Status & Progress of the WG

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WG twiki https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGExoticDecay

Meeting indico page https://indico.cern.ch/event/379779/timetable/#all

Goals of the WG

- Taking the optimistic perspective: our main goal is to make sure we find exotic Higgs decay

- For that we need
  - Broad program for exotic Higgs decays
  - Deep understanding of possible signatures
  - Large variety of signal models
    - Including MC tools for providing signal events and good description of Higgs production
  - Growing activity in the collaborations
    - Adding more search channels

- Constructive relations between theorists and experimentalists
- Nature to cooperate

From the kick-off meeting

https://indico.cern.ch/event/379779/timetable/#20150326

- Introduction
- Two experimental talk
  - ATLAS & CMS quick review of relevant results
- Two theory-oriented sessions
  - SM Higgs rare decays
    - Constraining the charm Yukawa (Gilad Perez)
    - Rare Hadronic Higgs decays (Frank Petriello)
  - Higgs decays to exotic particles
    - Uncovering light scalars $H \to bb\mu\mu$ (Yiming Zhong)
    - Hidden naturalness & non SM Higgs decays (Matthew Strassler)
- Long discussion sessions
  - Main focus on ***experimentalist wish list*** from the group

From the kick-off meeting

ATLAS BSM Higgs searches

- Possible categorization (following a work shop on this topic)
  - Higgs decays with displaced signatures or lepton-jets
  - Exotic Higgs decay with leptons (hadrons)

  } Decays to non-SM particles

  - LFV & FCNC — Decays to SM particles; forbidden in the SM
  - Higgs to invisible
  - Rare decays

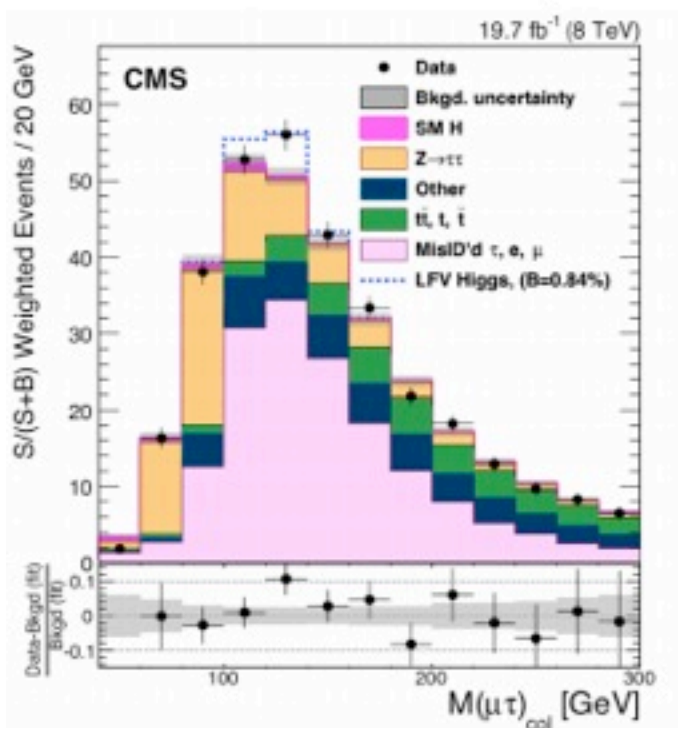
  } Allowed in the SM

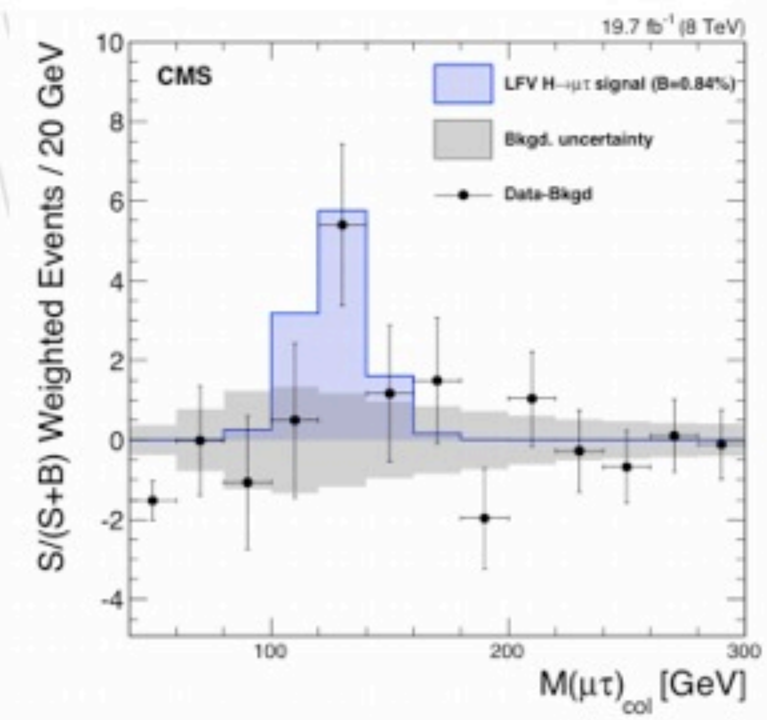
CMS BSM Higgs searches

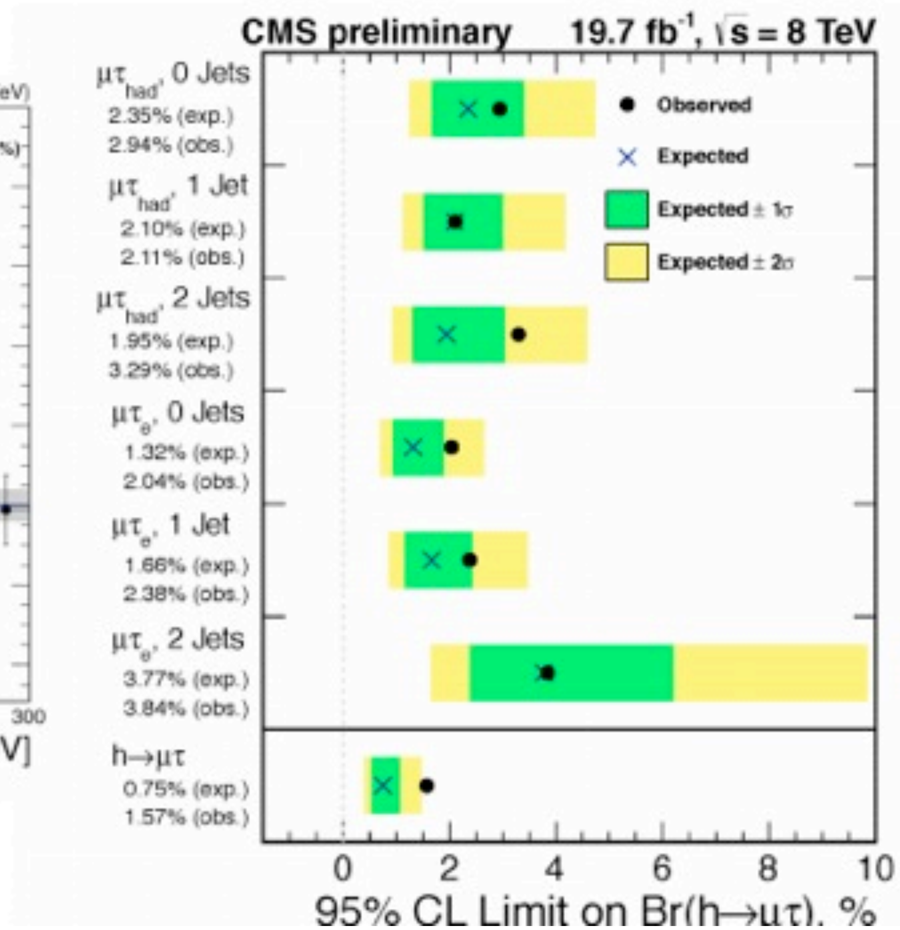
- Lepton Flavor Violating (LFV) Higgs125 Decays
- Flavor-changing-neutral-currents (FCNC)
- Invisible Decays of the Higgs125
- Non Standard Model Decay of Higgs125
- Exotic decays of the Other Higgs bosons
- Ongoing Analyses on Exotic Higgs Decay at CMS

