The Standard Model Higgs and beyond

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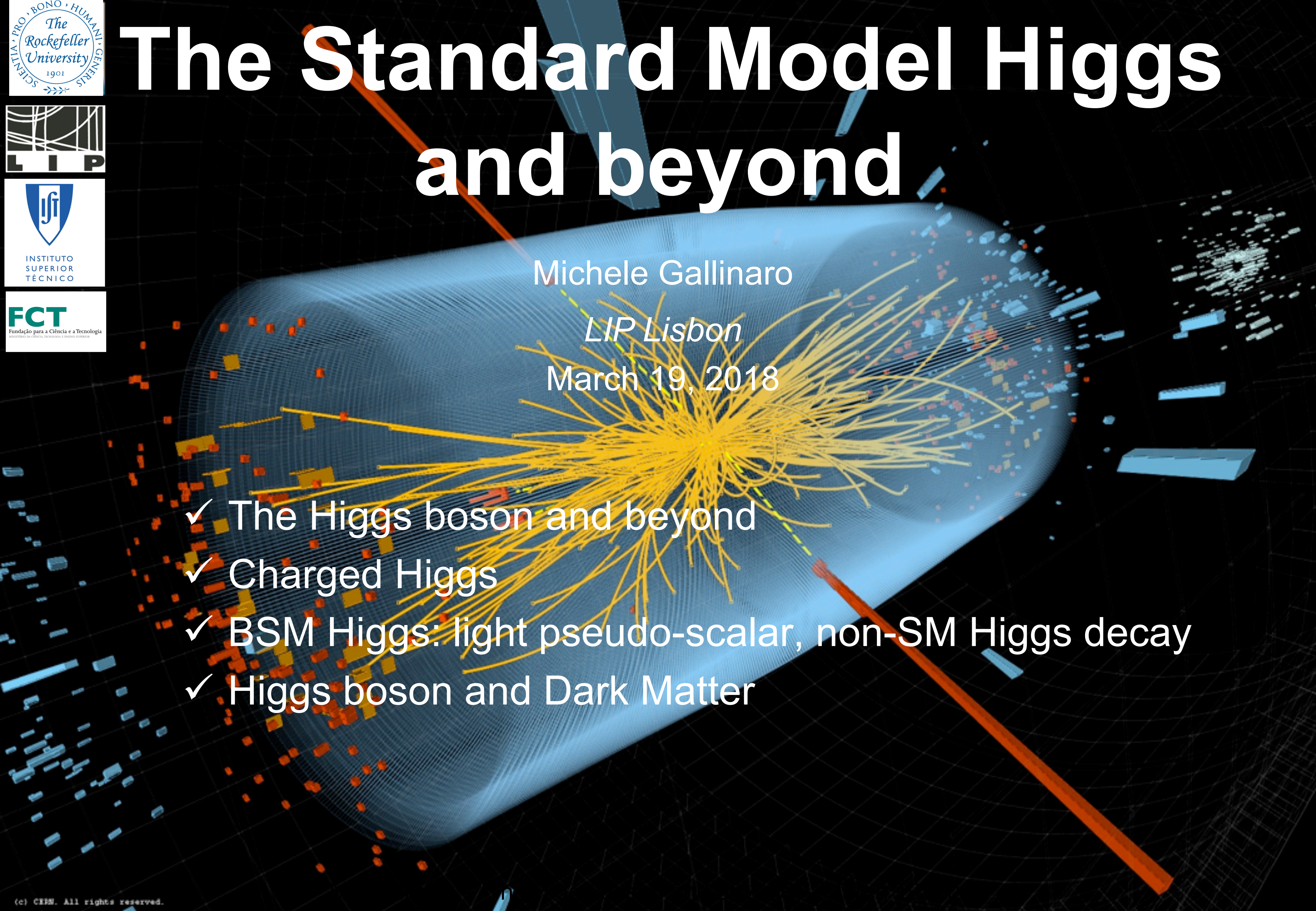
LIP Lisbon

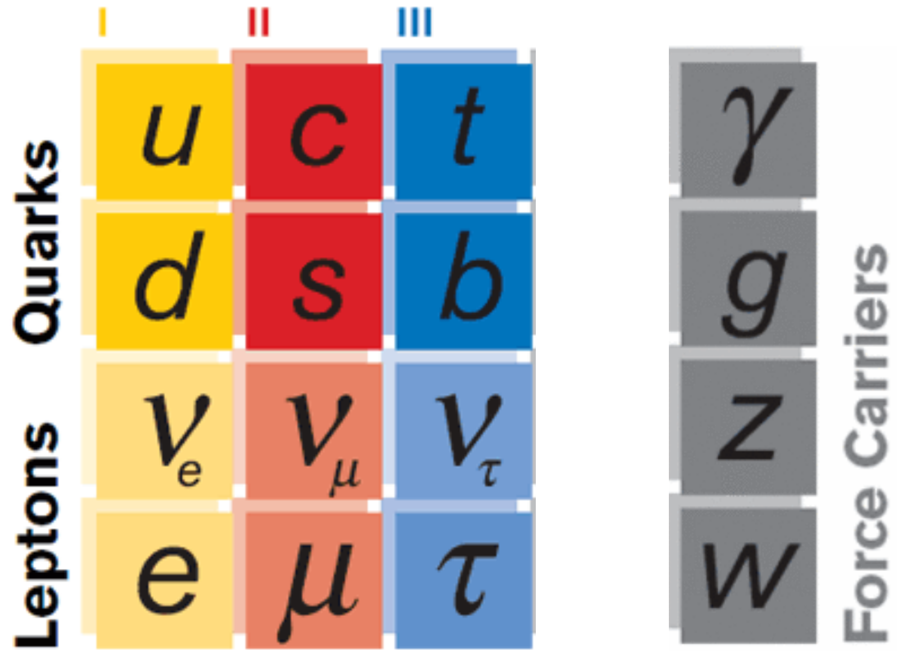
March 19, 2018

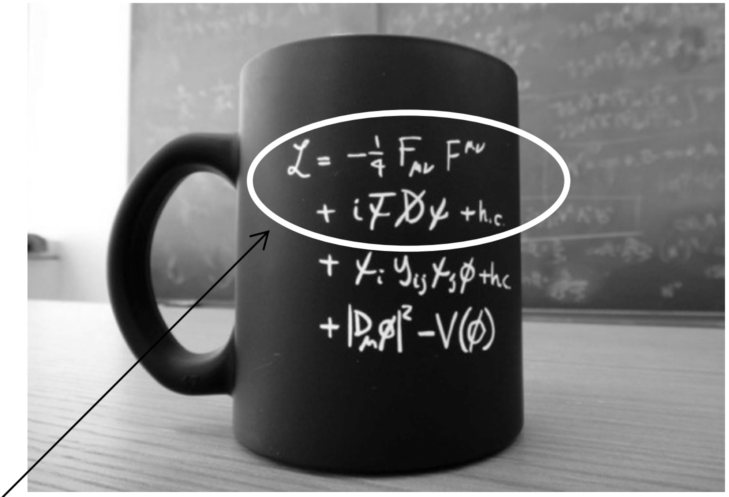
- ✓ The Higgs boson and beyond
- ✓ Charged Higgs
- ✓ BSM Higgs: light pseudo-scalar, non-SM Higgs decay
- ✓ Higgs boson and Dark Matter



The Standard Model…

Building blocks: matter (fermions), forces (bosons)



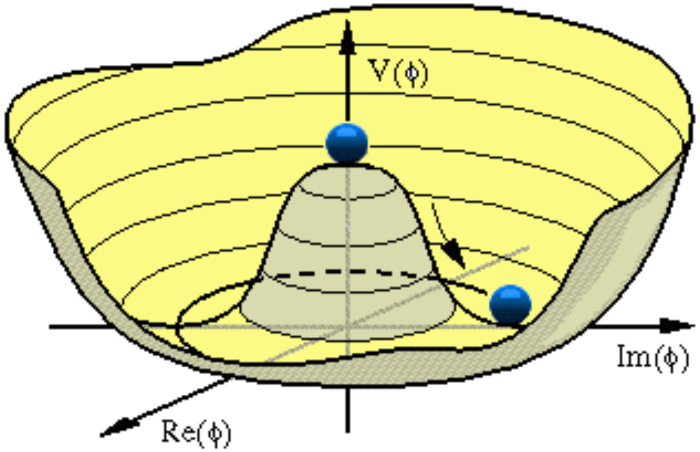


- Electroweak theory is based on underlying symmetry between the two interactions
- Simple Lagrangian formalism describes this very well but only for massless particles....

…and the Higgs boson

How do particles acquire their masses?

- Hand inserted mass terms destroy gauge invariance (local)
- Need gauge invariant mechanism to generate mass terms
- Higgs mechanism is simplest way to do it



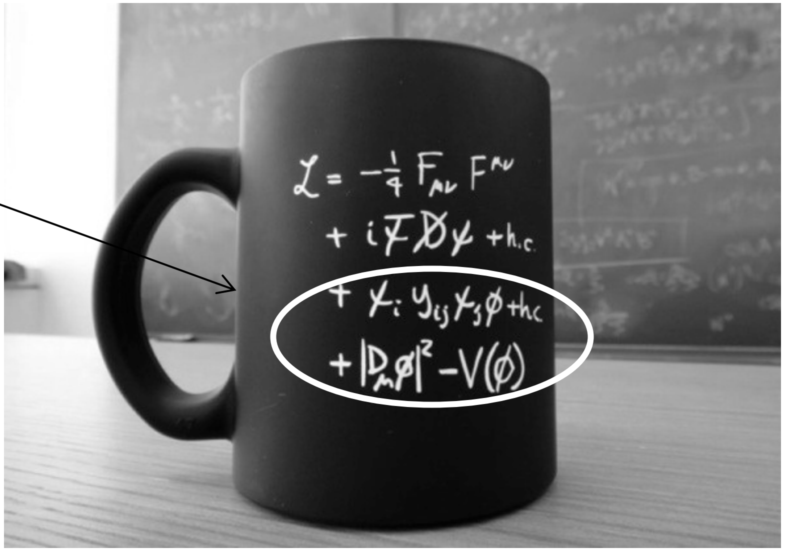
The Higgs mechanism

- Introduce additional scalar field
- Additional terms with mass appear
- Vacuum expectation value ≠0
- Particles move through field which gives them mass

massive

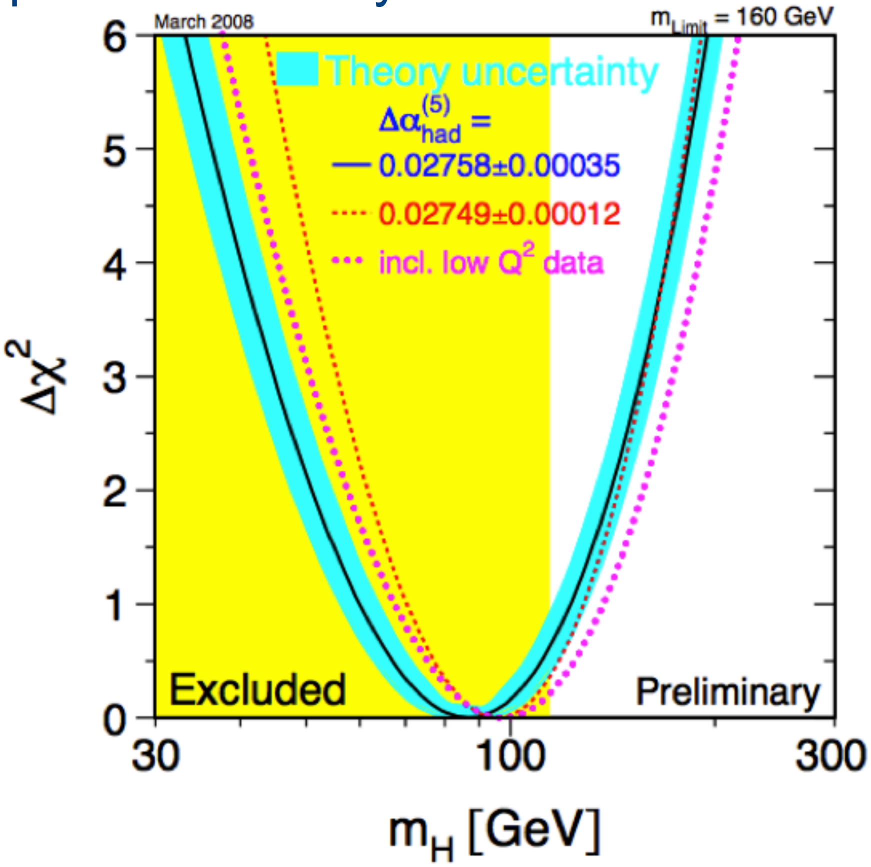
“*what makes everything ~~solid~~*”

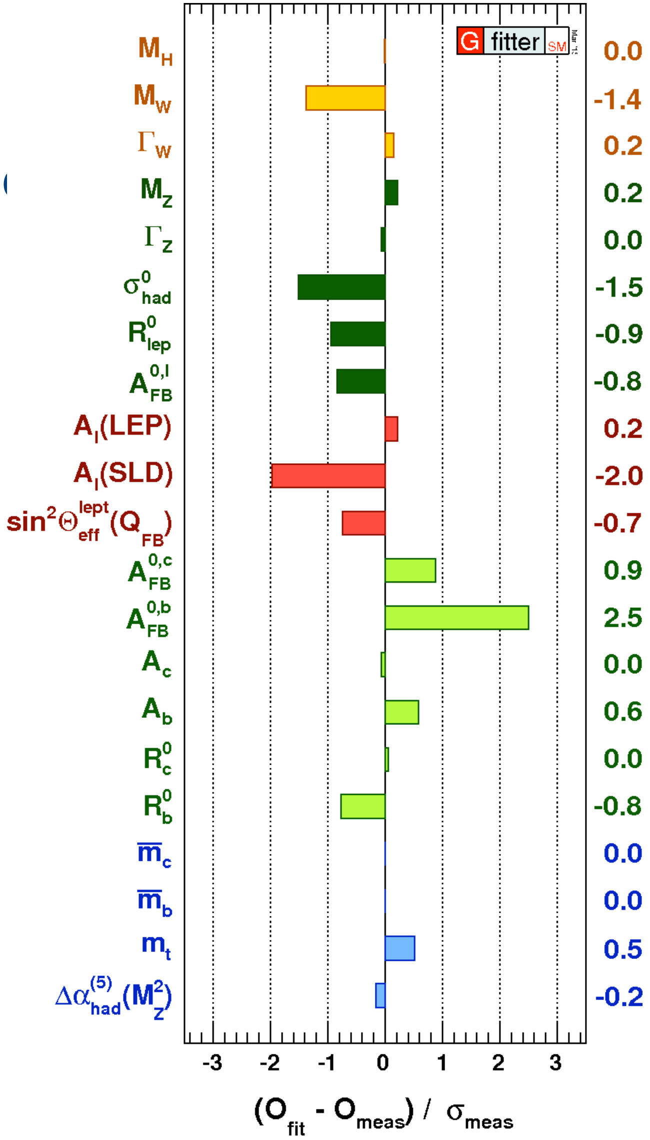
Bruce Springsteen



Testing the SM

- Measured to incredible precision
- Largest deviations to 3%
- After LEP: scale of the “missing piece” accurately predicte
- SM is a predictive theory

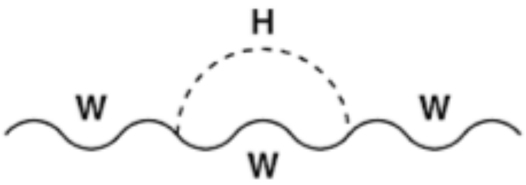


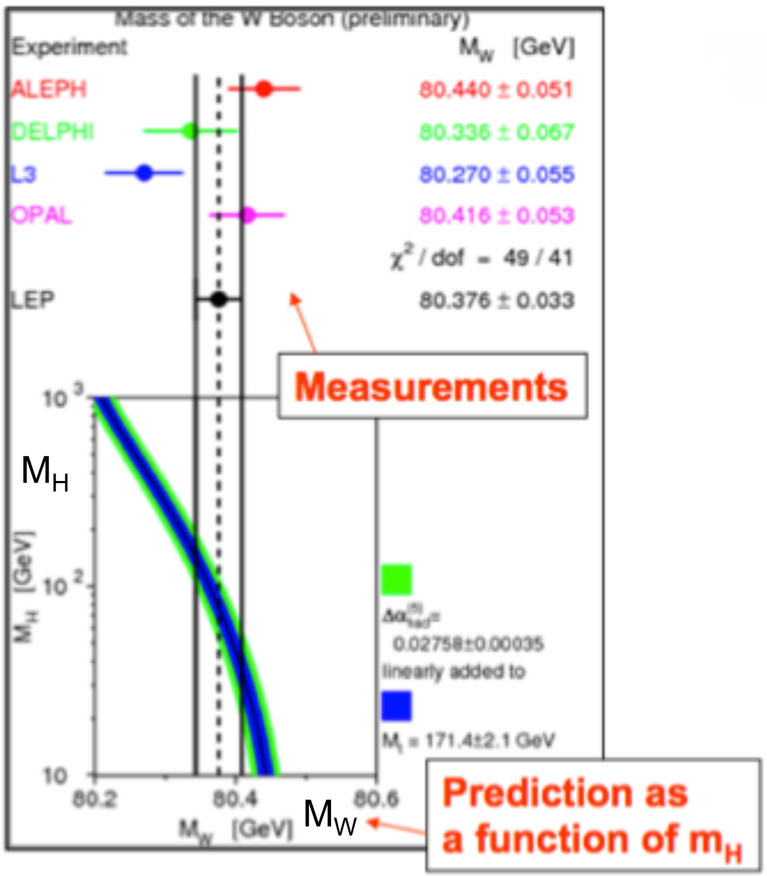


The Higgs

- Higgs mass is not predicted in the SM
- But it can be related directly or via loops to the mass of known particles and other observables
- Before the top quark was found
- Including the top, precision measurements yielded

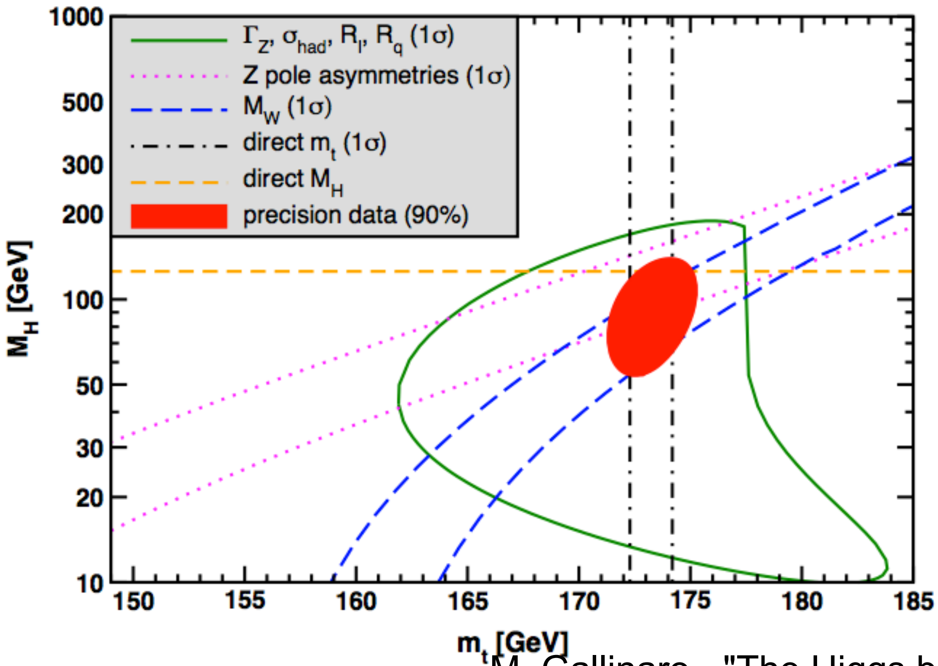
$$M_H = 89^{+22}_{-18}\ \text{GeV}$$





Measurements

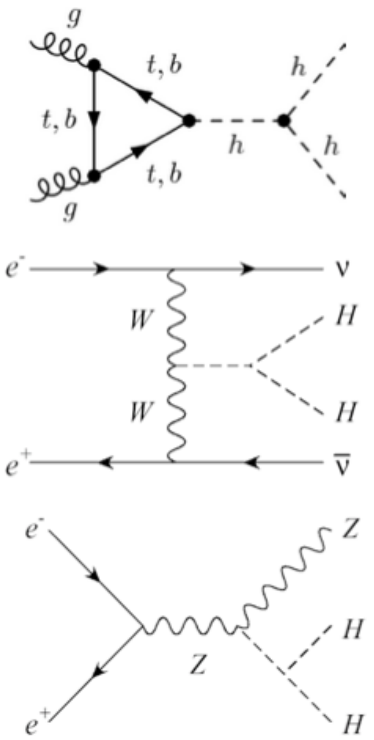
Prediction as a function of m_H



Higgs “self-coupling”

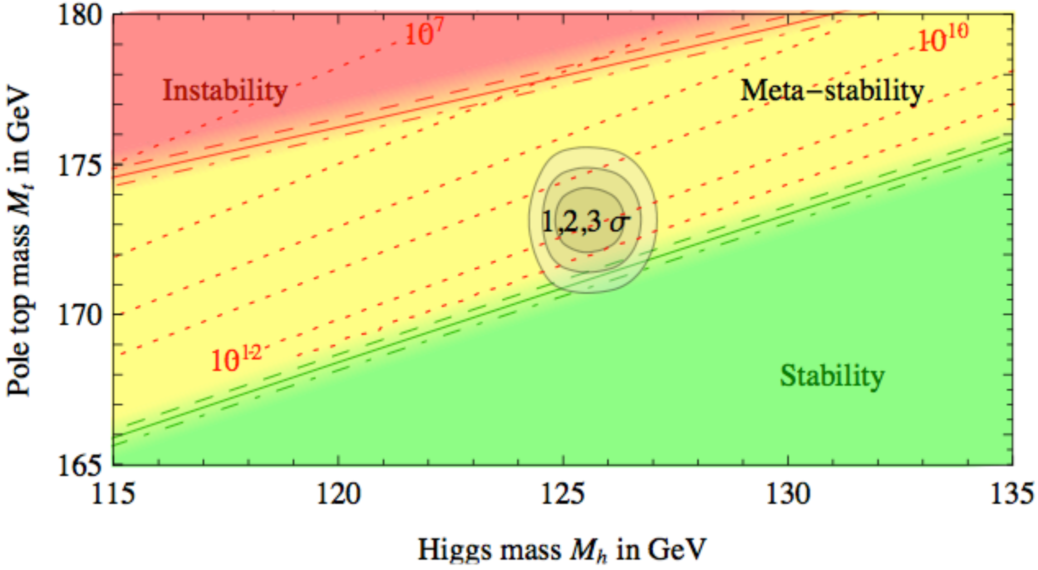
Drives the stability of the Higgs potential

- We can measure self-coupling through rare processes, eg h→hh

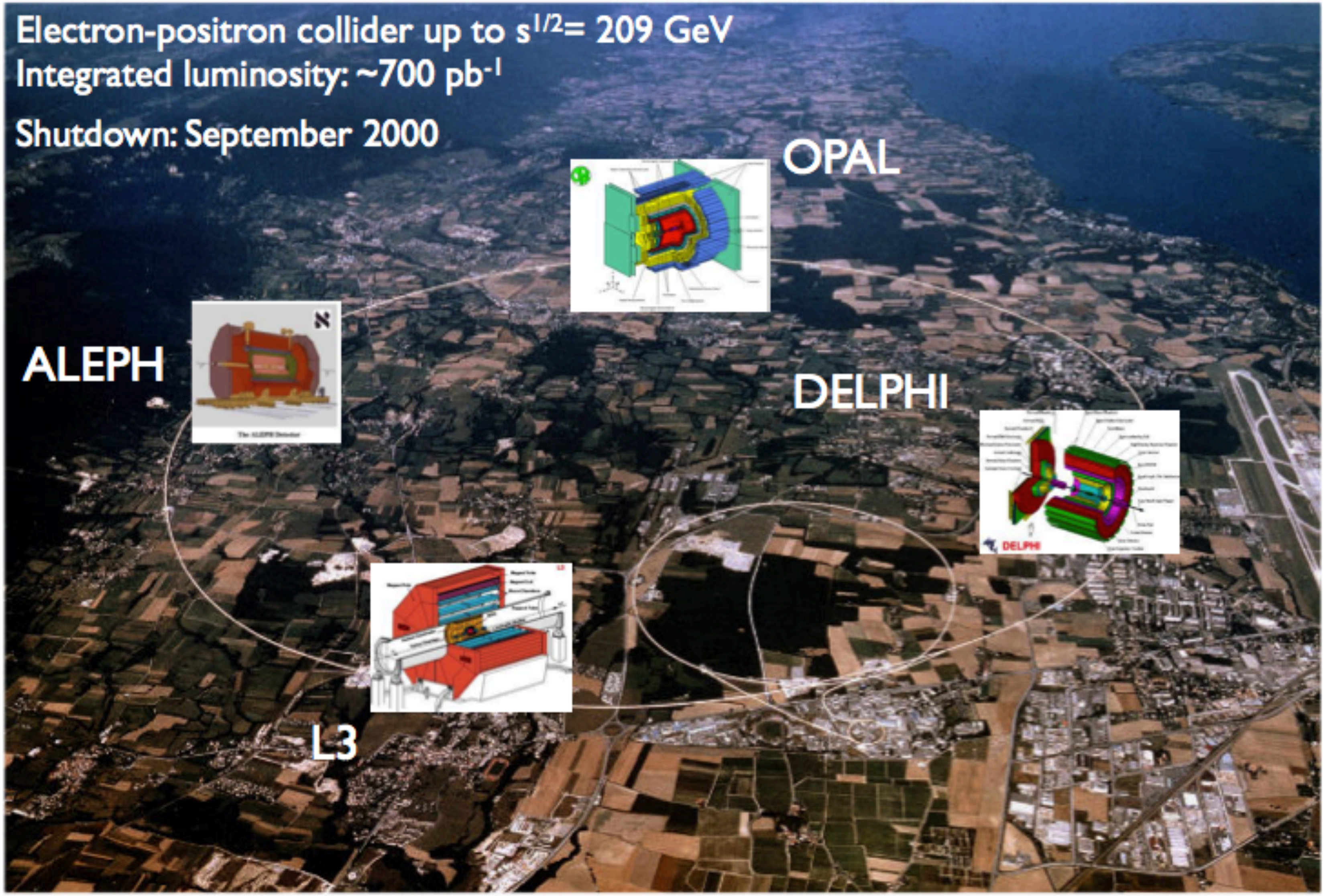


- Alternatively, test if SM is consistent at higher scales

⇒ Depending on the top mass, Universe may be unstable



LEP: Hunting for the Higgs boson

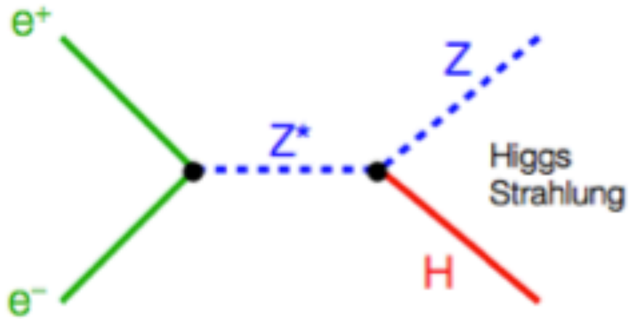


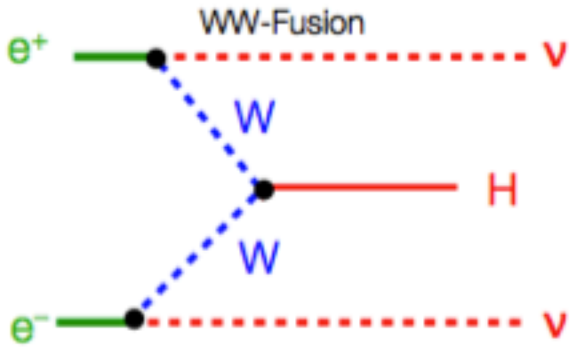
Electron-positron collider up to $s^{1/2}$= 209 GeV

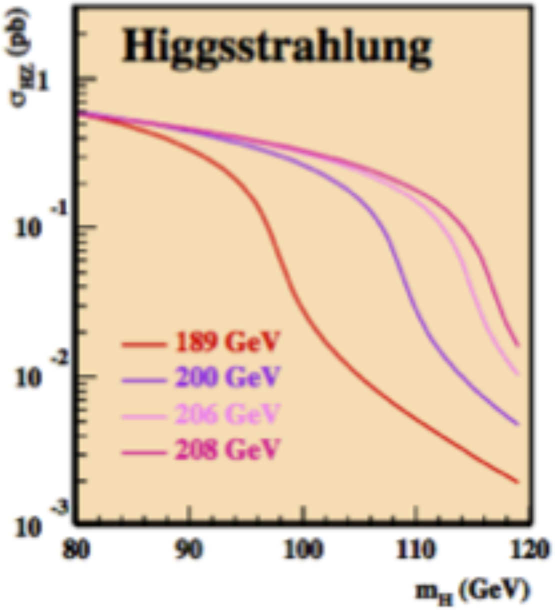
Integrated luminosity: ~700 pb^{-1}

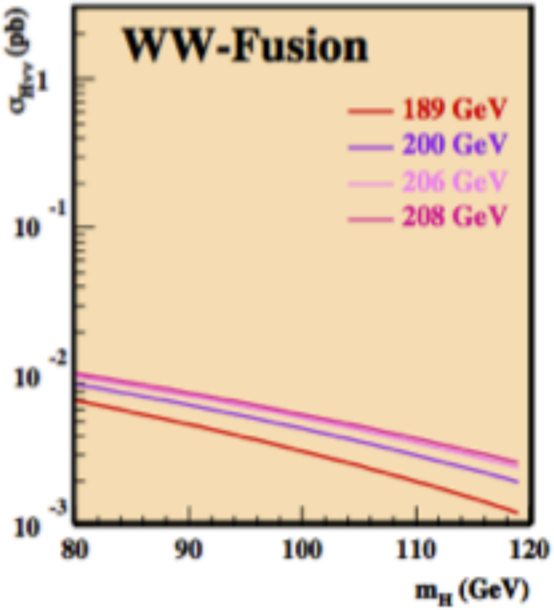
Shutdown: September 2000

Higgs production at LEP

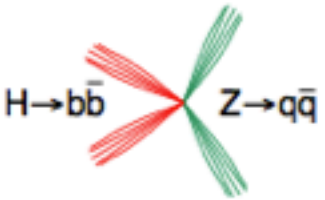
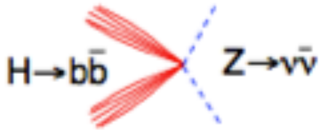
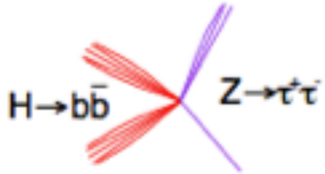
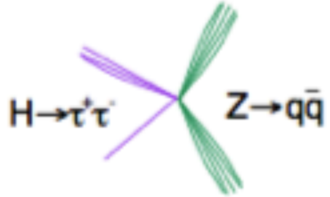




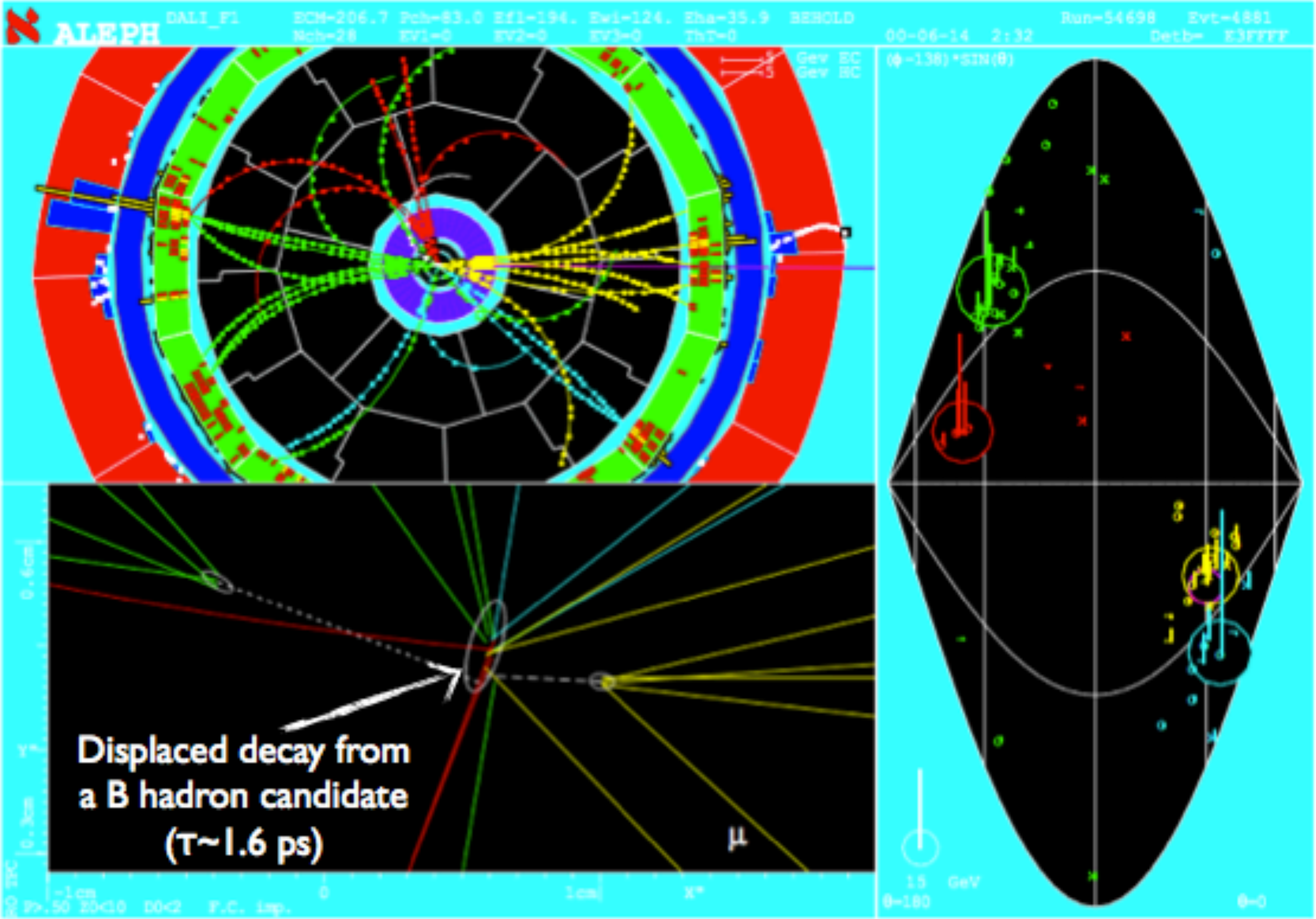




At LEP: look for 3^{rd} generation decays

	4-jets	51%	$WW\to qqqq$ $ZZ\to qqqq$ QCD 4-jets
	missing energy	15%	$WW\to qql\nu$ $ZZ\to bb\nu\nu$
	τ-channel	2.4%	$WW\to qq\tau\nu$ $ZZ\to bb\tau\tau$ $ZZ\to qq\tau\tau$ QCD low mult. jets
	τ-channel	5.1%	
	lepton channel	4.9%	$ZZ\to bbee$ $ZZ\to bb\mu\mu$

LEP H→bb candidate



Displaced decay from a B hadron candidate (τ~1.6 ps)

Summary of LEP candidates

- Invariant mass of all candidates

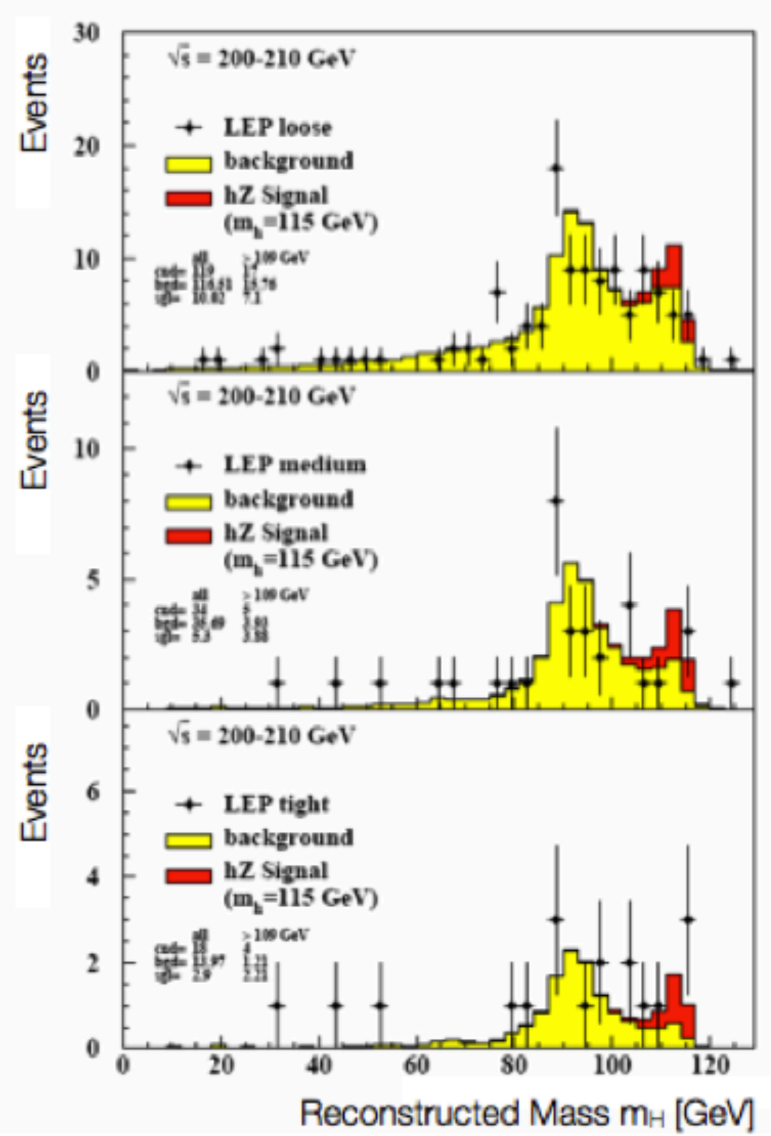
- Total of 17 candidates selected
  - 15.8 bkg expected

