NEW PHYSICS AT THE LHC

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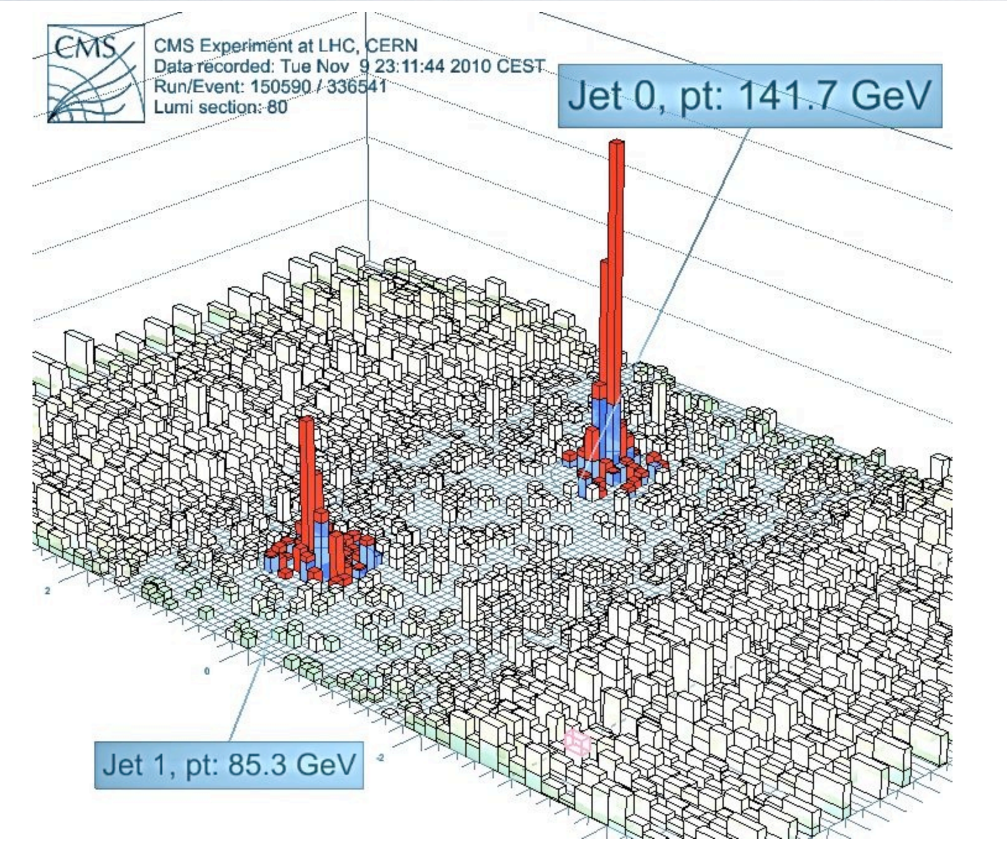
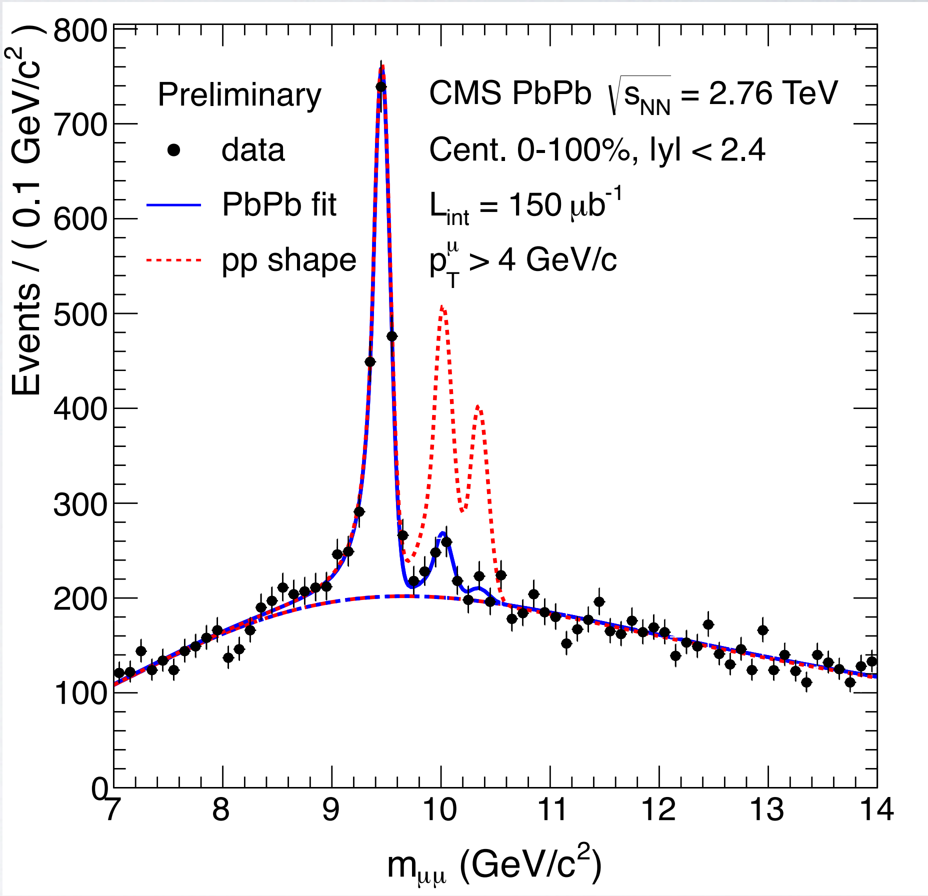
FERMILAB

45TH ANNUAL FERMILAB USERS MEETING
12-13 JUNE 2012

New Physics at the LHC?

New Physics at the LHC?
Yes! in Heavy Ions





what kind of medium did this?

is this deconfinement?

What is our strongest evidence for new physics in pp collisions at LHC?

