A new resonance at 750 GeV?

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1. A new resonance at 750 GeV? Who ordered that?

2. Main features and first interpretations

3. Example of scenario: hMSSM+VLFs

4. Implications: looking at the bright side of life

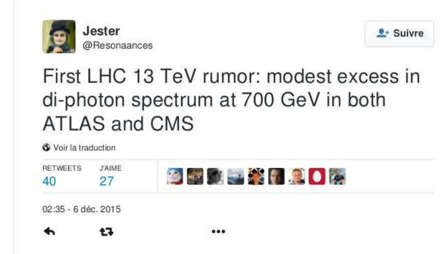
5. Summary

A. Angelescu, G. Moreau, AD: 2HDMs/MSSM+VLFs, arXiv:1512.04921

Y. Mambrini, G. Arcadi, AD: Dark Matter issues, arXiv:1512.04913

J. Ellis, R. Godbole, J. Quevillon, AD: Collider Signatures, arXiv:1601.03696

1. A new resonance at 750 GeV?



It all started with a rumor on Resonances:
and the smiles in LAL-Orsay ATLAS group...
I was not the only one to guess apparently:
CERN auditorium not empty on December 15!

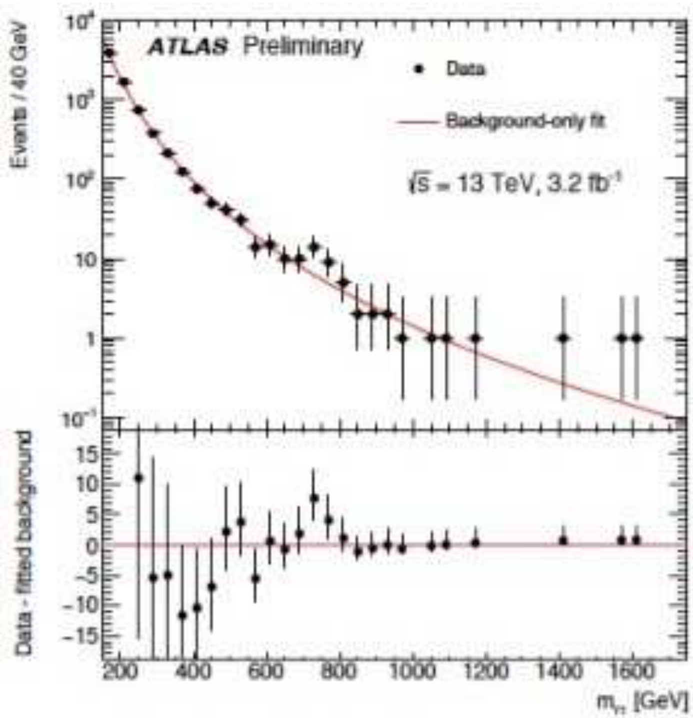
It had a smell of December 2011, the other Higgstorical day....

1. A new resonance at 750 GeV?

CERN Jamboree: LHC results at $\sqrt{s} = 13$ TeV and L= 3.2 fb^{-1} or 2.6 fb^{-1}

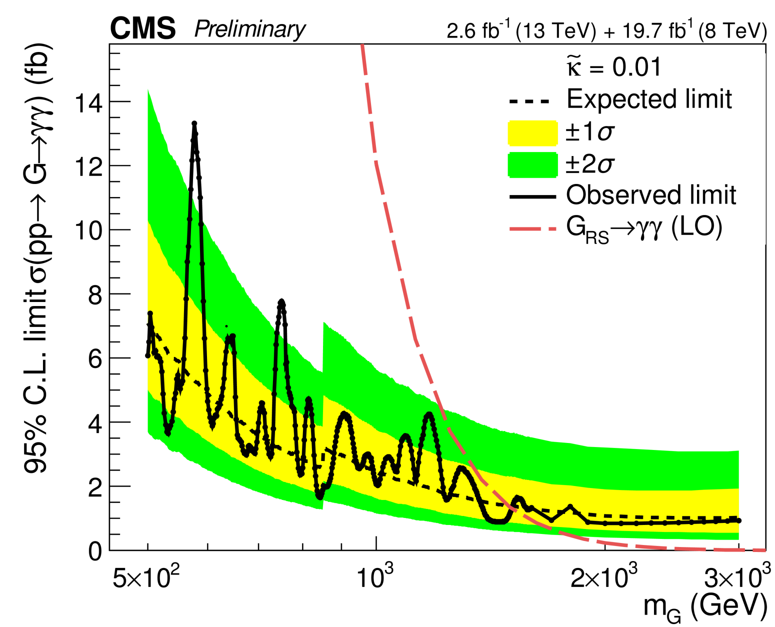
ATLAS di-photon results:

3.9σ local excess at 750 GeV
(but only 2.3σ after LEE?).
Total width of about 45 GeV
(but smaller width possible).



CMS di-photon results:

2.6σ local excess at 760 GeV
(but only 1.2σ after LEE?).
Signal larger with 8TeV data.
Total width apparently small.
(and analysis targets spin-2).



1. A new resonance at 750 GeV?

And?

Experimentalists:

Too early to say anything!

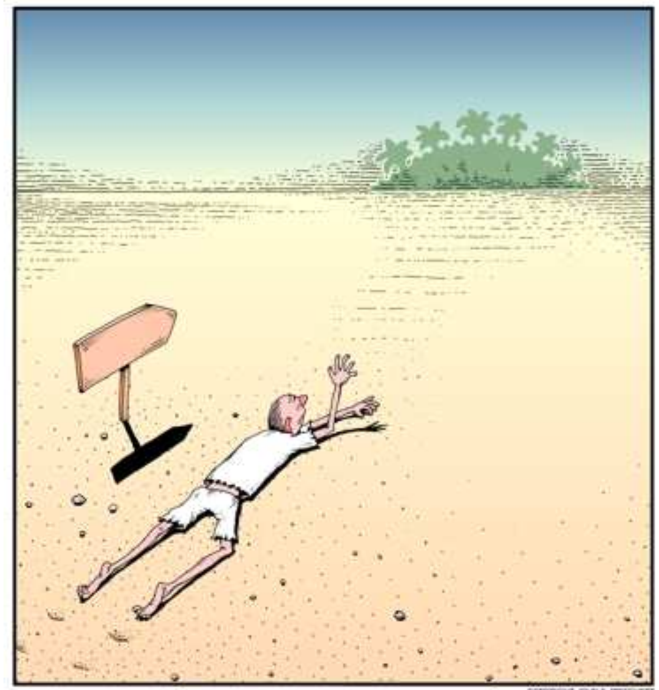
It is only three poor sigmas!

and if you insist a little bit:

So do your job and collect data (and leave the theorists enjoy!)

Poor theorists:

Waiting for 30 years for NP, starting to get desperate... something interesting appears.



Do your job and interpret data! (healthy exercise anyway...)

1. A new resonance at 750 GeV?

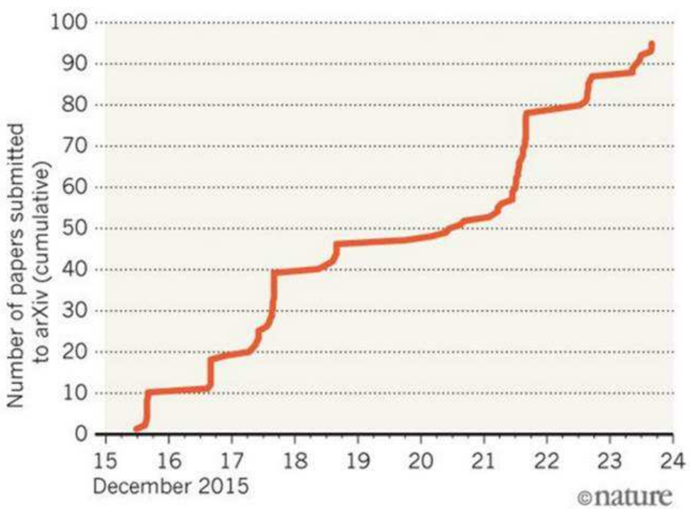
Tsunami of theory papers trying to interpret the 750 GeV diphotons:

10 papers the very first day,

100 at the end of the year,

about 170 papers as of today..

Nature article/Dorigo blog:



Florilège of explanations:

- **cascading heavy quarks,**
- **collimated 2x2 photons,**
- **new gauge bosons Z'+X**
- **sgoldstinos and other SUSY,**
- **quirks, hidden valleys?**
- **statistical fluctuation...**

But most papers are thinking about a new heavy resonance:

- **Dark matter mediators**
- **Technipions/Goldstones, ..**
- **Axions,Radions/Dilatons,..**
- **Gravitons or any spin 2...**
- **Higgs bosons...**

and other possibilities...

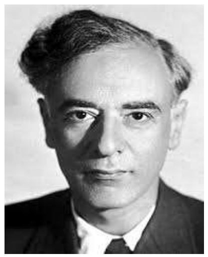
I try some quick/basic interpretations...

2. Main features and first interpretations

If resonance: obviously integer spin:

the observation is made in $X \to \gamma\gamma$:

the Landau–Yang theorem



(orbital momentum conservation):

rules our case of spin-one particle.

(ways to evade that but curious...).

Either spin–zero or spin–two.

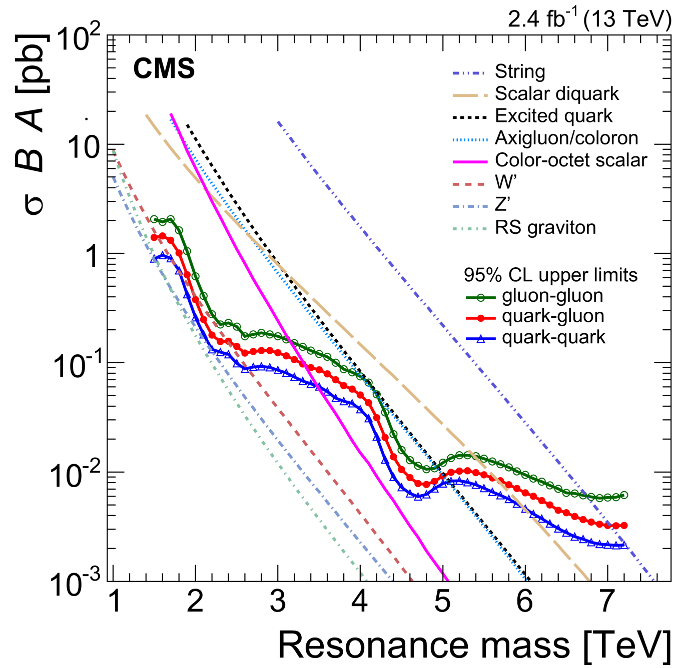
Spin–2 has democratic couplings:

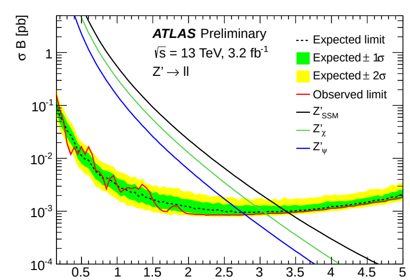
(as in the case of KK gravitons eg):

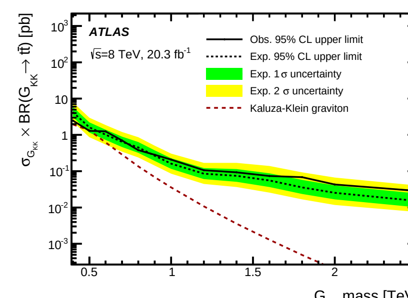
should also appear in $\ell\ell$, jj, VV, Vh

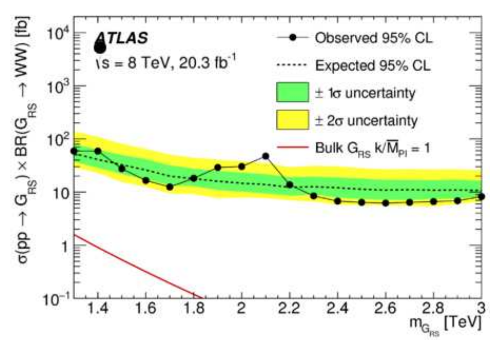
no sign of that in other searches.

