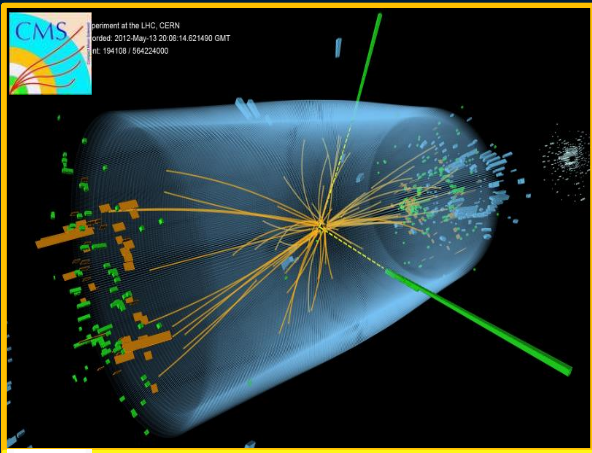
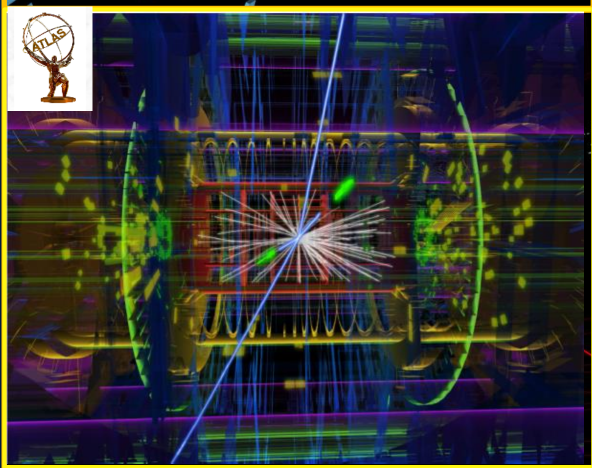
Higgs Discovery, Measurements
BSM Searches, Prospects at the LHC
A New Window on the Universe





Harvey B Newman

LISHEP 2015, Manaus

August 4, 2015

LHC Run2:
Embarking on a
River of Discovery

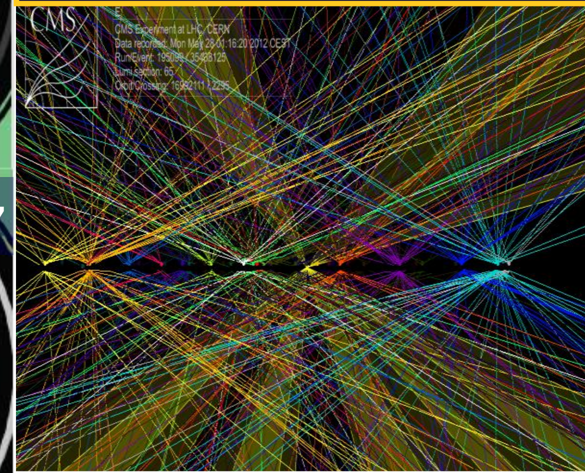
The LHC: Spectacular Performance

A new era of opportunity; a new era of challenges

Data Complexity: The Challenge of Pileup

~3.5 X 10^{15} pp Collisions

1M Higgs Bosons created in Run 1



~50 Vertices, 14 Jets, 2 TeV

Run2 and Beyond will bring:

- Higher energy and intensity
- Greater science opportunity
- Greater data volume & complexity
- A new Realm of Challenges

Average Pileup

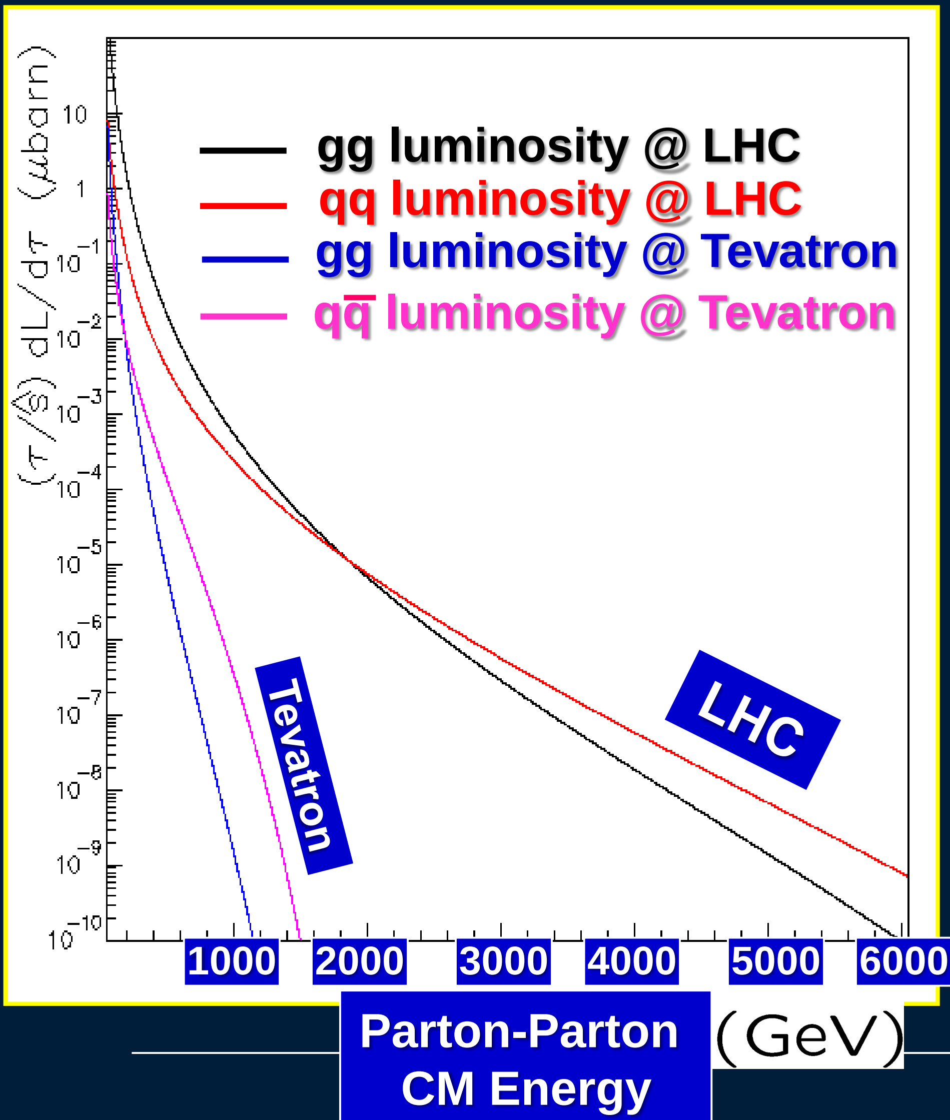
Run 1 21

Run 2 42

Run 3 53

HL LHC 140-200

The LHC Mission: Opening a Realm of High Energies and a New Era of Discovery



- The LHC is a **Discovery Machine**
- The first accelerator to probe deep into the Multi-TeV scale
- Its mission is ***Beyond the SM***
- There are many reasons to expect new physics

SUSY, Substructures, *Graviton Resonances, Black Holes, Low Mass Strings, … the Unexpected*

We do not know what we will find

Nature is More Subtle

The Higgs Sector: A New Realm
Exploration in the Post-Discovery Era

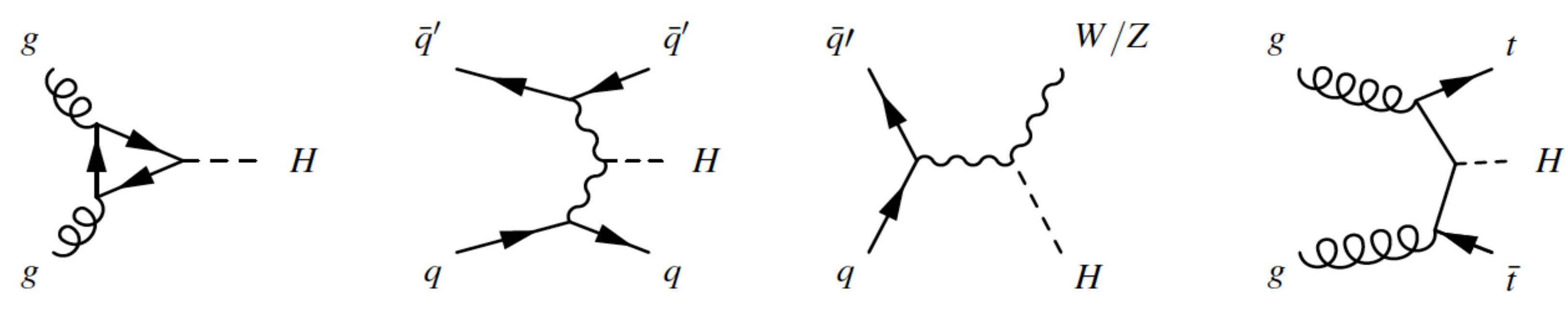
- The LHC
- Post Higgs Discovery Progress
  - Is it the “perfect” Higgs Boson of the SM ?
  - Is there just one ?
- Updates on Signals: Individual Channels and Combined
- Properties
  - The Mass
  - Couplings to Fermions as well as Vector Bosons
  - Spin/Parity
- BSM Higgs Searches: MSSM, Exotic
- LHC Run2 and Beyond
- Outlook

Higgs Talks from ATLAS and CMS

- Higgs Properties from CMS: Carlos Avila Bernal, UNIANDES
- ATLAS Results on Higgs Boson Couplings and Properties: Fernando Monticelli Univ. Nacional de La Plata (AR)
- BSM Higgs Properties from CMS: Albert De Roeck, CERN
- Search for BSM Higgs Bosons in ATLAS: Gabriela Navarro Universidad Antonio Nariño

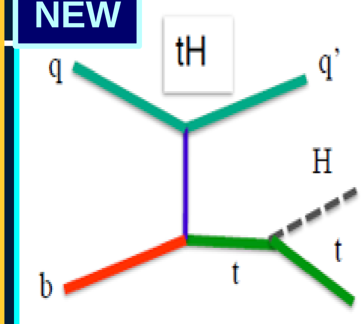
Higgs Production at the LHC

Run 1: 7-8 TeV pp Colllsions; 13 TeV at Run2



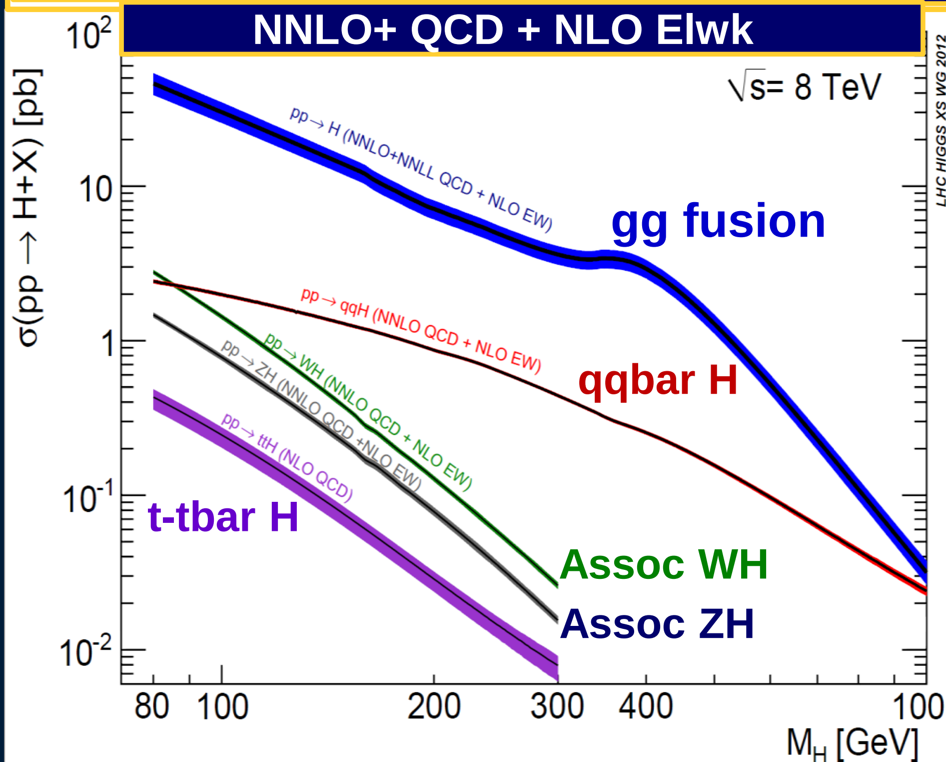
gg fusion gg→ H | VB fusion (VBF) | Assoc Prod: WH, ZH | Assoc. Prod: t-tbar H

NEW



Single Top: tHq

NNLO+ QCD + NLO Elwk



Dominant production gg→H

125 GeV; 8 TeV subdominant, with larger S/B

VBF: ~13X
WH+ZH: ~18X
ttH ~150X Less

ttH Grows Quickly with Ecm
σ(13 TeV)/σ (8 TeV) ~4X

	process	8 TeV	13 TeV
ggF	gluon-gluon fusion	19 pb	44 pb
VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
ttH	associated production	0.13 pb	0.51 pb
tH	Associated production	~20 fb	~90 fb

Theory Uncertainties ⇒

process	QCD scale	PDF
ggF	~8%	~8%
VBF	~0.2%	~3%

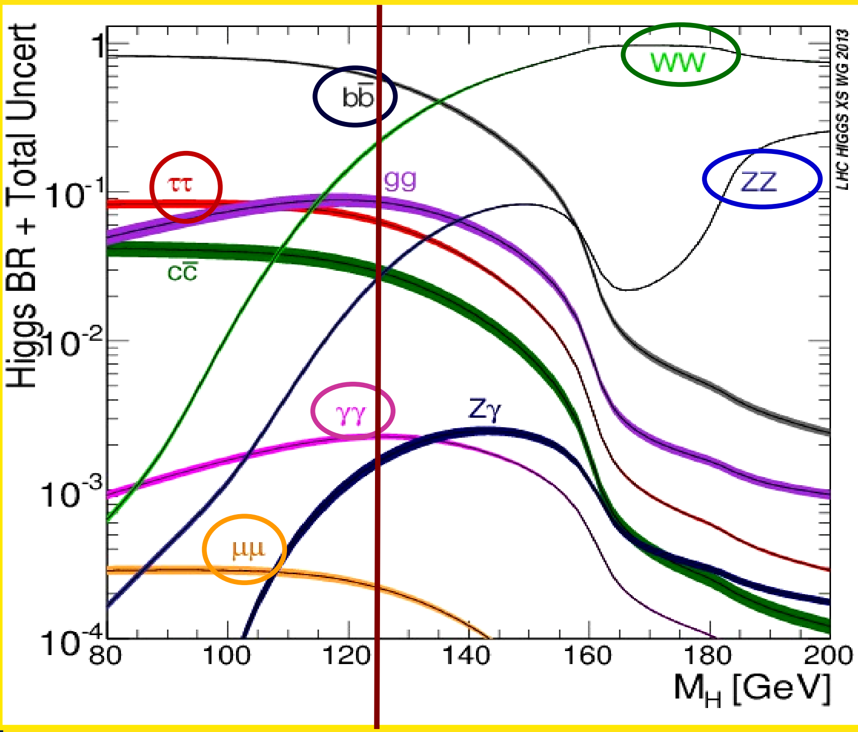
Higgs Boson Decays

Many Modes Contribute near 125 GeV

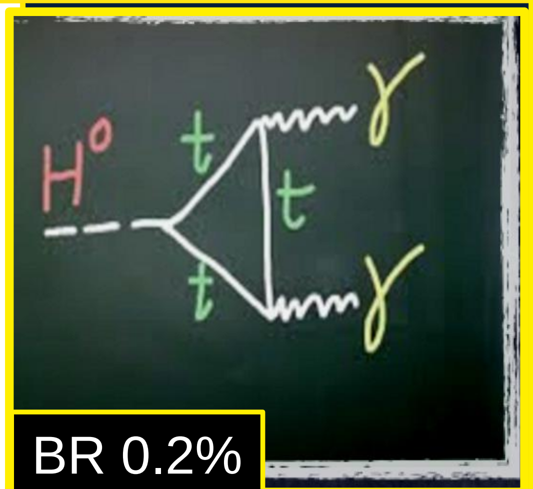
ZZ, γγ, WW, ττ, bb [the big 5*]

Rare High Mass Resolution Channels Have a Special Role:

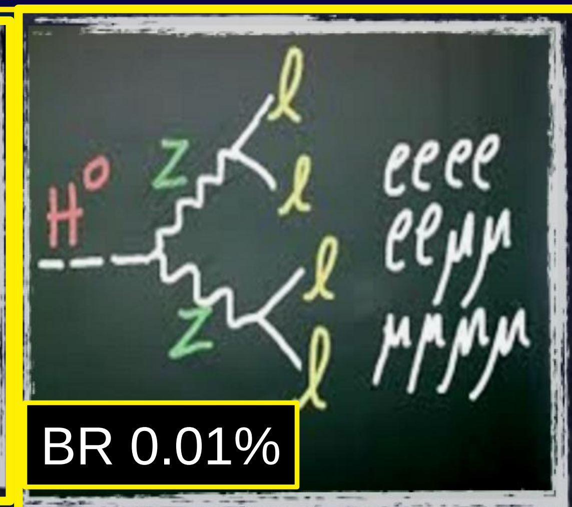
H→γγ and H→ ZZ → 4 Leptons



125 GeV – A Spectacular Mass:
~89% of final states studied



BR 0.2%



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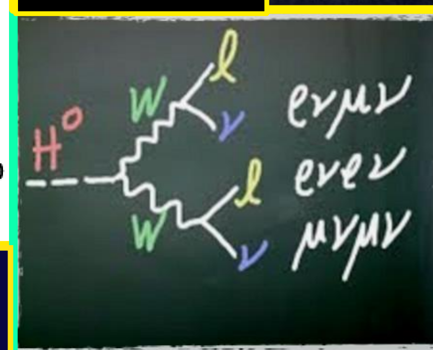


- *+ ***Low Mass:*** *W/Z + H → (WW) → 3l 3ν; H → Zγ;* WH + ZH → qq′ 2l 2ν
- *+ ***High Mass*** ZZ → 2l 2ν; ZZ → qq′ 2l; WW → qq′ lν; *H → ZZ → 2l2τ*

CMS Recent Higgs Results

Mass, Widths, Couplings, Susy/Exotic BSM, Rare Decays

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

CMS (Preliminary)	
May 15	H/A → Z+A/h, Z to ll, A/h to Fermions
Mar 15	VBF H → Invisible Decays
Mar 15	Light NMSSM Higgs Produced in SUSY Cascades → bb
Feb 15	A→Zq at High Mass
Feb 15	tHq, H → WW
Sep 14	tHq, H → bb
Sep 14	H+ → τ ν
Sep 14	H+ → tb, dilepton final states
Jul 14	High Mass Diphoton Resonances
Jun 14	H+ → c sbar
May 14	X → HH →2γ + 2b
Mar 14	H → γγ → μμγ
Mar 14	tHq, H → γγ
Mar 14	t → cH: multilepton or diphoton

CMS Publications (submission)		
Jul 15	H Exotic Decays → Photons + Invisible	Arxiv 1507.00359
Jun 15	MSSM H → bb	Arxiv 1506.08329
Jun 15	Diphoton resonances 150 – 850 GeV	Arxiv 1506.02301
Jun 15	VBF H → bb at High Mass	Arxiv 1506.01010
May 15	H → a1 a1 → muon pairs	Arxiv 1506.00424
Apr 15	Pseudoscalar A → Z H→ll bb	Arxiv 1504.04710
Apr 15	H of 145-1000 GeV → WW ZZ	Arxiv 1504.00936
Mar 15	Combined H Mass by ATLAS and CMS	Arxiv 1503.07589
Mar 15	Di-Higgs Res. X → HH → 4b	Arxiv 1503.04114
Feb 15	LFV H→ τμ	Arxiv 1502.07400
Feb 15	ttH → bb with Matrix Element method	Arxiv 1502.02485
Dec 14	H Combination and Properties (Legacy)	Arxiv 1412.8662

ATLAS Recent Higgs Results

http://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults#Higgs_Group_Publications

Many Recent Results Since March

Higgs Group Publications

Full Title
Search for an additional, heavy Higgs boson in the $H\rightarrow ZZ$ decay channel at $\sqrt{s}$ = 8 TeV in pp collision data with the ATLAS detector
Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s}=7$ and 8 TeV in the ATLAS experiment
Study of $(W/Z)H$ production and Higgs boson couplings using $H \rightarrow WW^{\ast}$ decays with the ATLAS detector
Search for the associated production of the Higgs boson with a top quark pair in multilepton final states with the ATLAS detector
Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector
Modelling $Z\to\tau\tau$ processes in ATLAS with τ-embedded $Z\to\mu\mu$ data
Search for Dark Matter in Events with Missing Transverse Momentum and a Higgs Boson Decaying to Two Photons in pp Collisions at $\sqrt{s}=8$~TeV with the ATLAS Detector
Search for new light gauge bosons in Higgs boson decays to four-lepton final states in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector at the LHC
Search for Higgs bosons decaying to aa in the $\mu\mu\tau\tau$ final state in pp collisions at $\sqrt{s} = $ 8 TeV with the ATLAS experiment
Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^{(*)}\rightarrow 4\ell$ Decay Channels at $\sqrt{s}=8$ TeV with the ATLAS Detector
PUBLISHED Search for invisible decays of the Higgs boson produced in association with a hadronically decaying vector boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector
PUBLISHED Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS and CMS Experiments
Search for the Standard Model Higgs boson produced in association with top quarks and decaying into $b\bar{b}$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector
PUBLISHED Search for a Charged Higgs Boson Produced in the Vector-boson Fusion Mode with Decay $H^\pm \to W^\pm Z$ using pp Collisions at $\sqrt{s}=8$ TeV with the ATLAS Experiment
PUBLISHED Determination of spin and parity of the Higgs boson in the $WW^{*} \to e \nu \mu \nu$ decay channel with the ATLAS detector

Peter Onyisi March 17 Seminar

Inputs for combination:

	gluon fusion	vector boson fusion (VBF)	associated prod. with W/Z	associated prod. with tt
γγ	✓	✓	✓	✓
ZZ	✓ + offshell	✓	✓	✓ NEW!
WW	✓ + offshell	✓	✓ NEW!	✓ NEW!
ττ	✓	✓		✓ NEW!
bb			✓	✓ NEW!
Zγ	✓	✓		
μμ	✓	✓		
invisible	✓ (monojet)	✓ NEW!	✓ NEW!	

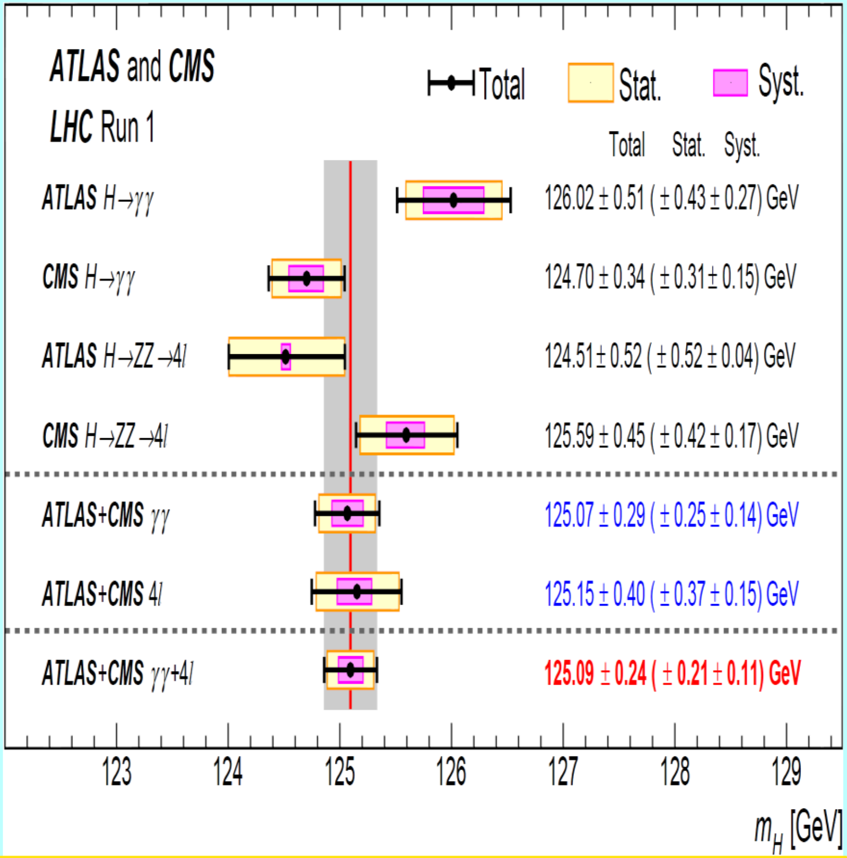
- Search for CP admixture
- Differential cross section combination
- Search for invisible decays
- Off-shell couplings

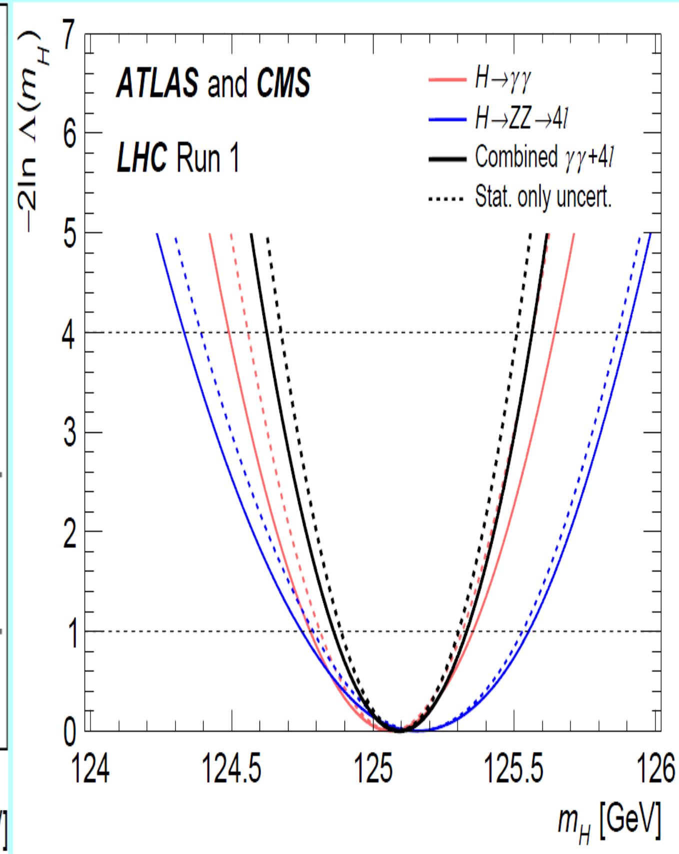
+ searches for new particles decaying to Higgs bosons, Higgs bosons decaying to new particles

Combined Mass Measurement
from H → ZZ → 4ℓ, H → γγ

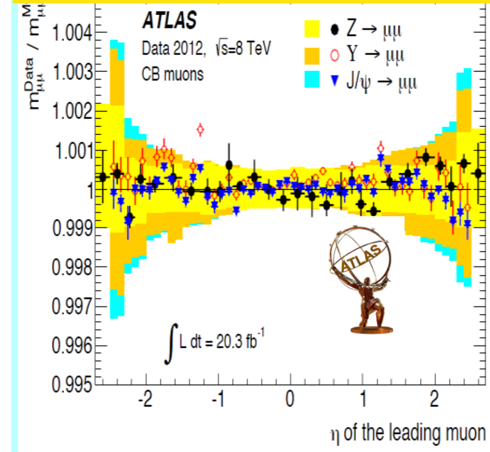
arXiv:1503.7589

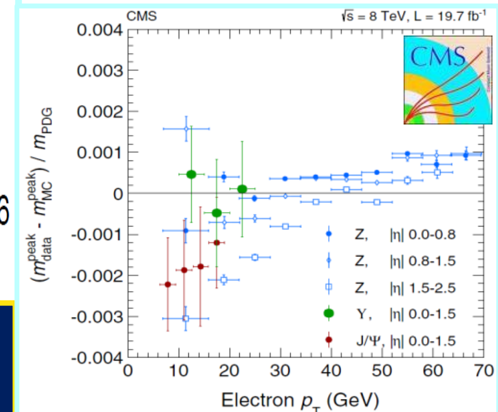
Profiling M_H; μ(ggH,ttH) and μ(VBF, VH) for γγ; μ(4ℓ) for ZZ





Calibration with Z, Υ, J/ψ → ee, μμ





Improvement on syst. uncertainties
- final e, γ, μ calibrations
- final detector simulation

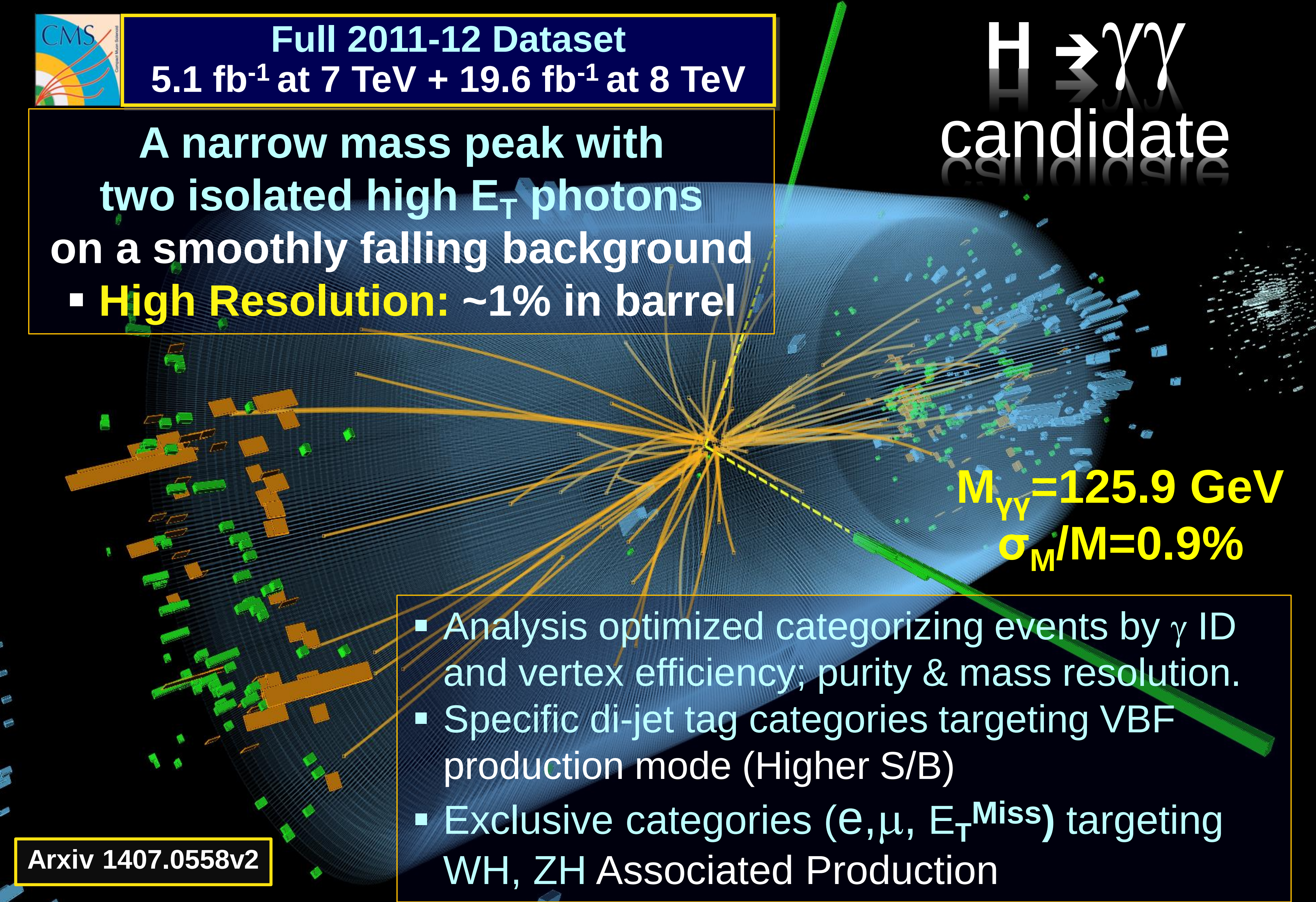
Impressive ±0.2% accuracy:
Statistical uncertainty dominates

M_H Values (ATLAS+CMS)
H → γγ: 125.07 ± 0.25 ± 0.14
H → 4l: 125.15 ± 0.37 ± 0.15
Combined Channels:
M_H = 125.09 ± 0.21 ± 0.11

Impressive 0.1 – 0.3% Mass Scale Accuracy

Full 2011-12 Dataset
5.1 fb^{-1} at 7 TeV + 19.6 fb^{-1} at 8 TeV

$H \rightarrow \gamma\gamma$ candidate



A narrow mass peak with two isolated high E_T photons on a smoothly falling background

- **High Resolution: ~1% in barrel**

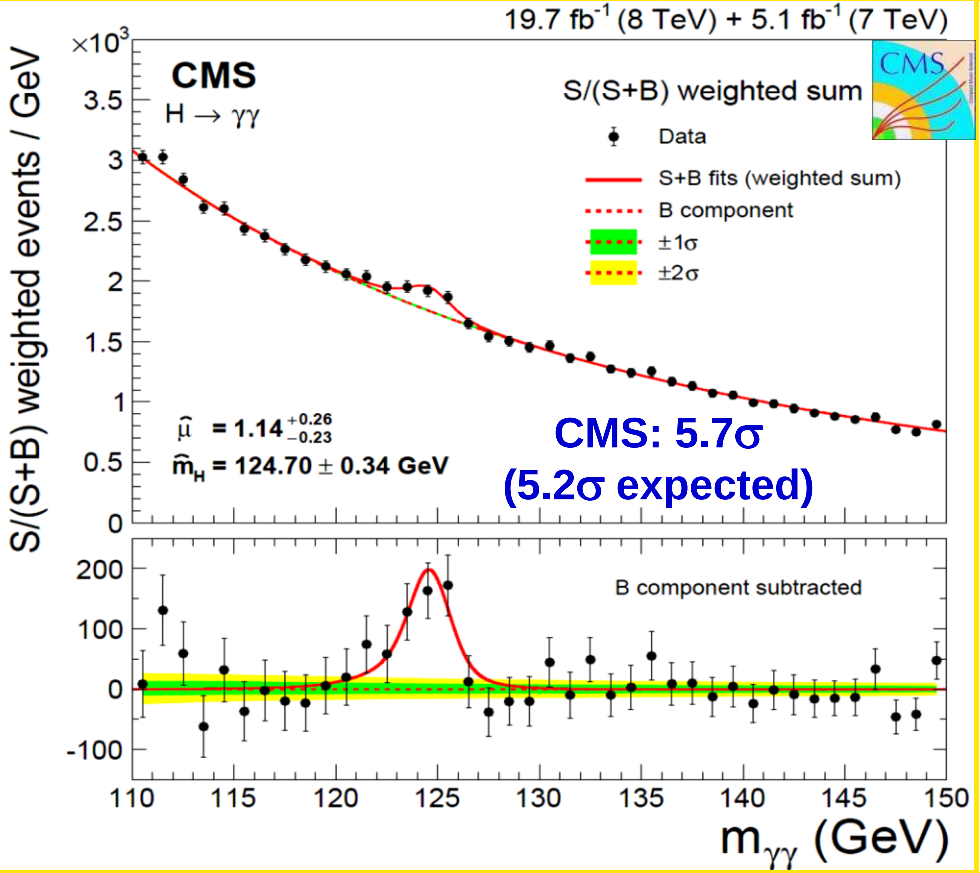
$M_{\gamma\gamma}$=125.9 GeV
σ_M/M=0.9%

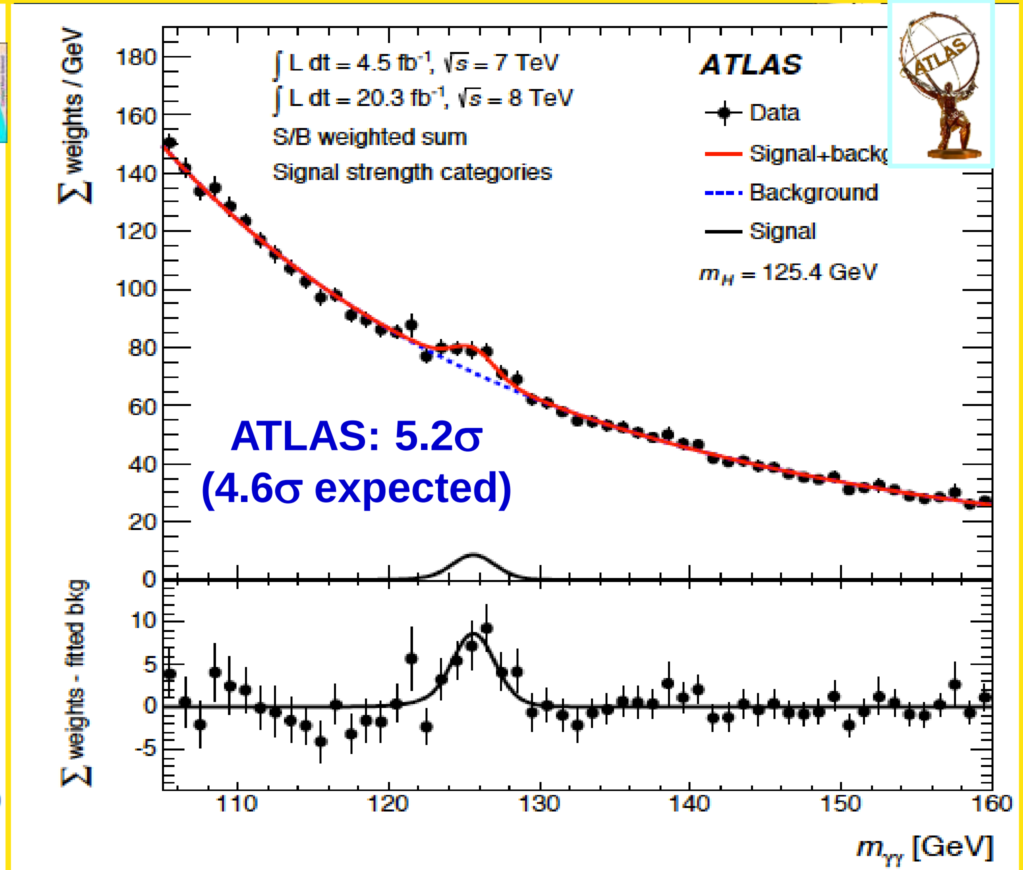
- Analysis optimized categorizing events by γ ID and vertex efficiency; purity & mass resolution.
- Specific di-jet tag categories targeting VBF production mode (Higher S/B)
- Exclusive categories (e, μ, E_T^{Miss}) targeting WH, ZH Associated Production

Arxiv 1407.0558v2

$H \rightarrow \gamma\gamma$ at LHC Run 1

Enough for Discovery in this channel alone





Arxiv 1407.0558v2 EPJ C74 (2014) 3076

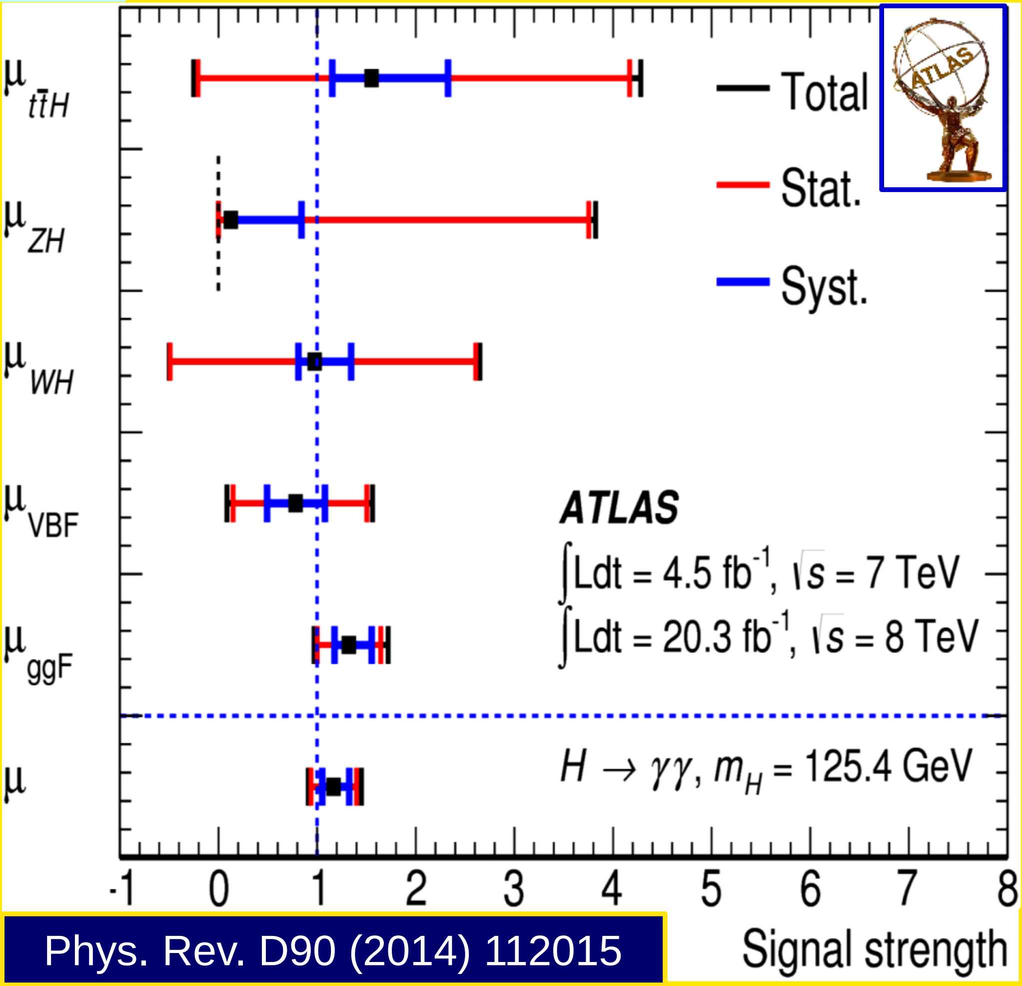
Phys. Rev. D90 (2014) 112015

ATLAS and CMS Each Observe a Signal with Local Significance > 5σ

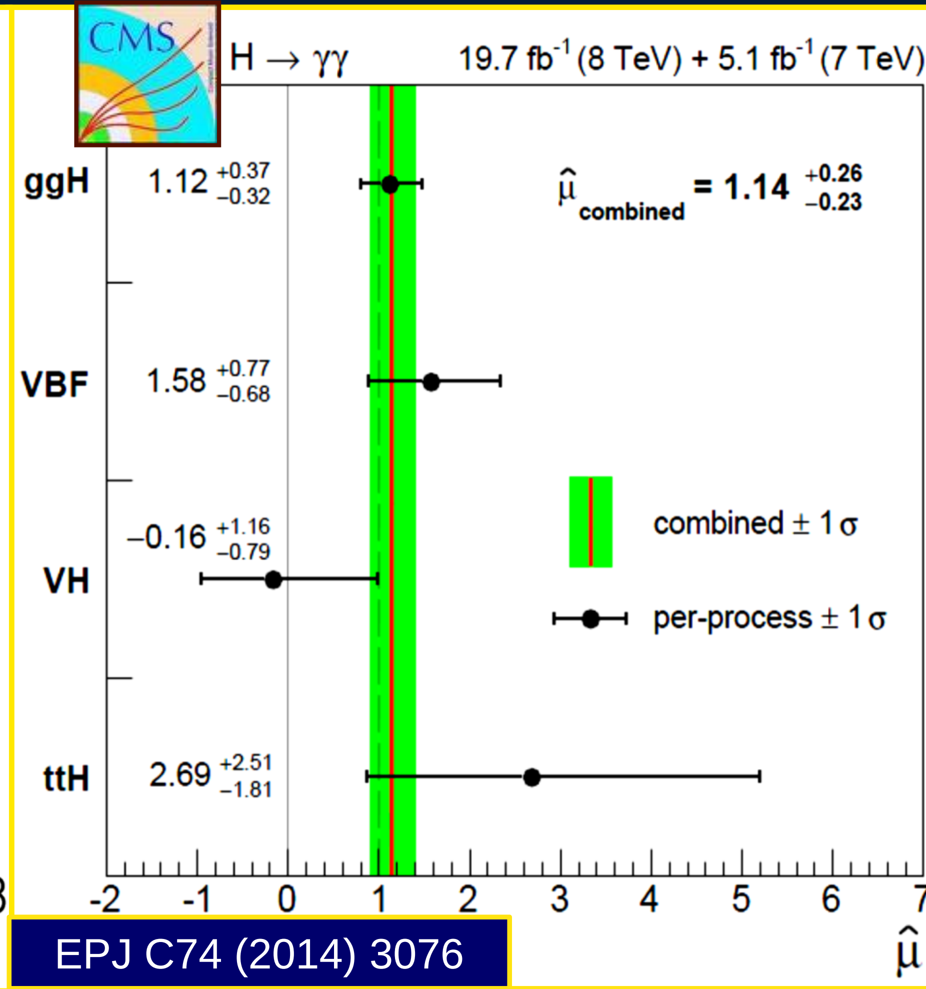
CMS	$\mu(m_H=124.7\ \text{GeV}) = 1.14 \pm 0.21\ (\text{stat})\ ^{+0.09}_{-0.05}\ (\text{syst})\ ^{+0.13}_{-0.09}\ (\text{theo})$
ATLAS	$\mu(m_H=125.6\ \text{GeV}) = 1.17 \pm 0.23\ (\text{stat})\ ^{+0.10}_{-0.08}\ (\text{syst})\ ^{+0.12}_{-0.08}\ (\text{theo})$

