LHC – Why Terascale?

Stabilization of the Higgs mechanism
→ $\Lambda \sim 1$ TeV

Unitarization of EW vector boson and heavy quark amplitudes
→ $\Lambda \sim 1$ TeV

If Mh ~ 1 TeV → SM Higgs width ~ 0.5 TeV, strong coupling regime

Dark Matter density: in most popular scenarios masses of DM candidates are less than 1 TeV

$$\Omega_{\mathrm{WIMP}} \sim 0.2 \left(\frac{m_\chi}{200\,\mathrm{GeV}}\right)^2 \left(\frac{0.1}{g^2}\right)^2$$

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?

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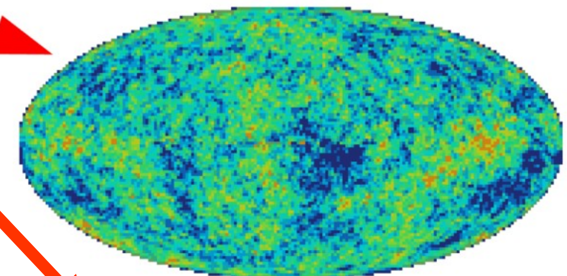
Facts which can not be explained in SM

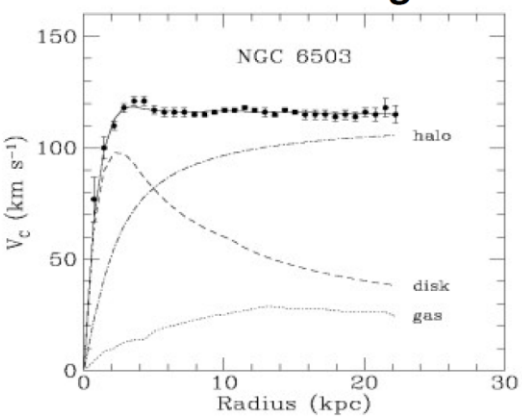
- EW symmetry is broken – photon is massless, W and Z are massive prticles
Fermions have very much different masses
(Mtop ≈ 172 GeV, Me ≈ 0.5 MeV, ΔMν ≈ 10^{-3} eV)

- Dark Matter exists in the Universe

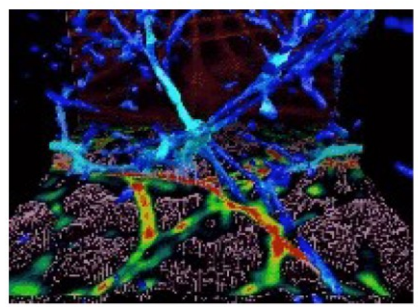
CMB



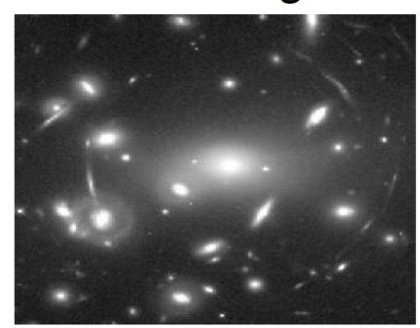
Rotation curves of galaxies

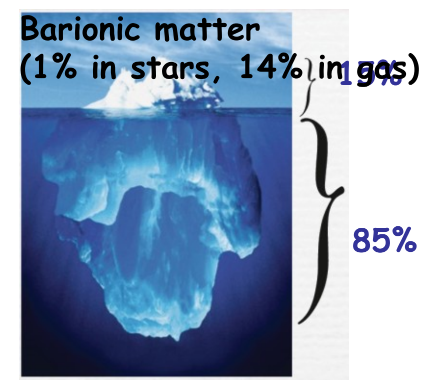


Large Scale Structure



Lensing





Dark unknown matter

- (g-2)μ (about 3.5 σ)
- Neutrino masses, mixing, oscillations

- Particle – antiparticle asymmetry in the Universe,
CP violation

baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

CKM phase – too small efect

In addition to mentioned problems (naturalness/hierarchy, dark matter content, CP violation) SM does not give answers to many questions

What is a generation? Why there are only 3 generations?

How quarks and leptons related to each other, what is a nature of quark-lepton analogy?

What is responsible for gauge symmetries, why charges are quantize? Are there additional gauge symmetries?

What is responsible for a formation of the Higgs potential?

To which accuracy the CPT symmetry is exact?

Why gravity is so weak comparing to other interactions?

....

Main options beyond SM

1. Fundamental Higgs:
- Supersymmetric models
(MSSM, NMSSM…)

2. Composite Higgs:
- Models with new strong dynamics
(Chiral Lagrangians from holography, latest technicolor variants, Little Higgs models, Twin Higgs models…)

3. Mixed cases:
-Models with extra space dimensions
-Partially composite models…

4. Many more (hidden valleys, landscape ….)

BSM searches

Collision energy > particle production threshold

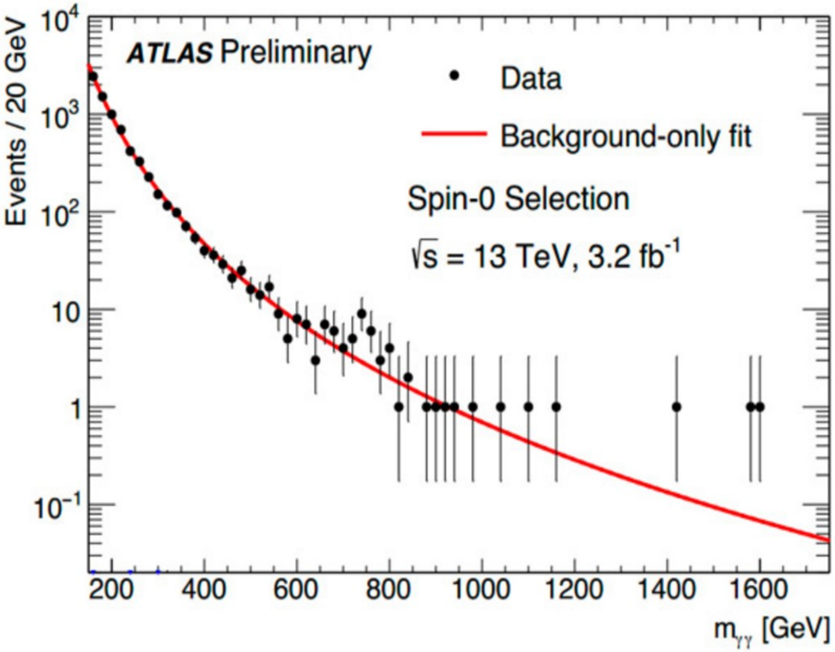
-Searches for new particles
strongly interacting new particles with large cross sections (squarks, gluinos…)
top partners motivated by naturalness (stop, sbottom, vector like quarks, t* …)
new resonances predicted by many BSM extensions (Z', W', π_T, ρ_T , KK states, …)
extended Higgs sector (new neutral Higgses, charged Higgs)

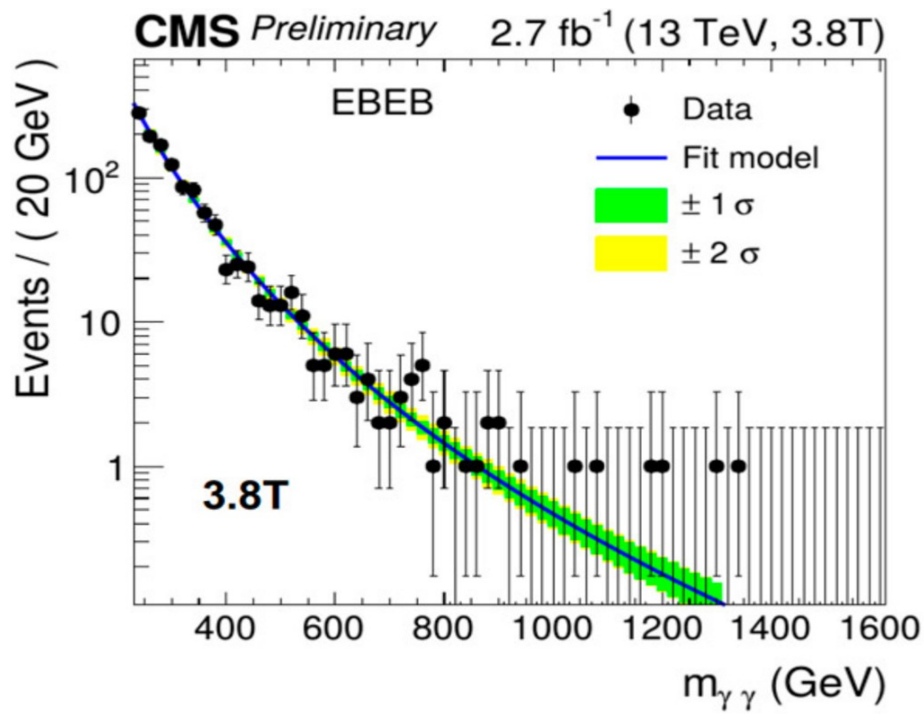
Collision energy < particle production threshold

-Anomalous/new interactions of SM particles (EFT)
(anom. gauge boson couplings, anom. Wtb couplings, FCNC …)
-New particle contributions via quantum loops

More Higgses, more scalars practically in all BSM models

The 750 GeV diphoton excess presented by CMS and ATLAS experiments in Dec. 2015





Local significance = 3,9 σ
Global significance = 2 σ

Local significance = 3.4 σ
Global significance = 1.6 σ

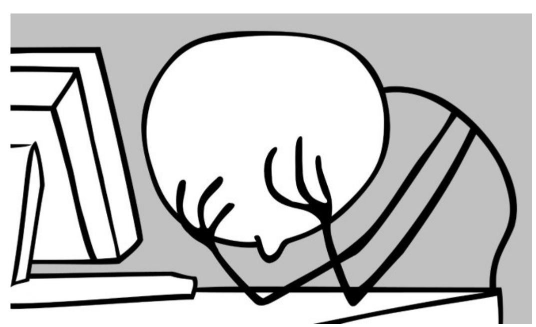
- Lot of proposals but no generally accepted explanations of the 750 GeV diphoton excess (> 550 submissions to arXiv)

Composite Pseudo-Nambu-Goldstone boson, Dilaton, Radion, KK graviton, Quarkonium-like bound state, Sgoldstino, Heavy axion (axizilla), …

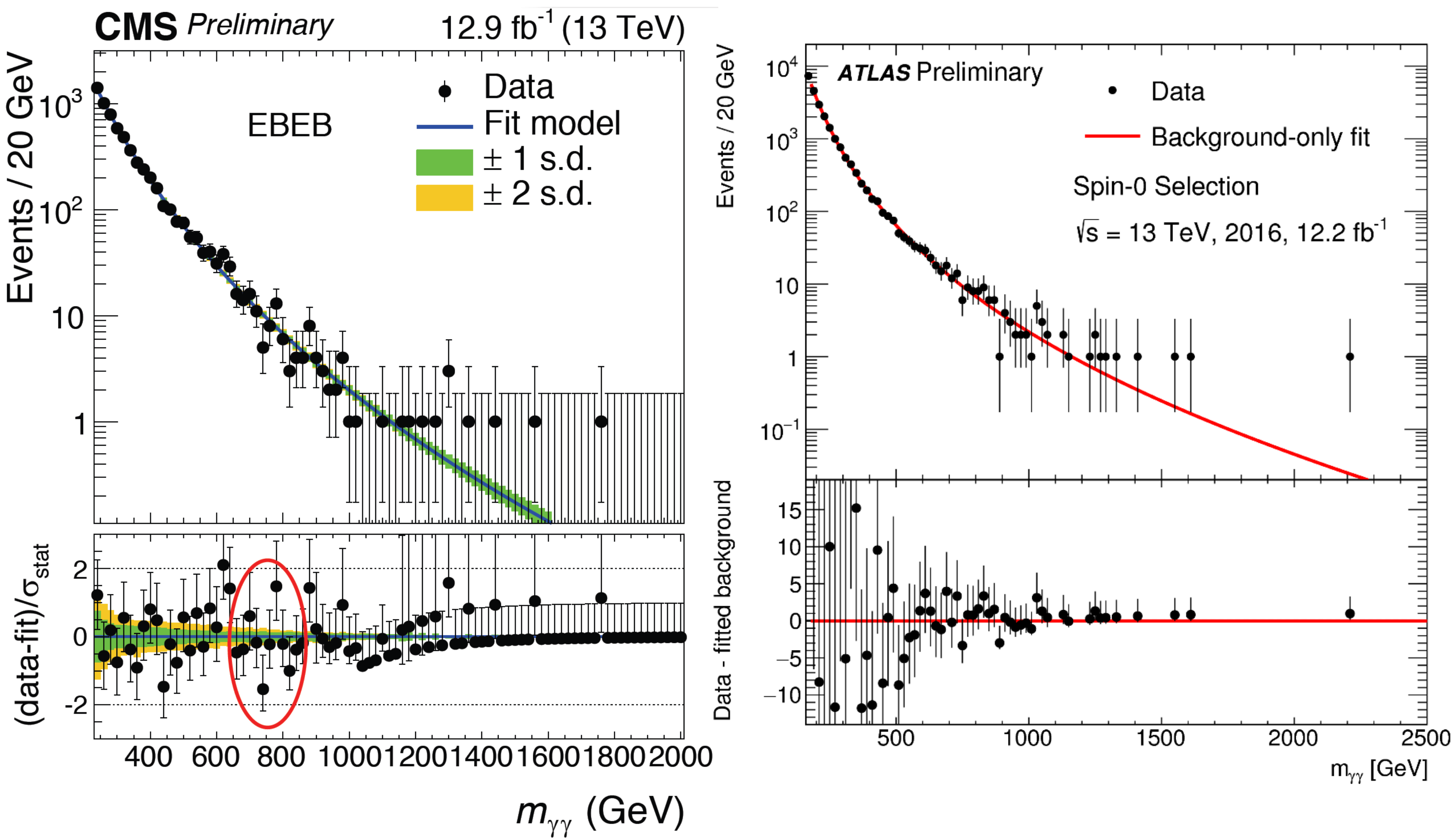
- Important to rule out the scenarios, which cannot explain the excess

750 GeV excess

RS Radion



No signal with new much larger data set



Statistical fluctuation !