Spin–zero is more likely.









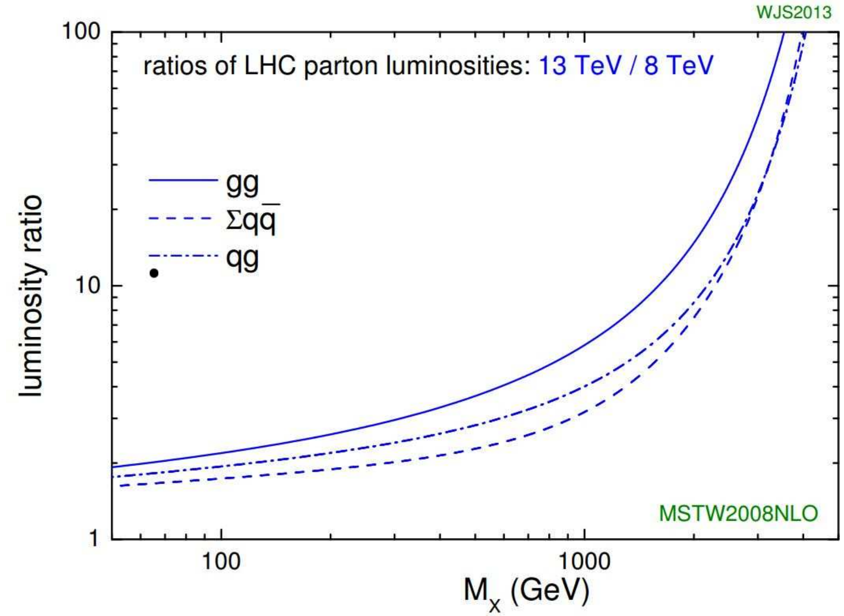
2. Main features and first interpretations

Does it come from gg or $q\bar{q}$?
Well, to cope with 8 TeV data,
it should better come from gg:

$$\mathcal{R}_i = \frac{(\sigma_S^i/\sqrt{\sigma_B})_{\text{13 TeV}}}{(\sigma_S^i/\sqrt{\sigma_B})_{\text{8 TeV}}}$$

$$\mathcal{R}_{i=gg} \simeq 3 \text{ v.s.} \mathcal{R}_{i=q\bar{q}} \simeq 1.7$$

gg: still tension with 8 TeV data...

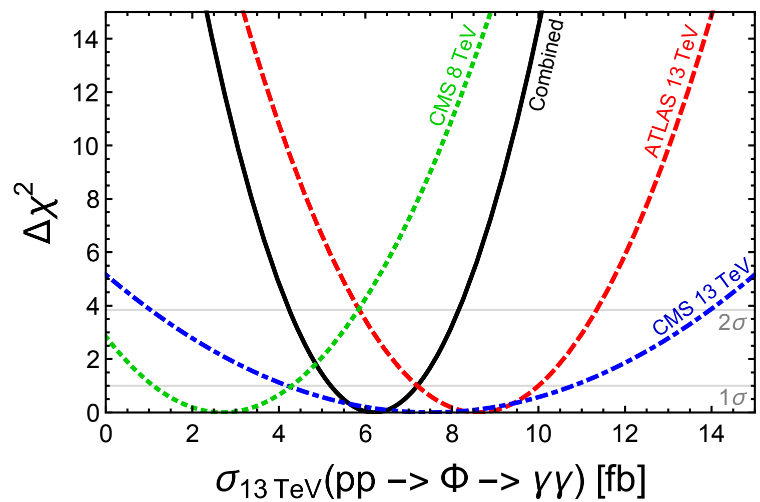


Prefers gg via heavy particles to light quarks: likely to be Higgs–like!
It is a scalar or pseudoscalar Higgs boson: we baptize it Φ =H or A.

Φ production cross section?
Fit all data and make a χ^2:
ATLAS at 13 TeV run only,
CMS at both 8 and 13 TeV runs,

$$\Rightarrow \sigma(\Phi) = 6 \pm 2 \text{ fb}$$

pretty large cross section!



2. Main features and first interpretations

The Φgg and $\Phi\gamma\gamma$ couplings should be induced by heavy fermion loops:

$$\Gamma(\Phi \to gg, \gamma\gamma) \propto g^2_{s,w} \left| \sum_F \lambda_{\Phi FF}/m_F \times A^{\Phi}_{1/2}(\tau_F) \right|^2$$

$$A^S_{1/2} = 2\left[\tau_F + (\tau_F - 1) f(\tau_F)\right] \tau_F^{-2} \qquad \tau_F = M^2_\Phi/4m^2_F$$

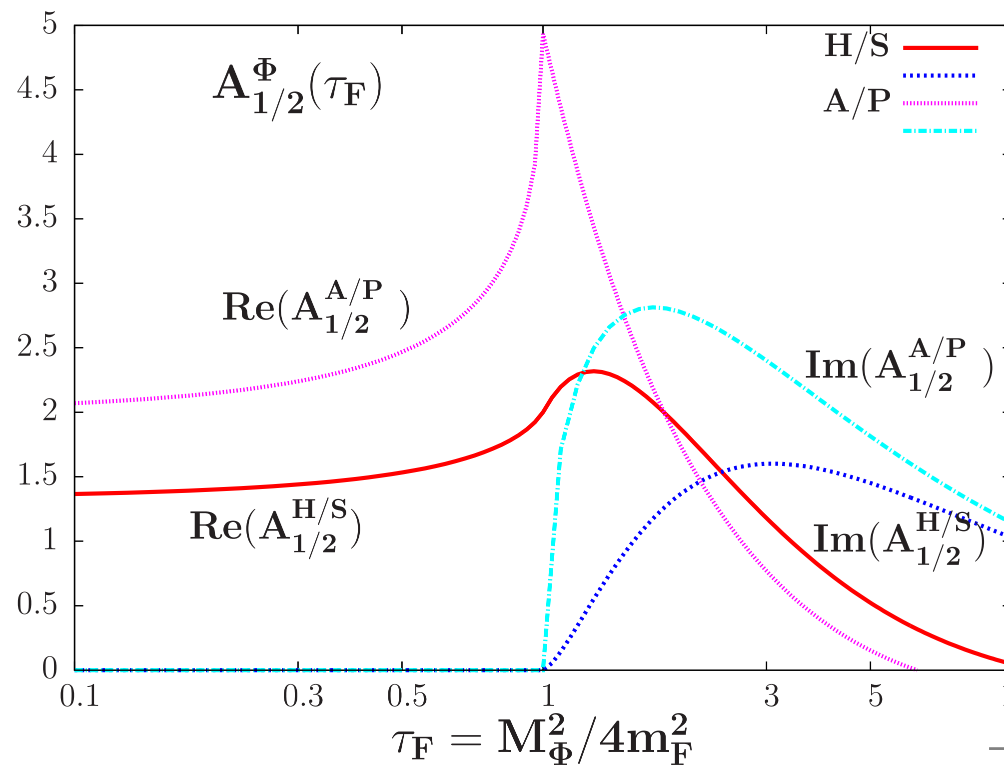
$$A^P_{1/2} = 2\tau_F^{-1} f(\tau_F) \qquad f(\tau_F) = \arcsin^2(\tau_F^{-1/2}) \text{ for } \tau_F \geq 1$$

$$m_F \gg M_\Phi \Rightarrow \begin{array}{l} A^P_{1/2} \to +2 \\ A^S_{1/2} \to +\frac{4}{3} \end{array}$$

For big loop contributions,

we need (simultaneously?):

- **big Yukawas,**
- **big charge/color,**
- $m_F \approx \frac{1}{2} M_\Phi$,
- **many fermions...**



2. Main features and first interpretations

Narrow width (as in CMS?): Φ couples only via loops, also to WW, ZZ, Zγ

In addition, one has $m_F \gtrsim \frac{1}{2} M_\Phi$ so that there are no decays $\Phi \to f\bar{f}, F\bar{F}$

Effective Lagrangian approach with the field strengths and their duals:

$$\mathcal{L}_{\rm eff}^{S/P} = \frac{e^2}{4v} c_{\Phi\gamma\gamma} \Phi F_{\mu\nu} F^{\mu\nu} / \tilde{F^{\mu\nu}} + \frac{g_s^2}{4v} c_{\Phi gg} \Phi G_{\mu\nu} G^{\mu\nu} / \tilde{G^{\mu\nu}}$$

$$\mathrm{BR}(\Phi \to \gamma\gamma) = \frac{\Gamma(\Phi\to\gamma\gamma)}{\Gamma(\Phi\to\gamma\gamma)+\Gamma(\Phi\to gg)} \approx \frac{\Gamma(\Phi\to\gamma\gamma)}{\Gamma(\Phi\to gg)} \approx \frac{c_{\Phi\gamma\gamma}^2}{c_{\Phi gg}^2} \frac{\alpha}{8\alpha_s} \approx 10^{-2}$$

Only vector-like fermion loops,

discuss several possibilities:

model 1: an $e_Q = \frac{2}{3}$ $T_{R,L}$ singlet.

model 2: $e_Q = \frac{2}{3}, -\frac{1}{3}$ $(U, D)_{R,L}$.

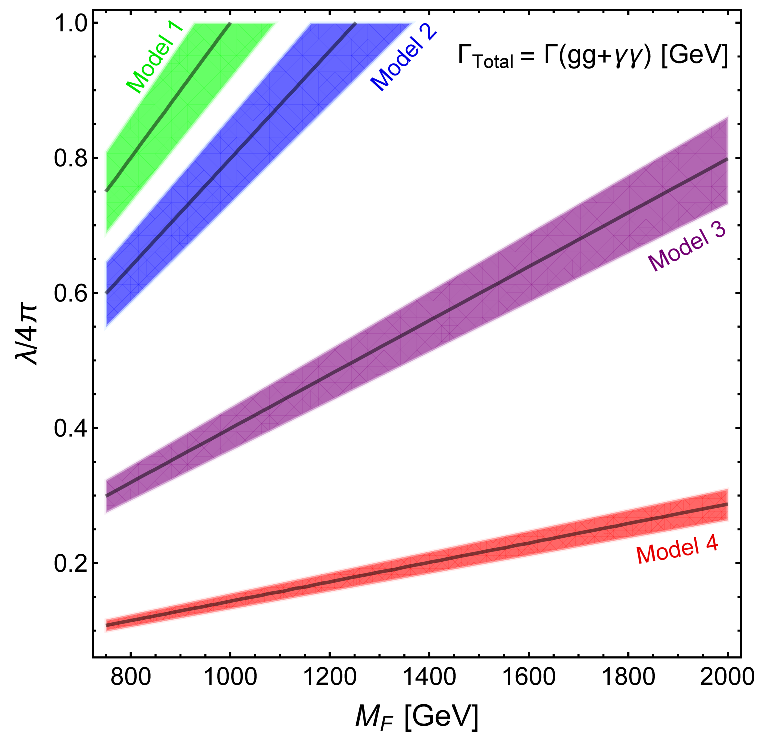
model 3: $(U, D)_{R,L}, T_{R,L}, B_{R,L}$.

model 4: $(U, D)_{R,L}, T_{R,L}, B_{R,L},$ $(L^1, L^2)_{R,L}, E_{R,L}$

LHC Φ xsection reproduced

for perturbative $\lambda^2/4\pi < 1/2$

and not too large VLF masses...



