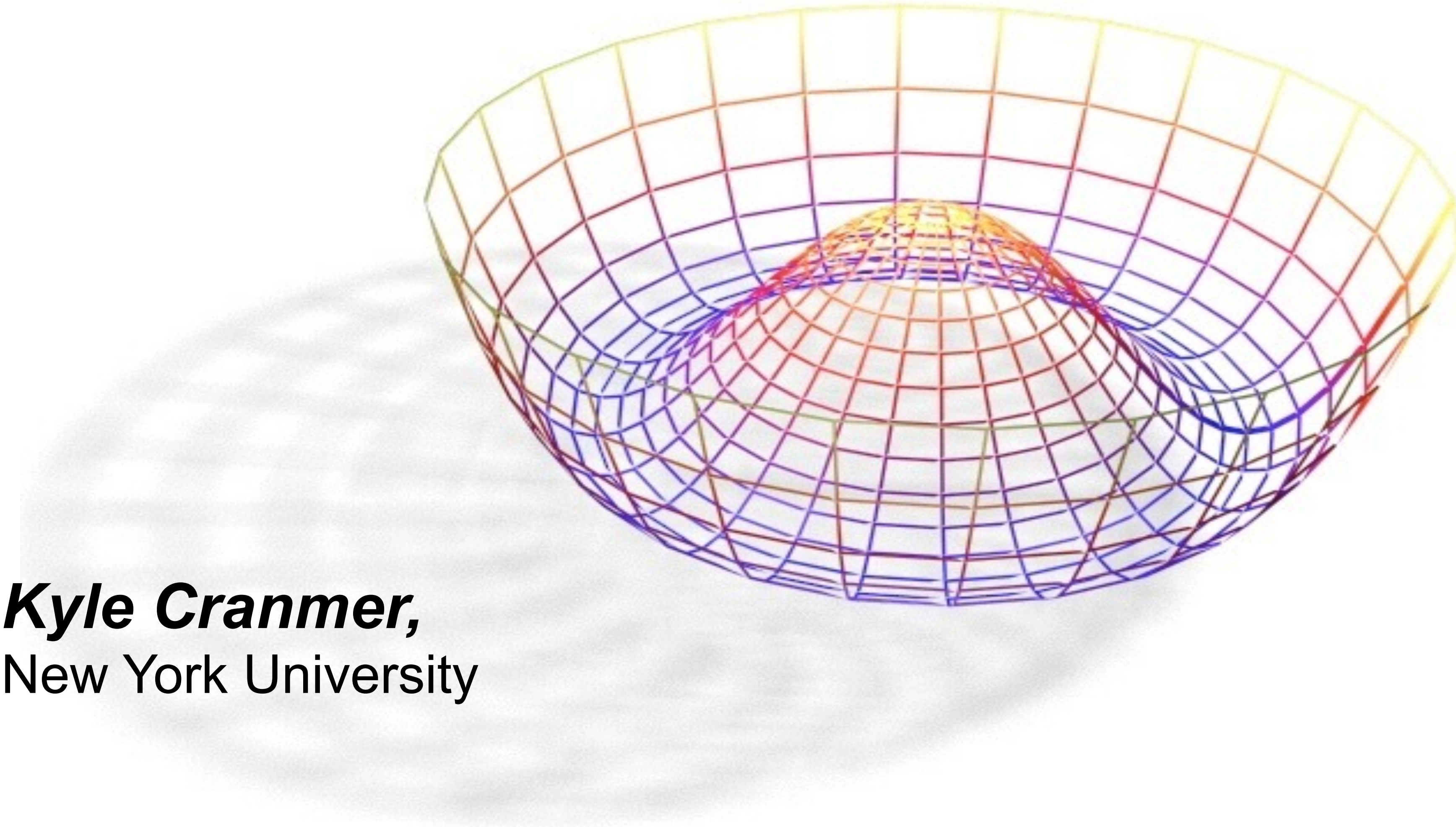
Center for
Cosmology and
Particle Physics

Higgs property measurements and future collider prospects



Kyle Cranmer,
New York University

Other presentations

Impossible to cover everything, please see detailed presentations:

Study of Higgs boson production in bosonic decay channels at the LHC
Presented by **Roberta VOLPE** on **21 May 2014** at **14:00**

Study of Higgs boson production in fermionic decay channels at the LHC
Presented by **Vivek JAIN** on **21 May 2014** at **14:20**

Combinations of results of Higgs boson production at the LHC (production rates, couplings)
Presented by **Christian MEINECK** on **21 May 2014** at **14:40**

Higgs boson studies at the Tevatron
Presented by **Lidija ZIVKOVIC** on **21 May 2014** at **15:00**

Higgs and EW precision data
Presented by **Andrea TESI** on **21 May 2014** at **15:20**

Measurements of the Higgs Boson Spin and CP at the LHC
Presented by **Roko PLESTINA** on **21 May 2014** at **16:30**

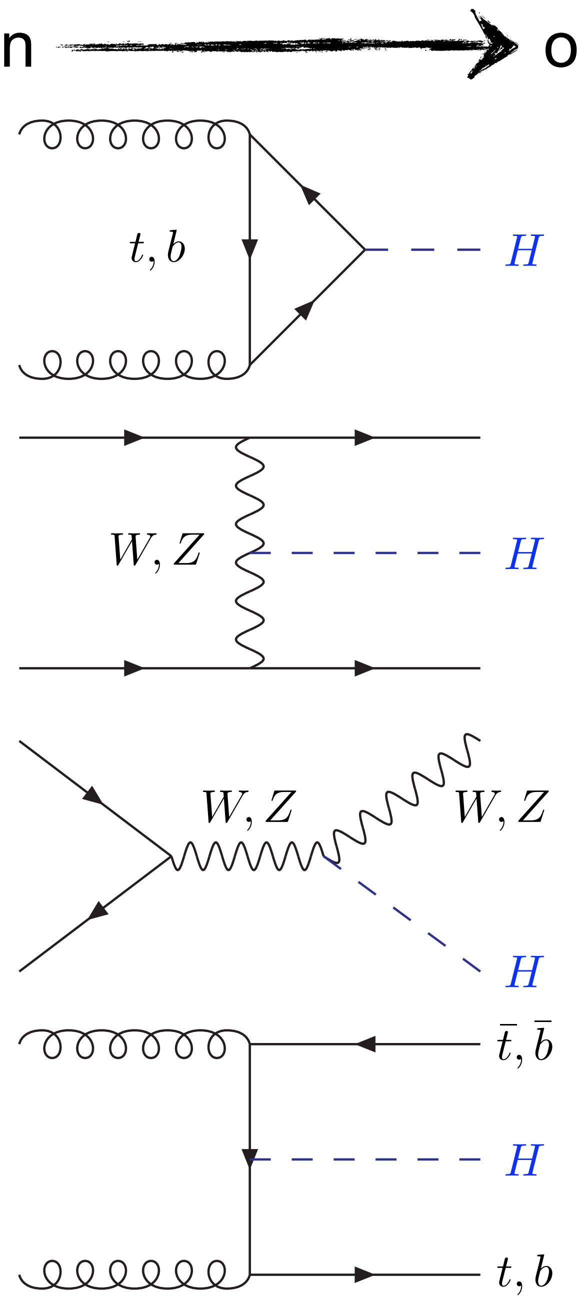
Searches for BSM Higgs Bosons at the LHC
Presented by **Claire SHEPHERD-THEMISTOCLEOUS** on **21 May 2014** at **16:50**

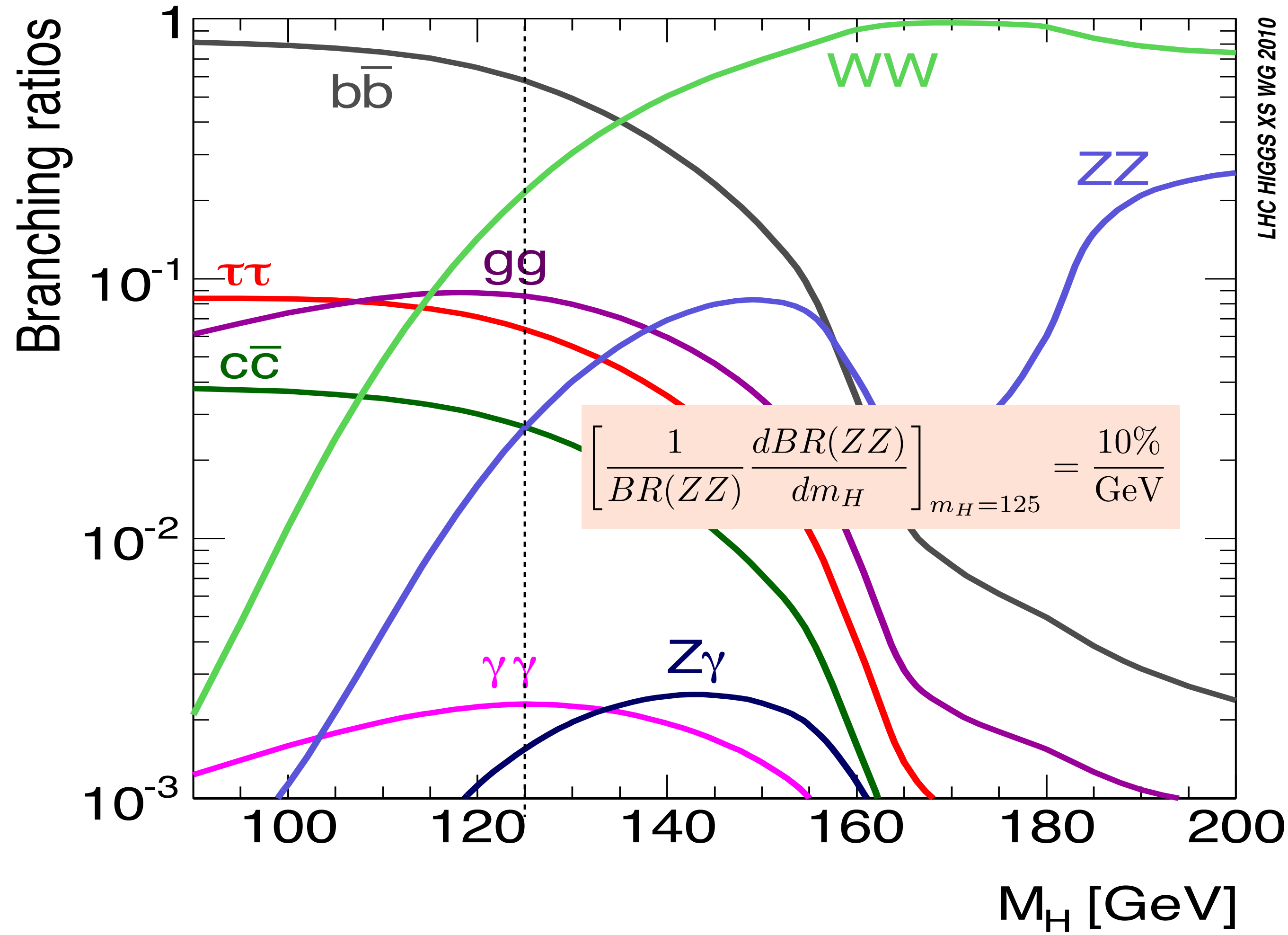
Higgs exotic decays
Presented by **Prerit JAISWAL** on **21 May 2014** at **18:10**

Studies of Higgs Boson Properties in Future LHC Runs (Snowmass & ECFA studies)
Presented by **Rostislav KONOPLICH** on **21 May 2014** at **18:30**

SM Higgs @ the LHC

in → out





$$\left[\frac{1}{BR(ZZ)}\frac{dBR(ZZ)}{dm_H}\right]_{m_H=125} = \frac{10\%}{\text{GeV}}$$

Many decays accessible with 126 GeV

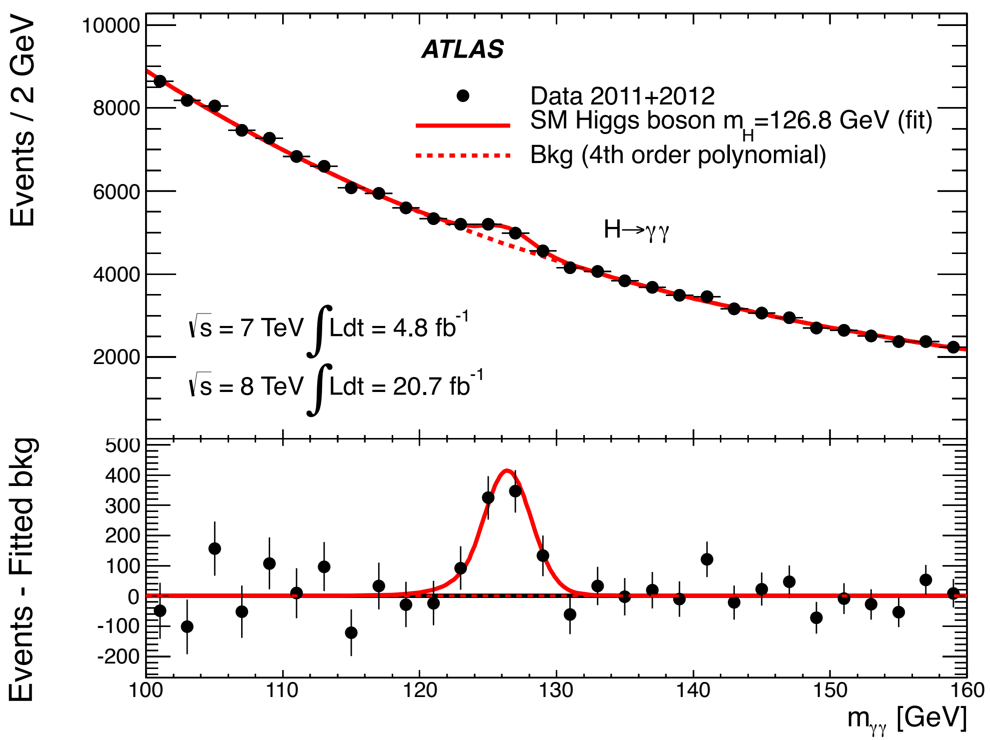
Vector boson fusion: forward jets, high pT

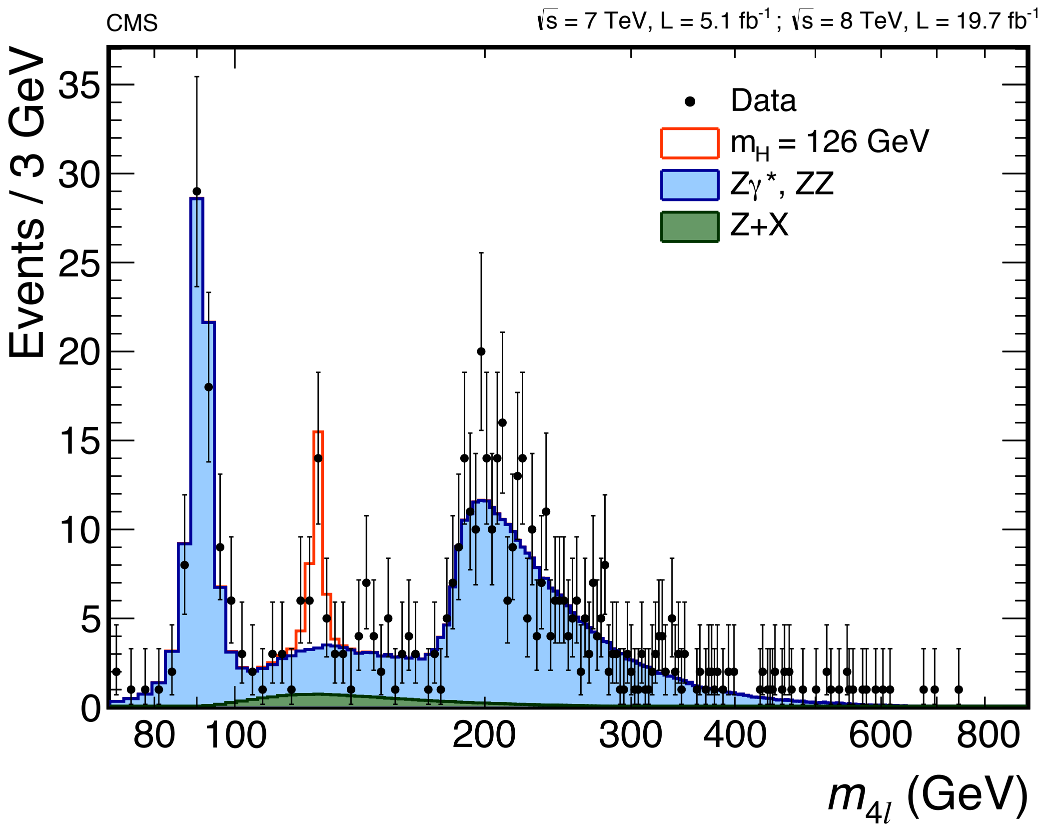
$b\bar{b}$ common, but is difficult

Associated: extra handle from leptons

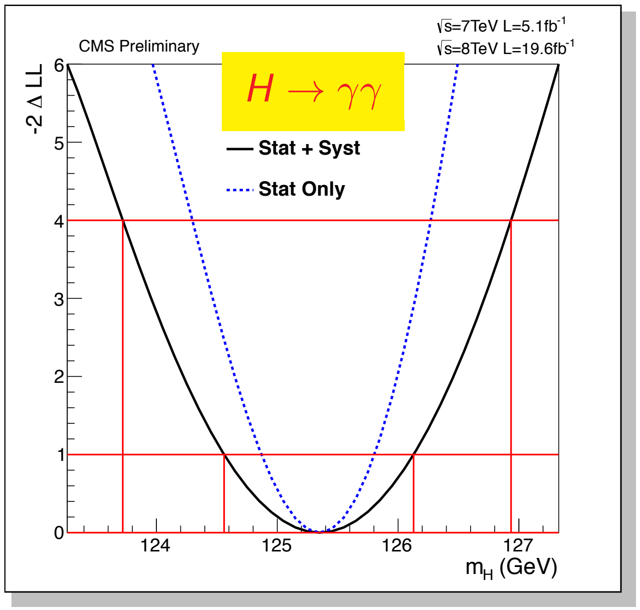
$\gamma\gamma$ small branching ratio, but clean

Discovery!