- Expectations for m_H=115GeV
- 8.4 evts

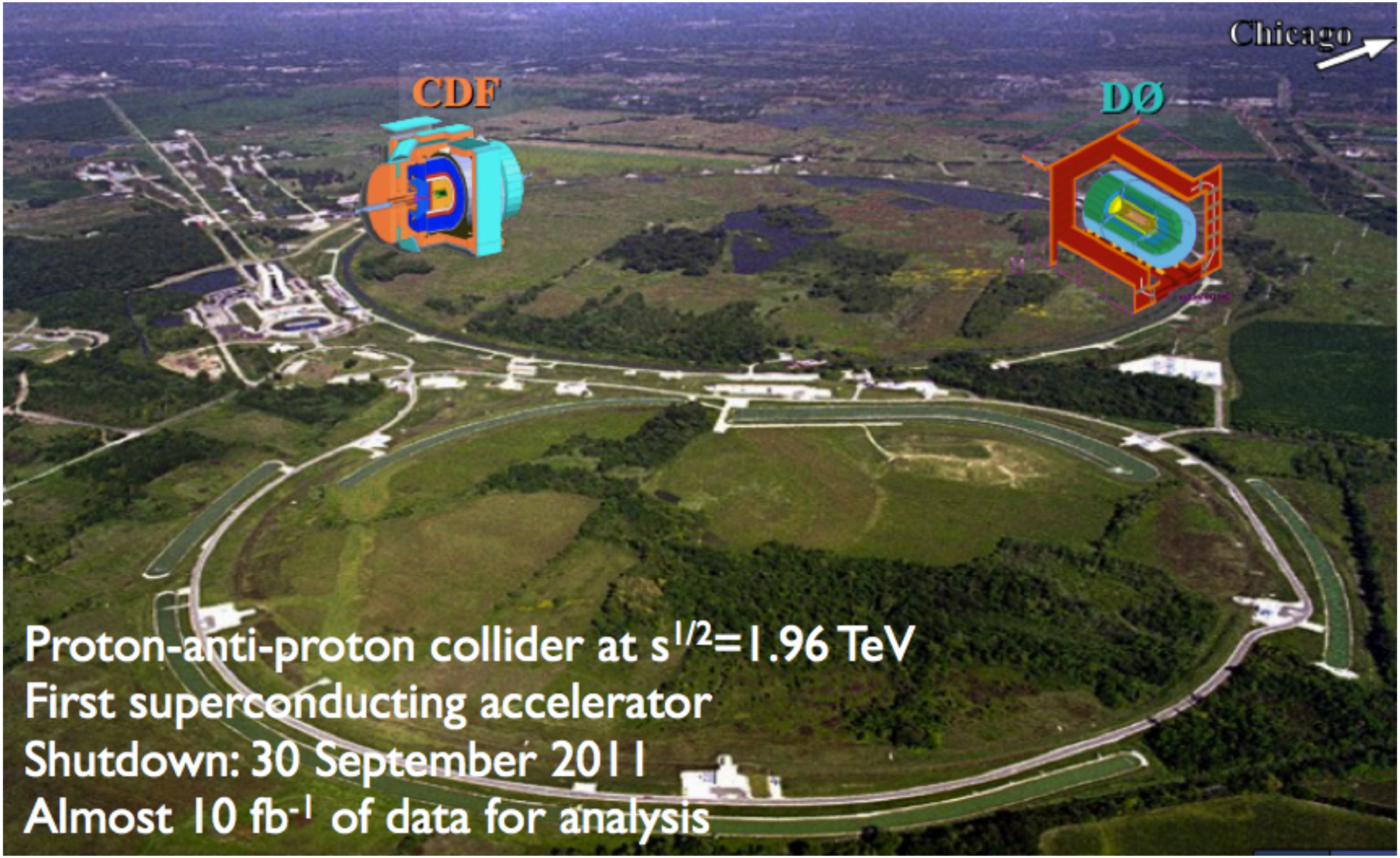
- Corresponding excess not observed

- Set limits:

  $\Rightarrow m_H$>114.4 GeV @95%CL



Searches at the Tevatron



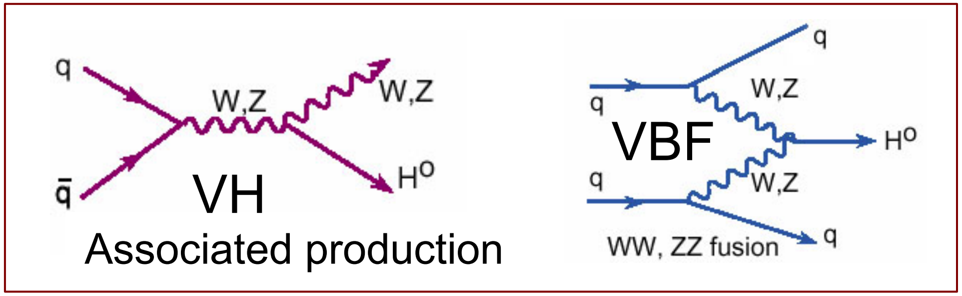
Proton-anti-proton collider at $s^{1/2}$=1.96 TeV

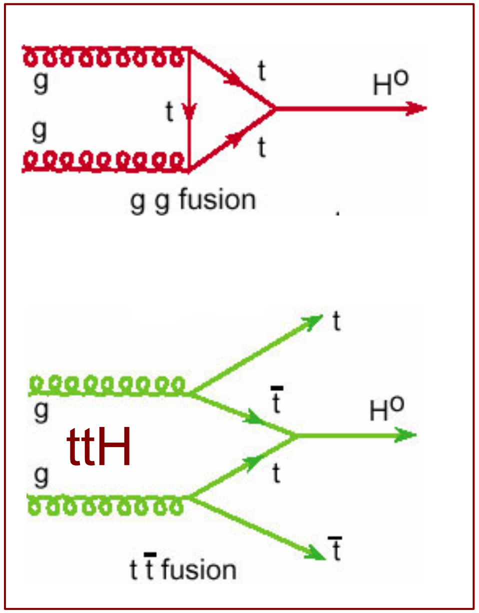
First superconducting accelerator

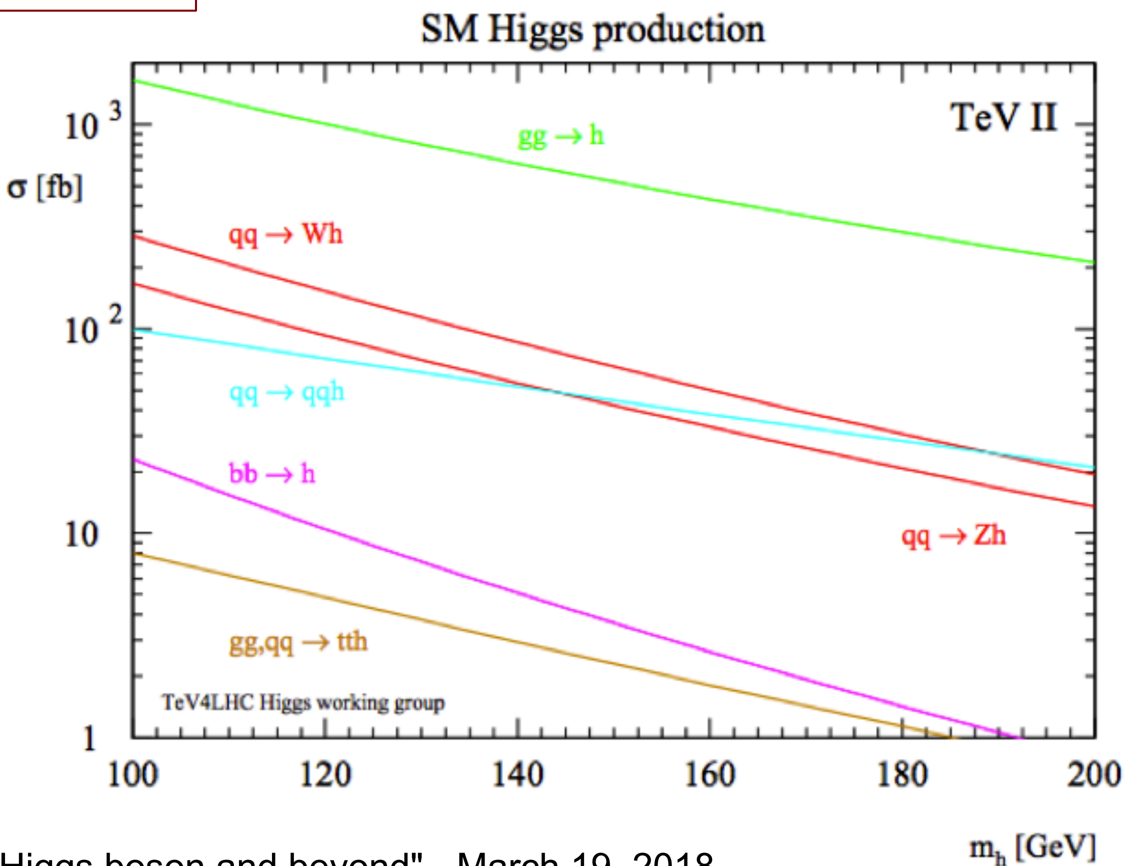
Shutdown: 30 September 2011

Almost 10 fb^{-1} of data for analysis

Higgs production at Tevatron

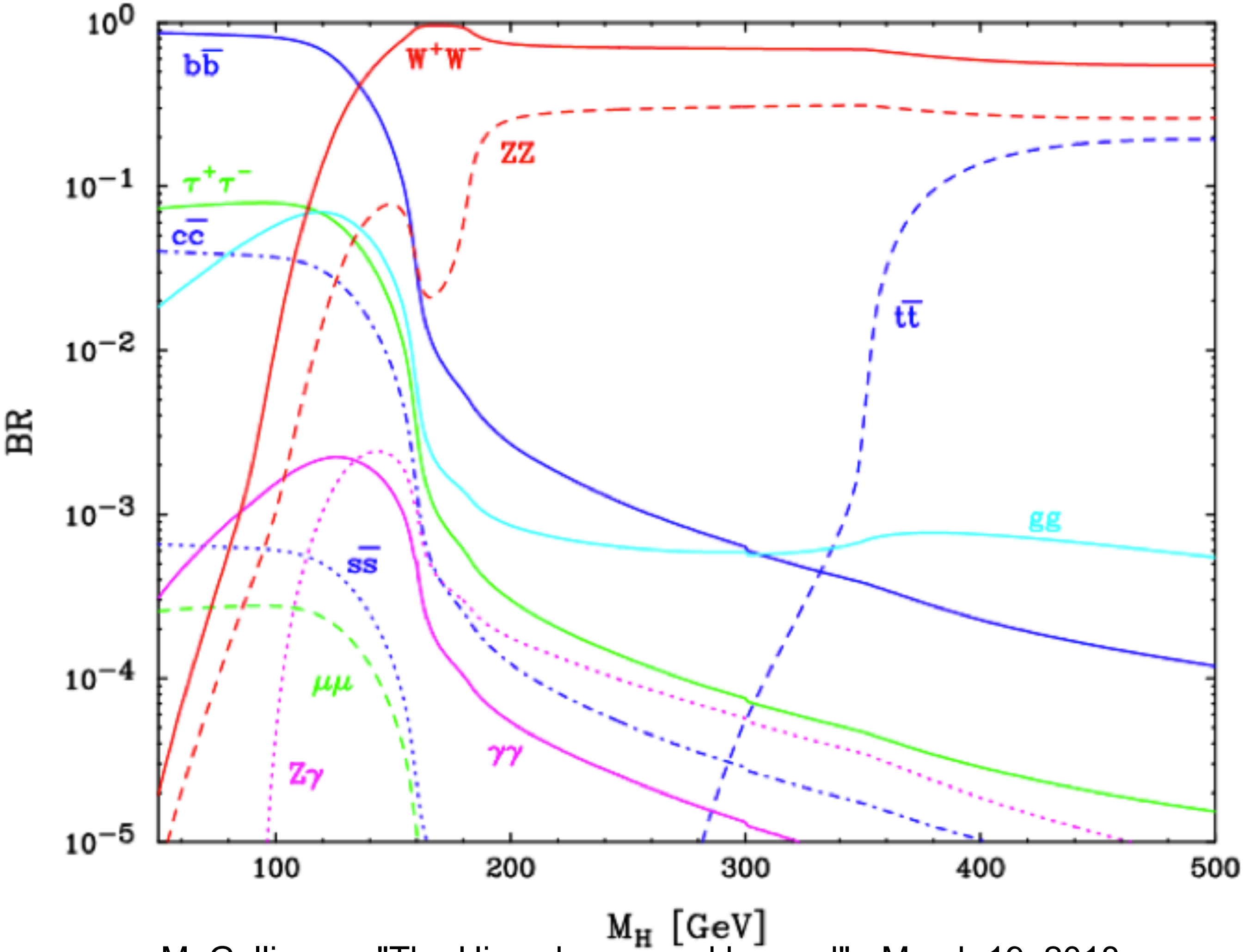




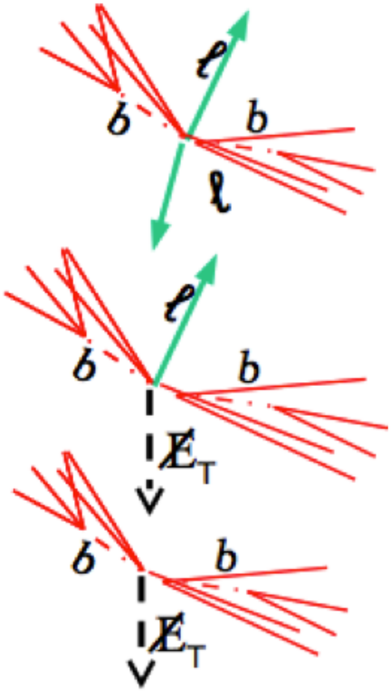


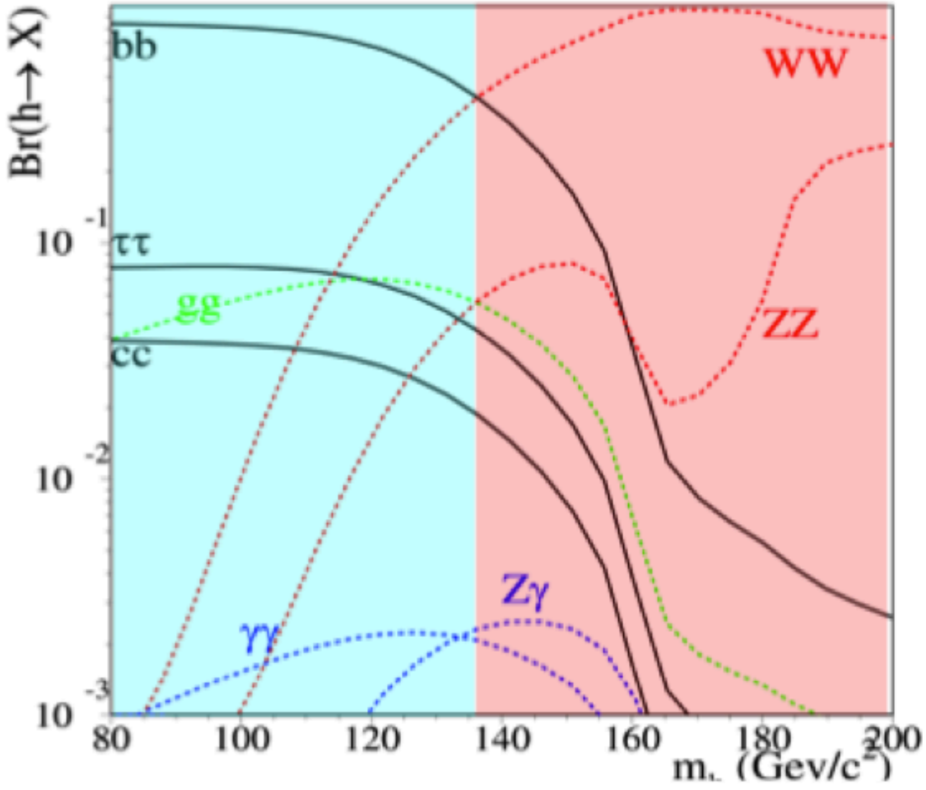
Look for all possible decays

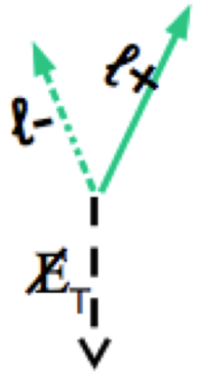
- Window of maximum opportunity (most “democratic”) at ~125 GeV
- Couplings to gluons and photons available through top and W loops



Most sensitive channel at the Tevatron







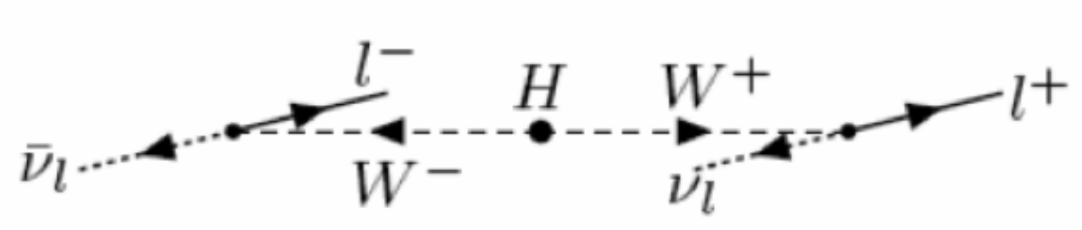
- At low mass, use h→bb final state
  - Associated production with W or Z
  - Challenging b-tagging, jet resolution
  - Backgrounds: top, W/Z+heavy flavor, VV
- At high mass, use H→WW final state
  - Benefit from high gluon-gluon cross section
  - Challenging lepton acceptance, MET
  - Backgrounds: top, VV

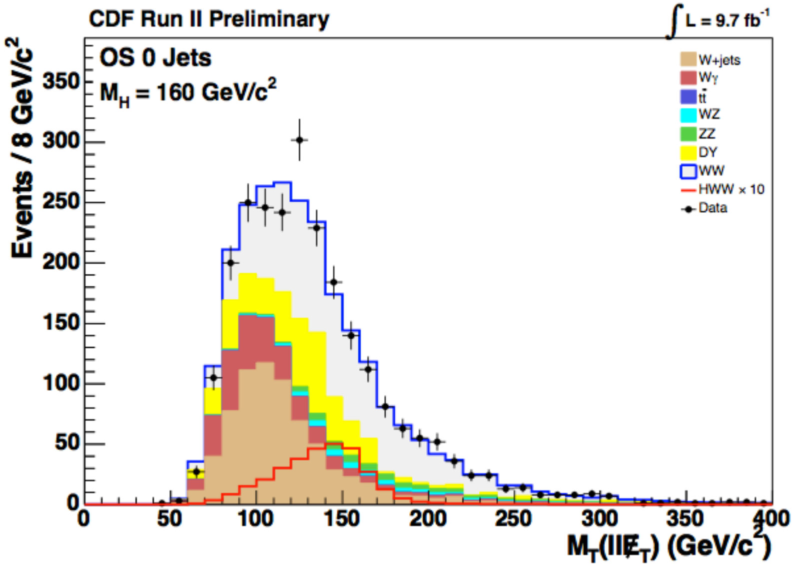
WW channel

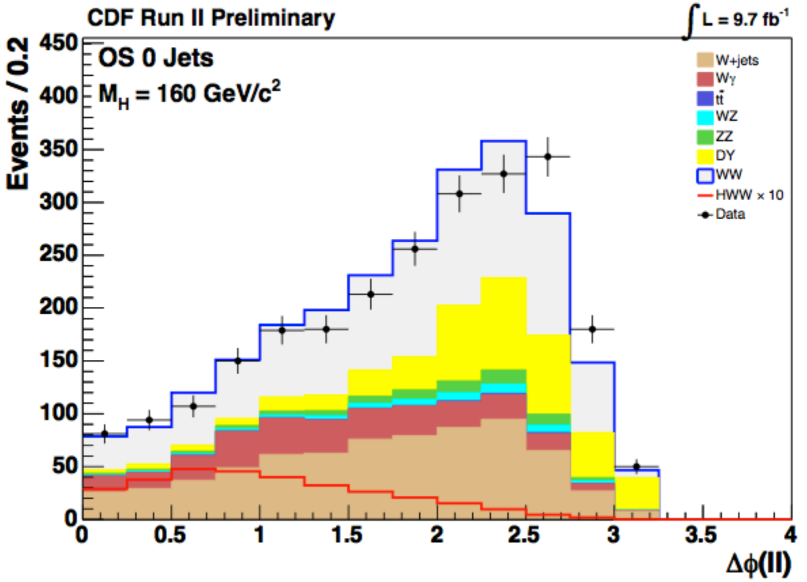
- Decay products from resonance
  - –2ν take one degree of freedom
  - –Cannot reconstruct full mass
  - –Use transverse mass (Jacobian peak)

$$M_{T_{WW}} = \sqrt{(\not{E}_T + E_{T_{\ell^+\ell^-}})^2 - (\vec{p}_{T_{\ell^+\ell^-}} + \vec{\not{p}}_T)^2}$$

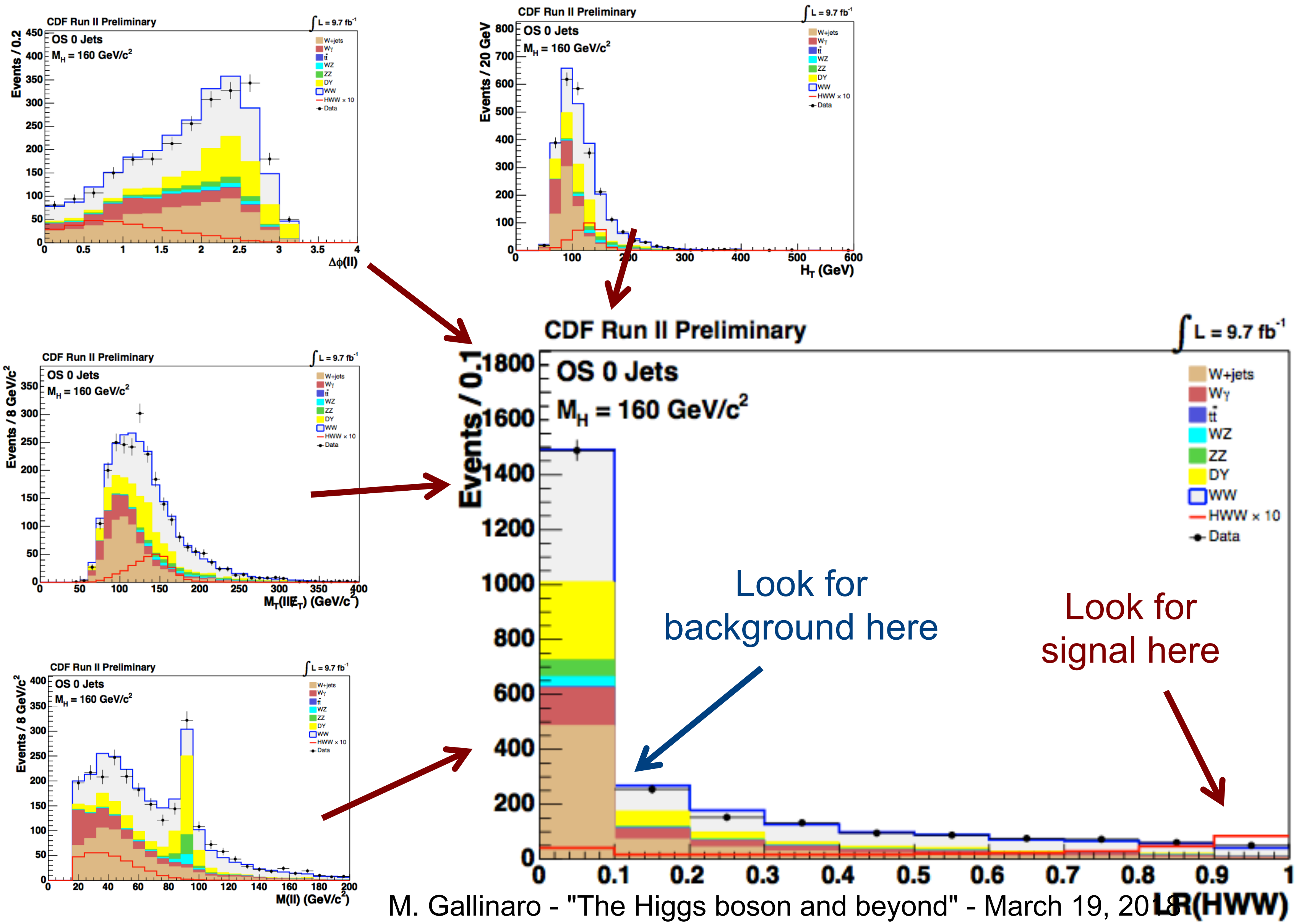
- Helicity conservation after H decay
  - –N helicity is pre-determined (massless)
  - –Dileptons recoils against 2ν preferentially







The H→WW discriminator



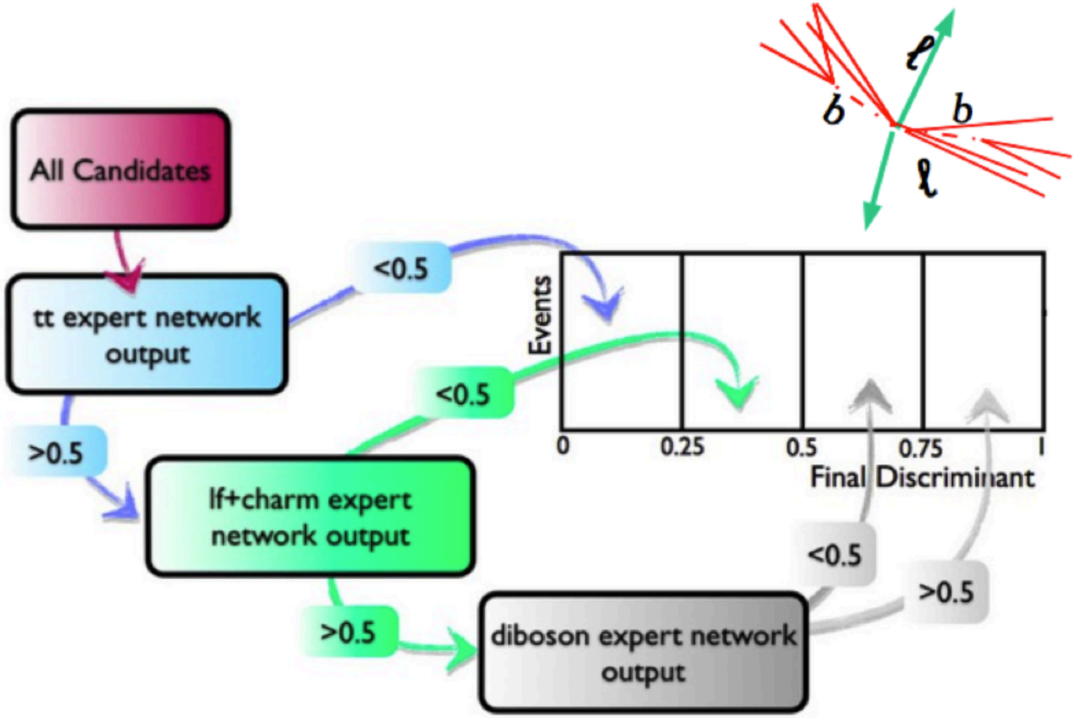
Look for background here

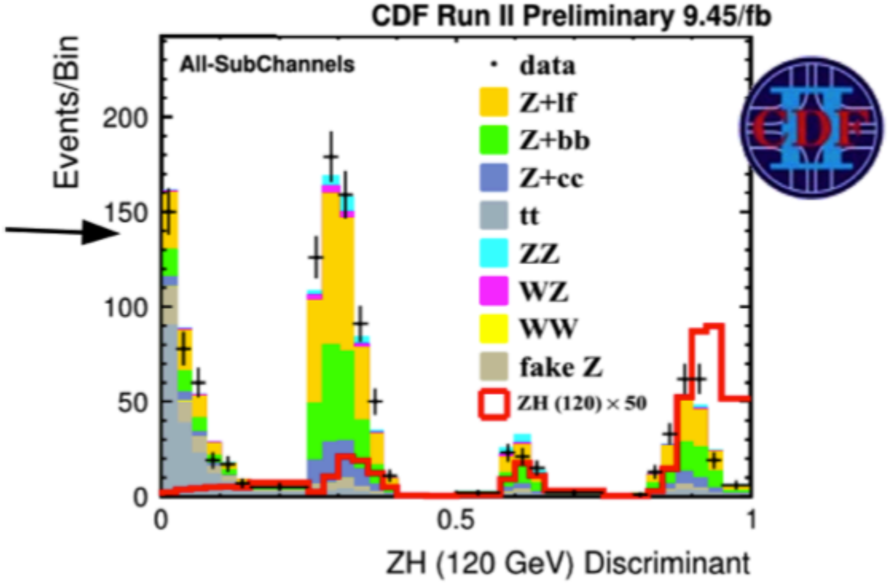
Look for signal here

More complex multivariate analyses

Generalize MVA concept

- Signal and control regions
- Address specific experimental effects: improve resolution, energy scale, identification criteria
- Reject specific backgrounds
- Keep everything in the analysis: if there is any problem it will appear in the control region





Limits, measurements, etc.

How much “space” is statistically allowed for the signal?

- Free parameters is signal strength $\mu=\sigma_{obs}/\sigma_{theory}$
- Compare data with expectations using max likelihood

$$\mathcal{L}(\text{data}\,|\,\mu,\theta) = \text{Poisson}\,(\,\text{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,)\cdot p(\tilde{\theta}|\theta)$$

signal
expected

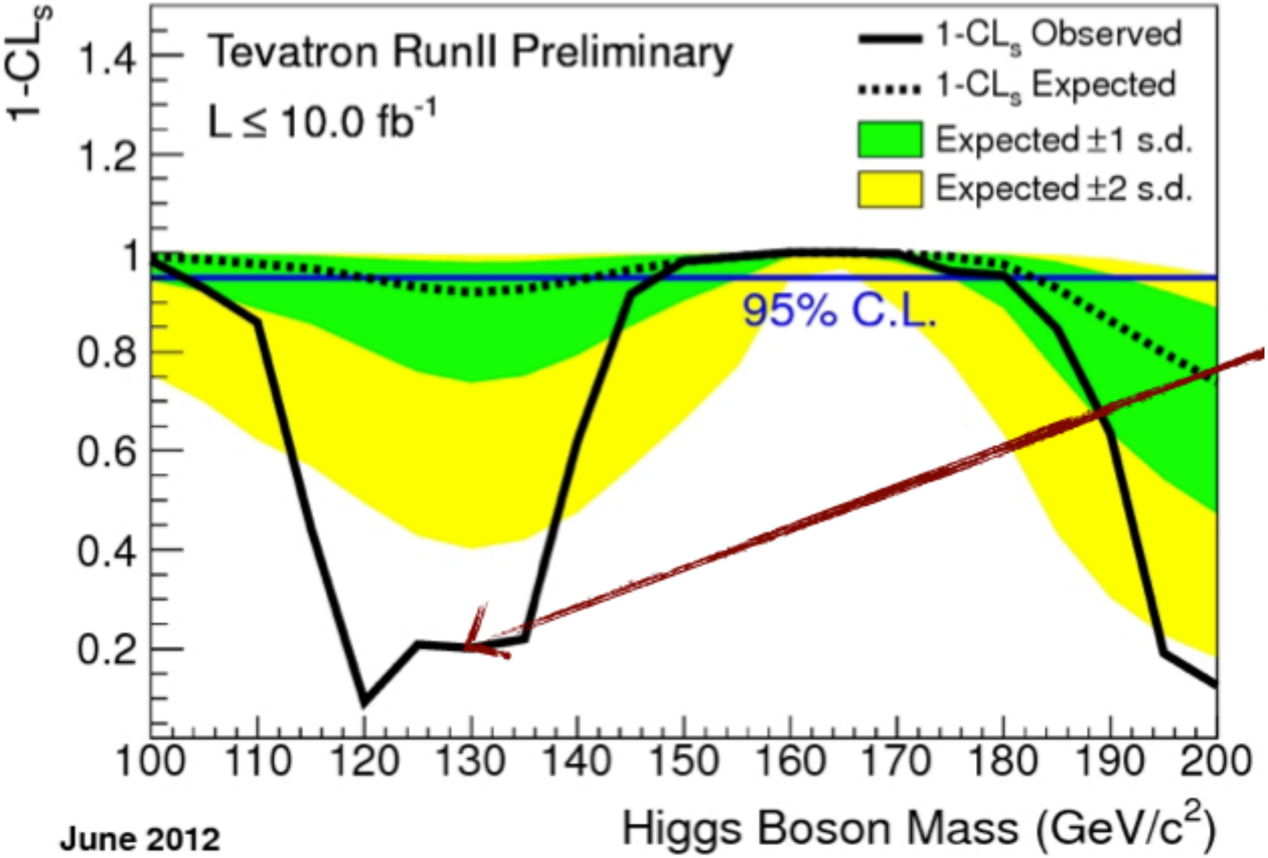
background
expected

nuisance parameters
affecting rates or
shapes

Nuisance parameters quantify uncertainty in the rates

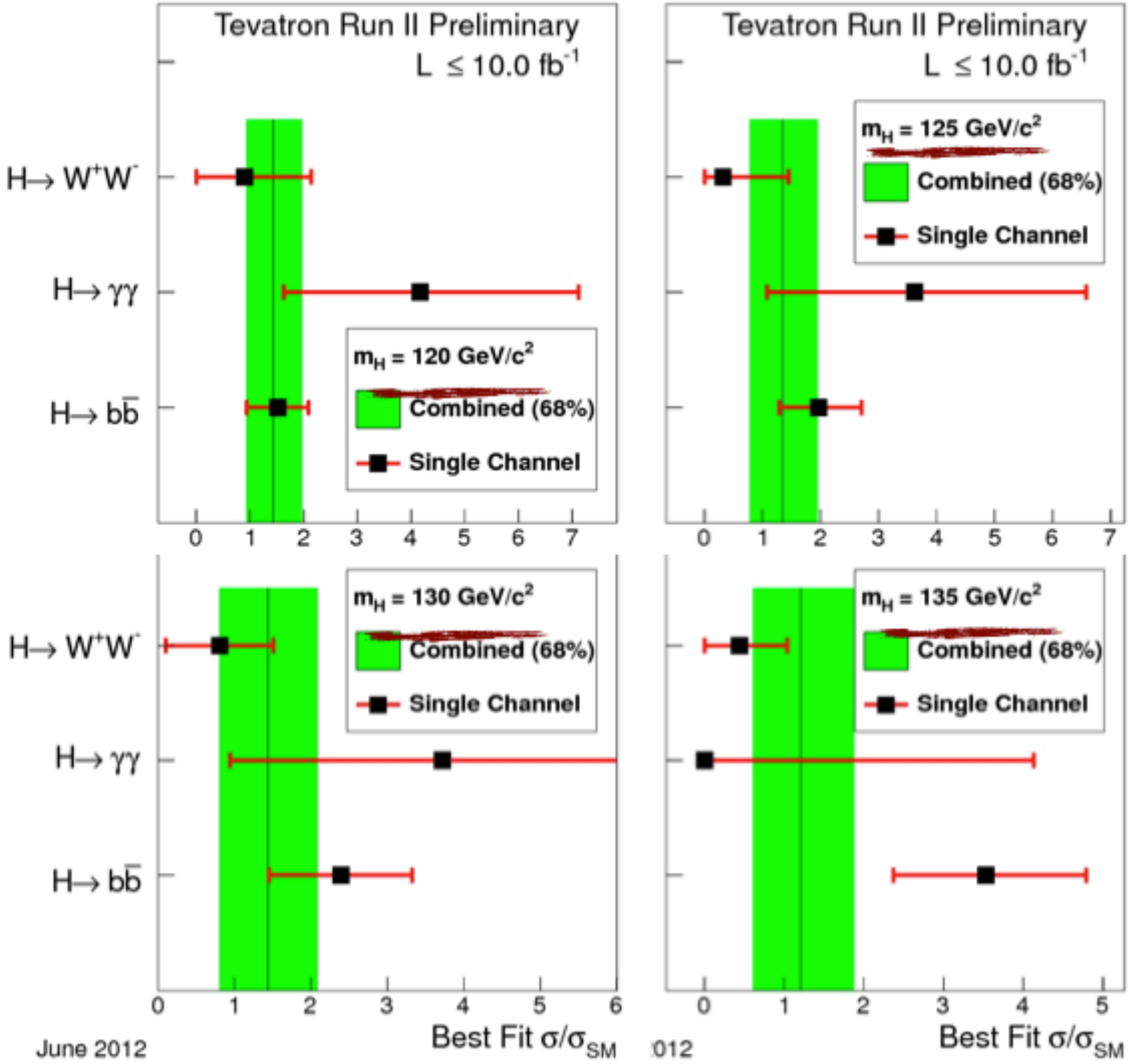
Limit settings

- Use pseudo-experiments and obtain distribution of test statistics
- Background-only case μ=0 signal+background case μ=1
- Best values for the nuisances fit to data in each case must be used coherently
- What is the probability that each case exceeds the observed value



Combination points to something incompatible with background-only hypothesis at 3σ level

Quantifying the excess at the Tevatron



- Scan the mass looking for compatibility of different channels
- At m_H=125 GeV

  $\Rightarrow \mu = 1.4 \pm 0.7$
- Consistent between different channels and with indirect limits from precision measurement

When to claim discovery?

Signal significance:

$$S = \frac{N_S}{\sqrt{N_S + N_B}}$$

S>5: Signal $N_S = N_{tot} - N_B$ is 5 times larger than statistical uncertainty on $N_B + N_S$

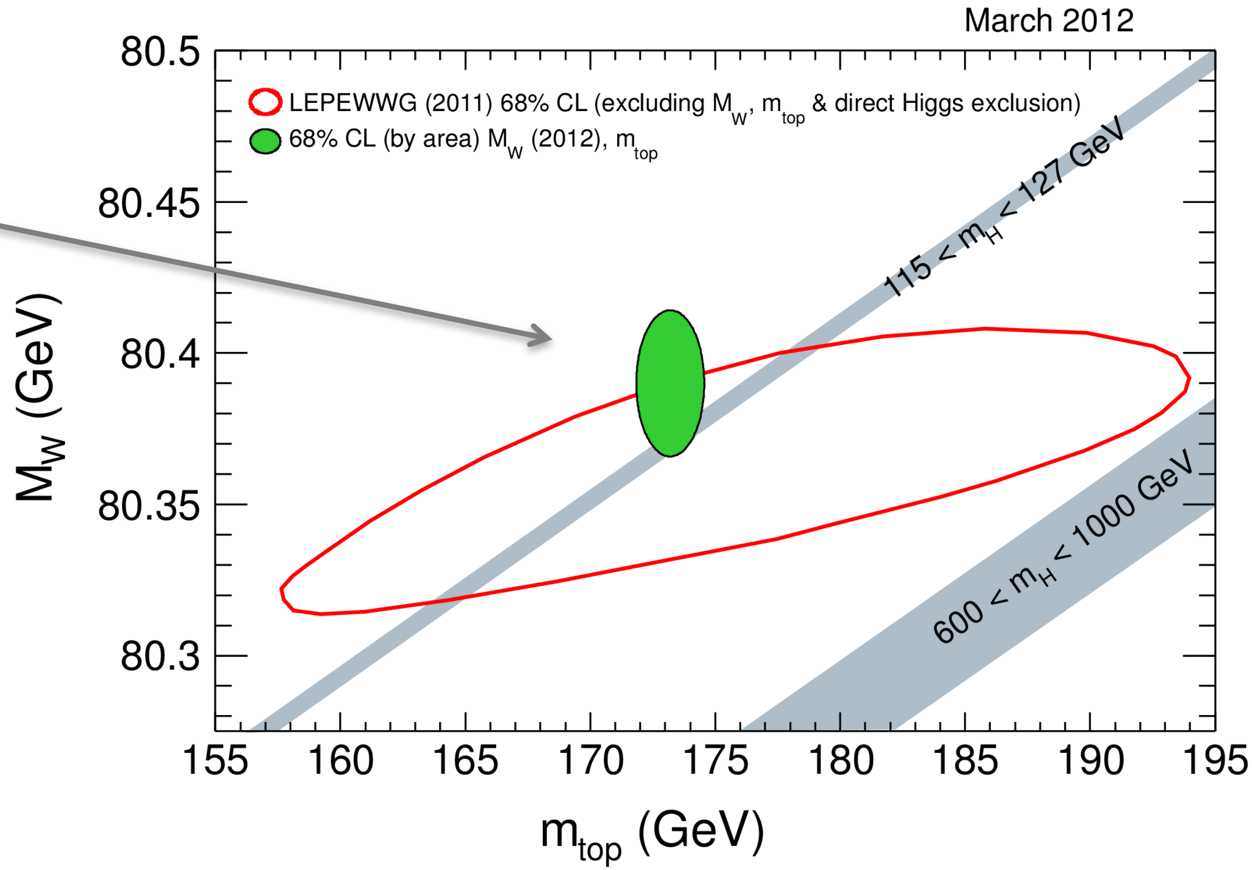
Gaussian probability upward fluctuation by more than 5σ is observed…

$$P_{5\sigma} = 10^{-7}$$

⇒discovery

Situation in early 2012

Very precise measurement of M_W = 80.390 ± 0.016 GeV, driven mainly by the Tevatron.