$H \rightarrow \gamma\gamma$ Best Fit Signal Strengths $\mu = \sigma/\sigma_{SM}$

For the Various Production Modes



Phys. Rev. D90 (2014) 112015



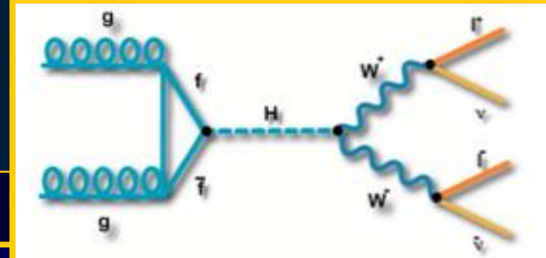
EPJ C74 (2014) 3076

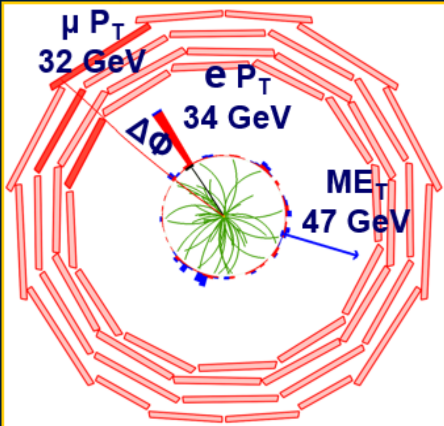
Best fit signal strengths for individual production processes are consistent with SM expectations. Need more data for VH, ttH

$H \rightarrow WW \rightarrow 2l\,2\nu,\ 3l3\nu\ (l = e, \mu)$

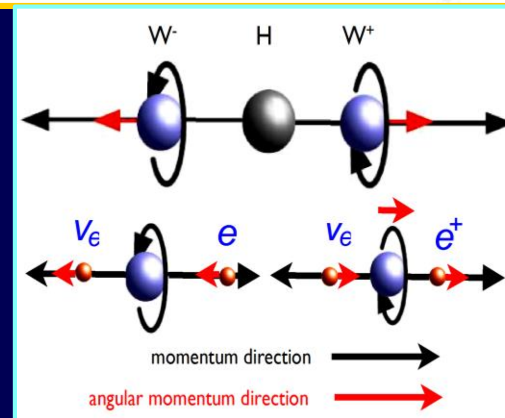
High Sensitivity, Low Resolution

Arxiv 1312.1129 JHEP 01 (2014) 096



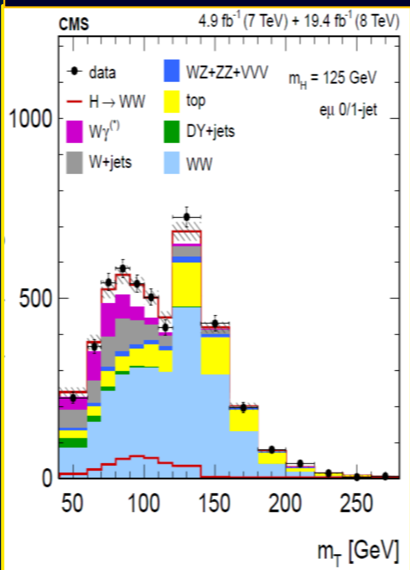


- ➡ Significant E_T^{Miss} ➡ No Mass Peak
- ➡ Smaller $\Delta\Phi\ (l^+l^-)$ and hence M_{ll} for low M_H: Higgs is a scalar, V-A
- ➡ Categories for ggF, VBF, VH, ttH
- ➡ Greatest sensitivity: $e\nu\ \mu\nu$ + 0,1 Jet
- ➡ Main backgrounds WW, tt, DY, W+Jet

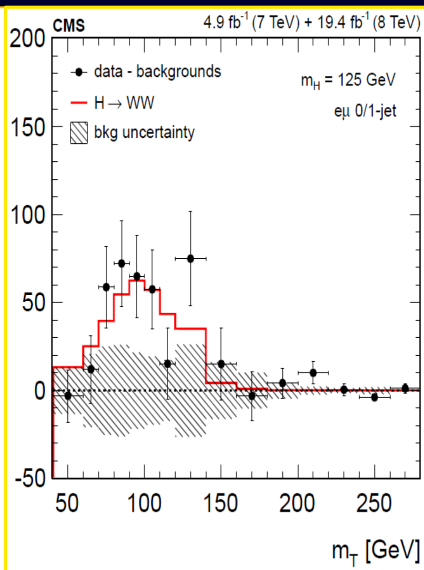


M_T in eμ + 0,1 Jet S/(S+B) Weighted

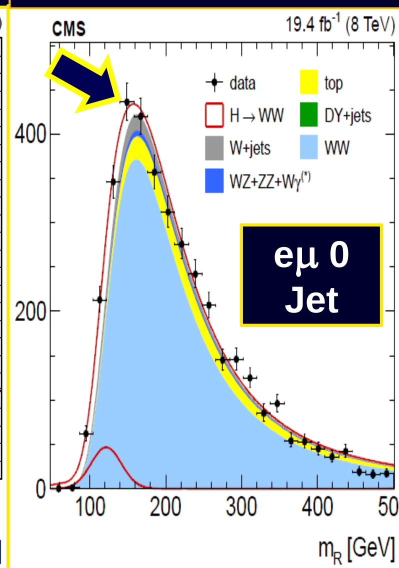
Extracting M_H, $\mu = \sigma/\sigma_{SM}$ with the Razor in $e\mu\nu\nu$



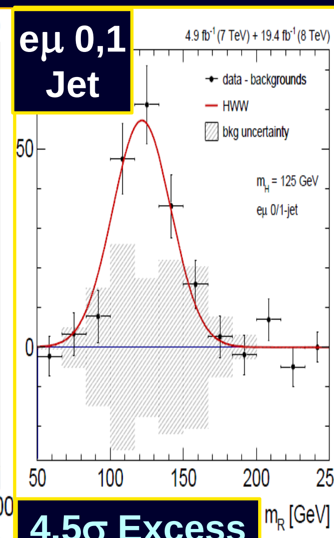
Signal at Low MT



Bckground Subtracted

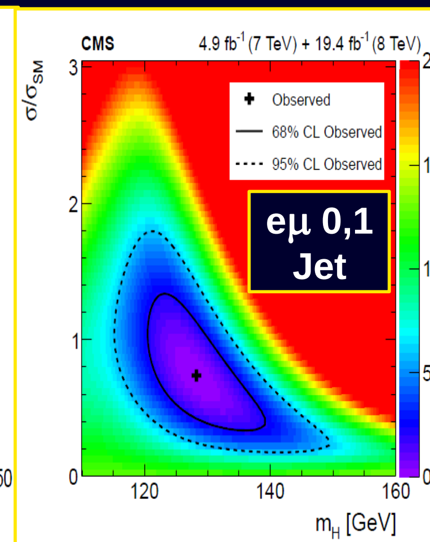


Signal at $M_R \sim M_H$



4.5σ Excess

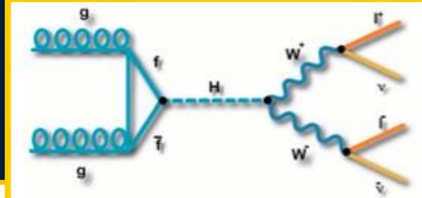
Backgrd subtracted S/(S+B) Weighted



Best fit Mass = 125.5 + 3.6 – 3.8 GeV (μ=1)

$H \rightarrow WW \rightarrow 2l\,2\nu$ ($l = e, \mu$)

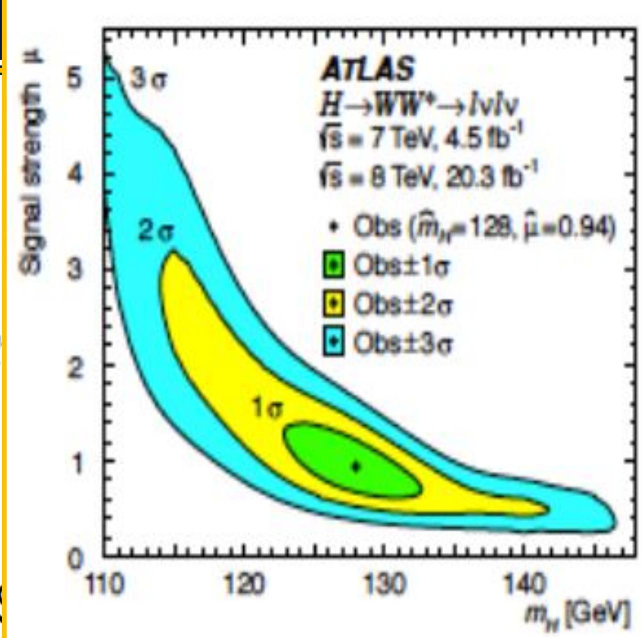
Most Sensitive for 130-200 GeV

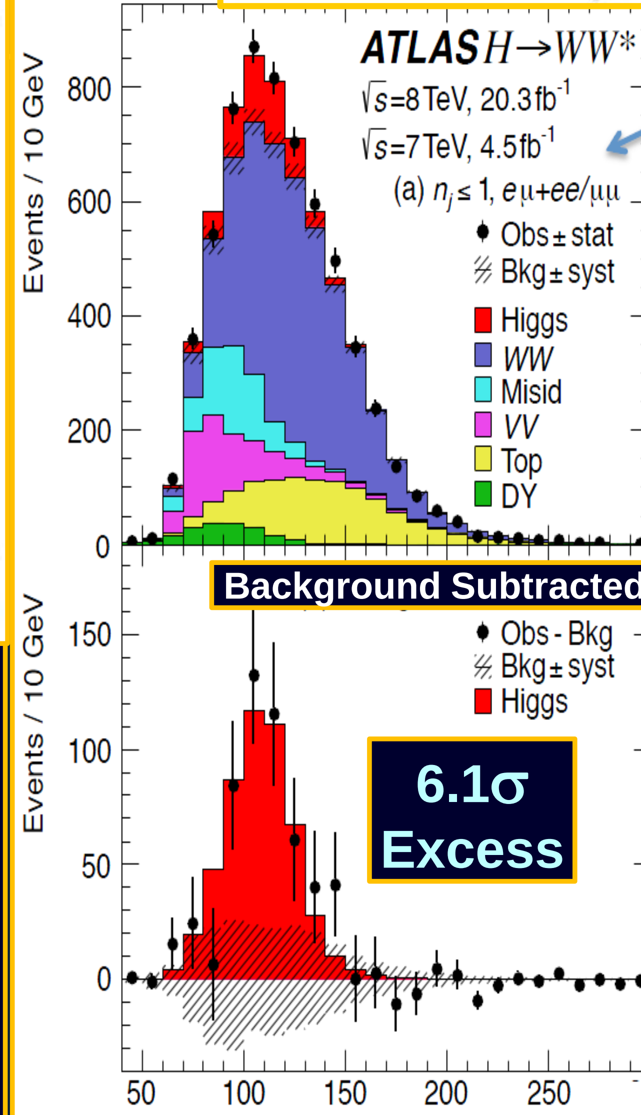


ATLAS Arxiv 1412.2641

Analysis Outline:

- ❒ 2 OS Lepton, E_T^{Miss}
- ❒ 0, 1, 2 Jet Categories
- ❒ Topological Cuts on Lepton Pair: M, P_T, $\Delta\phi$
- ❒ Background estimates from sidebands





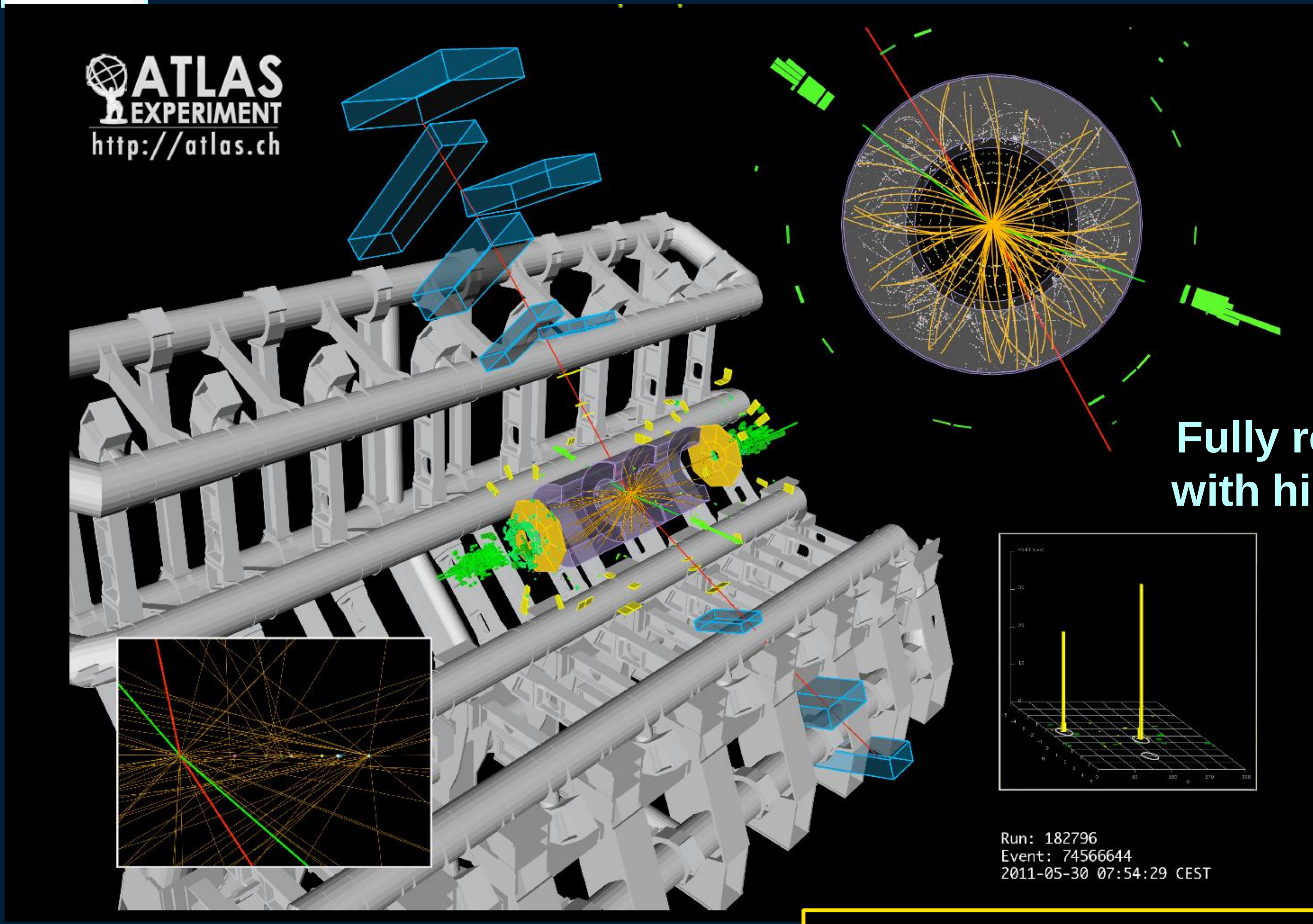
M_T for full selection with 0,1 Jet

- ❒ **Signal Seen** at 4.5-6σ Level by CMS, ATLAS
- ❒ **Signal Strengths** σ/σ_{SM}

ATLAS $\mu(m_H{=}125.36) = 1.09\,^{+0.16}_{-0.15}\,(stat)\,^{+0.17}_{-0.14}\,(sys)$

CMS $\mu(m_H{=}125.6) = 0.72\,^{+0.12}_{-0.12}\,(stat)\,^{+0.12}_{-0.10}\,(th)\,^{+0.10}_{-0.10}\,(sys)$

H ➡ZZ ➡ e+e−μ+μ− Candidate Event



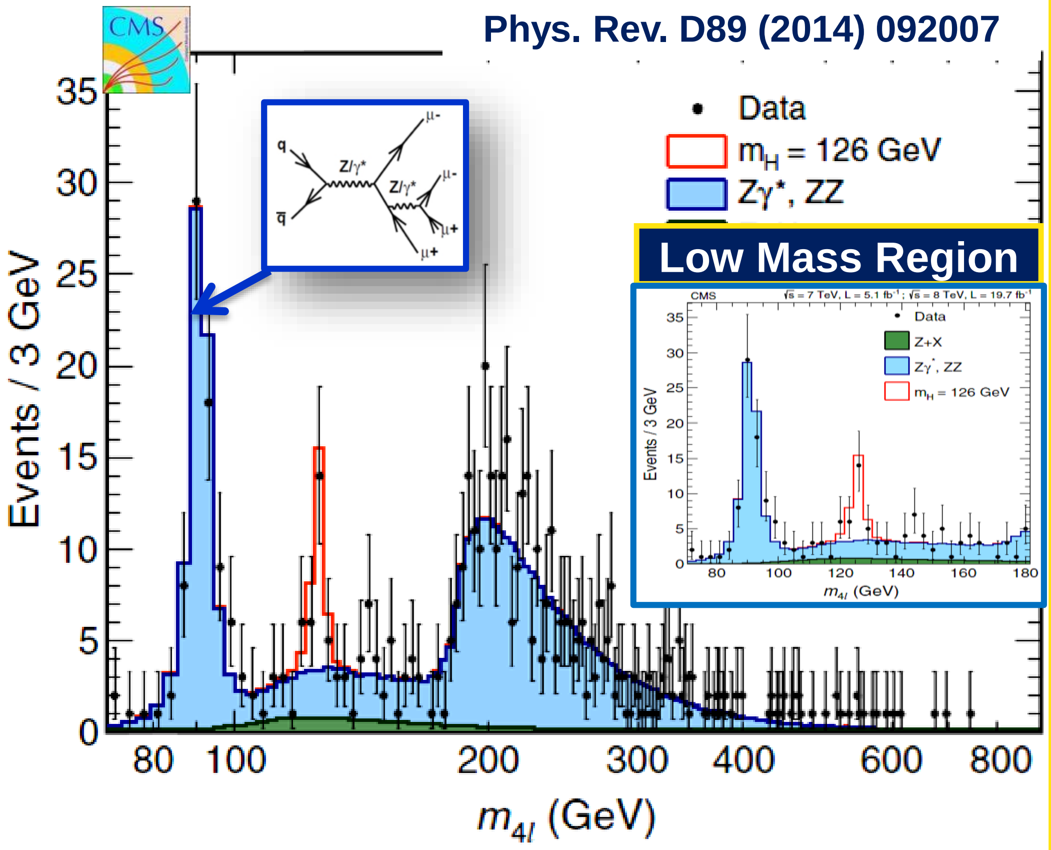
Fully reconstructed with high resolution

Phys. Rev. D91 (2014) 012006

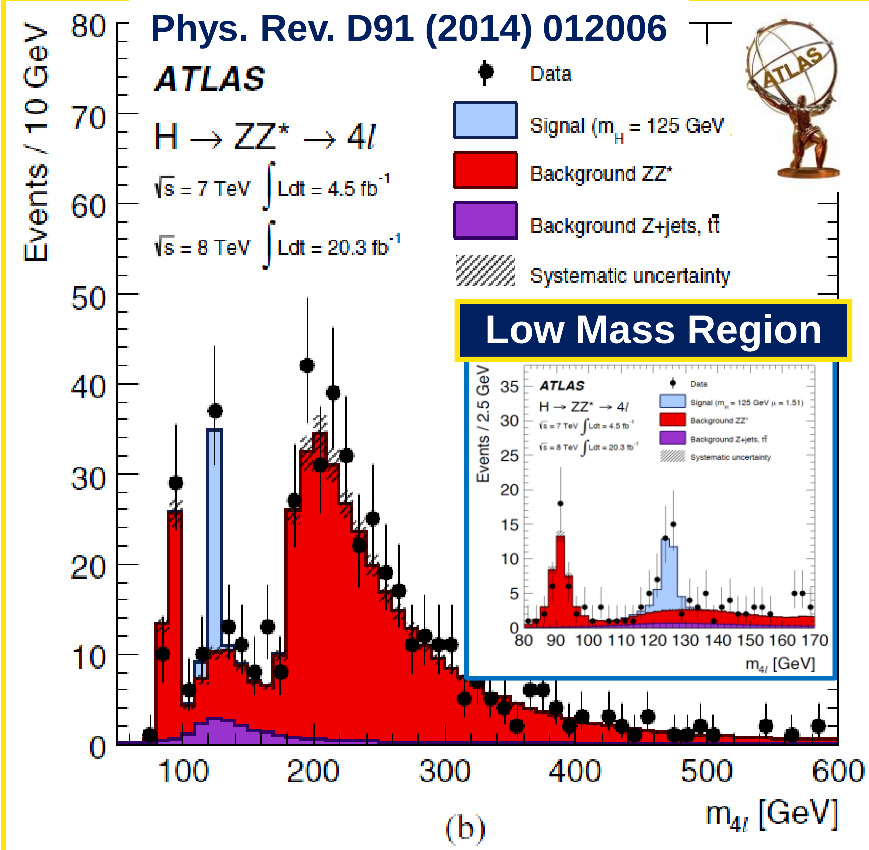
H → ZZ(*): Reconstructed Mass Spectra from 4ℓ decays

ZZ → 4e, 4μ, 2e2μ Candidates; Z →4l Peak Provides Cross Check

Phys. Rev. D89 (2014) 092007



Phys. Rev. D91 (2014) 012006



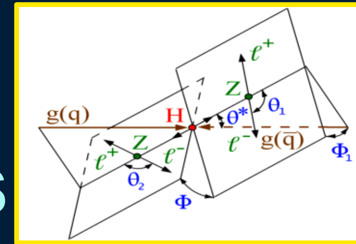
μ (CMS) = $0.93^{+0.29}_{-0.23}$

μ (ATLAS) = $1.44^{+0.40}_{-0.33}$

Significance in Each Experiment > 6 σ

$H \to ZZ \to 4\ell$

Spin and Parity Measurements



- We know it is a boson, not Spin 1, not 100% 0- [PRL 110 081803 (2013)]
- To go further: build discriminants $\mathcal{D}$ based on complete LO Matrix Elements

1. $\mathcal{D}_{\rm bkg}$ to separate Signal from Background, combined with mass info.

$$\mathcal{D}_{\rm bkg} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm bkg}(m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_{0^+})}\right]^{-1}$$

2. $\mathcal{D}_{JP}$ to Separate SM Higgs from alternate J^P

$$\mathcal{D}_{J^P} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

5 Angles and 3 Masses
Many *Discriminants*…
***Templates*…**
***Details*…**

ArXiv:1411.3441

- Test (in ZZ and WW) several well-motivated alternatives using fully correlated information in the ($D_{\rm bkg}$, D_{JP}) plane: Pure States

Production model independent

$\mathcal{D}_{0^-}$	Pseudoscalar (0^-), discriminates against SM Higgs boson.
$\mathcal{D}_{0_h^+}$	Non-SM scalar with higher-dimension operators (0_h^+).

For $J^P \neq 0$ integrate over prod. angles θ, Φ_1

$\mathcal{D}_{1^-}$	Exotic vector (1^-), $q\bar{q}$ annihilation.
$\mathcal{D}_{1^+}$	Exotic pseudovector (1^+), $q\bar{q}$ annihilation.
$\mathcal{D}^{gg}_{2_m^+}$	Graviton-like with minimal couplings (2_m^+), gluon fusion.
$\mathcal{D}^{q\bar{q}}_{2_m^+}$	Graviton-like with minimal couplings (2_m^+), $q\bar{q}$ annihilation.
$\mathcal{D}^{gg}_{2_b^+}$	Graviton-like with SM in the bulk (2_b^+), gluon fusion.
$\mathcal{D}^{gg}_{2_h^+}$	Tensor with higher-dimension operators (2_h^+), gluon fusion.
$\mathcal{D}^{gg}_{2_h^-}$	Pseudotensor with higher-dimension operators (2_h^-), gluon fusion.

Anomalous CP Couplings of a Spin 1 or 2 Higgs Using $H \rightarrow V^{(*)}V^{(*)}$ (V= Z, W, γ) Decays

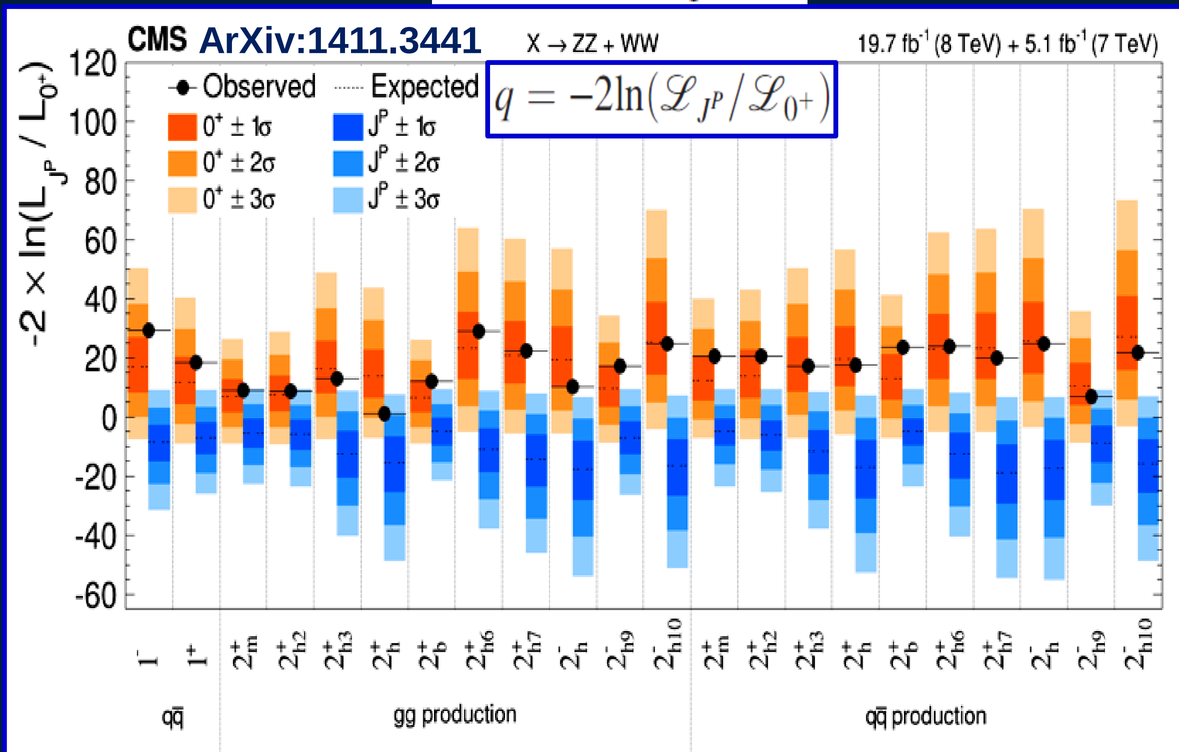
Effective Amplitude Parametrization

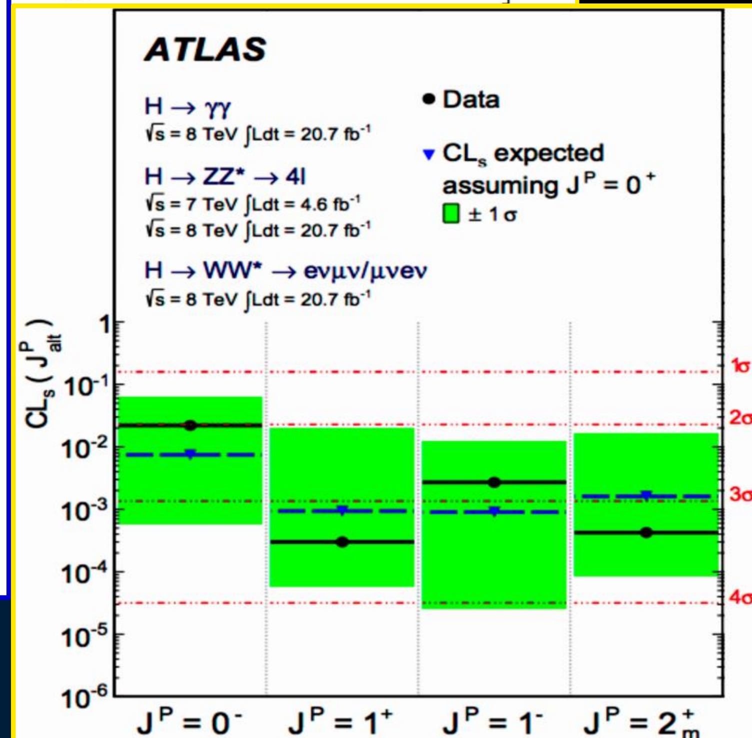
SPIN 1

$$A(X_{J=1} \rightarrow V_1 V_2) \sim b_1 \left[(\epsilon^*_{V_1} q)\,(\epsilon^*_{V_2} \epsilon_X) + (\epsilon^*_{V_2} q)\,(\epsilon^*_{V_1} \epsilon_X) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon^{\alpha}_{X} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} \tilde{q}^{\beta}$$

SPIN 2

$$\begin{aligned} A(X_{J=2} \rightarrow V_1 V_2) \sim \Lambda^{-1} \Big[& 2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\ & + c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\ & + m_V^2 \left(2c_5 t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2}) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_{V_1} \epsilon^*_{V_2} \right) \\ & + c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma \\ & + \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V_1} (q \epsilon^*_{V_2}) + \epsilon^{*\nu}_{V_2} (q \epsilon^*_{V_1}) \right) \Big], \end{aligned}$$





CMS: J^P Values: many models Other than 0+ Ruled out with ≥ 4σ significance

ATLAS : results on spin/parity (using *H→γγ, ZZ and WW*) Also favor 0+

Anomalous CP Couplings of a Spin 0 Higgs Using $H \to V^{(*)}V^{(*)}$ (V= Z, W, γ) Decays

Effective Amplitude Parametrization

- a_1: SM CP-even coupling
- Λ_1: BSM Scale (GeV)
- a_2 (a_3): CP even (odd) anomalous Couplings
- Results in cross section fractions f, phases ϕ

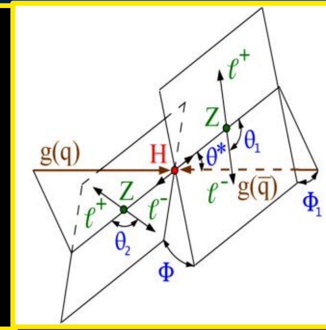
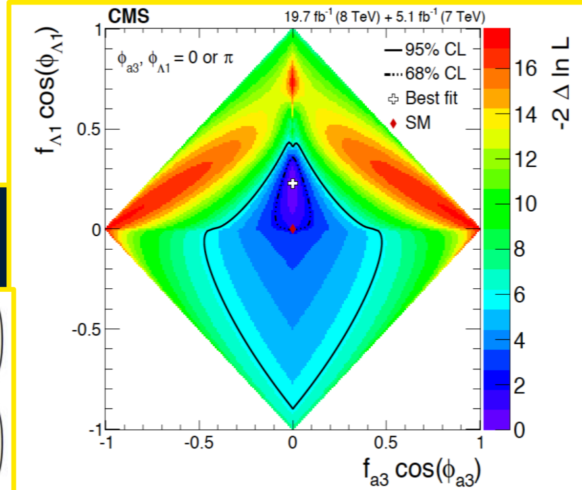


Illustration: $f_{\Lambda 1}$ vs f_{a3} constraints with ϕs 0, π



Starting with Spin-0 :

SM HZZ decay (a1)

Leading momentum dependent correction

$$
\begin{aligned}
A(X_{J=0}\to V_1V_2) = v^{-1}\Bigg(&\left[a_1 - e^{i\phi_{\Lambda_1}}\frac{q^2_{Z_1}+q^2_{Z_2}}{(\Lambda_1)^2}\right] m_Z^2\epsilon^*_{Z_1}\epsilon^*_{Z_2} \\
&+ a_2 f^{*(Z)}_{\mu\nu} f^{*(Z),\mu\nu} + a_3 f^{*(Z)}_{\mu\nu}\tilde{f}^{*(Z),\mu\nu} \\
&+ a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu}\tilde{f}^{*(\gamma),\mu\nu} \\
&+ a_2^{\gamma\gamma} f^{*(\gamma)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma)}_{\mu\nu}\tilde{f}^{*(\gamma),\mu\nu}\Bigg),
\end{aligned}
$$

non-SM scalar (a2)

SM Zγ

SM $\gamma\gamma$

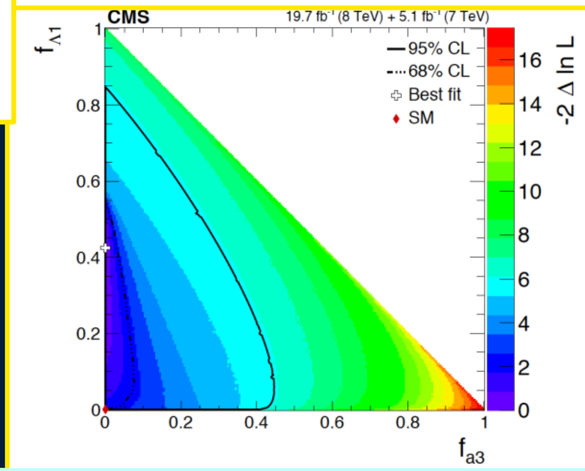
Pseudo-scalars (a3)

ArXiv:1411.3441

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1+|a_2|^2\sigma_2+|a_3|^2\sigma_3+\tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1+|a_2|^2\sigma_2+|a_3|^2\sigma_3+\tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4} \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4}{|a_1|^2\sigma_1+|a_2|^2\sigma_2+|a_3|^2\sigma_3+\tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^4} \qquad \phi_{\Lambda 1},$$



$H \to Z(\gamma^*)Z(\gamma^*) \to 4\ell$: Full 8D phase space: (5 angles, M_{Z1}, M_{Z2}, M_{4l})

$H \to WW \to \ell\nu\ell\nu$: dilepton mass and transverse masses constrain the fractions

Scenarios: Real phases; floating phases

Best Fit Results very close to SM expectations

Constraints on Anomalous Spin 0 Mixtures with $J^P = 0+$

Arxiv 1506.05669

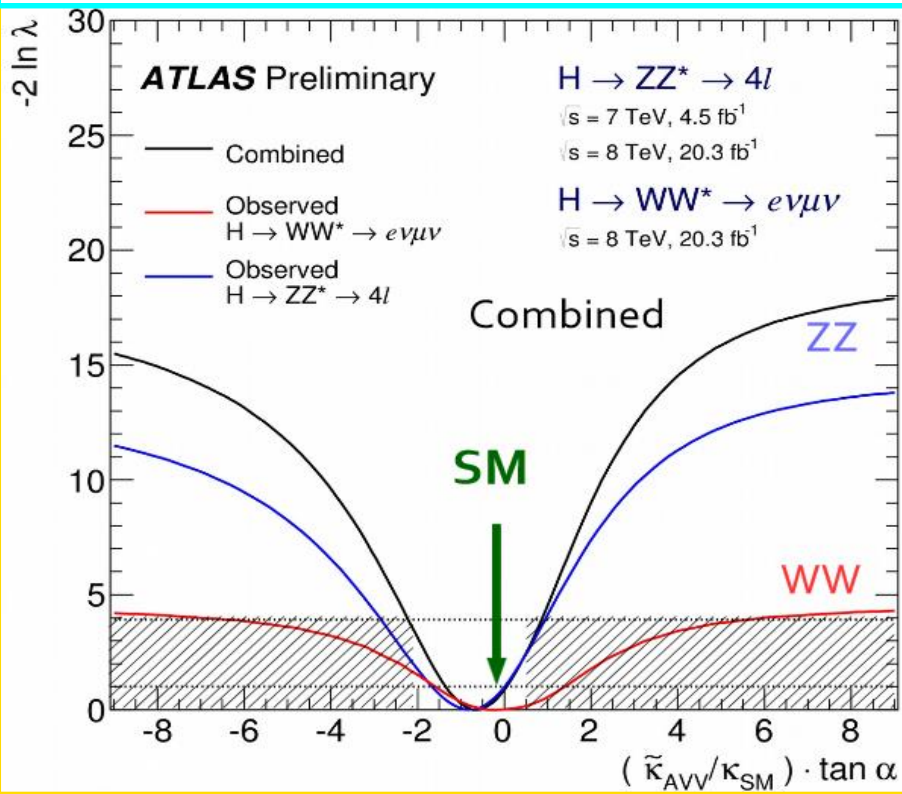
$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV} \quad \tilde{\kappa}_{HWW} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HWW}$$

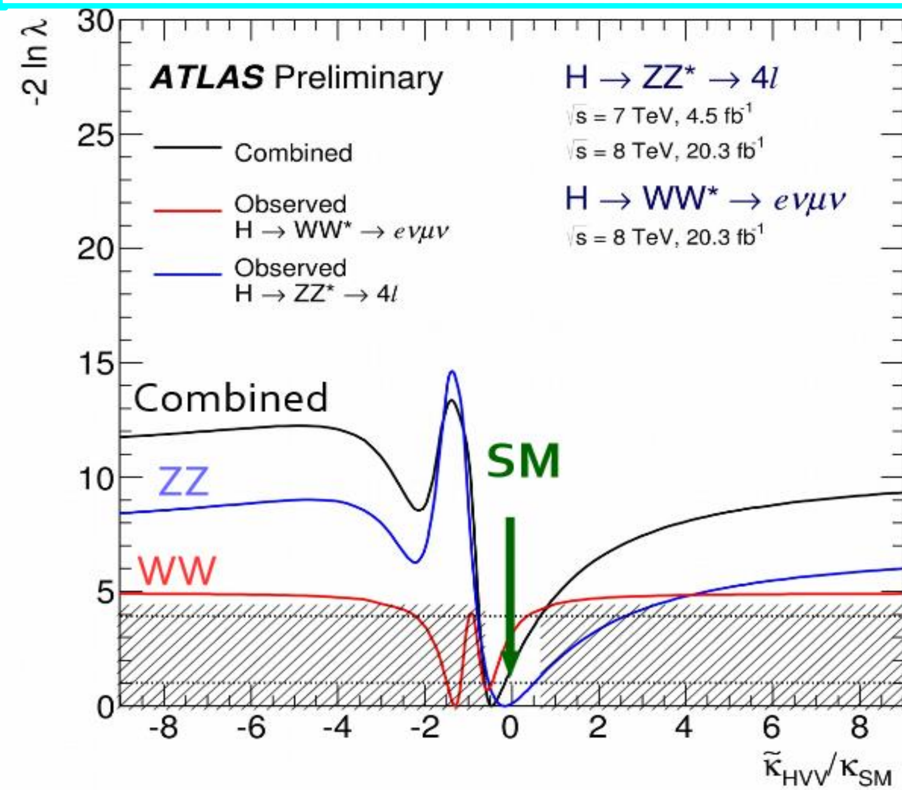
α is a CP-mixing angle

Scan coupling ratios (only one at a time):

$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha \qquad \tilde{\kappa}_{HVV}/\kappa_{SM}$

Rate information not used in fit





Exclude $(-\infty, -2.18] \cup [0.83, \infty)$ $\qquad (-\infty, -0.73] \cup [0.63, \infty)$

No evidence for mixing with J^P = 0- or BSM 0+

Is it a **PURE** scalar?