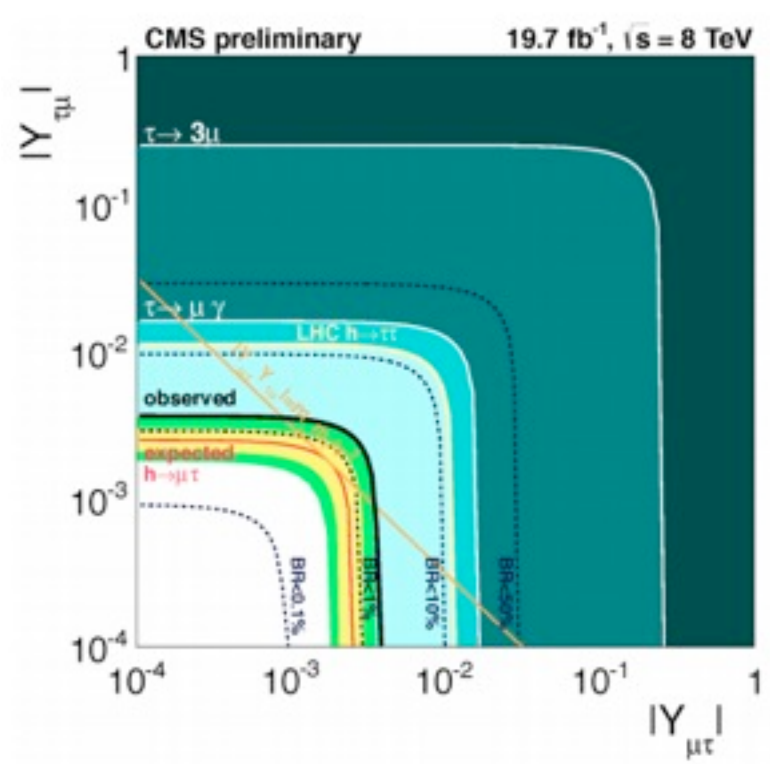
CMS - One 2.5σ excess LFV H→τμ

- Best fit value BR(H→τμ) = 0.9 ± 0.4% → 2.5σ
- Observed limit BR(H→τμ) < 1.57 % (0.75 ± 0.38 % expected)









From the kick-off meeting

H LFV in ATLAS

- Hadronic channel
  - $H \rightarrow \tau\mu$
  - Analysis based on the lep-had $H \rightarrow \tau\tau$ methodology
  - Passed unblinding approval last week
- Leptonic channel
  - $H \rightarrow \tau\mu$ & $\boldsymbol{H \rightarrow \tau e}$
  - New methodology based on eμ/μe symmetry
  - Unblinding approval next week
- Sensitivity similar to that of CMS

From the kick-off meeting

SM Higgs - rare decays

Decays to light quarks

Status: two paths to measuring light-quark Yukawas

Recent rapid (th+exp) progress (things are still preliminary, tons of info missing)

Slide from Gilad Perez

	Inclusive (c-tagging, this talk)	exclusive (see Frank's talk)
quarks	*c*	*udsc*
th.	Delaunay, Golling, GP & Soreq (13) GP, Soreq, Stamou & Tobioka (15)	Bodmin, Petriello, Stoynev & Velasco (13); Kagan, GP, Petriello, Soreq, Stoynev & Zupan; Bodwin, Chung, Ee, Lee & Petriello (14); GP, Soreq, Stamou & Tobioka (15) [Z: Huang, Frank Petriello; Mangano & Melia (14) Grossmann, Konig & Neubert (15)]
exp.	ATLAS: 1407.0608; 1501.01325	ATLAS: 1501.03276

SM: BR(H→cc) ~ 4%

- Well below the current experimental sensitivity
- Enlarging charm Yukawa by few leads to dramatic changes
  - Various (many) existing model

Experimental progress

- **Charm tagging can improve a lot the sensitivity**

SM Higgs - rare decays

H→cc

Executive sum.: Constraining Higgs-charm univ.

GP, Soreq, Stamou & Tobioka (Feb/15)

- Existing data already constrain Higgs-quarks Univ..

(i) Direct constraint: recast *VH(bb)*, taking advantage of 2 working point $c_c < 230.$

(ii) the recent ATLAS search to $h \to J/\psi\gamma$ (see later) yield $c_c < 220$;

(assumes Higgs coupling to two photons and/or four leptons is not significantly modified by new physics);

(iii) the direct measurement of the total width yield $c_c <$ 140 (ATLAS),120 (CMS).;

