Center for
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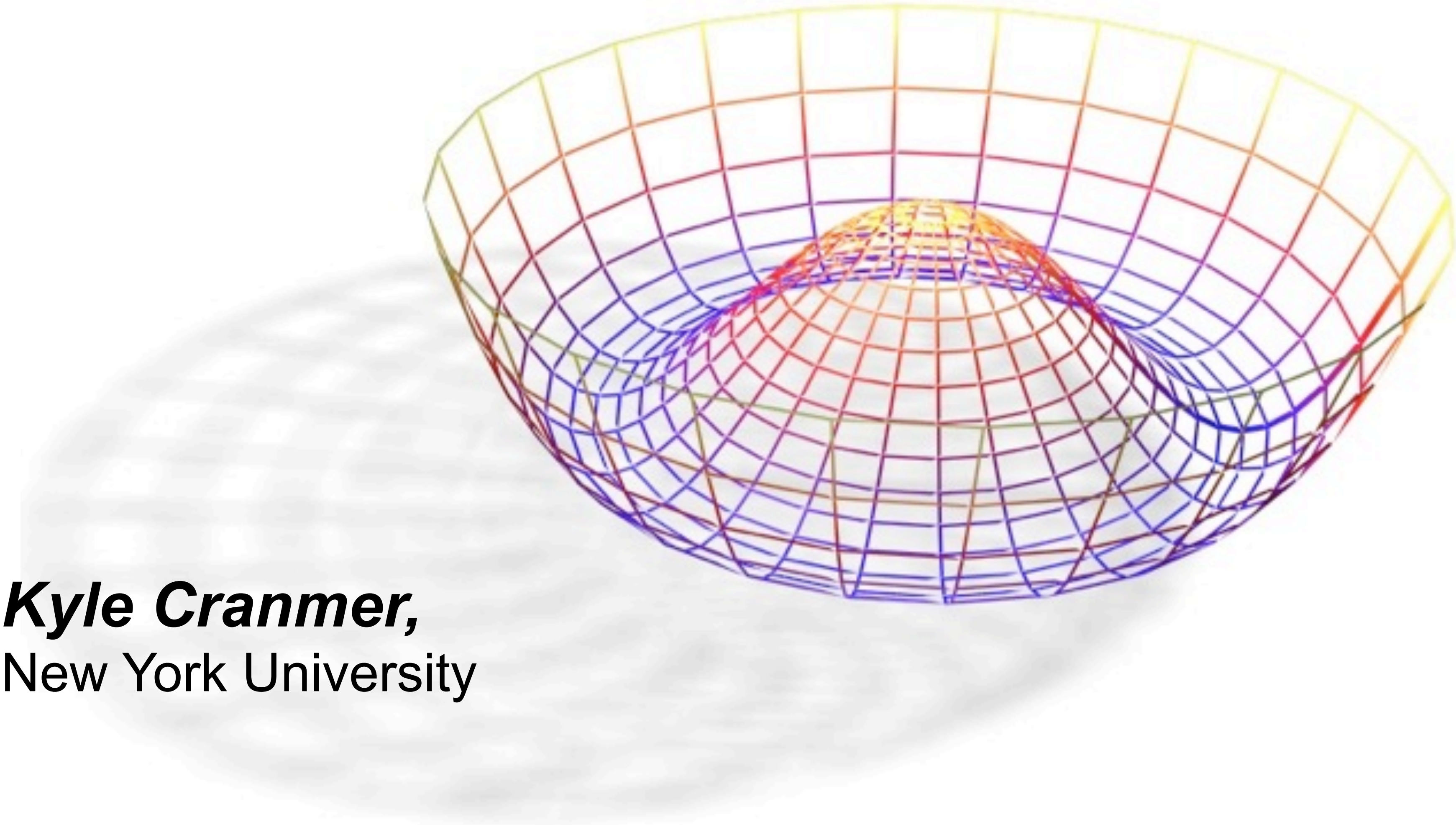
Particle Physics

EWSB and the Higgs Sector



Kyle Cranmer,
New York University

Fermi's theory of beta decay

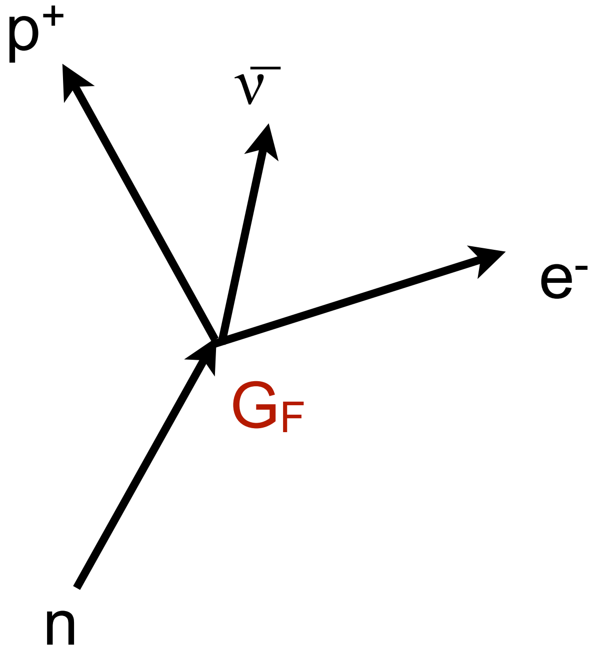
In 1933 Fermi proposed a theory of beta decay

- four-fermion vertex with coupling constant G_F

The theory has a serious sickness

- **unitarity violation:** interaction probability grows with energy until probabilities are greater than 1.
- The theory is non-renormalizable.

Now we see Fermi theory as an "**effective theory**" valid to energy scales comparable with the mass of the W-boson.



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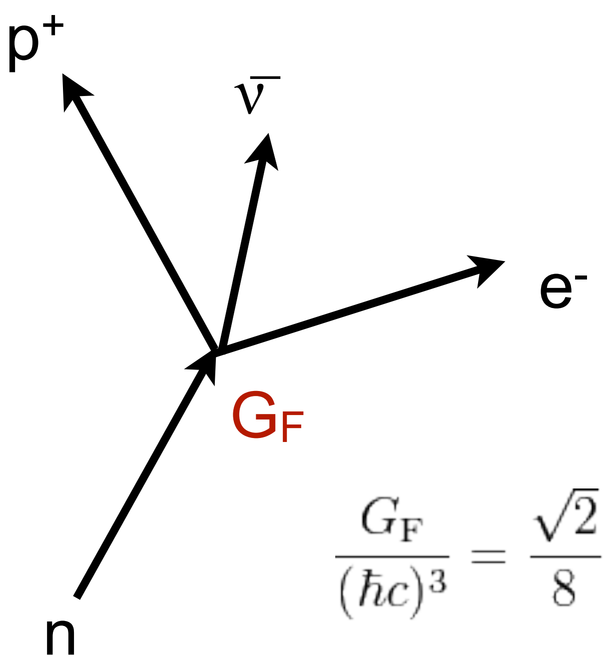
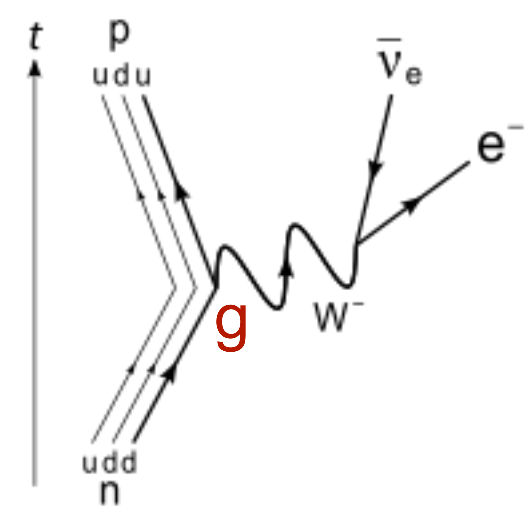


$$\frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2} = 1.16637(1) \times 10^{-5}\mathrm{GeV}^{-2} \,.$$



The LHC: a no loose proposition

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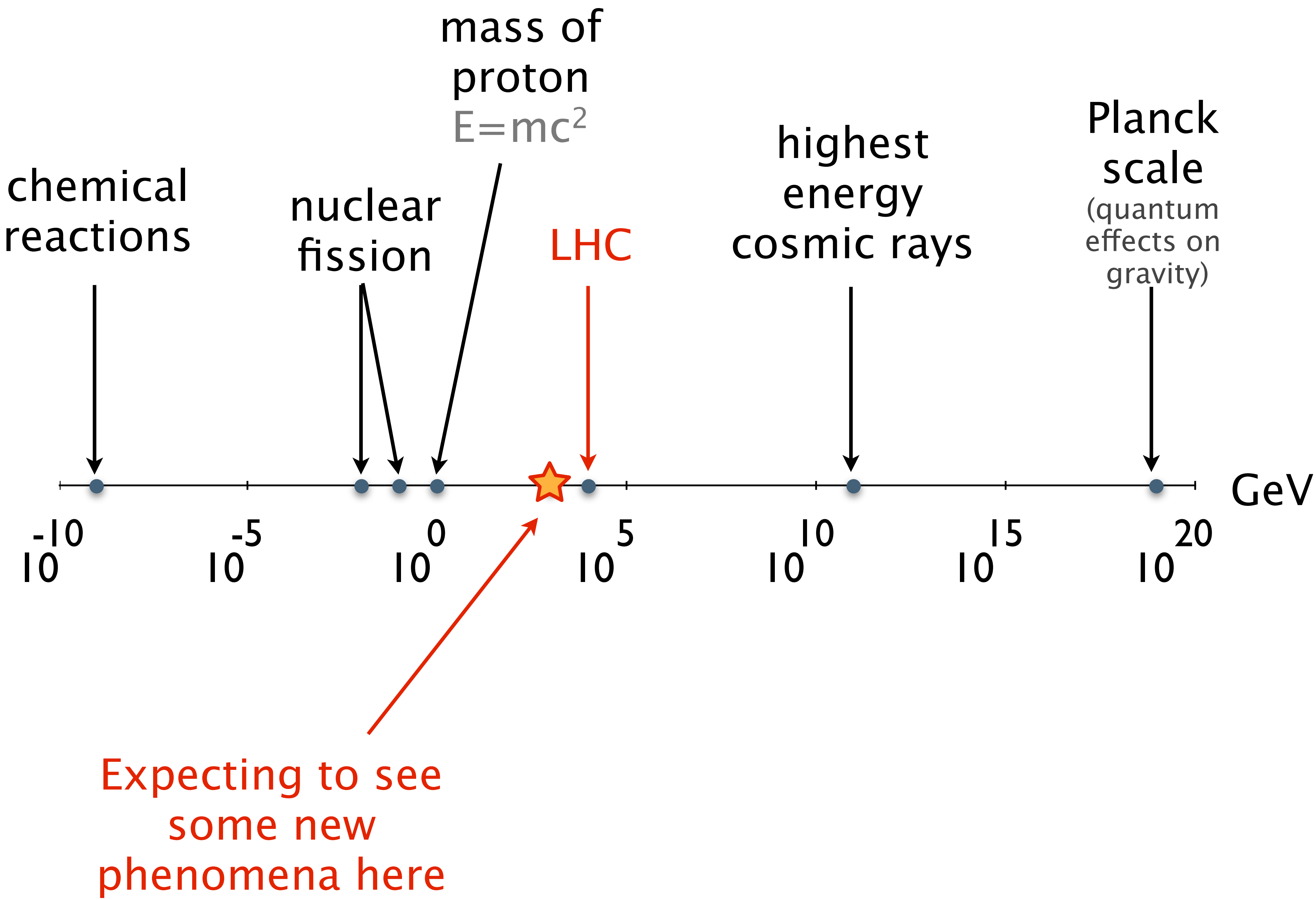

The LHC: a no loose proposition

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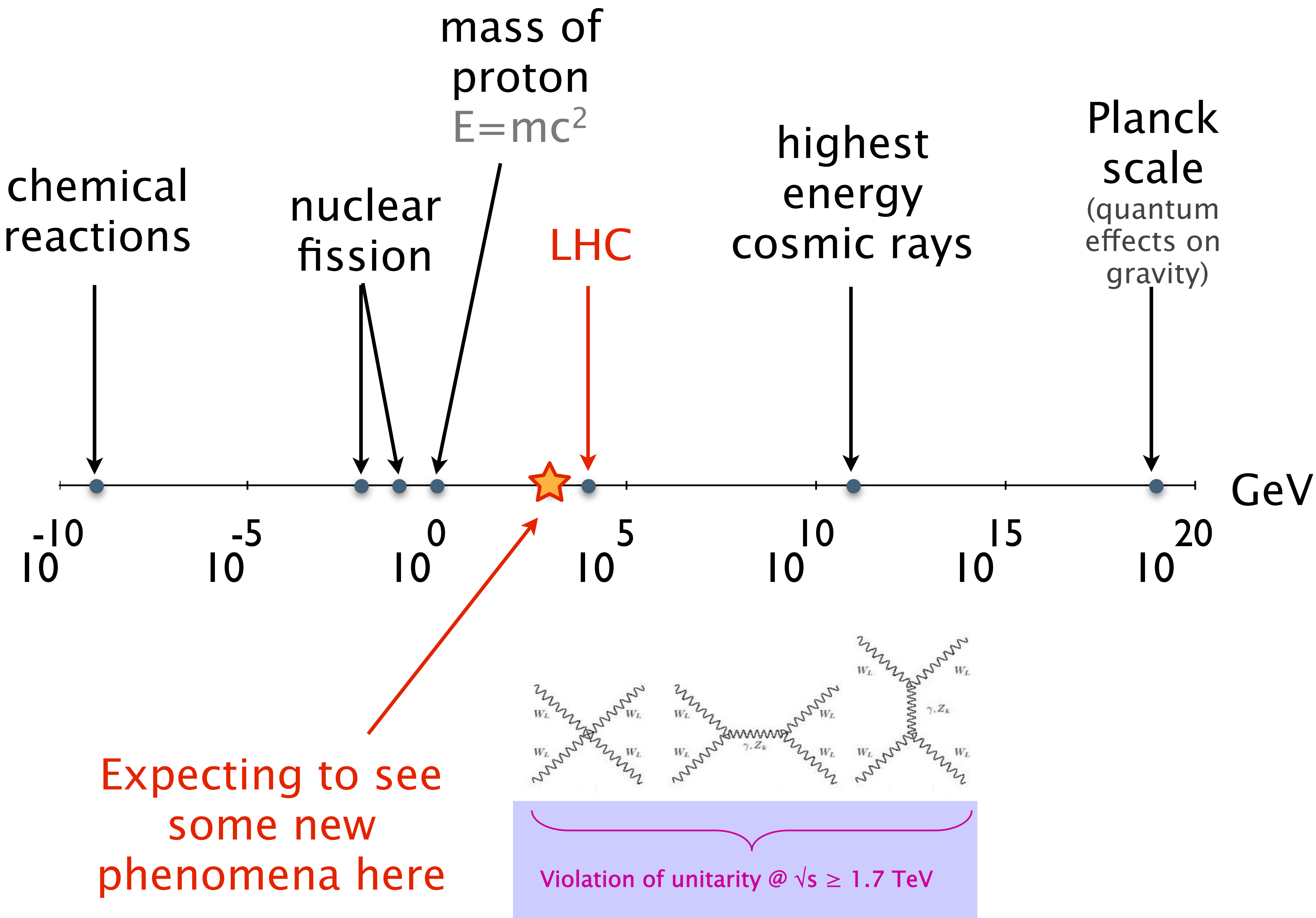
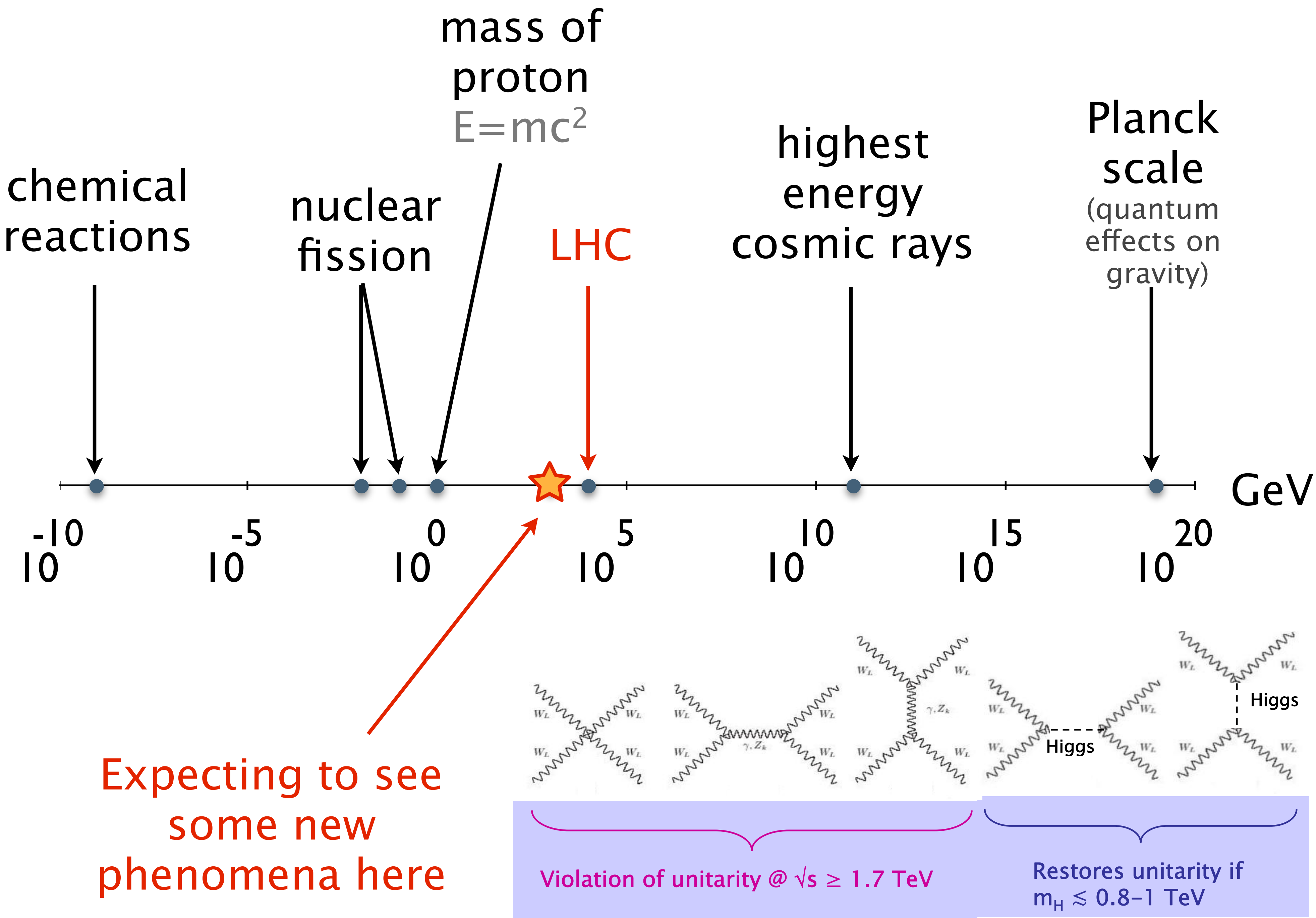
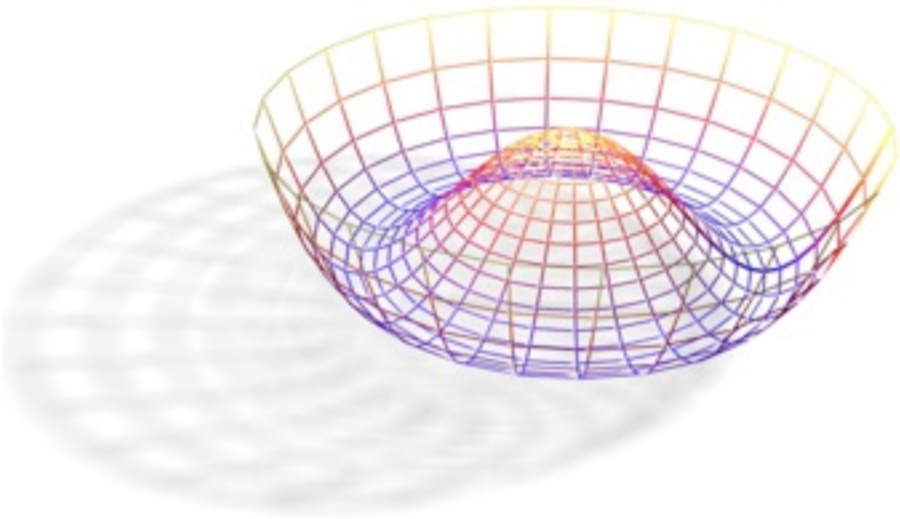


The LHC: a no loose proposition

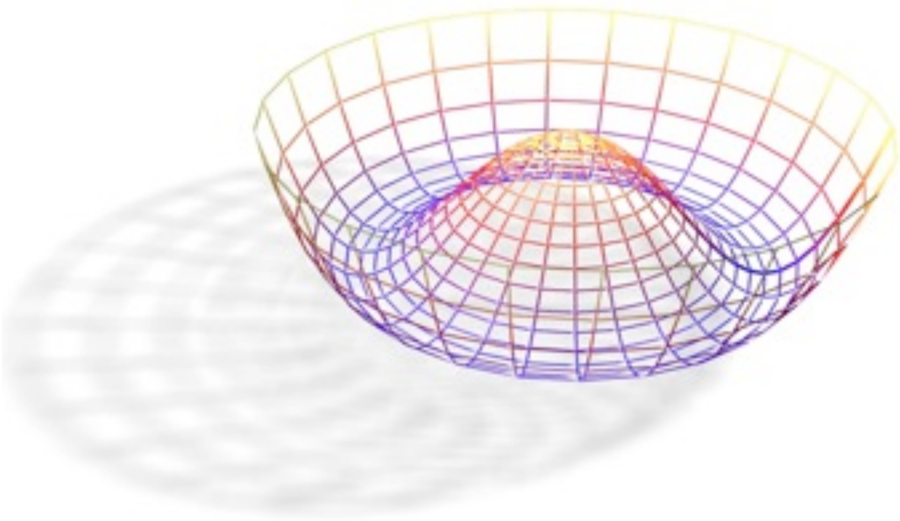


The Higgs and Mass



The Higgs and Mass

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$



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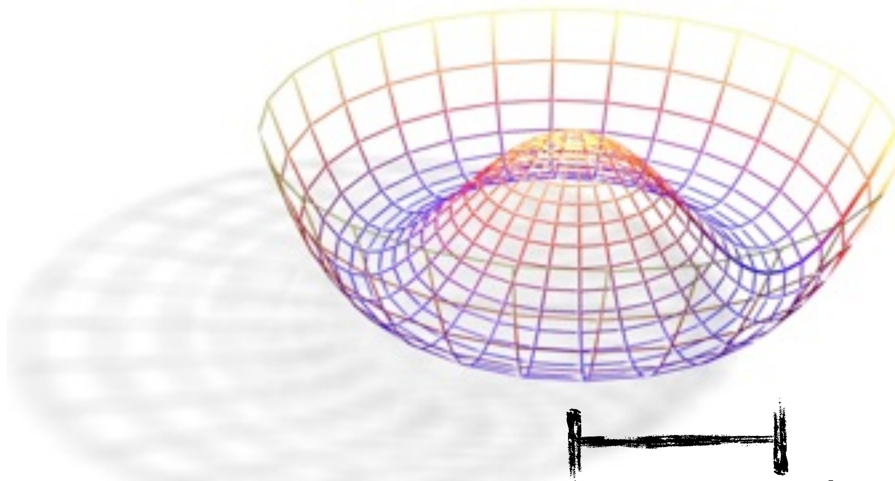


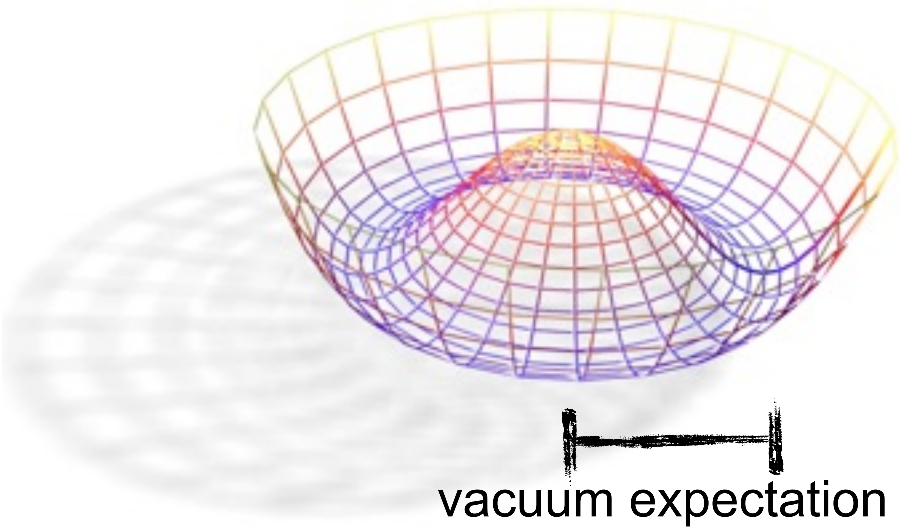
vacuum expectation v

fluctuations (the Higgs particle)

$$\phi = \frac{1}{\sqrt{2}}(v + h)$$

The Higgs and Mass

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$



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Interactions with fermions:

The Higgs and Mass

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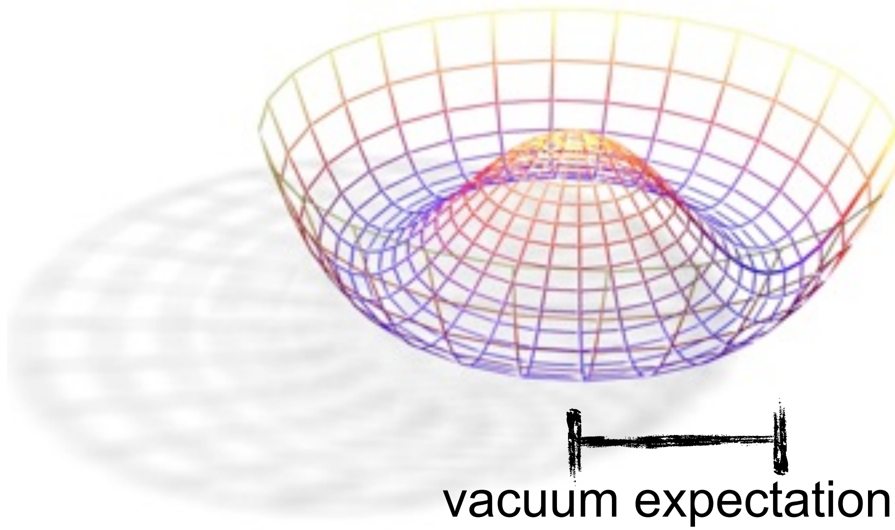

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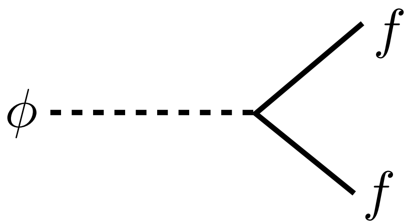

$$y\, f_L f_R \phi$$

The Higgs and Mass

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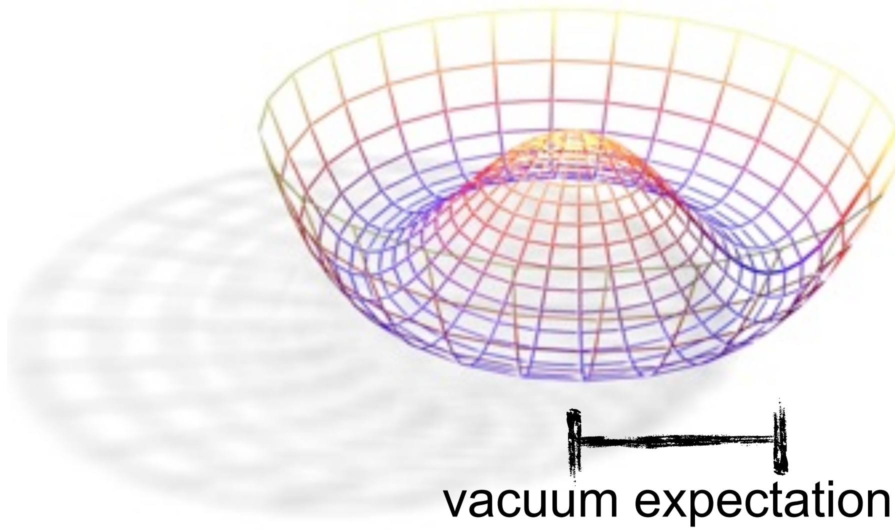

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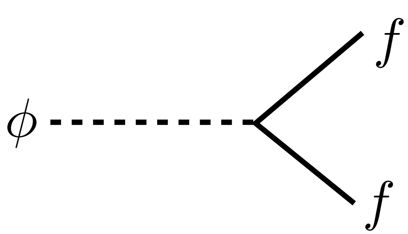

$$y\, f_L f_R \phi \longrightarrow \underbrace{\frac{yv}{\sqrt{2}}}_{m_f} f_L f_R + \underbrace{\frac{y}{\sqrt{2}} f_L f_R h}_{\text{interaction}}$$

- coupling arbitrary, but proportional to mass

The Higgs and Mass

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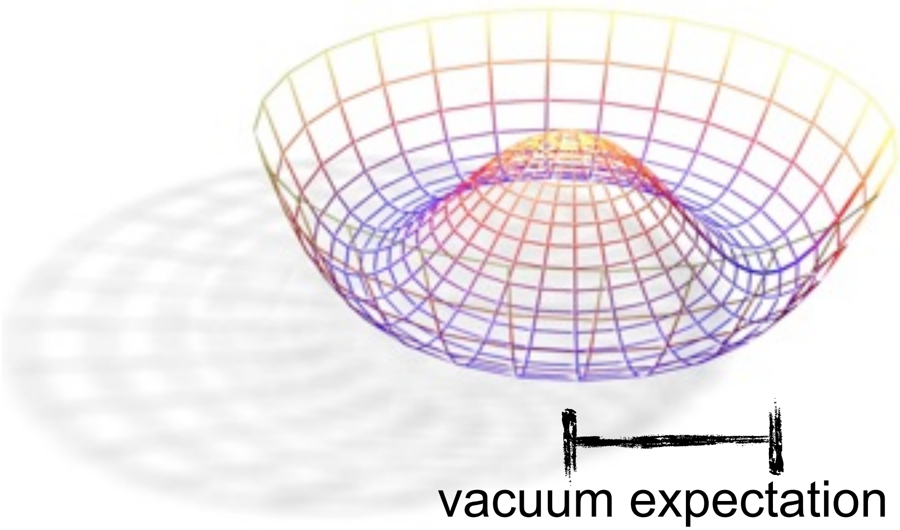
$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$