➡ Full 8D ME-Based Analysis

Calculate probability density for the observables as function of parameters

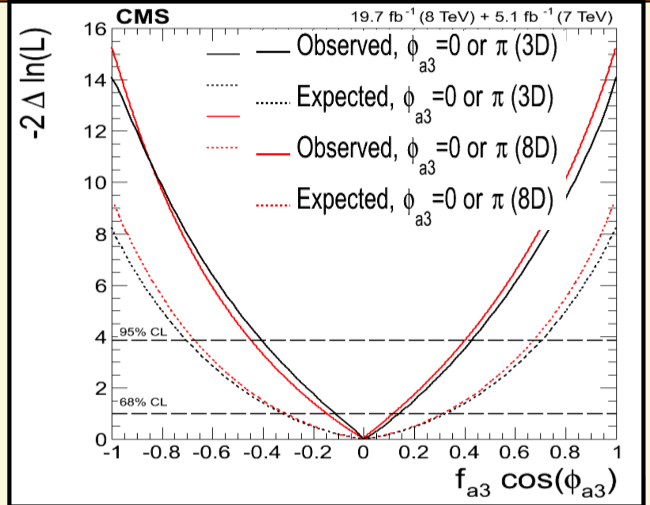
$$P(\vec{p}_T, Y, \phi, m_{4\ell}, m_1, m_2, \vec{\Omega} | \vec{\zeta}) =$$
$$W_{\mathrm{prod}}(\vec{p}_T, Y, \phi, \hat{s}) \times \frac{d\sigma_{4\ell}(m_{4\ell}, m_1, m_2, \vec{\Omega} | \vec{\zeta})}{dm_1^2 dm_2^2 d\vec{\Omega}}$$

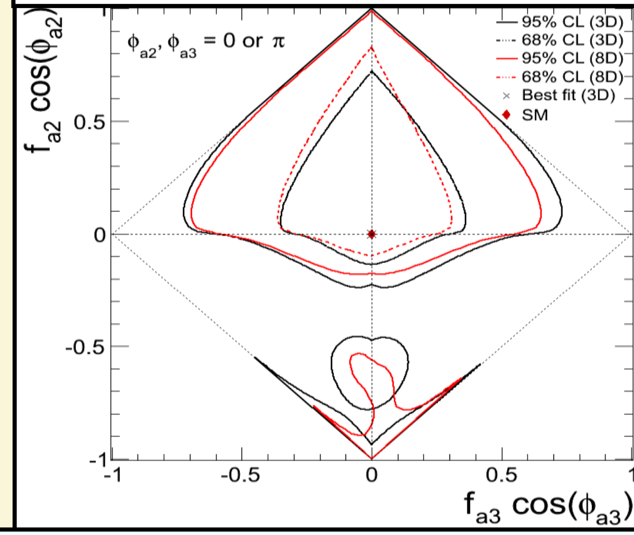
Matrix Element Calculation

Production Spectrum

$$P(\vec{x}^R | \vec{\zeta}) = \int P(\vec{x}^G | \vec{\zeta}) T(\vec{x}^R | \vec{x}^G) d\vec{x}^G$$

Convolution with transfer functions





Lots of Integrals…
Computation…
Ingenuity…
***Tractable* for the first time**

Yi Chen Thesis

Best fit point very close to SM
Pseudoscalar mixture above ~2 x SM Higgs ruled out
(Equivalent to ~40% by cross section)

Si Xie

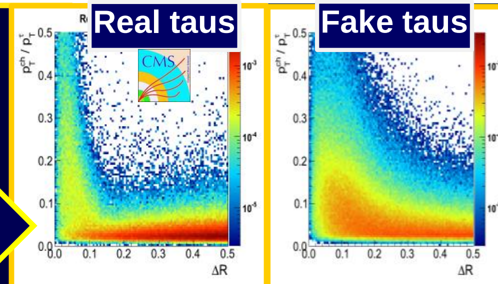
$H \rightarrow \tau\tau$: $\mu+\tau_h$, $e+\tau_h$, $\mu+e$, $\mu\mu$, $\tau_h\tau_h$

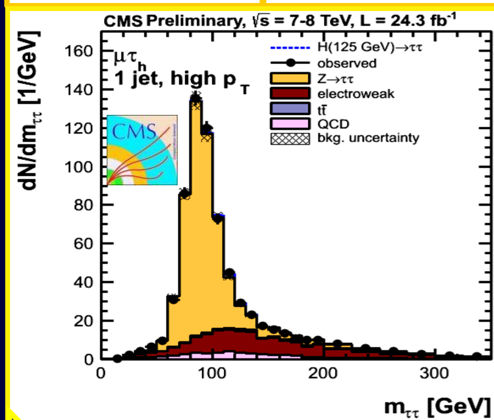
Coupling to Fermions

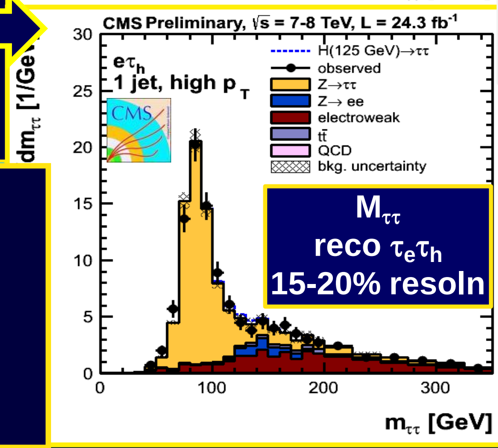
- Large backgrounds especially $Z \rightarrow \tau\tau$ and Di-bosons
- Categories using Jets and $P_T(\tau)$ different production, decay modes
- Improved lepton & τ_{had} ID
- Consistency of E_T^{Miss} being from ν_τs
- ✸ $m_{\tau\tau}$ reconstruction with event-by-event likelihood; &/or kinematics to estimate E_T^{Miss} : 10-20% resoln
- Results: Combine many channels

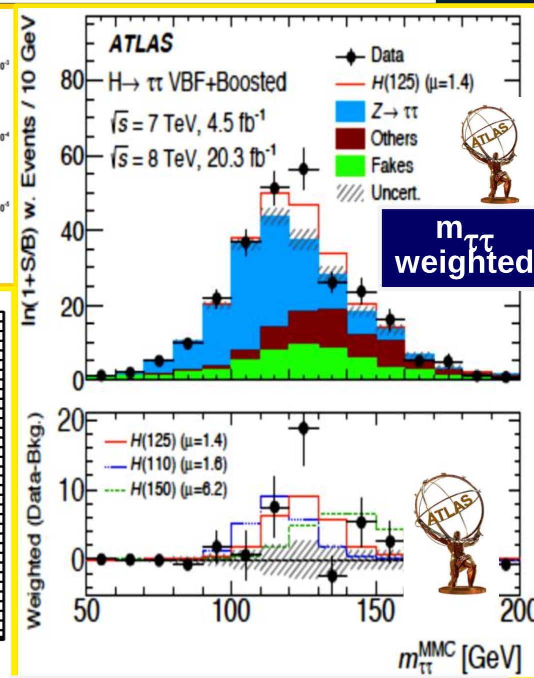
Emphasis On:

- Efficient pure τ ID
- Reconstruction with good $\tau\tau$ mass resolution in various τ decay modes

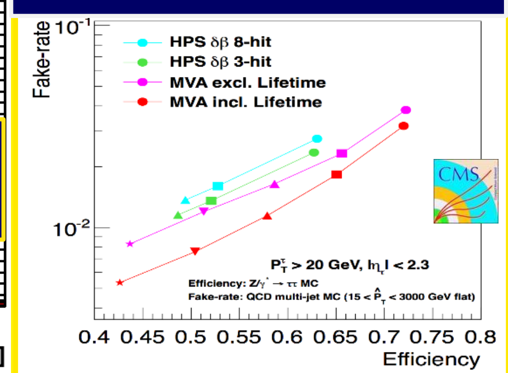








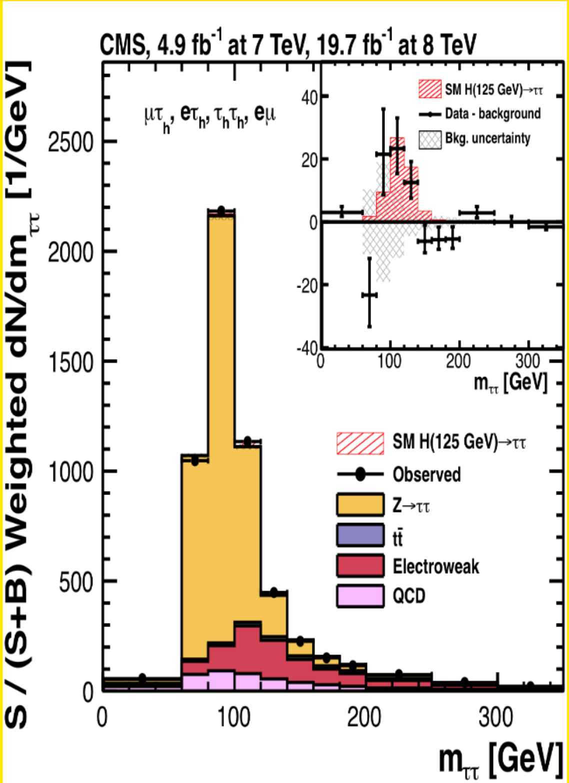
PF τ reconstruction:
ε = 60% at 1-2% MisID

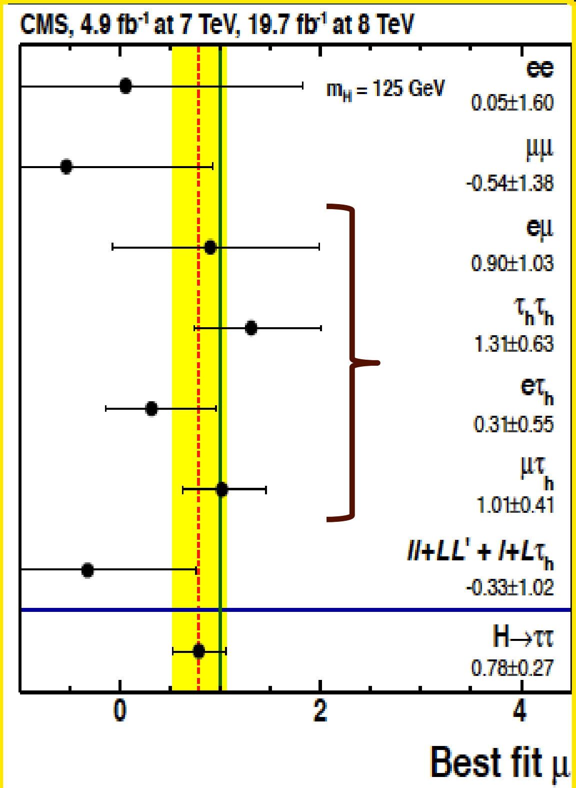


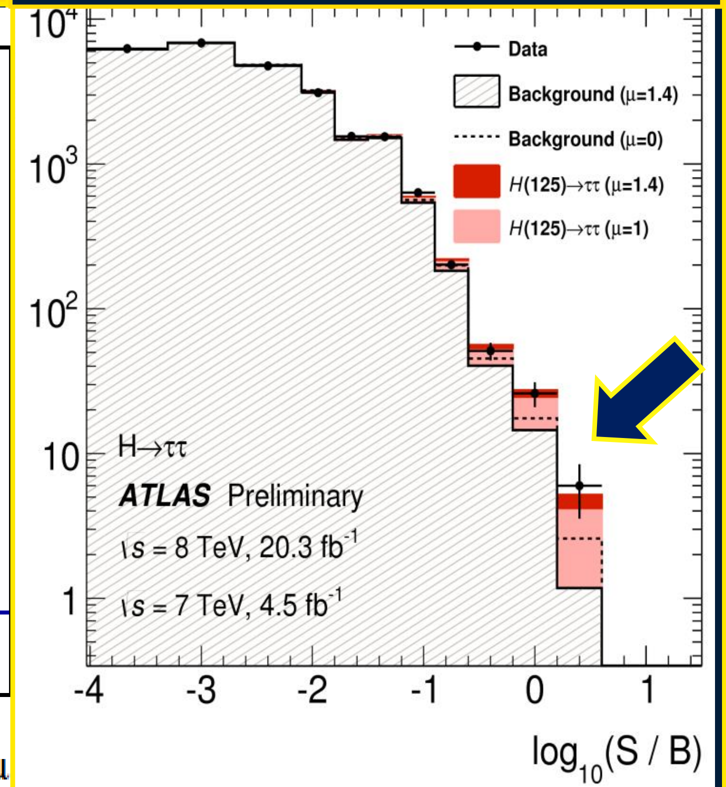
Higgs → ττ

Evidence for Couplings to Fermions

Combined $dN/dM_{\tau\tau}$	$\mu = \sigma/\sigma_{SM}$ by decay mode	Multivariate Analysis to classify events by S/B







Higgs to ττ Signal: Evidence for Coupling to Fermions

ATLAS: $\mu = 1.43^{+0.43}_{-0.37}$ (4.5σ)   CMS: $\mu = 0.78 \pm 0.27$ (3.2σ)

Higgs→ $b\bar{b}$ Analysis

Coupling to Fermions

- Largest σ•BR but very large QCD Background

➡ Use VH and VBF (CMS: New): Greater S/B

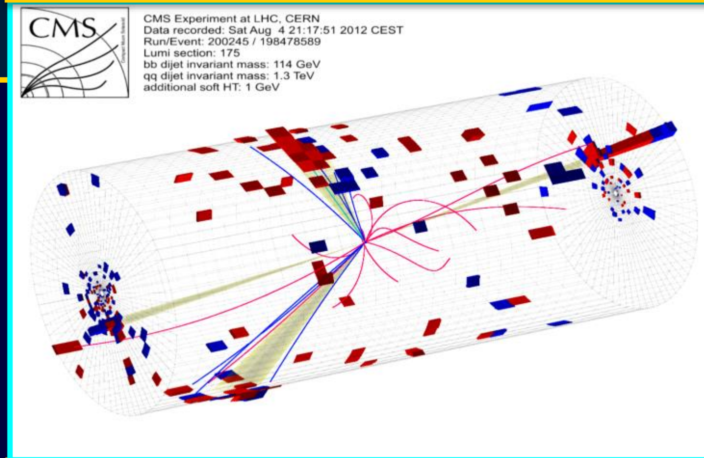
- Signatures: Leptons, b-jets and E_T^{Miss}

5 VH Channels Z(ℓℓ)+H(bb), Z(νν)+H(bb), W(ℓν)+H(bb)

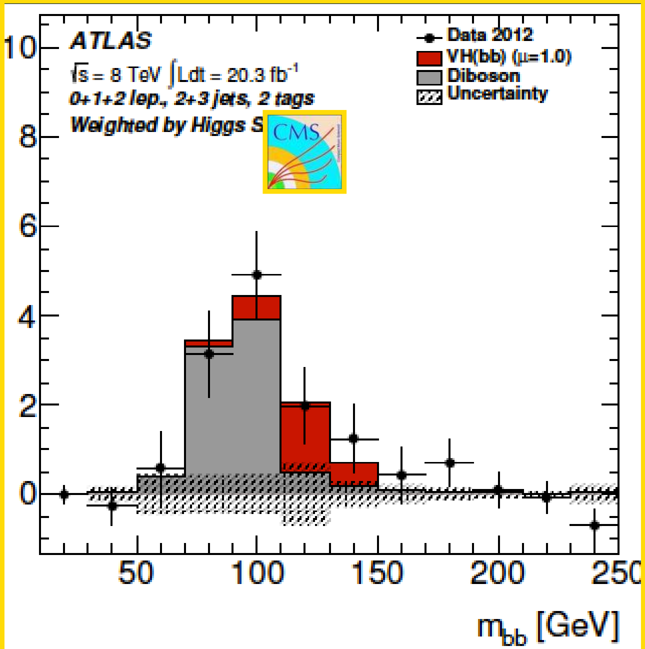
  - Reducible Background: W, Z + Jets, Top

- Cross checks with VZ, qqZ where Z → bb

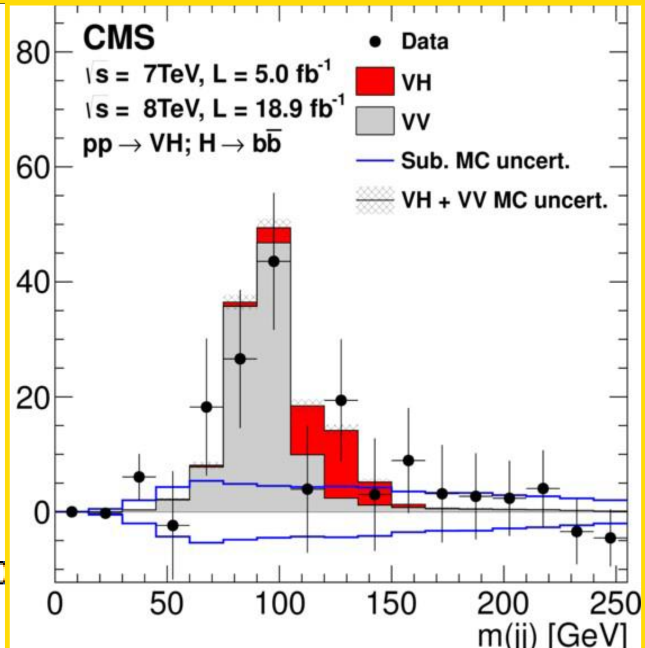
VBF H →bb Candidate



M_{bb} weighted by Higgs S/B

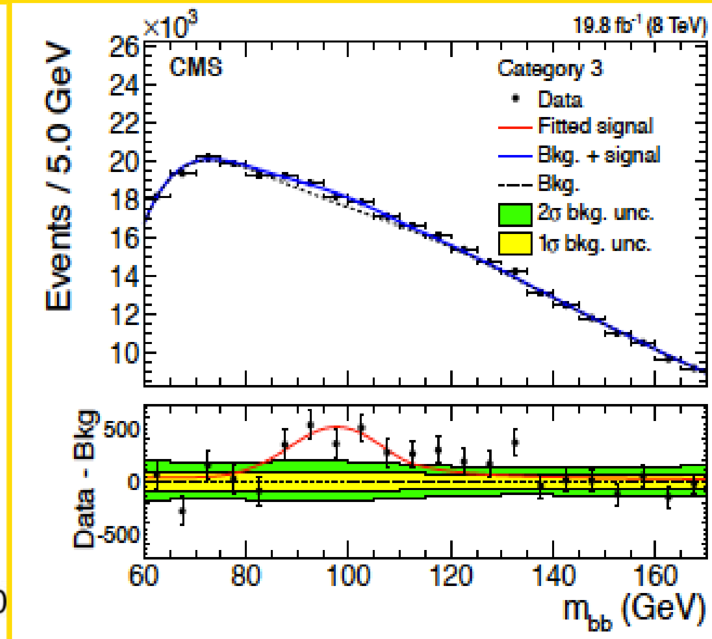


Mjj weighted by Higgs S/(S+B)



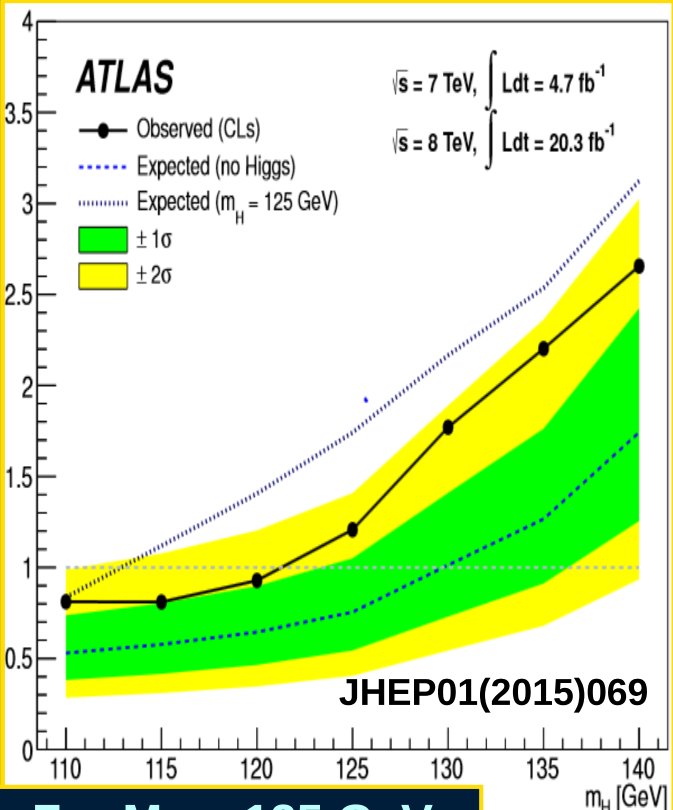
VBF Z → bb Cross-Check

Find $\mu_Z = 1.10^{+0.44}_{-0.33}$

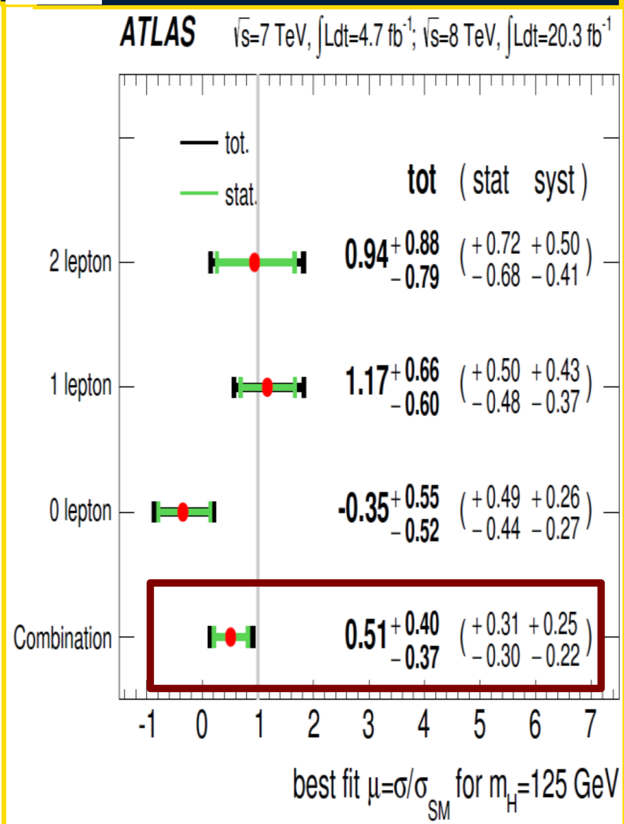


Higgs → $b\bar{b}$ Results

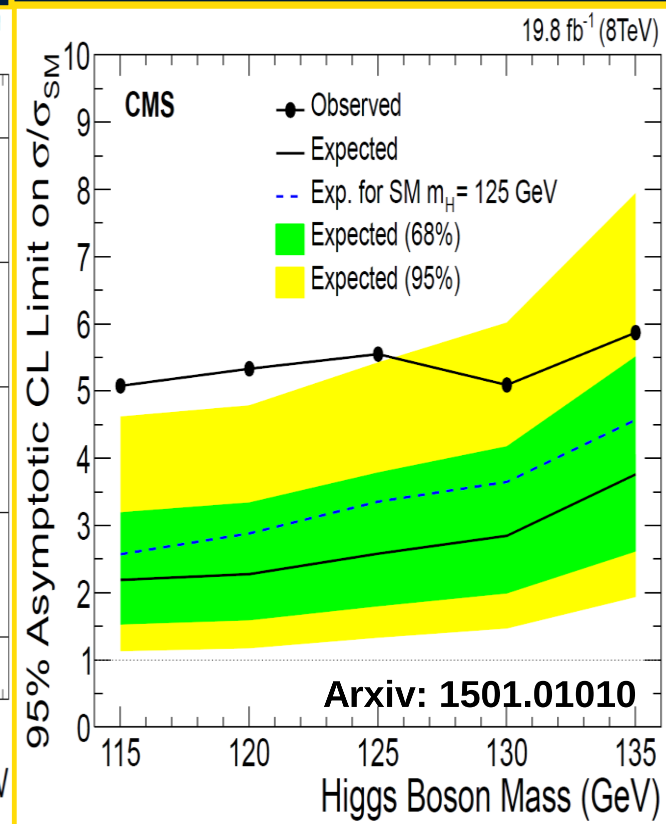
σ/σ_{SM} 95% CL UL vs expectations



Best Fit σ/σ_{SM} 0,1,2 Leptons + Combined



VBF σ/σ_{SM} 95% CL UL vs expectations



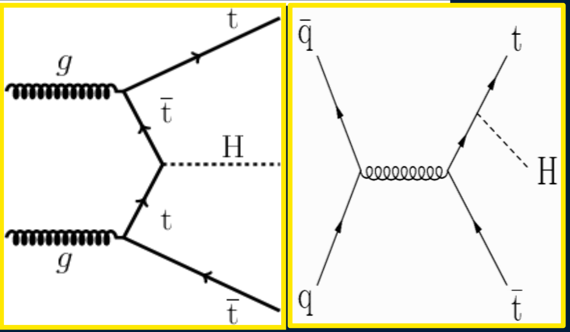
For M_H = 125 GeV:

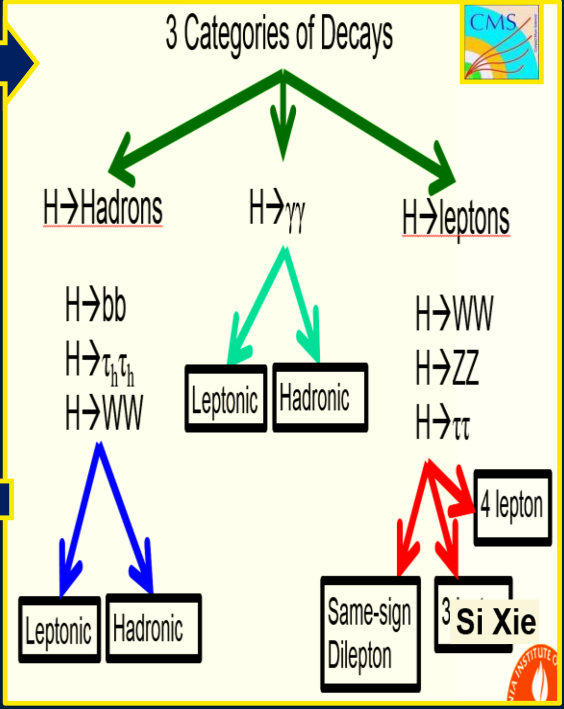
Higgs to bb Signal: ATLAS: 1.4σ (2.6σ exp.), μ = 0.51 ± 0.40 (VH)
CMS: 2.6σ (2.7σ exp.), μ = 1.0 ± 0.4 (Combined); 3.8σ for ττ + bb

ttH Production

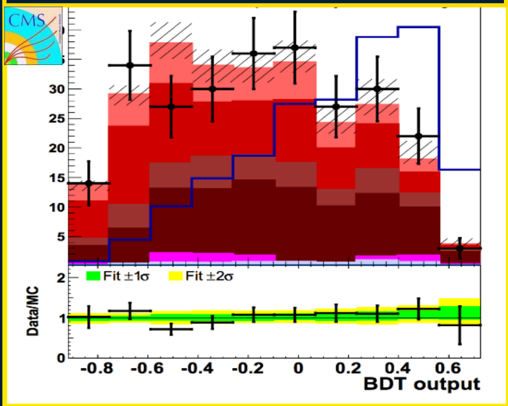
Direct Top Yukawa Measurement

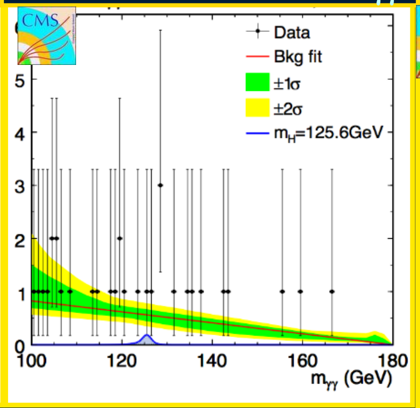
- SM Top Yukawa (~1) already probed through gluon fusion production and H→γγ decay
- But direct observation yields more information: e.g. disentangle possible BSM loop contributions
- ttH cross section: At 8 TeV: 0.13 pb
  At 13 TeV: 0.51 pb (4 X Larger)
- Small x-section but good S/B: Combine many channels: H→ hadrons (bb,ττ,WW), Photons (γγ), Leptons (WW,ZZ,ττ)
- Main backgrounds: t-tbar (measured)
  ttW, ttZ (from theory predictions)

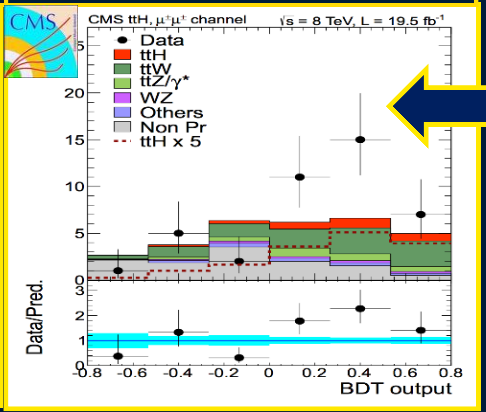




Hadrons: tt + H→ bb ≥6 Jets +≥4 b-tags MVA	Photons: tt + H→ γγ + hadronic: $m_{\gamma\gamma}$	Leptons: tt + H→ μμ + more lepton MVA

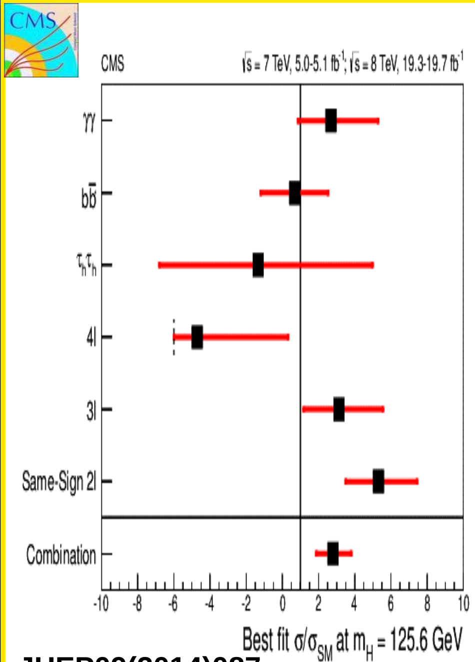






ttH Production Results

Best Fit $\mu = \sigma/\sigma_{SM}$ by mode, combined	Best Fit $\mu = \sigma/\sigma_{SM}$ multilepton channels	95% CL UL on $\mu = \sigma/\sigma_{SM}$ by decay mode, + combined	$\mu = \sigma/\sigma_{SM}$ 95% CL UL Multilepton Channels



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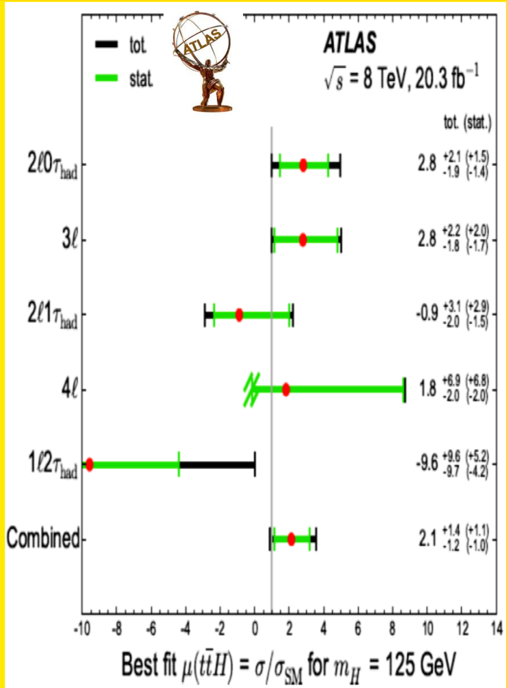
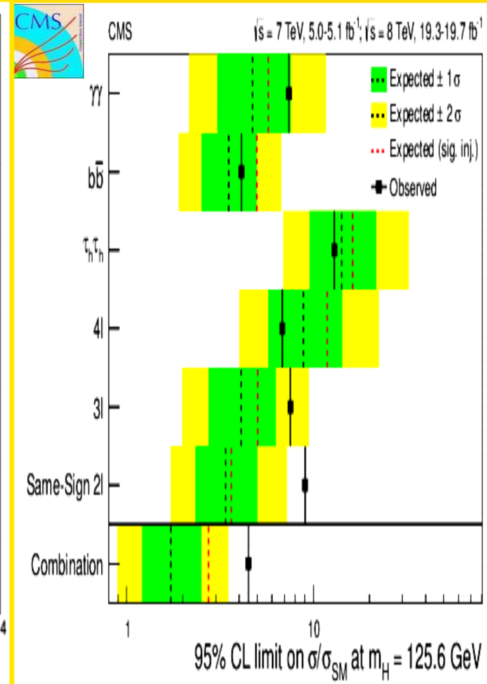
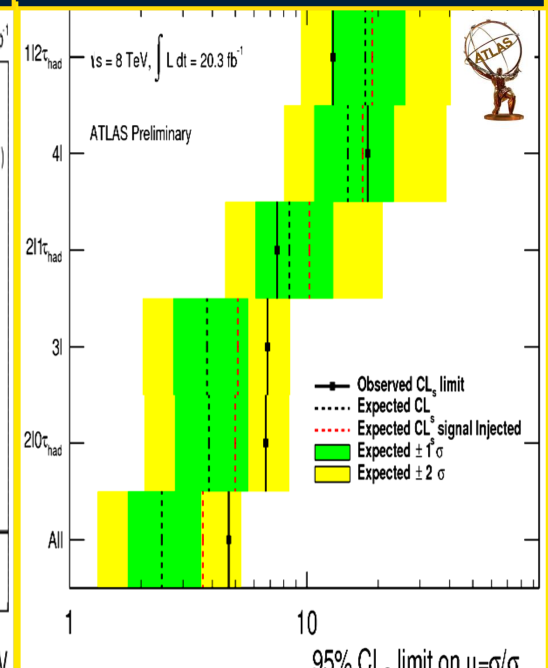






ATLAS-CONF-2015-006

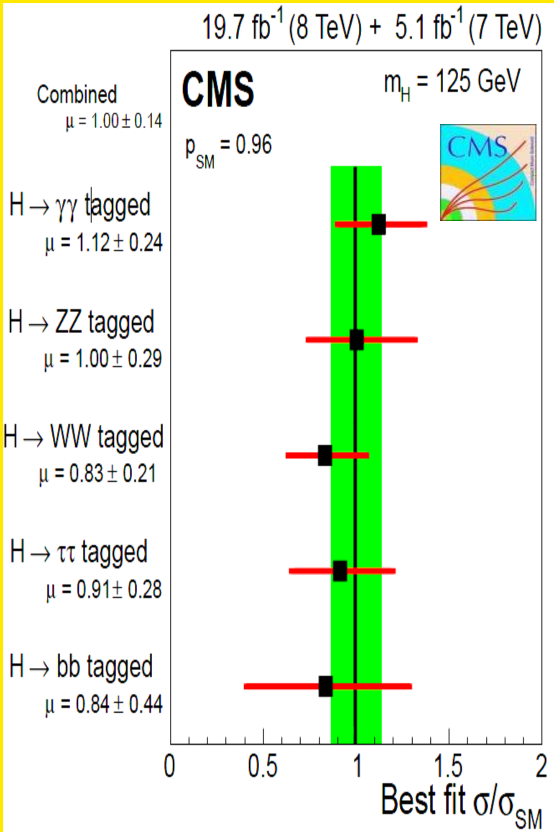
ATLAS: $\mu = 2.1^{+1.4}_{-1.2}$ (Multileptons) $\mu = 1.5 \pm 1.0$ ($H \rightarrow bb$)

CMS: $\mu = 2.8 \pm 1.0$ (Combined) ***Evidence: 3.4σ***

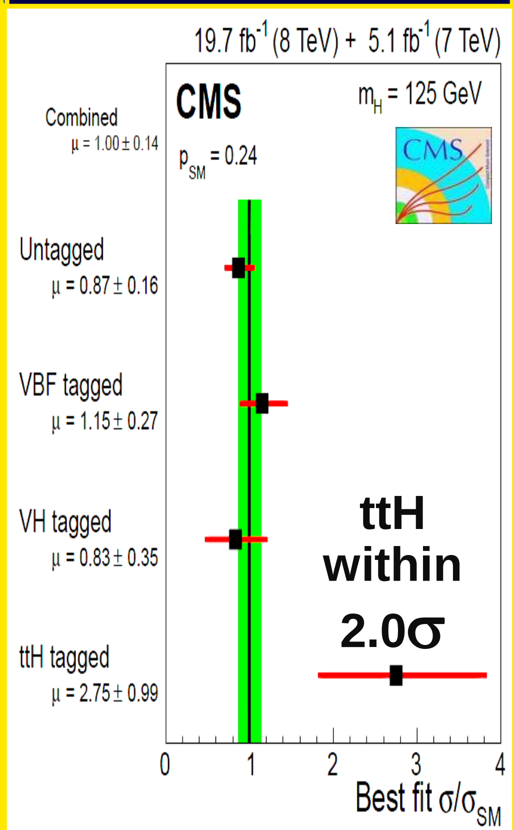
Hints of an Excess ? Stay Tuned:
ATLAS ~1σ, CMS ~2σ above SM prediction

SM Higgs Signal Strengths $\mu = \sigma/\sigma_{SM}$

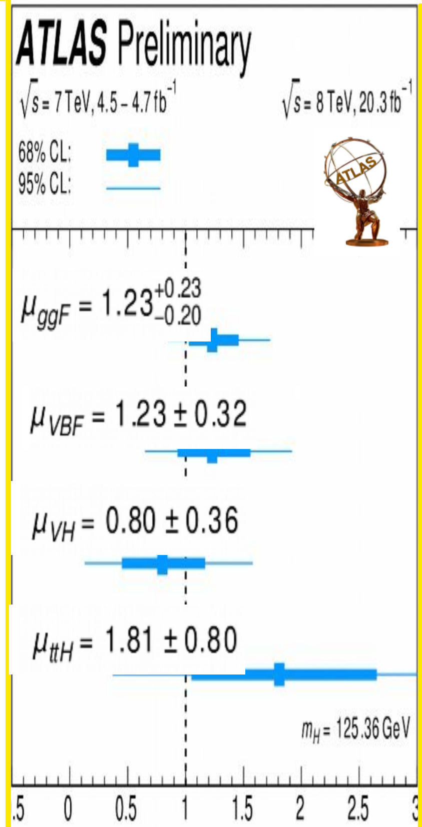
Best Fit σ/σ_{SM} by Decay Mode χ^2/NDF = 1.0/5



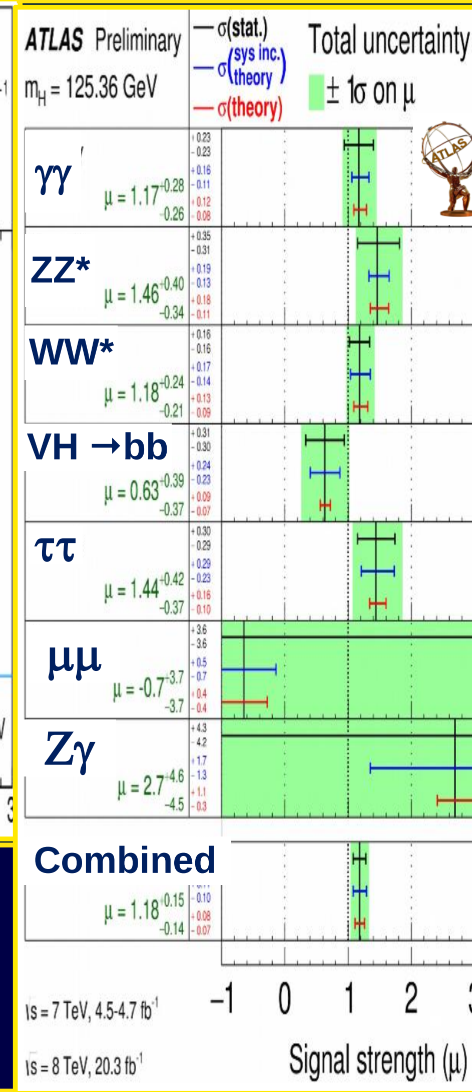
σ/σ_{SM} by Production mode χ^2/NDF = 5.4/4



σ/σ_{SM} by Production Mode



σ/σ_{SM} by Decay Mode



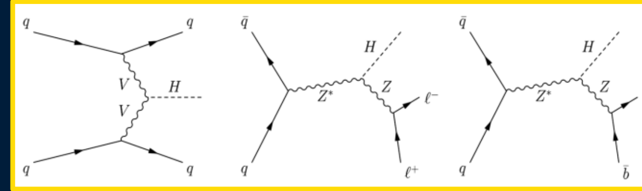
Best-fit overall signal strengths:

ATLAS $\sigma/\sigma_{SM} = 1.18^{+0.15}_{-0.14}$

CMS: $\sigma/\sigma_{SM} = 1.00 \pm 0.14$

+ H → SUSY H, exotics, Portal DM, …

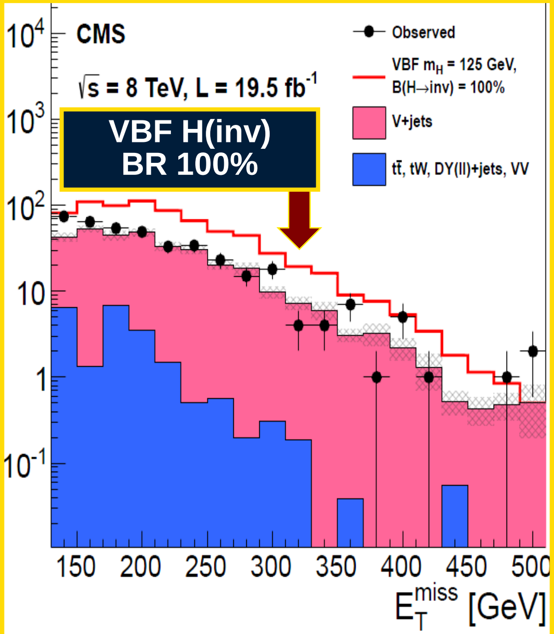
Search for Invisible Higgs Boson Decays



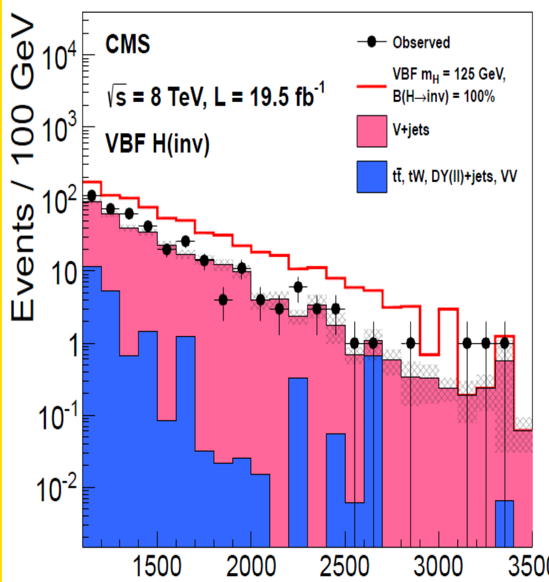
Dijet, dilepton, b-bbar + MET

- Some SM extensions allow Higgs boson decays to long lived or stable neutral weakly interacting particles
- Search for a MET excess in VBF or ZH assoc. production (Z→ ℓℓ, bb)

