Supersymmetry

in a nutshell

Outline

Goal: a self-contained overview of the main motivations, concepts, and how the pieces fit together for various applications

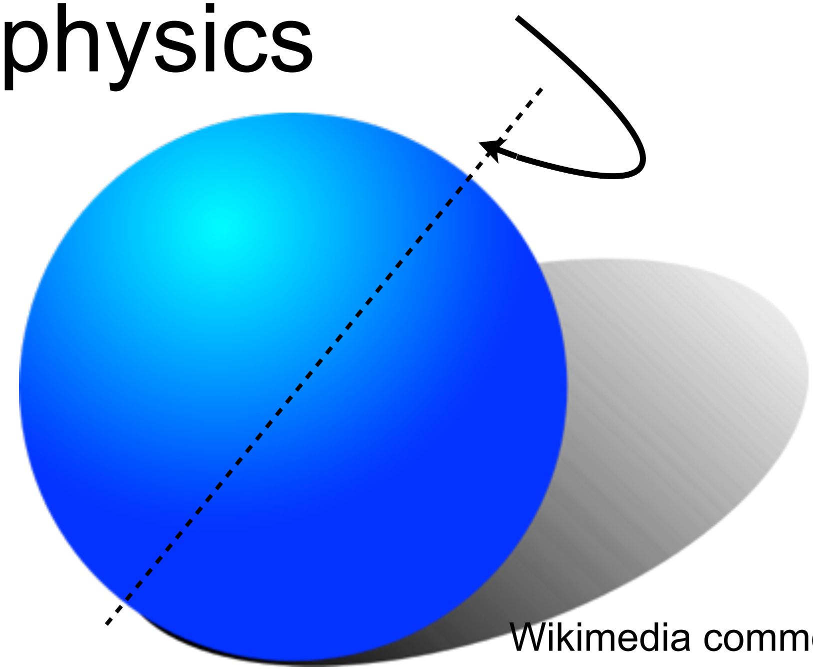
No space for detailed calculations (as with anything, real grasp of the subject will require working through these) - will give references

Focus more on concepts, less on models, constraints, etc

1. What is (super)symmetry?
2. SUSY in quantum field theory and its consequences
3. Spontaneous SUSY breaking, goldstino/gravitino. Soft breaking.
4. MSSM
5. Theoretical and experimental constraints

Symmetry in physics

Def.: A symmetry is some operation that one can do to a thing such that it still looks the same afterwards (H Weyl)



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In physics we look at one of two "things":

(i) The equations of motion (classical or quantum). SUSY in particle physics may or may not be a symmetry of the EOM.

(ii) The ground state of a system (in field theory, this is the vacuum). Even if the EOM are symmetric, the ground state may not be: "Spontaneously broken" or (more correctly) "hidden" symmetry. This is an interesting case, because the dynamics is still constrained by symmetry.

In particular, there is a motivation to look for particle models with spontaneously broken supersymmetry - symmetry protects the weak scale, while allowing for unsymmetric ground state properties, such as $m_t \neq m_{\tilde{t}}$

Symmetry: classical and quantum

Ex. classical free particle (nonrelativistic)

$T = \frac{m}{2}\dot{x}^2$	kinetic energy
$V = 0$	(no) potential energy
$L = T - V = \frac{m}{2}\dot{x}^2$	does not depend on x, only on dx/dt
$p = \frac{\partial L}{\partial x}$	canonical momentum
$\frac{d}{dt}p = \frac{\partial L}{\partial x} = 0$	Euler-Lagrange: momentum conserved!
$m\ddot{x} = 0$	EOM (and L) unchanged under translation x -> x+a

The continuous symmetry of the Lagrangian and the equations of motion (translation invariance) implies a conservation law (of momentum)

Symmetry: classical and quantum

Quantum free particle (nonrelativistic)

$$\hat{H} = \frac{1}{2m}\hat{p}^2$$ Hamiltonian

$$|x+a\rangle = \exp\left(-\frac{i}{\hbar}a\hat{p}\right)|x\rangle$$ momentum generates translations in QM

$$[\hat{H},\hat{p}] = 0 \iff i\hbar\frac{d}{dt}\exp\left(-\frac{i}{\hbar}a\hat{p}\right)|\psi\rangle = \hat{H}\exp\left(-\frac{i}{\hbar}a\hat{p}\right)|\psi\rangle$$ Schroedinger eq. invariant

if and only if

$$[\hat{H},\hat{p}] = 0 \iff \frac{d}{dt}\langle\psi|\hat{p}|\psi\rangle = 0$$ momentum is conserved

The continuous symmetry of the Hamiltonian and the (Schroedinger) equation of motion (translation invariance) implies a conservation law (of momentum)

One-to-one correspondence between classical and quantum cases
This is general.

Symmetry in fundamental physics

possible spacetime symmetry operations:

1) translations

2) rotations, Lorentz boosts

3) supersymmetry

4) conformal symmetry (change of scale; invert-translate-invert)

1), 2) generally assumed to be exact symmetries in particle physics.
3), 4) not manifest symmetries of nature (but could be hidden symmetries)

internal symmetries:

isospin, strangeness, baryon number, ... mostly approximate

gauge symmetries:

exact: necessary for massless spin-1 particles (Weinberg, Witten)

Supersymmetric quantum mechanics

(Witten, Nucl.Phys.B184 (1981) 513-554)

1-dimensional wave mechanics with an internal degree of freedom

$$\psi(x) = \begin{pmatrix} \phi_1(x) \\ \phi_2(x) \end{pmatrix} \qquad \hat{H} = \frac{1}{2}\hat{p}^2 + \frac{1}{2}W(x)^2 + \hbar\sigma_3\frac{dW}{dx}$$

There are two conserved quantities

$$\hat{Q}_1 = \frac{1}{2}(\sigma_1\hat{p} + \sigma_2 W(x)), \qquad \hat{Q}_2 = \frac{1}{2}(\sigma_2\hat{p} - \sigma_1 W(x))$$

which generate continuous symmetries (like with momentum)

Special about them is that they are “square roots” of the Hamiltonian

$$\{\hat{Q}_i, \hat{Q}_j\} = \delta_{ij}\hat{H}$$ in particular: $$2\hat{Q}_1^2 = 2\hat{Q}_2^2 = \hat{H}$$

Immediate consequence:

ground state supersymmetric $\Longleftrightarrow \; \hat{Q}|0\rangle = 0 \; \Longleftrightarrow \; \hat{H} = 0 \; \Longleftrightarrow \; E_0 = 0$

These properties carry over to relativistic field theory.

Relativistic supersymmetry

Relativistic quantum theory means, in practice, relativistic (quantum) field theory (or string theory)

The Hamiltonian is part of the momentum 4-vector

$$P_\mu = (\hat{H}, \hat{P}_x, \hat{P}_y, \hat{P}_z)_\mu$$

hence if there is a relativistic analog of SUSY QM, the supercharges must generate momentum, too. *NB - will drop hats above operators henceforth.*

This actually works with the algebra (Golfand, Likhtman 1971; Wess, Zumino 1974)

$$\left\{Q_\alpha, \bar{Q}_\beta\right\} = 2iP_\mu \gamma^\mu_{\alpha\beta}$$

where Q_α is a 4-component Majorana spinor (operator)

The generators (supercharges) carry spin 1/2 (must, as rhs has spin 1).

In field theory, the supercharges are built out of the fields, and by the spin-statistics theorem must be fermionic.

Supermultiplets

Given a boson with mass M at rest (ie E = M), act on it with supercharge:

$$Q_\alpha |M; \vec{p}=0\rangle = |?; \vec{p}=0; \alpha\rangle$$

which is a fermionic, spin-1/2 state.
NB - Q_α cannot all annihilate the bosonic state, as then E = M = 0.

$$P^2|?; \vec{p}=0; \alpha\rangle = [P^2, Q_\alpha]|M; \vec{p}=0\rangle + Q_\alpha P^2|M; \vec{p}=0\rangle = 0 + M^2 Q_\alpha|M; \vec{p}=0\rangle = M^2|?; \vec{p}=0; \alpha\rangle$$

hence

$$Q_\alpha |M; \vec{p}=0\rangle = |M; \vec{p}=0; \alpha\rangle$$

supermultiplets are mass-degenerate!

In summary, super(symmetry)multiplets contain at least two different particles with
- (i) different spin
- (ii) different statistics
- (iii) equal mass

For example, there should be scalar tops (or spin-1 tops) with M=m_t. Not observed !

An important loophole

We have tacitly assumed that the vacuum is supersymmetric and that supersymmetry acts linearly on the fields, such that one-particle states are mapped to one-particle states.