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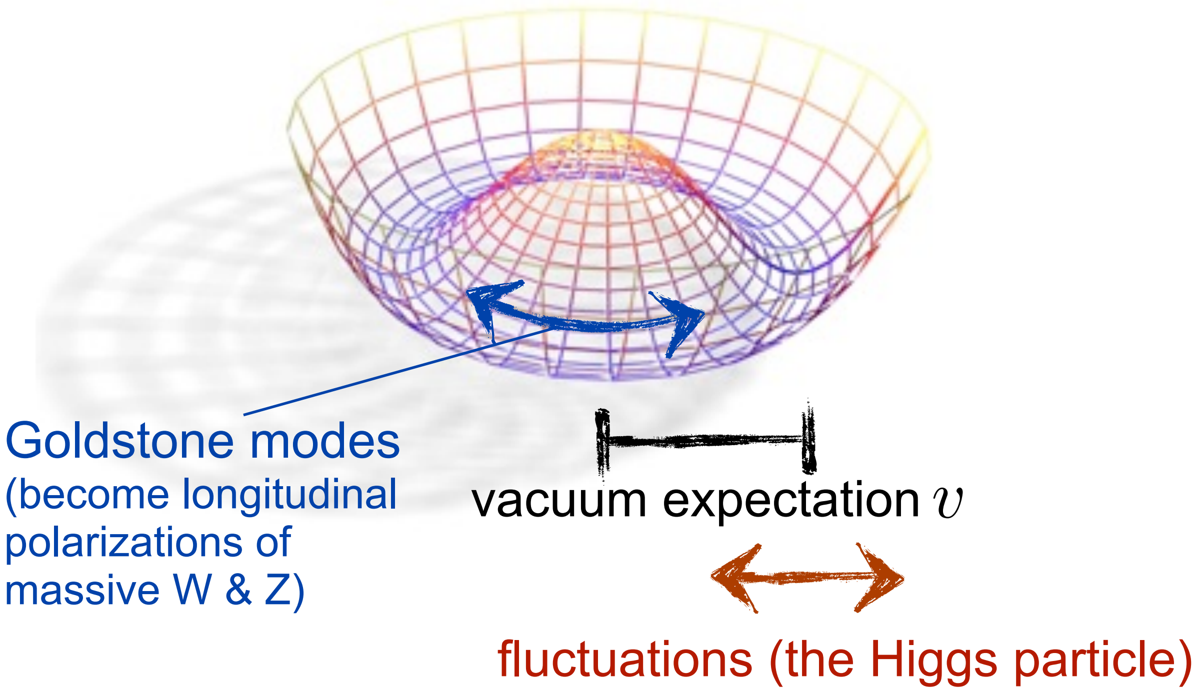

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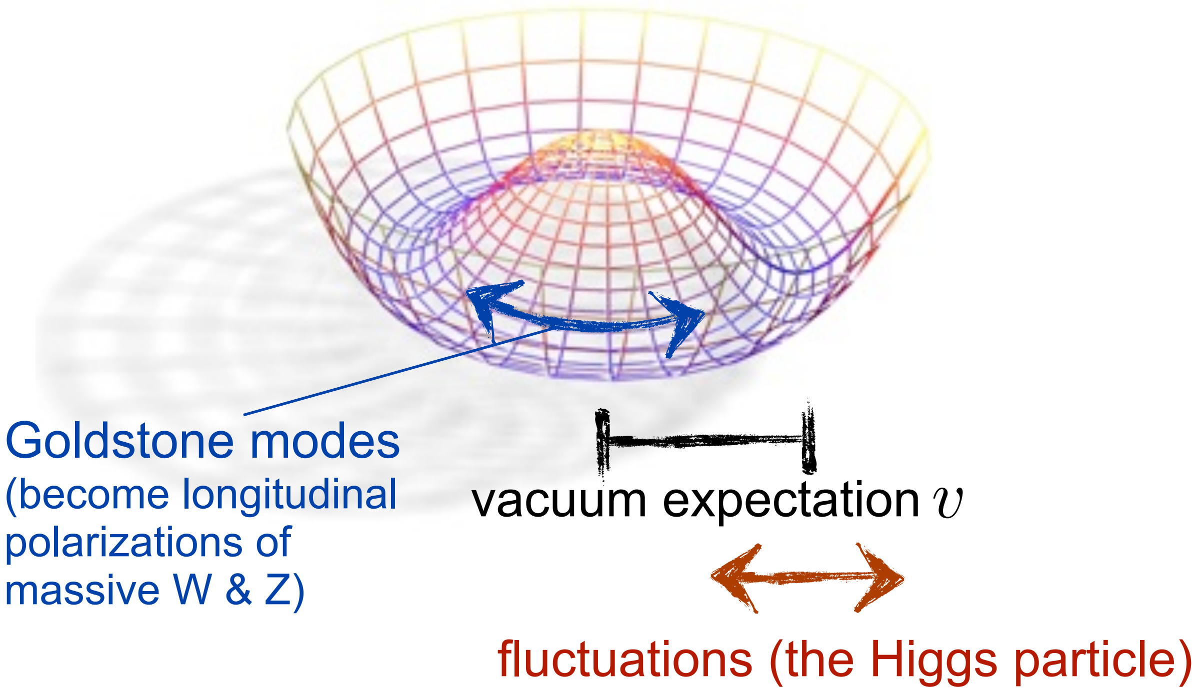
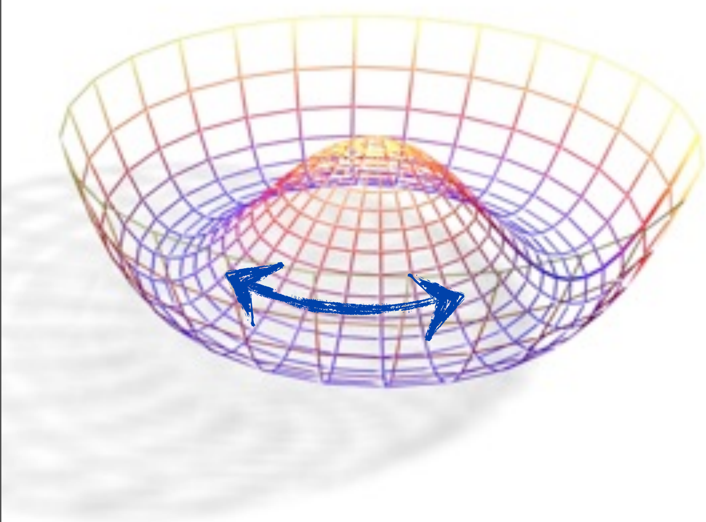


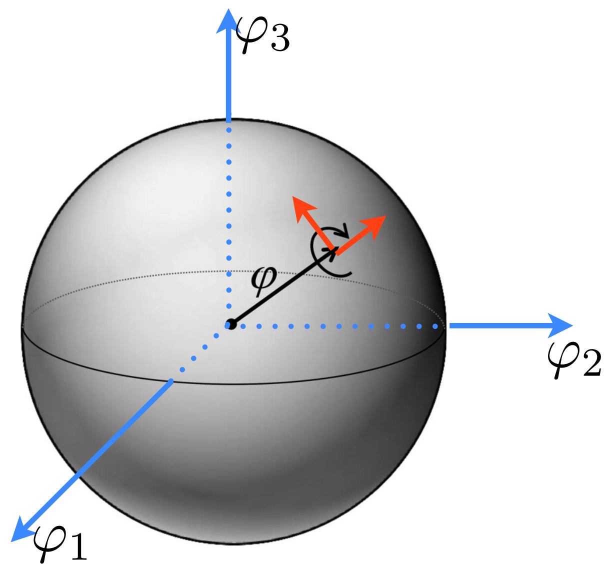
$$\phi = \frac{1}{\sqrt{2}}(v+h)$$

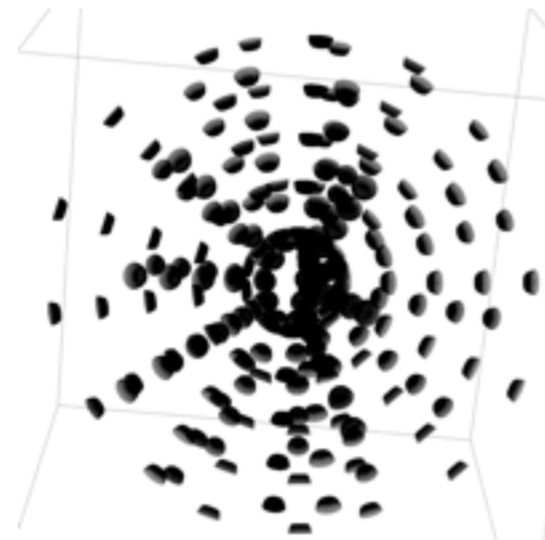
The flat directions in the potential Goldstone modes are related to massive force carriers.

We say these degrees of freedom are "eaten"

U(1) SO(3) SU(2)xU(1)







The Higgs mechanism leaves open the underlying symmetry and the representation of the Higgs multiplet(s). For example:

- Failed Georgi-Glashow model for EWSB without Z boson
- Higgs triplets with doubly charged Higgs
- more than one multiplet in SUSY and Type 1-4 2HDMs

A busy EWSG & Higgs section!

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Electroweak Symmetry Breaking and the Higgs Sector - Classroom Unit 1 (08:30-10:00)

- Conveners: Dr. Draper, Patrick; Dr. Piacquadio, Giacinto

time	[id] title	presenter
08:30	[150] Observation and coupling measurements of Higgs boson in the diphoton decay mode in ATLAS	YANG, Hongtao
08:50	[155] Spin measurement of the Higgs-like resonance observed in the two photon decay channel in ATLAS	Mr. HARD, Andrew
09:10	[159] Property measurements with Higgs to gamma gamma at ATLAS	Mr. SAXON, James
09:30	[79] Observation Of A Higgs-Like Boson in the Decay H -> ZZ -> 4 lepton	Mr. VARTAK, Adish

Electroweak Symmetry Breaking and the Higgs Sector - Classroom Unit 1 (10:30-12:00)

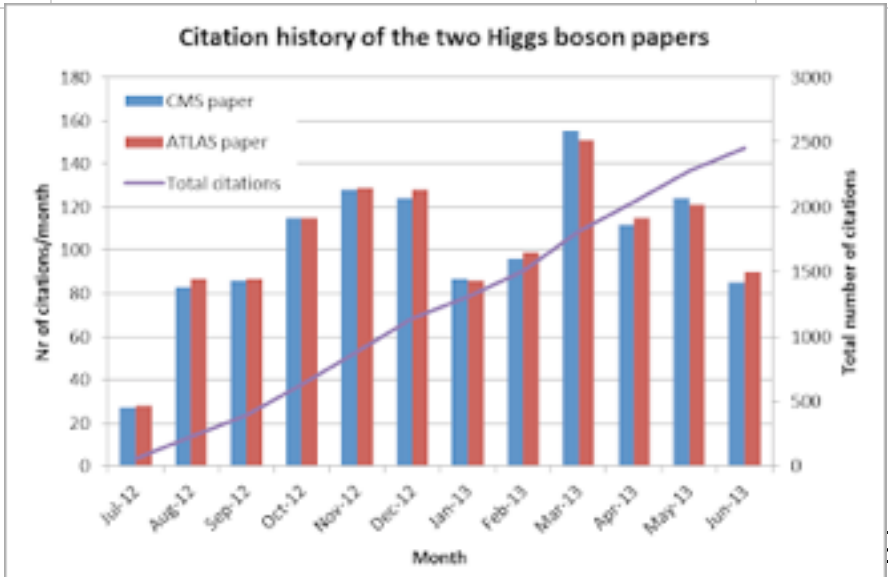
- Conveners: Dr. Draper, Patrick; Dr. Piacquadio, Giacinto

time	[id] title	presenter
10:30	[288] Searching for neutral Higgs bosons in non-standard channels	Dr. MENON, Arjun
11:00	[172] Search for Non-Standard-Model Higgs Boson Decays Using Collimated Muon Pairs at the CMS	TATARINOV, Aysen
11:30	[198] ATLAS Searches for BSM Higgs Bosons	POTTER, Christopher

Electroweak Symmetry Breaking and the Higgs Sector - Classroom Unit 1 (13:30-15:30)

- Conveners: Dr. Draper, Patrick; Dr. Piacquadio, Giacinto

time	[id] title	presenter
13:30	[287] Electroweak Baryogenesis and Higgs Signatures	Dr. COHEN, Tim
14:00	[69] Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS	XU, Lailin
14:30	[109] Searches for low-mass Higgs at BaBar	Mr. SO, Rocky
15:00	[156] Searches for Exotic Higgs decays in CMS	Dr. CASTANEDA, Alfredo



Electroweak Symmetry Breaking and the Higgs Sector - Classroom Unit 1 (16:00-17:40)

- Conveners: Dr. Draper, Patrick; Dr. Piacquadio, Giacinto

time	[id] title	presenter
16:00	[307] Search for invisible Higgs decays at CMS	CHASCO, Matthew
16:30	[80] Search for the SM Higgs Boson Produced in Association with a Vector Boson and Decaying to Bottom Quarks	Mr. MOONEY, Michael
16:55	[202] Search for associated production WH, ZH with H decaying to b bbar at ATLAS.	Dr. MORANGE, Nicolas
17:15	[146] Statistical treatment in the search for the Standard Model Higgs boson produced in association with a vector boson and decaying to bottom quarks with the ATLAS detector	MING, Yao

Electroweak Symmetry Breaking and the Higgs Sector - Classroom Unit 1 (10:30-12:00)

- Conveners: Dr. Draper, Patrick; Dr. Piacquadio, Giacinto

time	[id] title	presenter
10:30	[86] Searches for decays of the Higgs-like boson to tau lepton pairs with the ATLAS detector	Mr. TUNA, Alexander Naip
11:00	[149] Search for the standard model Higgs boson in the Zgamma decay mode with ATLAS	WANG, Fuquan
11:30	[289] Implications of a 125 GeV SM-like Higgs	Dr. DRAPER, Patrick

Electroweak Symmetry Breaking and the Higgs Sector - Classroom Unit 1 (14:30-17:00)

- Conveners: Dr. Draper, Patrick; Dr. Piacquadio, Giacinto

time	[id] title	presenter
14:30	[98] Evidence for a particle decaying to W+W- in the fully leptonic final state in a standard model Higgs boson search	Mr. YOO, Jae Hyeok
15:00	[129] Higgs to WW production at ATLAS	Mr. SCHAEFER, Doug
15:20	[217] Vector boson fusion Higgs production in H\rightarrow{WW}\rightarrow{l \nu l \nu} in ATLAS	Mr. CERIO, Benjamin
15:40	[152] Spin measurements of the Higgs-like resonance in the WW->lvlv decay mode in ATLAS	Dr. KASHIF, Lashkar
16:00	[247] Properties of a Higgs-like particle of mass 125 GeV	SHAW, Savanna
16:30	[147] Higgs property measurements in ATLAS	Mr. JI, haoshuang

SM Higgs @ the LHC

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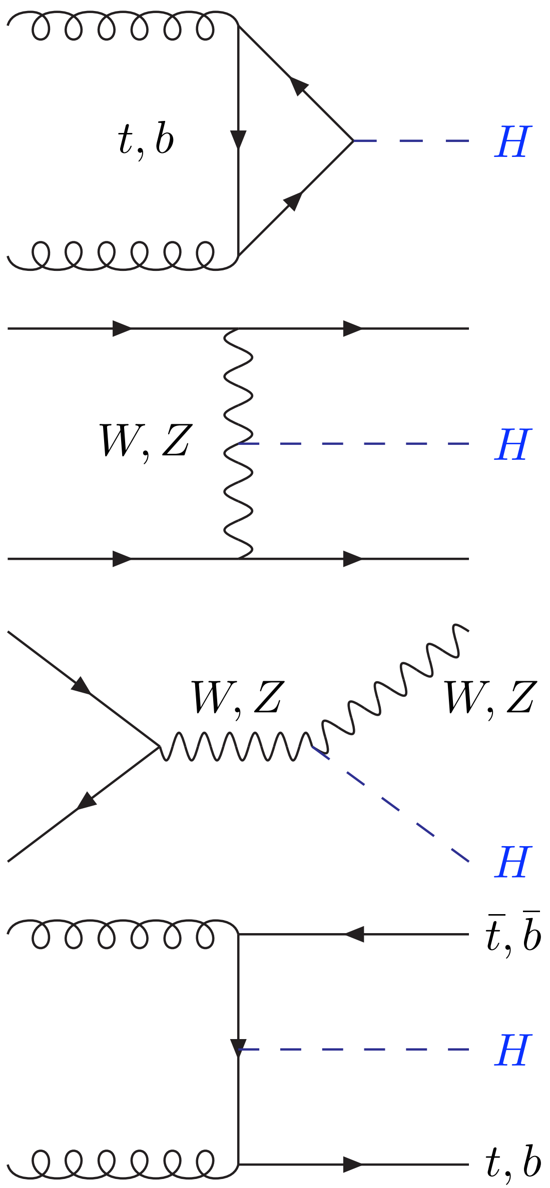
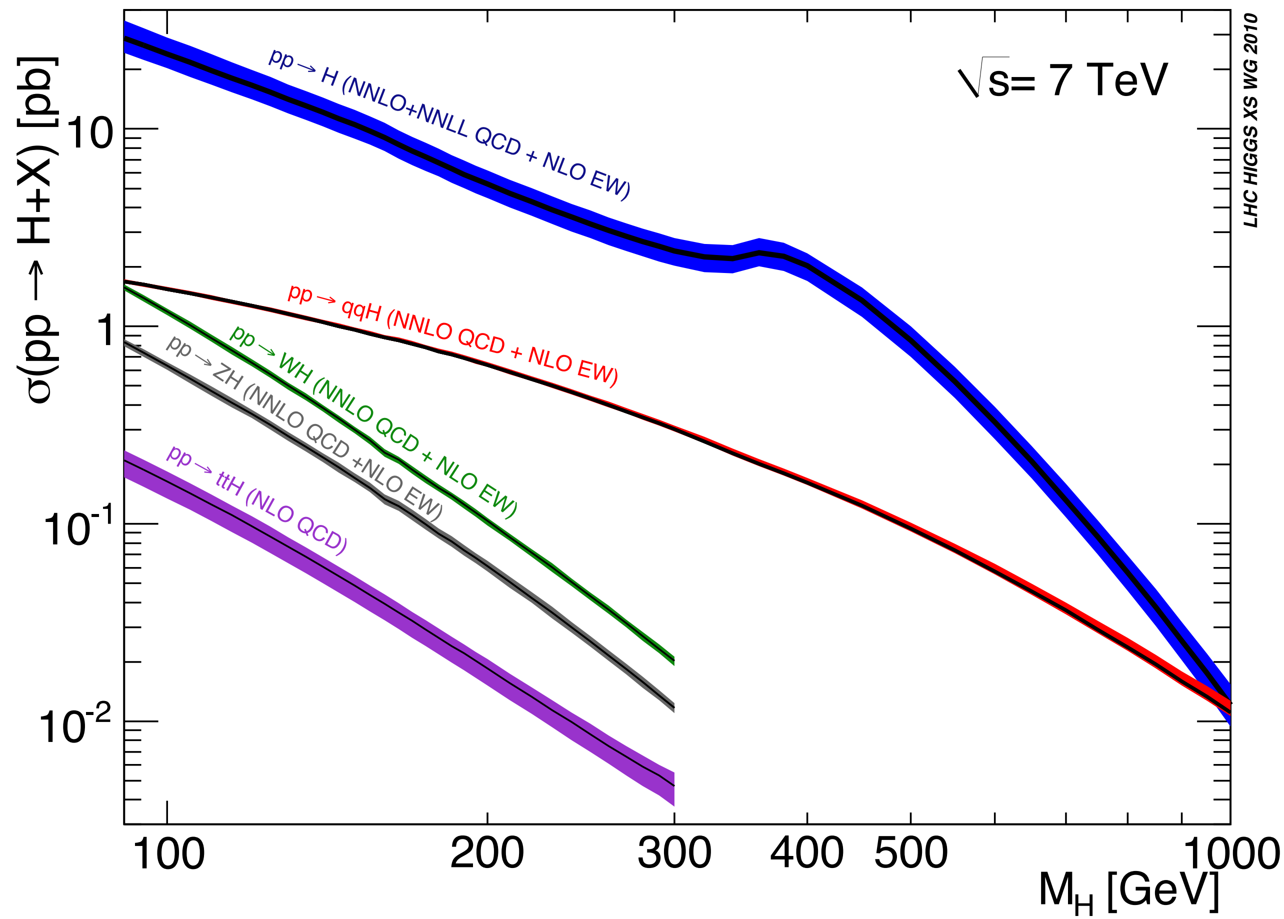
in → out





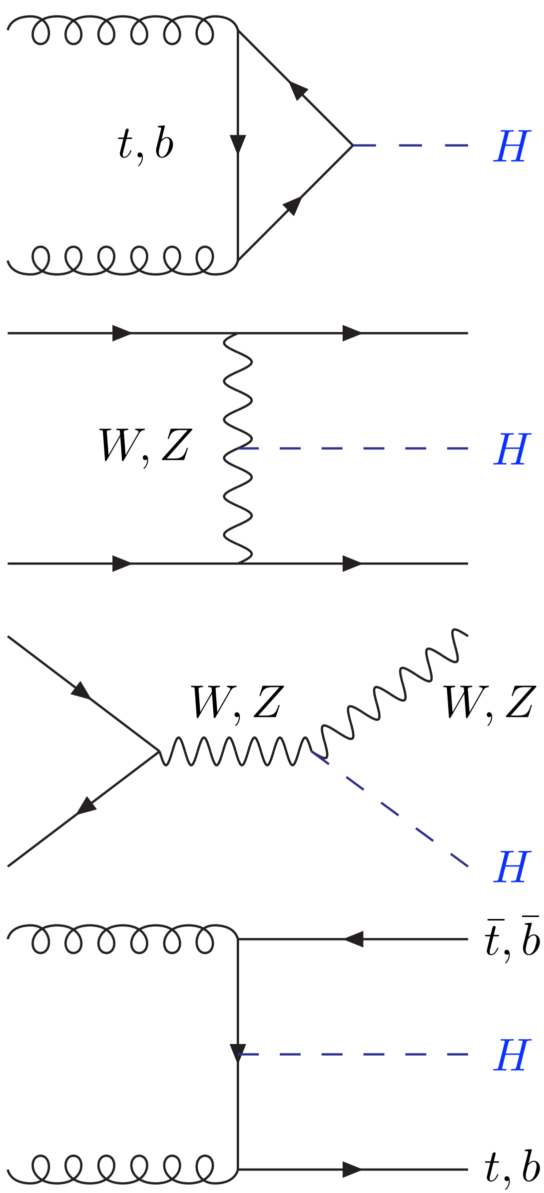
Gluon fusion: produced with little pT

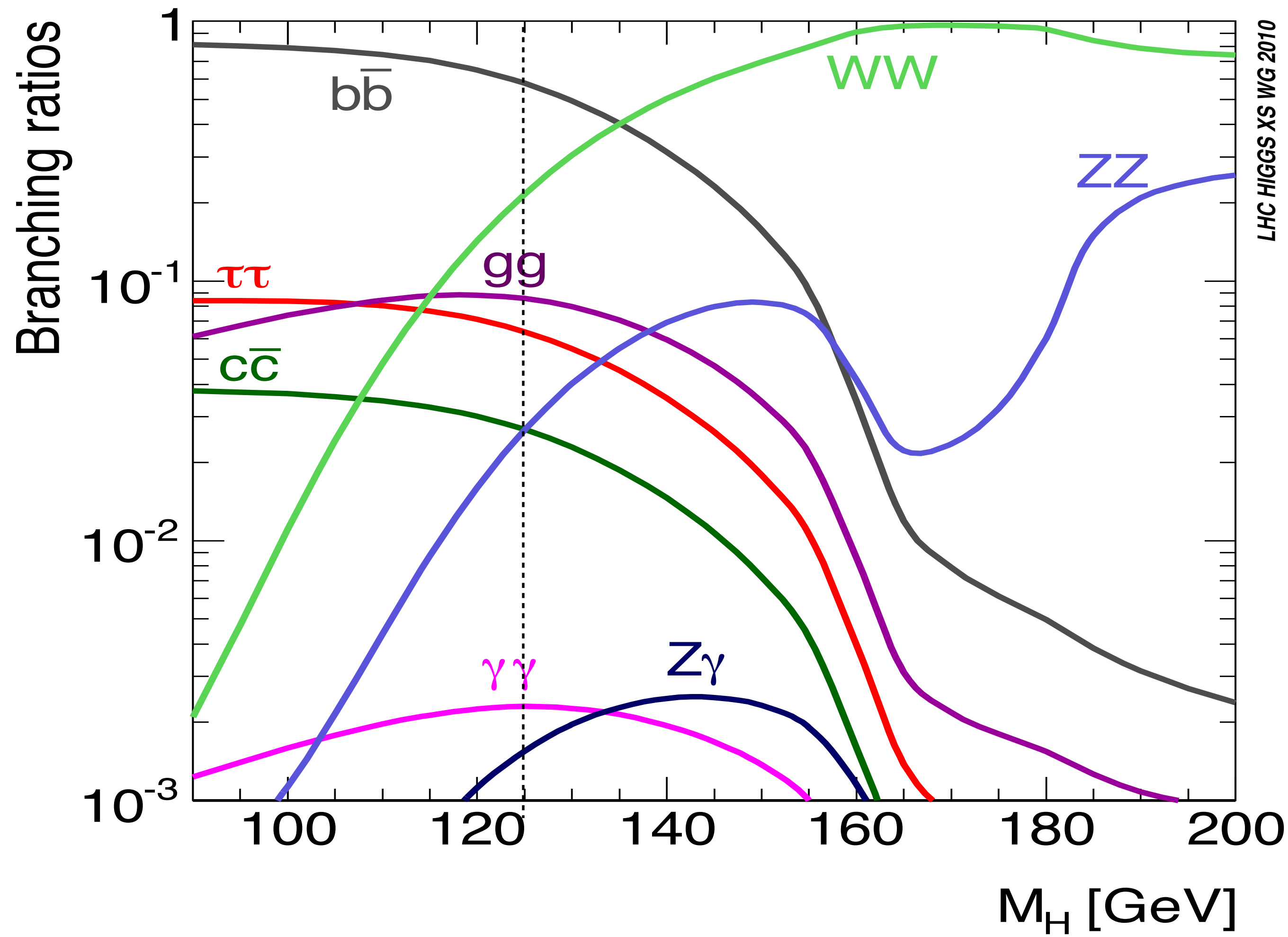
Vector boson fusion: hard jets, high pT

Associated: extra handle from leptons

SM Higgs @ the LHC

in → out





Many decays accessible at 126 GeV

bb dominates, but is difficult

$\gamma\gamma$ small branching ratio, but clean

SM Higgs @ the LHC

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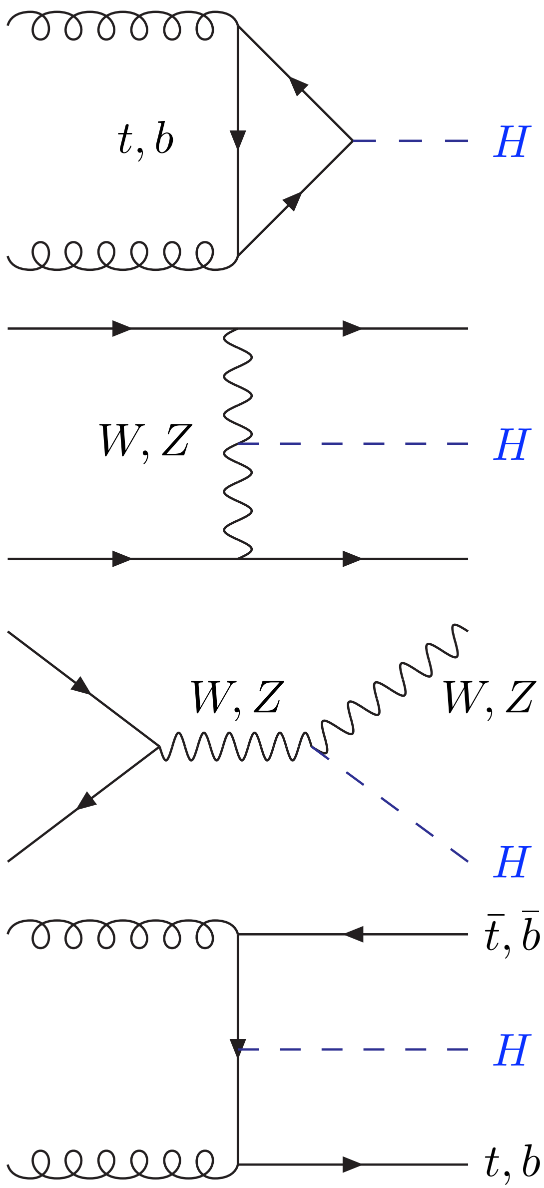
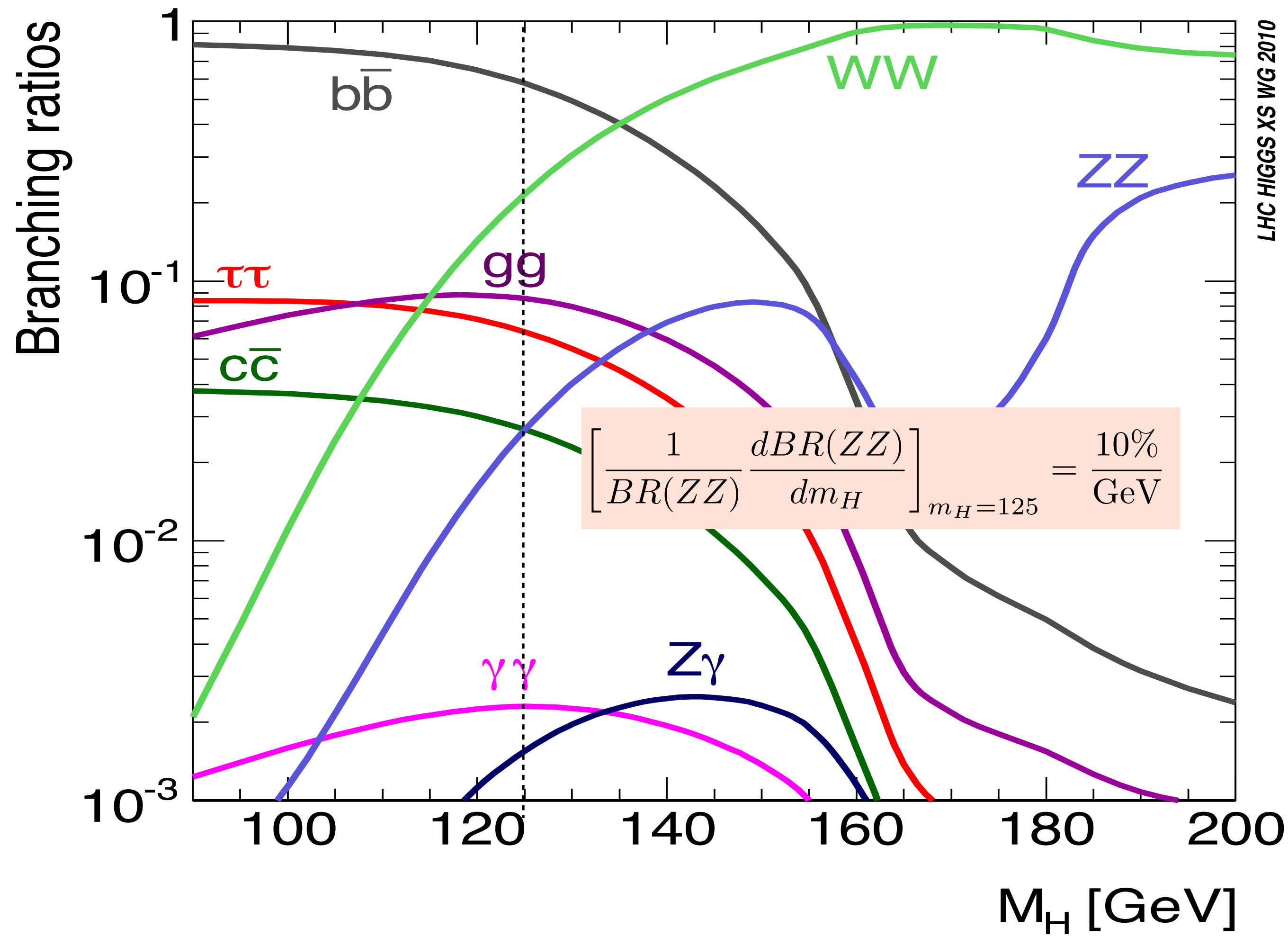
in → out





