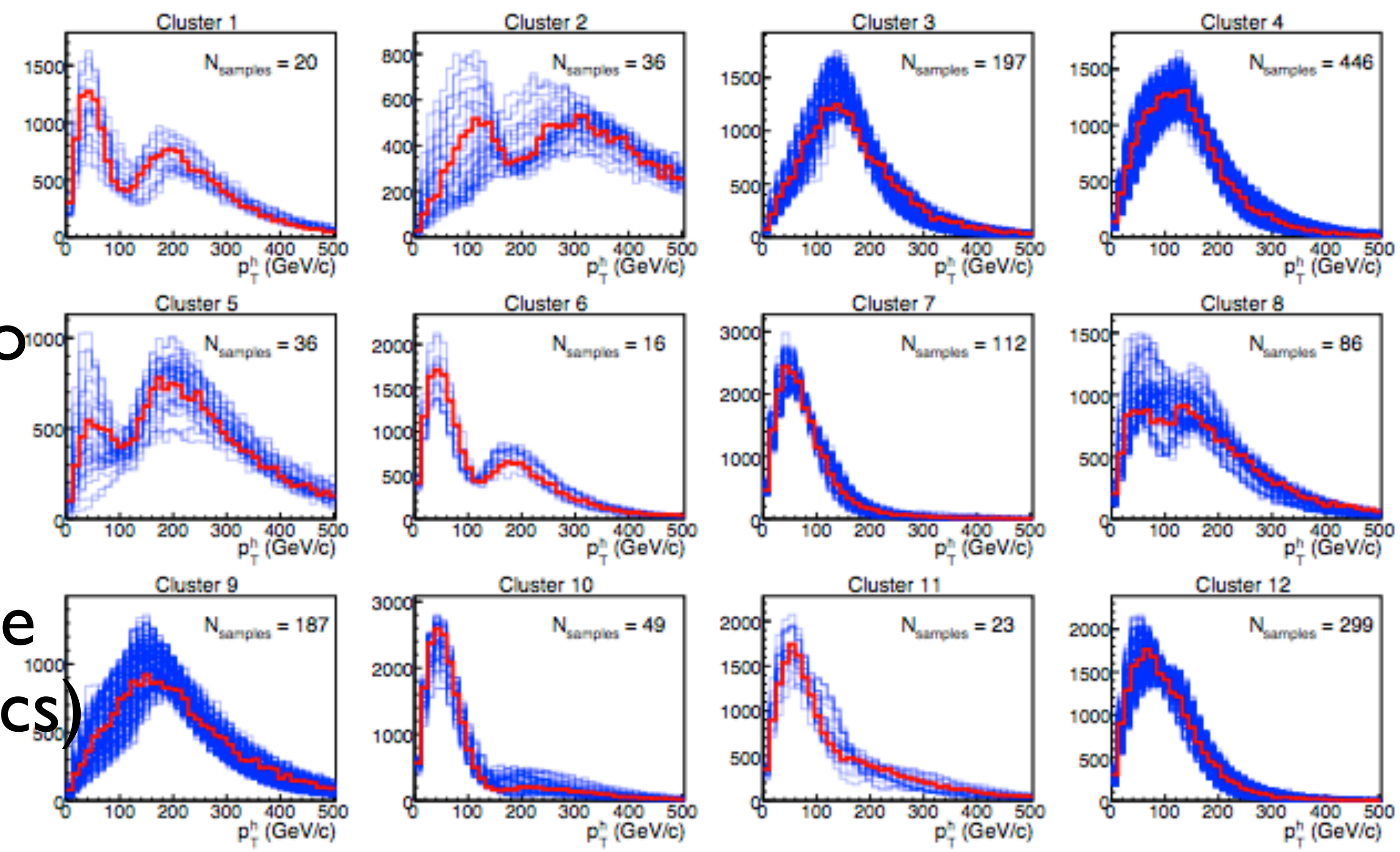
$$R_{hh} \equiv \frac{\sigma_{hh}}{\sigma_{hh}^{SM}} \stackrel{LO}{=} A_1\kappa_t^4 + A_2 c_2^2 + (A_3\kappa_t^2 + A_4 c_g^2)\kappa_\lambda^2 + A_5 c_{2g}^2 + (A_6 c_2 + A_7\kappa_t\kappa_\lambda)\kappa_t^2$$
$$+(A_8\kappa_t\kappa_\lambda + A_9 c_g\kappa_\lambda)c_2 + A_{10}c_2 c_{2g} + (A_{11}c_g\kappa_\lambda + A_{12}c_{2g})\kappa_t^2$$
$$+(A_{13}\kappa_\lambda c_g + A_{14}c_{2g})\kappa_t\kappa_\lambda + A_{15}c_g c_{2g}\kappa_\lambda\,.$$

JHEP **04** (2016) 126

2D (M_{HH},cosϑ^*) signal shapes from different points in the 5D EFT phase space are clustered together.

12 clusters are identified according to there kinematical properties

Inside each cluster, a representative shape is identified, as the one with the minimum distance (in the test statistics) from all other shapes in the cluster



Each point of the phase space can be mapped by means of its cross-section and representative shape