Game changers at the LHC

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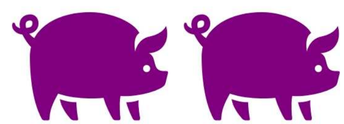
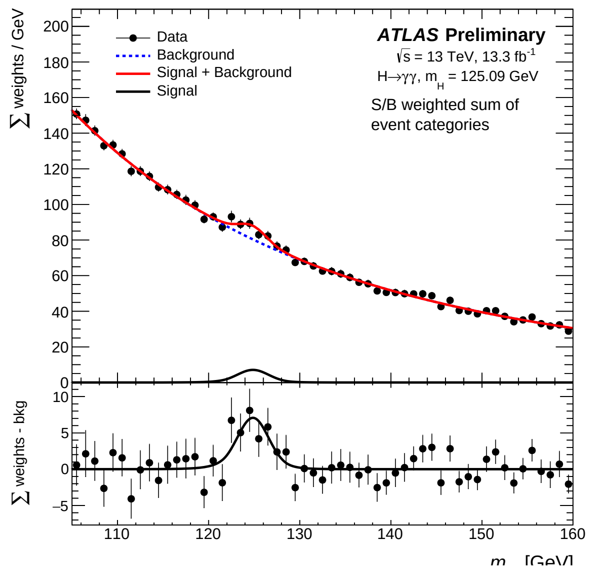
When discussing possible LHC game-changers, personal bias is a necessary ingredient.

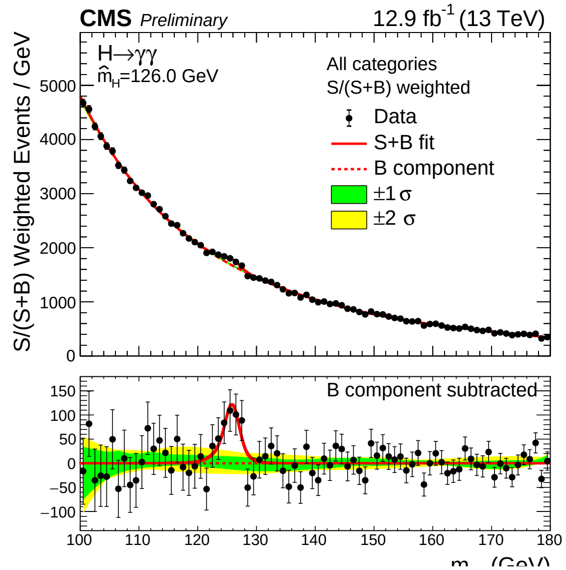
Otherwise we could consider purple pig pair-production:

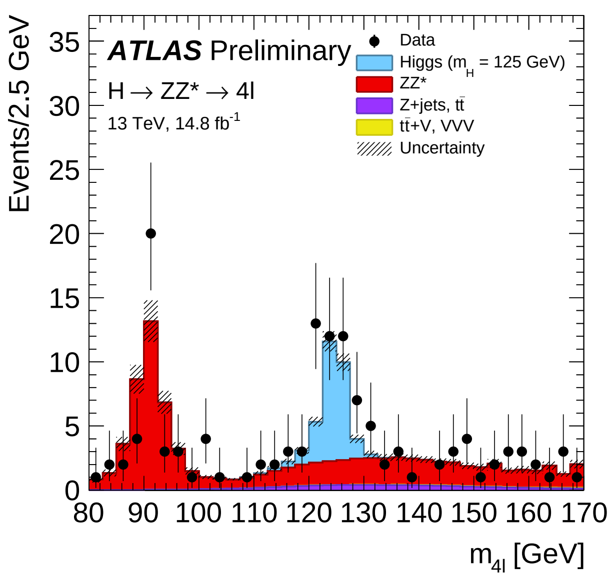
$$pp \rightarrow$$ 

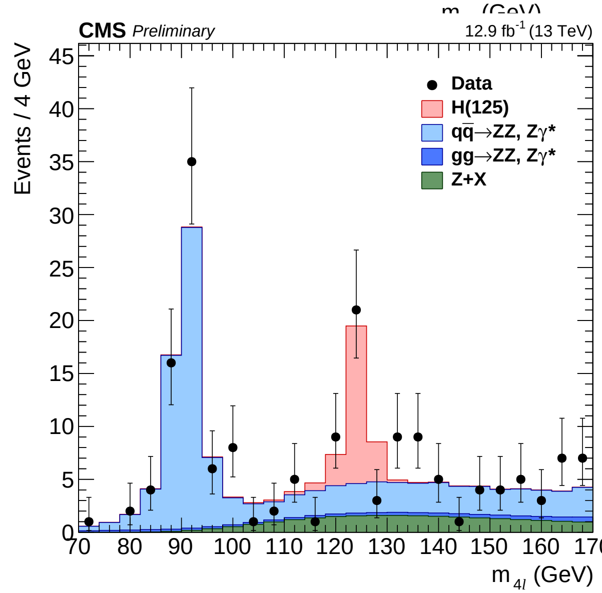
My own background is mostly in supersymmetry, which may or may not be more likely at this point.

The only real game-changer from LHC so far: the Higgs boson exists!









Comments:

- Measurements of properties are still very much statistics limited, but Run 2 will eventually fix that, at least for some modes
- Angular distributions in 4-lepton final state consistent with $J^P = 0^+$
- When looking for a game-changer at the LHC, the Higgs boson is a natural suspect
- Quest: attempt to prove that it **isn't** actually The Standard Model Higgs Boson

From Run 1 ATLAS+CMS combination 1503.07589,

$$M_H = 125.09 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})\ \ \mathrm{GeV}$$

This completes the Standard Model, and measures the parameters of the Higgs potential:

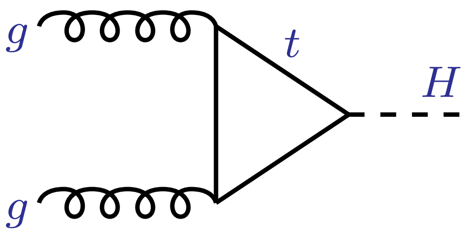
$$V(\Phi) \;\; = \;\; m^2|\Phi|^2 + \lambda|\Phi|^4$$

where, in the $\overline{\text{MS}}$ scheme at renormalization scale M_{top},

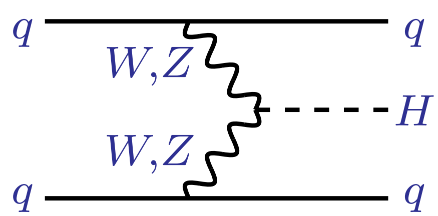
$$\begin{aligned} m^2 \;\; &= \;\; -(92.9\,\mathrm{GeV})^2 \\ \lambda \;\; &= \;\; 0.126 \end{aligned}$$

This is remarkably close to the critical value that will give $\lambda_{\mathrm{UV}} \to 0$ from renormalization group **extrapolation** to very high energies; a jumping-off point for Beyond the Standard Model ideas.

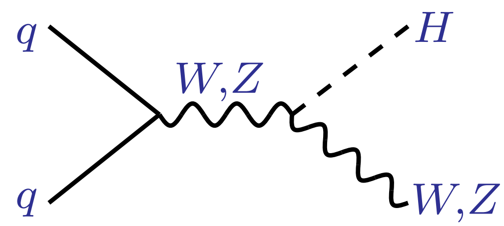
The main production modes for the Higgs boson at the LHC:



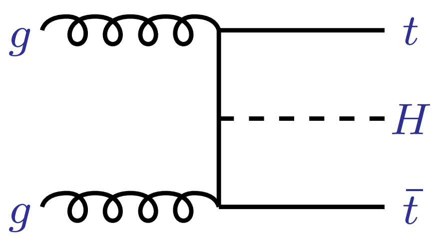
gluon-gluon fusion



Vector Boson Fusion



VH associated



$t\bar{t}H$

The relative weights of these contributions provide information about the Higgs couplings. $\mu \equiv \sigma/\sigma_{\rm SM}$ = normalized signal strength.

The $t\bar{t}H$ mode gives direct, and the gg fusion indirect, information about the top Yukawa coupling, with $y_t^{\rm SM} = 0.937$.

The VBF mode gives the best opportunity to check $H \to$ invisible, because of the forward tagging q jets.

From Run 1 (= 7,8 TeV data):

ATLAS + CMS combination

legacy paper, 1606.02266

Combined $t\bar{t}H$ was too large by slightly over 2σ.

$$\mu_{t\bar{t}H}^{\text{Run 1, combined}} = 2.3^{+0.7}_{-0.6}$$

Preliminary 13 TeV data from ICHEP:

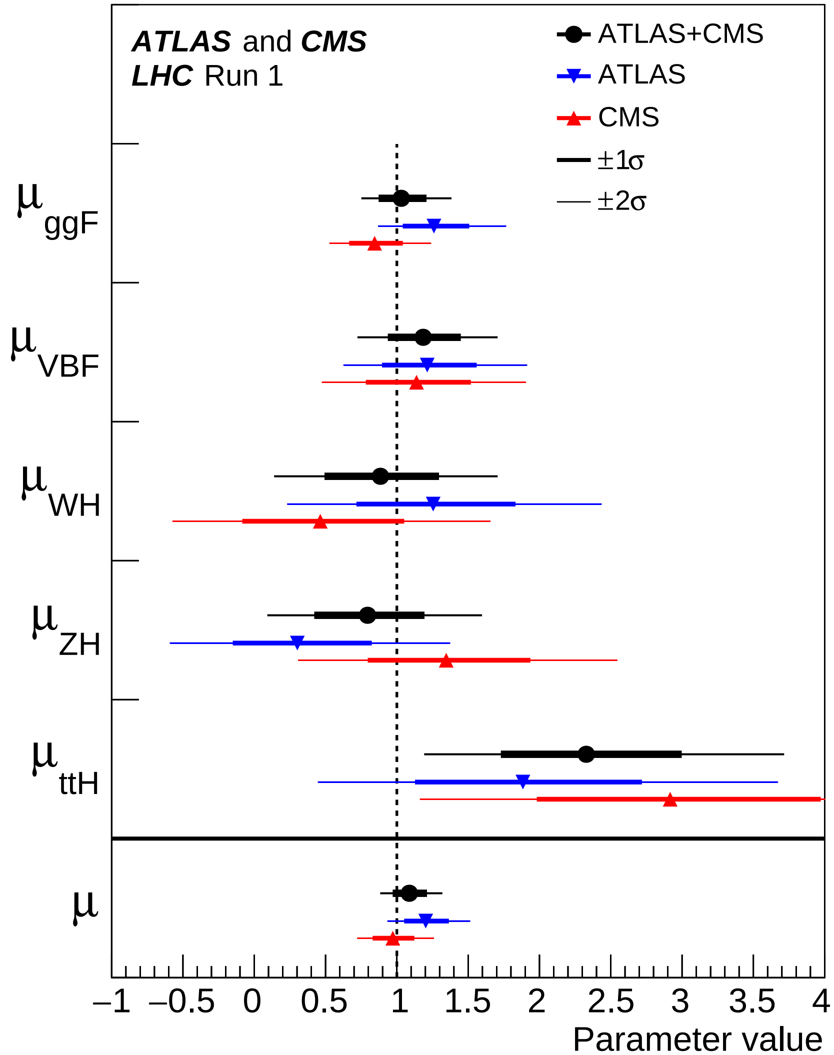
$$\mu_{t\bar{t}H}^{\text{Run2, ATLAS}} = 1.8 \pm 0.7$$

$$\mu_{t\bar{t}H}^{\text{Run2, CMS } \gamma\gamma \text{ only}} = 1.91^{+1.5}_{-1.2}$$

Backgrounds large; statistics poor.

No excess in gluon-gluon fusion.

