Lecture:

Standard Model of Particle Physics

Heidelberg SS 2016

Searches Beyond the SM I

Contents

New Physics Check List

Standard Model is incomplete

New Physics should address following points:

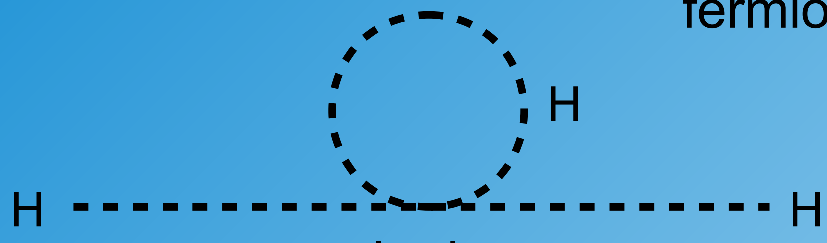
- dark matter candidate
- number of fermion generations
- fermion masses (in particular light neutrino masses)
- CP-violation
- Fermion-Number Violation (BNV or LNV)
- Unification
- (Hierarchy problem)

The SM Hierarchy Problem

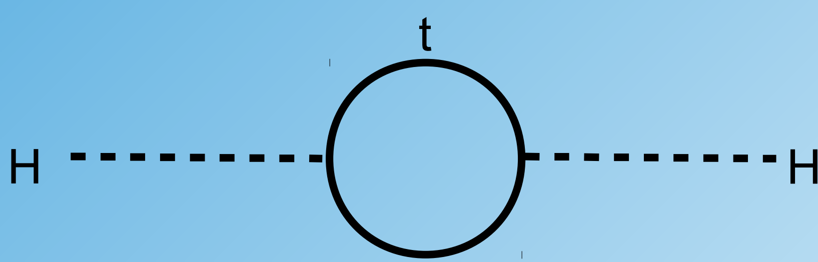
SM Fine Tuning “Problem”

Fermion-Higgs Coupling does not decouple in the SM: $\propto \frac{g}{2}\frac{m_t}{M_W}$
leading to UV divergences

fermion



scalar boson



fermion

$$\delta M_{HS}^2 = \frac{|\lambda_s^2|}{16\pi^2}\left[\Lambda^2 + 2m_s^2 \log \Lambda / m_s\right]$$

$$\delta M_{HF}^2 = \frac{|g_f^2|}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 \log \Lambda / m_f\right]$$

note factor 2

$$\delta M_H^2 = \delta M_{HS}^2 + \delta M_{HF}^2 \propto -\Lambda^2 \quad \rightarrow M_{Planck}$$

Higgs mass given by: $M_H^2 = M_{H,bare}^2 + \delta M_H^2$

$M_{Higgs} / M_{Planck} = 10^{-17}$

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 1000000000000000000000000000000000
 -999999999999999999999999999999999
=                                 1
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→ fine tuning “problem”

Two Higgs Doublet Model

One Higgs Doublet Model (Standard Model):

SM Higgs Doublet generates:

- 1 physical Higgs (neutral)
- 3 Goldstone Bosons (charged+neutral) eaten by vector bosons
- Higgs field generates masses of all fermions

Two Higgs Doublet Model:

$$\Phi_1 = \begin{pmatrix} \phi_1^A \\ \phi_1^B \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^A \\ \phi_2^B \end{pmatrix}$$

→ eight degrees of freedom (complex fields)

in addition to the 3 Goldstone bosons there are 5 physical Higgs states:

h: light neutral Higgs

H: heavy neutral Higgs

A: pseudo scalar Higgs (CP=P=-1)

$H^\pm$: charged Higgs bosons → induces extra charged currents

→ Rich phenomenology!

2HDM Lagrangian

The vector potential in the most general form:

$$V = \frac{1}{2}\lambda_1(\Phi_1^+\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^+\Phi_2)^2 + \frac{1}{2}\lambda_3(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_2)$$

$$+ \lambda_4(\Phi_1^+\Phi_2)(\Phi_2^+\Phi_1) + \frac{1}{2}[\lambda_5(\Phi_1^+\Phi_2)^2 + h.c.]$$

$$+ \{[\lambda_6(\Phi_1^+\Phi_1) + \lambda_7(\Phi_2^+\Phi_2)](\Phi_1^+\Phi_2) + h.c.\}$$

$$- \frac{1}{2}\{m_{11}^2(\Phi_1^+\Phi_1) + m_{12}^2[(\Phi_1^+\Phi_2) + h.c.] + m_{22}^2(\Phi_2^+\Phi_2)\}$$

10 parameters, 4 complex → 14 d.o.f.

Vacuum expectation values

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}, \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2 e^{i\xi}\end{pmatrix}$$

$$v_1^2 + v_2^2 = v^2, \quad v = 246\,GeV$$

$$m_{ii}^2 \sim v_i^2 \qquad \nu = \Re\, m_{12}^2/(2 v_1 v_2)$$

$$\tan\beta = v_2/v_1$$

2HDM Yukawa couplings

$$L_Y = \bar{Q}_L \left[\left(\Gamma_1 \varphi_1 + \Gamma_2 \varphi_2 \right) d_R + \left(\Delta_1 \tilde{\varphi}_1 + \Delta_2 \tilde{\varphi}_2 \right) u_R \right] + h.c.$$

similar for leptons!

The four constants Γ_1 , Γ_2 , Δ_1 , Δ_2 define the type of the model

$$\underset{(Y=+1)}{\Phi_i} = \begin{pmatrix} \varphi_i^+ \\ \varphi_i^0 \end{pmatrix} , \quad \underset{(Y=-1)}{\tilde{\Phi}_i} = \begin{pmatrix} \varphi_i^0 \\ \varphi_i^- \end{pmatrix} \qquad i = 1,2$$

In general, the following 4 model types are possible if $\Phi_1 \Phi_2 = 0$ and $\Phi_1 \Phi_2 = 0$ (no mixing)

type	u	d	e
I	$\tilde{\Phi}_2$	Φ_2	Φ_2
II	$\tilde{\Phi}_2$	Φ_1	Φ_1
III (Y)	$\tilde{\Phi}_2$	Φ_1	Φ_2
IV (X)	$\tilde{\Phi}_2$	Φ_2	Φ_1

(Supersymmetry Realisation) [beside type II]

2HDM Mixing and Symmetries

In general mixing between states is possible:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix},$$

$$\begin{pmatrix} G \\ A \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + i\varphi_i)/\sqrt{2} \end{pmatrix}$$

G, $G^\pm$ are Goldstone bosons giving mass to Z, $W^\pm$

Model described by two parameters: $\tan\beta$ and $\cos(\alpha-\beta)$

Alignment limit: if $\cos(\alpha-\beta)=0$ then h is SM Higgs boson

Z_2 symmetry:

$$\Phi_1 \to \Phi_1 \quad , \quad \Phi_2 \to -\Phi_2$$

this implies CP-conservation and no FCNC!

If Z_2 symmetry broken → direct CP-Violation

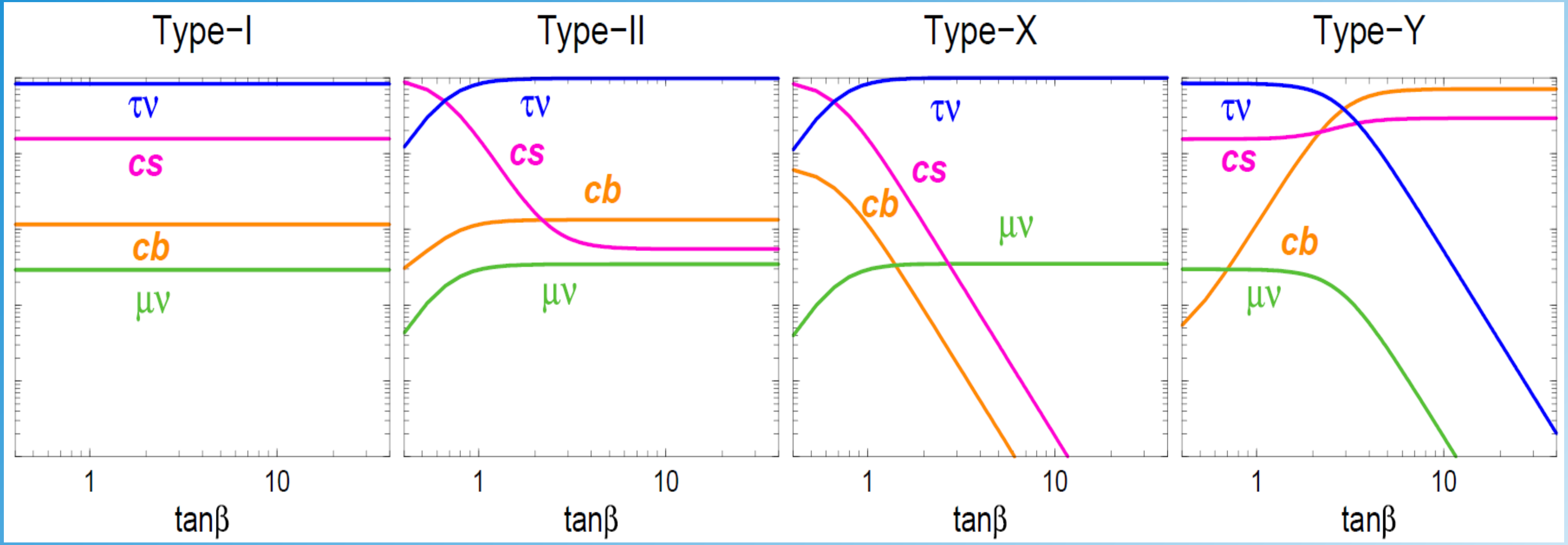
(CP violation even with only 2 fermion generations)

Check List 2HDM

- dark matter candidate
- number of fermion generations
- fermion masses (in particular light neutrino masses)
- CP-violation
- Fermion-Number Violation (BNV or LNV)
- Unification
- (Hierarchy problem)

Branching ratios of H^+ decays

$m_A = m_{H+} = 150\text{GeV}$



$\tan\beta$ modifies vacuum expectation value for Φ_1 and Φ_2

Note: H^+ mediates flavor changing charged currents (similar to W^+)

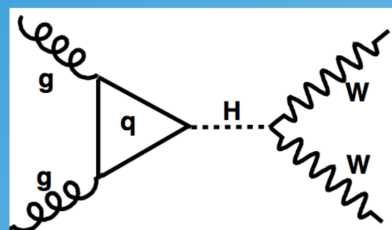
Also note: Type II is realised in Supersymmetric Theories

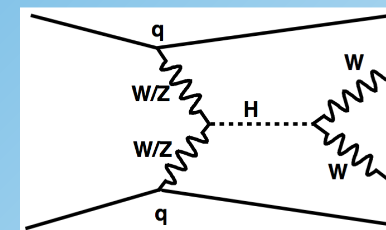
Search for neutral H (2HDM) at ATLAS

Search strategy: look for H production and decay of H → W W → lν lν

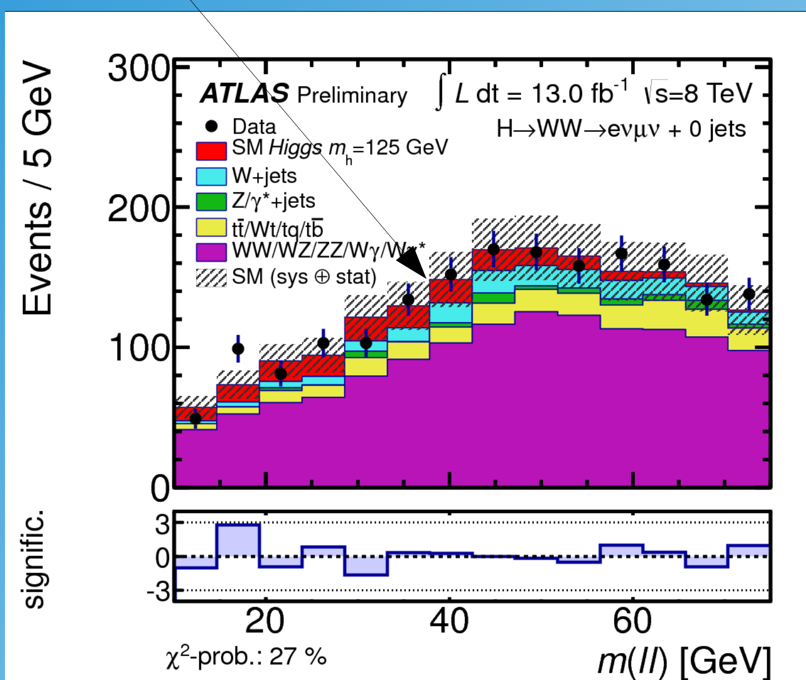
A) production via fermions
(type dependent!)

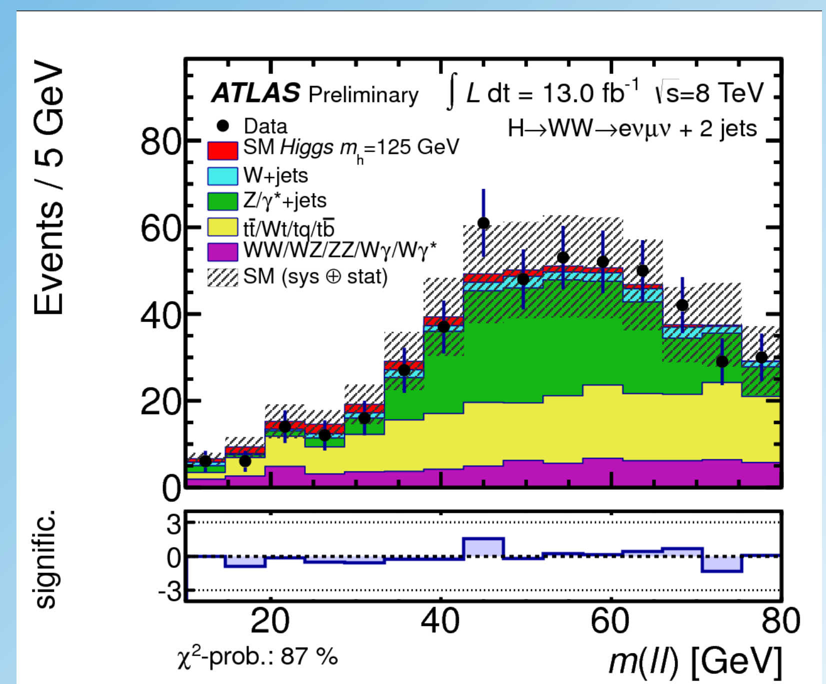
B) production via W/Z
(two extra jets!)