If the vacuum is not supersymmetric then this need not be the case (eg a SUSY transformation can “take particles from the vacuum” and add them to the state, and the symmetry becomes “nonlinearly realised”).

If SUSY is relevant to particle physics, it should be spontaneously broken.

Superspace and superfields

Analogously to representing translations on fields in spacetime, the supercharges can be represented as translation-rotations on an extended "superspace" with a fermionic (anticommuting) "coordinate" θ_α

This is just a formal trick, but extremely useful in practice

Fields are replaced by superfields, such as the chiral superfield

$$\Phi(x, \theta^\alpha) = A(x) + \theta^\alpha \psi_\alpha(x) + \theta^\alpha \theta_\alpha F(x)$$

scalar field (creates/destroys spin 0)

fermion field (creates/destroys spin 1/2)

auxiliary field (spin 0 no kinetic terms)

The action integral can be written as superspace integrals of superfields

Supersymmetry is extremely constraining on the allowed terms.

Provides very quick route to nonrenormalisation theorems

SUSY Lagrangians

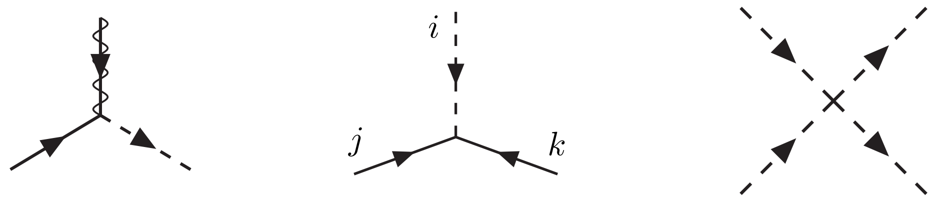
(skipping many steps) one finds that the most general renormalisable SUSY gauge theory is obtained as follows:

(1) specify chiral "matter" multiplets in a representation (set of multiplets) of the gauge group. These contain spin-1/2 fermions and complex scalars.

(2) add so-called vector superfields containing the gauge fields (spin-1) and gauginos (spin-1/2). This is completely fixed by the gauge group.

(3) Specify a third-order polynomial "superpotential" W made out of the chiral superfields, but not making use of complex conjugation.

The interaction terms consist of regular gauge interactions, plus
(a) gaugino couplings
(b) Yukawa interactions
(c) scalar self-interactions



(board)

[SP Martin, a supersymmetry primer]

Nonrenormalisation theorems

The quantum corrections are described by a “quantum effective action”. For SUSY this means an “effective” superpotential (a general function, not a polynomial, of the chiral superfields) and an effective “Kahler function” generalising the kinetic term

Nonrenormalisation theorem: The effective superpotential equals the original one to all orders in perturbation theory.

The Kahler potential does get quantum correction, but as far as UV divergences go all this implies is a so-called wave function (or field) renormalisation.

Hence quantum corrections, beta-functions, etc are extremely constrained in SUSY. This is what prevents large corrections to the weak scale, in particular.

Noether current

In field theory a symmetry implies not just a conserved quantity, but a conserved local current

Important role in discussing spontaneous symmetry breaking (Goldstone theorem)

$$
\begin{aligned}
J^\mu_\alpha \;=\; & (\sigma^\nu \overline{\sigma}^\mu \psi_i)_\alpha \, \nabla_\nu \phi^{*i} + i(\sigma^\mu \psi^{\dagger i})_\alpha \, W_i^* \\
& -\frac{1}{2\sqrt{2}}(\sigma^\nu \overline{\sigma}^\rho \sigma^\mu \lambda^{\dagger a})_\alpha \, F^a_{\nu\rho} + \frac{i}{\sqrt{2}} g_a \phi^* T^a \phi \, (\sigma^\mu \lambda^{\dagger a})_\alpha
\end{aligned}
$$

Spontaneous supersymmetry breaking

(Unbroken) supersymmetry makes predictions (degenerate multiplets) that appear obviously inconsistent with experiment.

Let us investigate the consequences of an unsymmetric vacuum

vacuum unsymmetric <-> not annihilated by supercharge <-> vacuum energy > 0

If the vacuum is not annihilated by the supercharge Q, then the new state is a spin-1/2 particle. One can show it is massless: “goldstino”

One can show that SUSY is broken if an auxiliary field (F or D) obtains a vacuum expectation value.

Goldstino and gravitino

If coupled to gravity (which we know to exist), supersymmetry *must* be made a local symmetry: supergravity.

Superpartner of the graviton: gravitino

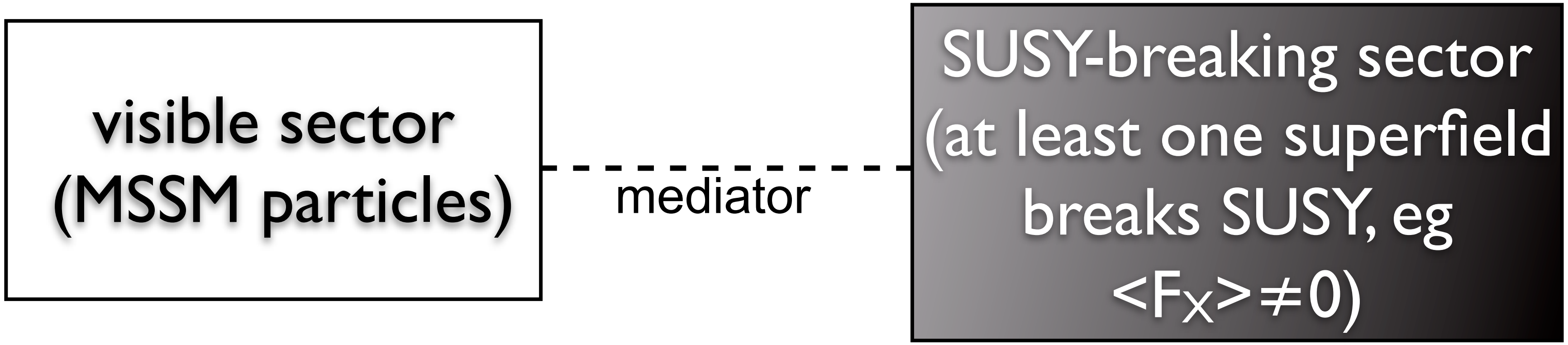
In broken SUSY, the gravitino "eats" the goldstino and becomes a massive spin-3/2 particle - also called the "super-Higgs" mechanism.

$$m_{\tilde{G}} \sim \frac{F}{M_{\mathrm{Pl}}}$$

Note that there is, generally, no "Higgs fermion"

SUSY breaking scenarios

Most models look like this:



$f_{vis}(\Phi_i^\dagger, \Phi_j)\quad W_{vis}(\Phi_i)$ $\qquad$ $f_{hid}(X_i^\dagger, X_j)\quad W_{hid}(X_i)$

SUSY breaking can be mediated [dominantly] by:

- gauge interactions (some fields in breaking sector are charged under SM gauge group): gauge mediation
- pure gravity interactions: anomaly mediation
- generic nonrenormalizable interactions

$$m_{\tilde{p}} \sim \frac{F}{M_{\text{messenger}}} \qquad\qquad m_{\tilde{G}} \leq m_{\tilde{p}}$$

SUSY breaking scenarios

(visible sector)

hidden sector with mediation through messengers:

$$m_{\tilde{p}} \sim \frac{F}{M_{\text{messenger}}} \qquad\qquad m_{\tilde{G}} \leq m_{\tilde{p}}$$

dynamical SUSY breaking

soft SUSY breaking

(board)

The MSSM

Multiplets

superpotential and R-parity

soft-breaking terms

Higgs mass

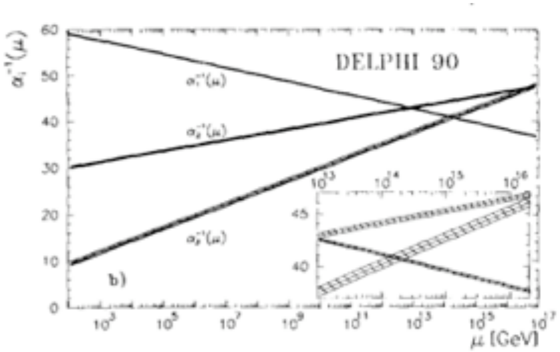
Planck-scale mediation

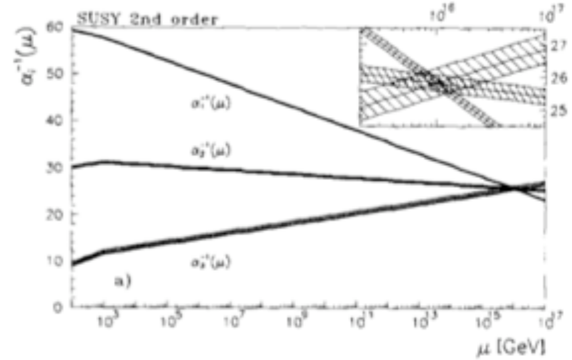
gauge mediation

(board)

Circumstantial evidence for SUSY

- The MSSM strongly hints at grand unification:





Relevant energy scales

hierarchy
$M_W \ll M_{Pl} \sim M_{seesaw} \sim M_{GUT}$
stabilized

improved unification
of couplings

(thermal relic) dark matter candidate, baryogenesis, strings, ...