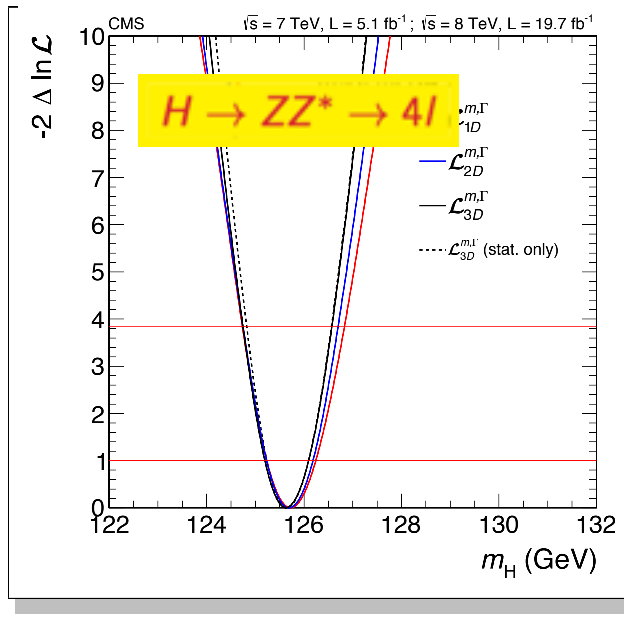

ATLAS
Data 2011+2012
SM Higgs boson m_H=126.8 GeV (fit)
Bkg (4th order polynomial)
$H\rightarrow\gamma\gamma$
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
Events / 2 GeV
Events - Fitted bkg
$m_{\gamma\gamma}$ [GeV]


CMS
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} ; $\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}
Data
m_H = 126 GeV
$Z\gamma^*$, ZZ
Z+X
Events / 3 GeV
m_{4l} (GeV)

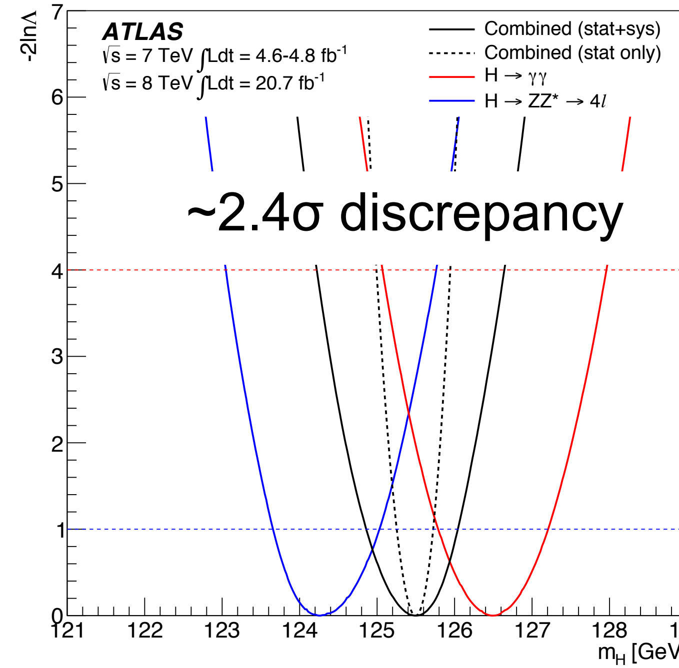
Mass measurement



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



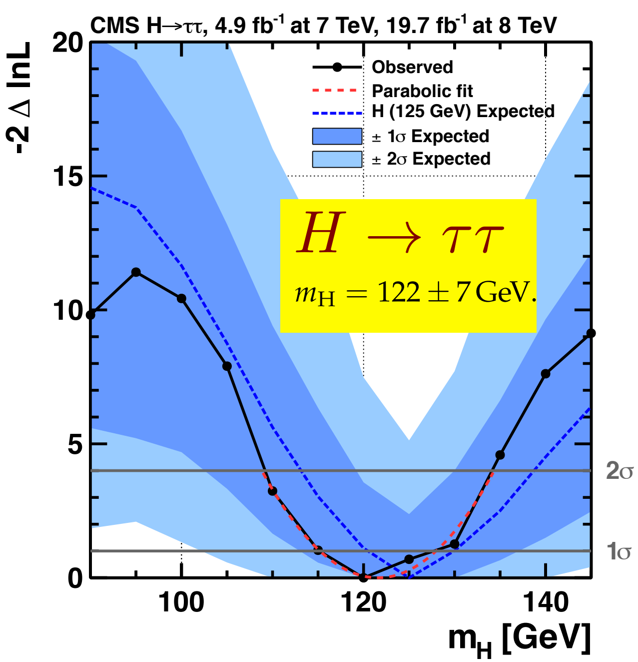
$m_X = 125.6 \pm 0.4\,(\text{stat.}) \pm 0.2\,(\text{syst.})$



	$H \to ZZ^{(*)} \to \ell\ell\ell\ell$	$H \to \gamma\gamma$
$\hat{m}_H$ (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



Measuring the mass fixes all properties of SM Higgs

Look for deviations from SM in

- exotic production or decay modes
- deviation from SM predictions
  - there are 59 dim 6 operators
  - several can be tested at LHC

Higgs Width at the LHC

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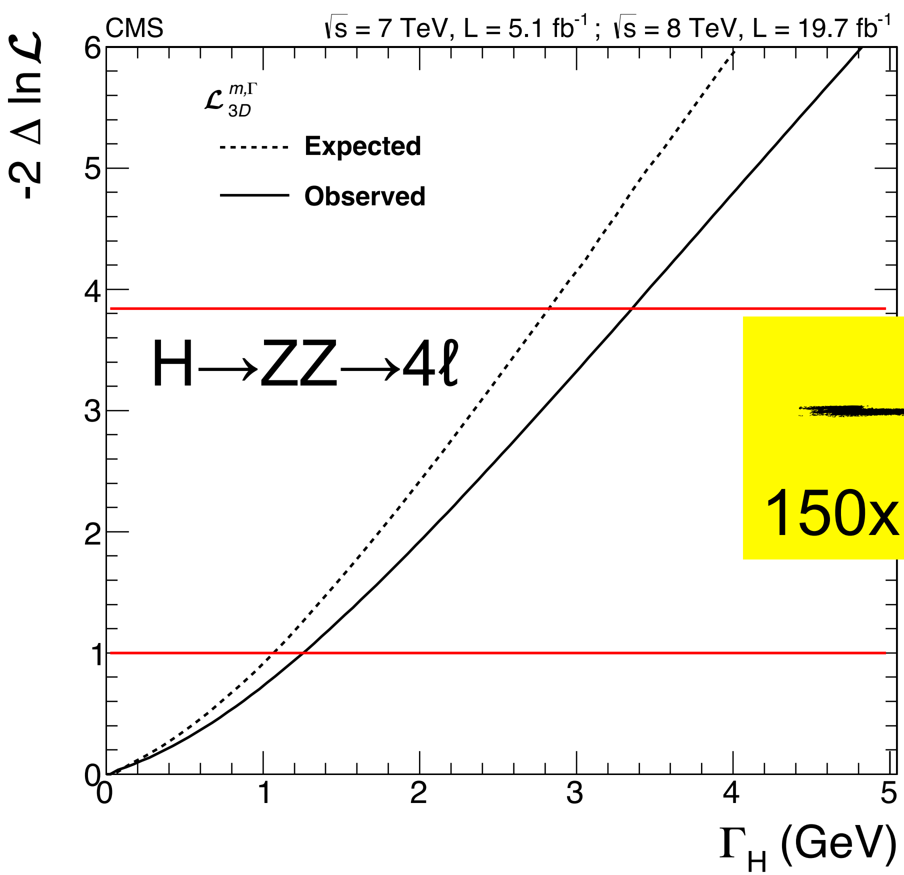
The width of the Standard Model Higgs is 4.15 MeV << O(GeV) resolution

➡ ambiguity as Rate ∝ Br = Γ/Γ_{SM}

$\Gamma_H < 3.4$ GeV at a 95%

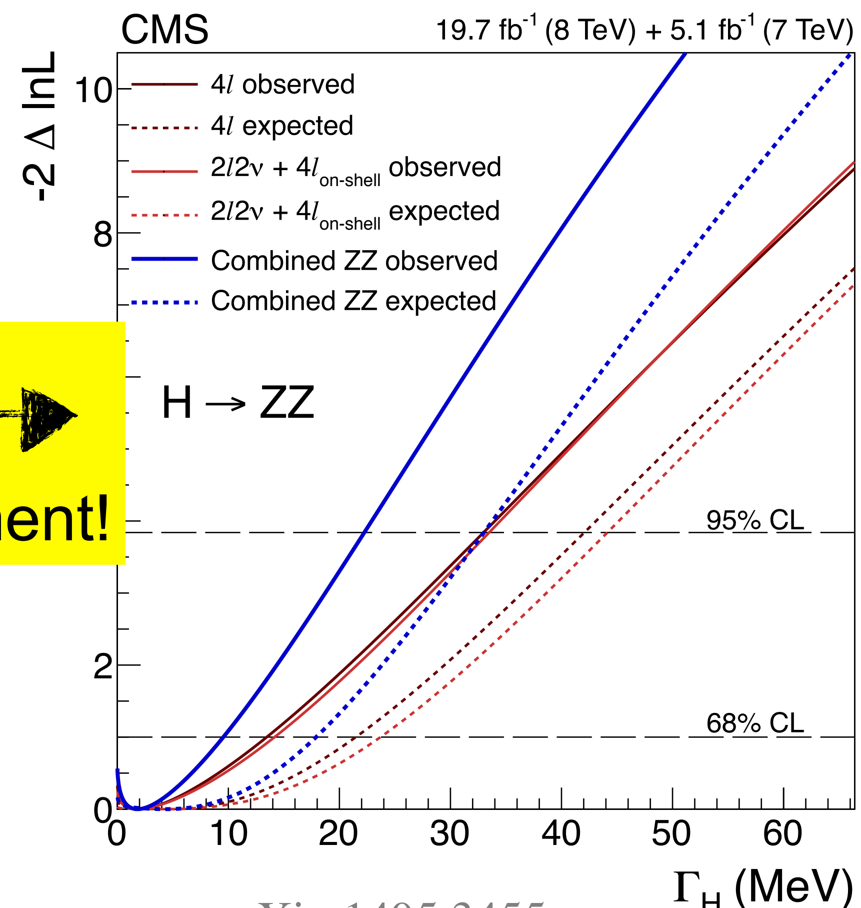


off-shell effects sensitive to width

F. Caola and K. Melnikov, [arXiv:1307.4935]
See also: N. Kauer, G. Passarino, Campbell et al

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

$\Gamma_H < 22$ MeV



150x improvement!

arXiv:1405.3455

Spin & CP Properties

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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

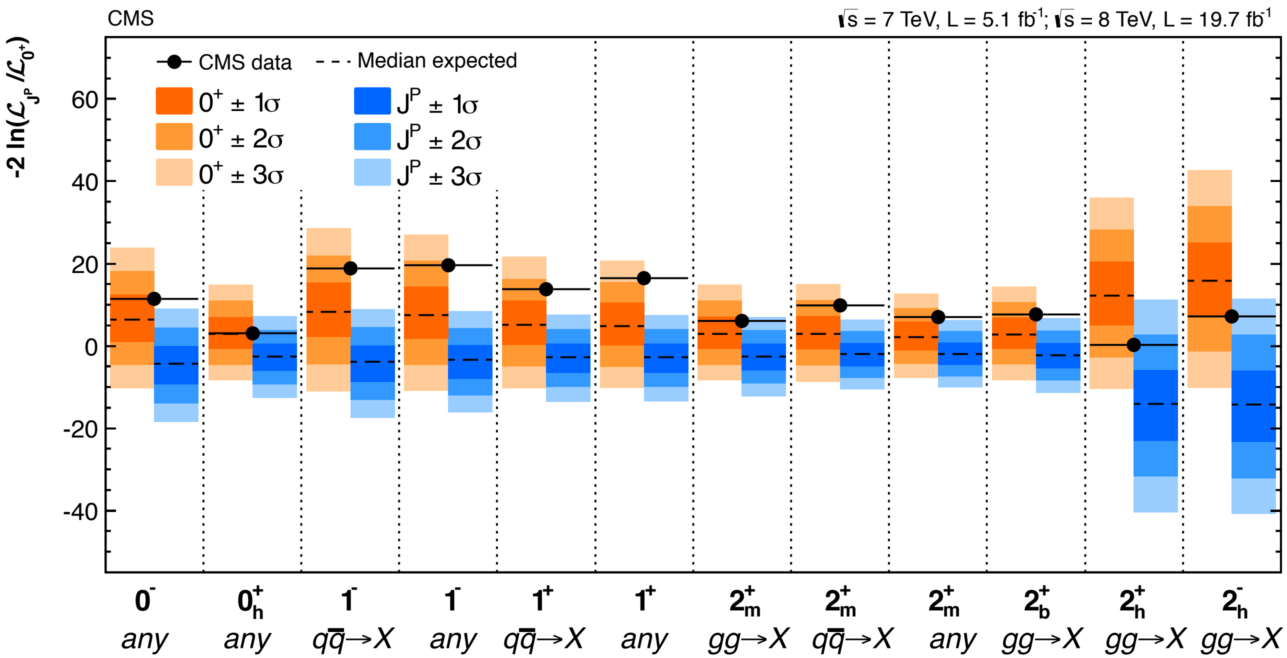
Parity $\leftrightarrows$ angular distribution of final decay products

- ☑ 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

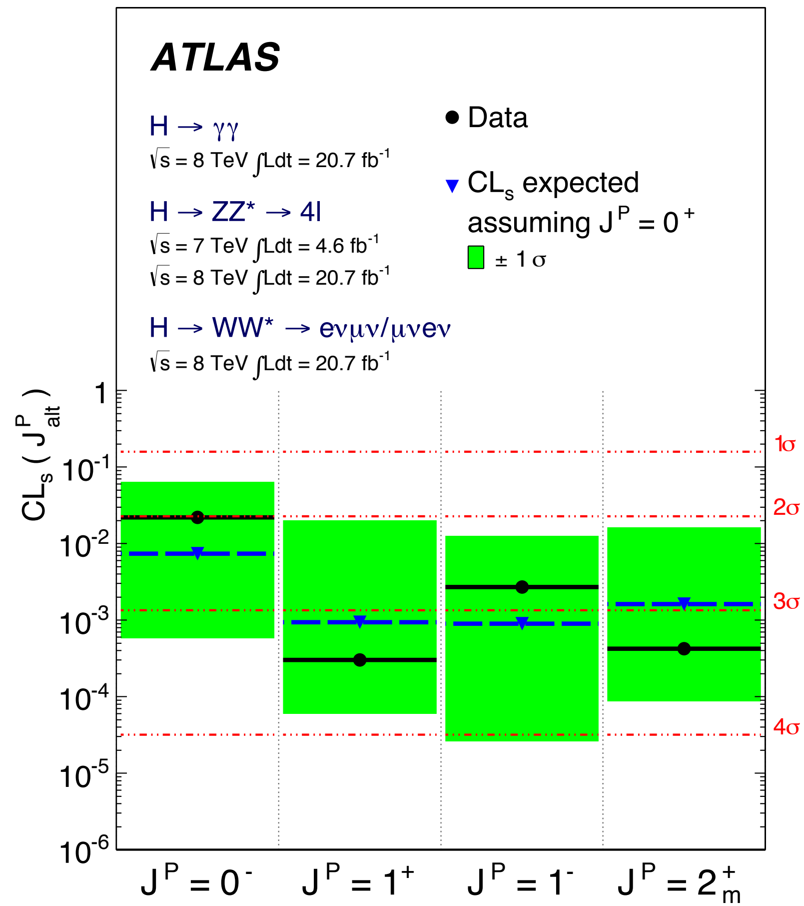
Can be solved at LHC_8 (may be), LHC_{14} (for sure)

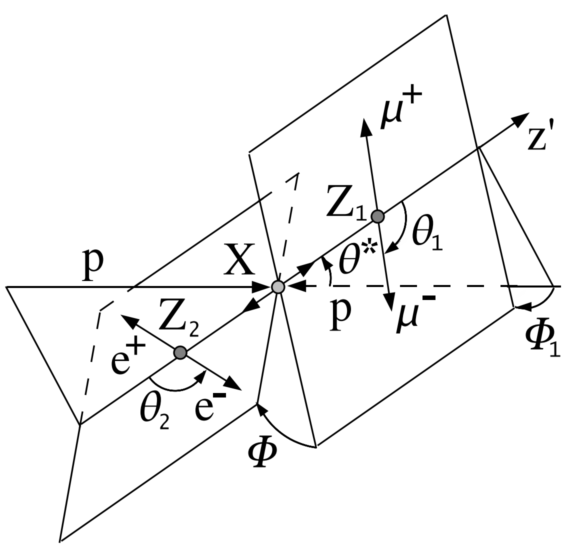
too academic questions? Sensitivity to degree admixture of admixture even/odd?