Much of the SM Higgs range had been ruled out by 2011 LHC running.

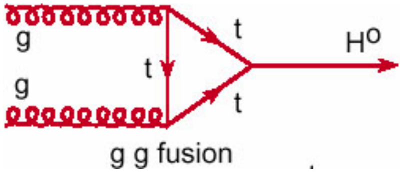
Excess of events in the low mass region seen in ATLAS and CMS

Exclusions of M_H:

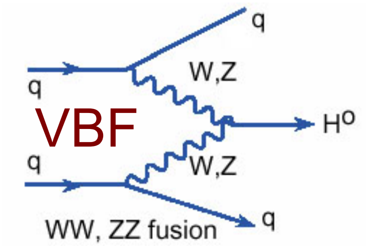
- LEP < 114 GeV (arXiv:0602042v1)
- Tevatron [156,177] GeV (arXiv:1107.5518)
- LHC [~127, 600] GeV arXiv:1202.1408 (ATLAS) arXiv:1202.1488 (CMS)

Higgs production

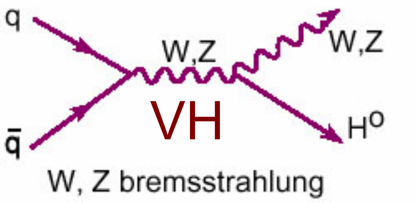
87%



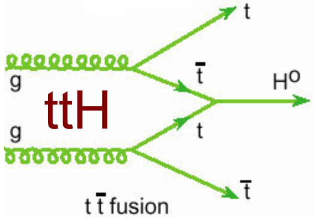
7.1%

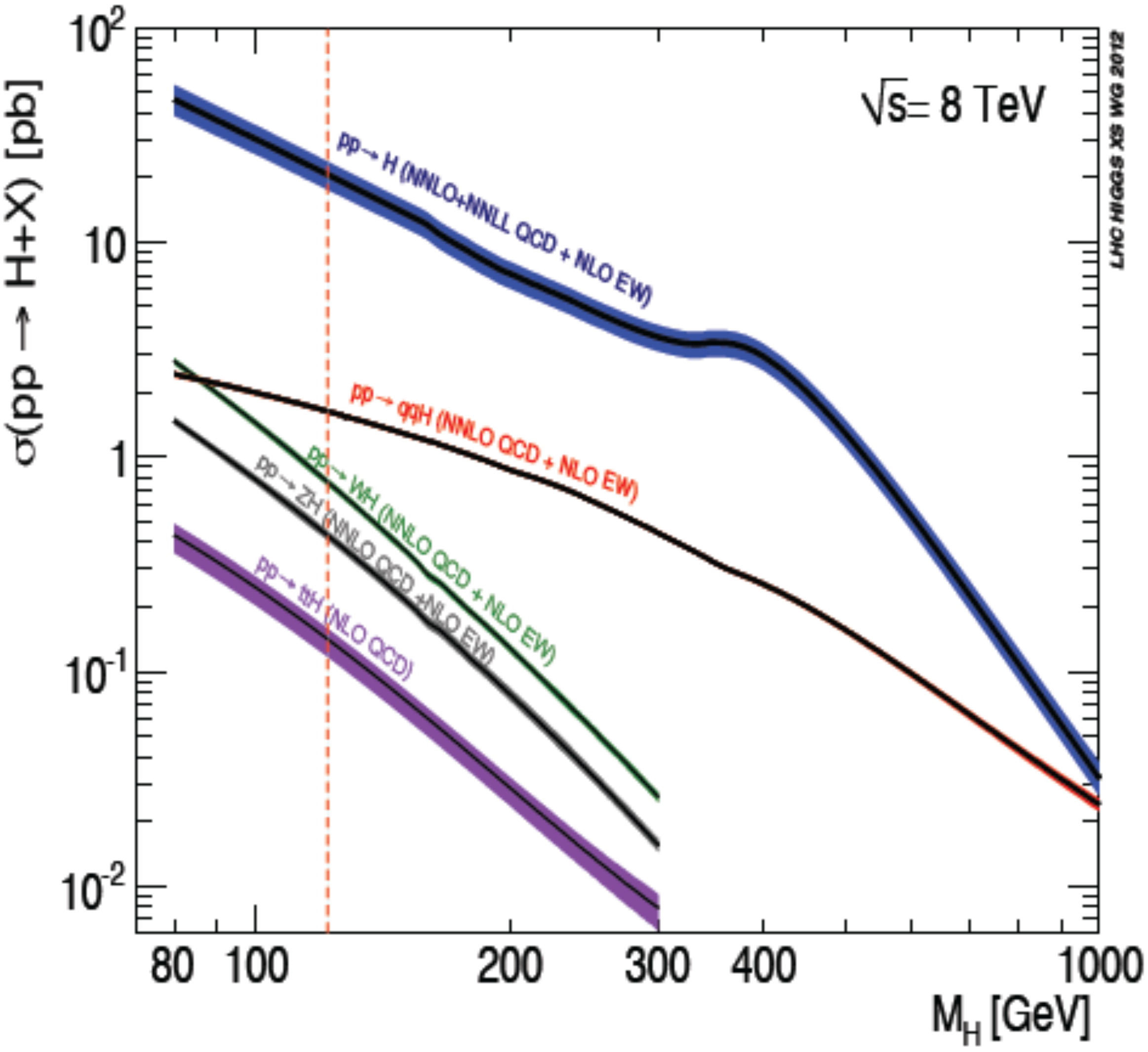


4.9%



0.6%



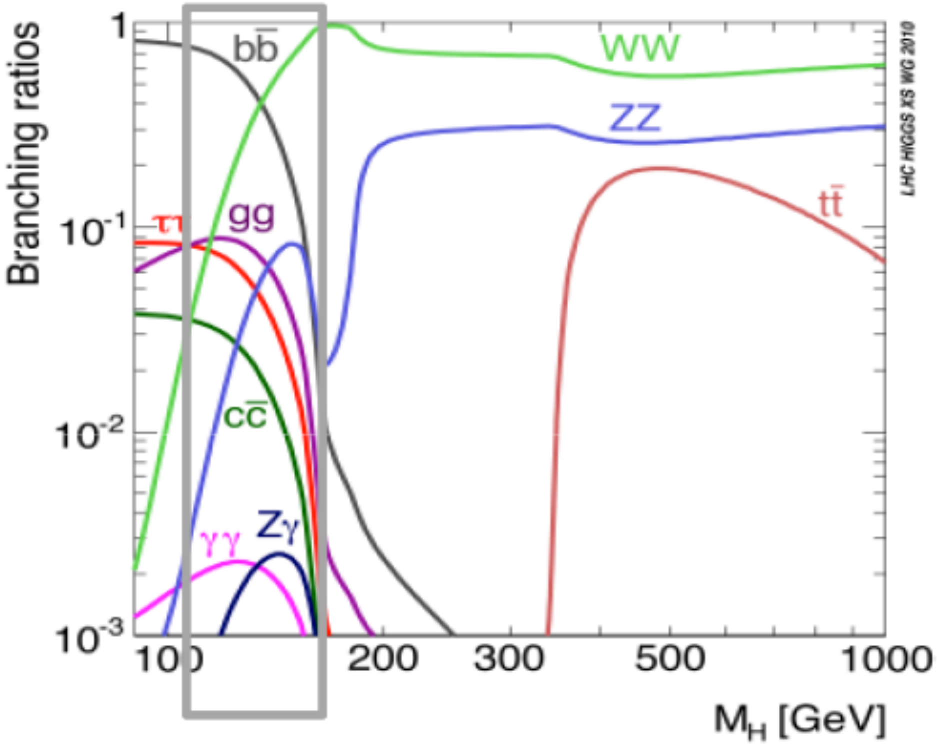


Higgs decays

5 decay modes studied:

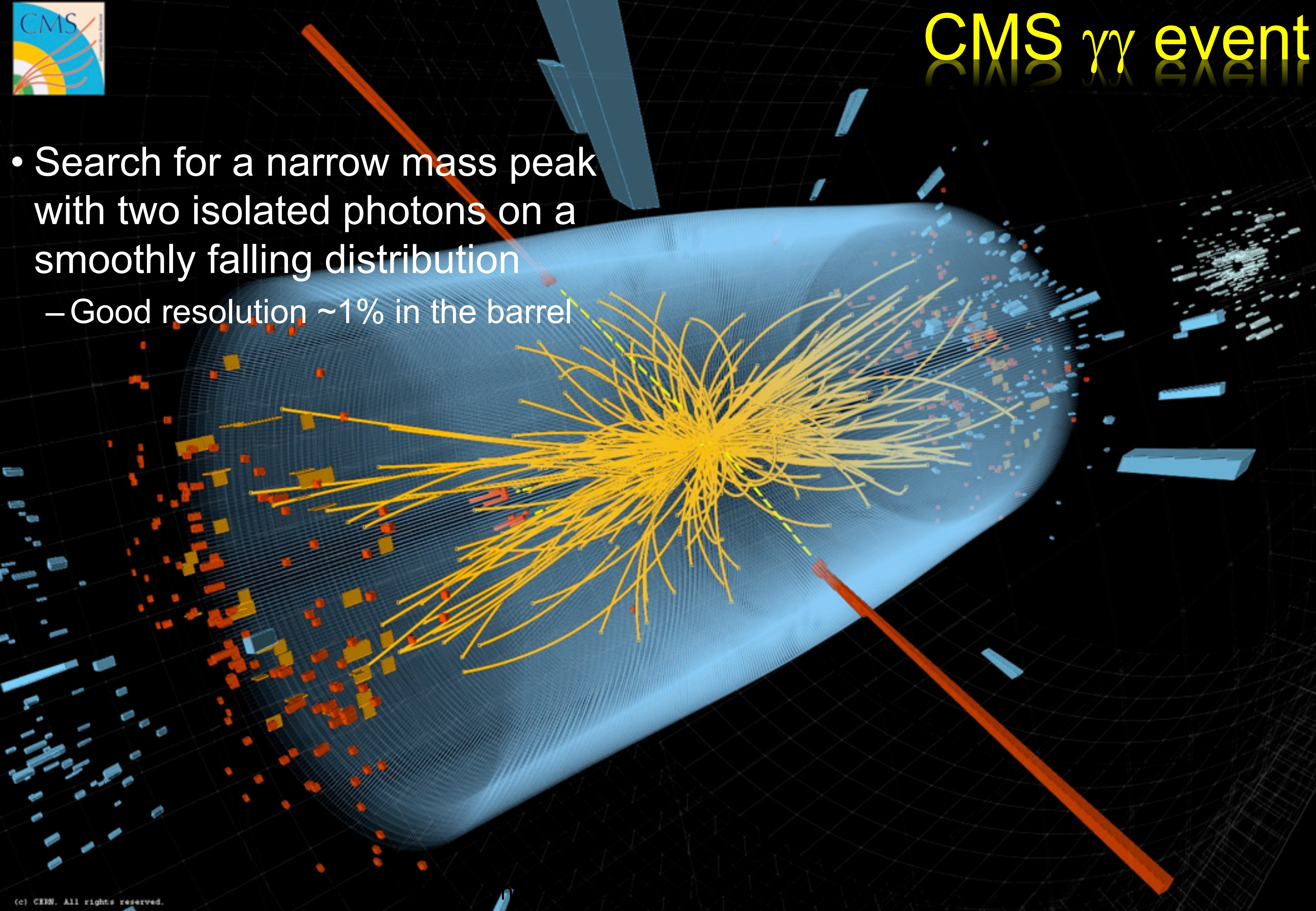
- High mass: WW, ZZ
- Low mass: bb, $\tau\tau$, WW, ZZ, $\gamma\gamma$
- Low mass region is very challenging
- Very good mass resolution ~1% ($\gamma\gamma$, 4l)

Decay mode	Production tagging	No. of subchannels	m_H range (GeV)	Int. Lum. (fb^{-1}) 7 TeV	8 TeV
$\gamma\gamma$	untagged dijet (VBF)	4 1 or 2	110–150	5.1	5.3
ZZ	untagged	3	110–600	5.1	5.3
WW	untagged dijet (VBF)	4 1 or 2	110–600	4.9	5.1
$\tau\tau$	untagged dijet (VBF)	16 4	110–145	4.9	5.1
bb	lepton, E_T^{miss} (VH)	10	110–135	5.0	5.1



CMS $\gamma\gamma$ event

- Search for a narrow mass peak with two isolated photons on a smoothly falling distribution
  - Good resolution ~1% in the barrel

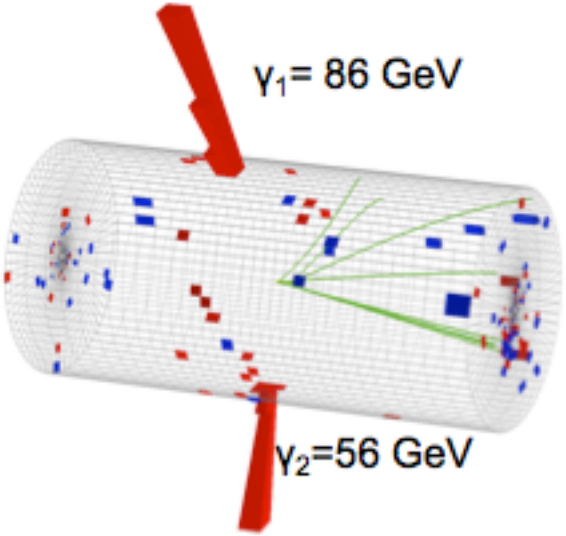


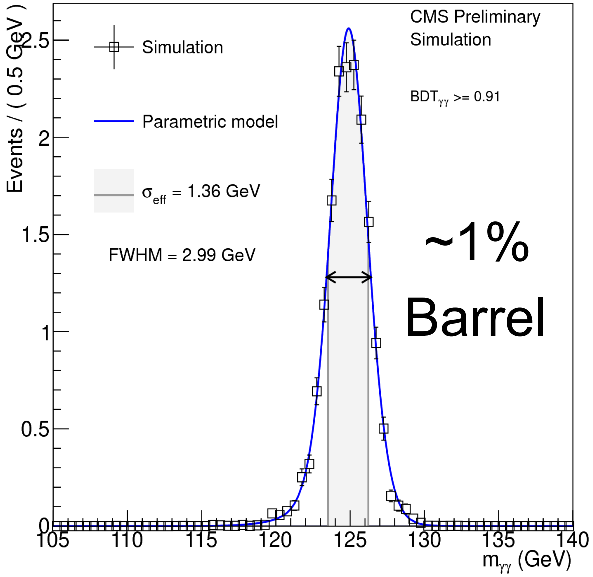
H→γγ: analysis strategy

Two inclusive analyses:

- MVA: photons selected with BDT
- Cut-based: photons selected with cuts

- Analysis optimized by categorizing events by γ ID
  - MVA analysis for γ-ID and event classification
  - Divide events into non-overlapping samples
  - Cross-check with cut-based analysis
  - MVA gives ~15% better sensitivity





~1%

Barrel

H→γγ: analysis strategy

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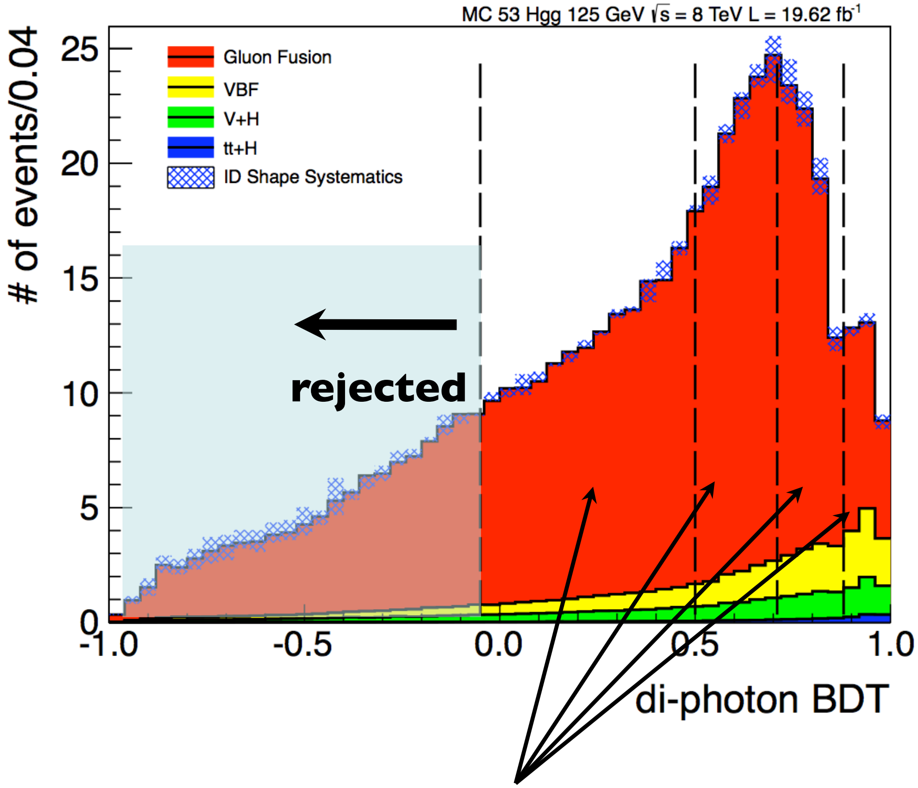

MVA event categories

H→γγ: analysis strategy

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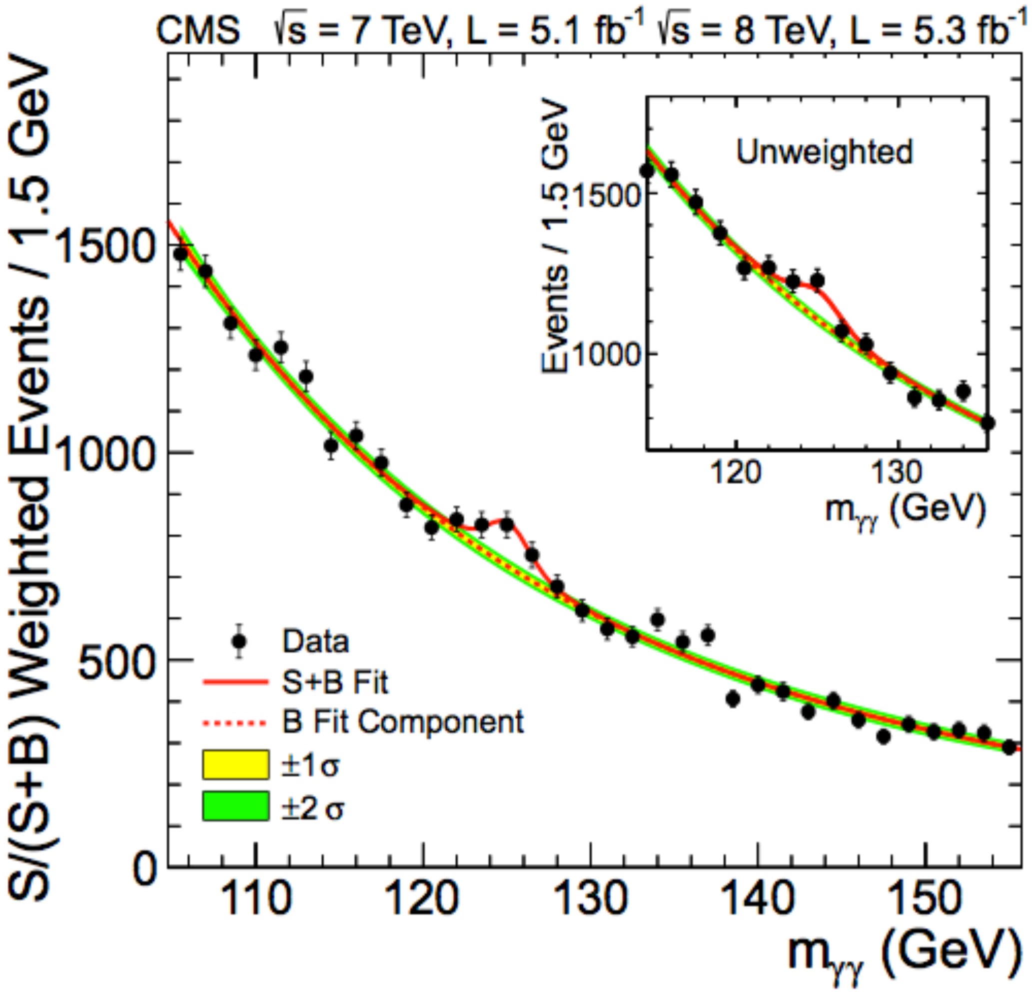
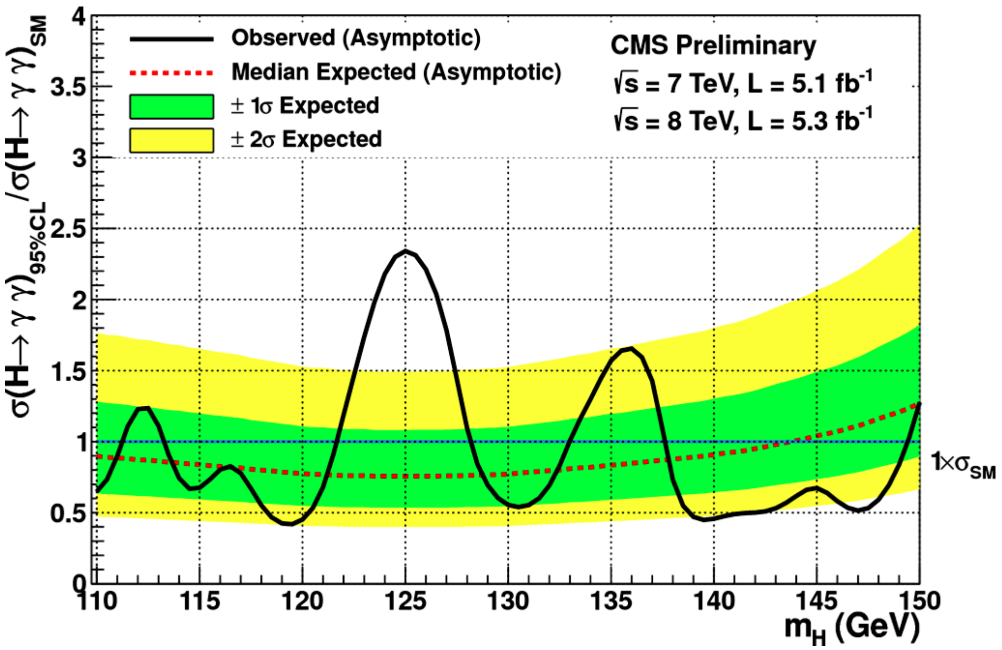
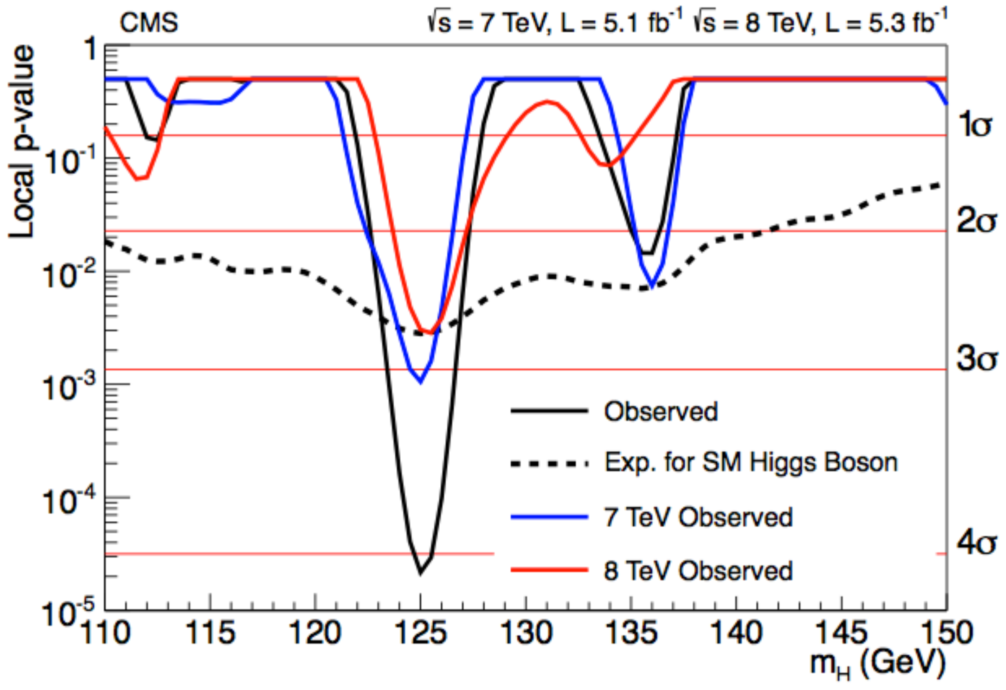


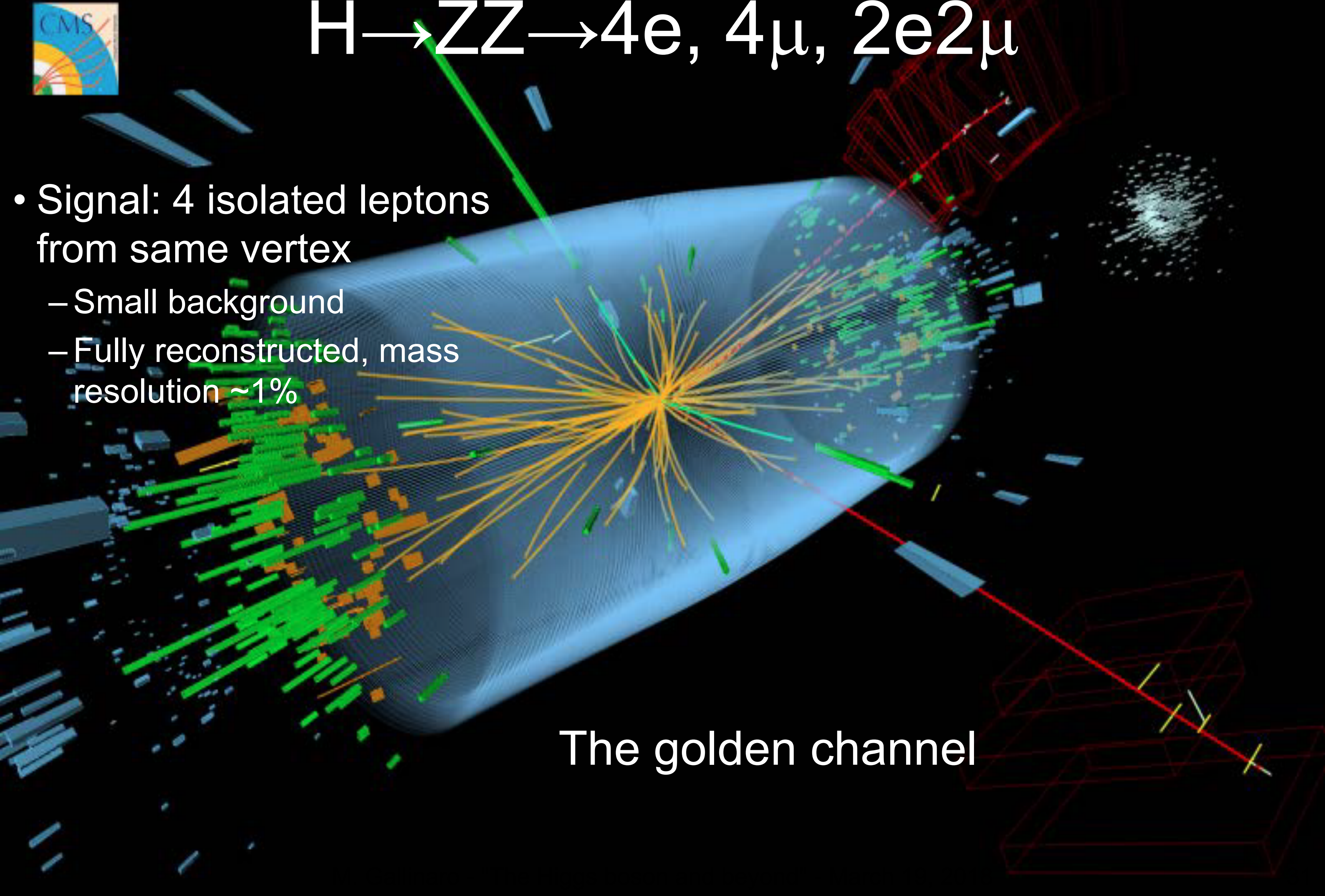
H→γγ: results





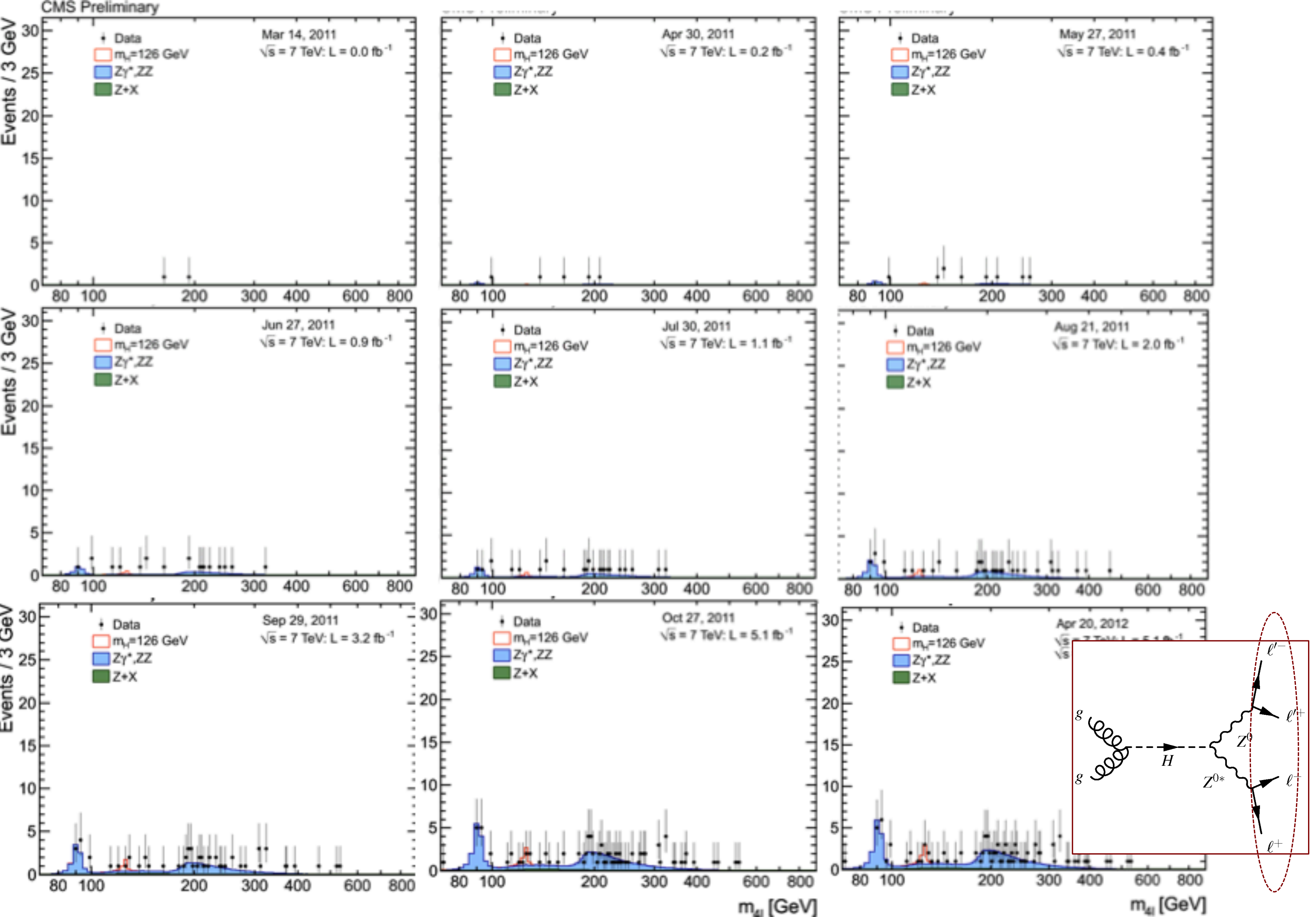
- Largest excess at ~125 GeV
  - Similar excess in 2011 and 2012

H→ZZ→4e, 4μ, 2e2μ



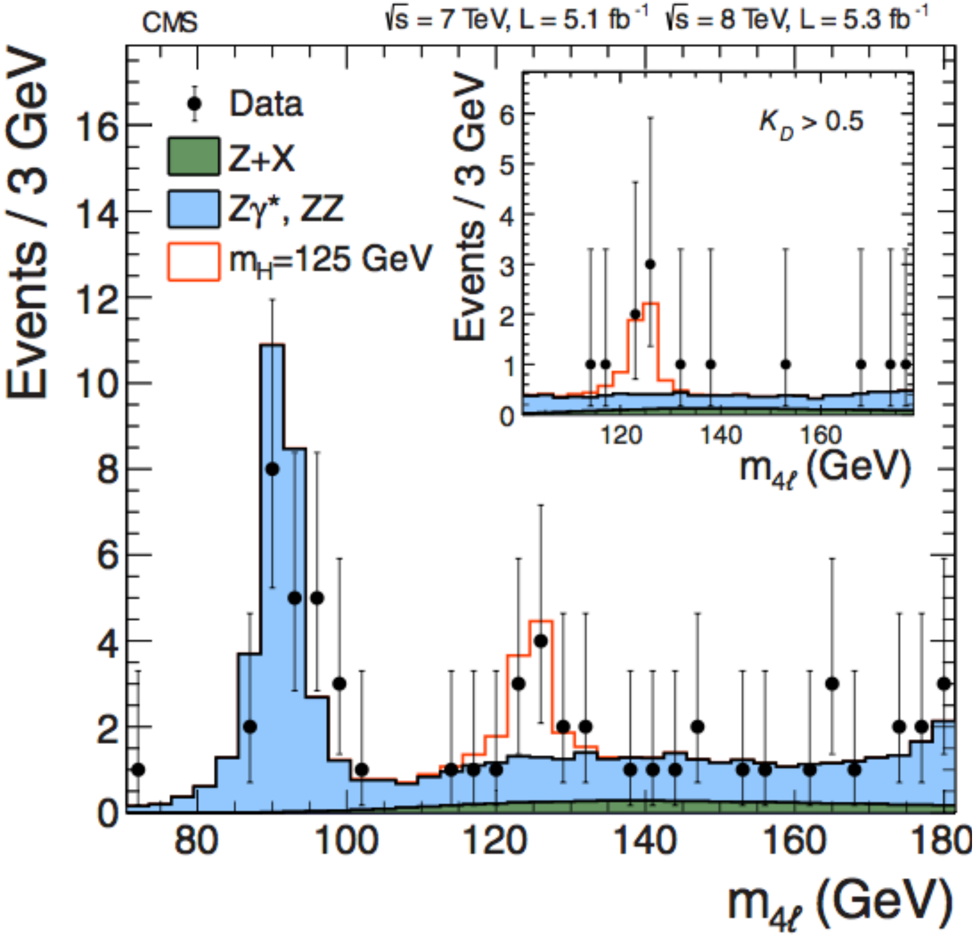
- Signal: 4 isolated leptons from same vertex
  - Small background
  - Fully reconstructed, mass resolution ~1%

The golden channel

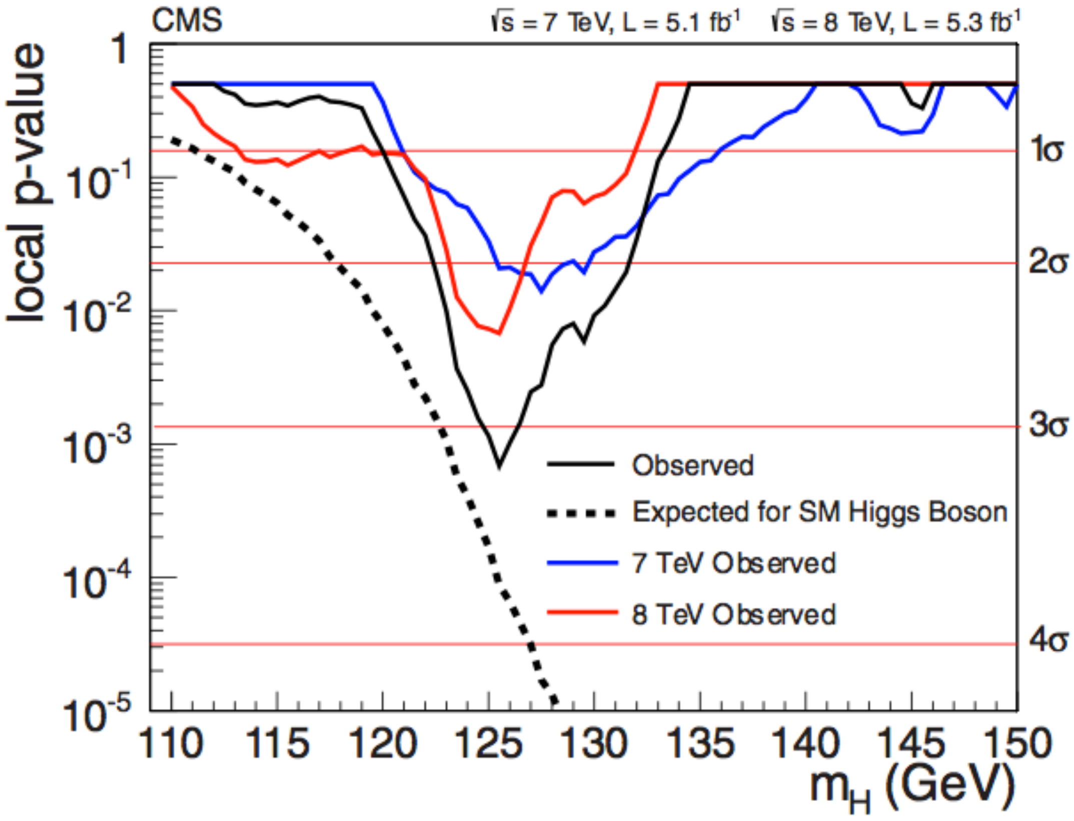

CMS Preliminary
Events / 3 GeV
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Mar 14, 2011
√s = 7 TeV: L = 0.0 fb⁻¹
Apr 30, 2011
√s = 7 TeV: L = 0.2 fb⁻¹
May 27, 2011
√s = 7 TeV: L = 0.4 fb⁻¹
Jun 27, 2011
√s = 7 TeV: L = 0.9 fb⁻¹
Jul 30, 2011
√s = 7 TeV: L = 1.1 fb⁻¹
Aug 21, 2011
√s = 7 TeV: L = 2.0 fb⁻¹
Sep 29, 2011
√s = 7 TeV: L = 3.2 fb⁻¹
Oct 27, 2011
√s = 7 TeV: L = 5.1 fb⁻¹
Apr 20, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
0
5
10
15
20
25
30
80
100
200
300
400
600
800
m_4l [GeV]
g
g
H
Z^0
Z^{0*}
ℓ'⁻
ℓ'⁺
ℓ⁻
ℓ⁺