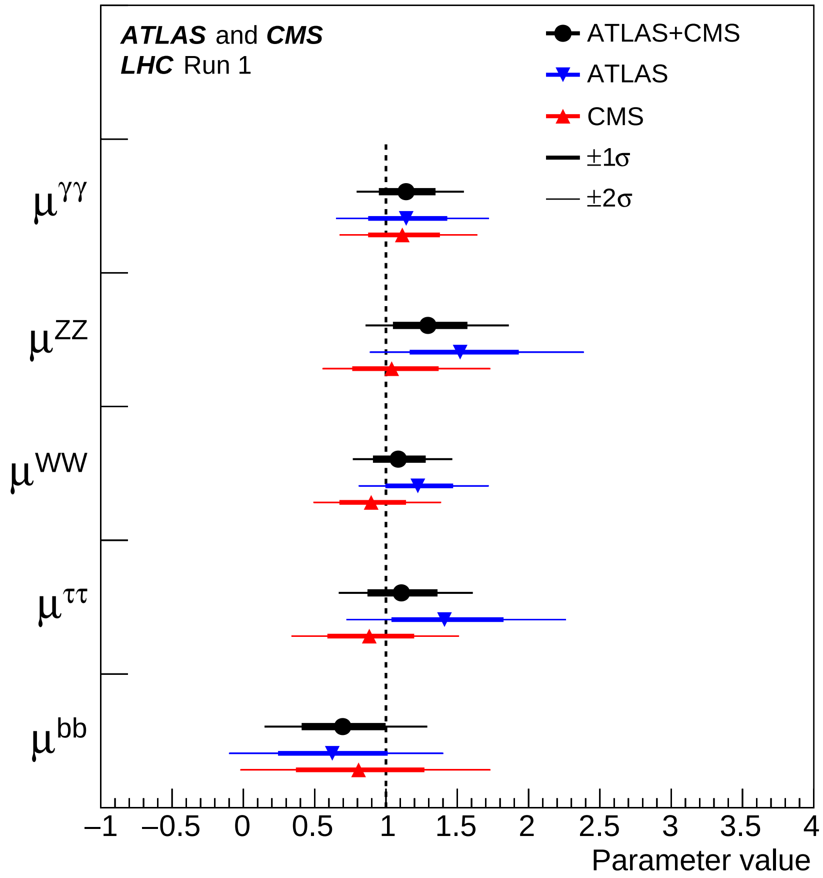
However, bears watching. What is the $t\bar{t}H$ coupling?



Run-1 combined normalized signal strengths, organized by final state:

No surprises. The Higgs boson couples like the Standard Model says it should, within errors.

(Sensitivity to top Yukawa coupling is indirect and suppressed.)



The Standard Model provides an opportunity due to $M_H < 2M_W, 2M_Z, 2M_t$.
It is very narrow: $\Gamma_H = 0.0041$ GeV.
Amplifies the potential impact of any non-standard decay mode.

Look for exotic decays of Higgs competing with the known narrow partial width final states:

H	$\rightarrow$	$\phi\phi$	$\phi =$ (pseudo-)scalar
		invisible	(dark matter sector?)
		$?$	(decays thru hidden sector, back to SM sector)
		$\mu^+\mu^-$	(under the lamp-post)
		$\tau^\pm\mu^\mp$	
		$\cdots$	

Upper limits are being produced, for example ATLAS-CONF-2016-041:

$$\mathrm{BR}(H \rightarrow \mu^+\mu^-) < 3.5\,(\text{Standard Model prediction})$$

This is stronger than the expected Branching Ratio limit of 4.5.

The **minimal** extension of the Standard Model: add a real singlet scalar S.

One new degree of freedom.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - m_S^2 |S|^2 - \lambda' |S|^2 |H|^2 - \lambda'' |S|^4 .$$

If $m_H > 2m_S$, then get decays

$$H \to SS \to \text{invisible}$$

with

$$\Gamma(H \to SS) \quad \propto \quad |\lambda' v|^2$$

Branching ratio could be anything! “Higgs portal” to dark matter sector, many other models predict invisible Higgs decays: graviscalars, Kaluza-Klein neutrinos, . . .

Recent result from CMS-HIG-PAS-16-016, 13 TeV data:

$$\mathrm{BR}(H \to \text{invisible}) < 0.24$$

in line with expected limit. Best sensitivity from VBF.

Can we measure the Higgs potential $V(\phi)$?

Present measurements only give us the position of the minimum v =VEV (from Fermi constant) and the curvature of V at its minimum with $\phi = (v+H)/\sqrt{2}$:

$$m_H^2 = \frac{\partial^2 V}{\partial H^2}\Big|_{\phi=v} = (125\ \mathrm{GeV})^2.$$

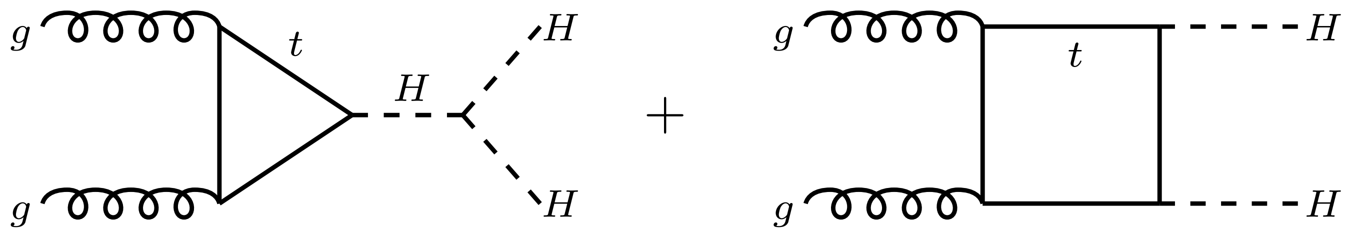
Higher derivatives at the minimum are related to HHH and $HHHH$ couplings:

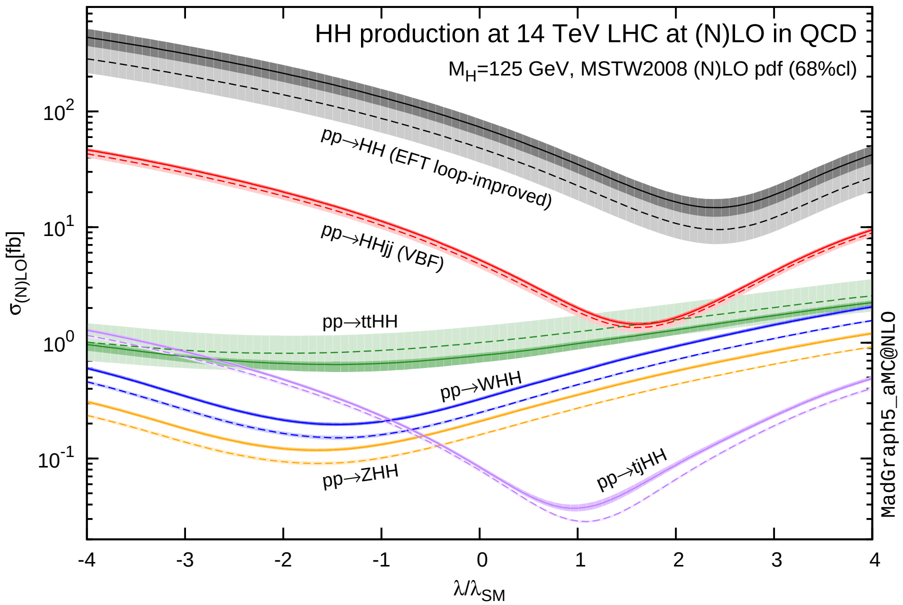
$$\lambda_{HHH} = \frac{\partial^3 V}{\partial H^3}\Big|_{\phi=v}, \qquad \lambda_{HHHH} = \frac{\partial^4 V}{\partial H^4}\Big|_{\phi=v}.$$

Unfortunately, it seems to be impossible to measure λ_{HHHH} at forseeable colliders (Plehn and Rauch, 0507321).

Can access λ_{HHH} at LHC through HH production, with a cross-section now known through NNLO. Eboli et al 1987, Glover van der Bij 1988, Dicus Kao Willenbrock 1988, Plehn Spira Zerwas 9603205, Dawson Dittmaier Spira 9805244, Djouadi Kilian Muhlleitner Zerwas 9904287, Baur Plehn Rainwater 0206024, de Florian Mazzitelli 1305.5206 and 1309.6594, Frederix et al 1401.7340, Maltoni Vryonidou Zaro 1408.6542, Grober et al 1504.06577, Grigo Hoff Steinhauser 1508.00909, Dawson Lewis 1508.05397, Borowka et al 1604.06447

Negative interference between λ_{HHH} and the top-quark loop diagram. . .





Frederix et al 1401.7340

Destructive interference maximal for $\lambda_{HHH} \approx 2.5\,\lambda_{HHH}^{\mathrm{SM}}$.

Due to low cross-section, viable signal probably needs at least one H to decay to $b\bar{b}$:

$$pp \to HH \to b\bar{b}\gamma\gamma \quad \text{or} \quad b\bar{b}\tau^+\tau^- \quad \text{or} \quad b\bar{b}W^+W^- \quad \text{or} \quad b\bar{b}b\bar{b}$$

Baur Plehn Rainwater 0304015 and 0310056, Dolan Englert Spannowsky 1206.5001, Papaefstathiou Yang Zurita 1209.1489, Baglio et al 1212.5581, Barr et al 1309.6318 and 1412.7154, Barger et al 1311.2931, Maierhoffer, Papaefstathiou 1401.0007, Goertz et al 1410.3471, Azatov et al 1502.00439, . . .

Consider as an example a toy effective theory:

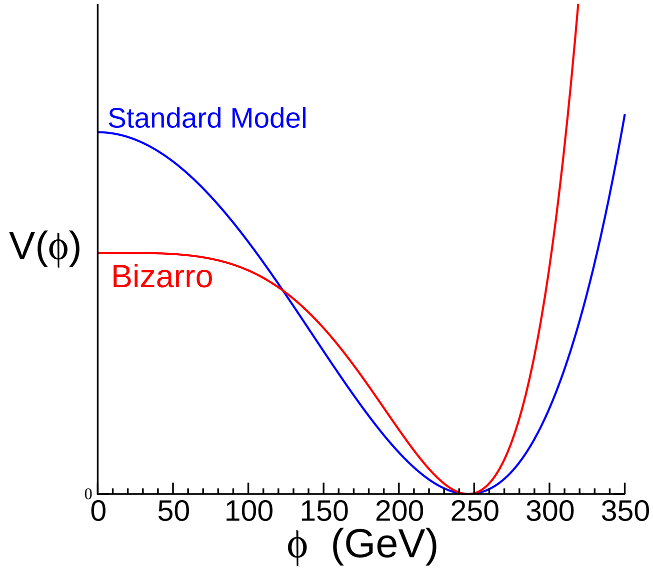
$$V(\phi) = m^2|\phi|^2 + \lambda|\phi|^4 + |\phi|^6/\Lambda^2.$$

where one of m^2 or λ is negative. Then can show

$$\frac{\lambda_{HHH}}{\lambda_{HHH}^{\rm SM}} = 1 + \frac{2v^4}{m_H^2\Lambda^2} = 1 + (690\ {\rm GeV}/\Lambda)^2\ .$$

Special case: in a Bizarro World with $m^2 = 0$,
get $\lambda_{HHH}/\lambda_{HHH}^{\rm SM} = 7/3$.

Negative interference is stronger than in Standard Model, $pp \to HH$ cross-section nearly minimal.