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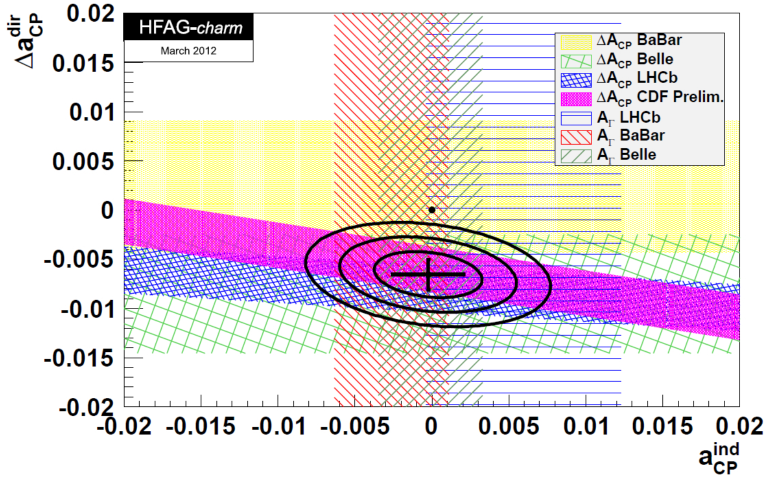
Charm CPV $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$

Measure the difference of CP asymmetries $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

with $A_{\mathrm{CP}}(D^0 \to f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$



$$\Delta A_{CP} = \underbrace{(a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+))}_{\text{direct CP asymmetry}} + \underbrace{\frac{\Delta\langle t\rangle}{\tau_{D^0}} a_{CP}^{ind}}_{\text{indirect CP asymmetry}}$$

HFAG average: $\Delta a_{CP}^{\mathrm{dir}} = (-0.645 \pm 0.18)\%$ 3.6σ away from 0 !

(results dominated by [LHCb, PRL 108, 111602 (2012)], [CDF, Public Note 10784, 2012])

SM hadronic effects or New Physics !?

Olivier Leroy (CPPM) Mixing and CP violation 7 June 2012 9 / 26

The State of the Particle Theory Community, circa June 2012

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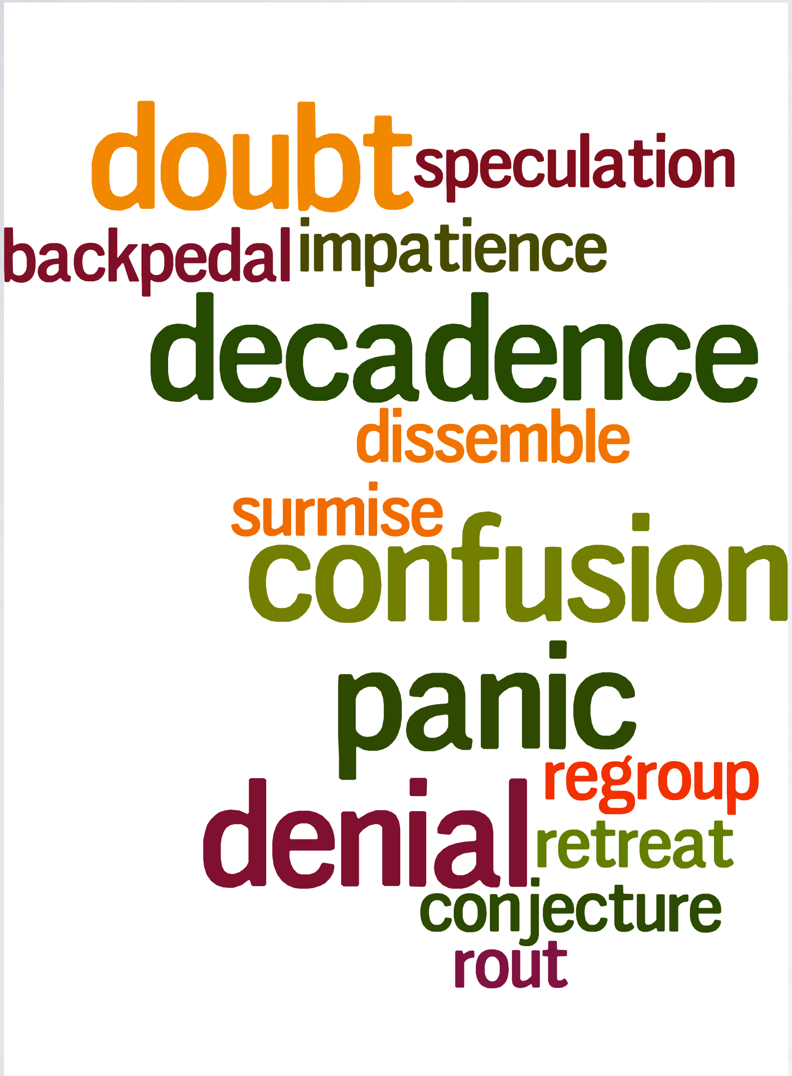
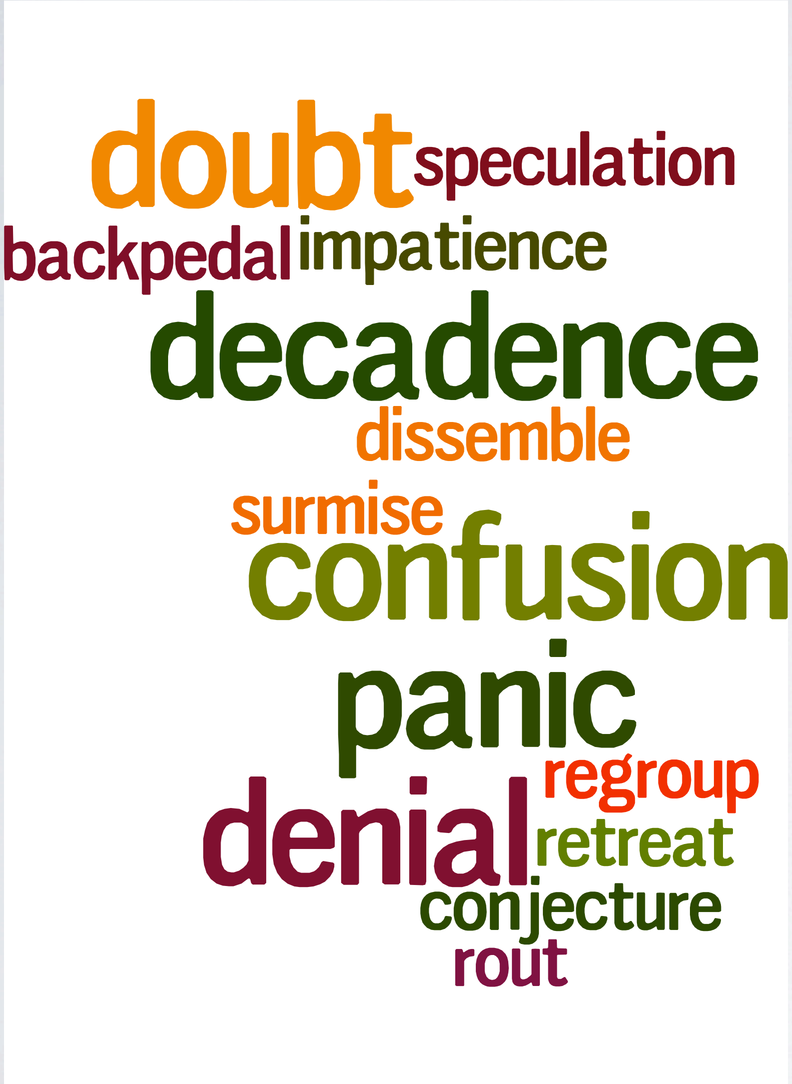