H→ZZ→4l

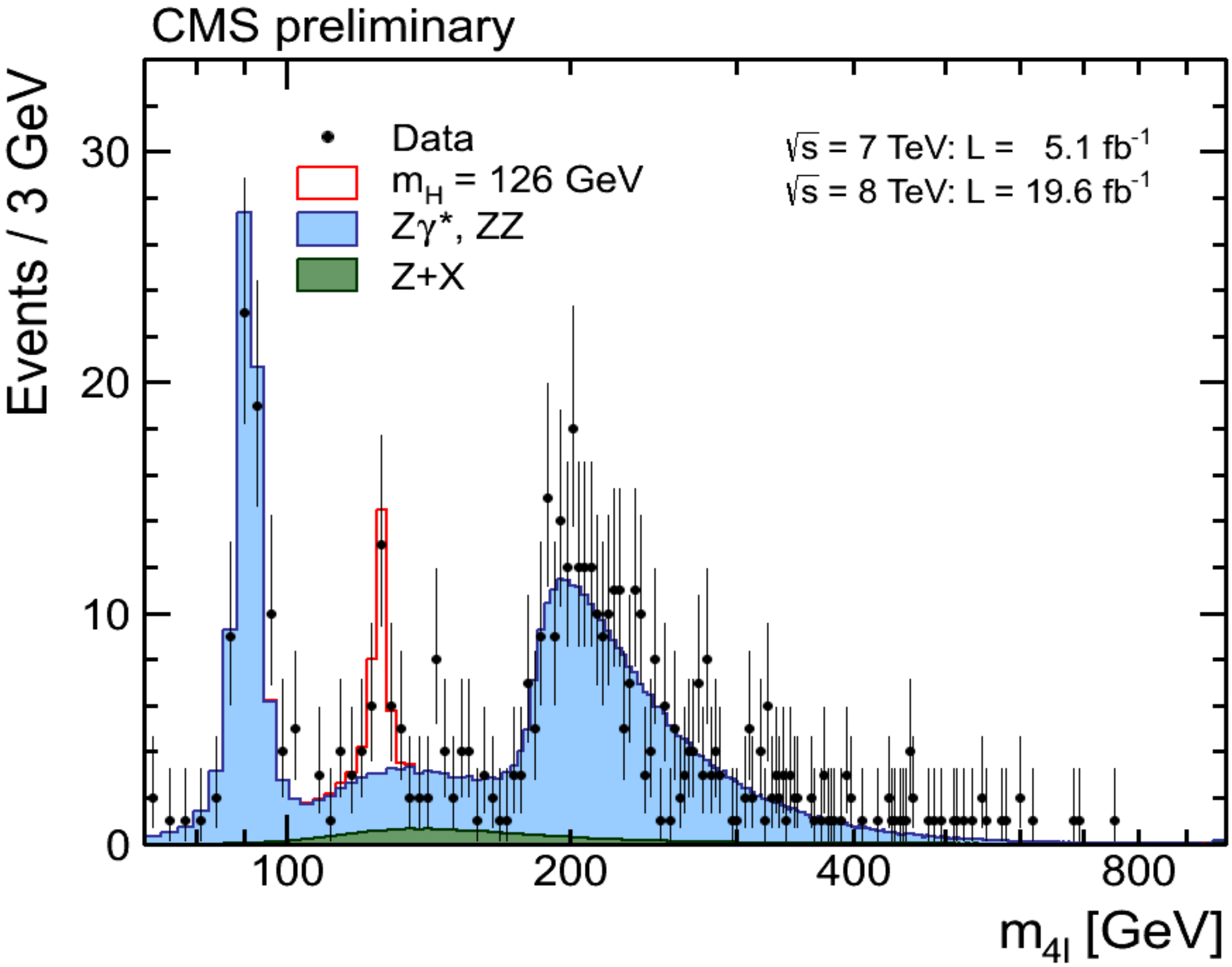
Mass distribution



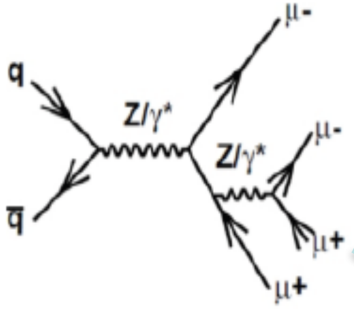
Significance slightly smaller than expectations



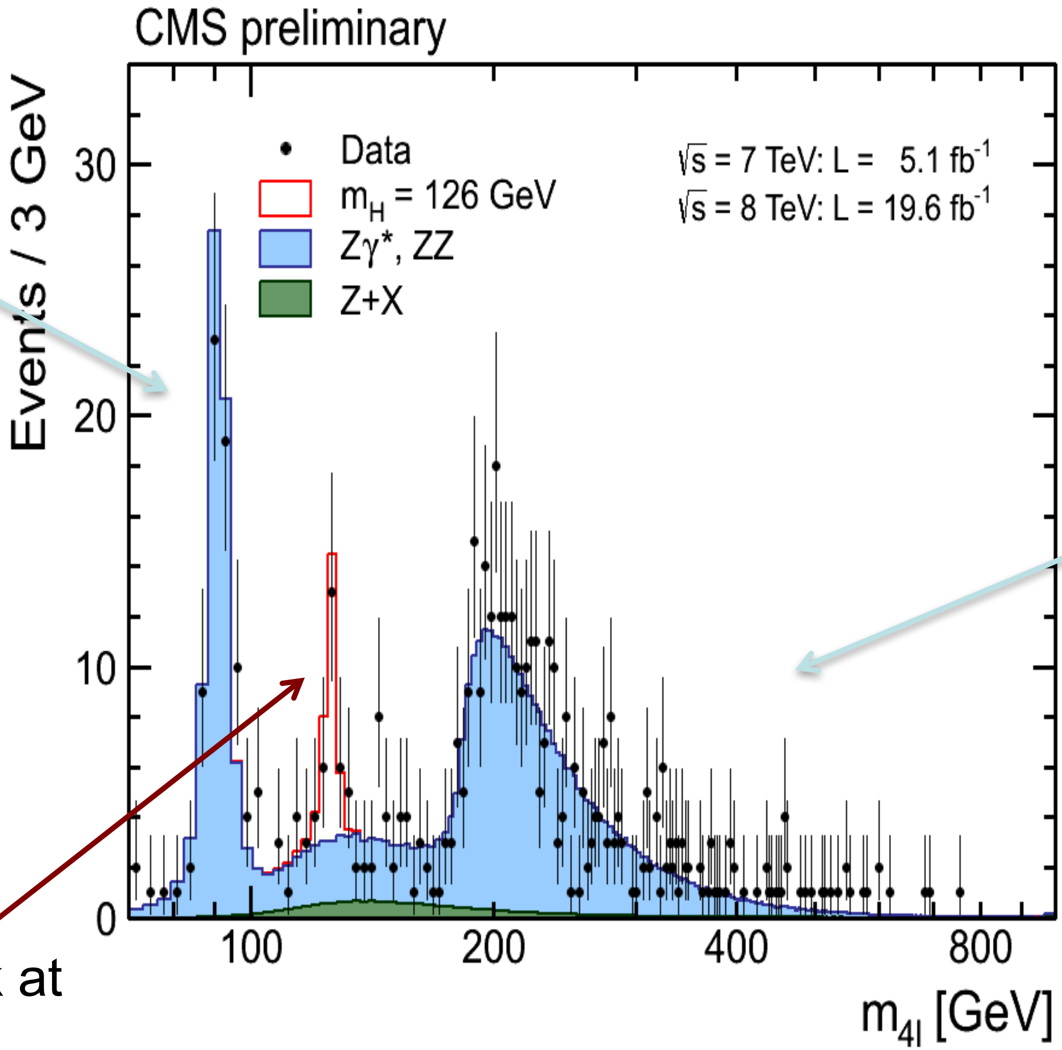
A beautiful peak



Mass spectrum



Offline selection cuts:
5 (7) GeV for μ (e)
in |η| < 2.4 (2.5).



Clean signal peak at ~126 GeV

Very good control of the dominant ZZ background

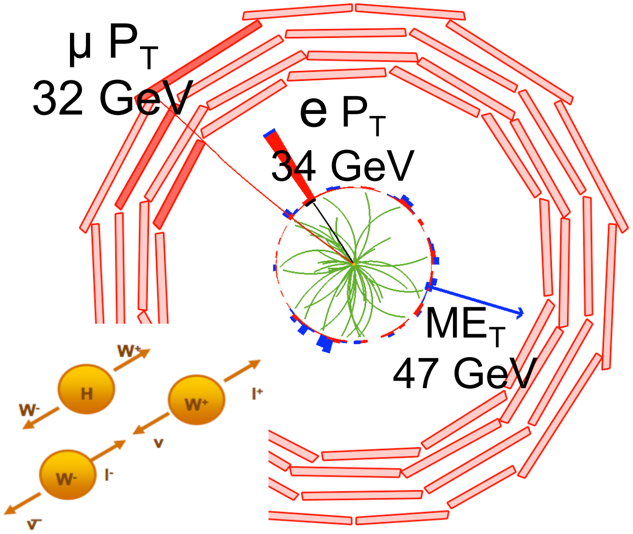
M(4l)>160 GeV

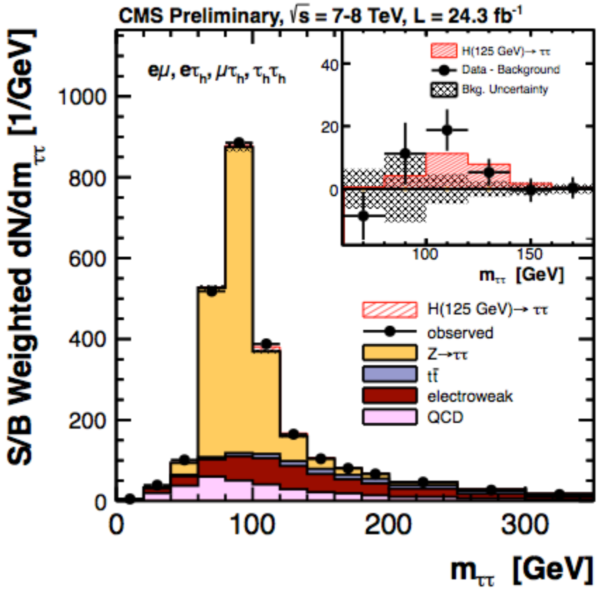
Data	380
MC	364.5

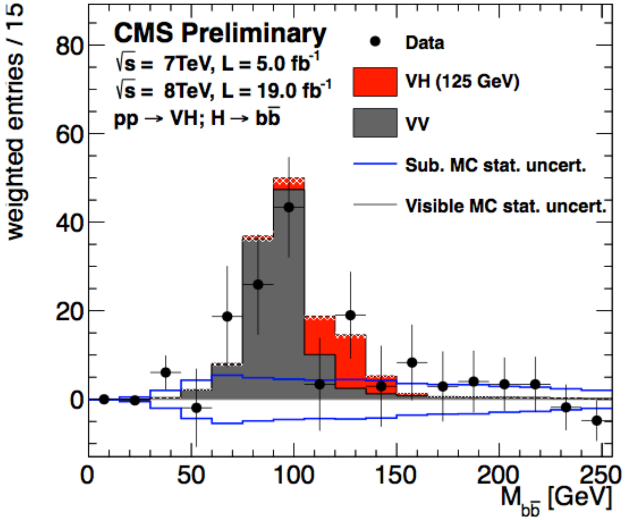
$\sigma_{SM}(th) = 7.8 \pm 0.6$ pb

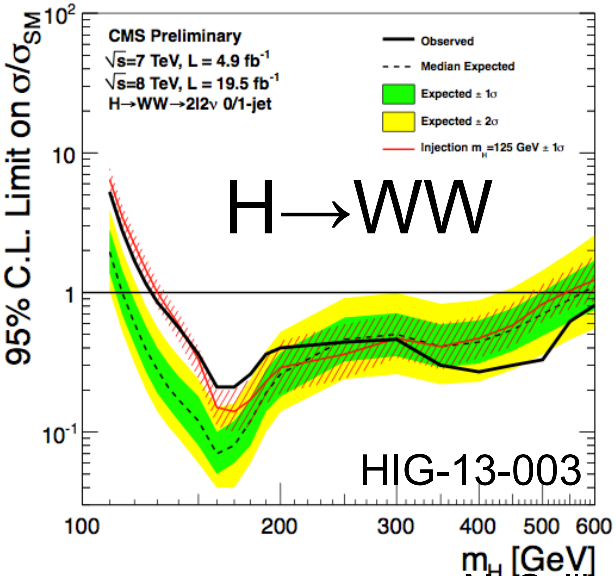
$\sigma(pp \rightarrow ZZ, 8TeV) = 8.4 \pm 1.0$ (stat.) $\pm$ 0.7 (syst.) $\pm$ 0.4(lum.) pb

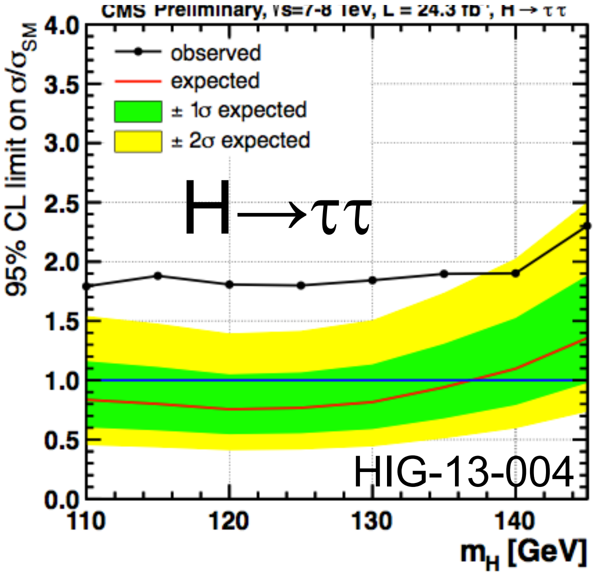
Low mass-resolution channels

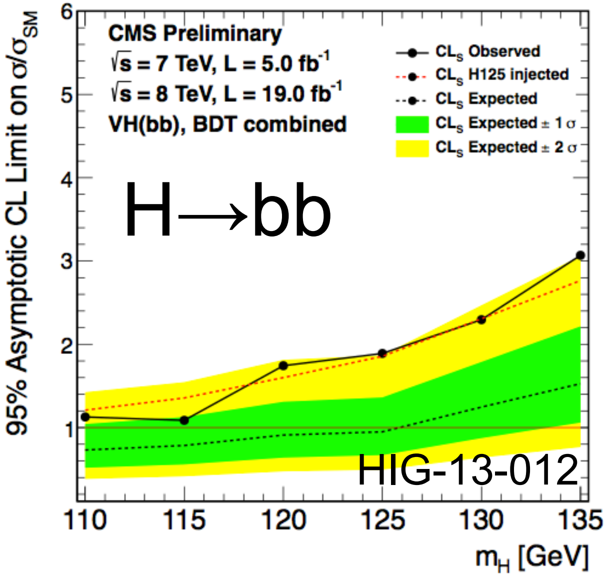




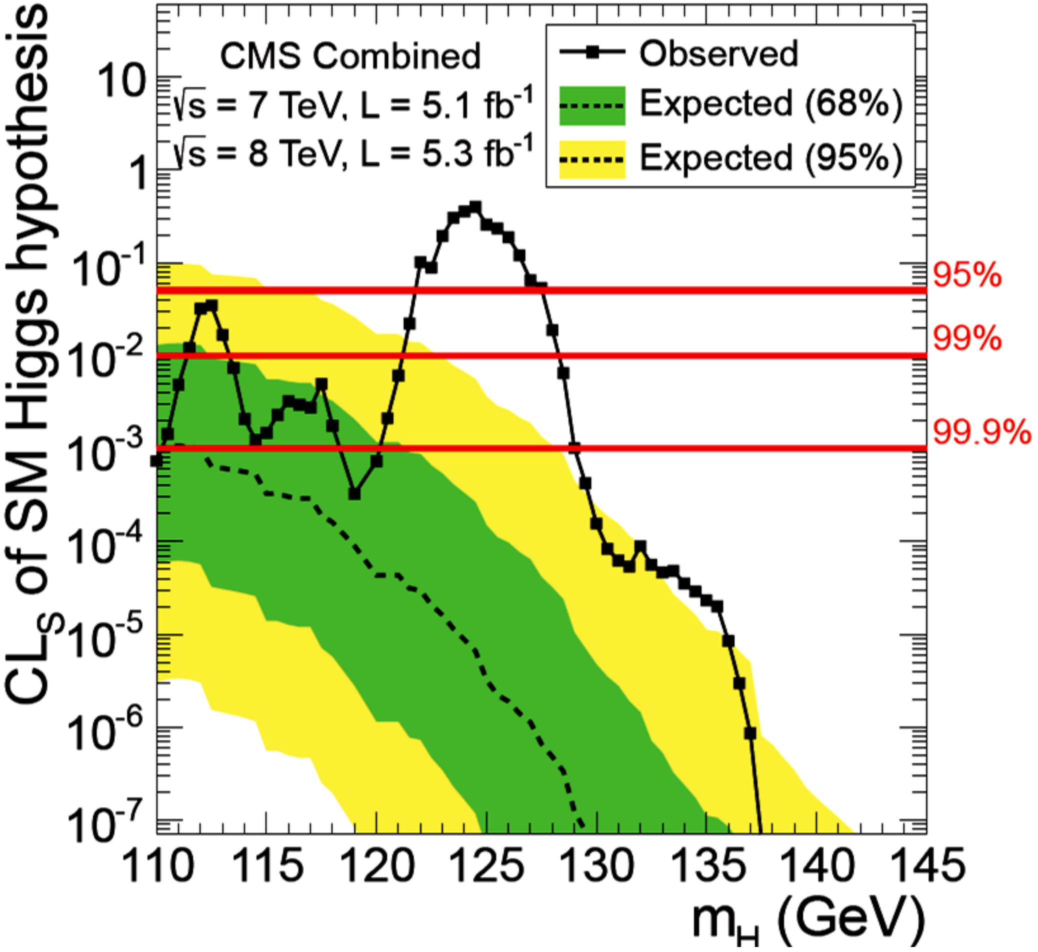


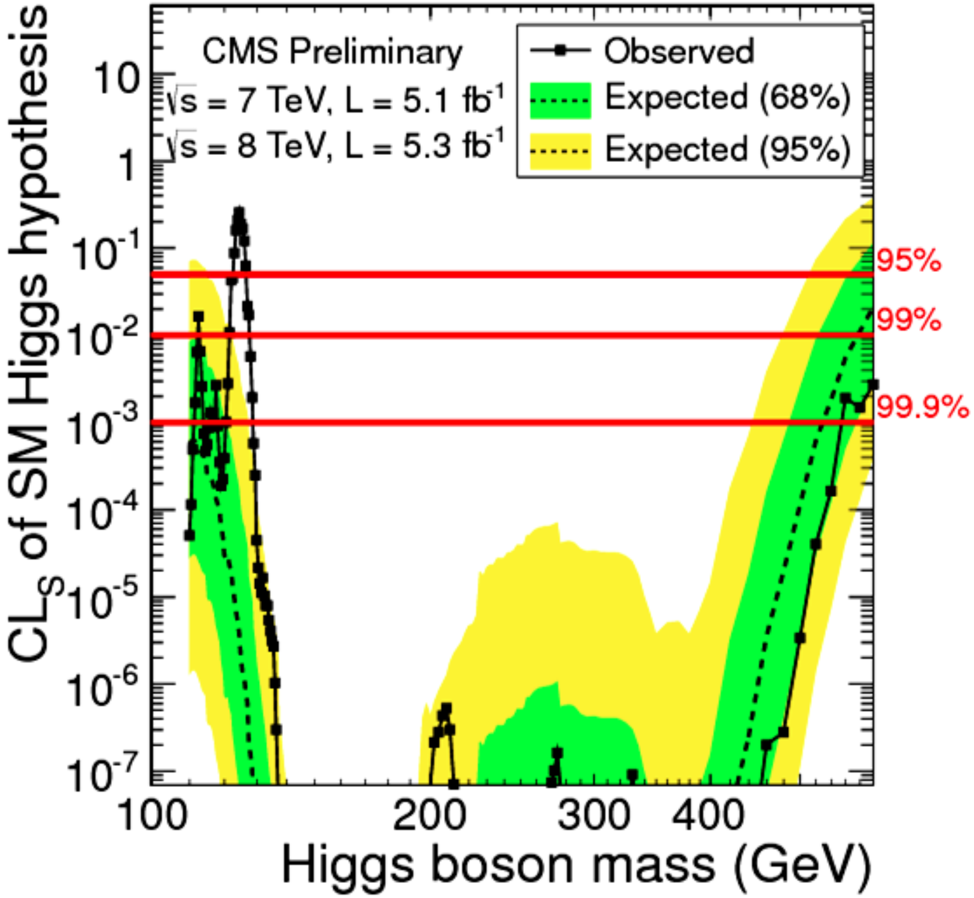






Combined: SM Higgs limits



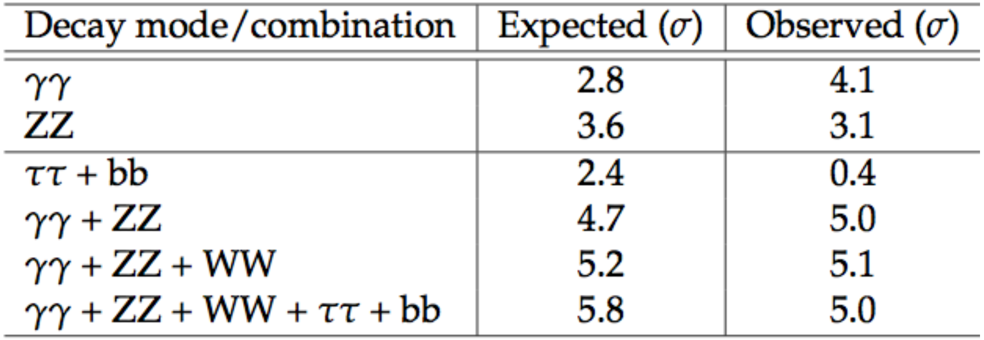


Combined results

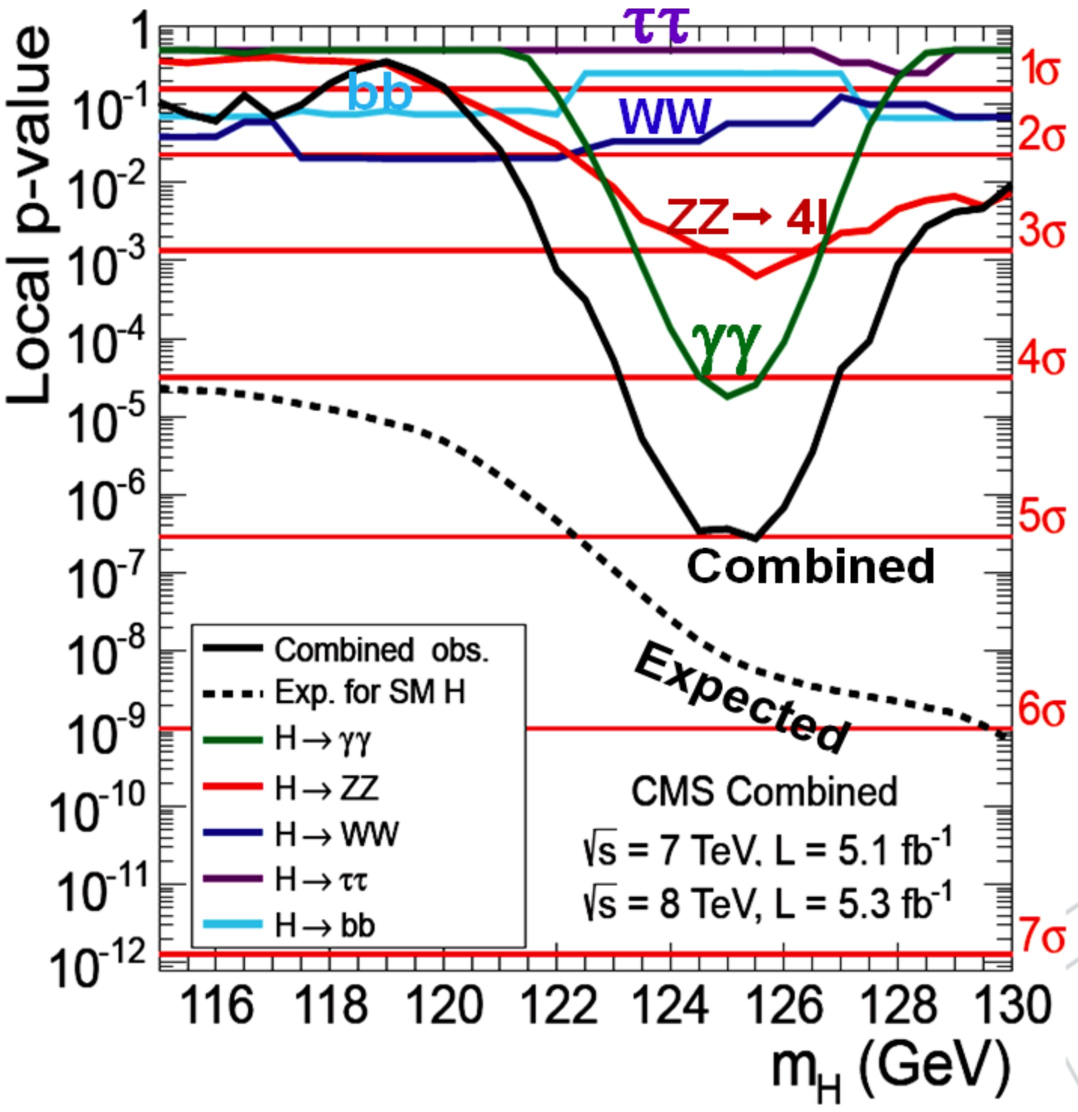
Excess at 125 GeV:

- in 7 TeV data: 3.0 σ
- in 8 TeV data: 3.8 σ

High sensitivity channels: γγ, 4l

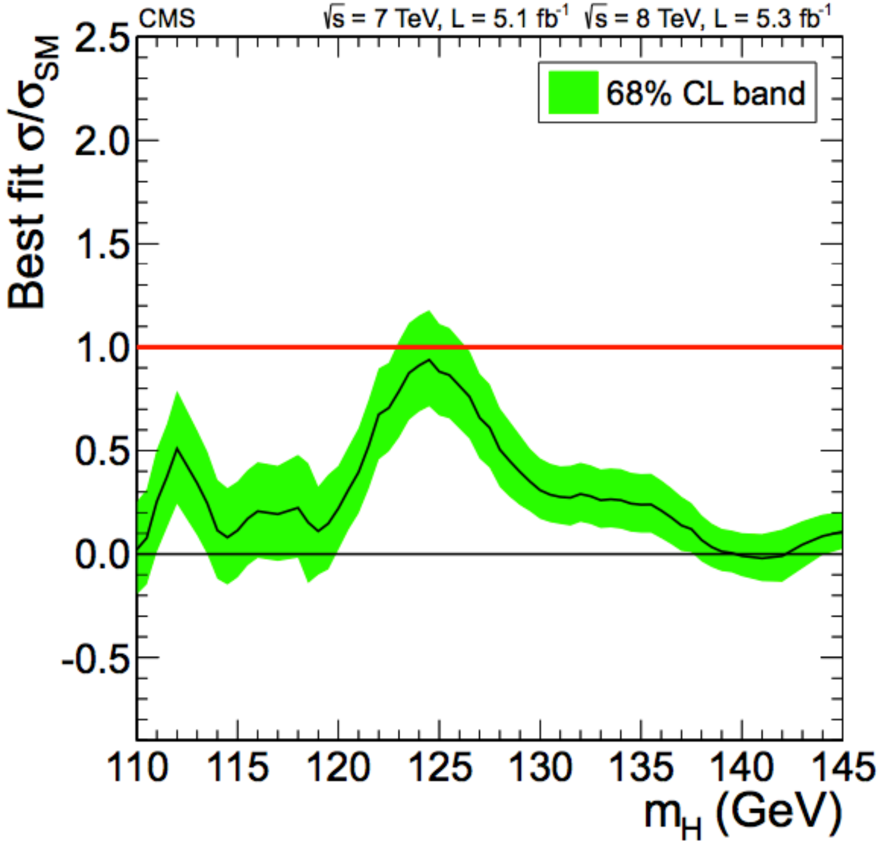


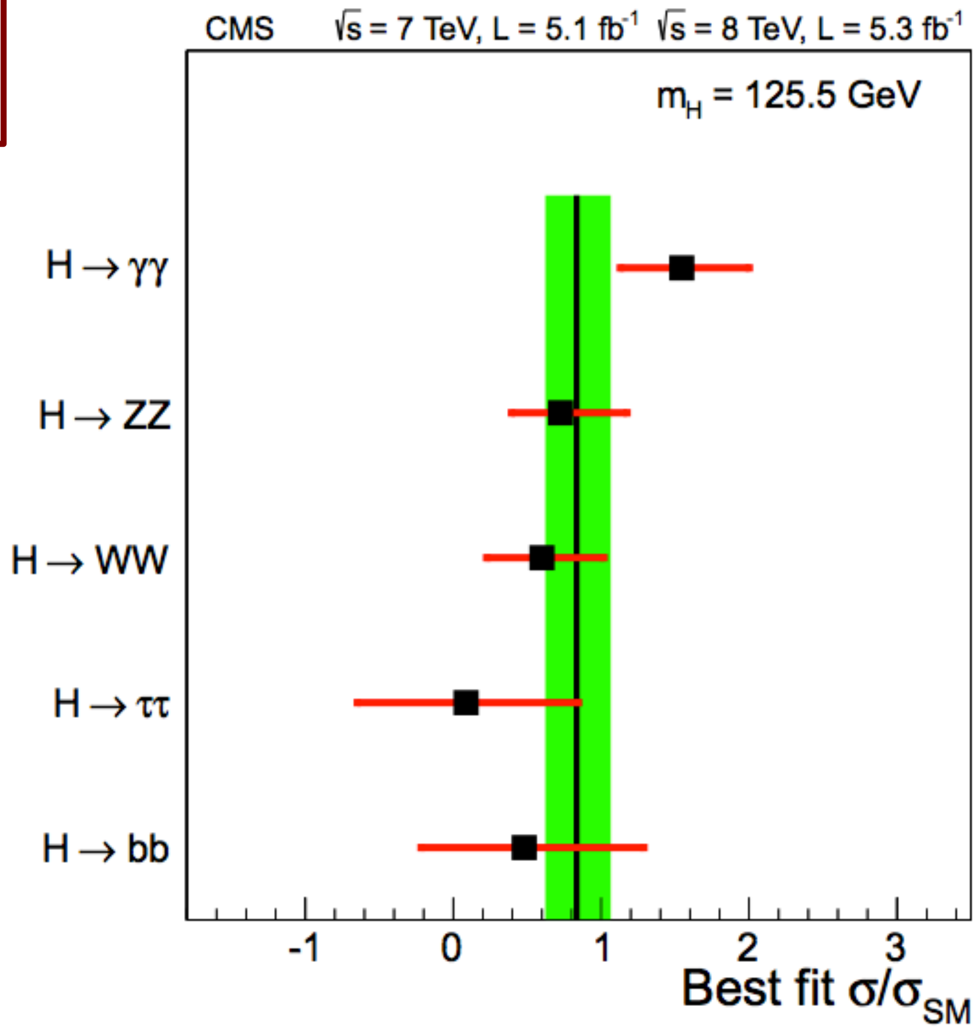
Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau$ + bb	2.4	0.4
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0



Combined results

Overall strength:
σ/σ_{SM}=0.87±0.23

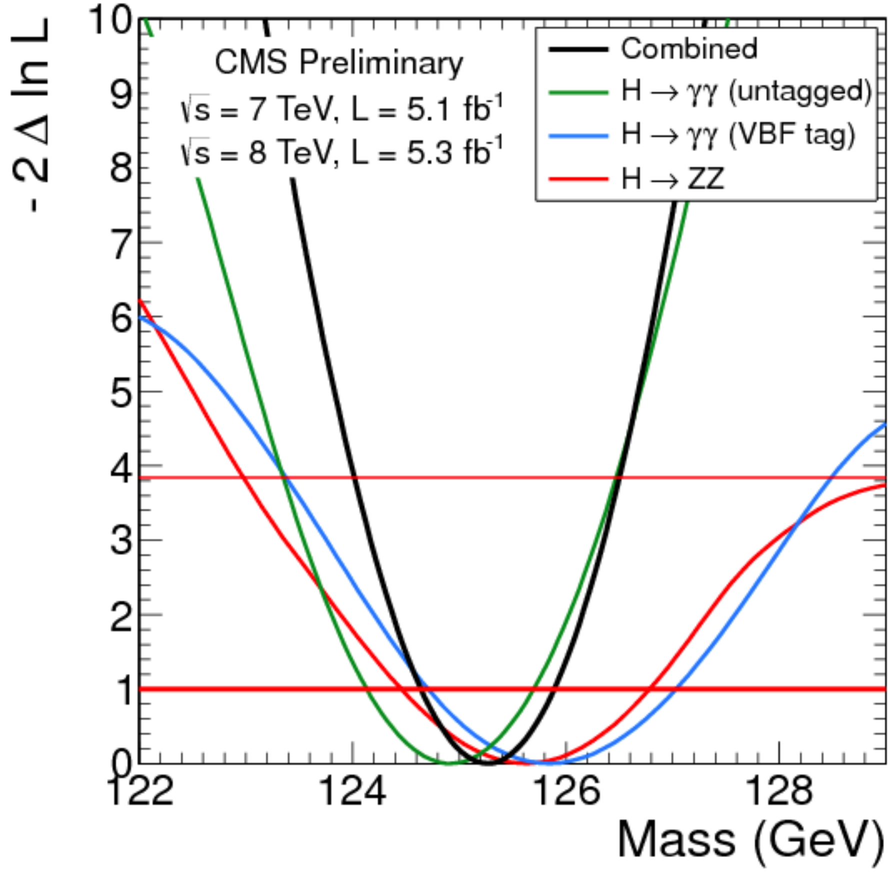


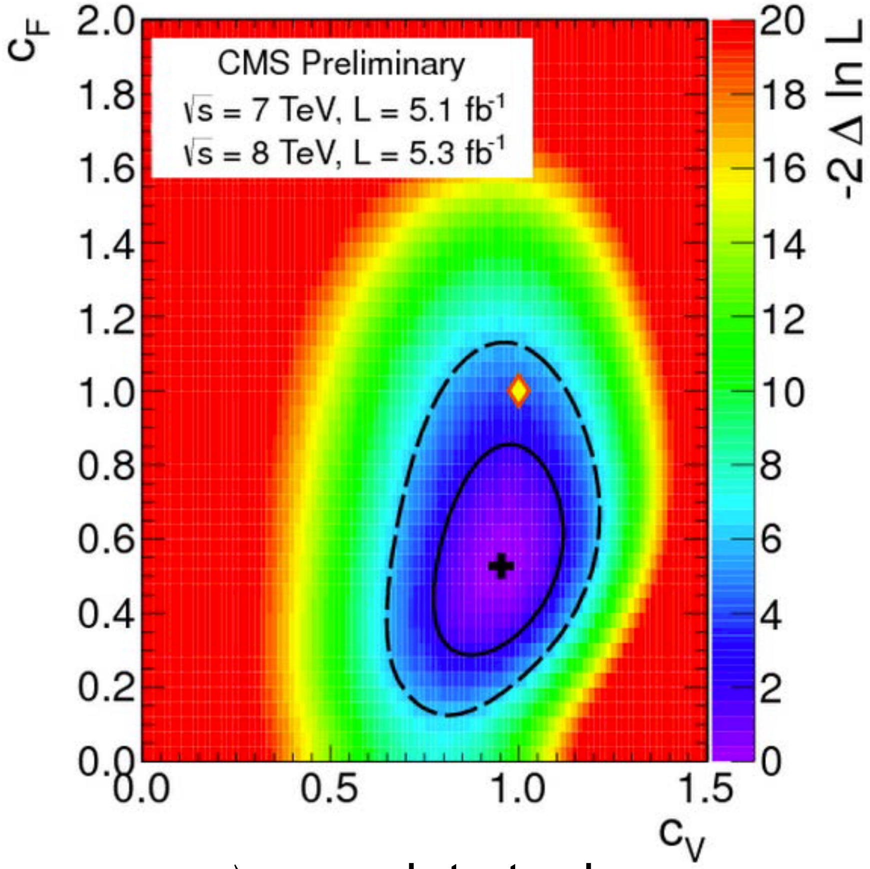


Mass & couplings

Model-independent mass measurement from high resolution channels:

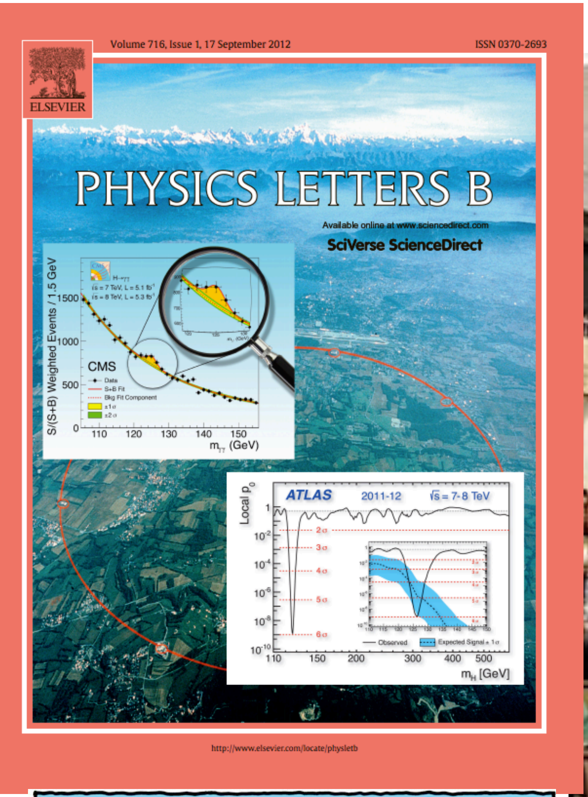
⇒ m_X=125±0.4(stat)±0.5(syst) GeV





⇒more data to draw definite conclusions

2012: A new boson discovery


Volume 716, Issue 1, 17 September 2012

ISSN 0370-2693

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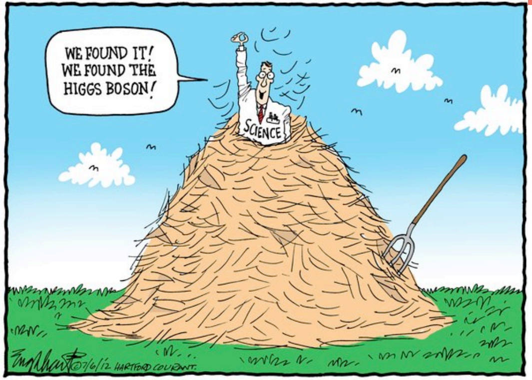
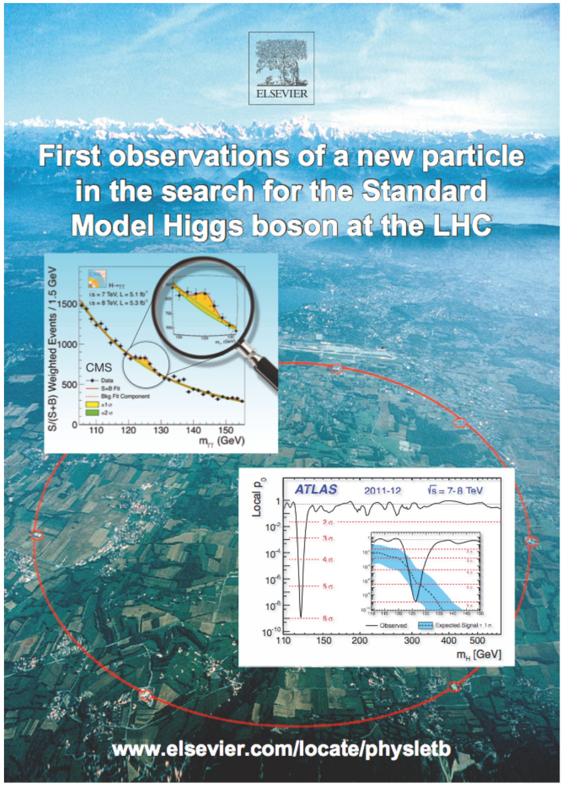
http://www.elsevier.com/locate/physletb



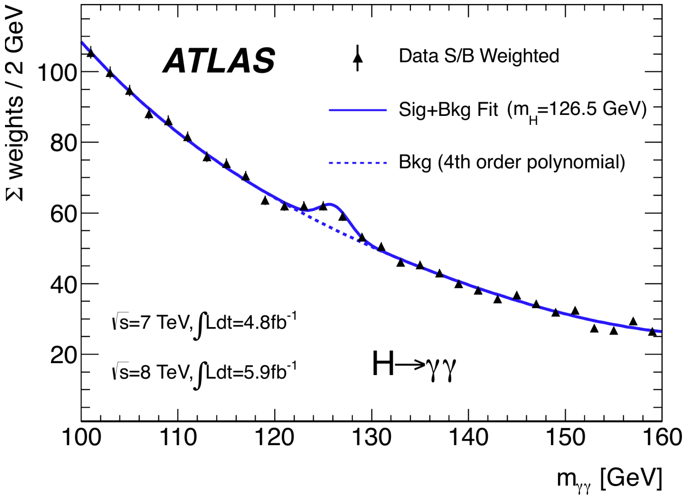
July 4th, 2012: A Higgs boson

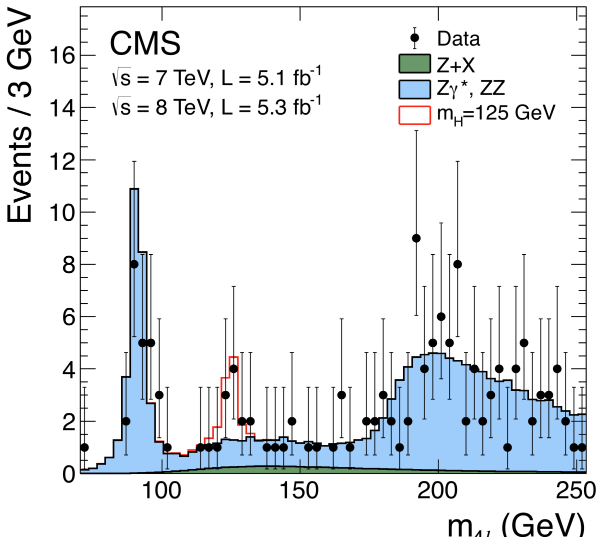


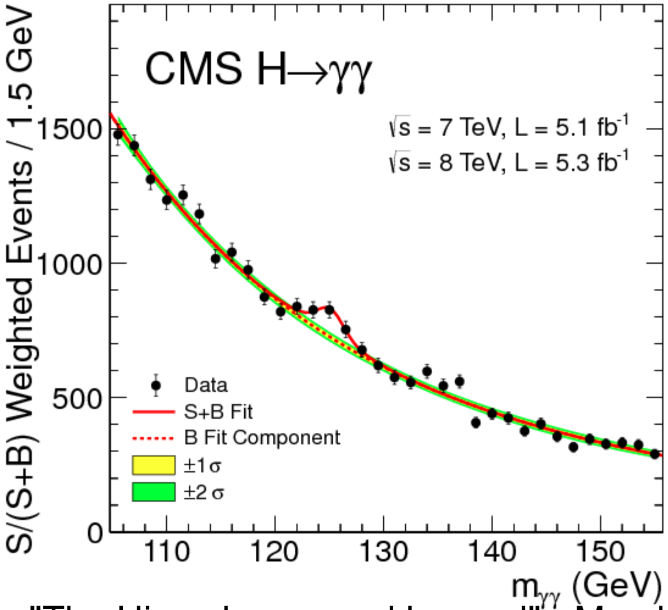
ELSEVIER

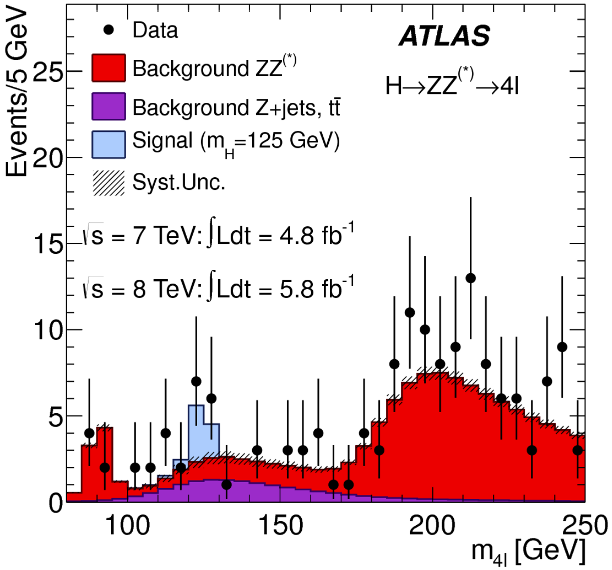
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

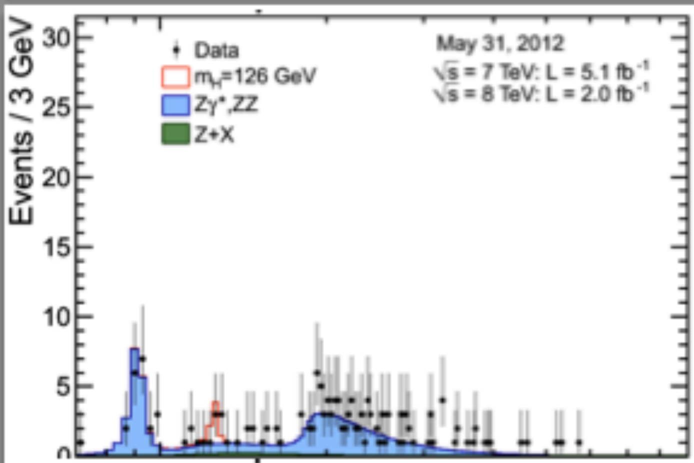
www.elsevier.com/locate/physletb

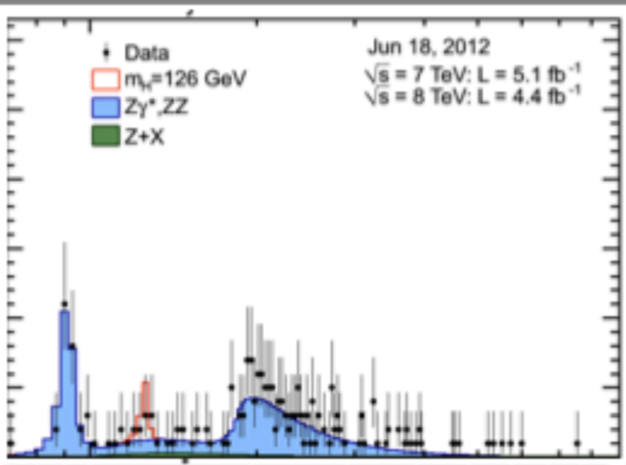


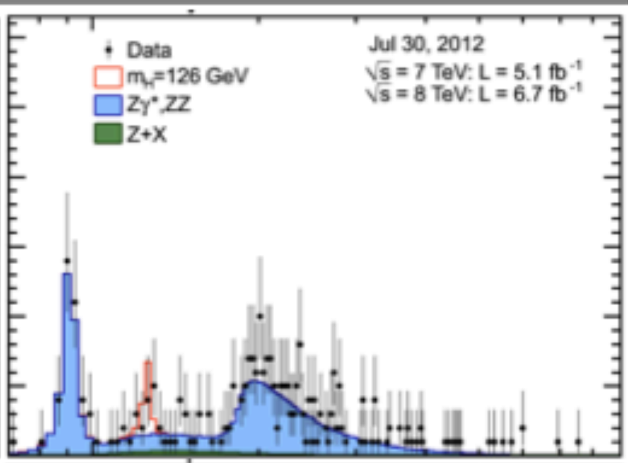


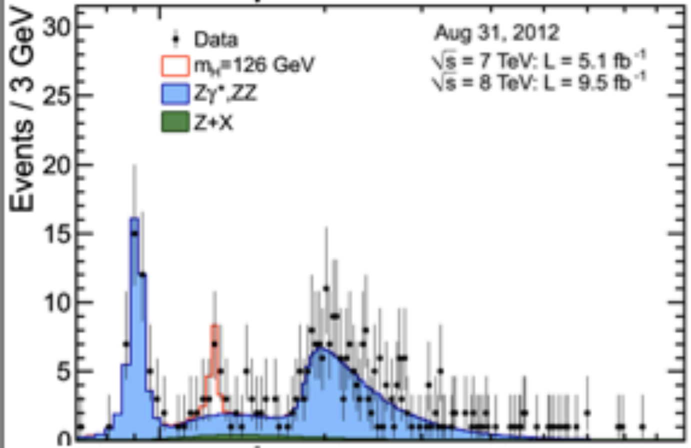


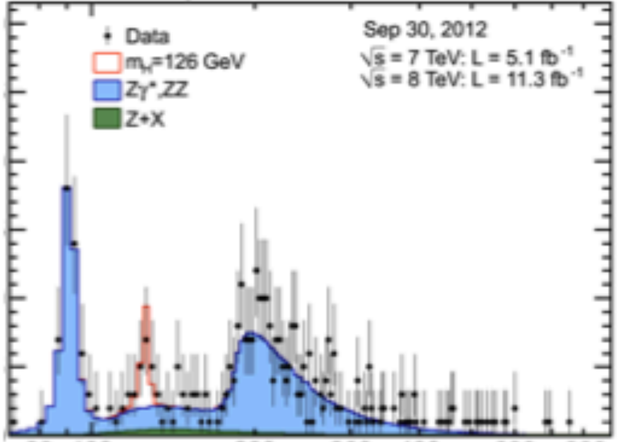


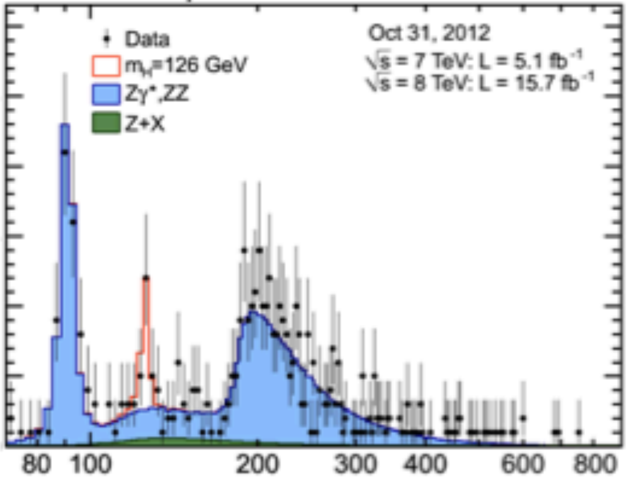

Events / 3 GeV
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
May 31, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
√s = 8 TeV: L = 2.0 fb⁻¹
0
5
10
15
20
25
30

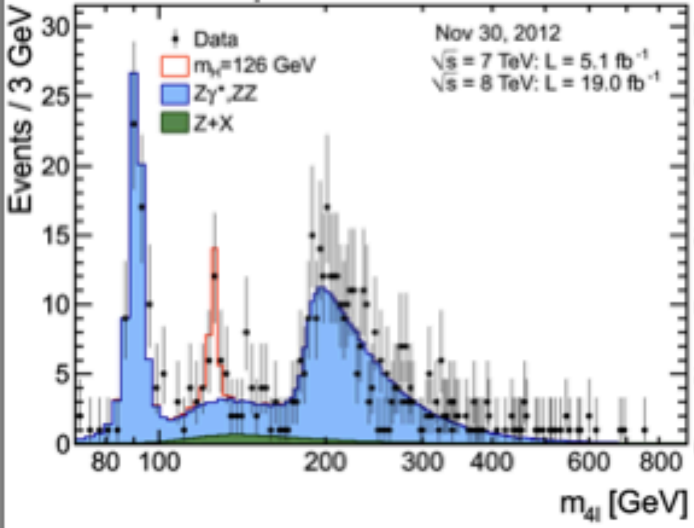

Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Jun 18, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
√s = 8 TeV: L = 4.4 fb⁻¹

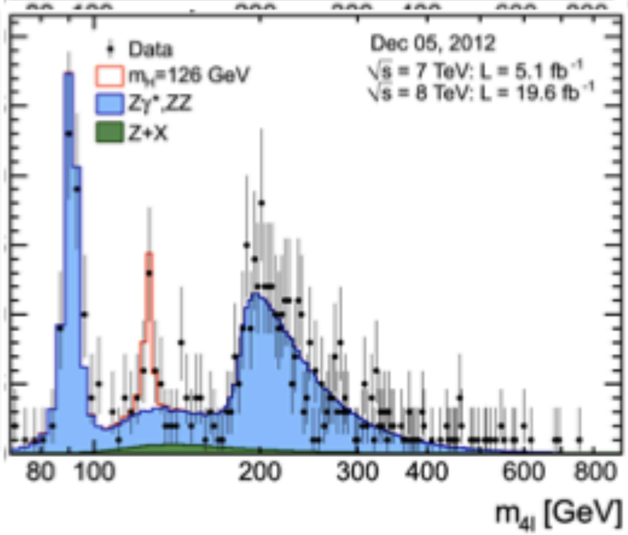

Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Jul 30, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
√s = 8 TeV: L = 6.7 fb⁻¹

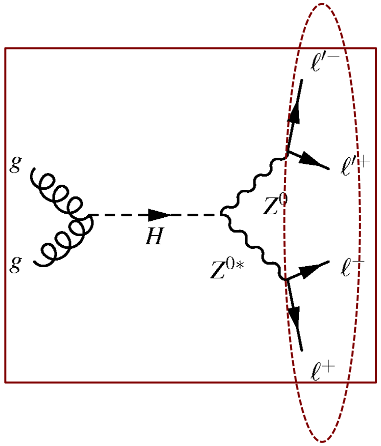

Events / 3 GeV
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Aug 31, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
√s = 8 TeV: L = 9.5 fb⁻¹
0
5
10
15
20
25
30


Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Sep 30, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
√s = 8 TeV: L = 11.3 fb⁻¹


Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Oct 31, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
√s = 8 TeV: L = 15.7 fb⁻¹
80
100
200
300
400
600
800


Events / 3 GeV
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Nov 30, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
√s = 8 TeV: L = 19.0 fb⁻¹
0
5
10
15
20
25
30
80
100
200
300
400
600
800
m_4l [GeV]

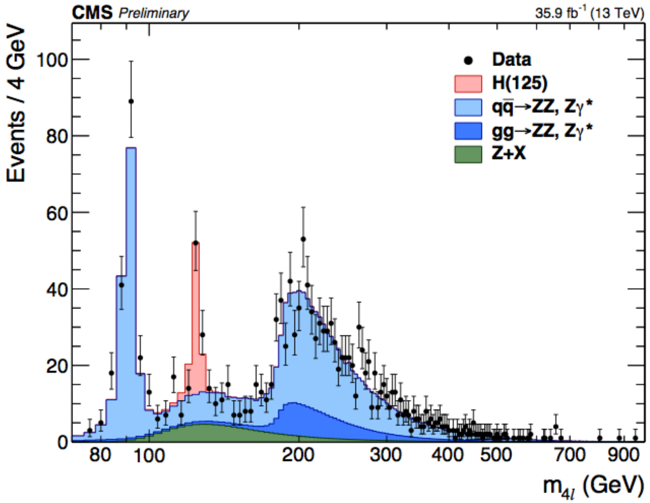

Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Dec 05, 2012
√s = 7 TeV: L = 5.1 fb⁻¹
√s = 8 TeV: L = 19.6 fb⁻¹
80
100
200
300
400
600
800
m_4l [GeV]

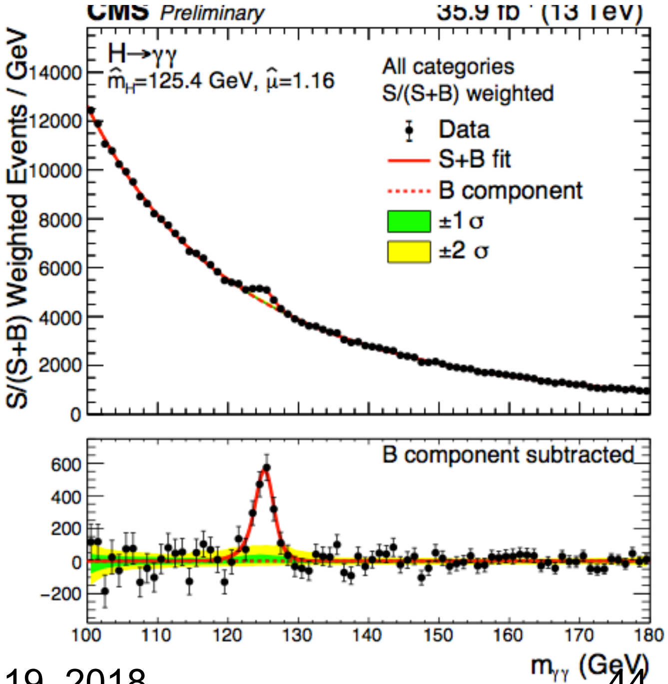

g
g
H
Z⁰
Z⁰*
ℓ′⁻
ℓ′⁺
ℓ⁻
ℓ⁺

Higgs boson

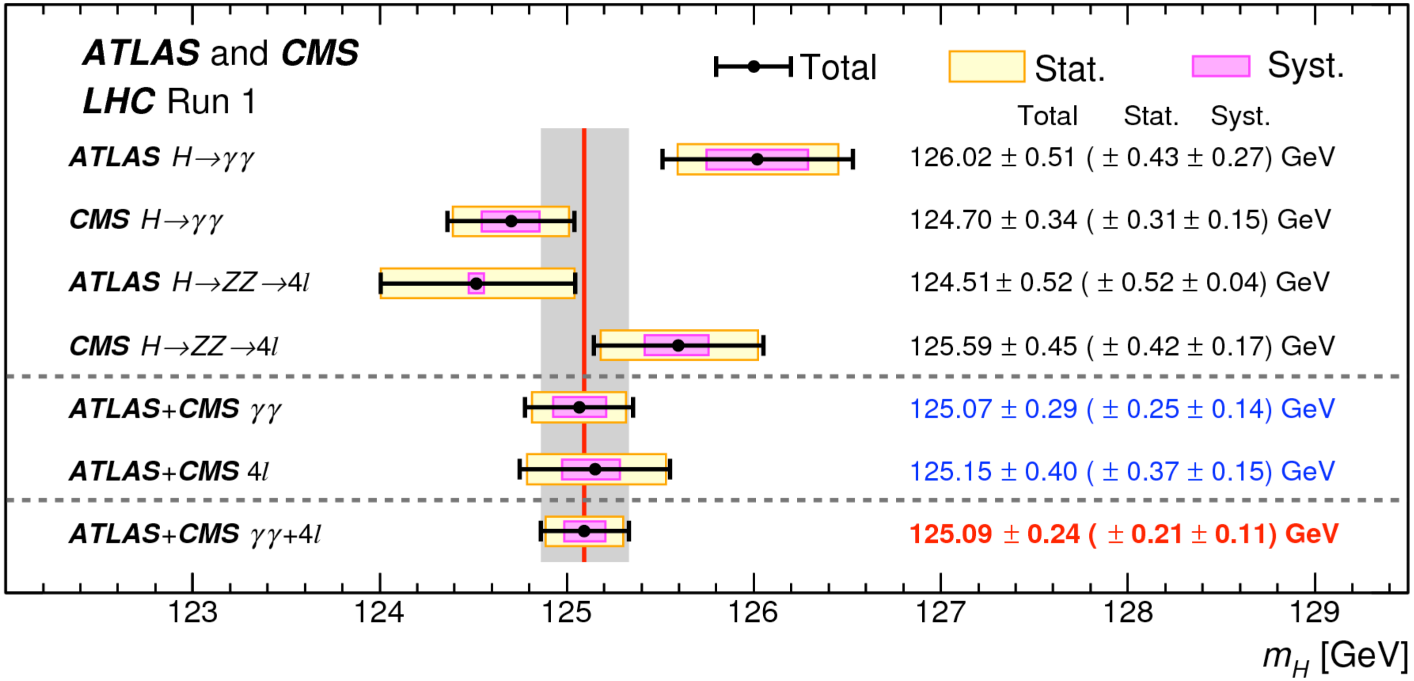
PRD 89 (2014) 092007, PLB726(2013)088, HIG-16-040, HIG-16-041

- Progress since Higgs discovery (July 2012)
  - Observation in boson channels
  - Evidence for fermion couplings
  - Precision mass measurement (~125 GeV)
  - Spin determined
- It looks more like SM Higgs boson





Mass in the individual channels

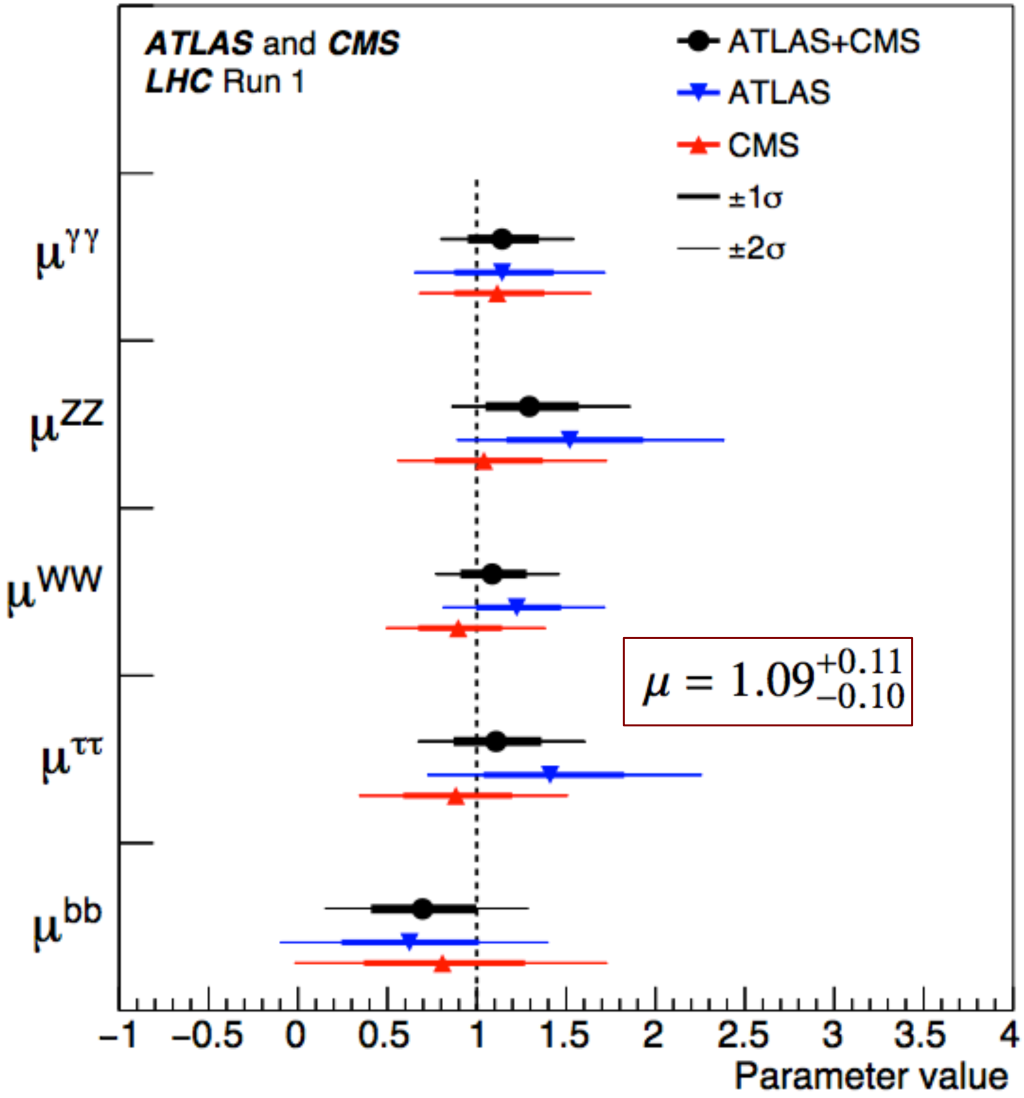


- Most accurate measurement in the $\gamma\gamma$ and 4l channels
- Some “tension” between the four measurements (p-value ~10%)

Couplings: individual channels

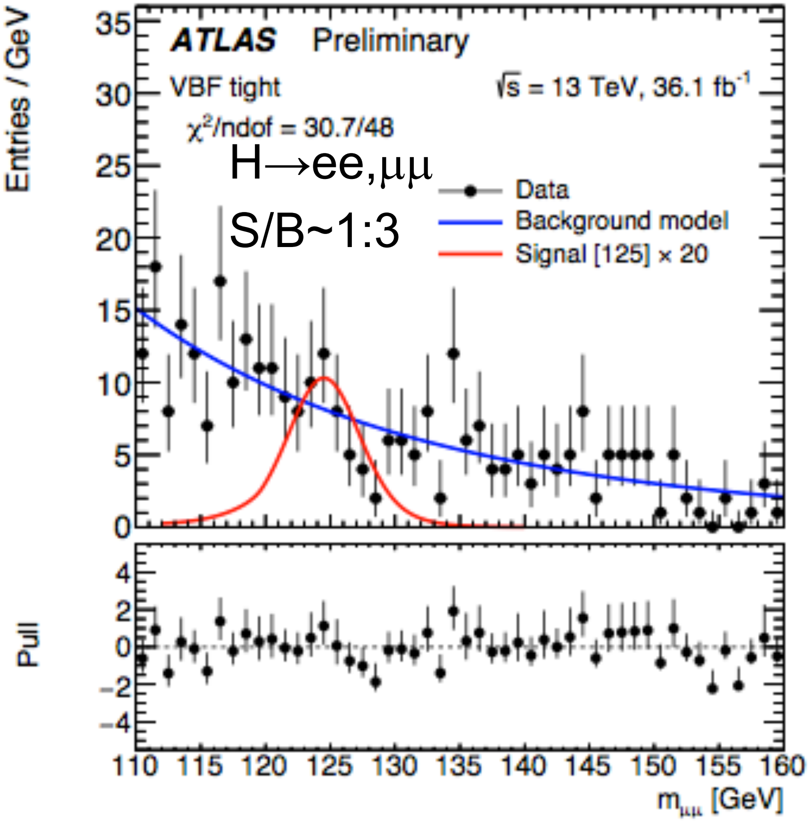
EPJC 75(2015)212, arXiv:1507.04548, arXiv:1606.02266

Results based on the full Run 1 data samples



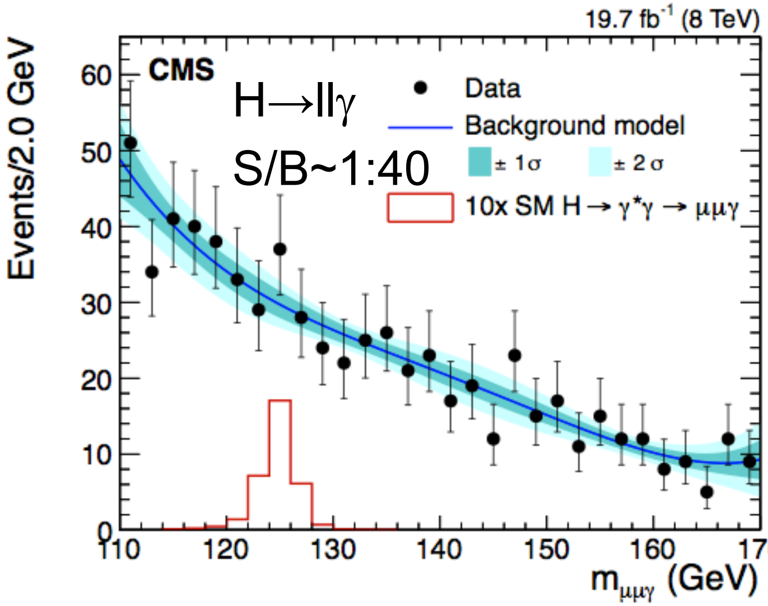
Search for rare decays

PLB 726(2013)587, arXiv:1507.03031, HIG-15-012, PRL 114(2015)121801, ATLAS-CONF-2016-041 , ATLAS-CONF-2017-014



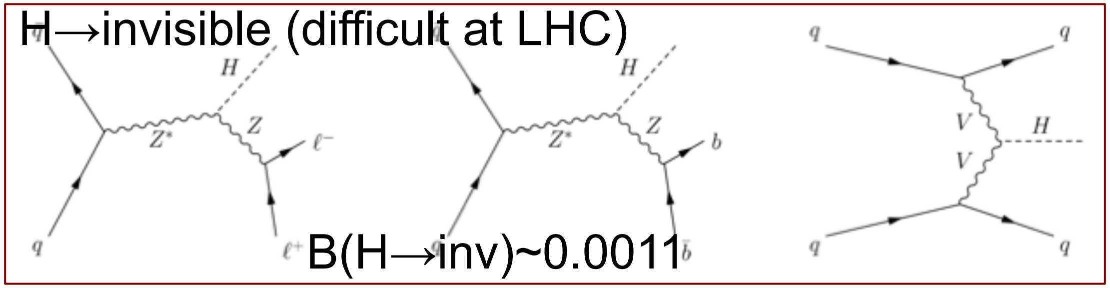
H→ee,μμ

S/B~1:3



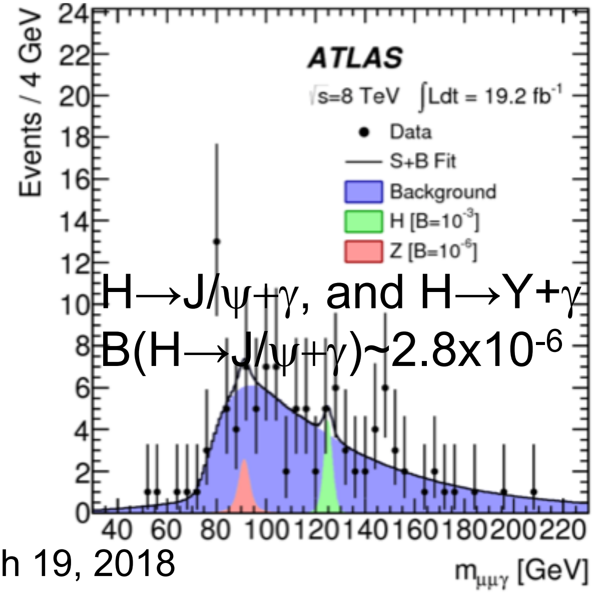
H→llγ

S/B~1:40



H→invisible (difficult at LHC)

B(H→inv)~0.0011



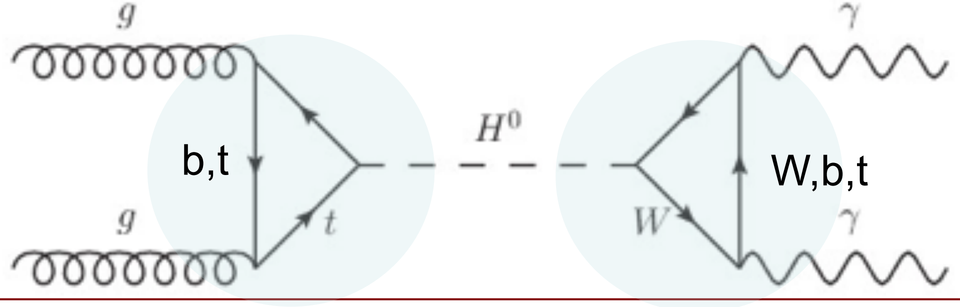
H→J/ψ+γ, and H→Y+γ

B(H→J/ψ+γ)~2.8x10^{-6}

Higgs and BSM

ATLAS-CONF-2015-044, CMS-HIG-15-002

- Is there BSM physics hidden in the “Higgs sector”?