VBF E_T^{Miss} vs backgrounds



M_{jj} vs backgrounds



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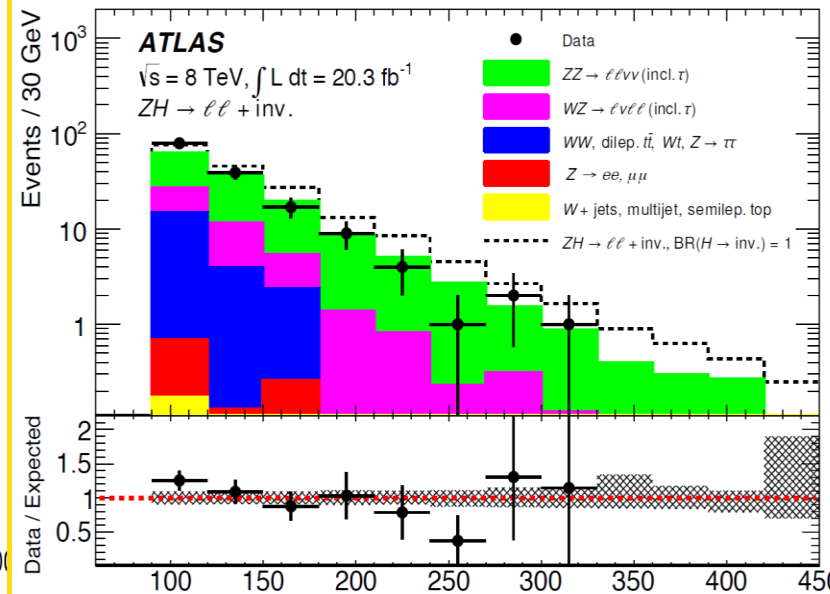
ZH → ℓℓ + E_T^{Miss} vs backgrounds



PRL 112 (2014) 201802

Assuming SM ZH and VBF production rates (M_H = 125 GeV)

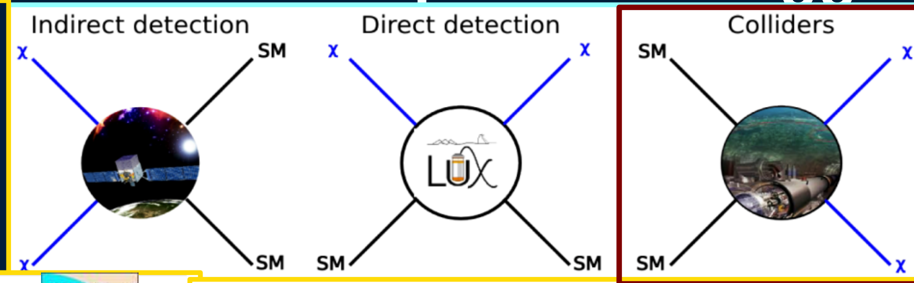
ATLAS: BR (H → Inv) < 0.29 from VBF; < 0.75 from ZH production

CMS: BR (H → Inv) < 0.58 from VBF and ZH production combined

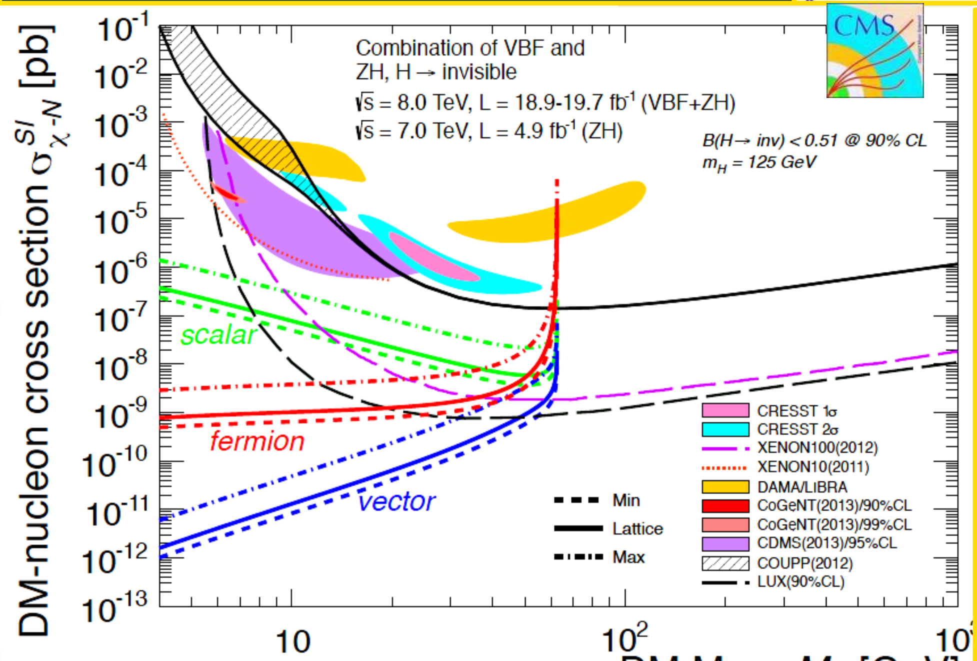
Higgs Portal Dark Matter Models

Stable DM Particles that Couple to the Higgs Boson

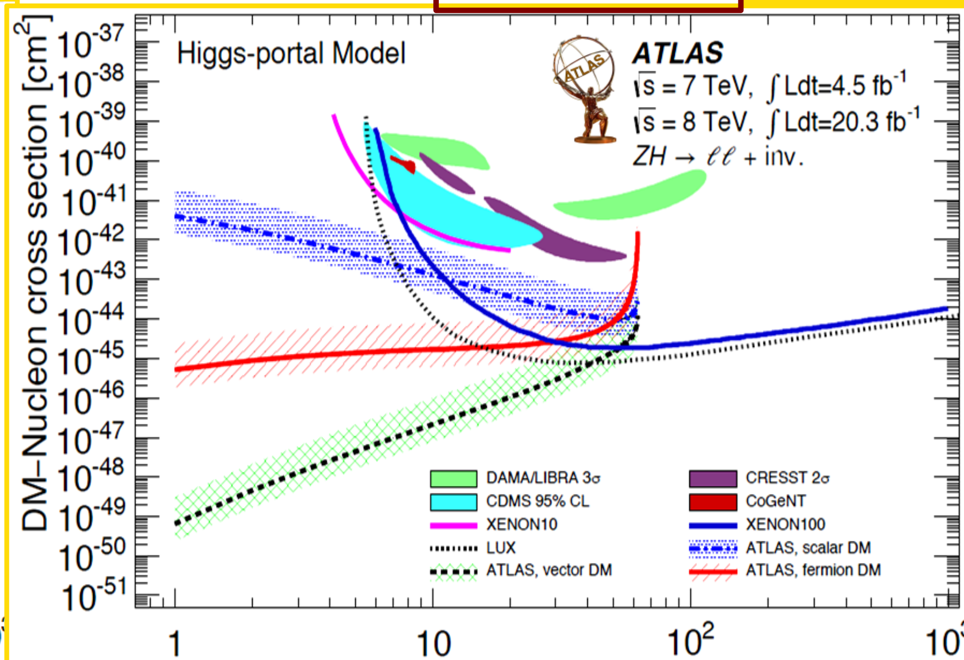
For $M_\chi < M_H/2$, Limits on the invisible decay width Γ_{Inv} can be interpreted as the Spin independent DM-nucleon elastic cross section for scalar, vector and fermionic DM particles.



C. Doglioni, Moriond Elwk 2015



EPJ C74 (2014) 2980



PRL 112 (2014) 201802

Higgs – Nucleon Coupling is model dependent: use $0.33^{+0.30}_{-0.07}$ (Djouadi et al., Phys. Lett. B709 (2012) 65 lattice calculations)

Results: Interesting at low M_χ mass relative to underground experiments

Issue: Use of EFT; being further studied

Coupling Compatibility Tests

LHC Higgs Cross-Section WG 2012: arXiv:1209.0040

- **Assumptions: Single resonance, zero width, SM tensor structure**
- **There are 8 parameters to describe the currently relevant decays & production mechanisms:**

$$\Gamma_{ZZ}, \Gamma_{WW}, \Gamma_{\tau\tau}, \Gamma_{bb}, \Gamma_{\gamma\gamma}, \Gamma_{gg}, \Gamma_{tt} \text{ and } \Gamma_{TOT}$$

$$N(xx \rightarrow \mathrm{H} \rightarrow yy) \sim \sigma(xx \rightarrow \mathrm{H}) \cdot B(\mathrm{H} \rightarrow yy) \sim \frac{\Gamma_{xx}\Gamma_{yy}}{\Gamma_{tot}}$$

- **We cannot extract all 8 parameters with current data. So we do Coupling Compatibility Tests using scaling factors κ relative to SM and their ratios λ**

Example: For the gg → H → $\gamma\gamma$ process:

$$\sigma \times \mathrm{BR}(gg \rightarrow H \rightarrow \gamma\gamma)/\sigma_{SM}\,\mathrm{BR}(gg \rightarrow H \rightarrow \gamma\gamma) = \kappa_g^2 \kappa_\gamma^2 / \kappa_H^2$$

κ Factors for Production and Decay

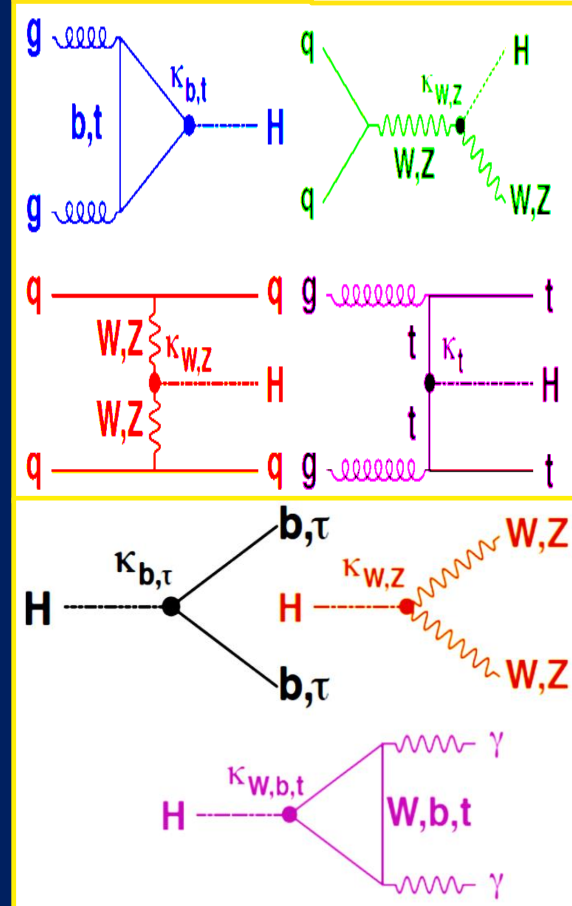
$\sigma_i \sim \kappa_i^2\, \sigma_i^{SM}$

$\Gamma_i \sim \kappa_i^2\, \Gamma_i^{SM}$

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

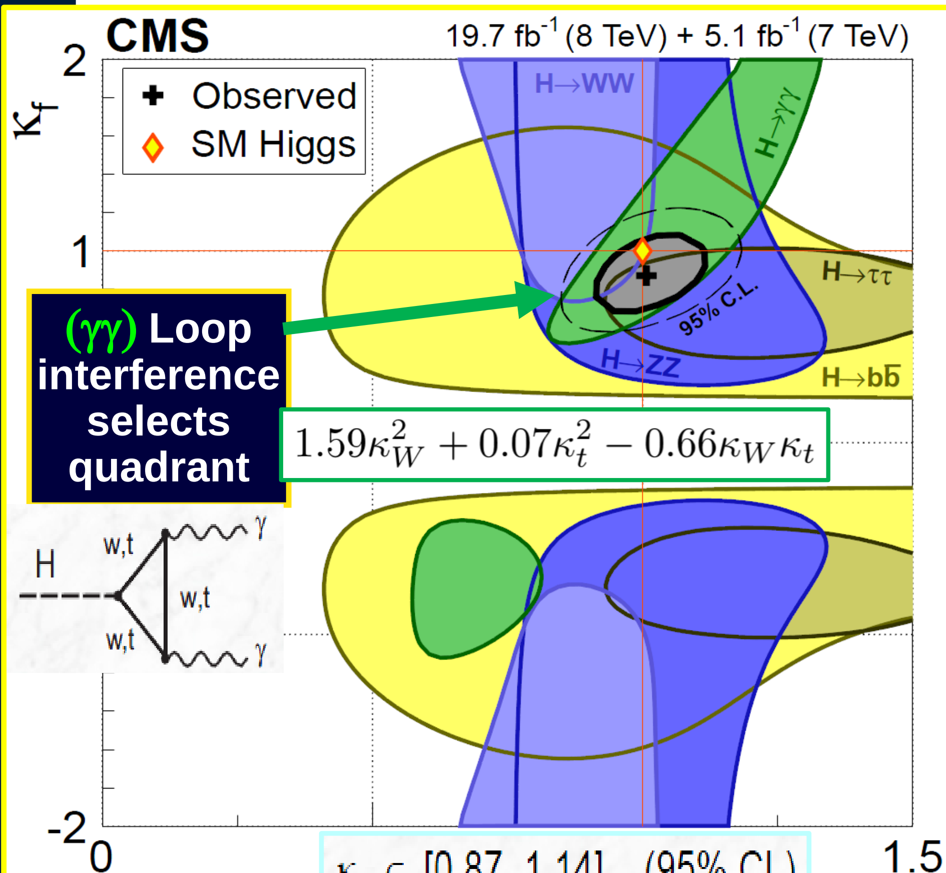
$g_F = \kappa_F \frac{\sqrt{2} m_F}{v}$

$g_V = \kappa_V \frac{2 m_V^2}{v}$



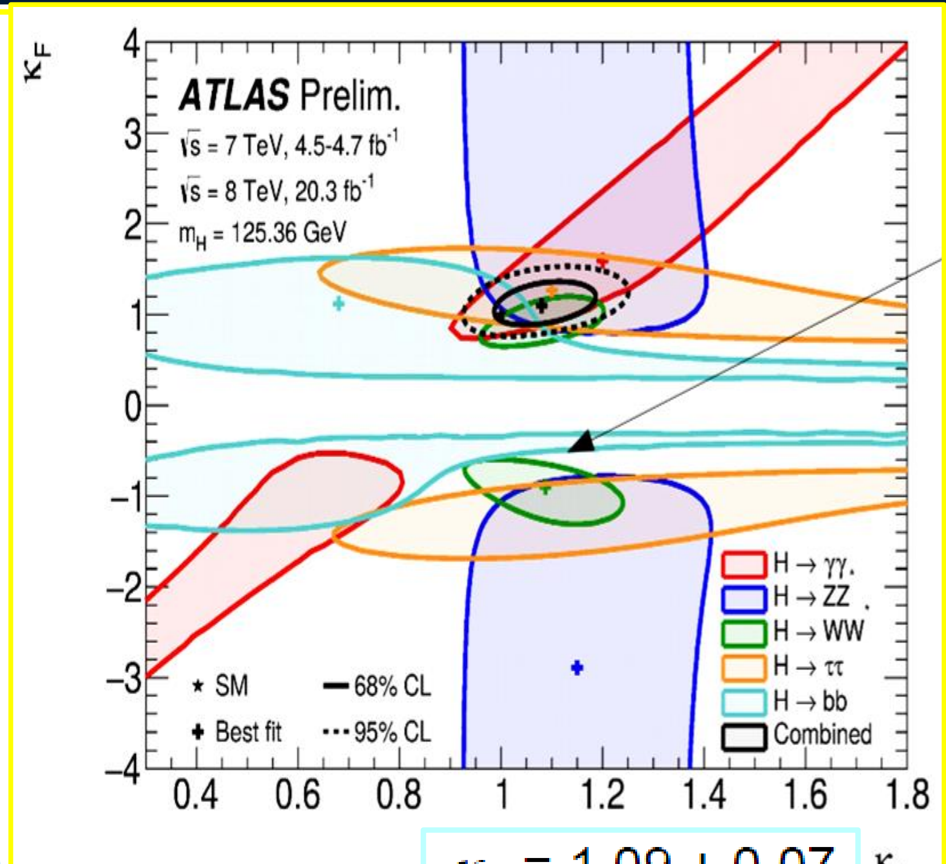
Assume custodial symmetry + fermion universality

Set all fermion scale factors to κ_F, W/Z scale factors to κ_V. No BSM particles, all loops resolved



EPJ C75 (2015) 5, 212

$\kappa_V \in [0.87, 1.14]$ (95% CL)
$\kappa_F \in [0.63, 1.15]$ (95% CL)



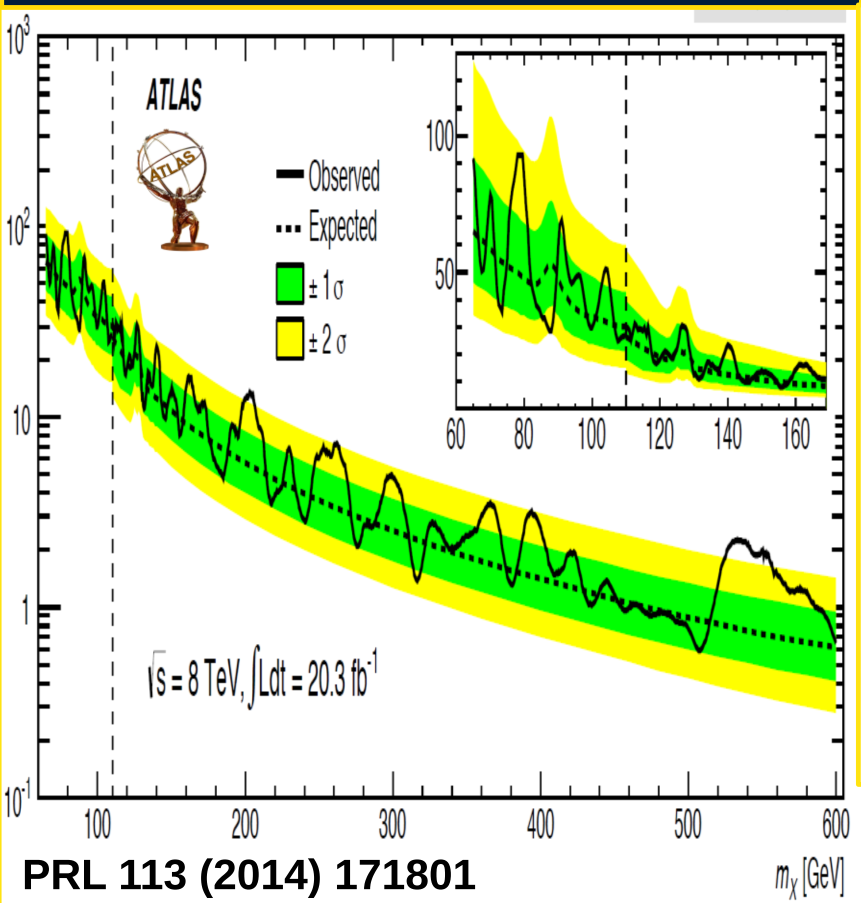
ATLAS-CONF-2015-007

$\kappa_V = 1.09 \pm 0.07$
$\kappa_F = 1.11 \pm 0.16$

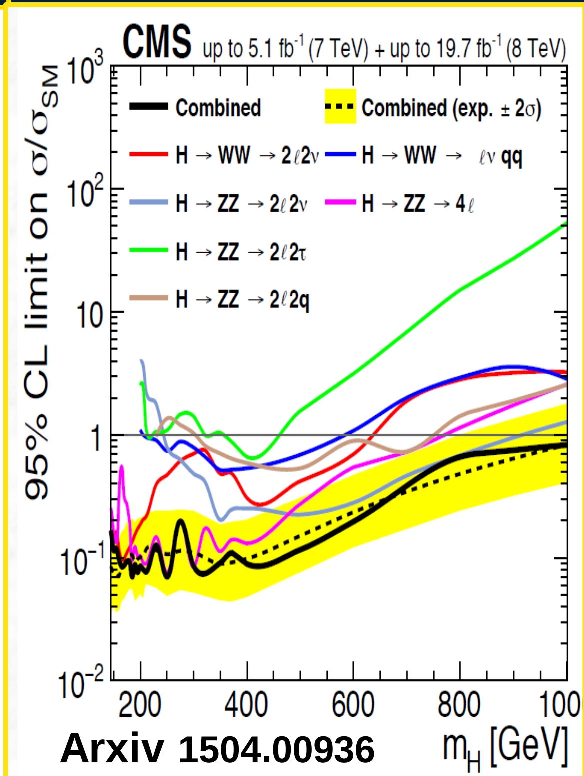
Data are closely consistent with the SM: $\kappa_V = 1$; $\kappa_F = 1$
Each experiment excludes non-SM relative sign at ≥ 4 σ

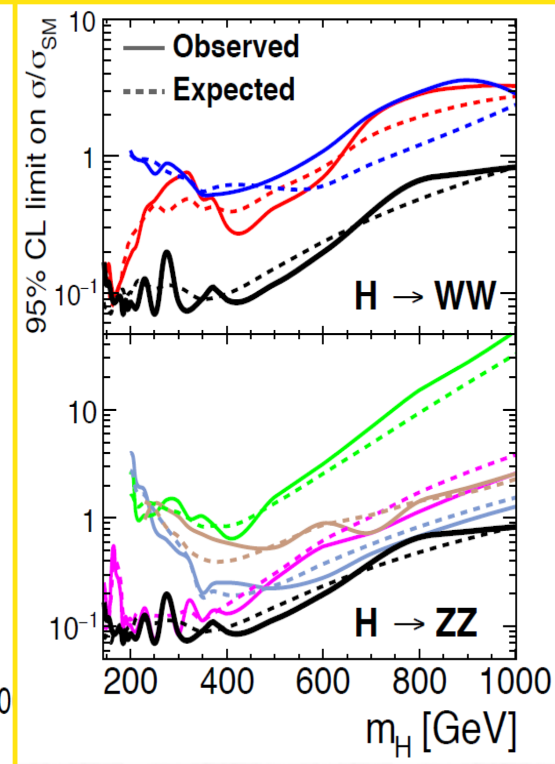
Searches for Additional Higgs Bosons X: Examples

X → γγ Search:
95% CL UL on σ_{FID} BR (X → γγ)



X → ZZ, WW Search: 95% CL UL on σ/σ_{SM} by mode, + combined





Add'l Higgs Bosons with SM-like couplings Ruled Out for 145 < M_H < 1000 GeV

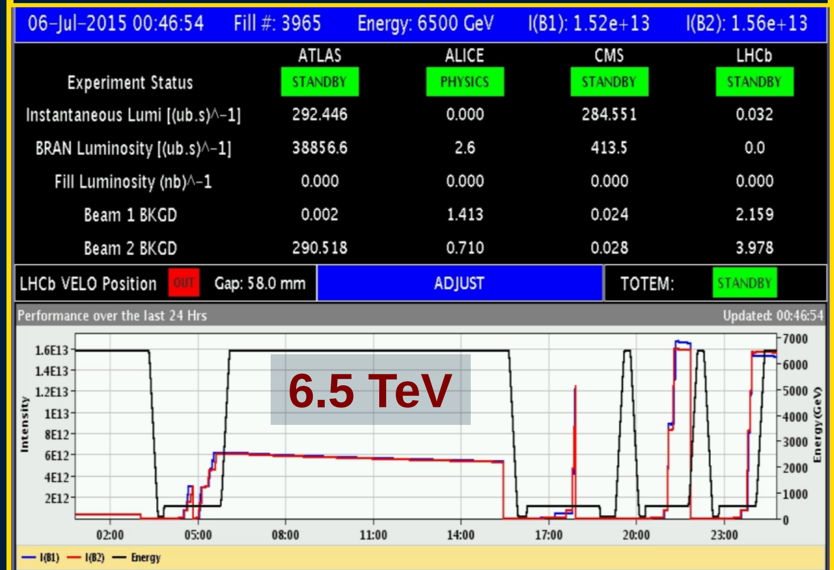
SM Higgs Boson is confirmed at 125 GeV: and What Else?

- Higgs Mass: Radiative Corrections

$$\delta m_h^2 = \frac{3}{16\pi^2 v^2}(m_h^2 + 2m_W^2 + m_Z^2 + 4m_t^2)\Lambda^2 \sim \left(\frac{\Lambda}{500GeV}\right)^2$$

- Tend to push m_H to high energy scales (GUT, Planck) unless there is extreme fine tuning
- We need something to "stabilize" the theory
  If it is to describe the early universe
- We are also seeking:
  - Dark matter candidate(s)
  - Deeper symmetries: Unifications; particle physics ↔ spacetime
  - An Intermediate mass scale ?
- So we expect new physics at the TeV scale
- We have Just Begun our Search

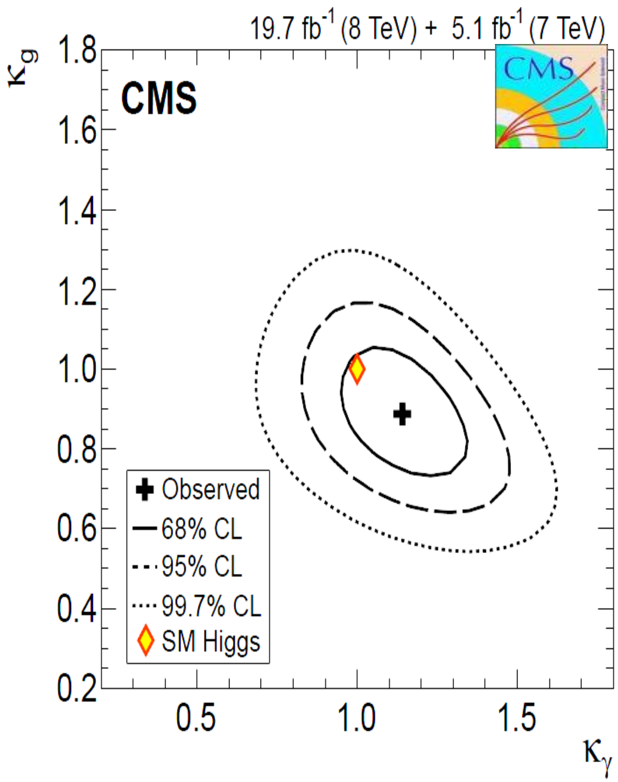
Run 2 is Well Underway !



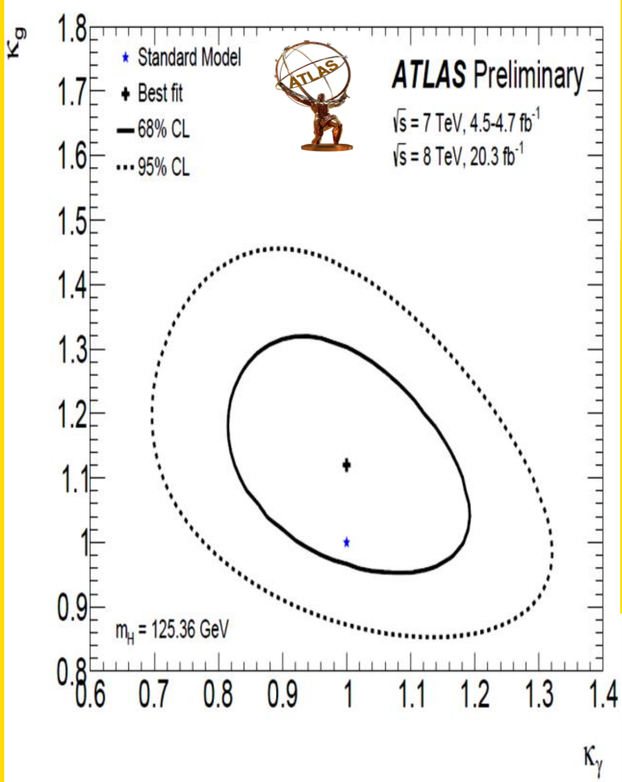
Tests for BSM Physics in Loops

- **Loop induced processes: ggH production, $\gamma\gamma$ and $Z\gamma$ decays, are sensitive to BSM particles in the loops**
- **Model: Tree level processes as in SM (κ = 1 for W,Z,f); fit for κ_γ, κ_g**
- **Results compatible with SM, but can be used to set limits on $BR_{BSM} = BR_{inv} + BR_{undetected}$ through the total width** $\kappa_H^2 \sim (0.0857\,\kappa_g^2 + 0.0023\,\kappa_\gamma^2 + 0.912)/(1 - BR_{BSM})$

2D Likelihood scan for κ_γ, κ_g (Γ_{BSM}=0)



2D Likelihood scan for κ_γ, κ_g (Γ_{BSM}=0)



CMS: 95% CL Interval

$BR_{BSM} \in (0,0.57)$ [(0,0.52 exp)]

Including H(inv) Search Results

$BR_{BSM} \in (0,0.49)$ [(0,0.32 exp)]

ATLAS: 95% CL Interval

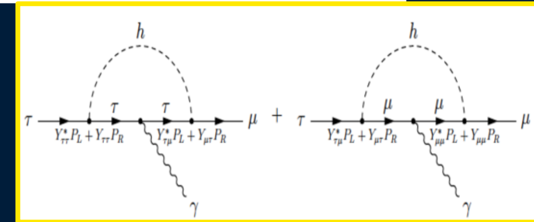
$BR_{BSM} \in (0,0.58)$ [(0,0.44 exp)]

Including $\kappa_V < 1$ constraint

$BR_{BSM} \in (0,0.13)$

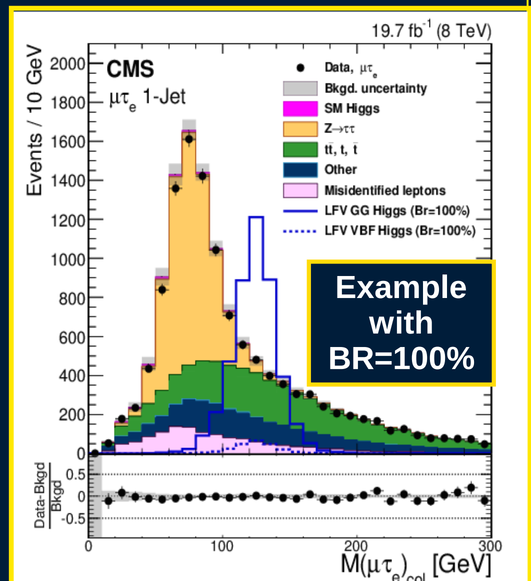
Search for LFV Higgs Decays: $H \rightarrow \mu\tau$

- **Off diagonal Yukawa couplings** occur in many models [*] with >1 Higgs doublet, composite Higgs, EFTs etc.
- Existing constraints on LFV couplings from indirect processes $\tau \rightarrow \mu\gamma$, $\tau \rightarrow 3\mu$, muon g-2, allow $BR(H \rightarrow \mu\tau, e\tau)$ up to ~10%



- Search in $H \rightarrow \mu\tau_e$ and $H \rightarrow \mu\tau_h$ channels

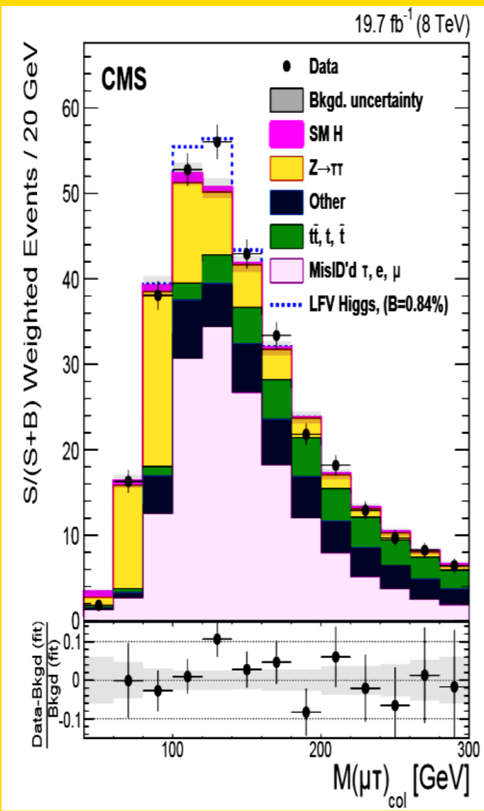
  Signature is similar to SM $H \rightarrow \tau\tau$ except:
  - Muon from prompt decay: larger momentum
  - Only one neutrino: MET tends to be collinear with visible tau decay products
- Main backgrounds: $Z \rightarrow \tau\tau$, t-tbar, single top
- **Analysis:**
  - Categorize by N_{Jet} bins
  - Kinematic selection on lepton p_T, m_T, $\Delta\Phi_{\mu,\tau,MET}$
  - Final discriminant is Higgs mass from collinear approximation

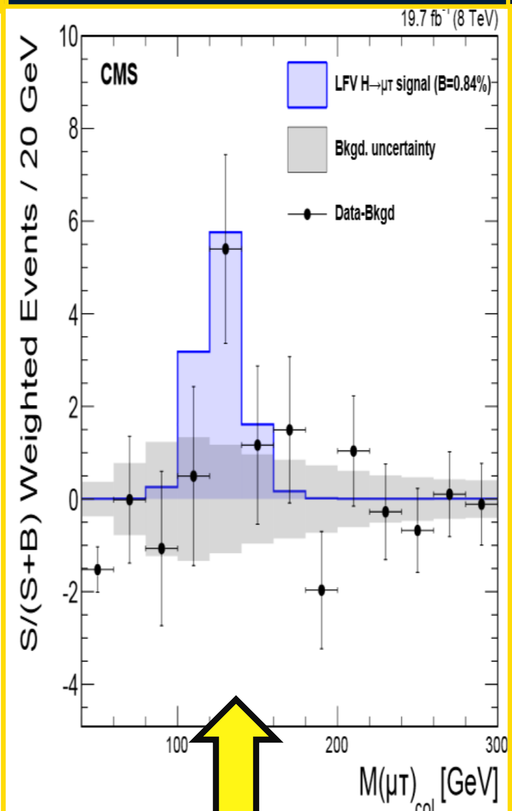


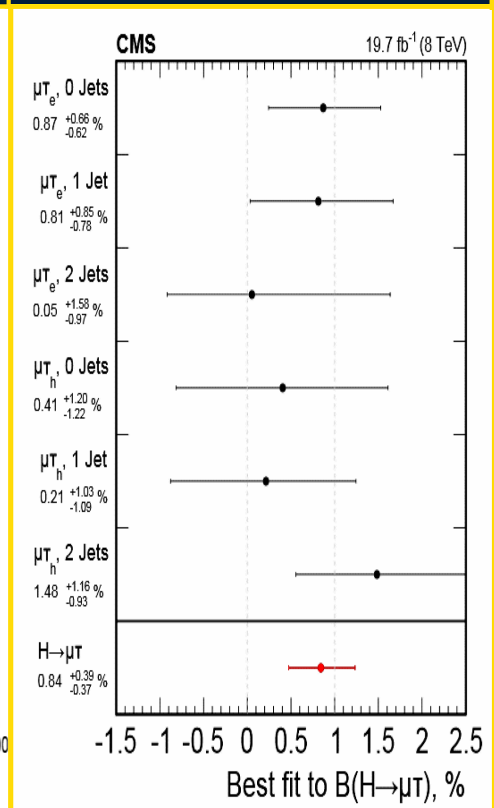
[*] J. D. Bjorken and S.Weinberg, "Mechanism for Nonconservation of Muon Number", Phys. Rev. Lett. 38 (Mar 1977) 622–625, doi:10.1103/PhysRevLett.38.622, K. Agashe and R. Contino, "Composite Higgs-Mediated FCNC", Phys.Rev. D80 (2009) 075016, doi:10.1103/PhysRevD.80.075016, arXiv:0906.1542, A. Azatov, M. Toharia, and L. Zhu, "Higgs Mediated FCNC's in Warped Extra Dimensions", Phys.Rev. D80 (2009) 035016, doi:10.1103/PhysRevD.80.035016, arXiv:0906.1990. , H. Ishimori et al., "Non-Abelian Discrete Symmetries in Particle Physics", Prog.Theor.Phys.Suppl. 183 (2010) 1–163, doi:10.1143/PTPS.183.1, arXiv:1003.3552, G. Perez and L. Randall, "Natural Neutrino Masses and Mixings fromWarped Geometry", JHEP 0901 (2009) 077, doi:10.1088/1126-6708/2009/01/077, arXiv:0805.4652, G. Blankenburg, J. Ellis, and G. Isidori, "Flavour-Changing Decays of a 125 GeV Higgs-like Particle", Phys.Lett. B712 (2012) 386–390, doi:10.1016/j.physletb.2012.05.007, arXiv:1202.5704., R. Harnik, J. Kopp, and J. Zupan, "Flavor Violating Higgs Decays", JHEP 1303 (2013) 026, doi:10.1007/JHEP03(2013)026, arXiv:1209.1397.