2HDM

Why the only one Higgs doublet?
- No fundamental reasons

Simple extension – two Higgs doublets (2HDM)

MSSM prototype, strong CP and axion, CP violation and baryogenesis

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix} \qquad v^2 \equiv v_1^2 + v_2^2 \qquad \tan\beta \equiv \frac{v_2}{v_1}$$

2 complex scalar doublets => 8 degrees of freedom

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2$$

As in the SM 3 Goldstone bosons are absorbed (“eaten”) by $W^\pm$ and Z

5 physics degrees of freedom

h, H – CP even scalars,
A – CP odd scalar,
$H^\pm$ - sharged scalars

Generic Higgs potential is not that simple

$$V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\},$$

Gunion, Haber, Kane, Dawson '00…

Mostly studied cases with Z_2 symmetry $\Phi_1 \to +\Phi_1 \quad \Phi_2 \to -\Phi_2$ → $\lambda_6, \lambda_7 = 0$

Physics states – the states with definite masses

$$\begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

$$H = (\sqrt{2}\text{Re}\,\Phi_1^0 - v_1)c_\alpha + (\sqrt{2}\text{Re}\,\Phi_2^0 - v_2)s_\alpha\,,$$
$$h = -(\sqrt{2}\text{Re}\,\Phi_1^0 - v_1)s_\alpha + (\sqrt{2}\text{Re}\,\Phi_2^0 - v_2)c_\alpha$$

Notations: cosα = c_α, sinα = s_α, cosβ = c_β, sinβ = s_β,
cos(β-α) = $c_{\beta-\alpha}$, sin(β-α) = $s_{\beta-\alpha}$

Several types of 2HDM depending on Yukawa arrangement

Glashow, Weinberg, Paschos condition '77

Avoid FCNC: if all fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC are absent

Branco, Ferreira, Lavoura, Rebelo, Sher, Silva '11,12

Model	u_R^i	d_R^i	e_R^i	
Type I	Φ_2	Φ_2	Φ_2	
Type II	Φ_2	Φ_1	Φ_1	**MSSM like**
Lepton-specific	Φ_2	Φ_2	Φ_1	**Type III**
Flipped	Φ_2	Φ_1	Φ_2	**Type IV**

Yukawa couplings to the Higgs bosons normalized to SM Higgs

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

$s_{(\beta-\alpha)} + c_{(\beta-\alpha)}/t_\beta$

$s_{(\beta-\alpha)} - t_\beta * c_{(\beta-\alpha)}$

MSSM

MSSM potential after supersymmetry breaking

$$V(H_1,H_2) = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_3^2 (H_1^T i\tau_2 H_2 + h.c.) +$$
$$\frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left|\left(H_1^T i\tau_2 H_2\right)\right|^2$$

2HDM type II with quartic couplings fixed due to the gauge nature

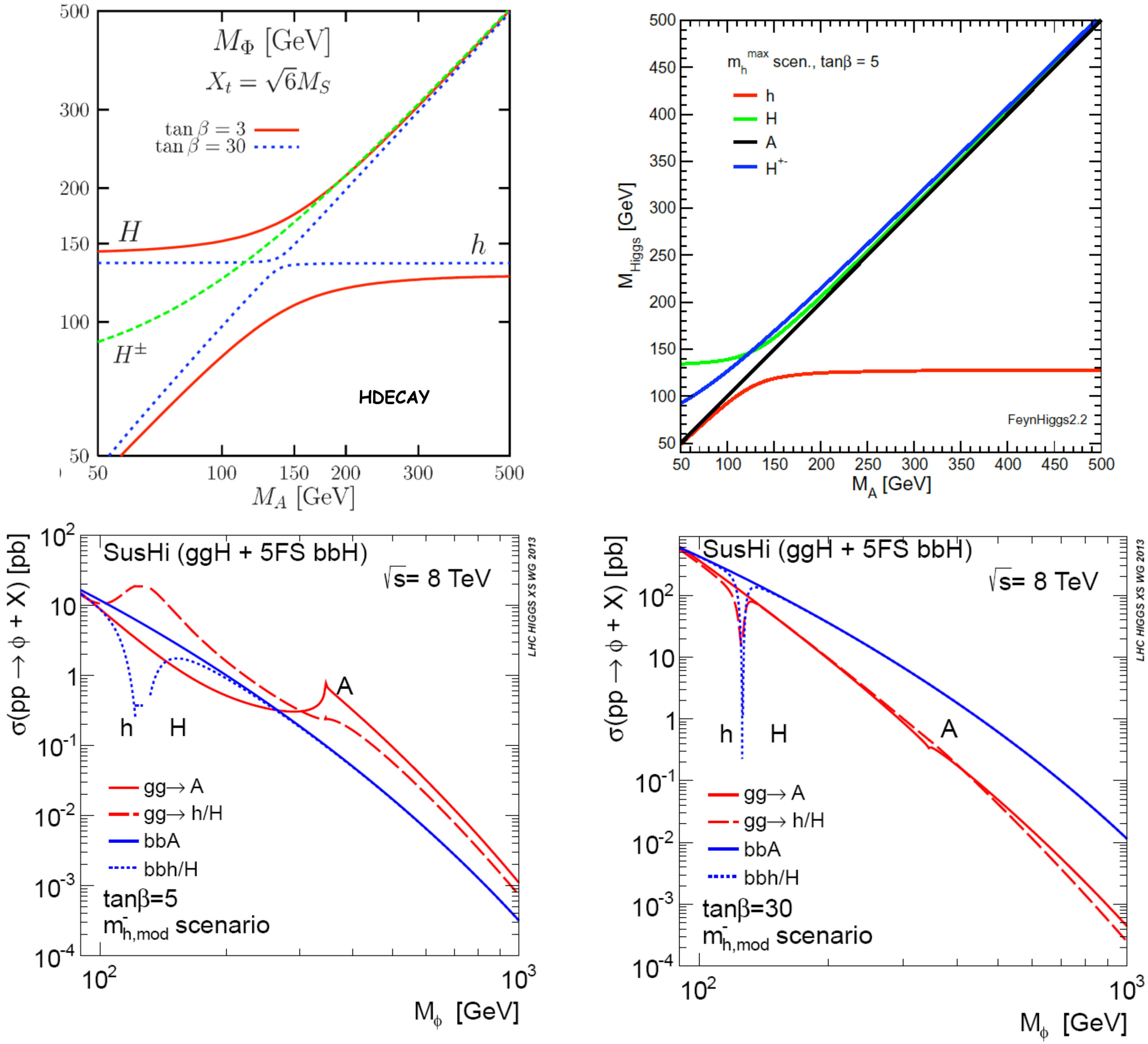
$$\lambda_1 = \lambda_2 = \frac{g_1^2 + g_2^2}{4}, \qquad \lambda_3 = \frac{g_2^2 - g_1^2}{4}, \qquad \lambda_4 = -\frac{g_2^2}{2}$$

8-3=5 physics states

h, H - CP even scalars,
A - CP odd scalar,
$H^\pm$ - charged scalars

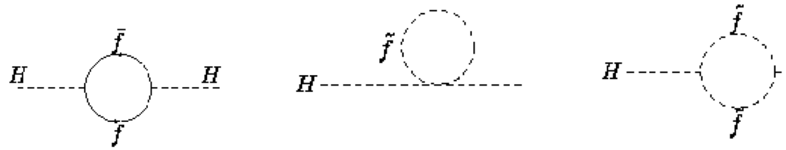
Φ	$g_{\Phi \bar{u} u}$	$g_{\Phi \bar{d} d}$	$g_{\Phi VV}$	$g_{\Phi AZ} / g_{\Phi H^+ W^-}$
h	$\cos\alpha / \sin\beta$	$-\sin\alpha / \cos\beta$	$\sin(\beta-\alpha)$	$\propto \cos(\beta-\alpha)$
H	$\sin\alpha / \sin\beta$	$\cos\alpha / \cos\beta$	$\cos(\beta-\alpha)$	$\propto \sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	$\propto 0/1$

Couplings are shared between the Higgses: $\sum_i g_{H_i VV}^2 = \left(g_{HVV}^{\rm SM}\right)^2$



MΦ [GeV]
Xt = √6MS
tan β = 3
tan β = 30
H
h
H±
HDECAY
MA [GeV]
mh max scen., tanβ = 5
h
H
A
H+-
MHiggs [GeV]
FeynHiggs2.2
MA [GeV]
SusHi (ggH + 5FS bbH)
√s= 8 TeV
σ(pp → φ + X) [pb]
LHC HIGGS XS WG 2013
h
H
A
gg→ A
gg→ h/H
bbA
bbh/H
tanβ=5
mh,mod scenario
Mφ [GeV]
SusHi (ggH + 5FS bbH)
√s= 8 TeV
σ(pp → φ + X) [pb]
LHC HIGGS XS WG 2013
h
H
A
gg→ A
gg→ h/H
bbA
bbh/H
tanβ=30
mh,mod scenario
Mφ [GeV]

M_H is protected due to cancellation of Λ^2 dependence!



$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right]$$

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$X_t = A_t - \mu\cot\beta$$

($X_t = \sqrt{6}\, M_{SUSY}$ Maximal mixing scenario)

Only two parameters at tree level $\tan\beta \equiv \frac{v_2}{v_1}$, M_A

But large loop correction

$M_h^2 \leq M_Z^2 + \Delta m_h^2$

125 GeV² → M_h^2; 91 GeV² → M_Z^2; 86 GeV² → Δm_h^2

Available parameter range after all constrains ?

Carena, Heinemeyer, Stal, Wagner, Weiglein'13

Parameter	$m_h^{\max}$	$m_h^{\text{mod}+}$	$m_h^{\text{mod}-}$	*light stop*	*light stau*	τ*-phobic*	*low-*M_H
m_t	173.2	173.2	173.2	173.2	173.2	173.2	173.2
M_A	varied	varied	varied	varied	varied	varied	110
$\tan\beta$	varied	varied	varied	varied	varied	varied	varied
M_{SUSY}	1000	1000	1000	500	1000	1500	1500
$M_{\tilde{l}_3}$	1000	1000	1000	1000	245 (250)	500	1000
$X_t^{\text{OS}}/M_{\text{SUSY}}$	2.0	1.5	−1.9	2.0	1.6	2.45	2.45
$X_t^{\overline{\text{MS}}}/M_{\text{SUSY}}$	$\sqrt{6}$	1.6	−2.2	2.2	1.7	2.9	2.9
A_t	Given by $A_t = X_t + \mu\cot\beta$						
A_b	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$	$= A_t$
A_τ	$= A_t$	$= A_t$	$= A_t$	$= A_t$	0	0	$= A_t$
μ	200	200	200	350	500 (450)	2000	varied
M_1	Fixed by GUT relation to M_2						
M_2	200	200	200	350	200 (400)	200	200
$m_{\tilde{g}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{q}_{1,2}}$	1500	1500	1500	1500	1500	1500	1500
$M_{\tilde{l}_{1,2}}$	500	500	500	500	500	500	500
$A_{f\neq t,b,\tau}$	0	0	0	0	0	0	0