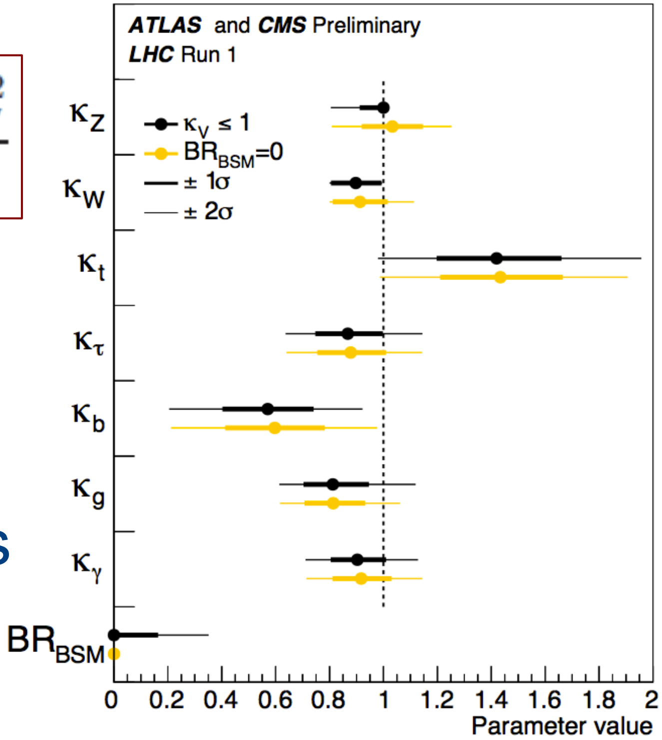


$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Experimental approach

- Measure H(125) properties
- Search for additional Higgs bosons
- Search for BSM in signatures with Higgs bosons
- Search for BSM Higgs decays

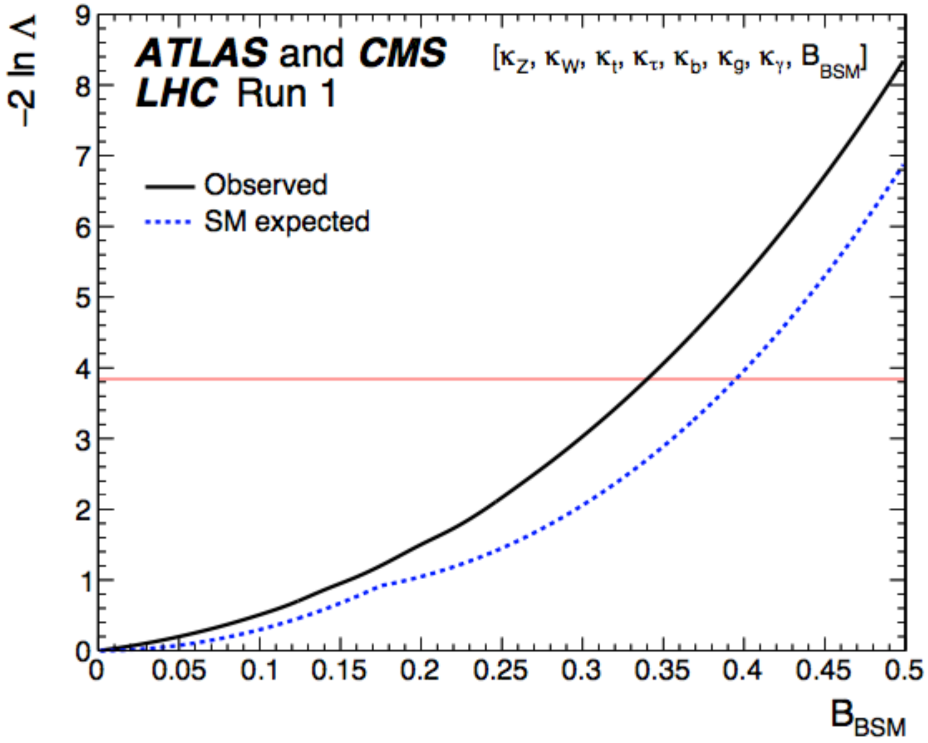
Strategy: parametrize deviations wrt SM in production and decay
⇒ loops are sensitive to BSM physics



Looking for new particles

JHEP08(2016)045

- Constrain BR_{BSM} in a scenario with free parameters
- $\Gamma_{tot}=\Gamma_{WW}+\Gamma_{ZZ}+\Gamma_{bb}+\ldots+\Gamma_{BSM}$
- Likelihood scan vs BR_{BSM}
- Assuming couplings bound by SM expectations ($k_v<1$)
- $0 \leq BR_{BSM} \leq 0.34$ at 95%CL



Constraining Higgs width

PLB 736(2014)64

obs.(exp.) @95%CL:

$\Gamma_H < 5.4 (8.0) \Gamma_H^{SM}$

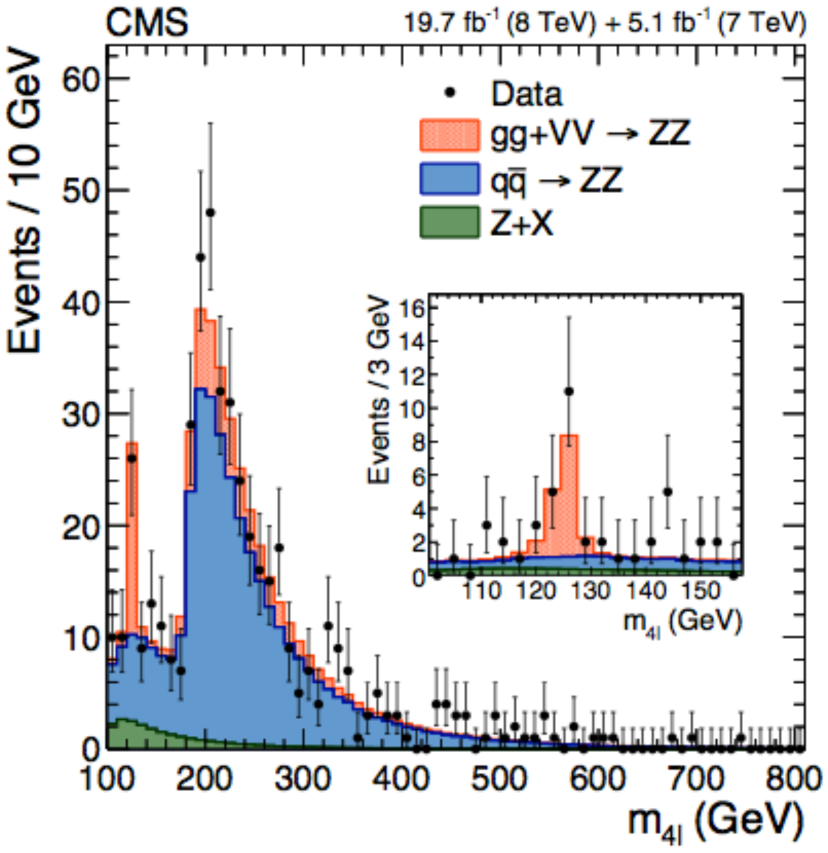
$\Gamma_H < 22 (33)$ MeV

- couplings and width sensitive probes to BSM
- indirectly constrained in coupling fits
- off-peak to on-peak ratio proportional to Γ_H
- constrain Higgs boson width by using off-shell production/decay
- measure ratio of $\sigma^{\text{off-peak}}$ to $\sigma^{\text{on-peak}}$

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

F. Caola, K. Melnikov PRD88(2013)054024
J. Campbell et al. arXiv:1311.3589

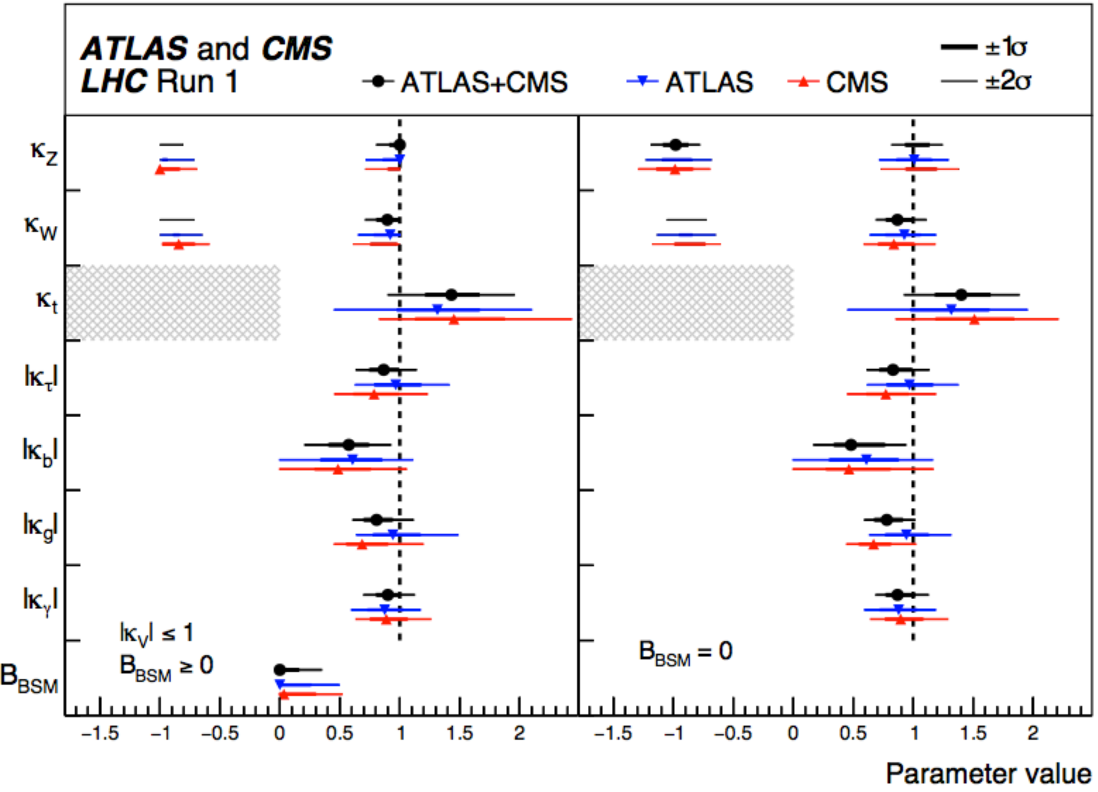
  - g_{ggH} and g_{HZZ}: couplings to gluons and bosons
- measurement of Γ_H



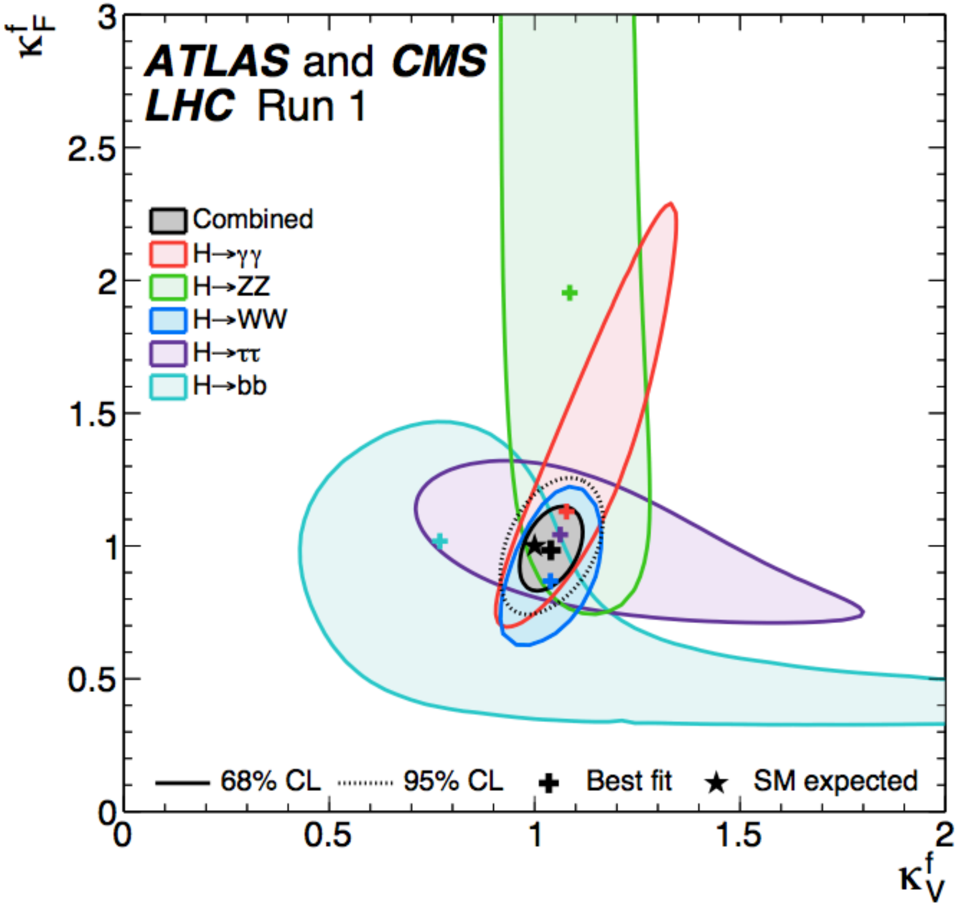
Couplings: decays

ATLAS-CONF-2015-044, CMS-HIG-15-002, JHEP08(2016)045

BSM physics in the loop



Vector and fermion couplings



BR_{BSM} can be measured

$BR_{BSM} < 0.34$ at 95% C.L. (assuming $\kappa_V \leq 1$)

BR_{BSM} includes non standard decays, visible or invisible

⇒Results in agreement with SM ($k_V = k_F = 1$) within 1σ

High mass: $H\to WW/ZZ$

JHEP 10(2015)144, HIG-16-033, HIG-16-034

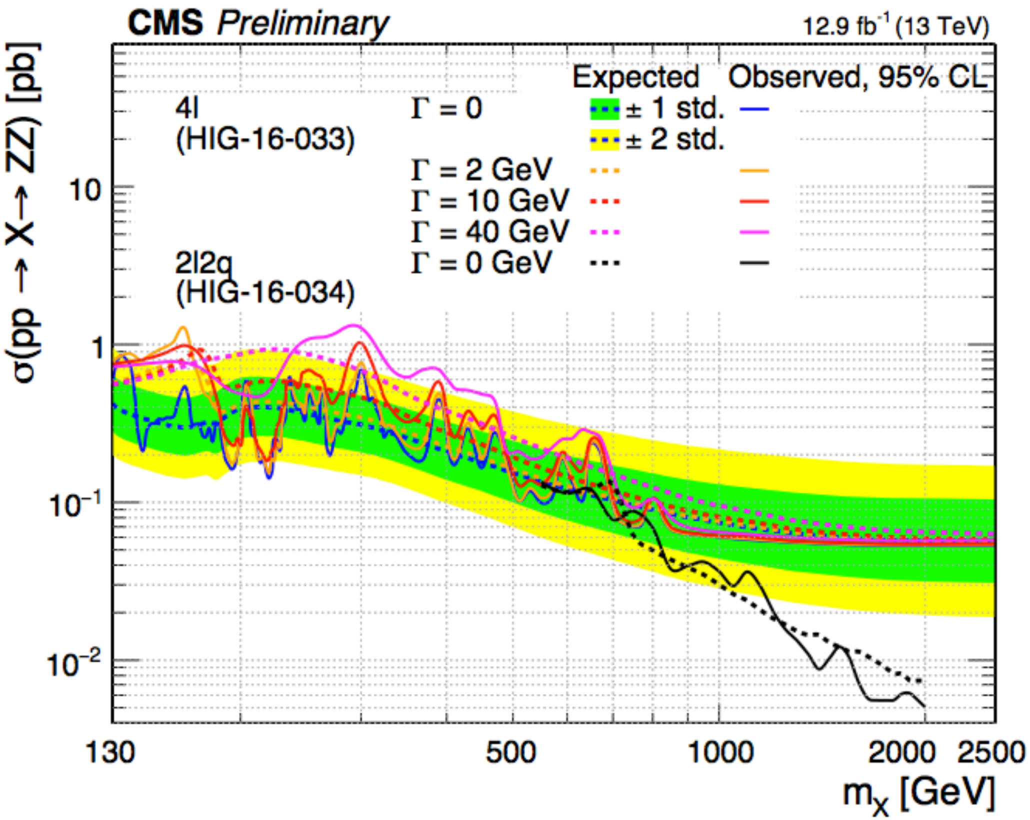
- Search for a heavy Higgs boson
  - $H\to ZZ\to 4\ell$, $2\ell 2\nu$, $2\ell qq$
  - $H\to WW\to 2\ell 2\nu$, $2\ell qq$
- optimized separately for VBF and gluon fusion production processes
- SM-like Higgs boson excluded in 4ℓ and $2\ell 2\nu/\ell\nu qq$ channels at 95%CL in mass ranges up to 1000 GeV
- Search interpreted in BSM scenario (heavy Higgs, heavy EWK singlet state)
  - evolution of signal strength of the singlet state with modified couplings/width wrt SM.
  - assume new scalar does not decay to any new particle

No significant excess

$\Rightarrow$set limits: $\sigma\cdot B(X\to ZZ\to 4\ell)$

~ a few fb@m_X=400GeV

~1fb@m_X=1TeV



high-mass searches improve at 13TeV

Extending searches

- Minimal Supersymmetric SM (MSSM)
  - Neutral Higgs: $\phi \rightarrow \tau\tau/bb/\mu\mu$
  - Charged Higgs
- Next-to-MSSM
  - Light pseudoscalar: $h \rightarrow aa$
  - Non-SM decays: $h \rightarrow 2a \rightarrow 4\tau/4\mu$
  - Heavy Higgs: $H \rightarrow h_{125}h_{125}$ or $A \rightarrow Zh_{125}$
- FCNC: $t \rightarrow cH$

Higgs sector in the MSSM

Higgs sector in SUSY contains two scalar doublets:

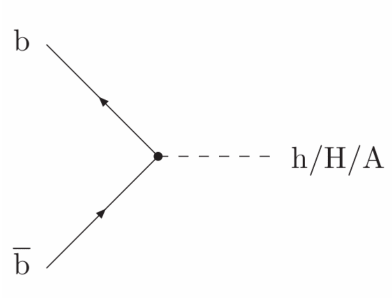
- 5 physical Higgs bosons
  - 3 neutral: CP-even ϕ=h,H CP-odd A
  - 2 charged $H^{\pm}$
- SM-like Higgs boson: h

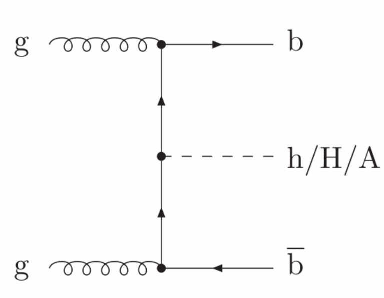
Neutral Higgs ϕ decay modes:

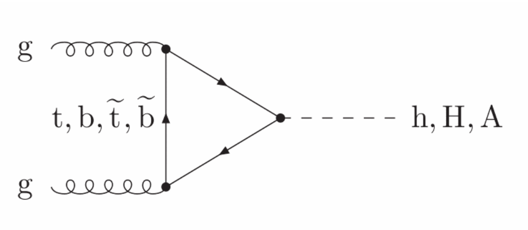
- BR($\phi \rightarrow$bbar)~90%
- BR($\phi \rightarrow \tau\tau$)~10%
- BR($\phi \rightarrow \mu\mu$)~0.1%

Two main production modes:

- gg→H
- $b\bar{b}H$

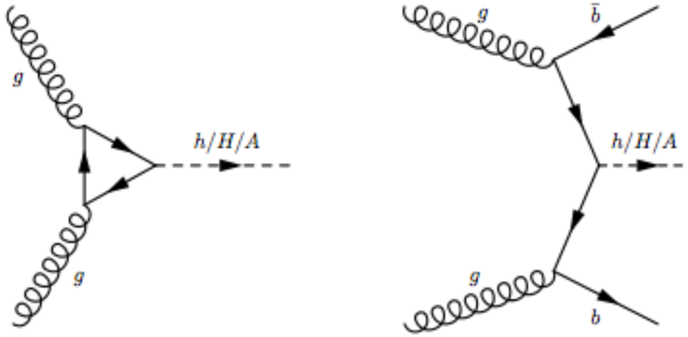






Neutral MSSM Higgs

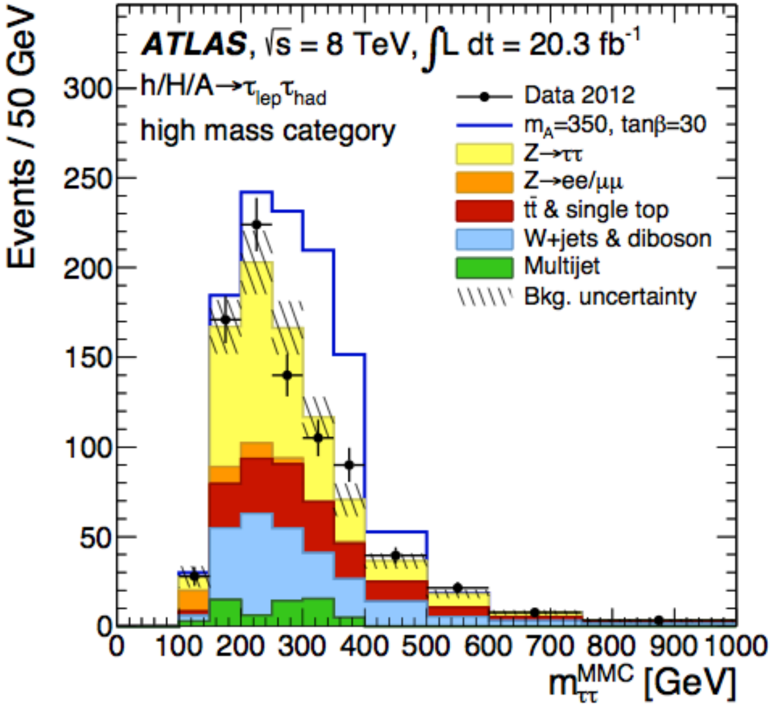
JHEP 10(2014)212, arXiv:1409.6064



- Enhanced couplings of MSSM Higgs to down-type fermions (large tanβ)

⇒increased BR to τ leptons and b-quarks

- Search for neutral MSSM Higgs boson
- 5 final states used: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$, $\mu\mu$
  - Reconstruct tau-pair invariant mass
  - Split in b-tag/no b-tag categories to enhance sensitivity
- Main backgrounds: $Z\to\tau\tau$, QCD/W+jets, DY,ttbar, dibosons

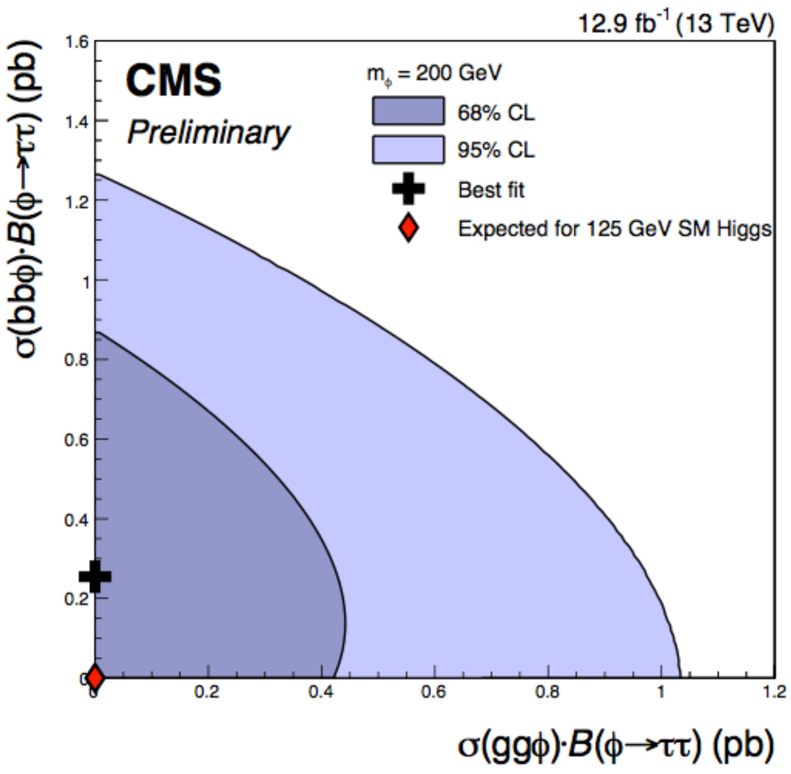


Neutral MSSM Higgs: $\phi \to \tau\tau$

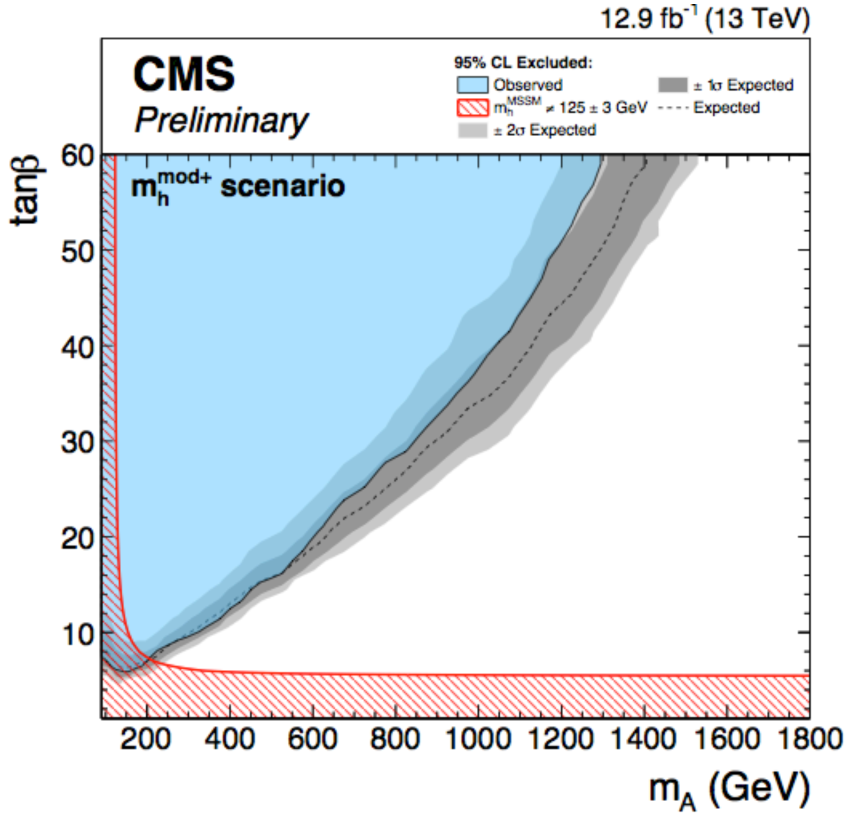
JHEP 10(2014)212, arXiv:1409.6064, CMS-HIG-16-037

- Direct search: inclusive and b-tagged
- τ in both leptonic and hadronic decays

tanβ vs m_A window becoming smaller



Model-independent limits by separating production modes

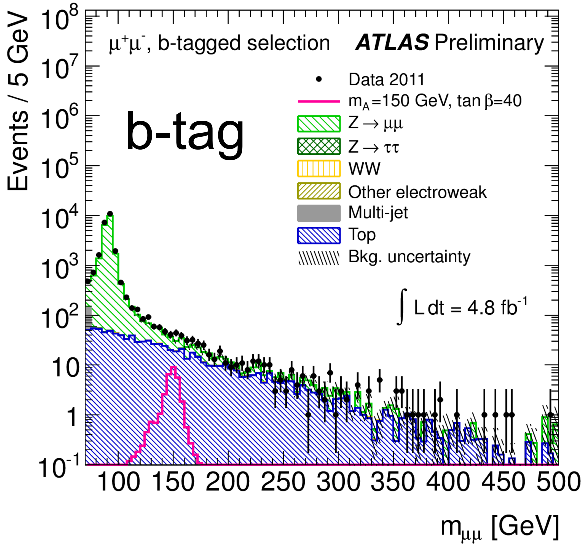


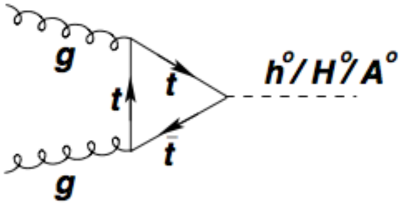
No significant excess over bkg expectations

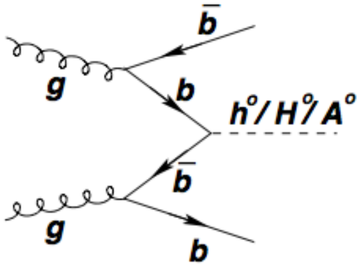
Neutral MSSM Higgs: $\phi \rightarrow \mu\mu$

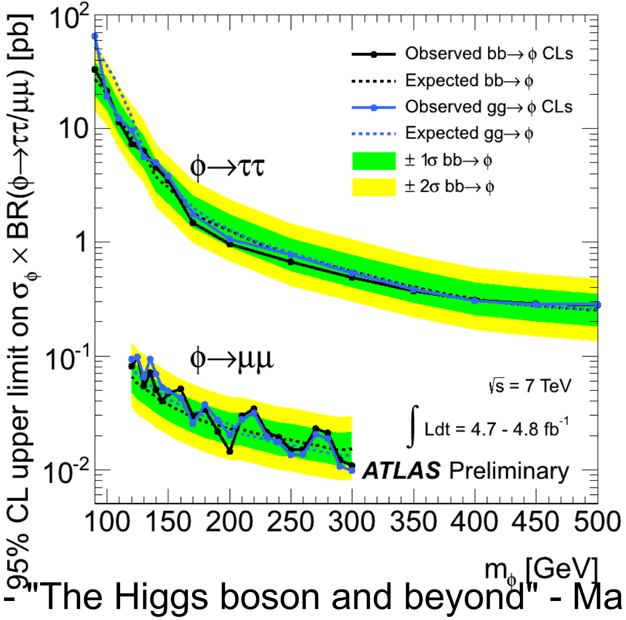
arXiv:1508.01437, ATLAS-CONF-2012-094

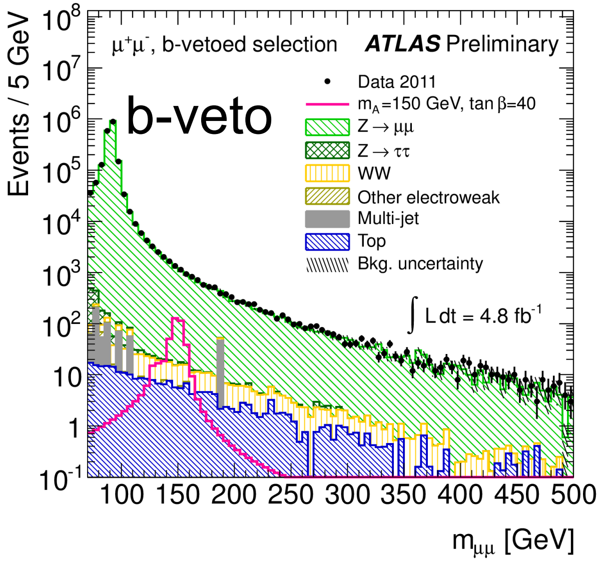
- Search for a $\mu\mu$ mass resonance
- Good mass resolution
  - full and clean reconstructed final state
- Split in b-tagged and non b-tagged categories to be sensitive to $gg \rightarrow \phi$ and $bb\phi$ production modes
- Main backgrounds: Z(bbar), ttbar, WW





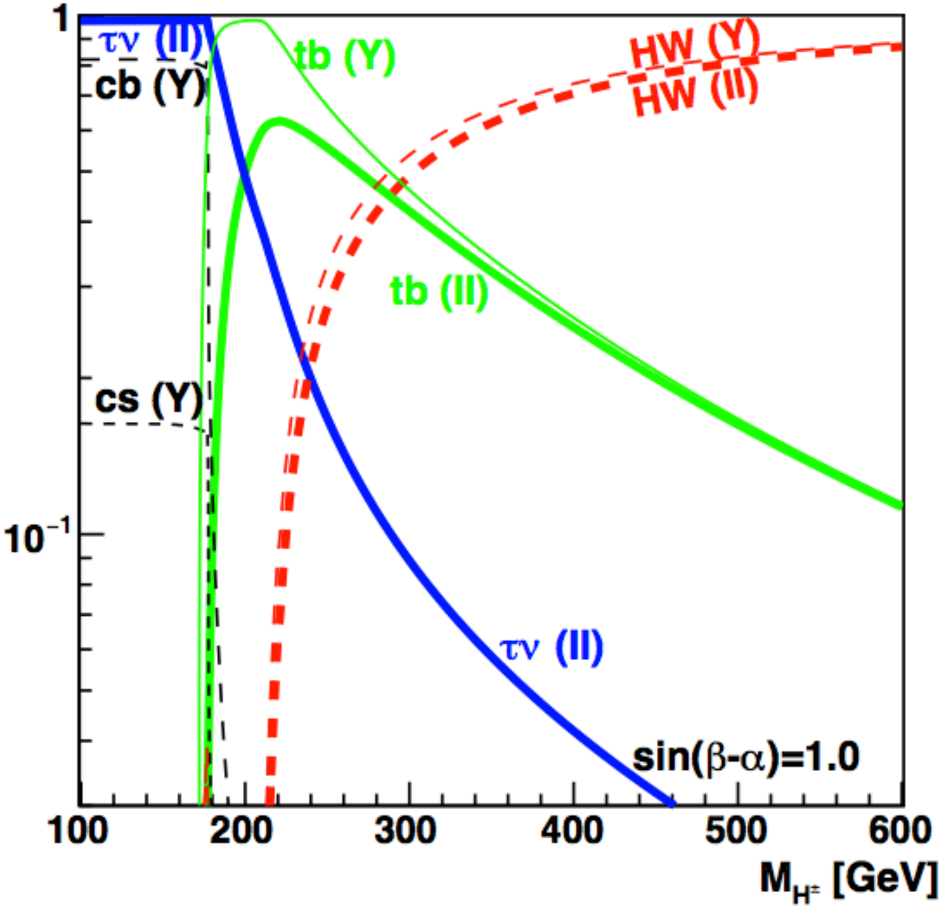






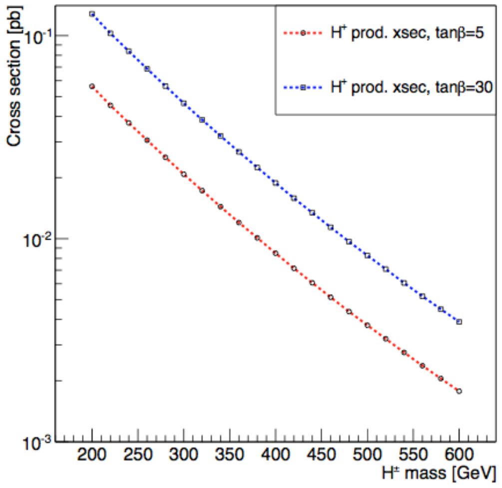
Charged Higgs

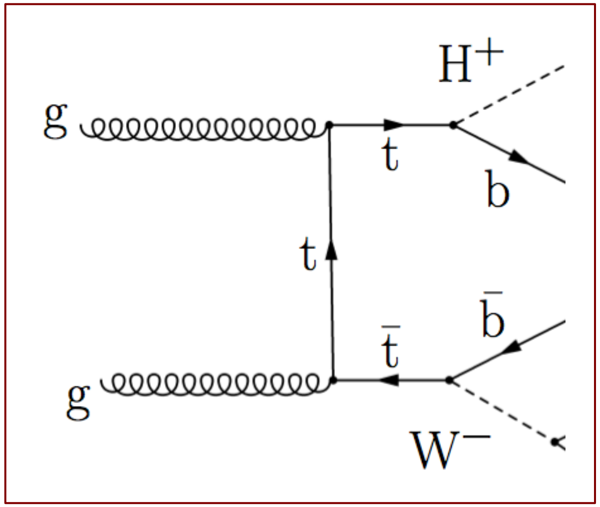
- If found, a clear indication of BSM
- Study non-SM Higgs in two mass regimes:
- $m_H < m_{top}$
  - Mostly produced in top quark decays
  - Large tanβ: $H^{\pm} \rightarrow \tau^{+}\nu$
  - Small tanβ (<1): $H^{+} \rightarrow c\bar{s}$
- $m_H > m_{top}$
  - Produced in gluon-gluon fusion
  - Main decays: $H^{+} \rightarrow tb$, $H^{+} \rightarrow \tau^{+}\nu$
- Main backgrounds: ttbar, W+jets



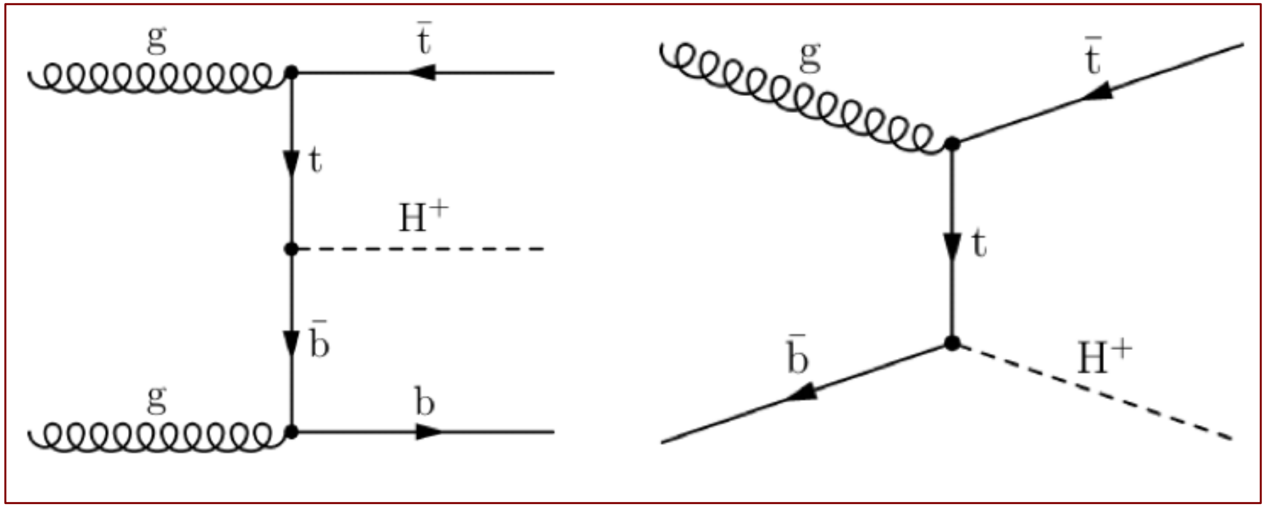
Charged Higgs (cont.)