SM Higgs h





→ **data consistent with SM expectation**

Interpretation of Results

Higgs decays into ZZ:

$$g_{hZZ} = \frac{2im_Z^2}{v} s_{\beta-\alpha}, \quad g_{HZZ} = \frac{2im_Z^2}{v} c_{\beta-\alpha}$$

Higgs decays into WW:

$$g_{hWW} = \frac{2im_W^2}{v} s_{\beta-\alpha}, \quad g_{HWW} = \frac{2im_W^2}{v} c_{\beta-\alpha}$$

Other exotic decays:

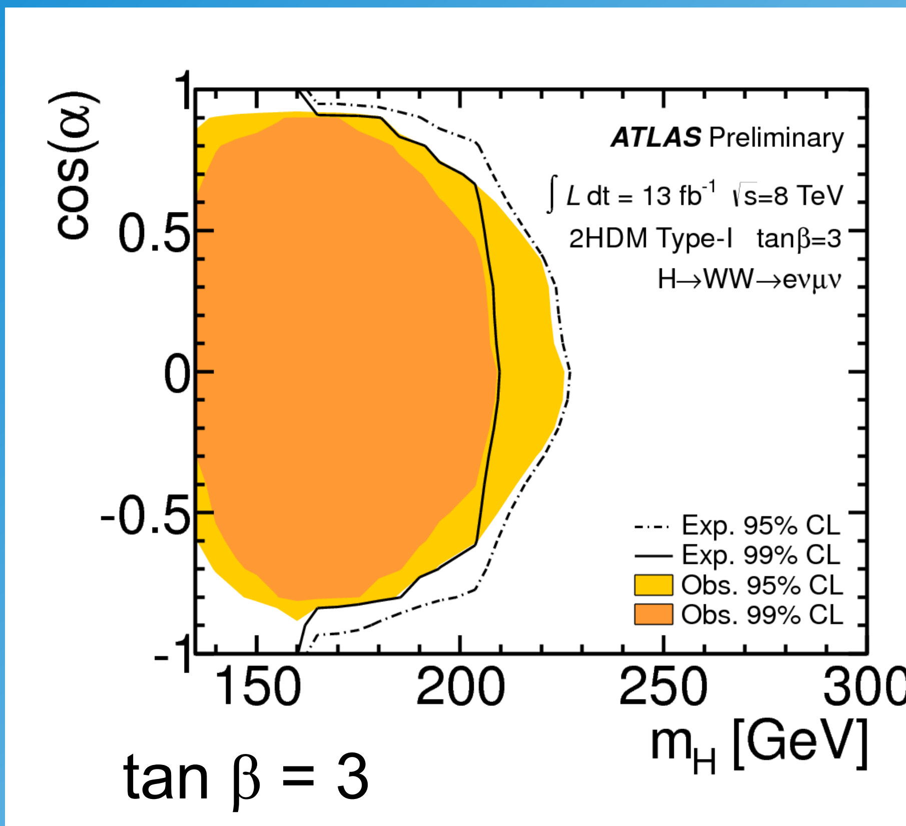
$$g_{Hhh} = -\frac{1}{4\, s_{2\beta}\, v}\left(\frac{4m_{12}^2}{s_\beta c_\beta}(c_{\beta-\alpha}^2 s_{\beta+\alpha} - 2 s_{\beta-\alpha} c_{\beta-\alpha} c_{\beta+\alpha}) - (2m_h^2 + m_H^2)(s_{3\alpha-\beta} + s_{\alpha+\beta})\right),$$

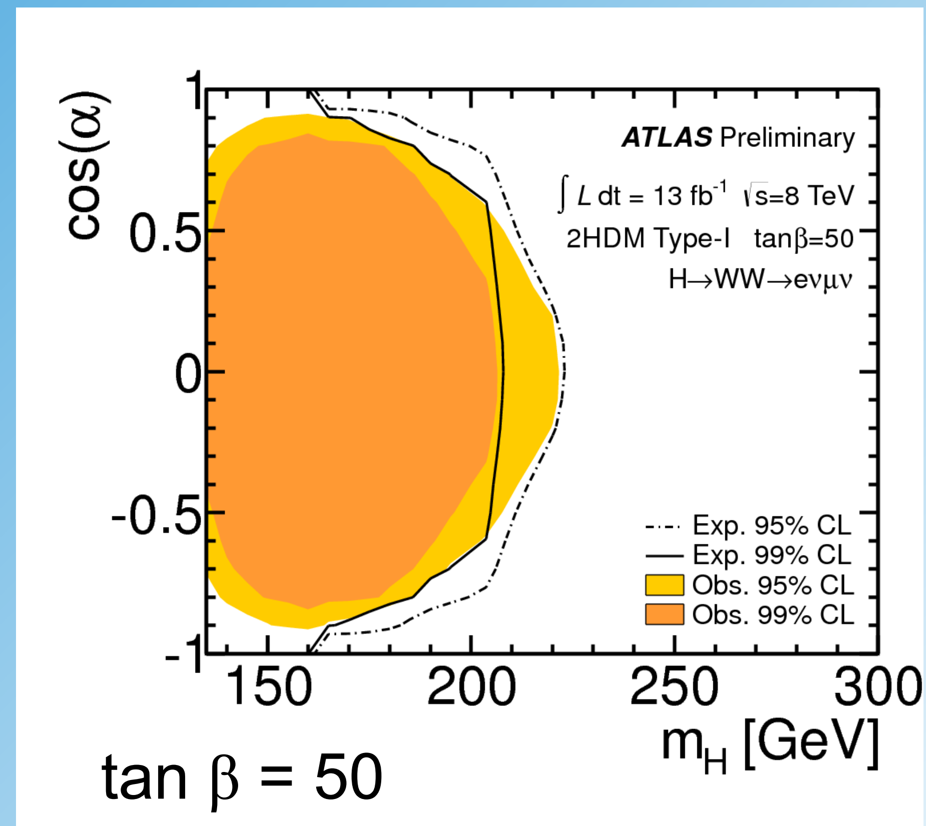
$$g_{HAA} = -\frac{1}{4\, s_{2\beta}\, v}\left(\frac{4m_{12}^2}{s_\beta c_\beta} s_{\beta+\alpha} - 8m_A^2 c_{\beta-\alpha} s_\beta c_\beta - m_H^2(s_{\alpha-3\beta} + 3s_{\alpha+\beta})\right),$$

$$g_{HH^+H^-} = -\frac{1}{4\, s_{2\beta}\, v}\left(\frac{4m_{12}^2}{s_\beta c_\beta} s_{\beta+\alpha} - 8m_{H^\pm}^2 c_{\beta-\alpha} s_\beta c_\beta - m_H^2(s_{\alpha-3\beta} + 3s_{\alpha+\beta})\right),$$

Preliminary 2HDM limits from ATLAS

→ **limits using 2HDM type I model**
→ **m_h constraint to 125 GeV**

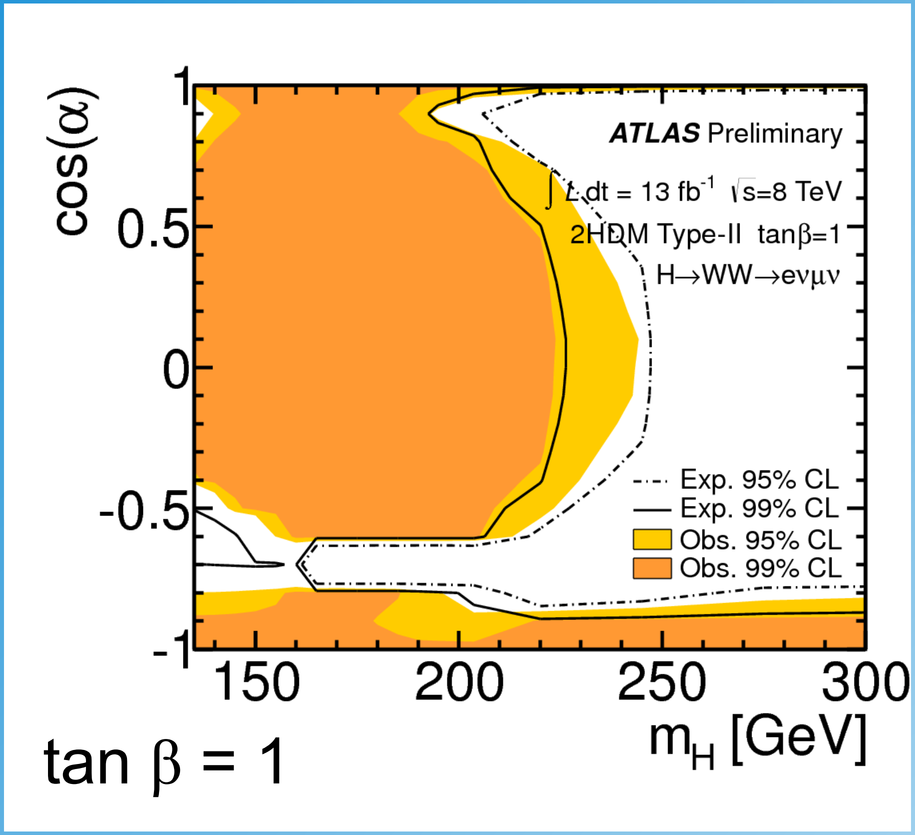


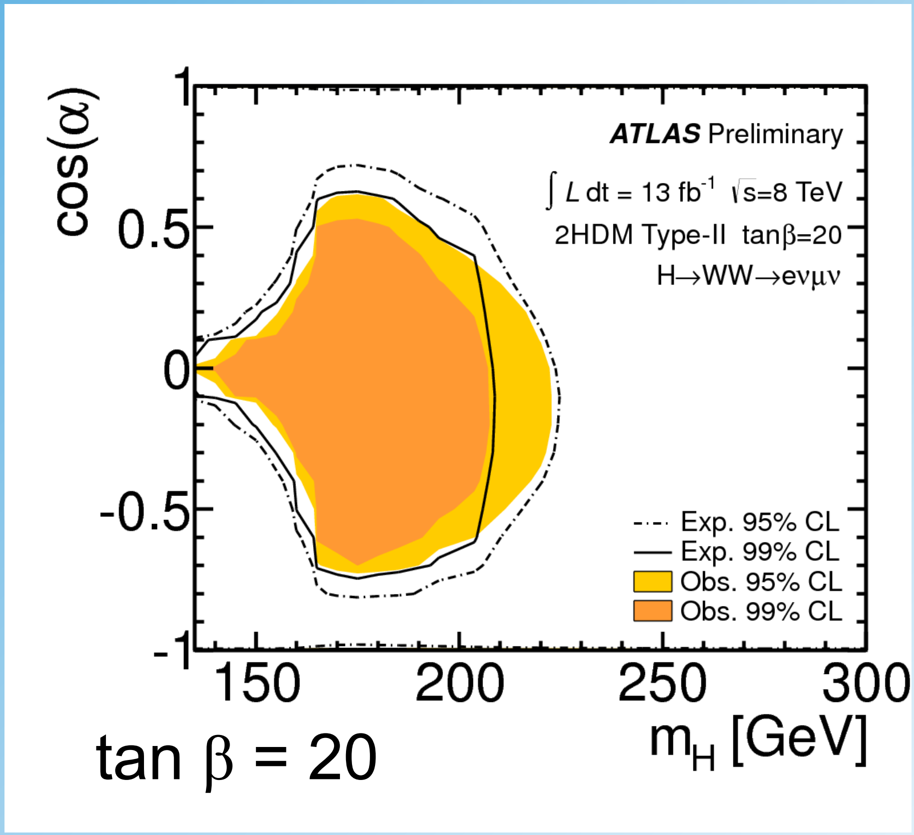


→ **"light" H can be excluded**
→ **no strong dependence on tan β**

Preliminary 2HDM limits from ATLAS

→ **limits using 2HDM type II model**
→ **m_h constraint to 125 GeV**

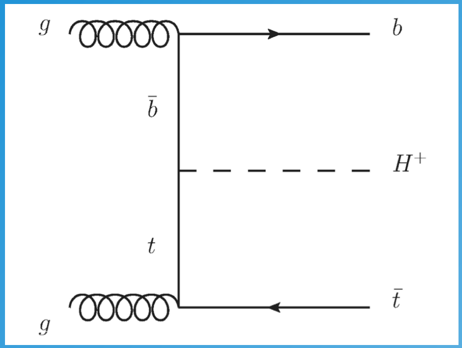




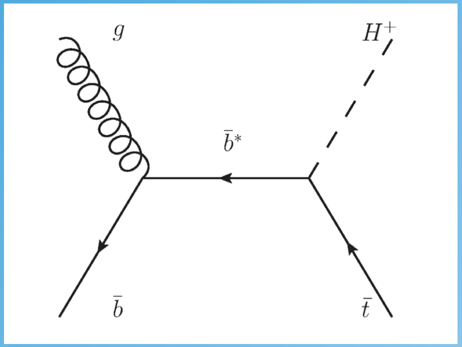
→ **limit shows strong dependence on tan β**

Search for Charged Higgs (2HDM)

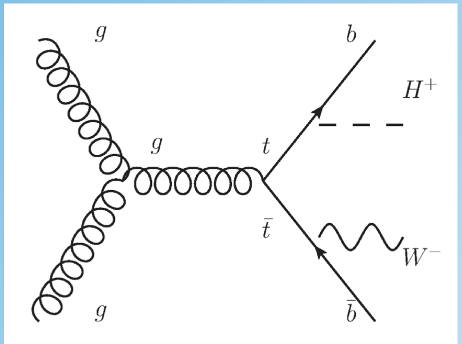
Dominant production via heavy particles!



bt → H^+ fusion

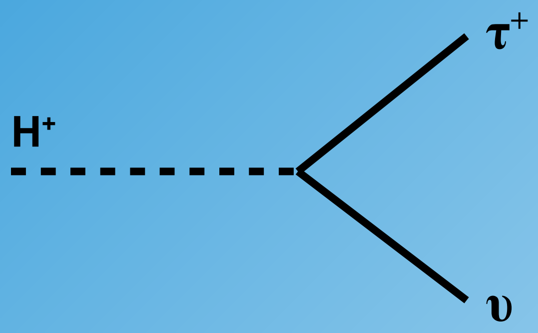


b → tH^+ Strahlung



t → bH^+ Strahlung

Decay $H^+ \to \tau\upsilon$:



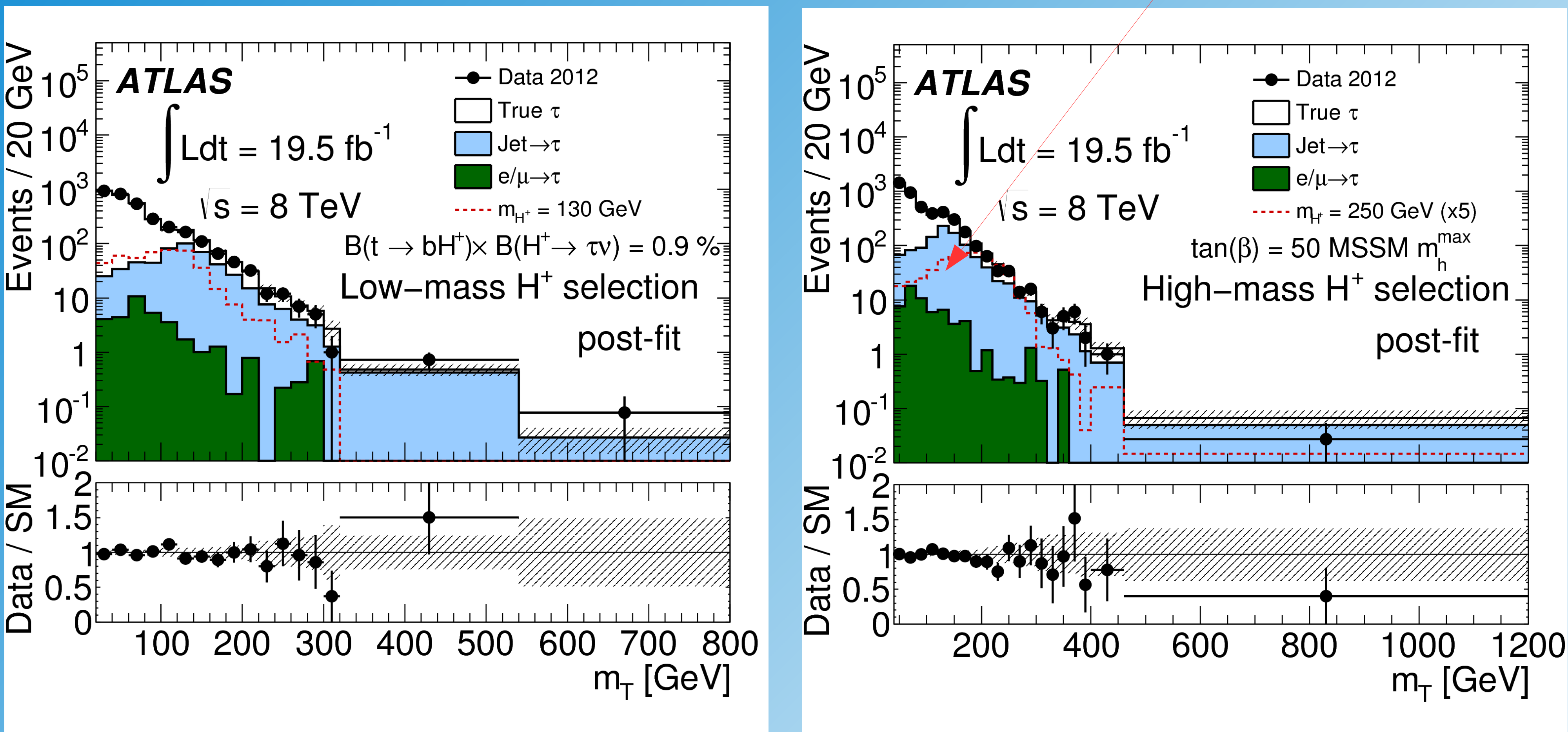
(isolated) taus represent a good search signature at LHC

Distribution m_T published be ATLAS

m_T is the reconstructed transverse mass of tau and neutrino:

$$m_T^2 = (p_x^\tau + p_x^\nu)^2 + (p_y^\tau + p_y^\nu)^2$$

hypothetical signal



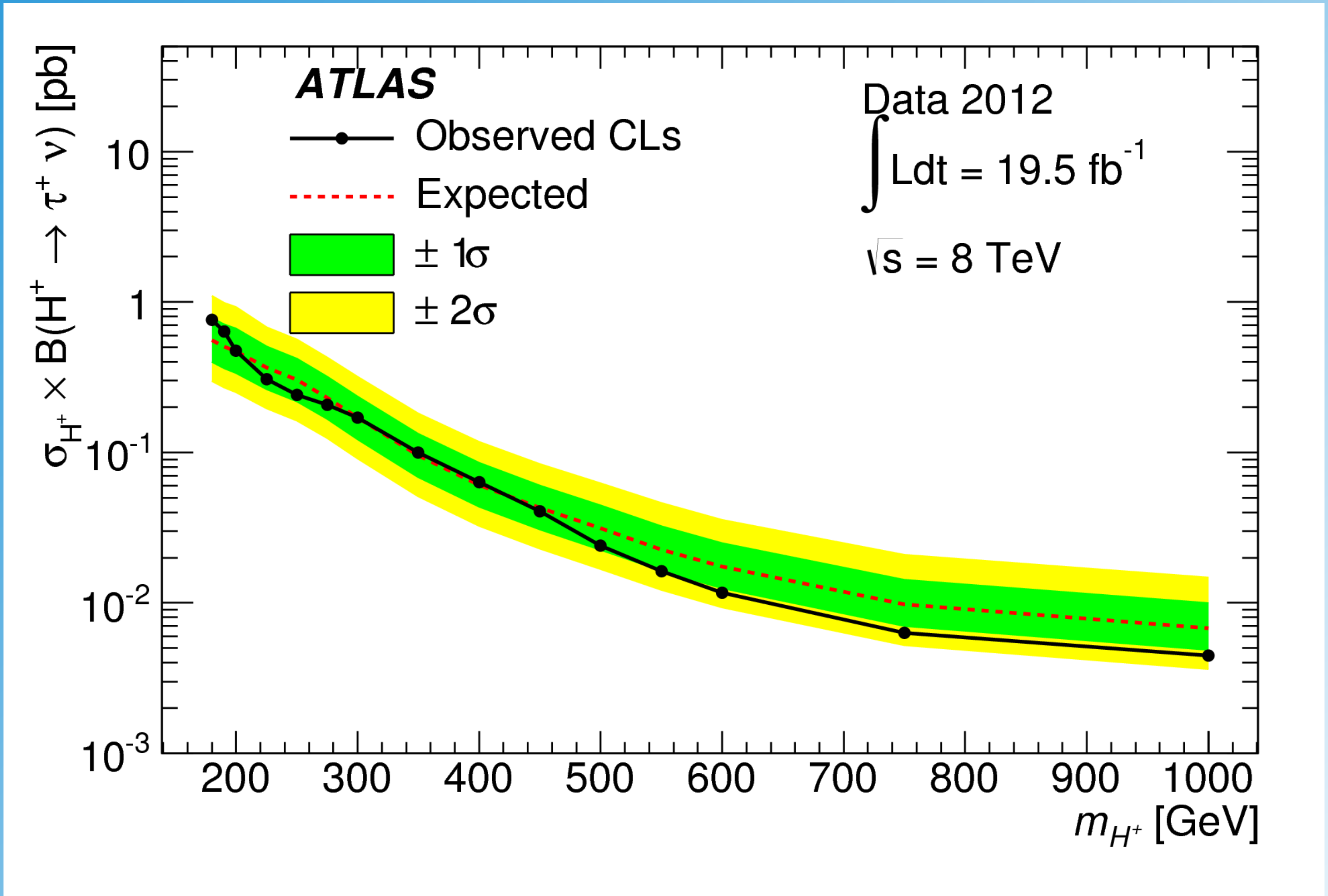
Low H⁺ mass selection

High H⁺ mass selection

→ no deviation from SM expectation

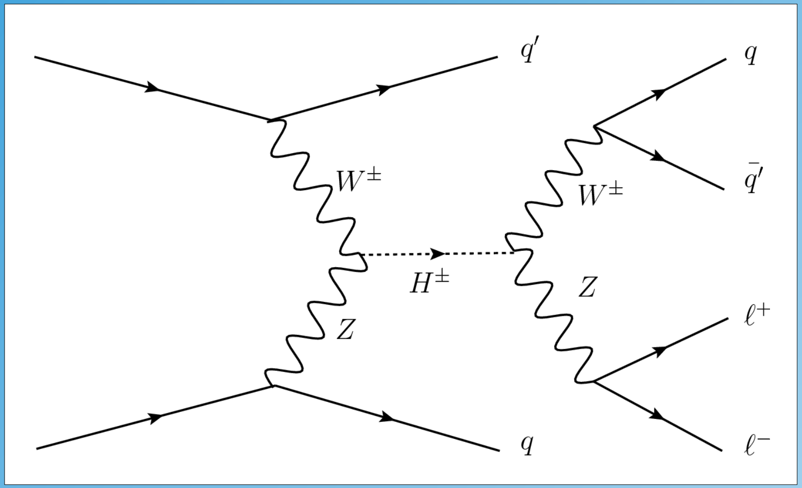
Search for Charged Higgs (2HDM)

Note: Limit assumes production via Higgs-fermion couplings



2nd Search for Charged Higgs (2HDM)

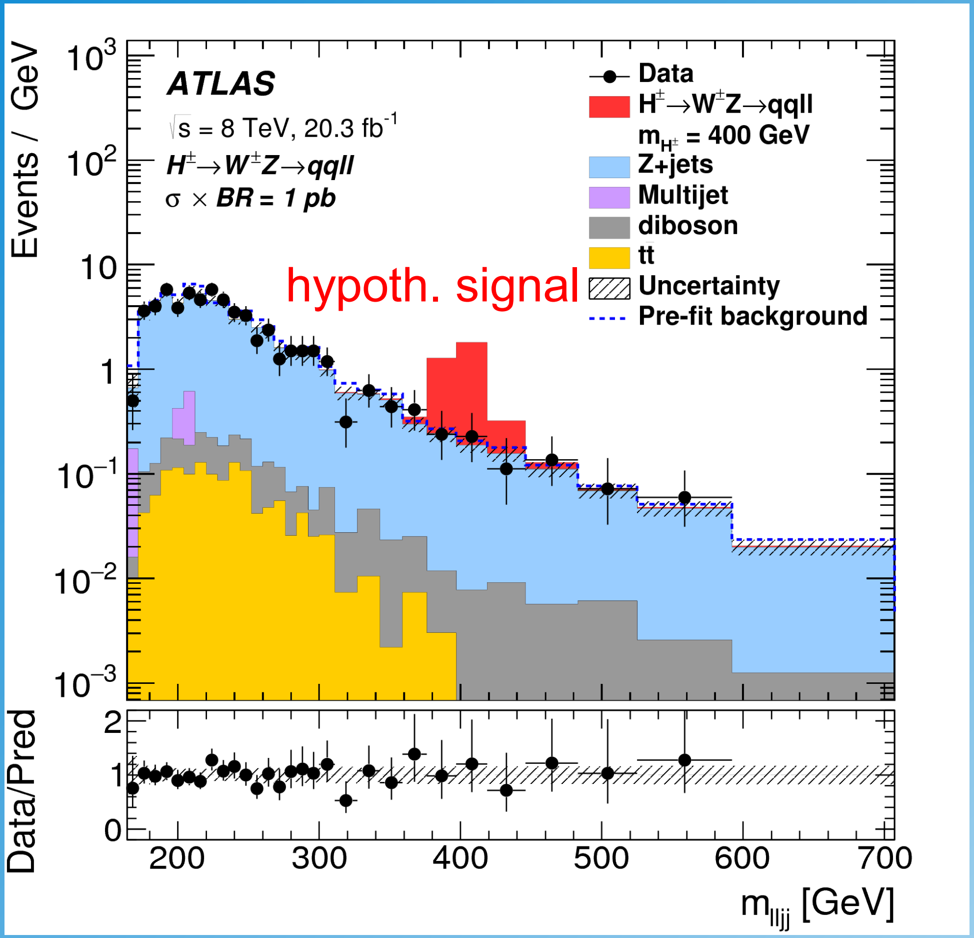
H^+ production via WZ fusion, decay into WZ pair:



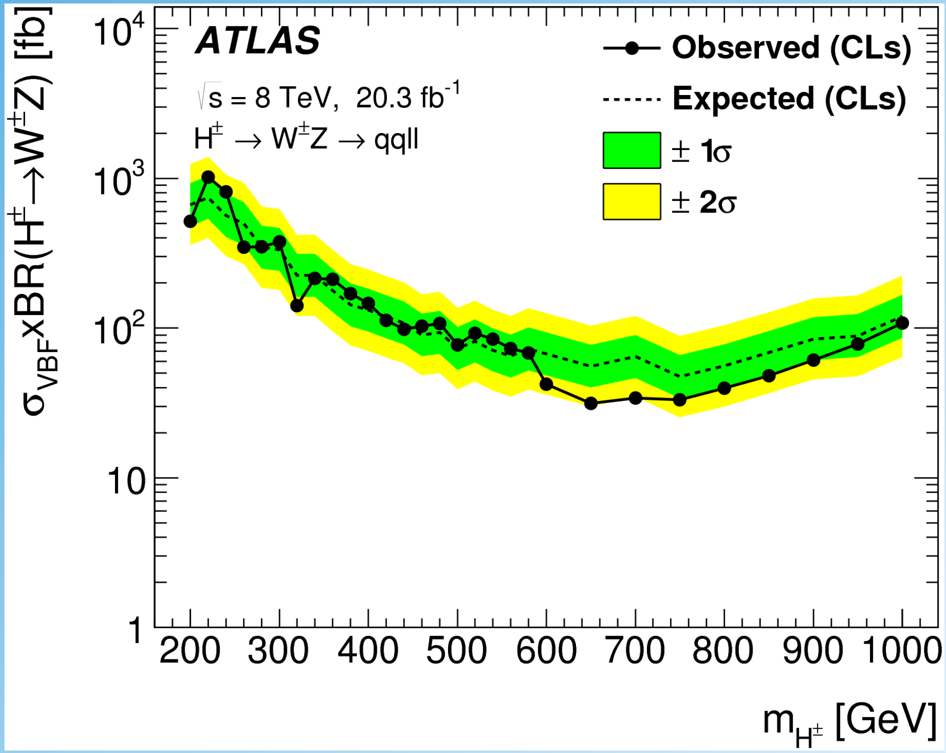
→ H^+ can be interpreted as WZ resonance!