2. Main features and first interpretations

Large width scenario (as in ATLAS): Φ couples directly to heavy particles:

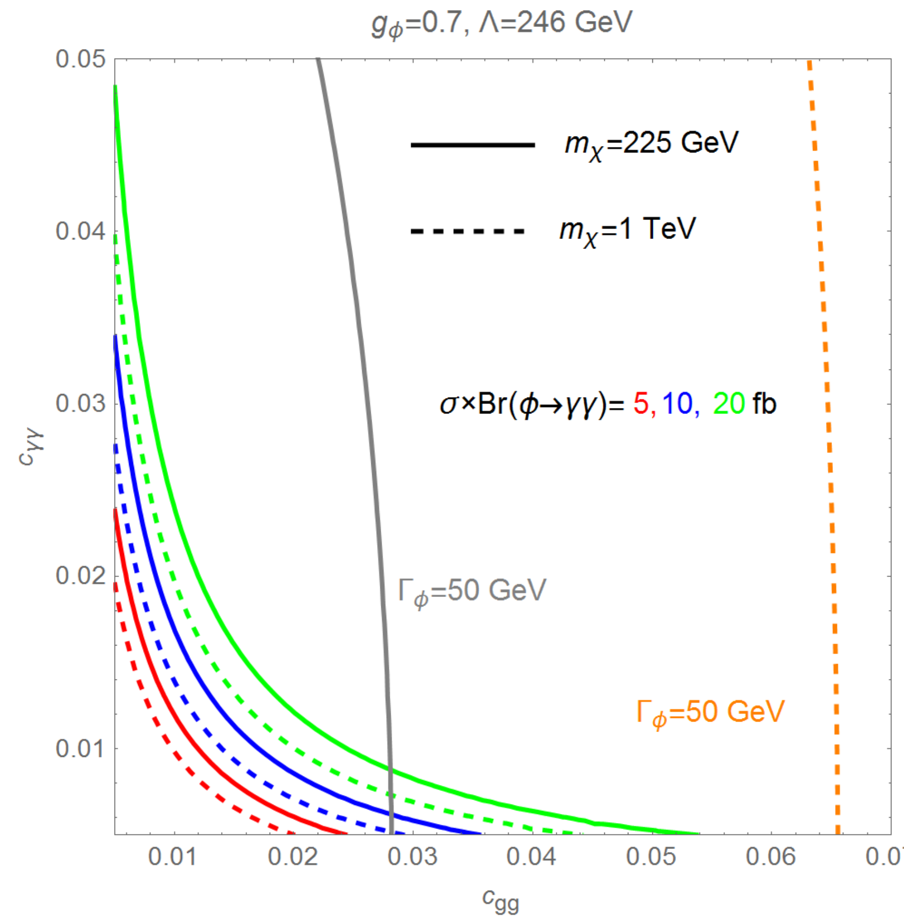
– the couplings to W and bosons: are all eaten by the SM-like h state,
– only fermion couplings allowed: either tops, bottoms, or new ones...

Again in the effective approach:

$$\mathcal{L}_1 = \mathcal{L}_S + c_f m_F/v \times \Phi \bar{f} f$$

$$\mathcal{L}_1 = \mathcal{L}_P + i c_f m_F/v \Phi \bar{f} \gamma_5 f$$

with the SM vev $v \approx$ 246 GeV; can fit $\sigma \times \mathrm{BR}$ and $\Gamma_\Phi \approx 50$ GeV for reasonable $c_{\Phi gg}, c_{\Phi\gamma\gamma}$ and m_F.



The best way to describe the large width possibility is the 2HDM/MSSM
An example would be the hMSSM: AD, Maiani, Polosa, Quevillon, Riquer arXiv:1307.5205 [hep-ph] and arXiv:1502.05653 [hep-ph].

3. Example of interpretation: hMSSM+VLFs

In the MSSM: two Higgs doublets: $\mathbf{H_1} = \begin{pmatrix} \mathbf{H_1^0} \\ \mathbf{H_1^-} \end{pmatrix}$ and $\mathbf{H_2} = \begin{pmatrix} \mathbf{H_2^+} \\ \mathbf{H_2^0} \end{pmatrix}$,

After EWSB (which can be made radiative: more elegant than in the SM):

Three dof to make $\mathbf{W_L^\pm, Z_L} \Rightarrow$ 5 physical states left out: $\mathbf{h, H, A, H^\pm}$

Only two free parameters at tree-level: $\tan\beta, \mathrm{M_A}$ but rad. cor. important:

$$\mathbf{M_h \lesssim M_Z |\cos 2\beta| + RC \lesssim 130\ GeV}\ ,\ \mathbf{M_H \approx M_A \approx M_{H^\pm} \lesssim M_{EWSB}}$$

– Couplings of $\mathrm{h, H}$ to VV are suppressed; no AVV couplings (CP).

– For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

In the decoupling limit: MSSM reduces to SM but with a light SM Higgs.

This decoupling limit occurs in 2HDM extension: alignment limit...

a SM-like light and two CP-odd like heavy Higgses with cplg to t,b,τ only

$$\Rightarrow \mathbf{h \equiv H_{SM}}\ ,\ \mathbf{\Phi = H, A}$$

3. Example of interpretation: hMSSM+VLFs

MSSM Higgs sector simple at tree level: only two basic inputs, $\tan\beta, M_A$

Radiative corrections make it complicated as $RC = f(M_S, X_t, X_b, \mu, M_i ...)$

ex: $M_h^2 \overset{M_A \gg M_Z}{\to} M_Z^2 |\cos^2 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$

Only information so far on the MSSM from the LHC $\Rightarrow \begin{cases} M_h = 125 \text{ GeV} \\ M_S \gtrsim 1 \text{ TeV} \end{cases}$

hMSSM: trade the value $M_h = 125$ GeV **against the radiative corrections.**

Back to tree-level: only two inputs for Higgs sector and no SUSY parameters:

$$M_H^2 = \frac{(M_A^2 + M_Z^2 - M_h^2)(M_Z^2 c_\beta^2 + M_A^2 s_\beta^2) - M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

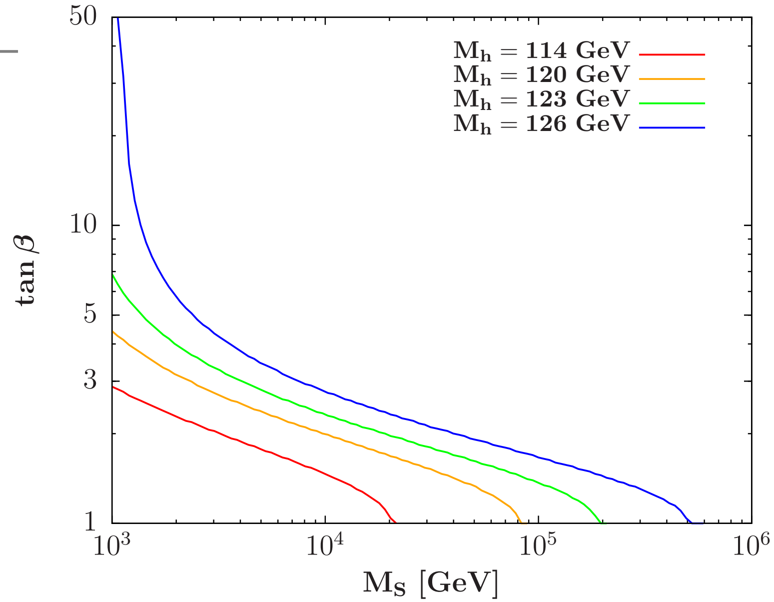
$$\alpha = -\arctan\left(\frac{(M_Z^2 + M_A^2) c_\beta s_\beta}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}\right)$$

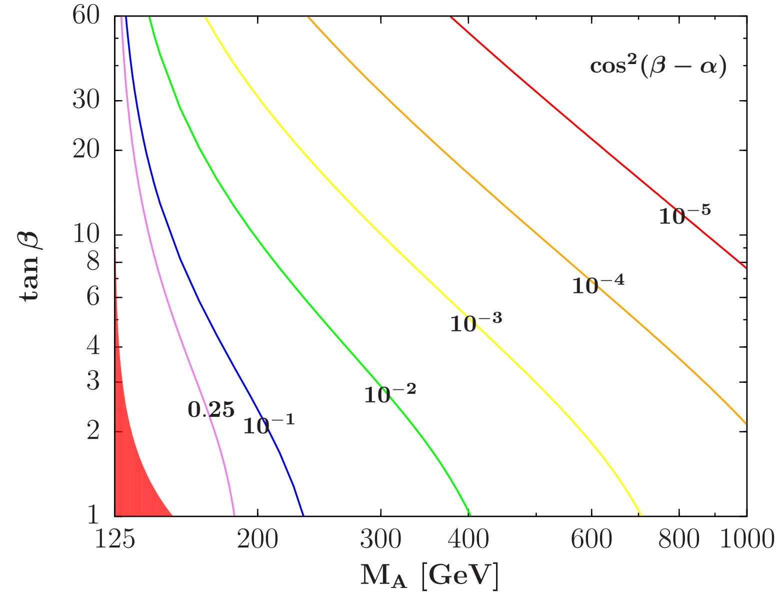
One also has the relation $M_{H^\pm}^2 \simeq M_A^2 + M_W^2$ **which is more general...**

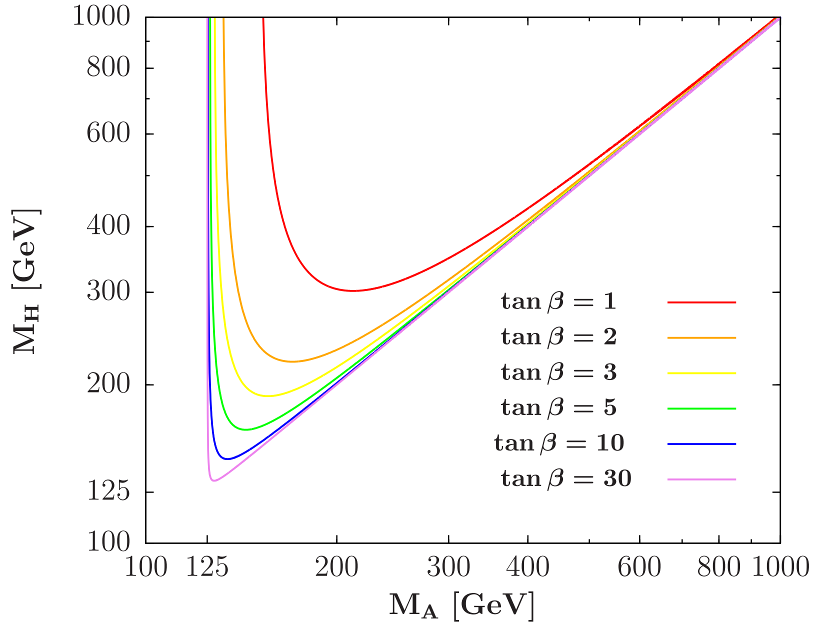
Effective and "model-independent" approach of the MSSM Higgs sector:

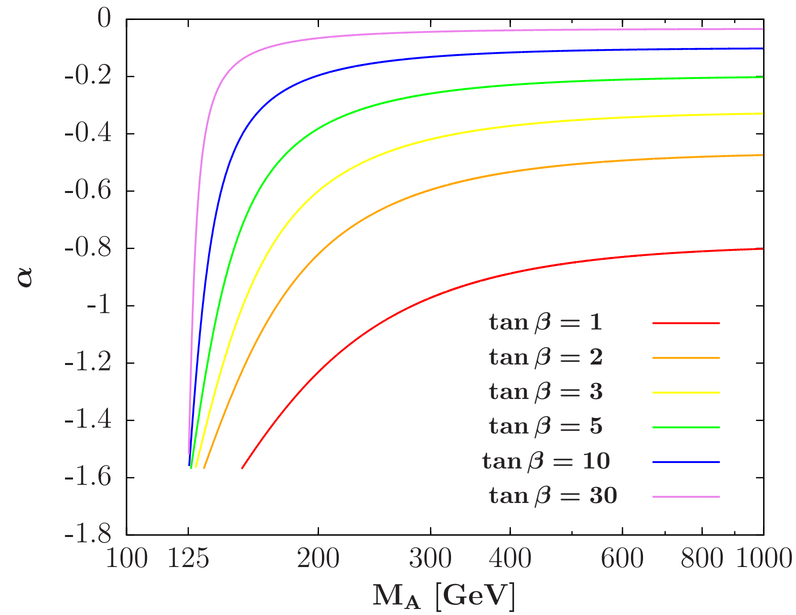
- **good: very simple, economical, .. and opens the possibility of low tan**β
- **bad: requires large** M_S **at low tan**β **(but apparently this is the case...?)**
- **ugly: needs large fine-tuning (but theory already fined-tuned anyway..).**

3. Example of interpretation: hMSSM+VLFs









AD, Maiani, Polosa, Quevillon, Riquer

3. Example of interpretation: hMSSM+VLFs

Large width scenario (as in ATLAS): obtained from Φ–fermion couplings

– couplings to massive gauge bosons all eaten by the SM–like 125 GeV h,

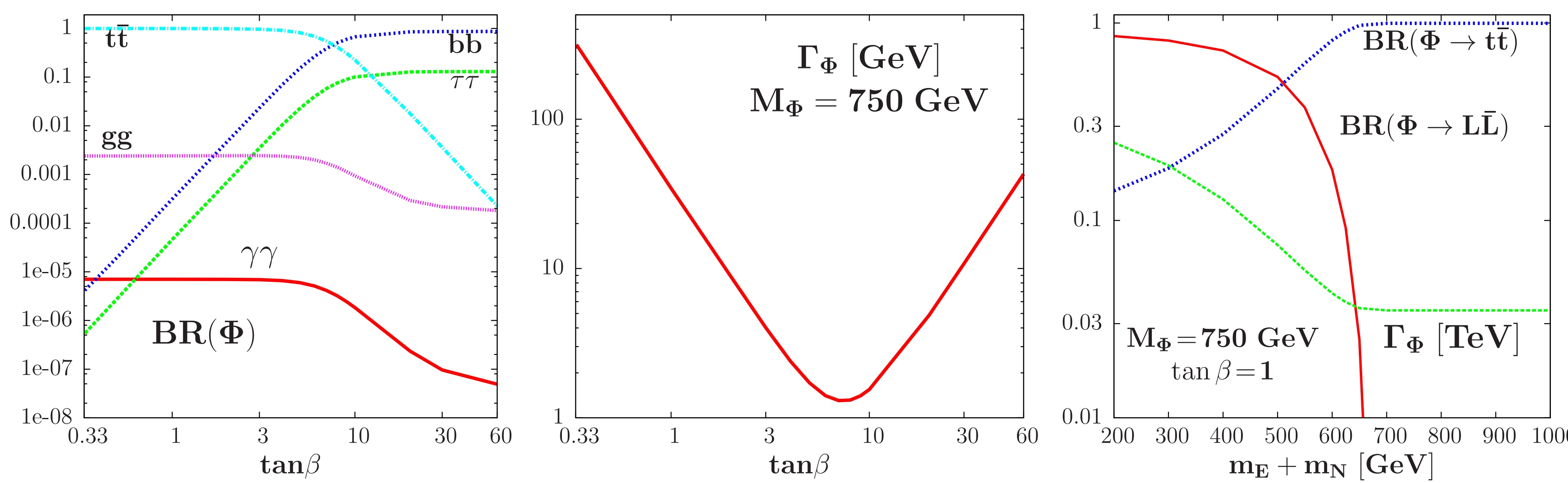
– only couplings to fermions allowed: either tops, bottoms, or new ones...

$$g_{\Phi tt} = \frac{m_t}{v} \cot\beta, \; g_{\Phi bb} = \frac{m_b}{v} \tan\beta, \; g_{\Phi\tau\tau} = \frac{m_\tau}{v} \tan\beta$$

with $\tan\beta = v_2/v_1$ small $\tan\beta \approx 1$ or large $\tan\beta \approx m_t/m_b \approx 60$

– $\tan\beta \approx 1$: $\mathrm{BR}(\Phi \to t\bar{t}) \approx 1, \mathrm{BR}(\gamma\gamma) \approx 10^{-5}, \; \Gamma_\Phi \approx 30$ GeV.

– $\tan\beta \approx 60$: $\mathrm{BR}(\Phi \to b\bar{b}) \approx .9, \mathrm{BR}(\gamma\gamma) \approx 10^{-7}, \; \Gamma_\Phi \approx 30$ GeV.



– $\tan\beta \approx$3–10: allow for light lepton (DM?) decays to get $\Gamma_\Phi \approx 30$ GeV.

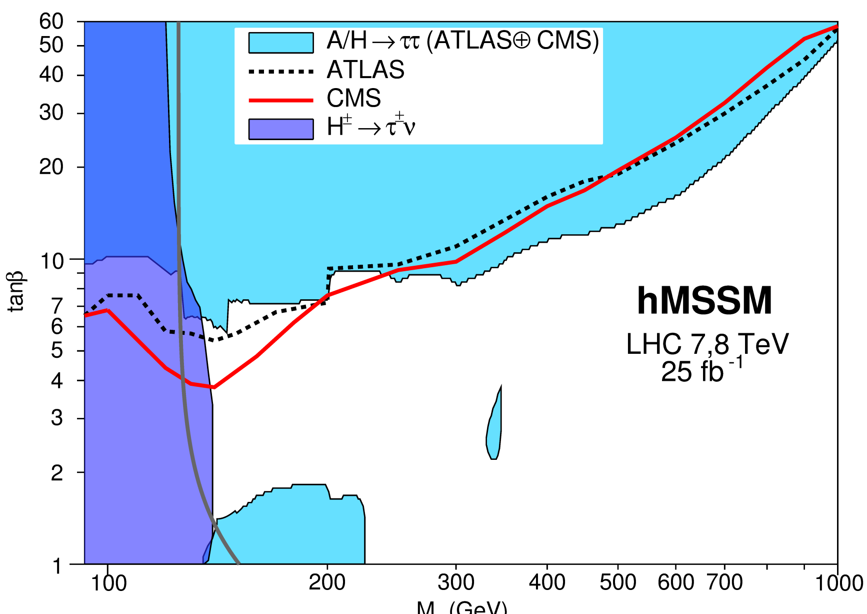
3. Example of interpretation: hMSSM+VLFs

Large values $\tan\beta \gtrsim 30$:

$\sigma(gg, b\bar{b} \to \Phi \to \tau\tau)$ **too large**

ATLAS+CMS very sensitive

$\Rightarrow$ **region totally excluded.**



NB: valid only if no SUSY decays

so that BR(H/A$\to\tau\tau$) maximal

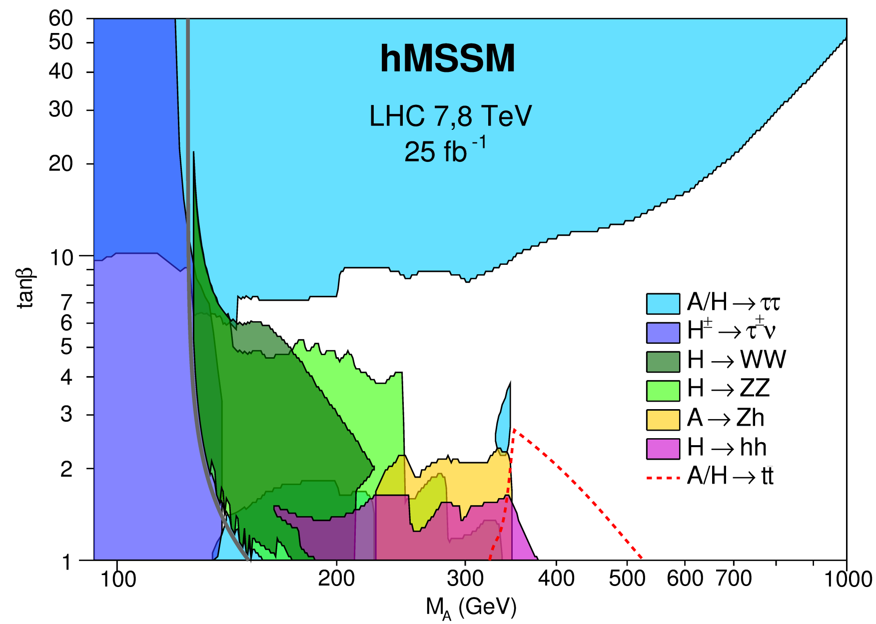
OK in the hMSSM with large M_S.

Low values $\tan\beta \lesssim 1$:

$\sigma(gg \to \Phi \to t\bar{t})$ **too large**

ATLAS+CMS searches sensitive

$\Rightarrow$ **region being excluded.**



NB: analysis valid for spin–1

(no interference with gg→tt bkg)

full Φ analysis in progress

3. Example of interpretation: hMSSM+VLFs

Unfortunately hMSSM or 2HDM without any new particle does not make it!

Rates for $gg \to \Phi \to \gamma\gamma$:

$\sigma(H) = 0.85$ **fb at 8 TeV**

$BR(H \to \gamma\gamma) \approx 6 \times 10^{-6}$

$\sigma(A) = 1.70$ **fb at 8 TeV**

$BR(A \to \gamma\gamma) \approx 7 \times 10^{-6}$

$\sigma \times BR(H + A) \approx 10^{-2}$ **fb**

We are short by a factor 500...