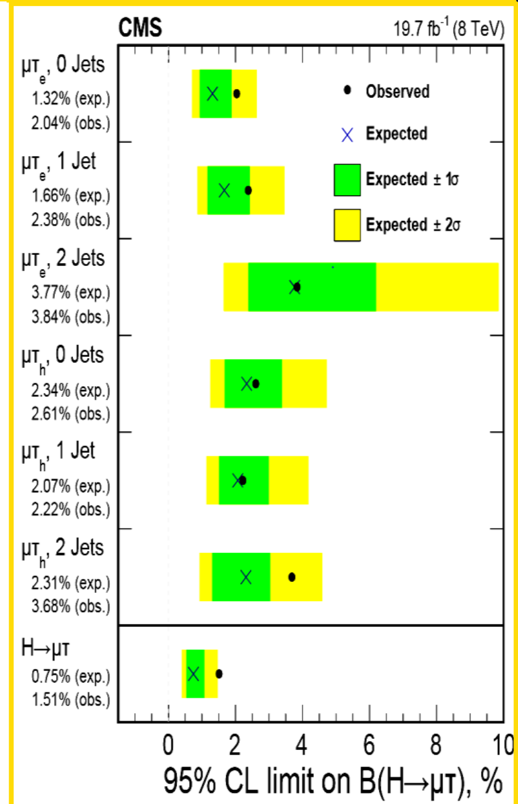
LFV H→ $\mu\tau$ Results

M_{col} ($\mu\tau$) S/(S+B) Weighted. Best Fit BR($\mu\tau$) = 0.84 ± 0.4%	M_{col} ($\mu\tau$) with BR($\mu\tau$) = 0.84%, background subtracted	Best Fit $\mu = \sigma/\sigma_{SM}$ by mode, combined	95% CL UL on $\mu = \sigma/\sigma_{SM}$ by mode+ combined









BR > 0 ? Significance ~2.4σ (p value 0.007)

Arxiv 1502.07400

+ … recent results from ATLAS: Navarro Talk

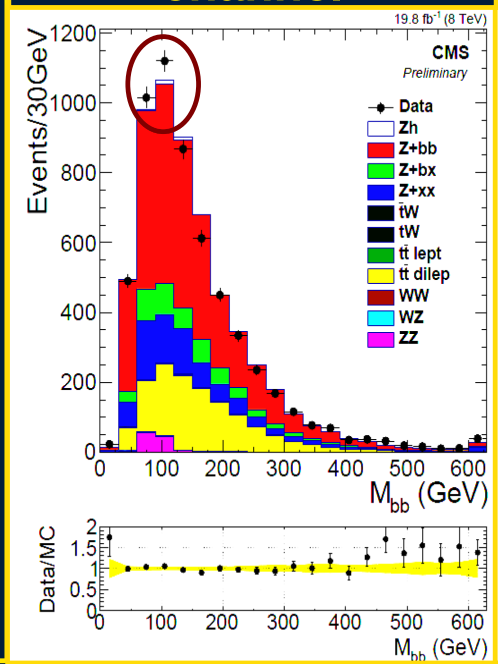
Search for Another Higgs in 2HDMs CP Odd A ➡ ZH ➡ ℓℓbb, ℓℓττ

HIG-15-001
+ Arxiv 1504.04701v1

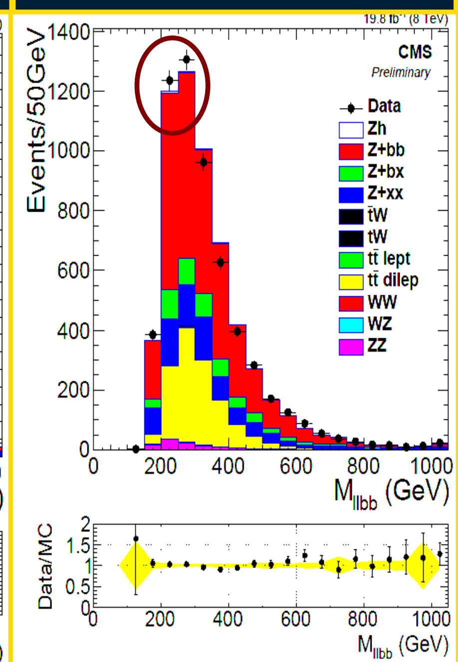
- 2 HDMs Include: SUSY, Axion, EFTs etc. (accommodate muon g-2)
- 5 Higgs: 2 Neutral CP-Even (H,h), One CP-Odd A, H+ and H-; tan β: Ratio of vevs; α: Mixing angle of two doublets
- Large mass splitting between A and H said to favor the elwk phase transition leading to baryogenesis (then A → ZH dominates)

- **Analysis:** A → ZH or H → ZA where Z → e+e– or Z → μ+μ– and (H or A) →(bb or ττ)
  - Select Z→ee & Z→μμ decays or τ signatures, + (2 b-tagged jets) $\mu+\tau_h$, $e+\tau_h$, $\mu+e$, $\mu\mu$, $\tau_h\tau_h$
  - Suppress t-tbar by requiring low MET significance
  - Search for excesses in bins of m_{bb} and $m_{\ell\ell bb}$, or $m_{\tau\tau}$

M_{bb} in the ℓℓbb channel



M (ℓℓbb)



$A \rightarrow ZH \rightarrow \ell\ell bb, \ell\ell\tau\tau$ Results

HIG-15-001

Two most significant excesses are in $\ell\ell$ bb channel in regions centered at:

(1) M_{bb} ~93 GeV, $m_{\ell\ell bb}$ ~ 286 GeV:

- Local significance: 2.6 σ
- Global Significance (with LEE): 1.6 σ

This is in a region where one might expect sensitivity to a signal, e.g. SUSY

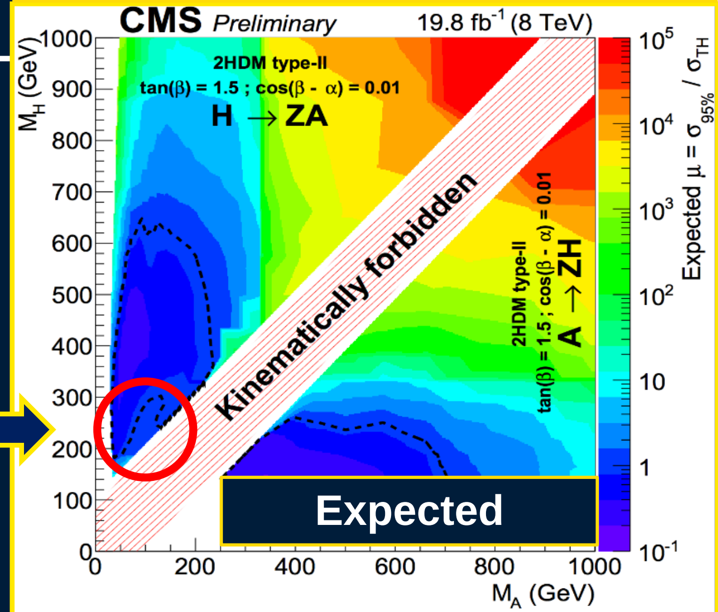
(2) M_{bb} ~575 GeV, $m_{\ell\ell bb}$ ~ 662 GeV

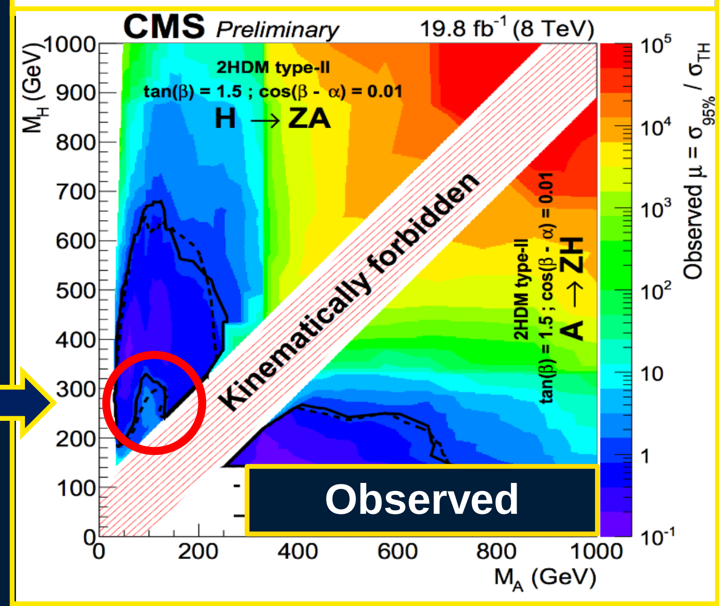
- Local significance: 2.85 σ
- with LEE: 1.9 σ

✸ Atlas A ➡ ZH Analysis: Hints as well ? ➡

Excess (1) is here

M_H versus M_A
95% CL UL on $\mu = \sigma/\sigma_{Theory}$



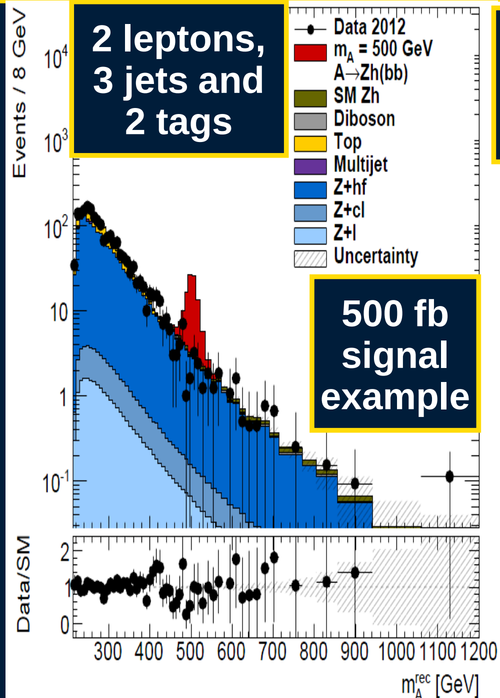


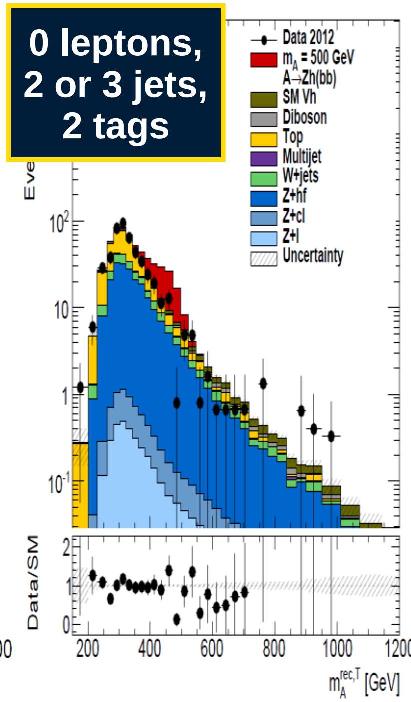
Search for Another Higgs in 2HDMs

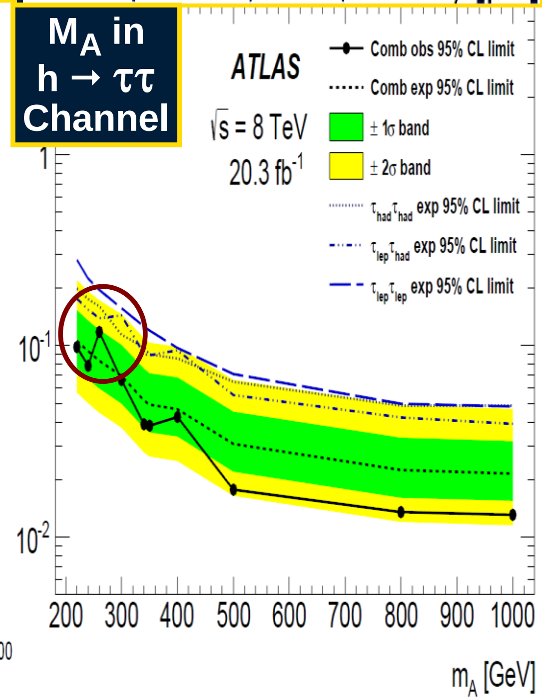
CP Odd A ➡ ZH ➡ $\ell\ell bb$, $\ell\ell\tau\tau$, $\nu\nu bb$

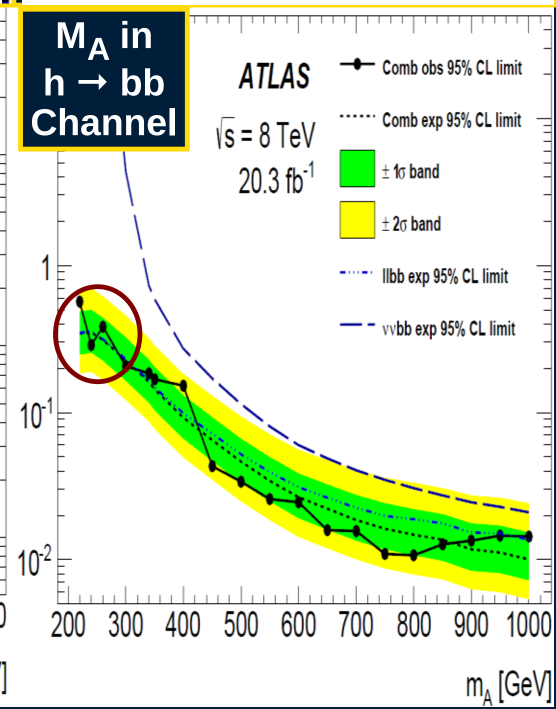
Arxiv 1502.04478

M_A in the $\ell\ell bb$ channel	M_A in the $\nu\nu bb$ channel	95% CL UL on $\sigma\times BR(A\to Zh)\times BR(h\to\tau\tau)$ [pb]	95% CL UL on $\sigma\times BR(A\to Zh)\times BR(h\to b\bar{b})$ [pb]









Most significant excess is in the combined $\ell\ell$ bb and $\ell\ell$ $\tau\tau$ channels in the region centered at: M_A ~ 220 GeV

Local p value = 0.014 corresponding to ~2.5 σ

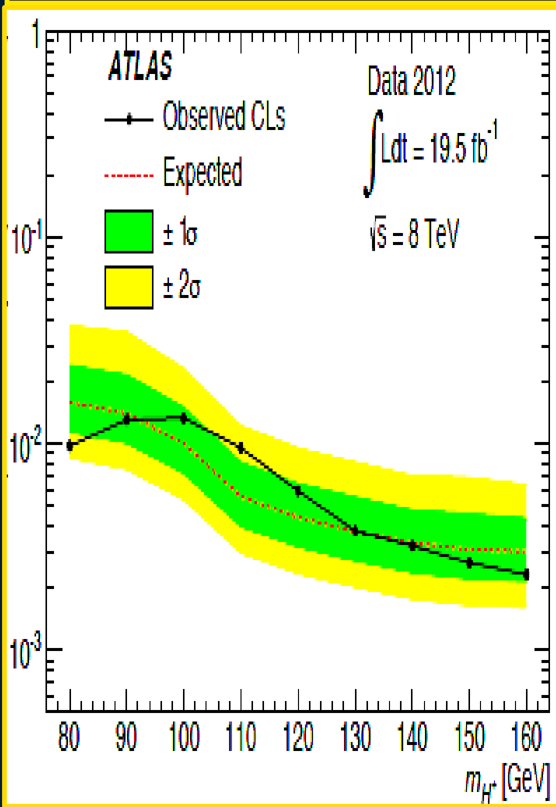
We will soon see what the ATLAS-CMS Combination brings

Searches for MSSM Higgs Bosons

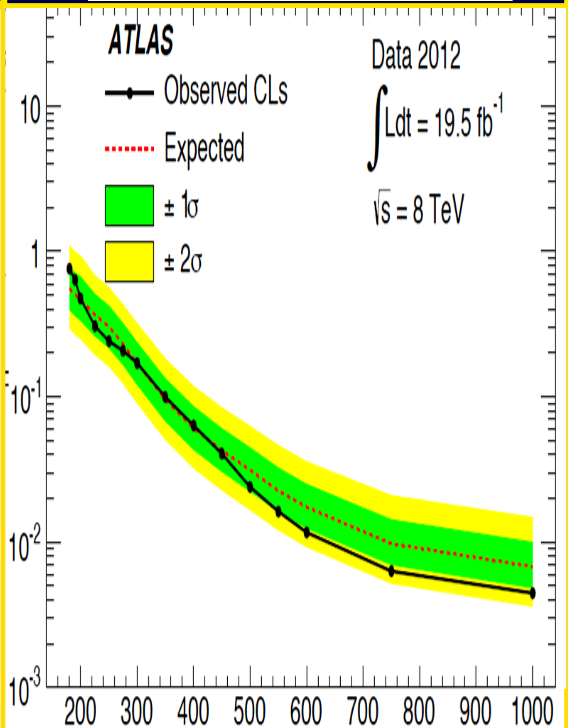
$H^{\pm}$ or Neutral h,H,A

$H^{\pm} \rightarrow \tau\nu$ Search via: tt with $t \rightarrow bH$ or tH Assoc. production

95% CL Exclusion of $B(t \rightarrow bH^{+}) \times B(H^{+} \rightarrow \tau^{+}\nu)$



95% CL Exclusion of $\sigma_{H^{+}} \times B(H^{+} \rightarrow \tau^{+}\nu)$ [pb]



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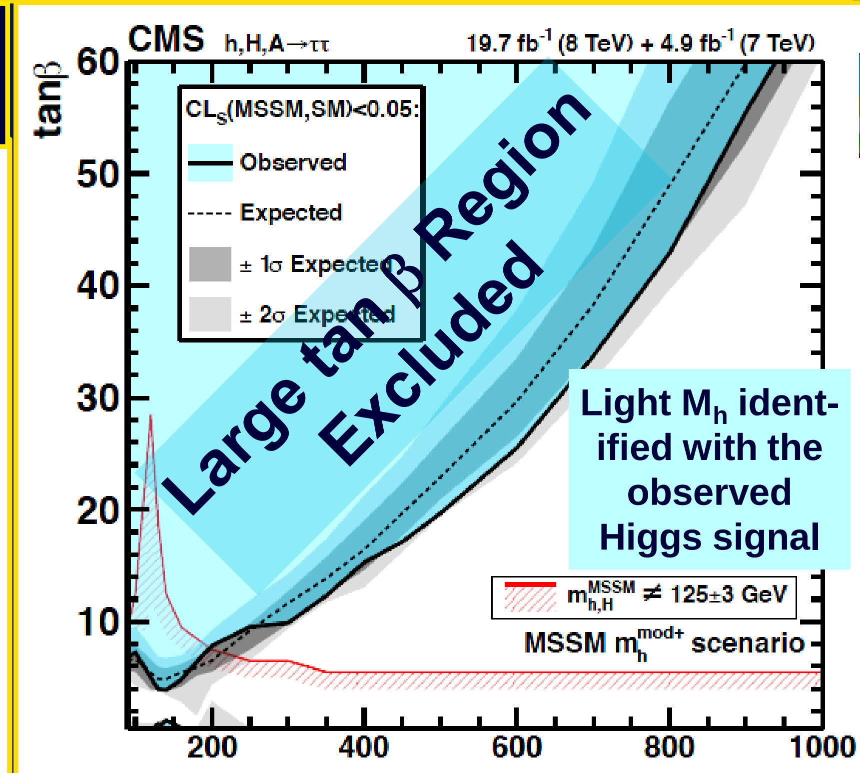
MSSM Higgs Search

95% CL Exclusion in $m_A - \tan\beta$ plane for the m_h^{mod+} scenario



JHEP 10 (2014) 160

New MSSM scenarios

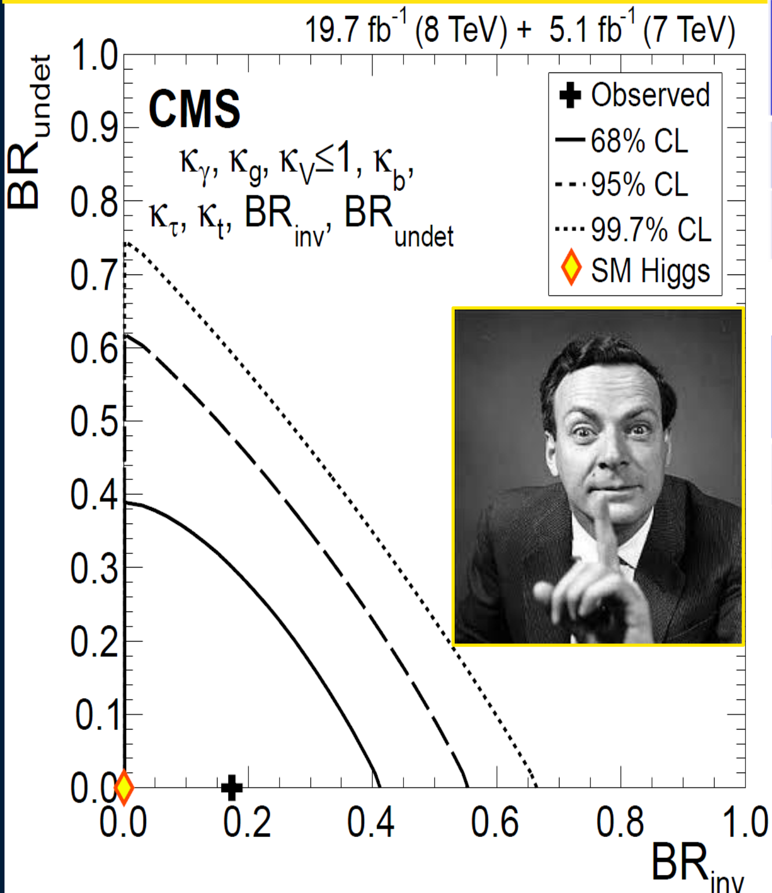
Arxiv:1302.7033v2

Prospects for Run2 and Beyond

"There's Plenty of Room at the Bottom"

An Invitation to Enter a New Field of Physics
(Feynman Lecture at Caltech, December 29, 1959)

There is So Much Room



We have only just begun

CMS

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{invis}
300	7%	6%	6%	8%	13%	15%	8%	41%	23%	28%
3000	5%	5%	4%	5%	7%	10%	5%	12%	8%	17%

ATLAS

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{invis}
300	9%	9%	8%	14%	23%	22%	14%	24%	21%	22%
3000	5%	5%	4%	9%	12%	11%	10%	14%	8%	14%

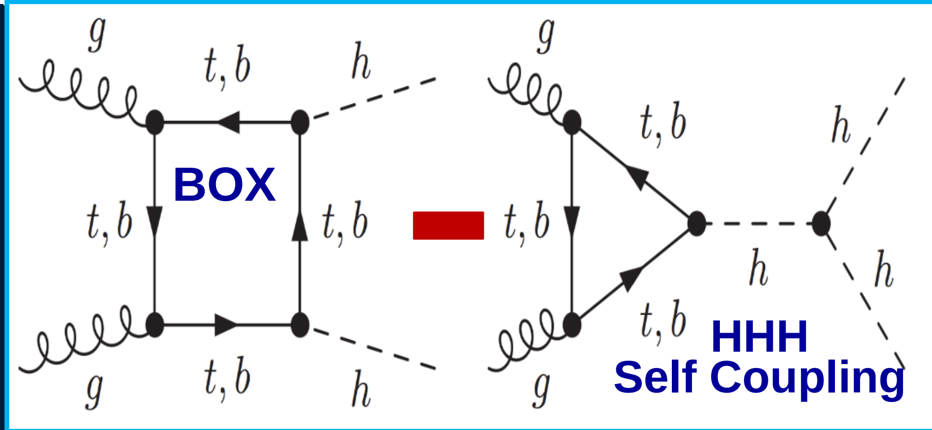
To Improve

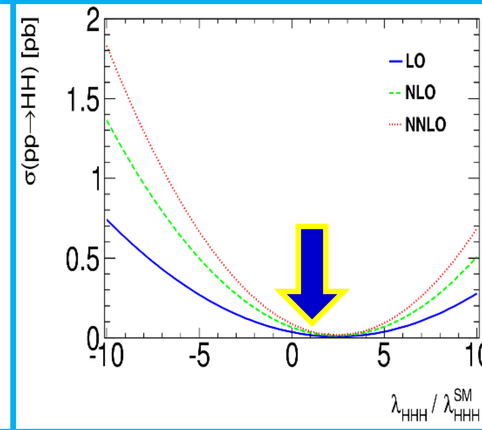
→ Reduce Theory Systematics by 50% | → Reduce Exp Syst by √Lumi

	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{invis}
ATLAS	5→4	5→5	4→4	9→7	12→11	11→9	10→9	14→14	8→7	14→11
CMS	5→2	5→2	4→2	5→3	7→4	10→7	5→2	12→10	8→8	17→6

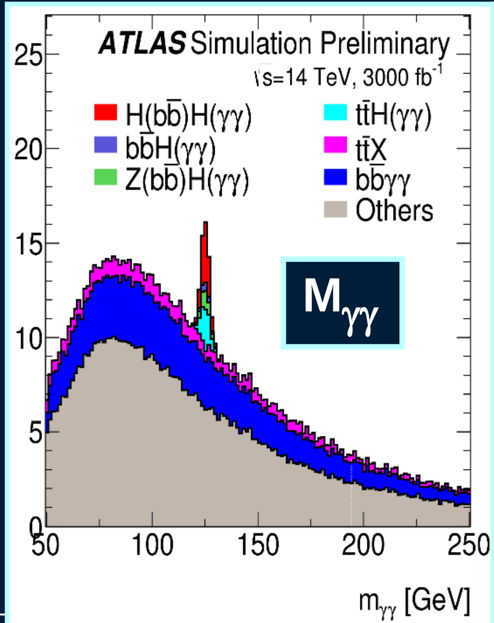
HH → bb γγ at HL LHC (3000/fb)

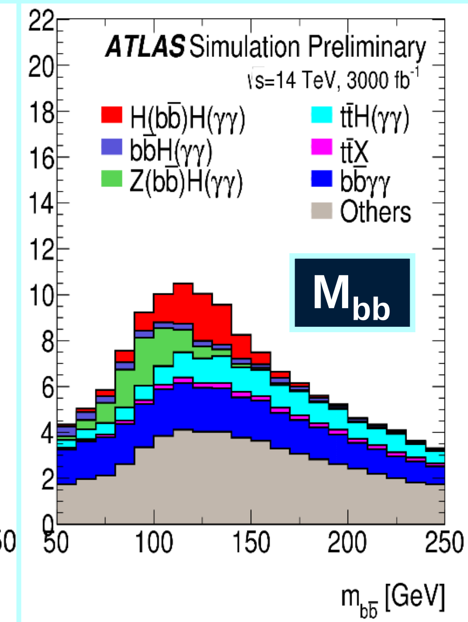
- Two interfering diagrams: (destructive)

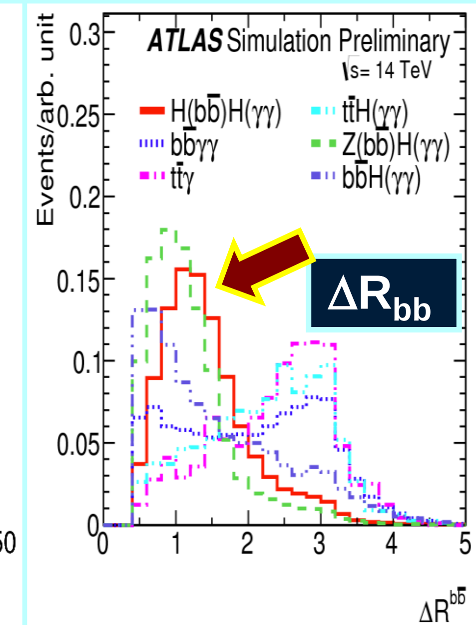




- Bkg suppressed by resonances & decay kinematics
- Resonant bkg : ZH & ttH , H → γγ
- Non-resonant bkg: bbγγ, fake photons, mistags







ATL-PHYS-PUB-2014-019

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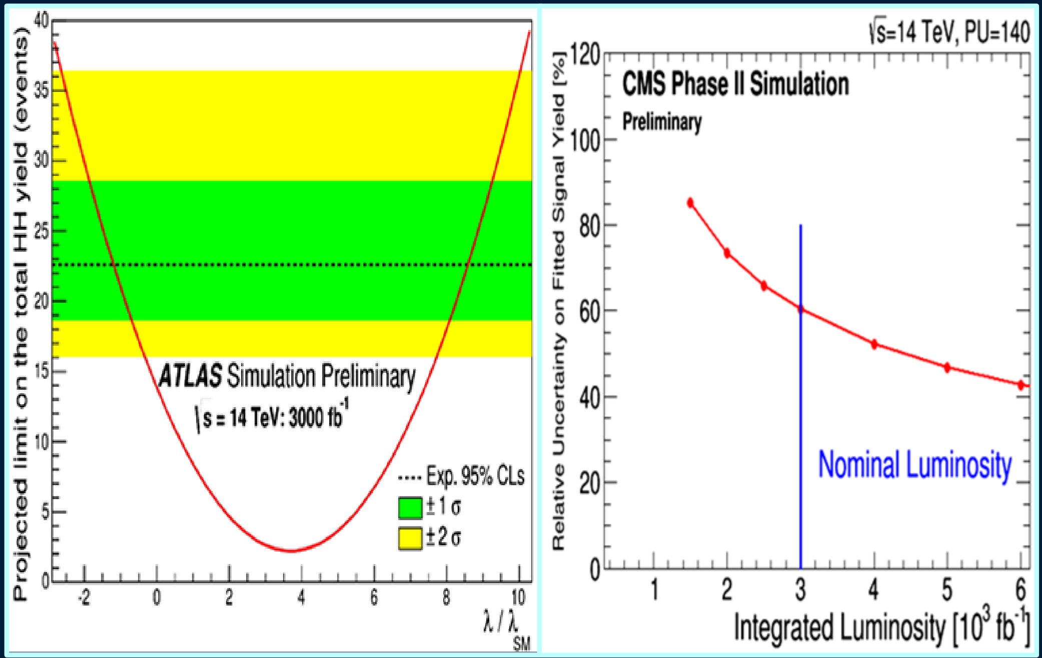
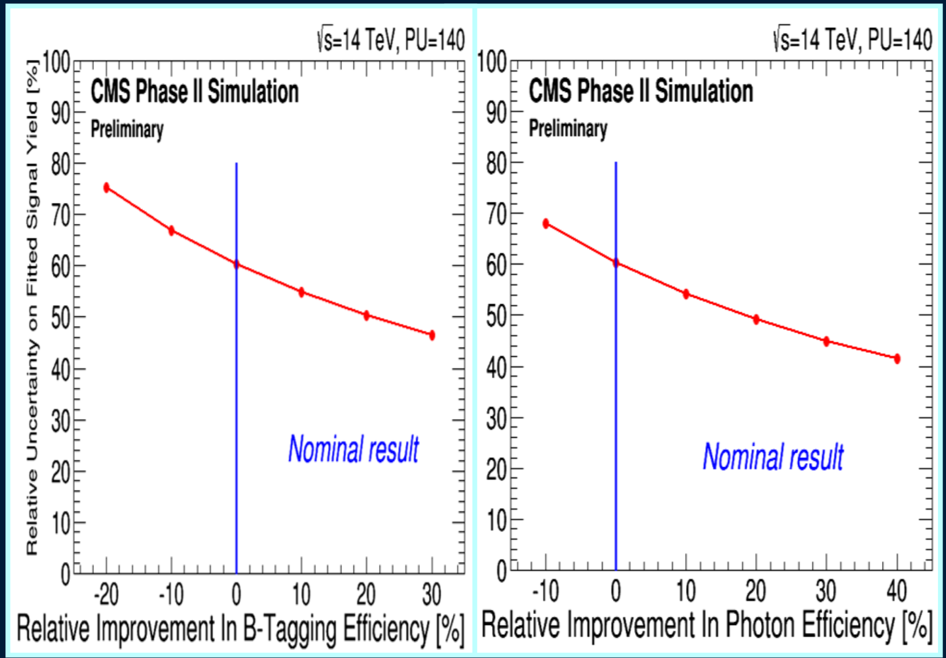
$HH \rightarrow bb\,\gamma\gamma$ at HL LHC

Cross section sensitivity projection (preliminary)

Cross section relative $\Delta\sigma/\sigma$ ~60-80% per experiment → 50% for combination

But sensitive to detector performance: Improvements are still possible (b-tag, photon ID)





Possibility to reach the 30-40% range

Recall we have a delicate cancellation

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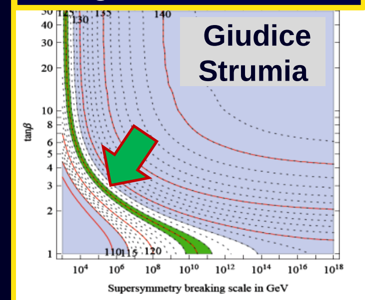
The Outlook

- ✸ SM or not: the 125 GeV Higgs boson has taken us to the threshold of an era of new physics, with a host of questions
- ✸ Natural, Split or High Scale SUSY ?:
  - ✸ A nearby 3rd generation at <~1 TeV ?
  - ✸ Another nearby scale at ~5-50 TeV ?
- ✸ *OR: new singlets, doublets, triplets; new scalars, vectors, composites, extra dim. ?…*
- ✸ Vacuum (meta)stability ➡ Another new scale at ~$10^{10\text{-}12}$ GeV ?
- ✸ Neutrino masses (via seesaws or RH ν): A "similar" intermediate scale ?
- ✸ *The Discovery has Expanded our Vision*
- ➡ Run2 : a new horizon to explore and test our ideas: on EWSB and beyond

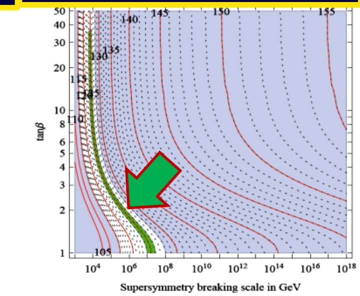
Apologies for all I could not cover

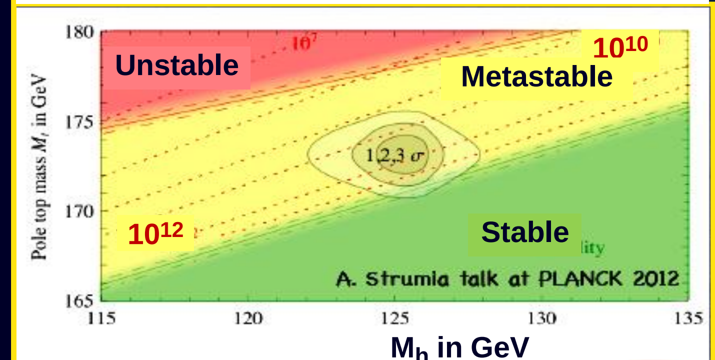
$$M_h^2 \overset{M_A \gg M_Z}{\approx} M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

High Scale SUSY

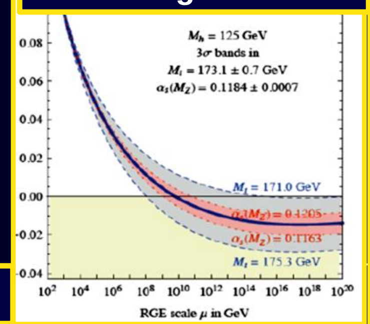


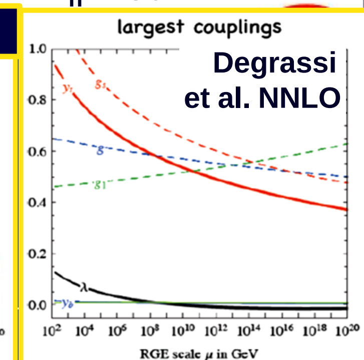
Split SUSY





λ at High Scales






LHC Run2
We have launched on a River of Discovery
Amazon Sunrise

Many More
Public Higgs Physics Results

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResult-

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

Backup Slides Follow

On Behalf of the CMS and ATLAS Collaborations

With Many Thanks to

The LHC Team
The Theory community
The Worldwide Computing Grid
The World's R&E Networks
Previous Experiments (narrowing the search; detectors; methods)
The many funding agencies
The millions of followers

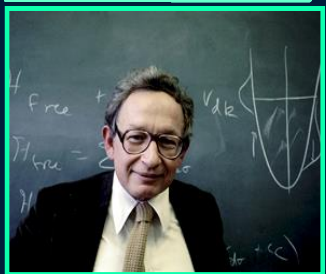
And to Our Hosts

We are grateful for the Discovery and the chance to explore

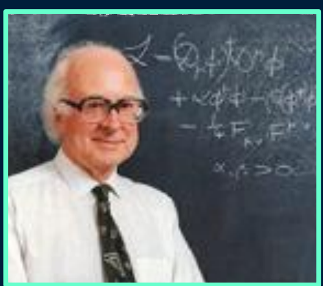
Spontaneous Symmetry Breaking

the "Higgs Mechanism" and Electroweak Theory

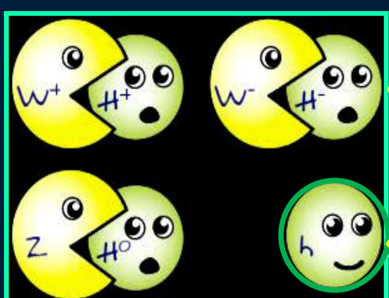
Nambu and Goldstone (1960-1): Spontaneous Symmetry Breaking and massless particles. *Does not explain mass.* *Massless particles in the theory are not seen in nature.*



It is likely, then, considering the superconducting analog, that the way is now open for a degenerate-vacuum theory of the Nambu type without any difficulties involving either zero-mass Yang-Mills gauge bosons or zero-mass Goldstone bosons. These two types of bosons seem capable of "canceling each other out" and leaving finite mass bosons only.

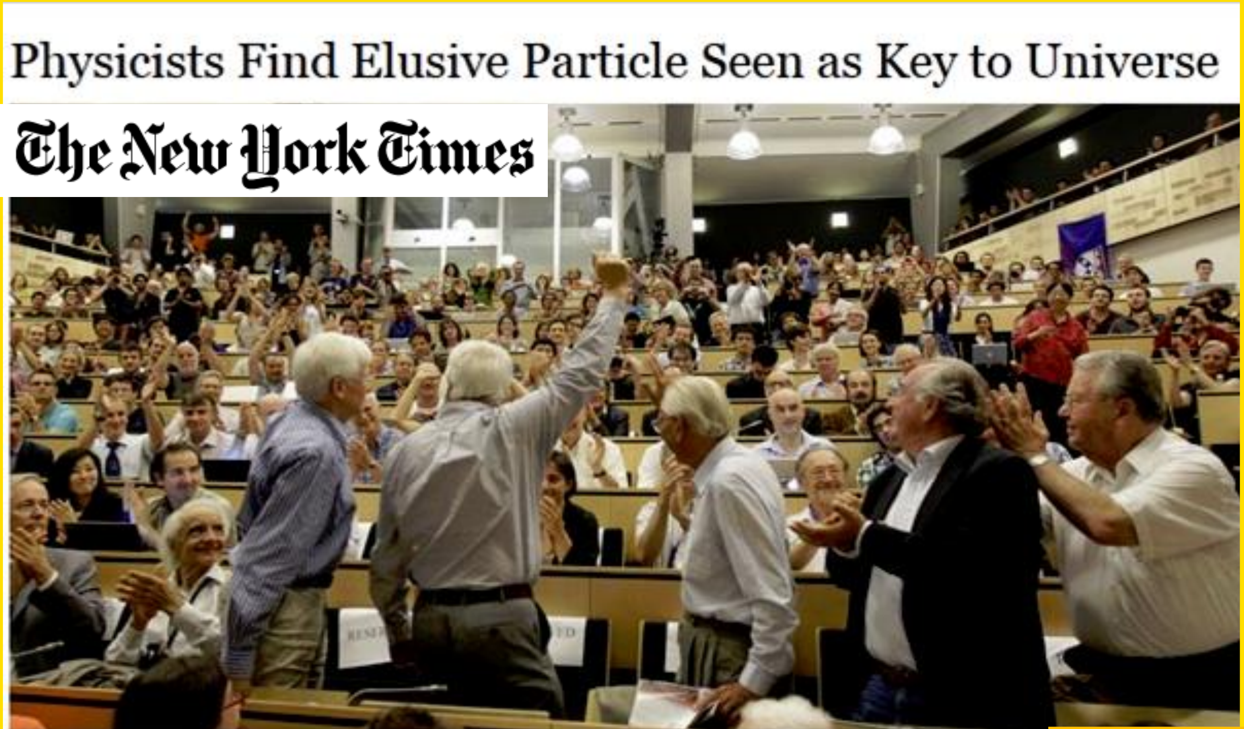


Peter Higgs (Phys. Lett. July 1964), **and others (EB; GHK)** show how in a relativistic theory, to **"transform away" the massless Nambu-Goldstone bosons, yielding massive ones**



1967: Weinberg and Salam; and Glashow put it all together: A *unified* electroweak theory. The massless ones are "eaten" and **the W & Z get mass, while the photon remains massless.** *And* - **the Higgs Boson appears.**

Discovery of a Higgs Like Boson
July 4, 2012

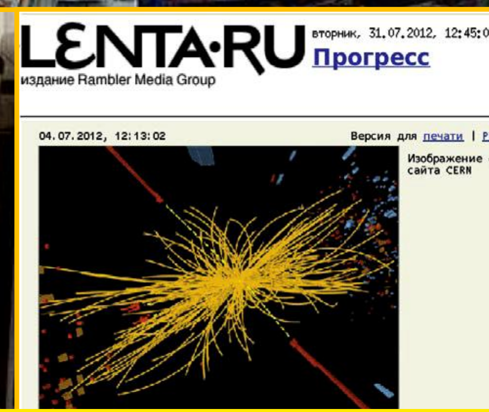


Theory : 1964

LHC + Experiments Concept: 1984

Construction: 2001

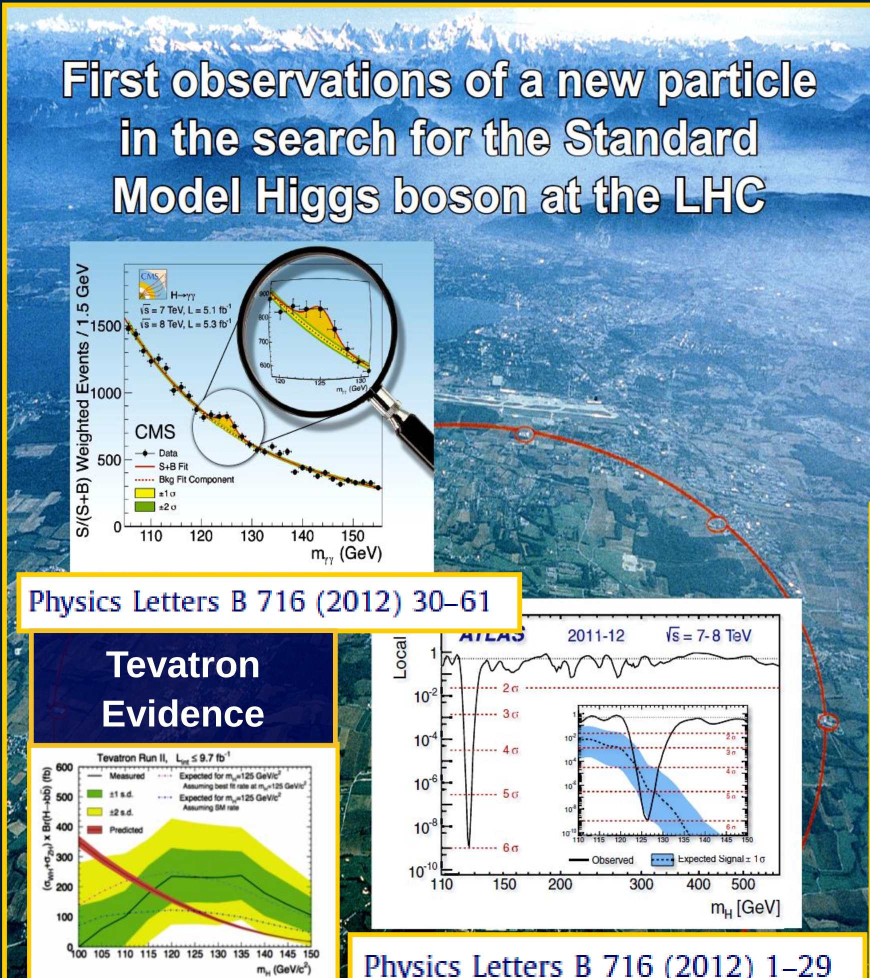
Operation: 2009-12

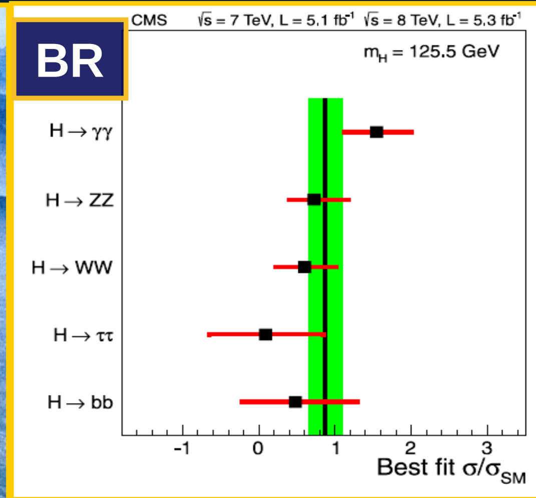


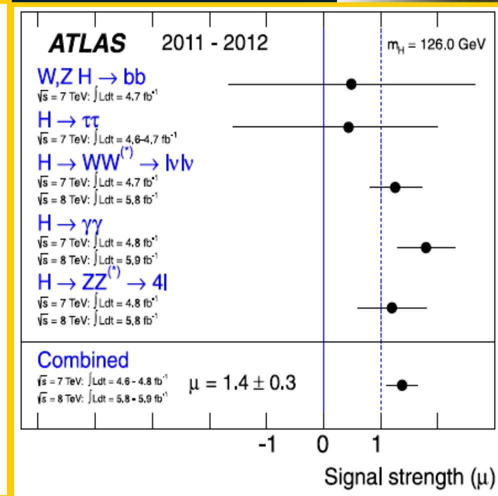
A billion people watched

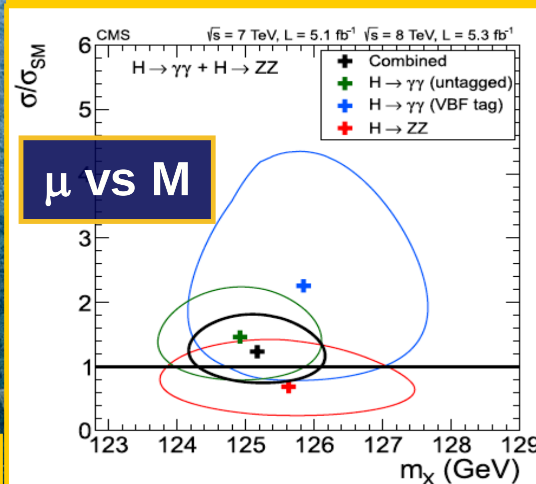
Observation of a New Boson Near 125 GeV

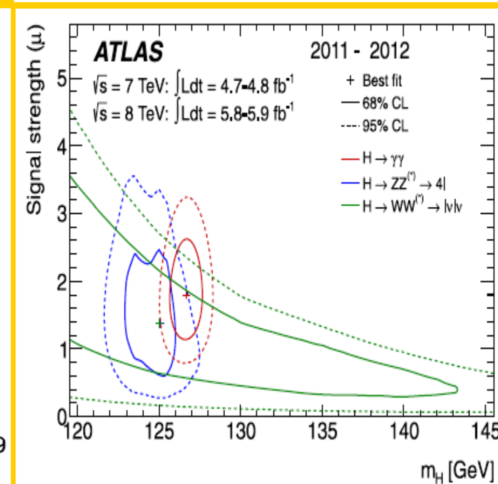
“The Discovery of the Century”