- Search is independent of H^+ - fermion couplings!
- Search channel: jjlv (2+2 jets, lepton and missing energy)

2nd Search for Charged Higgs (2HDM)



reconstructed WZ invariant mass



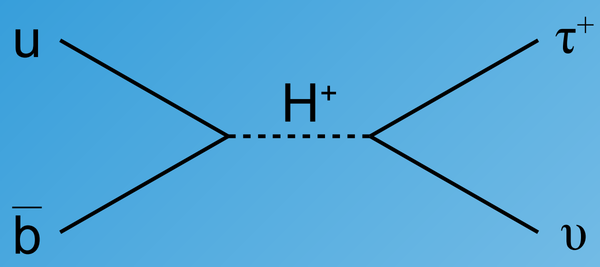
cross section limit

2HDM Constraints from Decays

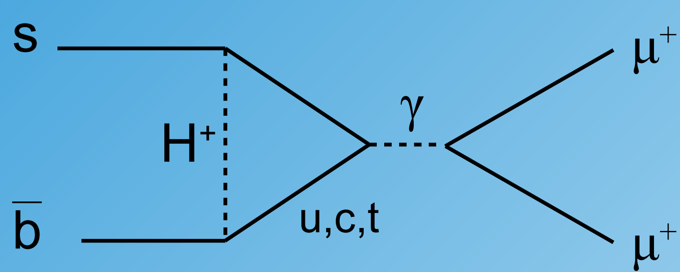
H^+ Constraints can also be obtained from particle decays

Examples:

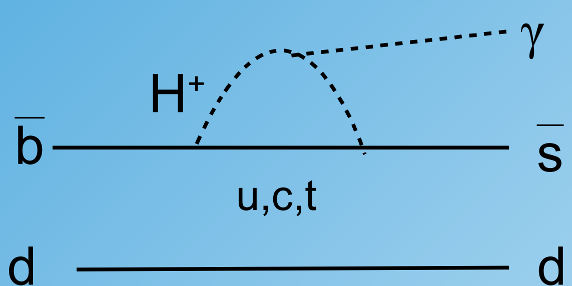
$B^+ \rightarrow \tau\upsilon$:



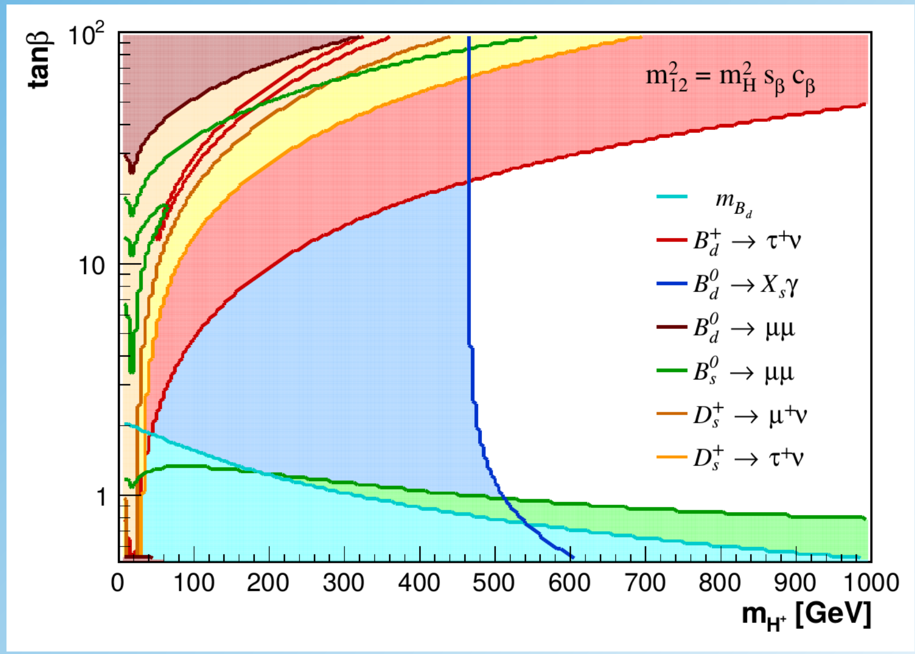
$B_s \rightarrow \mu^+\mu^-$:



$B_d \rightarrow X_s\,\gamma$:



with $X_s = K_s$ or K_s^* , etc.



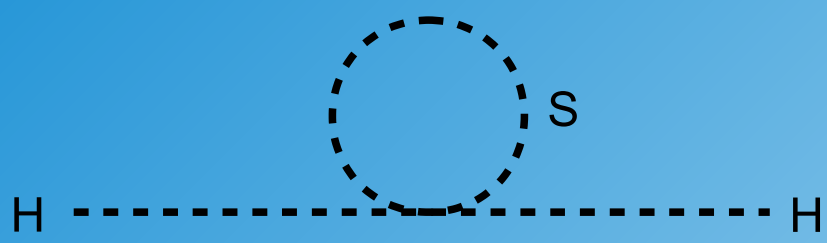
→ Large and low tan β regions excluded!

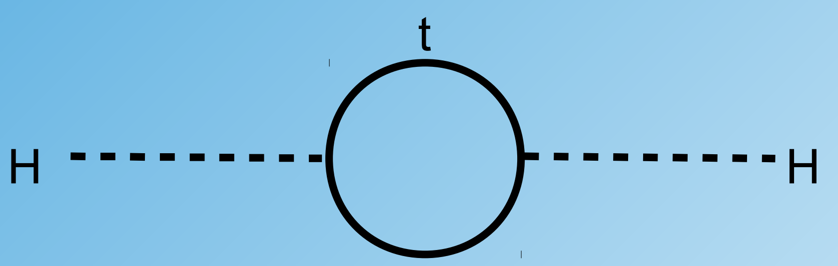
low energy limits are competetive!

Supersymmetry I

Motivation:

• the fine tuning problem





$$\delta M_{HS}^{2} = \frac{|\lambda_s^2|}{16\pi^2}\left[\Lambda^2 + 2m_s^2 \log \Lambda / m_s\right]$$

$$\delta M_{HF}^{2} = \frac{|g_f^2|}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 \log \Lambda / m_f\right]$$

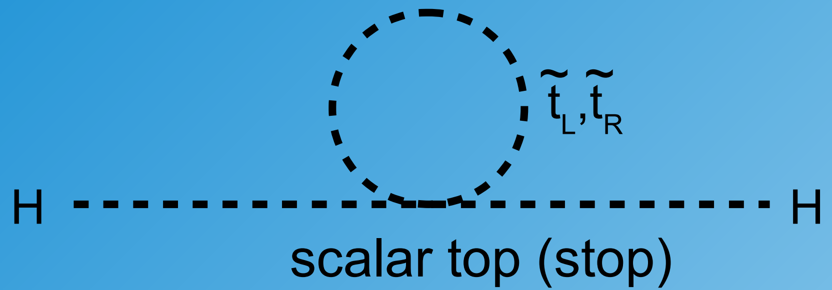
Lambda terms cancels if #(scalars) = 2 #(fermions)

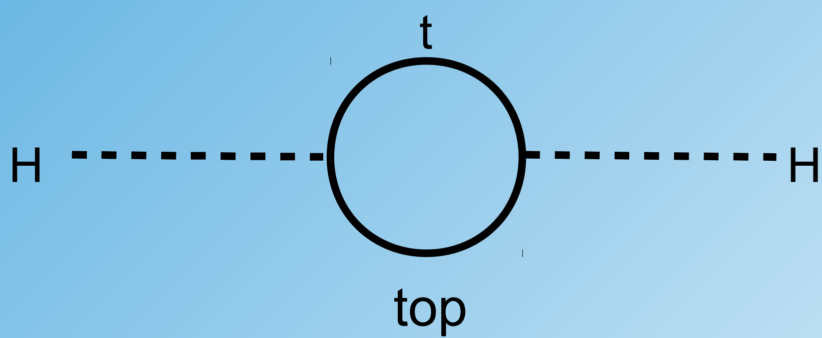
note: fermions exist in two chiral states

postulate: every chiral fermion has a supersymmetric scalar partner (and vice versa)

$\rightarrow n_B = n_F$!

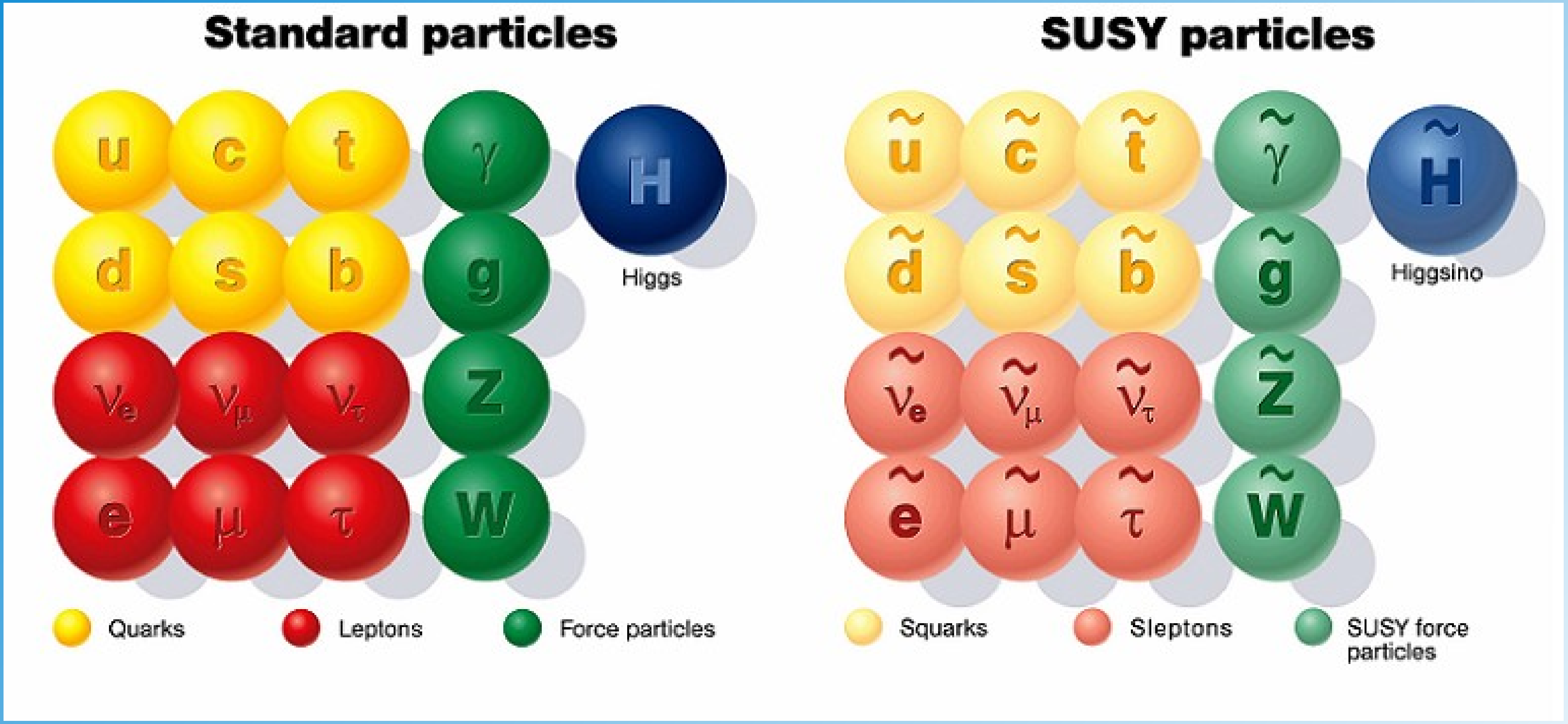
Supersymmetry II





cancellation of quadratic fermion loops with scalar fermion (sfermion) loops

Supersymmetry III



supersymmetric particles have identical gauge quantum numbers but differ in spin by ½

Supersymmetry IV

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

← 2HDM type 2

Note: mixing between states with identical quantum numbers possible!

MSSM Parameters

MSSM=Minimum Super-Symmetric Model

- Coulings: g_s, g, g' corresponding to the SU(3) x SU(2) x U(1) gauge groups
- Higgsino mass parameter μ
- Higgs-Fermion Yukawa coupling y_u, y_d, y_e (fermion-Higgs, sfermion-Higgsino)

<u>SUSY breaking parameters:</u> $M_{SUSY} > M_{SM}$

Masses:

- gaugino masses M_3, M_2, M_1 associated to SU(3) x SU(2) x U(1)
- scalar squared mass parameters

$M^2_{\tilde{Q}}$, $M^2_{\tilde{U}}$, $M^2_{\tilde{D}}$, $M^2_{\tilde{L}}$, $M^2_{\tilde{E}}$ corresponding to $(u,d)_L$, u^c_L, d^c_L, $(\nu, e^-)_L$, e^c_L

- trilinear Higgs-sfermion-sfermion couplings: $\lambda_u A_u$, $\lambda_d A_d$, $\lambda_e A_e$
- scalar Higgs mass parameters: $m_1^2+\mu^2$, $m_2^2+\mu^2$, $m_{12}^2 = B\mu$

  can also be re-expressed by: $\tan\beta = v_u/v_d$ $\quad v_u^2+v_d^2 = (246\,GeV)^2$

In total 124 parameters in MSSM

SUSY R-Parity

R-parity is a multiplicative quantum number:

$$R|particle\rangle = 1 \qquad R|SUSY\ particle\rangle = -1 \qquad R=(-1)^{3B+L+2S}$$

If R-parity is conserved SUSY particles (sparticle) can only be produced in pairs. The <u>lightest sparticle</u> (LSP) is stable (usually neutralino)!

If the LSP is charged → heavy ionising particle
If the LSP is neutral → candidate for dark matter

R-parity conservation prevents from large radiative corrections and FCNC if the SUSY particles are light

R-parity can be broken by bilinear (e.g LH) or trilinear terms (e.g. UDD)

$$L_{\Delta L=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu^i L_i H_u \qquad \text{lepton number violation}$$

$$L_{\Delta B=1} = \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k \qquad \text{baryon number violation}$$

Note, either R-Parity is (mostly) conserved or SUSY mass scale is high to stabilize proton!