Spin & Parity now

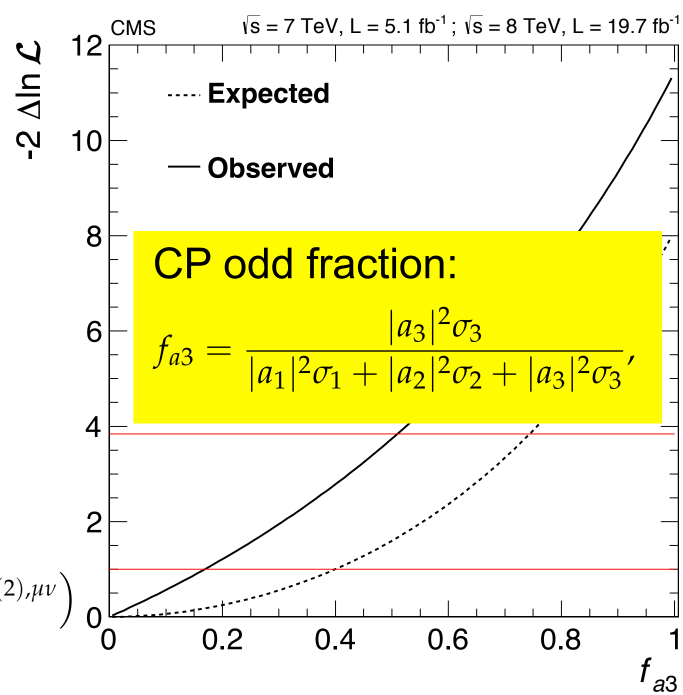


0^+ preferred





$$= v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}\right)$$



Cross-sections and Branching Ratios

(assuming 0^+ SM tensor structure)

Details

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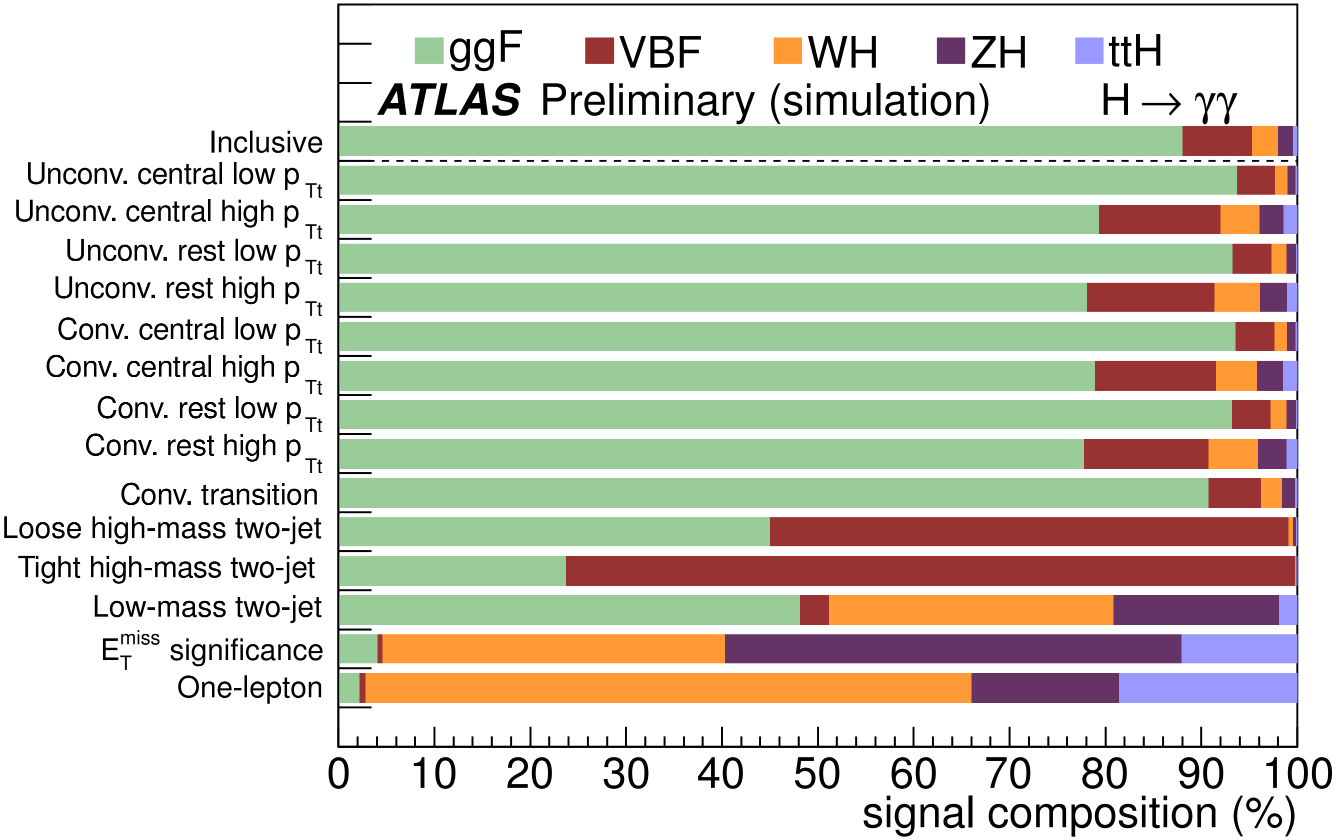
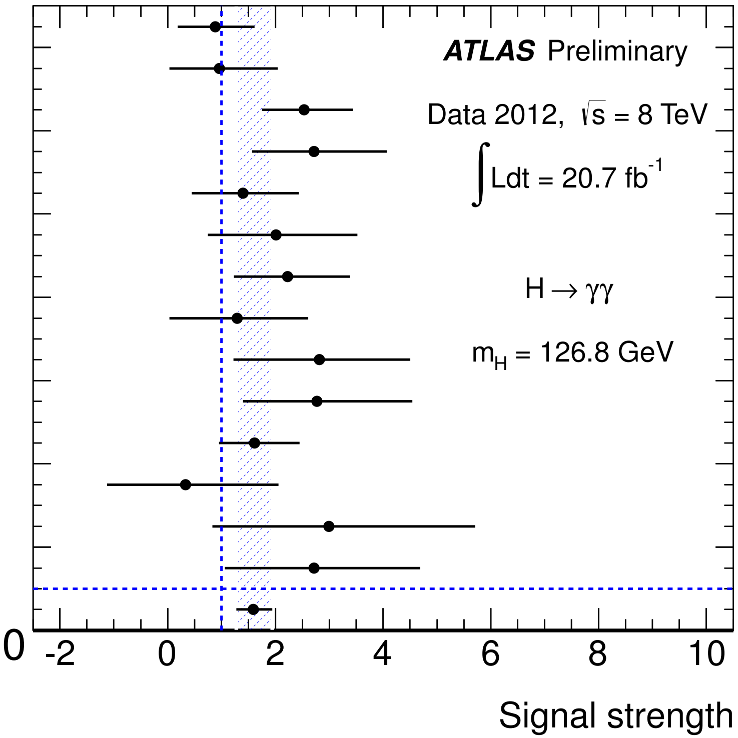
Channels are sub-divided to enhance sensitivity either for experimental reasons or take advantage of production features

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]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	20.7	[9]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	13	[10]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	13	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	13	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	13	[11]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	

Disentangling multiple production modes

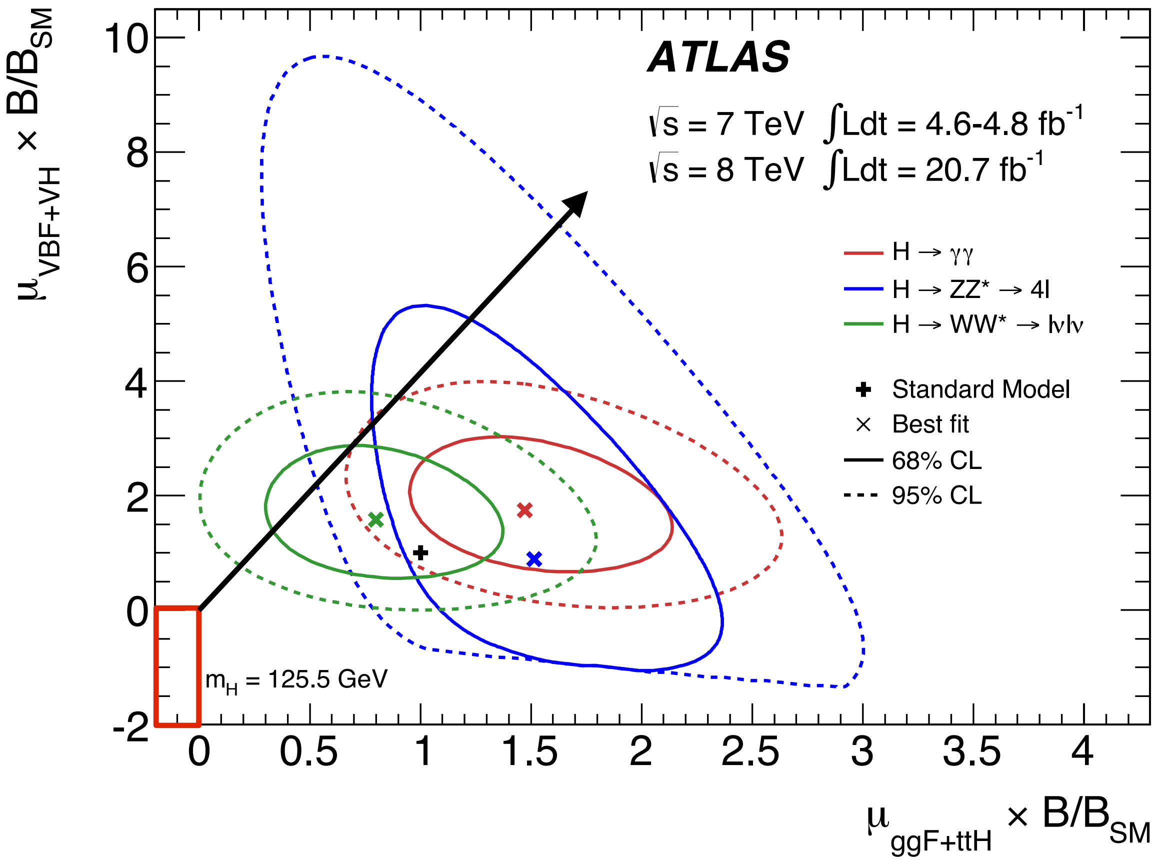


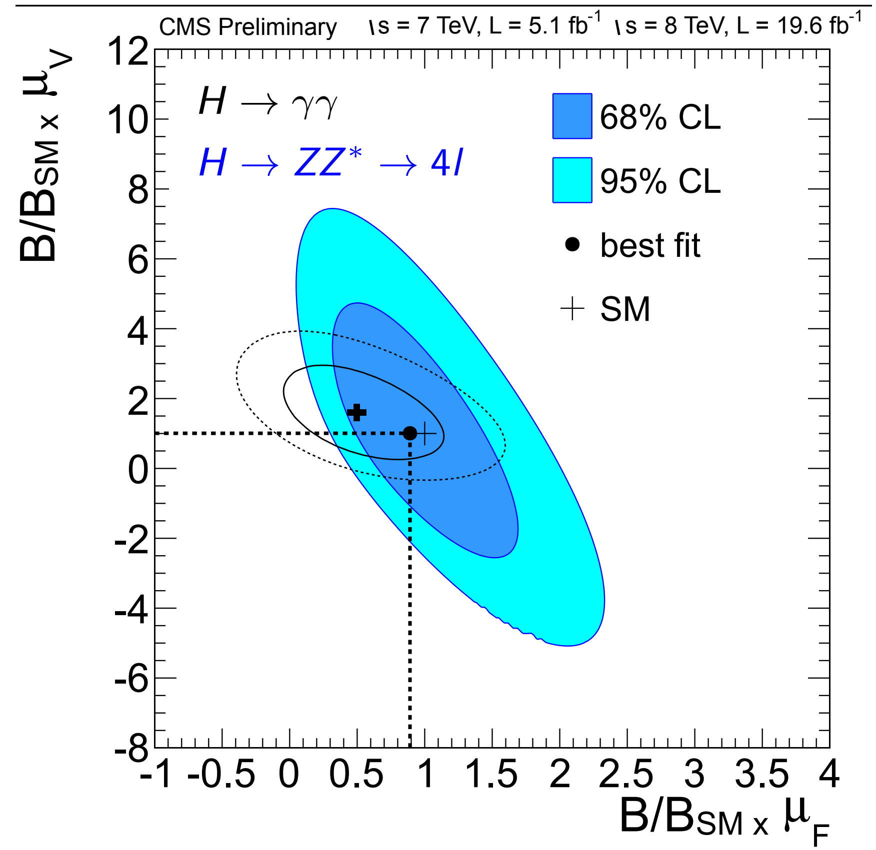


$$n^k_{\text{Signal}} = \left(\sum \mu_i \sigma_{i,SM} \times A^k_{if} \times \varepsilon^k_{if}\right) \times \mu_f \mathcal{B}_{f,SM} \times \mathcal{L}^k$$

- $\sigma_i = \mu_i \sigma_{i,SM}$ 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





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

All coupling measurements pass through this $\sigma_i \times BR_j$ space

See also [arXiv:1401.0080] for new approach to decouple theory uncertainty from experimental results

Information | Citations (4) | Files

Data from Figure 7 from: Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC

ATLAS Collaboration (Aad, Georges (Freiburg U.) [...]) *Show all 2923 authors*

Cite as: ATLAS Collaboration (2013) HepData, http://doi.org/10.7484/INSPIREHEP.DATA.A78C.HK44

Model-independent presentation

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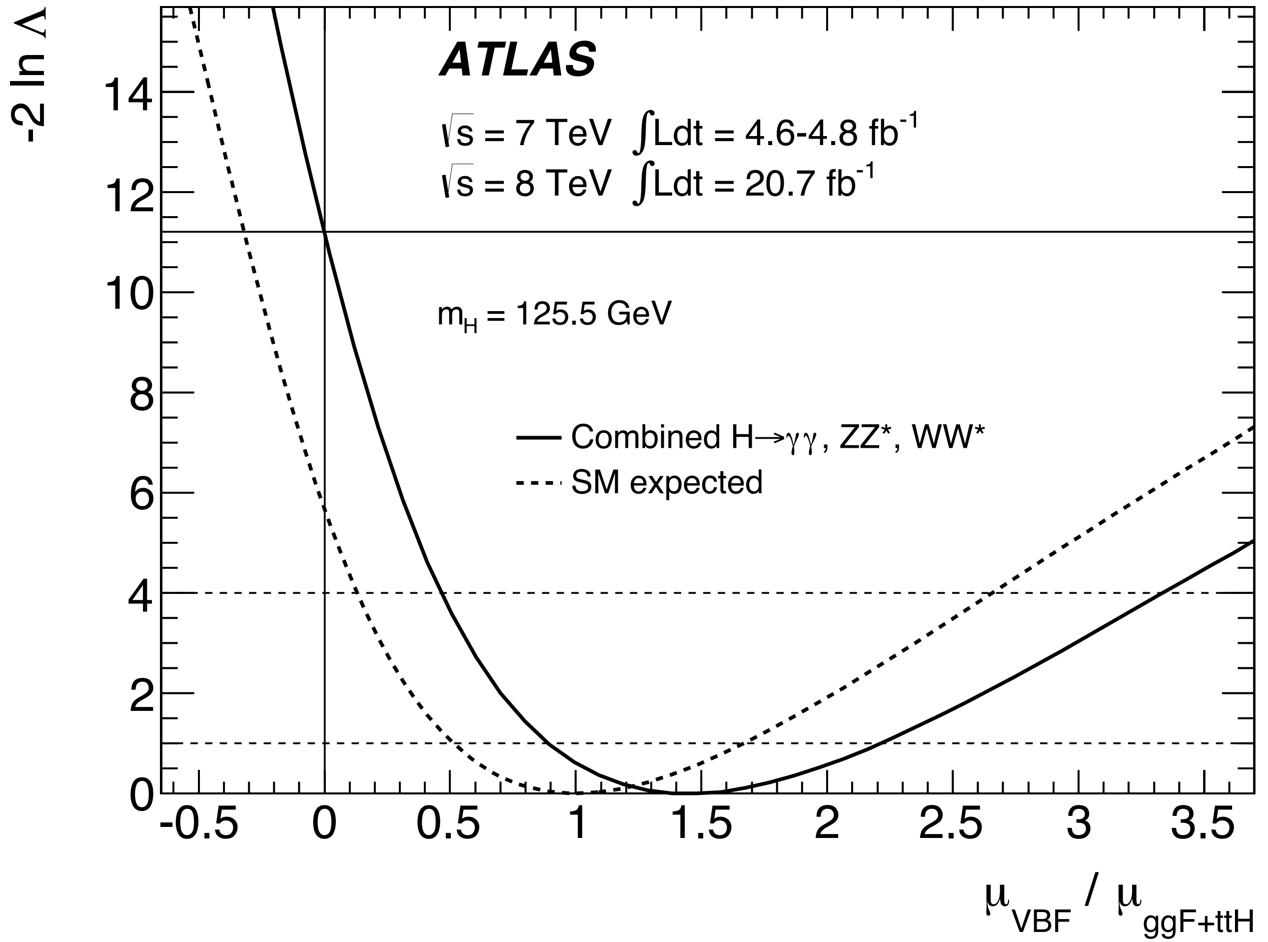
Can't compare contours directly, b/c there is a different BR for axis

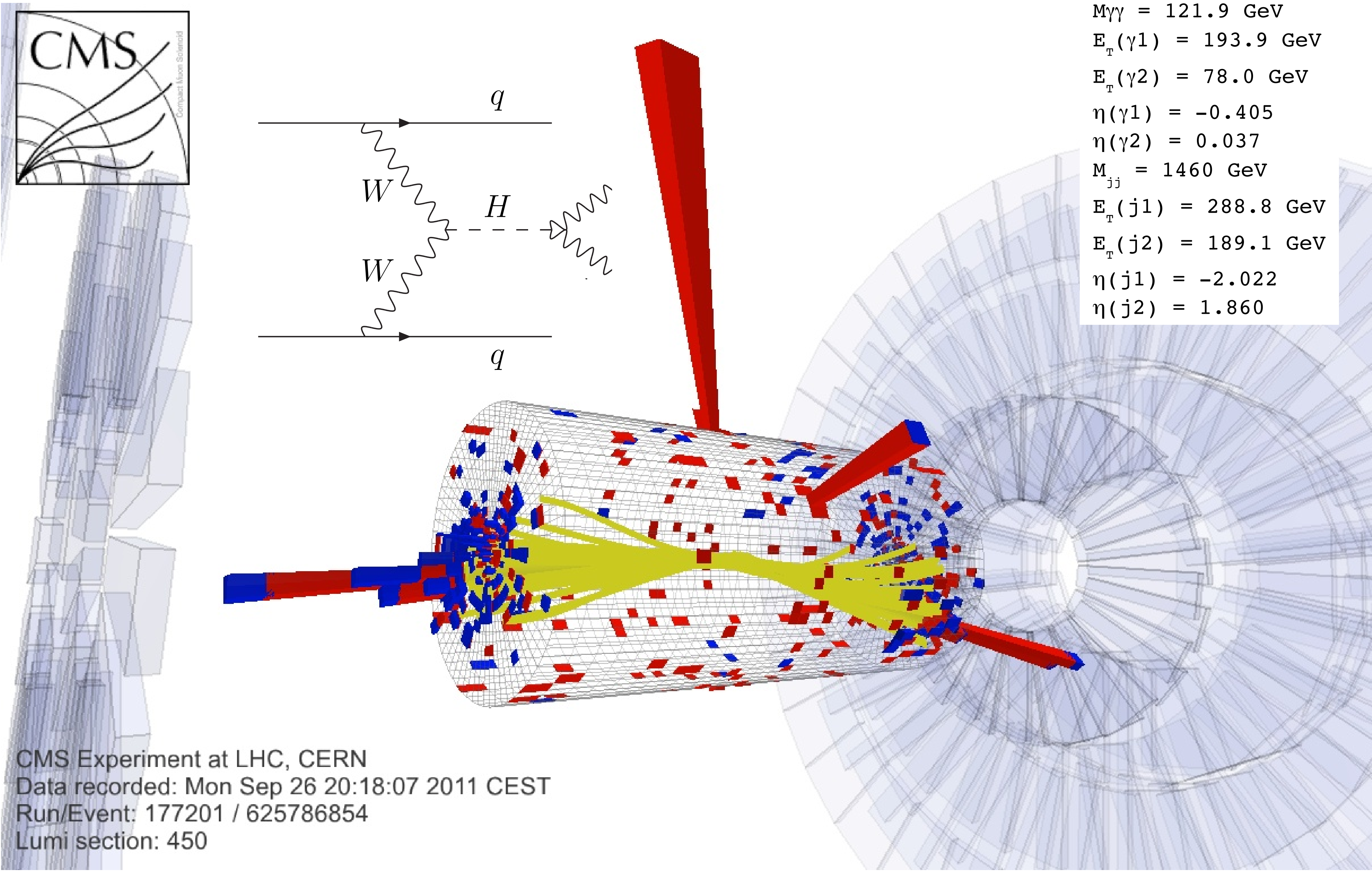
But, BR cancels when considering slope in this plane