Intensively used in experimental analyses

hMSSM

M_h is fixed to be 125 GeV

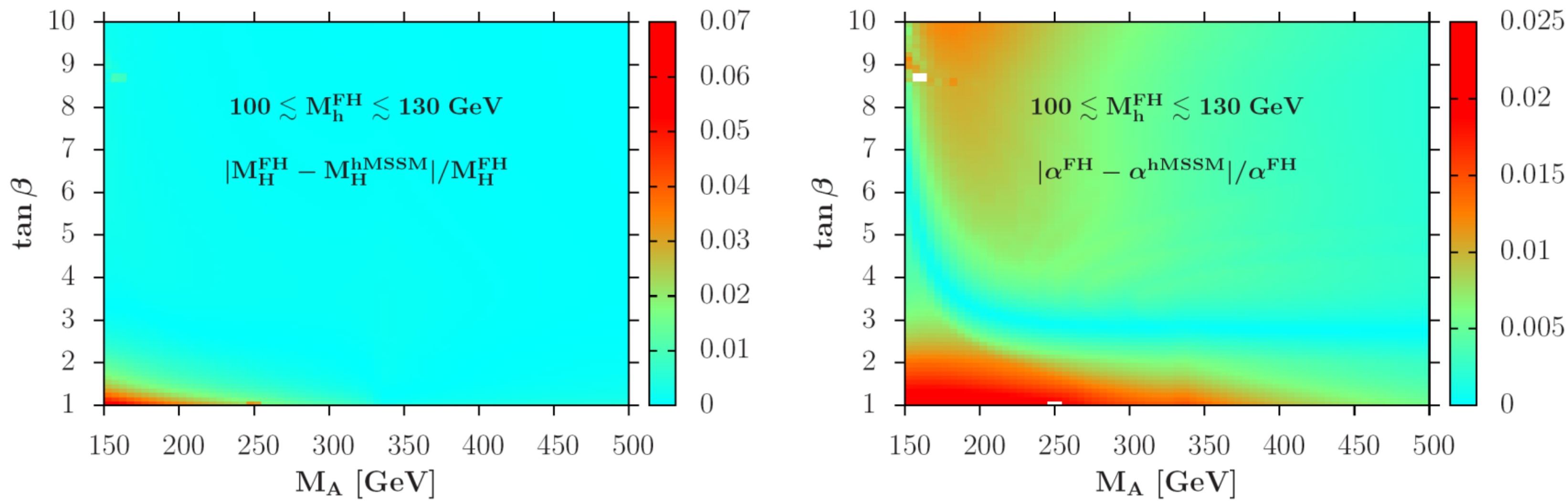
With few simplified assumptions one gets (including leading loops)

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

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

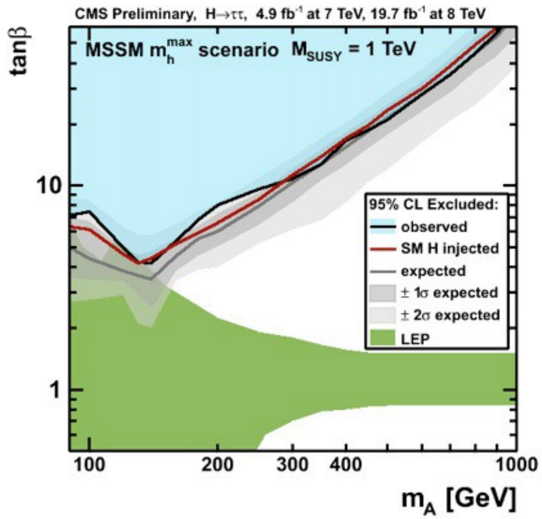
Djouadi, Maiani, Moreau, Polosa, Quevillon, Riquer (1502.05653)

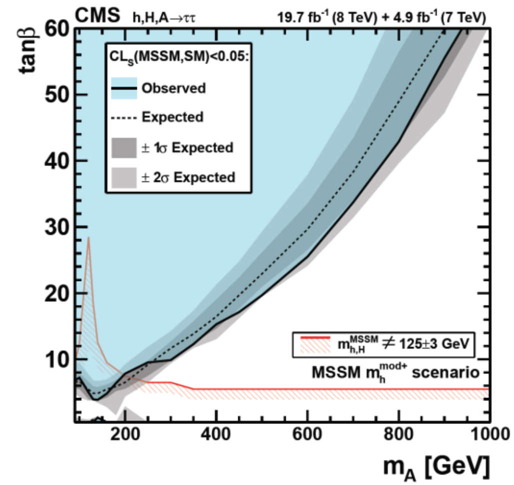
Validation with FeynHiggs

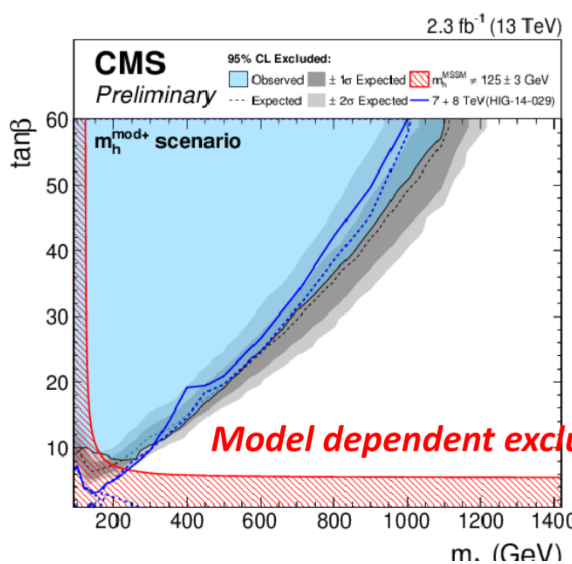


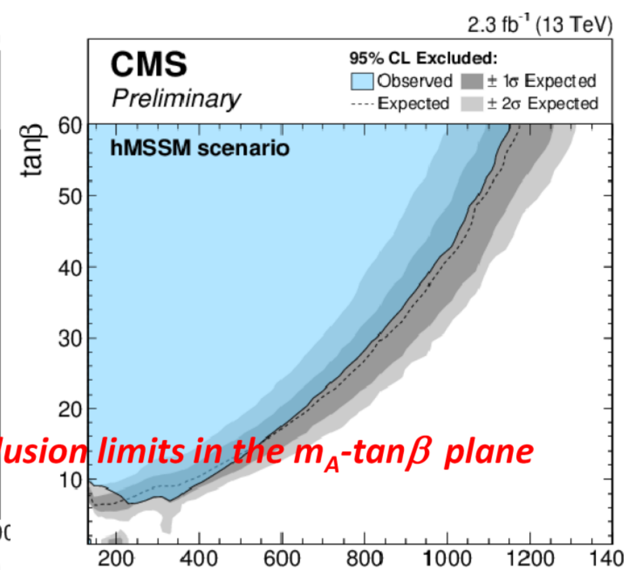
CMS searches as an example

1408.3316





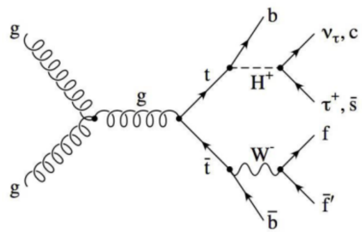


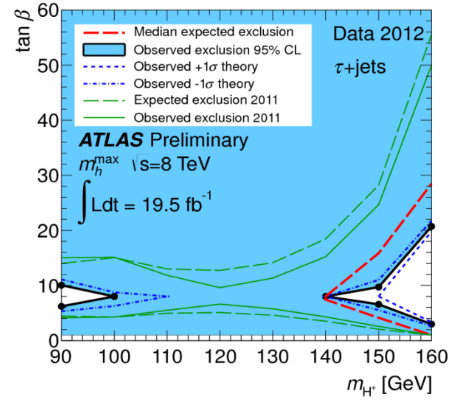


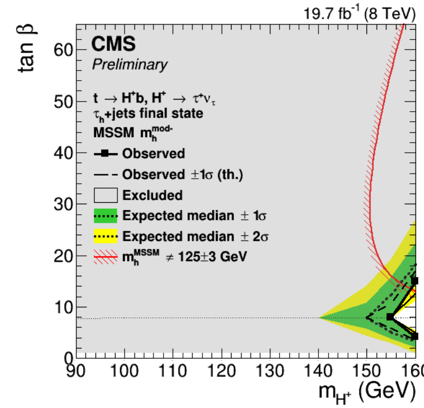
Model dependent exclusion limits in the m_A-tanβ plane

Charged Higgses are predicted in many BSM (2HDM, MSSM, NMSSM…)

Light H± in top decays

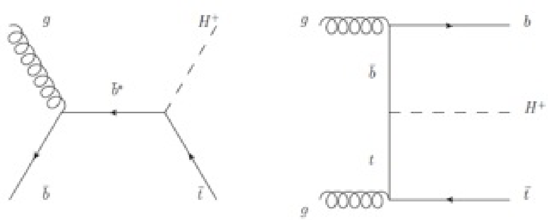


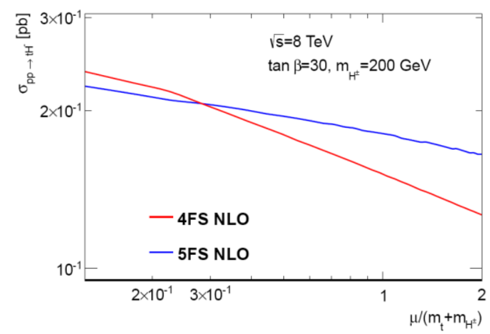


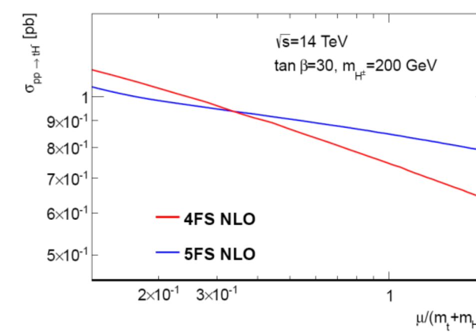


Flechl, Klees, Kraemer, Spira, Ubiali '14

Heavy H± in associated production

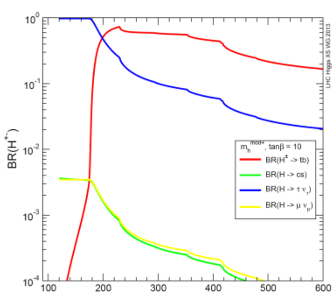


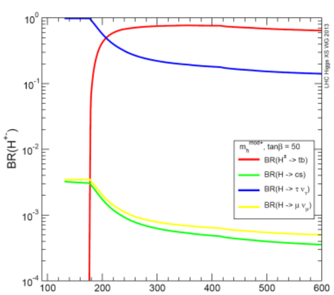


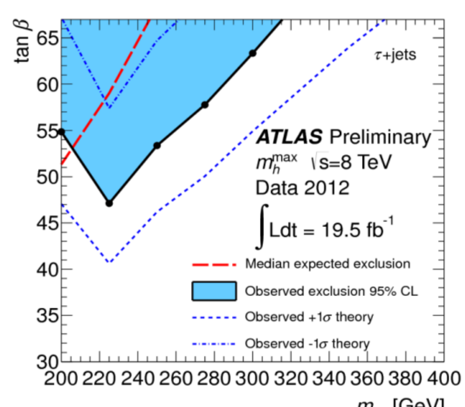


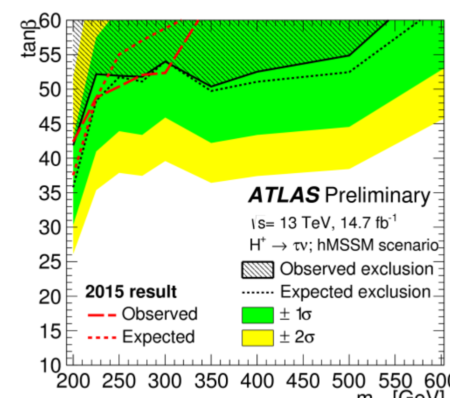
Decay modes

Heinemeyer et al. '13









Supersymmetry is one of the most favorite BSM ideas, relating spin ½ fermions with spin 0,1 bosons

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle \qquad Q^\dagger|\text{Boson}\rangle = |\text{Fermion}\rangle$$

Fermion degrees of freedom ←→ boson degrees of freedom

Minimal particle content

❑ Gauge / Gaugino Sector

Standard Bosons	Supersymmetric Partners
$W^\pm$ $H^\pm$	Charginos $\chi_1^\pm$ $\chi_2^\pm$
g Z h H A	Neutralinos χ_1^0 χ_2^0 χ_3^0 χ_4^0
g_i	Gluinos $\tilde{g}_i$

[Two Higgs doublets] [All fermions]

And also …

Graviton G	Gravitino $\tilde{G}$

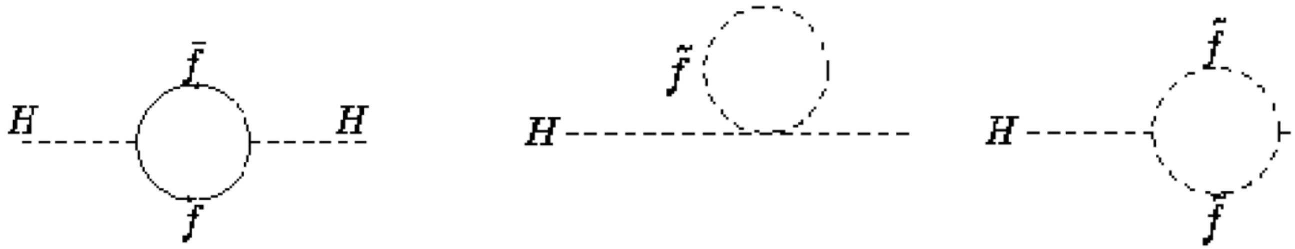
❑ Particle / Sparticle Sector

Standard Particles	Supersymmetric Partners
Leptons ℓ	Sleptons $\tilde{\ell}_{R,L}$
Neutrinos ν_ℓ	Sneutrinos $\tilde{\nu}_\ell$
Quarks q	Squarks $\tilde{q}_{R,L}$

[All scalars]