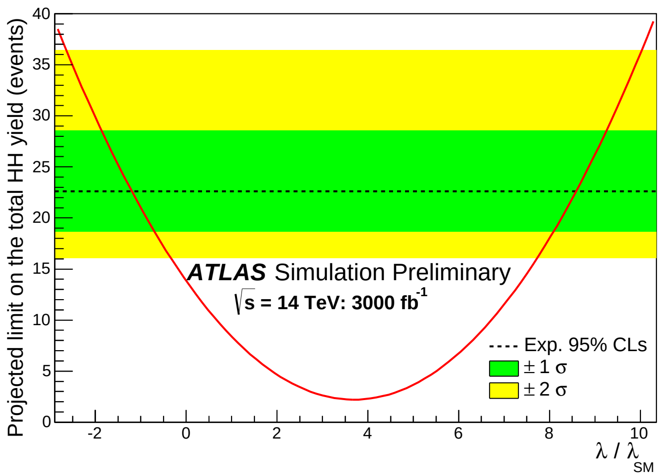
More sophisticated effective field theory treatments give larger effects of both signs.

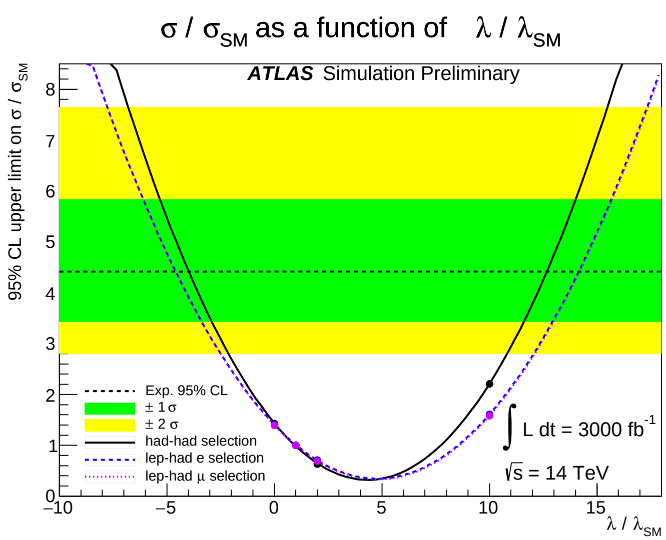
Two Higgs models, SUSY, Little Higgs, Higgs portal, Composite Higgs, Strongly interacting Higgs... See e.g. Pierce Thaler Wang 0609049, Contino et al 1205.5444, Dolan Englert Spannowsky 1206.5001, Kribs A. Martin 1207.4496, Liu Wang Zhu 1310.3634, Goertz et al 1410.3471, Azatov et al 1502.00539, Dawson Ismail Low 1504.05596

Experimentalist projections are a bit less optimistic about $pp \to HH$.

Projections from ATLAS PHYS-PUB-2015-046 and PHYS-PUB-2014-019, for 3000 fb^{-1} at $\sqrt{s} = 14$ TeV:

$b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$





From $b\bar{b}\tau^+\tau^-$, can expect to exclude only $\lambda_{HHH}/\lambda_{HHH}^{\rm SM} < -4$ and $\lambda_{HHH}/\lambda_{HHH}^{\rm SM} > 12$.

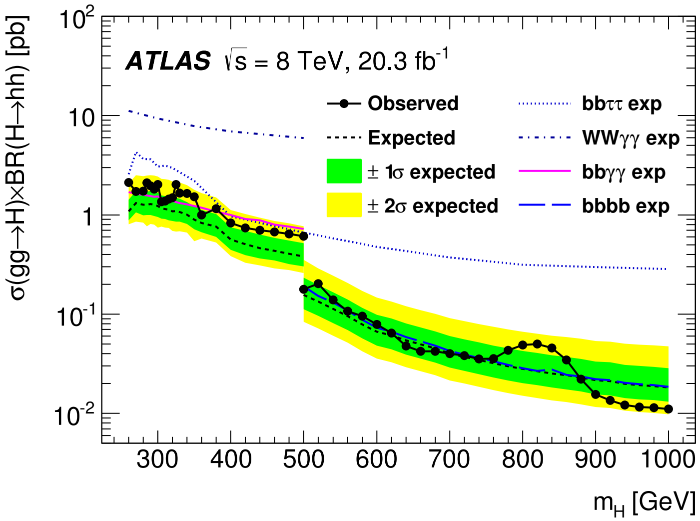
From $b\bar{b}\gamma\gamma$, expect only 8 events from Standard Model.

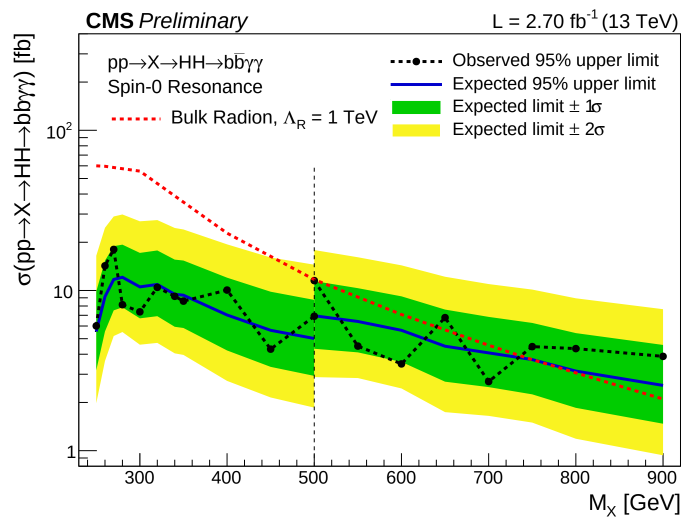
Investigating the Standard Model Higgs potential is both very important and very difficult, due to a conspiracy of low cross-sections and negative interference.

However, for **resonant** HH production, LHC is already putting limits.

$$pp \to X \to HH$$

due to X with $m_X > 2M_H$. Limits on cross-sections for $pp \to X \to HH$:

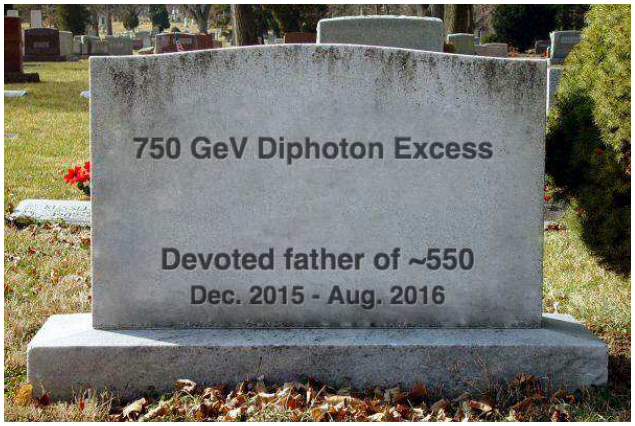


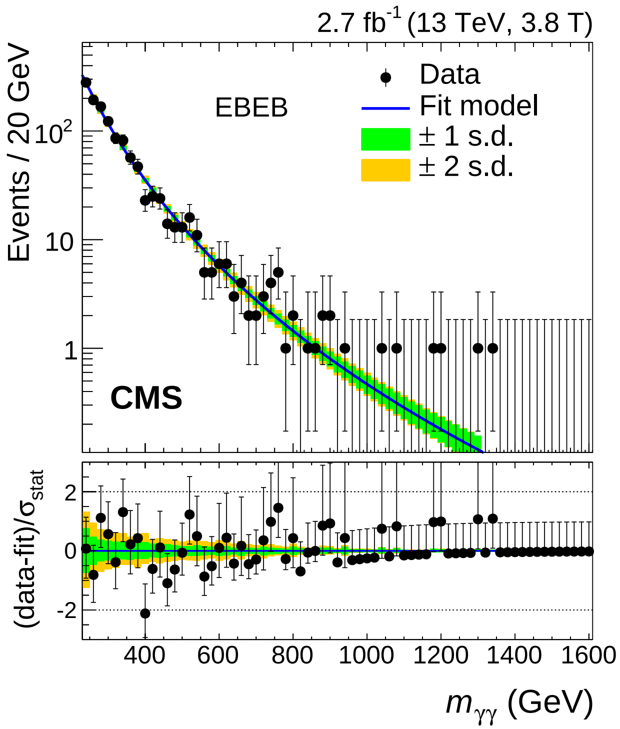


Every theorist has at least one favorite candidate for X. Mine is stoponium, a bound state of top squark and top antisquark. Others inspired by. . .

The game-changer that wasn't:

An excess of $pp \to \gamma\gamma$ events with $M_{\gamma\gamma} \approx 750$ GeV was observed in **both** ATLAS and CMS with 2015 data at $\sqrt{s} = 13$ TeV.





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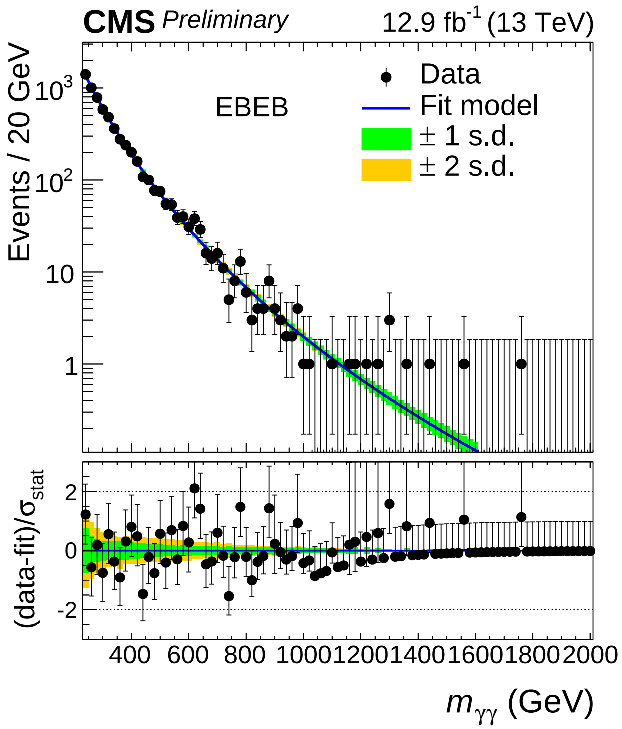


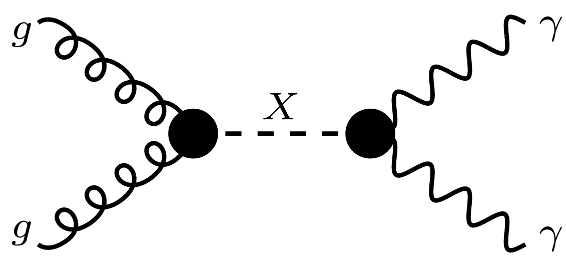
It turned out to be a statistical fluctuation.

Despite passing away at a young age, the 750 GeV Diphoton Excess was the devoted father of about 550 theory papers, by many different mothers.





Most of the “new” models were found beautiful, and loved, only by their mothers, and a plurality were variations of this:



with the black dots representing loops of extra stuff.

What did we learn? Some say:

- HEP theorists don't understand statistics
- HEP theorists are shameless ambulance chasers
- HEP theorists can build some horribly ugly models
- HEP experimentalists are capable of bump hunting without theorists' help
- Citation counts are not so significant

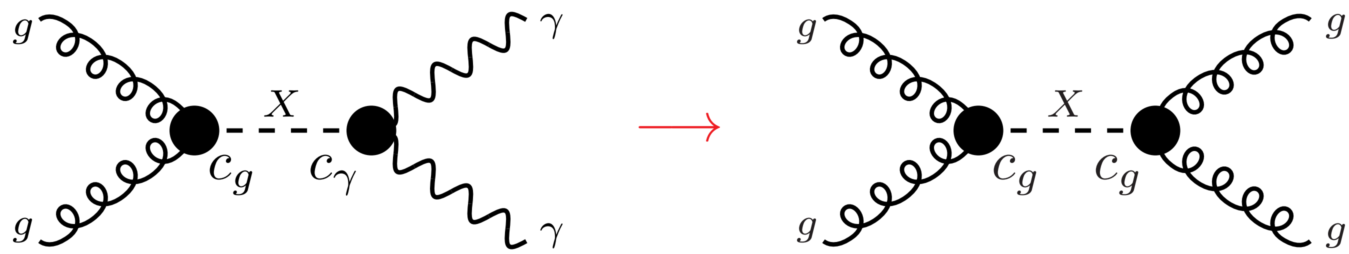
However, perhaps all of these conclusions, except the last, are too cynical.