Unification of Couplings

x

1-loop renormalisation group equation (RGE) for couplinga a=1,2,3:

$$\frac{d}{d\ \ln(Q/q_0)} g_a = \frac{1}{16\pi^2} b_a g_a^3 \quad \Rightarrow \quad \frac{d}{d\ \ln(Q/q_0)} \alpha_a^{-1} = -\frac{b_a}{2\pi}$$

Q is the energy scale

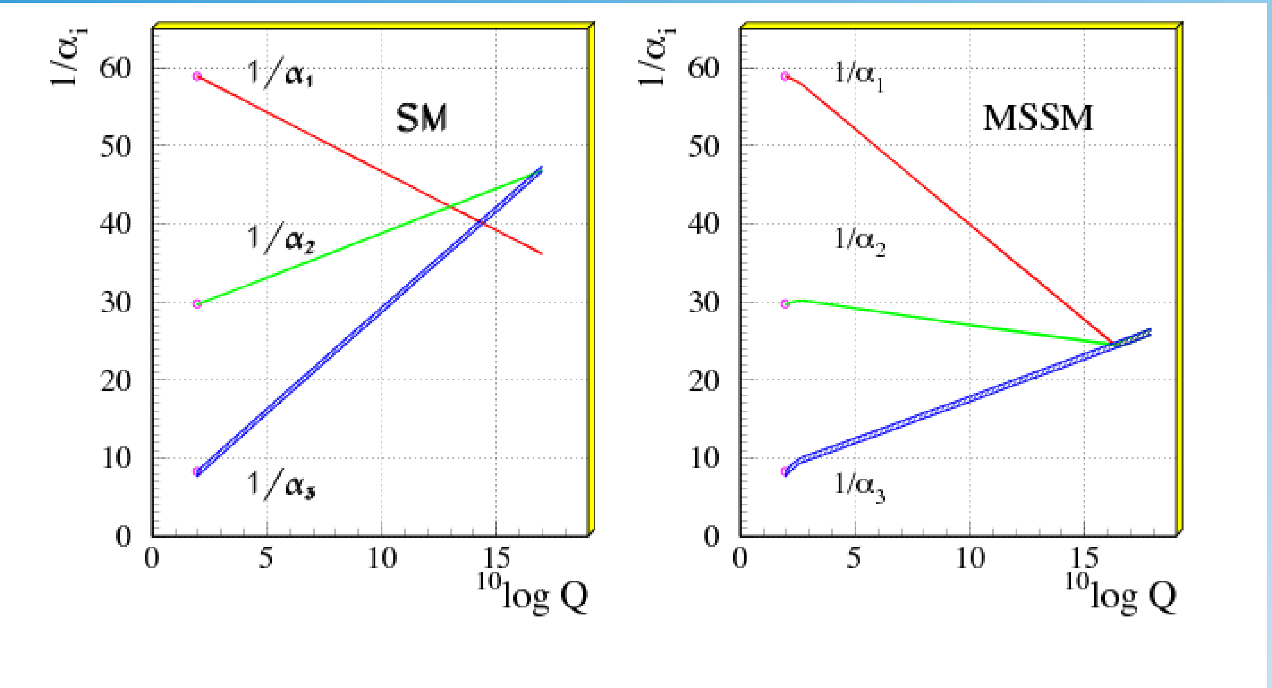
The slopes can be calculated for models:

SM: $\vec{b}^{SM} = (41/10, -19/6, -7)$

SUSY: $\vec{b}^{SM} = (33/5, 1, -3)$

Relation between mass scales:

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2}$$



coupling unification in SUSY

$$g_2 = g; \quad g_1 = g\sqrt{5/3}\, g'$$

$$M_{unification} \approx 10^{16}\, GeV$$

Higgs Yukawa Couplings

The ratio of SUSY Yukawa couplings and SM Yukawa couplins (g m_f / 2m_W) is given by (like 2HDM):

$$h b \bar{b}: \quad -\sin(\alpha)/\cos(\beta)$$
$$h t \bar{t}: \quad \cos(\alpha)/\sin(\beta)$$
$$H b \bar{b}: \quad \cos(\alpha)/\cos(\beta)$$
$$H t \bar{t}: \quad \sin(\alpha)/\sin(\beta)$$

$$A b \bar{b}: \quad \gamma_5 \tan(\beta)$$
$$A t \bar{t}: \quad \gamma_5 \cot(\beta)$$

(similar for other generation and leptons)

note: if $\alpha \approx 0$

$$y_{tt} \sim g \frac{m_t}{2 m_W} \frac{1}{\sin\beta} \approx y_{bb} \sim g \frac{m_b}{2 m_W} \frac{1}{\cos\beta}$$

$$\Rightarrow \frac{m_t}{m_b} \approx \tan\beta$$

If A dominant:

$$\Rightarrow \frac{m_t}{m_b} \approx \tan^2\beta$$

large β value might explain top-bottom mass splitting!

Check List SUSY

- dark matter candidate
- number of fermion generations
- fermion masses (in particular light neutrino masses)
- CP-violation
- Fermion-Number Violation (BNV or LNV)
- Unification of forces
- (Hierarchy problem)

Higgs Mass in SUSY

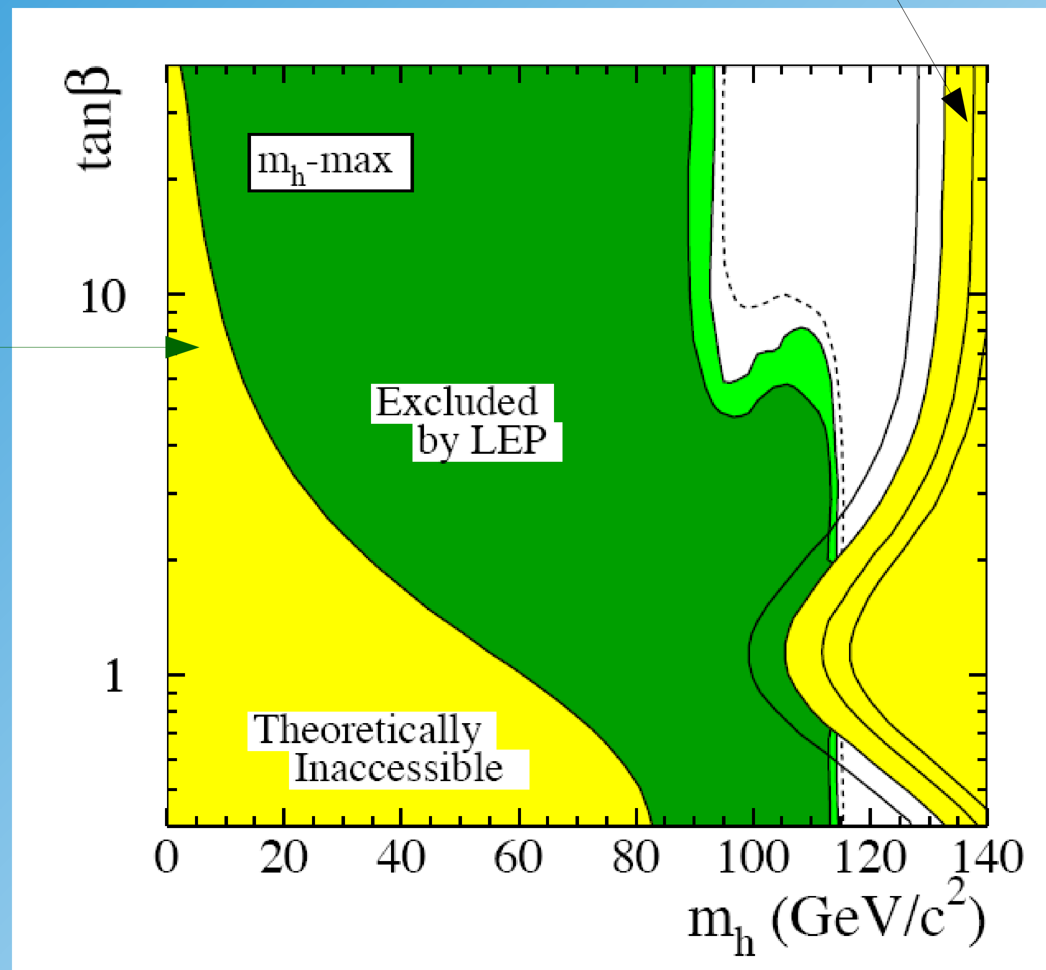
- m_h corresponds to the SM Higgs particle
- however, there is an upper limit on the mass (theory constraint)

LEP Searches:

$e^+e^- \rightarrow hZ$

$e^+e^- \rightarrow AZ$

$m_h > 92$ GeV



found Higgs at 125 GeV lies in the allowed SUSY band!!!

mSUGRA and SUSY Particle Masses

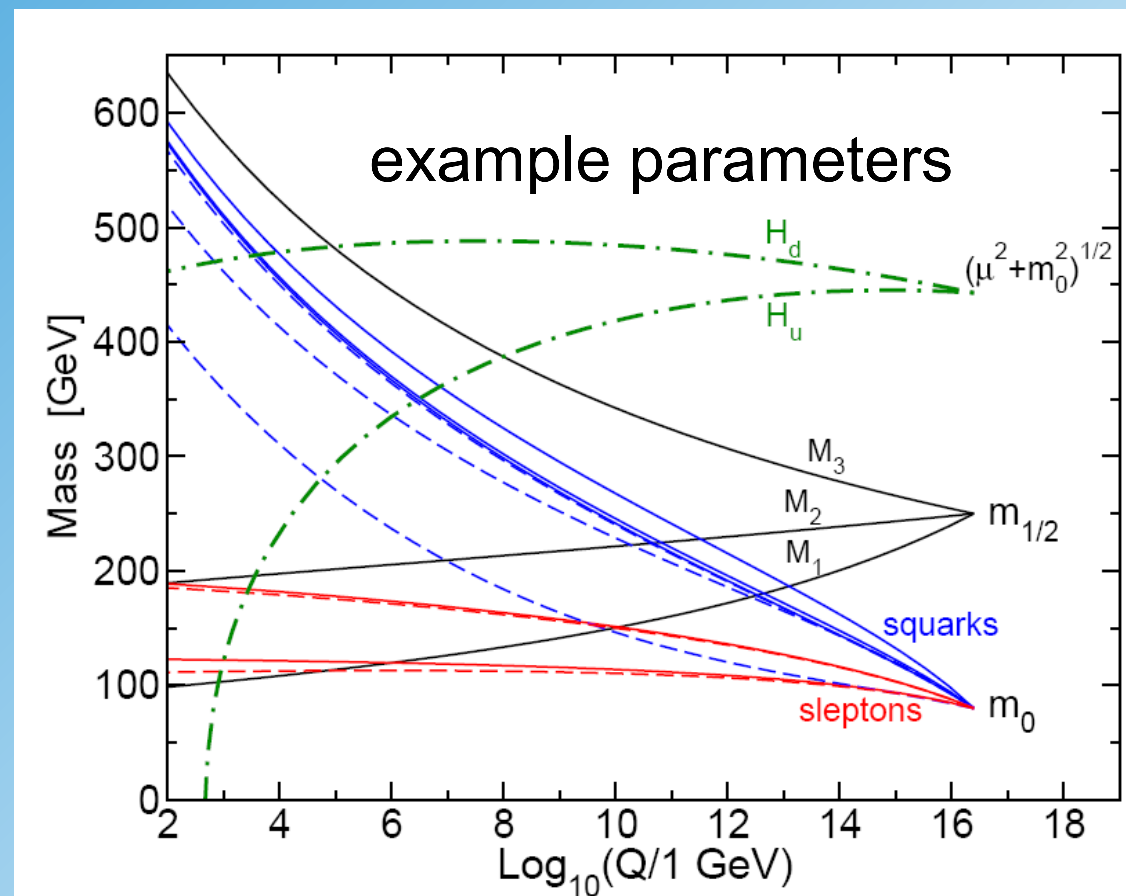
- Origin of SUSY breaking is unclear → many models
- mSUGRA (minimal Supergravity model):
  → breaking mediated by gravity in hidden sector

Renormalisation Group Equations:

$$\frac{dm^2_{H_u}}{dt} = \left[\frac{3X_t}{4\pi} - 6\alpha_2 M_2^2 - \frac{6}{5}\alpha_1 M_1^2\right] \Big/ 4\pi$$

$$\frac{dm^2_{\tilde{Q}_3}}{dt} = \left[\frac{X_t}{4\pi} - \frac{32}{3}\alpha_3 M_3^2 - 6\alpha_2 M_2^2 - \frac{2}{15}\alpha_1 M_1^2\right] \Big/ 4\pi$$

$$\frac{dm^2_{\tilde{u}_3}}{dt} = \left[\frac{2X_t}{4\pi} - \frac{32}{3}\alpha_3 M_3^2 - \frac{32}{15}\alpha_1 M_1^2\right] \Big/ 4\pi,$$



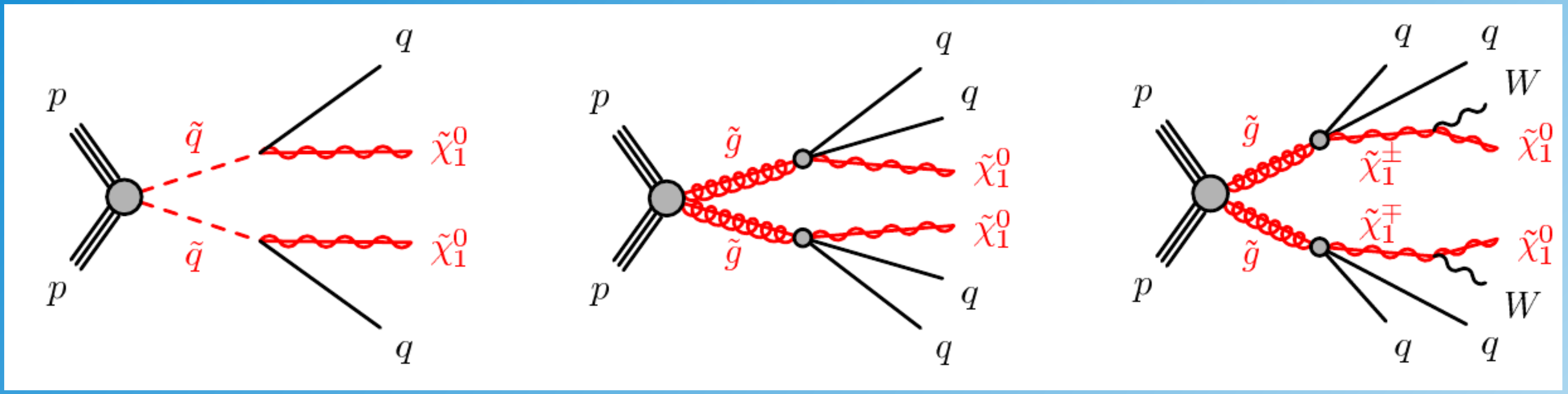
note, that the Higgs mass gets negative, provoking electroweak symmetry breaking!

→ unification

But, mSUGRA is excluded by experimental data!