EW symmetry breaking is SUSY breaking effect
SUSY nonrenormalization theorem forces this to be
either tree level or nonperturbative = $\mathcal{O}(e^{-c/g^2(\mu)}) = \mathcal{O}((\Lambda/\mu)^{c'})$

disfavoured
(mass sum rules etc)

hierarchy generated,
not only stabilized

M_{Pl} M_{GUT} M_{mess} Λ $M_{sparticle} \sim M_{EW}$

$M_{sparticle}$, M_{EW} $= O(\Lambda^2/M_{mess})$

planck-scale mediation

[for reviews, see Brignole et al hep-ph/9707209; Chung et al, Phys Rept 407 (2005)]

Planck-scale physics (quantum black holes, strings, ...) should generate effective higher-dimensional operators coupling MSSM and breaking sector:

$$f_{med}(\Phi_i, X_j) \supset \frac{k_{ij}}{M_{Pl}^2}(\Phi_i^\dagger, \Phi_j)(X^\dagger X) \quad W_{med}(\Phi_i, X_j) \supset \frac{\omega_{ijk}}{M_{Pl}}\Phi_i\Phi_j\Phi_k X$$

After X → F_X θ^2, these give rise to scalar masses and trilinears:

$$m_{ij}^2 = k_{ij}|F_X|^2/M_{Pl}^2 \qquad [M_{\text{sparticle}} = |F_X|/M_{Pl}]$$

$$A_{ijk} = Y_{ijk}F_X/M_{Pl}$$

Flavour structure from Planck-scale physics: *anything goes*

Ad hoc assumption (“msugra”): $k_{ij} \propto \delta_{ij}$, $\omega_{ijk} \propto Y_{ijk}$
⇨ universal sfermion masses, special A-terms

not stable under radiative corrections (-> RGE running) but consistent with bounds from flavour physics

anomaly mediation

[Randall, Sundrum 98; Giudice, Luty, Murayama, Rattazzi 98]

If SUSY-breaking sector fully neutral under SM gauge group and if nonrenormalizable direct couplings can be neglected, leading contribution is due to (super)gravity

- determined in terms of RGE functions - UV insensitive

$$m_{\text{gaugino}} = -\frac{\beta(g)}{2g^2} m_{3/2} \qquad m^2_{sfermion,ij} = \frac{1}{2}\left(\beta(g)\frac{\partial\gamma_{ij}}{\partial g} + \mu\frac{dY}{d\mu}\frac{\partial\gamma_{ij}}{\partial Y}\right)|m_{3/2}|^2 \qquad \ldots$$

- possible realization: moderate-size extra dim. ($r\,M_{Pl} \sim 10^2$)

visible fields on one brane

breaking sector on “sequestered” brane

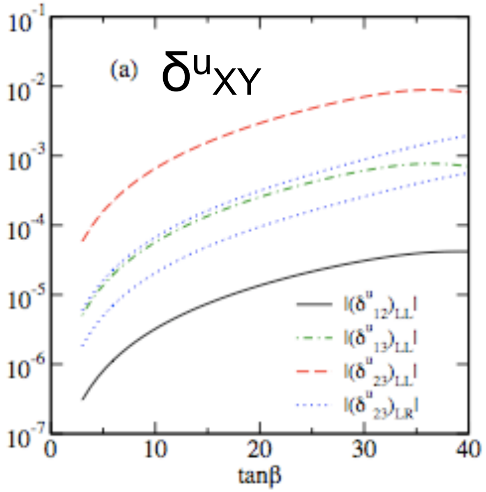
- flavour bounds ok (suppression by small Yukawa couplings)

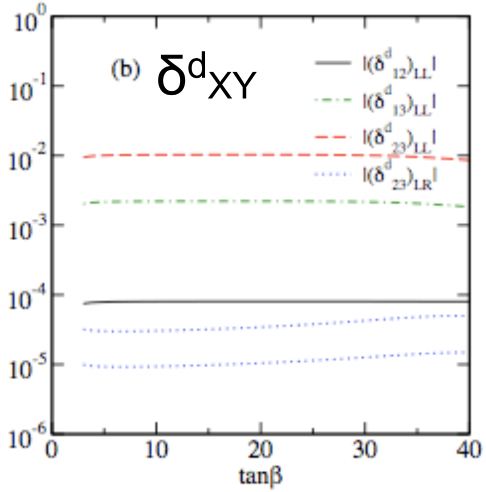
- tachyonic slepton spectrum from pure anomaly mediation

anomaly mediation

eg comprehensive study of FCNC arXiv:0902.4880 [hep-ph]

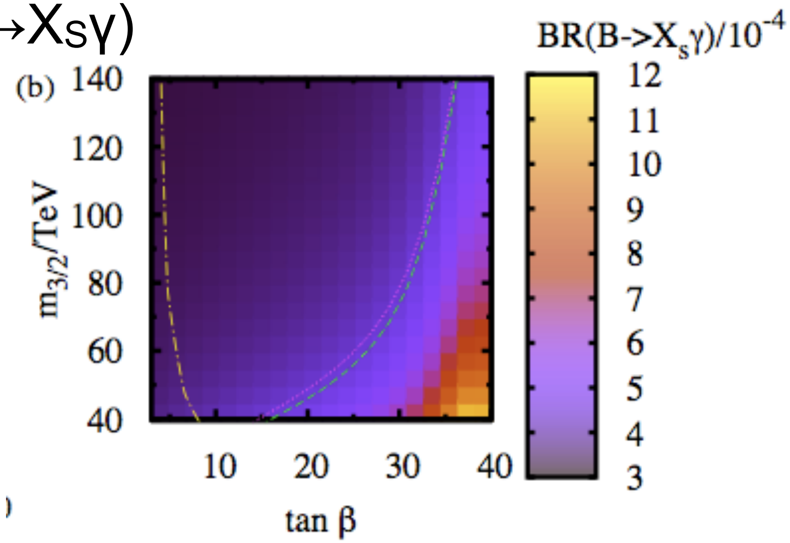
[Allanach, Hiller, Jones, Slavich]

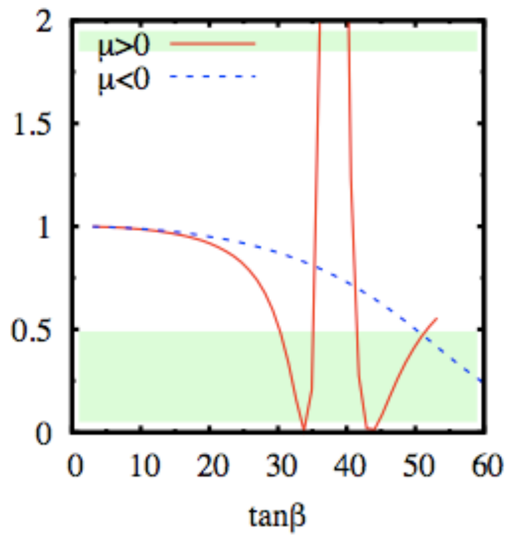




small off-diagonal δ´s
origin: CKM mixing
angles (MFV)

BR($B \to X_S \gamma$)