(iv) Global fit to the Higgs signal strength, $c_c < 6.$

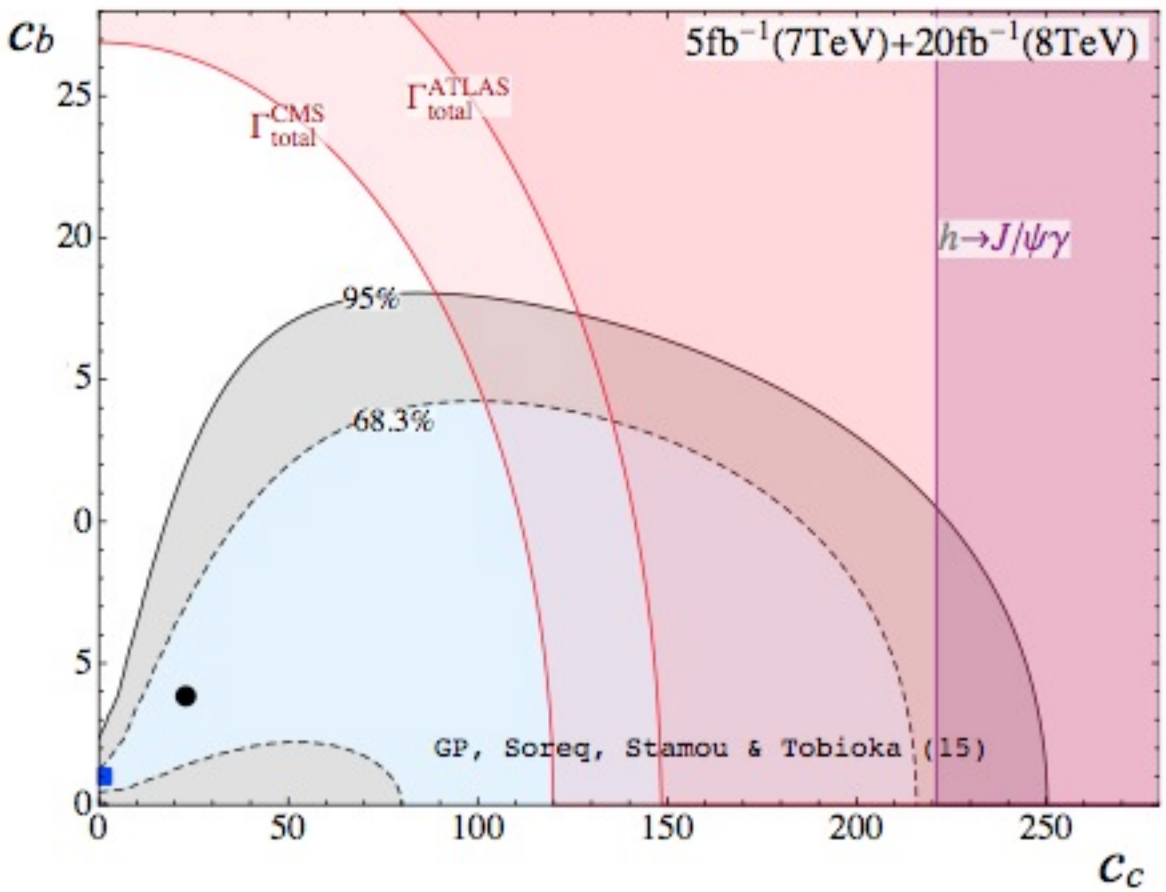
(v) *tth* data => $c_t > 1.0$ (equivalence to $c_c > 310$).

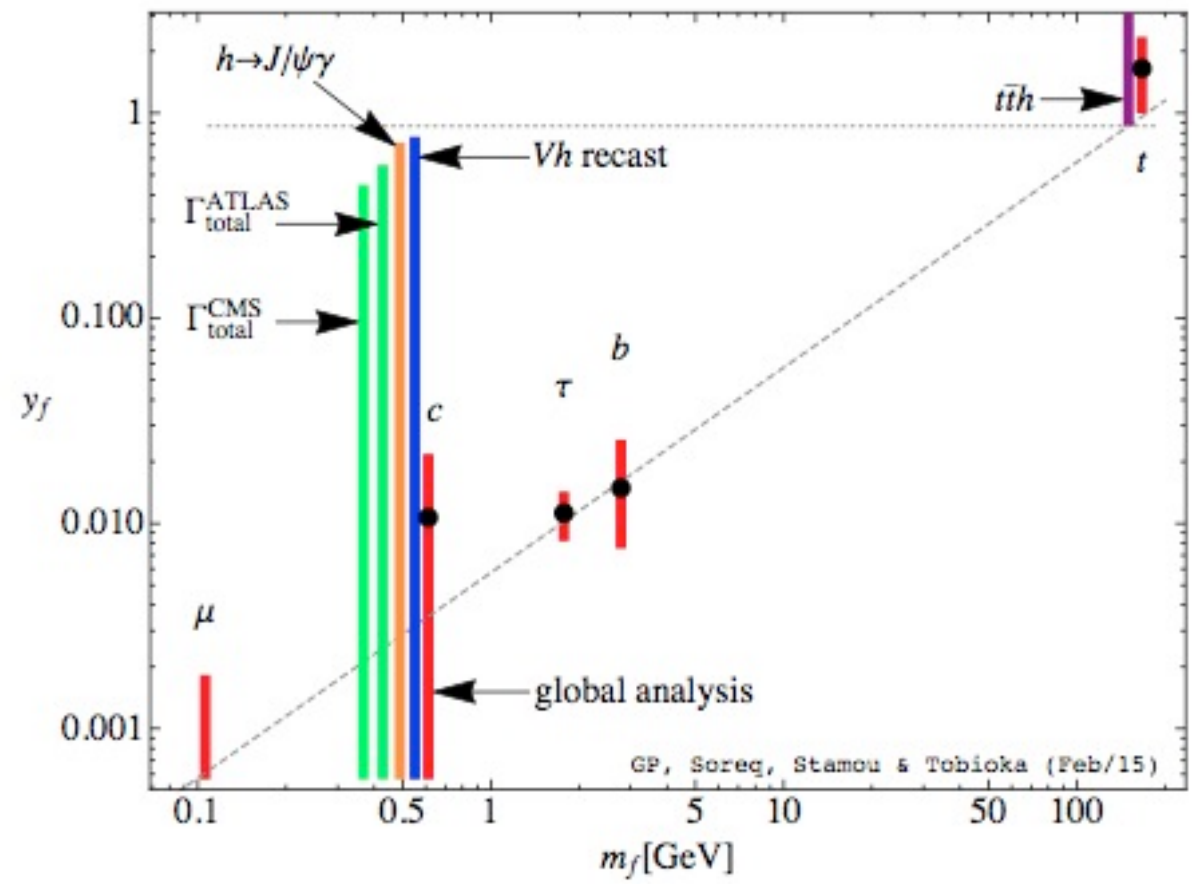
Slide from Gilad Perez

From the kick-off meeting

SM Higgs - rare decays

H→cc





The global analysis results proves non universality of quark Yukawa

From the kick-off meeting

SM Higgs - rare decays

H to light quarks (cc)

Interesting for many reason, for example

Model	$\frac{Y_{tt}}{Y_{tt}^{SM}}$	$\frac{Y_{cc}/Y_{tt}}{m_c/m_t}$	Y_{ct}/Y_{tt}
SM	1	1	0
2HDM-NFC	c_α/s_β	1	0
2HDM-MFV	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(Y_b^2 V_{cb})$
1HDM-FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(V_{cb} v m_t/\Lambda^2)$

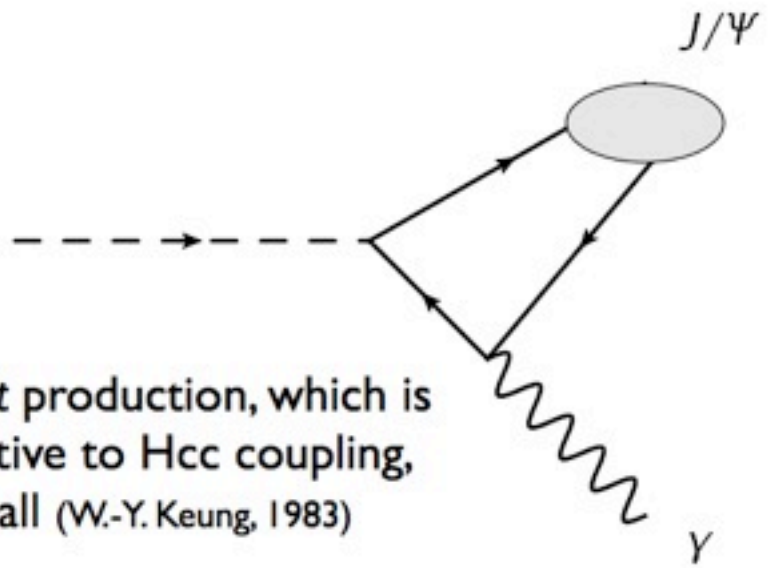
??? (Y_{cc}/Y_{tt})