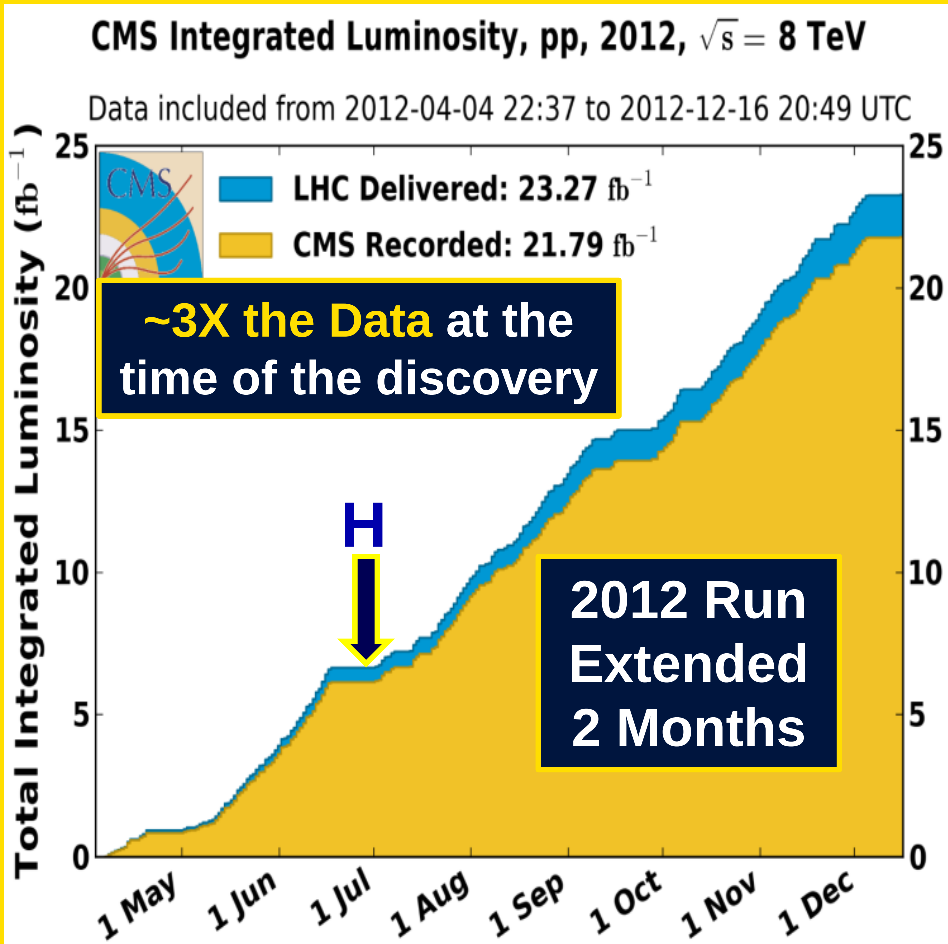


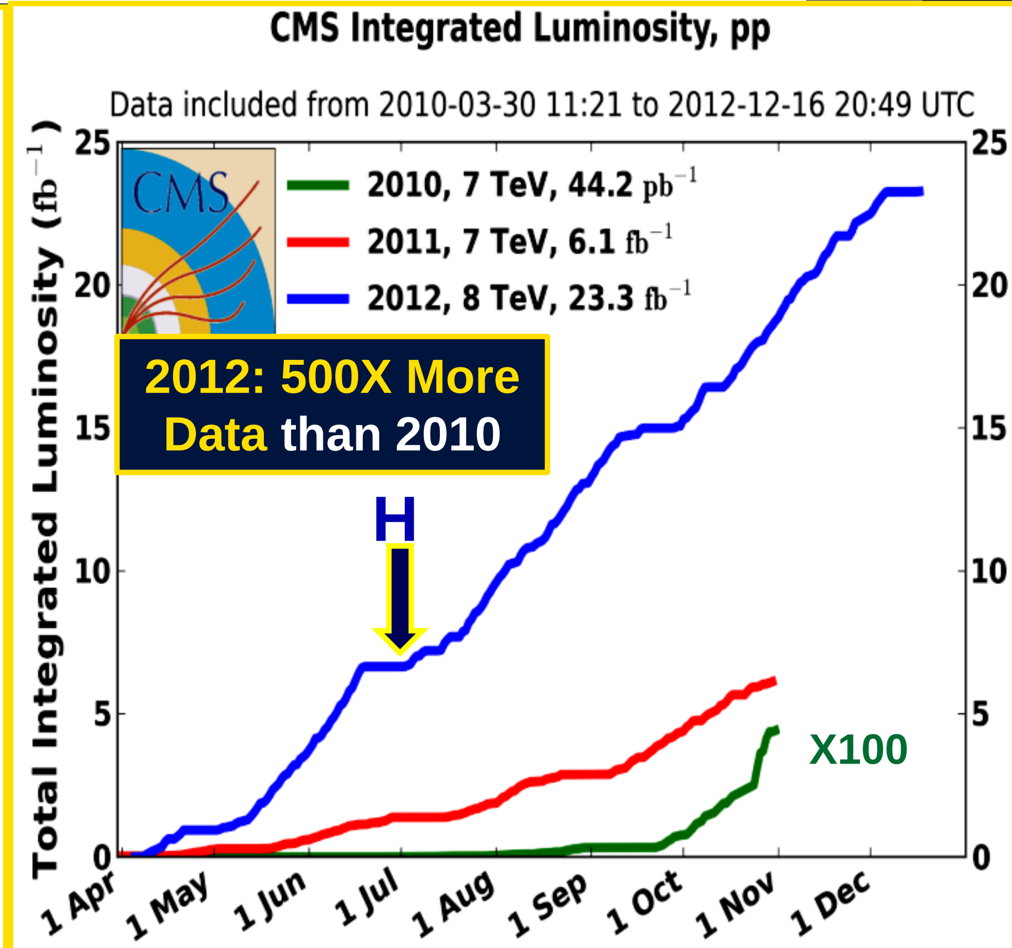


"Combined results of searches for the SM Higgs boson in pp collisions at s=7TeV" (http://www.sciencedirect.com/science/article/pii/S0370269312002055)
"Combined search for the SM Higgs boson with the ATLAS detector at the LHC" (http://www.sciencedirect.com/science/article/pii/S0370269312001852).

LHC: Remarkable Performance in 2012

Luminosity "Greater than design"

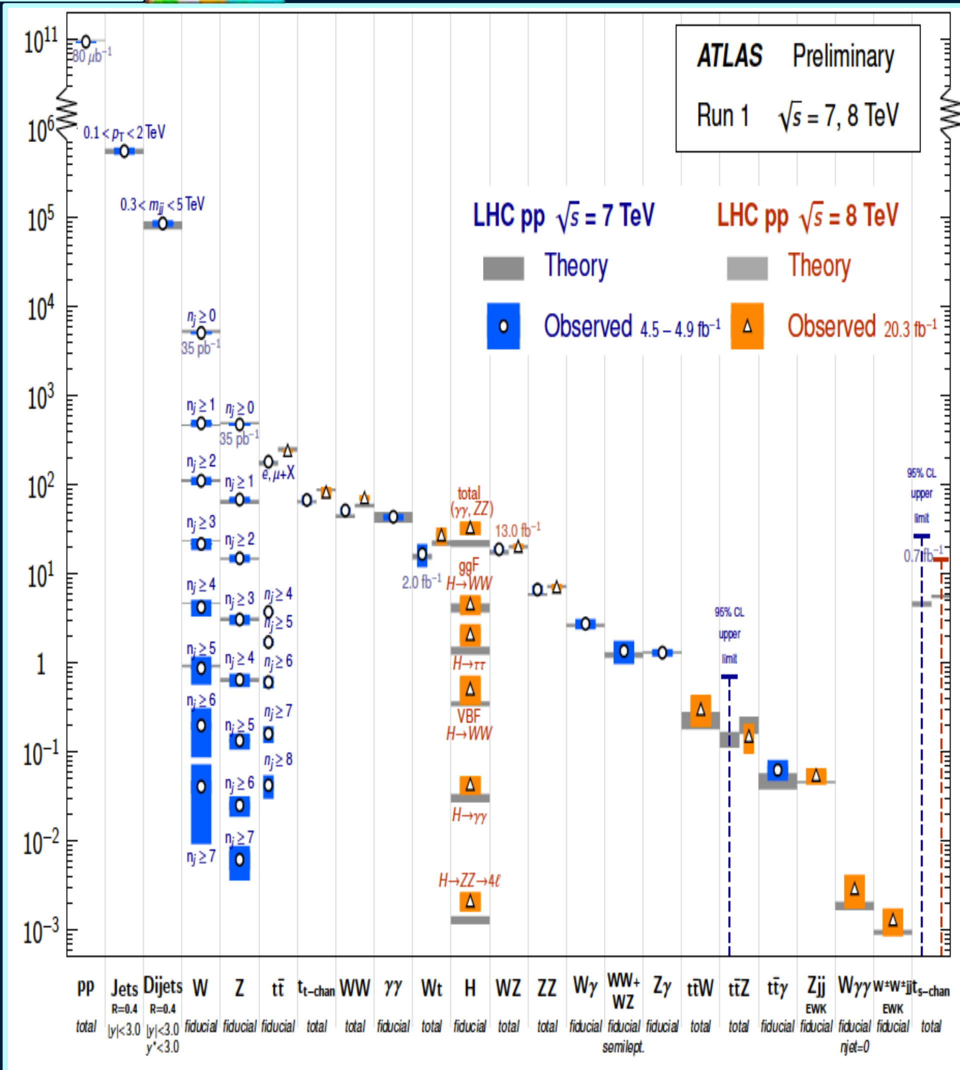


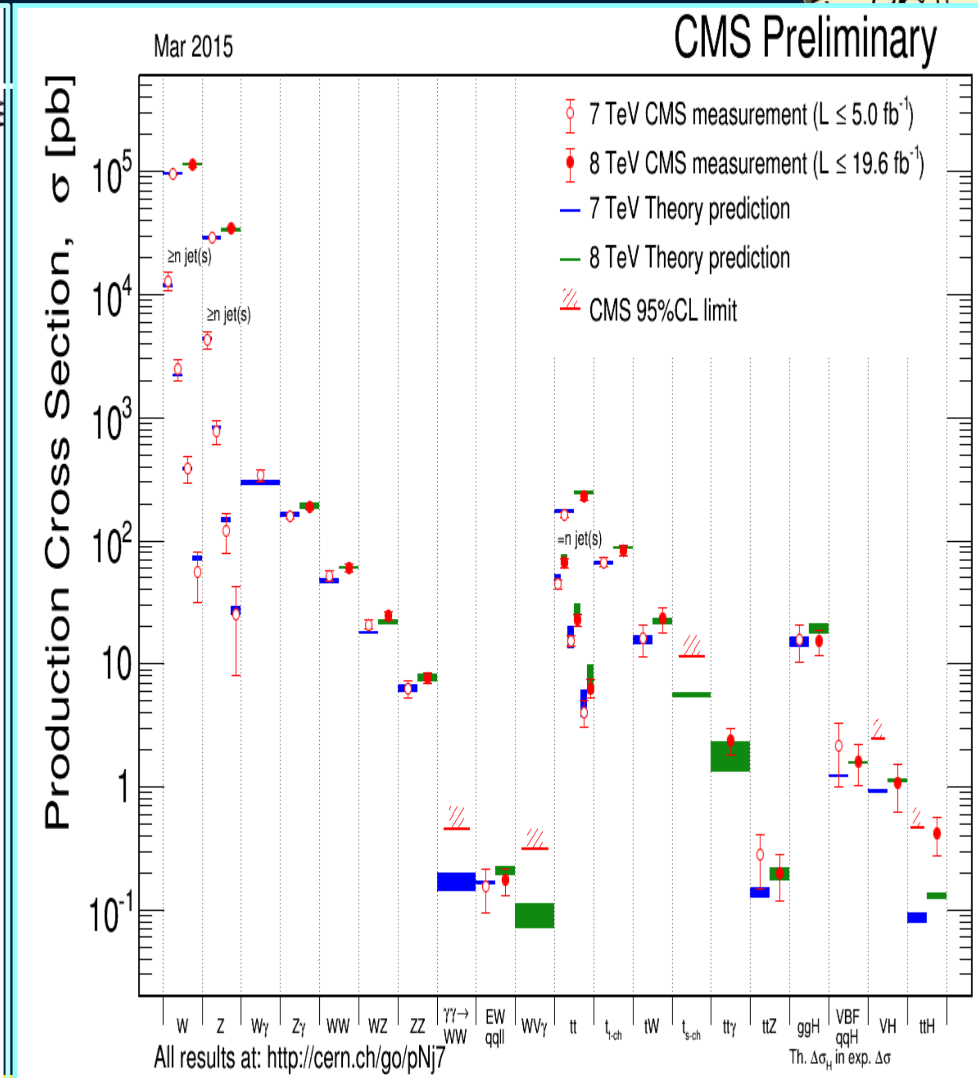


6 fb^{-1} by July Discovery: ~23+ fb^{-1} Delivered by Dec. 2012

~3.5 X 10^{15} pp Collisions, and 1M Higgs Bosons were created in Run 1

Standard Model at the LHC



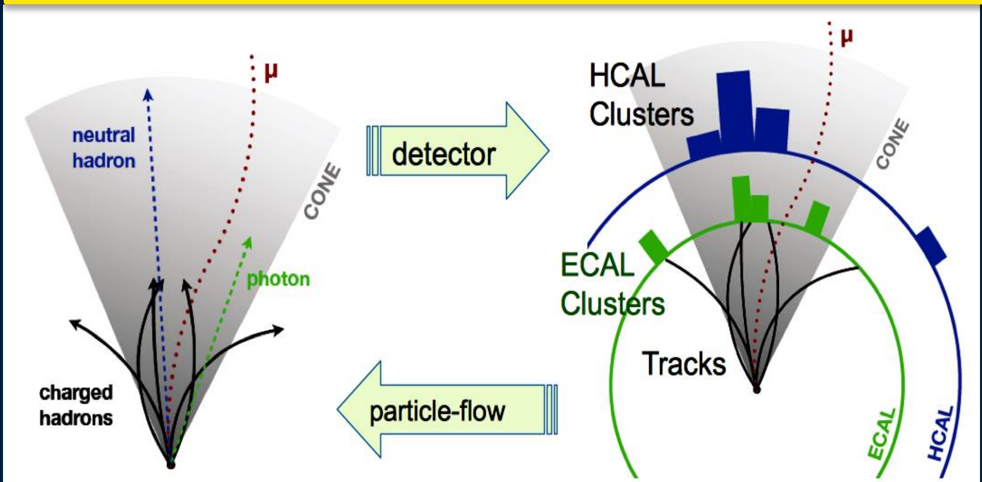


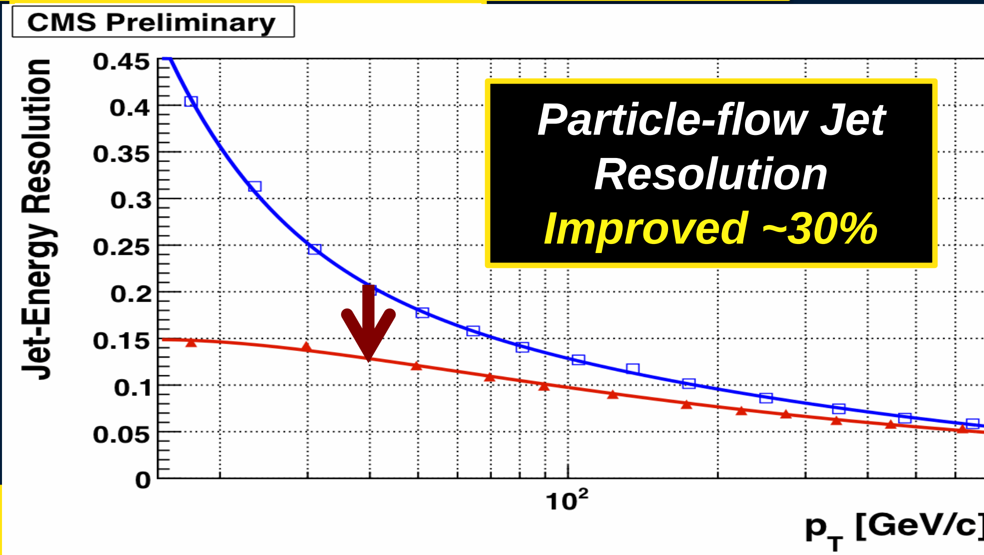
Good Understanding of the SM

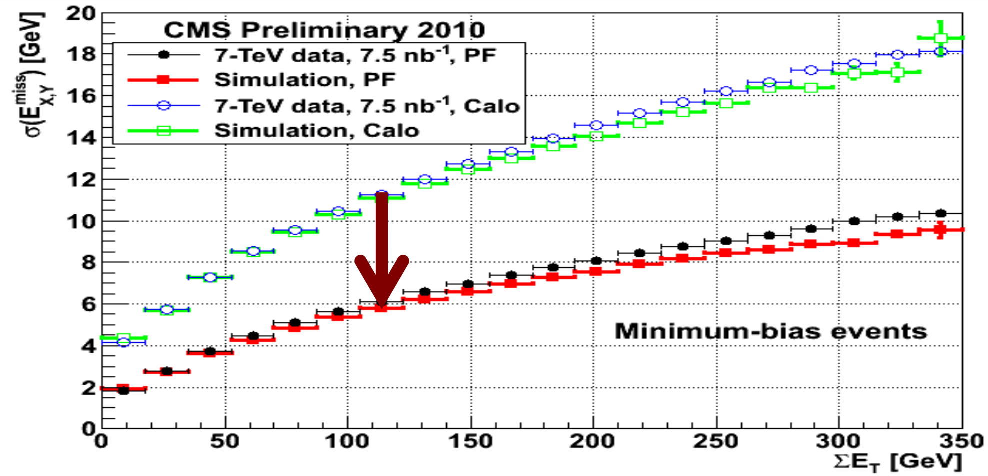
Measured Cross Sections Span 8 Orders of Magnitude

CMS Global Event Reconstruction

Made possible by CMS granularity and high magnetic field



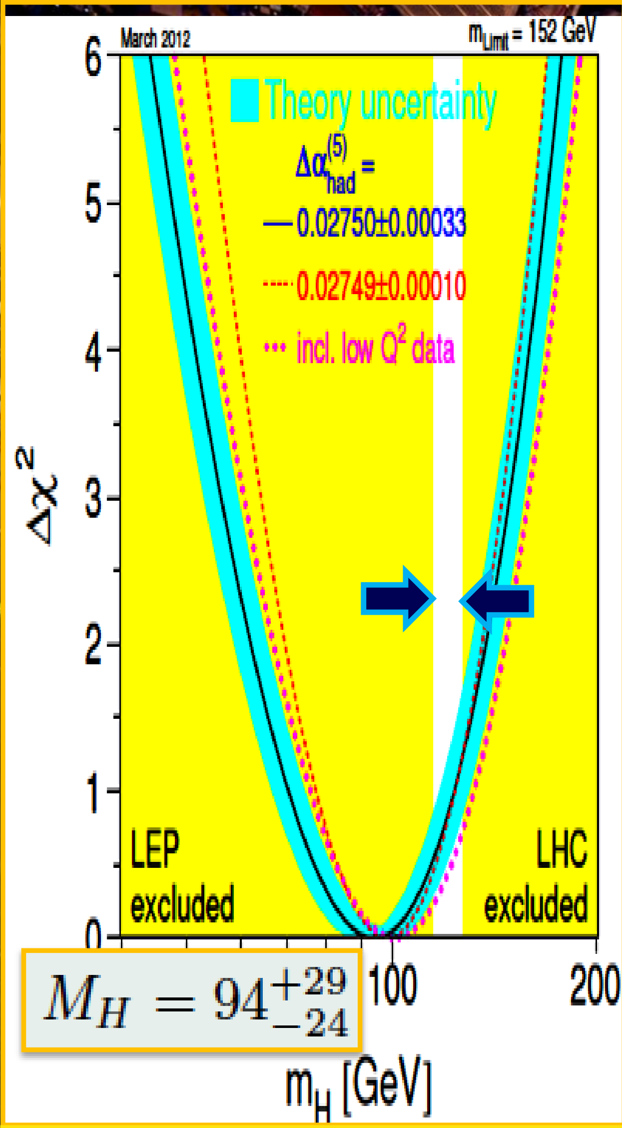


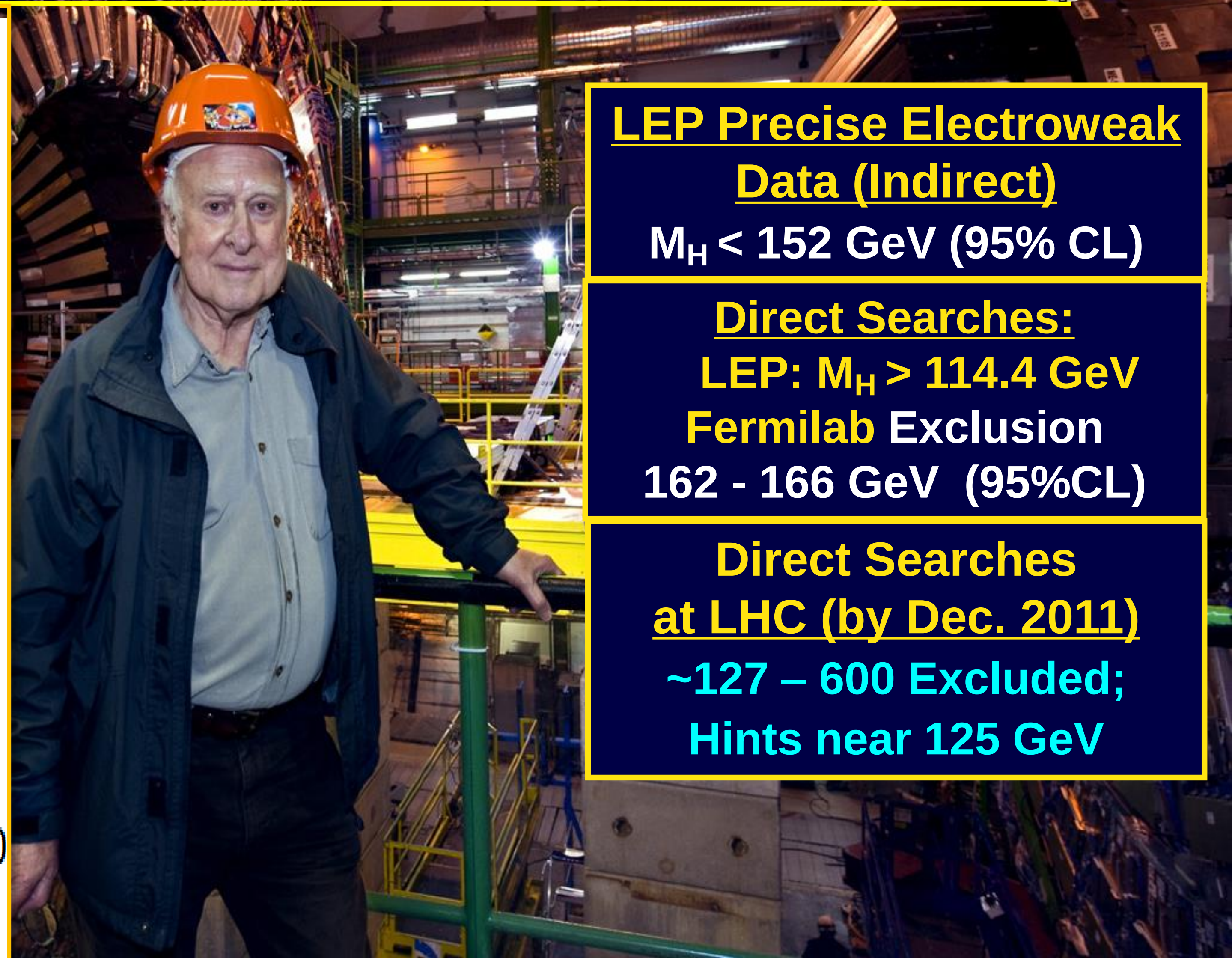


Missing ET Resolution Improved ~40%

- **Optimal combination of information from all subdetectors**
- **Returns reconstructed "particles": e, μ, γ, Charged & Neutral Hadrons**
- **Used as building blocks for jets, τs, Missing E_T, lepton isolation**
- **Tags charged particles from pile-up**
- **Minimized Impact: on jet reco., lepton & photon ID, isolation**
- **Restored Low pileup performance**

State of the Higgs on July 1 2012





LEP Precise Electroweak Data (Indirect)

M_H < 152 GeV (95% CL)

Direct Searches:

LEP: M_H > 114.4 GeV

Fermilab Exclusion 162 - 166 GeV (95%CL)

Direct Searches at LHC (by Dec. 2011)

~127 – 600 Excluded;

Hints near 125 GeV

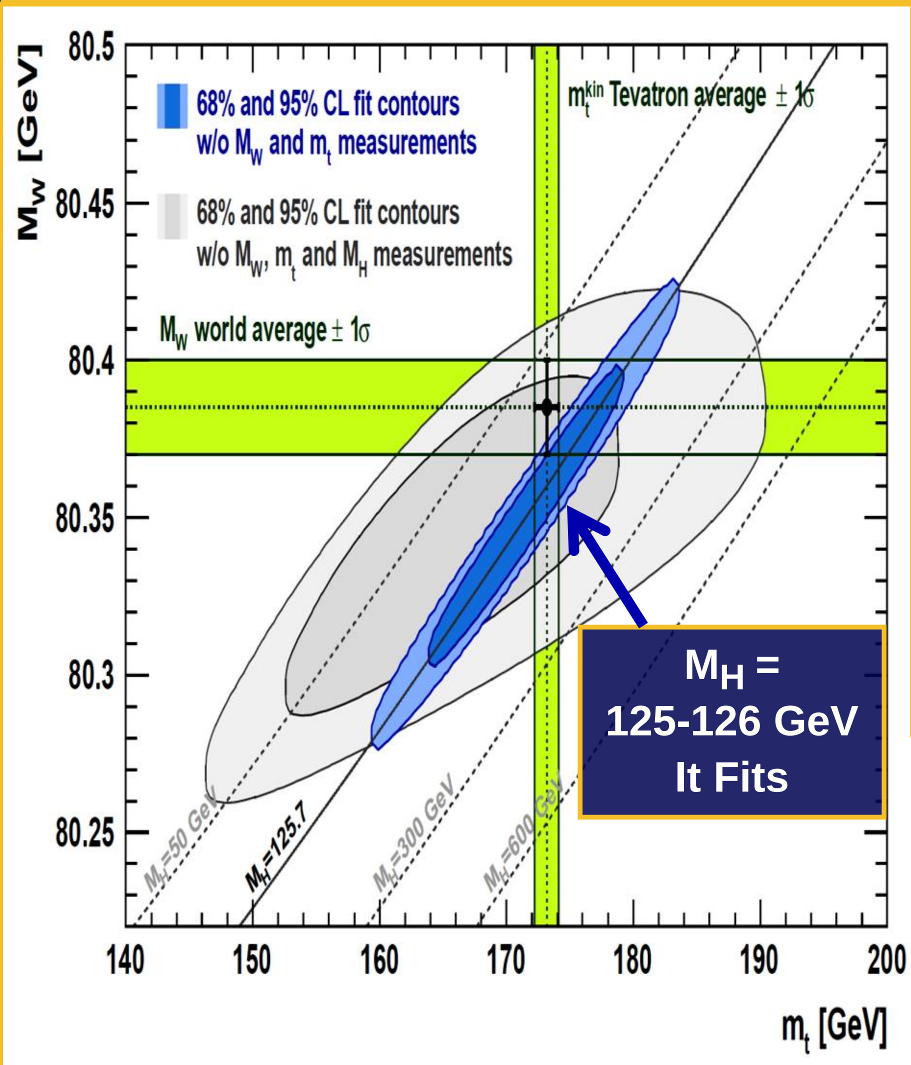
Closing In: Only a Narrow 13 GeV Gap Remained

LHC Run2
Higgs Sector Missions

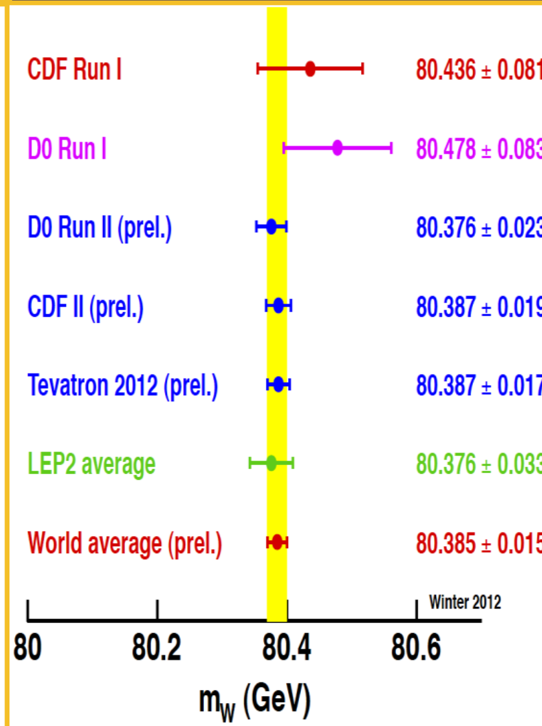
- Within the SM, Establish
  - $H \rightarrow bb$ decay
  - VBF production mode
  - ttH production mode
- More precise measurements of
  - Production and decay rates
  - Couplings
  - Rare Decays
  - Kinematics: Lorentz Structure
  - … DSD
- BSM Higgs: SUSY, Exotica
  - The Higgs Boson as a Portal to What lies Beyond

Precision Electroweak, Including the "SM Higgs": It Fits

Gfitter Post July 4 2012

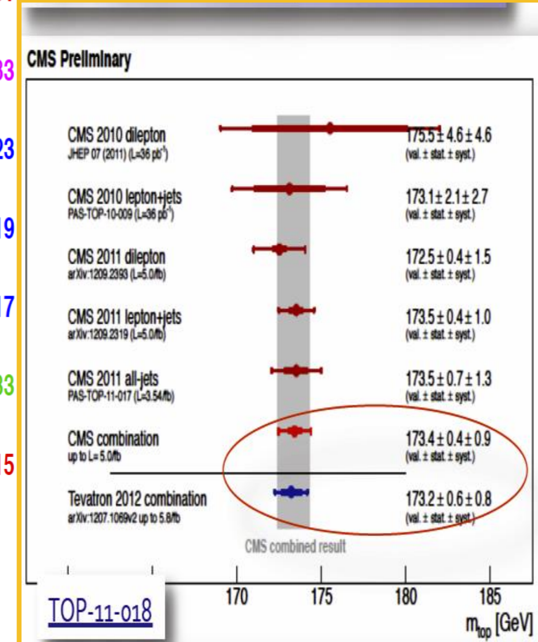


Precision W Mass

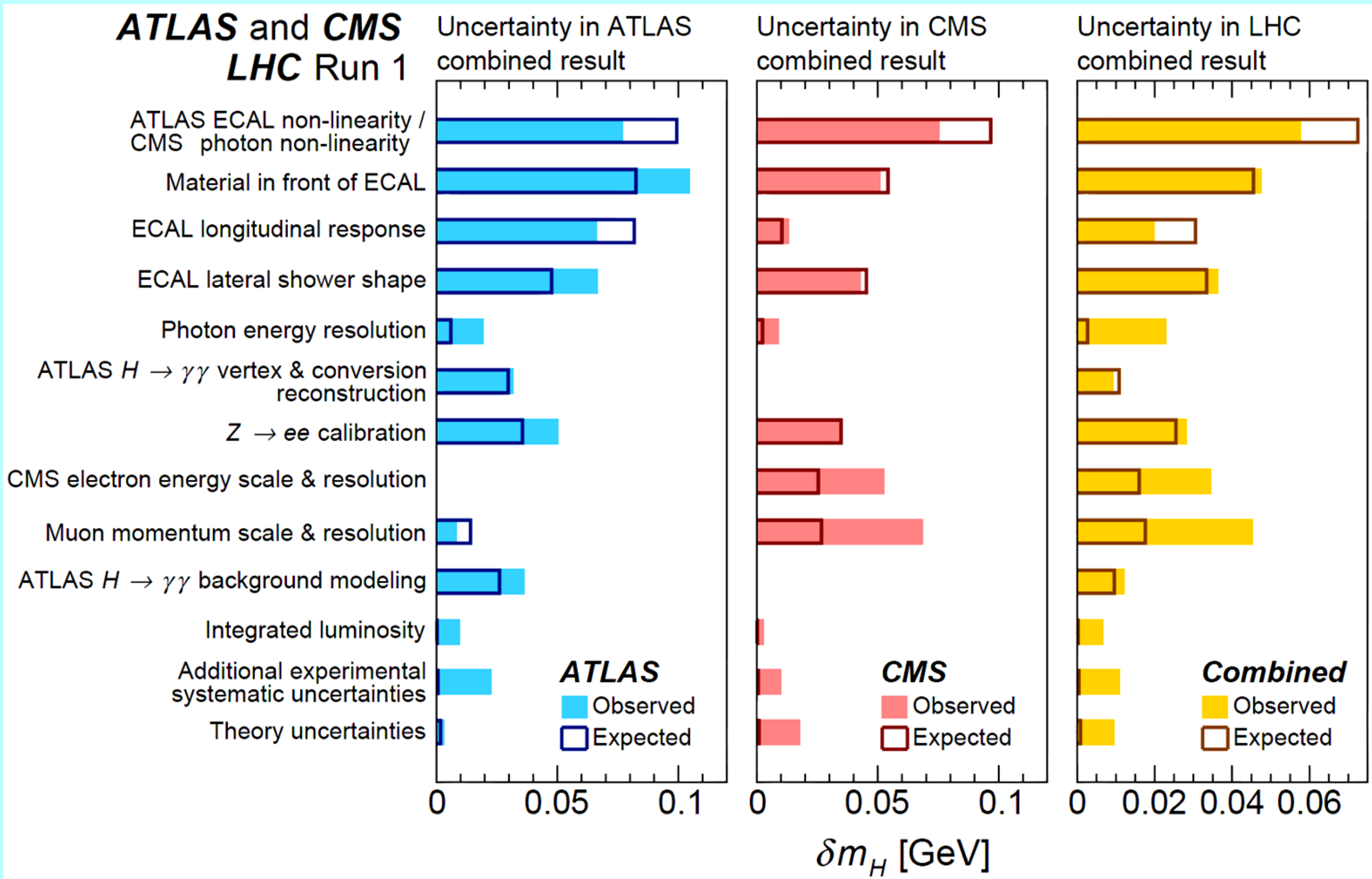


Precision Top Mass

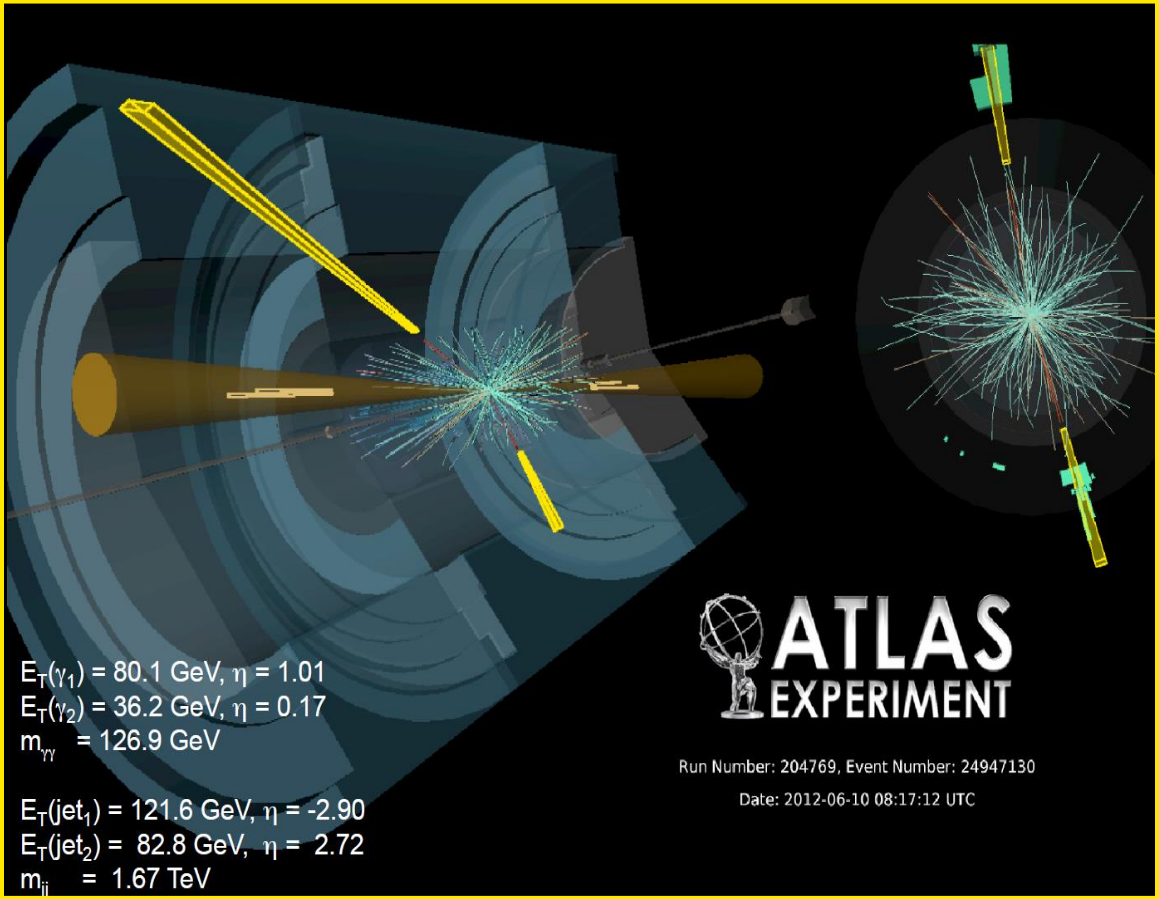
173.36 ± 0.38 ± 0.91 GeV

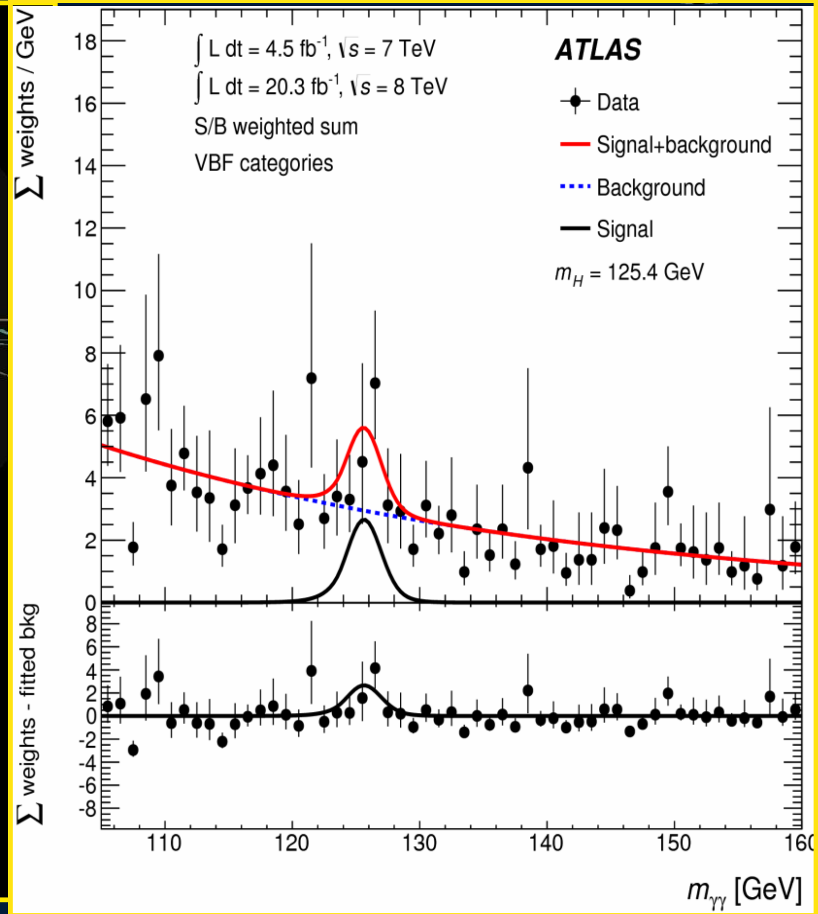


Combined Mass Measurement
from H → ZZ → 4ℓ, H → γγ
Detailed M_H Uncertainty Breakdown