BR($B \to \tau\nu$) /
BR($B \to \tau\nu$)^{SM}

gauge mediation

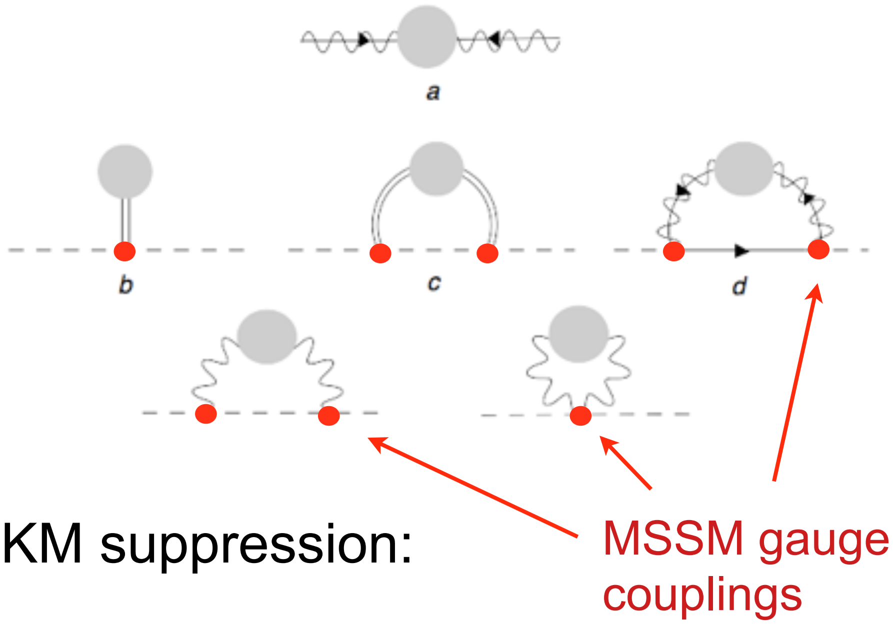
[Dine, Nelson 93; Dine et al 94-95]
[Giudice, Rattazzi (review) 98]

general definition: breaking sector decouples as gauge couplings → 0 [must augment to get μ, Bμ]

[Meade, Seiberg, Shih 08]

- masses calculable in terms of 3 two-point functions [blobs] flavour-blind up to higher orders (via Yukawas)

- A-terms small (higher orders)



Flavour bounds ok (Yukawa & CKM suppression: “minimal flavour violation”)

One mass relation only - more predictivity in concrete weakly-coupled models such as minimal gauge mediation

SUSY flavour problem

SuperCKM basis: Superfield basis that diagonalizes Yukawas

Squark mass matrices are still 6x6 with independent flavour structure:

3x3 flavour-violating

$$\mathcal{M}^2_{\tilde{d}} = \begin{pmatrix} \hat{m}^2_{\tilde{Q}} + m^2_d + D_{dLL} & v_1 \hat{T}_D - \mu^* m_d \tan\beta \\ v_1 \hat{T}_D^\dagger - \mu m_d \tan\beta & \hat{m}^2_{\tilde{d}} + m^2_d + D_{dRR} \end{pmatrix} \equiv \begin{pmatrix} (\mathcal{M}^2_{\tilde{d}})^{LL} & (\mathcal{M}^2_{\tilde{d}})^{LR} \\ (\mathcal{M}^2_{\tilde{d}})^{RL} & (\mathcal{M}^2_{\tilde{d}})^{RR} \end{pmatrix}$$

LR mass terms are $SU(2)_W$-breaking - related to trilinear scalar couplings

similar for up squarks, charged sleptons. 3x3 LL for sneutrinos

$$(\delta^{u,d,e,\nu}_{ij})_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)^{AB}_{ij}}{m^2_{\tilde{f}}}$$

33 flavour-violating parameters

45 CPV (some flavour-conserving)

SUSY flavour problem

$$\left(\delta_{ij}^{u,d,e,\nu}\right)_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)_{ij}^{AB}}{m_{\tilde{f}}^2}$$

where are their effects?

Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{LL}\rvert}$	4.0×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{RR}\rvert}$	4.0×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})^2_{LR}\rvert}$	4.4×10^{-3}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{ds})_{LL}(\delta^d_{ds})_{RR}\rvert}$	2.8×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{LL}\rvert}$	3.2×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{RR}\rvert}$	3.2×10^{-3}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})^2_{LR}\rvert}$	3.5×10^{-4}
$\sqrt{\lvert\mathrm{Im}(\delta^d_{ds})_{LL}(\delta^d_{ds})_{RR}\rvert}$	2.2×10^{-4}

Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{LL}\rvert}$	9.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{RR}\rvert}$	9.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})^2_{LR}\rvert}$	3.3×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{db})_{LL}(\delta^d_{db})_{RR}\rvert}$	1.8×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{LL}\rvert}$	4.8×10^{-1}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{RR}\rvert}$	4.8×10^{-1}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})^2_{LR}\rvert}$	1.62×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^d_{sb})_{LL}(\delta^d_{sb})_{RR}\rvert}$	8.9×10^{-2}

Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LL}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{ud})^2_{RR}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LR}\rvert}$	1.20×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})_{LL}(\delta^{u}_{uc})_{RR}\rvert}$	6.6×10^{-3}

[Gabbiani et al 96; Misiak et al 97]
these numbers from [SJ, 0808.2044]

- elusiveness of deviations from SM in flavour physics seems to make MSSM look unnatural

- SUSY flavour physics = physics of SUSY breaking !

Addendum: MSSM and diphoton

The MSSM contains a two-Higgs-doublet model, and in addition also sfermions, higgsinos, and gauginos.

If R-parity conserved, (visible-sector) candidate states are H^0 and A^0 [nb bound states like stoponium can be ruled out]

- 2HDM is model II, giving a fast approach to decoupling limit and a strong suppression of W and H^+ loops

- gluon fusion only plausible production mode as Yukawa couplings to light quarks small

- would require substantial loop-induced couplings to gluons from squarks, and to photons from squarks, sleptons, and charginos

MSSM: how to bound?

Sfermion loop functions almost step-function like in magnitude, steep fall-off at threshold m_{sferm} = 375 GeV

- difficult in light of direct searches, but blind spots exist

- difficult to have light stops with 126 GeV Higgs. However, combinations of one light and one heavy and/or large trilinears conceivable

- even for stop contribution have six-dimensional parameter space, difficult to scan numerically

Main idea: use/assume stability of our charge- and colour-conserving, EW symmetry-breaking vacuum

get bounds on each sfermion contribution that only depend on the 2 sfermion masses and tan(beta).

This turns out to be numerically tractable and sufficien

MSSM: vacuum stability

Many directions in MSSM scalar field space can develop charge- and colour-breaking minima. Consider:

$$T_L = T_R = H_u^0, \quad B_L = B_R = H_d^0, \quad B_L = T_R = H_d^-, \quad T_L = B_R = H_u^+$$

For instance, requiring the minimum along the first two directions to be at the origin implies (after some reworking of the usual form):

$$|A_t| \leq \sqrt{3}\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - 2m_t^2 + \frac{M_{H^0}^2}{2}\left[1 + \cos(2\beta)\right] - \frac{m_Z^2}{2}\cos(2\beta)}$$

$$|\mu| \leq \sqrt{1 + \frac{m_Z^2}{m_t^2}\sin^2\beta} \times \sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - 2m_t^2 + \frac{M_{H^0}^2}{2}\left[1 - \cos(2\beta)\right] - m_Z^2\cos(2\beta)}$$

only the stop mass eigenvalues and tan(beta) appear on r.h.s!

as a result, the sum of the two stops' contributions is rigorously bounded by a simple function of m_{t1}, m_{t2}, tan(beta).

MSSM: verdict

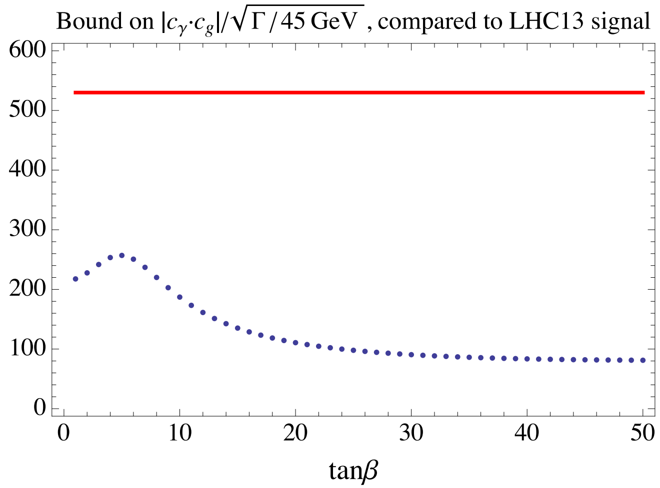
Gupta, SJ, Kats, Perez, Stamou 1512.05332

Put signal strength constraint in the following form:

$$\frac{|c_\gamma c_g|}{\sqrt{\Gamma(\tan\beta)/(45\,\mathrm{GeV})}} = \rho_g \approx 530$$

(width dominated by decays to top and bottom)

Bounding the l.h.s. by adding bounds on individual contributions [including charginos, W, Higgs, top, bottom] linearly (in c_{gam} and c_g) gives:



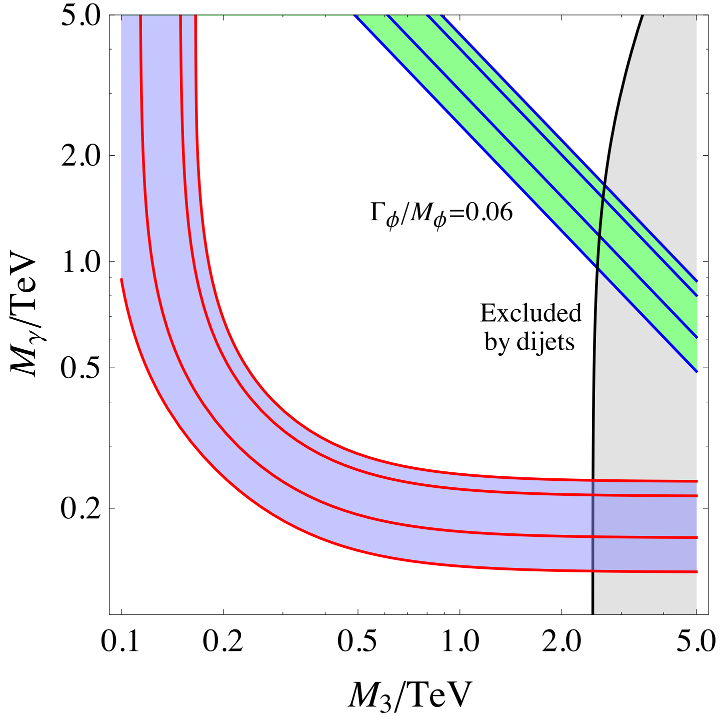
Unless metastability (or some unexpectedly large higher-order correction) saves it, H and A candidates would be ruled out. (Argument generalises to RPV sneutrino scenario)

Sgoldstino

Petersson, Torre 1512.05333
Bellazzini et al 1512.05330
Demidov,Gorbunov 1512.05723
Casas,Espinosa,Moreno 1512.07895

Couplings to photons and gluons given in terms of photino and gluino mass (F = SUSY-breaking F-term)

$$\mathcal{L} \supset \frac{M_3}{2\sqrt{2}F} \, \mathrm{tr} \, G^a_{\mu\nu}(\phi_S G^{a\mu\nu} - i\phi_P \tilde{G}^{a\mu\nu}) \; + \; \frac{M_{\tilde{\gamma}}}{2\sqrt{2}F} \, \mathrm{tr} \, F_{\mu\nu}(\phi_S F^{\mu\nu} - i\phi_P \tilde{F}^{\mu\nu})$$



Casas,Espinosa,Moreno 1512.07895

(width can be enhanced through decays to hh, higgsinos, via mixing with Higgs)

SUSY might be feasible if SUSY-breaking scale (F) is close to the TeV scale

Literature

(very incomplete selection)

S P Martin, A Supersymmetry Primer, arXiv:hep-ph/9709356
easy pedagogical introduction, including good account of MSSM

J Wess & J Bagger, Supersymmetry and Supergravity (Princeton)
concise and complete account of the formalism by one of the inventors

M Drees, R Godbole, P Roy, Theory and Phenomenology of Sparticles (World Scientific)
more complete than the "primer", detailed phenomenology of MSSM

Weinberg, The Quantum Theory of Fields, Vol 3: Supersymmetry
very complete, with many references to original literature

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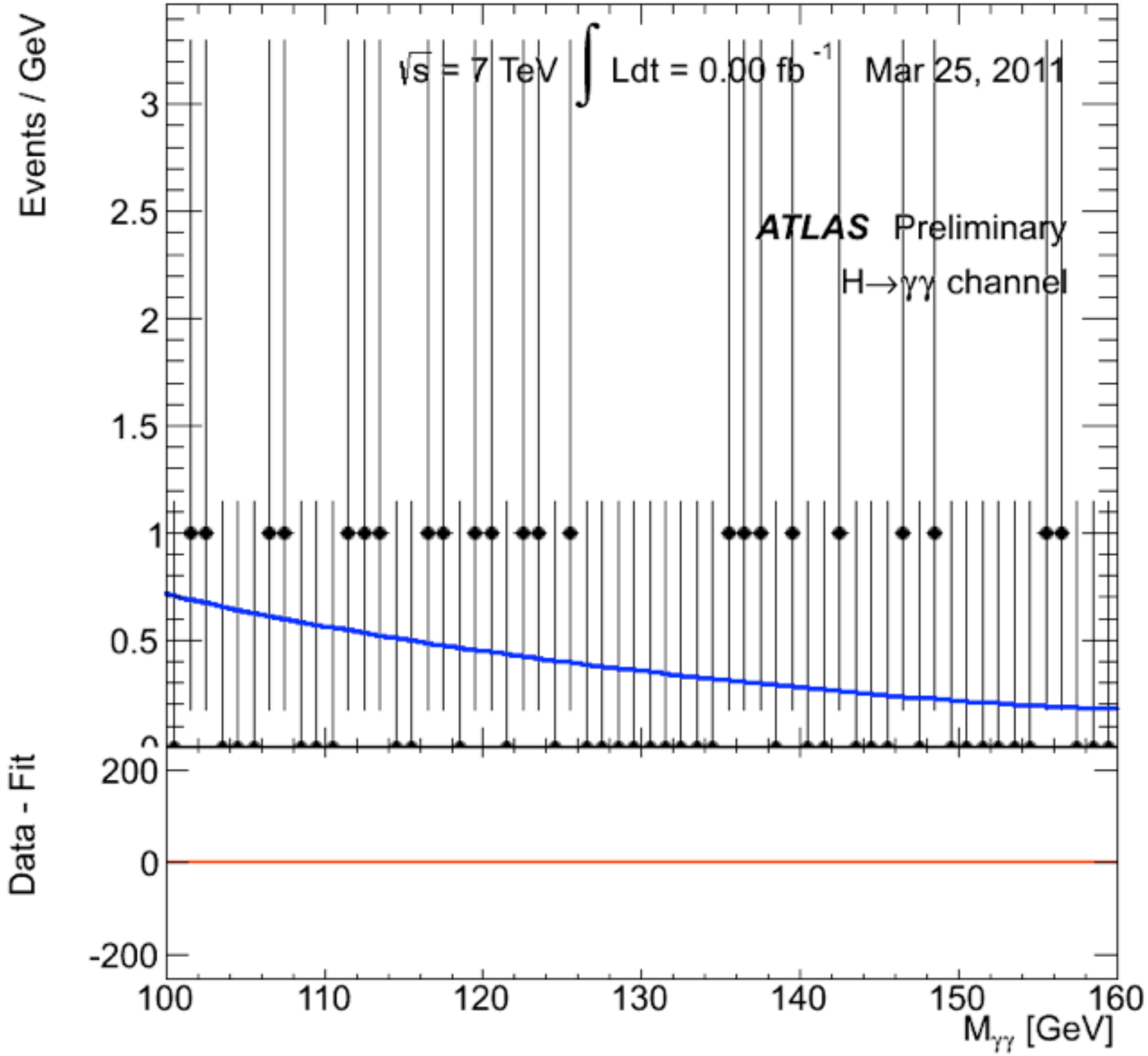

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults#Animations

Suzanne Moore Stuart Jeffries Lucy Mangan Martin Kettle Zoe Williams Richard Sennett