Include a bunch of VLFs:

– 3 families of 2 VLL doublets

– 3 doubly charged leptons

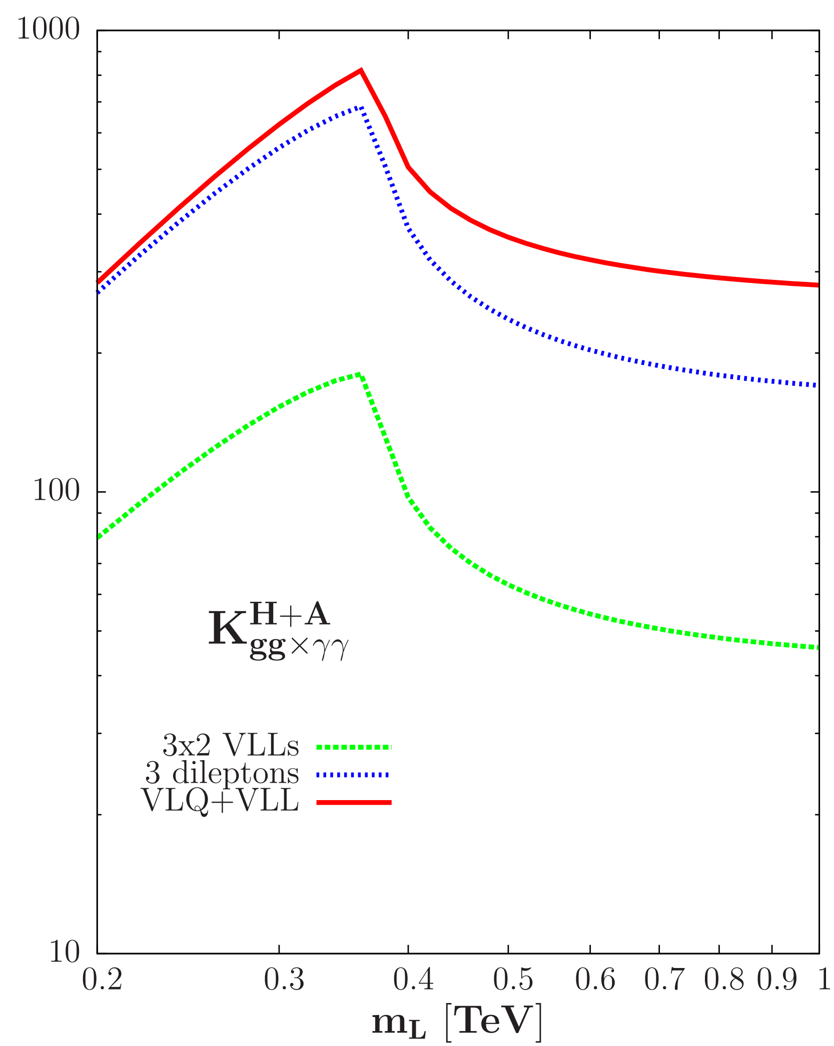
– one family of VLQ and VLL

(we set tanβ=3 to reduce Γ_Φ)

with usual Yukawa couplings

optimal effect at $m_F = \frac{1}{2} M_\Phi$

(But watch out for light Higgs).



3. Example of interpretation: hMSSM+VLFs

VLFs will also contribute to SM–like Higgs gg and $\gamma\gamma$ loops!

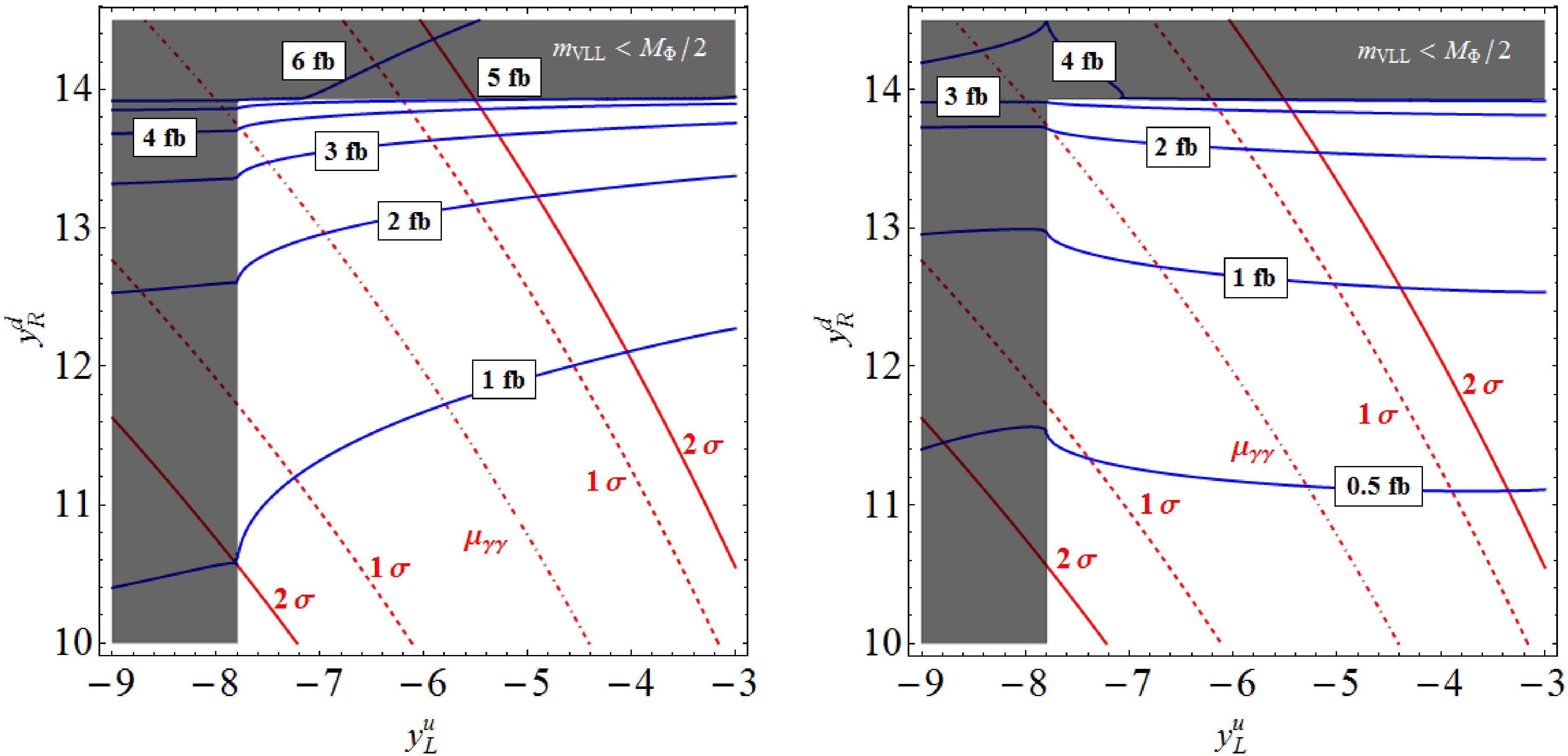
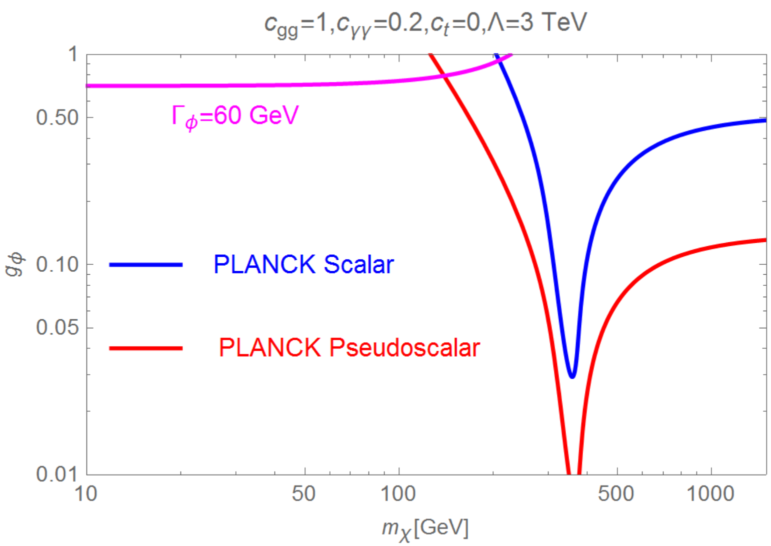


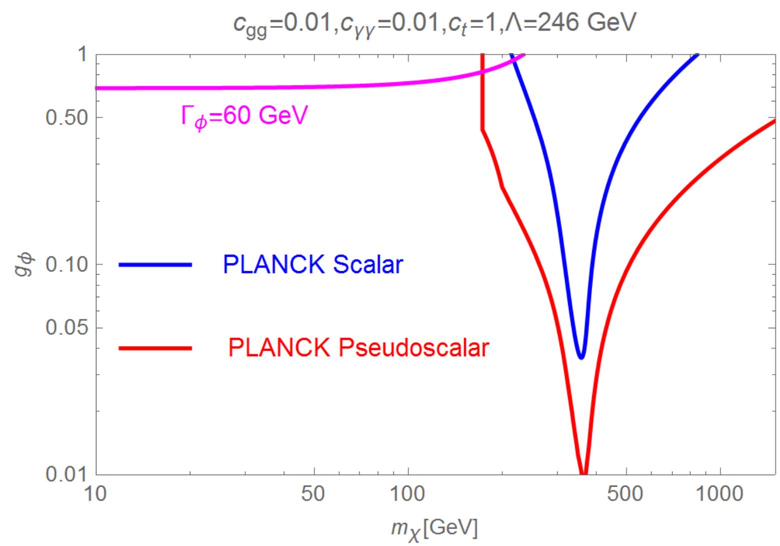
Figure 1: Contours of constant $\sum \sigma(gg \to \Phi) \times {\rm BR}(\Phi \to \gamma\gamma)$ and $\mu_{\gamma\gamma}$ in the $\{y^u_L, y^d_R\}$ plane, for MSSM (left) and type II 2HDM (right) including the $\mu_{\gamma\gamma} = 1.16 \pm 0.18 \pm 0.15$ constraint.