Y_{tt}: get from gg production indirectly, or ttH directly

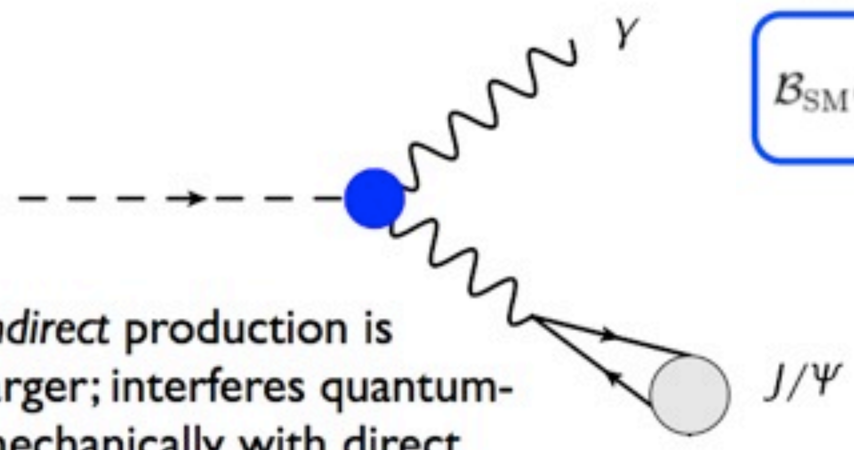
Y_{ct}/Y_{tt}: get from t→cH decays

Slides from Frank Petriello

- Access this coupling using H→J/Ψ+γ! Bodwin, FP, Stoynev, Velasco 1306.5770



Direct production, which is sensitive to Hcc coupling, is small (W.-Y. Keung, 1983)



Indirect production is larger; interferes quantum-mechanically with direct production

- Branching ratio in the SM:

$$\mathcal{B}_{SM}(H \to J/\psi + \gamma) = 2.79^{+0.16}_{-0.15} \times 10^{-6}$$

- Larger indirect mechanism drags up the direct one; provides sensitivity to the Hcc coupling
- Theoretically very clean; few-percent uncertainties: Bodwin, Chung, Ee, Lee, FP 1407.6695
- Interference gives unique information on the phase of the Hcc coupling

SM Higgs - rare decays

Run I - ATLAS results

Full 2012 data set:

[arXiv:1501.03276]

Search for Higgs and Z Boson Decays to $J/\psi\,\gamma$ and $\Upsilon(nS)\,\gamma$ with the ATLAS Detector

Main analysis features:

- Nonparametric data-driven approach using templates to model the dominant QCD background

TABLE II. Expected and observed branching fraction limits at 95% CL_s for $\sqrt{s} = 8$ TeV. The $\pm 1\sigma$ fluctuations of the expected limits are also given. For the Higgs decay search, limits are also set on the cross section times branching fraction $\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$.

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

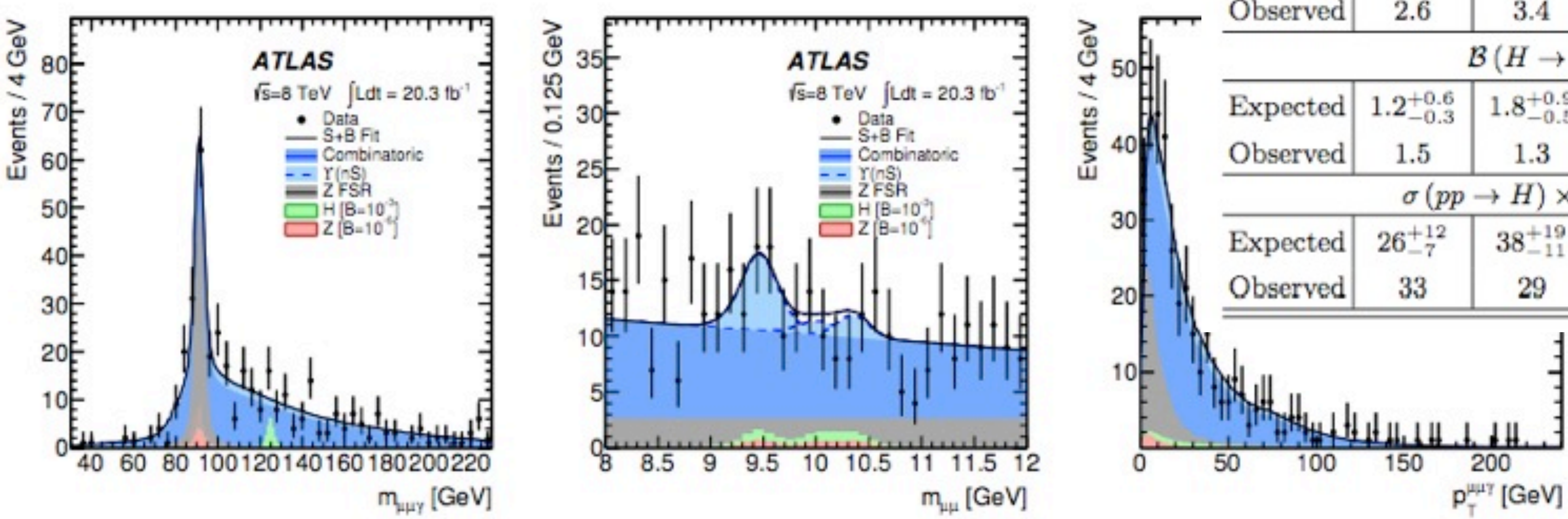
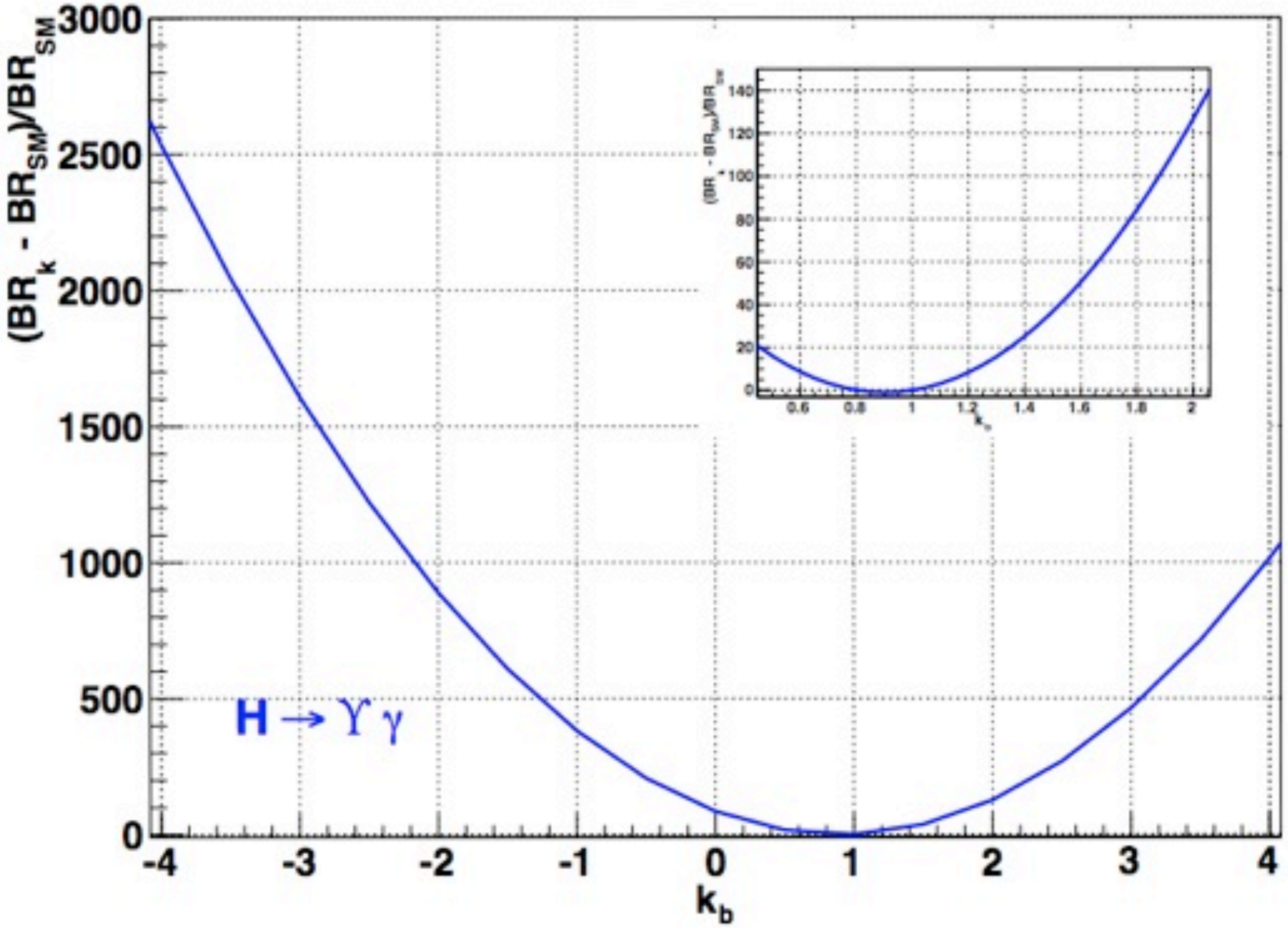