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

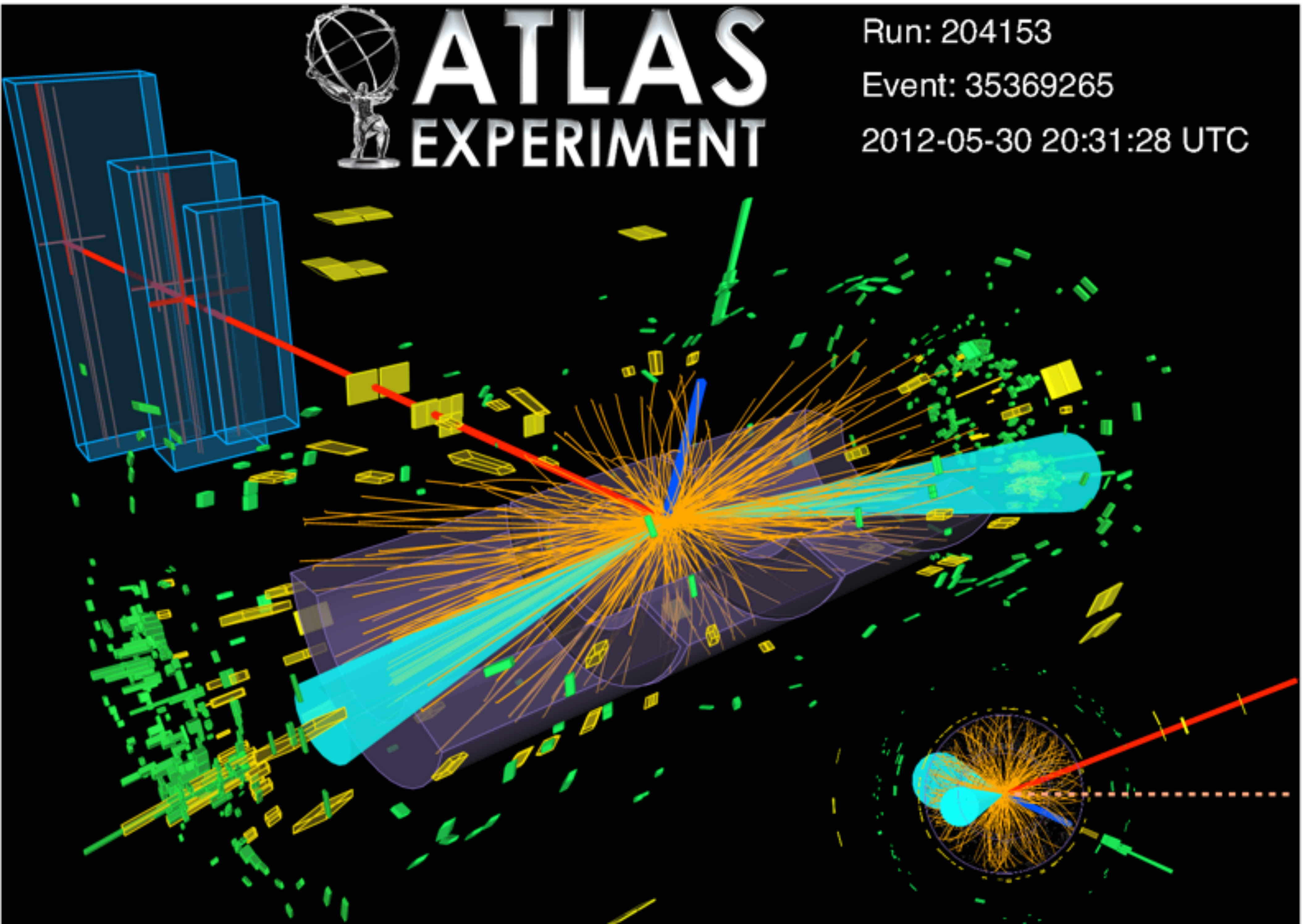


>3σ evidence for VBF Higgs production!

VBF 2-photon candidate



ETmiss=102 GeV, m_{jj}=1.04 TeV and $m_{\tau\tau}$=127 GeV



VBF H→ 4l candidate

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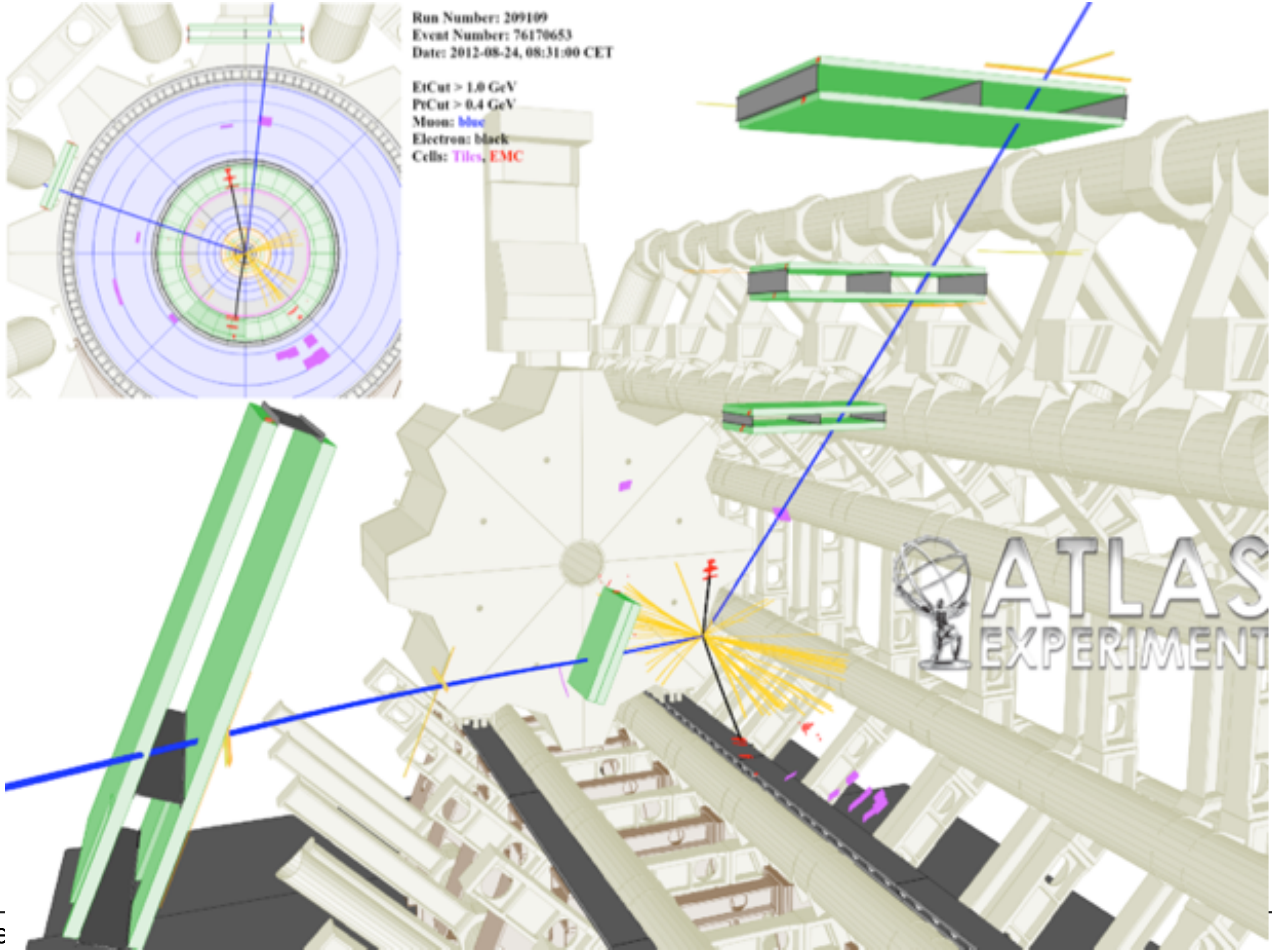
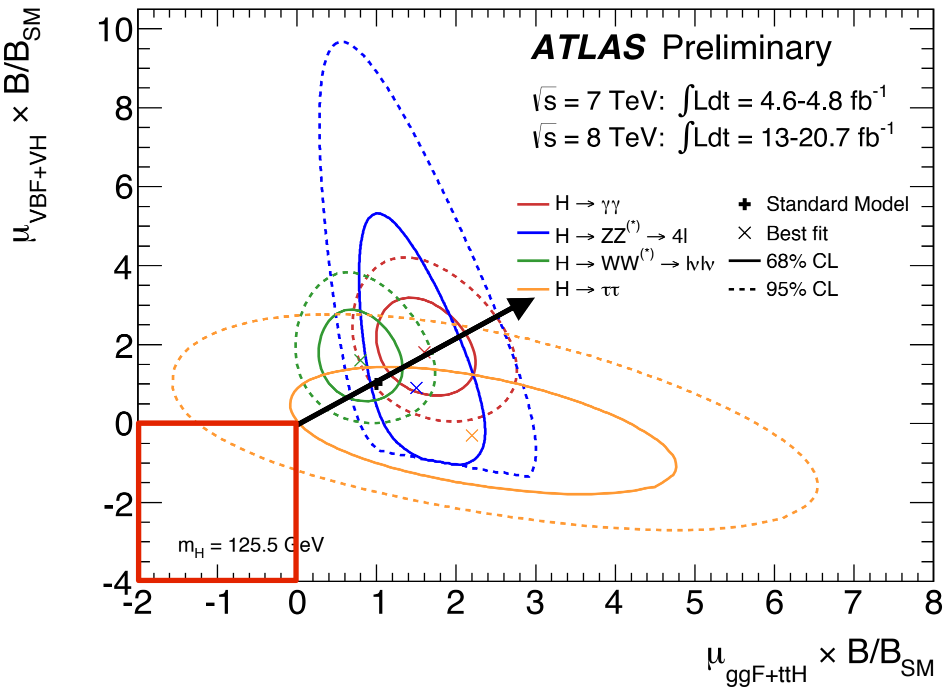
1 VBF candidate observed (m_{4l}=123.5 GeV)   [0.7 expected, S/B~5]



Ratio of Branching Ratios

A model independent approach less sensitive to theory uncertainties

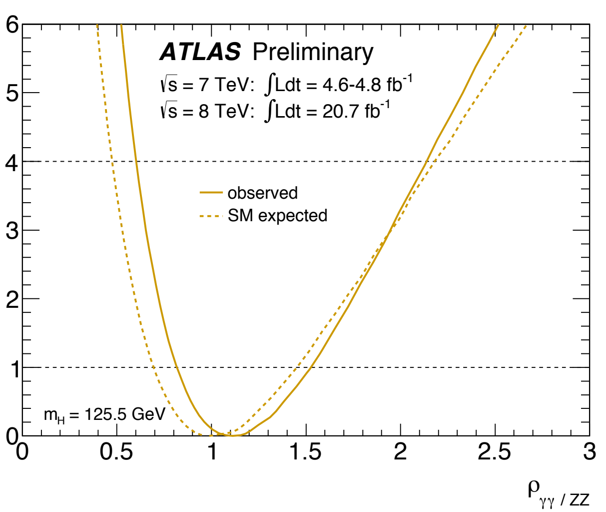


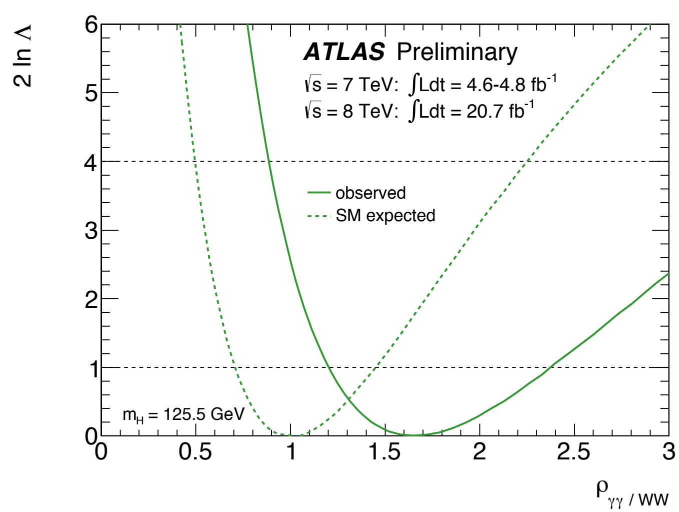
$$\rho_{\gamma\gamma/ZZ} = \frac{\mathrm{BR}(H \to \gamma\gamma)}{\mathrm{BR}(H \to ZZ^{(*)})} \times \frac{\mathrm{BR_{SM}}(H \to ZZ^{(*)})}{\mathrm{BR_{SM}}(H \to \gamma\gamma)}$$

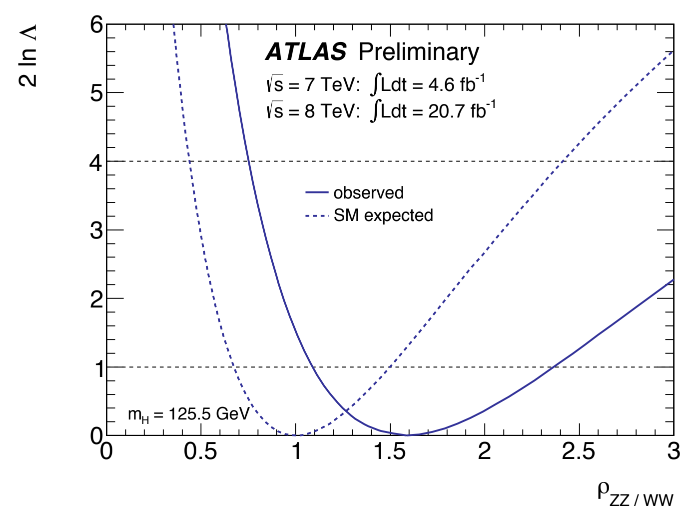
$$\rho_{\gamma\gamma/ZZ} = 1.1^{+0.4}_{-0.3}$$

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

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







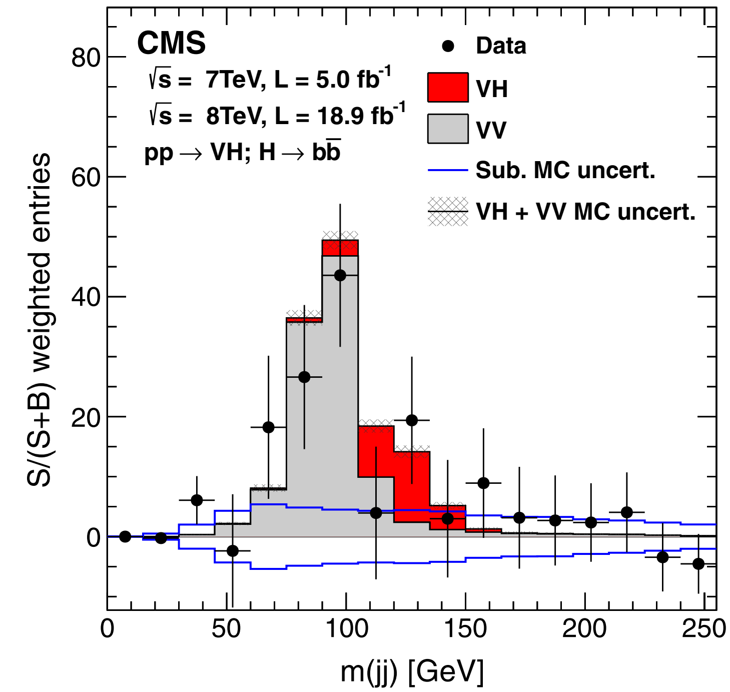
Status of VH production

VH production not yet firmly established

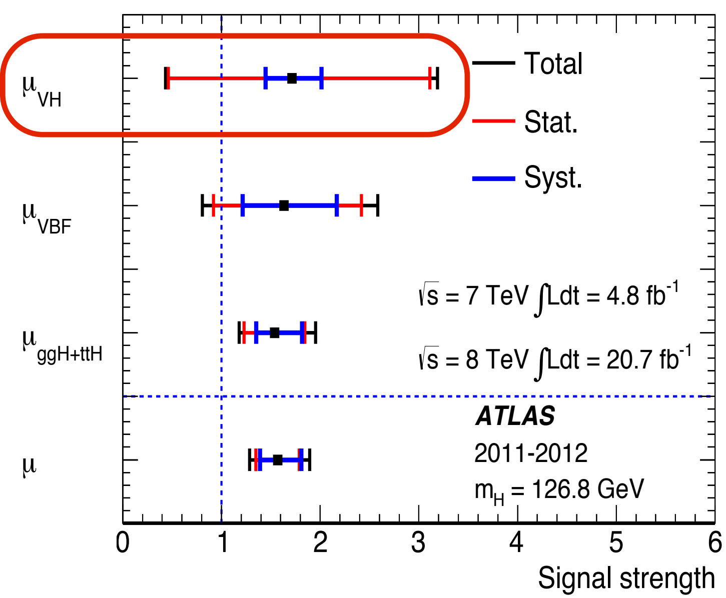
- Channels:
  - H→ $\gamma\gamma$: simple lepton tag, few events
  - H→ bb: complicated analyses
- Sensitivity at ~2x SM rate