The State of the Particle Theory Community, circa June 2012



- Obviously a segment of the theory community oversold the prospects for low-hanging fruit at LHC, because they didn't want to miss the party if there had been one...
- Now there is too much retreat towards the other direction: "There won't be any new physics at LHC ever!"
- Meanwhile a whole new generation of young theorists are learning how to pay attention to data and talk to experimentalists
- This is the most important thing happening now on the theory side

Higgs scenarios for 2012

What we might know by the end of the 2012+ LHC run:

three mutually-exclusive scenarios:

1. There is (at least one) narrow resonance with mass ~ 125 GeV and with $\sigma \times BRs$ consistent (within large-ish errors) with a SM Higgs

2. Same as above but with significant tension between the SM and one or more of the measured $\sigma \times BRs$

3. There is no resonance consistent with a SM Higgs over the entire mass range

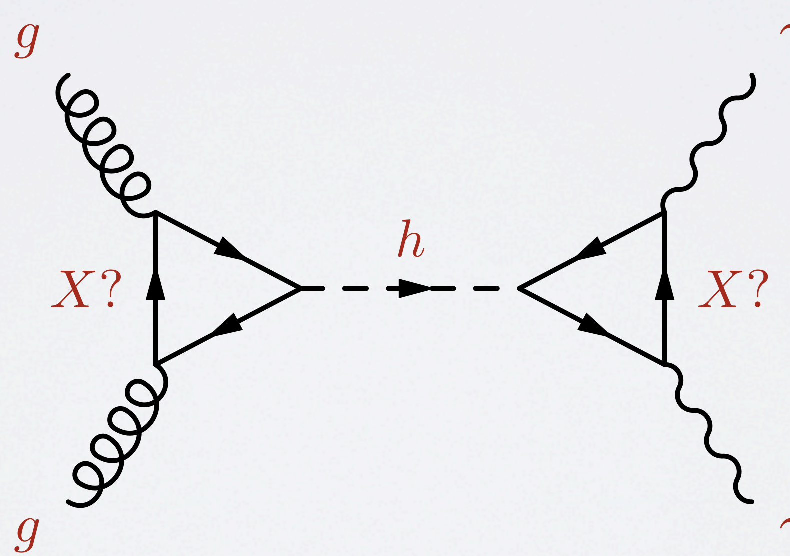
and in all cases:

- Additional constraints on many kinds of non-SM resonances over the entire mass range

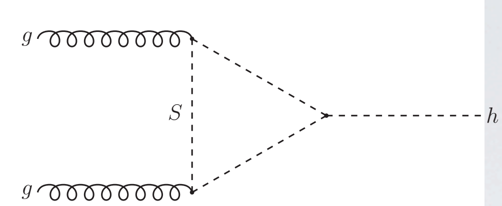
A not-quite-SM Higgs

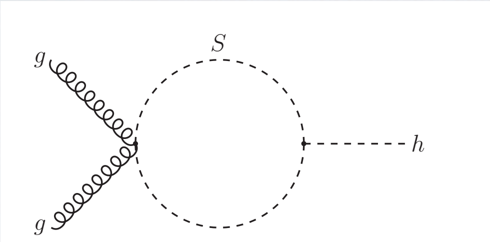
2. Same as above but with significant tension between the SM and one or more of the measured $\sigma \times BRs$

- **Scenario #2 is getting a lot of recent attention from theorists**
- **It is especially interesting for $\mathrm{gg} \to \mathrm{h}$ production, and for $\mathrm{h} \to \gamma\gamma$ decay, since in the SM both proceed through a loop:**

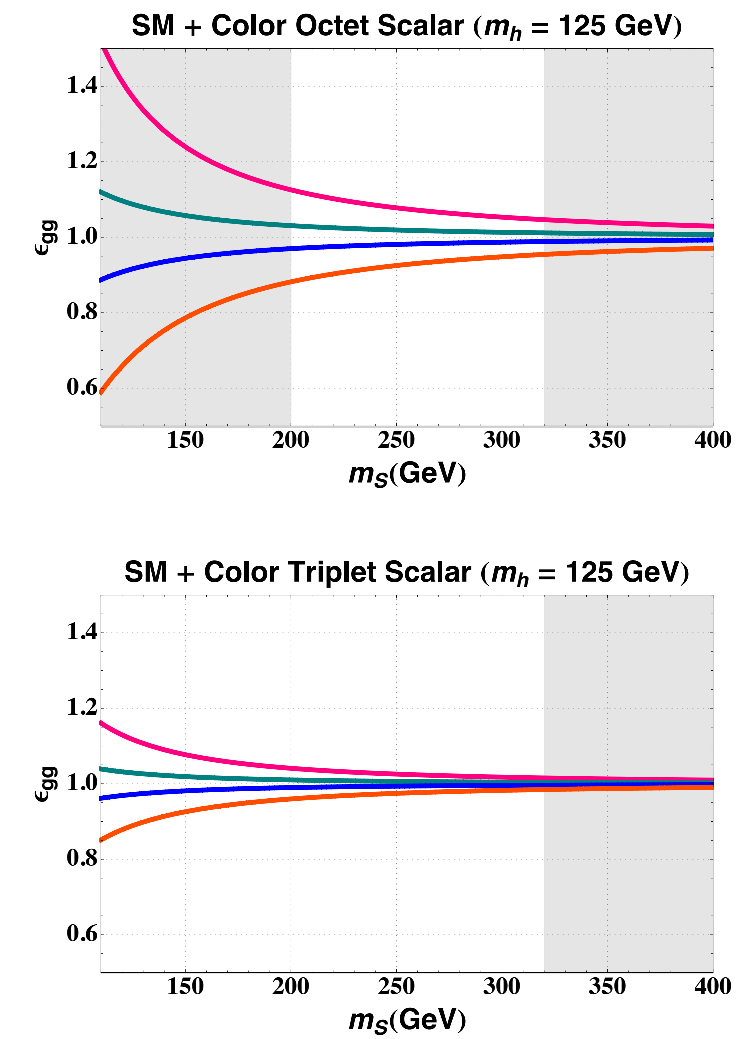


Enhancing $gg \to h$





$$\mathcal{L}_S = |D_\mu S|^2 - m_0^2 S^\dagger S - \kappa |S^\dagger S|^2 + \lambda_{hp} S^\dagger S H^\dagger H$$