FIG. 2. (color online) The $m_{\mu\mu\gamma}$, $m_{\mu\mu}$ and $p_T^{\mu\mu\gamma}$ distributions of the selected $\Upsilon(nS)\,\gamma$ candidates, along with the results of the maximum likelihood fit to the signal and background model (S+B fit). The Higgs and Z boson contributions as expected for branching fraction values of 10^{-3} and 10^{-6}, respectively, for each of the $\Upsilon(nS)$ are also shown.

SM Higgs - rare decays

H to light quarks (bb)



- This is the same deviation plot for $H \to \Upsilon(1S)+\gamma$
- The y-axis is not a typo! Almost a complete cancellation between direct and indirect amplitudes in the SM.

$$\mathcal{B}_{SM}(H \to \Upsilon + \gamma) = 8.39^{+19.25}_{-8.16} \times 10^{-10}$$

- Any modification of Hbb leads to O(100)-O(1000) deviations in this rate

Observation of this decay mode conclusively indicates a non-SM Hbb coupling!

Slide from Frank Petriello

Some discussion also on Hss

All measurements (if possible) are only possible in HL-LHC too rare for e+e- collider

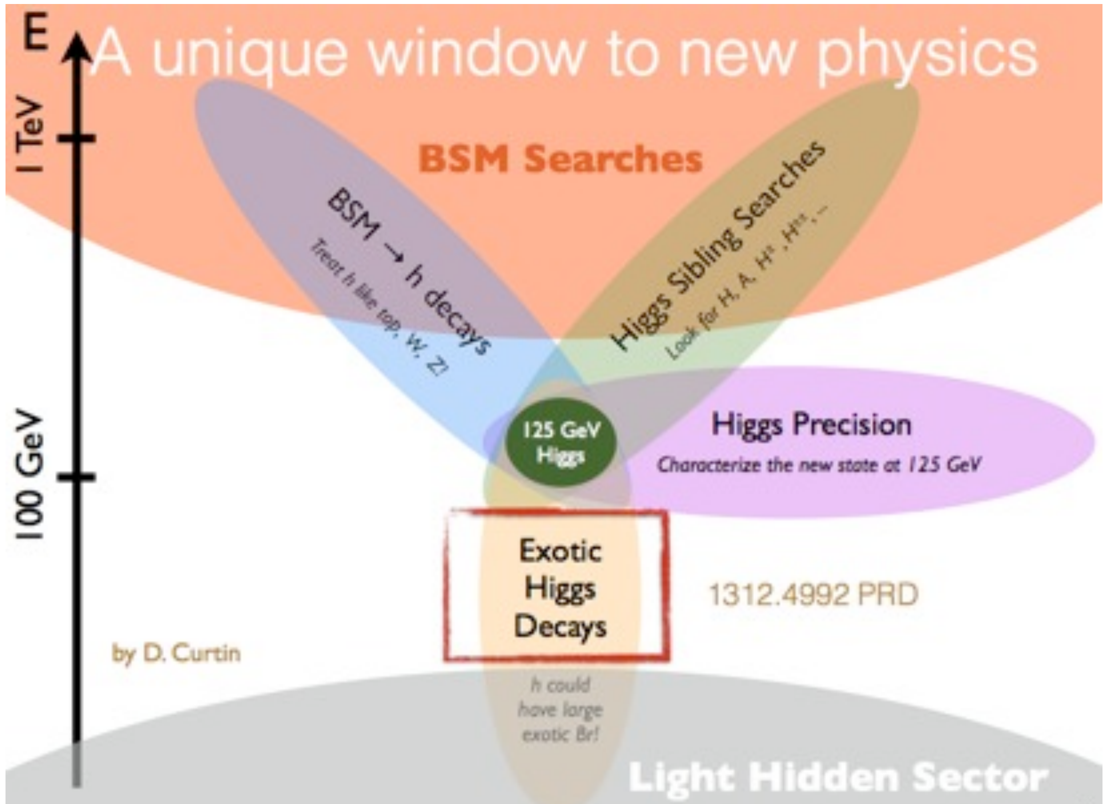
H to light quarks (bb)

Followup discussion - trigger issue

- Need trigger for photon + meson - is it doable?
- Action for the WG: facilitate interaction with Pythia authors to implement angular distributions in these decays
  - Expecting farther discussion in the next meeting

Higgs decays to exotic particles $H \to 2s(a) \to 2\mu 2b$

Strong motivation



Standard Model plus a real scalar singlet (SM+S)

$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\kappa S^2|H|^2$$

- after symmetry breaking, two neutral CP-even scalars
  h = the SM Higgs & s: a **light** scalar ($m_s < m_h/2$)
- s inherits couplings of H to fermions
- Br($h \to 2s$) can easily be sizable