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

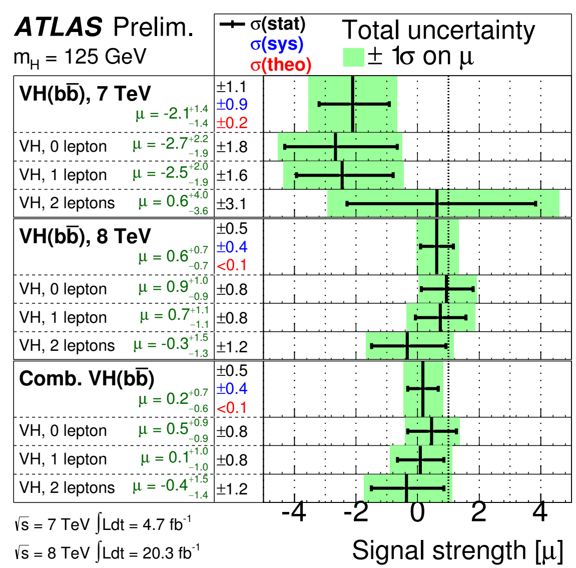
- evidence for VH at Tevatron



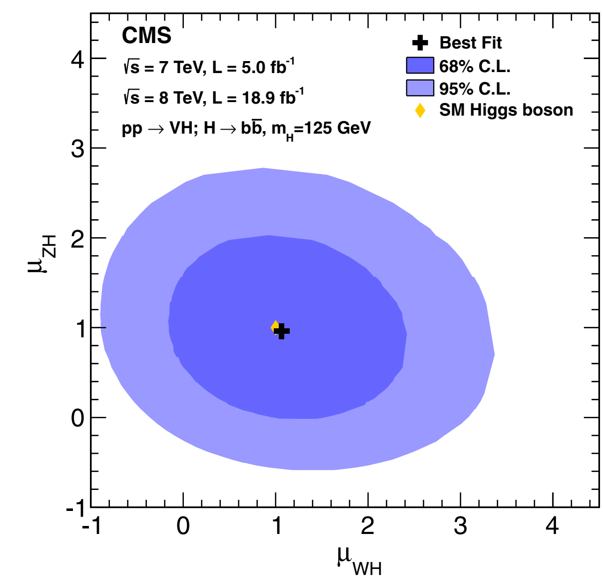
H→ $\gamma\gamma$ @ ATLAS



H→bb @ ATLAS



H→bb @ CMS



Couplings

Narrow width approximation

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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 (but getting close)

- 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 $\Gamma_V^2/\Gamma = \mathrm{meas} \;\; \Rightarrow \;\; \Gamma_{\mathrm{vis}} \leq \Gamma \leq \Gamma_{V,SM}^2/\mathrm{meas}$

Parametrizing the couplings

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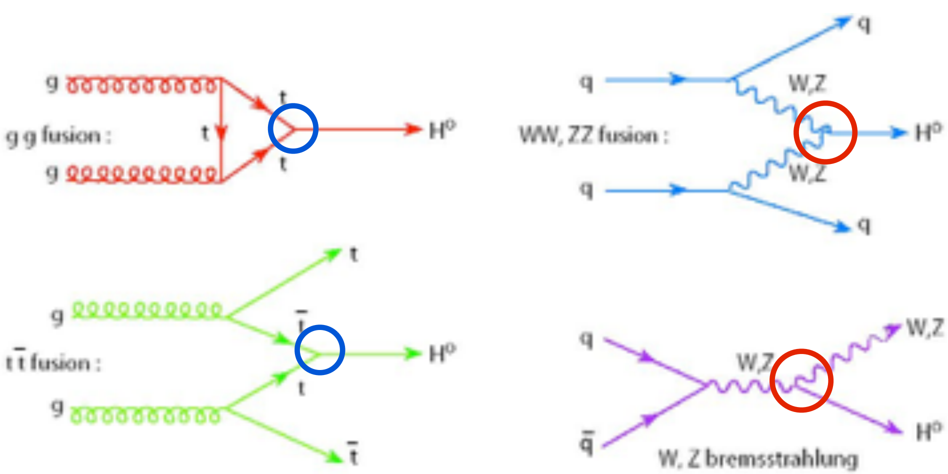
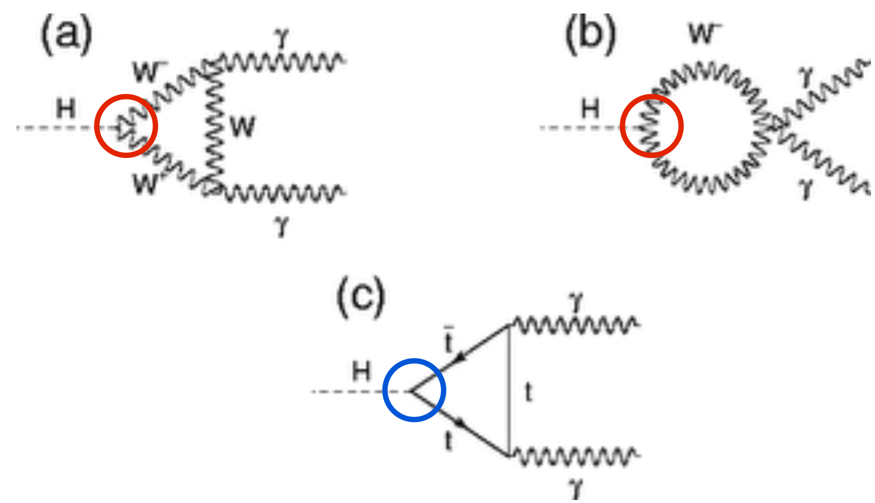
Approach: scale couplings w.r.t. SM values by factor κ

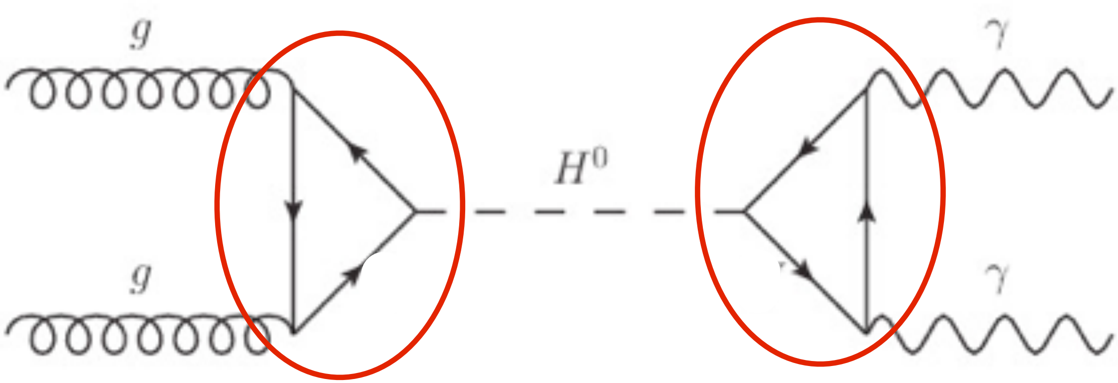
- Expansion around SM point with state-of-the-art predictions

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

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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:

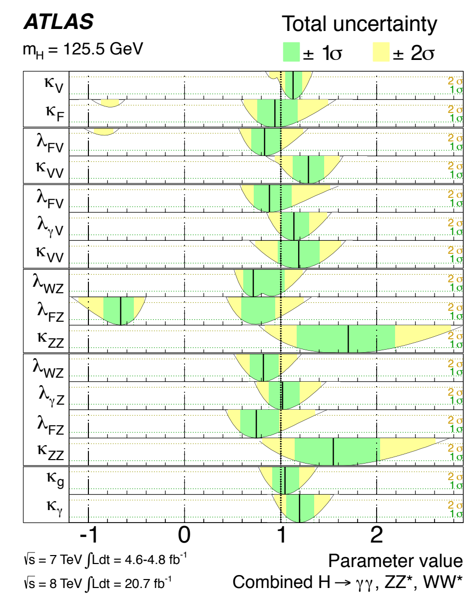
Probe W vs. Z couplings (custodial symmetry)

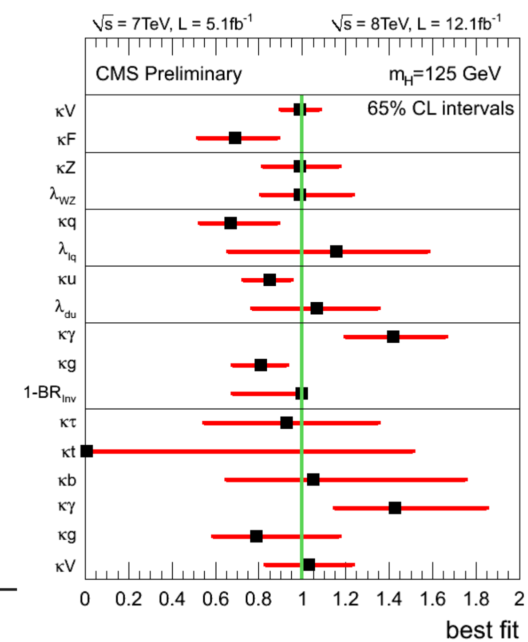
Probe up. vs. down fermion couplings

Probe quark vs. lepton couplings

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

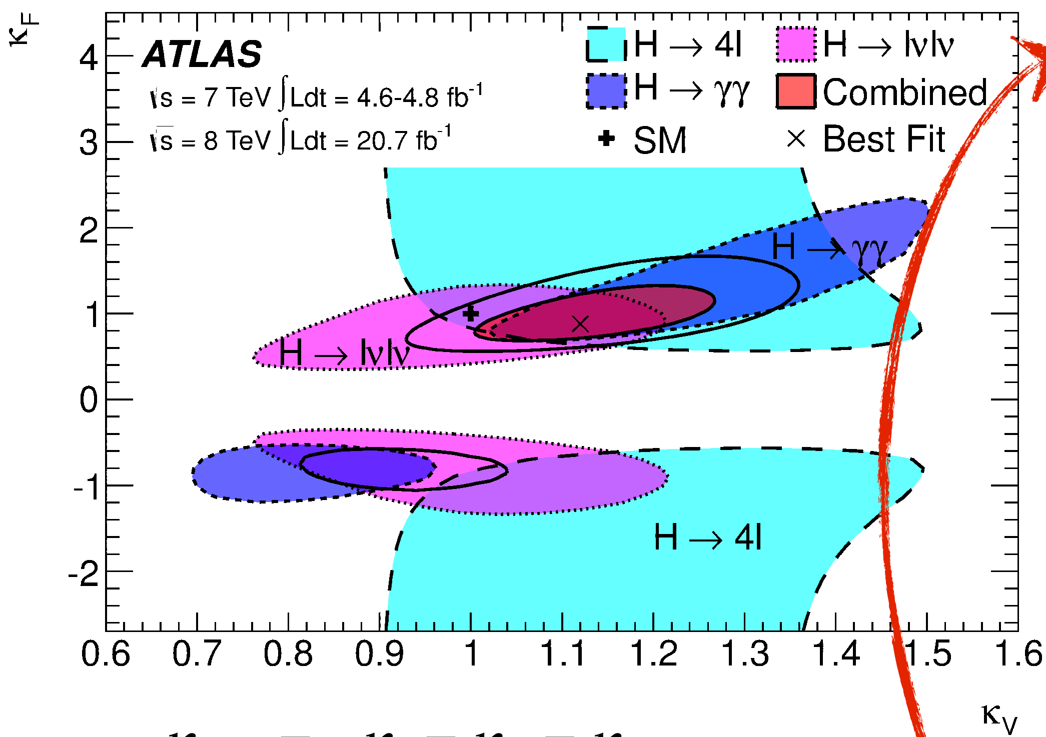
Probe invisible decays

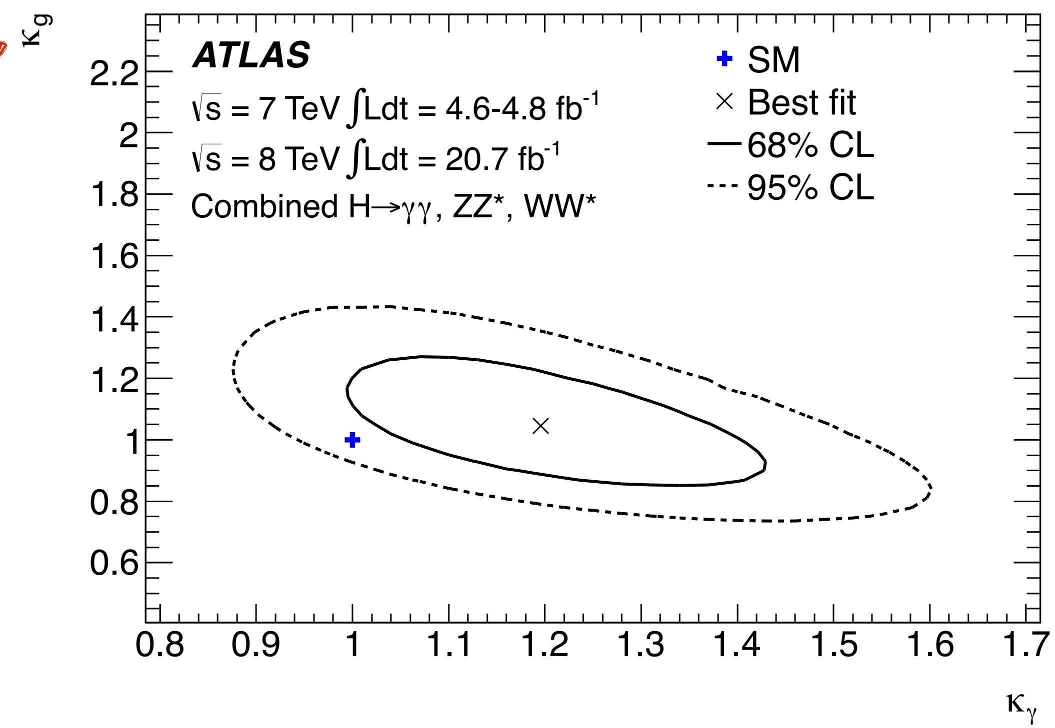




Example Coupling results

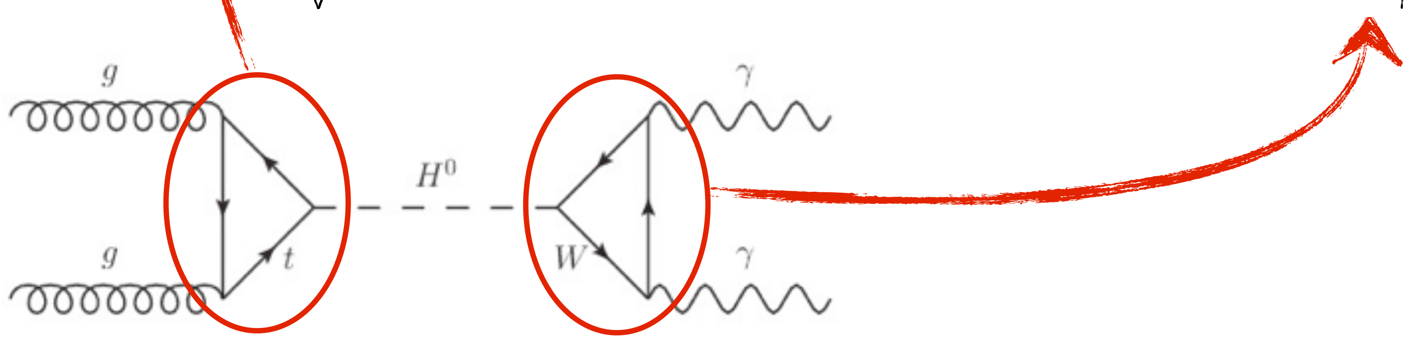
Here, evidence for fermion couplings is indirect