The first anomaly/ambulance chase I remember: the CDF $e^+e^-\gamma\gamma + E_T^{\rm miss}$ event, from the last century. Even though a fluke, it resulted in many theorists and experimentalists becoming aware of Gauge Mediated Supersymmetry Breaking (Dine, Nelson, Nir, Shirman) as an important possibility. Many significant model building and phenomenology advances resulted.

The 750 GeV diphoton episode stimulated model building, and eventually the system worked, as it always eventually does. Some model building and phenomenology lessons from it will endure.

I'll discuss one that resonated for me (1606.03026), involving signal/background interference, which has much wider applicability than just 750 GeV.

Some papers put constraints on the 750 GeV diphoton resonance by noting that it implies there should also be a dijet resonance:



If X has mass M, total width Γ, and partial width to gg is Γ_{gg}, then

$$\Gamma_{gg} = |c_g|^2/2M$$

and

$$\sigma(pp \to X \to gg) \quad \approx \quad \frac{\Gamma_{gg}^2}{M\Gamma} \times \begin{cases} 1.1 \times 10^3 \text{ pb} & \text{(for } \sqrt{s} = 8 \text{ TeV),} \\ 4.9 \times 10^3 \text{ pb} & \text{(for } \sqrt{s} = 13 \text{ TeV).} \end{cases}$$

for $M = 750$ GeV. This is large enough to set a non-trivial limit from dijet searches, even with $\sqrt{s} = 8$ TeV data. However...

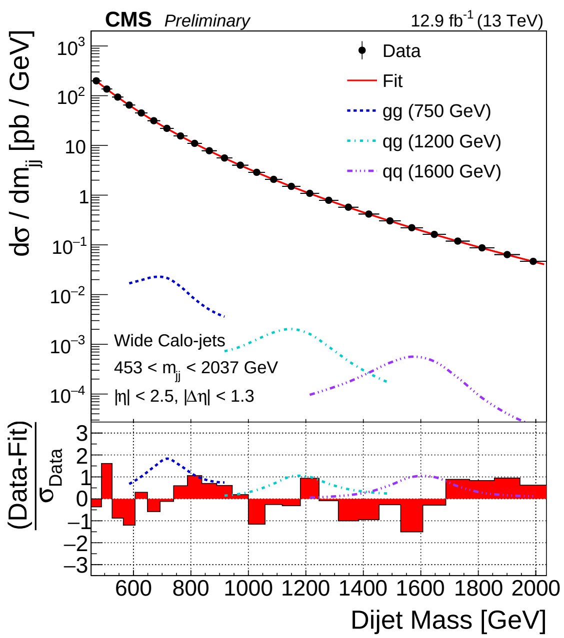
Dijet resonances at LHC are difficult for $M \lesssim 1000$ GeV, because very large backgrounds $\rightarrow$ trigger rescaling $\rightarrow$ most events don't make it to tape.

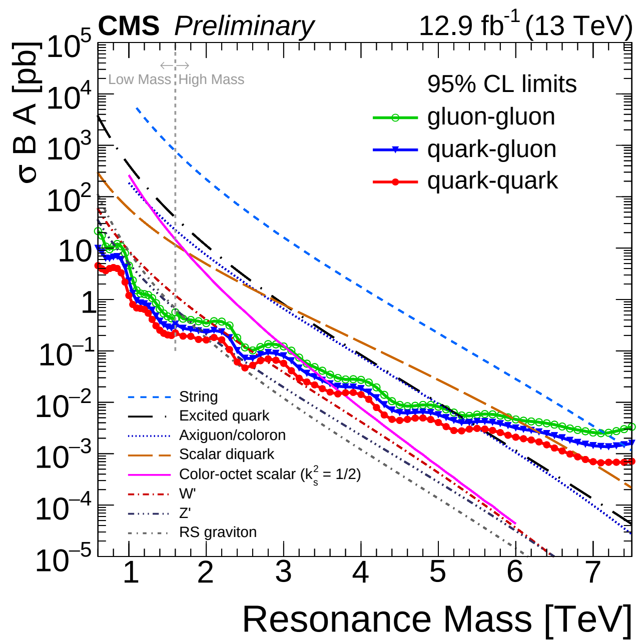
CMS **Data Scouting** technique: record dijet data at much higher rates, by keeping only high-level trigger information.

Recent "low" mass $(< 2$ TeV) dijet searches:

CMS 1604.08907 (18.8 fb^{-1} at 8 TeV)

CMS-PAS-EXO-16-032 (12.9 fb^{-1} at 13 TeV)





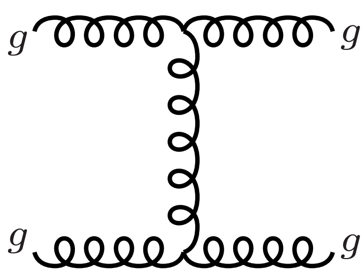
The CMS $\sqrt{s} = 8$ TeV paper, 1604.08907, was used by theorists to estimate limits on the partial width to gluons, for $M = 750$ GeV:

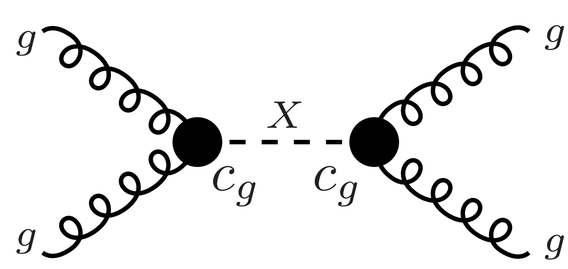
$$\sigma(pp \to X \to gg) \lesssim 2.5\,\text{pb}.$$

- If Γ_{gg} is the dominant width, then $\Gamma_{gg} = \Gamma \lesssim 0.0016M$.
- If $\Gamma = 0.06M$ (2015 ATLAS best fit) then $\Gamma_{gg} \lesssim 0.01M$.

However, these limits based on dijet bump hunting are not justified; they ignore signal-background interference, which is crucial because near the resonance mass M:

(continuum $gg \to gg$ amplitude) $\gg$ (resonant $gg \to X \to gg$ amplitude)





Signal-background interference for digluon resonance (SPM 1606.03026)

At parton level:

$$\frac{d\sigma}{d\cos\theta} = \left.\frac{d\sigma}{d\cos\theta}\right|_{\text{continuum QCD}} + \left.\frac{d\sigma}{d\cos\theta}\right|_{\text{resonant } X} + \left.\frac{d\sigma}{d\cos\theta}\right|_{\text{interference}}$$

where

$$\left.\frac{d\sigma}{d\cos\theta}\right|_{\text{resonant } X} = \frac{c_g^4}{32\pi\hat{s}[(\hat{s}-M^2)^2 + M^2\Gamma^2]},$$

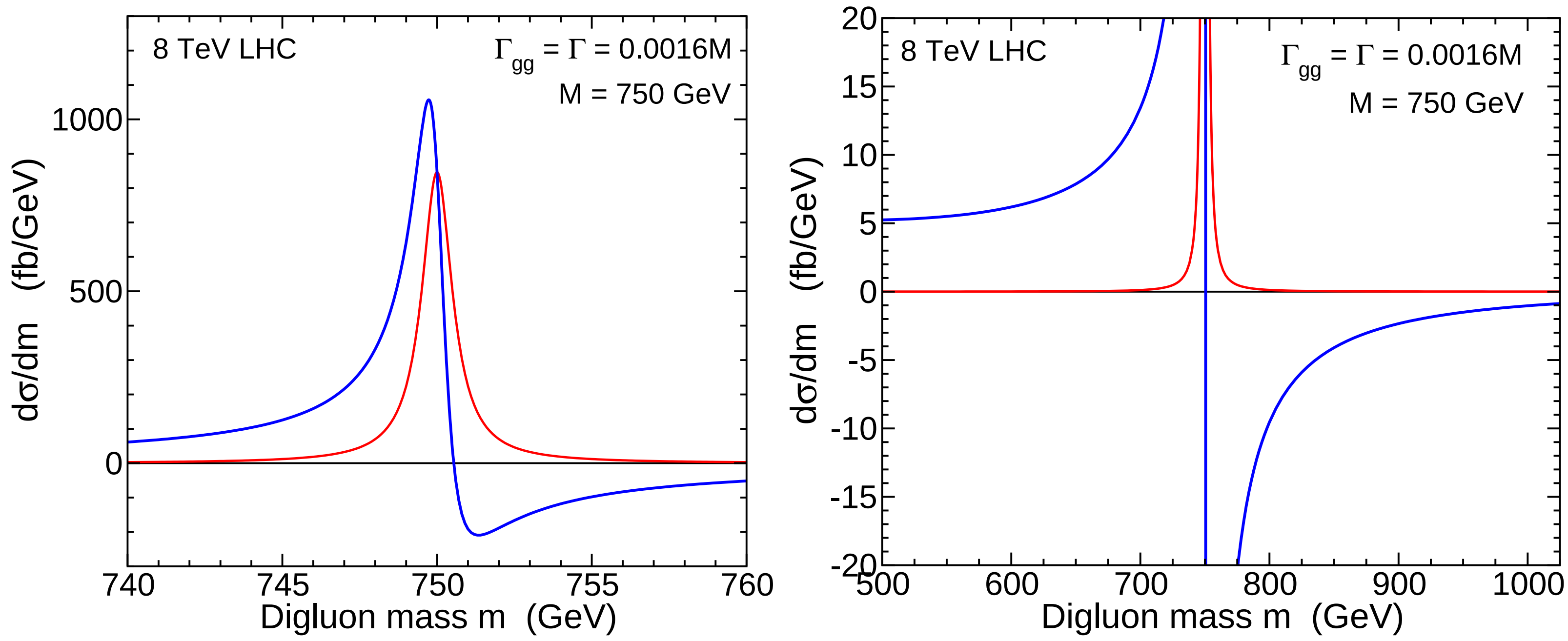
$$\left.\frac{d\sigma}{d\cos\theta}\right|_{\text{interference}} = -\frac{3\alpha_S c_g^2}{8\sin^2\theta}\,\frac{\hat{s}-M^2}{\hat{s}[(\hat{s}-M^2)^2 + M^2\Gamma^2]},$$

The pure resonant part is a Breit-Wigner lineshape peaked at $\hat{s} = M^2$.

The interference part is positive for $\hat{s} < M^2$, and negative for $\hat{s} > M^2$, enhanced by QCD coupling and in forward/backward directions $(\sin\theta \to 0)$.