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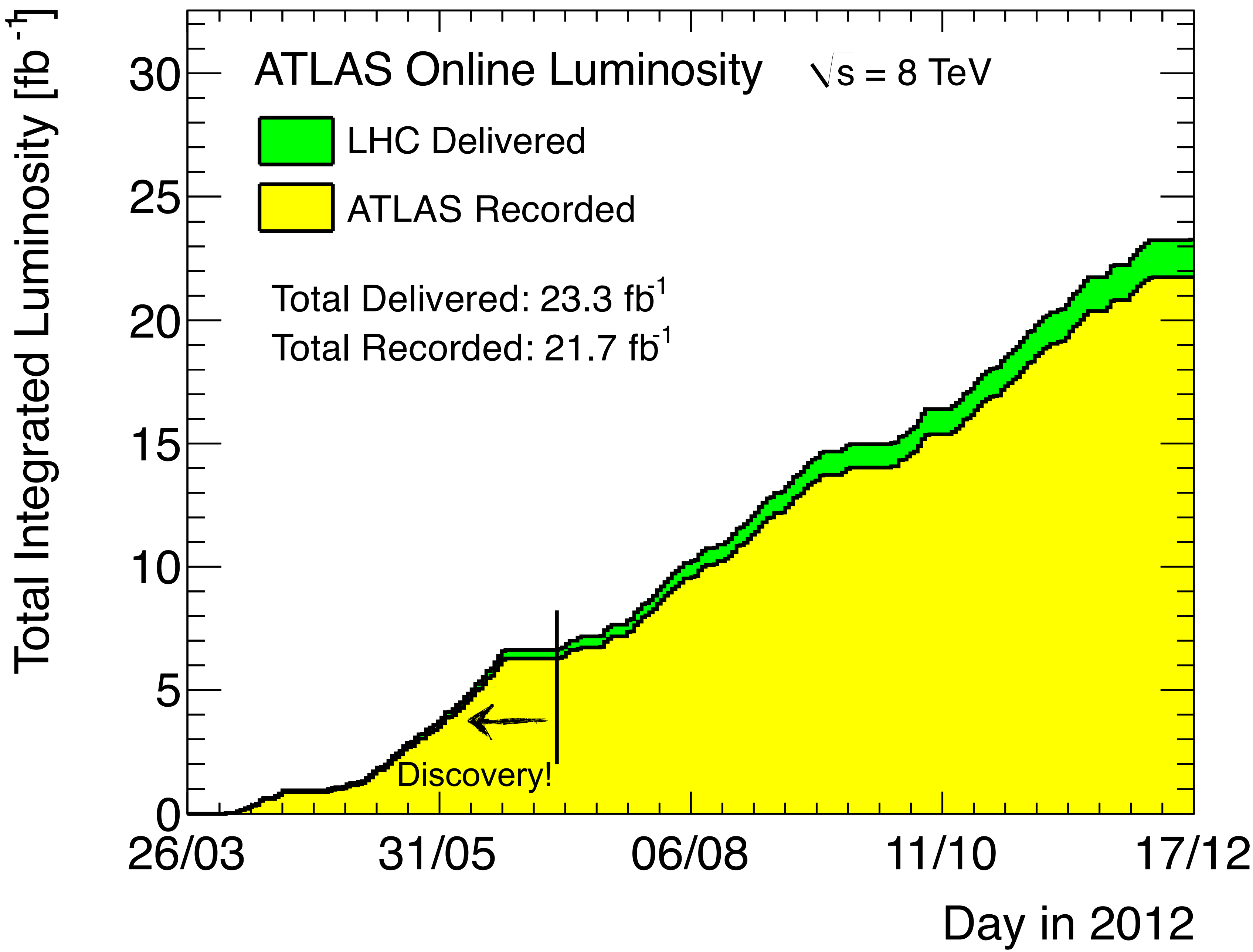
bb dominates, but is difficult

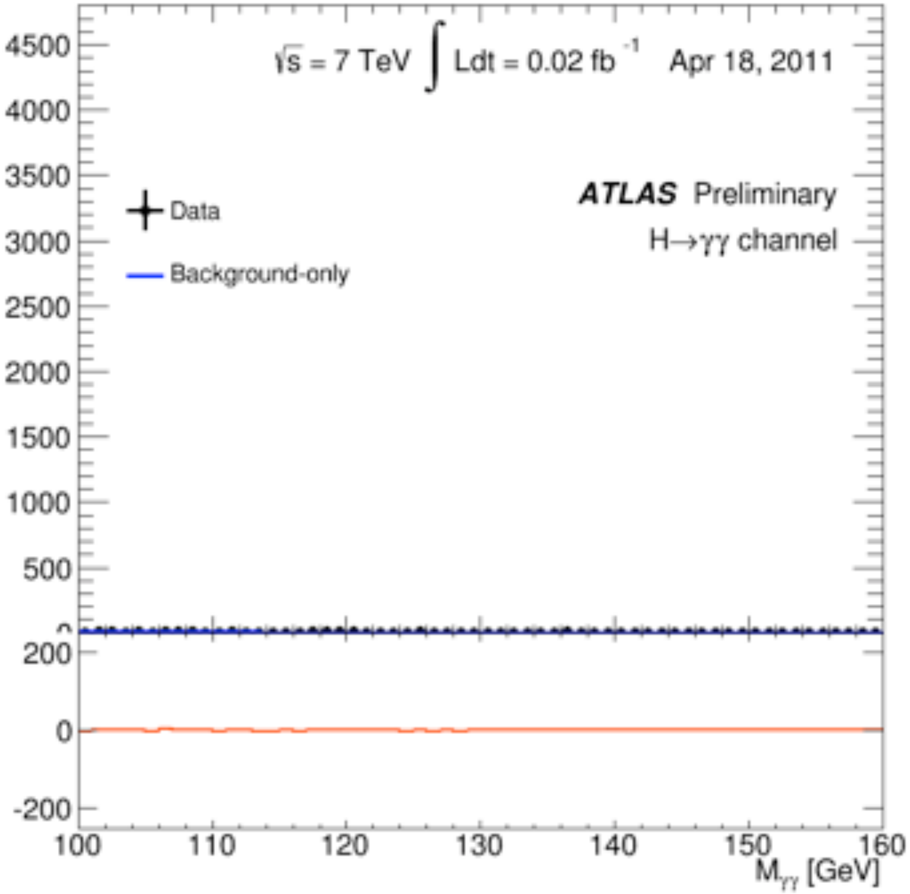
γγ small branching ratio, but clean

LHC Data

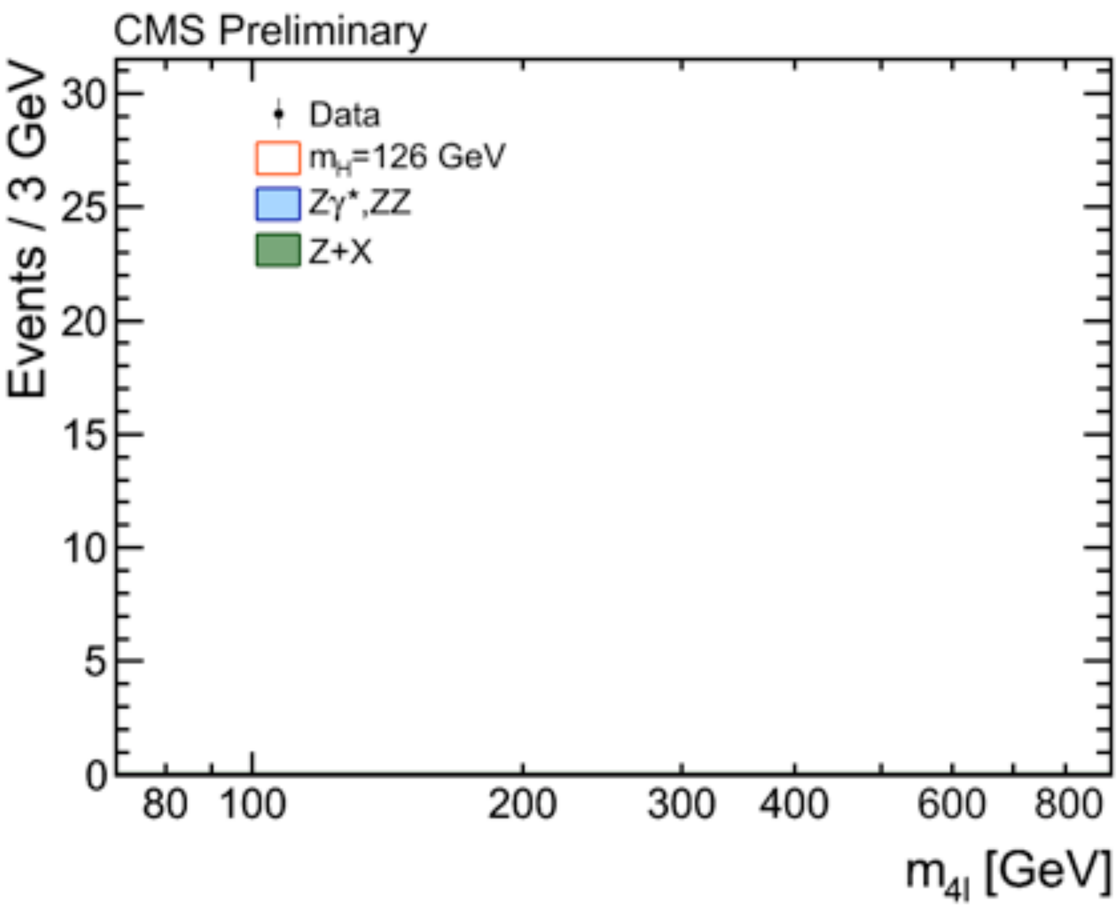
Fantastic running at the LHC leading to $>10^{15}$ p-p collisions !



Discovery!

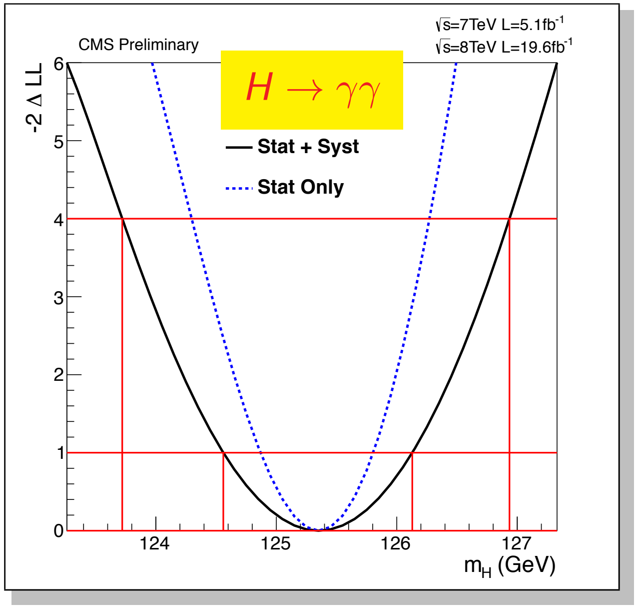


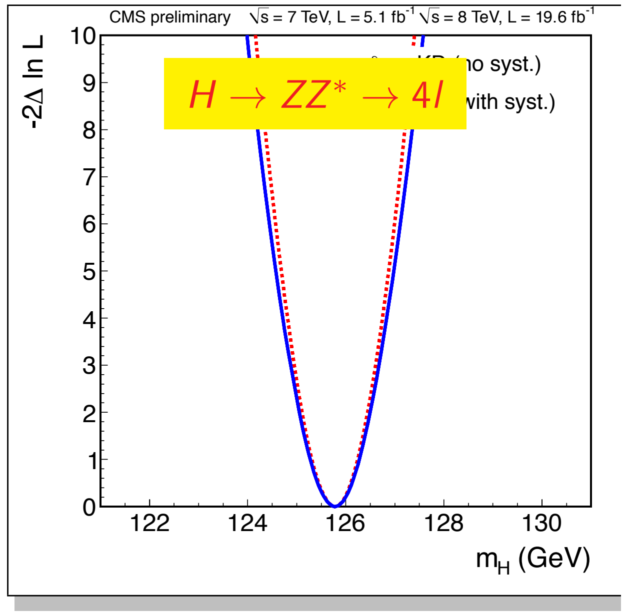
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
4500
4000
3500
3000
2500
2000
1500
1000
500
200
0
-200
100
110
120
130
140
150
160
$M_{\gamma\gamma}$ [GeV]



CMS Preliminary
Events / 3 GeV
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
30
25
20
15
10
5
0
80
100
200
300
400
600
800
m_{4l} [GeV]

Mass measurement

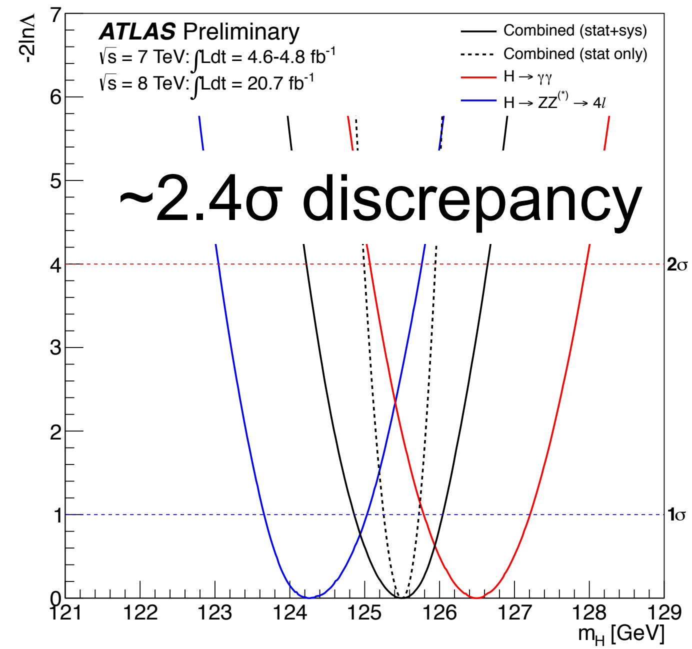




$m_X = 125.4 \pm 0.5\ (stat) \pm 0.6\ (syst)\ GeV$

$m_X = 125.8 \pm 0.5\ (stat) \pm 0.2\ (syst)\ GeV$

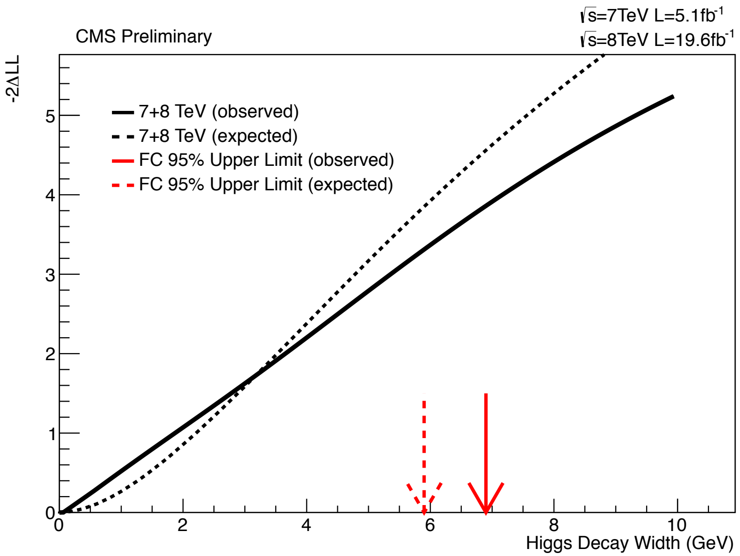
Mass from $H \to \tau\tau$ ($m_X = 120^{+9}_{-6}(stat) \pm 4(sys)\ GeV$) consistent



	$H \to ZZ^{(*)} \to \ell\ell\ell\ell$	$H \to \gamma\gamma$
$\hat{m}_H$ (GeV)	$124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{sys})$	$126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{sys})$

Combined mass:

$125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV



Spin & CP Properties

J^{PC} outlook < 1 year ago

Higgs' J^{PC}

Have we observed a scalar?

Spin $\leftrightarrows$ angular distribution of final decay products

- ☑ spin-1: forbidden by Landau-Yang's theorem (ie Bose symmetry)
- ☑ $gg \to X \to \gamma\gamma$ and $q\bar{q} \to X \to \gamma\gamma$ e.g., Gao et al '10
  - ❖ spin-0: flat in cos θ*
  - ❖ spin-2: quartic in cos θ*: $\frac{d\sigma}{d\Omega} \propto \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$
- ☑ $gg \to X \to ZZ^\star \to 4l$ Choi et al '02 De Rujula et al. '10
- ☑ $gg \to X \to WW^\star \to 2l2\nu$ Ellis, Hwang '12

Parity $\leftrightarrows$ angular distribution of final decay products

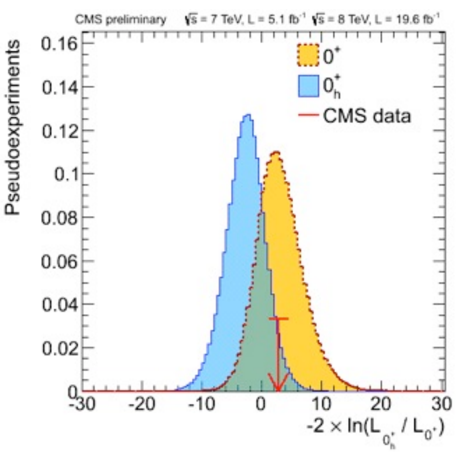
- ☑ CP-odd: couplings to W and W are loop-induced only! Hard to explain data.
- ☑ angular distribution of leptons in $gg \to X \to ZZ^\star \to 4l$
- ☑ angular distribution of jets produced in VBF Plehn et al '01
- ☑ spin correlations in $X \to \tau\tau$ Berge et al '08

Can be solved at LHC_8 (may be), LHC_{14} (for sure)

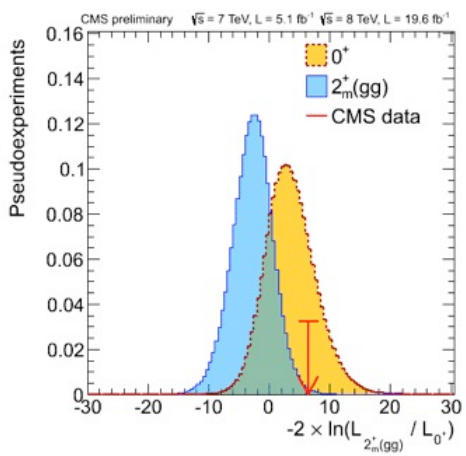
too academic questions? Sensitivity to degree admixture of admixture even/odd?

Spin & Parity @ CMS with $H \rightarrow ZZ \rightarrow 4l$

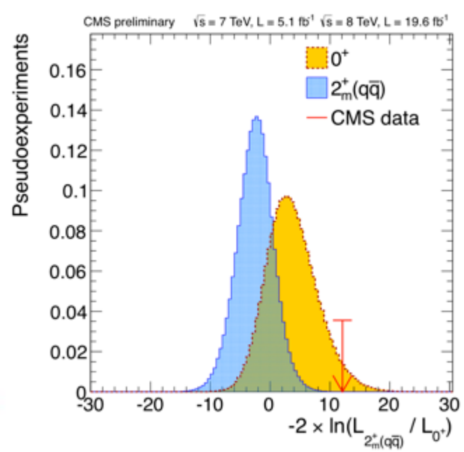
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \rightarrow X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \rightarrow X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \rightarrow X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \rightarrow X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \rightarrow X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \rightarrow X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%



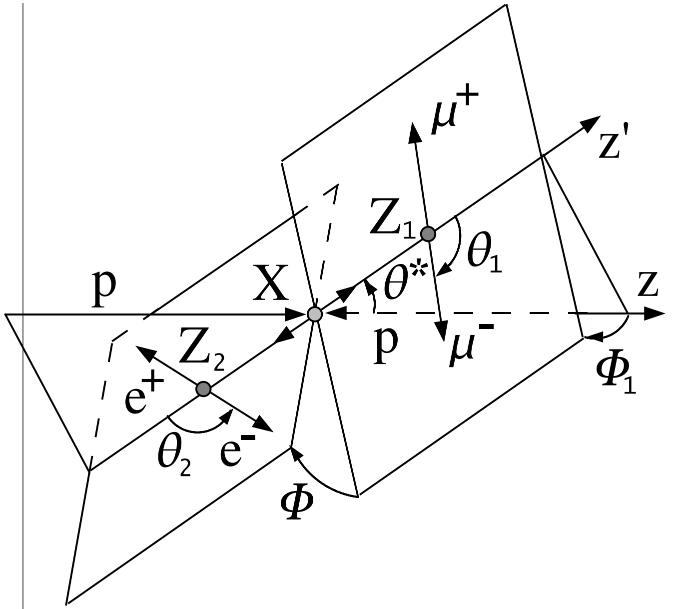
0^+_h v/s 0^+

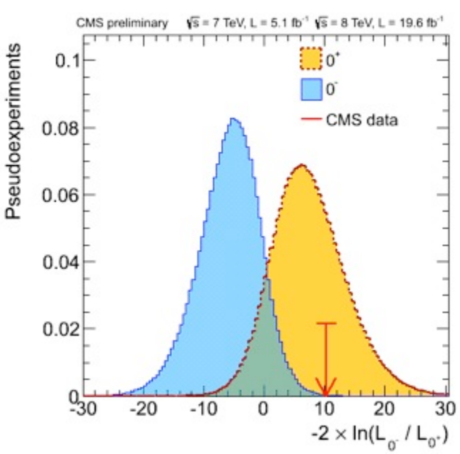


$2^+_m(gg)$ v/s 0^+

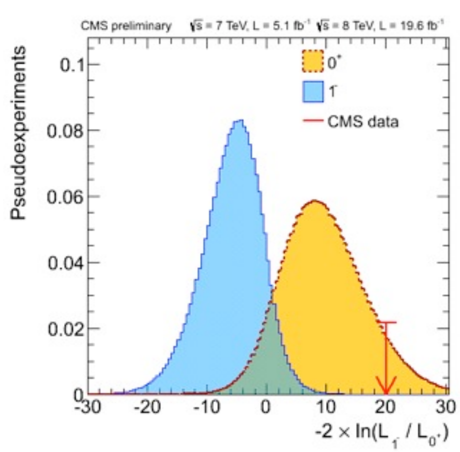


$2^+_m(qq)$ v/s 0^+

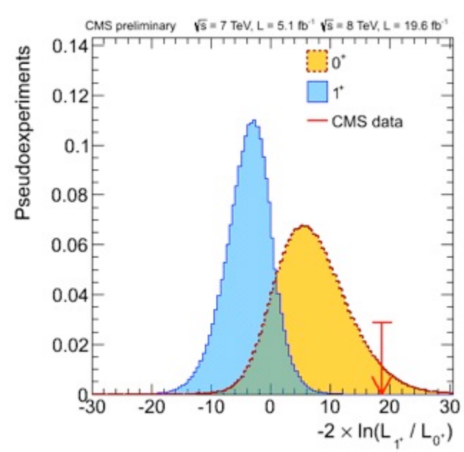




0^- v/s 0^+



1^- v/s 0^+



1^+ v/s 0^+

Spin & Parity @ CMS with H→ ZZ→ 4l

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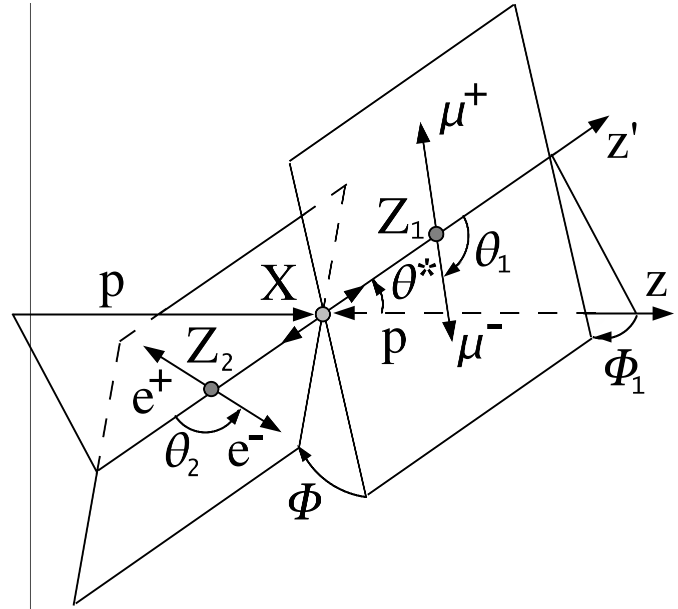
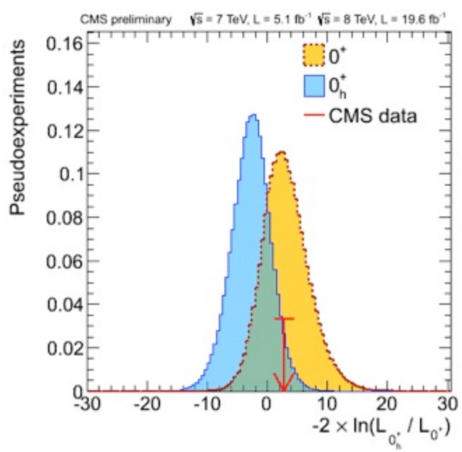
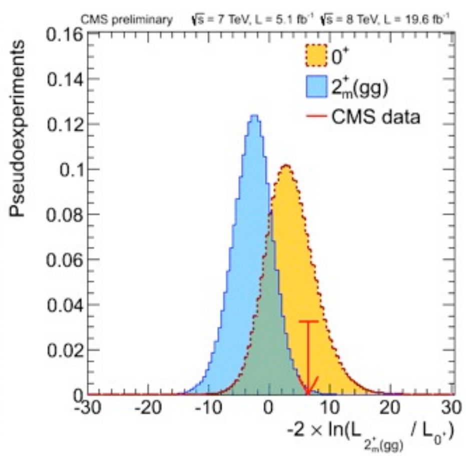
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0^+_h	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