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

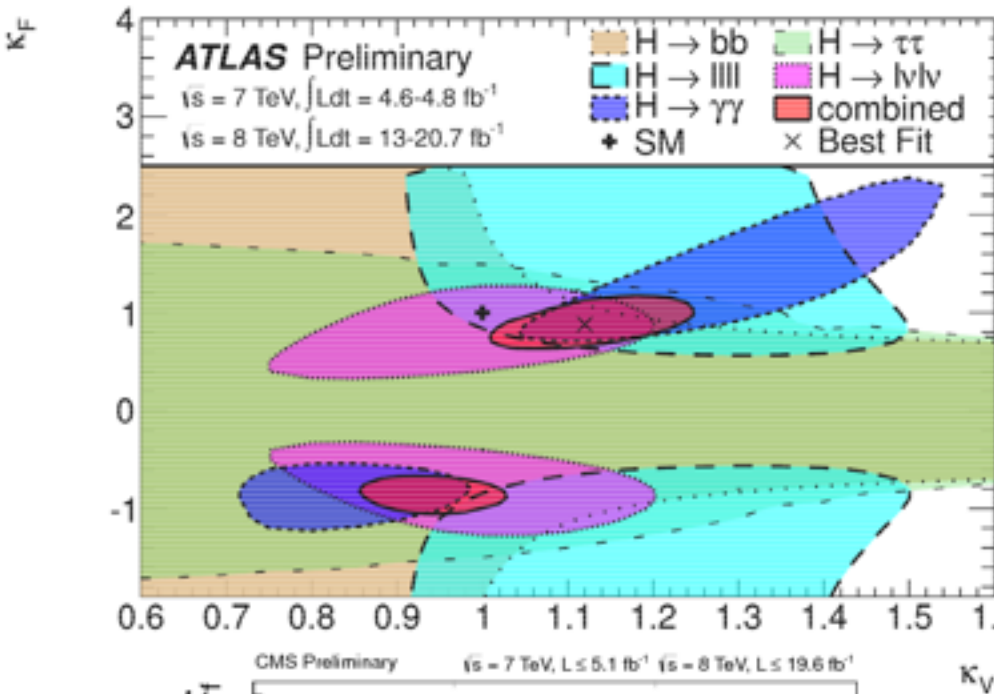
$$\kappa_V = \kappa_W = \kappa_Z$$

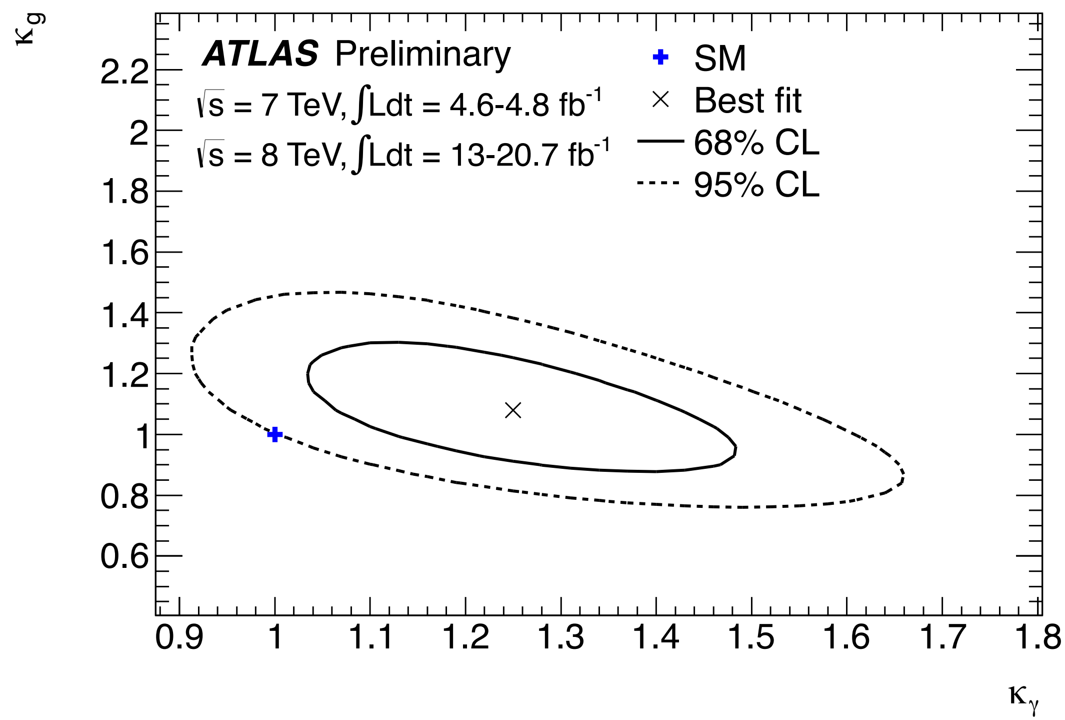


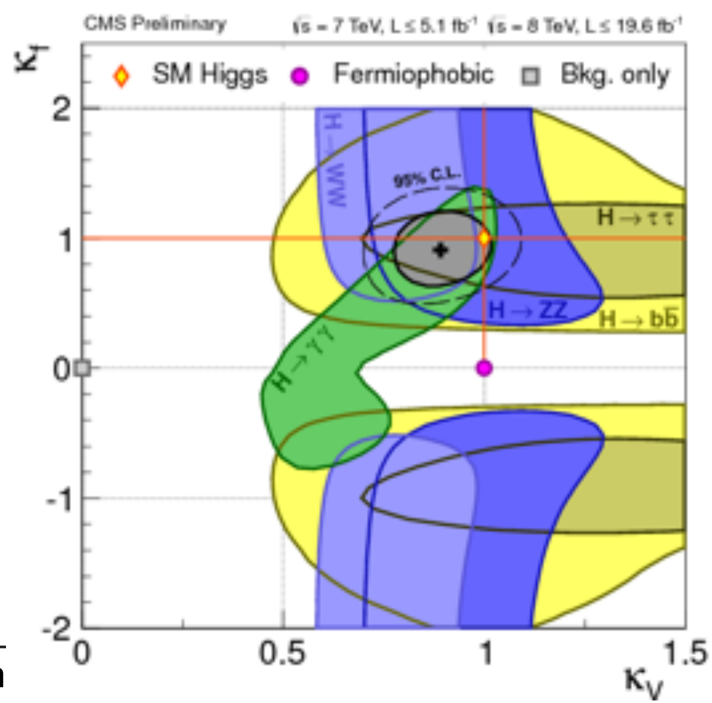
Example Coupling results

Center for Cosmology and Particle Physics

Updated results from ATLAS with fermionic channels







Main coupling results from CMS coming soon after update to H→γγ

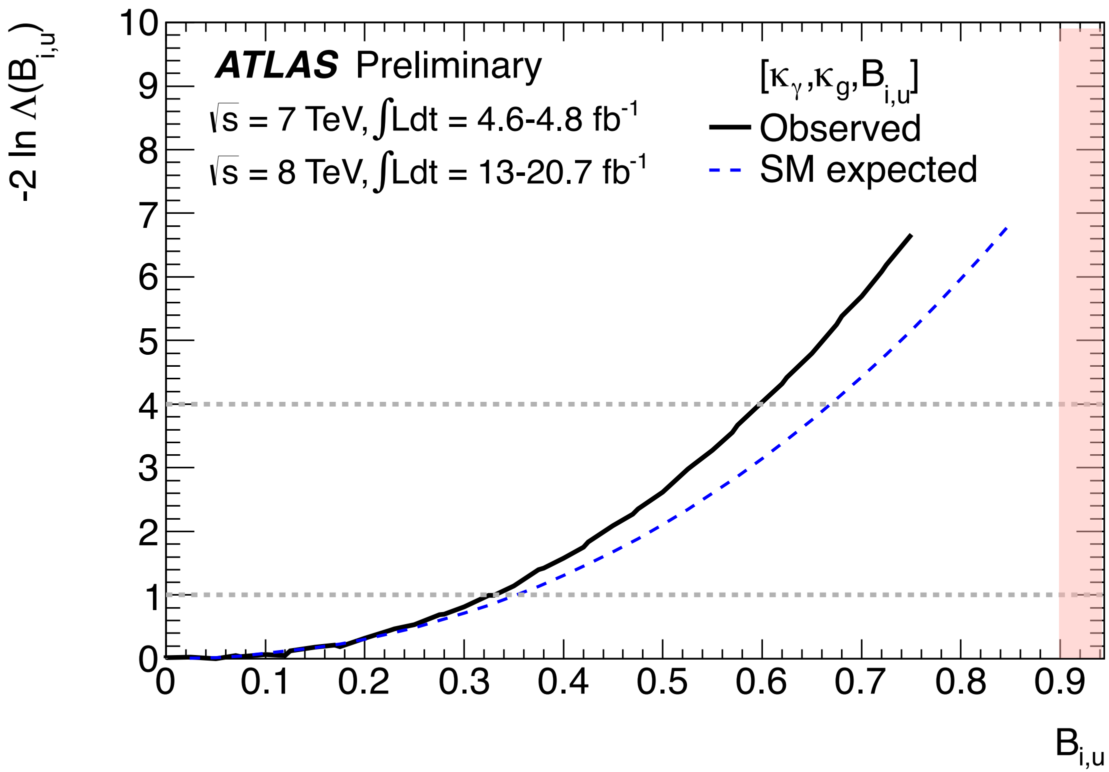
See: Combinations of results of Higgs boson production at the LHC (production rates, couplings)
Presented by **Christian MEINECK** on **21 May 2014** at **14:40**

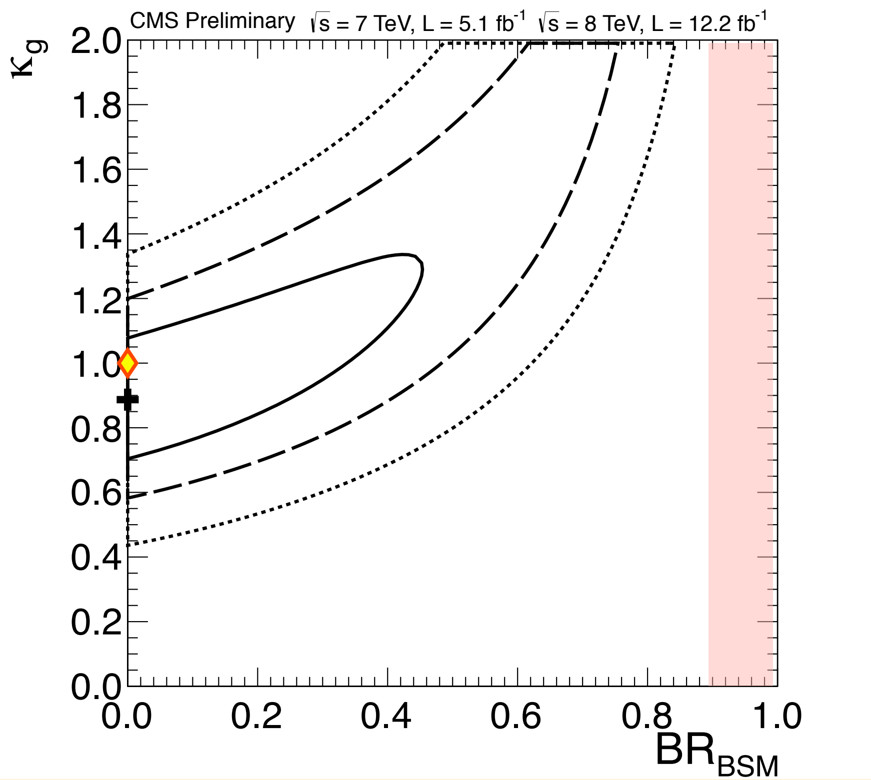
Probing undetected decays

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

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

Disfavors large BR to invisible

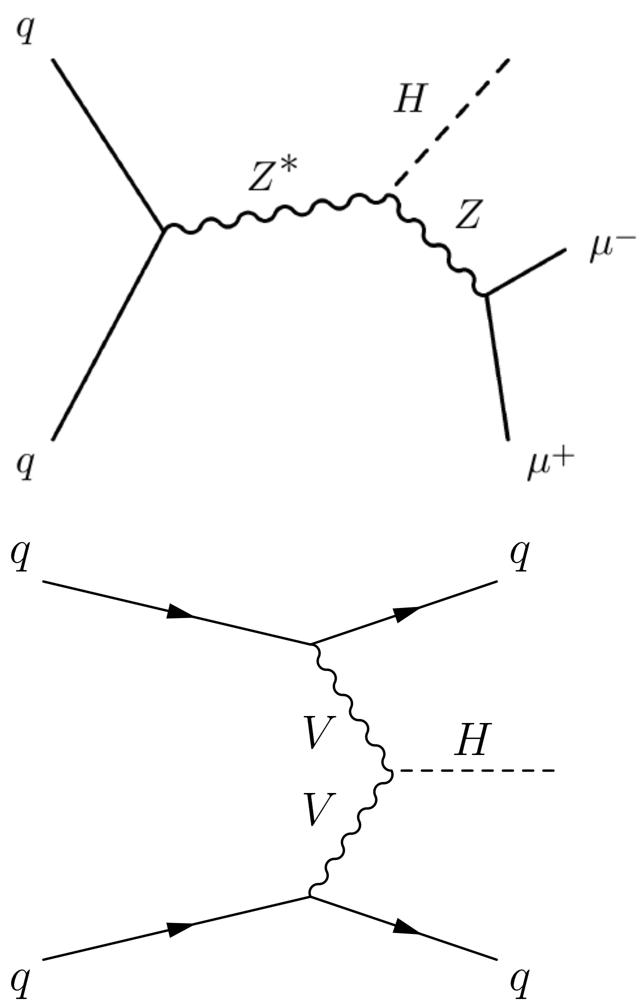


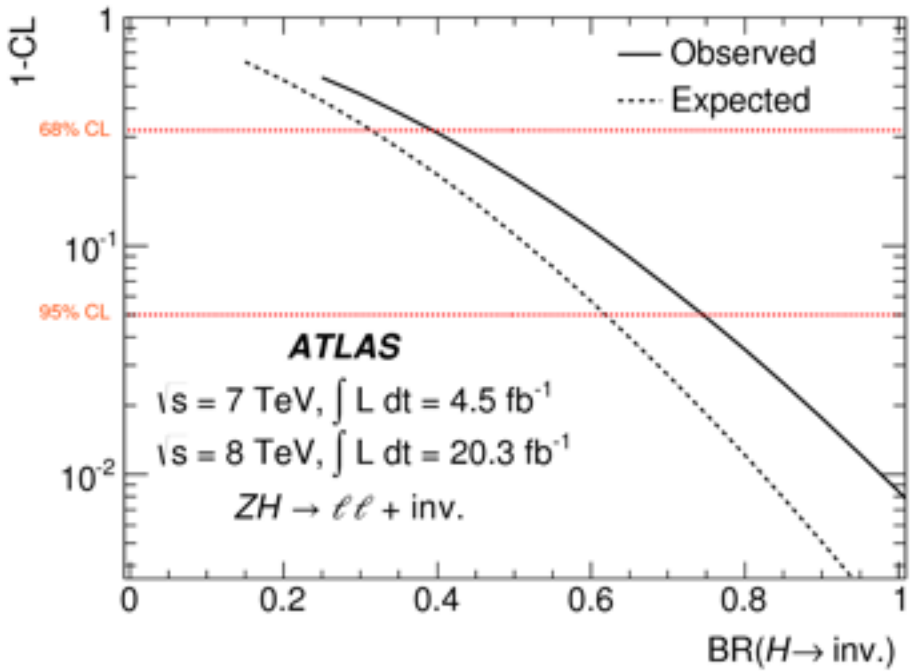


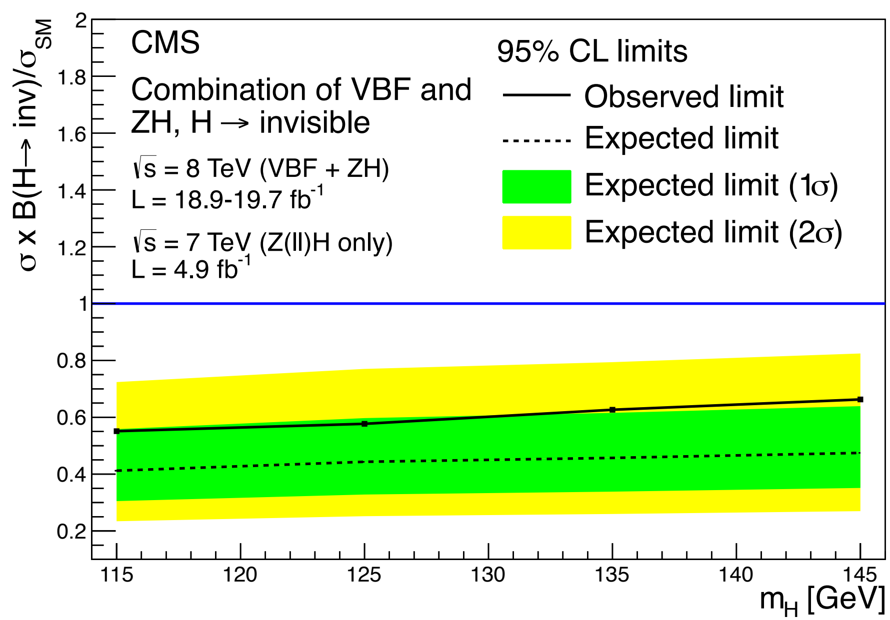
See: "Higgs exotic decays"
Presented by **Prerit JAISWAL** on **21 May 2014** at **18:10**

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)$_{SM}$

ATLAS & CMS directly probing invisible decays with associated production







Summary of what we have established

Mass, spin, CP, and flavor

- mH ~125.5 ± 0.5 GeV
- looks like 0^+ as in SM, though only marginally favored over some alternatives
- fraction of CP odd coupling in ZZ is < ~50%
- no FCNC seen, BR($t \rightarrow Hc$) ≲ 1%

Production:

- discovery established ggF production & now VBF production also firmly established
- evidence for VH ~2σ
- ttH: not yet, look out for Run-II

Decays:

- γγ, WW, ZZ >> 5σ
- ττ at ~4σ (lack of μμ as expected ⇒ not a flavor-universal coupling)
- bb ~2σ
- BR(H→invisible/undetected) < ~60%
- total width < ~4.2x SM

Overall coupling pattern:

- consistent with the SM, though ~2σ tension seen

Future Colliders

A very active area

European Strategy for Particle Physics

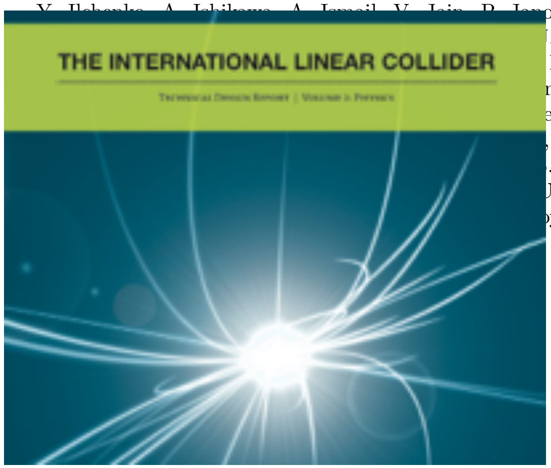
The European strategy for particle physics

ECFA
European Committee for Future Accelerators

Higgs working group report

Conveners: Sally Dawson (BNL), Andrei Gritsan (Johns Hopkins), Heather Logan (Carleton), Jianming Qian (Michigan), Chris Tully (Princeton), Rick Van Kooten (Indiana)

Authors: A. Ajaib, A. Anastassov, I. Anderson, D. Asner, O. Bake, V. Barger, T. Barklow, B. Batell, M. Battaglia, S. Berge, A. Blondel, S. Bolognesi, J. Brau, E. Brownson, M. Cahill-Rowley, C. Calancha-Paredes, C.-Y. Chen, W. Chou, R. Clare, D. Cline, N. Craig, K. Cranmer, M. de Gruttola, A. Elagin, R. Essig, L. Everett, E. Feng, K. Fujii, J. Gainer, Y. Gao, I. Gogoladze, S. Gori, R. Goncalo, N. Graf, C. Grojean, S. Guindon, H. Haber, T. Han, G. Hanson, R. Harnik, S. Heinemeyer, U. Heintz, J. Hewett, ...t, S. Kanemura, S. Kawada, R. Kehoe, M. Klute, ... Kunkle, M. Kurata, I. Lewis, Y. Li, L. Linssen, ... Low, T. Ma, P. Mackenzie, B. Mellado, K. Melnikov, ...n, H. Neal, J. Nielsen, N. Okada, H. Okawa, J. Olsen, ...ello, T. Plehn, C. Pollard, C. Potter, K. Prokofiev, ... R. Ruiz, V. Sanz, J. Sayre, Q. Shafi, G. Shaughnessy, ... Su, T. Suehara, T. Tanabe, T. Tajima, V. Telnov, ...Un, M. Velasco, C. Wagner, S. Wang, S. Watanuki, ...ya, S. Zenz, D. Zerwas, Y. Zhang, Y. Zhou



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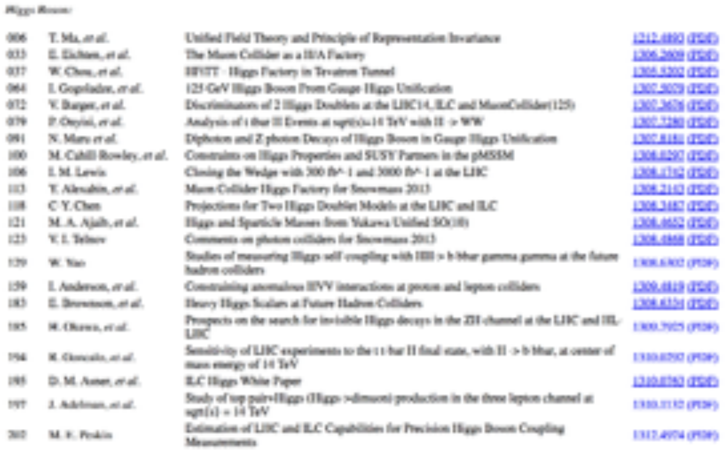
Future Circular Collider Study Kickoff Meeting

12-15 February 2014
University of Geneva - UNI MAIL
Europe/Zurich timezone

Search

Webcast: Please note that this event will be available live via the Webcast Service.