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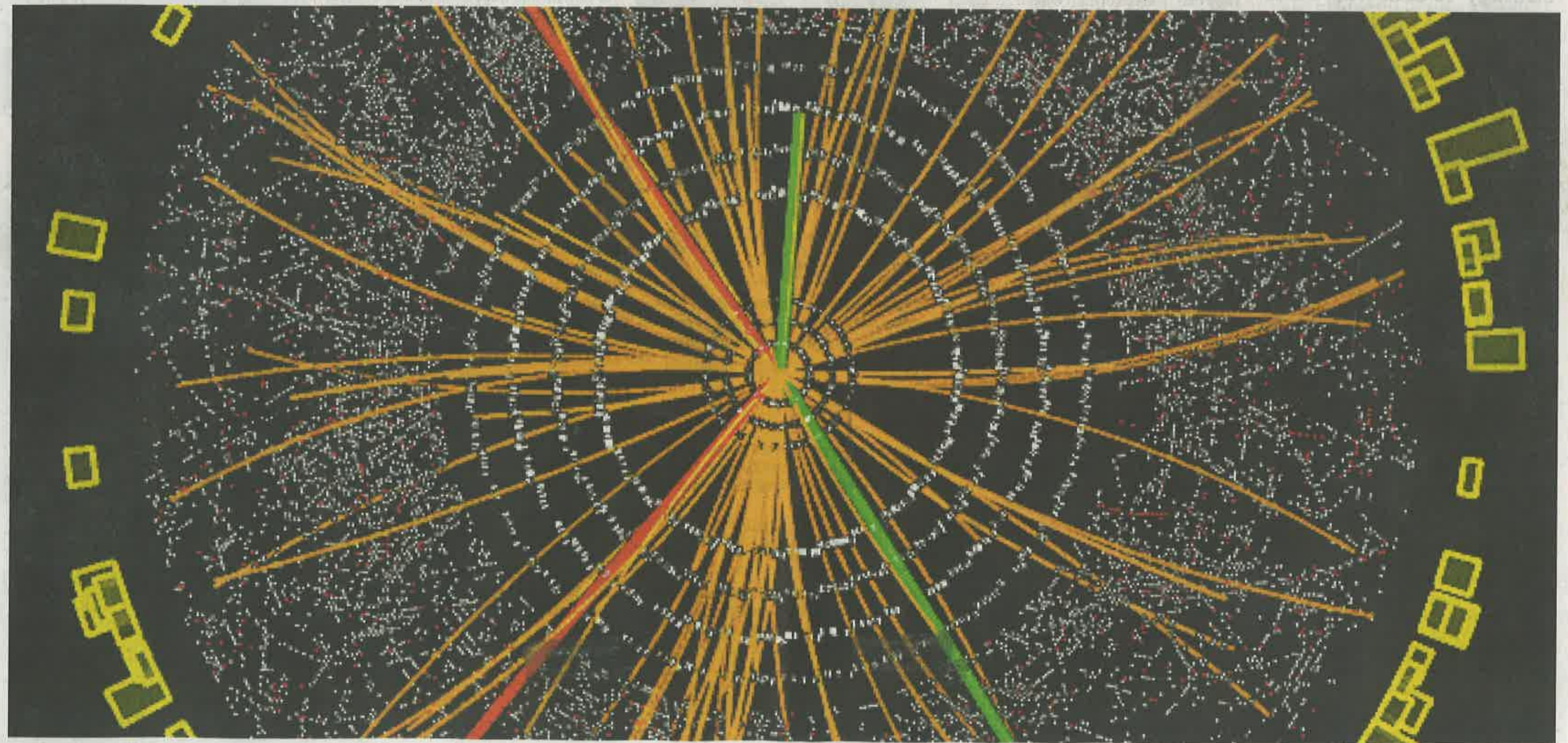
Higgs was right Picture that changes the way we see the universe for ever

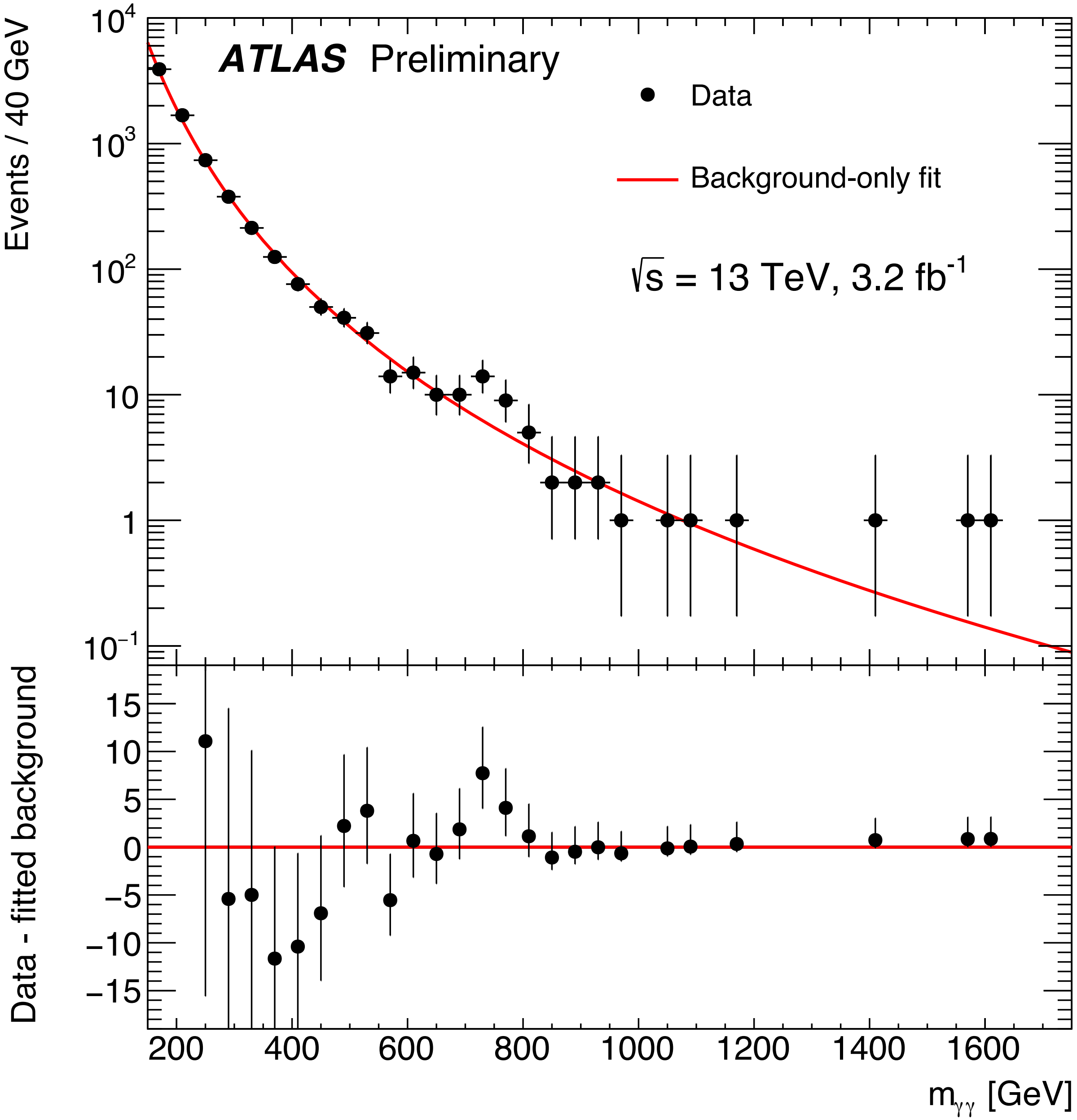


Osborne accuses Labour

Ian Sample Geneva

There comes a time in a scientist's life when the weight of evidence can no longer be ignored. That moment came yesterday for physicists at Cern, near

CERN LHC jamboree, 15/12/2015



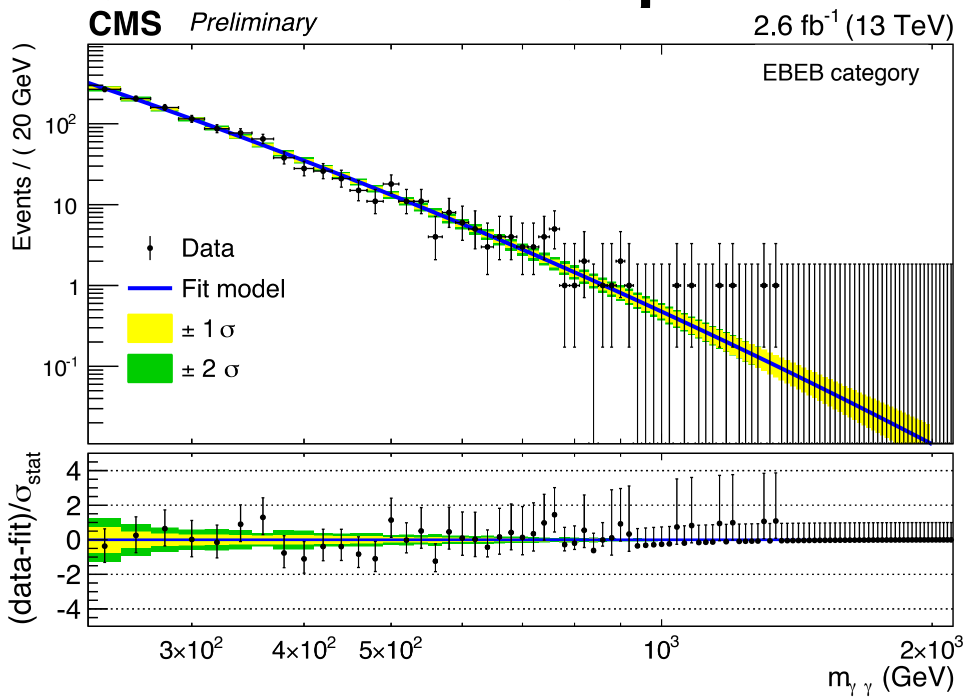
most significant
deviation from BG model
at M ≈ 750 GeV