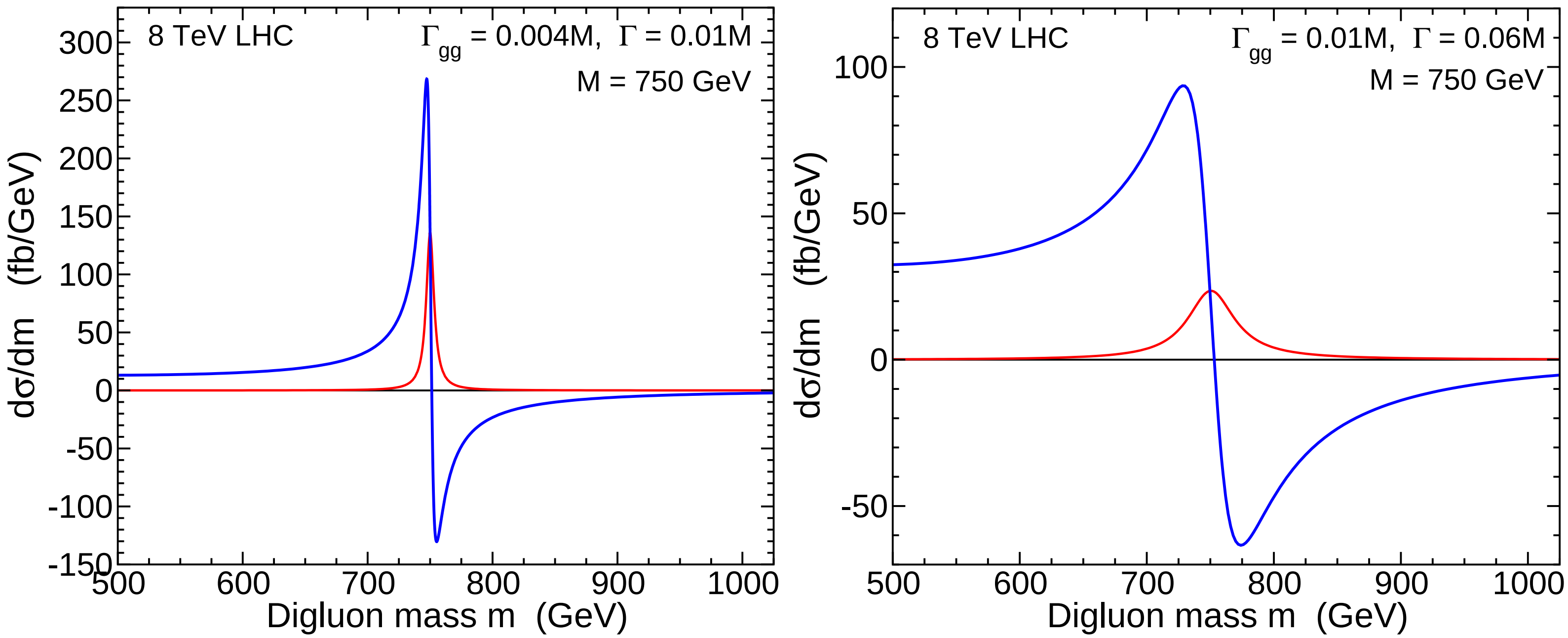
(t-channel and u-channel X-exchange diagrams are of lesser importance, but are included in the figures below.)

For $M = 750$ GeV, minimal width consistent with $\sigma_{\rm tot}(pp \to X \to gg) = 2.5$ pb:



- Blue = resonance + interference, Red = pure resonance (fiction)
- Peak-dip structure, not pure peak
- Graphs above are the same thing, but with different axis scales
- Interference part has fat "square root of Breit-Wigner" tails
- Resonant + interference can be negative; pure QCD part (not shown) renders the total positive

Two cases with larger total width Γ, keeping $\sigma_{\rm tot}(pp \to X \to gg) = 2.5$ pb fixed:



- Importance of interference grows with total width Γ, for a given fixed $\sigma_{\rm tot}$.
- Chose $M = 750$ GeV for obvious historical reasons, but qualitative features hold for larger masses as well
- $\Gamma = 0.06M$ (last figure) was the ATLAS best fit for the diphoton excess

Need to account for effects of QCD radiation, hadronization, and detector resolution. Dijet mass distributions by smearing with a double-sided “crystal ball” response function, Gaussian core with power law tails, with parameters fit by comparison with CMS 1604.08907:

$$f(m, m_{gg}) \quad = \quad N \begin{cases} (A_L + B_L m)^{-n_L} & \text{for } (m - \overline{m})/\sigma \leq -\alpha_L\,, \\ \exp[-(m - \overline{m})^2/2\sigma^2] & \text{for } -\alpha_L \leq (m - \overline{m})/\sigma \leq \alpha_H\,, \\ (1 - m/m_{\max})^\nu (A_H + B_H m)^{-n_H} & \text{for } (m - \overline{m})/\sigma \geq \alpha_H\,. \end{cases}$$

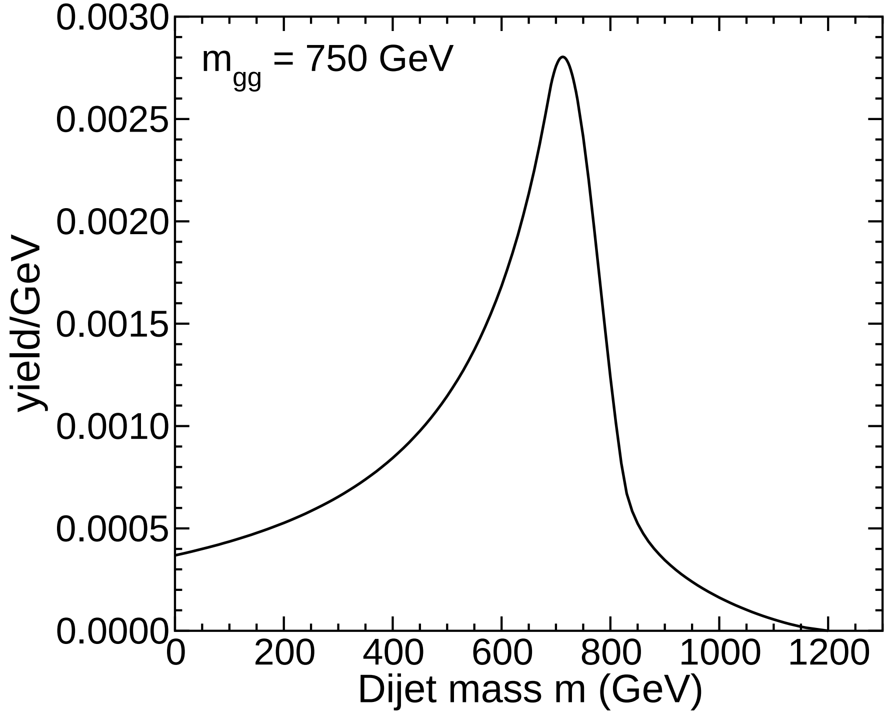
with:

$\sigma/m_{gg} = 2.09/\sqrt{m_{gg}} + 0.015,$

$\overline{m} = 0.95 m_{gg},\;\; m_{\max} = 1.6 m_{\rm gg},$

$n_L = 1.5,\;\; \alpha_L = 0.4, n_H = 0.25,$

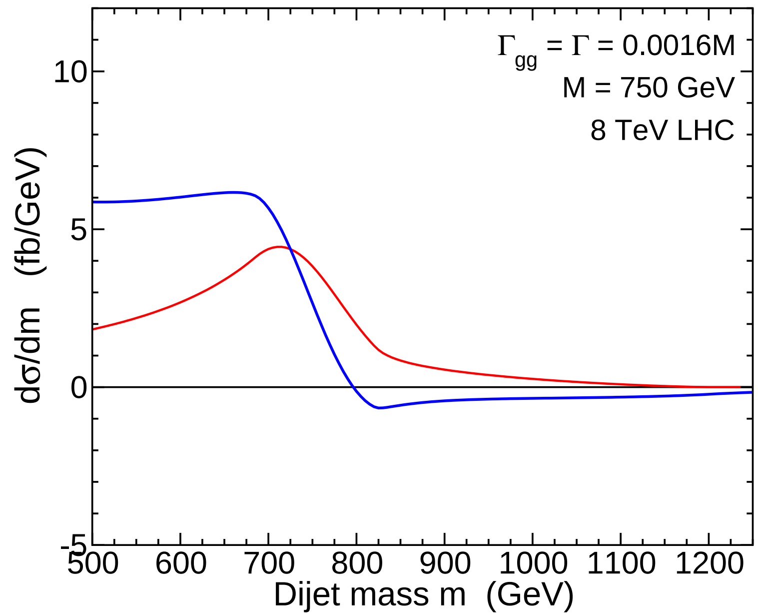
$\alpha_H = 1.6,$ and $\nu = 1.4.$

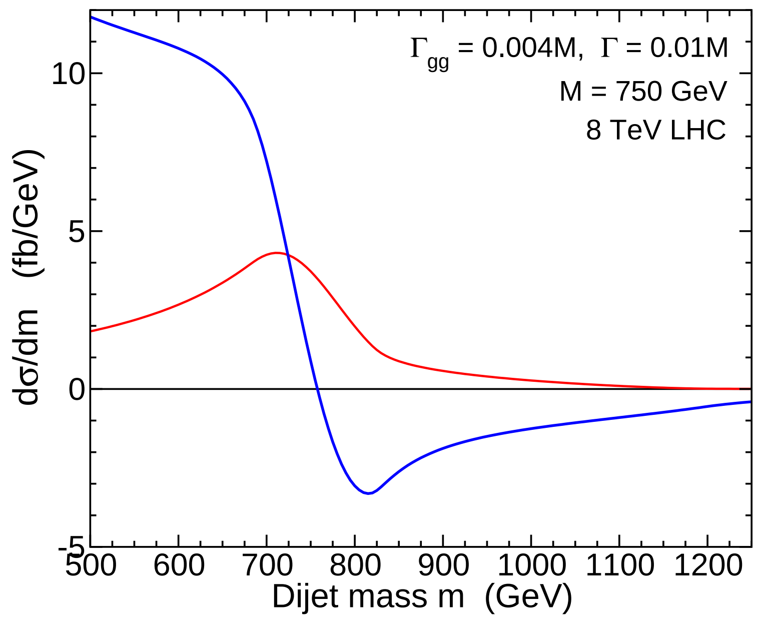


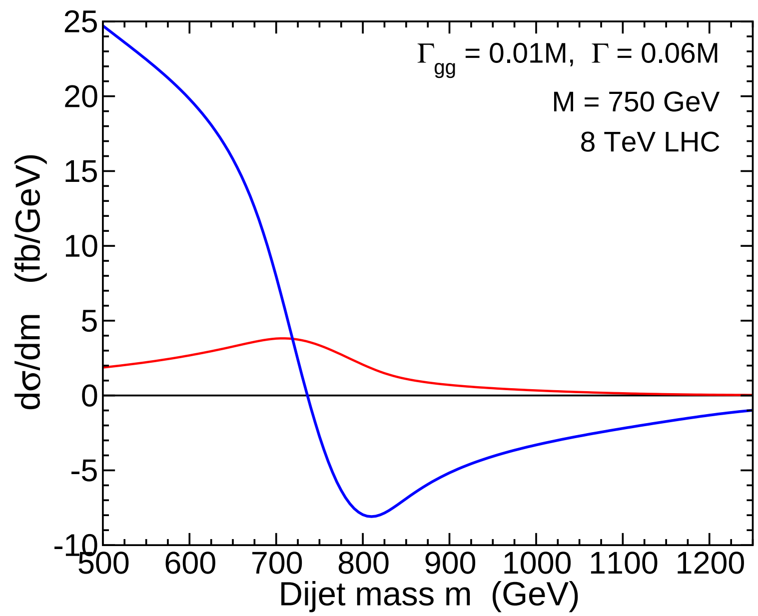
After smearing to account for QCD radiation, hadronization, and detector effects.

At right is the “minimal width” case.

Signals are not at all “peak-like”.