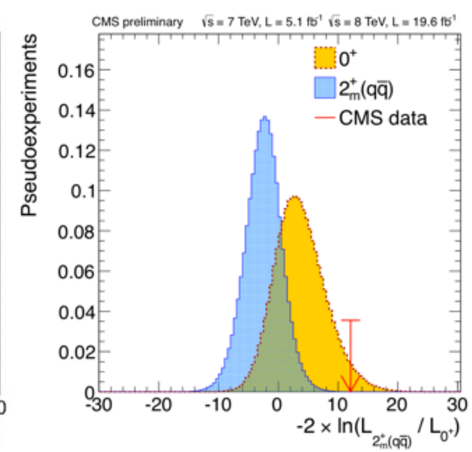




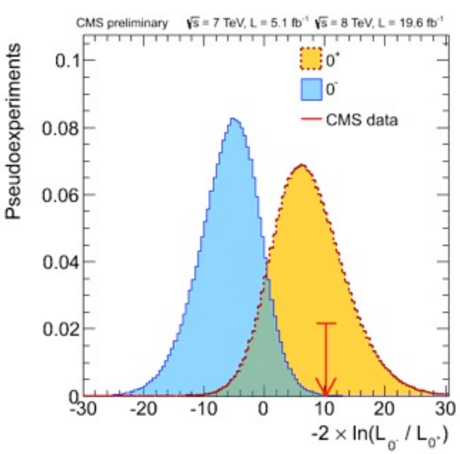
0^+_h v/s 0^+



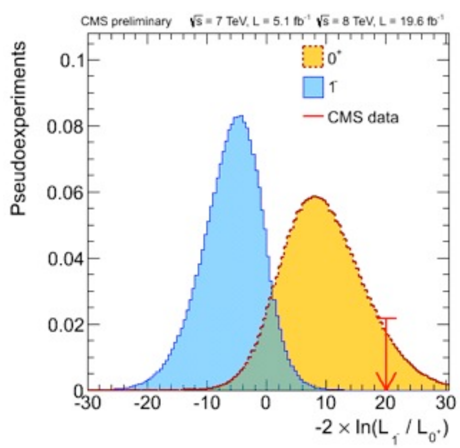
$2^+_m(gg)$ v/s 0^+



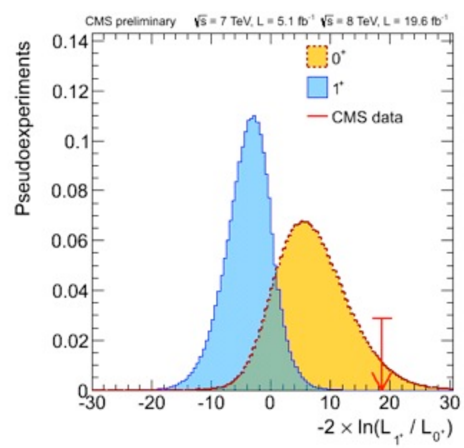
$2^+_m(qq)$ v/s 0^+



0^- v/s 0^+

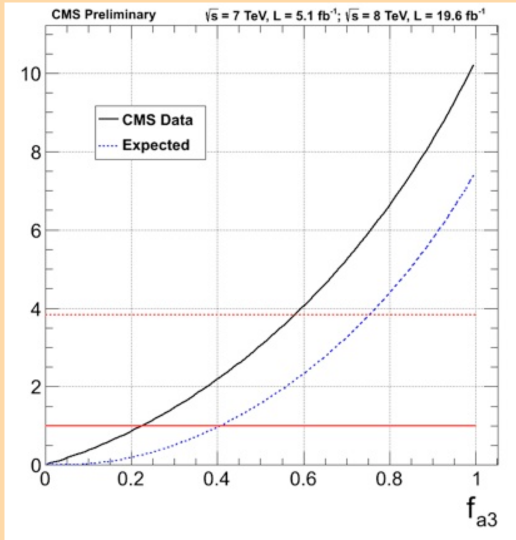


1^- v/s 0^+



1^+ v/s 0^+

Limit on $^{-/+}$ admixture

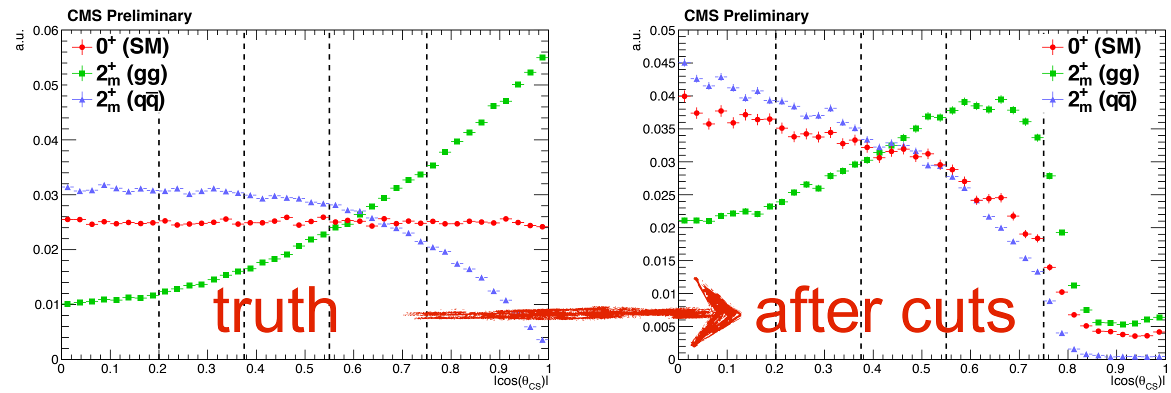


Best fit value of $f_{a3} = 0.00^{+0.23}_{-0.00}$

0+ vs. 2+

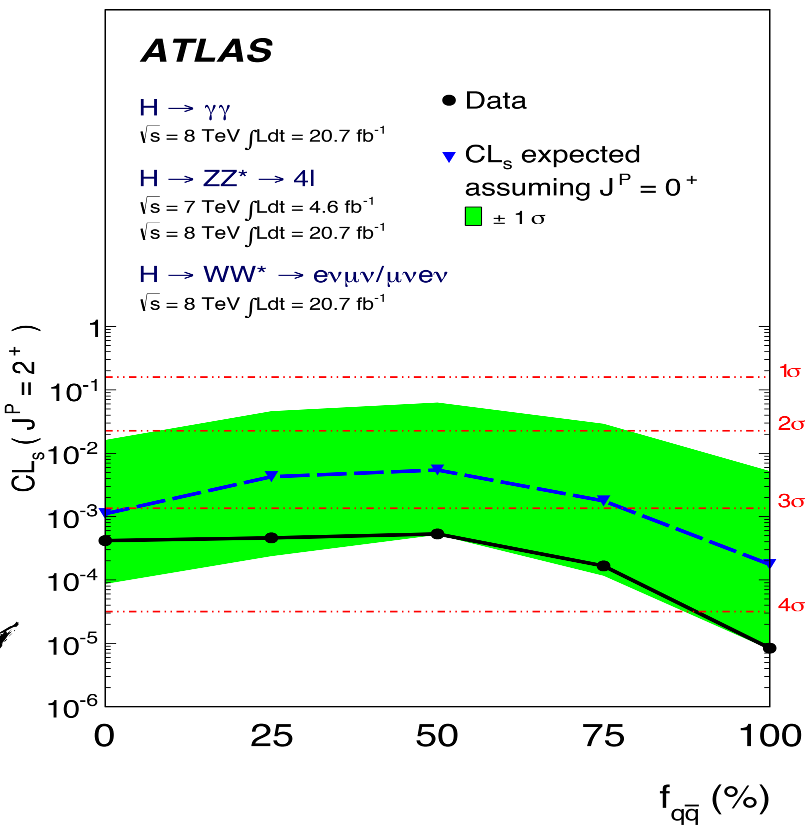
Several spin-2 models possible:

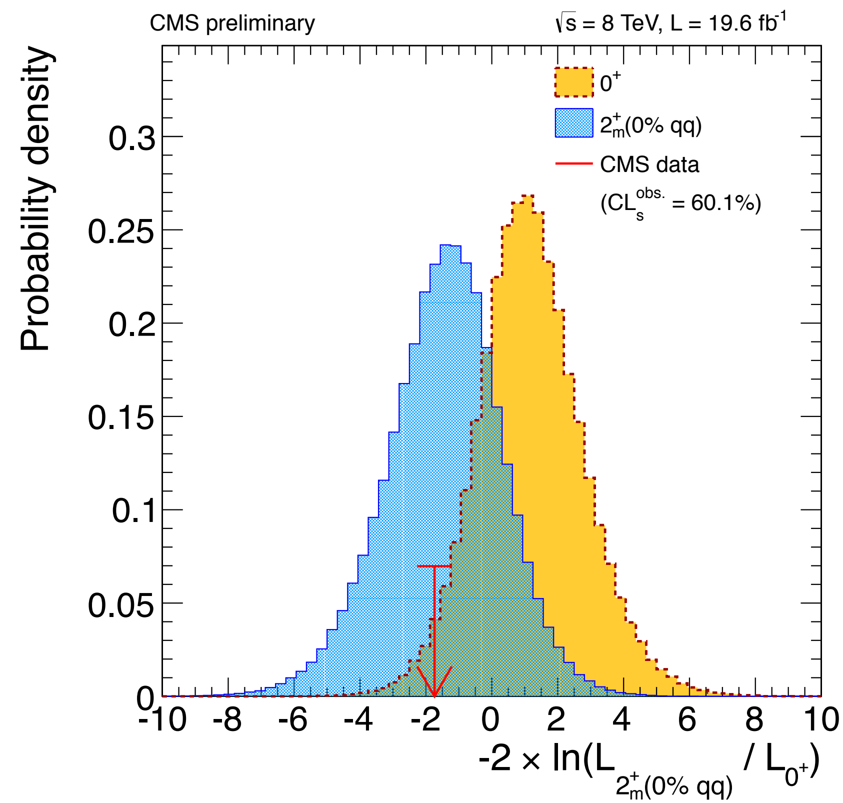
- start with graviton-inspired model with minimal couplings
- vary qq vs gg initial state frac



ATLAS result with γγ, ZZ, & WW

Spin 2 more excluded





A case 0+ is not preferred

Cross-sections and Branching Ratios

(assuming 0^+ SM tensor structure)

Details

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Channels are sub-divided to enhance sensitivity either for experimental reasons or take advantage of production features

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}$	4.6	[8]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\}$	4.8	[7]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	4.6	[9]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{$0-jet$\} \oplus \{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	4.6	[10]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	4.6	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	4.6	[11]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}\}$	20.7	[8]
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH$\}$	20.7	[7]
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Evolution of Model Complexity

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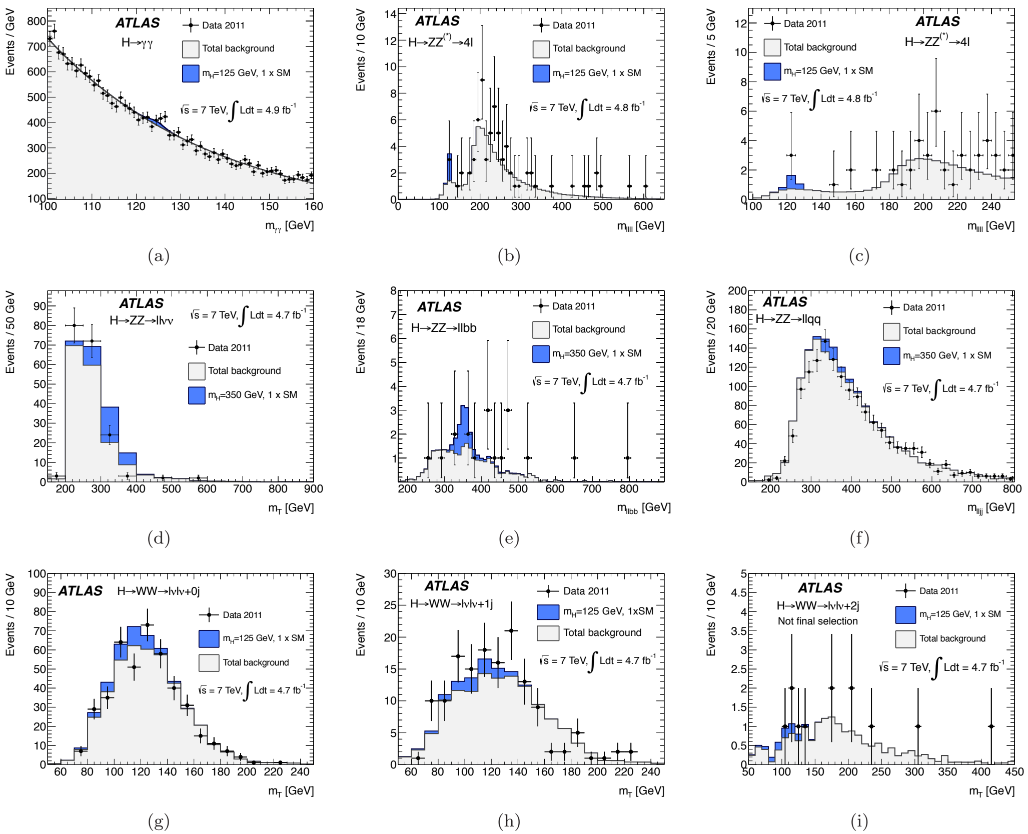
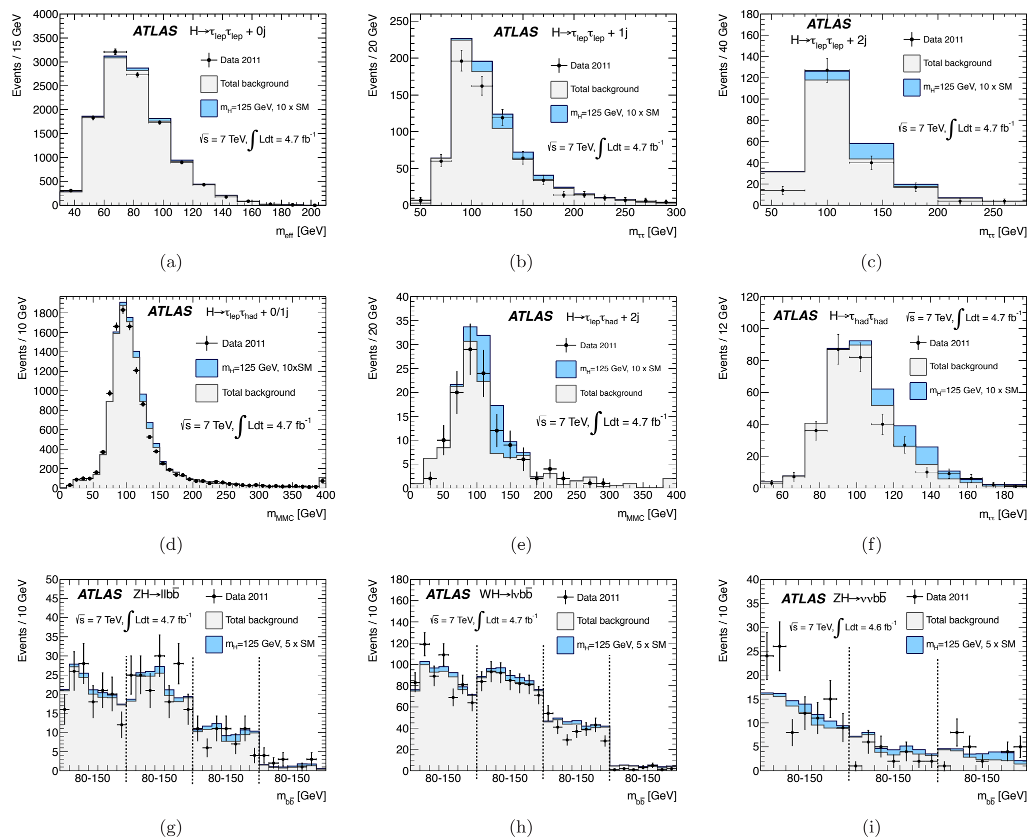
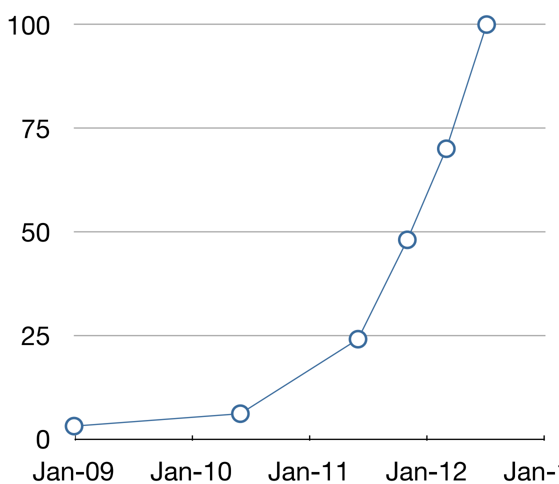
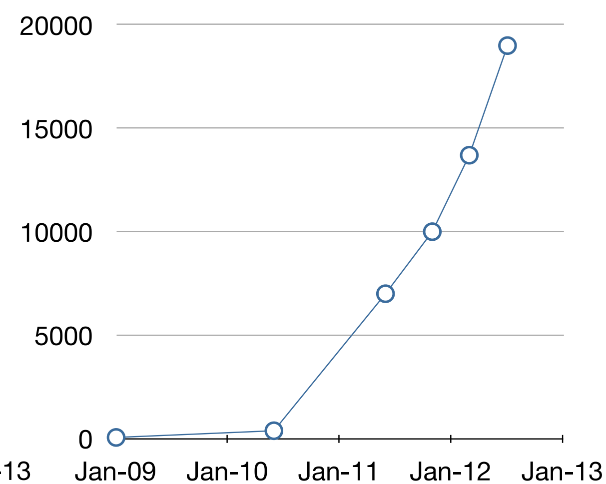




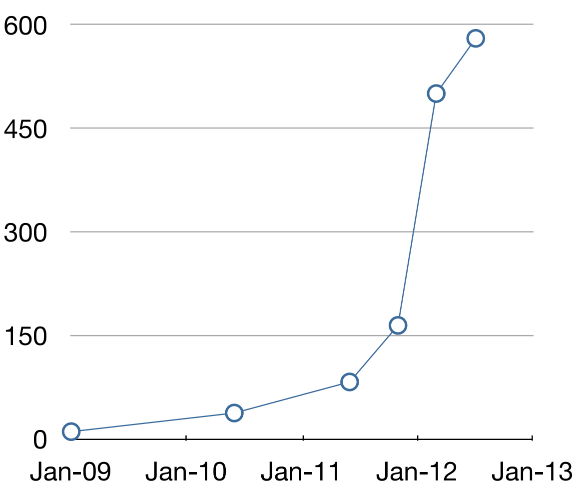
Number of Datasets Combined



Number of Model Components

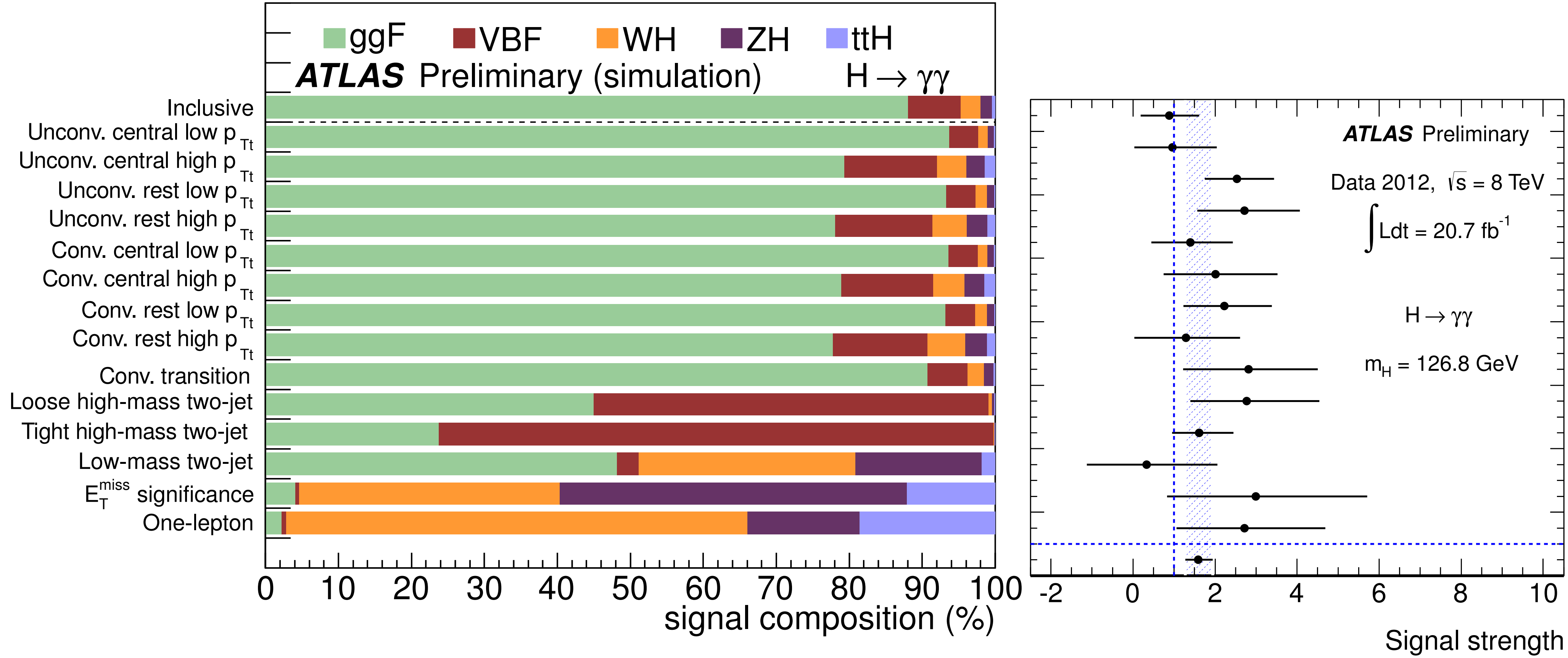


Number of Parameters in Likelihood



Disentangling multiple production modes

Center for Cosmology and Particle Physics

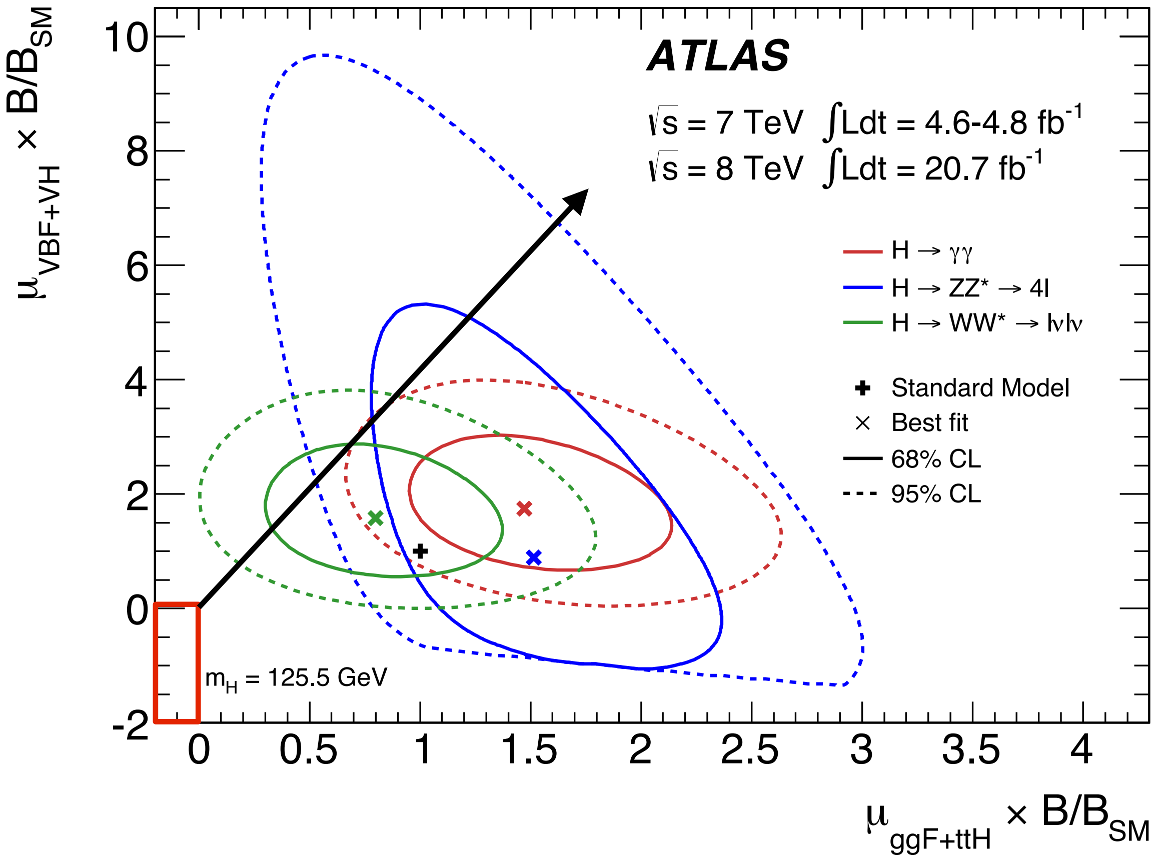


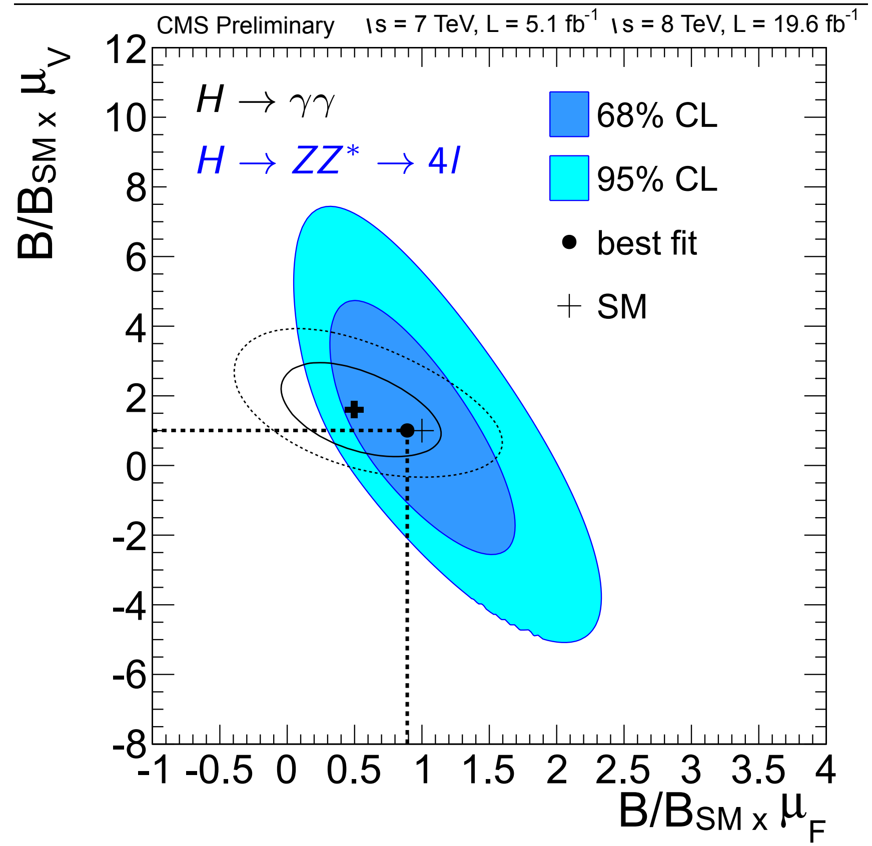
$$n^k_{\text{Signal}} = \left(\sum \mu_i \sigma_{i,SM} \times A^k_{if} \times \varepsilon^k_{if}\right) \times \mu_f \mathcal{B}_{f,SM} \times \mathcal{L}^k$$

- $\sigma_i = \mu_i \sigma_{i,SM}$ is the i^{th} hypothesized production cross section
- $\mathcal{B}_f = \mu_f \mathcal{B}_{f,SM}$ is the f^{th} hypothesized branching fraction
- Detector acceptance A^k_{if}, reconstruction efficiency ε^k_{if}, and integrated luminosity $\mathcal{L}^k$ are fixed by above assumptions

Model-independent presentation

CENTER FOR COSMOLOGY AND PARTICLE PHYSICS





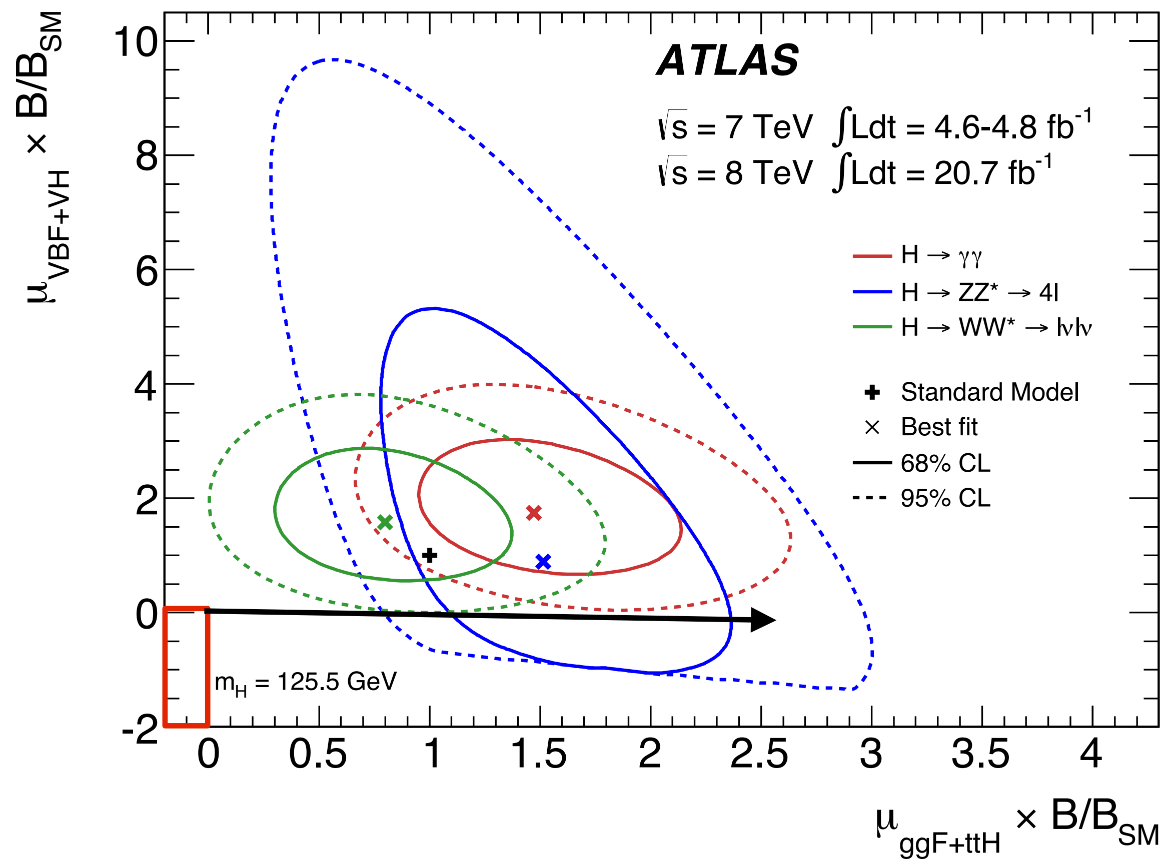
Can't compare contours directly, b/c there is a different BR for axis

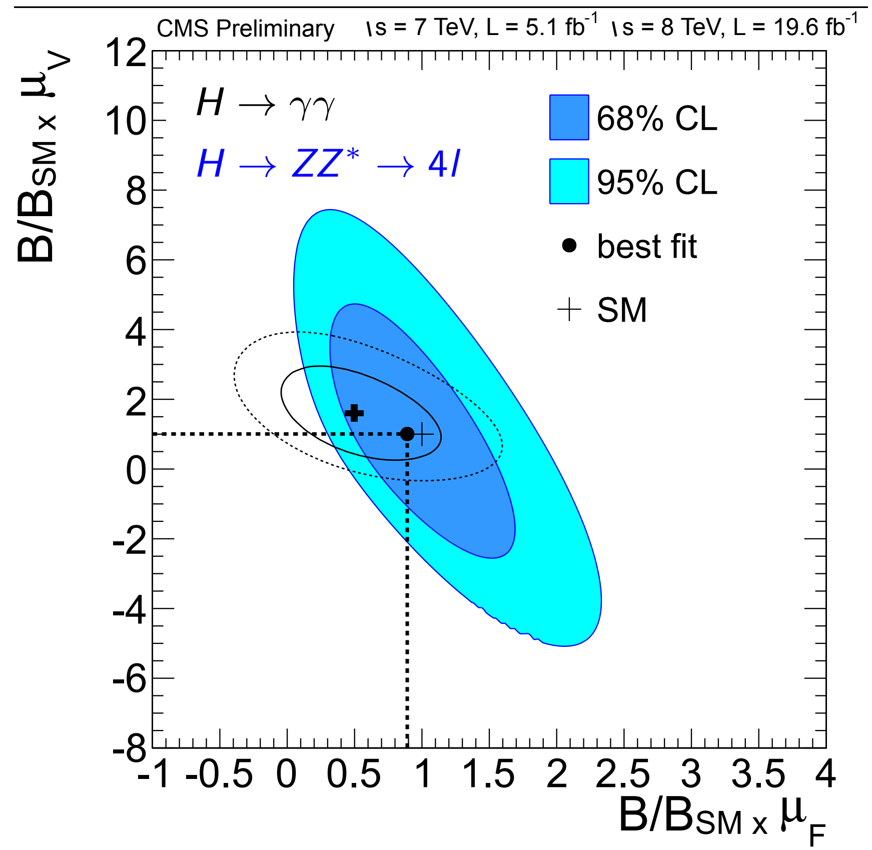
But, BR cancels when considering slope in this plane

- still sensitive to theory uncertainties (jet veto, ggH+2jet contamination,...)