SUSY

1. Cancellation of Λ^2 dependence



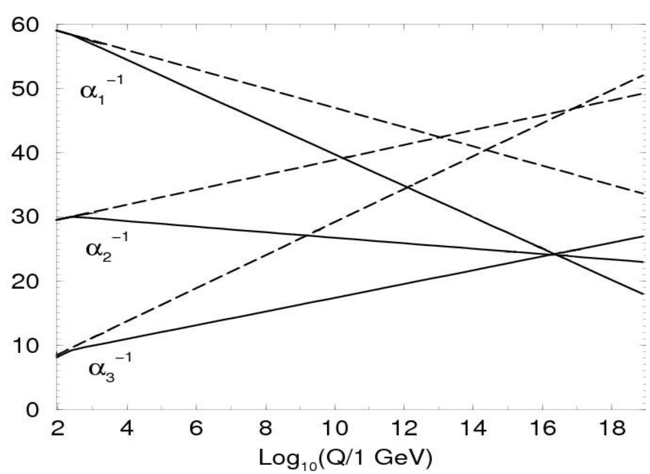
=>

$$\Delta M_H^2\big|^{tot} = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right]$$

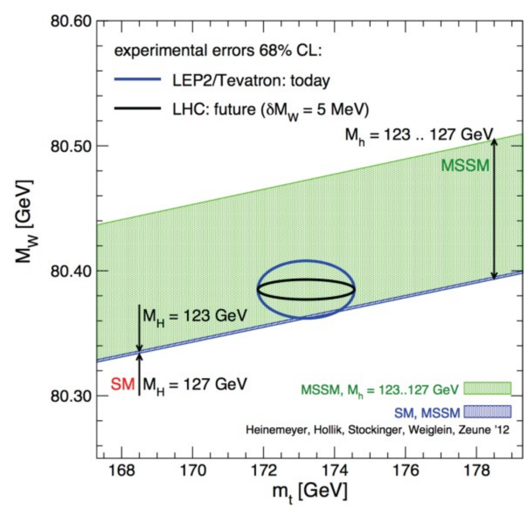
M_H **is protected!**

2. Lightest SUSY particle is stable (if R-parity) – Dark Matter candidate

3. Unification of couplings in contrast to SM

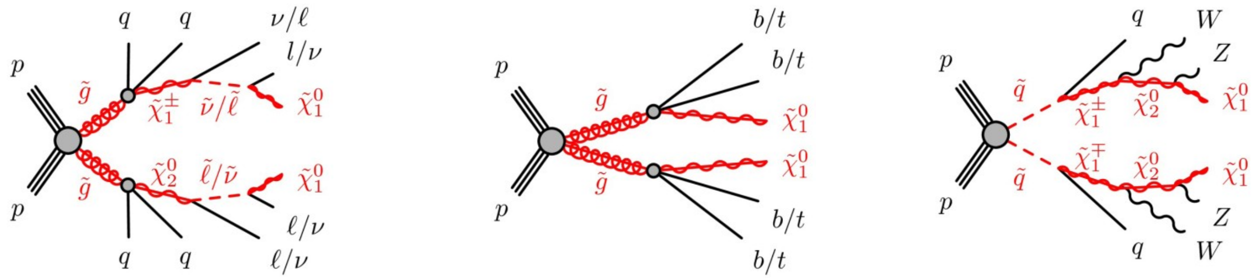


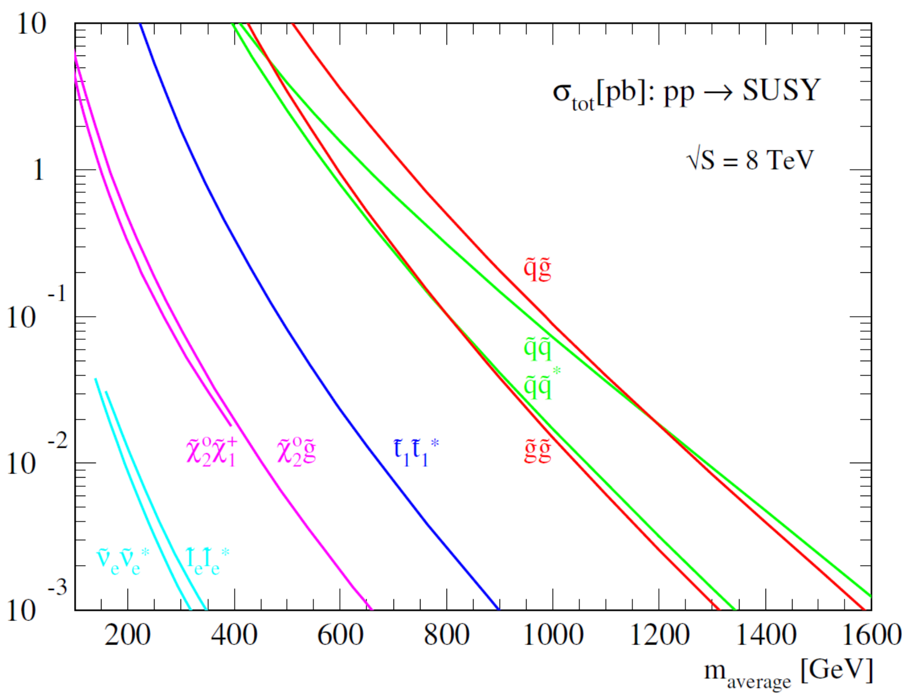
4. Fit of EW precision data

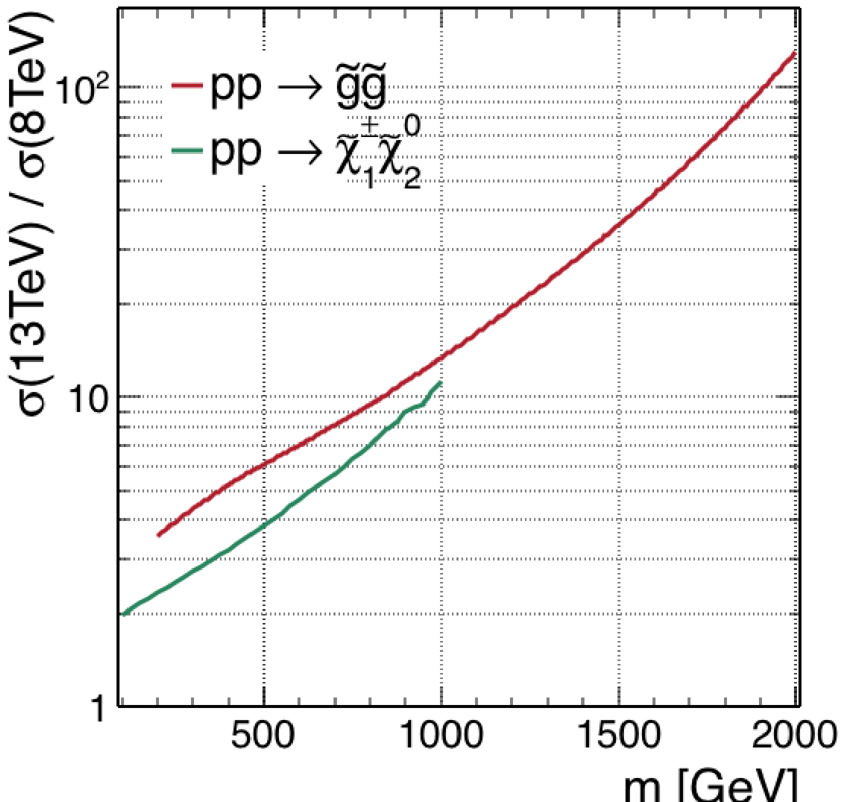


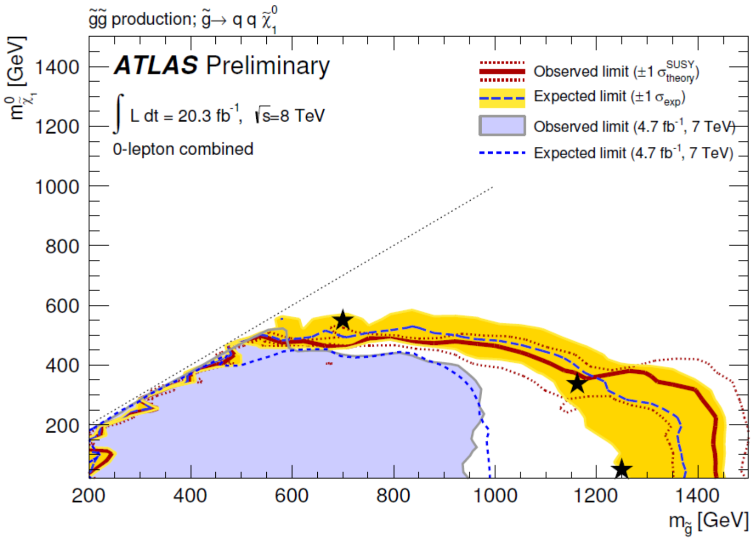
Searches for strongly interacting superpartners

Gluino and squark signatures:

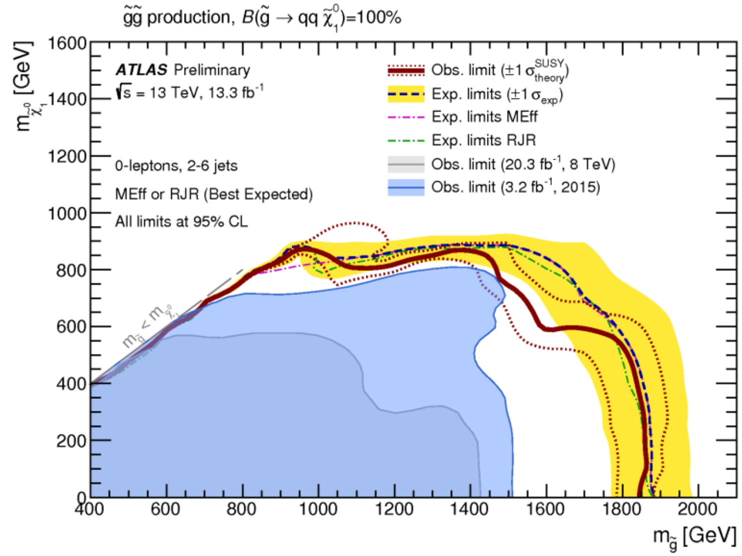




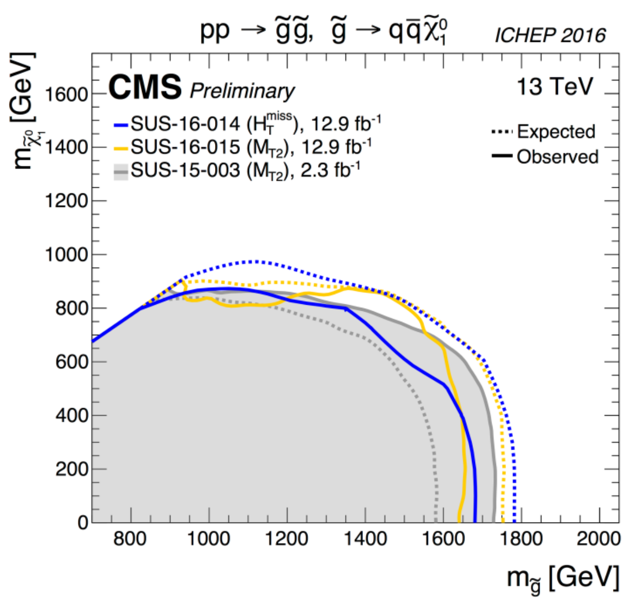




$\tilde{g}\tilde{g}$ production; $\tilde{g}\to q\,q\,\tilde{\chi}_1^0$
ATLAS Preliminary
$\int L\,dt$ = 20.3 fb^{-1}, $\sqrt{s}$=8 TeV
0-lepton combined
Observed limit ($\pm1\,\sigma^{SUSY}_{theory}$)
Expected limit ($\pm1\,\sigma_{exp}$)
Observed limit (4.7 fb^{-1}, 7 TeV)
Expected limit (4.7 fb^{-1}, 7 TeV)
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]