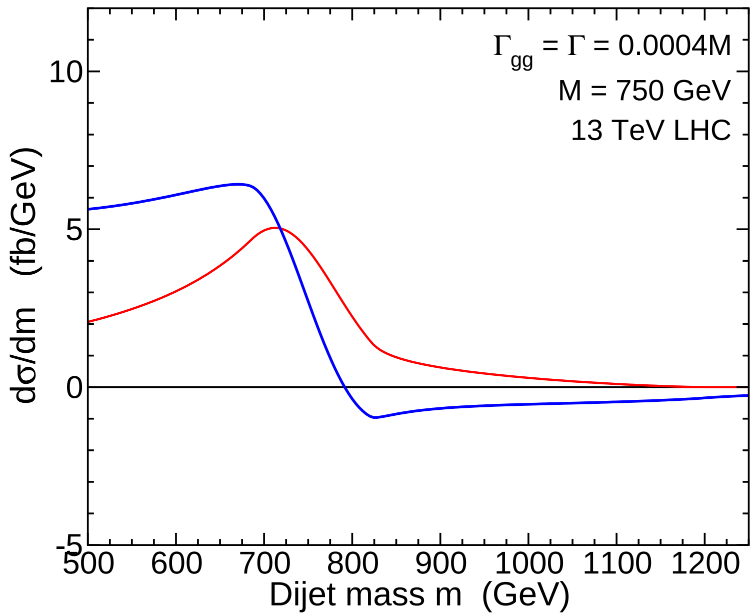


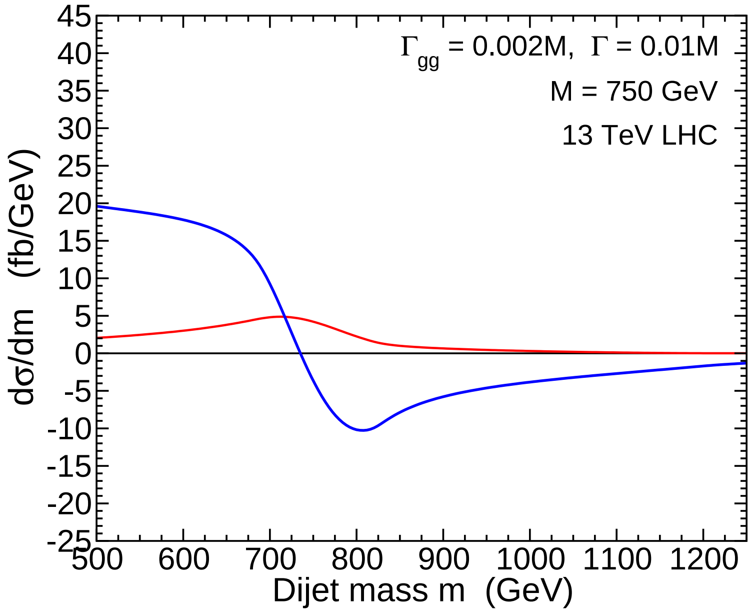


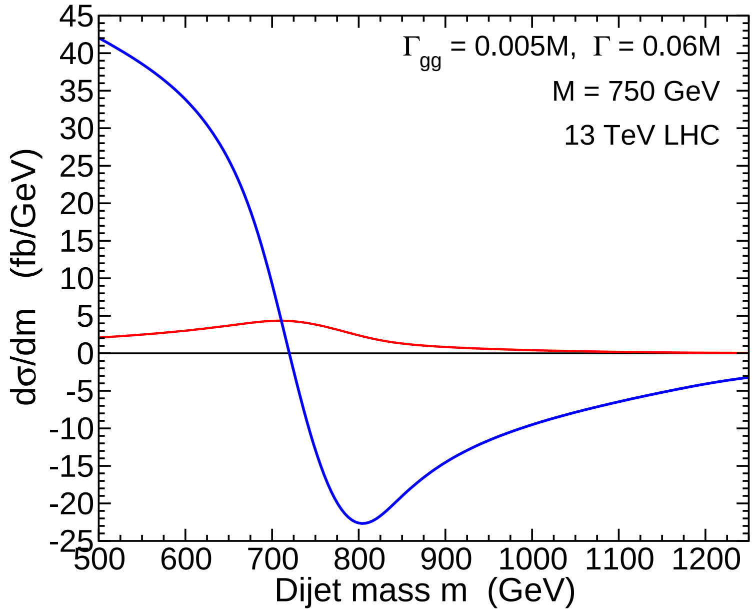


At 13 TeV, for $\sigma_{\mathrm{tot}} = 3$ pb, after smearing, for three different widths:

Shapes mostly depend on partonic physics, soft QCD effects and detector resolution; mostly insensitive to proton beam energy.







General lessons for signal-background interference in $pp \to X \to jj$

- Resonance-hunting is not just bump-hunting! Real signal may be peak-dip, shelf-dip, or even just dip. (In part, depends on fit of background.)
- Limits on dijet resonances need to be examined critically, but may actually get stronger (?)
- Should be carried out to Next-to-Leading Order, at least.
- Needs full detector simulation (by ATLAS and CMS, not theorists!)
- Extend to X = spin 0,1,2, and color = $\mathbf{1}, \mathbf{3}, \mathbf{6}, \mathbf{8}$, and initial states gg, gq, $q\bar{q}$, and qq.
- Relative importance increases as signal cross-section decreases (as limits get stronger)
- Might be critical: what if new physics only shows up in jets, with no $E_T^{\rm miss}$?

Quixotic new physics

A **quix** is an exotic fundamental fermion or scalar in the $\mathbf{6}$ representation of $SU(3)_c$.

- Not easy to incorporate in string/M theory (considered impossible in 1980's?)

  Daydream NY Times headline:

  `6000 Physicists Discover New Exotic Particle, Disprove String Theory`

- However, string theorists are very clever, and a quix could be a composite bound state of exotic heavy quarks, if nothing else

- LHC signal for fermionic quix is $pp \to (jjj)(jjj)$

  Each fermionic quix decays to $q\bar{q}\bar{q}$, due to $SU(3)_c$ and Fermi statistics

- LHC signal for bosonic quix is $pp \to (jj)(jj)$

  Each scalar quix decays to qq, due to $SU(3)_c$ and Bose statistics

LHC vs. Supersymmetry

In 2010: Eagerly confronting our fate.

LHC vs. SUSY after 2011: Just a flesh wound.

LHC vs. SUSY from 2012 on: Uh-oh. Now it is serious.

But I suspect that’s wrong, and SUSY isn’t like the Black Knight of Monty Python.

Instead, perhaps SUSY is the French Knight of Monty Python, in a high and secure place (just?) out of reach, taunting us:

Where should we expect SUSY to be?

Lighter SUSY favored by:

- Hierarchy problem: $M_Z \ll$ new physics mass scales
- Bino-like dark matter
- Weak-scale baryogenesis

Heavier SUSY favored by:

- $M_H > 114$ GeV (since 2001) $M_H^2 = M_Z^2 + \frac{3y_t^2}{4\pi^2} M_t^2 \ln(M_{\rm SUSY}^2/M_t^2)$
- $M_H = 125$ GeV (since 2012)
- Flavor constraints (since ancient times)
  - hadronic (e.g. K^0 mixing)
  - leptonic (e.g. $\mu \to e\gamma$)
  - CP violation (e.g. EDMs)
- Wino-like or Higgsino-like dark matter

Hindsight is 20-20, but $M_{\rm SUSY} \gtrsim 2$ TeV looks like a better bet, at least since 2012 when $M_H = 125$ GeV, and at least for minimal SUSY.

J. Wells, hep-ph/0306127 and hep-ph/0411041

Furthermore, LHC exclusions of SUSY are always based on assumptions, often strong:

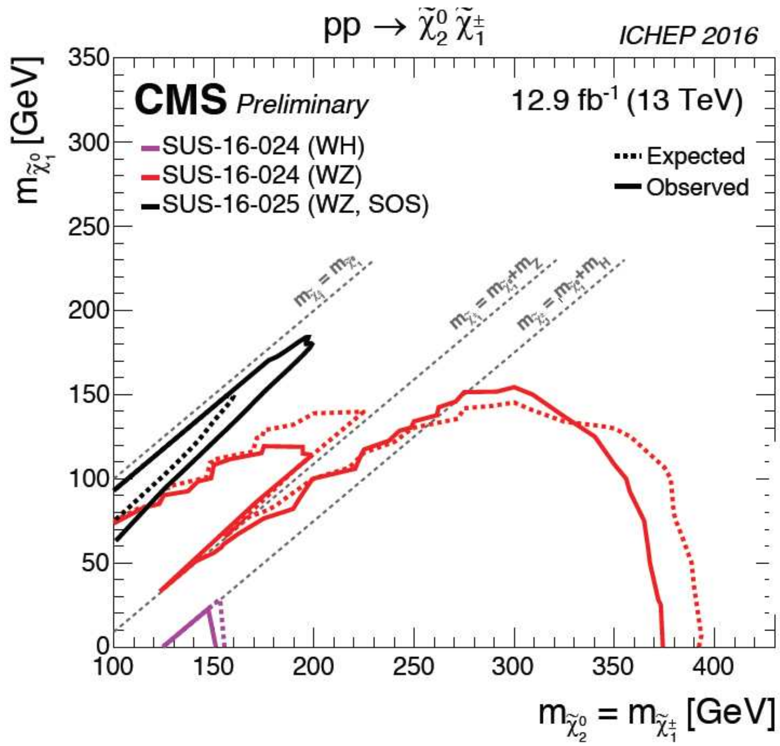
- Gauginos are Majorana; could be Dirac, with lower cross-sections
- R-parity conservation
- large mass differences
- simplified (and unrealistic!) decay modes

Chargino/neutralino searches at CMS, as of ICHEP 2016.

Impressive limits follow from assuming

$$\begin{aligned}\tilde{C}_1^{\pm} &\to W^{\pm}\tilde{N}_1\\ \tilde{N}_2 &\to Z\tilde{N}_1\end{aligned}$$

(or decays through sleptons on-shell).



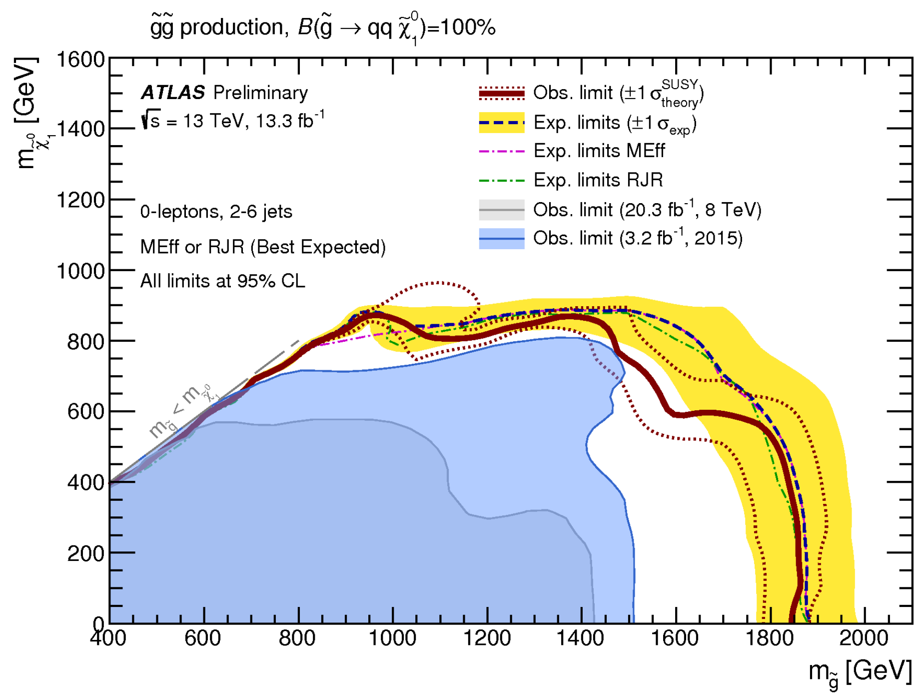
However, the dominant decay (BR $\gtrsim$ 90%) predicted for SUSY winos is actually much more challenging:

$$\tilde{N}_2 \to h\tilde{N}_1$$

Higgsino or wino LSPs have very small mass differences, very difficult to probe.