K. Kumar, R. Vega-Morales, F. Yu, arXiv:1205.4244

- A not-to-heavy color octet or color triplet scalar can make an interesting enhancement
- Such objects are constrained but not-yet ruled out by direct searches

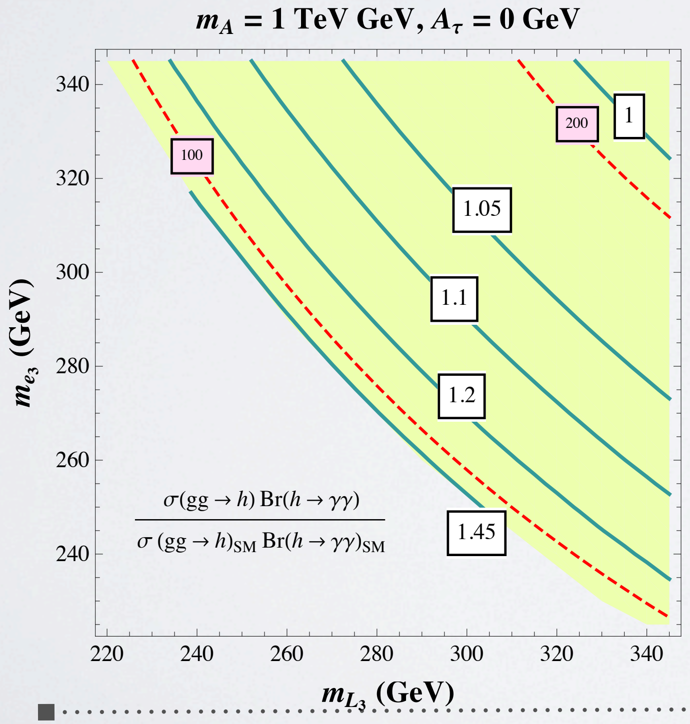
Enhancing $\mathbf{h} \to \gamma\gamma$

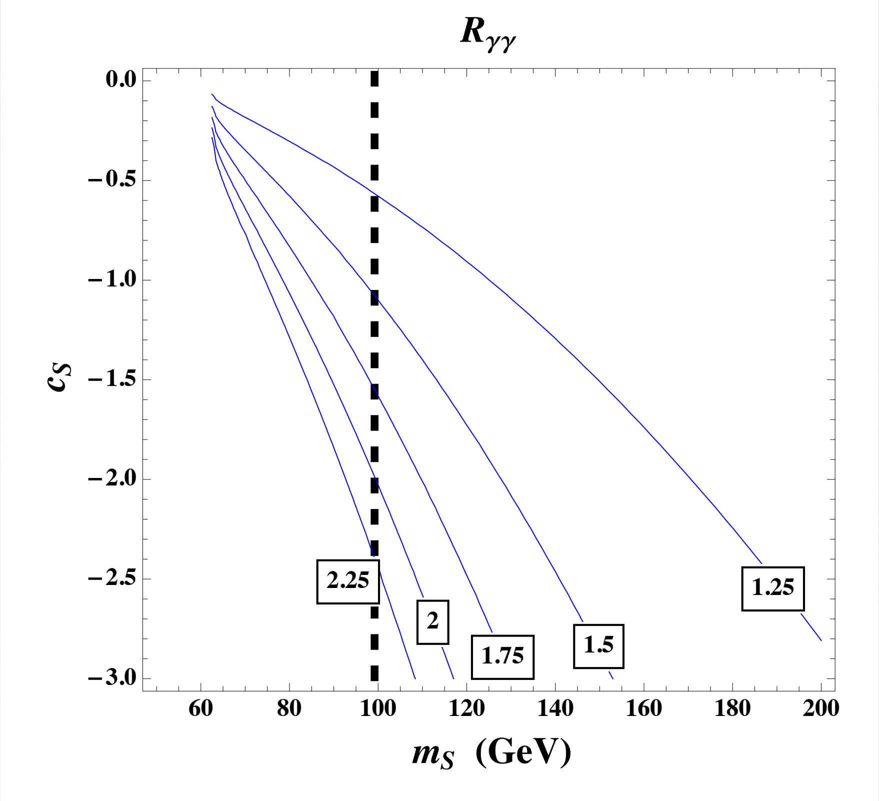
$$m_S^2 = m_{S0}^2 + \frac{1}{2} c_S\, v^2$$

$$\mathcal{O}_S = c_S H^\dagger H\, |S|^2$$

$$R_{\gamma\gamma} = \left| 1 + \frac{c_S}{2} \frac{v^2}{m_S^2} \frac{A_0(\tau_S)}{A_1(\tau_w) + N_c Q_t^2\, A_{1/2}(\tau_t)} \right|^2$$

- A not-too-heavy colorless but charged scalar can make an interesting enhancement
- This includes light staus in SUSY





M. Carena, I. Low, C. Wagner, arXiv:1206.1082

M. Carena, S. Gori, N. Shah, C. Wagner, L-T Wang, arXiv:1205.5842

Scenario #3: SM Higgs ruled out

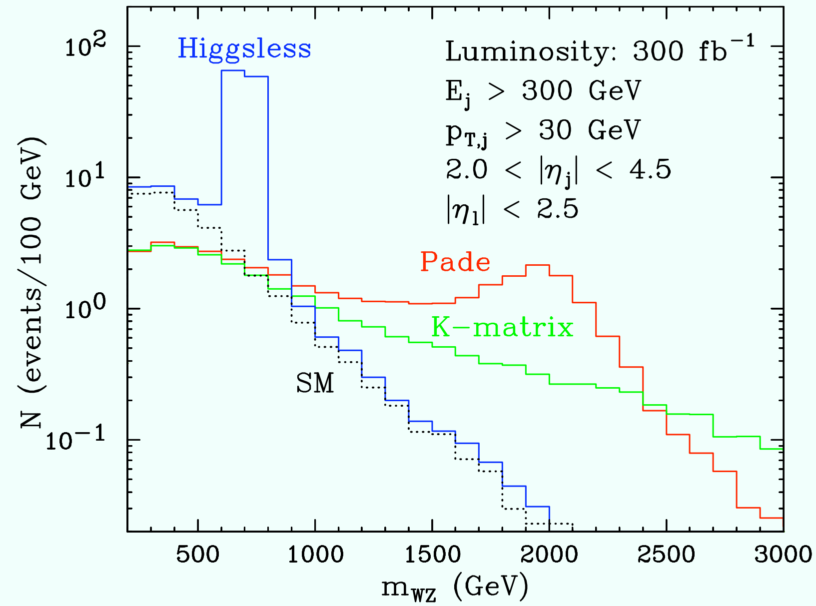


FIG. 4. The number of events per 100 GeV bin in the $2j + 3\ell + \nu$ channel at the LHC with an integrated luminosity of 300 fb^{-1} and cuts as indicated in the figure. The model assumptions and parameter choices are the same as in Fig. 2.