Searches at LHC

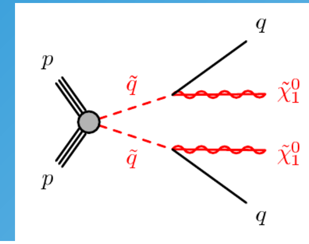
Search for Squarks and Gluinos at ALTAS

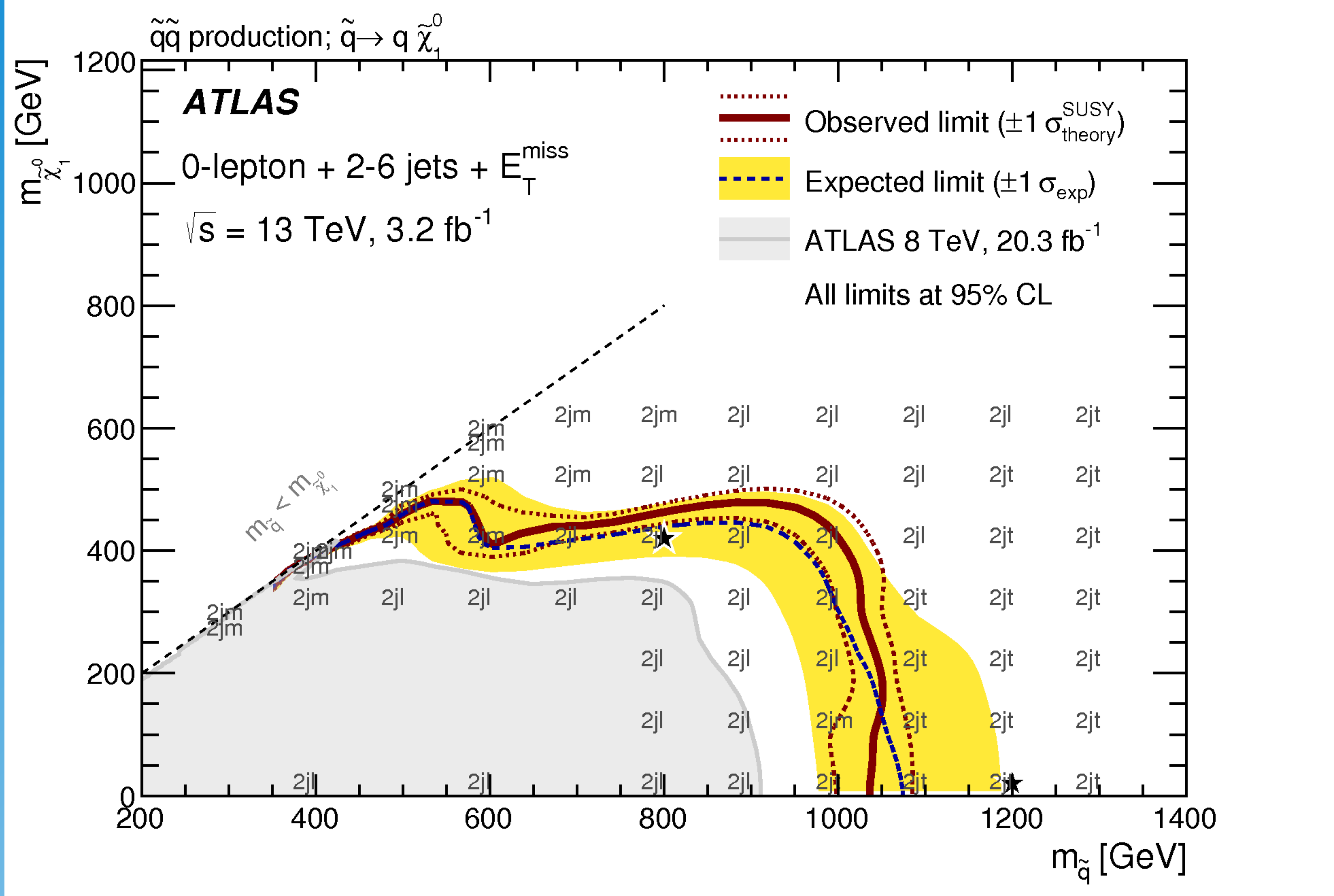


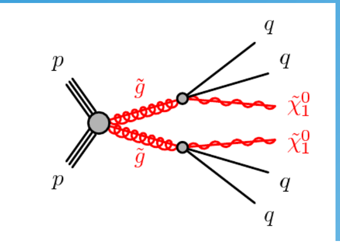
Selection Strategy:

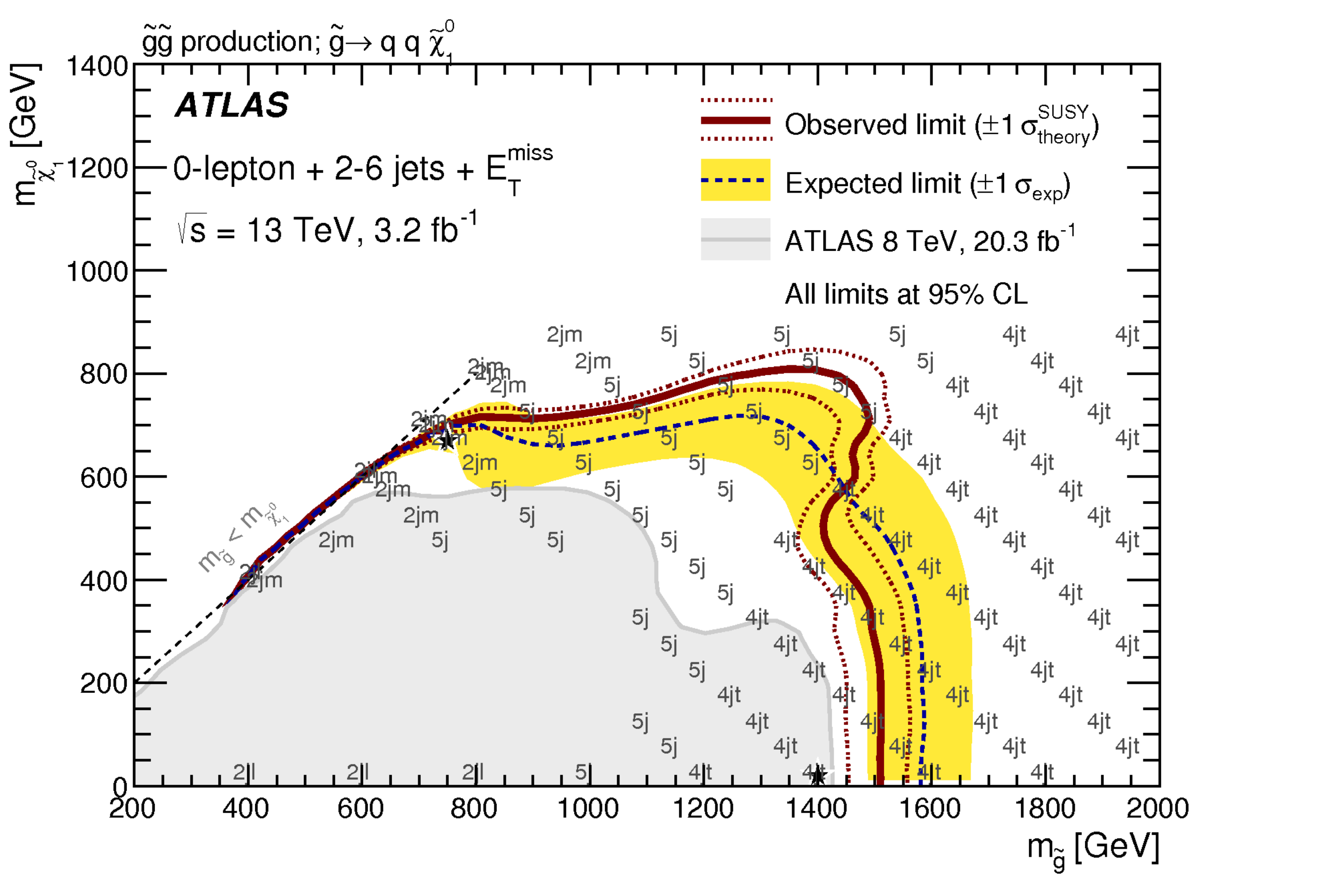
- multiple jets
- missing energy (neutralino)
- event topology

Requirement	Signal Region						
	2jl	**2jm**	**2jt**	**4jt**	**5j**	**6jm**	**6jt**
E_T^{miss} [GeV] >	200						
$p_T(j_1)$ [GeV] >	200	300	200				
$p_T(j_2)$ [GeV] >	200	50	200	100			
$p_T(j_3)$ [GeV] >	–			100			
$p_T(j_4)$ [GeV] >	–			100			
$p_T(j_5)$ [GeV] >	–				50		
$p_T(j_6)$ [GeV] >	–					50	
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_T^{miss})_{min}$ >	0.8	0.4	0.8	0.4			
$\Delta\phi(\text{jet}_{i>3}, \boldsymbol{E}_T^{miss})_{min}$ >	–			0.2			
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	15		20	–			
Aplanarity >	–			0.04			
$E_T^{miss}/m_{eff}(N_j)$ >	–			0.2	0.25		0.2
m_{eff}(incl.) [GeV] >	1200	1600	2000	2200	1600	1600	2000

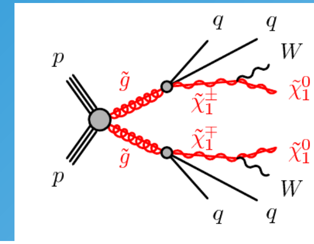

p
p
q̃
q̃
q
q
χ̃⁰₁
χ̃⁰₁

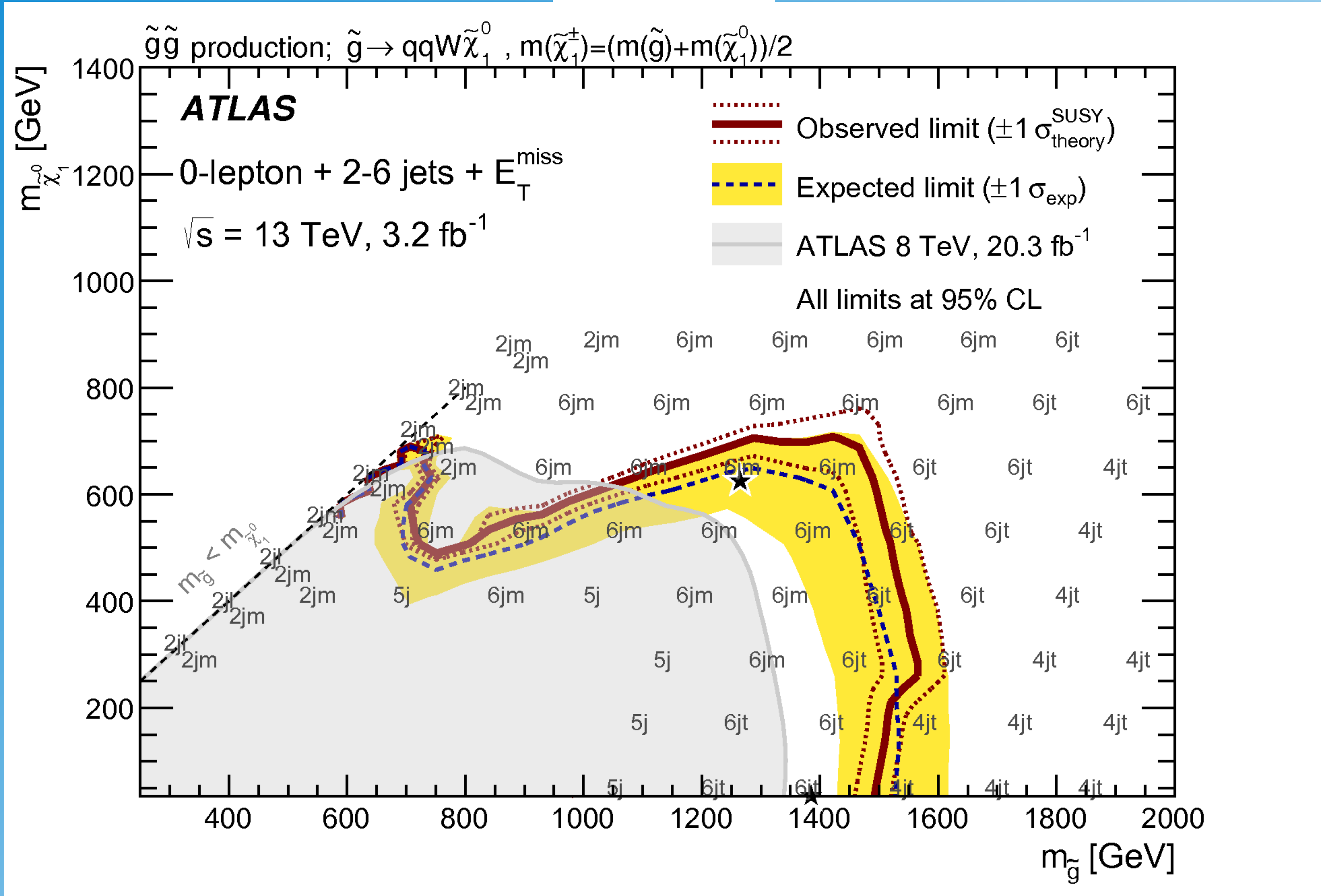

q̃q̃ production; q̃→ q χ̃⁰₁
ATLAS
0-lepton + 2-6 jets + E_T^miss
√s = 13 TeV, 3.2 fb⁻¹
Observed limit (±1 σ_theory^SUSY)
Expected limit (±1 σ_exp)
ATLAS 8 TeV, 20.3 fb⁻¹
All limits at 95% CL
m_q̃ < m_χ̃⁰₁
m_χ̃⁰₁ [GeV]
m_q̃ [GeV]
0
200
400
600
800
1000
1200
1400
2jm
2jl
2jt





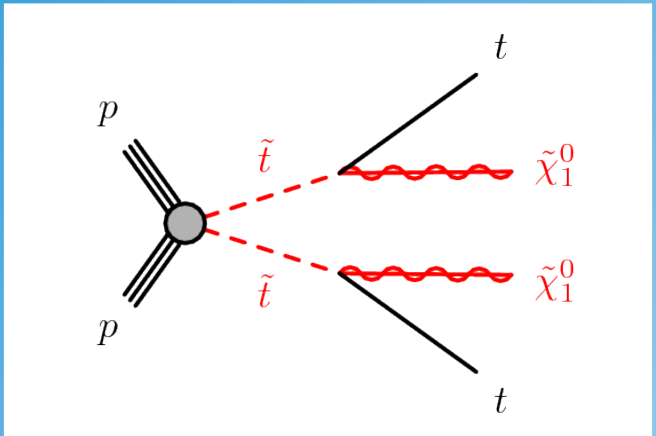
$\tilde{g}\tilde{g}$ production; $\tilde{g} \rightarrow q\,q\,\tilde{\chi}_1^0$
ATLAS
0-lepton + 2-6 jets + E_T^{miss}
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
Observed limit ($\pm 1\,\sigma_{theory}^{SUSY}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
ATLAS 8 TeV, 20.3 fb^{-1}
All limits at 95% CL
$m_{\tilde{g}} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]


p
p
q q
W
W
q q

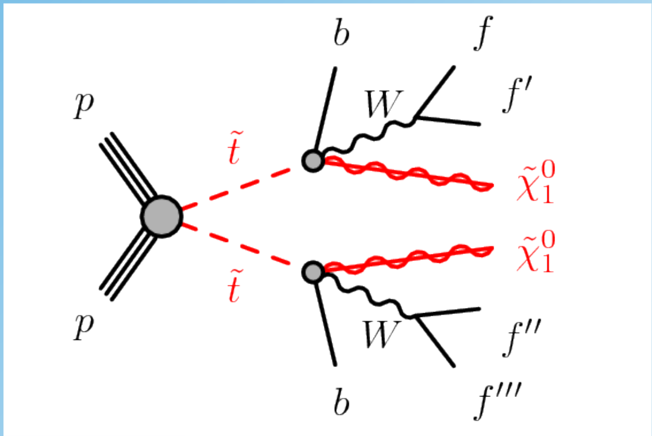

$\tilde{g}\tilde{g}$ production; $\tilde{g} \rightarrow qqW\tilde{\chi}_1^0$, $m(\tilde{\chi}_1^\pm) = (m(\tilde{g}) + m(\tilde{\chi}_1^0))/2$
ATLAS
0-lepton + 2-6 jets + E_T^{miss}
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm 1\,\sigma_{exp}$)
ATLAS 8 TeV, 20.3 fb^{-1}
All limits at 95% CL
$m_{\tilde{g}} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]
1400
1200
1000
800
600
400
200
400
600
800
1000
1200
1400
1600
1800
2000