ATLAS limits on gluinos with 3-body decays to light quarks and LSP, as of ICHEP 2016:

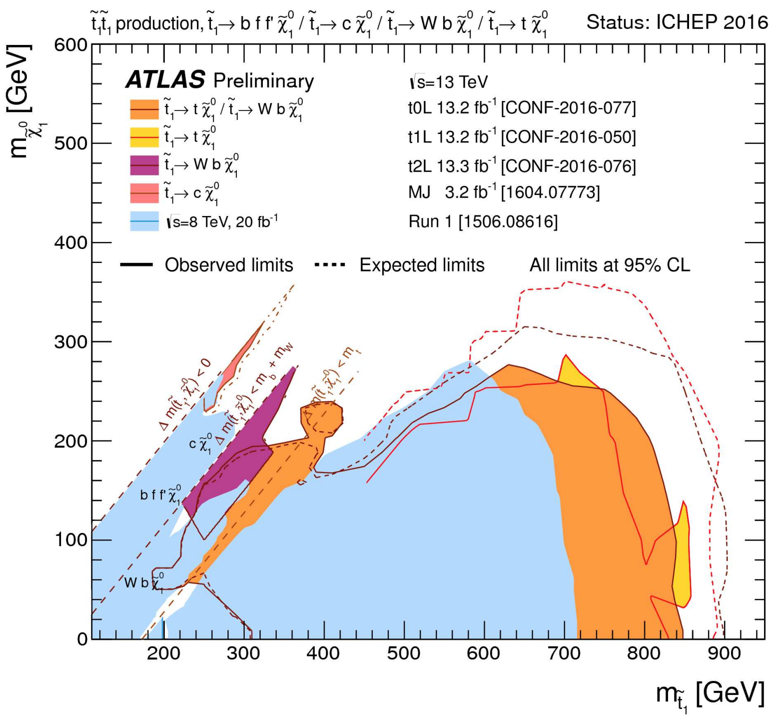
(CMS is similar)

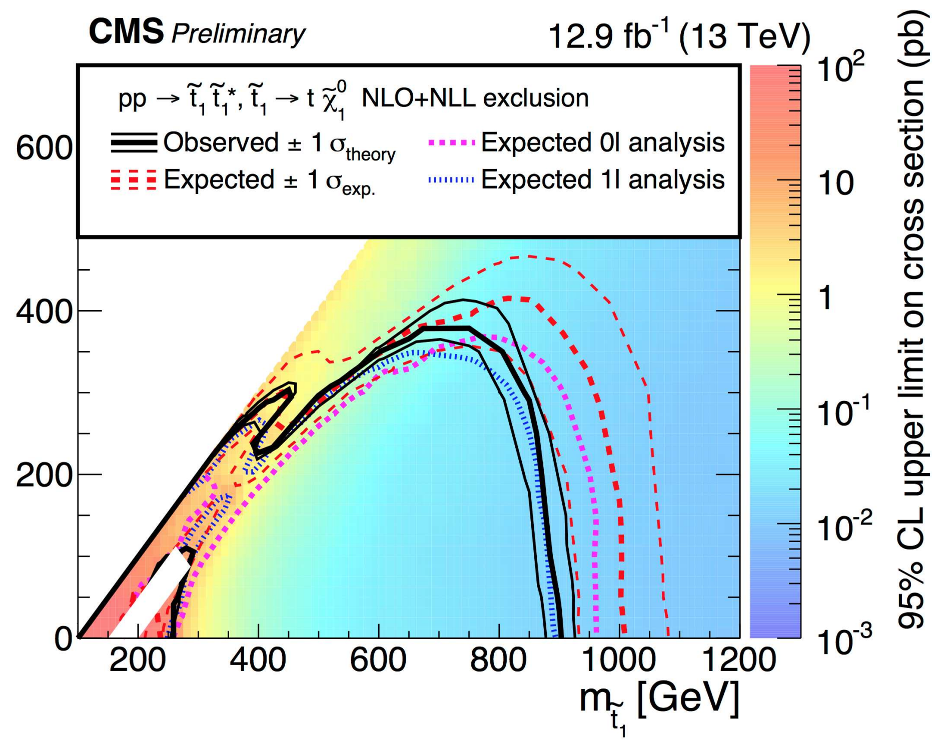


Abstracts and headlines say “Gluinos exclusions up to 1900 GeV”. However, it is also true that no exclusion here for $M_{\rm gluino} > M_{\rm LSP} > 900$ GeV.

“Compressed SUSY”: smaller mass hierarchies $\to$ weaker limits, or no limits.

LHC limits on top squarks, as of ICHEP 2016:





For the present, $M_{\rm stop} = 300$ GeV and $M_{\rm LSP} = 250$ GeV is OK.
So is $M_{\rm stop} = 500$ GeV and $M_{\rm LSP} \gtrsim 325$ GeV.

Dark matter still works! (Keith Olive's talk)

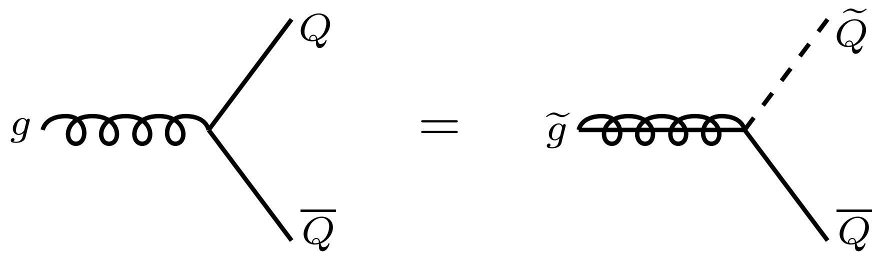
- co-annihilation of stop, LSP in early universe
- annihilation LSP+LSP $\to t\bar{t}$ through t-channel stop

When to give up on SUSY at the LHC?

The only cold-blooded scientific answer to this question is: when the LHC turns off.

- 10^{-4} fine-tuning is vastly favored over 10^{-32} fine-tuning
- SUSY is a decoupling theory.

This does **not** mean SUSY is not predictive and falsifiable:



SUSY breaking is the source of our ignorance:

$$M_Z^2 \quad = \quad 2(|\mu|^2 - |m_{H_u}^2|) + \ldots$$

Can one arrange for cancellation, “naturally”?

Two classes of attempted solutions for weak-scale cancellation $m_Z^2 \ll (1\mathrm{TeV})^2$:

- Sliding singlet: $\mu = \lambda\langle S\rangle$. Can dynamics of S prefer cancellation?
- RG quasi-fixed point for running: “focus point” (Feng+Matchev) and its generalizations

However, no completely compelling (in my opinion) version of these ideas has emerged.

If the first is correct, might expect evidence of a singlet scalar at the LHC **before** any evidence of superpartners. Can also help to explain $M_h = 125$ GeV.

More generally, **if** SUSY is to be accessible to the LHC, then the lesson of $M_h = 125$ GeV is that it its probably accompanied by something else. . .

Extra vectorlike fermions in SUSY

Moroi and Okada 1992, Babu Gogoladze Kolda 0410085, Babu et al 0807.3055, SPM 0910.2732, . . .

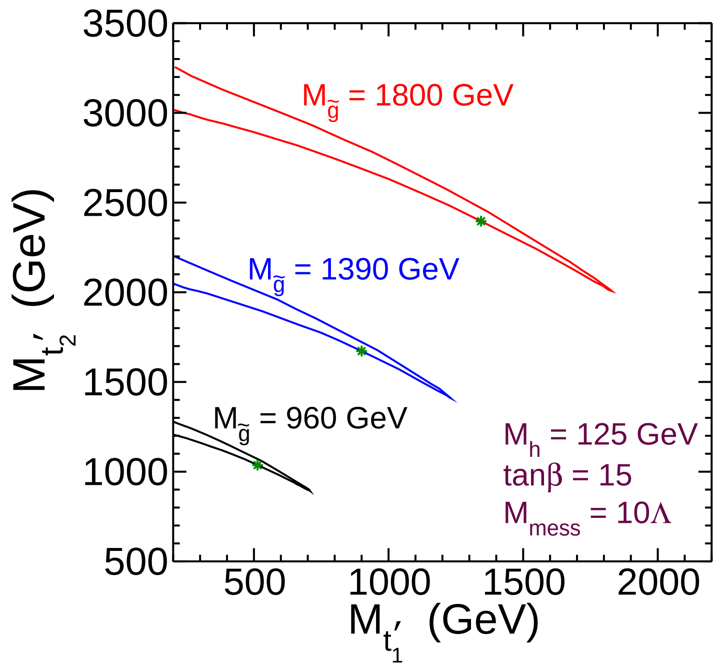
Chiral superfields transforming under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$$(Q, \overline{U}, \overline{E}) + (\overline{Q}, U, E) \quad = \quad (\mathbf{3}, \mathbf{2}, 1/6) + (\overline{\mathbf{3}}, \mathbf{1}, -2/3) + (\mathbf{1}, \mathbf{1}, +1) + \text{conjugate}$$

These particles can have vectorlike (electroweak-singlet) masses, and large Yukawa couplings that help raise the Higgs boson mass to 125 GeV, while not affecting precision electroweak constraints.

Can even rescue Gauge Mediated SUSY Breaking models, which solve the flavor problem but otherwise notoriously have a tough time getting $M_h = 125$ GeV.

Points on graph are consistent with M_h when t' Yukawa coupling is at its IR fixed point. (SPM + J. Wells, 1206.2956)



Searches for lighter t' depend on its mixing with ordinary top.

Pair produced in $pp \to t'\bar{t}'$.

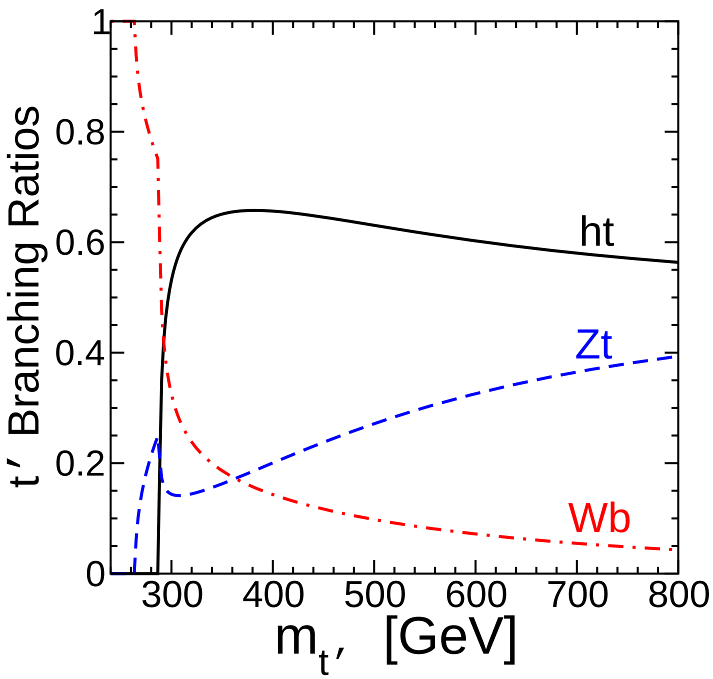
Possible decay modes are: W^+b, Zt, and ht.