A. Birkedal, K. Matchev, M. Perelstein, hep-ph/0412278

Some immediate questions:

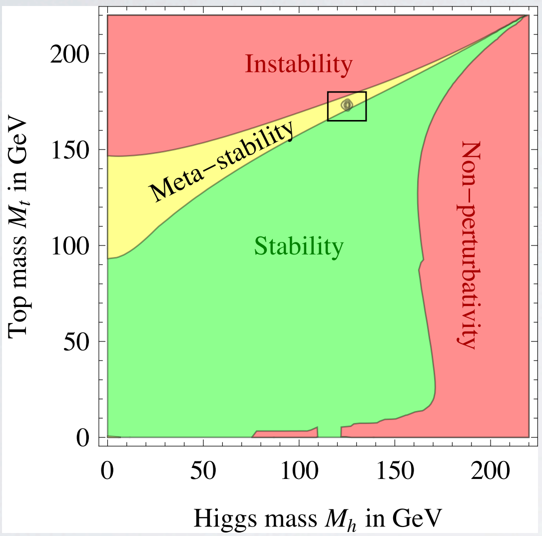
- Is it a non-SM Higgs with suppressed couplings, invisible and/or cascade decays?
- Are you in a "Higgsless" scenario where Kaluza-Klein tree-level exchanges replace Higgs exchange in unitarizing WW and WZ scattering?
- Are you in a "technicolor" scenario where new strong dynamics takes over before you reach the ~1.6 TeV unitarity bound? Do you see other heavy resonances?
- Is quantum field theory the wrong way to think about this problem?

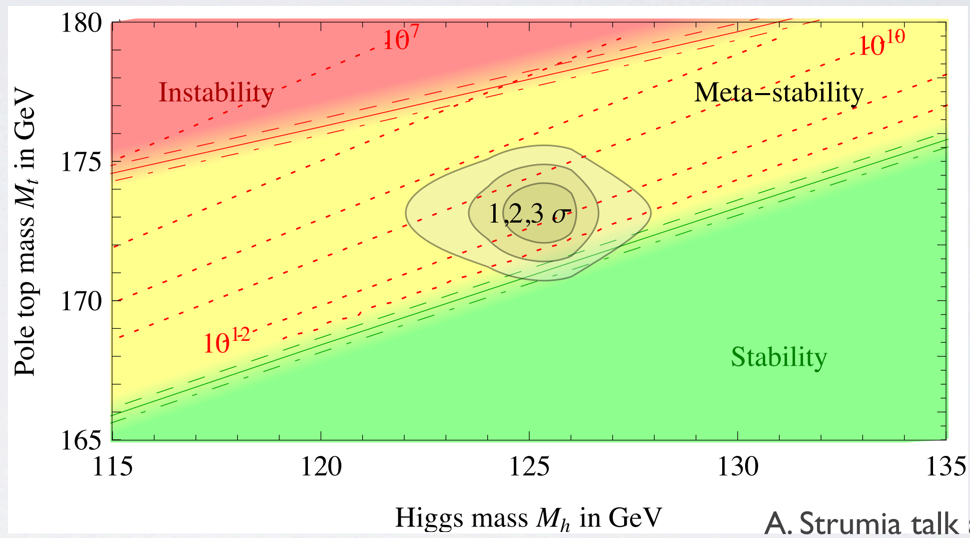
This scenario will require patience...

One GeV differences that destroy the universe

- A 125 GeV Higgs is quite heavy for minimal SUSY. Some people's favorite SUSY frameworks live or die on whether the mass is 124 or 126 GeV

- Also, a 125 GeV Higgs in the SM means you are close to the vacuum stability bound:





A. Strumia talk at PLANCK 2012

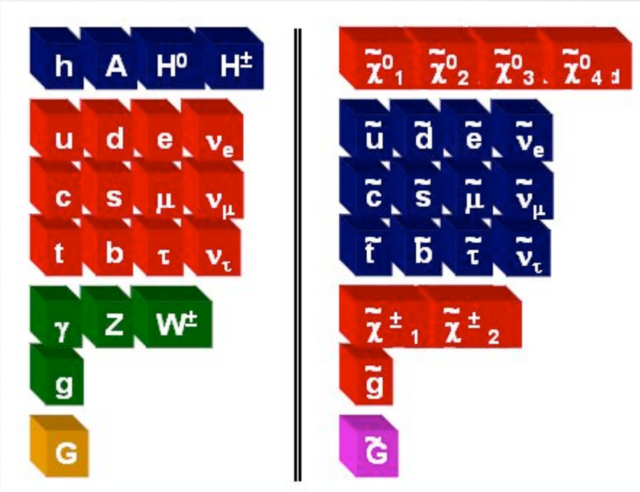
$$M_h \text{ [GeV]} > 129.4 + 1.4\left(\frac{M_t \text{ [GeV]} - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

we need to know both the Higgs mass AND the top mass to high precision

a suspiciously round number

Is SUSY hiding?

- Too early for general experimental claims about SUSY as generator and stabilizer of the electroweak scale
- On the theory side we have known for many years that if SUSY is tied to EWSB, we don't understand:
    - why superpartners weren't discovered at the Tevatron
    - why the Higgs wasn't discovered at LEP
    - why SUSY effects haven't been seen unequivocally in flavor physics



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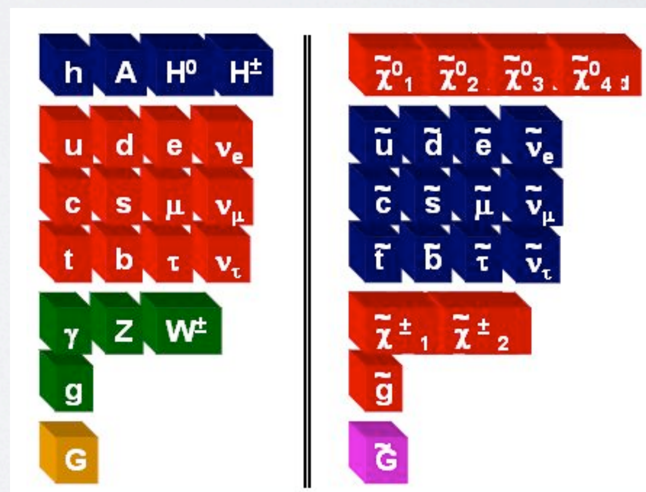
    - why SUSY effects haven't been seen unequivocally in flavor physics
- So either we have missed some important ingredient, or we have been barking up the wrong tree for 30 years
- But the other trees don't look so great either...



is SUSY hiding?

- The fate of the stops, the two scalar superpartners of the top quark, is especially interesting, since they are closely related to the key issue of connecting SUSY to EWSB
- In fact even if you jettison SUSY there is still a strong motivation to look for "top partners"
- It is not too hard to find reasonable models where the lightest stop is difficult to detect, because it is nearly degenerate in mass to its decay products
- Does this mean that light stops can hide under ATLAS+CMS's very expensive noses?

H_1	125 GeV	$\tilde{b}_1$	499 GeV
$\tilde{t}_1$	188 GeV	A_2	509 GeV
N_1	216 GeV	H_3	530 GeV
$H^\pm$	307 GeV	$\tilde{t}_2$	580 GeV
H_2	326 GeV	N_3	602 GeV
A_1	368 GeV	N_4	635 GeV
C_1	406 GeV	N_5	805 GeV
N_2	426 GeV	C_2	876 GeV

$\tilde{t}_1$	$\to t + LSP$	100%
C_1	$\to \tilde{t}_1 + b^\dagger$	84%
C_1	$\to N_1 + W^\pm$	16%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	97%
$\tilde{b}_1$	$\to \tilde{t}_1 + H^-$	3%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	51%
$\tilde{t}_2$	$\to t + N_1$	27%
$\tilde{t}_2$	$\to b + C_1^+$	11%
$\tilde{t}_2$	$\to \tilde{t}_1 + H_1$	10%

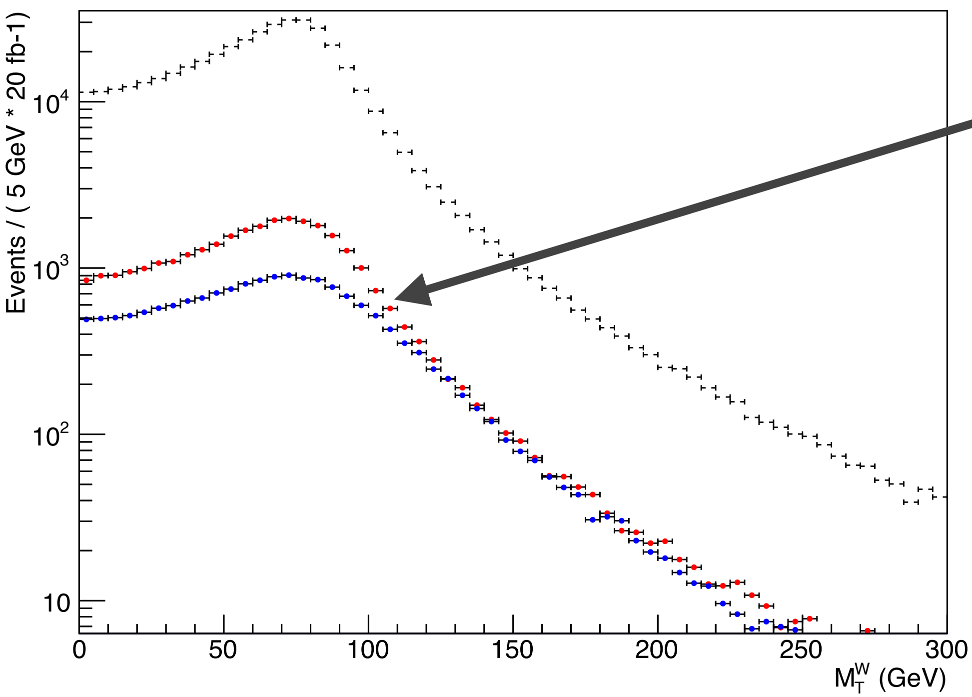
C. Csaki, L. Randall, J. Terning, arXiv:1201.1293

Light stops: they can run, but they can't hide

Pheno analyses attempting to mimic what ATLAS/CMS could do for various special cases:

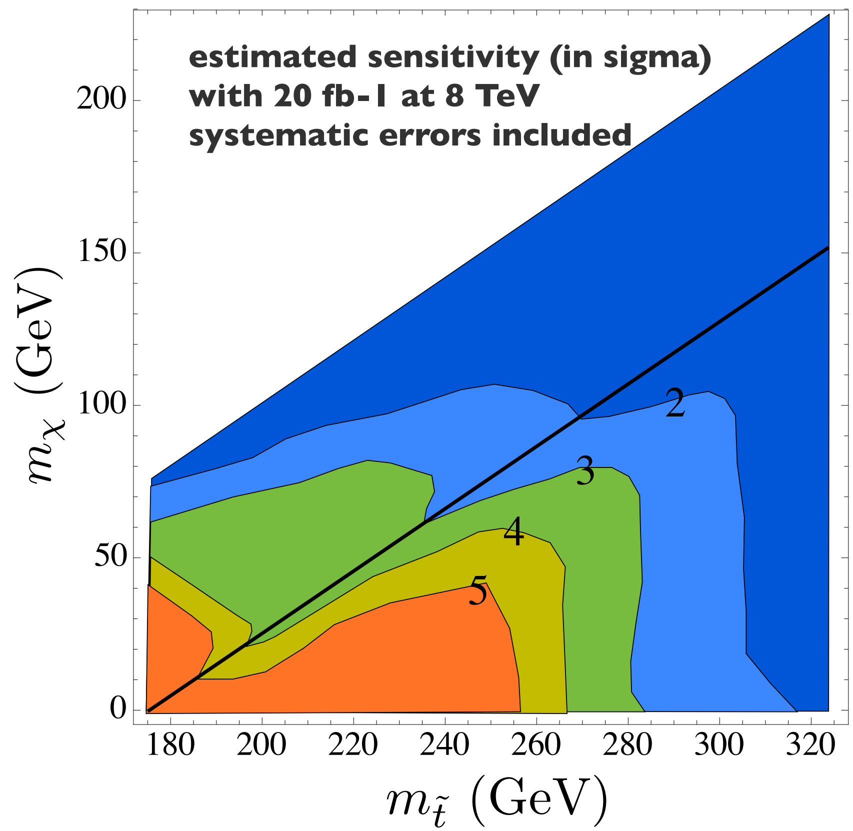
- **For very light stops (near Tevatron bounds) use monojets, monophotons**
  - M. Carena, A. Freitas, C. Wagner, arXiv:0808.2298
  - G. Belanger, M. Heikinheimo, V. Sanz, arXiv:1205.1463
- **For light stops with top-like signatures and suppressed MET, use spin-correlations for masses up to ~200 GeV...**
  - Z. Han, A. Katz, D. Krohn, M. Reece, arXiv:1205.5808
- **...and use MET-related kinematic shapes for masses up to ~ 300 to 500 GeV**
  - D. Alves, M. Buckley, P. Fox, JL, C-T Yu, arXiv:1205.5805
- **For stop masses above ~300 to 500 GeV, use boosted top tagging and/or kinematic shapes**
  - Y. Bai, H-C Cheng, J. Gallicchio, J. Gu, arXiv:1203.4813
  - D.E. Kaplan, K. Rehermann, D. Stolanski, arXiv:1205.5816
- **With a lot of work, it looks like LHC experiments in 2012 could exclude or discover just about any stop (including long-lived or RPV?) with mass < 300 GeV, and most stops <~ 700 GeV**

Light stops: they can run, but they can't hide



$$\mathrm{m}_{\tilde{t}_1} = 188 \text{ GeV}$$
$$\mathrm{m}_{\tilde{\chi}_1^0} \simeq 0$$
$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

D. Alves, M. Buckley, P. Fox, JL, C-T Yu, arXiv:1205.5805

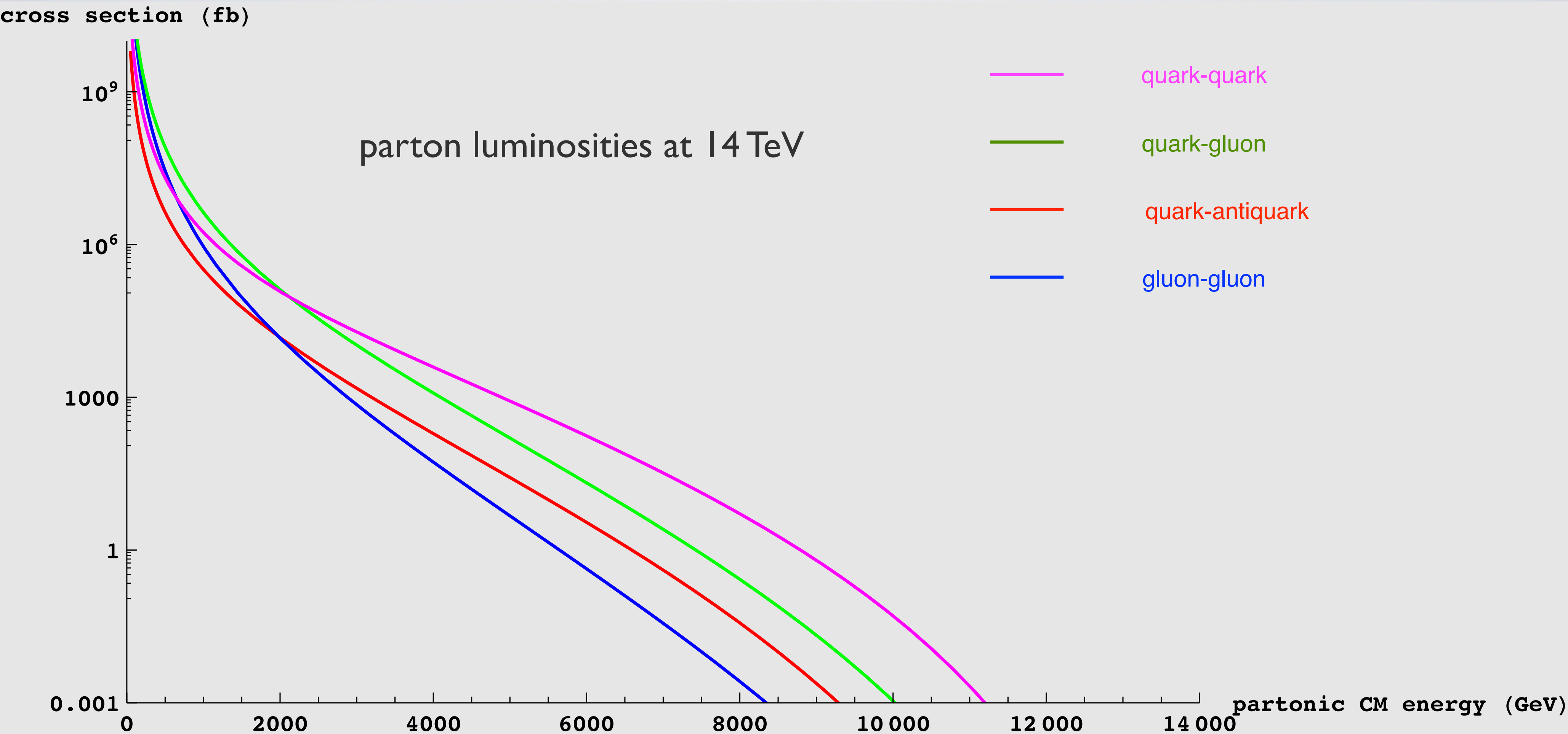


For the single lepton channel use transverse mass;
for all-hadronic use MET shape or the Razor

light stops, heavy stops

stop mass (GeV)	pair production cross section at 8 TeV
188	17 pb
300	2 pb
600	23 fb
700	4 fb
1000	0.2 fb

when do you give up looking for heavy superpartners at the LHC?