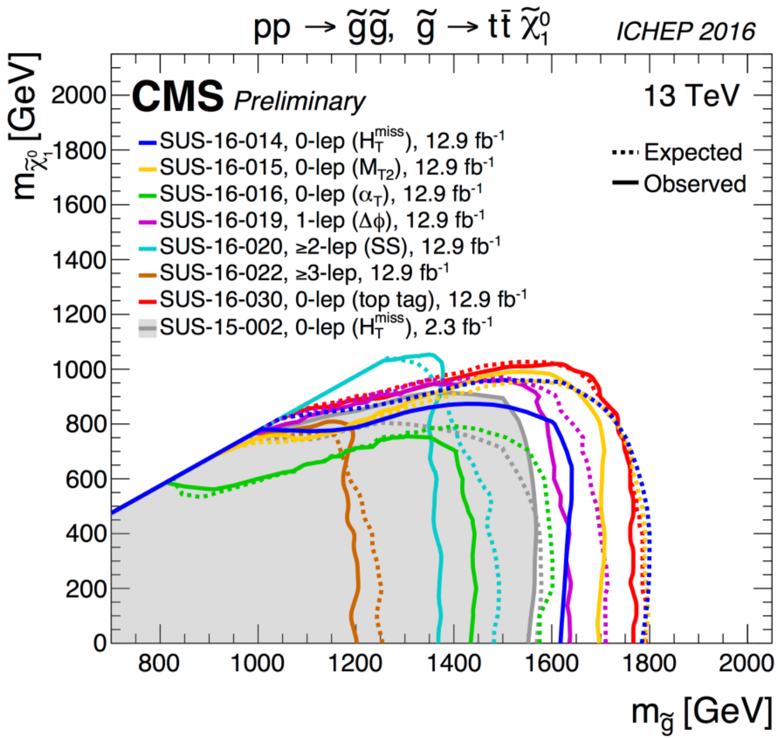


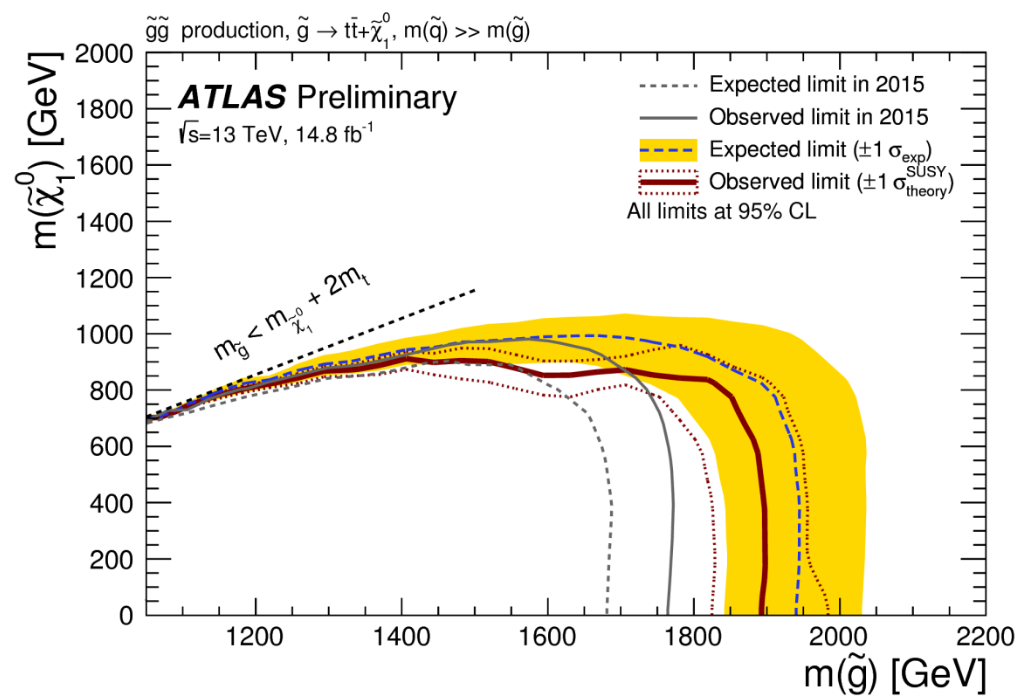
$\tilde{g}\tilde{g}$ production, $B(\tilde{g}\to qq\,\tilde{\chi}_1^0)$=100%
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 13.3 fb^{-1}
0-leptons, 2-6 jets
MEff or RJR (Best Expected)
All limits at 95% CL
Obs. limit ($\pm1\,\sigma^{SUSY}_{theory}$)
Exp. limits ($\pm1\,\sigma_{exp}$)
Exp. limits MEff
Exp. limits RJR
Obs. limit (20.3 fb^{-1}, 8 TeV)
Obs. limit (3.2 fb^{-1}, 2015)
$m_{\tilde{g}} < m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]



$pp\to\tilde{g}\tilde{g},\ \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$
ICHEP 2016
CMS Preliminary
13 TeV
SUS-16-014 (H_T^{miss}), 12.9 fb^{-1}
SUS-16-015 (M_{T2}), 12.9 fb^{-1}
SUS-15-003 (M_{T2}), 2.3 fb^{-1}
Expected
Observed
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]

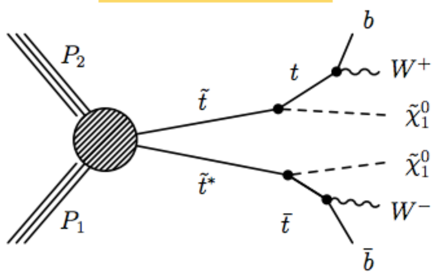
Gluino decays to tt+LSP



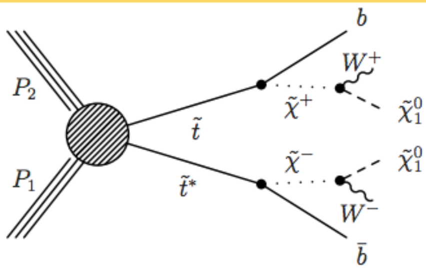


Searches for Stops

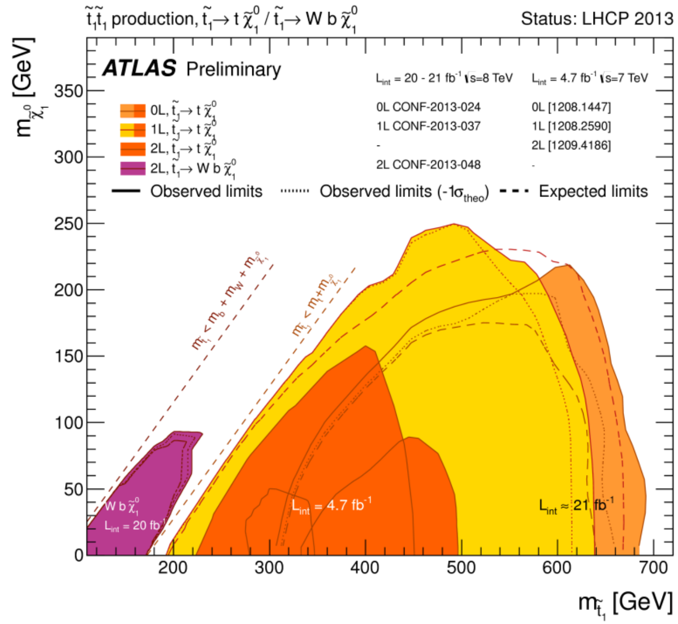
$\tilde{t}\tilde{t} \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$

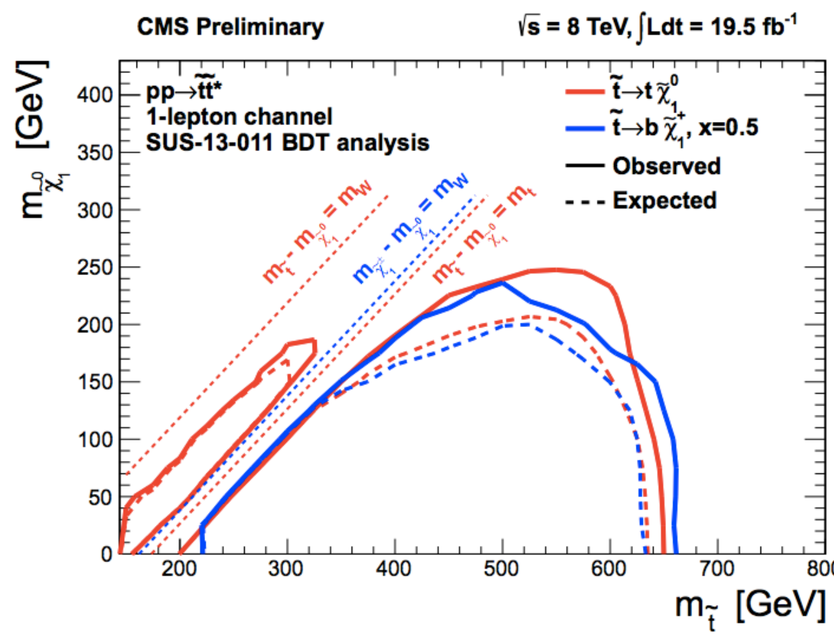


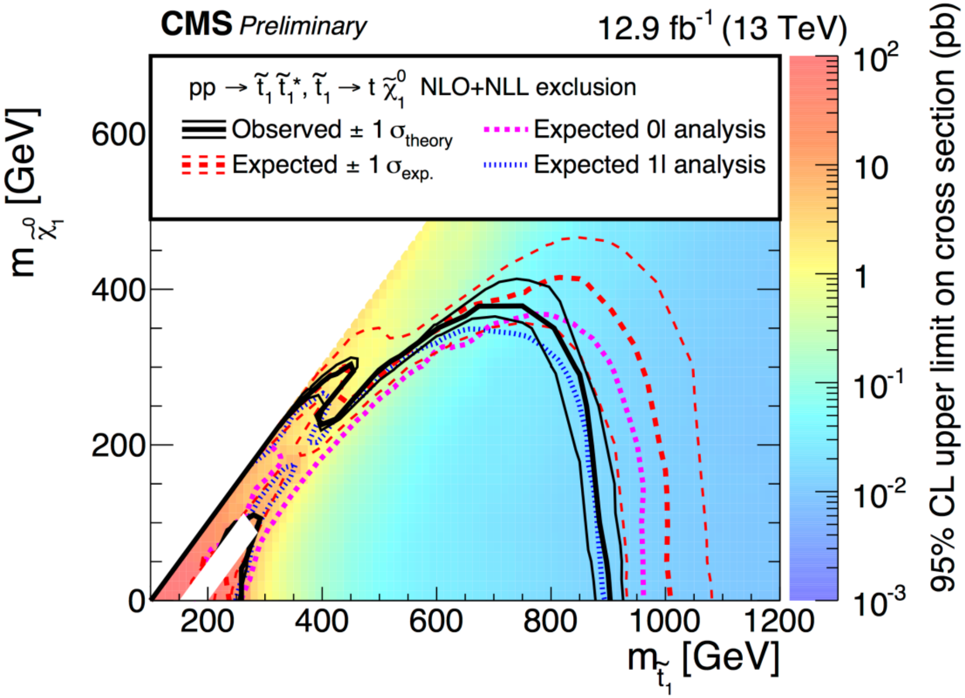
$\tilde{t}\tilde{t} \rightarrow b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$

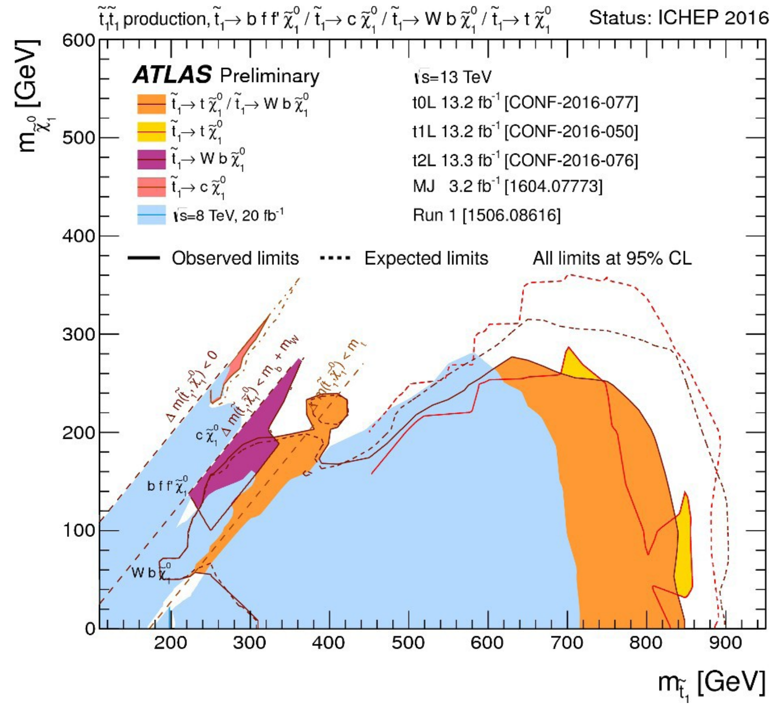


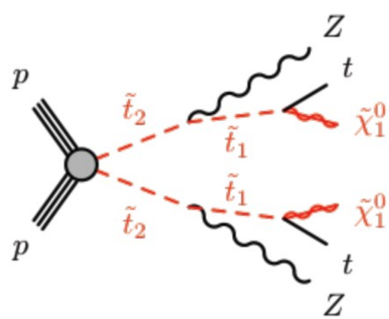
Mass exclusion limits:
Mstop ~660 GeV and
Msbottom ~630 GeV

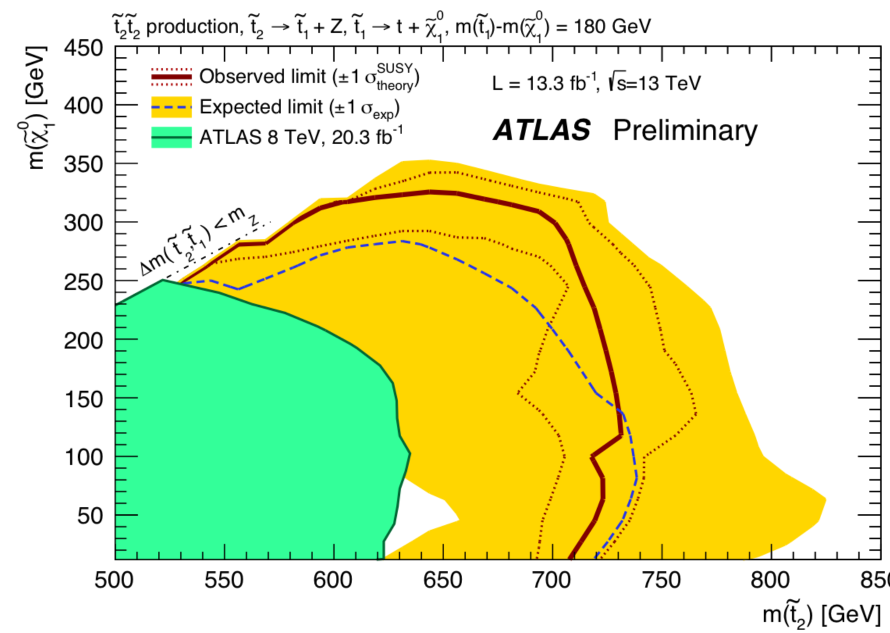





CMS Preliminary
12.9 fb-1 (13 TeV)
pp → t̃1 t̃1*, t̃1 → t χ̃01 NLO+NLL exclusion
Observed ± 1 σtheory
Expected ± 1 σexp.
Expected 0l analysis
Expected 1l analysis
m χ̃01 [GeV]
m t̃1 [GeV]
95% CL upper limit on cross section (pb)