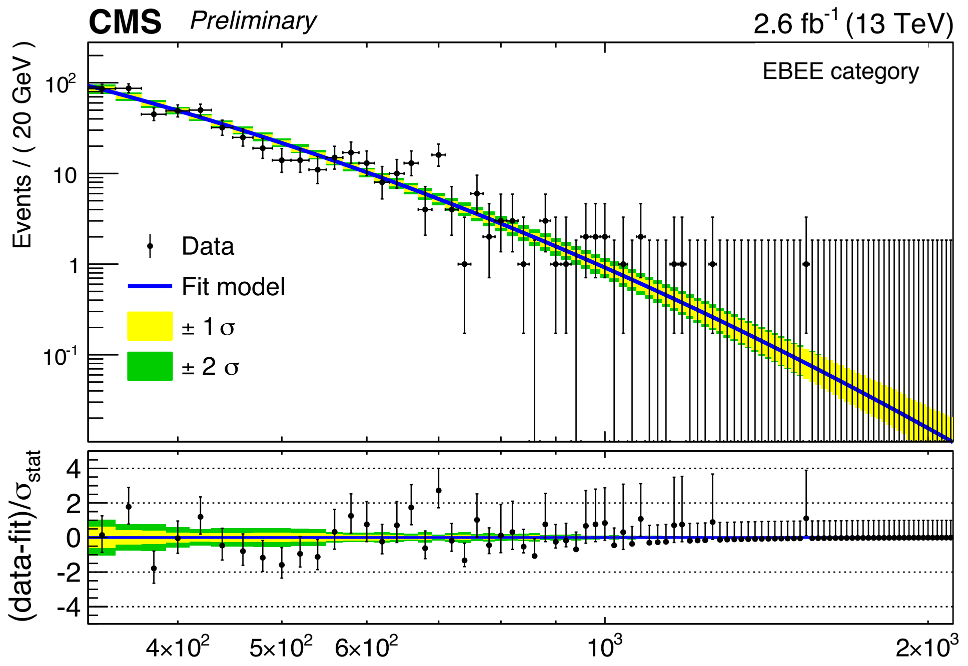
local significance 3.6 sigma
if assuming **narrow** width
(ie <energy resolution, ≈ 8 GeV
at M=750 GeV)
[global 2.0 sigma]

if width allowed to float:
local significance 3.9 sigma
for
width/mass ≈ 6%
(width ≈ 45 GeV)

ATLAS-CONF-2015-081

CERN LHC jamboree, 15/12/2015





most significant deviation from BG model at M ≈ 760 GeV

local significance 2.6 sigma if assuming **narrow** width

[global 1.2 sigma]

no improvement for larger width

CMS PAS EXO-15-004

But is it real? What if?

It could be a statistical fluctuation
- will know next summer at the earliest (req more data)

- look-elsewhere effect should only be applied either to ATLAS and CMS. Ie ATLAS 2.0 sigma global, then look only near 750 GeV in CMS, giving 2.6 sigma. Clearly above the evidence threshold if combined.

Small, smooth background, fitted to sidebands.
(See however Davis,Fairbairn,Heal,Tunney arXiv:1601.03153)

In the past correct UV picture has been guessed based on less significant anomalies (eg Cabibbo mixing).

no 13 TeV searches for other final states yet

Explanations tend to imply light exotics, within LHC reach

Characterisation of the resonance

If it’s real, what do data tell us?

Gupta, SJ, Kats, Perez, Stamou 1512.05332

Integer spin 0 or spin >=2 (Landau-Yang)

M = 750 GeV

Gamma <= 45 GeV

$$\sigma_{13} \times \mathrm{BR}_{\gamma\gamma} \approx 6.9 \text{ fb} \times \left(\frac{N}{20}\right)\left(\frac{50\%}{\epsilon}\right)\left(\frac{5.8 \text{ fb}^{-1}}{\mathcal{L}_{13}}\right)$$

The particle likely couples to quarks and/or gluons.

The particle is likely resonantly produced (no patterns in the data indicating a decay from heavier particles)

Will **assume** spin-0 s-channel resonance in the following.

Width

Gupta, SJ, Kats, Perez, Stamou 1512.05332

$$\mathcal{L} = -\frac{1}{16\pi^2}\frac{1}{4}\frac{c_\gamma}{M}\mathcal{S}F^{\mu\nu}F_{\mu\nu} - \frac{1}{16\pi^2}\frac{1}{4}\frac{c_g}{M}\mathcal{S}G^{\mu\nu,a}G^a_{\mu\nu} - c_W M_W \mathcal{S} W^{+\mu}W^-_\mu - \frac{1}{2}c_Z M_Z \mathcal{S} Z^\mu Z_\mu - \sum_f c_f \mathcal{S}\bar{f}f$$

The diphoton spectrum tells us, without assumptions on production,

$$\frac{\Gamma}{M} = \sum_i \frac{\Gamma_i}{M} = \sum_i n_i |c_i|^2 \approx 0.06$$

(or smaller, for more narrow width)

model-independent "width coefficients"

mode	Width coefficient n_i	n_i (#)
$\gamma\gamma$	$\frac{1}{16(4\pi)^5}$	1.99×10^{-7}
gg	$\frac{1}{2(4\pi)^5}$	1.60×10^{-6}
$q_i\bar{q}_i$	$\frac{3}{8\pi}$	0.119
$t\bar{t}$	$\frac{3}{8\pi}\sqrt{1-4m_t^2/M^2}$	0.106
W^+W^-	$\frac{1}{64\pi}\sqrt{1-4m_W^2/M^2}\frac{M^2}{m_W^2}\left[1-4\frac{m_W^2}{M^2}+12\frac{m_W^4}{M^4}\right]$	0.404
ZZ	$\frac{1}{128\pi}\sqrt{1-4m_Z^2/M^2}\frac{M^2}{m_Z^2}\left[1-4\frac{m_Z^2}{M^2}+12\frac{m_Z^4}{M^4}\right]$	0.154

NB - Yukawa coupling ~ 2/3 gives 45 GeV width

No strong coupling needed.

Signal strength

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$$\mathcal{L} = -\frac{1}{16\pi^2}\frac{1}{4}\frac{c_\gamma}{M}\mathcal{S}F^{\mu\nu}F_{\mu\nu} - \frac{1}{16\pi^2}\frac{1}{4}\frac{c_g}{M}\mathcal{S}G^{\mu\nu,a}G^a_{\mu\nu} - c_W M_W \mathcal{S}W^{+\,\mu}W^-_\mu - \frac{1}{2}c_Z M_Z \mathcal{S}Z^\mu Z_\mu - \sum_f c_f \mathcal{S}\bar{f}f$$

Assuming now a particular production mode, MadGraph gives

$$\mathrm{BR}_{\gamma\gamma}\times\mathrm{BR}_p = n_p\frac{M}{\Gamma}\frac{N}{\epsilon x_{\mathcal{S}}^{13,p}\mathcal{L}_{13}} = \kappa_p \times \left(\frac{N}{20}\right)\left(\frac{45\ \mathrm{GeV}}{\Gamma}\right)\left(\frac{5.8\ \mathrm{fb}^{-1}}{\mathcal{L}_{13}}\right)$$

$$\kappa_p \approx \{2.5,\ 5.5,\ 8.9,\ 96,\ 140,\ 310,\ 20000,\ 25000\}\times 10^{-5}$$

$$(\ gg,\ u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b},\ \mathrm{VBF}_{WW},\ \mathrm{VBF}_{ZZ}\ )$$