3 TeV gluinos + degenerate squarks at 14 TeV LHC?

Process results

s= 463.673± 0.651(ab)

Graph	Cross Sect(ab)	Error(ab)	Events (K)	Eff	Unwgt	Luminosity
Sum	463.673	0.651	1933	2.0		
Sub Group 10						
P10_qq_ururg	48.717	0.200	3	0.3		255.00
P10_qq_ululg	48.352	0.185	1	0.2		199.00
P10_qq_uldlg	32.575	0.156	1	0.2		142.00
P10_qq_urdrg	32.554	0.156	1	0.2		131.00
P10_qq_ulurg	24.075	0.140	12	0.6		153.00
Sub Group 9						
P9_qq_urur	26.842	0.179	0	0.0		167.00
P9_qq_ulul	26.770	0.157	0	0.0		139.00
P9_qq_urdr	17.878	0.104	0	0.0		147.00
P9_qq_uldl	17.805	0.232	0	0.0		151.00
P9_qq_ulur	11.915	0.070	1	0.2		134.00
Sub Group 2						
P2_gg_gogog	2.261	0.031	5	1.0		196.00
P2_gq_gogoq	1.457	0.014	27	1.6		621.00
P2_qq_gogog	0.394	0.007	22	2.5		599.00
Sub Group total = 4.11218						

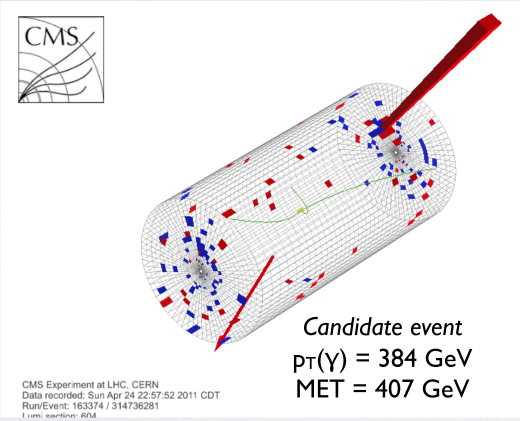
→ **gluino only**

MadGraph says: yes but most of your sensitivity is from qq initial state producing squark pairs

For a 3 TeV gluino alone, 1 ab-1 only buys you 4 signal events...

Let a 1000 analyses bloom

- If you look at the titles of the 137 Exotics analyses completed already by ATLAS+CMS, you might get the idea that the strategy is to do one search for every theory model
- Of course this is NOT the actual strategy, and to a large degree the searches are signature-based, as they should be
- Thus e.g. a seemingly esoteric ADD extra-dimensional mono-photon search can be recycled into a direct dark matter search, as CMS has already done!



Y. Bai, P. Fox, R. Harnik, J. Kopp, Y. Tsai, arXiv:1005.3797

J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. Tait, H-B Yu, arXiv:1008.1783

P. Fox, R. Harnik, J. Kopp, Y. Tsai, arXiv:1203.1662

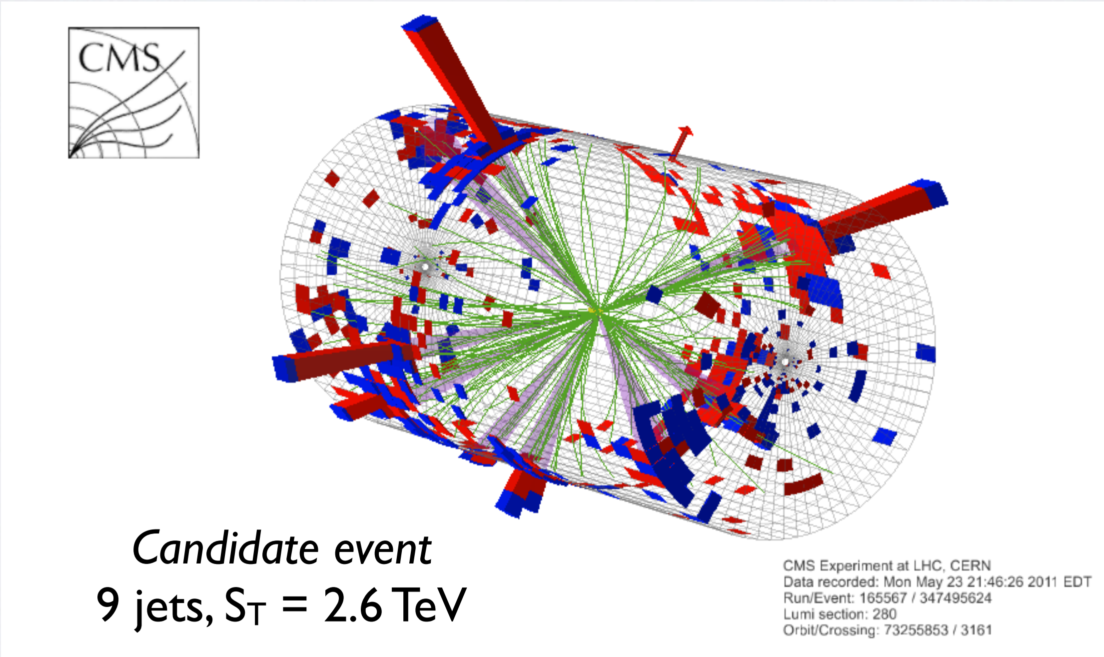
The CMS Collaboration, arXiv:1204.0821

- Now for 2012 recycle your mono-photons again into a light stop search...
- And recycle your Razor SUSY search into a direct dark matter search...

P. Fox, R. Harnik, R. Primulando, C-T Yu, 1203.1662

Let a 1000 analyses bloom

- Even the super-esoteric-sounding black hole and string ball searches are actually quite generic:
- Generic question: is there some energy scale where pp collisions start to access a bunch of new degrees of freedom?
- Can we understand the most energetic high multiplicity events?



Big long-term questions where LHC overlaps with the Intensity Frontier

What can you say about flavor and the origin of matter?

- Minimal flavor violation or new sources?
- New sources of CP violation?
- Why are EDMs so small and FCNC so suppressed?
- Compositeness?
- Baryogenesis or Leptogenesis?
- Do fermion masses come from Yukawa couplings to a Higgs, or are the real couplings to the Higgs vev hierarchical? Are other vevs and/or condensates involved?

Big long-term questions where LHC overlaps with the Cosmic Frontier

What can you say about the dark sector?

- Do you have evidence for a WIMP dark matter candidate? What mass?
- What kind of particles decay into it?
- Can you see direct production or associated production?
- Does it carry electroweak charge and/or some new charge? What is its spin?
- What are the messengers between the dark sector and the visible?
- What are the LHC predictions for direct DM detection, indirect DM detection, and early universe cosmology (e.g. relic abundances)?

Conclusion

stolen from
Albert De Roeck