Future Circular Collider Study Kickoff Meeting

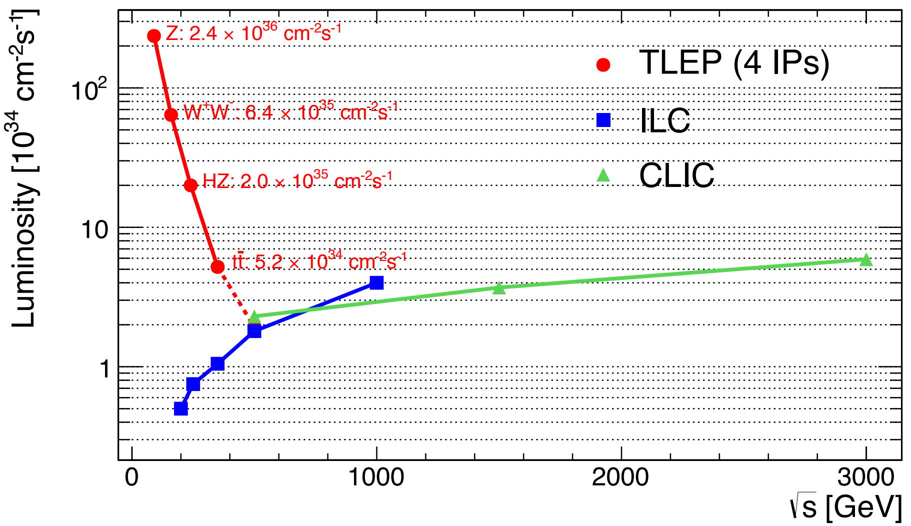


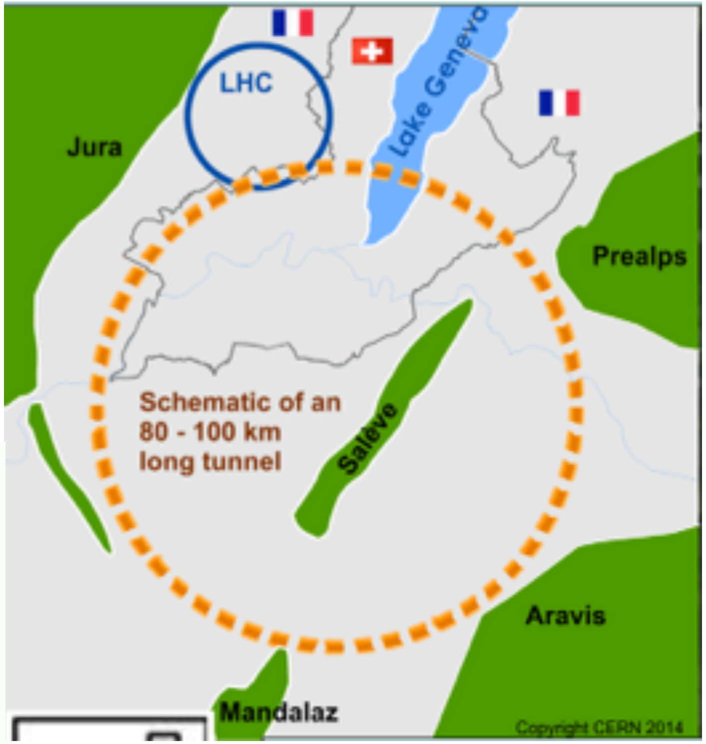
Higgs Boson:

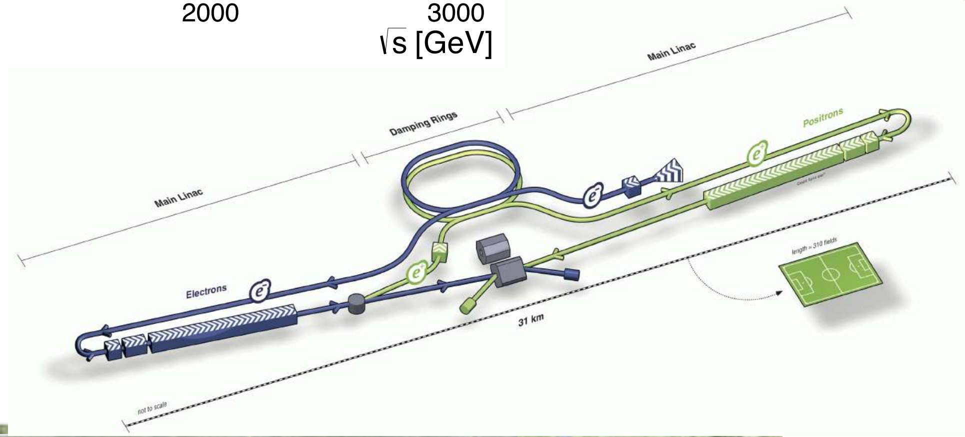
006	T. Ma, *et al.*	Unified Field Theory and Principle of Representation Invariance	[illegible] (PDF)
033	E. Eichten, *et al.*	The Muon Collider as a H/A Factory	[illegible] (PDF)
037	W. Chou, *et al.*	HFiTT - Higgs Factory in Tevatron Tunnel	[illegible] (PDF)
064	I. Gogoladze, *et al.*	125 GeV Higgs Boson From Gauge Higgs Unification	[illegible] (PDF)
072	V. Barger, *et al.*	Discriminators of 2 Higgs Doublets at the LHC14, ILC and MuonCollider(125)	[illegible] (PDF)
079	P. Onyisi, *et al.*	Analysis of t tbar H Events at sqrt(s)=14 TeV with H -> WW	[illegible] (PDF)
091	N. Maru *et al.*	Diphoton and Z photon Decays of Higgs Boson in Gauge Higgs Unification	[illegible] (PDF)
100	M. Cahill-Rowley, *et al.*	Constraints on Higgs Properties and SUSY Partners in the pMSSM	[illegible] (PDF)
106	I. M. Lewis	Closing the Wedge with 300 fb^-1 and 3000 fb^-1 at the LHC	[illegible] (PDF)
113	Y. Alexahin, *et al.*	Muon Collider Higgs Factory for Snowmass 2013	[illegible] (PDF)
118	C.Y. Chen	Projections for Two Higgs Doublet Models at the LHC and ILC	[illegible] (PDF)
121	M. A. Ajaib, *et al.*	Higgs and Sparticle Masses from Yukawa Unified SO(10)	[illegible] (PDF)
123	V. I. Telnov	Comments on photon colliders for Snowmass 2013	[illegible] (PDF)
139	W. Yao	Studies of measuring Higgs self-coupling with HH -> b-bbar gamma gamma at the future hadron colliders	[illegible] (PDF)
159	I. Anderson, *et al.*	Constraining anomalous HVV interactions at proton and lepton colliders	[illegible] (PDF)
183	E. Brownson, *et al.*	Heavy Higgs Scalars at Future Hadron Colliders	[illegible] (PDF)
185	H. Okawa, *et al.*	Prospects on the search for invisible Higgs decays in the ZH channel at the LHC and HL-LHC	[illegible] (PDF)
194	R. Goncalo, *et al.*	Sensitivity of LHC experiments to the t t-bar H final state, with H -> b bbar, at center of mass energy of 14 TeV	[illegible] (PDF)
195	D. M. Asner, *et al.*	ILC Higgs White Paper	[illegible] (PDF)
197	J. Adelman, *et al.*	Study of top pair+Higgs (Higgs->dimuon) production in the three lepton channel at sqrt(s) = 14 TeV	[illegible] (PDF)
202	M. E. Peskin	Estimation of LHC and ILC Capabilities for Precision Higgs Boson Coupling Measurements	[illegible] (PDF)

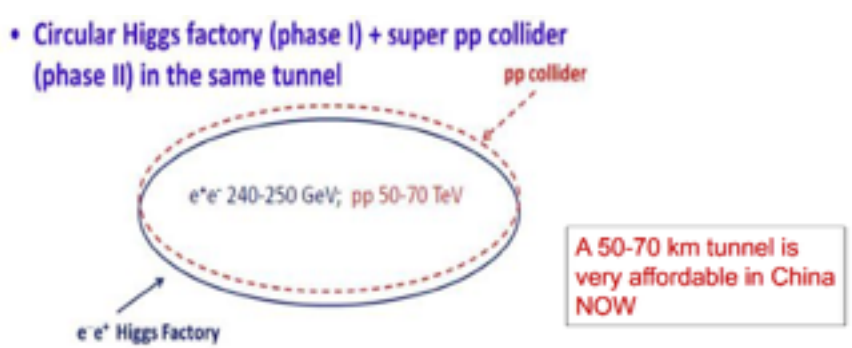
The dream machines

Center for Cosmology and Particle Physics





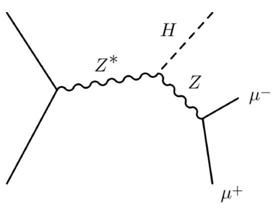




Some general comments on e^+e^-

CENTER FOR COSMOLOGY AND PARTICLE PHYSICS

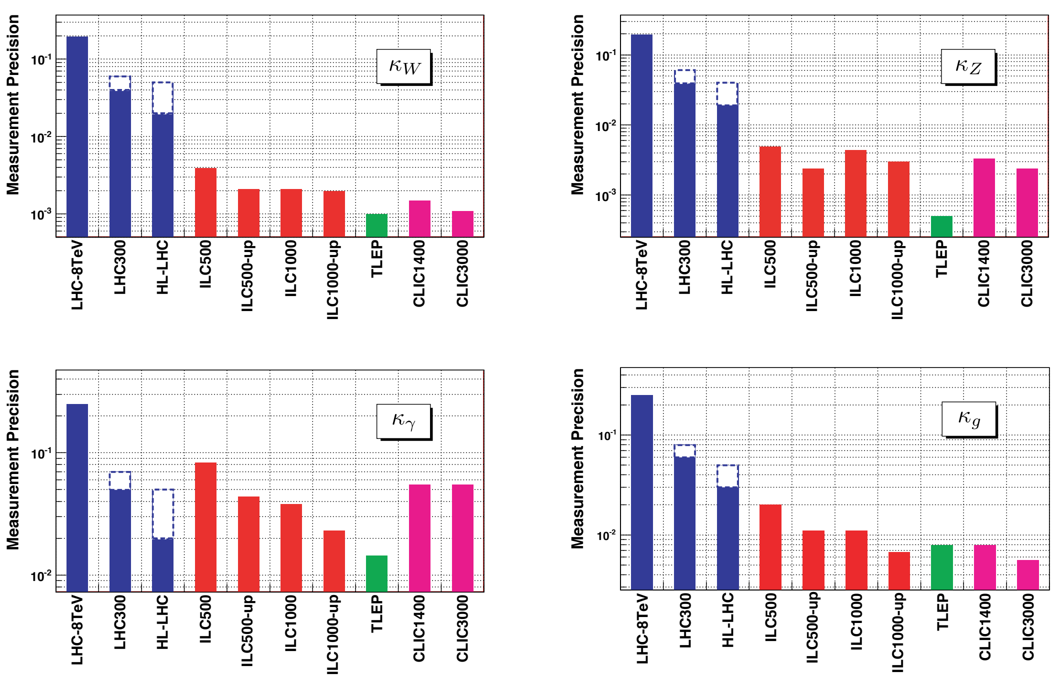
Because 4-momentum of initial state known at $e^+e^- \rightarrow ZH$, it is possible to use recoil of Z in to reconstruct Higgs in a decay-independent way

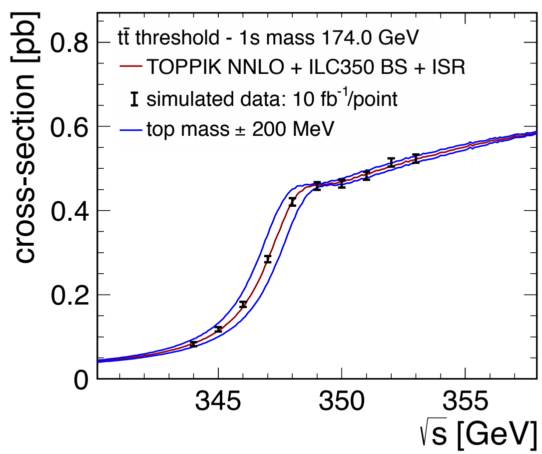


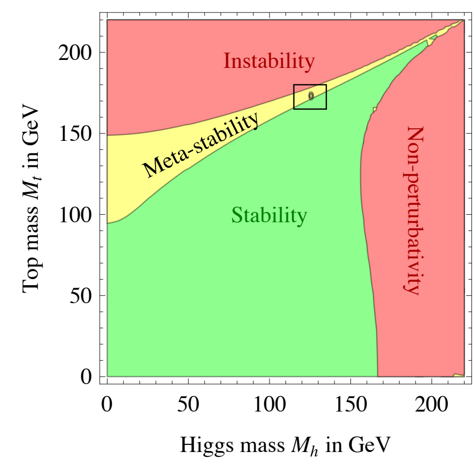
- allows for measurement of absolute branching ratios
- story changes a bit now that LHC probing Higgs width via interference, but not same level of precision (1-5%) achievable at lepton colliders
- theoretical uncertainties at e^+e^- generally much smaller than at hadron colliders

Top mass measurement at hadron colliders has large theoretical uncertainties in connecting to pole mass (needed for vacuum stability etc.).

- High-energy e^+e^- colliders can measure top mass via threshold scan.

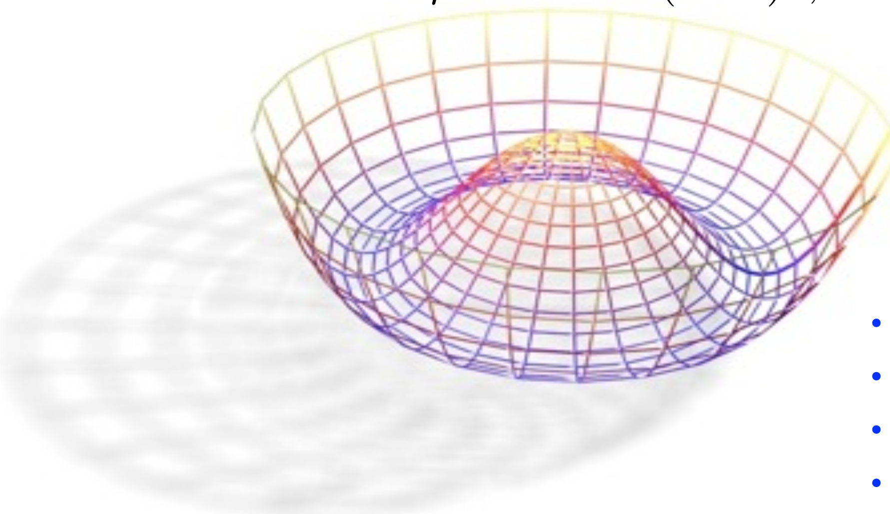




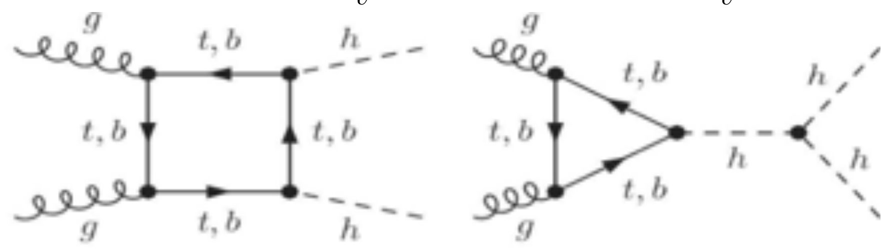


Higgs Self Coupling @ future hadron colliders

$$V = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2,$$



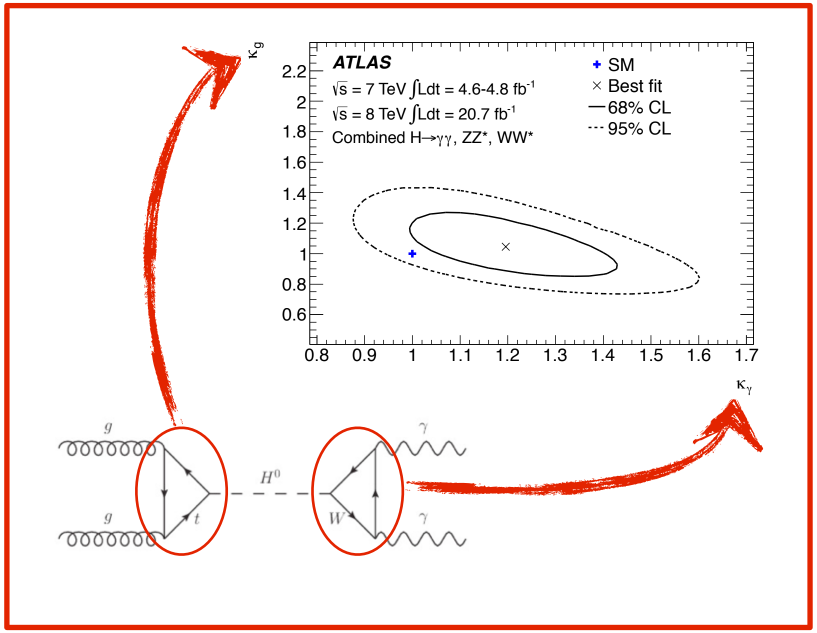
$$g_{HHH} = 6\lambda v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6\lambda = \frac{3m_H^2}{v^2}.$$



- HL-LHC could measure λ ~50%, more studies needed
- Need √s> 1TeV for ILC to improve
- Hard for TLEP/FCC-ee
- high energy hadron collider could measure λ at ~8%

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

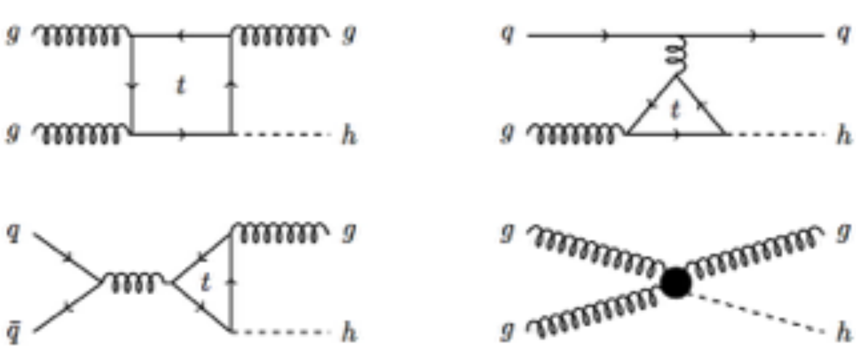
Probing new physics in high p_T tail



cut open the top loops

high p_T ≈ Higgs off-shell
we "see" the details of the particles running inside the loops