Note: All coupling measurements pass through this space

Model-independent presentation





Can’t compare contours directly, b/c there is a different BR for axis

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Note: All coupling measurements pass through this space

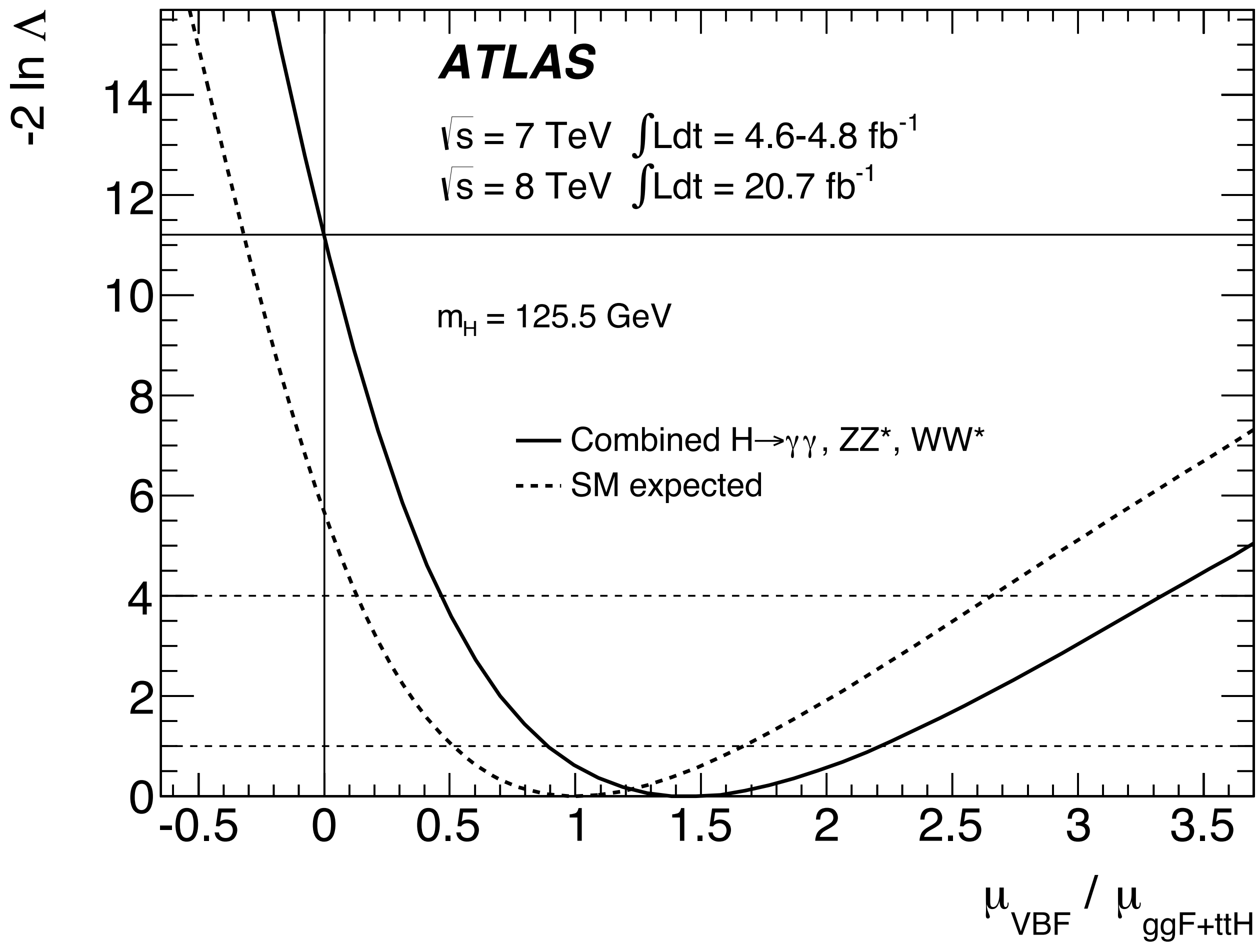
Model-independent presentation

Center for Cosmology and Particle Physics

Can't compare contours directly, b/c there is a different BR for axis

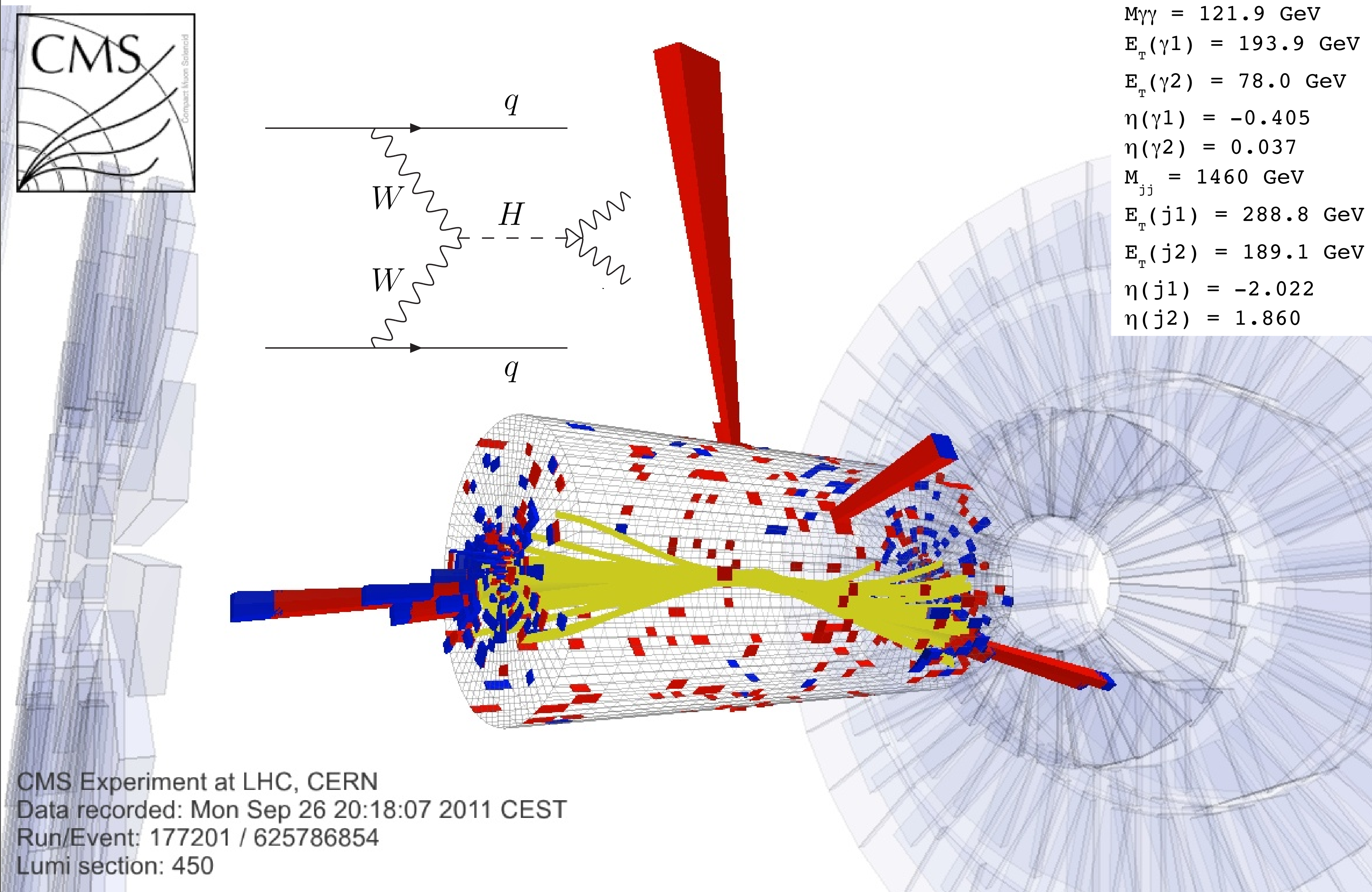
But, BR cancels when considering slope in this plane

- mild sensitivity to theory uncertainties (jet veto, ggH+2jet contamination,...)



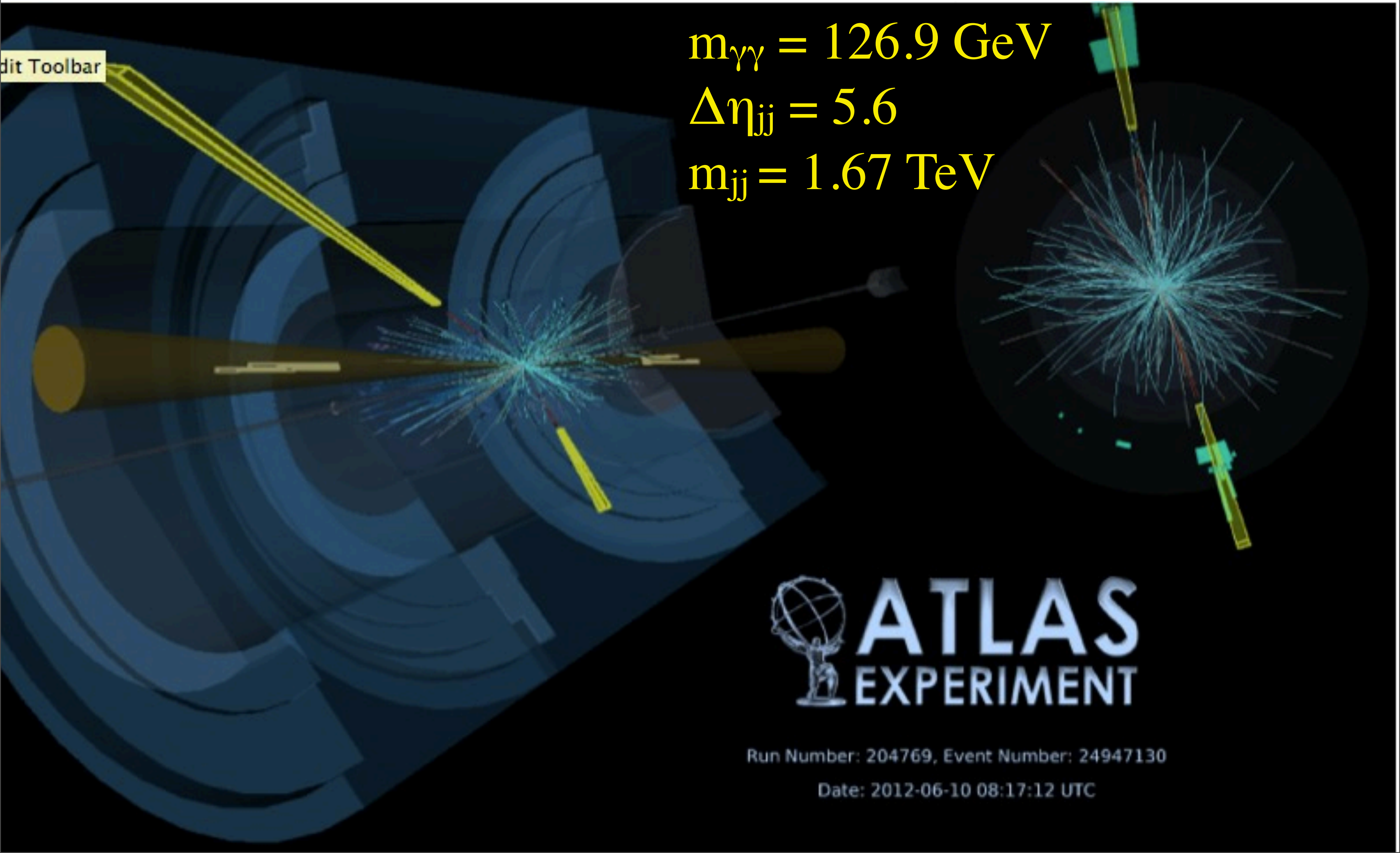
>3σ evidence for VBF Higgs production!

VBF 2-photon candidate



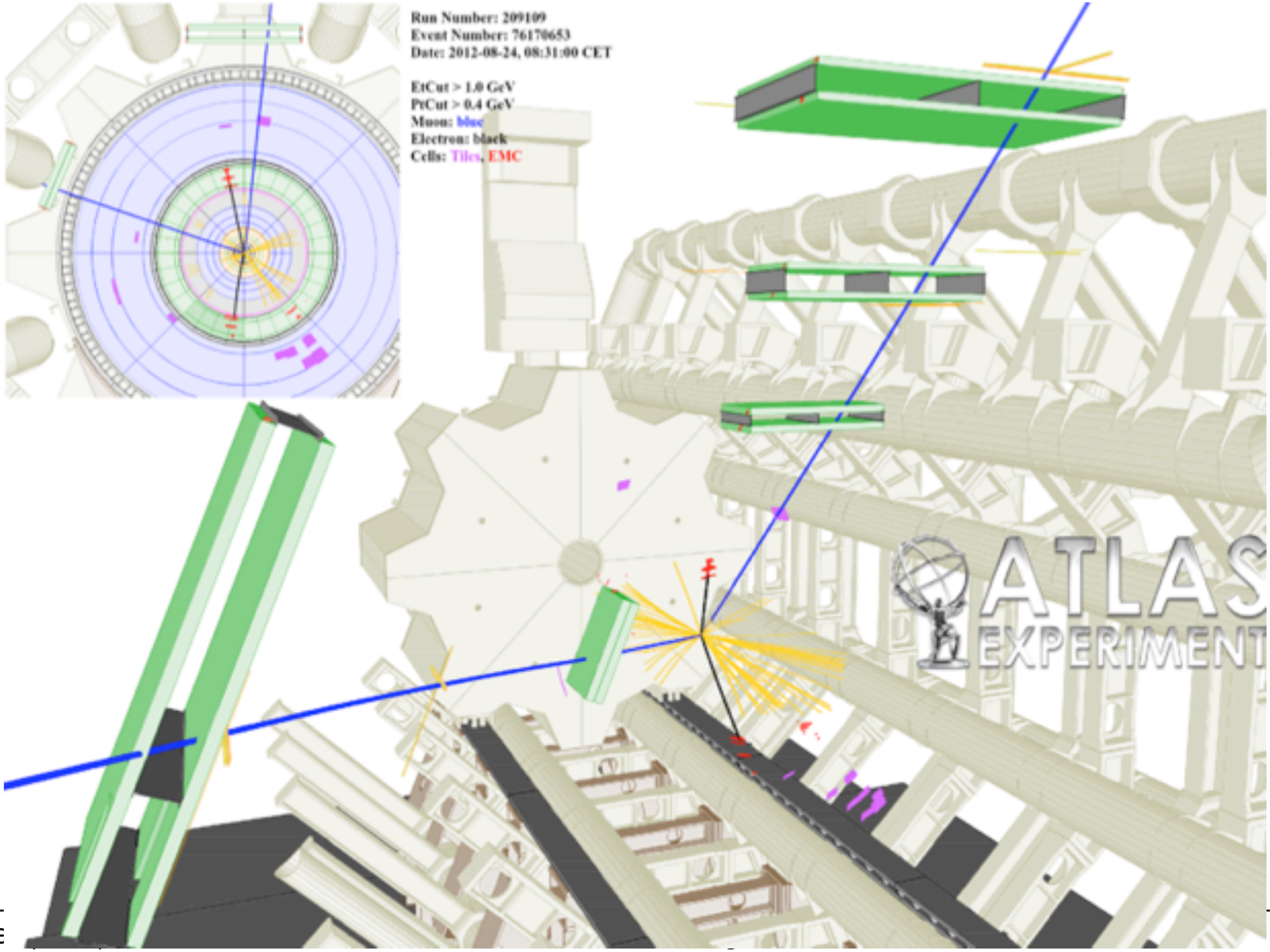
VBF 2-photon candidate

About 12 Higgs events expected in VBF-like categories



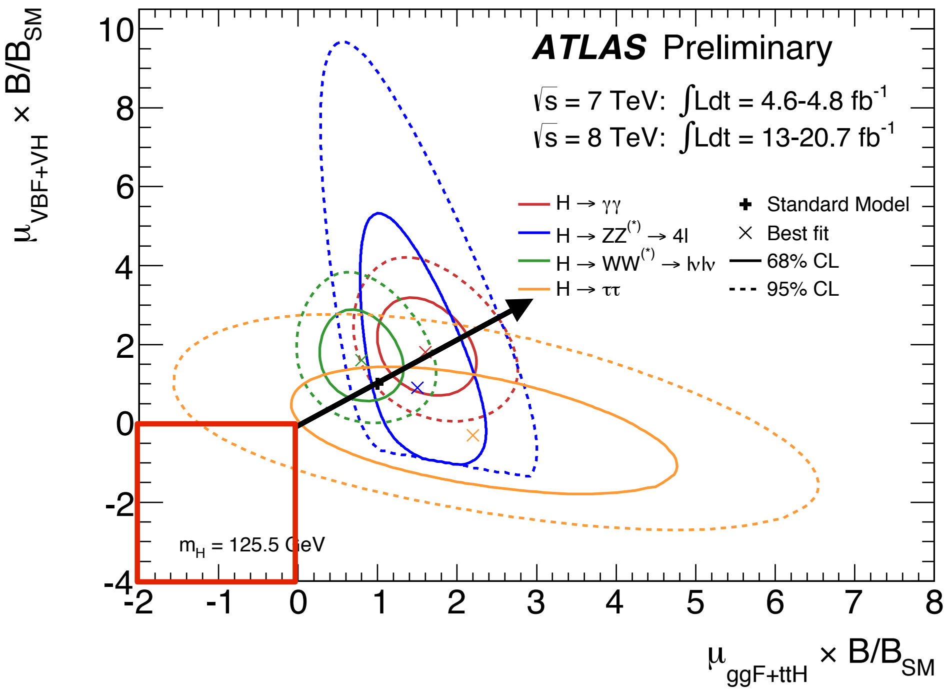
VBF H→ 4l candidate

1 VBF candidate observed (m_{4l}=123.5 GeV) [0.7 expected, S/B~5]



Ratio of Branching Ratios

A model independent approach less sensitive to theory uncertainties

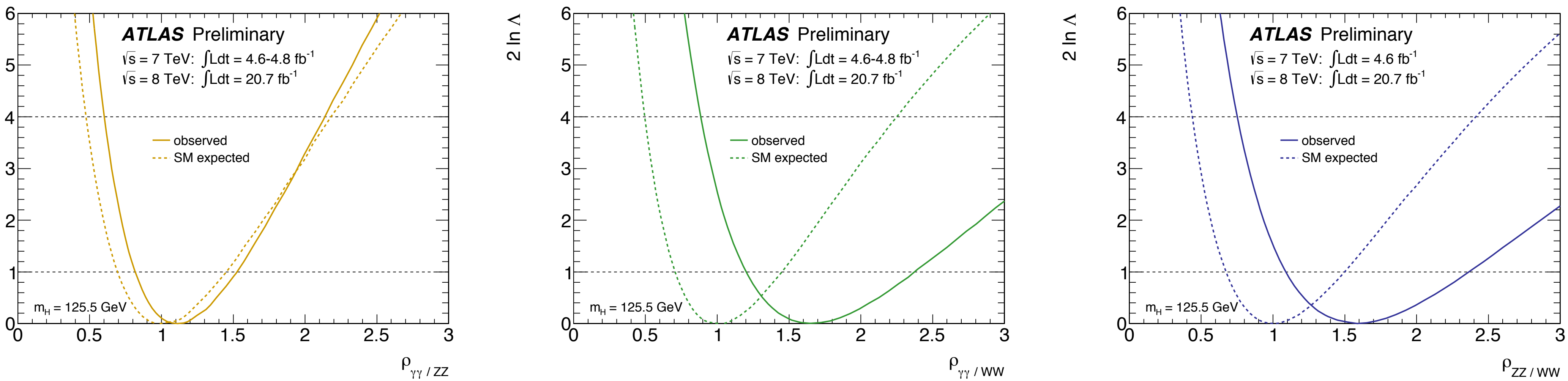


$$\rho_{\gamma\gamma/ZZ} = \frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^{(*)})} \times \frac{\mathrm{BR}_{\mathrm{SM}}(H\to ZZ^{(*)})}{\mathrm{BR}_{\mathrm{SM}}(H\to\gamma\gamma)}$$

$$\rho_{\gamma\gamma/ZZ} = 1.1^{+0.4}_{-0.3}$$

$$\rho_{\gamma\gamma/WW} = 1.7^{+0.7}_{-0.5}$$

$$\rho_{ZZ/WW} = 1.6^{+0.8}_{-0.5}$$



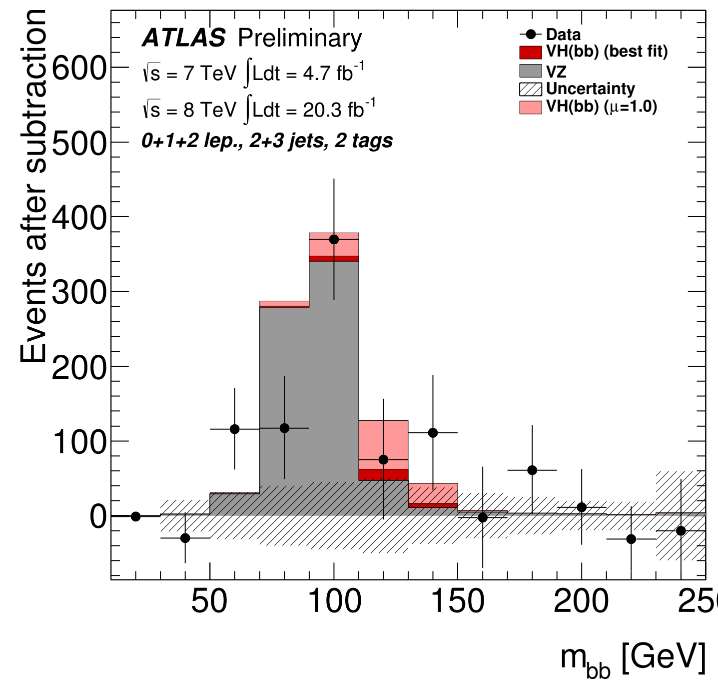
VH status

VH production not yet firmly established

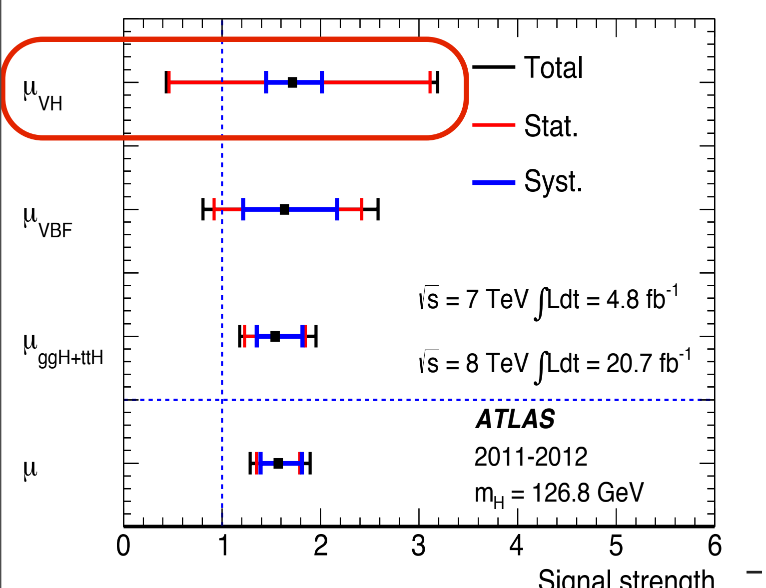
- Channels:
  - H→ $\gamma\gamma$: simple lepton tag, few events
  - H→ bb: complicated analyses
- Sensitivity at ~2x SM rate

ATLAS & CMS both see a convincing diboson peak in H→ bb with slight Higgs-like excess

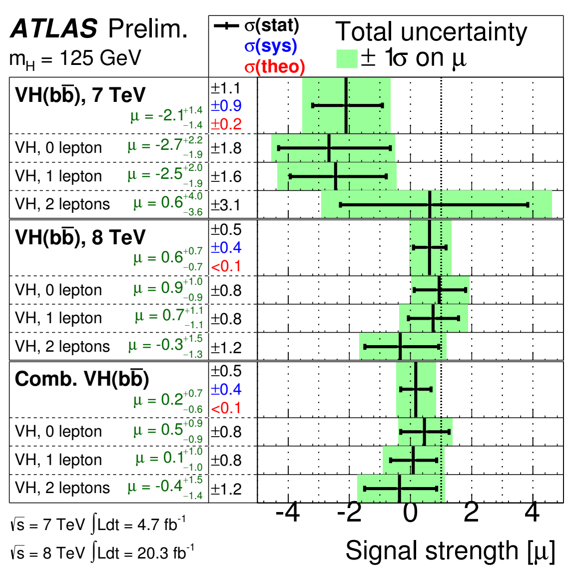
- evidence for VH at Tevatron



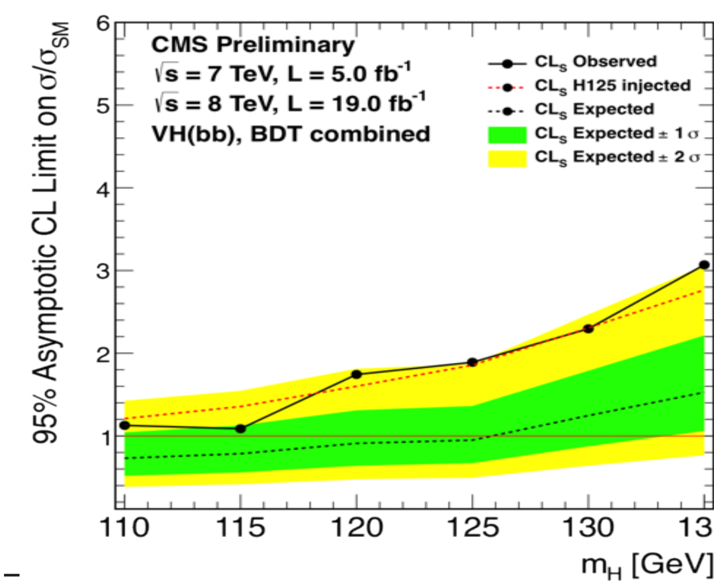
H→ $\gamma\gamma$ @ ATLAS



H→bb @ ATLAS



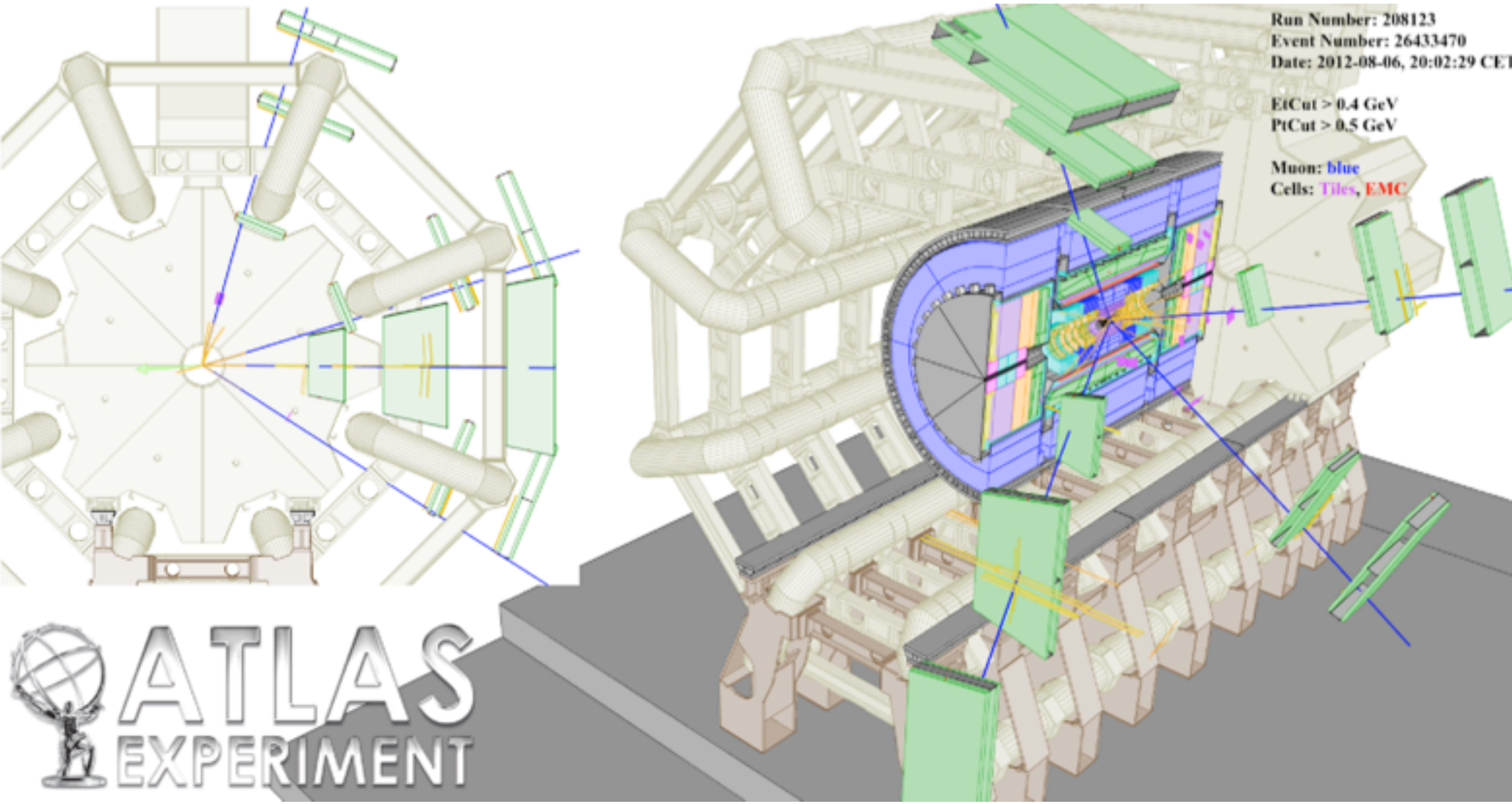
H→bb @ CMS



Our SM bias?