4. Implications: Dark Matter

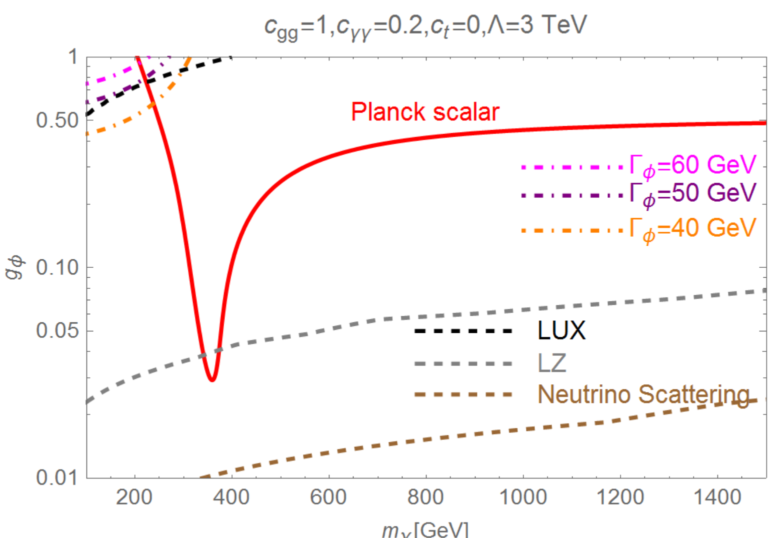
Φ **resonance is ideal mediator for Dark Matter: case of fermion X**

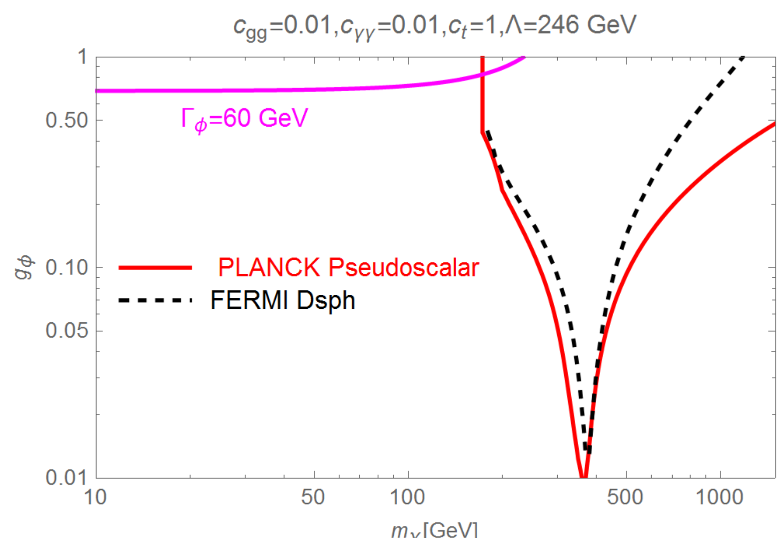
cosmological relic density Ωh^2 obtained by annihilation XX$\to \Phi \to$SM.





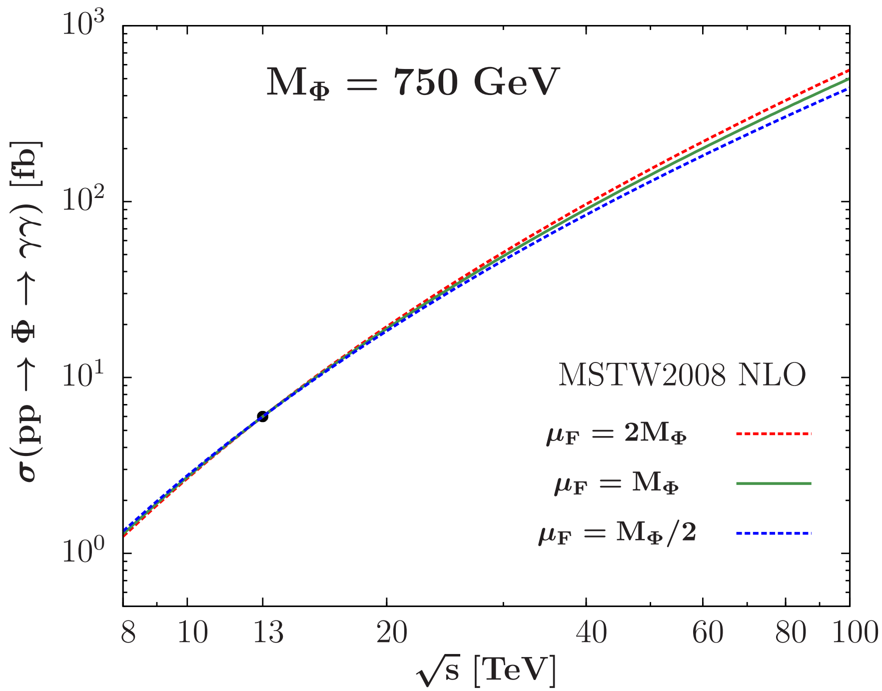
Good prospects for direct/indirect detection in astrophysical experiments.





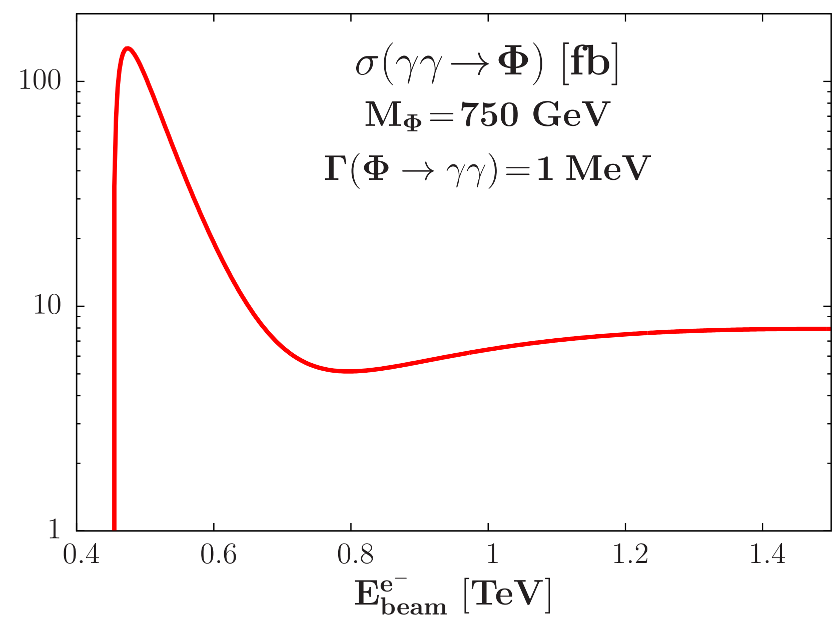
4. Implications: singlet resonance at colliders

Reproduce Φ resonance in pp:
same prod. process $gg \to \Phi\gamma\gamma$
grows with the gluon luminosity



Ideal for HE-LHC, FCC-hh, SPPC
2 orders magnitude more at 100TeV
check other WW,ZZ,Zγ final states.

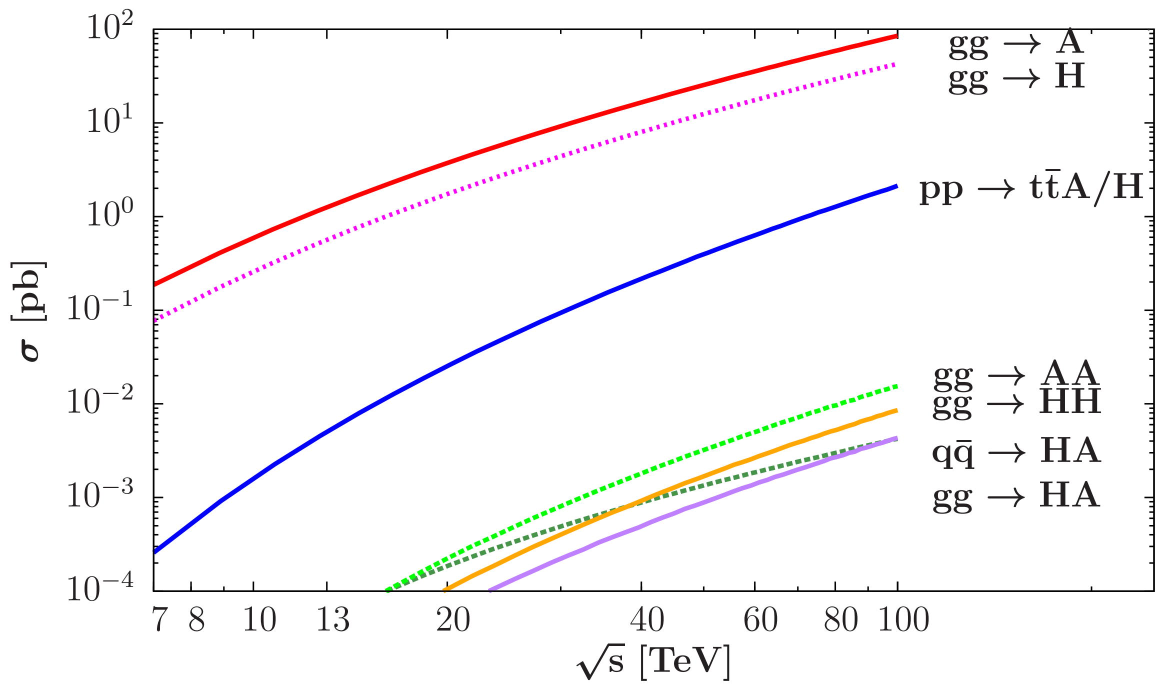
Future e+e- HE linear colliders
can be turned into $\gamma\gamma$ colliders
80% energy and same luminosity
$\Rightarrow$ **Φ production in $\gamma\gamma \to \Phi$**

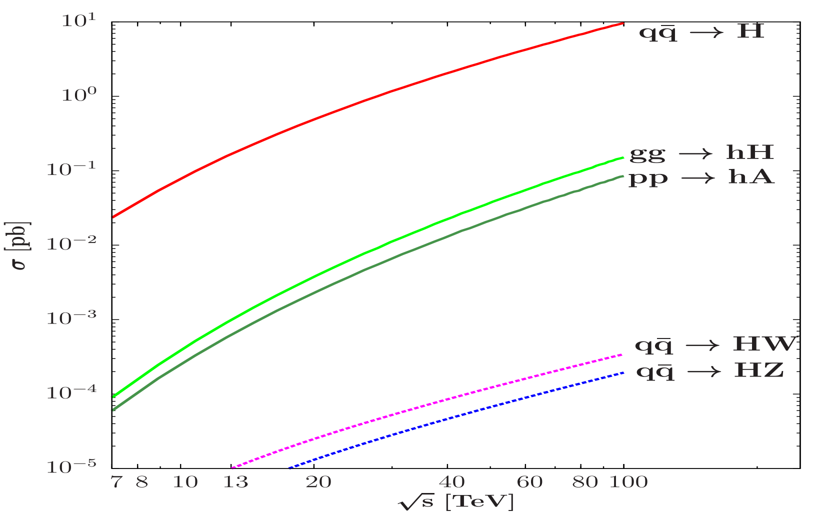


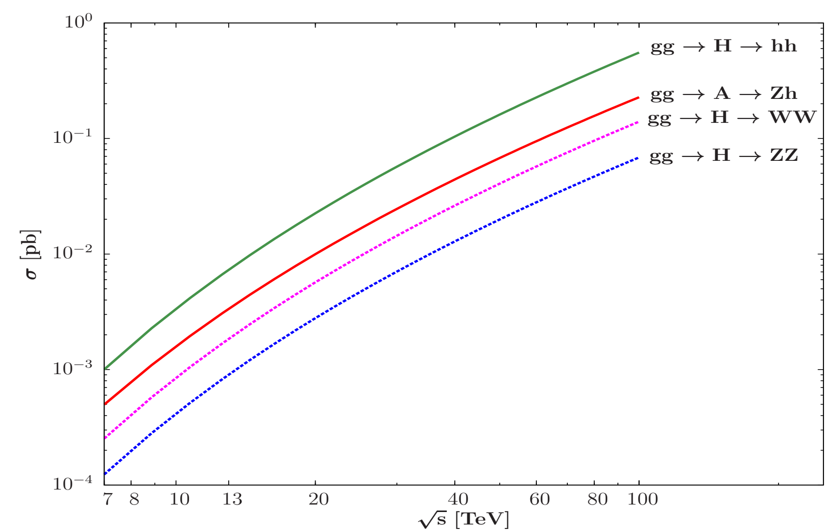
Ideal machine for a diphoton state:
Measure precisely $\Phi\gamma\gamma$ coupling
Check CP properties of resonance.