• VBF H →γγ candidate





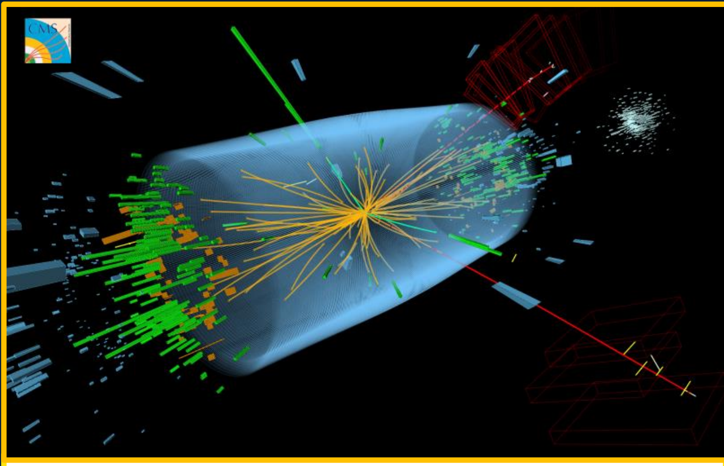
Phys. Rev. D90 (2014) 112015

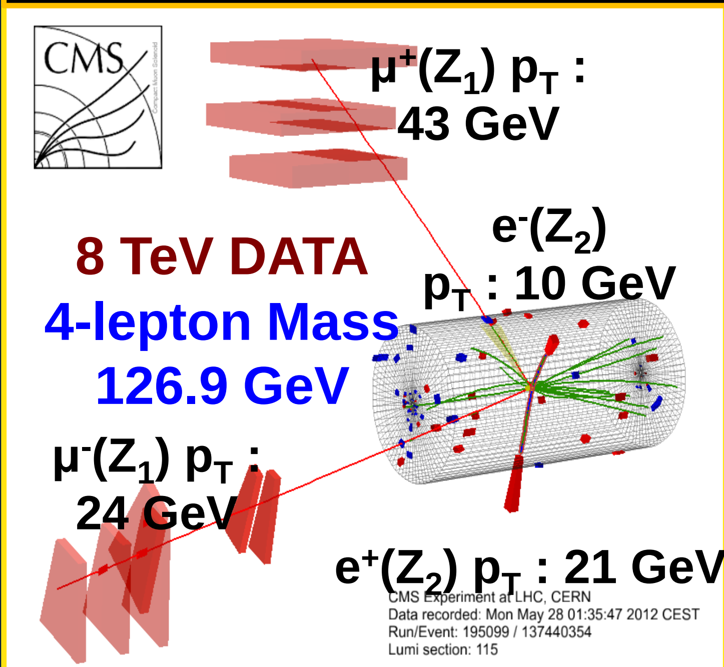
VBF enriched: tag-jet configuration, Δη, m_{jj}

H → ZZ(*) →4ℓ (ℓ = e,μ)
The Golden Channels

Arxiv 1406.3827

PhysRevD.89.092007





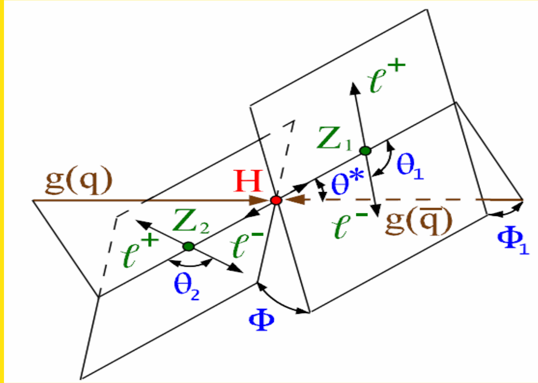
- **Signal:** 2 isolated lepton-pairs (SF, OS) from a common vtx; peak over small continuum BG
- **Fully reconstructed, Mass resolution ~1-2%**
- Kinematic info.➡ ideal for properties tests
  - Low lepton pT Thresholds; Special sel. for ττ
- **Selection:** Same flavor, opposite charge pairs
  - Z_1: P_T^{min} (e) > 7, P_T^{min} (μ) >5, 40 < M_{ll} <120 GeV
  - Z_2: 12 < M_{ll}< 120 GeV
  - 3D IP to vtx
- **Reducible Backgrounds:**
  - t-tbar → 2l 2ν 2b ; Z + bb: Removed by Isolation & Impact parameter requirements
- **Irreducible background:** pp → ZZ Continuum
  - Rate obtained from Z yield in data, + theory prediction for ratio of ZZ to Z cross sections
  - BG shape corrected to NLO (ttH) to NNLO

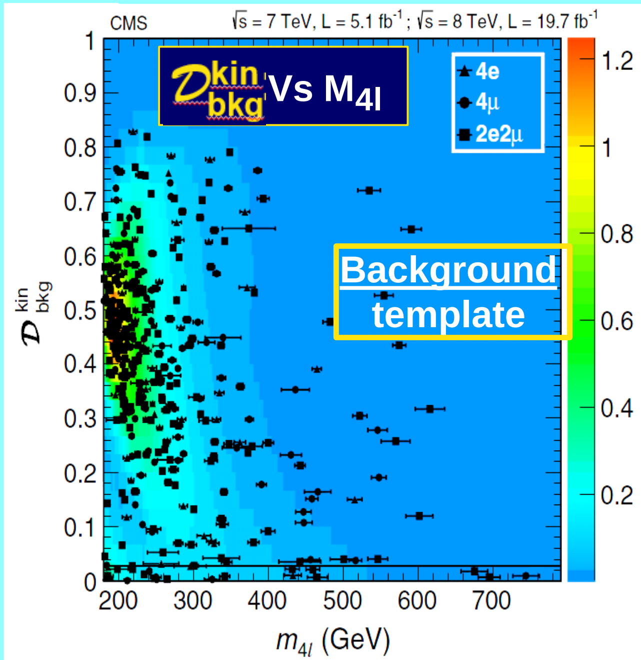
H ➡ ZZ(*) ➡ 4ℓ: 0+ Vs Background

$\mathcal{D}^{kin}_{bkg}$: Matrix Element Kinematic Discriminant

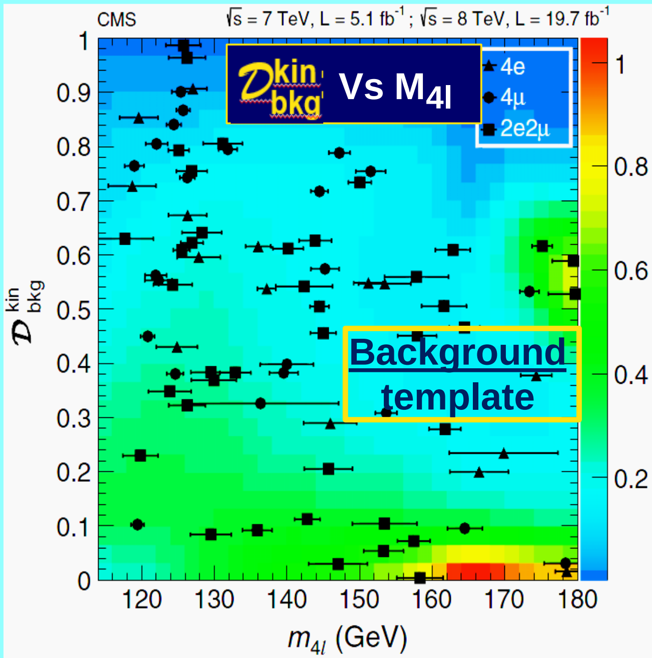
To further improve S Vs. B separation, construct a discriminant based on the kinematic information (5 angles and 3 masses)

$$\mathcal{D}^{kin}_{bkg} = \frac{\mathcal{P}^{kin}_{0^+}}{\mathcal{P}^{kin}_{0^+} + \mathcal{P}^{kin}_{bkg}} = \left[1 + \frac{\mathcal{P}^{kin}_{bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}{\mathcal{P}^{kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}\right]^{-1}$$

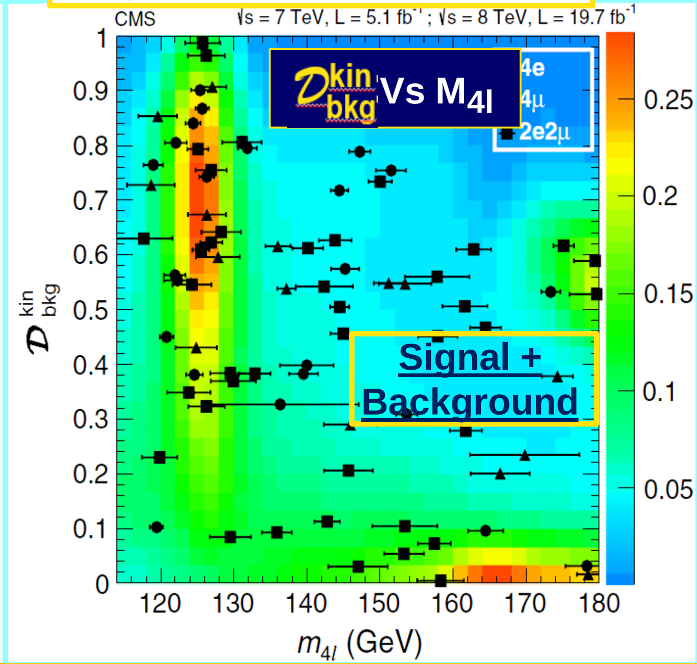




High mass data w/error bars Superimposed on background



Low mass data with error bars Superimposed on background



Low mass data: *Signal-like clustering near ~125 GeV*

Coupling Scaling factors

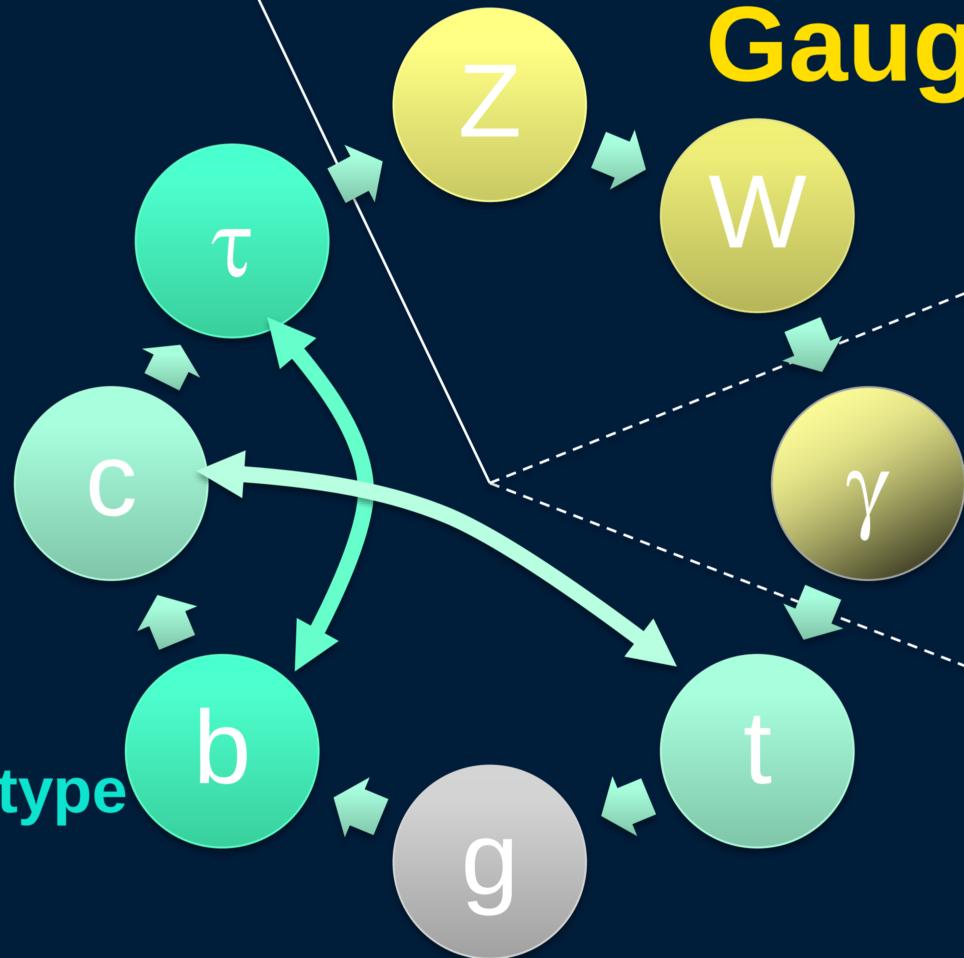
Yukawa sector

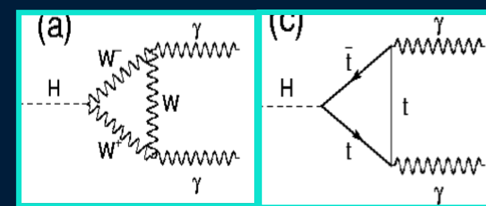
Gauge sector

Mixed sector

Up type

Down type





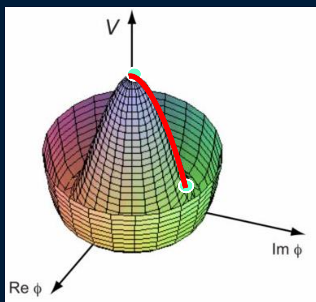
Loops (γ, g) are sensitive to BSM contributions.

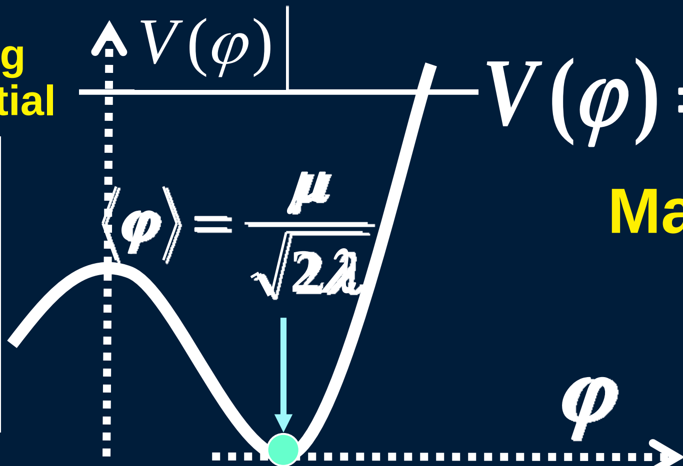
Quark loop

Higgs Self-Coupling:

Electroweak Vacuum: Structure of Phase Transition

Self-Interacting Effective Potential

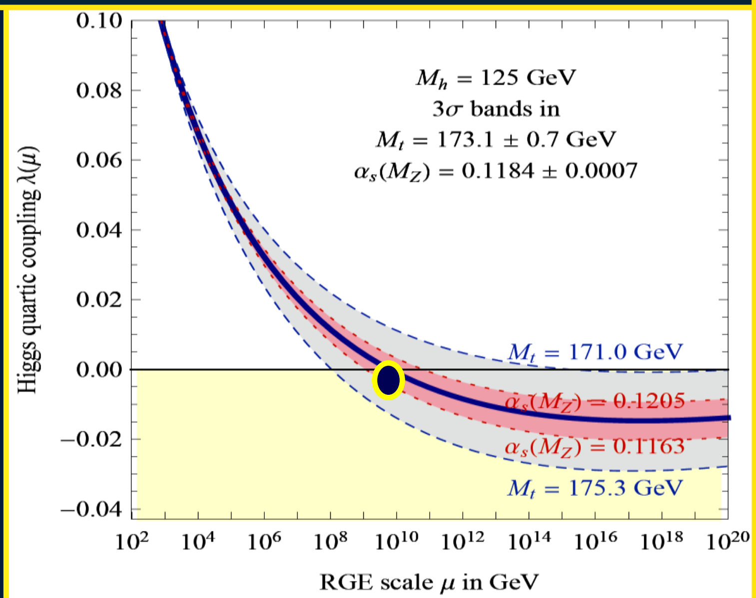




$$V(\varphi) = -\mu^2\varphi^2 + \lambda\varphi^4$$

Mass term **Self-coupling term**

NNLO Evolution of the Higgs Self-coupling λ(μ)



- **For Higgs mass of ~125 GeV**
- ➡ **λ goes negative ➡ Vacuum we are in is *metastable… ??***
- ➡ ***OR:* New physics at an intermediate energy scale ~10^{10-12} GeV**
- ***What lies between us and the Big Bang ?***

SM Higgs
Combined Analyses

CMS Arxiv 1214.8662	Significance Expected	Significance Observed
H ➡ ZZ	6.3 σ	6.5 σ
H ➡ γγ	5.3 σ	5.6 σ
H ➡ WW	5.4 σ	4.7 σ
H ➡ ττ	3.9 σ	3.8 σ
H ➡ bb	2.6 σ	2.0 σ
H ➡ μμ	< 0.1 σ	0.4 σ

ATLAS ATLAS-CONF-2015-007	Significance Expected	Significance Observed
H ➡ ZZ	6.2 σ	8.1 σ
H ➡ γγ	4.6 σ	5.2 σ
H ➡ WW	5.9 σ	6.5 σ
H ➡ ττ	3.4 σ	4.5 σ
H ➡ bb	2.6 σ	1.4 σ
H ➡ μμ	< 0.1 σ	0.4 σ

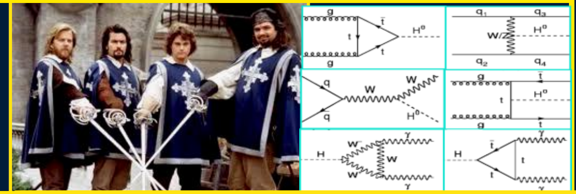
+ Many More

- H → μμ, Zγ, Invisible
- Offshell versus Onshell
- New particles decaying to H
- H decaying to new particles
- MSSM, NMSSM
- Fermiphobic, Doubly Charged
- …

	un-tagged	VBF-tag	VH-tag	ttH-tag
γγ	✔	✔	✔	✔
bb		✔	✔	✔
ττ	✔	✔	✔	✔
WW(lvlv)	✔	✔	✔	✔
ZZ(4l)	✔	✔	✔	✔

	gluon fusion	vector boson fusion (VBF)	associated prod. with W/Z	associated prod. with tt
γγ	✔	✔	✔	✔
ZZ	✔ + offshell	✔	✔	✔ NEW!
WW	✔ + offshell	✔	✔ NEW!	✔ NEW!
ττ	✔	✔		✔ NEW!
bb			✔	✔ NEW!

SM Higgs
Combined Analyses



ATLAS CONF-2015-007

Analysis	Signal		$\int \mathcal{L}dt$ (fb^{-1})	
Categorisation or final states	Strength	Significance [σ]	7 TeV	8 TeV
$H \to \gamma\gamma$ [12]	1.17 ± 0.27	5.2 (4.6)	4.5	20.3
ttH: leptonic, hadronic			✓	✓
VH: one-lepton, dilepton, E_T^{miss}, hadronic			✓	✓
VBF: tight, loose			✓	✓
ggF: 4 p_{Tt} categories			✓	✓
$H \to ZZ^* \to 4\ell$ [13]	$1.44^{+0.40}_{-0.33}$	8.1 (6.2)	4.5	20.3
VBF			✓	✓
VH: hadronic, leptonic			✓	✓
ggF			✓	✓
$H \to WW^*$ [14, 15]	$1.16^{+0.24}_{-0.21}$	6.5 (5.9)	4.5	20.3
ggF: (0-jet, 1-jet) $\otimes$ ($ee + \mu\mu$, $e\mu$)			✓	✓
ggF: $\geq$ 2-jet and $e\mu$				✓
VBF: $\geq$ 2-jet $\otimes$ ($ee + \mu\mu$, $e\mu$)			✓	✓
VH: opposite-charge dilepton, three-lepton, four-lepton			✓	✓
VH: same-charge dilepton				✓
$H \to \tau\tau$ [17]	$1.43^{+0.43}_{-0.37}$	4.5 (3.4)	4.5	20.3
Boosted: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
VBF: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
$VH \to Vb\bar{b}$ [18]	0.52 ± 0.40	1.4 (2.6)	4.7	20.3
0ℓ ($ZH \to \nu\nu bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V > $ and < 120 GeV			✓	✓
1ℓ ($WH \to \ell\nu bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V > $ and < 120 GeV			✓	✓
2ℓ ($ZH \to \ell\ell bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V > $ and < 120 GeV			✓	✓
		95% CL limit		
$H \to Z\gamma$ [19]		$\mu < 11$ (9)	4.5	20.3
10 categories based on $\Delta\eta_{Z\gamma}$ and p_{Tt}			✓	✓
$H \to \mu\mu$ [20]		$\mu < 7.0$ (7.2)	4.5	20.3
VBF and 6 other categories based on η_μ and $p_T^{\mu\mu}$			✓	✓
ttH production [21–23]			4.5	20.3
$H \to b\bar{b}$: single-lepton, dilepton		$\mu < 3.4$ (2.2)		✓
$ttH \to$ multileptons: categories on lepton multiplicity		$\mu < 4.7$ (2.4)		✓
$H \to \gamma\gamma$: leptonic, hadronic		$\mu < 6.7$ (4.9)	✓	✓
Off-shell H^* production [24]		$\mu < 5.1 - 8.6$ (6.7 − 11.0)		20.3
$H^* \to ZZ \to 4\ell$				✓
$H^* \to ZZ \to 2\ell 2\nu$				✓
$H^* \to WW \to e\nu\mu\nu$				✓

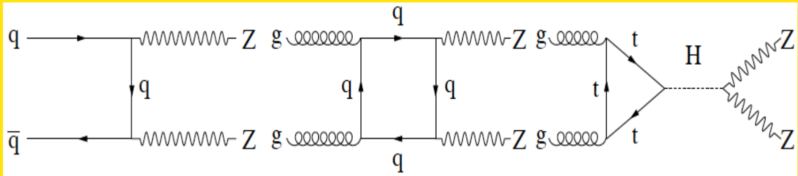
Arxiv 1214.8662

Decay tag and production tag		Expected signal composition	σ_{m_H}/m_H	Luminosity (fb^{-1}) No. of categories 7 TeV	8 TeV
$H \to \gamma\gamma$ [18], Section 2.1				5.1	19.7
$\gamma\gamma$	Untagged	76–93% ggH	0.8–2.1%	4	5
	2-jet VBF	50–80% VBF	1.0–1.3%	2	3
	Leptonic VH	≈95% VH (WH/ZH ≈ 5)	1.3%	2	2
	E_T^{miss} VH	70–80% VH (WH/ZH ≈ 1)	1.3%	1	1
	2-jet VH	≈65% VH (WH/ZH ≈ 5)	1.0–1.3%	1	1
	Leptonic ttH	≈95% ttH	1.1%	1†	1
	Multijet ttH	>90% ttH	1.1%		1
$H \to ZZ \to 4\ell$ [16], Section 2.2				5.1	19.7
4μ, $2e2\mu/2\mu 2e$, 4e	0/1-jet	≈90% ggH	1.3, 1.8, 2.2%‡	3	3
	2-jet	42% (VBF + VH)		3	3
$H \to WW \to \ell\nu\ell\nu$ [22], Section 2.3				4.9	19.4
ee + $\mu\mu$, eμ	0-jet	96–98% ggH	16%‡	2	2
	1-jet	82–84% ggH	17%‡	2	2
	2-jet VBF	78–86% VBF		2	2
	2-jet VH	31–40% VH		2	2
$3\ell 3\nu$ (WH)	SF-SS, SF-OS	≈100% WH, up to 20% $\tau\tau$		2	2
$\ell\ell + \ell'\nu$jj (ZH)	eee, eeμ, $\mu\mu\mu$, $\mu\mu$e	≈100% ZH		4	4
$H \to \tau\tau$ [23], Section 2.4				4.9	19.7
eτ_h, $\mu\tau_h$	0-jet	≈98% ggH	11–14%	4	4
	1-jet	70–80% ggH	12–16%	5	5
	2-jet VBF	75–83% VBF	13–16%	2	4
$\tau_h\tau_h$	1-jet	67–70% ggH	10–12%	—	2
	2-jet VBF	80% VBF	11%	—	1
eμ	0-jet	≈98% ggH, 23–30% WW	16–20%	2	2
	1-jet	75–80% ggH, 31–38% WW	18–19%	2	2
	2-jet VBF	79–94% VBF, 37–45% WW	14–19%	1	2
ee, $\mu\mu$	0-jet	88–98% ggH		4	4
	1-jet	74–78% ggH, ≈17% WW ⋆		4	4
	2-jet CJV	≈50% VBF, ≈45% ggH, 17–24% WW ⋆		2	2
$\ell\ell + LL'$ (ZH)	$LL' = \tau_h\tau_h, \ell\tau_h$, e$\mu$	≈15% (70%) WW for $LL' = \ell\tau_h$ (eμ)		8	8
$\ell + \tau_h\tau_h$ (WH)		≈96% VH, ZH/WH ≈ 0.1		2	2
$\ell + \ell'\tau_h$ (WH)		ZH/WH ≈ 5%, 9–11% WW		2	4
VH production with $H \to$ bb [21], Section 2.5				5.1	18.9
W($\ell\nu$)H(bb)	p_T(V) bins	≈100% VH, 96–98% WH	≈10%	4	6
W($\tau_h\nu$)H(bb)	—	93% WH		—	1
Z($\ell\ell$)H(bb)	p_T(V) bins	≈100% ZH		4	4
Z($\nu\nu$)H(bb)	p_T(V) bins	≈100% VH, 62–76% ZH		2	3
ttH production with $H \to$ hadrons or $H \to$ leptons [29], Section 2.6				5.0	≤19.6
$H \to$ bb	$t\bar{t}$ lepton+jets	≈90% bb but ≈24% WW in ≥6j + 2b		7	7
	$t\bar{t}$ dilepton	45–85% bb, 8–35% WW, 4–14% $\tau\tau$		2	3
$H \to \tau_h\tau_h$	$t\bar{t}$ lepton+jets	68–80% $\tau\tau$, 13–22% WW, 5–13% bb		—	6
2ℓ SS	≥ 2 jets, ≥ 1 b jet	WW/$\tau\tau$ ≈ 3		—	6
3ℓ		WW/$\tau\tau$ ≈ 3		—	2
4ℓ		WW : $\tau\tau$: ZZ ≈ 3 : 2 : 1		—	1
$H \to$ invisible [28], Section 2.7				4.9	≤19.7
H(inv)	2-jet VBF	≈94% VBF, ≈6% ggH		—	1
ZH → Z(ee, $\mu\mu$)H(inv)	0-jet	≈100% ZH		2	2
	1-jet			2	2
$H \to \mu\mu$ [30], Section 2.8				5.0	19.7
$\mu\mu$	Untagged	88–99% ggH	1.3–2.4%	12	12
	2-jet VBF	≈80% VBF	1.9%	1	1
	2-jet boosted	≈50% ggH, ≈50% VBF	1.8%	1	1
	2-jet other	≈68% ggH, ≈17% VH, ≈15% VBF	1.9%	1	1

† Events fulfilling the requirements of either selection are combined into one category.
‡ Values for analyses dedicated to the measurement of the mass that do not use the same categories and/or observables.
⋆ Composition in the regions for which the ratio of signal and background $s/(s + b) > 0.05$.

Constraints on the Higgs Width from On-Shell/Off-Shell Signal Ratio

[Note Γ_{SM} = 4.2 MeV]



$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2} \qquad \sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

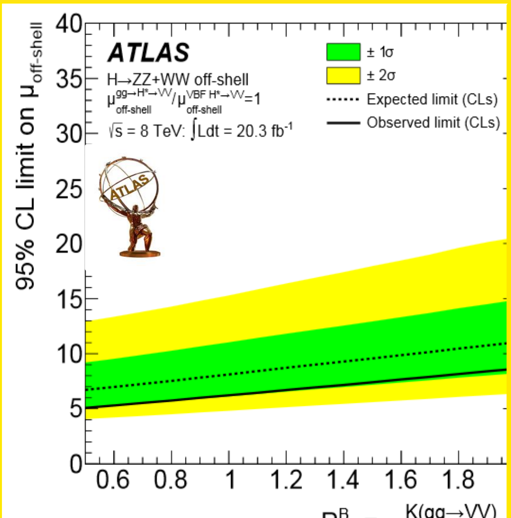
Γ_H from ratio of on- to off-shell signal rates

$H\to ZZ\to 4\ell$, $H\to ZZ\to \ell\ell\nu\nu$ (ATLAS+CMS)

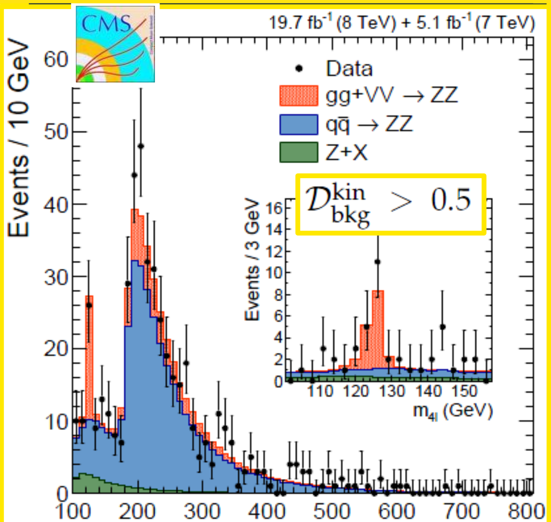
and $H\to WW\to e\nu\mu\nu$ (ATLAS)

Discriminants to Enhance S/B, Fit for Γ_H

LO Continuum gg → VV depends on K-Ratio	M(4ℓ) in 100 – 800 GeV $\mathcal{D}$s to enhance gg Signal	R8 in Signal Region > 450 GeV	CMS Limits on Γ_H

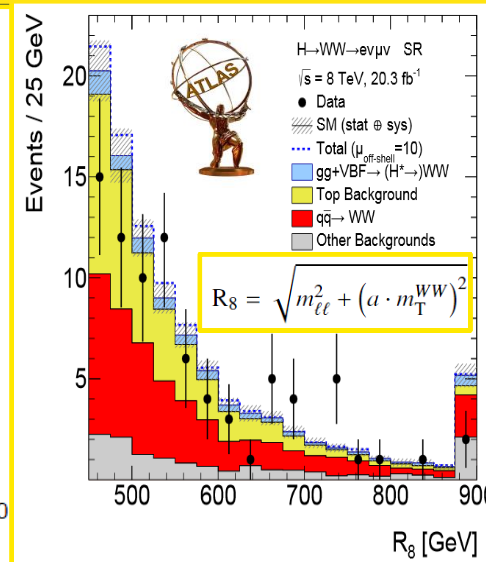


ArXiv:1503.01060

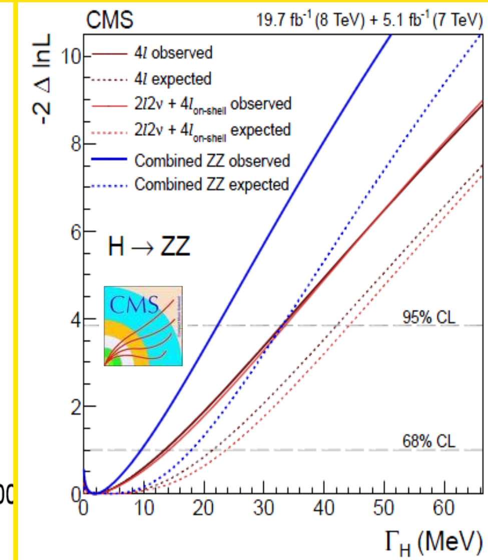


$\mathcal{D}^{\text{kin}}_{\text{bkg}} > 0.5$

Arxiv:1405.3455v2



$$R_8 = \sqrt{m^2_{\ell\ell} + (a \cdot m^{WW}_T)^2}$$



Assuming couplings g_{ggH} and g_{HZZ} are the same on- and off-shell

CMS Γ_H/Γ_{SM} < 5.4 at 95% CL (8.0 Expected)

ATLAS Γ_H/Γ_{SM} < 5.5 at 95% CL (8.0 *Expected*)

Arxiv 1501.03276v2
Phys. Rev. Lett. 114, 121801 (2015)

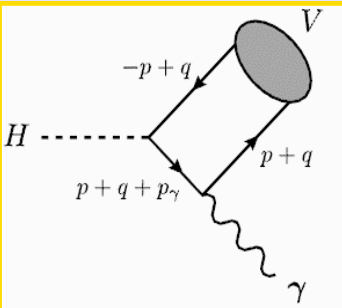
Probing Higgs Charm Yukawa Couplings with Rare Decays: Search for H, Z ➡ J/ψ γ, ϒ(nS) γ

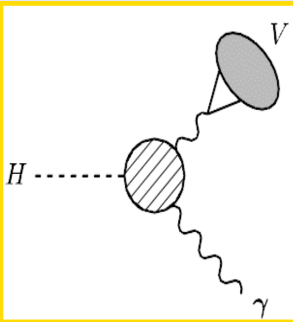
A. Chisholm, Birmingham

Intro: $H \to \mathcal{Q}\,\gamma$, $Z \to \mathcal{Q}\,\gamma$

- Direct Amplitude sensitive to $Hc\bar{c}$ and $Hb\bar{b}$ couplings
- Very rare SM decay (c.f. $\mathcal{B}(H \to \gamma\gamma) \approx 2 \times 10^{-3}$)
- Will need a HL-LHC with (at least) 3000 fb^{-1} to approach observation

$$\mathcal{B}(H \to J/\psi\,\gamma) = 2.8 \times 10^{-6\dagger}$$
$$\mathcal{B}(H \to \Upsilon(1S,2S,3S)\,\gamma) = \{0.6, 2.0, 2.4\} \times 10^{-9\dagger}$$

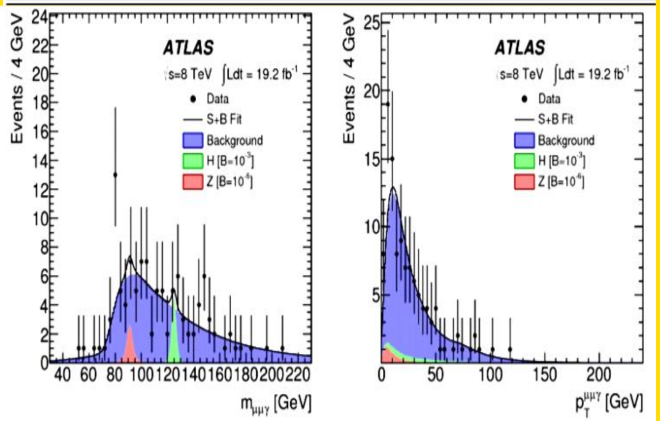




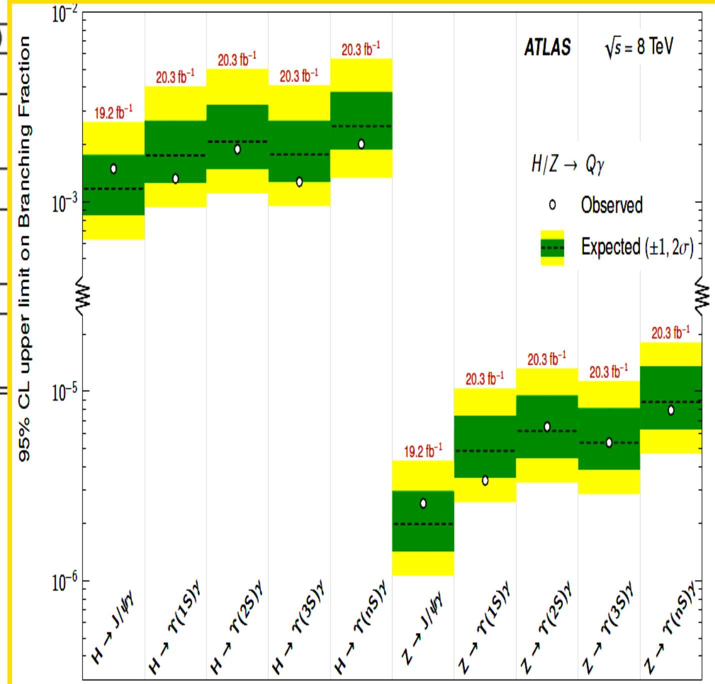
More details: Phys. Rev. D 88, 053003 (2013) (arXiv:1306.5770)
and † Phys. Rev. D 90, 113010 (2014) (arXiv:1407.6695)

95% CL UL on σ X $\mathcal{B}$ for $H \to \mathcal{Q}\,\gamma$, $Z \to \mathcal{Q}\,\gamma$

	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
	$\mathcal{B}(Z \to \mathcal{Q}\gamma)\,[10^{-6}]$				
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
	$\mathcal{B}(H \to \mathcal{Q}\gamma)\,[10^{-3}]$				
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
	$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]				
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44



Upper limits set on Higgs decays at the level of 10^{-3}!
Remember, this is at the level of the $H \to \gamma\gamma$ decay rate! (2×10^{-3})

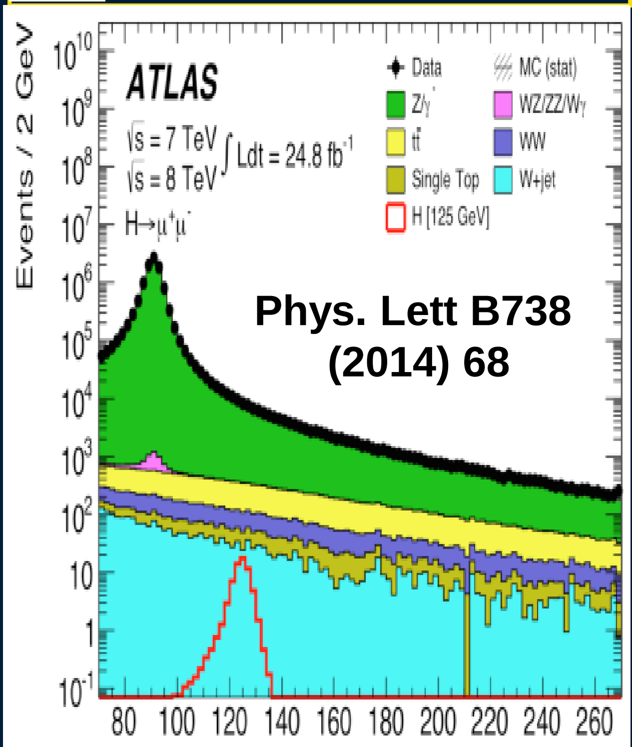


Upper limits set on Z decays rule out several predictions in the literature!
e.g. Theor. Math. Phys. 170, 39 (2012) (up to 10^{-5} predicted!)

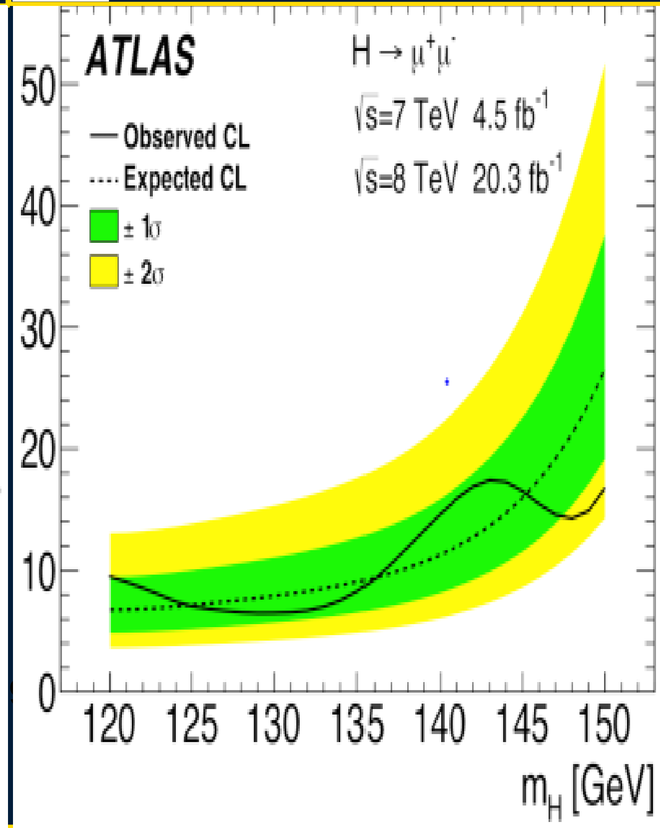
- Upper limit of around 540×SM rate for $H \to J/\psi\,\gamma$ decay
- Upper limit of around 26×SM rate for $Z \to J/\psi\,\gamma$ decay

Higgs → μμ Search Results

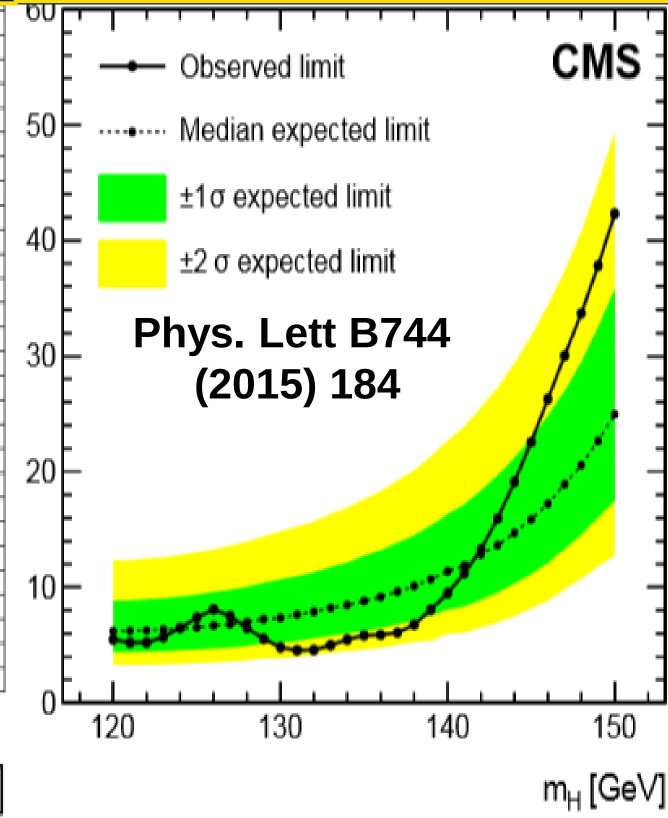
$dM/dM_{\mu\mu}$ vs the backgrounds + projected signal



$\mu = \sigma/\sigma_{SM}$ 95% CL UL vs expectations (ATLAS)



$\mu = \sigma/\sigma_{SM}$ 95% CL UL vs expectations (CMS)



For M_H = 125 GeV:

ATLAS: 95% CL: 7.0 σ_{SM} (7.2 expected, no Higgs); BR <~ 0.15%

CMS: 95% CL: 7.4 σ_{SM} (6.5 expected, no Higgs); BR <~ 0.16%

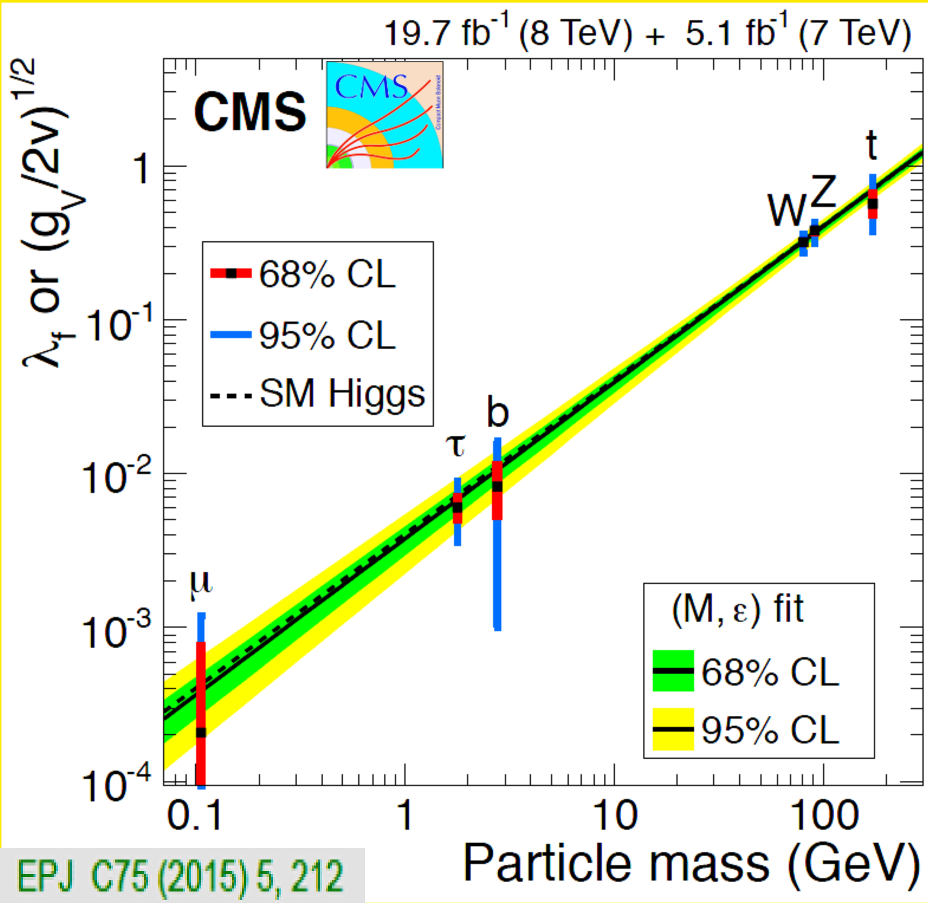
No evidence for flavor universal coupling (μμ smaller than ττ)

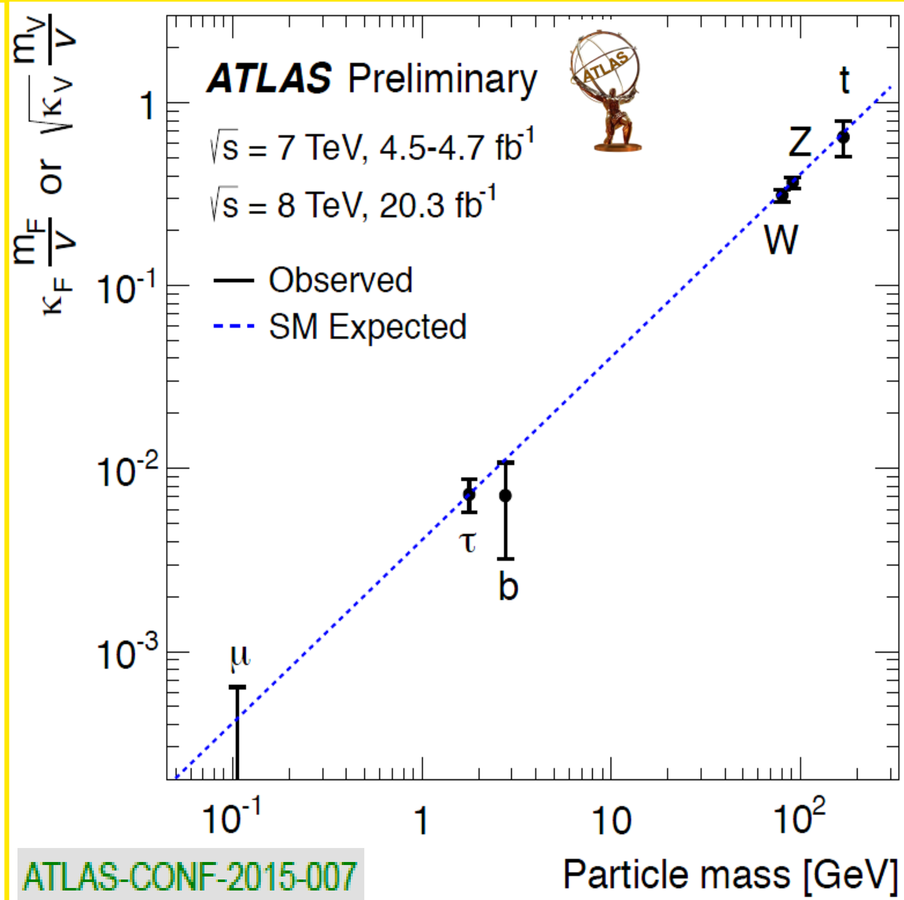
Higgs Boson Couplings

Expressed in Terms of the Particle Mass

Yukawa coupling for fermions = $m_f/v * \kappa_f$

$(g_V/2v)^{1/2}$ = coupling for bosons = $m_V/v * \kappa_V^{1/2}$





Quite Compatible with SM

Non-universal, mass dependent couplings observed for the first time

Ratios of Higgs Boson Couplings.