for nominal width, for VBF get BR(diphoton) ~ BR(WW/ZZ) ~ 50%

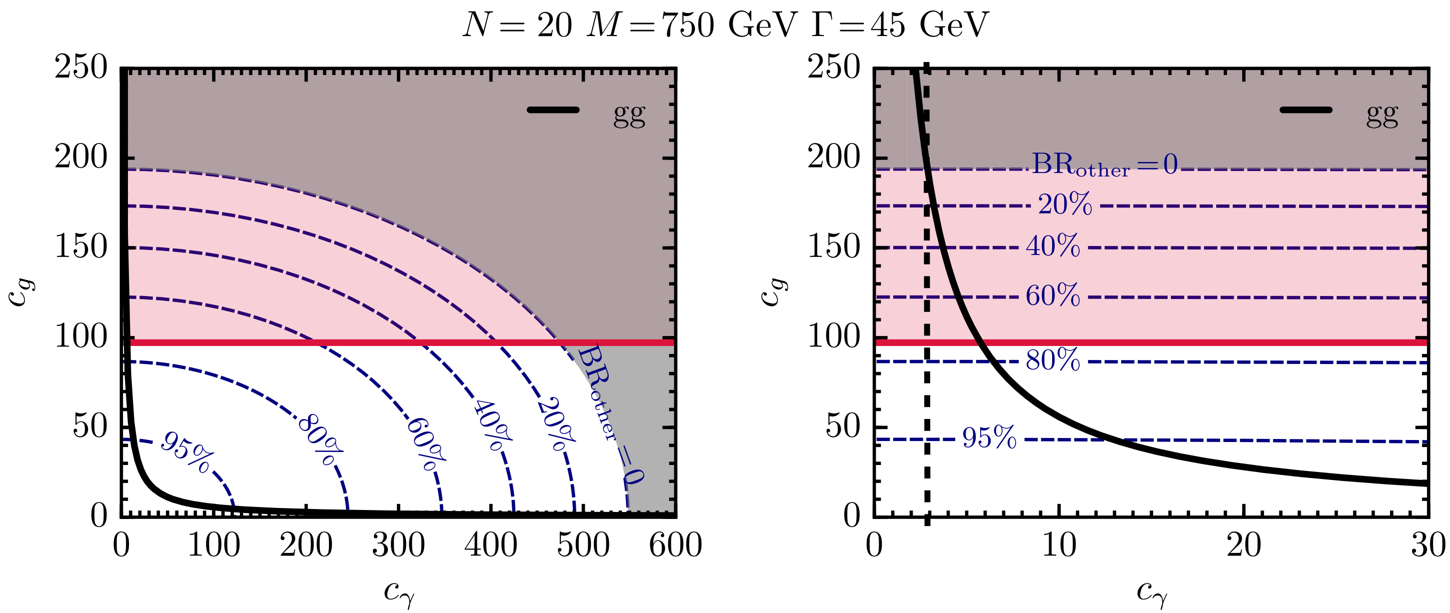
for smaller width, no solution for VBF production.

Model-independent bounds (13 TeV)

Gupta, SJ, Kats, Perez, Stamou 1512.05332

Decay back into the production mode is bounded by the measured width.

This in turn bounds the production cross-section, implying a lower bound on the coupling (or partial width, or branching fraction into) photons



$$|c_\gamma| > \sqrt{\frac{n_g}{n_\gamma}\frac{N}{\epsilon x_{\mathcal{S}}^{13,g}\mathcal{L}_{13}}} = 2.7 \times \sqrt{\left(\frac{N}{20}\right)\left(\frac{5.8\ \text{fb}^{-1}}{\mathcal{L}_{13}}\right)}$$

Conservative, valid for **any** mix of production modes.
Equal to bound if gg initial state assumed.
Independent of the width! (Cancels out.)

8 TeV search constraints

Gupta, SJ, Kats, Perez, Stamou 1512.05332

No other resonance searches with 13 TeV data below a TeV yet. But **many** at 8 TeV. Important constraint on possible explanations!

Production cross sections scales with parton luminosity:

$$\sigma_8 \times \mathrm{BR}_{\gamma\gamma} = \frac{\sigma_{13} \times \mathrm{BR}_{\gamma\gamma}}{r_p} \approx \left(\frac{N}{20}\right) \times \{1.6,\ 2.6,\ 2.6,\ 1.8,\ 1.7,\ 1.5,\ 1.6,\ 1.6\}\,\mathrm{fb}$$

$$(gg,\ u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b},\ \mathrm{VBF}_{WW},\ \mathrm{VBF}_{ZZ})$$

Diphoton searches at 8 TeV provide important constraints:

$$\sigma_8 \times \mathrm{BR}_{\gamma\gamma} \lesssim 2.5\ \mathrm{fb}$$ (CMS limit for 10% Gamma/M)

$$\sigma_8 \times \mathrm{BR}_{\gamma\gamma} \lesssim 1.3\ \mathrm{fb}$$ (CMS limit for narrow resonance)

(ATLAS limits weaker)

Slightly disfavours u-ubar and d-dbar initial states

Constraints on relative BR's

Gupta, SJ, Kats, Perez, Stamou 1512.05332

$$\sigma_8 \times \mathrm{BR}_{\gamma\gamma} = \frac{\sigma_{13} \times \mathrm{BR}_{\gamma\gamma}}{r_p} \approx \left(\frac{N}{20}\right) \times \{1.6,\, 2.6,\, 2.6,\, 1.8,\, 1.7,\, 1.5,\, 1.6,\, 1.6\}\,\mathrm{fb}$$

also implies simple bounds on ratios of BR's:

$$\left(\frac{\mathrm{BR}_i}{\mathrm{BR}_{\gamma\gamma}}\right)^{\max} = r_p \frac{(\sigma_8 \times \mathrm{BR}_i)^{\max}}{\sigma_{13} \times \mathrm{BR}_{\gamma\gamma}}$$

decay mode $i \rightarrow$		gg	$q\bar{q}$	$t\bar{t}$	WW	ZZ	hh	Zh	$\tau\tau$	$Z\gamma$	$ee+\mu\mu$
$(\sigma_8 \times \mathrm{BR}_i)^{\max}$ [fb]		4000 [13]	1800 [13]	500 [14]	60 [15]	60 [16]	50 [17]	17 [18]	12 [19]	8 [20]	2.4 [21]
production $p =$	gg	2600	1200	320	38	38	32	11	7.7	5.1	1.5
	$u\bar{u}$	1500	690	190	23	23	19	6.5	4.6	3.1	0.9
$\left(\frac{\mathrm{BR}_i}{\mathrm{BR}_{\gamma\gamma}}\right)^{\max}$	$d\bar{d}$	1600	700	200	23	23	20	6.7	4.7	3.1	0.9
	$s\bar{s}$	2300	1000	280	34	34	28	9.6	6.8	4.5	1.4
	$c\bar{c}$	2400	1100	300	36	36	30	10	7.3	4.8	1.5
	$b\bar{b}$	2700	1200	340	40	40	34	11	8.1	5.4	1.6

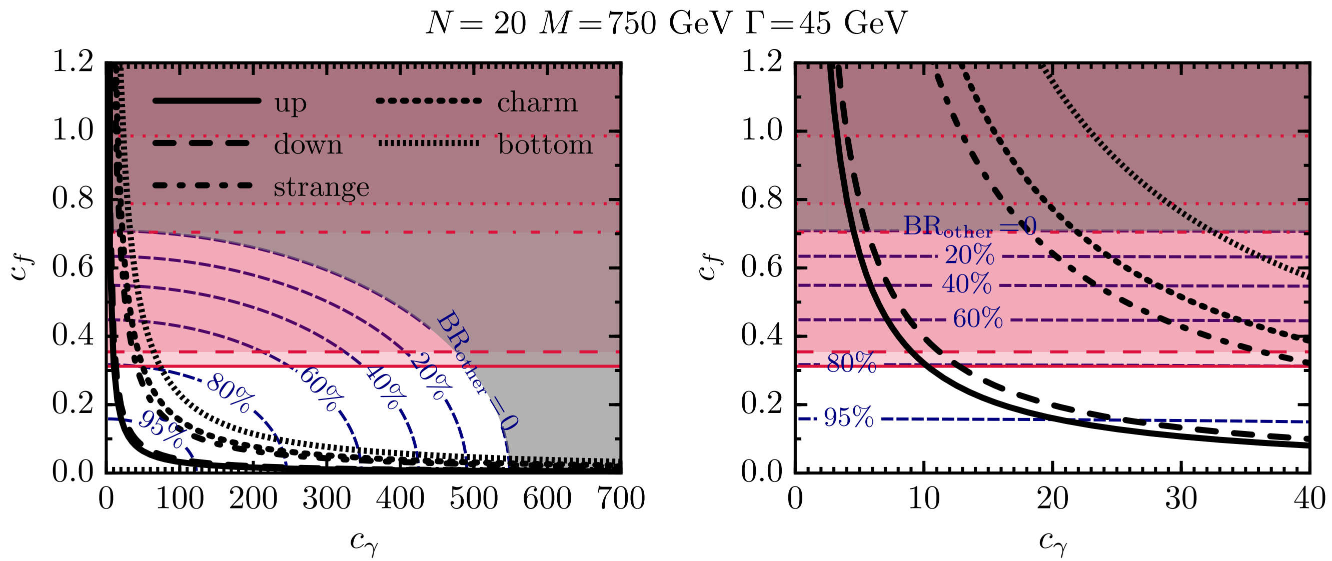
large couplings to photons, and/or suppressed couplings to weak bosons, Higgs, leptons, required

Special case: decay into the production mode.

Provides separate lower bound on photon coupling

$$|c_\gamma| > \{5.5,\ 9.4,\ 11,\ 17,\ 19,\ 22\} \times \sqrt{\left(\frac{N}{20}\right)\left(\frac{5.8\ \text{fb}^{-1}}{\mathcal{L}_{13}}\right)}\left(\frac{\Gamma}{45\,\text{GeV}}\right)^{1/4}$$

different dependence on production mode and on scaling with the width - can be stronger or weaker.



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