Search for scalar Top Quarks

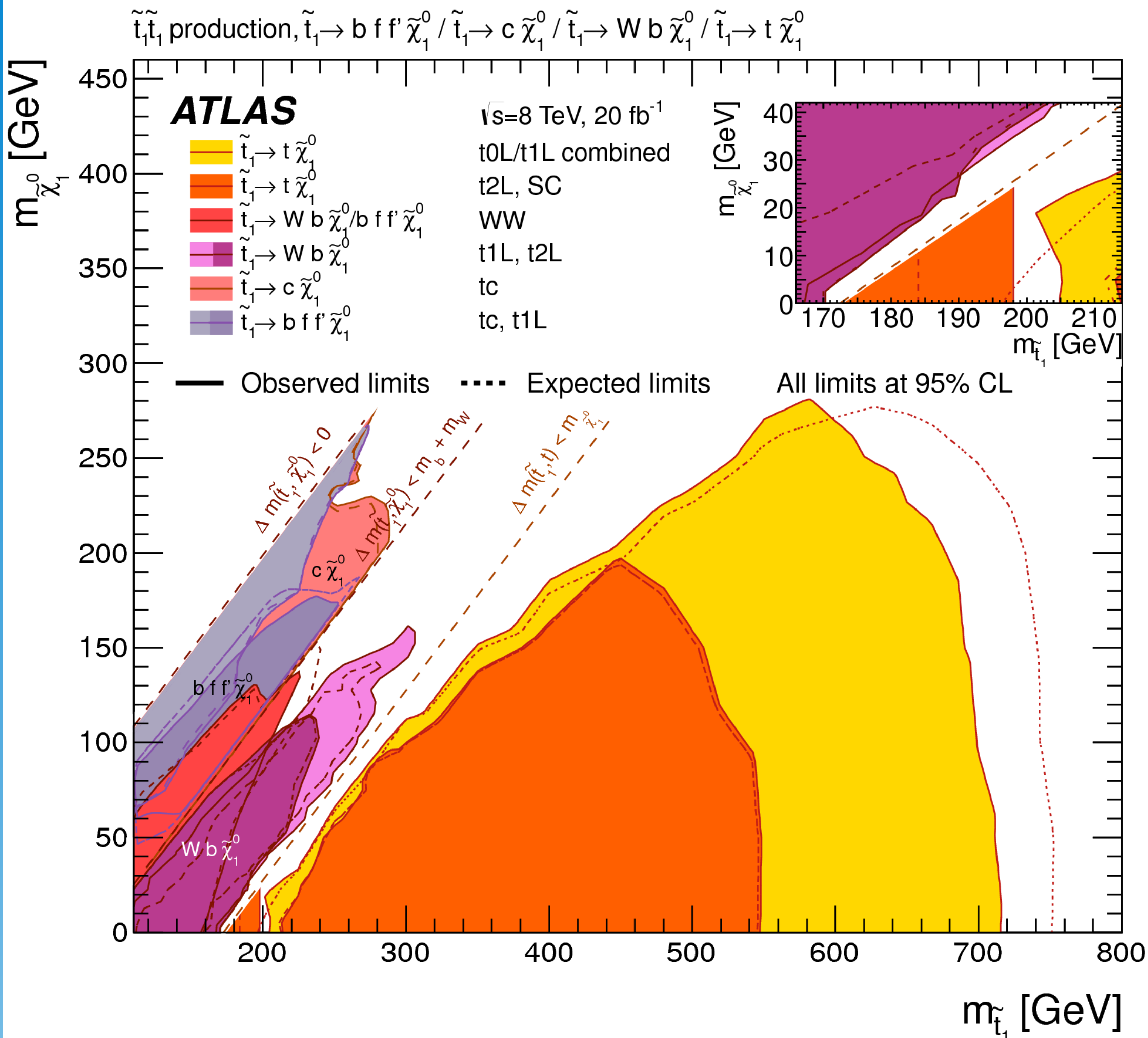
- stops are the lights squarks (sfermions) in most SUSY models
- very similar search as for scalar quarks
- extra cuts on top-decays (b-tagging, …)
- search topology is mass dependent:



$m_{t\sim} > m_t + m_\chi$



$m_\chi < m_{t\sim} < m_t + m_\chi$



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to b f f' \tilde{\chi}^0_1$ / $\tilde{t}_1 \to c \tilde{\chi}^0_1$ / $\tilde{t}_1 \to W b \tilde{\chi}^0_1$ / $\tilde{t}_1 \to t \tilde{\chi}^0_1$
ATLAS
$\sqrt{s}$=8 TeV, 20 fb^{-1}
$\tilde{t}_1 \to t \tilde{\chi}^0_1$ t0L/t1L combined
$\tilde{t}_1 \to t \tilde{\chi}^0_1$ t2L, SC
$\tilde{t}_1 \to W b \tilde{\chi}^0_1$/b f f' $\tilde{\chi}^0_1$ WW
$\tilde{t}_1 \to W b \tilde{\chi}^0_1$ t1L, t2L
$\tilde{t}_1 \to c \tilde{\chi}^0_1$ tc
$\tilde{t}_1 \to b f f' \tilde{\chi}^0_1$ tc, t1L
Observed limits
Expected limits
All limits at 95% CL
$\Delta m(\tilde{t}_1, \tilde{\chi}^0_1) < 0$
$\Delta m(\tilde{t}_1, \tilde{\chi}^0_1) < m_b + m_W$
$\Delta m(\tilde{t}_1, t) < m_{\tilde{\chi}^0_1}$
c $\tilde{\chi}^0_1$
b f f' $\tilde{\chi}^0_1$
W b $\tilde{\chi}^0_1$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]

Heavy Exotic Bosons

<u>Various models:</u>

- SU(3) x SU(2) x SU(1) x SU(1)'

  → exotic W' Z' partners (new vector bosons)

- SU(3) x $SU(2)_L$ x $SU(2)_R$ x SU(1)

  → left-right symmetric models
  → often with additional Higgs Triplets: Δ , Δ^+ , Δ^{++}

- Kaluzza-Klein Models

  → models with compactified extra dimensions
  → new particles are excited states in extra dimensions
  → could explain large Planck mass (weak gravitation)!

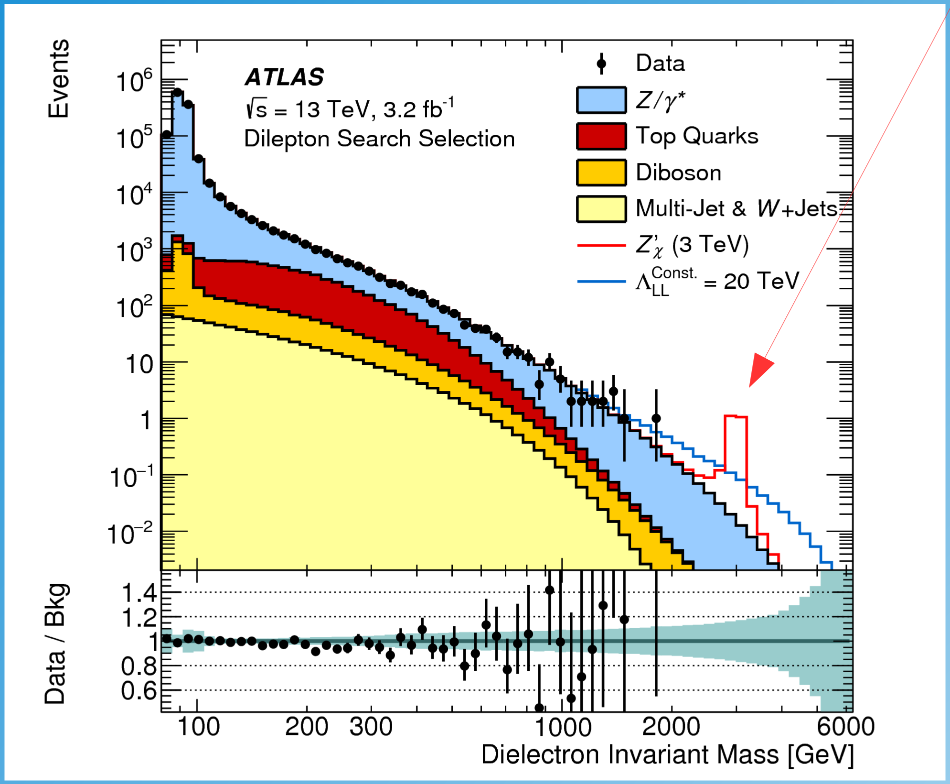
Heavy Exotic Bosons

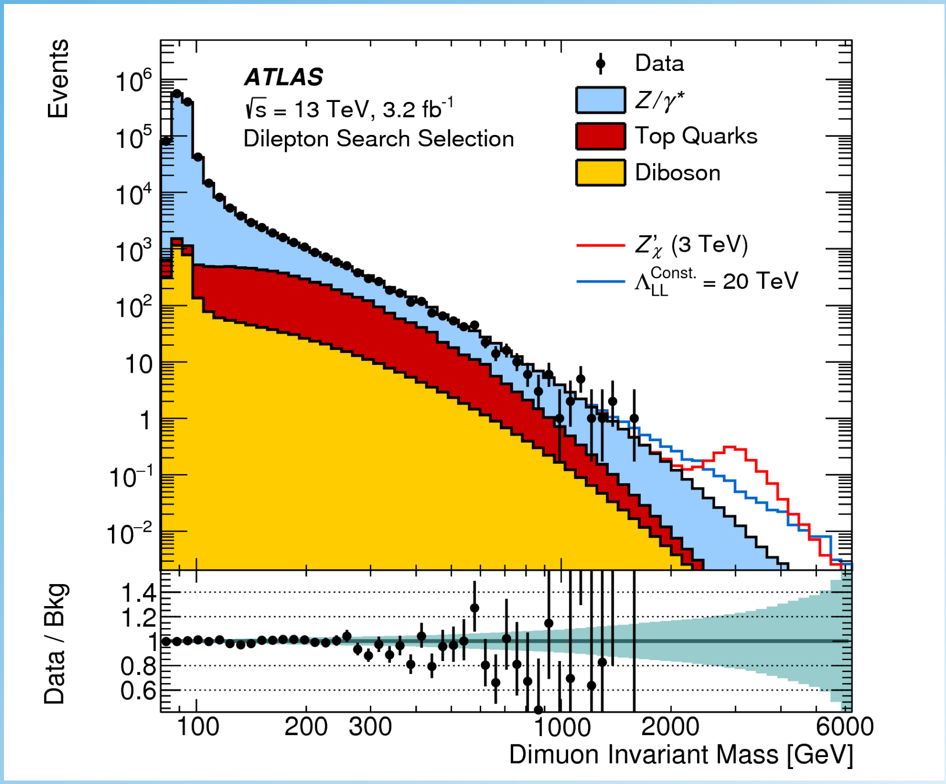
- dark matter candidate
- number of fermion generations
- fermion masses (in particular light neutrino masses)
- CP-violation
- Fermion-Number Violation (BNV or LNV)
- Unification of forces
- (Hierarchy problem)

Search for Z' → ll at ATLAS

13 TeV data from 2015

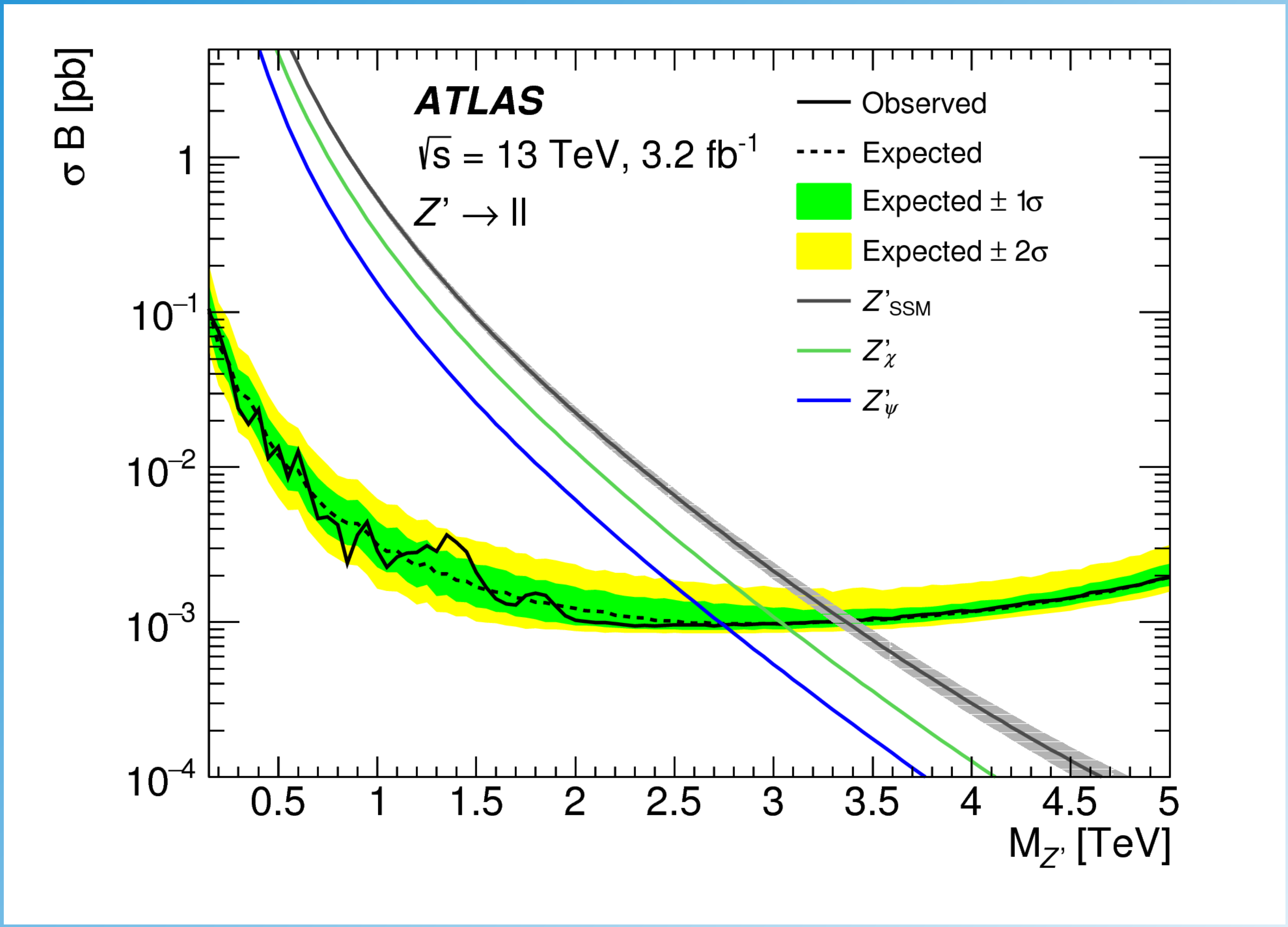
hypothetical signal





→ data compatible with SM expectation

Search for Z' → ll at ATLAS



masses up to 3-4 TeV excluded, deoending in model and BR(Z' → ll)