ATLAS does not have a Z(→ νν) H(→4l) b/c sensitivity in SM is small

m_{4l}=123.5 GeV, ETmiss=121.3 GeV



Couplings

Narrow width approximation

The basic starting point for the various parametrizations :

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma}$$

No useful direct constraint on total width at LHC

- ideally, allow for invisible or undetected partial widths
- leads to an ambiguity unless something breaks degeneracy

Various strategies / assumptions break this degeneracy

- Assume no invisible decays
- Fix some coupling to SM rate
- Only measure ratios of couplings
- Limit $\Gamma_V \leq \Gamma_V^{\mathrm{SM}}$ eg. Dührssen et. al, Peskin, ...
  - valid for CP-conserving H, no H^{++}, ... Gunion, Haber, Wudka (1991)
  - together with $\Gamma_V^2/\Gamma = \mathrm{meas} \quad \Rightarrow \quad \Gamma_{\mathrm{vis}} \leq \Gamma \leq \Gamma_{V,SM}^2/\mathrm{meas}$

Parametrizing the couplings

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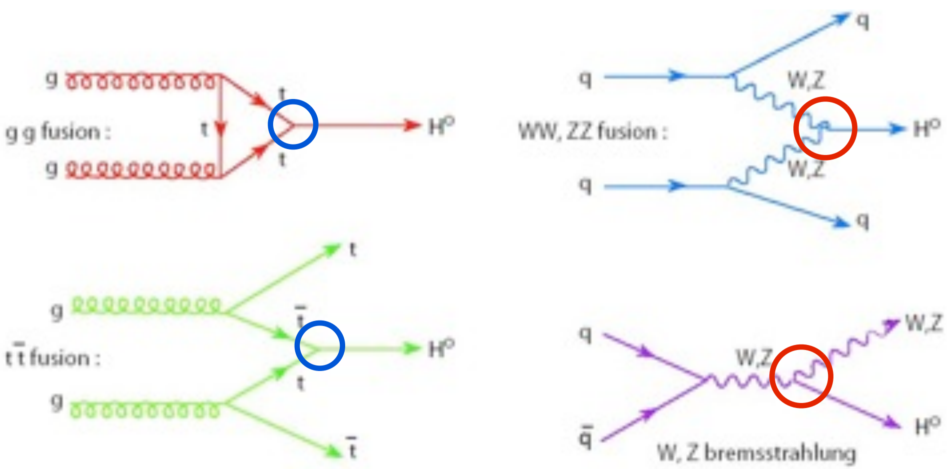
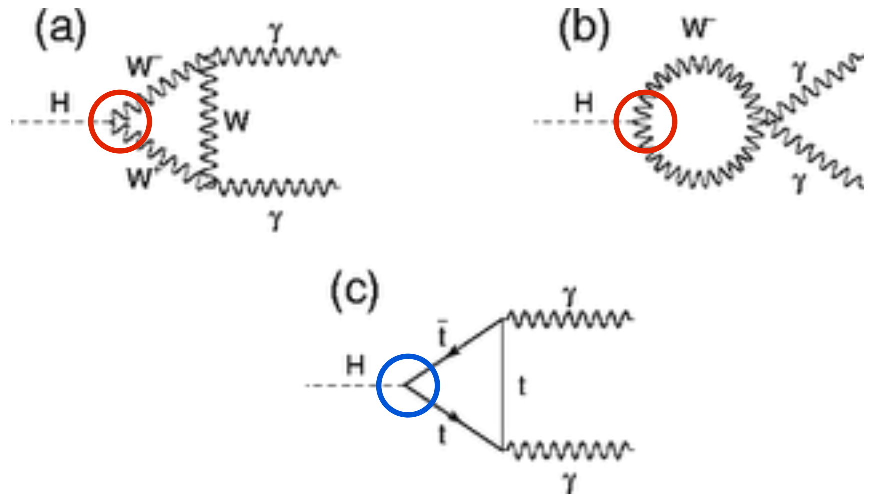
Approach: scale couplings w.r.t. SM values by factor κ

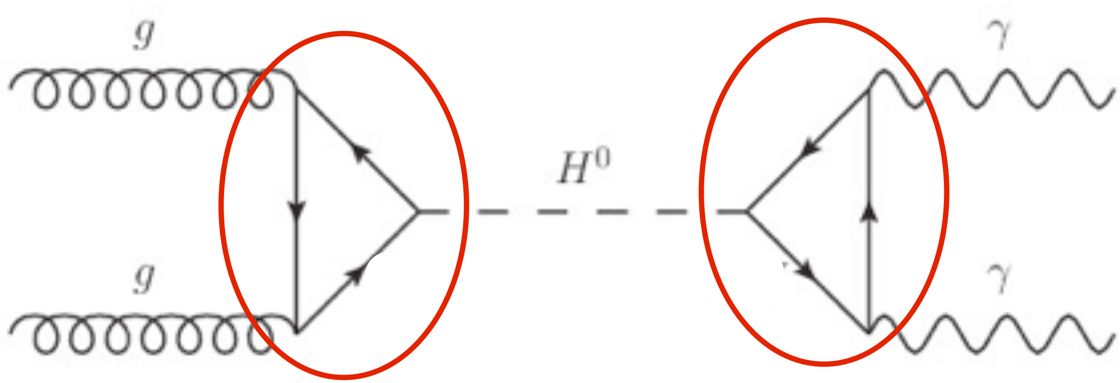
- Expansion around SM point with state-of-the-art predictions

Option 1) relate ggH and $\gamma\gamma$H assuming no new particles in loop





Option 2) introduce κ_g and κ_γ as effective coupling to ggH and $\gamma\gamma$H



Benchmark models

Fully model independent fit is not very informative with current data

- Benchmarks proposed by joint theory/experiment LHC XS group

arXiv:1209.0040

Probe Fermionic vs. Bosonic couplings:

- relevant for Type I 2HDM

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$$
$$\kappa_V = \kappa_W = \kappa_Z$$

Probe W vs. Z couplings (custodial symmetry)

Probe up. vs. down fermion couplings

Probe quark vs. lepton couplings

Probe new particles in ggH and $\gamma\gamma$H loops

Probe invisible decays

Example Coupling results

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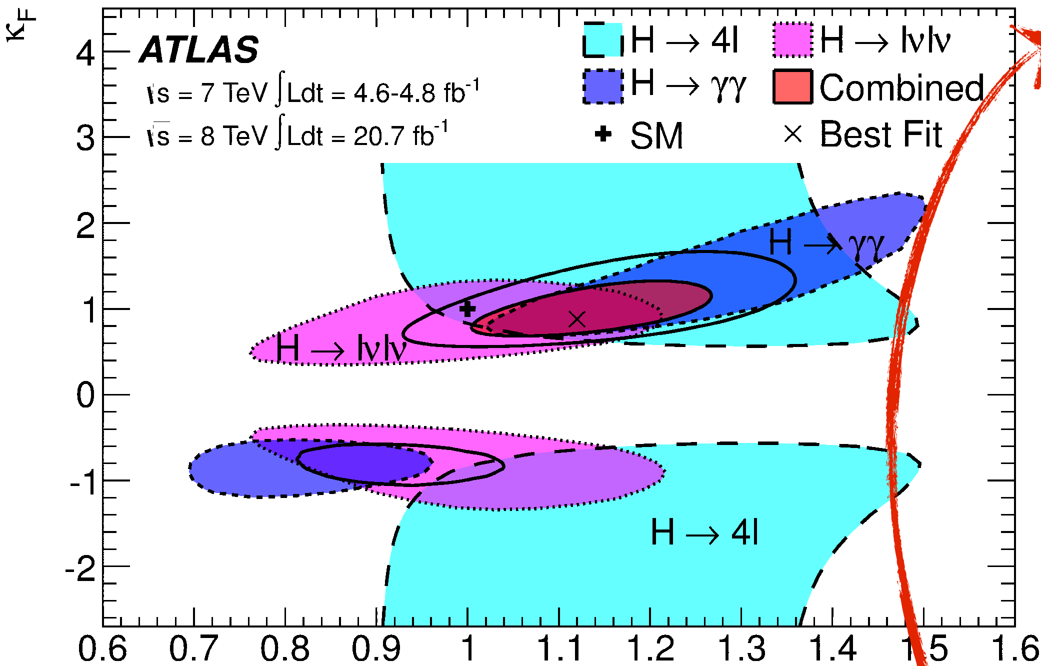
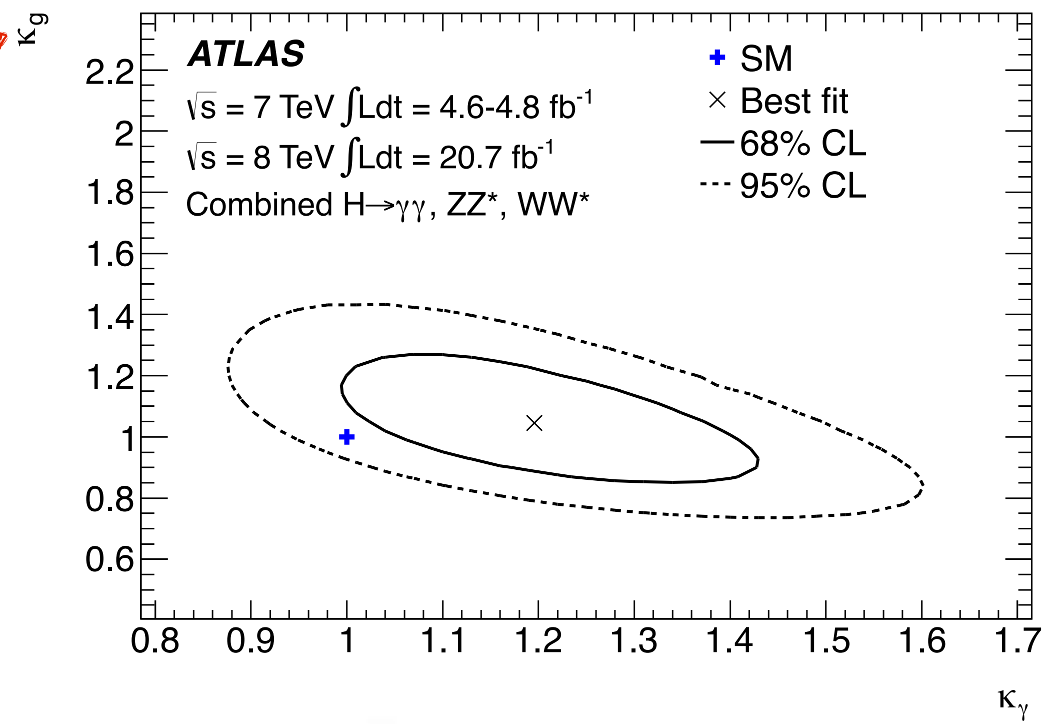
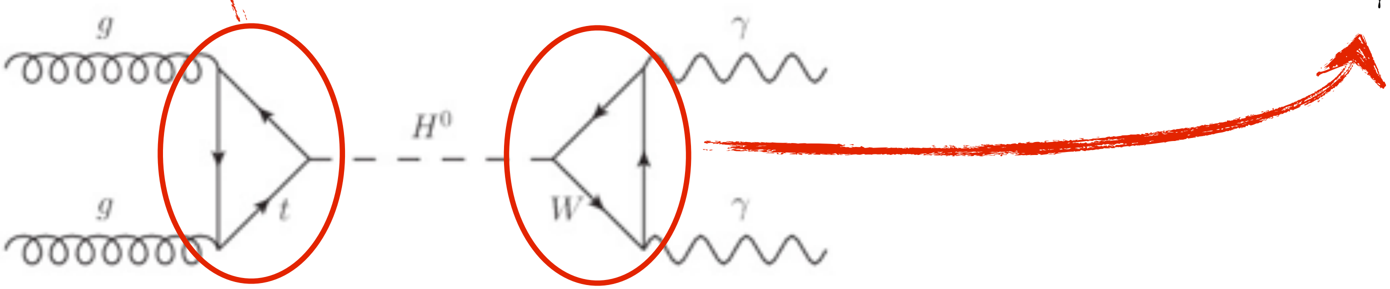
Here, evidence for fermion couplings is indirect





$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$$

$$\kappa_V = \kappa_W = \kappa_Z$$



Results from various fits

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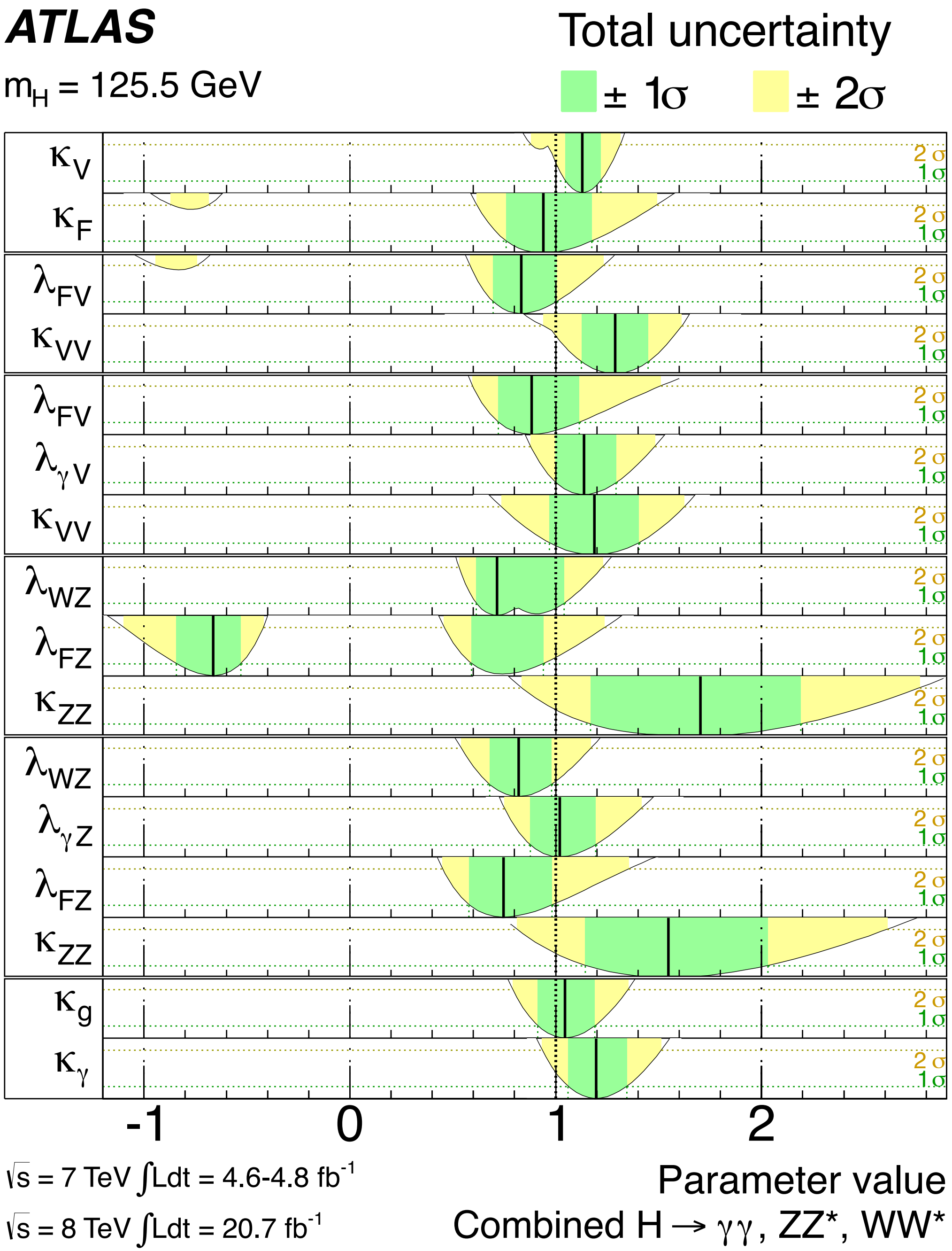

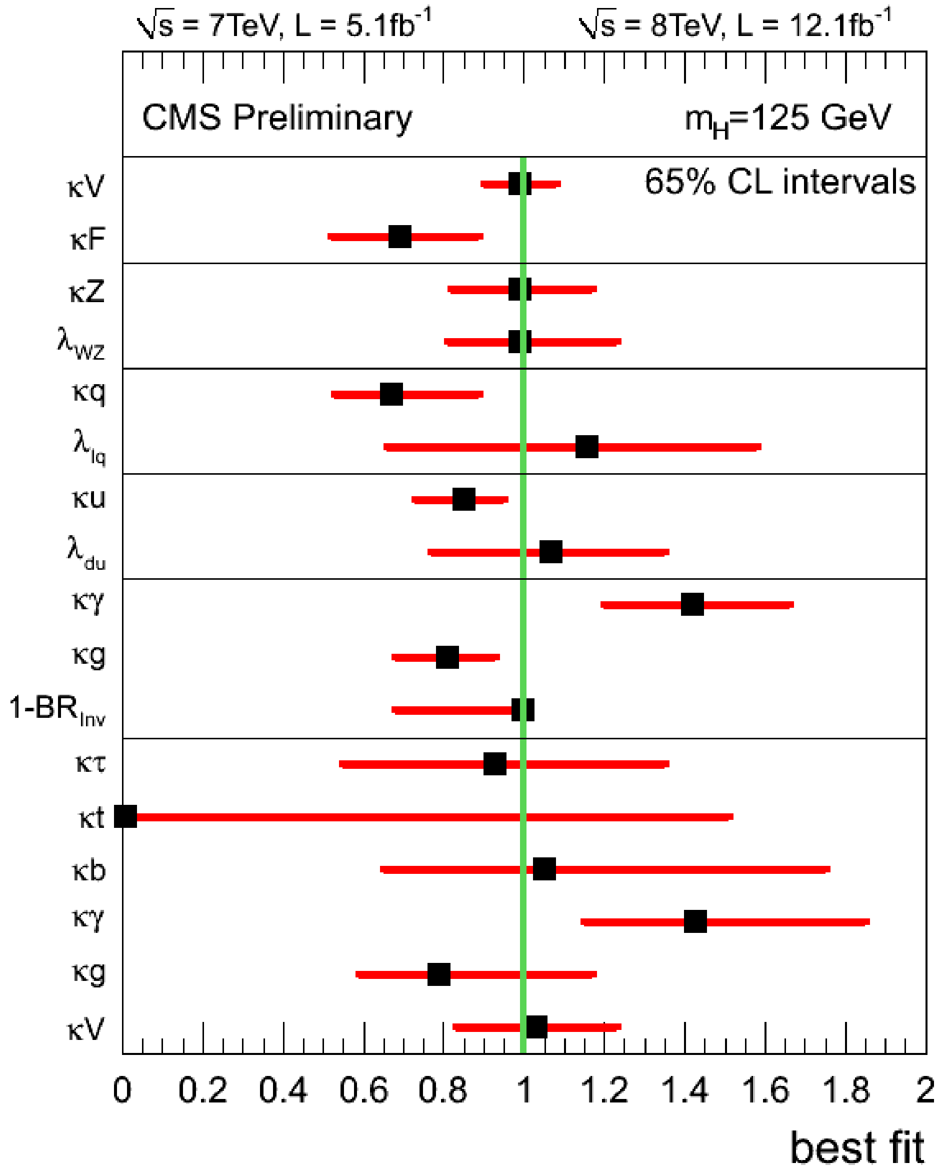

Tevatron results

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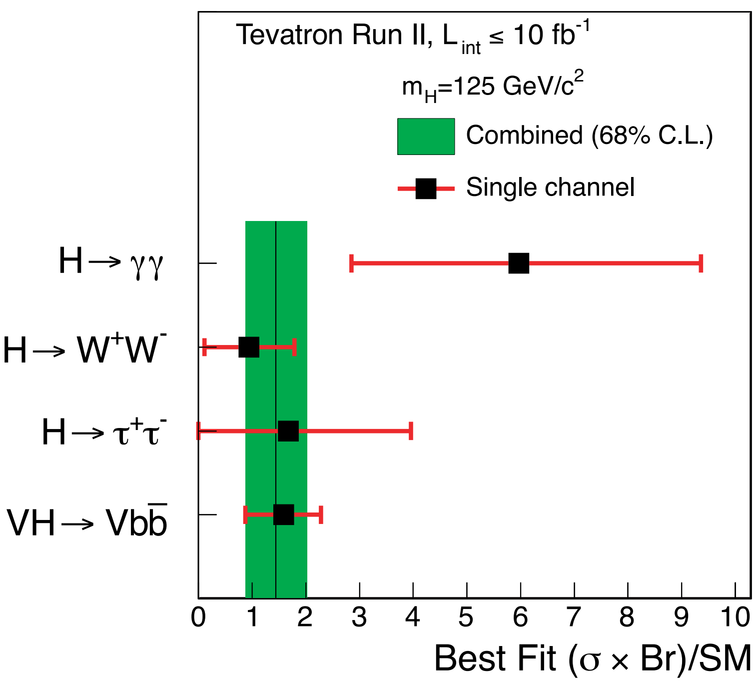
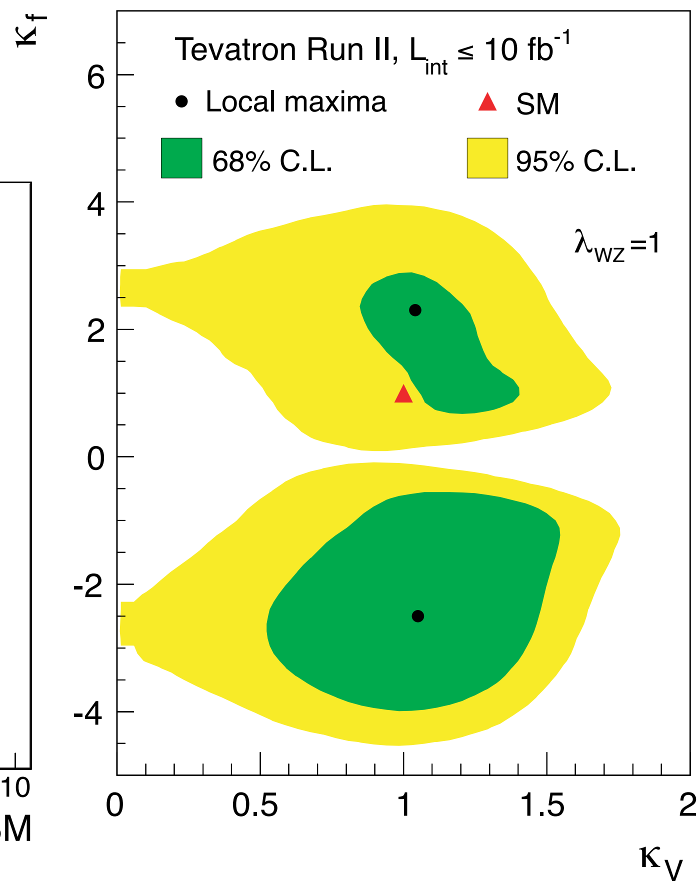
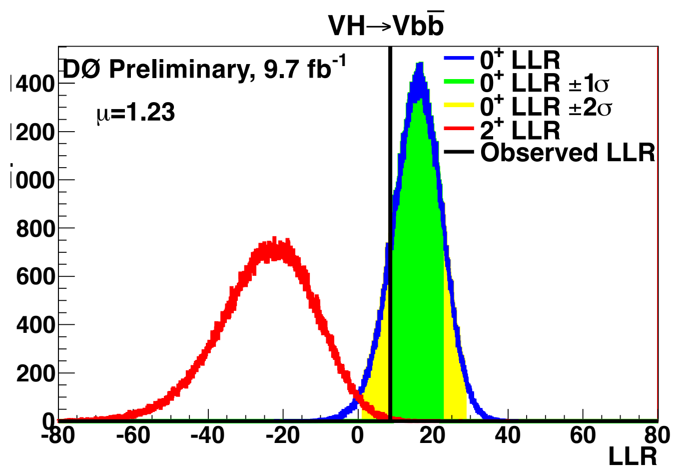
Tevatron is mainly sensitive to VH production

- sees evidence for H→ bb
- High H→$\gamma\gamma$ affects best-fit fermion coupling







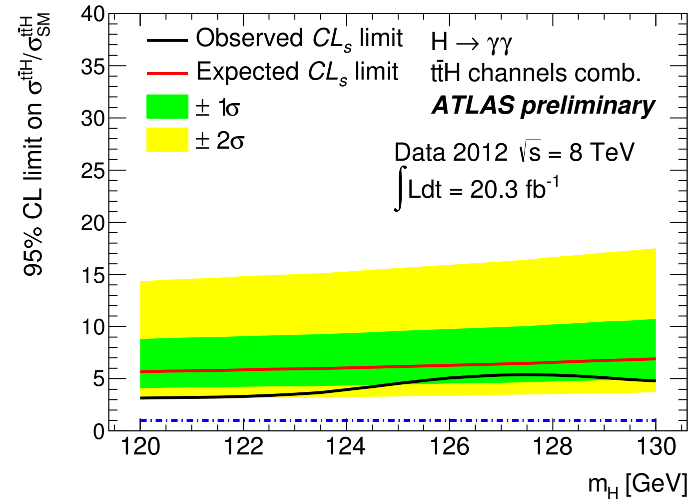
signal strength | fermion, vector coupling | spin 0+ vs 2+

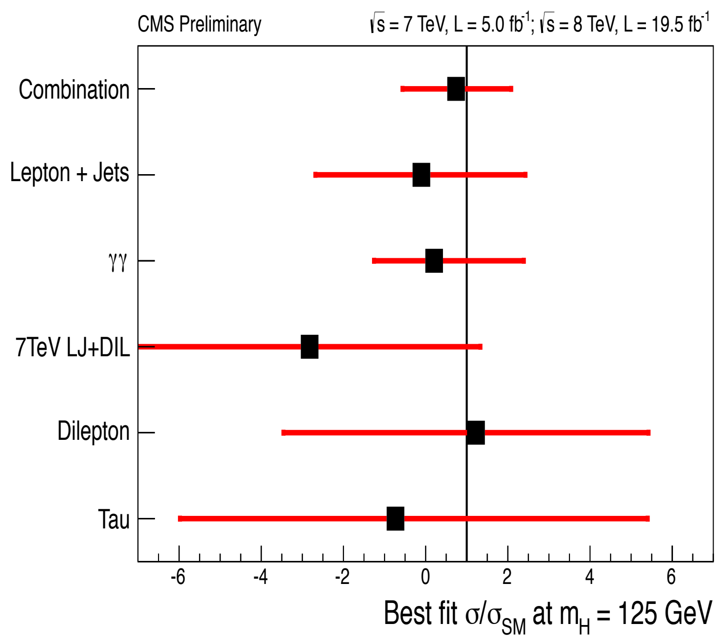
Searches for Additional Standard Model Signals

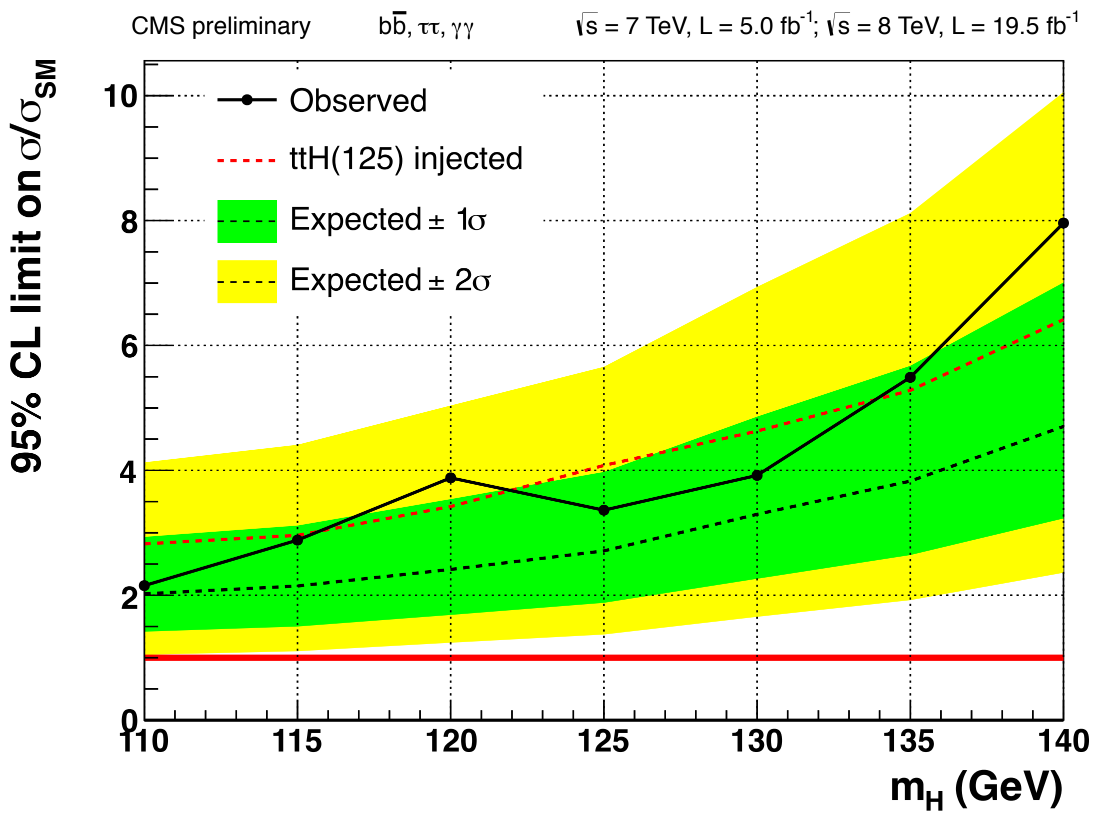
SM Production modes: ttH

ttH production not yet firmly established

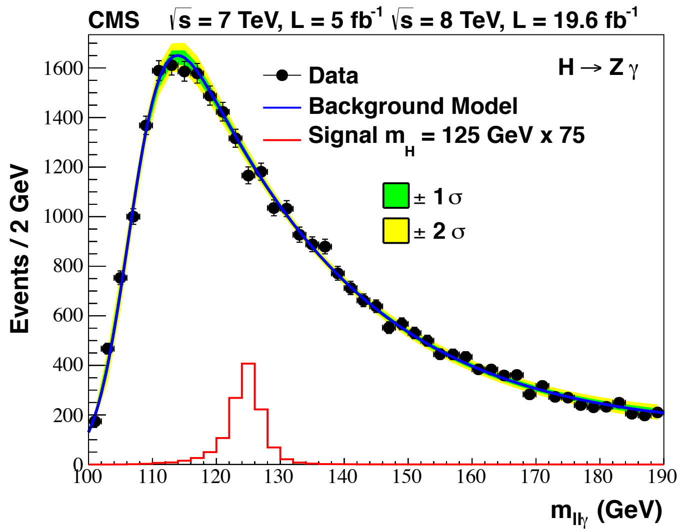
- Channels:
  - H→ $\gamma\gamma$: clean tag, few events
  - H→ $\tau\tau$, bb: complicated analyses
- Sensitivity at ~few x SM rate