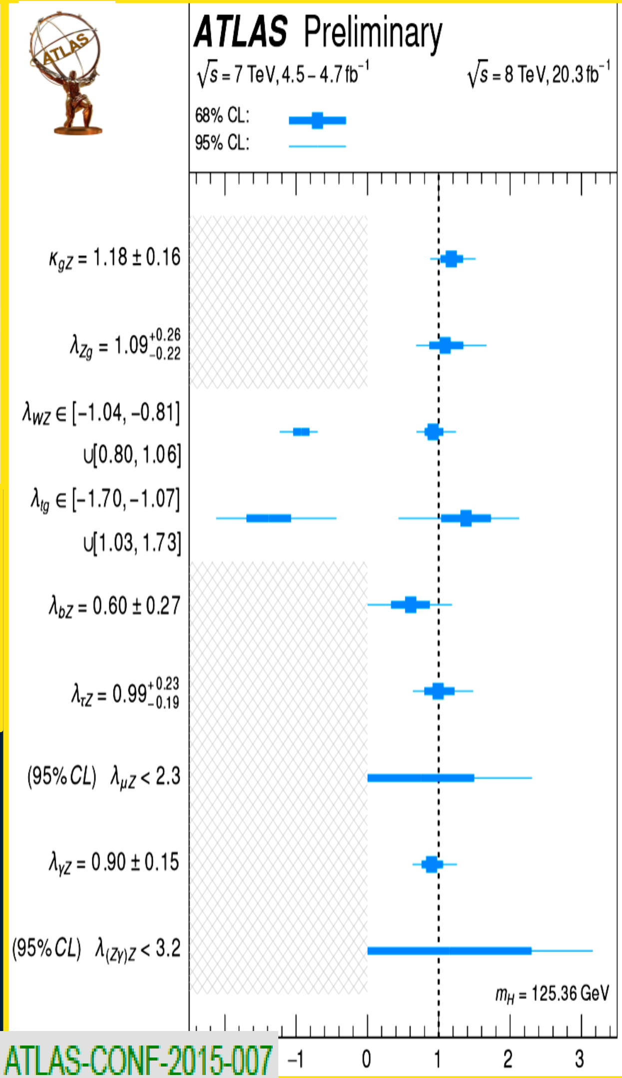
Most general fit: no assumptions on loops' coupling strengths or Higgs width

λ_{WZ}: test of custodial symmetry

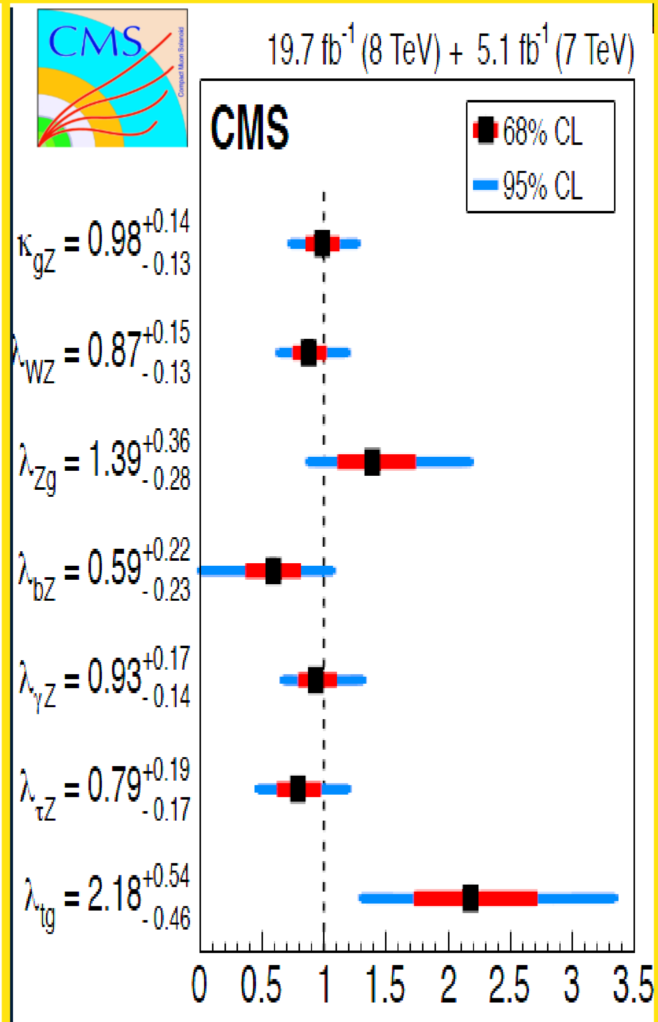
$\lambda_{\gamma Z}$: sensitive to new charged particles in $H \to \gamma\gamma$ loop w.r.t $H \to ZZ$ decays

λ_{tg}: sensitive to new coloured particles contributing to $gg \to H$ production w.r.t. ttH production

Good Consistency with SM Hypothesis Overall



ATLAS-CONF-2015-007



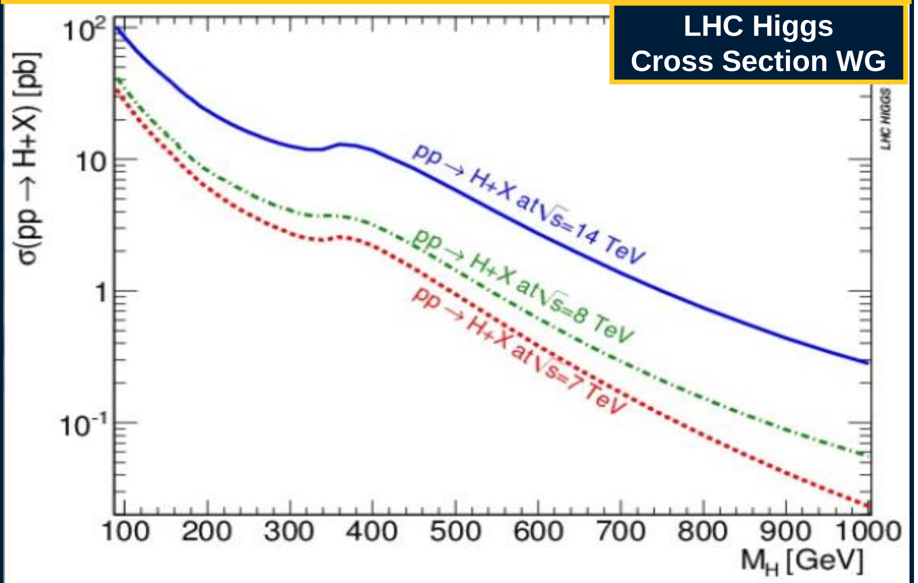
EPJ C75 (2015) 5, 212

LHC Outlook: Run 2 and Beyond

Run2/Run1: Cross Sections Increase

2.3X for ggH; to 4X for ttH !

LHC Higgs Cross Section WG



process	σ[pb] 8 TeV	σ[pb] 13 TeV	ratio
ggF	19.3	43.9	2.3
VBF	1.58	3.75	2.4
WH	0.705	1.38	2.0
ZH	0.415	0.870	2.1
ttH	0.129	0.509	3.9
bbH	0.204	0.512	2.5

Long Term Planning Update

Varoucas

2010–2012: **Run 1**: $\sqrt{s}$=7-8 TeV, $\int Ldt$=25 fb^{-1}, pileup $\mu\approx 20$
$L_{peak}=0.7\times10^{34}$ cm^{-2}s^{-1}

2013–2014: **LS1: phase 0 upgrade**

2015–2018: **Run 2** $\sqrt{s}\approx$13-14 TeV, $\int Ldt\approx$120 fb^{-1}, pileup $\mu\approx 43$
$L_{peak}=1.6\times10^{34}$ cm^{-2}s^{-1}

2018–2019: **LS2: phase 1 upgrade**

2020–2022: **Run 3** $\sqrt{s}\approx$14 TeV, $\int Ldt\approx$350 fb^{-1}, pileup μ=50-80
$L_{peak}\approx 2\text{-}3\times10^{34}$ cm^{-2}s^{-1}

2023–2025: **LS3: phase 2 upgrade**

To 10X the Lumi
10X the pileup

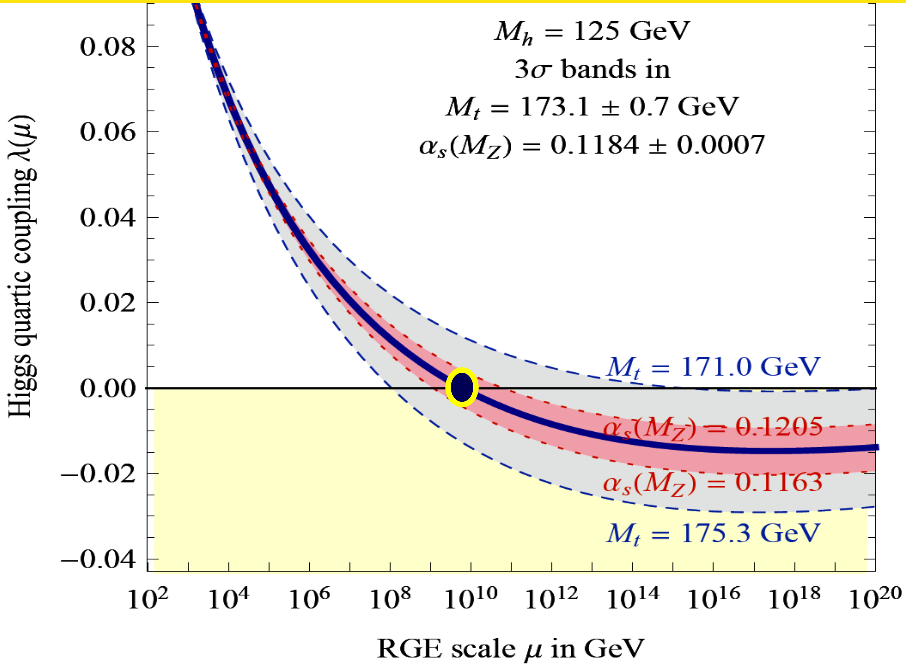
2026–2027 … 2035: **HL-LHC**: $\sqrt{s}\approx$14 TeV, $\int Ldt\approx$3000 fb^{-1}, pileup $\mu\approx$140-200
$L_{peak}=20\times10^{34}$ cm^{-2}s^{-1} leveled to $L_{peak}=(5\text{-}7.5)\times10^{34}$ cm^{-2}s^{-1}

In 2036+: HE LHC ? FCC ?

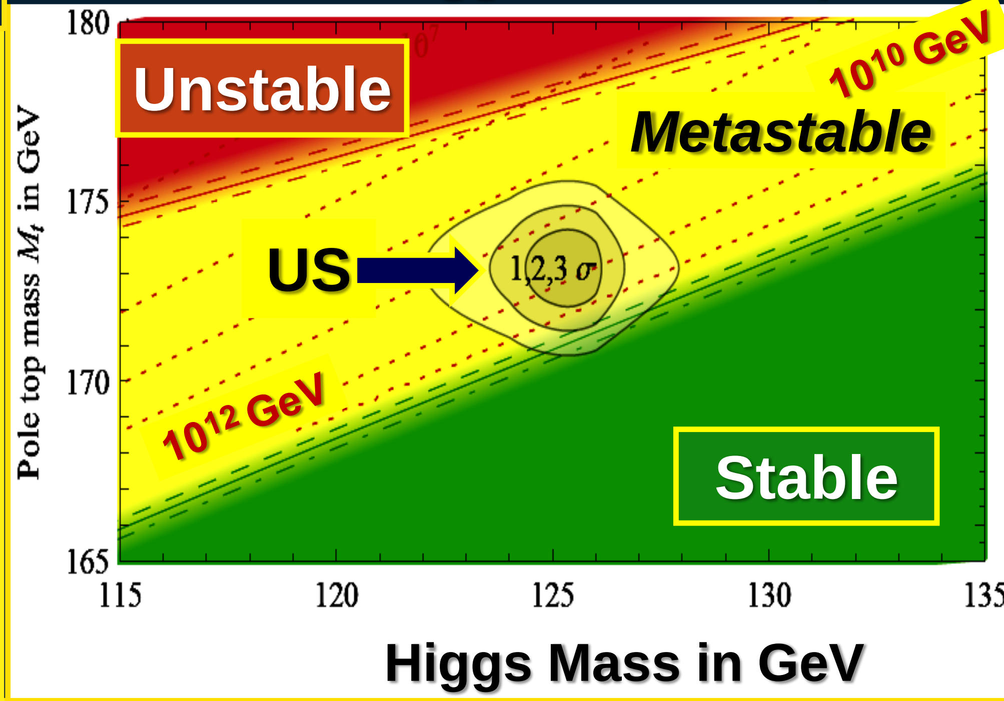
The 125 GeV Higgs Mass

Are we just on the wrong side of the Vacuum Stability Bound ?

NNLO Evolution of the Higgs Self-coupling λ(μ)



Precise Knowledge of the Top Mass as well as the Higgs Mass is Important



- For a Higgs mass of ~126 GeV
- ➡ λ goes negative ➡ Vacuum we are in is *metastable… ??*
- ➡ *OR:* New physics at an intermediate energy scale ~10^{10-12} GeV
- *What lies between us and the Big Bang ?*

Higgs and Supersymmetry

See Carena and Nath talks at SUSY2012

$$\tan\beta = v_2/v_1$$

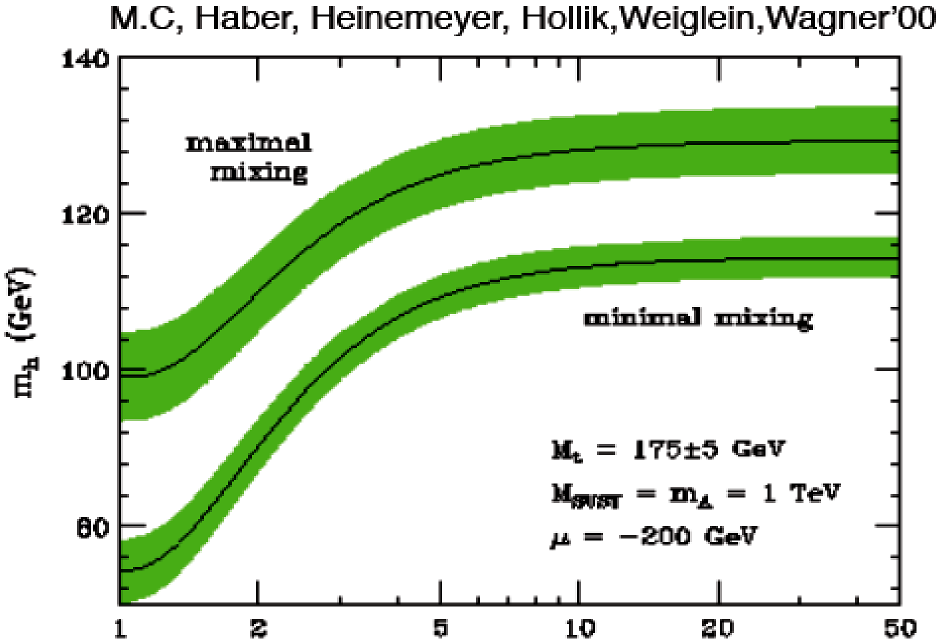
$$\Rightarrow v = \sqrt{v_1^2 + v_2^2} = 246\ \text{GeV}$$

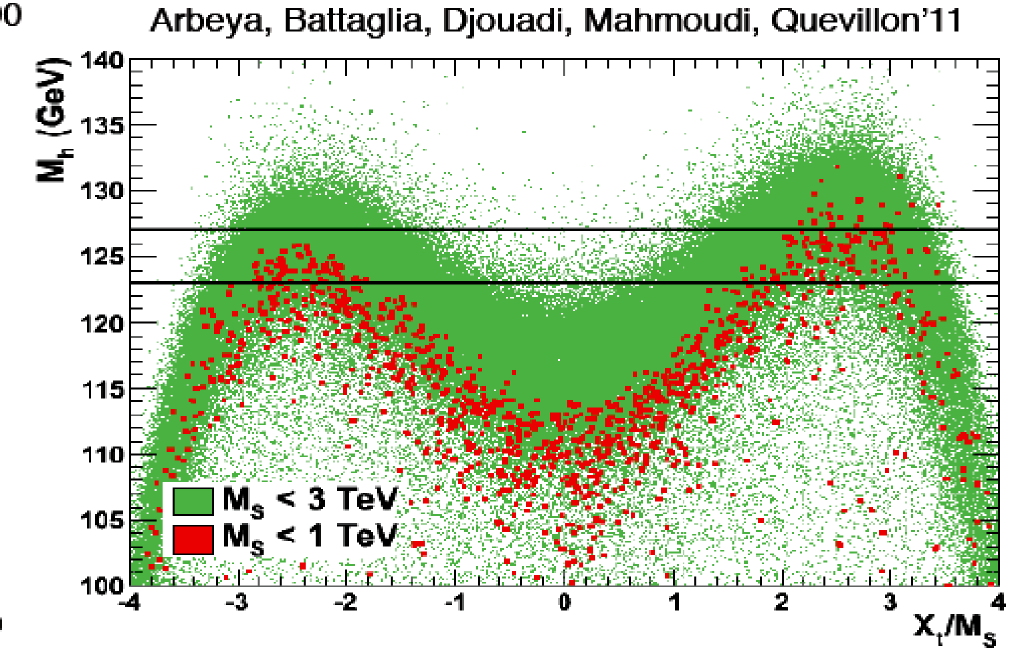
- MSSM has two Higgs Doublets, leading to:
  H, h (CP Even, Higgs-Like), A (CP Odd) and $H^{\pm}$
- H_u doublet couples only to up-quarks; H_d only to down-quarks; so SUSY is flavor diagonal if SUSY is unbroken
- Quartic Higgs couplings determined by SUSY gauge couplings
  - ➡ The lightest Higgs (h) mass is strongly correlated with the Z Mass, and is naturally light
  - ➡ Other Higges can be as heavy as the SUSY breaking scale M_S
- Important quantum corrections to the lightest Higgs mass due to incomplete cancellation of top and stop contributions in the loops
- A 125 GeV Higgs favors large LR Stop Mixing X_t and/or large M_S

$$m_h^2 \cong M_Z^2\cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

$$t = \log(M_{SUSY}^2/m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right) \qquad X_t = A_t - \mu/\tan\beta \rightarrow \text{LR stop mixing}$$

SM-Like MSSM Higgs
and Beyond





- A 125 GeV Higgs needs tan β > ~5, and large mixing X_t
- Also favors large M_S especially for less than maximal mixing
- But MS cannot be Too large, else theory is unstable at high scales

- M_H = 125 GeV + indications that the BR(γγ) was > BR(γγ) SM led to many speculations, and *an industry of model-space profile likelihood studies, both within and beyond the MSSM*

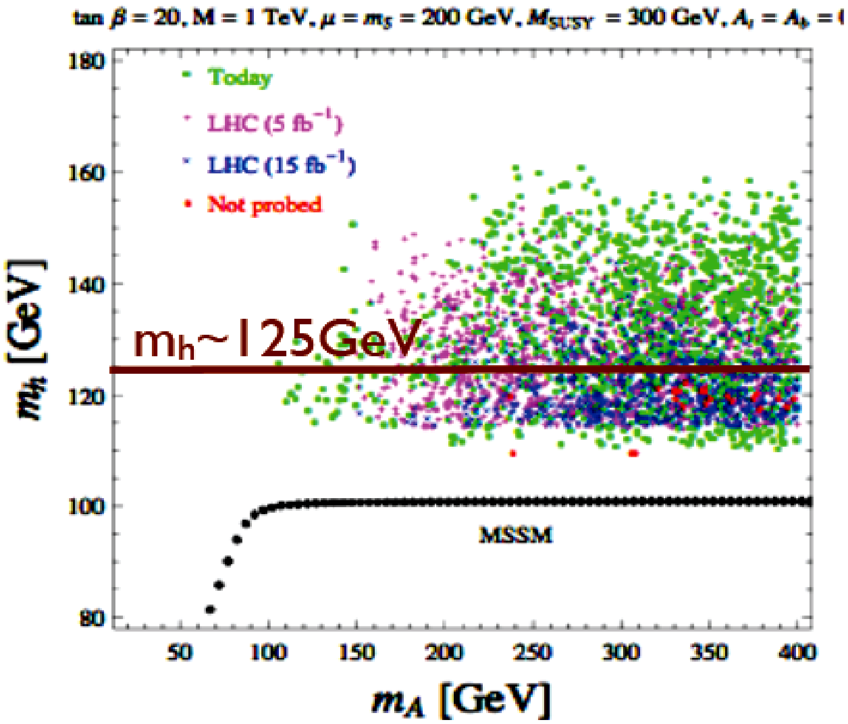
Beyond the MSSM Higgs

M. Carena at SUSY 2012

More general MSSM Higgs extensions: EFT approach

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2 \qquad W_X \supset \frac{\omega_1}{2M} X (H_u H_d)^2$$

Dine, Seiberg, Thomas;
Antoniadis, Dudas, Ghilencea, Tziveloglou
M.C, Kong, Ponton, Zurita



Scan over parameters including all possible dimension 5 and 6, SUSY Higgs operators

Higgs mass = 125 GeV easy to achieve for light stops, small mixing

Enhancement of h to di-photons due to bb suppression or light staus

Higgs cascade decays from large splitting in masses : h/H to AA

If the new physics is seen only indirectly via deviations from the SM Higgs properties, it will be hard to disentangle among new singlets, triplets, extra Z', W', a given mixture of the above

Higgs Mass in the MSSM and NMSSM

Many papers on NMSSM after M_H=126 GeV and hint of too high Br into $\gamma\gamma$, see arXiv:1301.6437, arXiv:1301.1325, arXiv:1301.0453, arXiv:1212.5243, arXiv:1211.5074, arXiv:1211.1693, arXiv:1211.0875, arXiv:1209.5984, arXiv:1209.2115, arXiv:1208.2555, arXiv:1207.1545, arXiv:1206.6806, arXiv:1206.1470, arXiv:1205.2486, arXiv:1205.1683, arXiv:1203.5048, arXiv:1203.3446, arXiv:1202.5821, arXiv:1201.2671, arXiv:1201.0982, arXiv:1112.3548, arXiv:1111.4952, arXiv:1109.1735, arXiv:1108.0595, arXiv:1106.1599, arXiv:1105.4191, arXiv:1104.1754, arXiv:1101.1137, arXiv:1012.4490, ...

MSSM

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1-\frac{X_t^2}{12m_{\tilde{t}}^2}\right)\right].$$

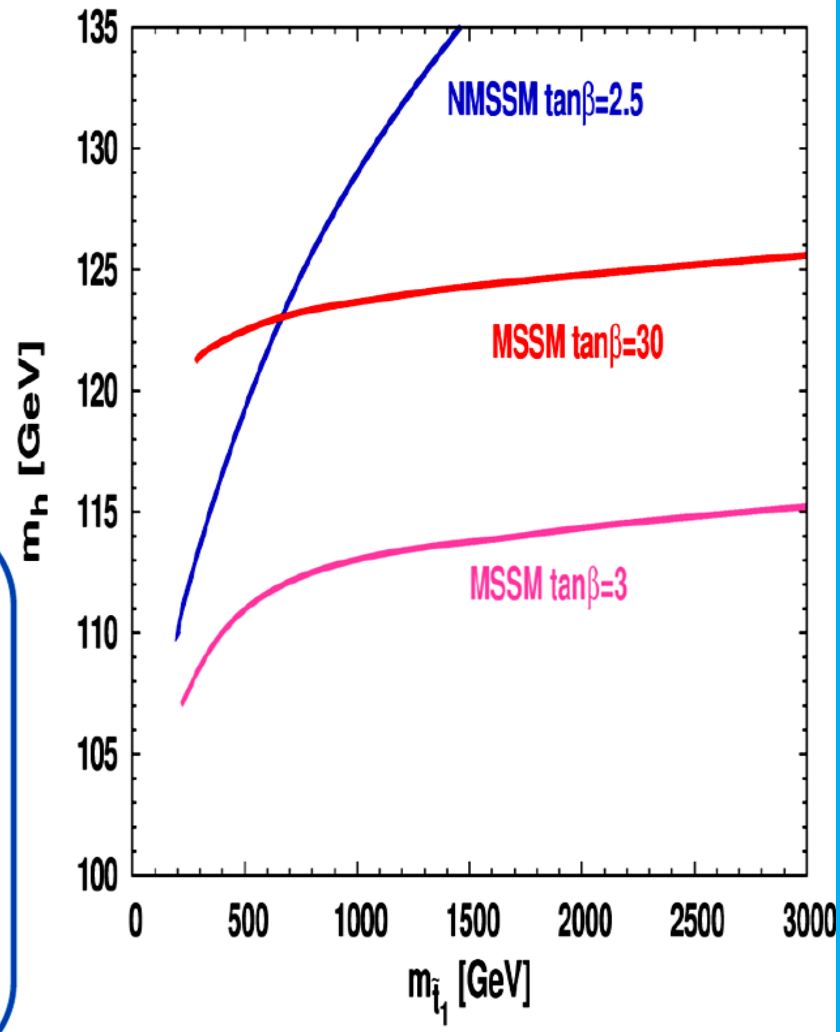
Higgs mass in MSSM ≈125 GeV for mstop ≈ 3 TeV (+ large tan β)

NMSSM: mixing with singlet

$$\mathcal{M}^2 = \begin{pmatrix} \lambda^2 v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta & \lambda v(\mu, M_S, A_\lambda) \\ \lambda v(\mu, M_S, A_\lambda) & m_S^2 \end{pmatrix}$$

increases Higgs mass at TREE level for small tanβ and large λ

NO MULTI-TEV stops needed

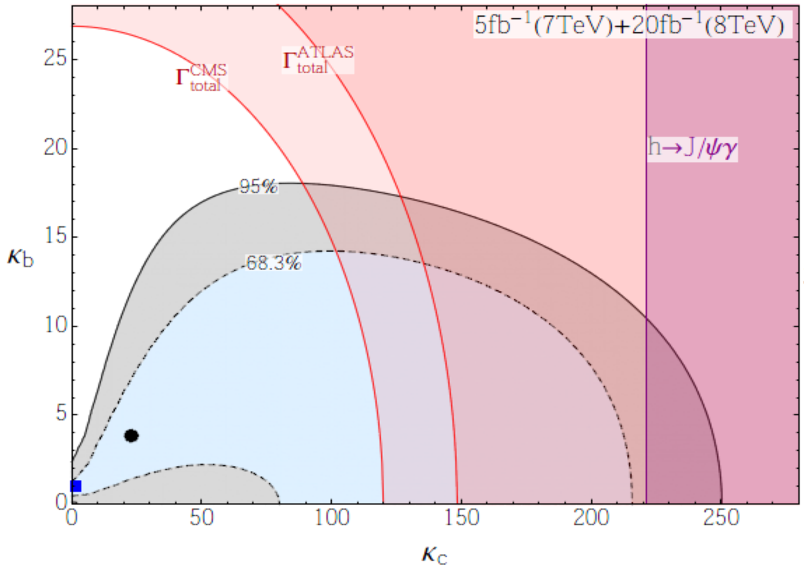


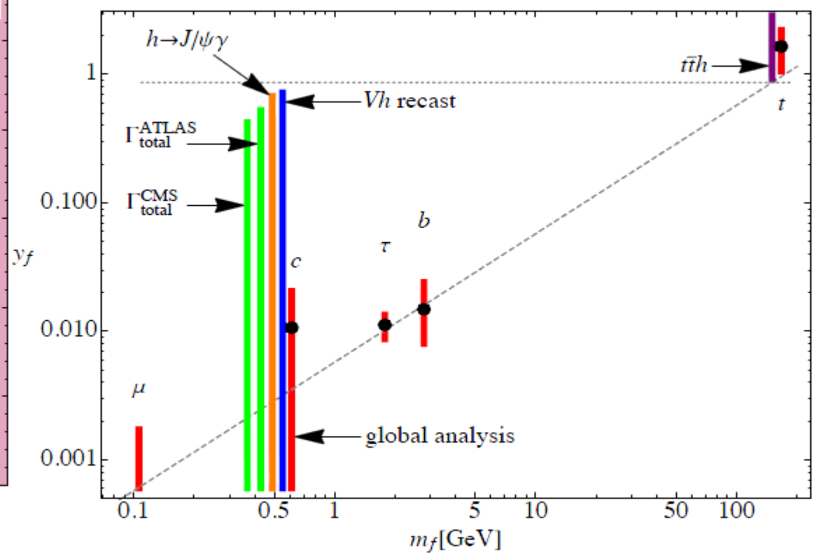
A. Chisholm, Birmingham

Probing Higgs Yukawa Couplings with Rare Decays.
Search for H, Z ➡ J/ψ γ, ϒ(nS) γ

Impact - **Constraint on Charm Yukawa Coupling**

The limit on $\sigma \times \mathcal{B}$ for the $H \to J/\psi\,\gamma$ channel was recently reinterpreted as a constraint on the charm Yukawa coupling (arXiv:1503.00290):



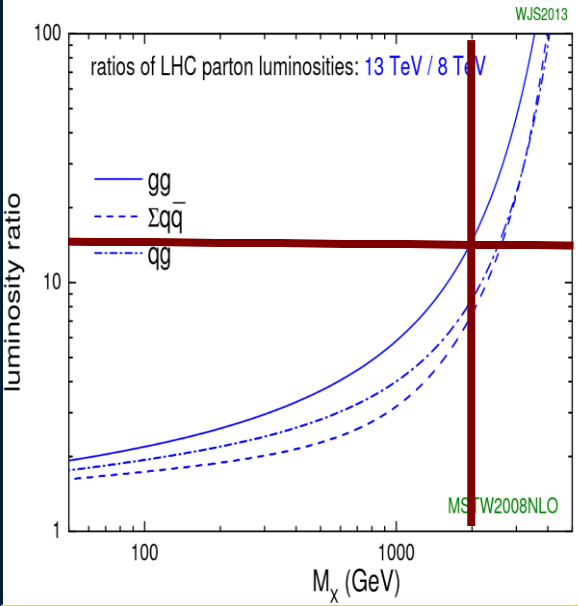


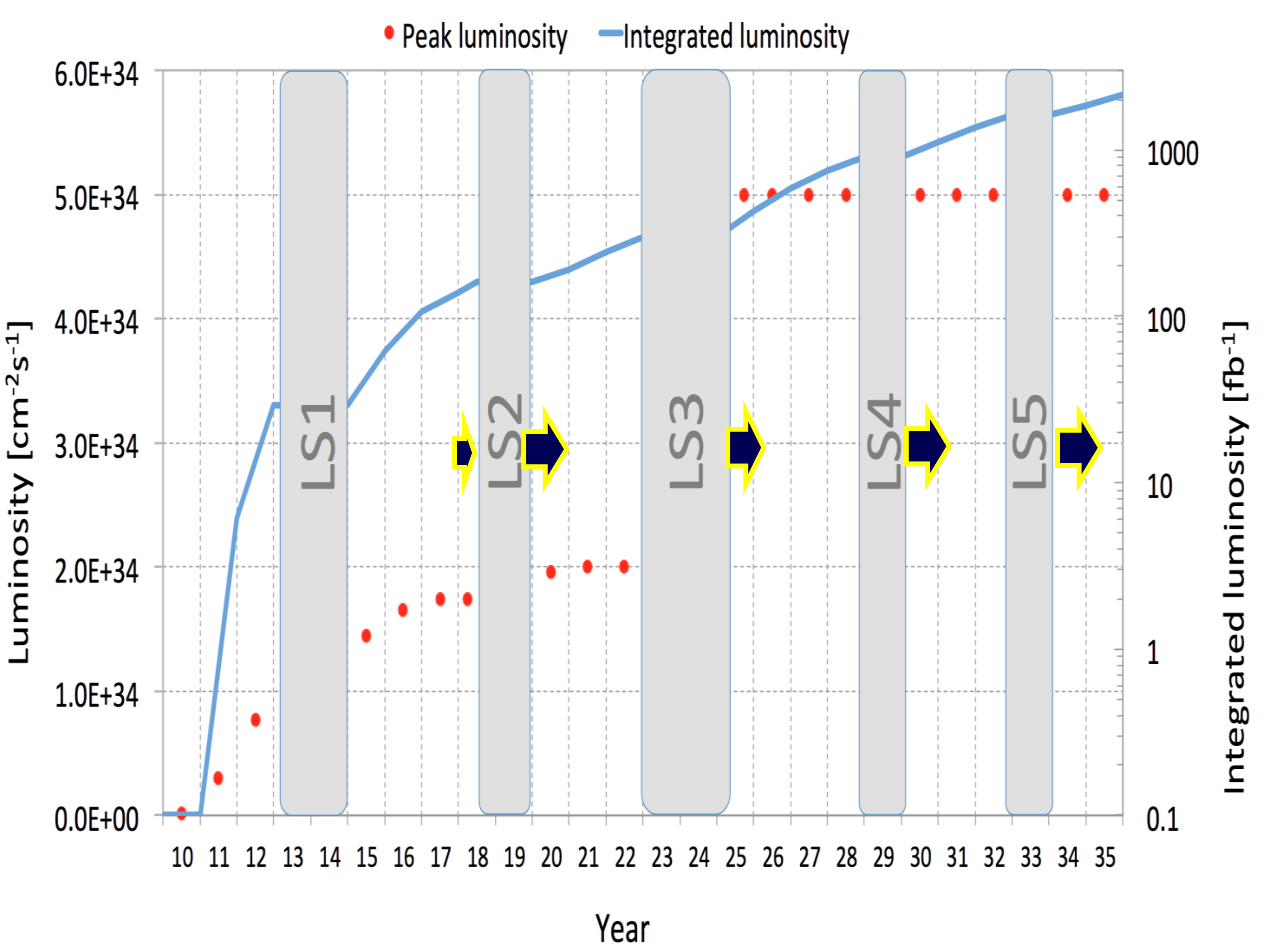
- In the SM the ratio of $y_t/y_c \approx 280$...
- Exploiting measured ATLAS $H \to ZZ^* \to 4\ell$ rate (to cancel Γ_H dependence), obtain a bound of $\boldsymbol{\kappa_c \leq 220}$

Suggests that limit on $H \to J/\psi\,\gamma$ (with world data on $t\bar{t}H$) can exclude universal quark Yukawa couplings!

LHC Planning: Run2 and Beyond

process	σ[pb] 8 TeV	σ[pb] 13 TeV	ratio
ggF	19.3	43.9	2.3
VBF	1.58	3.75	2.4
WH	0.705	1.38	2.0
ZH	0.415	0.870	2.1
ttH	0.129	0.509	3.9
bbH	0.204	0.512	2.5





Run2 2015-18, LS2 in 2019-20, LS3 2024-5; HL LHC 2026-36

With the usual caveats. Then HE – LHC (33 TeV) ? FCC ?

Statistics: Computing Limits
for the Higgs Search

CMS uses the CL_s method to set limits on $\mu = \sigma/\sigma_{SM}$

- Frequentist approach including systematic error evaluation

Likelihood function:

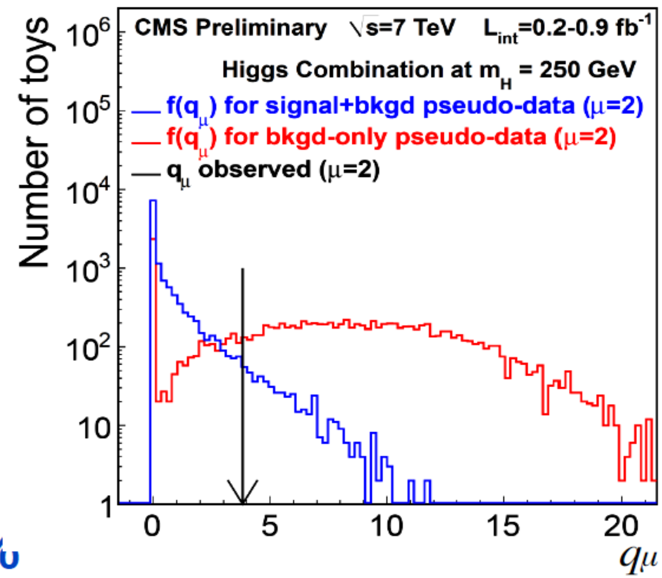
$$\mathcal{L}(data\,|\,\mu,\theta) = \text{Poisson}\,\big(\overbrace{data}^{\text{Observed}}\,|\,\underbrace{\mu\cdot s(\theta)+b(\theta)}_{\text{Expected S+B}}\big)\cdot\overbrace{p(\tilde{\theta}|\theta)}^{\text{Systematics}}$$

Test statistics:

$$q_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}$$

$\leftarrow$ fix μ, vary $\hat{\theta}_\mu$

$\leftarrow$ vary $\hat{\mu}$ and $\hat{\theta}$, $0 \le \hat{\mu} \le \mu$



Finally, calculate CL_s (toy MC):

$$CL_s = \frac{P\left(q_\mu \ge q_\mu^{obs}\,|\,\mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})\right)}{P\left(q_\mu \ge q_\mu^{obs}\,|\,b(\hat{\theta}_0^{obs})\right)}$$

95% C.L. is on μ value giving CL_s = 1 - 95%

CERN-CMS Note-2011-005: Procedure for the LHC Higgs Boson Search Combination in Summer 2011

Statistics: Computing Significance for the Higgs Search

To quantify observed excess (above background only hypothesis)

- Same machinery as on previous slide but to test probability of the null hypothesis

Approximate p-value (probability of the null hypothesis)**:**

$$\tilde{p} = \frac{1}{2}\left[1 - \mathrm{erf}\left(\sqrt{q_0^{\mathrm{obs}}/2}\right)\right]$$

where q_0^{obs} is the observed q_μ value for the null hypothesis ($\mu = 0$)

Significance (Z) corresponding to p-value

$$p = \int_Z^\infty \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)\, dx$$

Probability expressed in σ's of one-sided normal distribution.