Baur, Glover '90
Langenegger, Spira, Starodumov, Trueb '06



$$\frac{\sigma_{p_T^{\mathrm{min}}}(\kappa_t,\kappa_g)}{\sigma^{\mathrm{SM}}_{p_T^{\mathrm{min}}}} = (\kappa_t+\kappa_g)^2 + \delta\,\kappa_t\,\kappa_g + \epsilon\,\kappa_g^2$$

$\sqrt{s}$ [TeV]	p_T^{min} [GeV]	$\sigma^{\mathrm{SM}}_{p_T^{\mathrm{min}}}$ [fb]	δ	ϵ	gg, qg [%]
14	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57
100	500	970	1.8	3.1	72, 28
	2000	1.0	14	78	56, 43

×150 enhancement

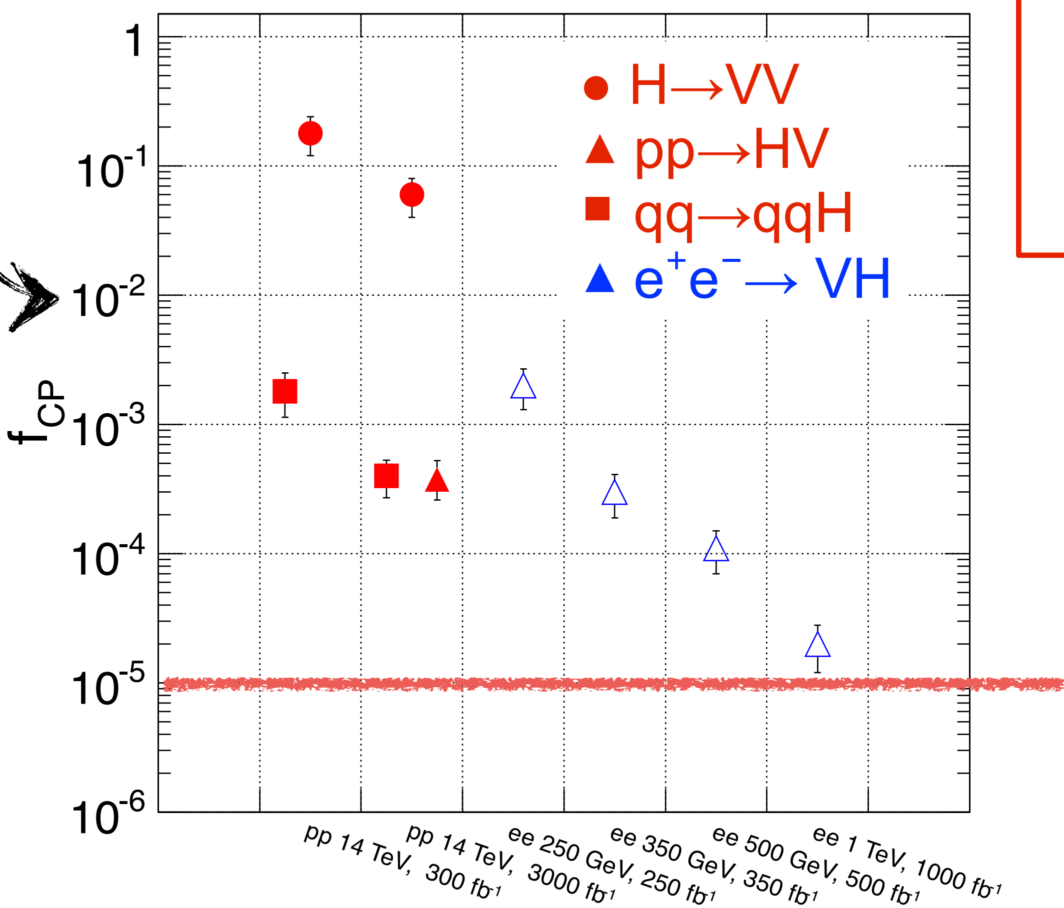
Christophe Grojean

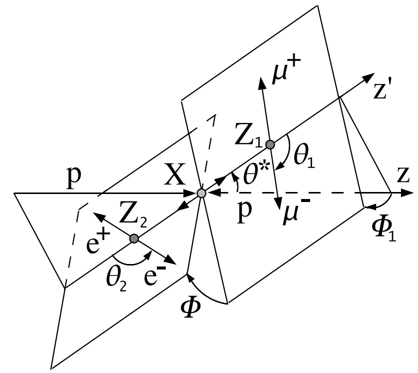
VHE-LHC is the machine
to decipher the gg→h process

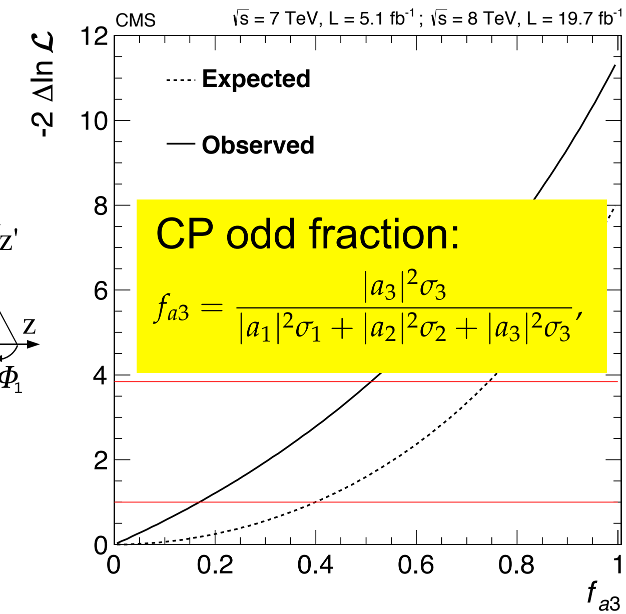
CP-odd fraction at future colliders

Center for Cosmology and Particle Physics

Target precision for CP-odd fraction in ττH, ttH, γZH is 1%, which may be attainable at ILC or HL-LHC, but more studies are needed







Target precision for CP-odd fraction to WWH, ZZH where pseudo-scalar coupling is loop suppressed

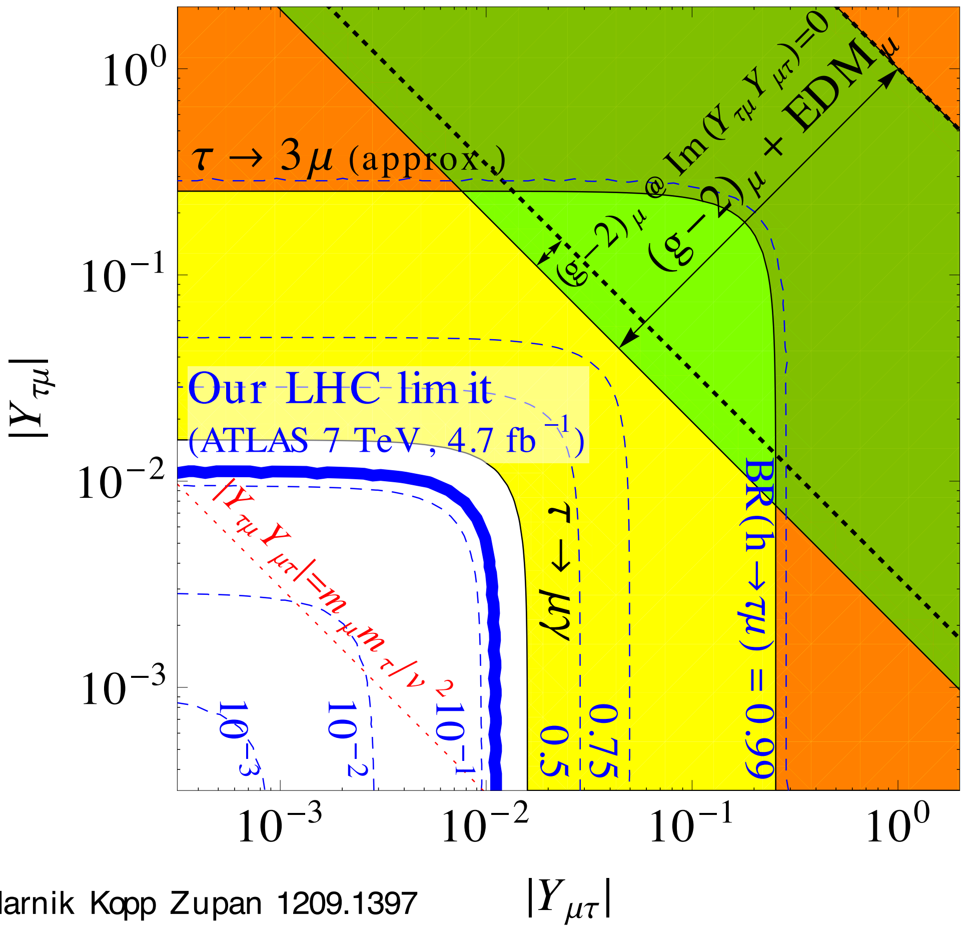
* Probing the Higgs requires many sensory tools!
    - LHC
    - Higgs Factory
    - A strong program of precision & rare processes.

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.



Harnik Kopp Zupan 1209.1397

LHC h→τμ gives dominant bound.

(currently just a theorist's re-interpretation)

"natural models" are within reach.

Lepton Flavor Violation

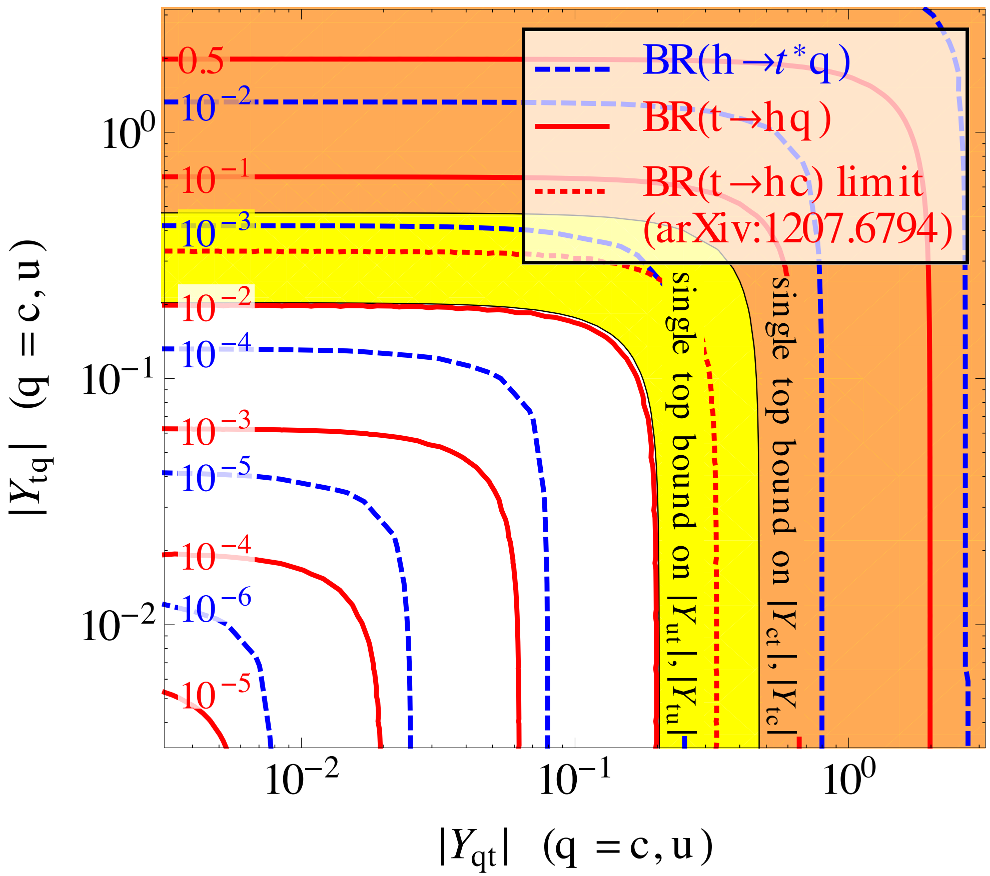
* Probing the Higgs requires many sensory tools!
  - LHC
  - Higgs Factory
  - A strong program of precision & rare processes.

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

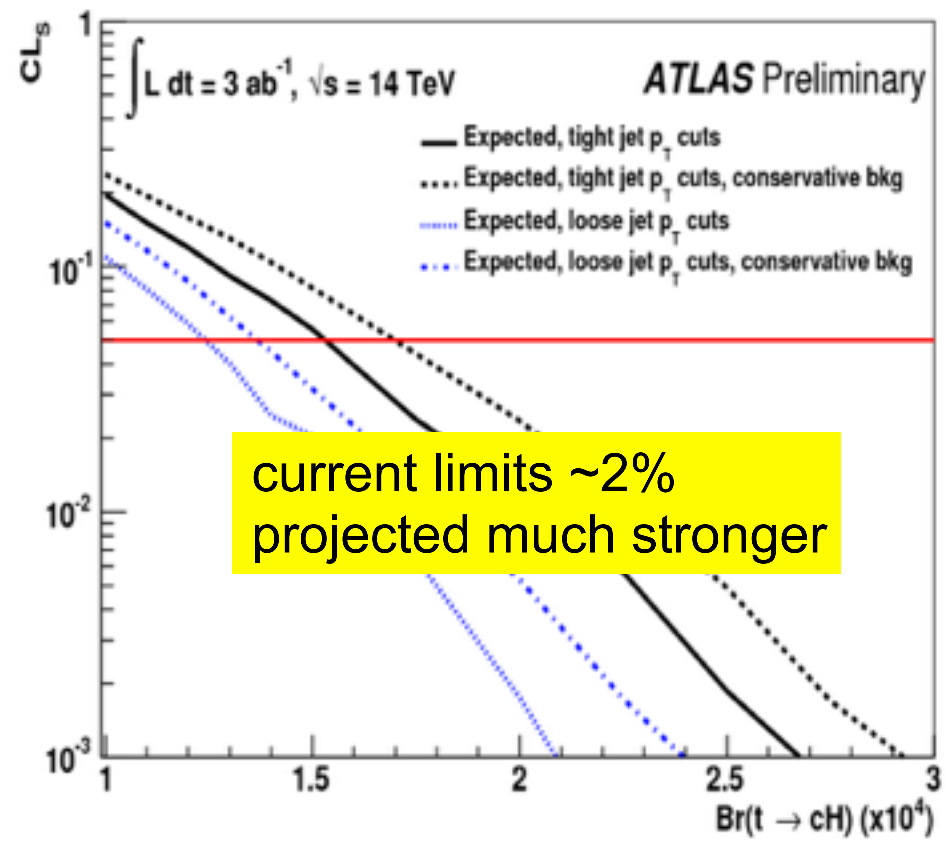
- or -

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.



Harnik Kopp Zupan 1209.1397



current limits ~2%
projected much stronger

Conclusions

Center for Cosmology and Particle Physics

Since the discovery less than two years ago enormous progress

- we are just getting to know our new friend
- there is much left to be done at the LHC and HL-LHC

The Higgs is one of the best handles we have to probe physics beyond the standard model

Future high-energy colliders and precision measurements will be necessary to probe at a satisfactory level of precision

- huge efforts to establish:
  - possible physics program of ILC
  - community study of possible future circular e^+e^- and hadron colliders

Thank you!

Other presentations

Center for Cosmology and Particle Physics

Impossible to cover everything, please see detailed presentations:

Study of Higgs boson production in bosonic decay channels at the LHC
Presented by **Roberta VOLPE** on **21 May 2014** at **14:00**

Study of Higgs boson production in fermionic decay channels at the LHC
Presented by **Vivek JAIN** on **21 May 2014** at **14:20**

Combinations of results of Higgs boson production at the LHC (production rates, couplings)
Presented by **Christian MEINECK** on **21 May 2014** at **14:40**

Higgs boson studies at the Tevatron
Presented by **Lidija ZIVKOVIC** on **21 May 2014** at **15:00**

Higgs and EW precision data
Presented by **Andrea TESI** on **21 May 2014** at **15:20**

Measurements of the Higgs Boson Spin and CP at the LHC
Presented by **Roko PLESTINA** on **21 May 2014** at **16:30**

Searches for BSM Higgs Bosons at the LHC
Presented by **Claire SHEPHERD-THEMISTOCLEOUS** on **21 May 2014** at **16:50**

Higgs exotic decays
Presented by **Prerit JAISWAL** on **21 May 2014** at **18:10**

Studies of Higgs Boson Properties in Future LHC Runs (Snowmass & ECFA studies)
Presented by **Rostislav KONOPLICH** on **21 May 2014** at **18:30**

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Center for Cosmology and Particle Physics

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10. ATL-PHYS-PUB-2013-012, "Sensitivity of ATLAS at HL-LHC to flavour changing neutral currents in top quark decays $t \to cH$, with $H \to \gamma\gamma$"
11. ATL-PHYS-PUB-2013-013, "Prospects for measurements of the HZZ vertex tensor structure in $H \to ZZ^* \to 4l$ decay channel with ATLAS"
12. ATL-PHYS-PUB-2013-014, "Projections for measurements of Higgs boson cross sections, branching ratios and coupling parameters with the ATLAS detector at a HL-LHC"
13. ATL-PHYS-PUB-2013-015, "Sensitivity to New Phenomena via Higgs Couplings with the ATLAS Detector at a High-Luminosity LHC"
14. ATL-PHYS-PUB-2013-016, "Beyond-the-Standard-Model Higgs boson searches at a High-Luminosity LHC with ATLAS"
15. CMS-PAS-HIG-13-002, "Properties of the Higgs-like boson in the decay H->ZZ->4l in pp collisions at sqrt(S)=7 and 8 TeV"
16. CMS-PAS-HIG-13-005, "Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV"
17. CMS-PAS-HIG-13-015, "Search for ttH production in events where H decays to photons at 8 TeV collisions"
18. CMS-PAS-HIG-14-002, "Constraints on the Higgs boson width from off-shell production and decay to ZZ ->lll'l' and llnunu"
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20. arXiv:1305.3854, "Bounding the Higgs Boson Width Through Interferometry"
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