- Different strategies for low- and high-mass searches
- tau+lepton, lep+jets, and eμ final states
- b-tagged jet categorization
- limited by statistics at high-mass





$m_H < m_{top}$

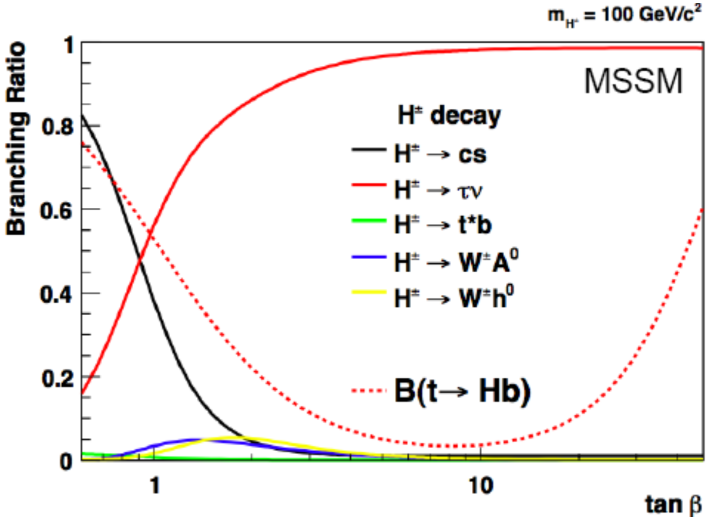


$m_H > m_{top}$

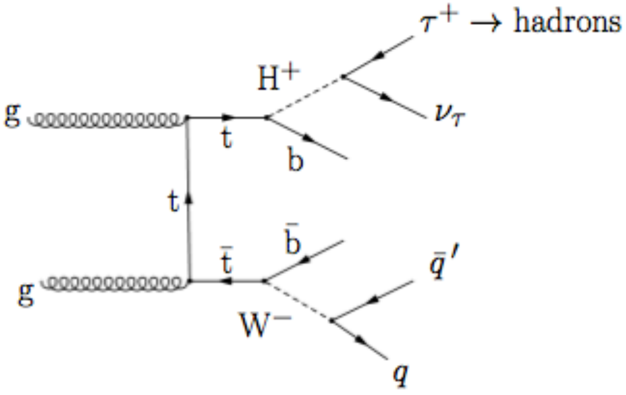
Charged Higgs and top quark decays

JHEP 07(2012)143, arXiv:1508.07774, HIG-16-031

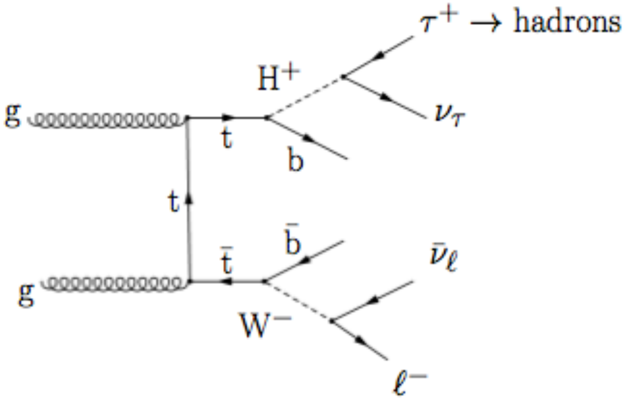
- Look for charged Higgs in four final states:
  - Tau+lepton (electron or muon)
  - Dilepton (tau decays leptonically)
  - lepton+jets
  - Fully hadronic: tau+jets



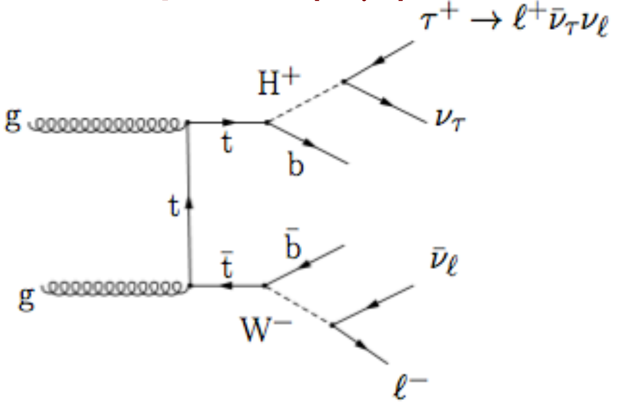
τ_h+jets



τ_h+lepton (e/μ)



di-lepton (eμ)



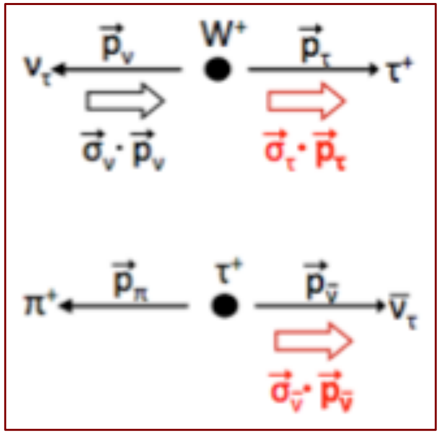
Looking at tau decays

CMS-HIG-12-052

Low H^+ mass:

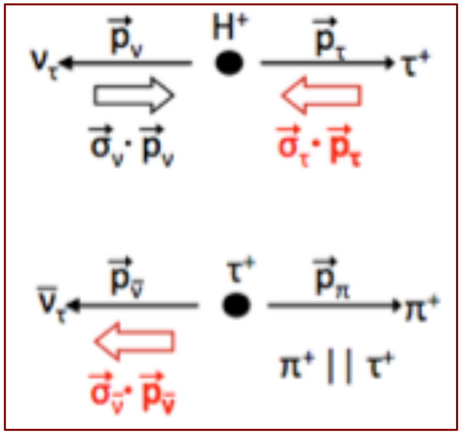
- Use R variable in the limit extraction: binned maximum-likelihood fit
- Tau fake component is data-driven, includes uncertainties

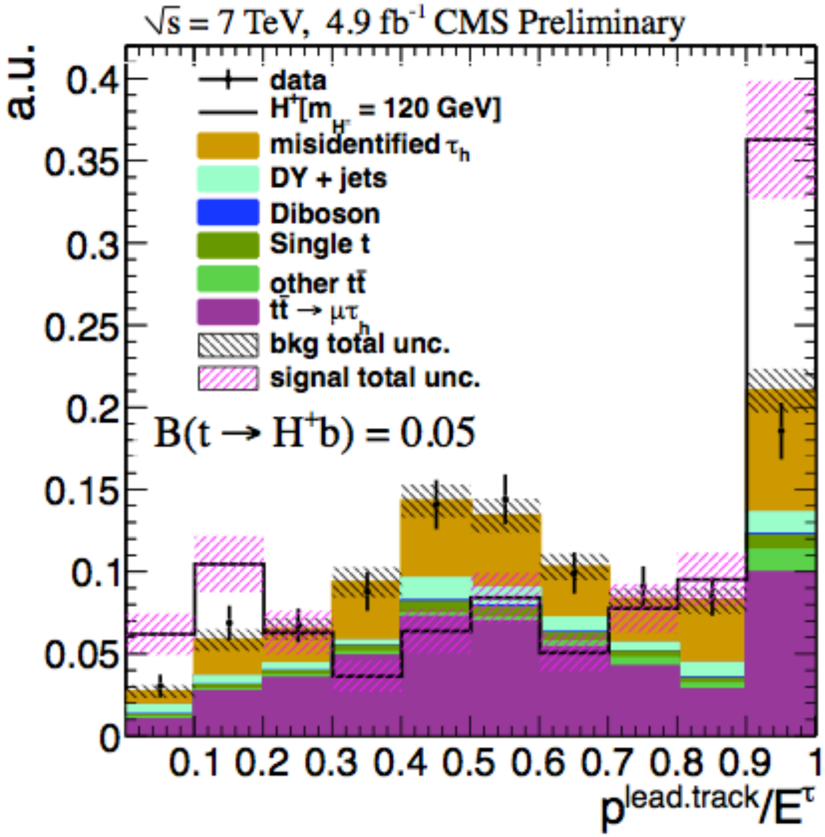
SM



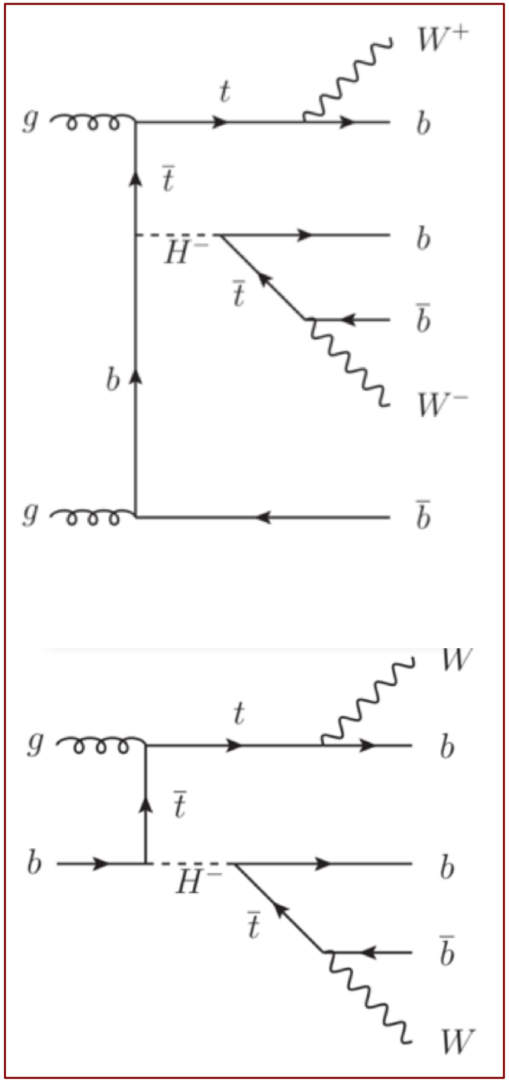
vs

BSM

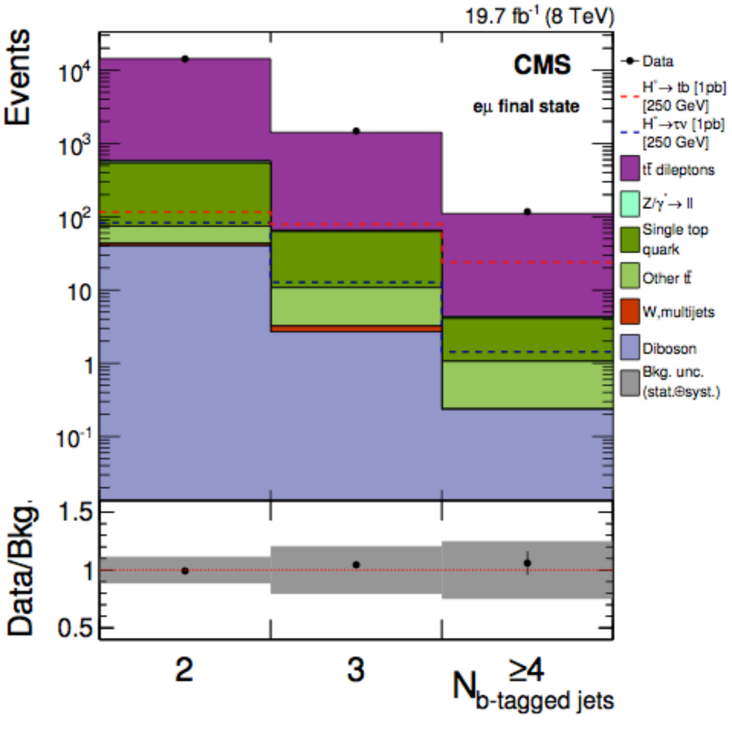


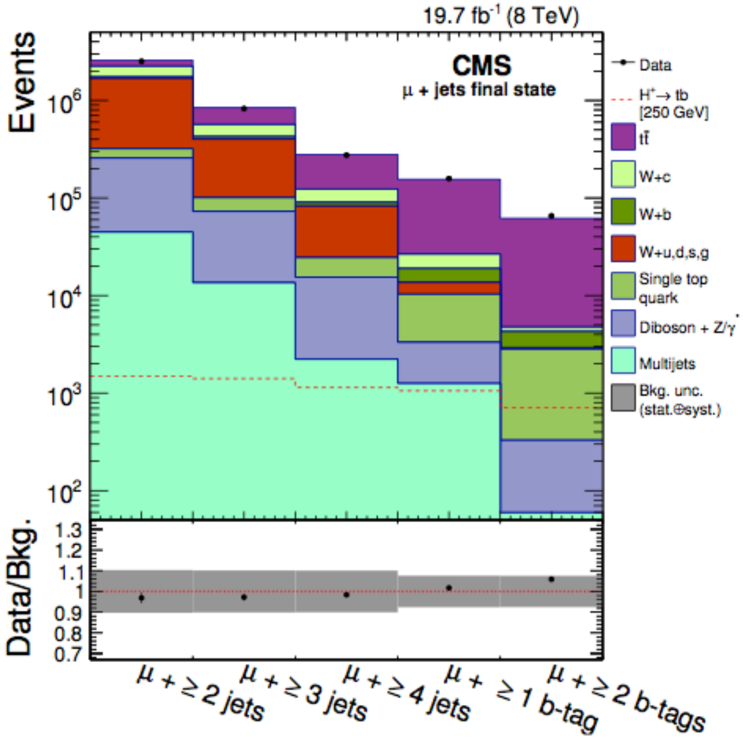


Number of b-tagged jets



High-mass H^+ search: look at b-tag multiplicity





Is there a charged Higgs?

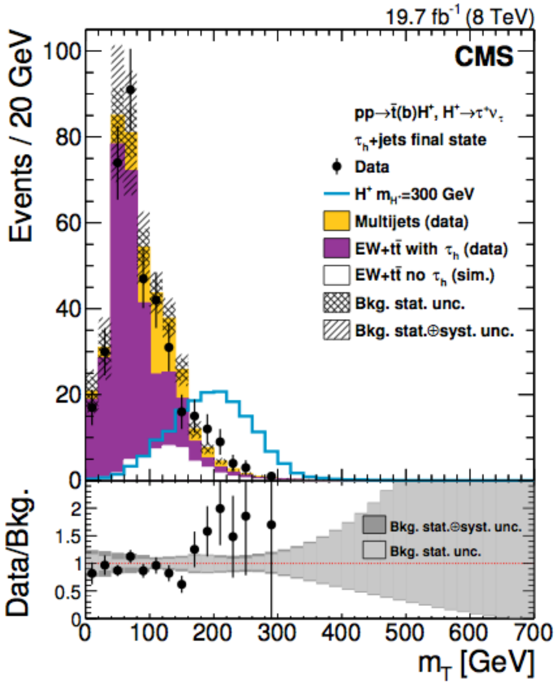
JHEP 07(2012)143, CMS-HIG-12-052, arXiv:1508.07774

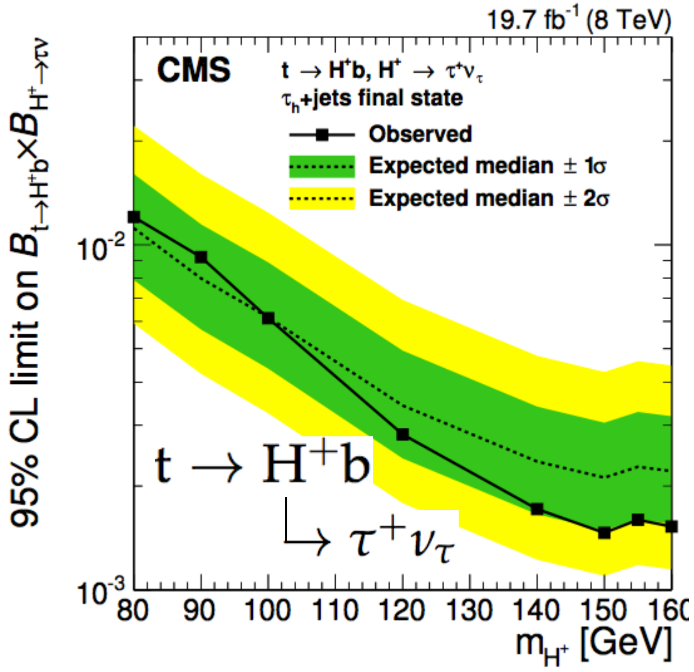
- If anomalous tau/lepton production in ttbar decays there may be contribution from H$^+$

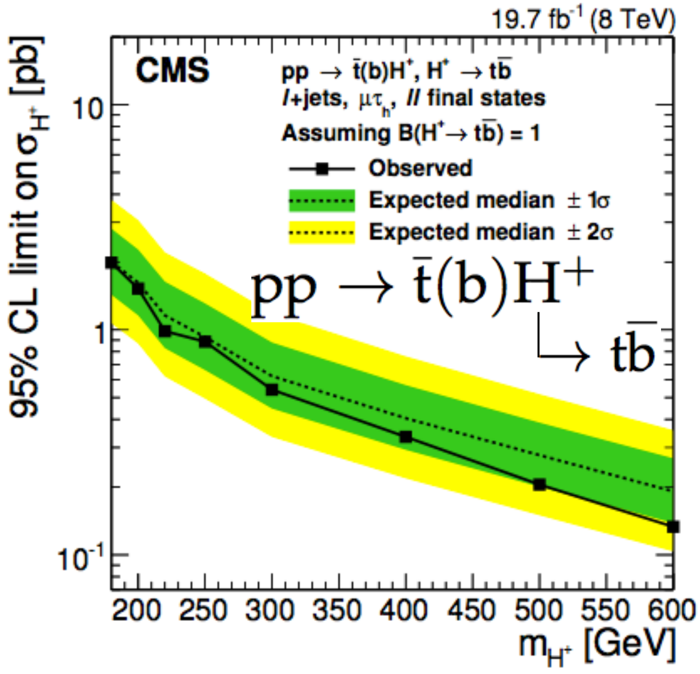
Yields in agreement with expectations ⇒ set limits

m_H: 80-160 GeV $\mathcal{B}(t \to bH^+)$< 1.2-0.3%

200-600 GeV $\sigma(pp \to \bar{t}(b)H^+)$< 2.0-0.2 pb







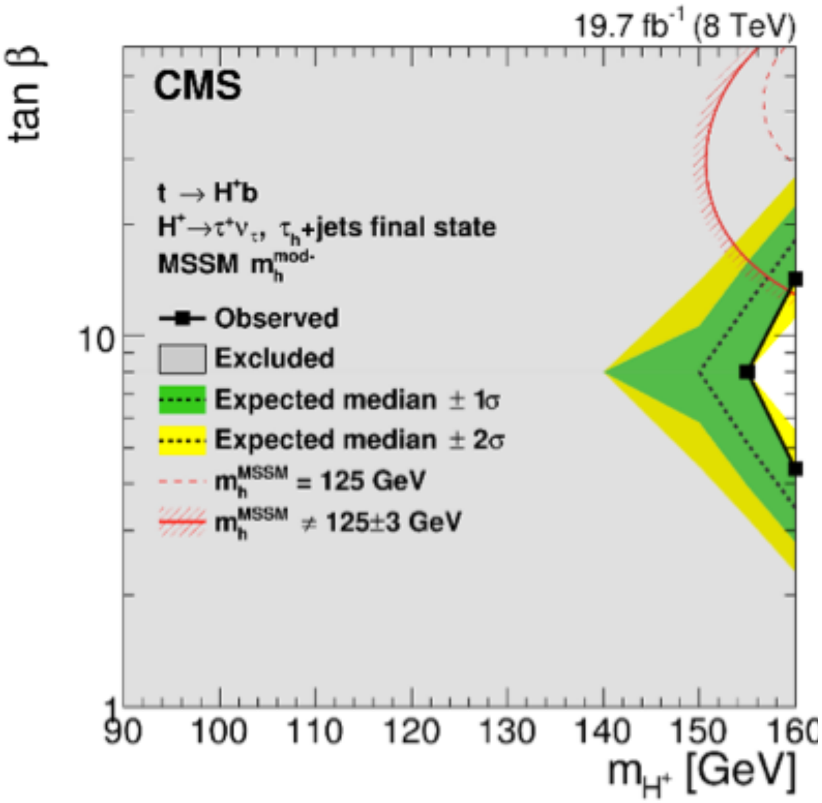
At 13TeV, expect improvement with 5-10/fb for m_{H+}>300GeV ⇒

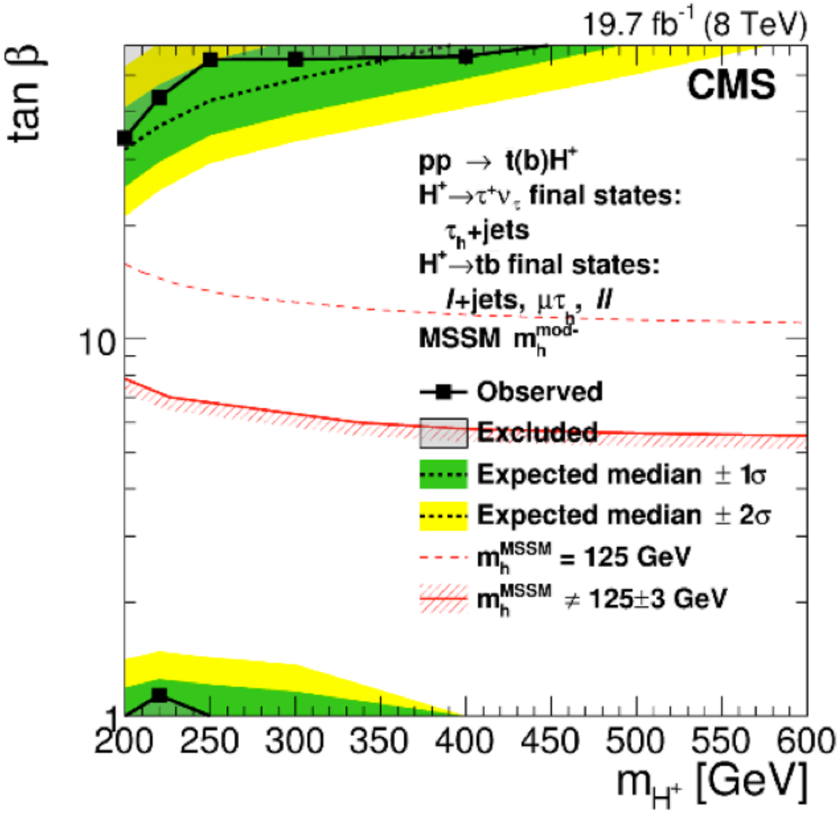
- ttbar xsection increases x3.3
- signal increases x6(x7) for m_{H+}=500(600)GeV

Still hope for MSSM?

JHEP 07(2012)143, CMS-HIG-12-052, arXiv:1508.07774

- A new modified MSSM scenario: m_h^{mod} (arXiv:1302.7033)
- Reduce amount of mixing in the stop sector (X_t/M_{SUSY})
- A/H decays to chargino/neutralinos allowed (arXiv:0709.1029)
- Allows for reduction of decays into ττ and bb





Cross section ratios

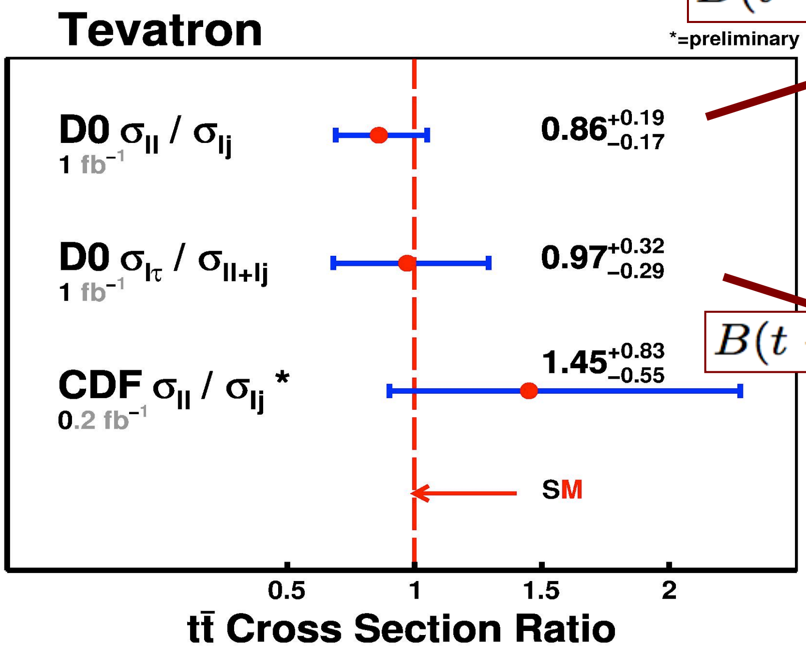
PRD 80(2009) 071102

Many systematic unc. cancel in the ratio

Study of cross section ratios

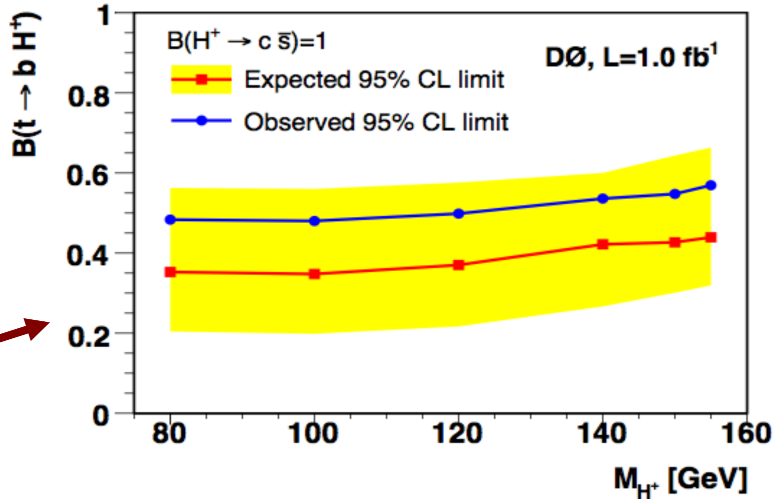
⇨sensitive to BSM

1. BR(ℓ+jets)/BR(ℓℓ)
2. BR(ℓ+tau)/BR(ℓℓ)



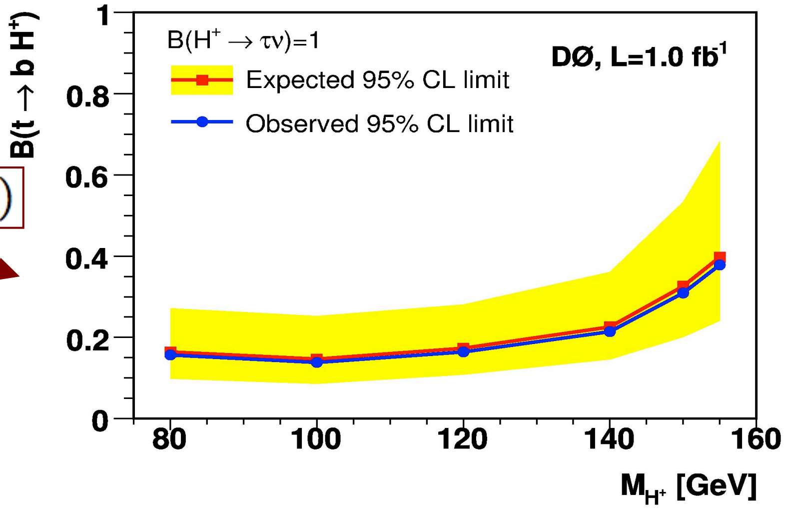
$B(t \to H^+b \to c\bar{s}b)$

lept.+jets



$B(t \to H^+b \to \tau^+\nu b)$

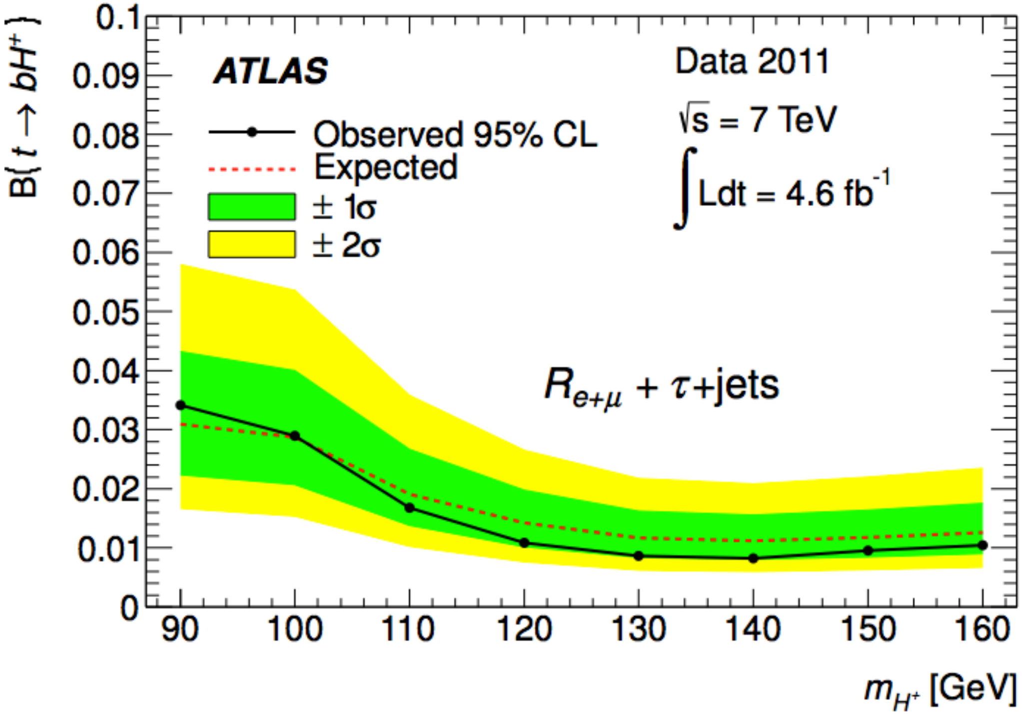
tau leptons

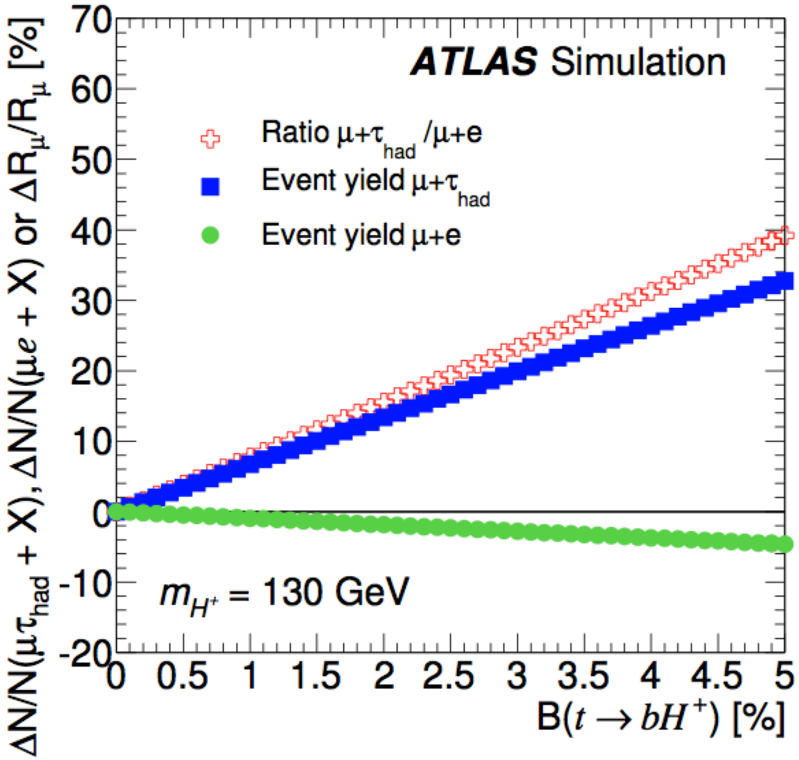


Combination of more channels

JHEP 03(2013)076

- Search for charged Higgs boson
- Use τ_{had}+lep and τ_{had}+jets final states
  - compare to eμ yields
- Search for anomalous decays





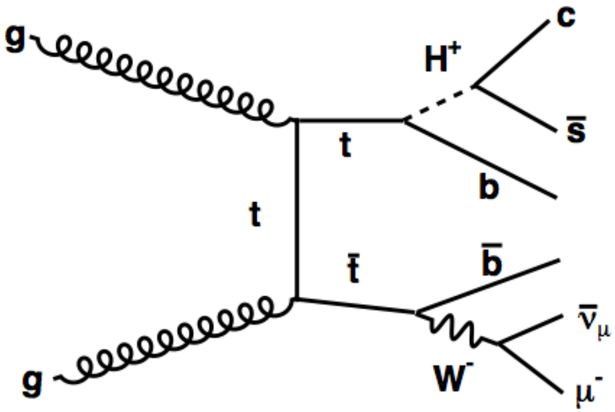
Set limits on:

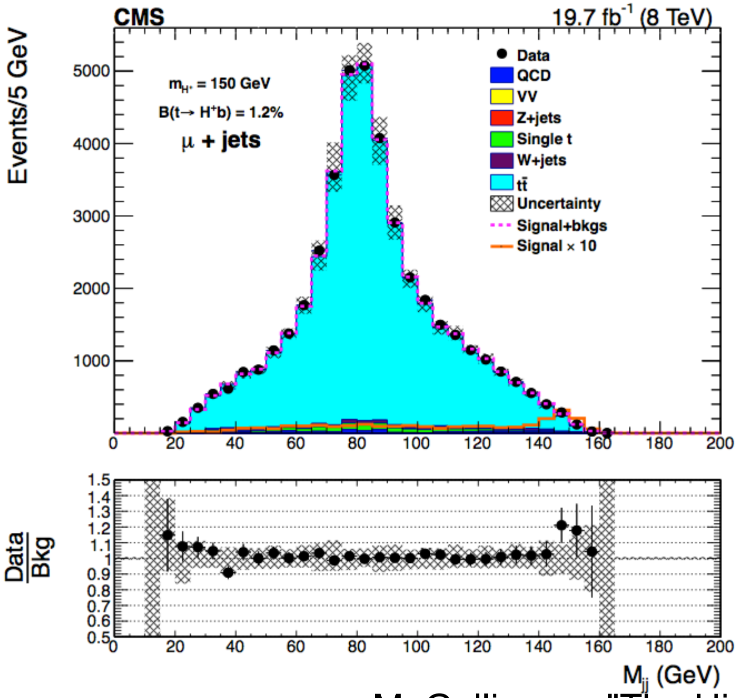
$$\boxed{\mathcal{B}(t \to bH^+)}$$

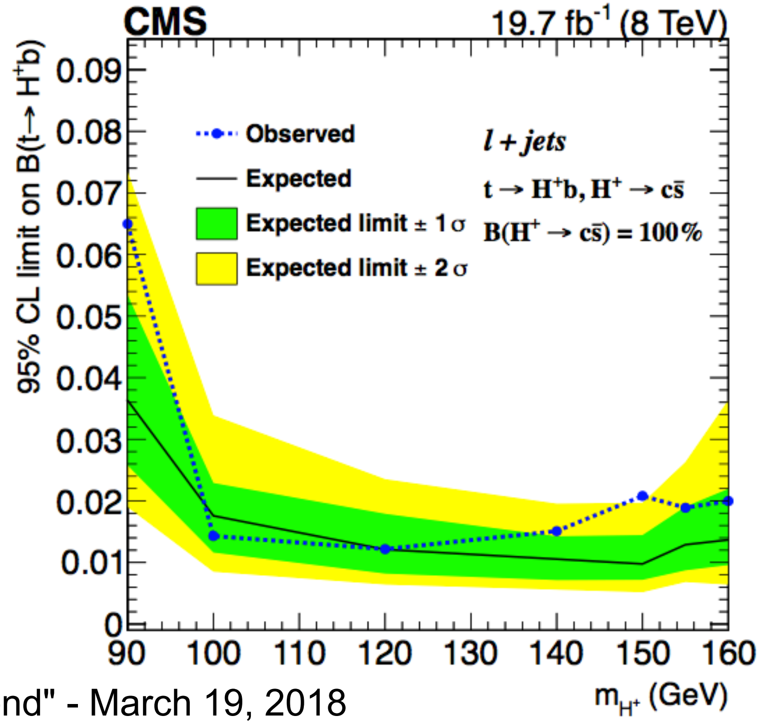
Light charged Higgs: csbar

JHEP 12(2015)1, arXiv:1510.04252

- H→csbar decay
  - – dominant in low tanβ region
- Lepton+jet final states
- Dominant bkg from ttbar
- Kinematic fit to reconstruct W/H mass
- Set model-independent limits on BR(t→H⁺b)~2-7%



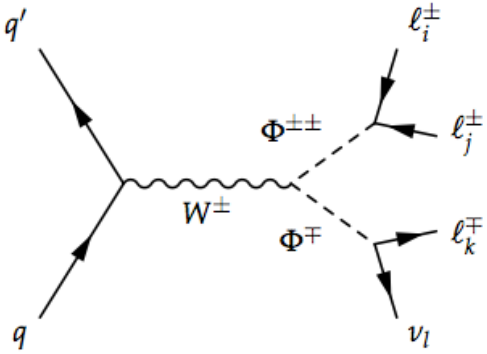


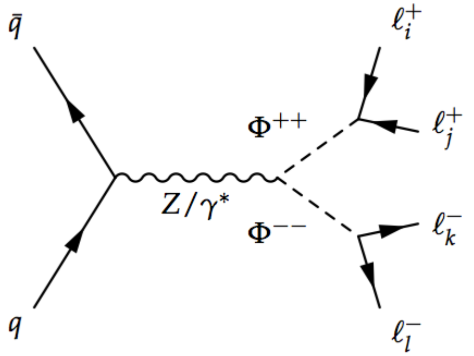


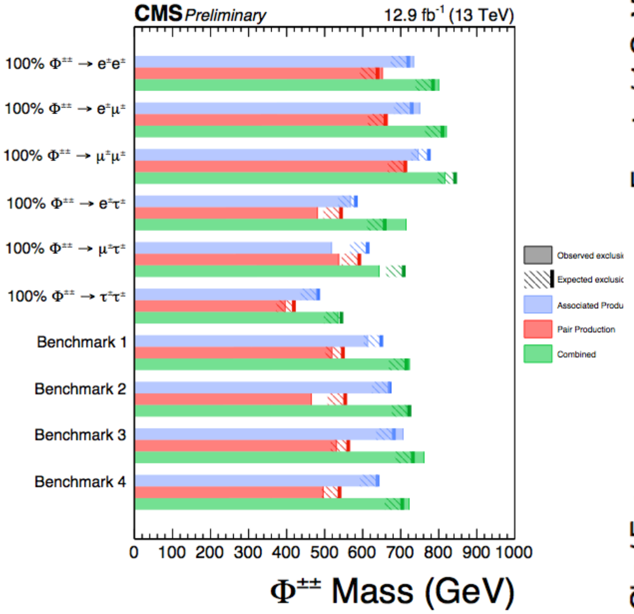
Doubly charged Higgs

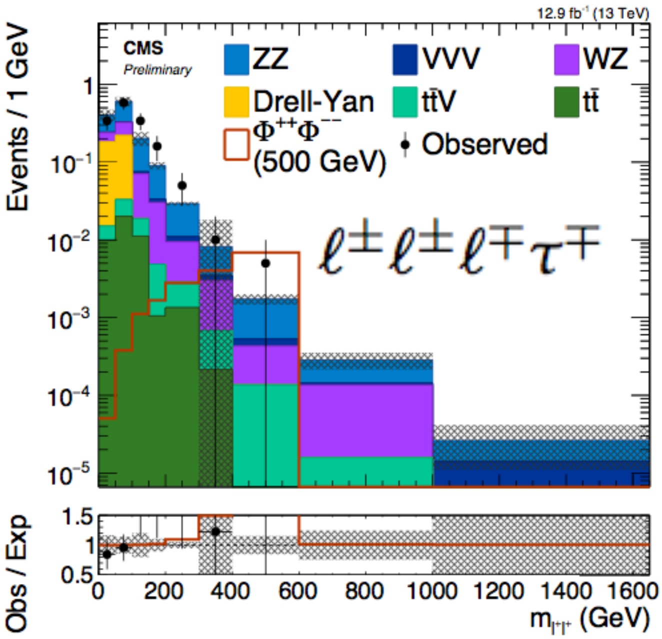
EPJC 72 (2012) 2189, CMS-HIG-14-039, HIG-16-036

- Model
  - SM extended with scalar triplet (Φ^{++}, Φ^{+}, Φ^{o})
  - Triplet responsible for neutrino masses
  - Search for doubly- and singly-charged
  - DY pair production is most common
  - SS lepton pair of any flavor combination
- Search with ≥3 leptons of any flavor
  - Search for excess of events in one or more flavor combinations of SS lepton pairs
- Dilepton invariant mass as discriminant



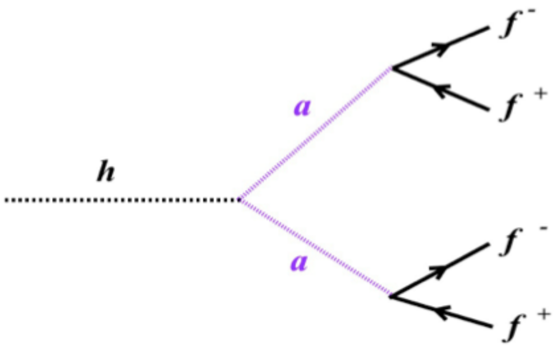


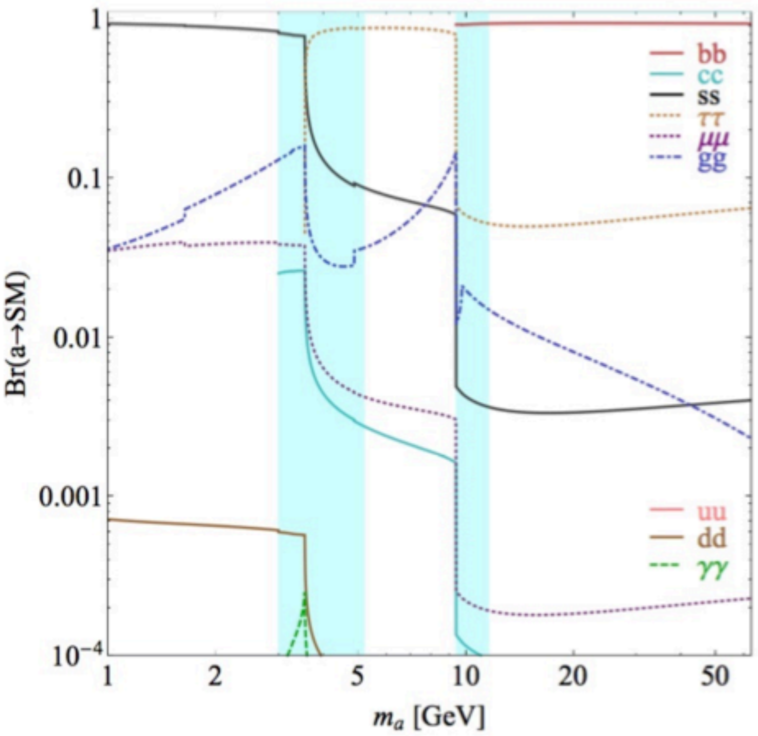




non-SM Higgs decay: h→aa→4X

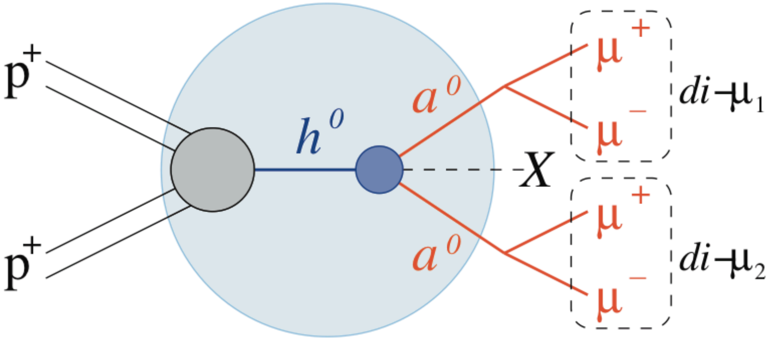
- Standard search for light (pseudo)- scalar Higgs with $m_a < m_h/2$
  - generic prediction of BSM theories (extended Higgs sector, NMSSM, etc)
  - Final states go to fermions (b, τ, μ, …)
  - BR depends on boson mass, model parameters