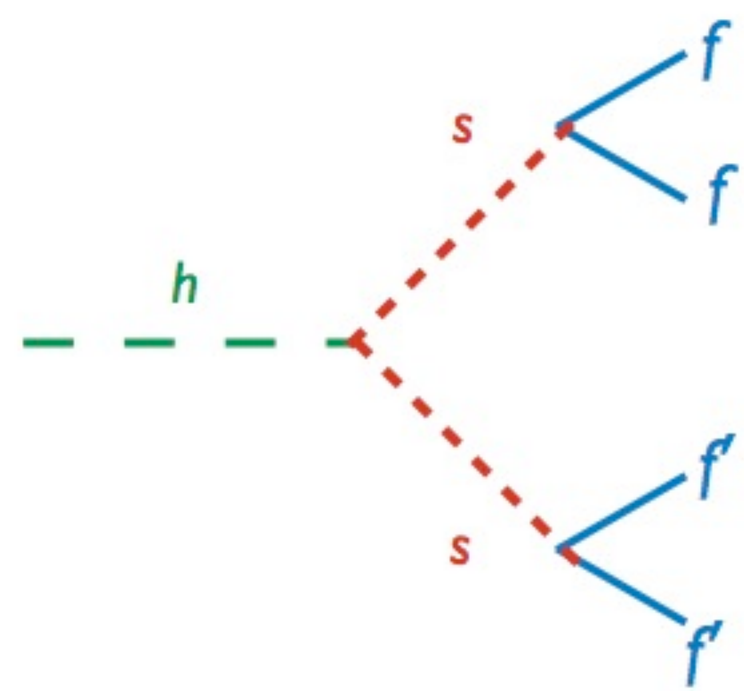
Slides from Yi-Ming Zhong

largely unconstrained   Yukawa dependent

$$\mathrm{Br}(h \to 2s \to 2f2f') = \mathrm{Br}(h \to 2s) \times 2 \times \mathrm{Br}(s \to 2f) \times \mathrm{Br}(s \to 2f')$$

$\propto m_f^2$

m_s = 40 GeV



Sensitivity to $h \to 2a$ can be competitive or better than other decay modes (depending on model).

Higgs decays to exotic particles $H \rightarrow 2s(a) \rightarrow 2\mu 2b$

Followup discussion

- Important to go to higher and lower pseudo scalars and not restrict to m_a of a few GeV
- $H \rightarrow 2s(a) \rightarrow 2b2b$ - also important (maybe search in WH associated production)

Hidden naturalness

Motivation

- Naturalness requires colored particles at the TeV scale
  - For effective cancelation of top loop
- Where are these colored particles?
  - Do not exist. Nature is fine tuned
  - 'Out there' but decaying and missed by LHC searches
  - They are heavy - moderate fine tuning
  - Top partners and αs-strength gluon-partner aren't colored
    - Uncolored Naturalness (Folded SUSY 2009)
    - **Hidden Naturalness (Twin Higgs 2005)**
      - detailed discussion of a new branches of these models
      - Many possible final states (some hard and some easy to search for)

Hidden naturalness

GENERAL MESSAGE

- Although Hidden Naturalness **may** be very difficult to find at LHC…
  - Precision Higgs measurements may be only hint, and not very clear
- …It equally **may** offer great opportunities!
  - Non-SM Higgs decays at the top of the list
  - Heavier Higgs decays (standard and exotic) second on the list

- *Well, SUSY can be tough too; but we exploit the opportunities, rather than giving up because we might fail.*

Slide from Matt Strassler

Some other comments

- Suggested to phrase WG recommendations in terms of set of fiducial observables
- The big exotic Higgs decay survey document (arXiv:1312.4992) provides benchmarks and prioritization for Higgs decays with up to 4 visible partons
  - But experimentalists are still asking for benchmarks and prioritization
  - What is lacking in the big document from an experimental point of view?
- Need for benchmark development at high multiplicity and with missing energy Currently the largest blind spot in coverage is partly-invisible decays

Since the kick-off meeting

New experimental results

[arXiv:1505.01609]

Search for Higgs bosons decaying to aa in the $\mu\mu\tau\tau$ final state in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS experiment

A search for the decay to a pair of new particles of either the 125 GeV Higgs boson (h) or a second CP-even Higgs boson (H) is presented. The dataset correspods to an integrated luminosity of 20.3 fb^{-1} of pp collisions at $\sqrt{s}$ = 8 TeV recorded by the ATLAS experiment at the LHC in 2012. The search was done in the context of the next-to-minimal supersymmetric standard model, in which the new particles are the lightest neutral pseudoscalar Higgs bosons (a). One of the two a bosons is required to decay to two muons while the other is required to decay to two τ-leptons. No significant excess is observed above the expected backgrounds in the dimuon invariant mass range from 3.7 GeV to 50 GeV. Upper limits are placed on the production of $h \to aa$ relative to the Standard Model $gg \to h$ production, assuming no coupling of the a boson to quarks. The most stringent limit is placed at 3.5% for m_a = 3.75 GeV. Upper limits are also placed on the production cross section of $H \to aa$ from 2.33 pb to 0.72 pb, for fixed m_a = 5 GeV with m_H ranging from 100 GeV to 500 GeV.

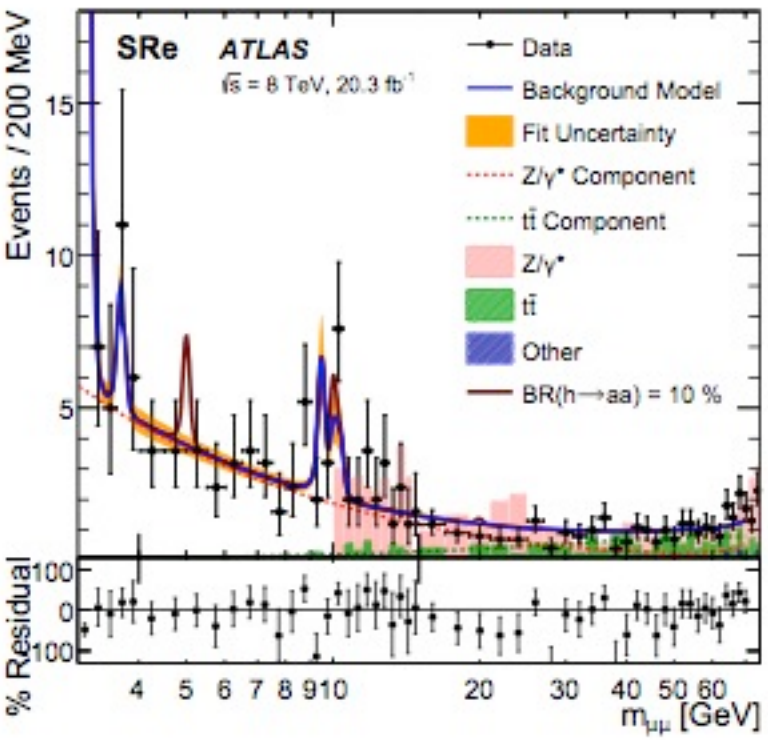
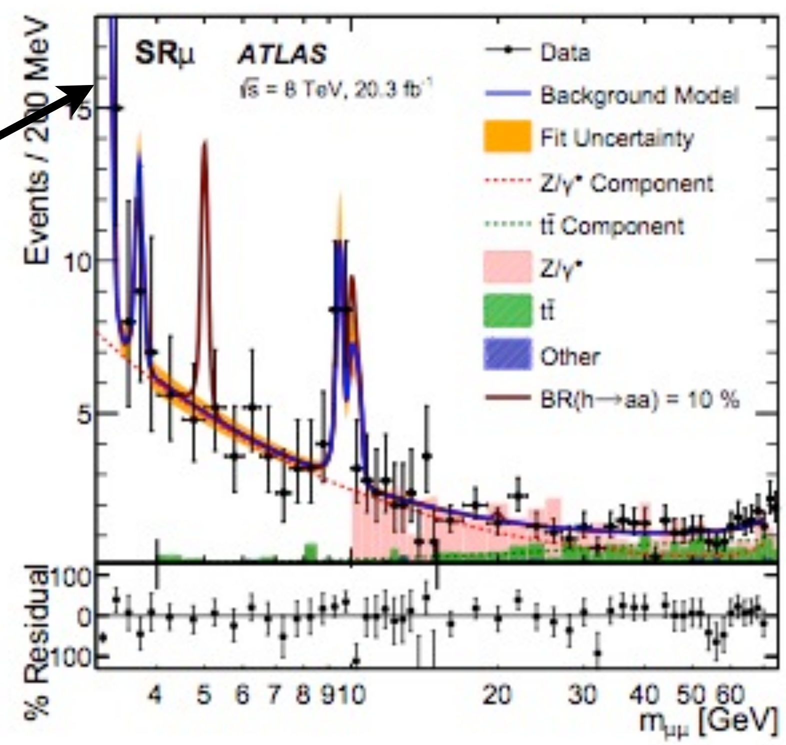