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.2 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	$2\ e, \mu$	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	3.6	M_{th} 8.3 TeV	$n = 6$	1512.01530
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	1 J	Yes	3.2	G_{KK} mass 1.06 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2015-075
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	3.2	G_{KK} mass 480-770 GeV	$k/\overline{M}_{Pl} = 1.0$	1606.04782
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	3.2	Z' mass 3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	3.2	W' mass 4.07 TeV		1606.03977
	HVT $W' \to WZ \to qq\nu\nu$ model A	$0\ e, \mu$	1 J	Yes	3.2	W' mass 1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-068
	HVT $W' \to WZ \to qqqq$ model A	–	2 J	–	3.2	W' mass 1.38-1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-073
	HVT $W' \to WH \to \ell\nu bb$ model B	$1\ e, \mu$	1-2 b, 1-0 j	Yes	3.2	W' mass 1.62 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	HVT $Z' \to ZH \to \nu\nu bb$ model B	$0\ e, \mu$	1-2 b, 1-0 j	Yes	3.2	Z' mass 1.76 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	LRSM $W'_R \to tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	3.6	Λ 17.5 TeV	$\eta_{LL} = -1$	1512.01530
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	3.2	Λ 23.1 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2015-070
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, 1-4 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	$0\ e, \mu, 1\ \gamma$	1 j	Yes	3.2	m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	$T_{5/3} \to Wt$	$1\ e, \mu$	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	3.6	q^* mass 5.2 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.01530
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	3.2	b^* mass 2.1 TeV		1603.08791
	Excited quark $b^* \to Wt$	1 or $2\ e, \mu$	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1 g_D$, spin 1/2	1509.08059

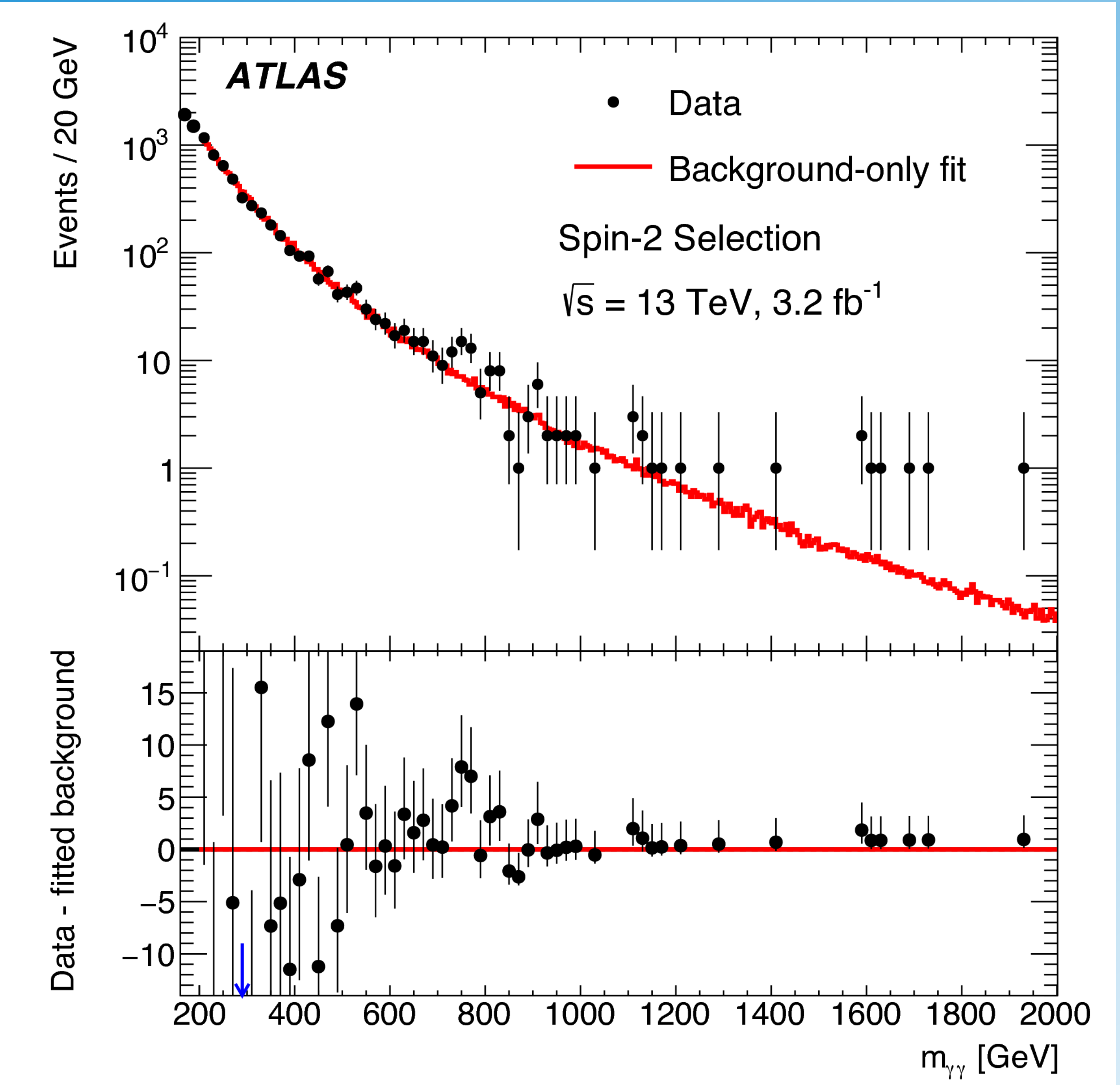
$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

Mass scale [TeV] (10^{-1}, 1, 10)

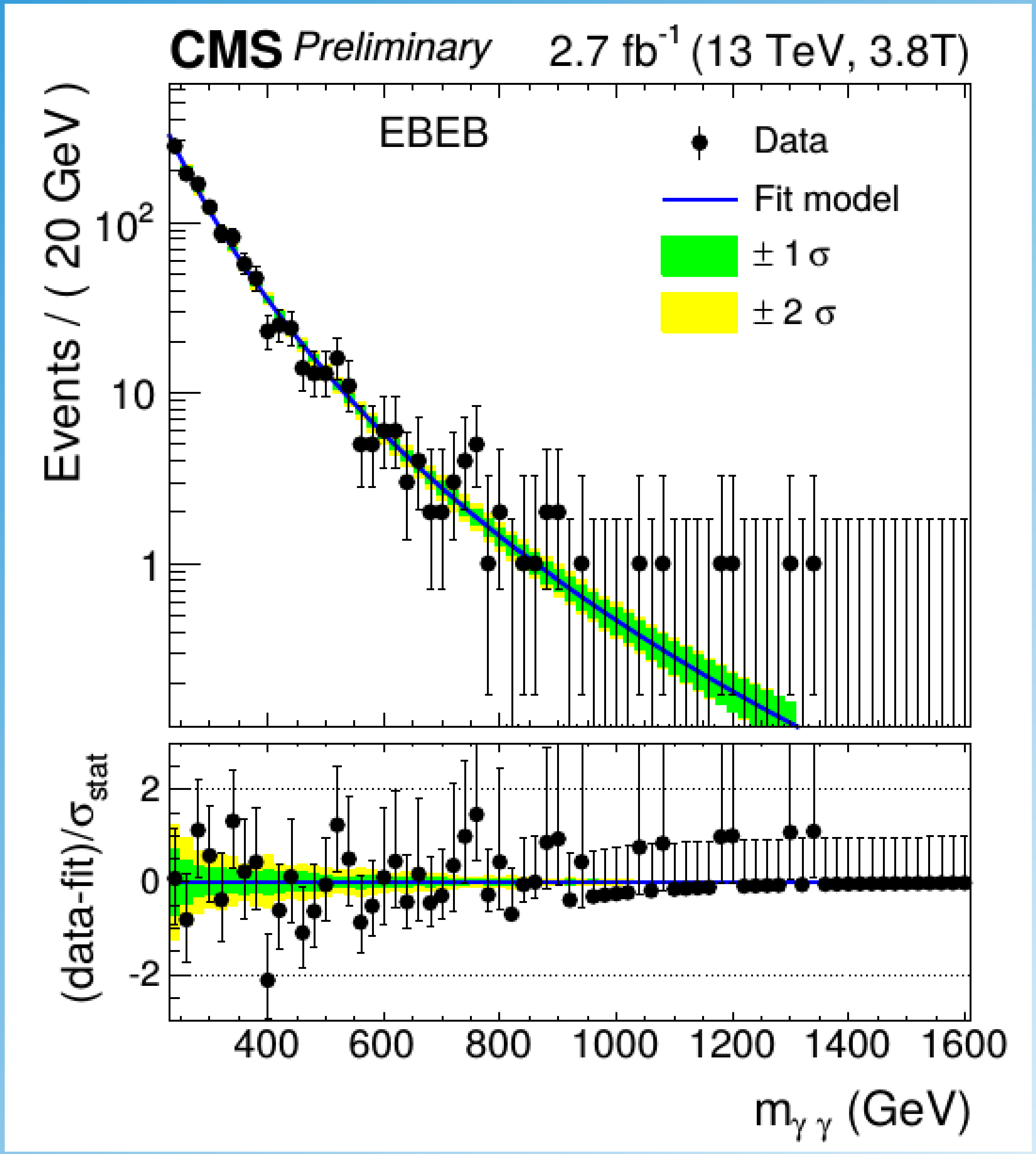
*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

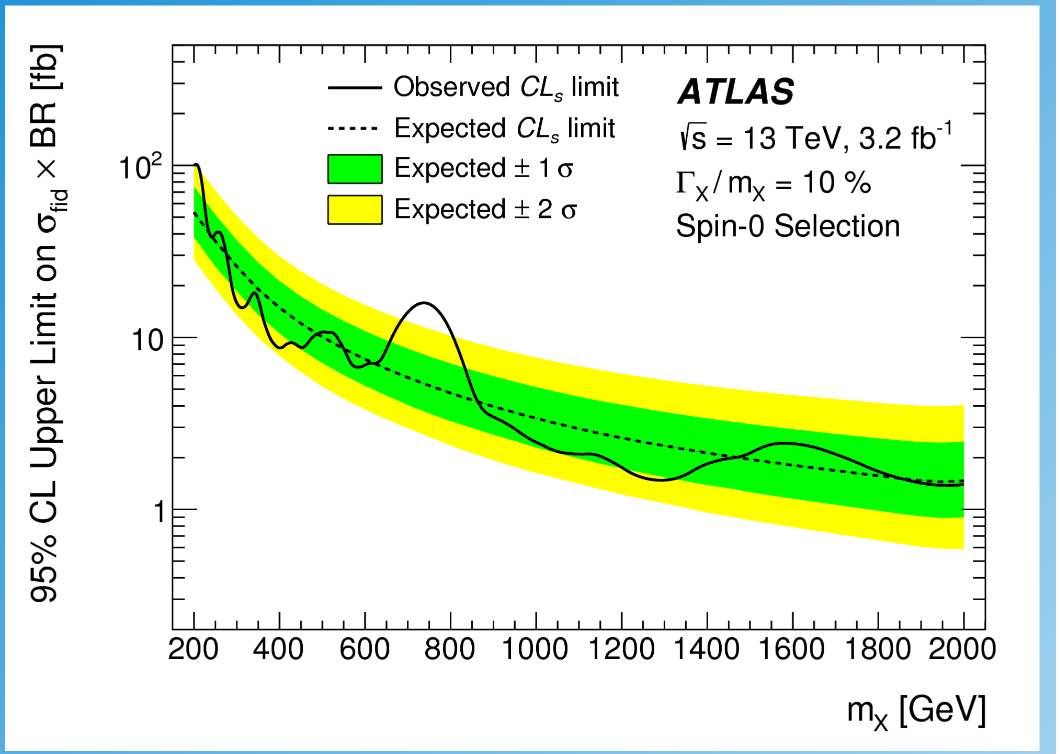
The diphoton peak at 750 GeV

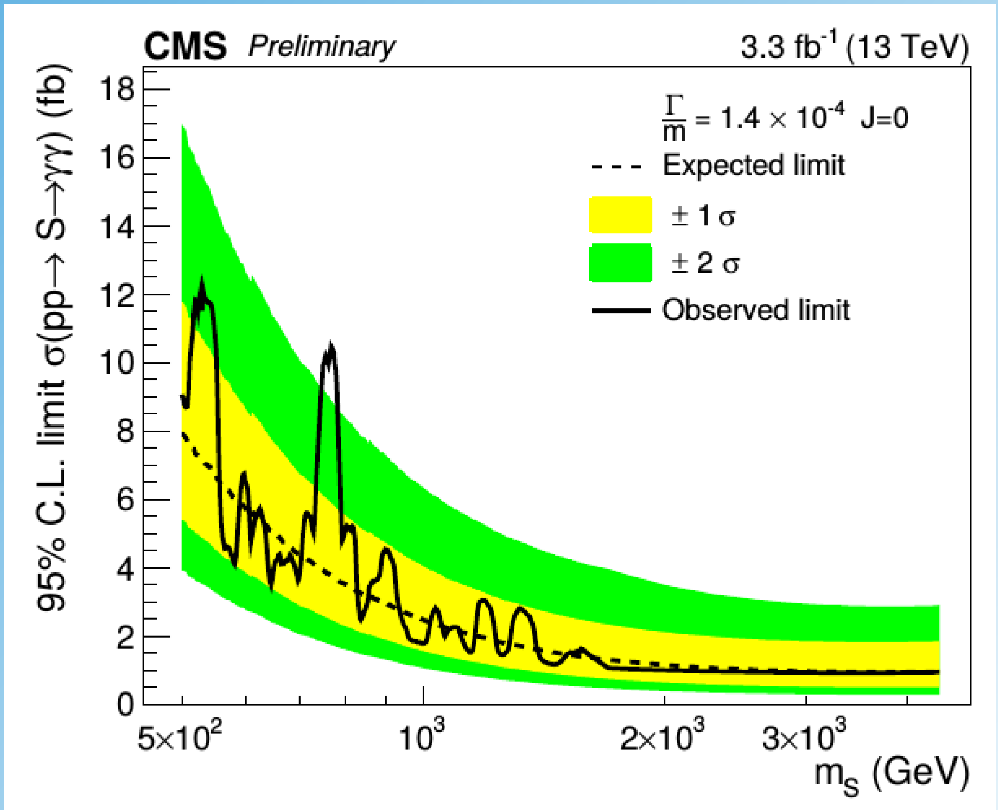


The diphoton peak at 750 GeV



The diphoton peak at 750 GeV





more data needed!