4. Implications: doublet resonance at colliders

Many more processes if Φ is in a 2HDM/hMSSM like scenario; in pp:

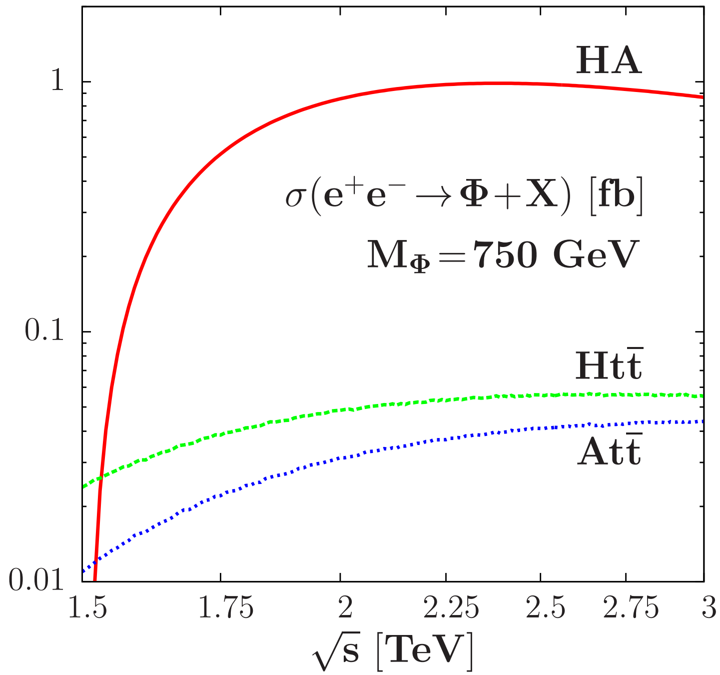


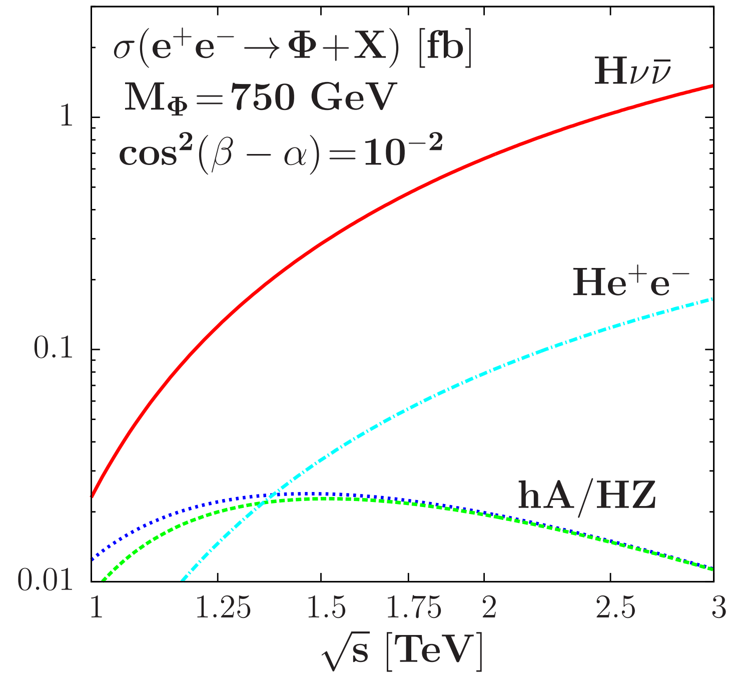


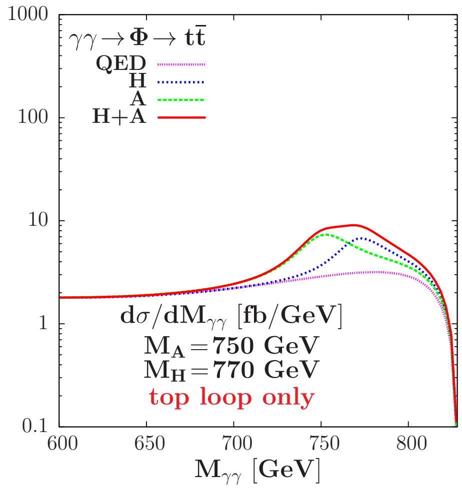


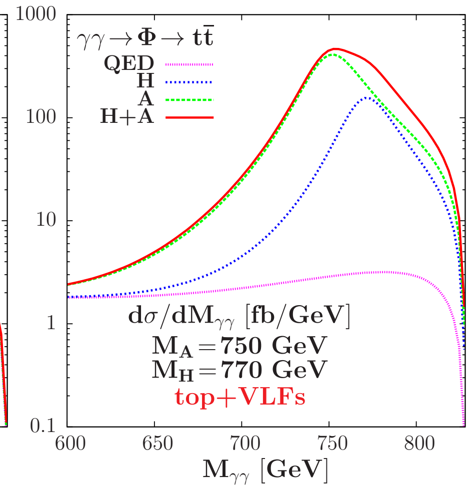
4. Implications: doublet resonance at colliders

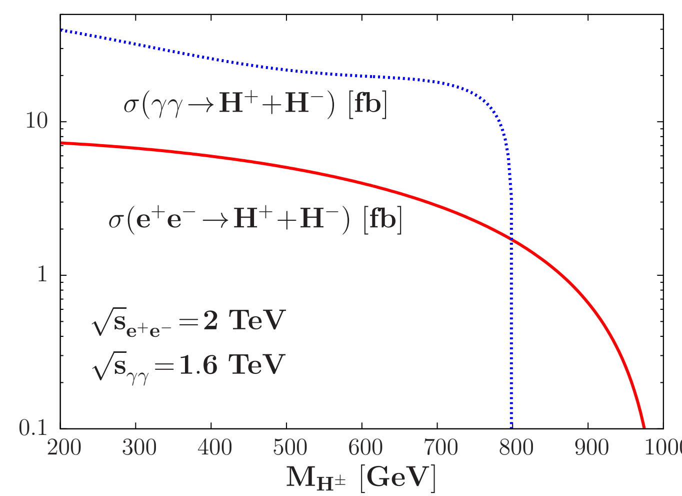
Many more processes if Φ is in a 2HDM/hMSSM like scenario; in e+e-:





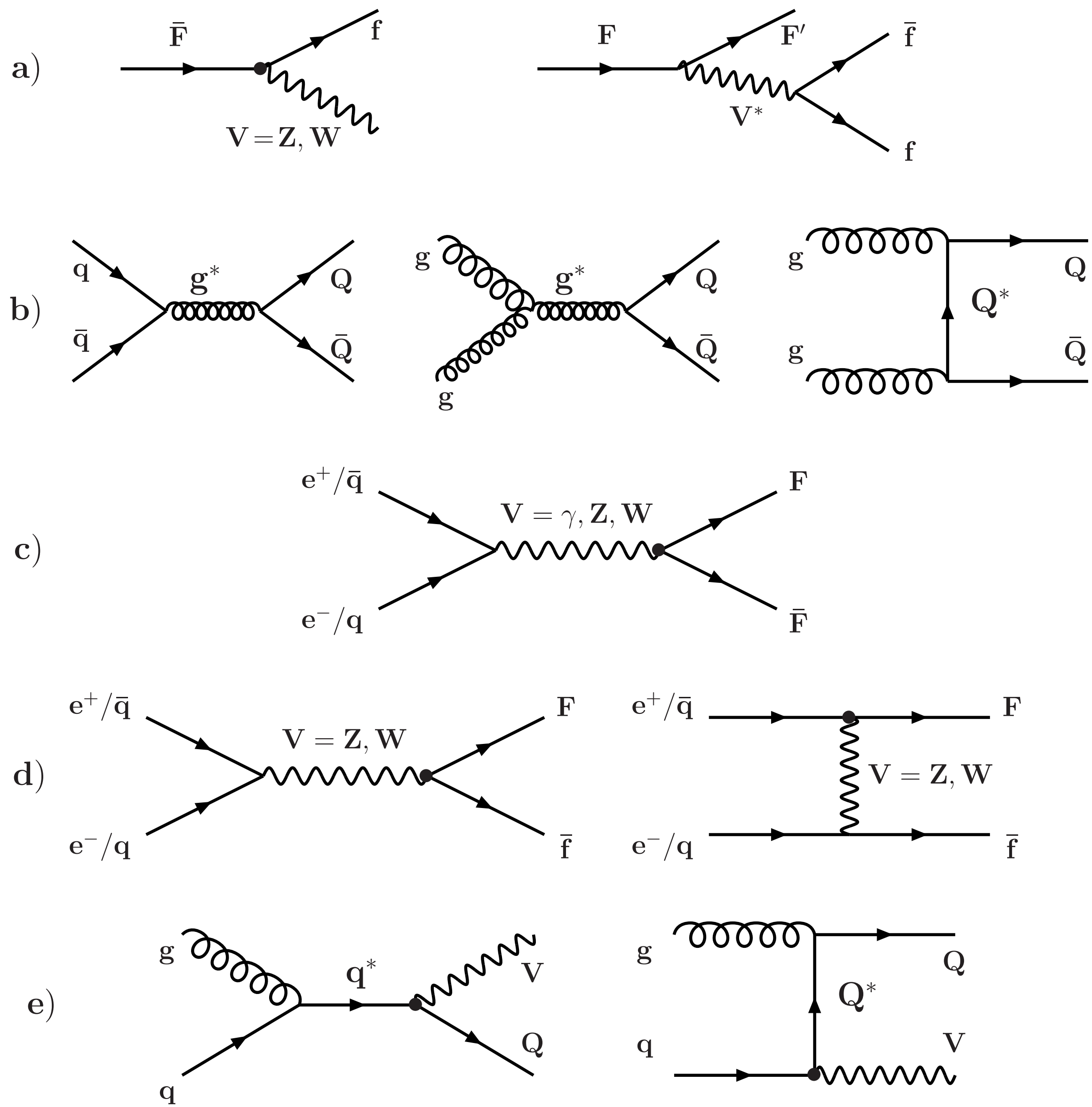






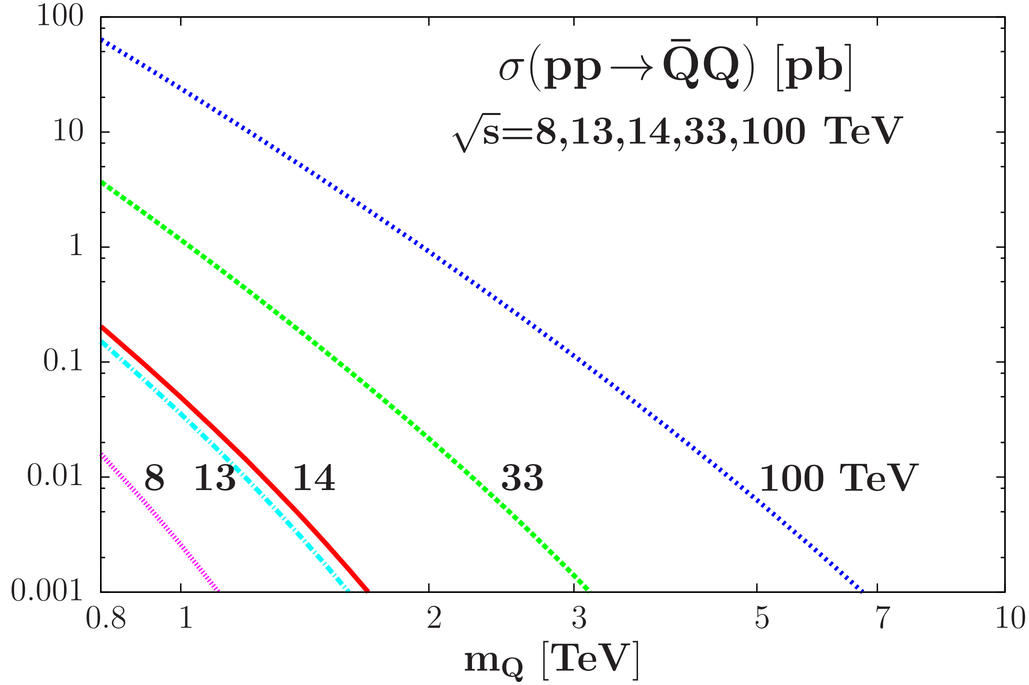
4. Implications: vector–like fermions

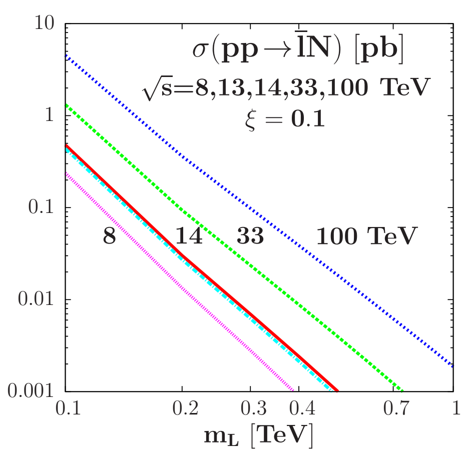
The vector–like fermions can be produced in pair or singly at colliders:

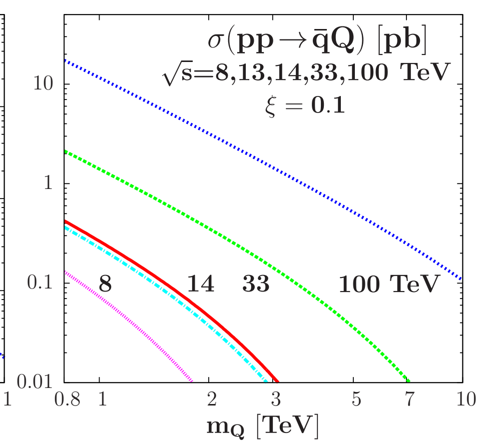


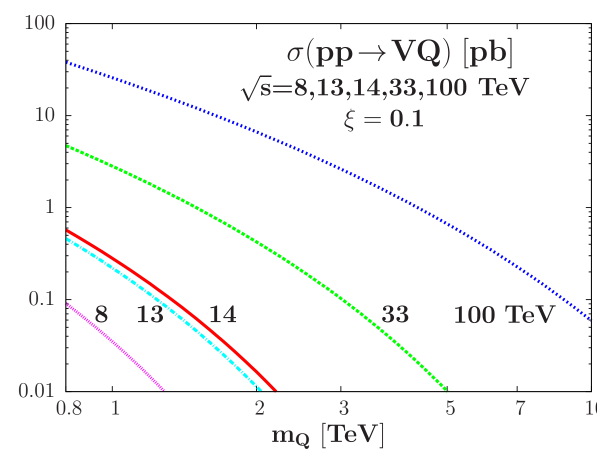
4. Implications: doublet resonance at colliders

First pair production of VLQs in pp and then single production via mixing:









4. Implications: vector–like fermions

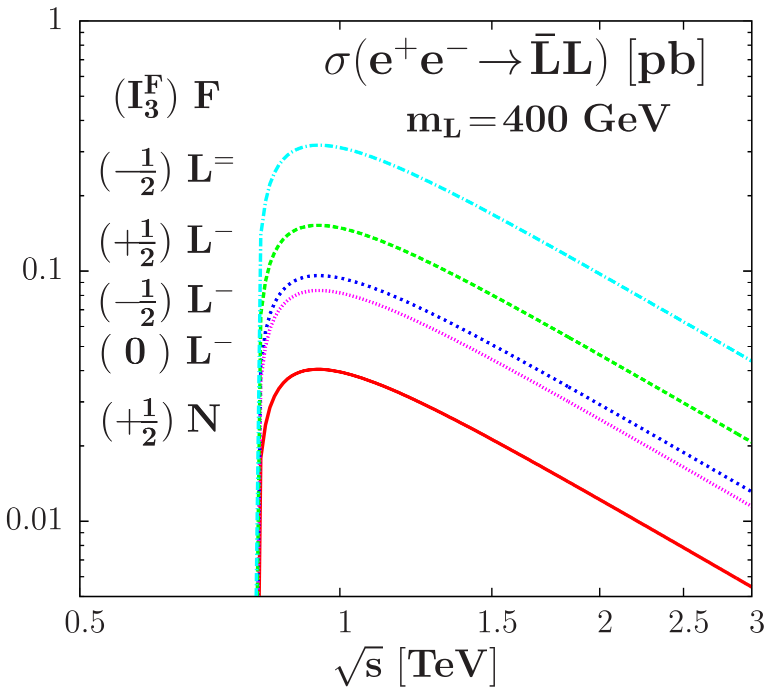
First pair production of VLQs in pp and then single production via mixing:

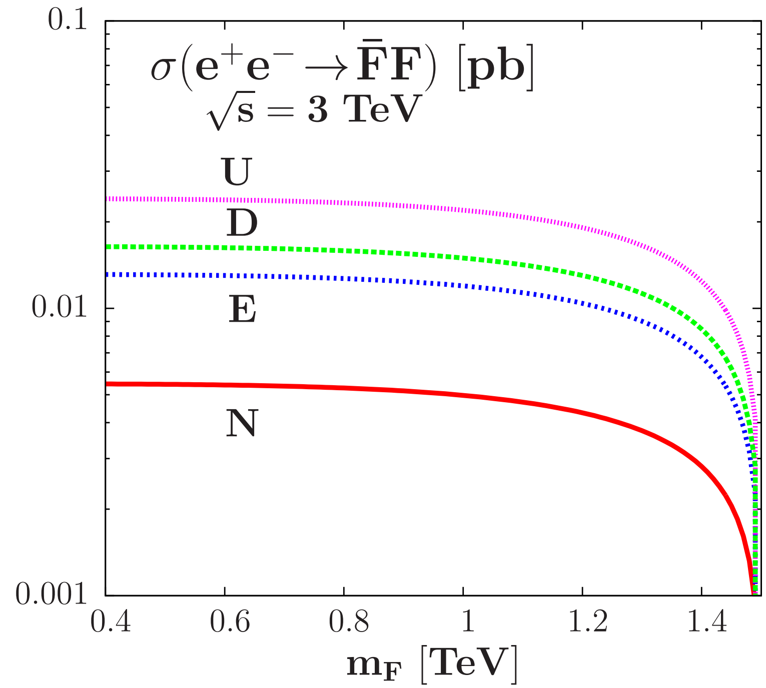
model	Vector-like quark mass sensitivity				Vector-like lepton mass sensitivity			
	100fb^{-1}	300fb^{-1}	300fb^{-1}	20ab^{-1}	100fb^{-1}	300fb^{-1}	300fb^{-1}	20ab^{-1}
	13 TeV	14 TeV	33 TeV	100 TeV	13 TeV	14 TeV	33 TeV	100 TeV
1	1.4	1.7	3.1	11.7	-			
2	1.5	1.8	3.4	12.7	-			
3	1.6	2.0	3.7	13.7	-			
4	1.6	2.0	3.7	13.7	0.56	0.73	1.7	5.3

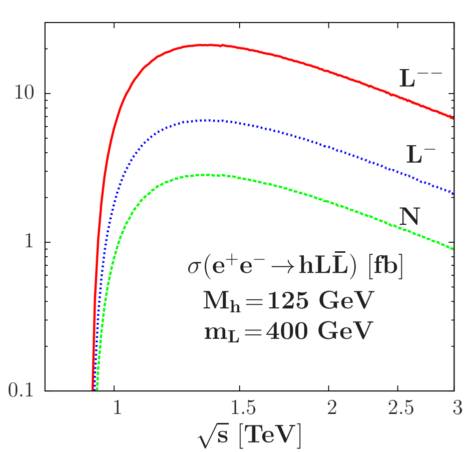
Table 1: Prospective model sensitivities to massive vector-like quarks (left) and leptons (right) [with the particle masses in TeV] in the indicated *pp* collider and scenario from extrapolations of the present LHC searches.

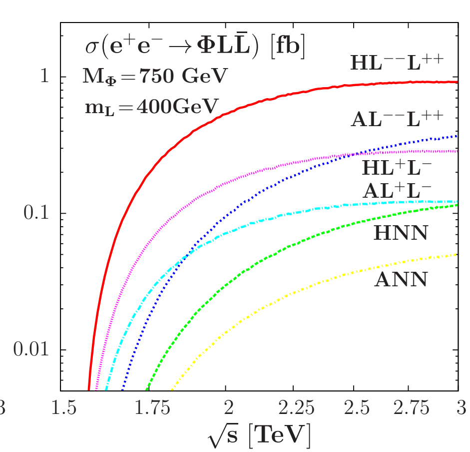
4. Implications: doublet resonance at colliders

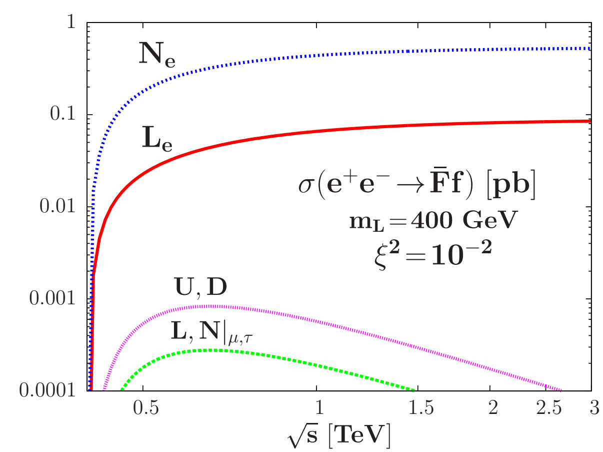
Pair production of VLLs in e+e- and then single production via mixing:











5. Summary

And? Too early to conclude. But life suddenly became bright...

It is really a new resonance?
Or is it simply a mirage?

If true then the future is bright!
(bye-bye the multiverse ...
and plenty of new physics!)

But again we should hear the experimentalists and their usual :

and wait for the coming data.
In summer we will now more
(but until then we can enjoy!)