Figure 4: Observed $m_{\mu\mu}$ distribution in SRμ (top) and SRe (bottom) and the background-only fit. The Z/γ^* component of the fit is the combination of the Z boson resonance and the γ^* continuum models. The % residuals are shown below each plot. Bins below 4 GeV are 200 MeV wide, between 4 GeV and 15 GeV they are 500 MeV wide, and above 15 GeV they are 2 GeV wide. The expected distribution from a signal with BR($h \to aa$)=10% is shown for three different m_a hypotheses (5 GeV, 10 GeV, and 20 GeV). Simulated SM backgrounds are shown in the stack, with the Z/γ^* sample only valid above $m_{\mu\mu}$ > 10 GeV.



New experimental results

[arXiv:1504.04324]

Search for invisible decays of the Higgs boson produced in association with a hadronically decaying vector boson in *pp* collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

A search for Higgs boson decays to invisible particles is performed using 20.3 fb^{-1} of *pp* collision data at a centre-of-mass energy of 8 TeV recorded by the ATLAS detector at the Large Hadron Collider. The process considered is Higgs boson production in association with a vector boson ($V = W$ or Z) that decays hadronically, resulting in events with two or more jets and large missing transverse momentum. No excess of candidates is observed in the data over the background expectation. The results are used to constrain VH production followed by H decaying to invisible particles for the Higgs mass range $115 < m_H < 300$ GeV. The 95% confidence-level observed upper limit on $\sigma_{VH} \times \text{BR}(H \to \text{inv.})$ varies from 1.6 pb at 115 GeV to 0.13 pb at 300 GeV. Assuming Standard Model production and including the $gg \to H$ contribution as signal, the results also lead to an observed upper limit of 78% at 95% confidence level on the branching ratio of Higgs bosons decays to invisible particles at a mass of 125 GeV.

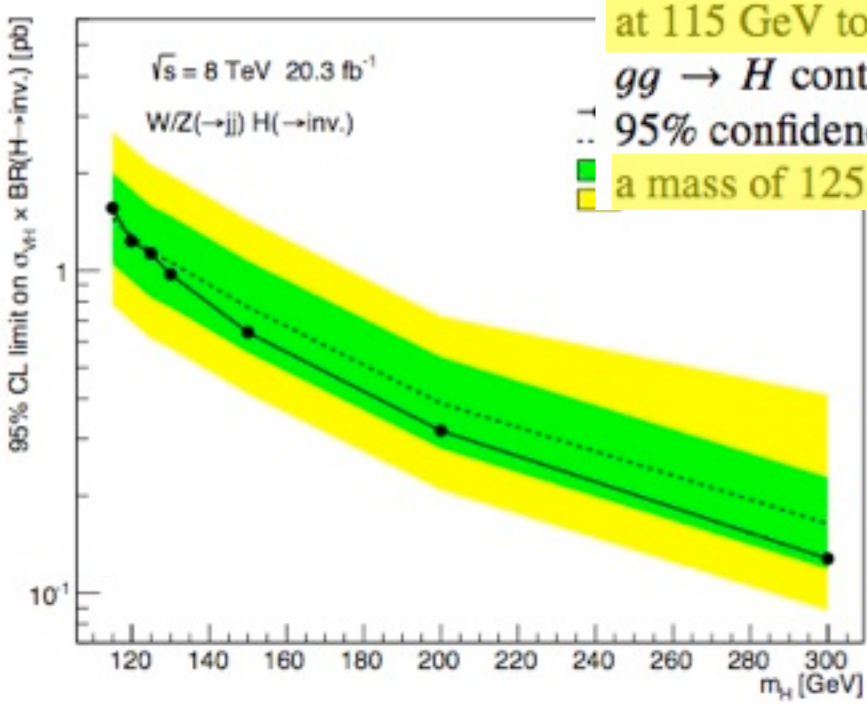


Figure 6: Upper limits on $\sigma_{VH} \times \text{BR}(H \to \text{inv.})$ at 95% CL for a Higgs boson with $115 < m_H < 300$ GeV. The full and dashed lines show the observed and expected limits, respectively.

New experimental results

[HIG-14-038-PAS]

Search for invisible decays of Higgs bosons in the vector boson fusion production mode

A search for invisible decays of Higgs bosons in the vector boson fusion production mode is carried out using data recorded by the CMS detector at the LHC in 2012 at a centre-of-mass energy of 8 TeV corresponding to an integrated luminosity of 19.2 fb^{-1}. Limits are set on the production cross section times invisible branching fraction, as a function of the Higgs boson mass. Assuming standard model Higgs boson cross sections and acceptances, the observed (expected) upper limit on the invisible branching fraction at $m_{\mathrm{H}=125}$ GeV is found to be 0.57 (0.40) at 95% confidence level. The previous CMS limit in this channel at the same confidence level was 0.65 (0.49).