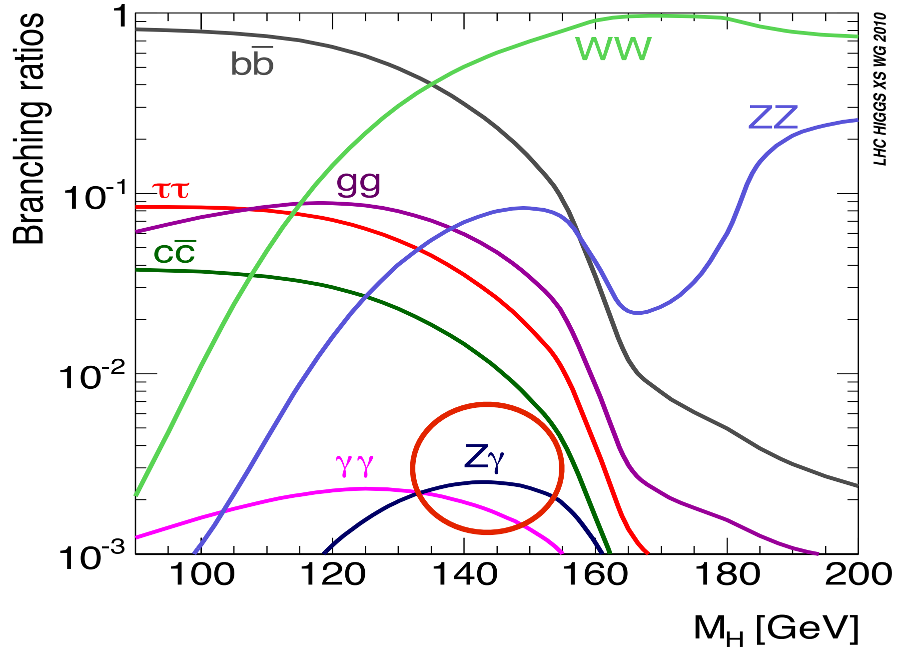


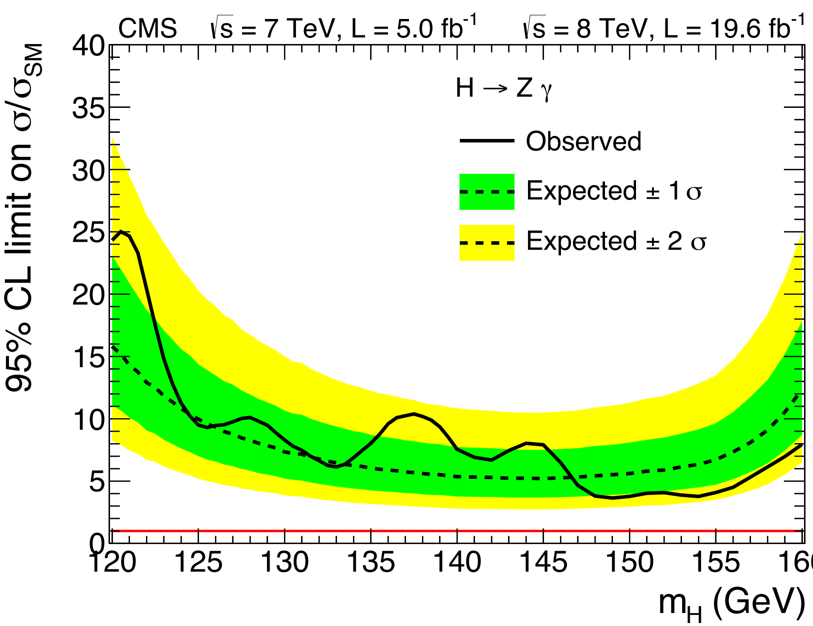


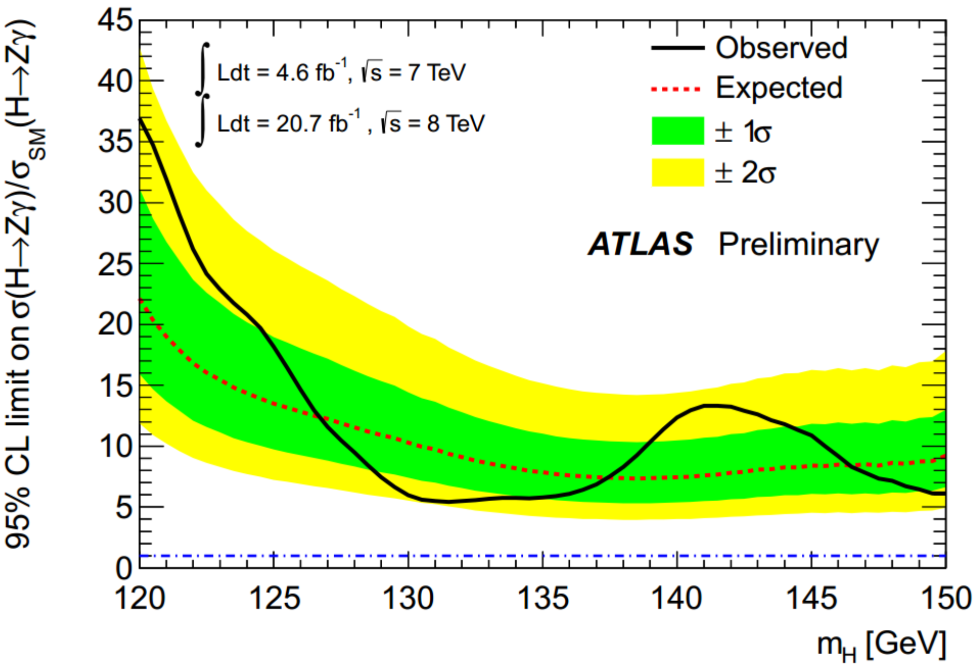


$Z\gamma$


CMS √s = 7 TeV, L = 5 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
H → Z γ
Data
Background Model
Signal m_H = 125 GeV x 75
± 1 σ
± 2 σ
Events / 2 GeV
m_llγ (GeV)

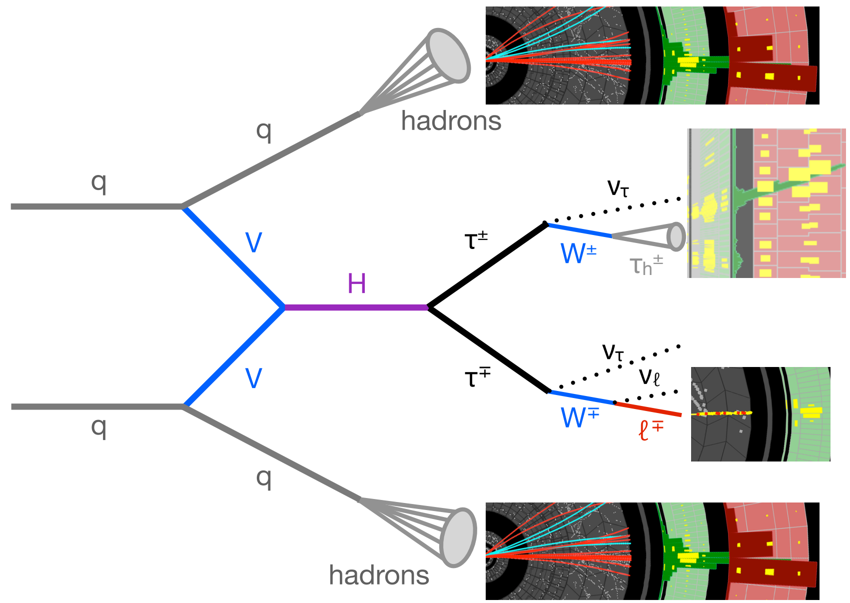

Branching ratios
bb̄
WW
ZZ
ττ
gg
cc̄
γγ
Zγ
LHC HIGGS XS WG 2010
M_H [GeV]

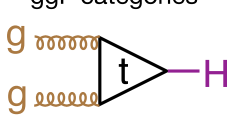
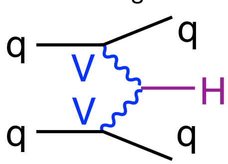

CMS √s = 7 TeV, L = 5.0 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
H → Z γ
Observed
Expected ± 1 σ
Expected ± 2 σ
95% CL limit on σ/σ_SM
m_H (GeV)

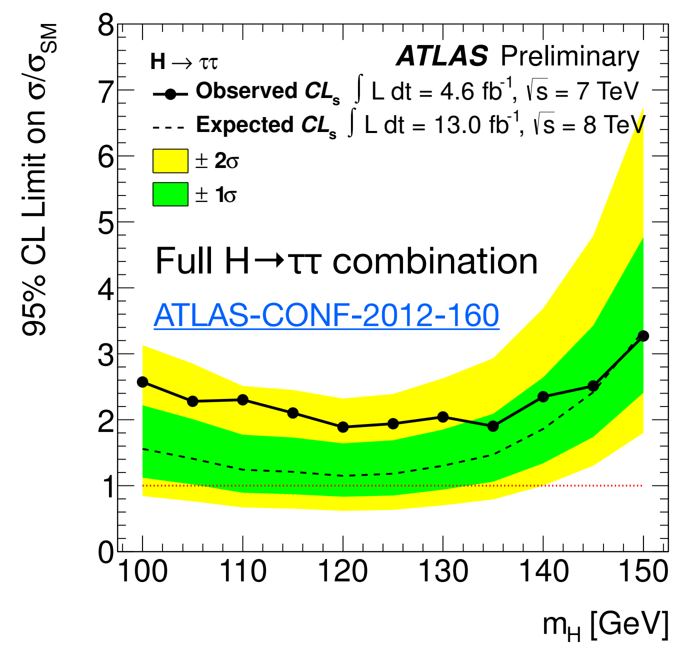

∫Ldt = 4.6 fb⁻¹, √s = 7 TeV
∫Ldt = 20.7 fb⁻¹ , √s = 8 TeV
Observed
Expected
± 1σ
± 2σ
ATLAS Preliminary
95% CL limit on σ(H→Zγ)/σ_SM(H→Zγ)
m_H [GeV]

$H \to \tau\tau$ analyses are challenging and complicated

- sensitivity in ATLAS still a few xSM
- mild 1.7σ excess



	$H \to \tau_\ell \tau_h$	$H \to \tau_h \tau_h$	$H \to \tau_\ell \tau_\ell$
Nickname	“lep-had”	“had-had”	“lep-lep”
Trigger	single ℓ $\ell + \tau_h$	di-τ_h	single ℓ di-ℓ
ggF categories 	0 jet 1 jet boosted H	boosted H	0 jet 1 jet boosted H
VBF categories 	2-jet VBF	2-jet VBF	2-jet VBF



Searches for Beyond the Standard Model Signals

Unfolded differential cross section in H→γγ

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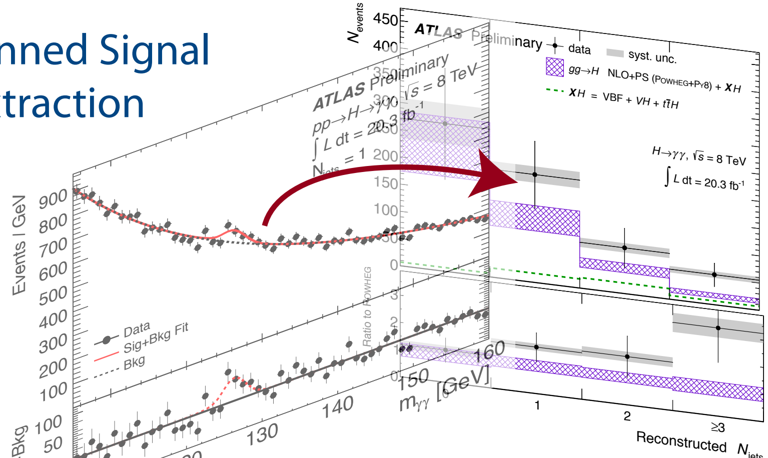
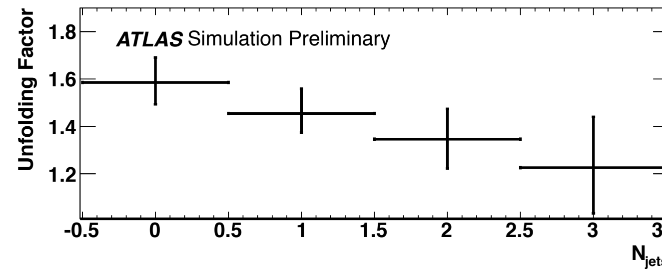
Binned Signal Extraction

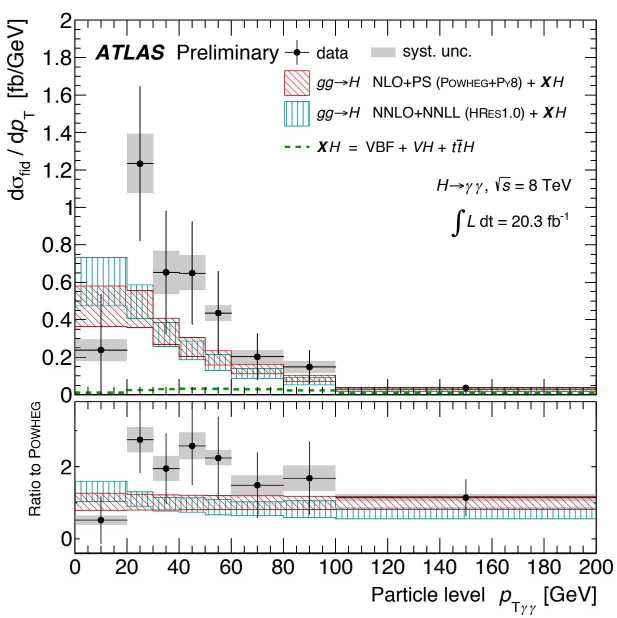


Raw Yields

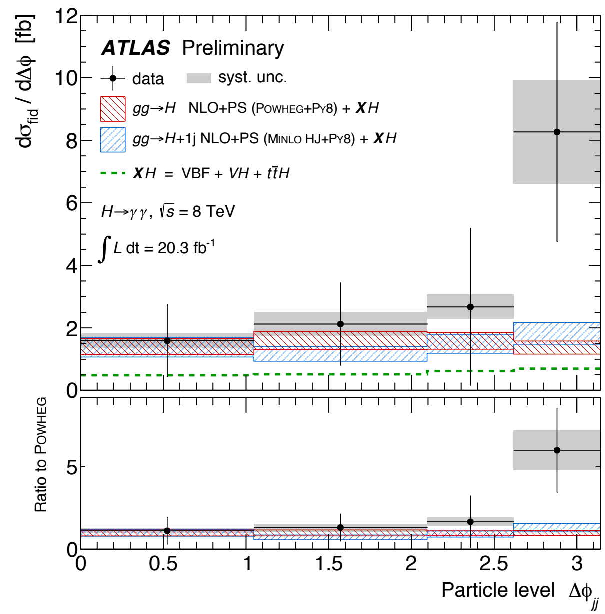
×



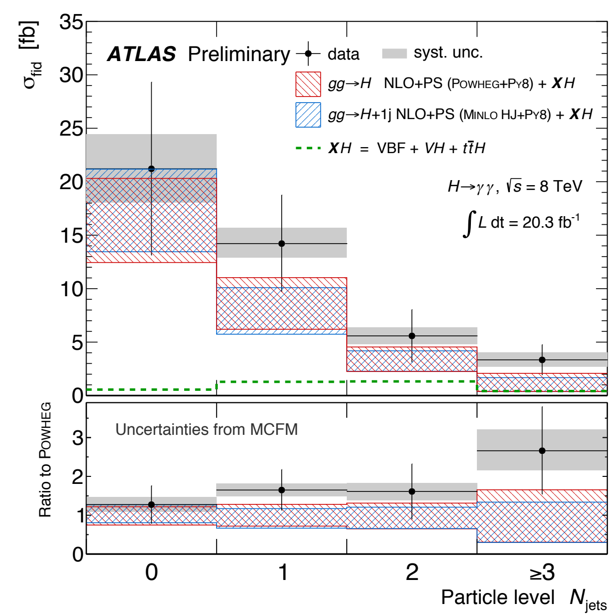
Correction Factors



Unfolded Differential Cross Section



Unfolded Differential Cross Section



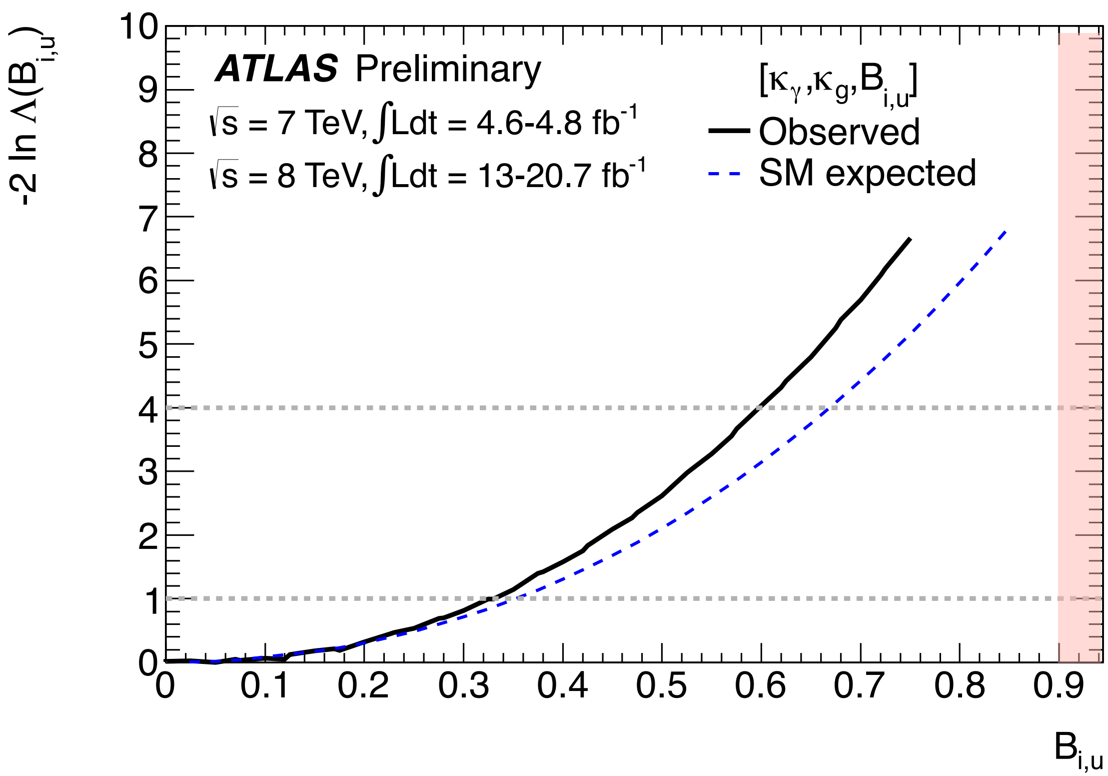
Probing undetected decays

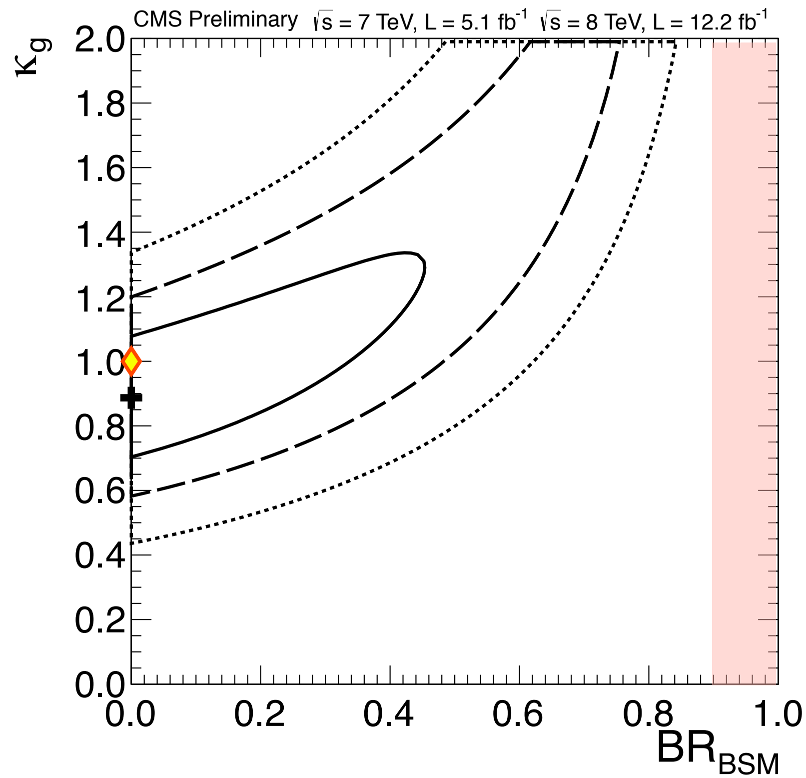
Here total width modified by: $$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{\text{inv.,undet.}})}\Gamma_H^{SM}$$

- uses effective coupling for ggH and $\gamma\gamma$H loops
- everything else is SM-like (namely VBF production)

Disfavors large BR to invisible

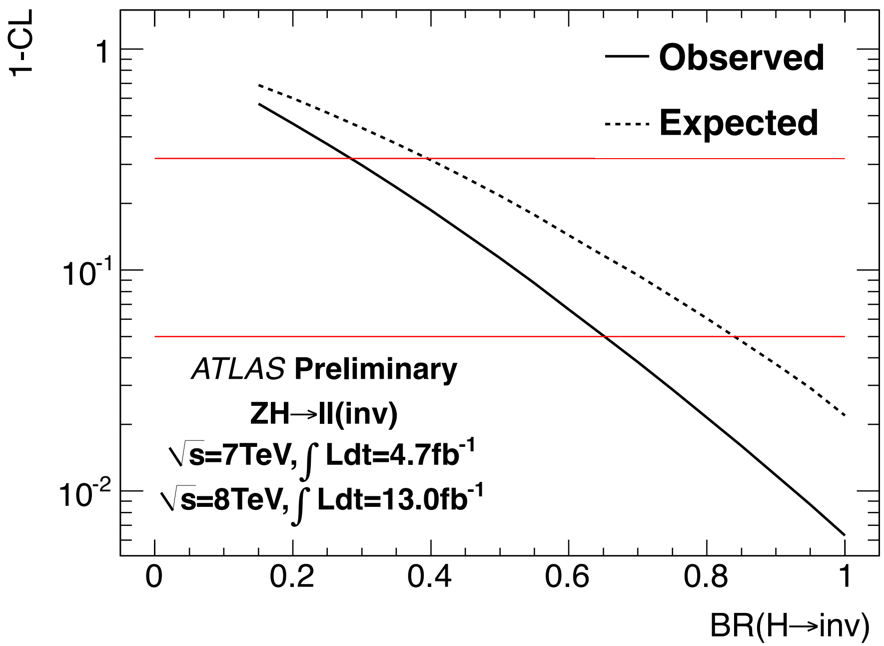
As BR(inv) increases, κ_g must increase
As $\kappa_g \to \infty$ B(gg)$\to$ B(gg)$_{SM}$ ~10%
Thus BR(inv) < 1-B(gg)$_{SM}$