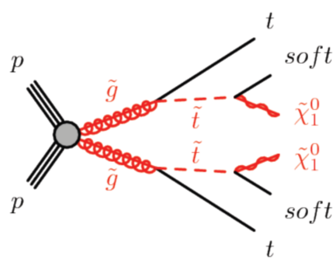

t̃1t̃1 production, t̃1→ b f f' χ̃01 / t̃1→ c χ̃01 / t̃1→ W b χ̃01 / t̃1→ t χ̃01
Status: ICHEP 2016
ATLAS Preliminary
√s=13 TeV
t̃1→ t χ̃01 / t̃1→ W b χ̃01
t0L 13.2 fb-1 [CONF-2016-077]
t̃1→ t χ̃01
t1L 13.2 fb-1 [CONF-2016-050]
t̃1→ W b χ̃01
t2L 13.3 fb-1 [CONF-2016-076]
t̃1→ c χ̃01
MJ 3.2 fb-1 [1604.07773]
√s=8 TeV, 20 fb-1
Run 1 [1506.08616]
Observed limits
Expected limits
All limits at 95% CL
m χ̃01 [GeV]
m t̃1 [GeV]

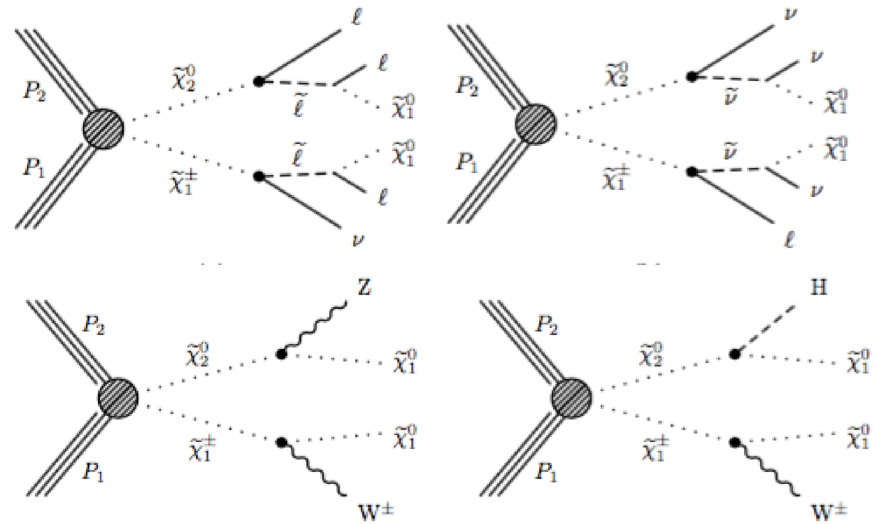

p
p
t̃2
t̃2
t̃1
t̃1
Z
Z
t
t
χ̃01
χ̃01


t̃2t̃2 production, t̃2 → t̃1 + Z, t̃1 → t + χ̃01, m(t̃1)-m(χ̃01) = 180 GeV
Observed limit (±1 σSUSYtheory)
Expected limit (±1 σexp)
ATLAS 8 TeV, 20.3 fb-1
L = 13.3 fb-1, √s=13 TeV
ATLAS Preliminary
Δm(t̃2,t̃1) < mZ
m(χ̃01) [GeV]
m(t̃2) [GeV]