Three distinct mixing Yukawa couplings ϵ_U, ϵ'_U, and ϵ_D, with superpotential:

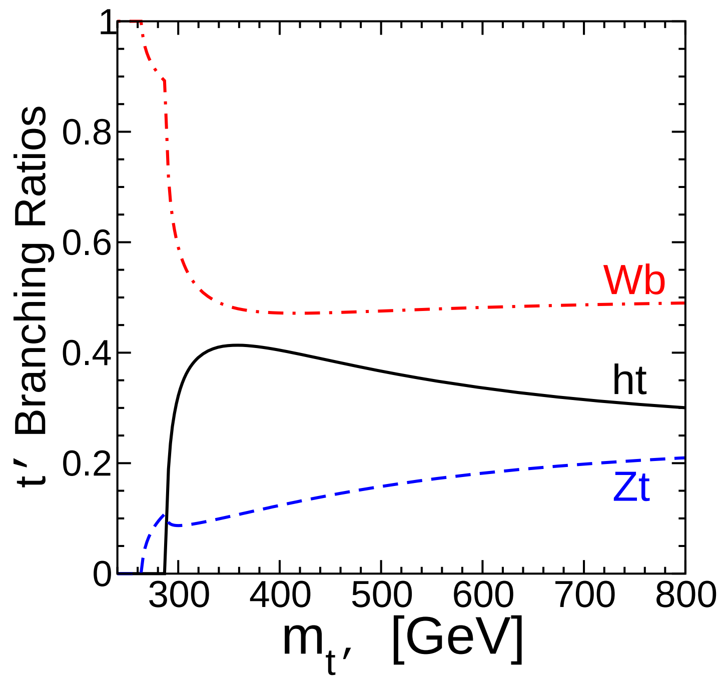
$$W_{\rm mix} \quad = \quad \epsilon_U H_u^0 t_L \bar{t}' + \epsilon'_U H_u^0 t' \bar{t}_R - \epsilon_D H_d^- t' \bar{b}_R$$

- If all of ϵ_U, ϵ'_U, $\epsilon_D \;\lesssim\; 10^{-7}$, then t' will have a macroscopic decay length.
- BR$(W^+b,\;\; Zt,\;\; ht)$ can be:
  - $(1,\;\; 0,\;\; 0)$ for ϵ_D dominant (charged current).
  - $(0,\;\; 0.5,\;\; 0.5)$ for ϵ'_U dominant (neutral current).
  - $(0.5,\;\; 0.25,\;\; 0.25)$ for ϵ_U dominant (democratic).
  - anything you want, for general mixing

t' Branching Ratio dependence on kinematics



Neutral current



Democratic

Charged current, BR($t' \to WB$) = 1, not shown.

Sample mass limits for vectorlike t' quarks:

BR$(t' \to Wb)$	BR$(t' \to Zt)$	BR$(t' \to ht)$	Limit (GeV)	source
1	0	0	920	CMS 1509.04177
0	1	0	790	CMS 1509.04177
0	0	1	900	ATLAS-CONF-2016-013
0	0.6	0.4	760	CMS 1509.04177
0.6	0.2	0.2	740	CMS 1509.04177
	any ($\sum = 1$)		700	ATLAS-CONF-2016-013
	stable		no limits,	but probably $>$ 1000 GeV from CMS stable $\tilde{t}$ searches

Top partners and bottom partners are also predicted in many other models, so this is a crucial search.

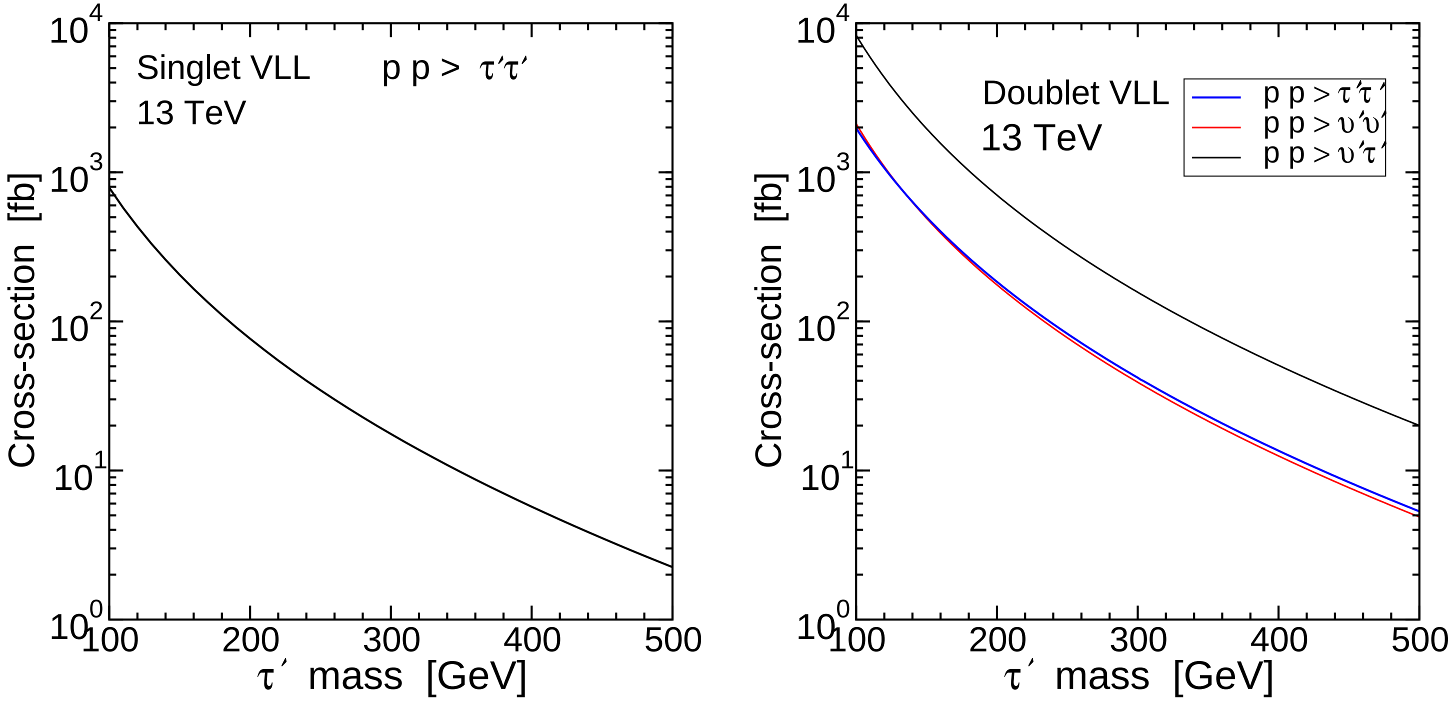
Vectorlike Leptons: SUSY models with vectorlike quarks often also predict a τ'

Prospects at LHC depend very strongly on whether $SU(2)_L$ doublet or singlet.

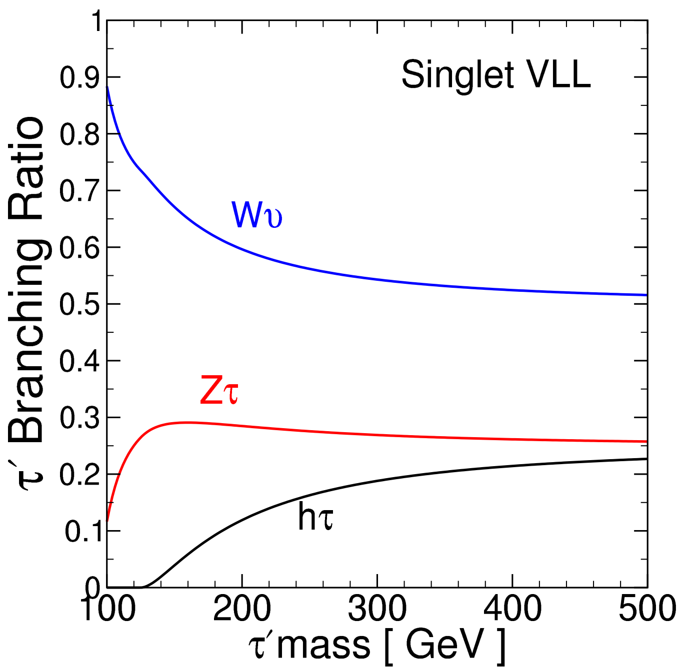
Falkowski Straub Vicente 1312.5329, Dermisek Hall Lunghi Shin 1408.3123, Holdom Ratzlaff 1412.1513,

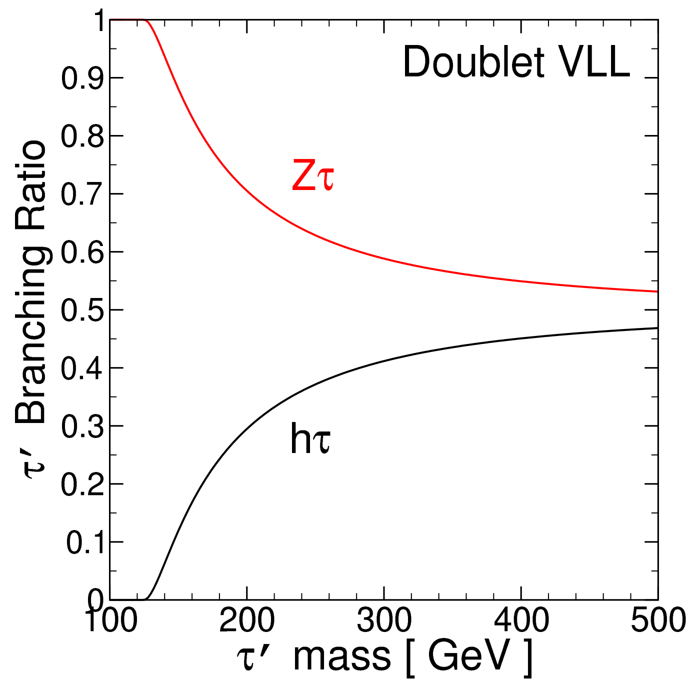
Kumar and SPM, 1510.03456

Production cross-sections much larger for doublet case, in part due to ν':



τ' branching ratios depend only on the mass:





Also BR$(\nu' \to \tau W) = 1$

Kumar and SPM, 1510.03456: Search with multileptons (including hadronic taus)

- Doublet (τ', ν'): with existing $\sqrt{s} = 8$ TeV data, should be able to exclude up to $M'_\tau = 275$ GeV. (However, no actual exclusion from ATLAS or CMS.) At $\sqrt{s} = 13$ TeV, exclusion (discovery) is possible with 100 fb^{-1} up to $M'_\tau = 440$ (300) GeV.

- Singlet τ': **very** difficult; need 1000 fb^{-1} to exclude $M_{\tau'} < 200$ GeV with 95% CL.

Outlook

A selection of possible game changers:

- Anomalous $t\bar{t}H$ production
- Unexpected H decays (e.g. $H \rightarrow$invisible)
- Non-Standard Model Higgs potential: λ_{HHH} from HH production
- Dijet resonances (not dijet bumps)
- Decoupling new physics:
  - SUSY
  - Quixes
  - Extra vectorlike quarks (easy)
  - Extra vectorlike leptons (doublets not too hard, singlets very tough)

But. . .

Outlook (continued)

The number of possible game-changers I didn't have time to mention is vast:

- "Neutral naturalness" (see Roni Harnik's talk)
- Heavy Higgs bosons $H^{\pm}$, H^0, A^0, singlets (see Zhen Liu's talk)
- Quirks = new particles charged under a gauge group with a low confinement scale (Kang + Luty 0805.4642)
- Dark matter particle observation at LHC
- Dirac gauginos
- Long-lived particles, e.g. axinos
- R-parity violation
- ...

Backup

Consider a historical reference point, from the previous century. . .

From “Naturalness and superpartner masses or when to give up on weak scale supersymmetry”, Anderson and Castaño, hep-ph/9412322: