HINTS FOR THE BSM PHYSICS AT THE LHC

THE SITUATION IN PARTICLE PHYSICS
IS BIZZARE AND INTRIGUING…

A HIGGS LIKE PARTICLE HAS BEEN DISCOVERED (A PARTICLE THAT LOOKS VERY MUCH LIKE THE ELEMENTARY HIGGS BOSON OF THE SM)

$$m_h = 125\ GeV$$

Simplest dynamical sector (considered by many as a toy model)– self interacting scalar field, a doublet of SU(2)- IS NOW PROMOTED TO A REAL THING

AT LEAST AT THE ELECTROWEAK SCALE, THE SM IS A CORRECT EFFECTIVE THEORY OF ELECTROWEAK INTERACTIONS

IS THE SM A CONSISTENT THEORY UP TO THE PLANCK SCALE ?

YES!

RENORMALIZABLE

NO LANDAU POLE UP TO Mp

(ALMOST) STABLE VACUUM UP TO Mp

THOSE CONCLUSIONS STRONGLY DEPEND ON

$$m_t = 173 GeV, \quad m_h = 125 GeV$$

THE SM IS A CONSISTENT THEORY UP TO THE PLANCK SCALE?

BUT….

ISNT IT INDEED JUST AN EFFECTIVE THEORY, AN APPROXIMATION TO A DEEPER ONE

(SIMILARLY AS QED, ALTHOUGH CONSITENT UP TO Mp, IS ONLY LOW ENERGY APPROXIMATION TO SM)?

WHY BSM IN SPITE OF THE SUCCESS OF THE SM?

CENTRAL MYSTERY OUTSIDE THE SM—
DARK MATTER AND THE ORIGIN OF THE
MATTER –ANTIMATTER ASYMMETRY

CENTRAL MYSTERY WITHIN THE STANDARD MODEL- THE TRUE IDENTITY OF THE HIGGS BOSON AND WHY ITS MASS REMAINS STABLE TO QUANTUM CORRECTIONS, IF IT WAS ELEMENTARY (NATURALNESS PROBLEM)

NO NEW PHYSICAL EFFECTS (NEW PARTICLES?)
PREDICTED BY VARIOUS „SIMPLE” SOLUTIONS TO THOSE
PUZZLES HAVE BEEN DISCOVERED SO FAR

INSTEAD…

SOME HINTS THAT LOOK A BIT SUPRISING

WHO ORDERED THAT ?   (I. RABI)

Diphoton excess at 750 GeV?

~ 300 theoretical papers on its interpretation

IS THE EFFECT REAL?

MANY PLAUSIBLE INTERPRETATIONS BUT:

- NONE OF THE „READY" BSM MODELS CAN EXPLAIN IT, ALTHOUGH IN PRINCIPLE THEY CONTAIN „SUFFICIENT INGREDIENTS"
- EVEN THEN, SOME DEGREE OF ARTIFICIALITY ALWAYS PRESENT

NEW PARTICLES NEEDED: SPIN 0 OR SPIN 2
AND NEW FERMIONS AROUND 1 TeV

PERTURBATIVE AND STRONGLY INTERACTING SCENARIOS
(MORE QUALITATIVE)

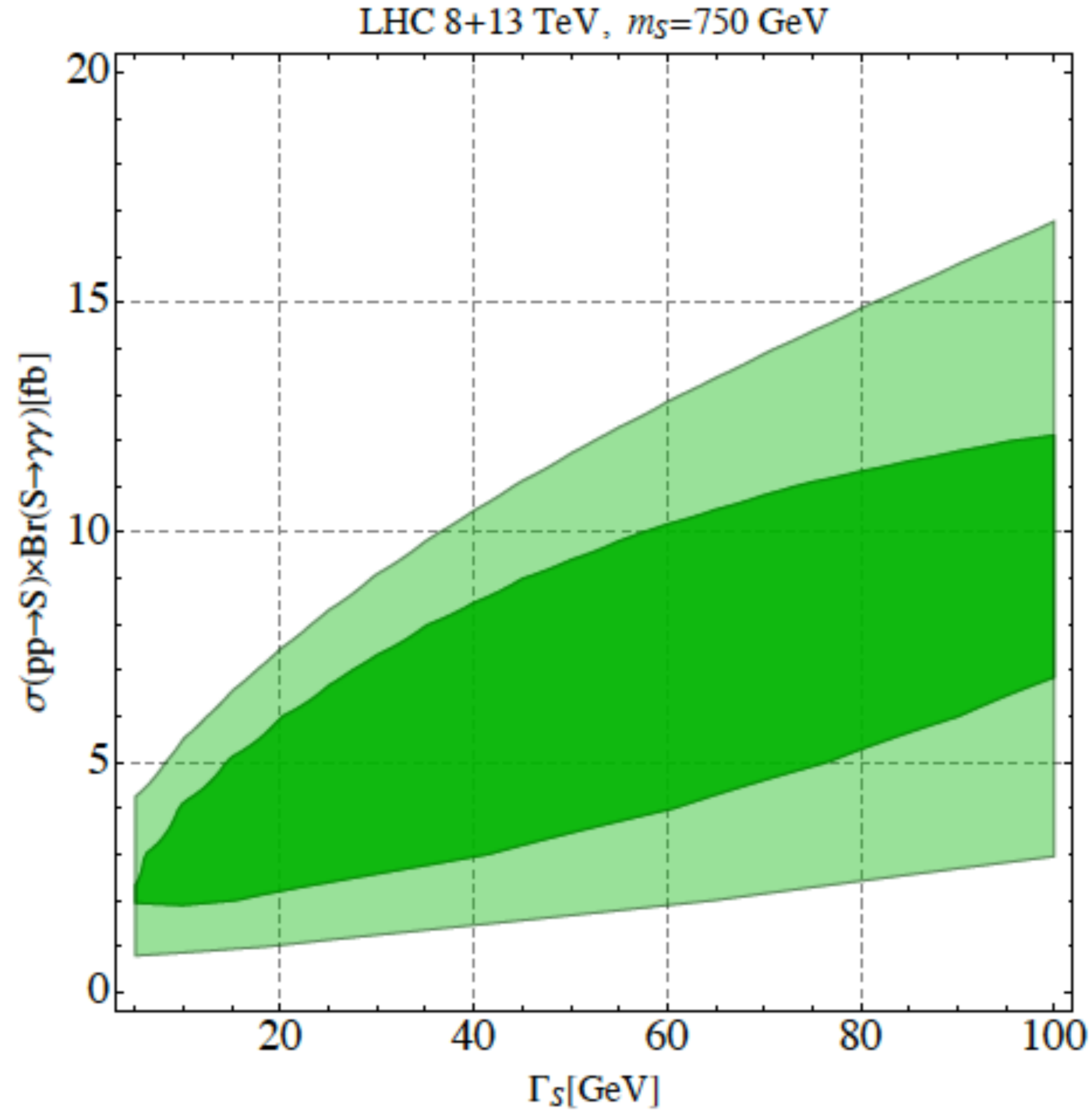
IN THE FOLLOWING: SPIN 0 (SCALAR OR PSEUDO-SCALAR)
EFFECTIVELY COUPLED AT LEAST TO GLUONS
(FOR PRODUCTION) AND PHOTONS (FOR THE OBSERVED
DECAY CHANNEL)

COUPLINGS TO OTHER SM PARTICLES ARE OF COURSE ALSO
POSSIBLE (MORE MODEL DEPENDENT ISSUE)

UNDER THE ASSUMPTION THAT THE NEW PARTICLE IS PRODUCED

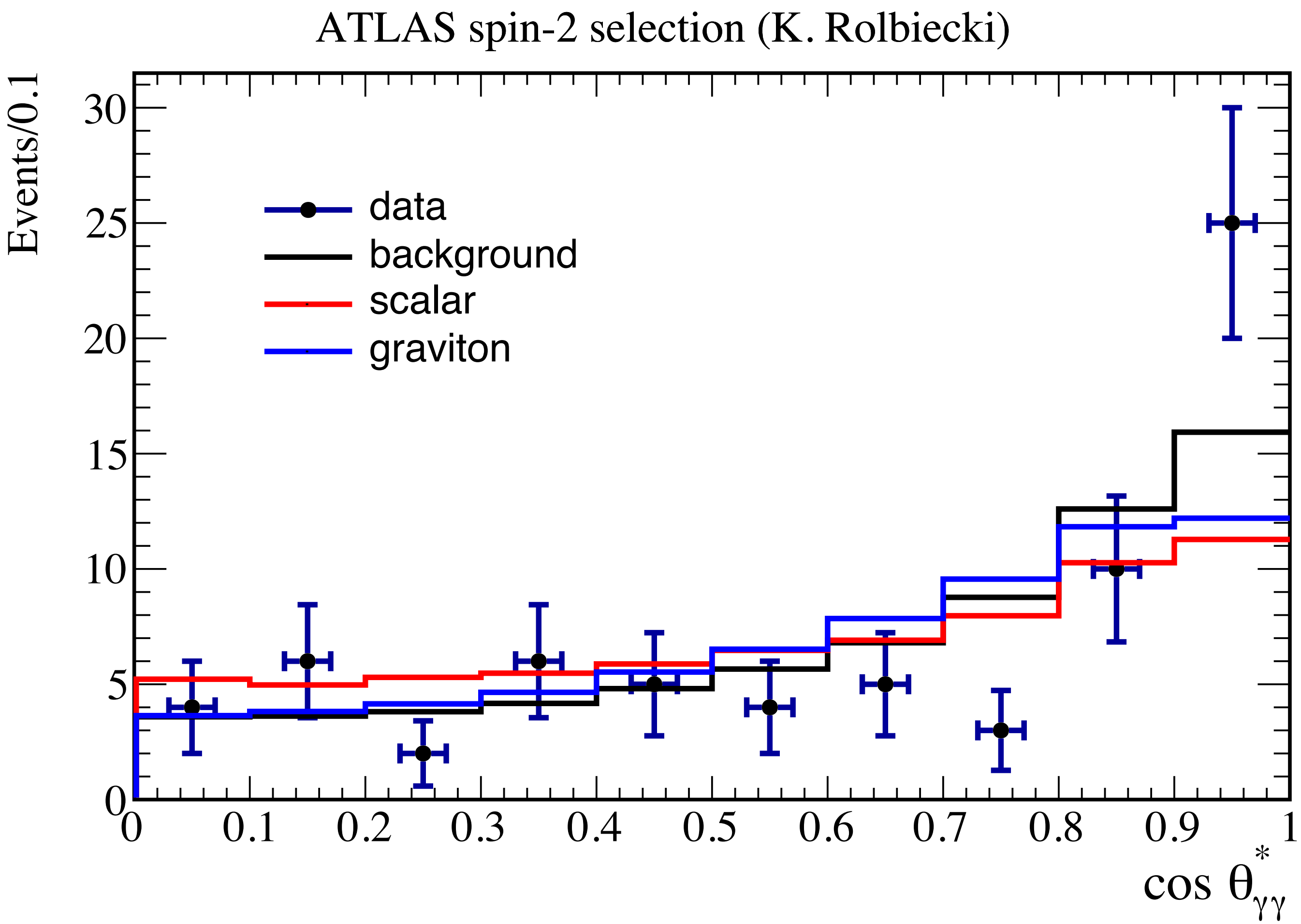
VIA GLUON FUSION, ONE CAN FIT ITS MASS, WIDTH AND

$$\sigma(pp \to X) \times BR(X \to \gamma\gamma)$$



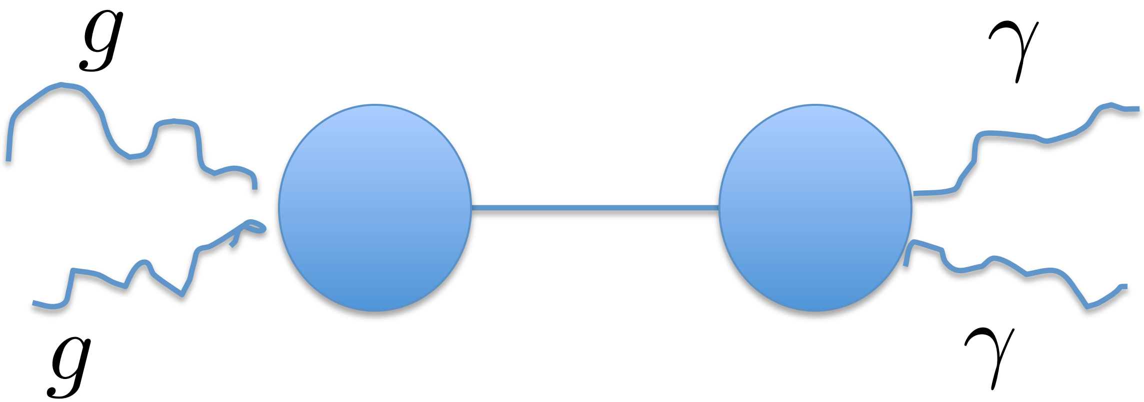
FALKOWSKI ET AL

Figure 4. The 68% CL (darker green) and 95% CL (lighter green) regions in the plane of width vs. cross-section of a 750 GeV scalar resonance decaying to 2 photons favored by the ATLAS and CMS run-1 and run-2 data .


ATLAS spin-2 selection (K. Rolbiecki)
Events/0.1
data
background
scalar
graviton
0
5
10
15
20
25
30
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
cos $\theta^*_{\gamma\gamma}$

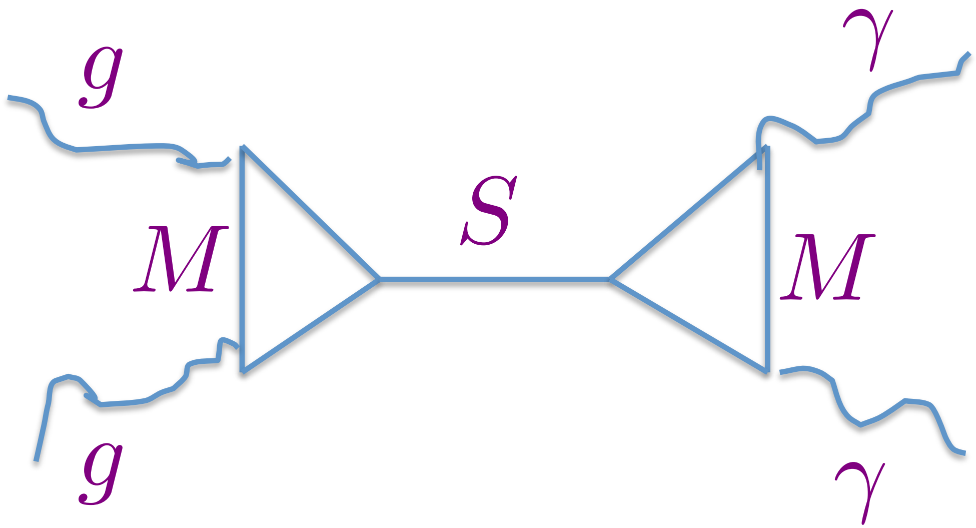
EFFECTIVE THEORY (AFTER ELECTROWEAK SYMMETRY BREAKING):

$$\mathcal{L} = \lambda_g \frac{\alpha_s}{12\pi v} S G^a_{\mu\nu} G^a_{\mu\nu} + \lambda_\gamma \frac{\alpha}{\pi v} S F_{\mu\nu} F^{\mu\nu} + ...$$



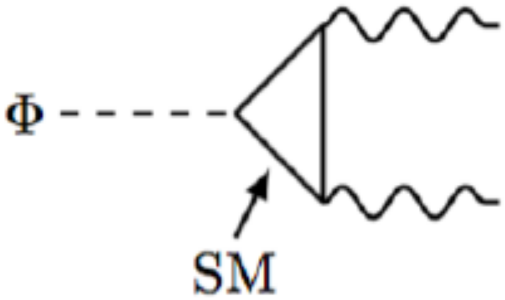
S- SM SINGLET

EXPLICIT MODELS, WITH RENORMALIZED COUPLINGS

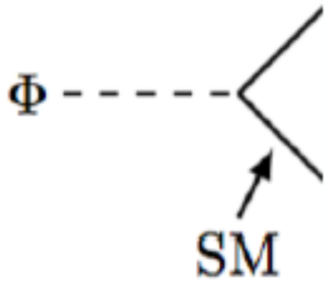


VECTOR-LIKE FERMIONS IN ALL INTERPRETATIONS OF 750 GeV EXCESS

BSM STATES are needed to make the signal strength!

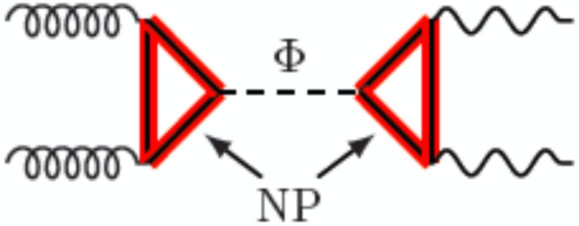


excluded by



1512.04928

$$\frac{\mathrm{BR}(\Phi \to \mathrm{SM\ SM})}{\mathrm{BR}(\Phi \to \gamma\gamma)} \approx \left(\frac{4\pi}{\alpha}\right)^2 \sim 0.2 \times 10^5$$



New physics controls both production & decay

$$\mathcal{L}_{even} = \frac{S}{\Lambda}(g_{GG}G^2 + g_{BB}B^2 + g_{WW}W^2) + \ldots$$

$$\mathcal{L}_{odd} = \frac{a}{\Lambda}(g_{G\tilde{G}}G\tilde{G} + g_{W\tilde{W}}W\tilde{W} + g_{B\tilde{B}}B\tilde{B}) + \ldots$$

These Lagrangians contains 90% of the paper have been written

S- SINGLET OF SU(2)xU(1)

$$\mathcal{L} = c_f S f \bar{f}$$

FERMIONS ARE COLORED AND CHARGED UNDER SU(2)xU(1) OR PART OF IT; BUT WE NEED Mf>Ms/2

THE LOOPS CONTRIBUTE TO THE EFFECTIVE LAGRANGIAN AND GIVE

$$\lambda_{g,\gamma} \approx c_f \frac{v}{M} \times \text{GROUP FACTORS}$$

GENERIC PREDICTIONS:

- SEVERAL VECTOR-LIKE FERMIONS AND/OR LARGE YUKAWA COUPLINGS c_f NEEDED
- OTHER DECAY CHANNELS PRESENT (WW, ZZ, Z γ)
- ONLY SMALL WIDTH SOLUTIONS
- ONLY SMALL MIXING OF S WITH h ACCEPTABLE (S→hh DANGEROUS FOR THE FIT)

S- SECOND HIGGS IN THE 2HDM OR IN MSSM:

TOO SMALL RATES WITH THE SM PARTICLES IN THE LOOPS (THE COUPLINGS TO GLUONS AND PHOTONS ONLY AT THE LOOP LEVEL BUT TREE LEVEL DECAYS TO THE SM FERMIONS MAKE THE
TOTAL WIDTH LARGE AND THE BR($H \to 2\gamma$) TOO SMALL

OVERALL CONCLUSION:

THE PICTURE IS A BIT FUZZY. VARIOUS OPTIONS ARE OPEN

BUT NONE IS REALLY STRIKING. AN OBVIOUS EXPERIMENTAL

DIRECTION (APART FROM CONFIRMING THE 2 PHOTON

EXCESS) IS TO SEARCH FOR SIGNALS IN OTHER CHANNELS, TO

UNDERSTAND THE ORIGIN OF THE EFFECTIVE LAGRANGIANS.

ON THE THEORY SIDE: DEVELOP MORE COMPLETE MODELS , WITH SOME ADDITIONAL MOTIVATION

Hints for New Physics in the Flavor Sector

SM AND FLAVOR (= FERMION FAMILIES)

IN CERTAIN SENSE, FLAVOR IS A BEYOND THE SM CONCEPT!

3 FAMILIES OF QUARKS AND LEPTONS WITH IDENTICAL QUANTUM NUMBERS, AND IN CONSEQUENCE IDENTICAL GAUGE INTERACTION, WHICH DIFFER ONLY BY THEIR INTERACTIONS WITH THE HIGGS FIELD **(FIFTH FORCE!)**

SM:
VERY IMPORTANT CONCLUSION FOR CHARGED LEPTONS (IN THE APPROXIMATION OF ZERO NEUTRINO MASSES):

LEPTON FLAVOUR CONSERVATION

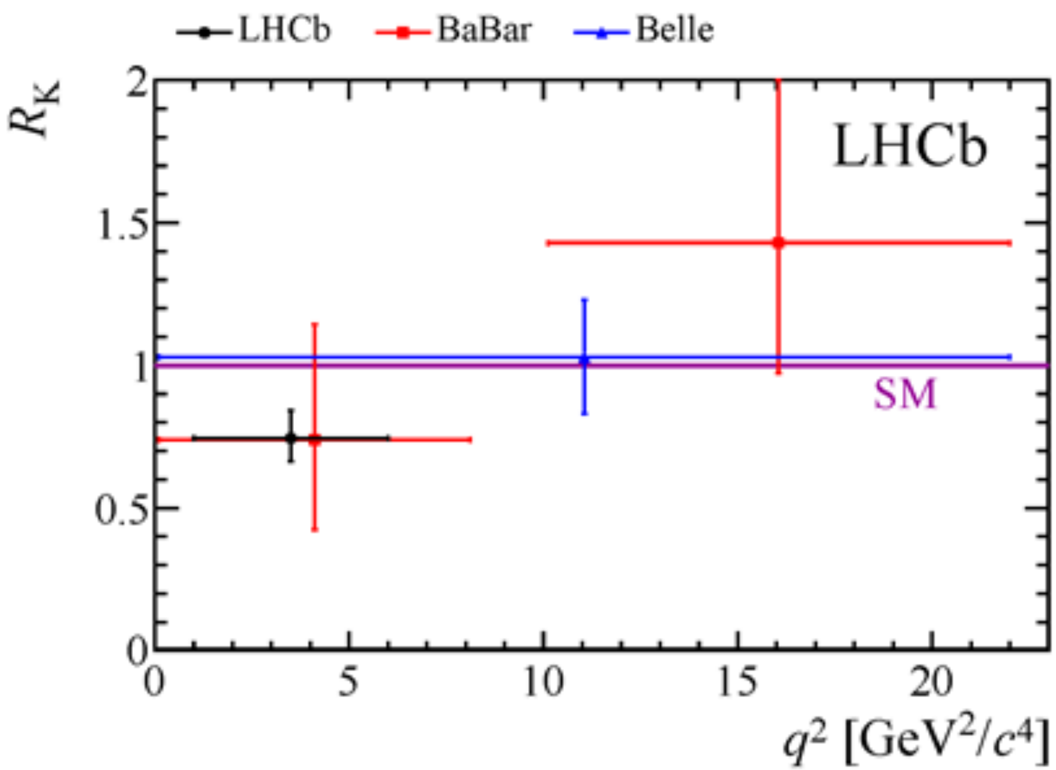
UNIVERSALITY OF LEPTON GAUGE INTERACTIONS, BOTH IN CHARGED AND NEUTRAL CURRENTS

$b \to s\gamma (B \to K\gamma)$ $\qquad\qquad$ $\mu \to e\gamma$

allowed $\qquad\qquad$ forbidden

R(K) = B→Kμμ/B→Kee

- Lepton flavour universality violation
- 2.6 σ deviation from the theoretically clean SM expectation



$B \rightarrow K^{*}\mu\mu$

2-3 σ deviation from the SM in some angular distributions

LEPTON UNIVERSALITY VIOLATION IN

$$R(D^{(*)}) \equiv \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$$

$3-4\ \sigma$ EFFECT

B→K*μμ

2-3 σ deviation from the SM in some angular distributions

LEPTON UNIVERSALITY VIOLATION IN

$$R(D^{(*)}) \equiv \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$$

$3 - 4\ \sigma$ EFFECT

Explanations of the Flavour Anomalies

$b \to s\mu^+\mu^-$

$b \to c\tau\nu$

Additional neutral gauge bosons (Z’)

Leptoquarks

Extended Higgs sector

IS FLAVOR A MORE INHERENT PART OF BSM PHYSICS?

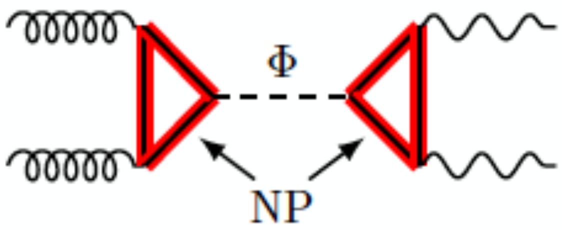
NEW INTERACTIONS WHICH ARE ALSO (LIKE THE HIGGS FORCE) NOT FLAVOR BLIND?

SUMMARY

LET’S WAIT AND SEE

It can make the signal because both production & decay are generated by dim 5 operators

$$\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \approx 10 \pm 3\mathrm{fb}$$



New physics controls both production & decay

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These Lagrangians contains 90% of the paper have been written

ASSOCIATED SIGNALS

CHANNELS	$\gamma\gamma$	ZZ	$Z\gamma$	WW	jj
coupling	$g_{BB}c_w^2 + g_{WW}s_w^2$	$g_{BB}s_w^2 + g_{WW}c_w^2$	$s_{2w}(g_{BB} - g_{WW})$	g_{WW}	g_{GG}
8 TeV bounds	<2 fb	<12 fb	<4 fb	<40 fb	<2.5 pb

I can tune the 2 parameters to set one of these 4 to zero

at least 2 channels with EW gauge bosons associated with di-photons are required for gauge invariance

tied to production

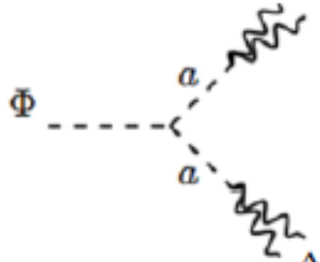
limits are weak (from CMS data scouting)

no ATLAS yet..

HOW GENERIC ARE THESE ASSOCIATED SIGNALS?

Two caveats related to collimated photons…

Spin 0:



the 4 photons collimated
look like 2!

1512.04928, 1512.05775, 1602.00949

$\Delta R = \frac{2m_a}{p_T}$

$m_a < 1$ Gev

axion-like states?

No extra channels required for gauge invariance.
Associated signal from production.

can we distinguish this from usual photons? 1603.00024

N.B. *with this & photon fusion we will see only di-photons*

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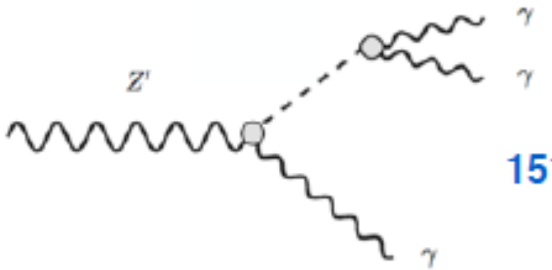
spin 1 cannot decay
into $\gamma\gamma$
then one has to play with kinematics



the 2 photons collimated
look like one!

1512.06833 & 1509.00476

Spin 1 viable ➡ Z+$\gamma\gamma$ associated signal

CP-even

$$c_V \frac{\sigma}{f}\left(m_Z^2 Z_\mu Z^\mu + 2m_W^2 W_\mu W^\mu + (\partial_\mu h)^2\right)$$

$$+\frac{\sigma}{f}\left(c_{gg}\frac{\alpha_3}{8\pi}G_{\mu\nu}^2 + c_{\gamma\gamma}\frac{\alpha_e}{8\pi}F_{\mu\nu}^2 + \ldots\right)$$

$$+c_f \frac{\sigma}{f} m_f \bar{f} f$$

CP-odd: suppression of VV, hh

$$\frac{\eta}{f}\left(C_{gg}\frac{\alpha_3}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + C_{\gamma\gamma}\frac{\alpha_e}{8\pi}F_{\mu\nu}\tilde{F}^{\mu\nu}\right)$$

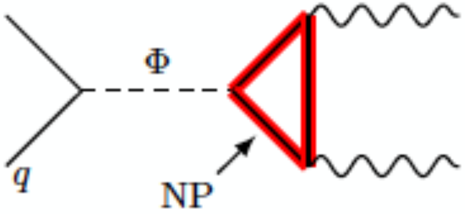
$$+\frac{\eta}{f}\left(C_{WW}\frac{\alpha_2}{4\pi}W_{\mu\nu}^{+}\tilde{W}^{-\mu\nu} + \ldots\right)$$

$$+c_f \frac{\eta}{f} m_f \bar{f}\gamma^5 f$$

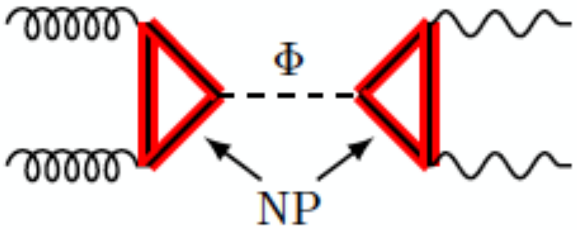
final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[6, 7]	$< 0.8\ (r/5)$
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	15 fb	[9]	$< 6\ (r/5)$
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]	$< 2\ (r/5)$
ZZ	< 12 fb	< 20 fb	[11]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[12]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[13]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[14, 15]	$< 20\ (r/5)$
$t\bar{t}$	< 550 fb	-	[16]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[17]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

-channel production of a single spin 0/2 resonance favoured by DATA

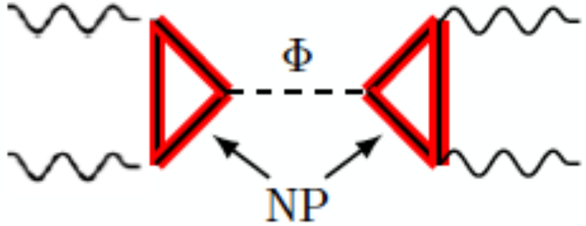
QUARKS



GLUONS



PHOTONS



$$\sigma(pp \to \Phi \to \gamma\gamma) = \frac{2J+1}{M\Gamma_\Phi s}\left[\sum_{\mathcal{P}} C_{\mathcal{P}\bar{\mathcal{P}}}\Gamma(\Phi \to \mathcal{P}\bar{\mathcal{P}})\right]\Gamma(\Phi \to \gamma\gamma)$$

PARTONIC INTEGRALS: $C_{\mathcal{P}\bar{\mathcal{P}}} \sim *\pi^2 \int_{m_\Phi^2/s}^{1} \frac{dx}{x}\left[f_{\mathcal{P}}(x) f_{\bar{\mathcal{P}}}(m_\Phi^2/sx) + \mathcal{P} \leftrightarrow \bar{\mathcal{P}}\right]$

$\frac{C_{\mathcal{P}\bar{\mathcal{P}}}(m_\Phi^2/s)}{s}$ controls 8 vs 13 TeV

DIFFERENCES:

MORE VECTOR-LIKE FERMIONS NEEDED, OF ORDER OF 10

STRONGER MASS SUPPRESSION MEANS LARGER YUKAWA COUPLINGS

ANOTHER INTERESTING POSSIBILITY: NONE OF THE VECTOR-LIKE FERMIONS IS CHARGED UNDER COLOR. S CAN BE PRODUCED THROUGH THE VECTOR BOSON FUSION. IT CAN WORK IF S IS NARROW. MAIN SIGNATURE: NO DI-JETS IN THE FINAL STATE.