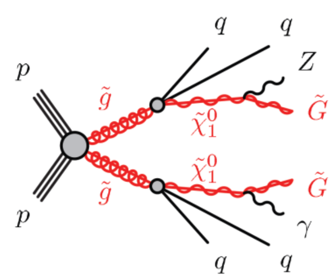
Many other searches for superpartners

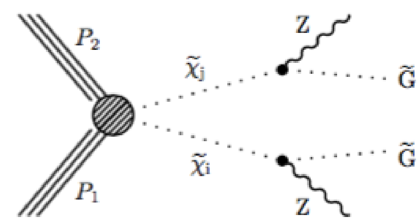
R-parity conserving scenarios



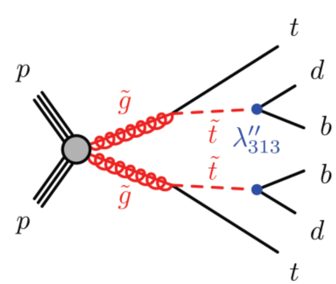


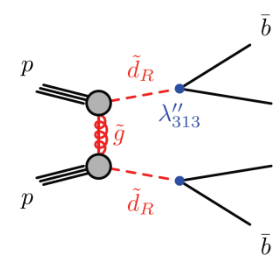
Gauge mediated scenarios

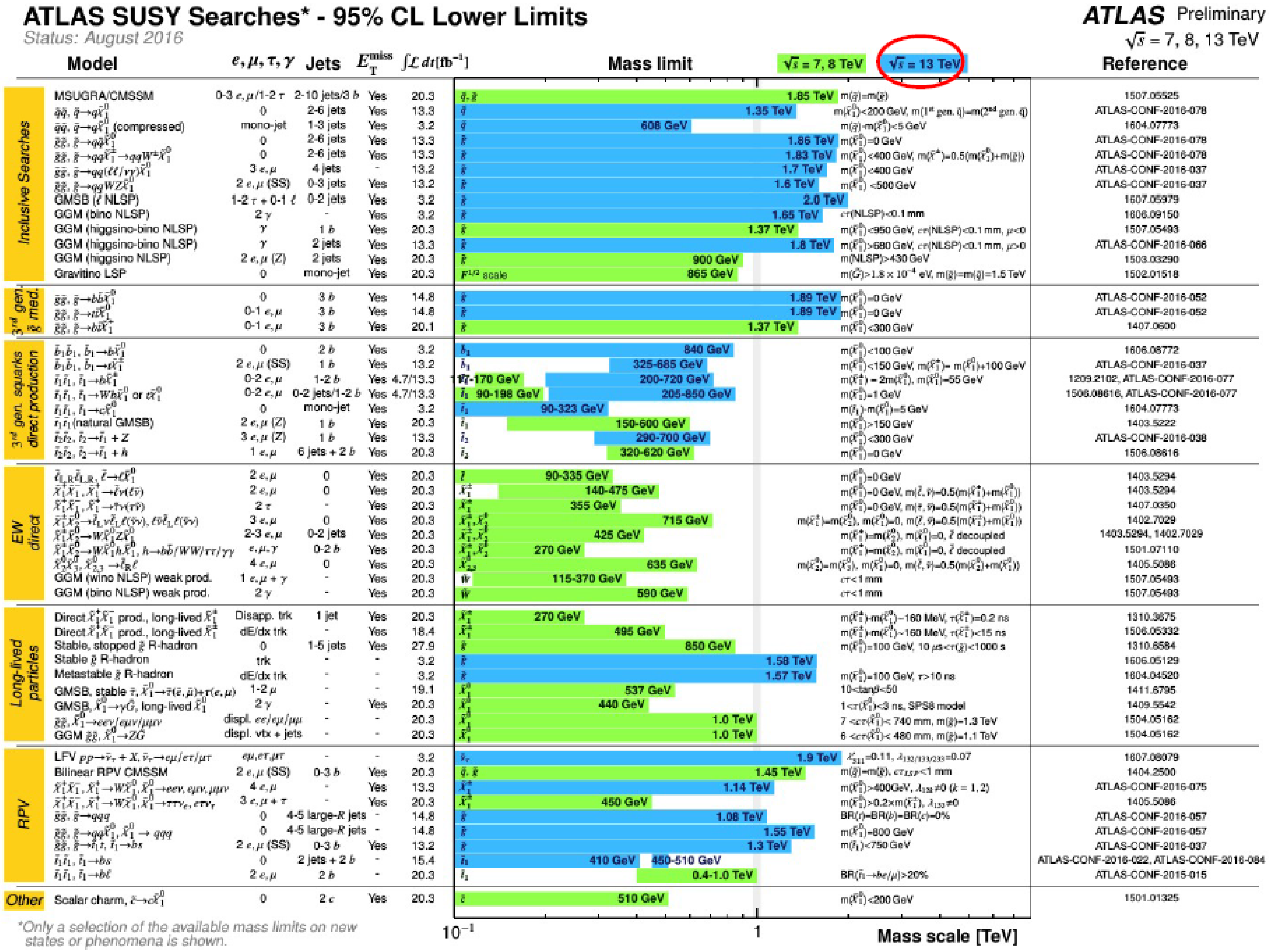




R-parity violating scenarios






ATLAS SUSY Searches* - 95% CL Lower Limits
Status: August 2016
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L}\, dt[fb^{-1}]$
Mass limit
$\sqrt{s}$ = 7, 8 TeV
$\sqrt{s}$ = 13 TeV
Reference
Inclusive Searches
MSUGRA/CMSSM | 0-3 e,μ/1-2 τ | 2-10 jets/3 b | Yes | 20.3 | $\tilde{q}, \tilde{g}$ 1.85 TeV | $m(\tilde{q})=m(\tilde{g})$ | 1507.05525
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 13.3 | $\tilde{q}$ 1.35 TeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$ | ATLAS-CONF-2016-078
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | $\tilde{q}$ 608 GeV | $m(\tilde{q})-m(\tilde{\chi}_1^0)$<5 GeV | 1604.07773
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 13.3 | $\tilde{g}$ 1.86 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2016-078
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 13.3 | $\tilde{g}$ 1.83 TeV | $m(\tilde{\chi}_1^0)$<400 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ | ATLAS-CONF-2016-078
$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$ | 3 e,μ | 4 jets | - | 13.2 | $\tilde{g}$ 1.7 TeV | $m(\tilde{\chi}_1^0)$<400 GeV | ATLAS-CONF-2016-037
$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$ | 2 e,μ (SS) | 0-3 jets | Yes | 13.2 | $\tilde{g}$ 1.6 TeV | $m(\tilde{\chi}_1^0)$ <500 GeV | ATLAS-CONF-2016-037
GMSB ($\tilde{\ell}$ NLSP) | 1-2 τ + 0-1 ℓ | 0-2 jets | Yes | 3.2 | $\tilde{g}$ 2.0 TeV | | 1607.05979
GGM (bino NLSP) | 2 γ | - | Yes | 3.2 | $\tilde{g}$ 1.65 TeV | $c\tau$(NLSP)<0.1 mm | 1606.09150
GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 20.3 | $\tilde{g}$ 1.37 TeV | $m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0 | 1507.05493
GGM (higgsino-bino NLSP) | γ | 2 jets | Yes | 13.3 | $\tilde{g}$ 1.8 TeV | $m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0 | ATLAS-CONF-2016-066
GGM (higgsino NLSP) | 2 e,μ (Z) | 2 jets | Yes | 20.3 | $\tilde{g}$ 900 GeV | m(NLSP)>430 GeV | 1503.03290
Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $F^{1/2}$ scale 865 GeV | $m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV | 1502.01518
3^{rd} gen. $\tilde{g}$ med.
$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 b | Yes | 14.8 | $\tilde{g}$ 1.89 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2016-052
$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 e,μ | 3 b | Yes | 14.8 | $\tilde{g}$ 1.89 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2016-052
$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 e,μ | 3 b | Yes | 20.1 | $\tilde{g}$ 1.37 TeV | $m(\tilde{\chi}_1^0)$<300 GeV | 1407.0600
3^{rd} gen. squarks direct production
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 b | Yes | 3.2 | $\tilde{b}_1$ 840 GeV | $m(\tilde{\chi}_1^0)$<100 GeV | 1606.08772
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$ | 2 e,μ (SS) | 1 b | Yes | 13.2 | $\tilde{b}_1$ 325-685 GeV | $m(\tilde{\chi}_1^0)$<150 GeV, $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_1^0)$+100 GeV | ATLAS-CONF-2016-037
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$ | 0-2 e,μ | 1-2 b | Yes | 4.7/13.3 | $\tilde{t}_1$ 117-170 GeV, 200-720 GeV | $m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV | 1209.2102, ATLAS-CONF-2016-077
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 e,μ | 0-2 jets/1-2 b | Yes | 4.7/13.3 | $\tilde{t}_1$ 90-198 GeV, 205-850 GeV | $m(\tilde{\chi}_1^0)$=1 GeV | 1506.08616, ATLAS-CONF-2016-077
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet | Yes | 3.2 | $\tilde{t}_1$ 90-323 GeV | $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$=5 GeV | 1604.07773
$\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 e,μ (Z) | 1 b | Yes | 20.3 | $\tilde{t}_1$ 150-600 GeV | $m(\tilde{\chi}_1^0)$>150 GeV | 1403.5222
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$ | 3 e,μ (Z) | 1 b | Yes | 13.3 | $\tilde{t}_2$ 290-700 GeV | $m(\tilde{\chi}_1^0)$<300 GeV | ATLAS-CONF-2016-038
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$ | 1 e,μ | 6 jets + 2 b | Yes | 20.3 | $\tilde{t}_2$ 320-620 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1506.08616
EW direct
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 e,μ | 0 | Yes | 20.3 | $\tilde{\ell}$ 90-335 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1403.5294
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 e,μ | 0 | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 140-475 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1403.5294
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ | 2 τ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 355 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1407.0350
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 e,μ | 0 | Yes | 20.3 | $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 715 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1402.7029
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$ | 2-3 e,μ | 0-2 jets | Yes | 20.3 | $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 425 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled | 1403.5294, 1402.7029
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$ | e,μ,γ | 0-2 b | Yes | 20.3 | $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 270 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled | 1501.07110
$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$ | 4 e,μ | 0 | Yes | 20.3 | $\tilde{\chi}_{2,3}^0$ 635 GeV | $m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ | 1405.5086
GGM (wino NLSP) weak prod. | 1 e,μ + γ | - | Yes | 20.3 | $\tilde{W}$ 115-370 GeV | $c\tau$<1 mm | 1507.05493
GGM (bino NLSP) weak prod. | 2 γ | - | Yes | 20.3 | $\tilde{W}$ 590 GeV | $c\tau$<1 mm | 1507.05493
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 270 GeV | $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns | 1310.3675
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ | dE/dx trk | - | Yes | 18.4 | $\tilde{\chi}_1^{\pm}$ 495 GeV | $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns | 1506.05332
Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 27.9 | $\tilde{g}$ 850 GeV | $m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s | 1310.6584
Stable $\tilde{g}$ R-hadron | trk | - | - | 3.2 | $\tilde{g}$ 1.58 TeV | | 1606.05129
Metastable $\tilde{g}$ R-hadron | dE/dx trk | - | - | 3.2 | $\tilde{g}$ 1.57 TeV | $m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns | 1604.04520
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ | 1-2 μ | - | - | 19.1 | $\tilde{\chi}_1^0$ 537 GeV | 10<tanβ<50 | 1411.6795
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 γ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 440 GeV | 1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model | 1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV | 1504.05162
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$ | displ. vtx + jets | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV | 1504.05162
RPV
LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ | - | - | 3.2 | $\tilde{\nu}_\tau$ 1.9 TeV | λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079
Bilinear RPV CMSSM | 2 e,μ (SS) | 0-3 b | Yes | 20.3 | $\tilde{q}, \tilde{g}$ 1.45 TeV | $m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm | 1404.2500
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$ | 4 e,μ | - | Yes | 13.3 | $\tilde{\chi}_1^{\pm}$ 1.14 TeV | $m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2) | ATLAS-CONF-2016-075
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$ | 3 e,μ + τ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 450 GeV | $m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$ | 1405.5086
$\tilde{g}\tilde{g}, \tilde{g}\to qqq$ | 0 | 4-5 large-R jets | - | 14.8 | $\tilde{g}$ 1.08 TeV | BR(t)=BR(b)=BR(c)=0% | ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$ | 0 | 4-5 large-R jets | - | 14.8 | $\tilde{g}$ 1.55 TeV | $m(\tilde{\chi}_1^0)$=800 GeV | ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$ | 2 e,μ (SS) | 0-3 b | Yes | 13.2 | $\tilde{g}$ 1.3 TeV | $m(\tilde{t}_1)$<750 GeV | ATLAS-CONF-2016-037
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$ | 0 | 2 jets + 2 b | - | 15.4 | $\tilde{t}_1$ 410 GeV, 450-510 GeV | | ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$ | 2 e,μ | 2 b | - | 20.3 | $\tilde{t}_1$ 0.4-1.0 TeV | BR($\tilde{t}_1\to be/\mu$)>20% | ATLAS-CONF-2015-015
Other
Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$ | 0 | 2 c | Yes | 20.3 | $\tilde{c}$ 510 GeV | $m(\tilde{\chi}_1^0)$<200 GeV | 1501.01325
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.

Searches for various resonances

Simplified models

Vector like top partners

Vector-like quarks - spin 1/2 particles with the same colour (triplet) and electroweak quantum numbers for left and right components
Masses not from the BEH mechanism
$\bar{Q}_L Q_R$ mass terms are allowed by EW gauge symmetry

VLQ appear in many BSM extensions

Matsedonskyia, Panicob, Wulzer

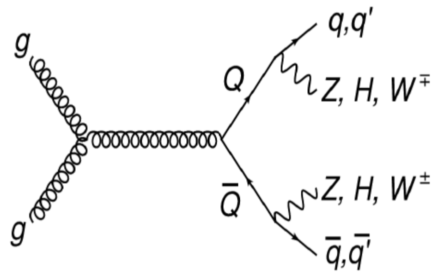
partner (MG name)	Q	$W^\pm$	Z	h	$W^\pm W^\pm$
$T_{2/3}$ (T23)	2/3	c_L^{TW}, c_R^{TW}	c_L^{TZ}, c_R^{TZ}	c_L^{Th}, c_R^{Th}	—
$B_{1/3}$ (B13)	-1/3	c_L^{BW}, c_R^{BW}	c_L^{BZ}, c_R^{BZ}	c_L^{Bh}, c_R^{Bh}	—
$X_{5/3}$ (X53)	5/3	c_L^{XW}, c_R^{XW}	—	—	—
$Y_{4/3}$ (Y43)	-4/3	c_L^{YW}, c_R^{YW}	—	—	—
$V_{8/3}$ (V83)	8/3	—	—	—	c_L^{VW}, c_R^{VW}

Example of the simplified model Lagrangian (after mixing and mass matrix diagonalization)

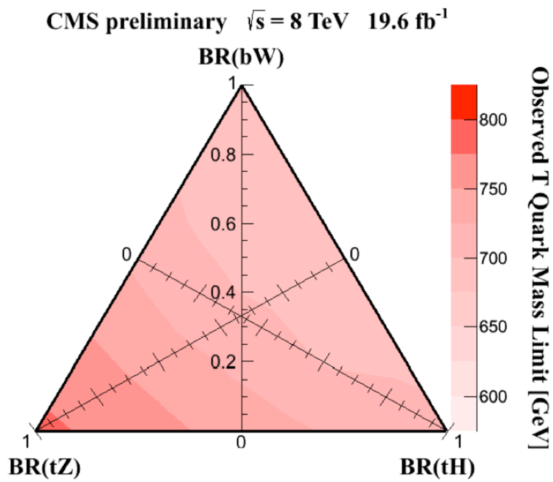
$$\frac{g_w}{2} c_L^{TW} \left[\overline{T}_L \gamma_\mu b_L W^\mu\right] + h.c.$$

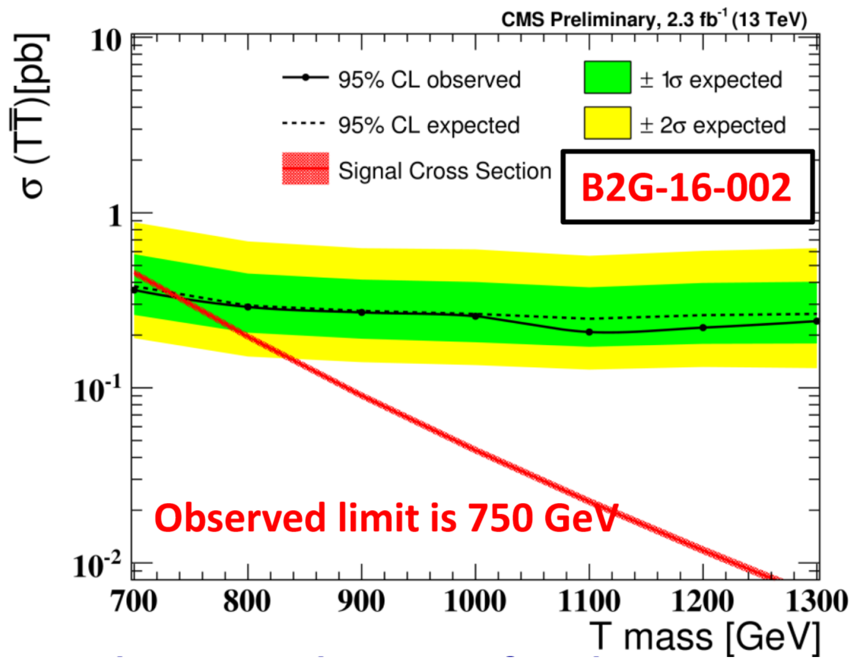
$$c_L^{Th} \left[\overline{T}_R t_L h\right] + h.c.$$

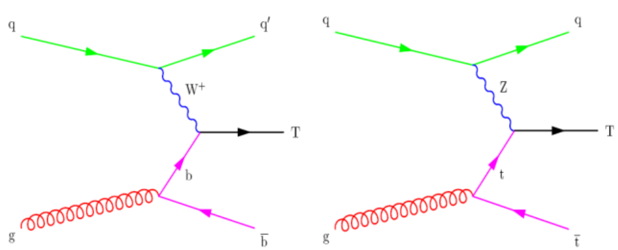
Similar limit at 13 TeV with just 2.3 fb^{-1} integrated luminosity



$T \rightarrow Zt$, $T \rightarrow Wb$, $T \rightarrow Ht$ for Q_T=2/3





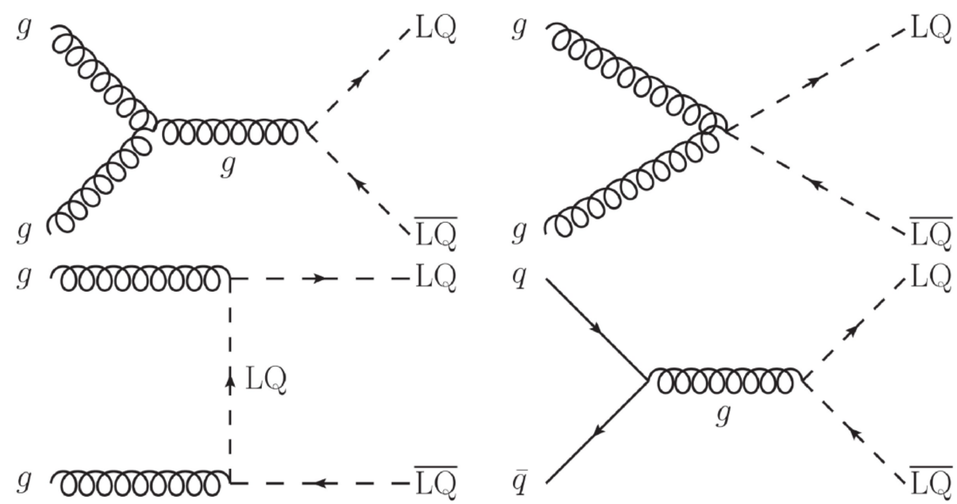


Also some limits are set on couplings and masses from single VLQ production

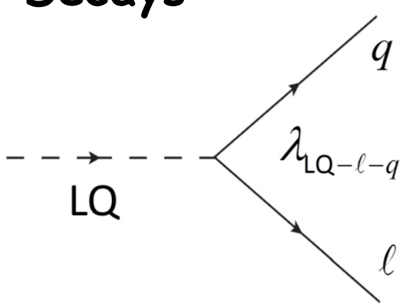
Leptoquark searches

LQs are predicted by composite models, GUT …

Production channels



Decays

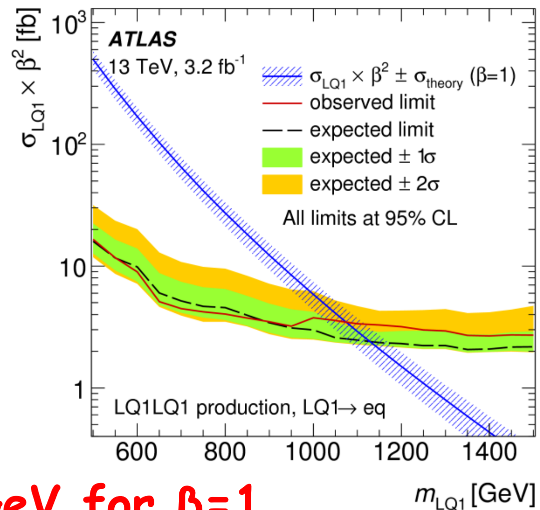


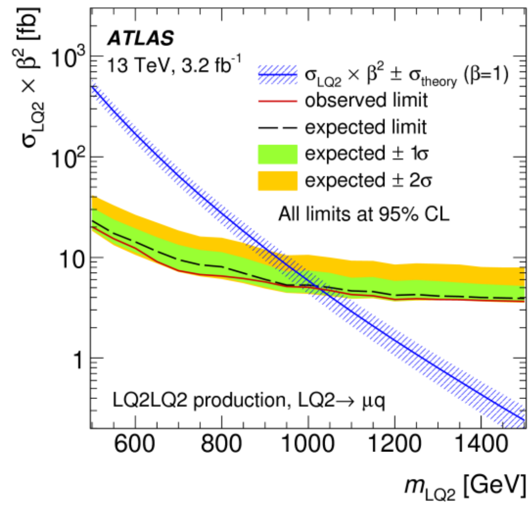
Final states for leptoquarks of three generations