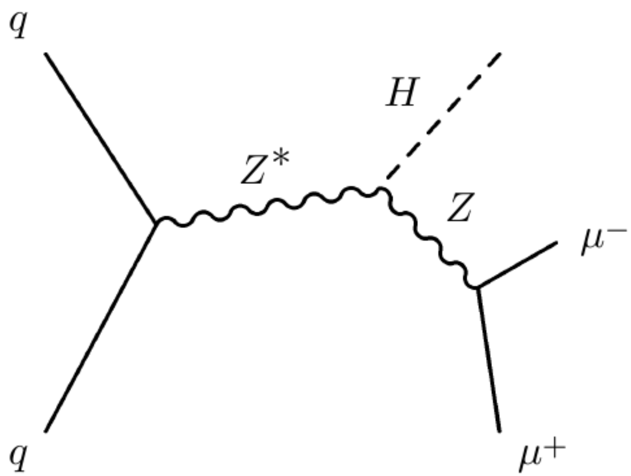


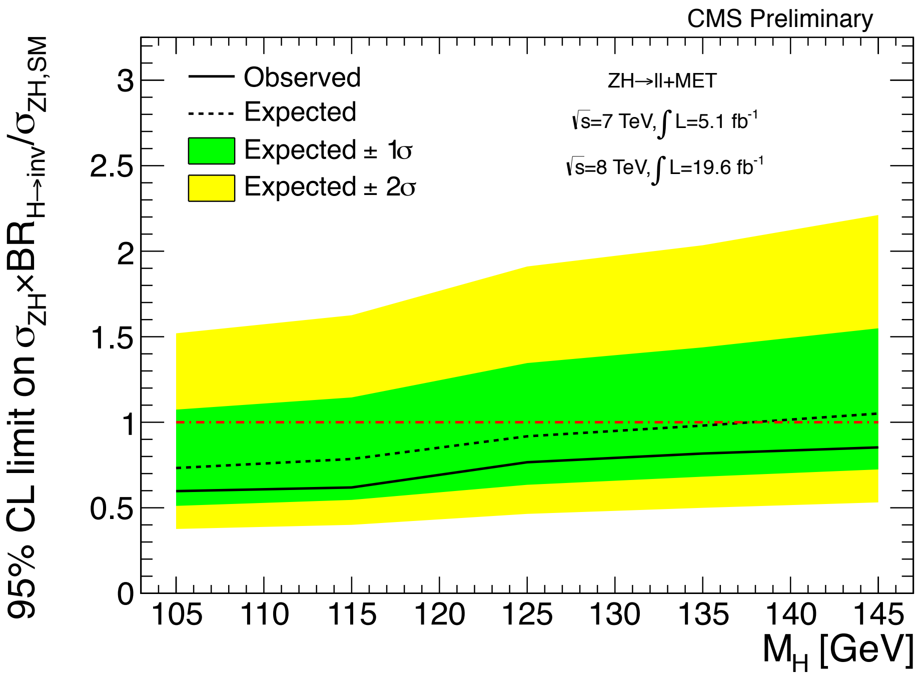


Invisible decays

ATLAS & CMS directly probing invisible decays with associated production



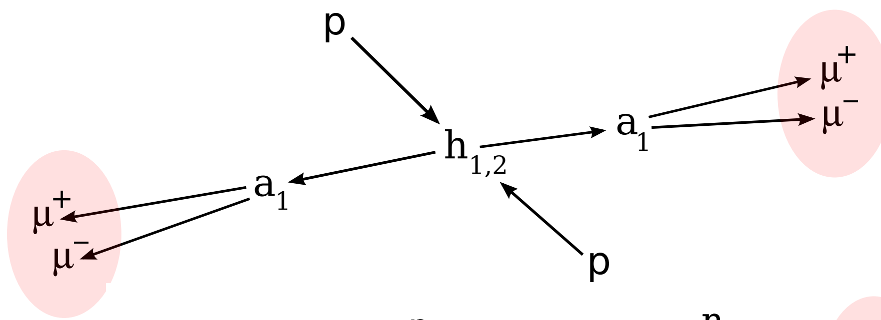


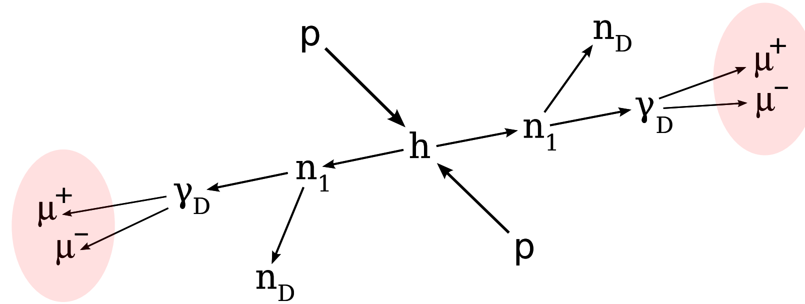


Exotic decays

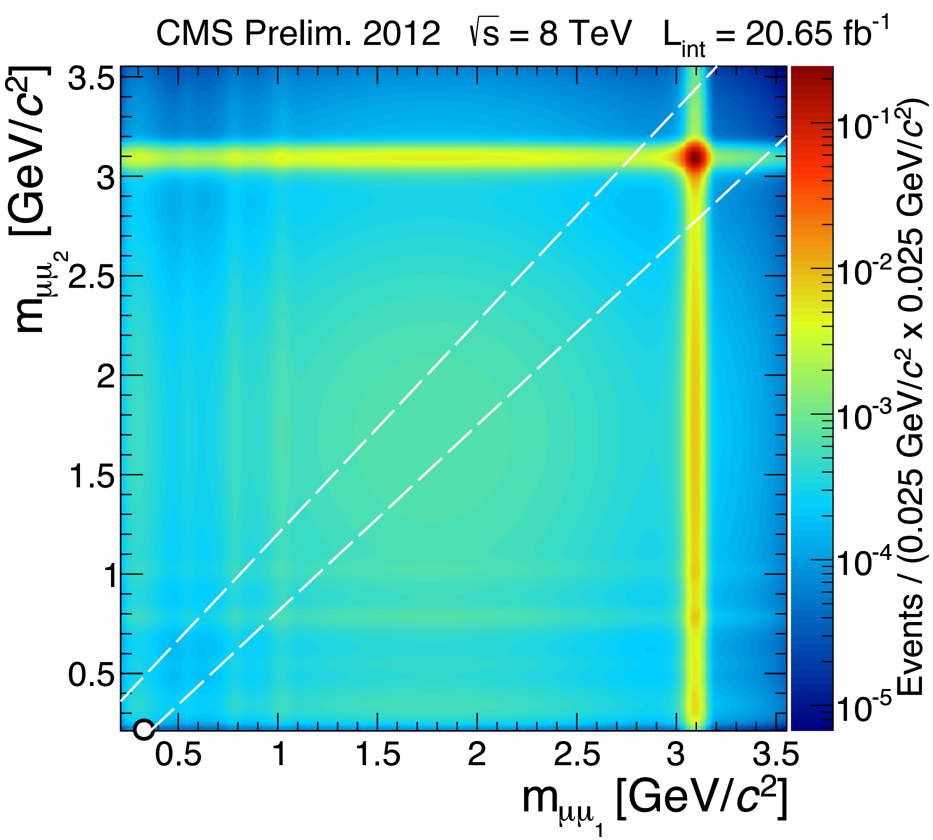
NMSSM gives h→ aa

- well motivated theory
- rich phenomenology

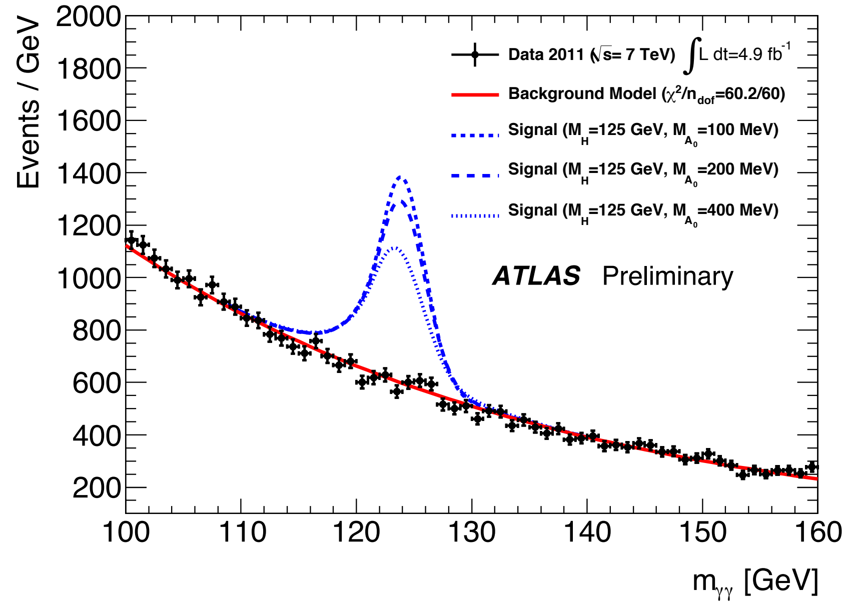




$$h \to aa \to 4\mu$$



$$h \to aa \to 4\gamma$$



Flavor changing $t \to cH$

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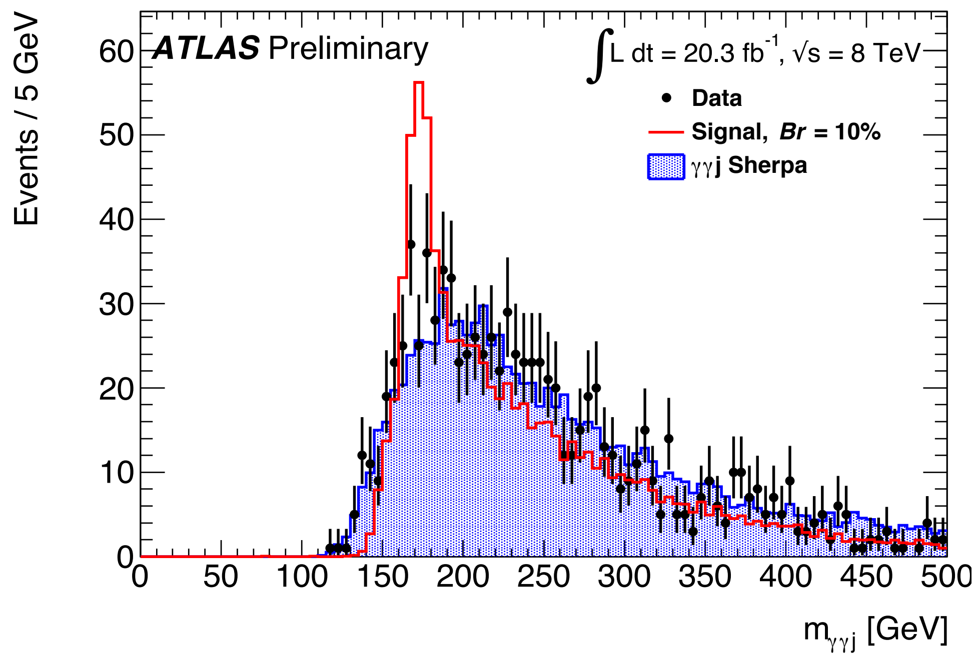
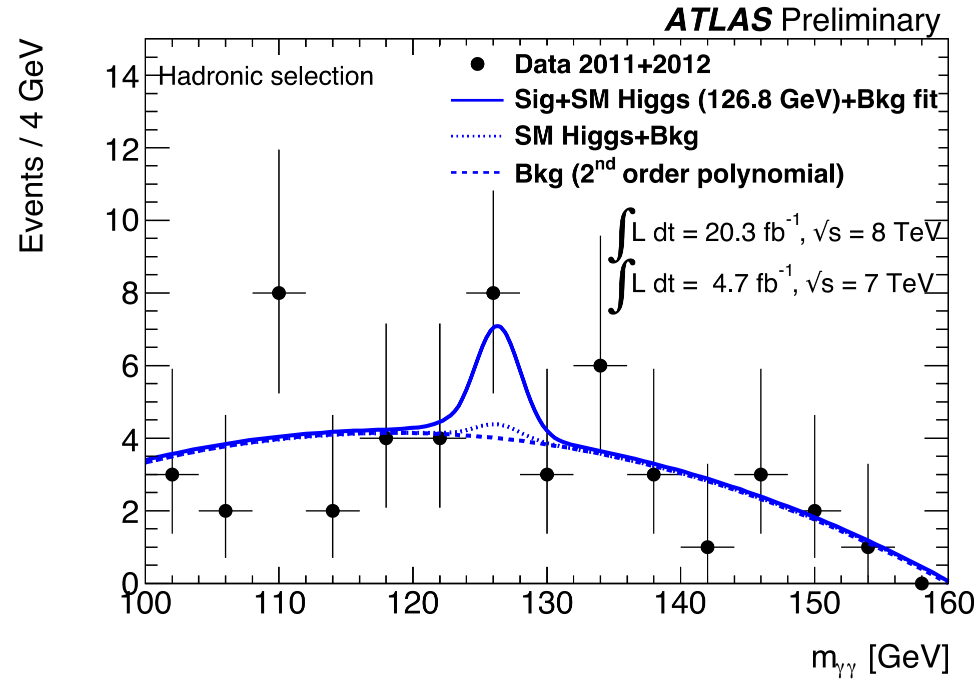
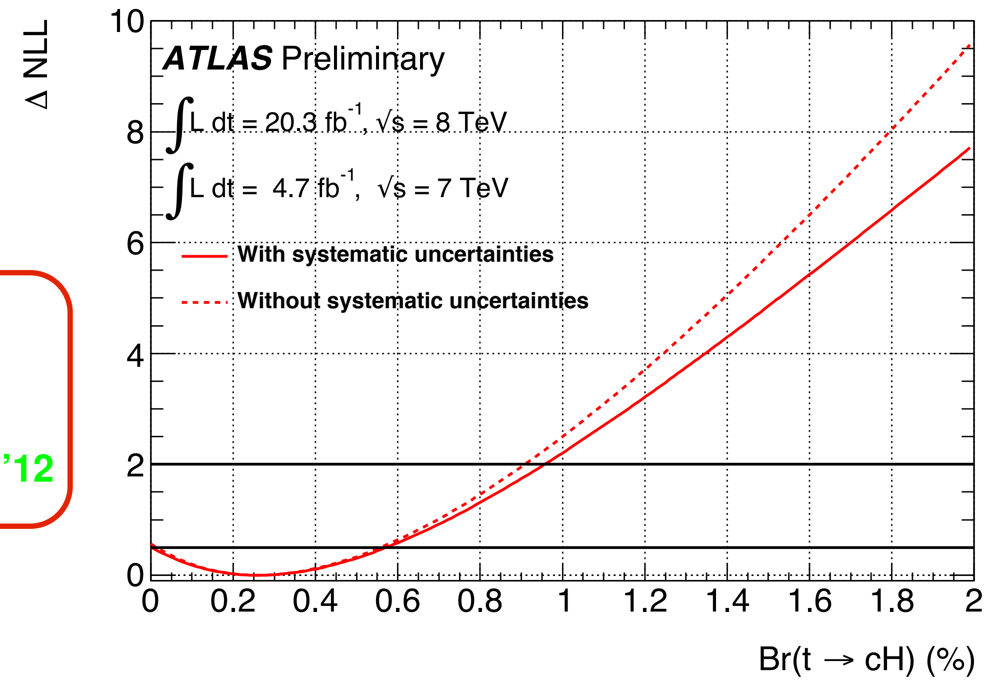






The CMS 2012 multi-lepton data puts limits on
$\mathcal{BR}(t \to ch) < 2.7\%$

N. Craig et.al. '12

Flavor changing decays

2 doublet model: $Y_1^{ij} H_1 f_L^i f_R^j + Y_2^{ij} H_2 f_L^i f_R^j$

- or -

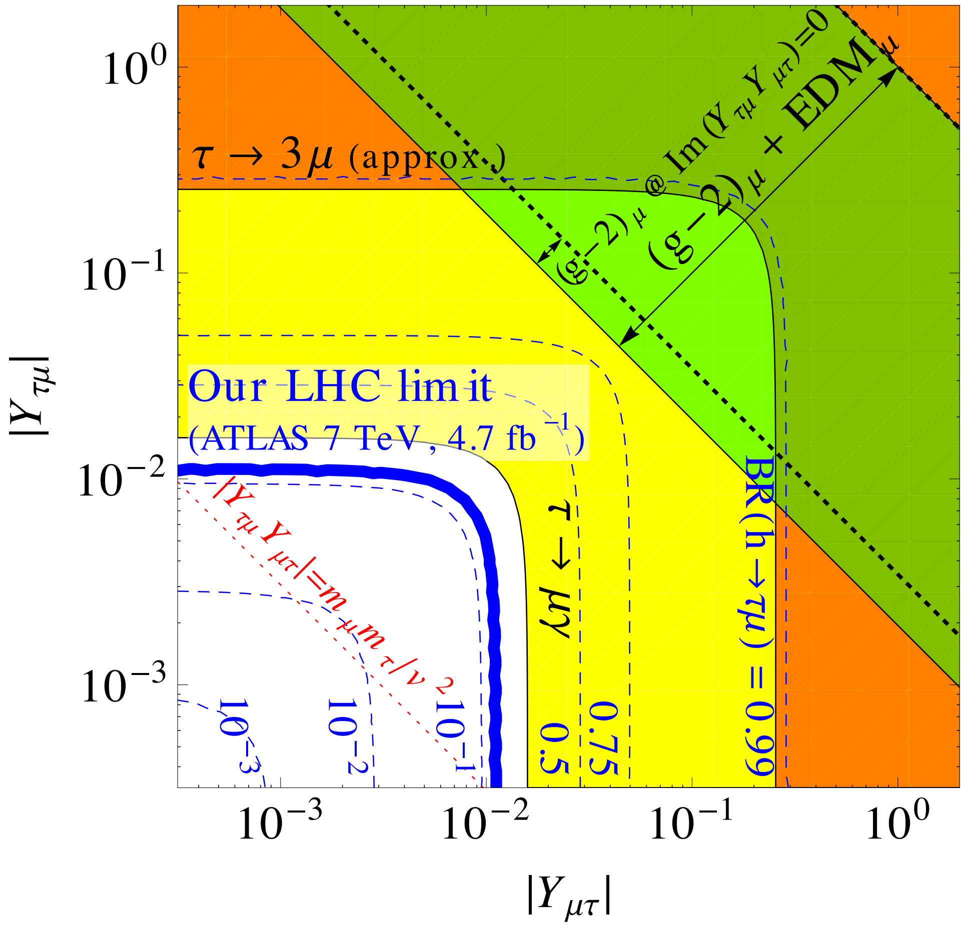
Higher dim. op: $Y^{ij} H f_L^i f_R^j + \hat{Y}^{ij} \frac{|H|^2}{\Lambda^2} H f_L^i f_R^j$

Two sources can be misaligned
in flavor and/or in phase.

To avoid tuning we expect $Y_{ij} \lesssim \frac{\sqrt{m_i m_j}}{v}$,

but phases can be of order one.

lets call couplings that satisfy this "natural"



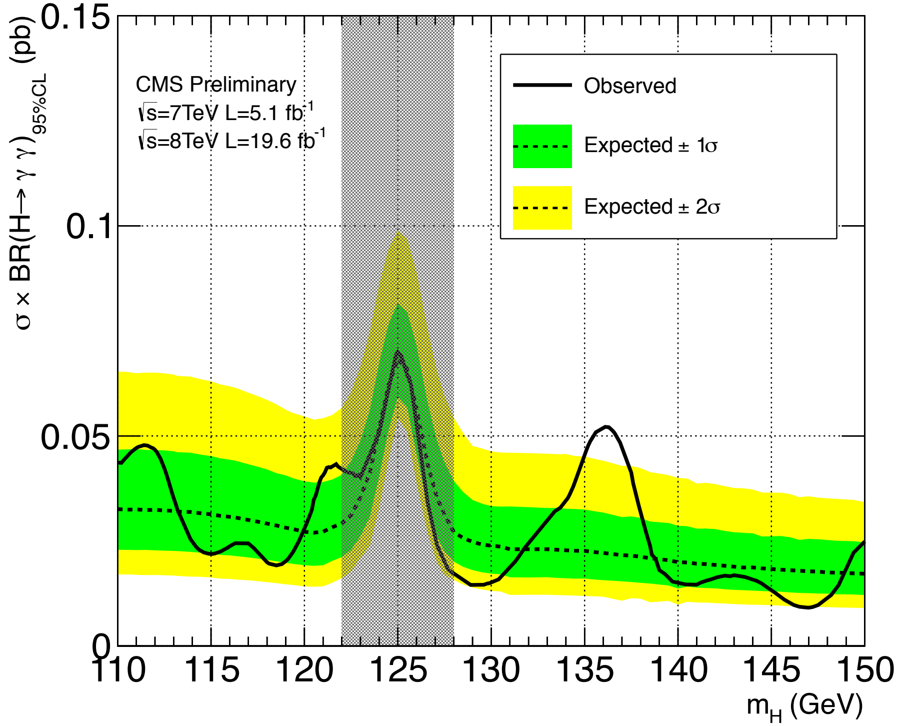
LHC $h \to \tau\mu$ gives dominant bound.

(currently just a theorist's re-interpretation)

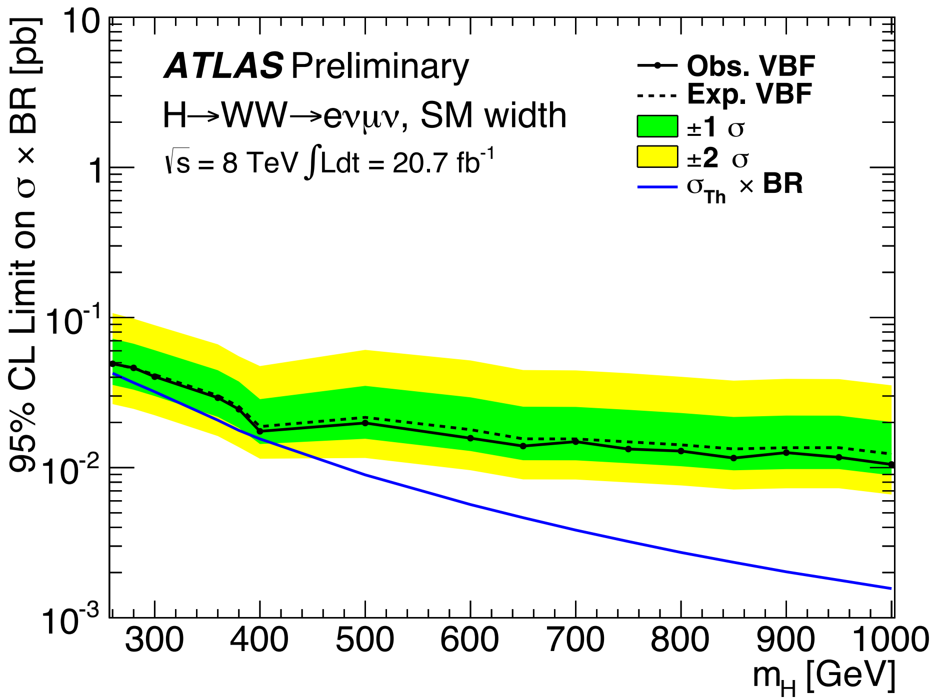
"natural models" are within reach.

Same distribution, more Higgs-like states

Searching for additional $H \rightarrow \gamma\gamma$ using SM Higgs as "background" @ CMS



Searching for High-mass Higgs in $H \rightarrow WW \rightarrow l\nu\ l\nu$ @ ATLAS

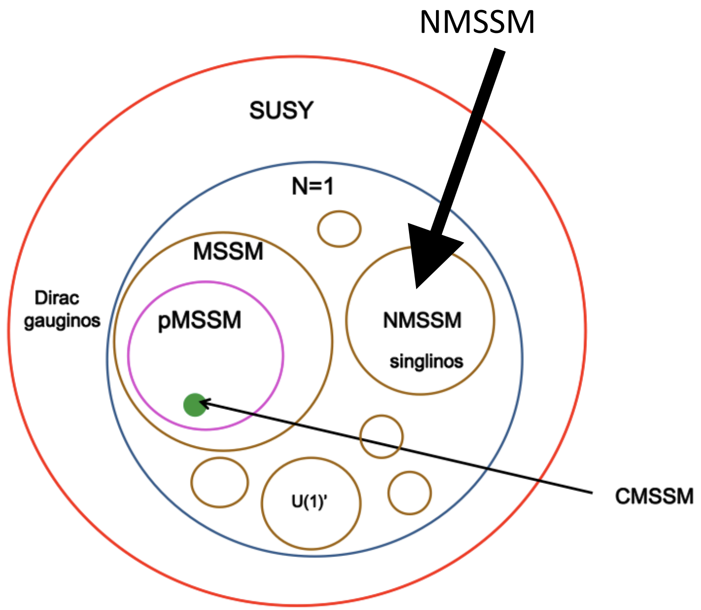


BaBar nMSSM searches

BABAR light Higgs searches

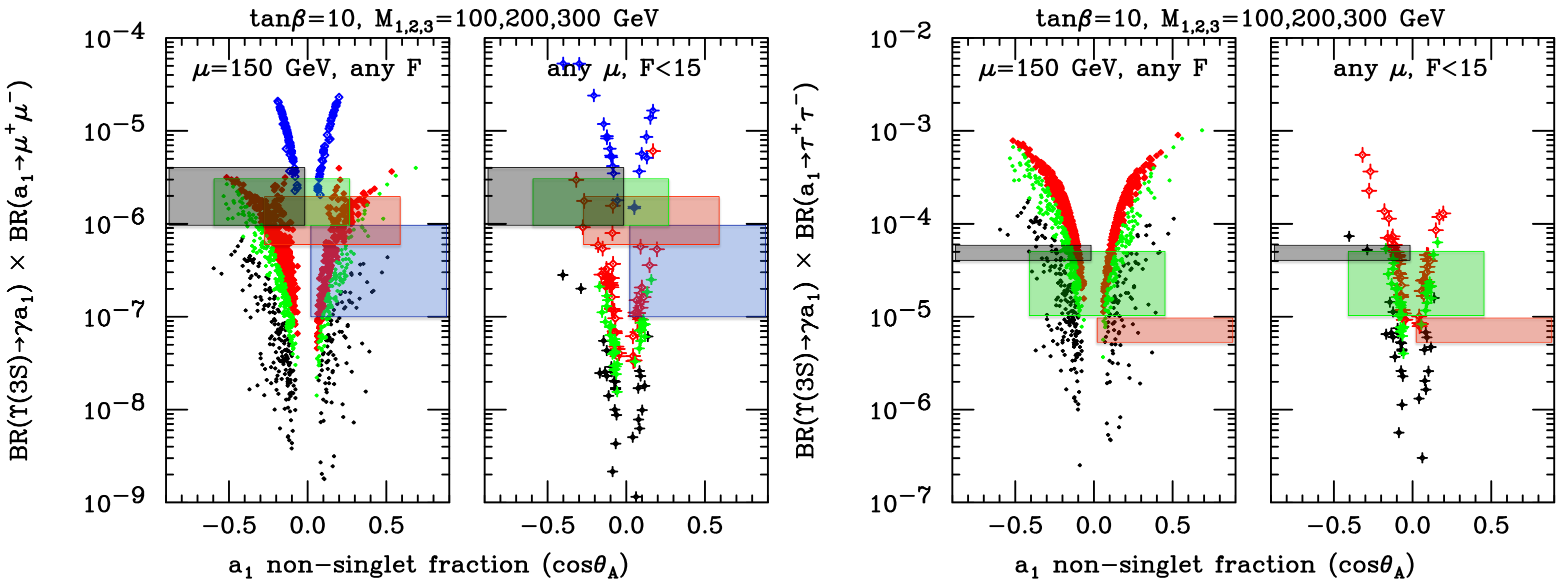
Rocky So

Presented in DPF 2011	
$\Upsilon(2,3S) \to \gamma A^0; A^0 \to \mu^+\mu^-$	PRL 103, 081803 (2009)
$\Upsilon(3S) \to \gamma A^0; A^0 \to \tau^+\tau^-$	PRL 103, 181801 (2009)
$\Upsilon(1S) \to \gamma A^0; A^0 \to$ invisible	PRL 107, 021804 (2011)
$\Upsilon(2,3S) \to \gamma A^0; A^0 \to$ hadrons	PRL 107, 221803 (2011)
Today's talk	
$\Upsilon(1S) \to \gamma A^0; A^0 \to \mu^+\mu^-$	PRD 87, 031102(R) (2013)
$\Upsilon(1S) \to \gamma A^0; A^0 \to \tau^+\tau^-$	arXiv:1210:5669
$\Upsilon(1S) \to \gamma A^0; A^0 \to gg$ or $s\bar{s}$	PRD 88, 031701(R) (2013)

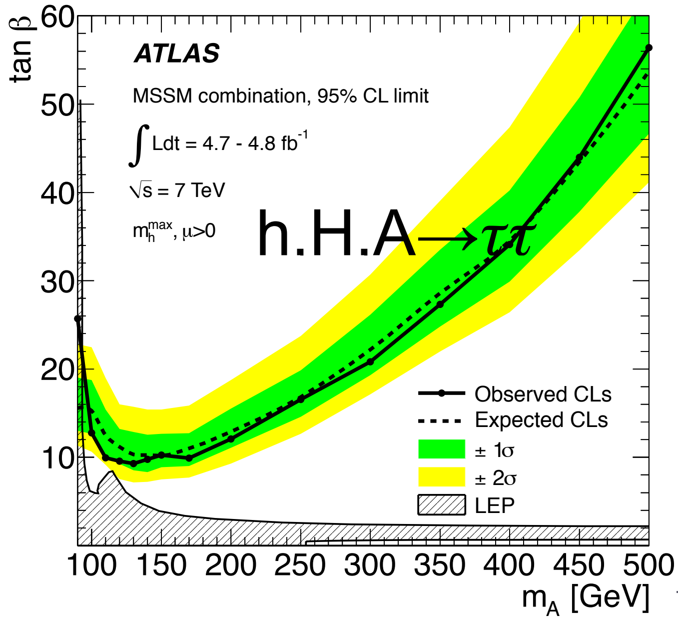


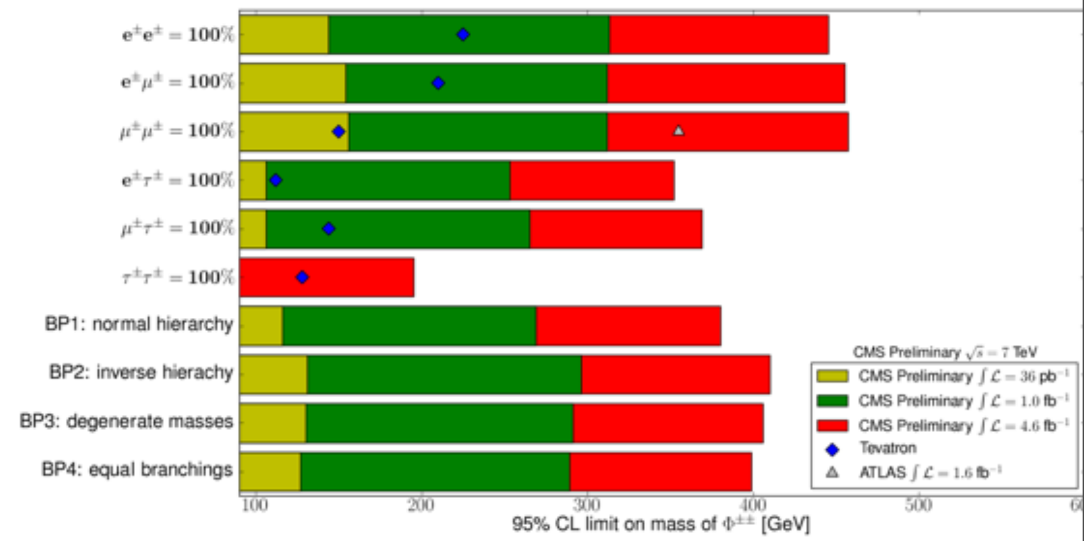
T. Rizzo (SLAC Summer Institute 2012)

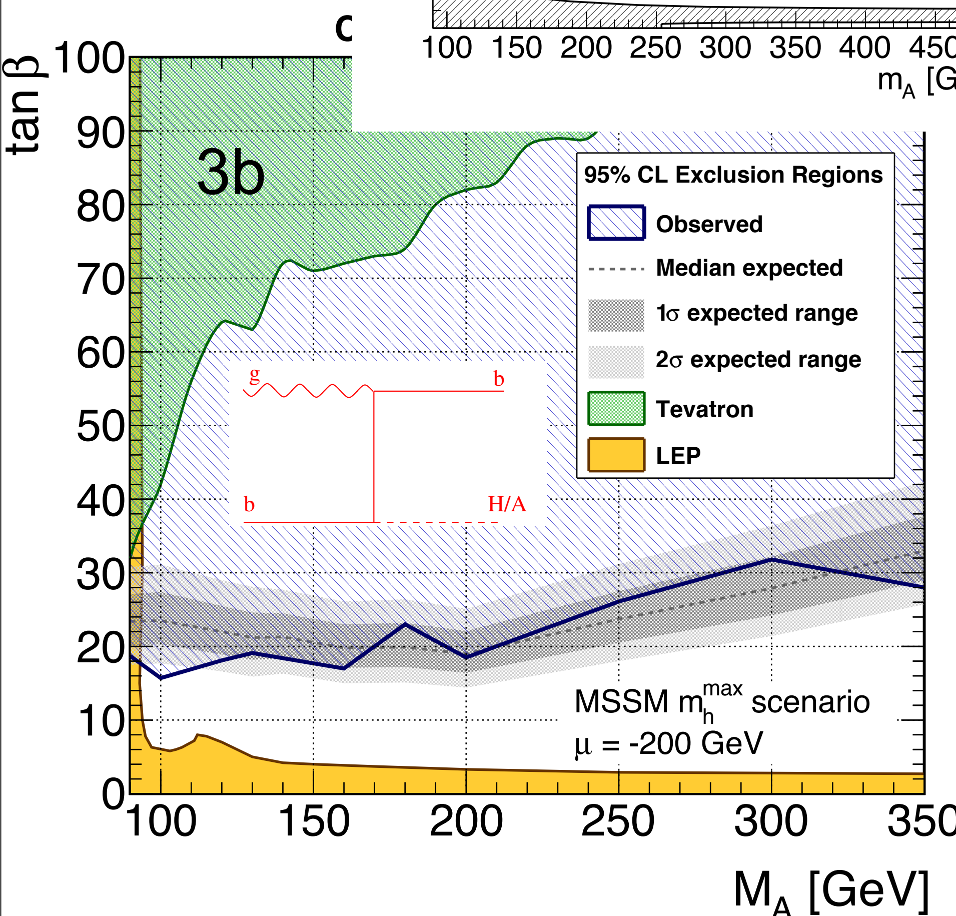
$\mu^+\mu^-$ PRD 81, 075003 (2010) $\tau^+\tau^-$

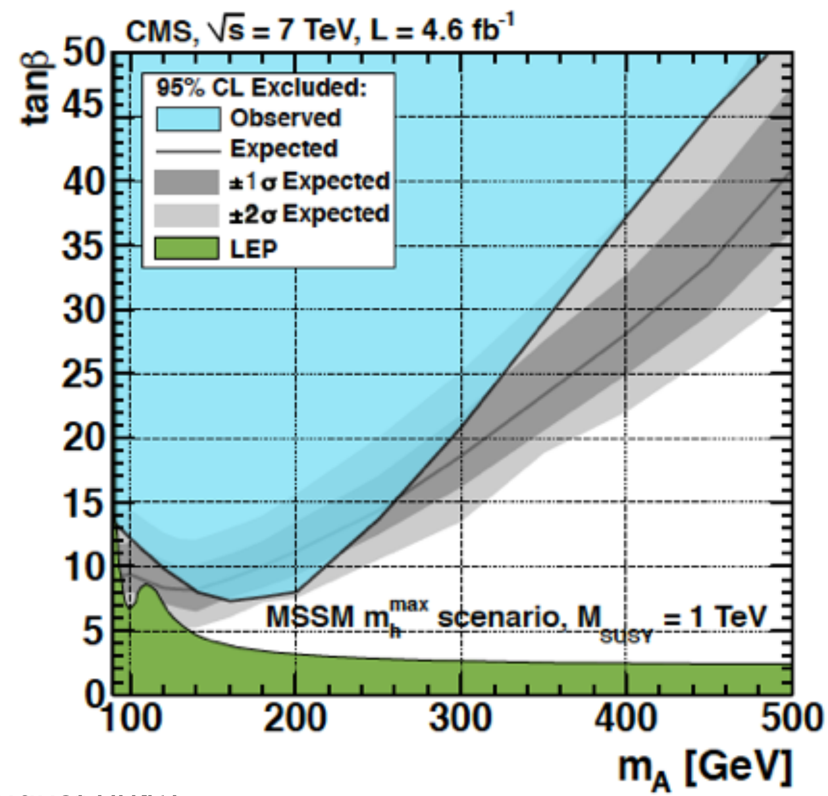


... and much much more









Conclusions

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We've found a new particle, and we've only just begun

- a profound step in our understanding of fundamental phyics