Nathaniel Craig
UCSB

Experimental Challenges for
the LHC Run 2 @ KITP

MUCH ADO ABOUT DIPHOTONS

Chala, **Grojean**, Riembau, Vantalon 1604.02029
Csaki, **Hubisz**, Terning 1512.05776
Csaki, **Hubisz**, Lombardo, Terning 1601.00638
Kanemura, Nishiwaki, Okada, Orikasa, Park, Watanabe 1512.09048
Kanemura, Machida, Odori, Shindou 1512.09053
Goertz, **Katz**, Son, Urbano 1602.04801
Goertz, Kamenik, **Katz**, Nardecchia 1512.08500
Cvetic, Halverson, **Langacker** 1512.07622
Cvetic, Halverson, **Langacker** 1602.06257
Bernon, Goudelis, **Kraml**, Mawatari, Sengupta 1603.03421
Low, Lykken 1512.09089
Altmannshofer, Galloway, **Gori**, Kagan, Martin, Zupan 1512.07616
Ahmed, Dillon, Grzadkowski, **Gunion**, Jiang 1512.05771
Craig, Draper, Kilic, **Thomas** 1512.07733
Giddings, Zhang 1602.02793

15 papers from 12 EXPERLHC16 *present* participants
(current participants: 15 theorists + 7 experimentalists)

HEP **2** records found Search took 0.10 seconds.

1. **Search for new physics in high mass diphoton events in proton-proton collisions at 13TeV**
   CMS Collaboration. 2015. 17 pp.
   CMS-PAS-EXO-15-004

   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server ; Link to Fulltext

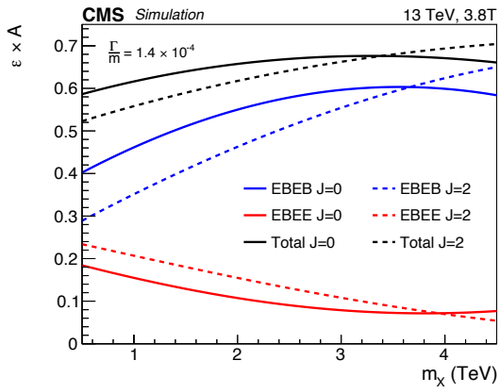
   Detailed record - Cited by 286 records 250+

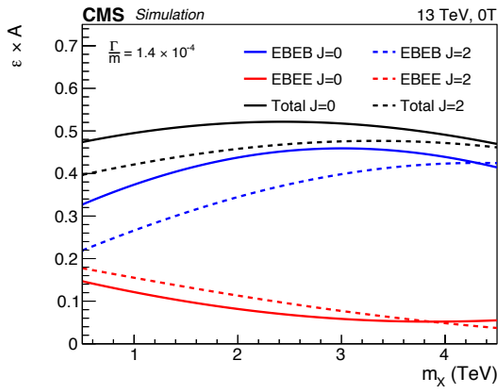
2. **Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector**
   The ATLAS collaboration. Dec 15, 2015.
   ATLAS-CONF-2015-081

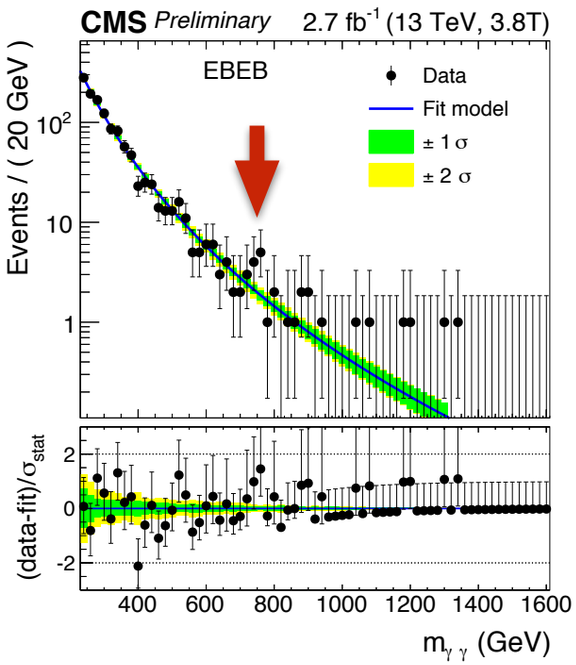
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server ; Link to Fulltext

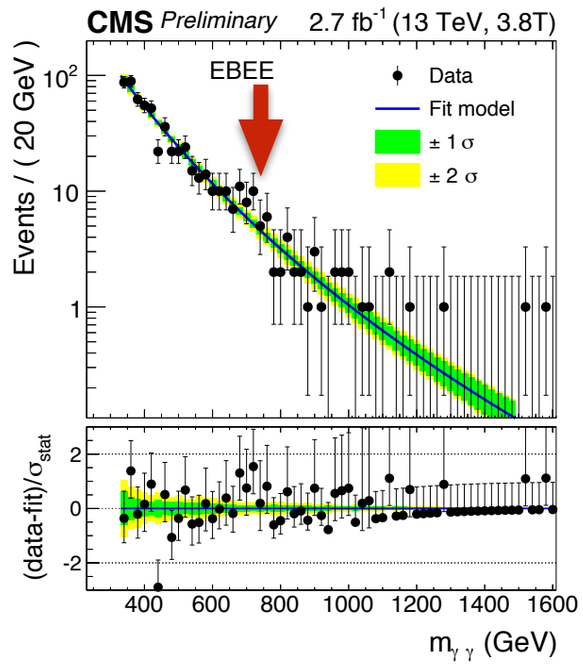
   Detailed record - Cited by 296 records 250+

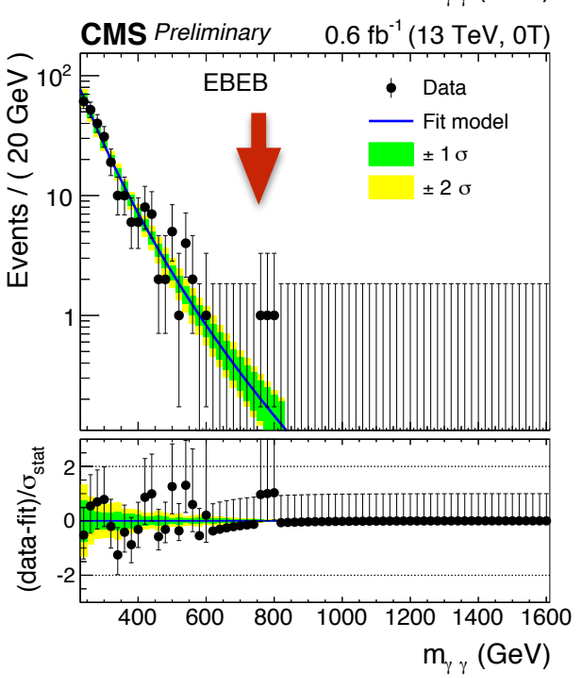
- Are we happy with the analysis? [Yes]
- If it's real, did we have to get lucky twice? [No]
- Is it wide or narrow? [??]
- Is it a resonance or a cascade? [A resonance]
- Is it a Higgs? [No]
- Who ordered that? [Nobody I know, maybe Paul?]
- What next? [Dibosons!]

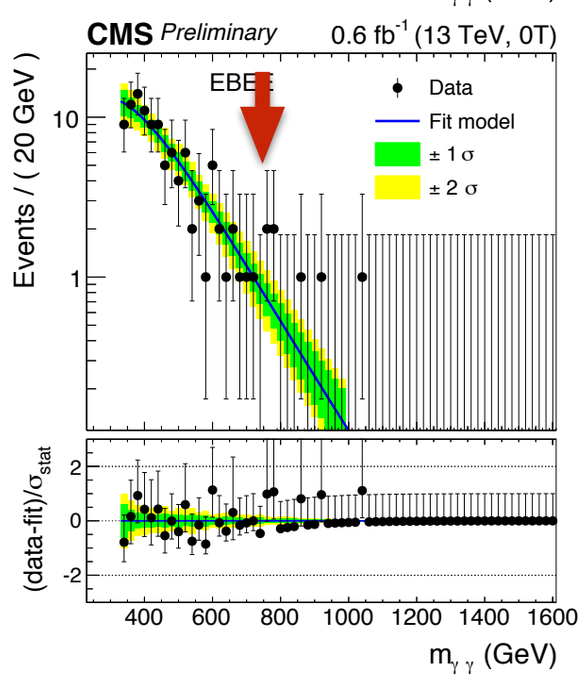












CMS 13 TeV

Search for new physics in high mass diphoton events in 3.3 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV and combined interpretation of searches at 8 TeV and 13 TeV

The CMS Collaboration

~10 excess γγ events peaked @ 760 GeV

One analysis, two signal interpretations (spin-0,2)

2.9σ local (spin-2), 2.85σ local (spin-0); <1σ global (13 TeV only)

Preference for *narrow* width

Best fit σ.Br~6.5fb for 750 GeV resonance @ 13 TeV

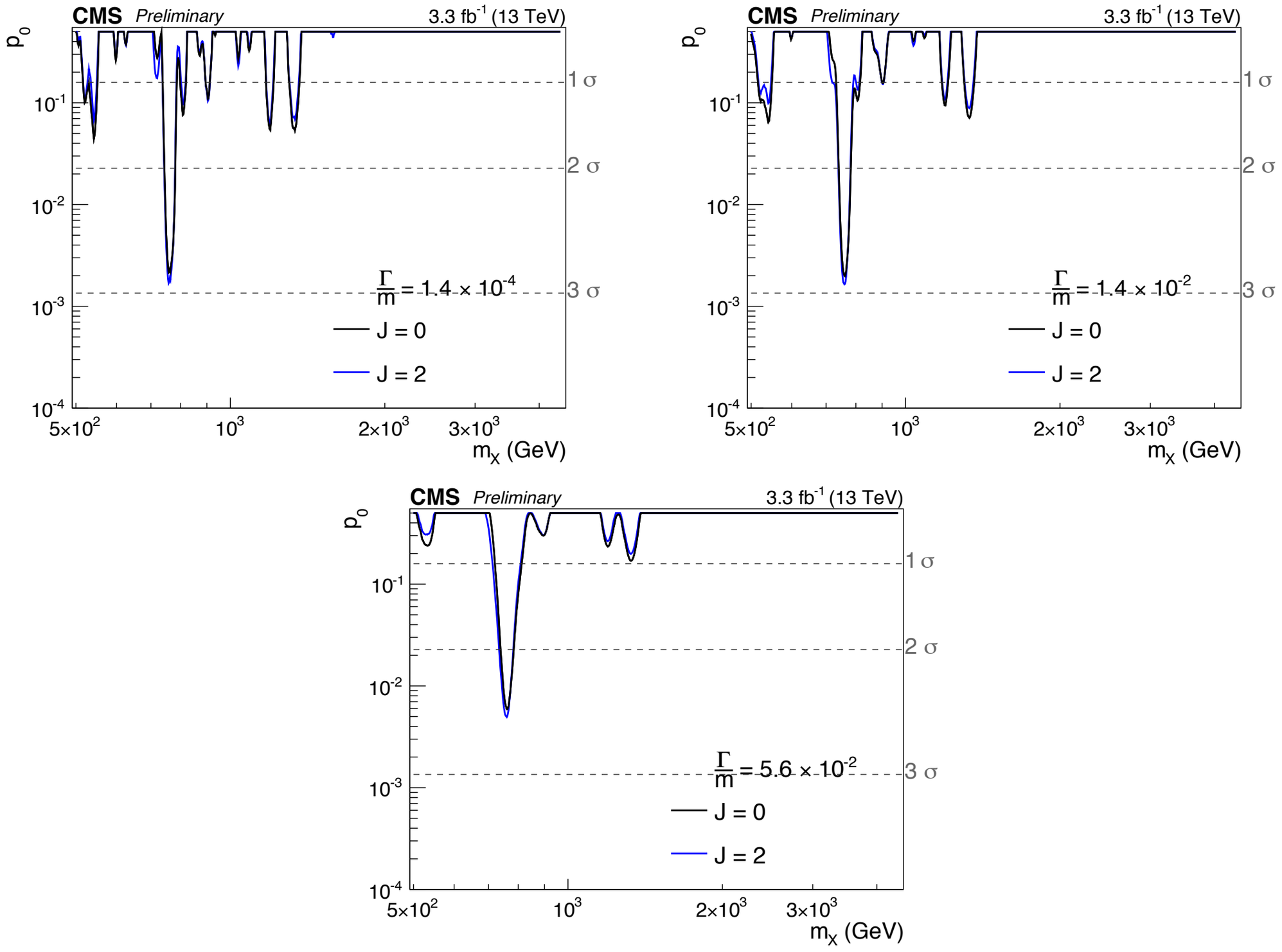


Figure 6: Observed background-only p-value for different signal hypotheses. The range $500\,\text{GeV} < m < 4.5\,\text{TeV}$ is shown for $\Gamma/m = 1.4 \times 10^{-4}, 1.4 \times 10^{-2}, 5.6 \times 10^{-2}$. Results corresponding to both the scalar and RS graviton hypotheses are shown.

ATLAS 13 TeV

Search for resonances in diphoton events with the ATLAS detector at $\sqrt{s}$=13 TeV

The ATLAS Collaboration

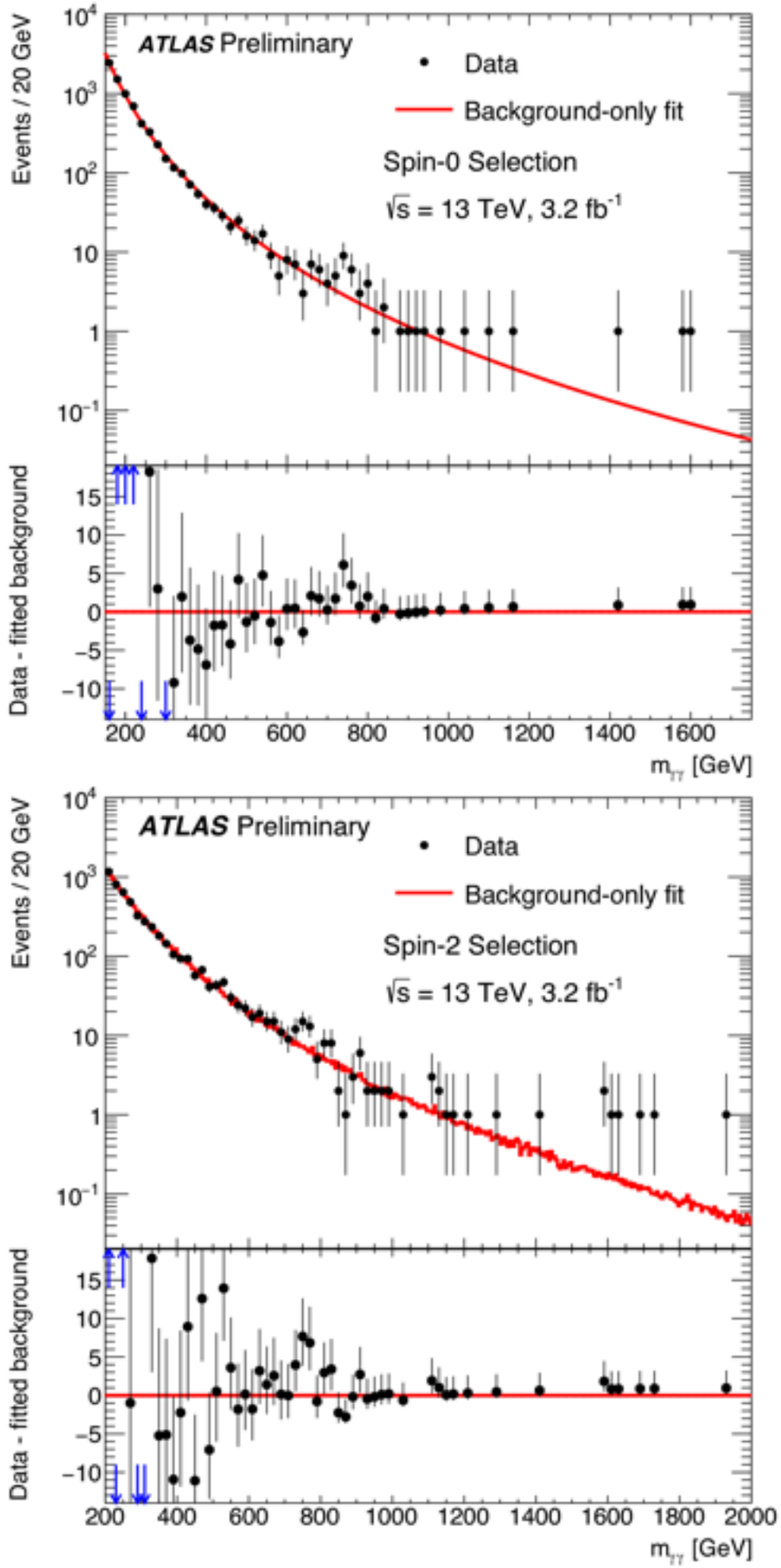
~10-15 excess γγ events peaked @ 750 GeV

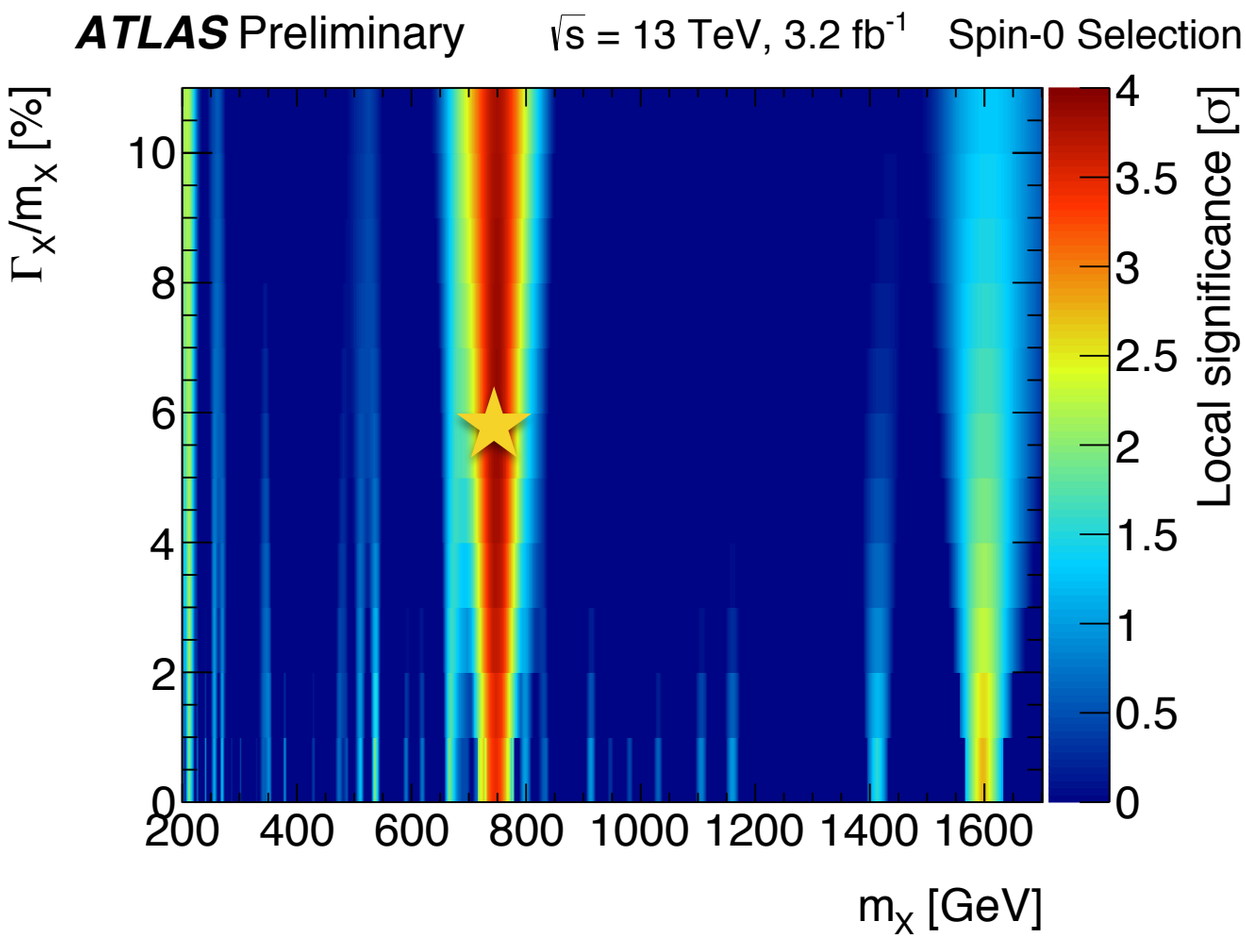
Two analyses (spin-0,2)
spin-0 ⊂ spin-2

"Spin-2" analysis: preselection + p_T > 55GeV
5066 events w/ $m_{\gamma\gamma}$ > 200 GeV
"Spin-0" analysis: additionally p_T > 0.4(0.3)$m_{\gamma\gamma}$
2878 events w/ $m_{\gamma\gamma}$ > 200 GeV

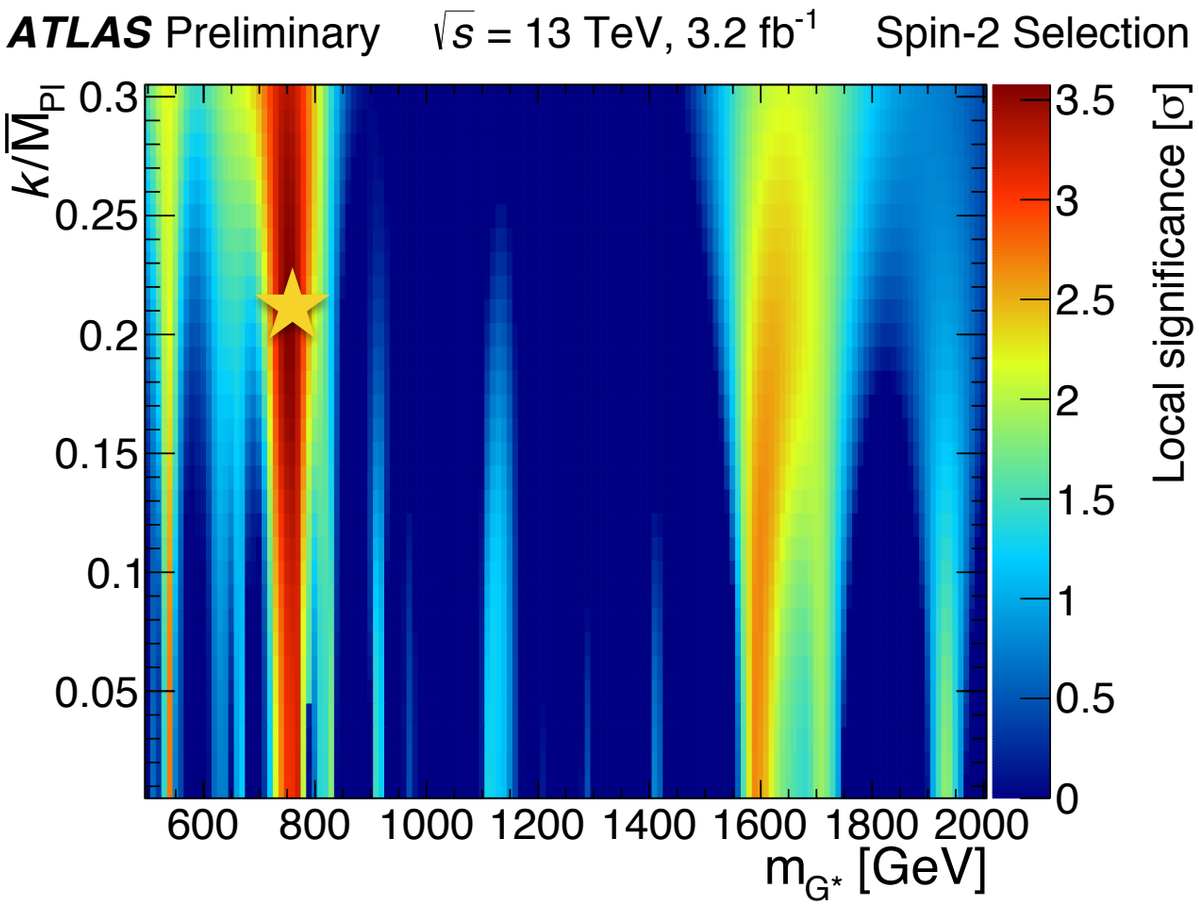
3.9σ local, 2.0σ global (spin-0);
3.6σ local, 1.8σ global (spin-2)

Preference for width > resolution
Best-fit width ~45 GeV (!!)





Best fit width 46 GeV

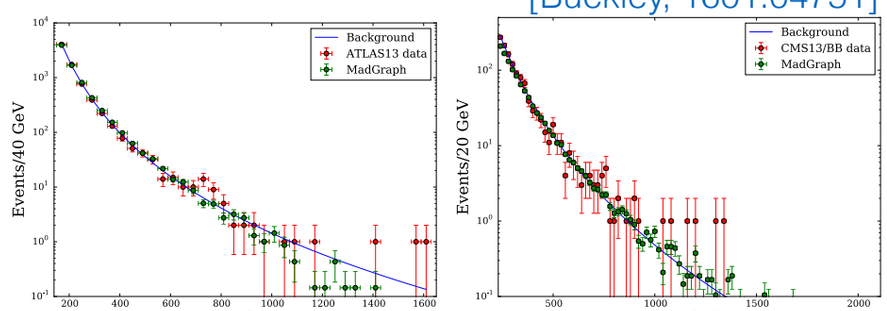


Best fit width 48 GeV

Are we happy with the analysis?

- Well-defined final state, well-studied physics objects
- Straightforward analysis, no obviously induced scales
- Insensitive to rare backgrounds
- Signal, background easily reproducible

[Buckley, 1601.04751]



Modest discomfort: no good sideband above 750 GeV, need to extrapolate background functional fit from lower invariant mass. Empirically chosen functional forms:

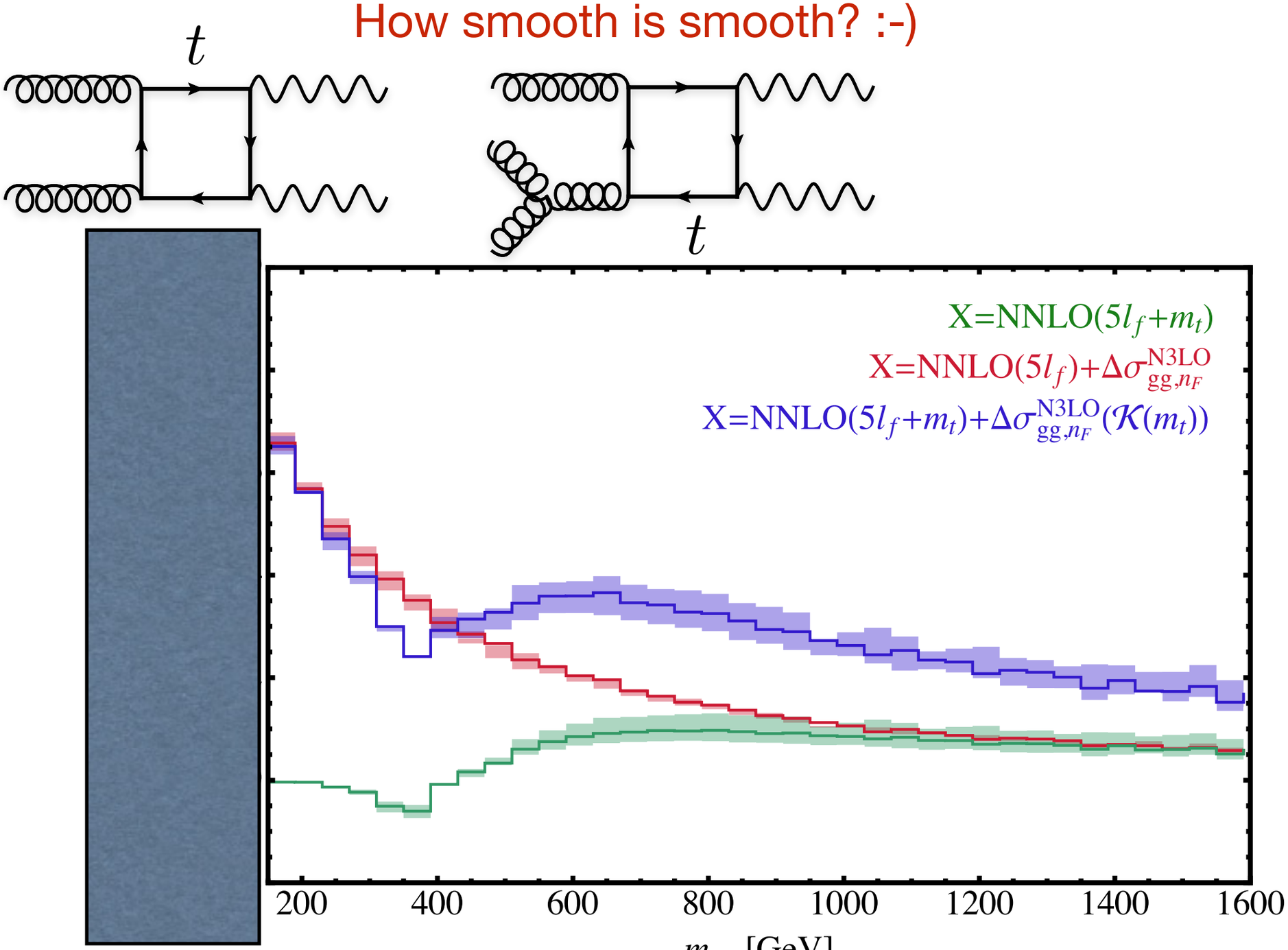
ATL $f(m_{\gamma\gamma}, a, b) = \left(1 - \left(\frac{m_{\gamma\gamma}}{\sqrt{s}}\right)^{1/3}\right)^{b} \left(\frac{m_{\gamma\gamma}}{\sqrt{s}}\right)^{a}$ **CMS** $f(m_{\gamma\gamma}, a, b) = m_{\gamma\gamma}^{a+b\log m_{\gamma\gamma}}$

But: no statistical preference for additional parameters; fits work well in other contexts

Predictions at high invariant masses.

As we all know, bump hunts in the diphoton system assume a smooth function which can be fitted to the data. Begging the question,

How smooth is smooth? :-)



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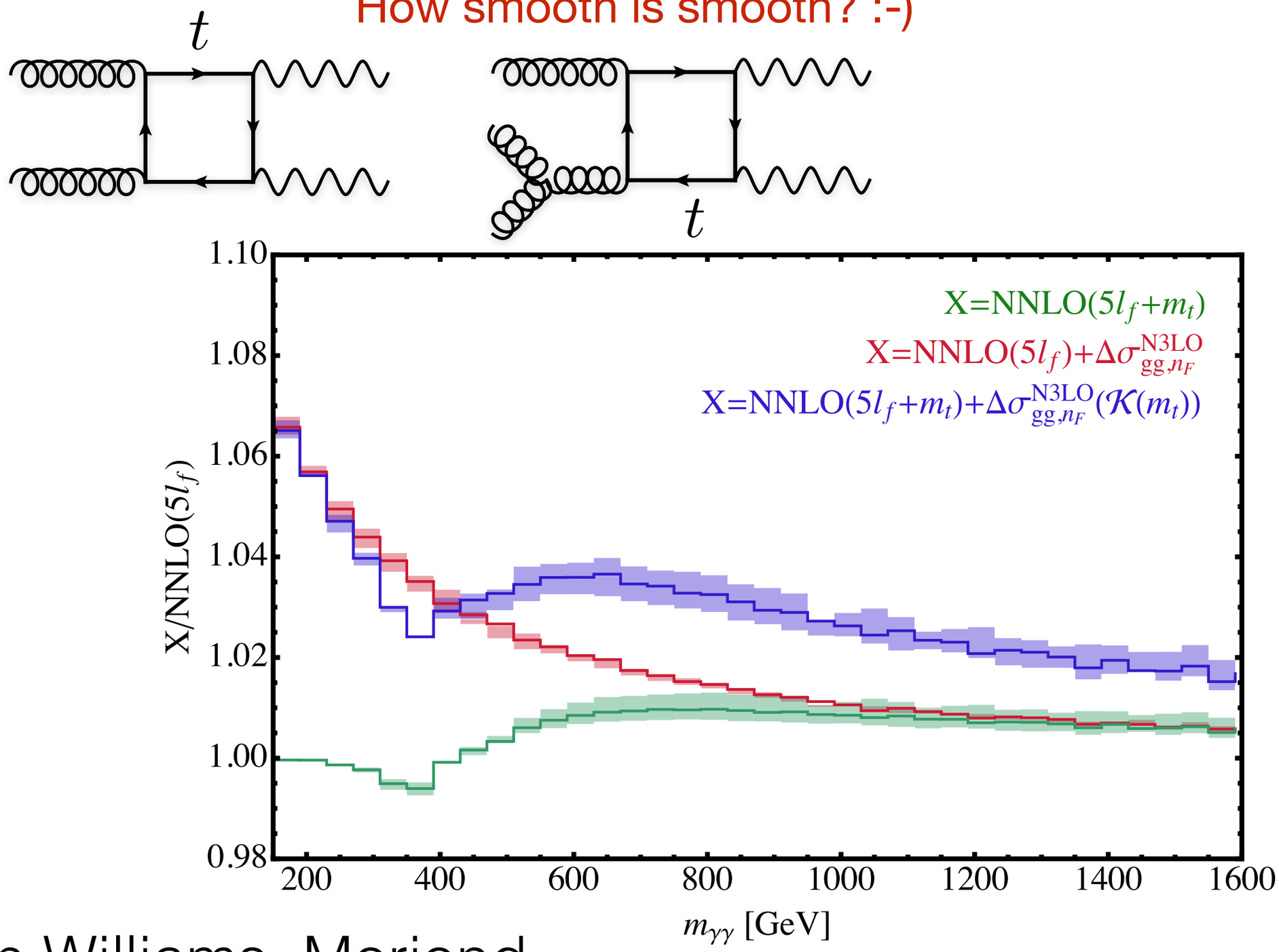
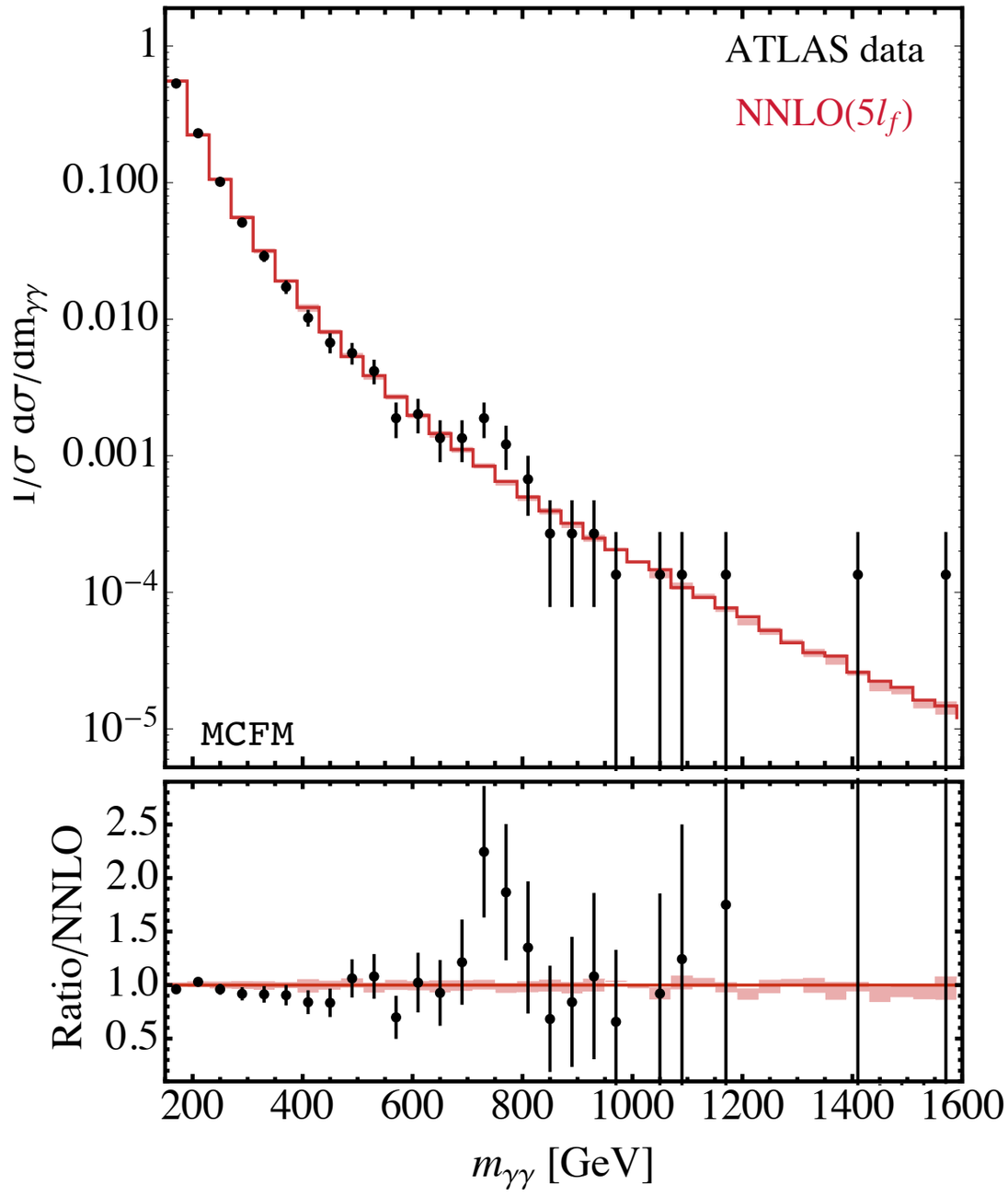
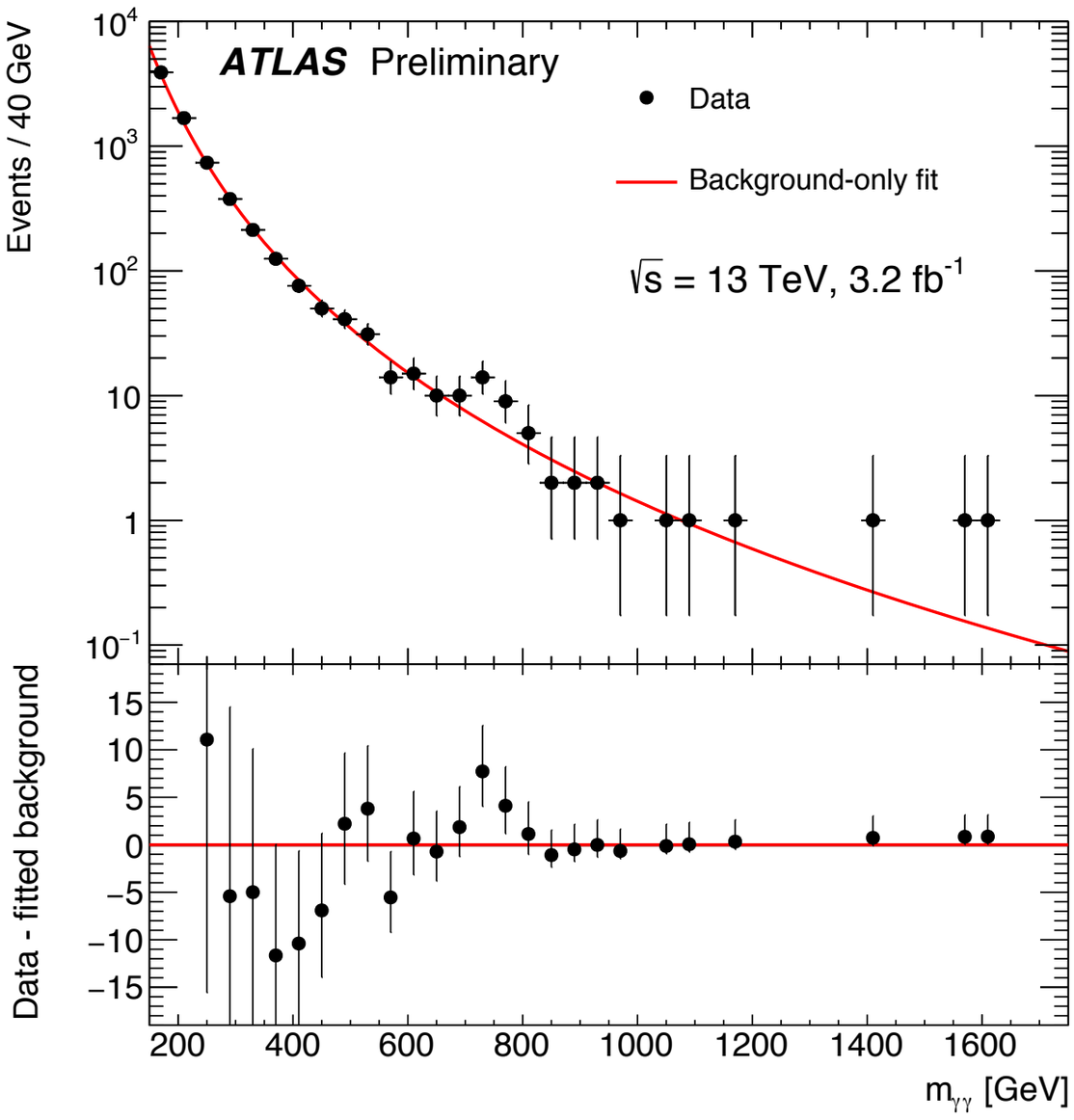


Diphoton invariant mass

Can check with a first principles calculation of the shape of the SM prediction and compare the shape to the data.

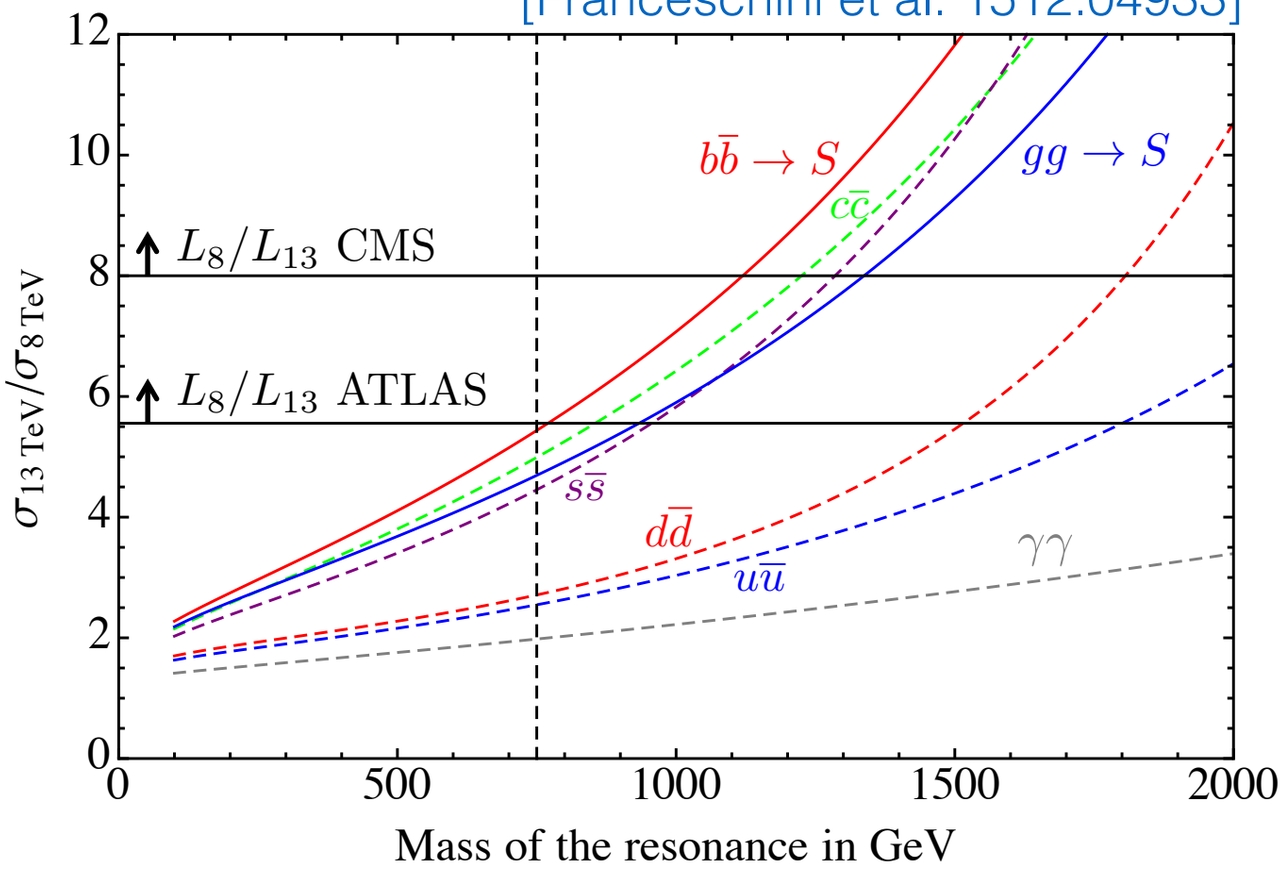




Did we have to get lucky twice?

i.e. for signal to be real, must other prohibitive limits be wrong?

[Franceschini et al. 1512.04933]



Nathaniel Craig
December 10, 2015 · Santa Barbara ·

Dear physics friends,

Let me see if I've got this one straight:

(1) The 8 TeV, 20/fb sensitivity to a gluon-initiated diphoton resonance at 700 GeV (marginally) exceeds that of 13 TeV with 3/fb.

(2) The CMS 8 TeV result has a 2 sigma downward fluctuation at 700 GeV.

(3) The ATLAS 8 TeV result is totally consistent with background at 700 GeV.

(4) The ATLAS 13 TeV spectrum with 78/pb is totally consistent with background at 700 GeV.

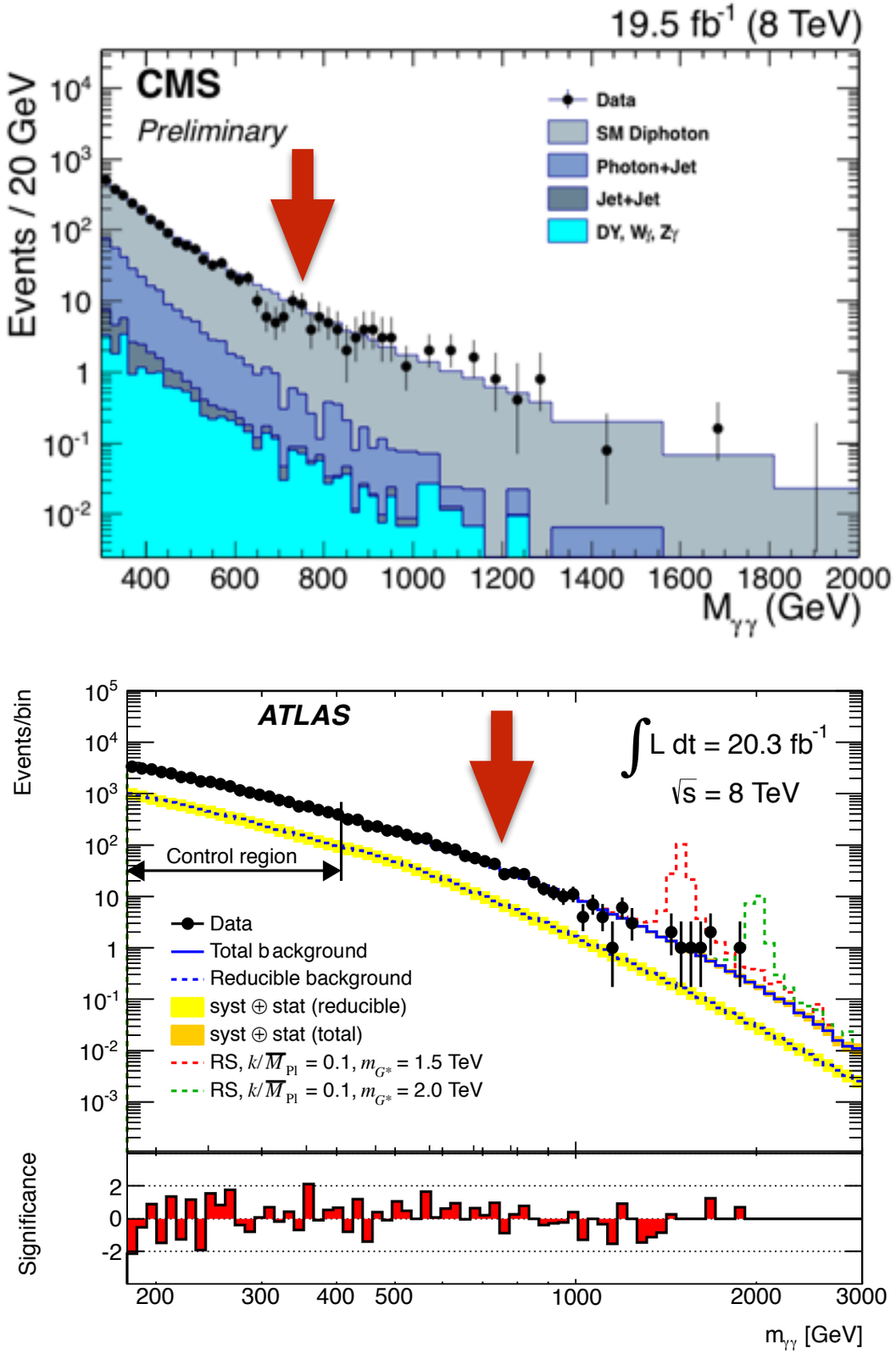
(5) People are still losing their minds about this rumor.

Love,
Your friendly grumpy rumor curmudgeon

*Reflects event #, not significance

A priori expect greater sensitivity at 8 TeV

Diphotons kill diphotons?



As of December 15, excess events around 750 GeV:

$$\sigma(pp \to \gamma\gamma) \approx \begin{cases} (0.5 \pm 0.6)\,\text{fb} & \text{CMS } [2] & \sqrt{s} = 8\,\text{TeV}, \\ (0.4 \pm 0.8)\,\text{fb} & \text{ATLAS } [3] & \sqrt{s} = 8\,\text{TeV}, \\ (6 \pm 3)\,\text{fb} & \text{CMS } [1] & \sqrt{s} = 13\,\text{TeV}, \\ (10 \pm 3)\,\text{fb} & \text{ATLAS } [1] & \sqrt{s} = 13\,\text{TeV}. \end{cases}$$

Consistency depends on production mode; change in luminosity function between 8, 13 TeV varies

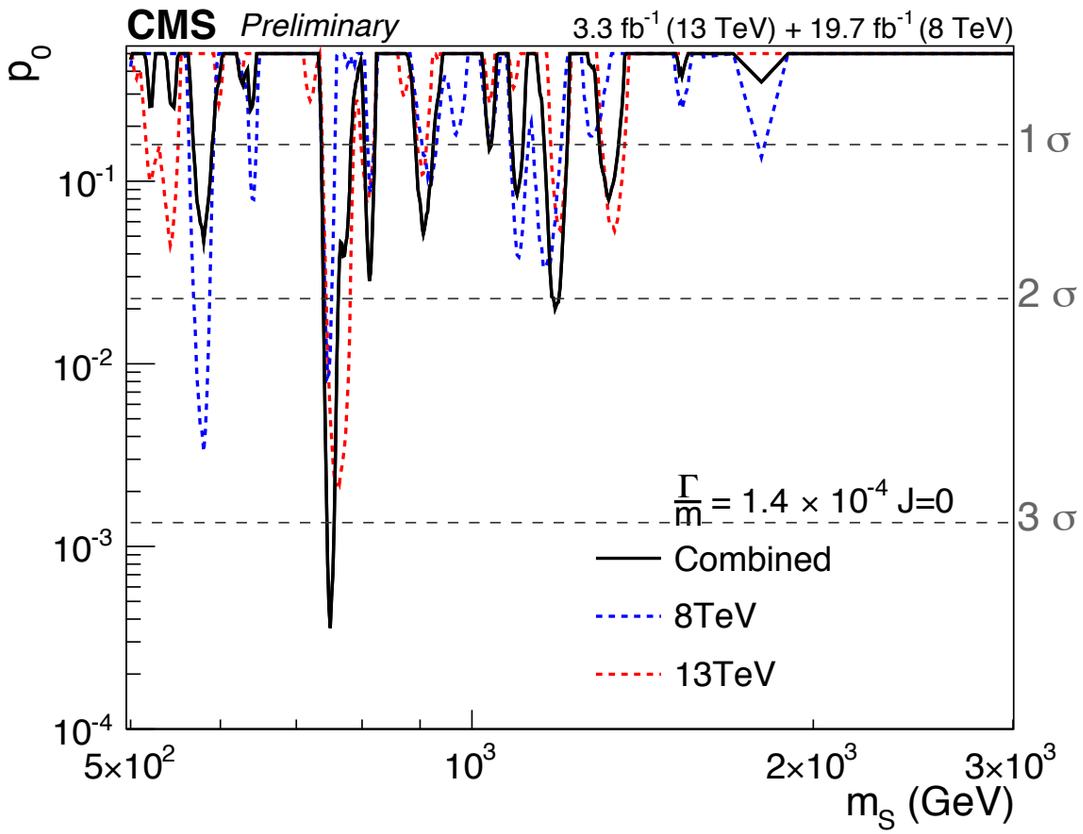
2σ consistency for r ≳ 5

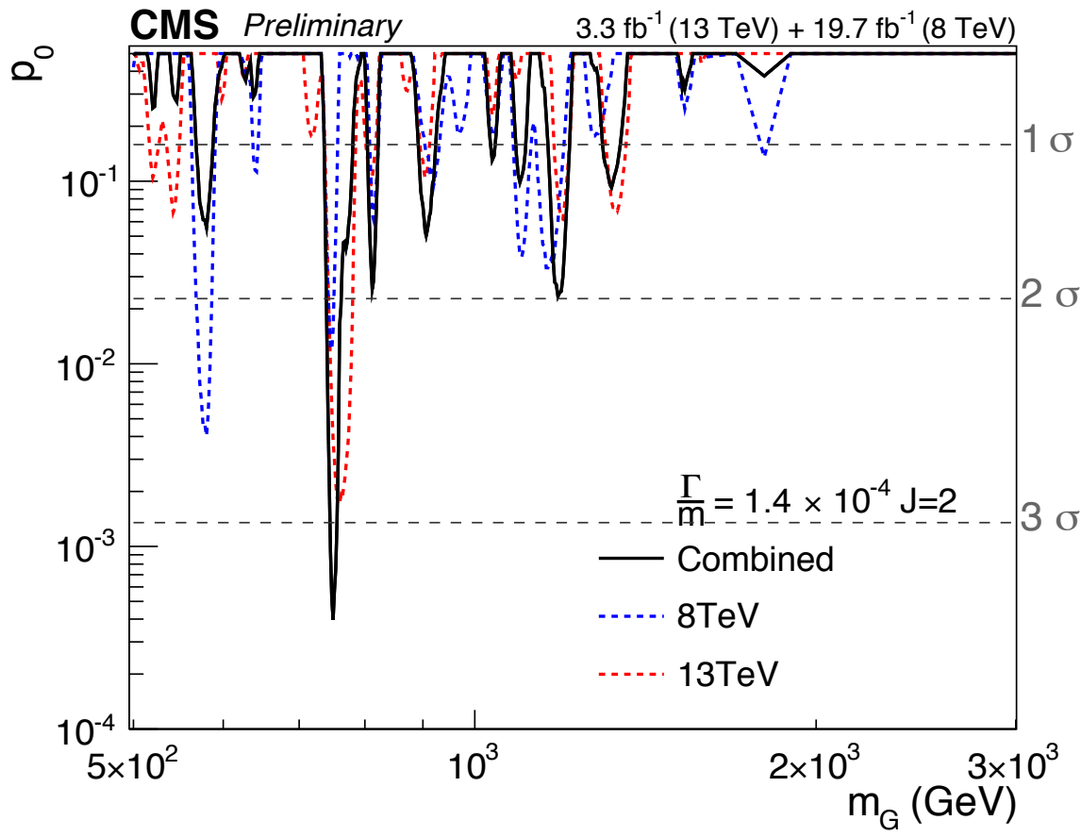
$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}	$r_{\gamma\gamma}$
5.4	5.1	4.3	2.7	2.5	4.7	1.9

E.g. compatible w/ gluon fusion

Diphotons kill diphotons?

CMS reanalysis of 8 TeV data, 8+13 TeV combination
(revised statistical procedure consistent with 13 TeV analysis)



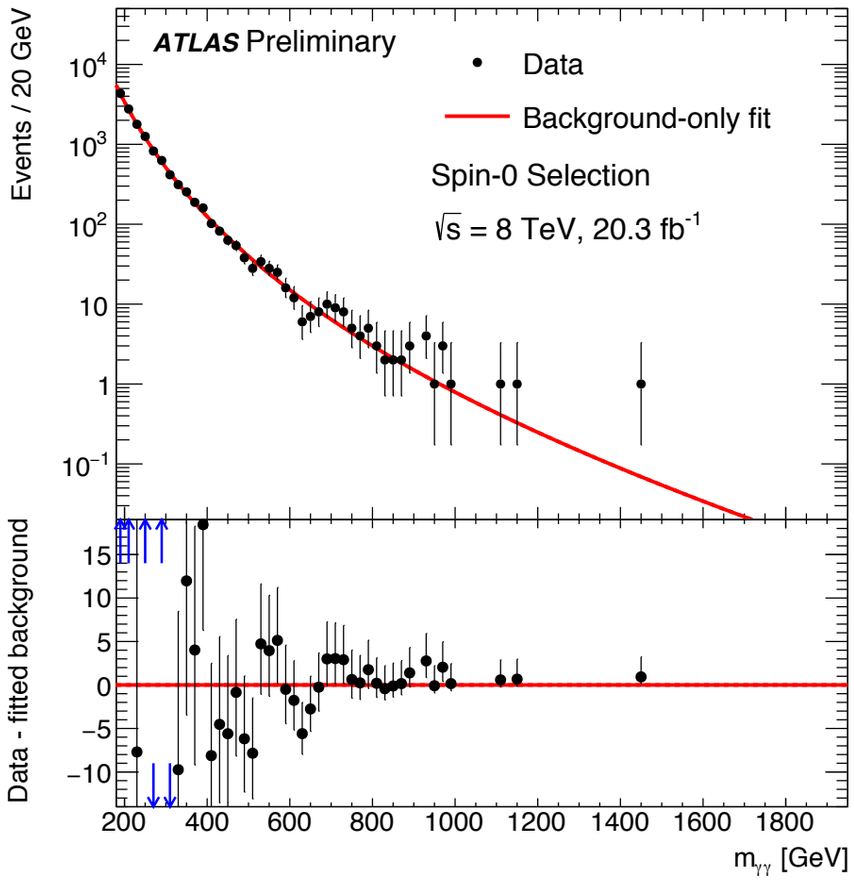


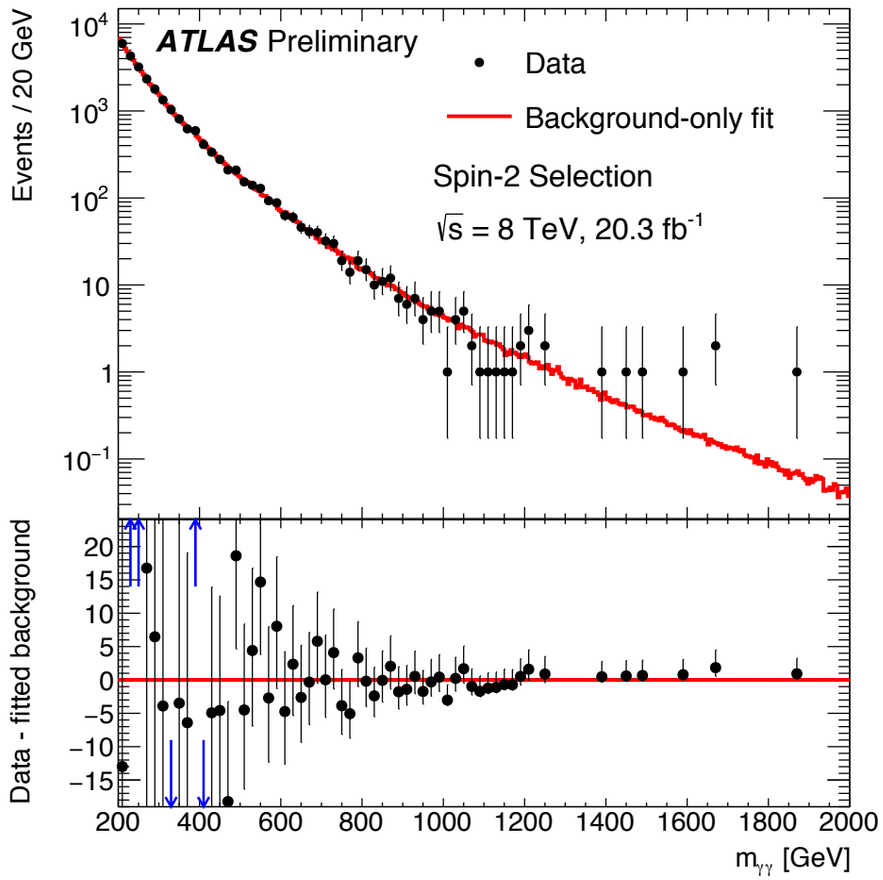
Combined significance: 3.4σ local, 1.6σ global

Diphotons kill diphotons?

ATLAS reanalysis of 8 TeV data, no combination

(revised energy calibration, statistical procedure consistent with 13 TeV analysis)





8 TeV significance: 1.9σ global spin-0 (w/6% width), no excess spin-2

Spin-0 8/13 TeV consistent @ 1.2σ, Spin-2 consistent @ 2.1σ

Other channels?

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[8, 9]	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[10]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[11]	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 11 fb	[12]	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	[13]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[14]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[15]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[16, 17]	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	[18]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[19]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[20]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[7]	$< 1300\ (r/5)$

[Franceschini et al. 1512.04933]

Compatible w/ resonance decaying to diverse final states

Minimal model

Diphoton signal implies couplings of form

$\phi F_{\mu\nu}F^{\mu\nu}$ ($J^{PC}=0^{++}$)

$\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ ($J^{PC}=0^{-+}$)

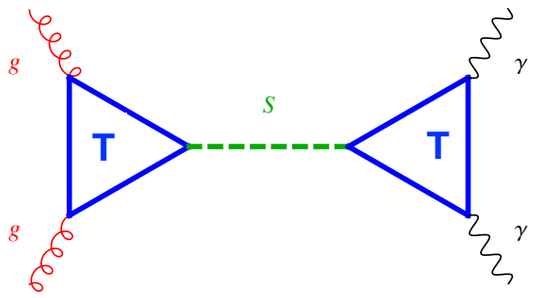
(assuming CP is good quantum #)

Assuming gluon fusion production, also

$\phi G_{\mu\nu}G^{\mu\nu}$

$\phi G_{\mu\nu}\tilde{G}^{\mu\nu}$

Most minimal: induce both via loop of top quarks a la SM

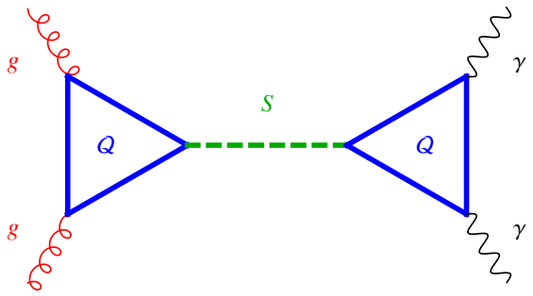


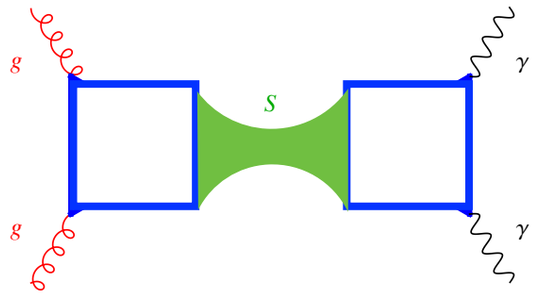
But decays to tops are open, so $\frac{\mathrm{Br}(\phi \to \gamma\gamma)}{\mathrm{Br}(\phi \to t\bar{t})} \sim 10^{-5}$

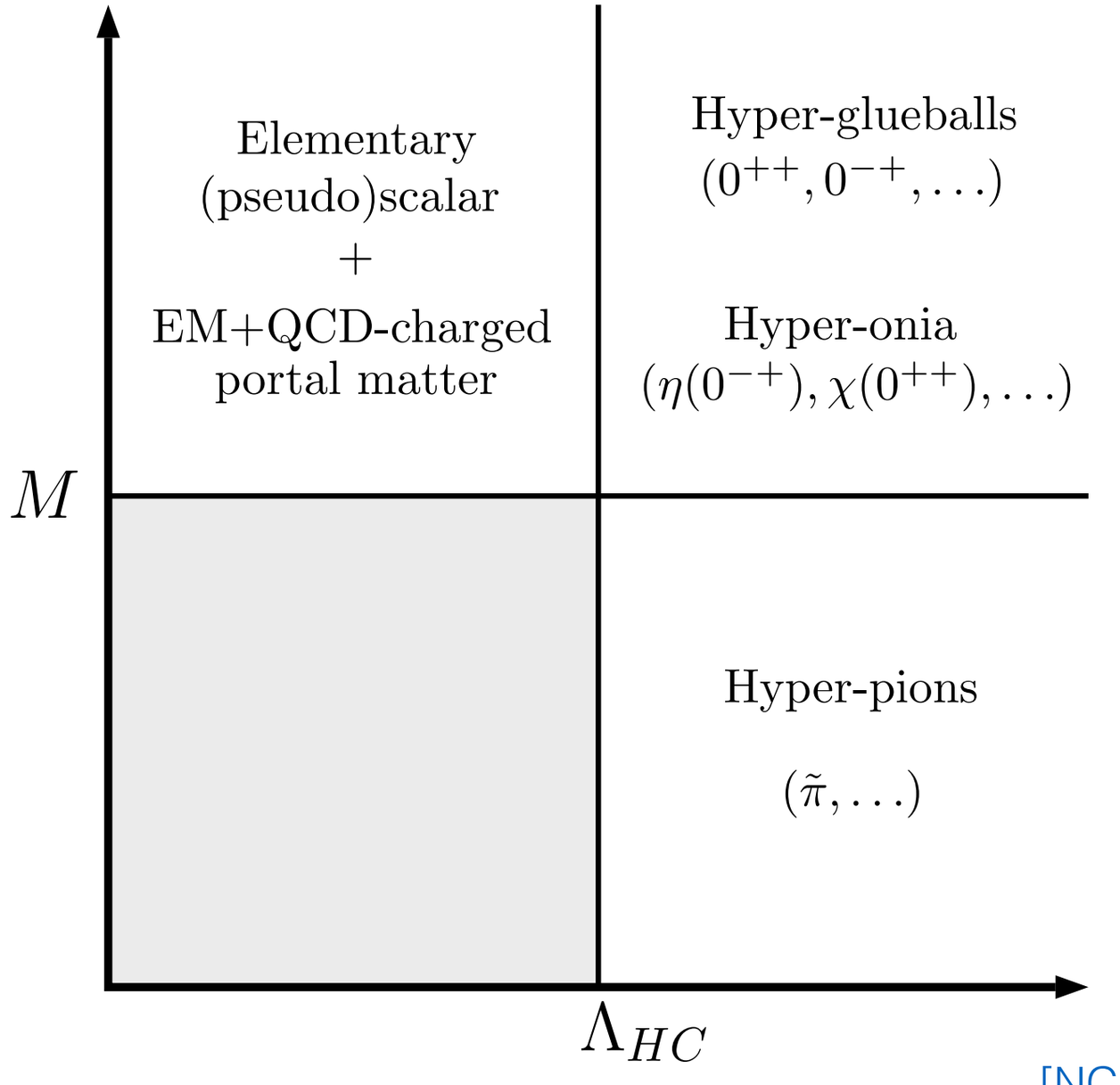
Probably excluded, and σ.BR can't be made to work

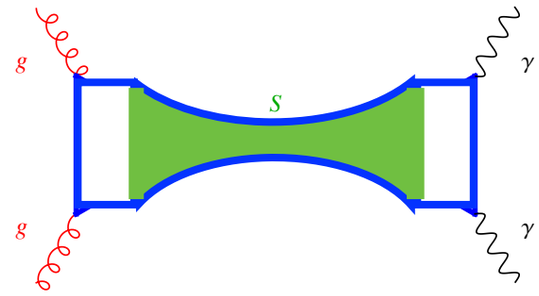
Need new matter charged under SM, heavier than 375 GeV

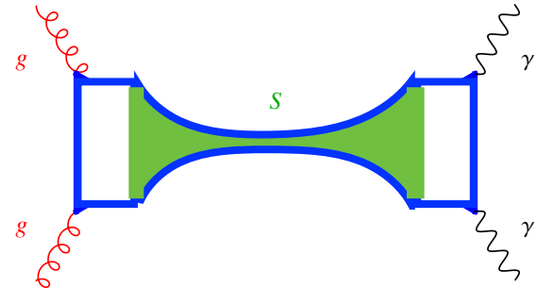
Ingredients: new matter charged under SM + *either* elementary scalar or new strong gauge group











[NC, Draper, Kilic, Thomas, arXiv:1512.07733]

Predictive channels

Portal matter generates various other modes with fixed BR ratios depending on quantum #s

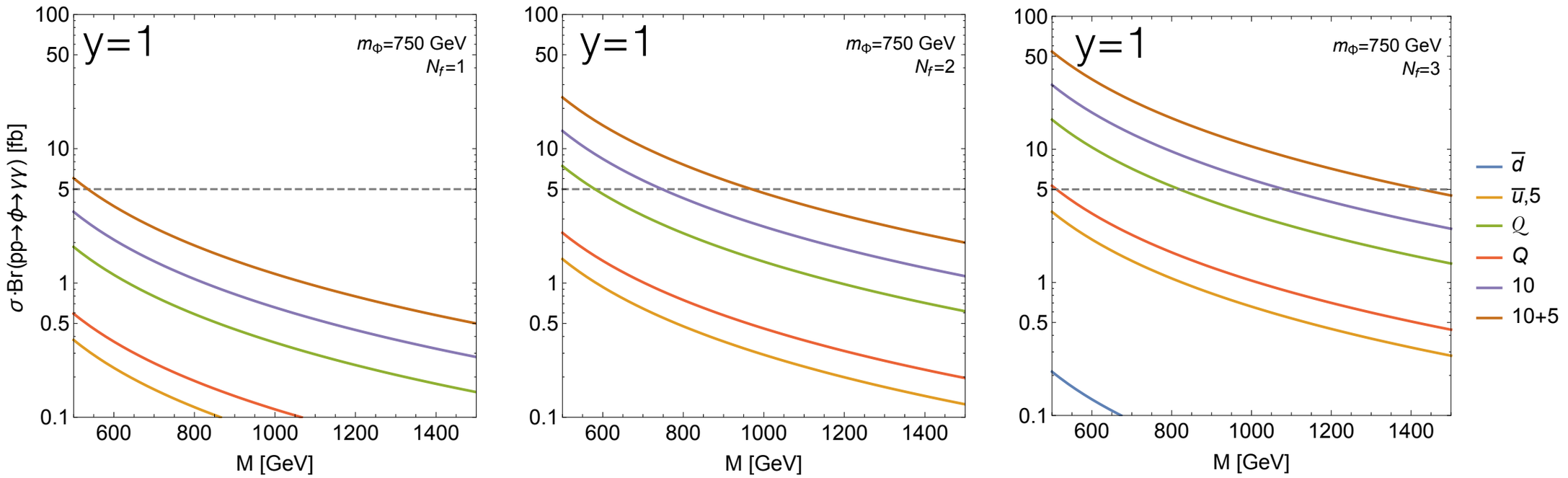
Also fix production rates in terms of fiducial xsec

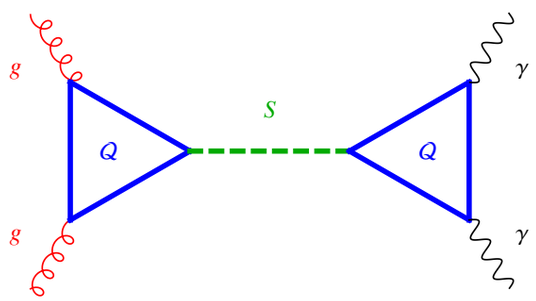
Matter Representation		$\frac{\mathrm{Br}(\phi\to Z\gamma)}{\mathrm{Br}(\phi\to\gamma\gamma)}$	$\frac{\mathrm{Br}(\phi\to WW)}{\mathrm{Br}(\phi\to\gamma\gamma)}$	$\frac{\mathrm{Br}(\phi\to ZZ)}{\mathrm{Br}(\phi\to\gamma\gamma)}$	$\frac{\mathrm{Br}(\phi\to\gamma\gamma)}{\mathrm{Br}(\phi\to gg)}$
$\bar{d}$	$(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}$	0.61	0	0.093	4.1×10^{-4}
$\bar{u}$	$(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}}$	0.61	0	0.093	6.6×10^{-3}
$\mathcal{Q}$	$(\bar{\mathbf{3}},\mathbf{1})_{1}$	0.61	0	0.093	3.3×10^{-2}
Q	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	4.5	26	7.4	2.6×10^{-3}
Unified		0.18	4.5	1.7	6.6×10^{-3}

Matter Representation		$\frac{\Gamma(\phi\to gg)_{\mathrm{LO}}\cdot\mathrm{Br}(\phi\to gg)/\mathrm{GeV}}{\sigma\cdot\mathrm{Br}(pp\to\phi\to\gamma\gamma)_{\mathrm{LO}}/5\,\mathrm{fb}}$	$\frac{\sigma\cdot\mathrm{Br}(pp\to\phi\to gg)_{\mathrm{LO}}/\mathrm{pb}}{\sigma\cdot\mathrm{Br}(pp\to\phi\to\gamma\gamma)_{\mathrm{LO}}/5\,\mathrm{fb}}$
$\bar{d}$	$(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}$	1.8	12
$\bar{u}$	$(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}}$	0.12	0.76
$\mathcal{Q}$	$(\bar{\mathbf{3}},\mathbf{1})_{1}$	0.023	0.15
Q	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	0.30	1.9
Unified		0.12	0.76

[NC, Draper, Kilic, Thomas, arXiv:1512.07733]

Minimal model





Rates readily fit; fermions much better than scalars in the loop, prefers more than one flavor of portal

Look at 750 GeV for: other diboson final states

Look elsewhere for: pair production/decay of portal states (e.g. vector-like fermion searches)

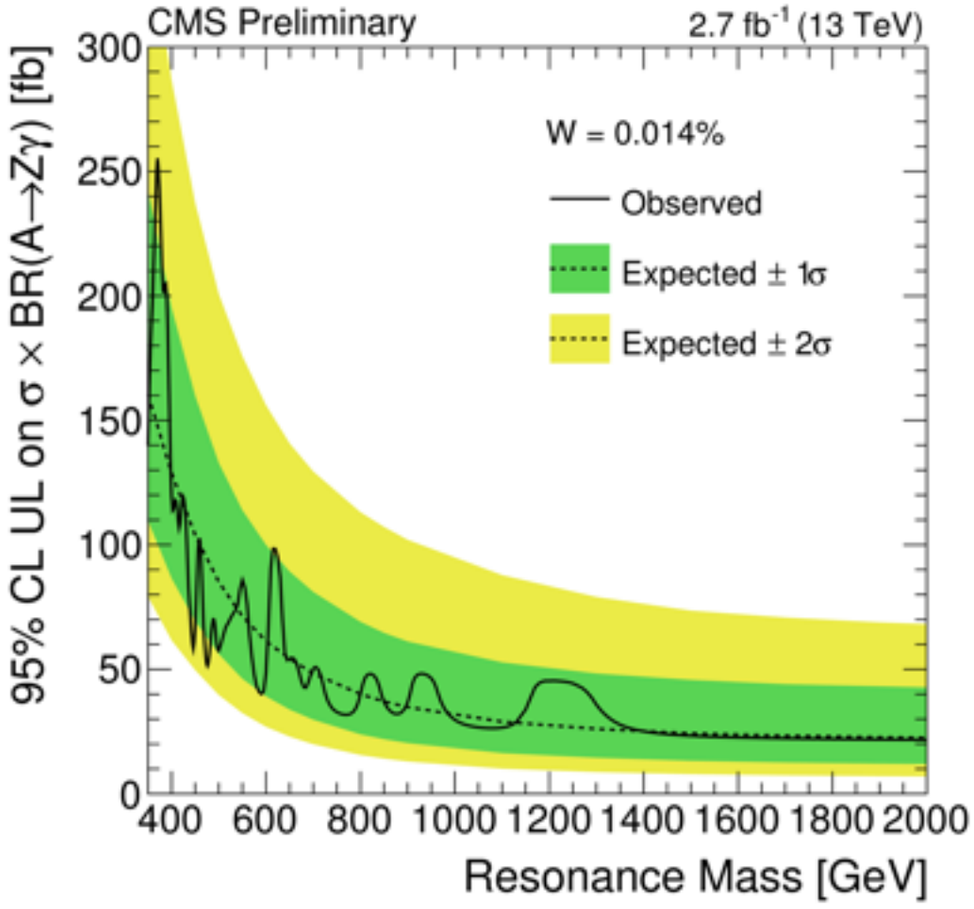
[NC, Draper, Kilic, Thomas, arXiv:1512.07733]

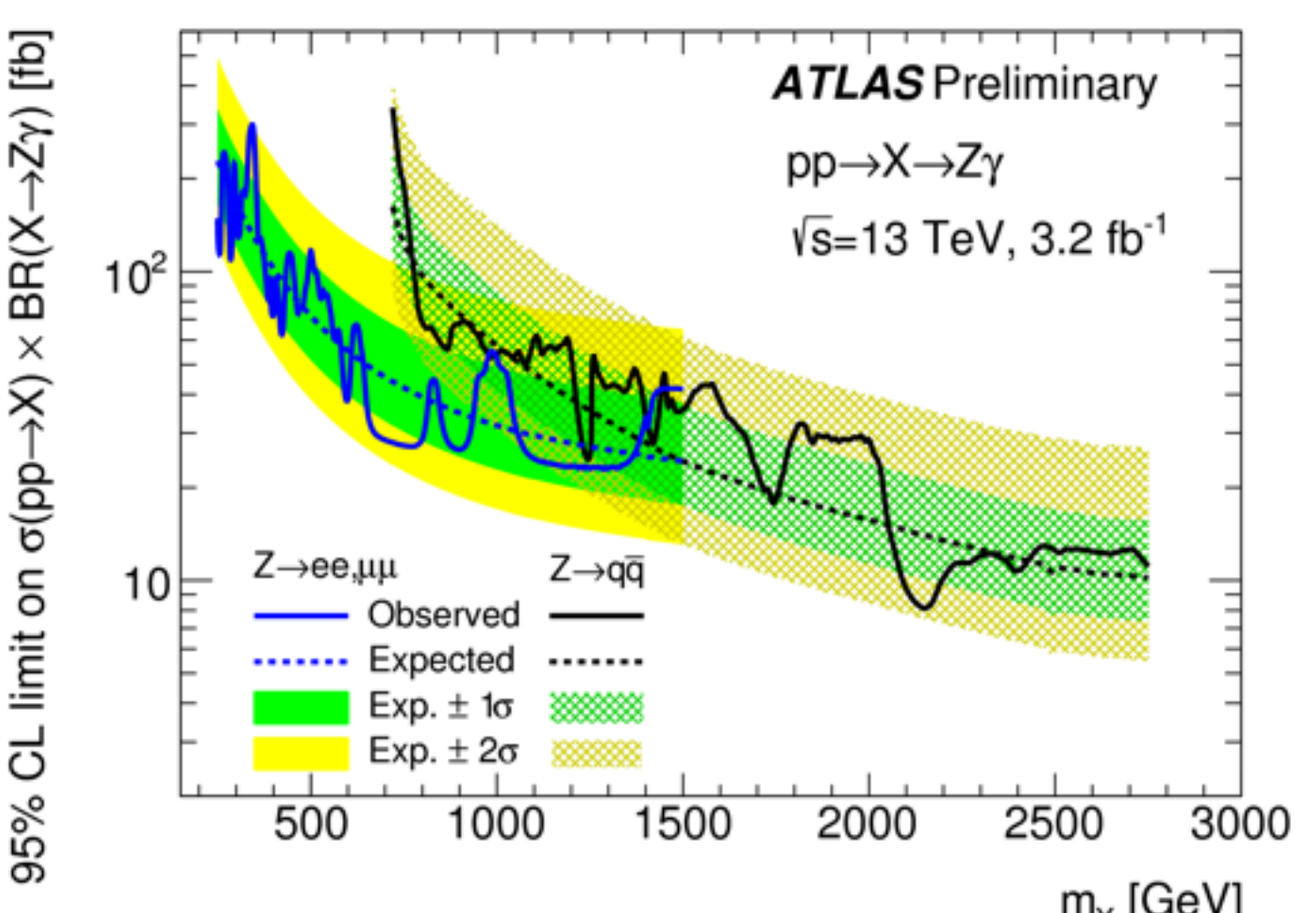
Relevant 13 TeV limits: Zγ

Matter Representation		$\frac{\mathrm{Br}(\phi\to Z\gamma)}{\mathrm{Br}(\phi\to\gamma\gamma)}$	$\frac{\mathrm{Br}(\phi\to WW)}{\mathrm{Br}(\phi\to\gamma\gamma)}$	$\frac{\mathrm{Br}(\phi\to ZZ)}{\mathrm{Br}(\phi\to\gamma\gamma)}$	$\frac{\mathrm{Br}(\phi\to\gamma\gamma)}{\mathrm{Br}(\phi\to gg)}$
$\bar{d}$	$(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}$	0.61	0	0.093	4.1×10^{-4}
$\bar{u}$	$(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}}$	0.61	0	0.093	6.6×10^{-3}
$\mathcal{Q}$	$(\bar{\mathbf{3}},\mathbf{1})_{1}$	0.61	0	0.093	3.3×10^{-2}
Q	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	4.5	26	7.4	2.6×10^{-3}
Unified		0.18	4.5	1.7	6.6×10^{-3}

σ·Br(750) < 25fb

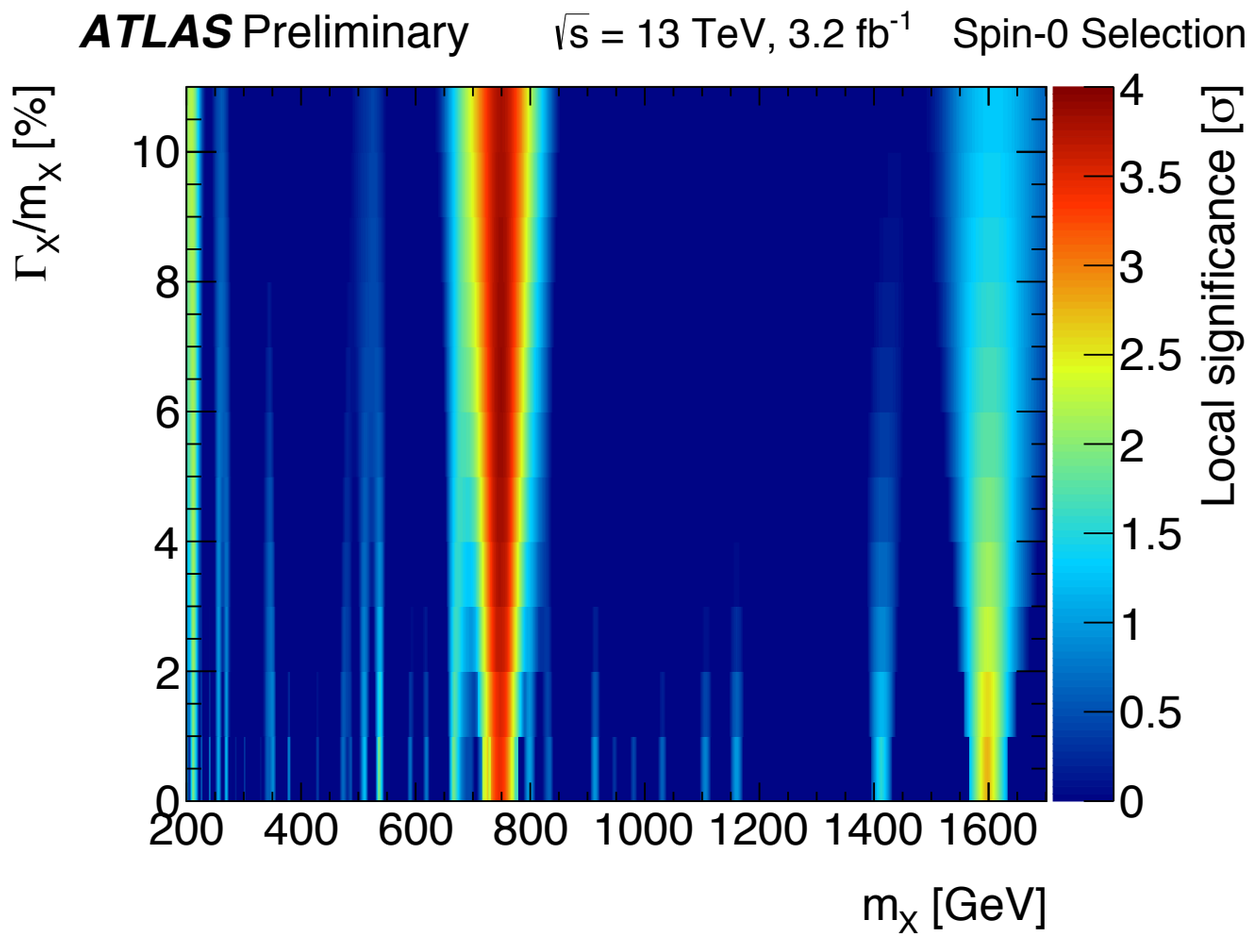
Does place $(3,2)_{1/6}$ portal under strain, irrelevant for all others



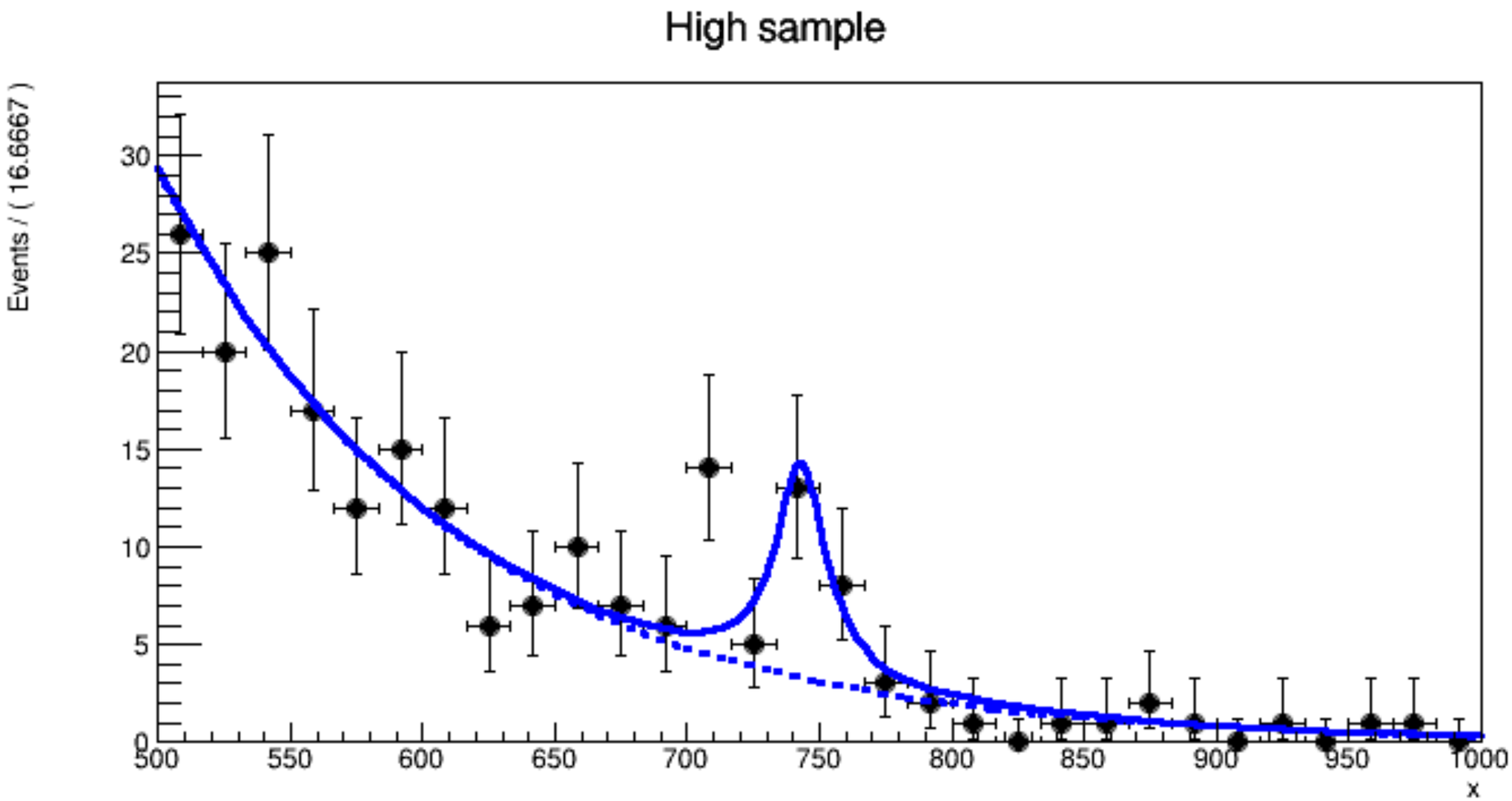


Wide or narrow?

Preference for finite width at ATLAS (~6%), none at CMS
Major implications for models

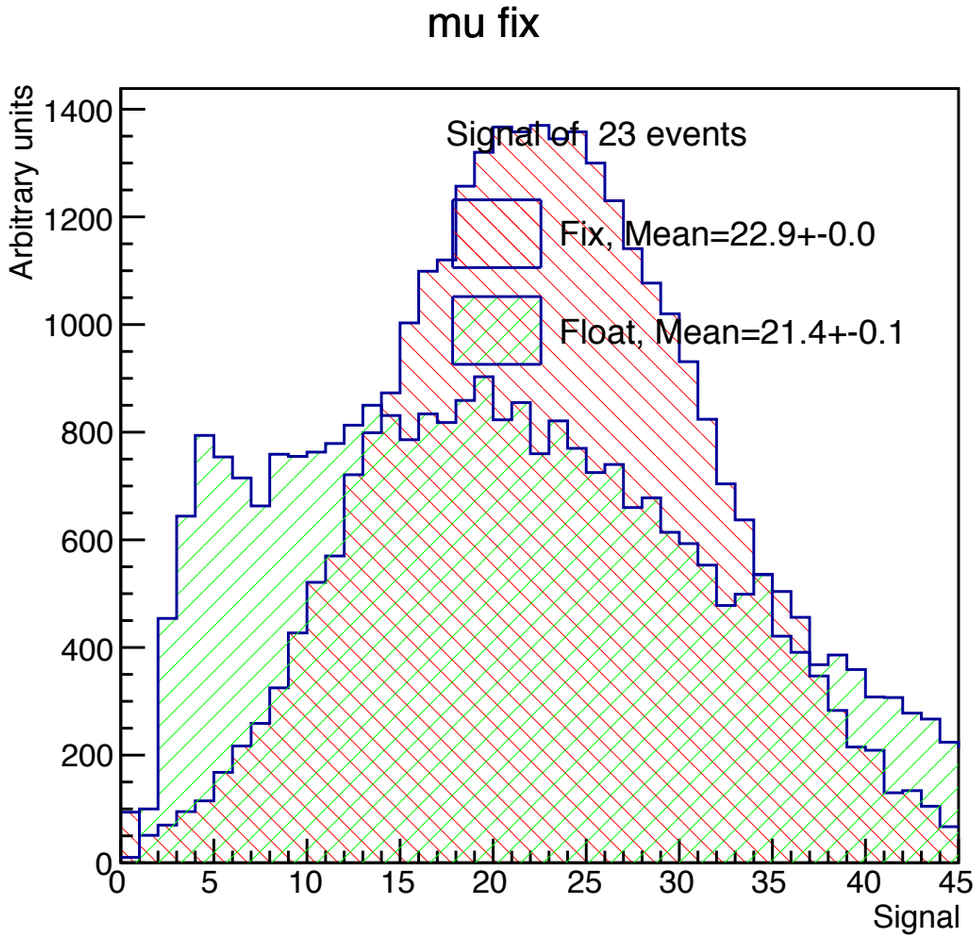


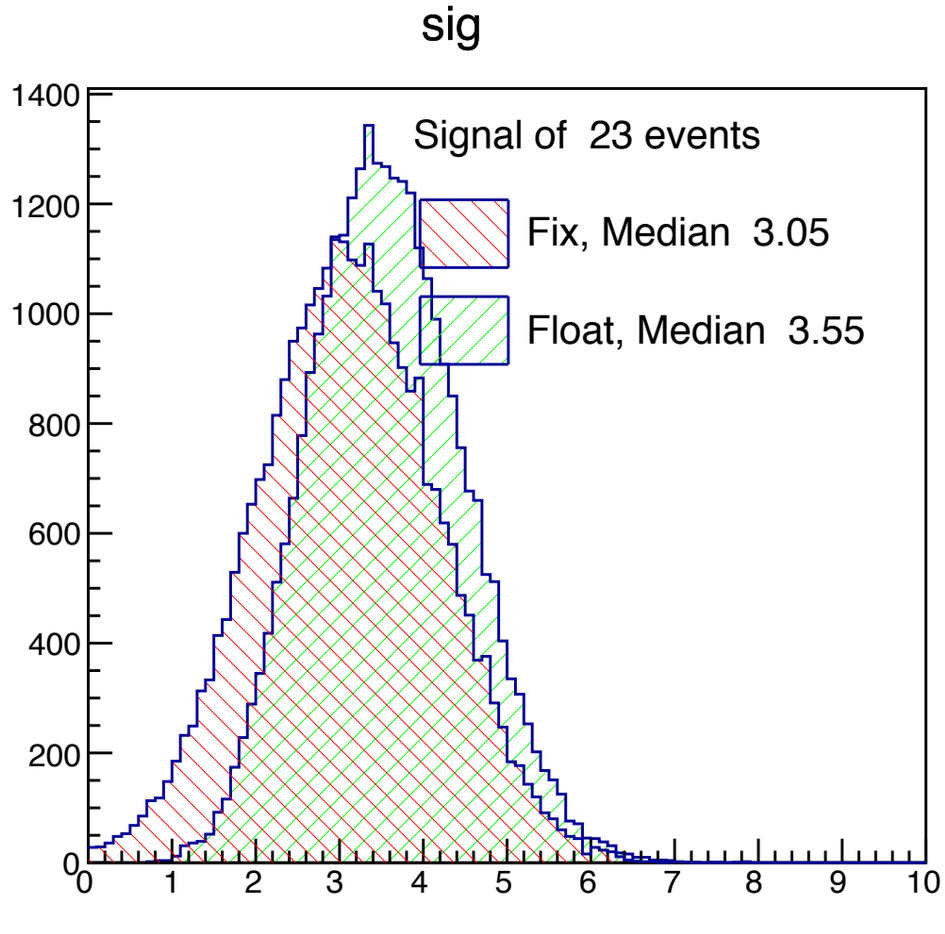
Wide or narrow?



W. Murray

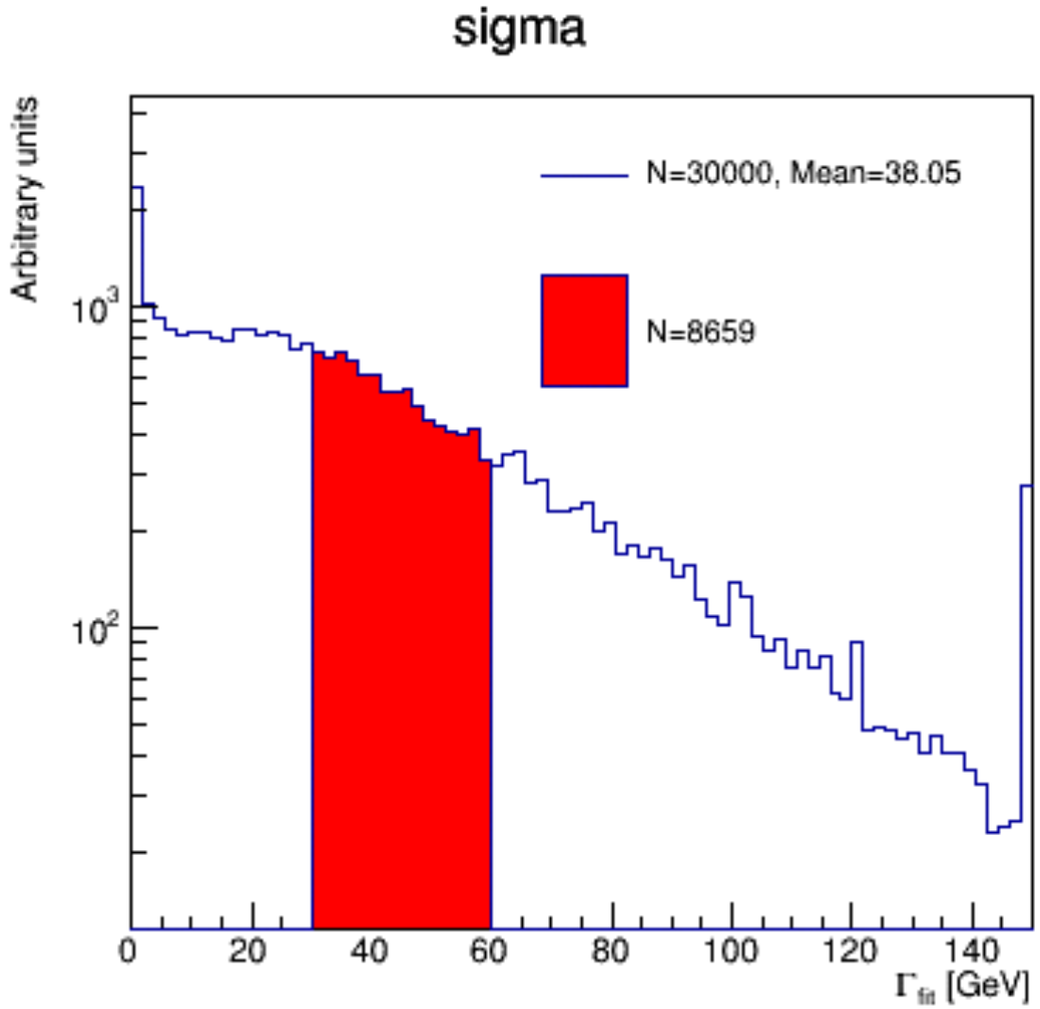
Wide or narrow?

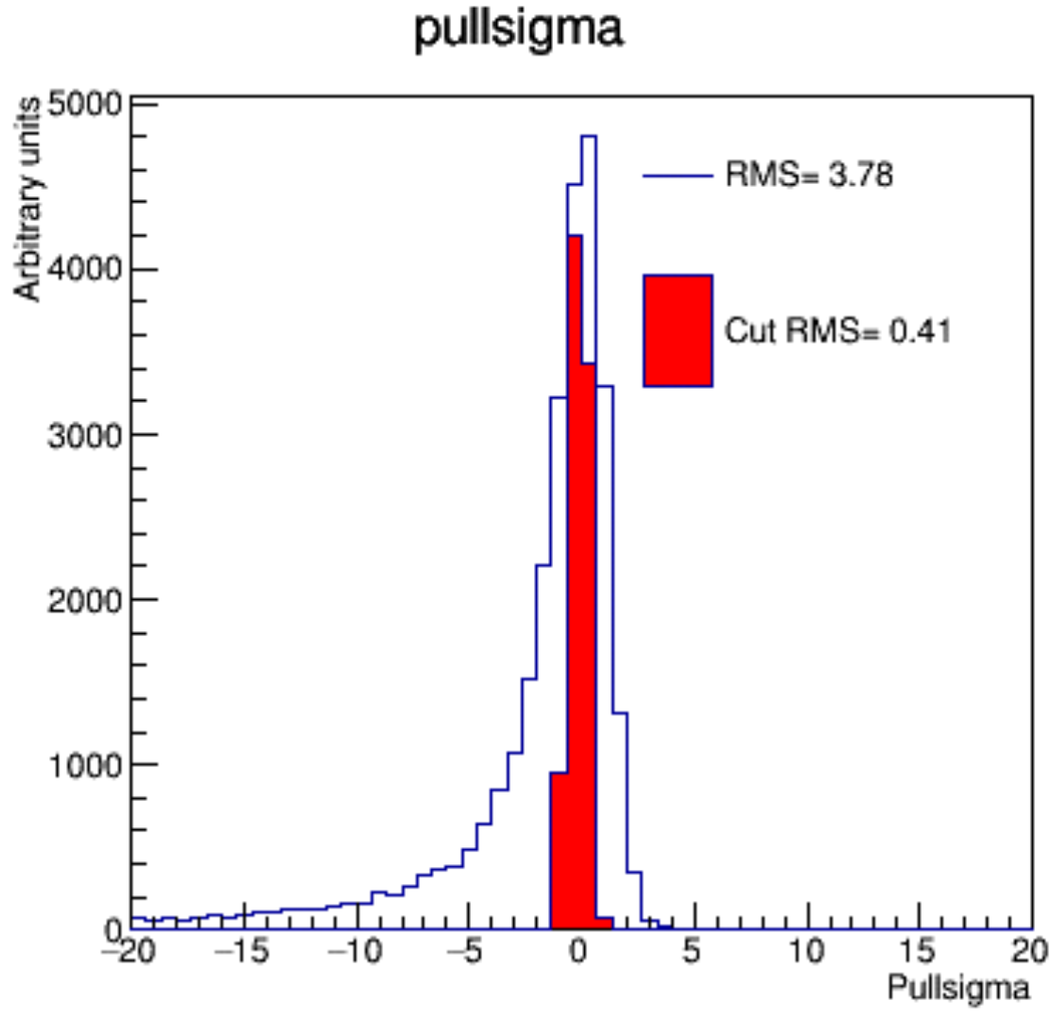




W. Murray

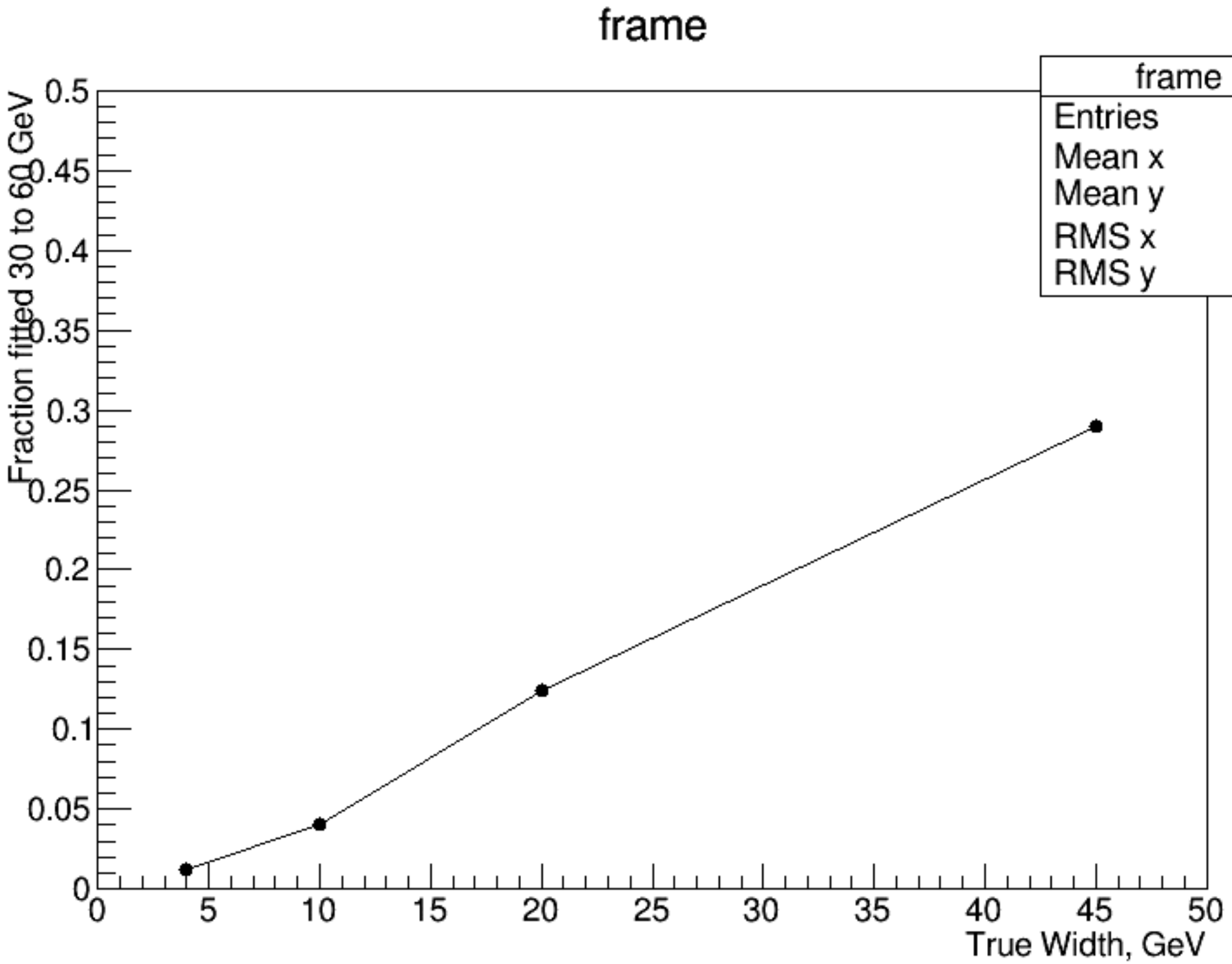
Wide or narrow?





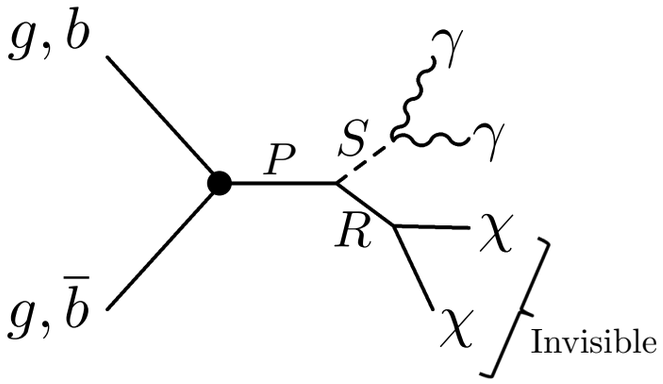
W. Murray

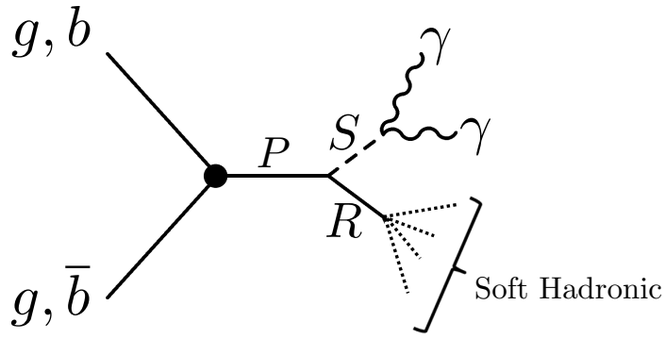
Wide or narrow?



W. Murray

Is it a resonance, or not?



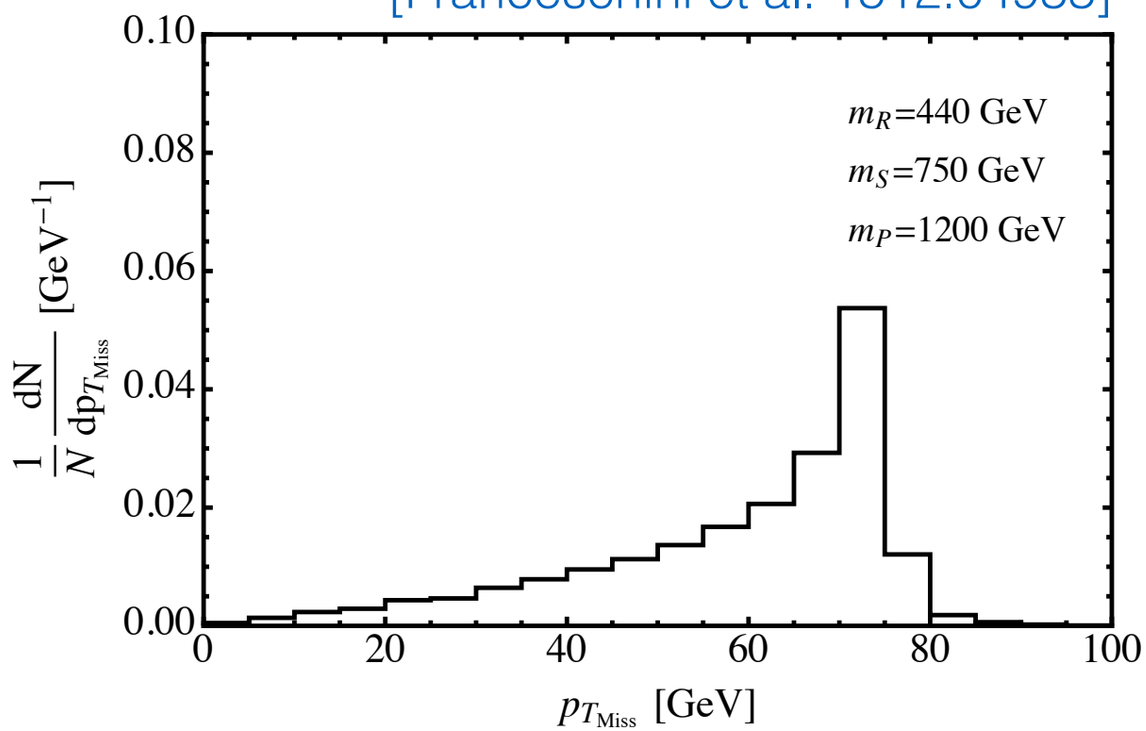


Could be a cascade decay w/ invisible or soft associated products

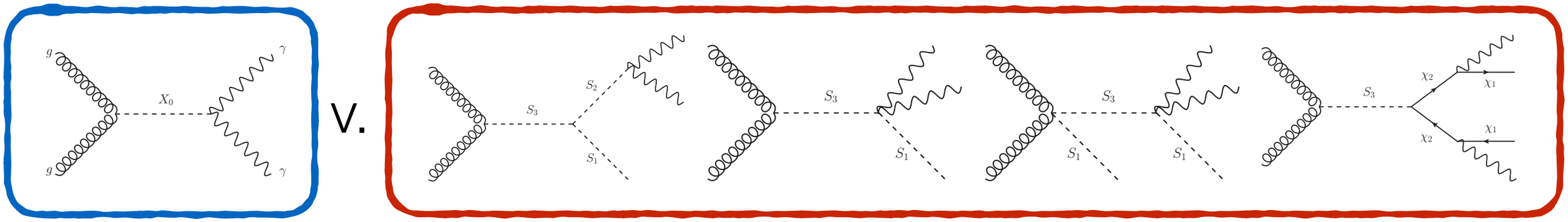
MET not necessarily enormous if spectrum compressed

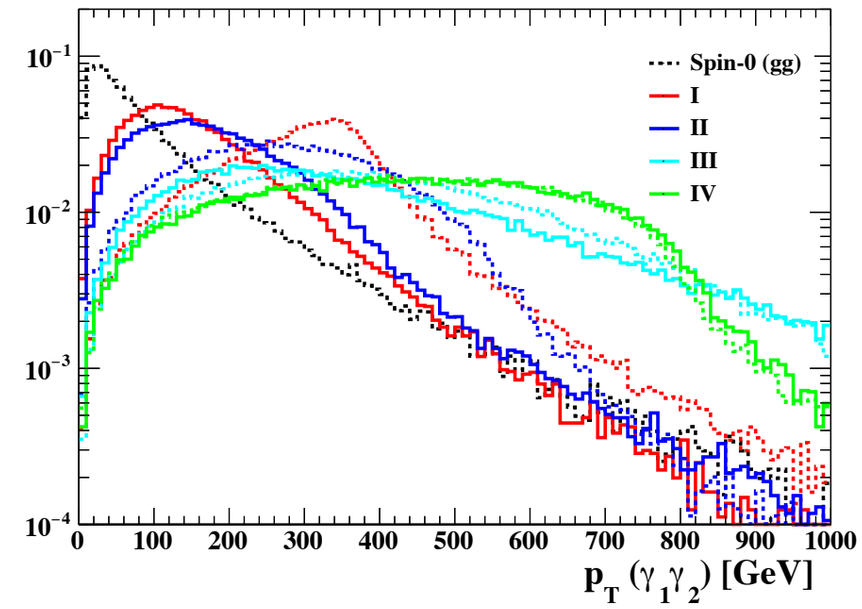
If soft hadronic instead of invisible, no MET but diphotons still have transverse boost.

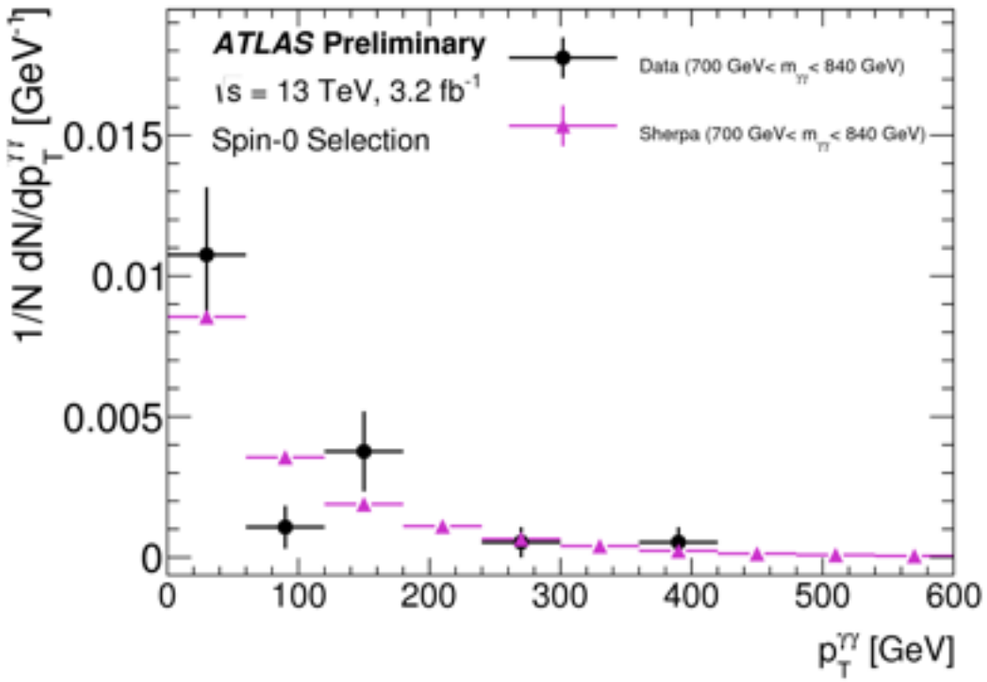
[Franceschini et al. 1512.04933]

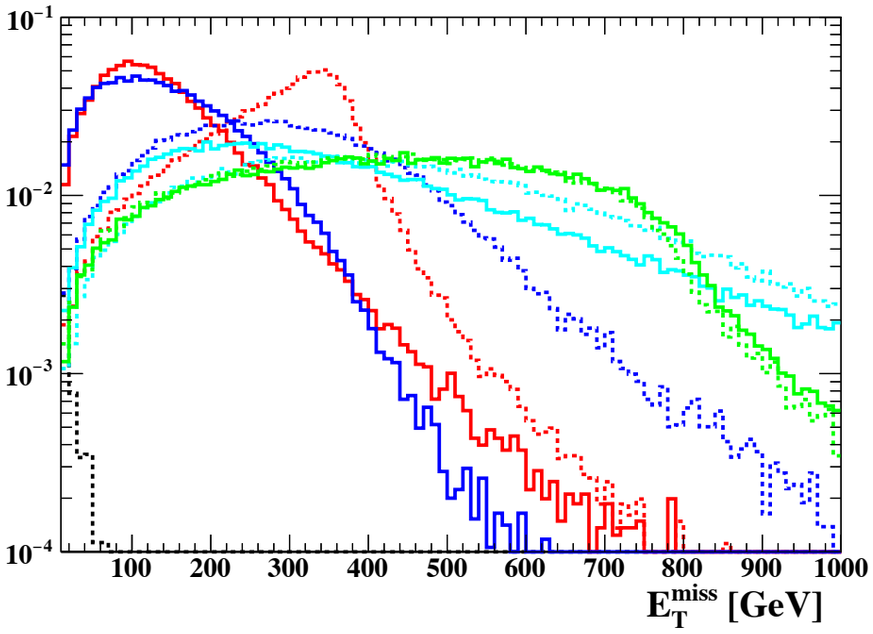


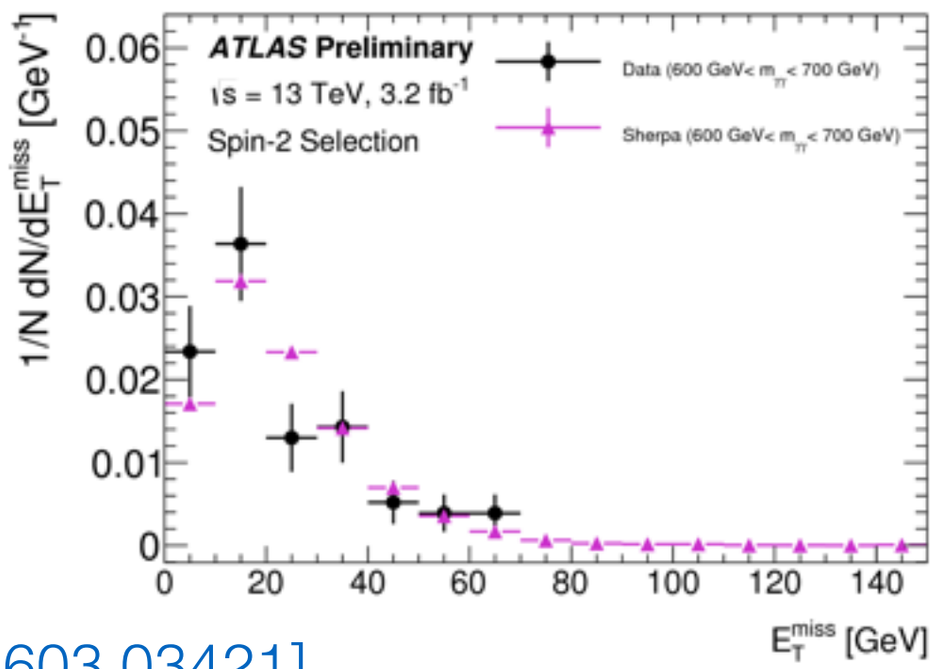
"No indication of additional MET or hadronic activity" in signal events, better quantified at Moriond…











[Bernon, Goudelis, Kraml, Mawatari, Sengupta 1603.03421]

Is it a Higgs?

Higgs-singlet mixing

Diphoton width:

$$\frac{1}{\theta^2}\Gamma(\phi \to \gamma\gamma) \sim 5Q^2 \frac{\alpha^2}{32\pi^3}\frac{M^3}{v^2}$$

Longitudinal WW width:

$$\frac{1}{\theta^2}\Gamma(\phi \to WW) \sim \frac{M^3}{16\pi^2 v^2}$$

So predict

$$\frac{\mathrm{Br}(\phi \to \gamma\gamma)}{\mathrm{Br}(\phi \to WW)} \sim Q^4 \times 10^{-5}$$

final state f	σ at $\sqrt{s} = 8\,\mathrm{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\mathrm{obs}}$
W^+W^-	< 40 fb	< 70 fb	[16, 17]	$< 20\ (r/5)$

…badly excluded

2HDM

Improvement relative to singlet mixing: turn off longitudinal *VV* in alignment limit

Production/decay via loop of top quarks

But decays to tops are open, so

$$\frac{\mathrm{Br}(\phi \to \gamma\gamma)}{\mathrm{Br}(\phi \to t\bar{t})} \sim 10^{-5}$$

Not directly ruled out by tt searches, but best you can hope for is

$$\sum_{H,A} \sigma(gg \to H, A) \cdot \mathrm{Br}(H, A \to \gamma\gamma) \sim 10^{-2}\ \mathrm{fb} \times \cot^2\beta$$

Who ordered that?

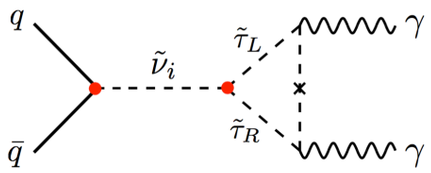
Supersymmetry

Not obvious out of the box, but necessity is the mother of invention…

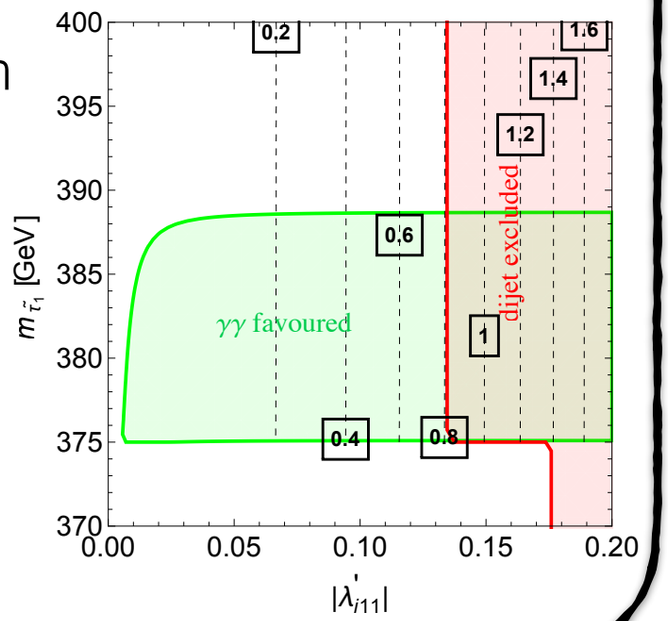
RPV sneutrino

[Allanach, Bhupal Dev, Renner, Sakurai 1512.07645]

W=QLD + LLE A-term



8 TeV tension since qq initiated?



"Sgoldstino"

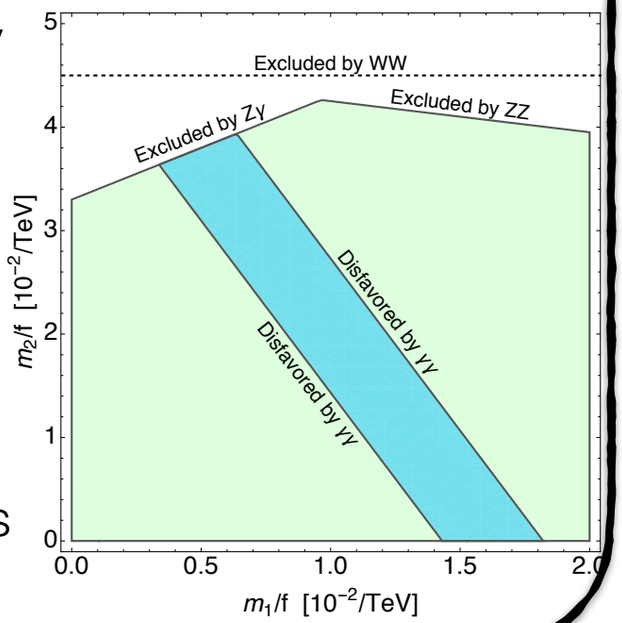
[Petersson, Torre 1512.05333]

(Not sgoldstino of primary SUSY breaking)

$$\Gamma(\phi \to \gamma\gamma) = \frac{(m_1^2 c_W^2 + m_2^2 s_W^2) M_\phi^3}{32\pi F^2}$$

$$\Gamma(\phi \to gg) = \frac{m_3^2 M_\phi^3}{4\pi F^2}$$

Ruled out by gluino mass limits in calculable models



Sbino in supersoft SUSY / dirac gauginos

[Carpenter, Colburn, Goodman 1512.06107]

$$\begin{pmatrix} & A_\mu & \\ \psi & & \lambda \\ & \Phi & \end{pmatrix}$$

Scalar adjoint of $U(1)_Y$, couples to sfermions via D-term

Fitting signal requires $m_D \sim$ 10 TeV, enormous splitting in multiplet

Who ordered that?

Compositeness

Not a *parametrically light* ingredient of minimal composite Higgs model, but can arise in non-minimal models with larger cosets. E.g.

[No, Sanz, Setford 1512.05700]

$$SO(6) \to SO(5) \to SO(4)$$

5 PNGBs + 4 PNGBs organize into 1 singlet + 2 doublets)

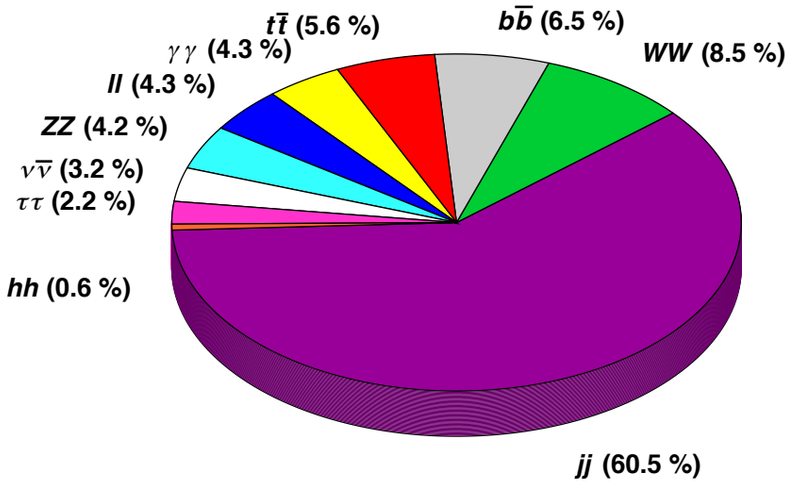
Additional vector-like fermions from fermionic resonances, no need for new ingredients there.

Singlet disfavored (intrinsic Higgs mixing), but second doublet inert, couples to SM via vector-like fermions, looks like elementary spin-0 scenario.

Could be hanging around, but not automatic.
Other candidates from compositeness?

Who ordered that?

KK graviton: avatar of strongly-warped extra dimension
[Giddings & Zhang 1602.02793]



Minimal model
highly predictive

$$\mathcal{L} \supset -\frac{1}{\Lambda}\phi_{\mu\nu}T^{\mu\nu}$$

→ *Strong tension with dileptons*

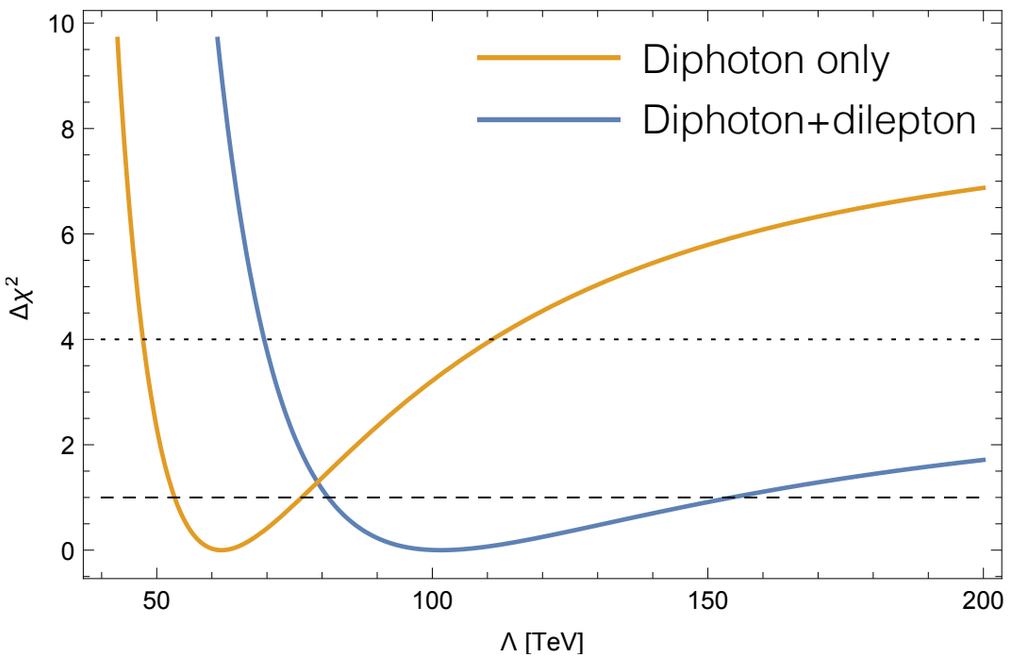


TABLE IV. The bounds on $\sigma\,(pp \to G_1^*)\,\mathrm{Br}\,(G_1^* \to \gamma\gamma)$ and Λ at 13 TeV LHC.

Channel	ATLAS (ee)	ATLAS $(\mu\mu)$	CMS (ee)	CMS $(\mu\mu)$
σ (fb)	9.2	24.6	5.7	14.7
Λ (TeV)	60	37	76	48

Can be made viable if SM fields are put into the bulk, so each field has independent coupling depending on geography, but then expect to see other KK modes.

Who ordered that?

- Most of the Standard Model field content isn't "deeply motivated by theory considerations"

- Nobody said BSM had to be "minimal"

- Many "complete" UV theories give SM field content + exotics [Cvetic, Halverson, Langacker 1512.07622]

- No atheists in foxholes, etc.: if it's real I don't much care if it fits with some theory prior.

What next?

	At 750 GeV	Elsewhere
Spin 0 **elementary**	Zγ, ZZ, possibly WW, dijets	Vector-like quark searches, SUSY-like searches (RPC,RPV)
glueball	Zγ, ZZ, possibly WW, dijets	γγ, Zγ, ZZ, possibly WW, dijets cascades
hyperonium	Zγ, ZZ, possibly WW, beaucoup dijets	γγ, Zγ, ZZ, possibly WW, dijets, dileptons
hyperpion	Zγ, ZZ, possibly WW, dijets	Zγ, ZZ, possibly WW, γj, Zj, beaucoup dijets
Spin 2	ZZ, WW, dileptons	Higher KK modes, other KK modes
Non Res	Met / soft radiation / stealth	Other decays of parent (dijets,…)

- Are we happy with the analysis?
- If it's real, did we have to get lucky twice?
- Is it wide or narrow?
- Is it a resonance or a cascade?
- Is it a Higgs?
- Who ordered that?
- What next?

Anything else?