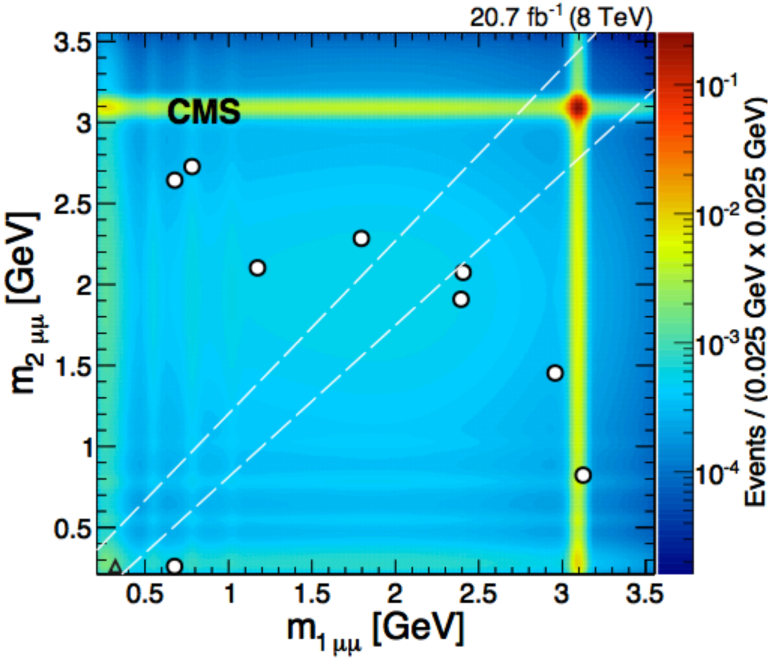


non-SM Higgs decay: h→aa→4μ

PLB 726(2013)564, arXiv:1506.00424, HIG-16-035



- Explore non-SM decays of a Higgs boson (h)
  - Higgs boson (h) can be SM or not
  - include production of two new light boson (a^0)
- Search for generic Higgs decays: h→2a+X→4μ+X
  - Require two dimuon pairs with consistent masses
  - Observe 9 events in off-diagonal region
  - Signal region: 1 event (2.2±0.7 bkg)
  - Limits on production rates, benchmark models

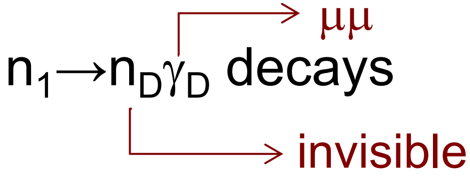


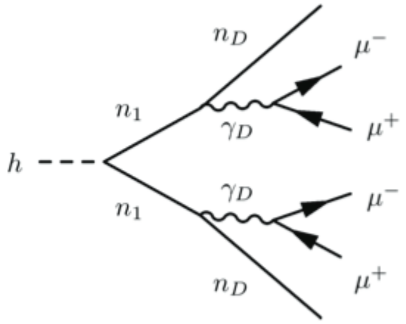
NMSSM and Dark SUSY Limits

PLB 726(2013)564, arXiv:1506.00424

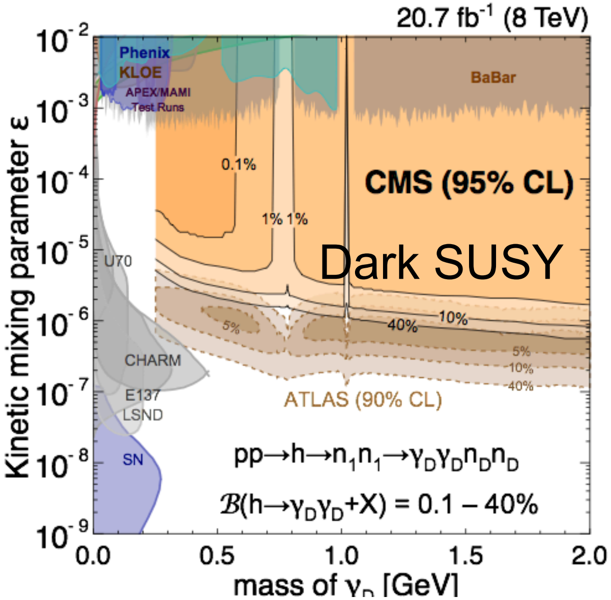
Results interpreted in NMSSM and dark SUSY

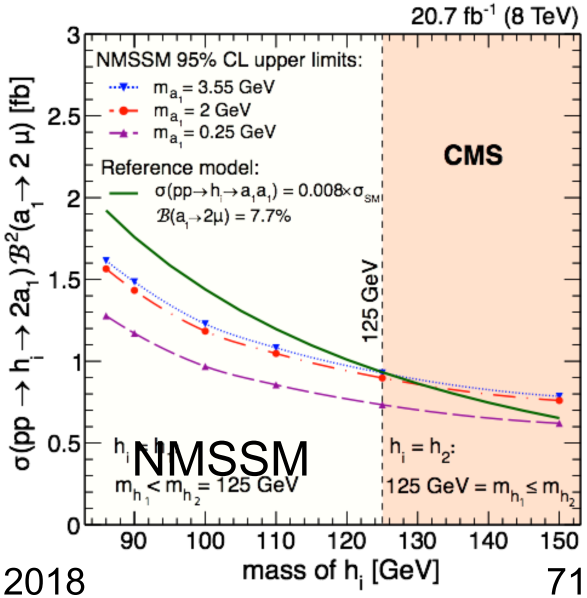
- Dark SUSY: h decay to pair of neutralinos (n_1): LSP


$n_1 \to n_D \gamma_D$ decays



- NMSSM: Extend MSSM by adding a complex singlet field (1 CP-even+1 CP-odd boson)
- NMSSM: $h_{1,2} \to 2a_1$; $a_1 \to 2\mu$
- Compare to SM Higgs cross section

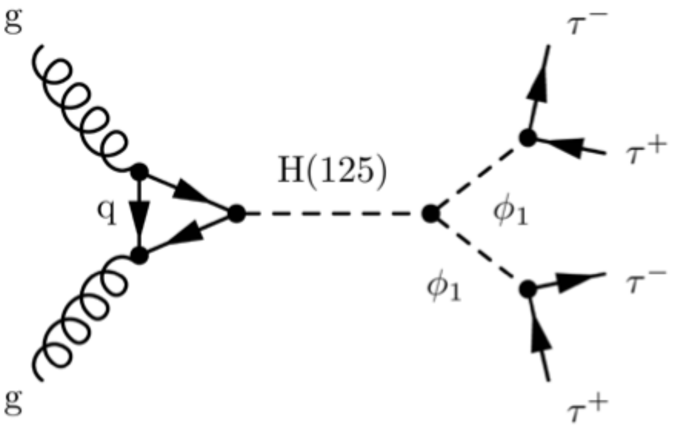

Dark SUSY

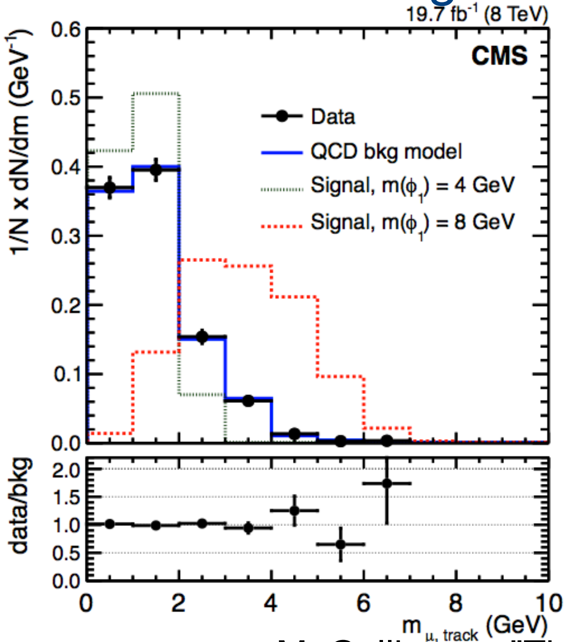

NMSSM

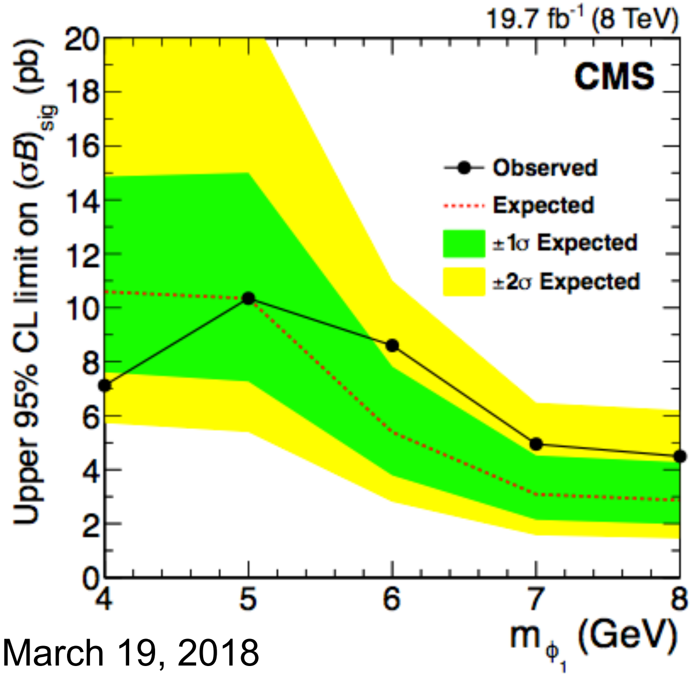
non-SM Higgs decay: $H_{125}\rightarrow 2h(a)\rightarrow 4\tau$

JHEP01(2016)079

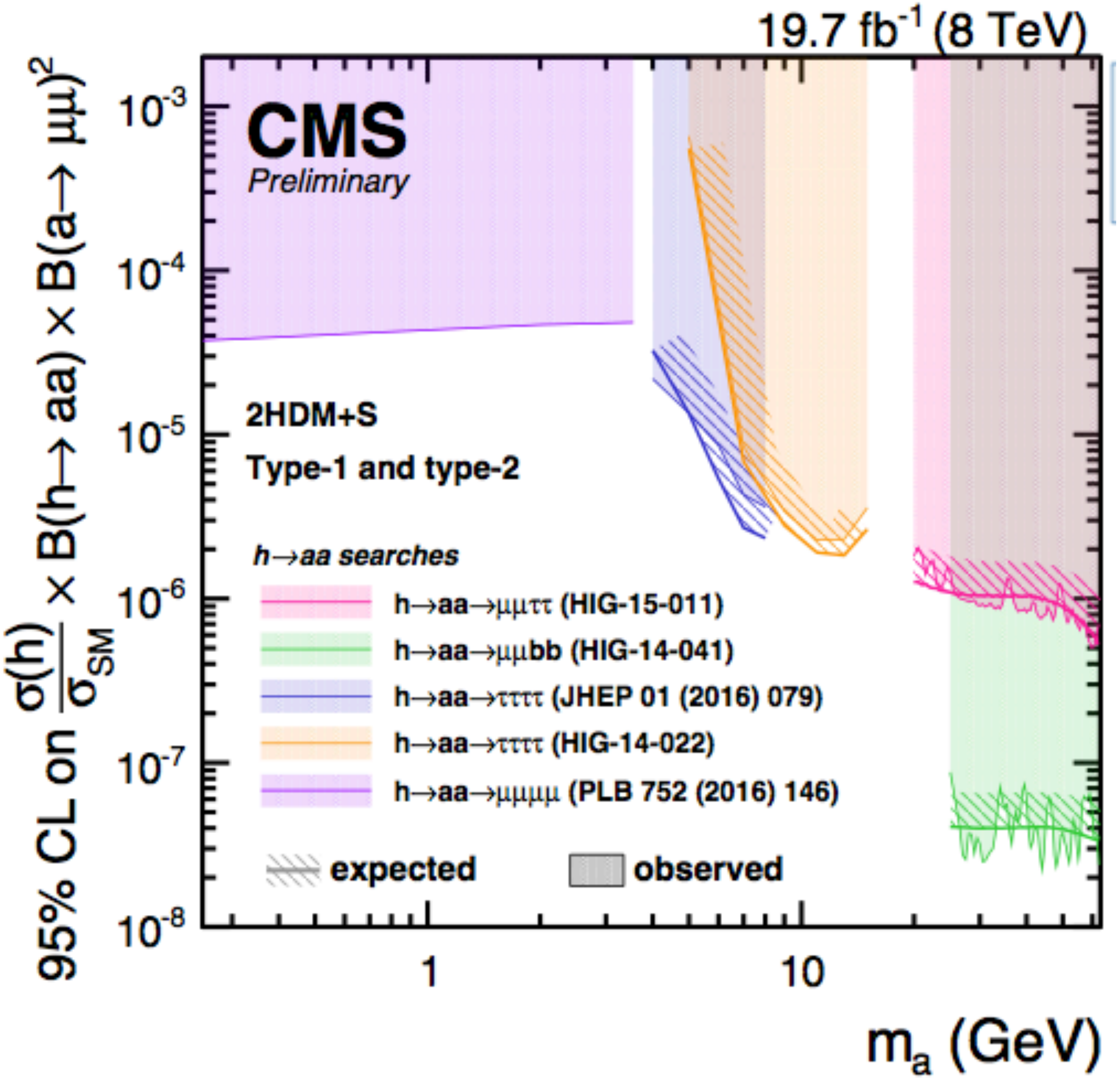
- Search for very light Higgs in NMSSM
  - $h_{1,2}$ (CP-even), $a_{1,2}$ (CP-odd) to a pair of τ leptons
  - $H(125)\rightarrow h_1h_2\,(a_1a_2)\rightarrow 4\tau$
- Reconstruct μ-track invar. mass (m_1,m_2)
  - SS dimuon sample (removes DY)
  - bin in 2-dim distribution, fit signal and bkg
  - QCD bkg from control region
- No excess over SM backgrounds







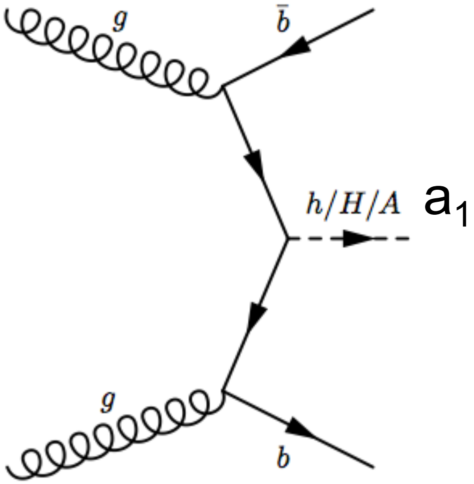
Summary for Higgs exotic decays

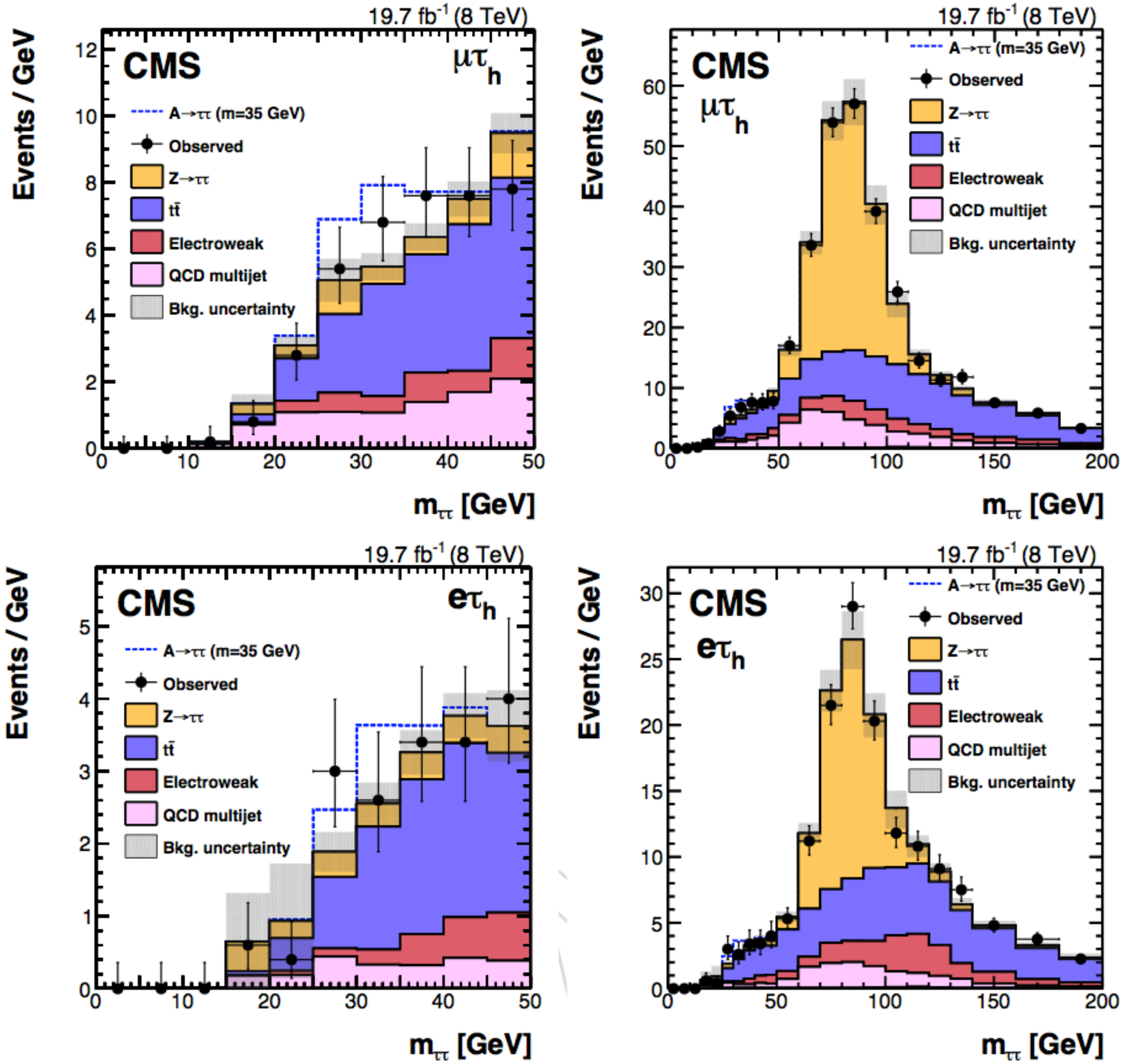


Low mass Higgs: a(→ττ)bb

arXiv:1511.03610

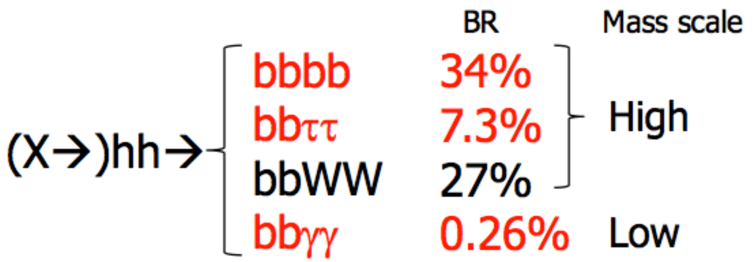
- Low mass Higgs in the NMSSM
- Low mass pseudo-scalar ($a_1 \to \tau\tau$) in association with bbar: $a_1 bb \to \tau\tau$ bb
- Similar strategy to $H \to \tau\tau$
- Search for a_1 masses below Z mass
- No evidence for signal
- Set limits: σxB~9-39 pb





di-Higgs searches

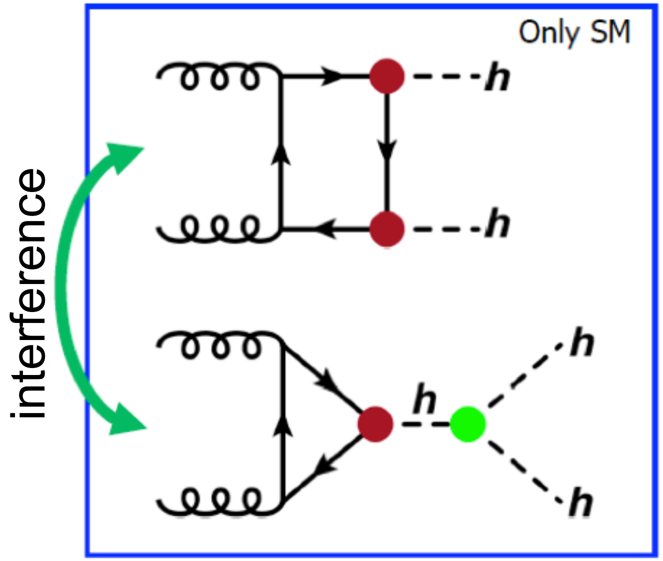
- Destructive interference in SM
- Could be altered in BSM
- If constructive, it could be large enhancement
- In SM, only σ=33fb at 13 TeV
- Study different final states



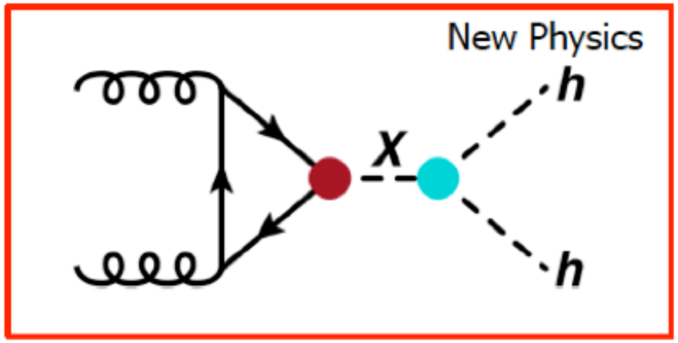
(X→)hh→

	BR	Mass scale
bbbb	34%	High
bbττ	7.3%	
bbWW	27%	
bbγγ	0.26%	Low

non-resonant production

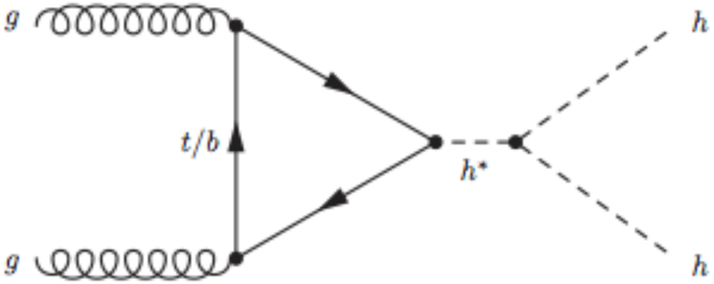


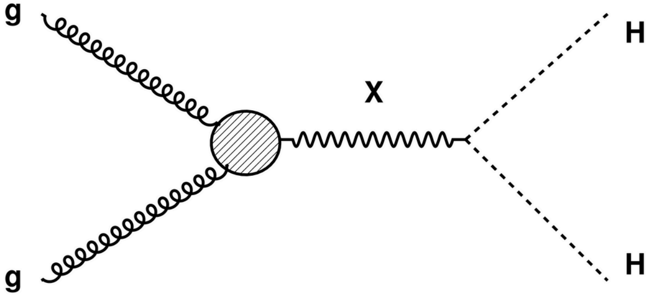
resonant production



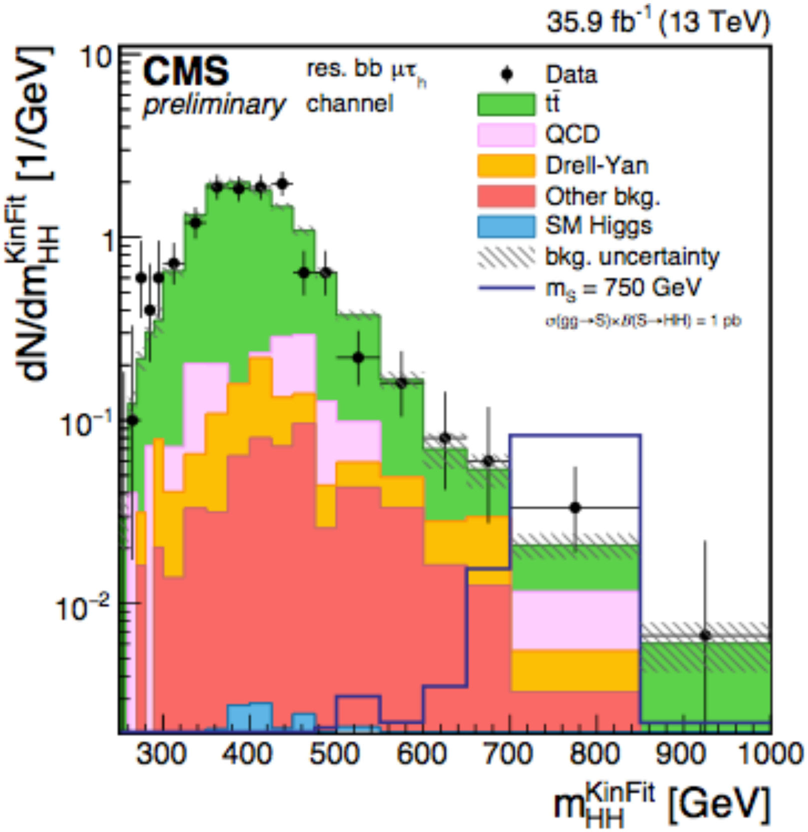
Heavy Higgs to $h_{125}h_{125} \rightarrow \tau\tau bb$

CMS-EXO-15-008, CMS-HIG-16-012, CMS-HIG-17-002





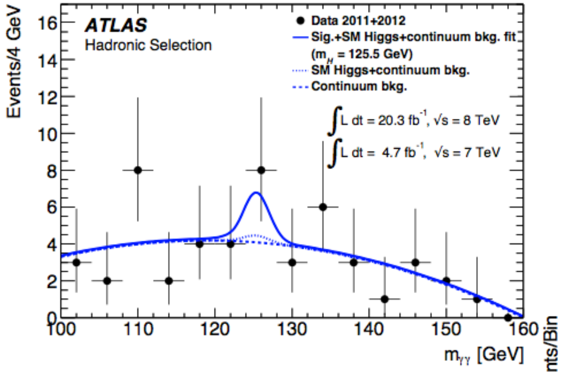
- Resonant and non-resonant production
  - Double Higgs production to determine λ_{hhh}
  - Check couplings: $\kappa_{\lambda}=\lambda_{hh}/\lambda_{hhh}^{SM}$; $\kappa_t=y_t/y_t^{SM}$
  - BSM could enhance non-resonant hh production
  - $H\rightarrow h_{125}h_{125}\rightarrow bb\tau\tau$
- h_{125} decay products nearly collinear
  - boosted “single” merged jet (→bb)
- use $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$ final states
  - sidebands/inverted isolation to estimate bkg
- set limits as function of mass



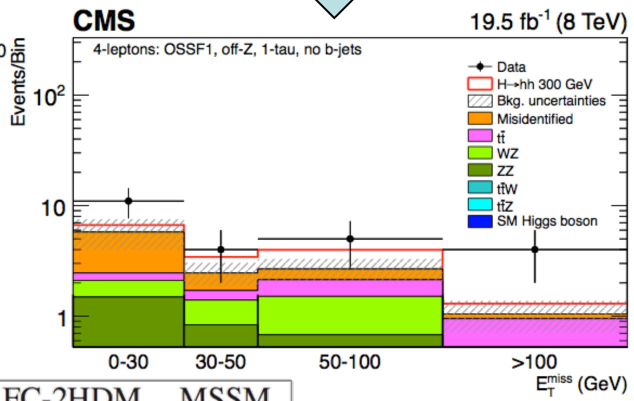
Heavy Higgs: $H \rightarrow h_{125}h_{125}$, $A \rightarrow Zh_{125}$

PRD90(2014)112013, PLB755(2016)217

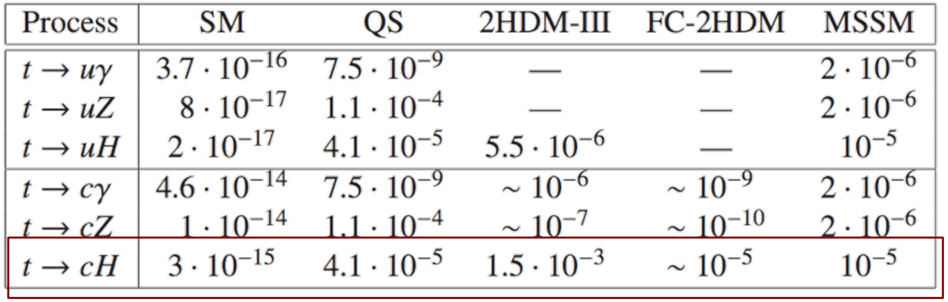
- MSSM: Heavy Higgs searches
  - Search for $A \rightarrow Zh_{125}$ and H→hh
- Exclusive search in multilepton and diphoton+lepton channels
- Search for FCNC decays



- $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$,
- $H \rightarrow \tau\tau$,
- $H \rightarrow ZZ^* \rightarrow jj\ell\ell, \nu\nu\ell\ell, \ell\ell\ell\ell$,
- $H \rightarrow \gamma\gamma$.



- Search for tt→(bW)(ch)
  - Not forbidden but highly suppressed
  - enhanced w/some parameter models
- SM Higgs now a background
  - ATLAS: H→γγ
  - CMS: H→γγ and multileptons
- b-tag provides bkg suppression



Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \rightarrow u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \rightarrow uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \rightarrow uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \rightarrow c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \rightarrow cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \rightarrow cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

FCNC decays

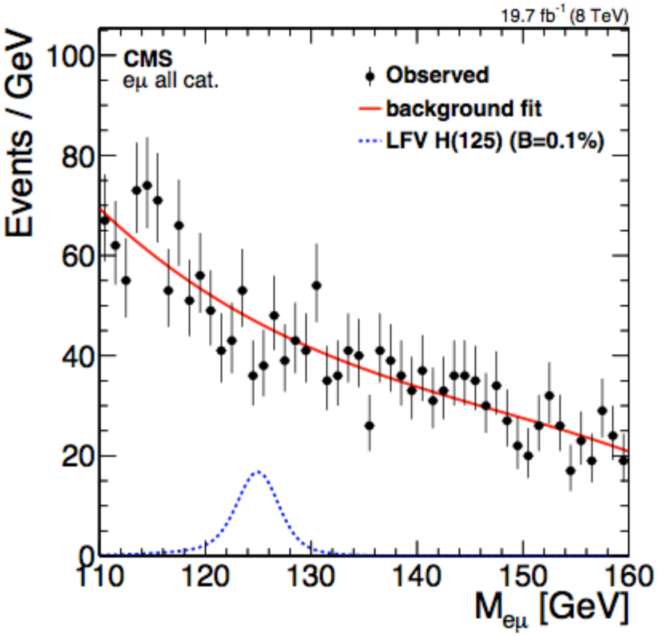
	ATLAS obs(exp)	CMS
BR(t→cH) (95%CL)	<0.79% (0.51%)	<0.56% (0.65%)

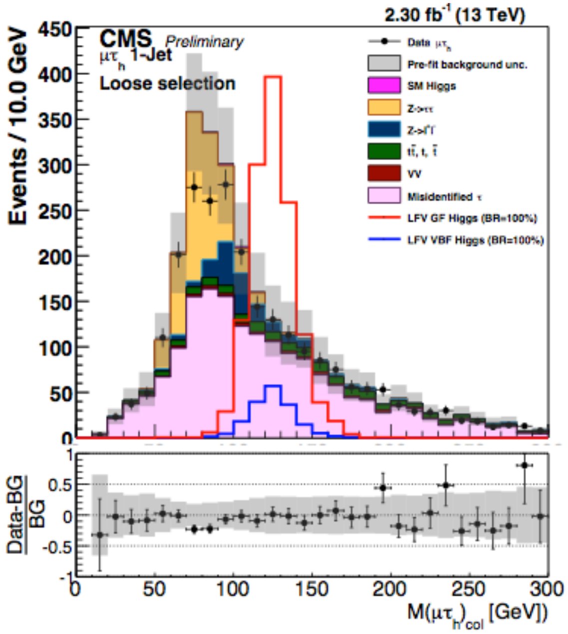
LFV in Higgs decays

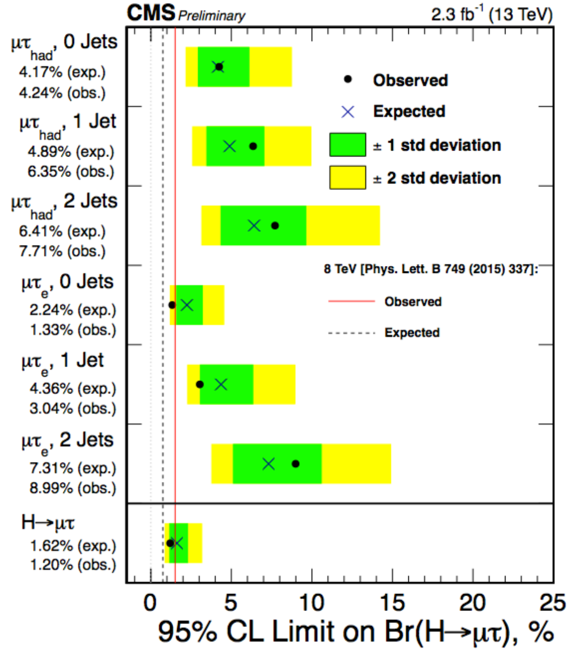
PLB 763(2016)472, CMS-HIG-16-005

- Some BSM models allow for LFV Higgs decays
- Search for H→eτ, eμ, μτ final states
- Categories: N_{jet}, lepton kinematics
  - N_{jet} to target ggH and VBF production
- Main background from DY, ttbar, WW

	95%CL (obs/exp)	Best fit
h->μτ (run1)	<1.51/0.75%	$0.84^{+0.39}_{-0.37}$%
h->μτ (run2)	<1.20/1.62%	$-0.76^{+0.81}_{-0.84}$%



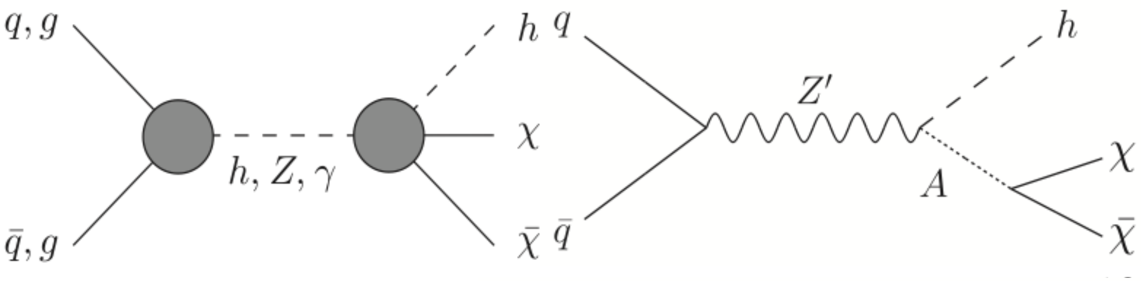




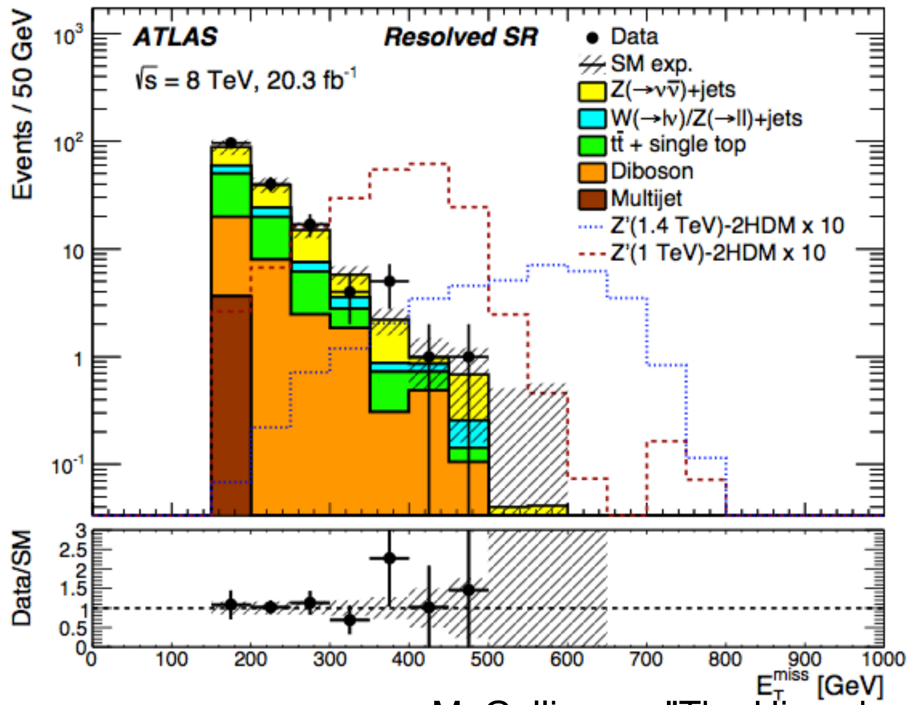
Dark Matter+Higgs

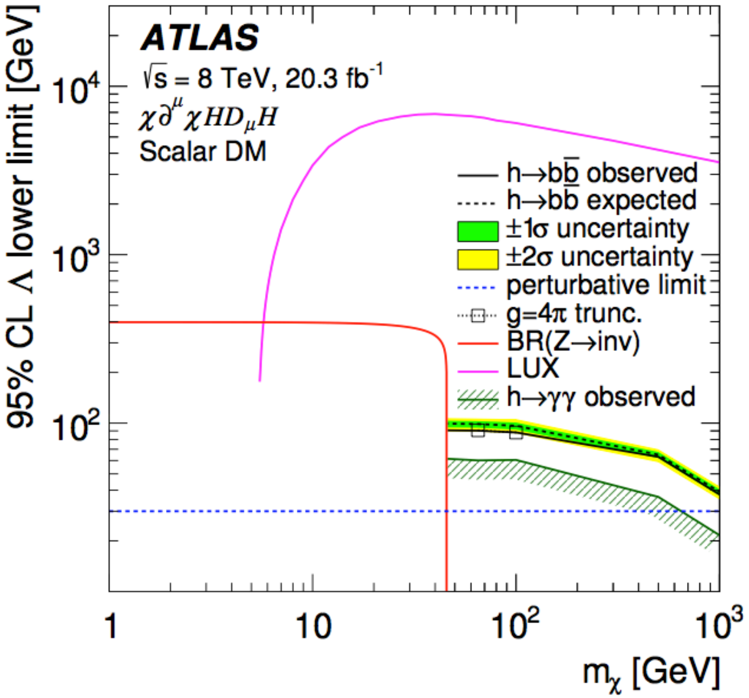
arXiv:1510.06218, arXiv:1506.01081

- Generic search: pp→X+MET
- Search for DM + h(→bb)
- Model-independent search
  - Signature: h(→ZZ/bb/γγ)+MET
  - Simplified model with Z’ or pseudo-scalar Higgs A(→χχ)
- Signal events at large MET



DM particle (χ): can be scalar or fermion
Pseudo-scalar Higgs A





Summary

- Excellent consistency of SM but SM is incomplete
- Extensions foresee existence of additional bosons
- Searches for BSM bosons natural companion to precision SM Higgs boson measurements
  - Charged Higgs searches with top quark decays
  - Other BSM searches show no indication of deviations
- Searches provide no hints for BSM yet