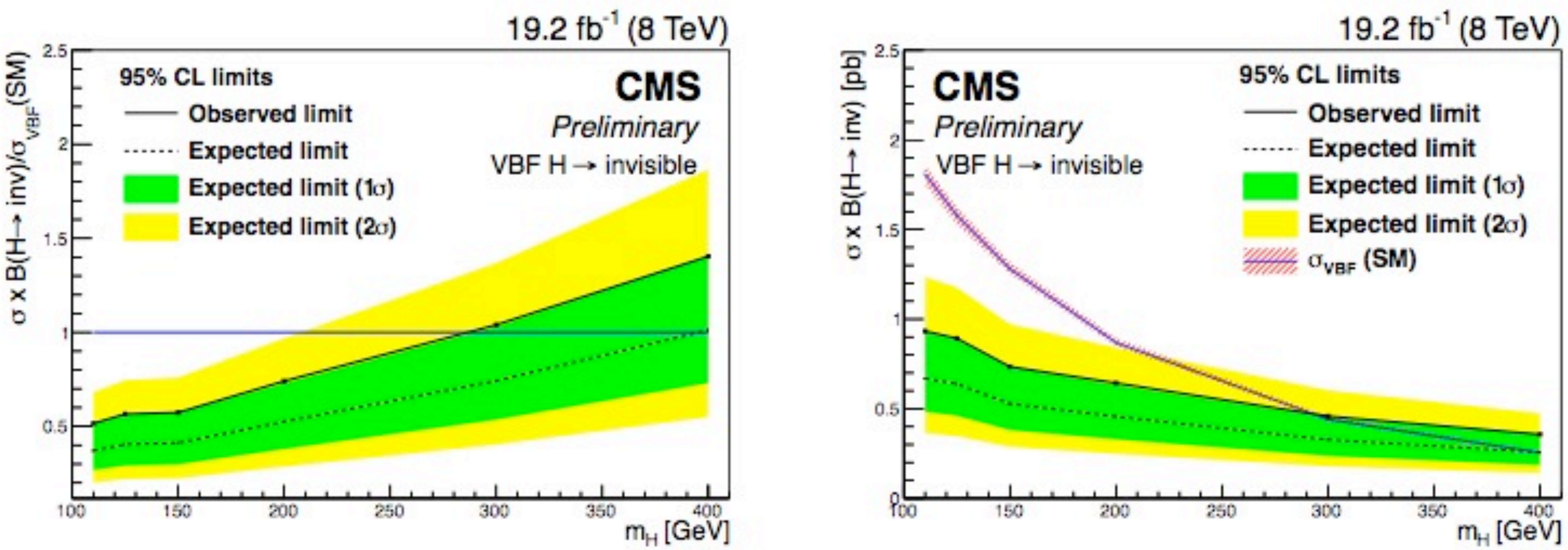
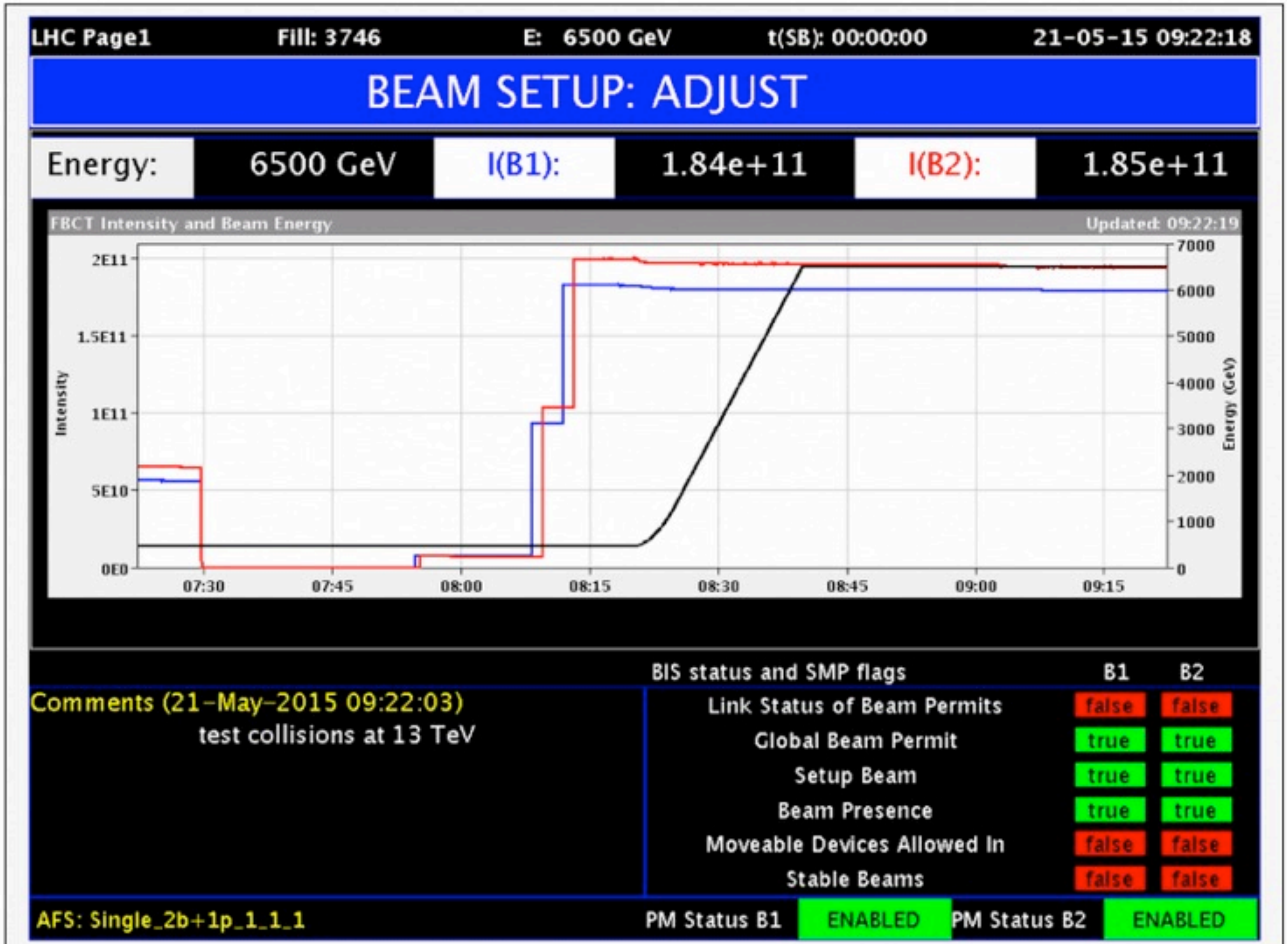


Figure 7: The 95% C.L. limit on $\mathcal{B}(\mathrm{H} \rightarrow \mathrm{inv})$ of a SM Higgs boson (left) and the 95% C.L. limit on the cross section times $\mathcal{B}(\mathrm{H} \rightarrow \mathrm{inv})$ (right)as a function of the Higgs boson mass, assuming SM Higgs boson acceptances.

Since the kick-off meeting

New experimental results



Test collisions continue today at 13 TeV in the Large Hadron Collider (LHC) to prepare the detectors ALICE, ATLAS, CMS and LHCb for data-taking, planned for early June (Image: LHC page 1)

This meeting

Organized in 4 sessions

- Displaced vertex signatures
- Neutrinos, SUSY, and decays involving MET
- LFV and rare decays
- 4-parton signatures

Both theory and experimental talks

- Try to focus on the region in the barrier between the two

Time for discussion

This meeting - more points to consider

- MVA Vs. Cut flows
- Missing MC tools
- Missing theoretical predictions

- Can predictions be made for possible studies with LHCb?

- Presentation and reinterpretation of results from displaced searches
- Development of a framework to guide semi-invisible/showering searches
  - Other signatures ?