LQ1 → eu, ed, ν_eu, ν_ed
LQ2 → μc, μs, ν_μc, ν_μs
LQ3 → τt, τb, ν_τt, ν_τb

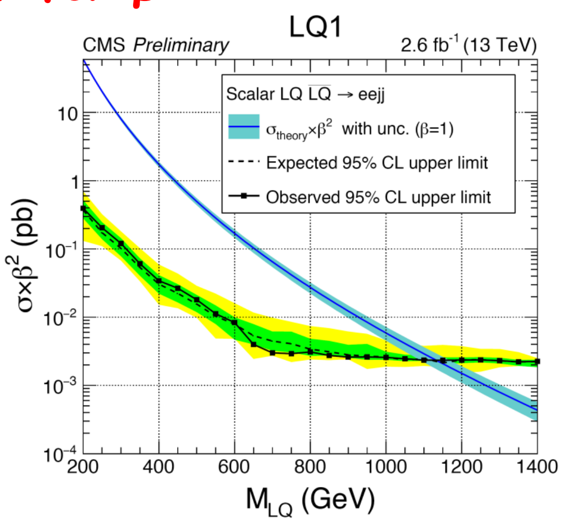
1st generation LQ mass limit for β=1 RUN1 • CMS: 1010 GeV; ATLAS 1060 GeV

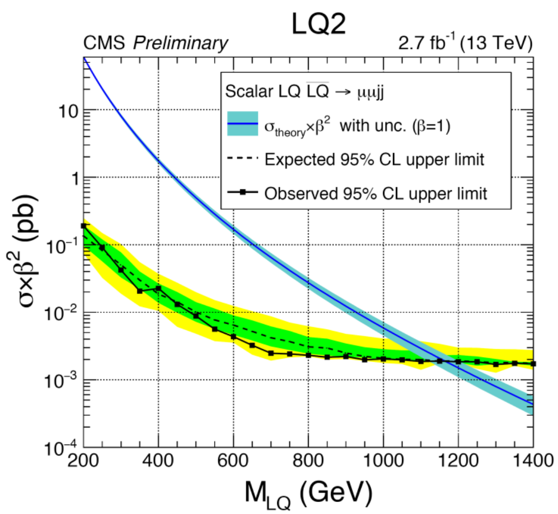
2nd generation LQ mass limit for β=1 RUN1 • CMS: 1080 GeV; ATLAS 1050 GeV





1130 GeV for β=1



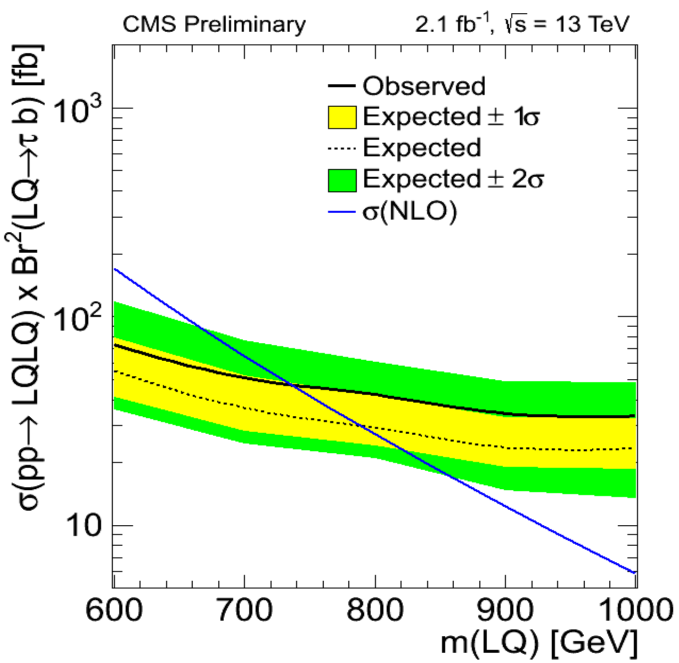


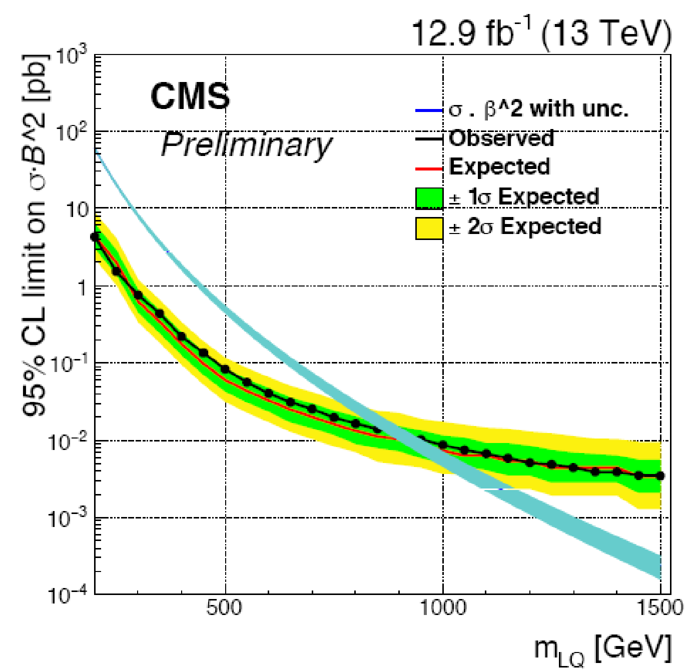
1165 GeV for β=1

Sensitivity is similar for ~20 fb^{-1} at $\sqrt{s}$ = 8 TeV and for ~3 fb^{-1} at $\sqrt{s}$ = 13 TeV

Limits on 3d generation leptoquarks

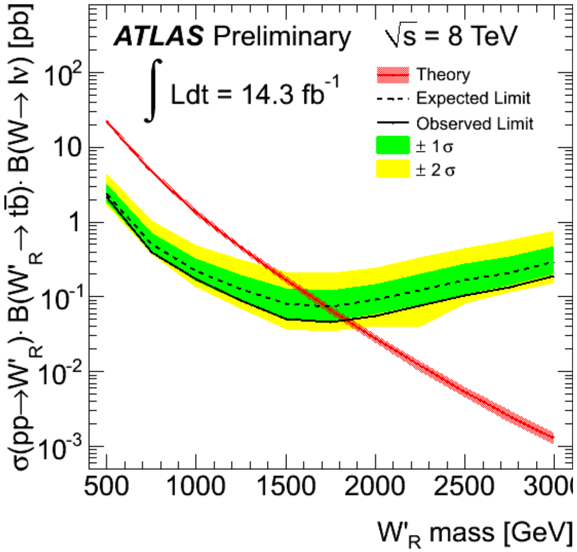
β = BR(LQ→lq)

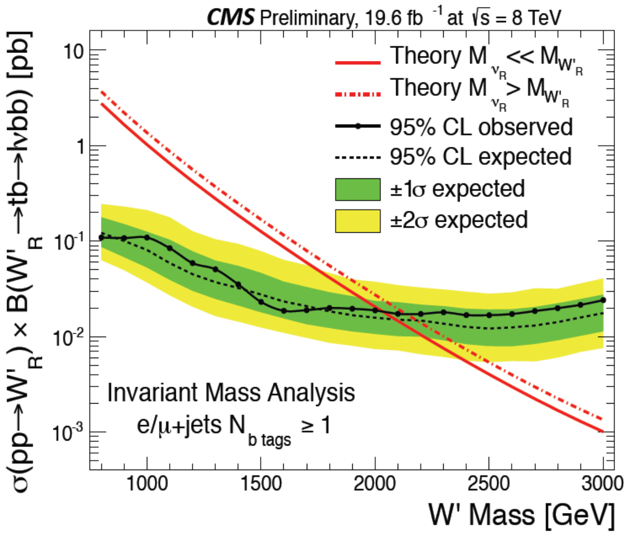


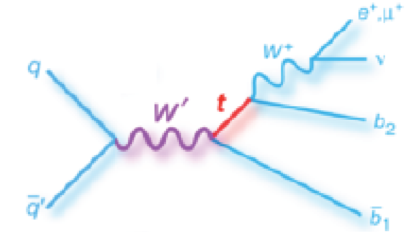


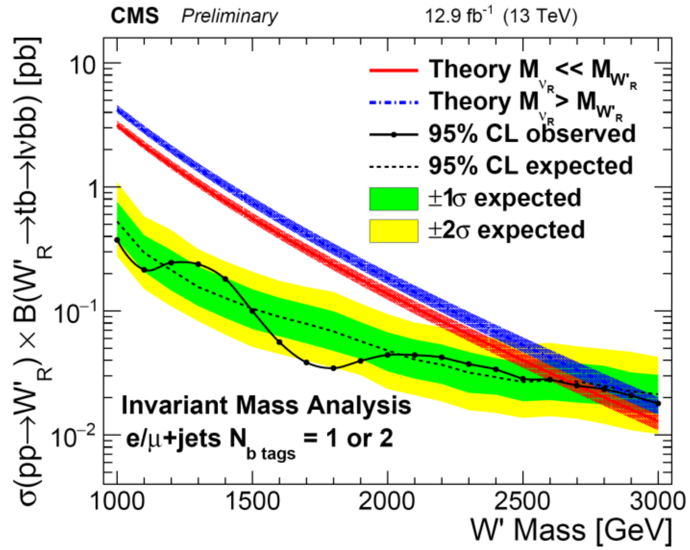
Limit: M(LQ3) > ~900 GeV

Searches for W' in top+b



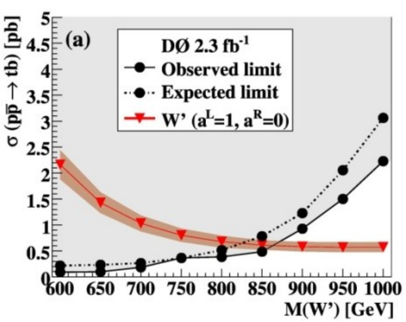


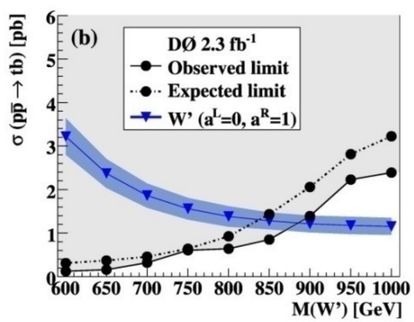


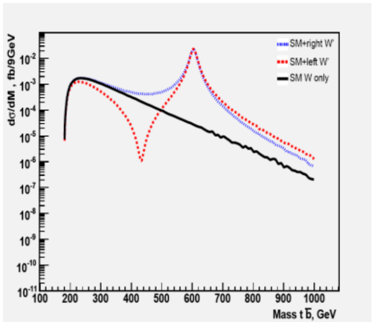


D0 limits: $M_{W'}$ > 830 (860) GeV L(R)

E.B., Bunichev, Dudko, Perfilov

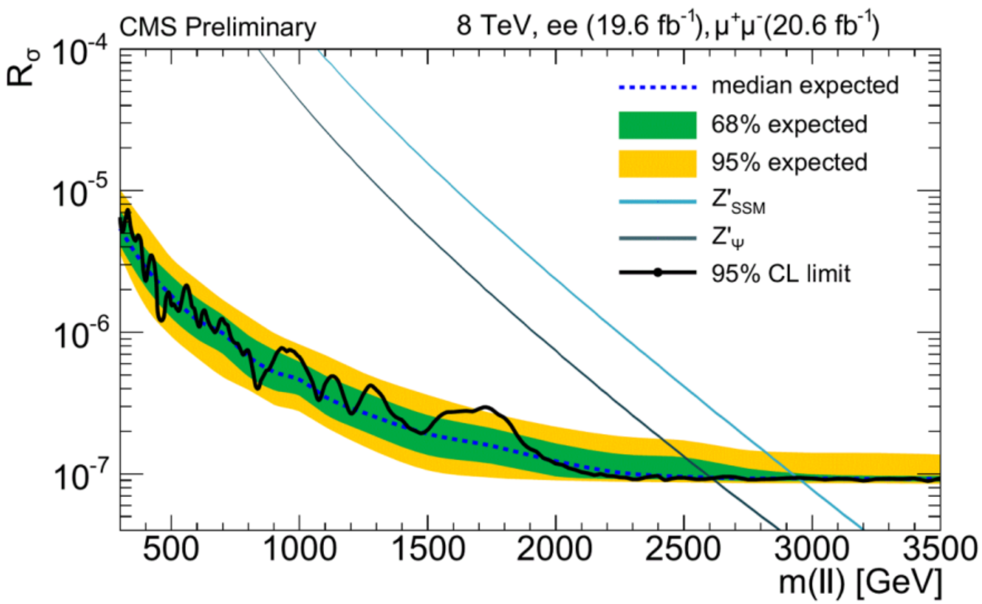




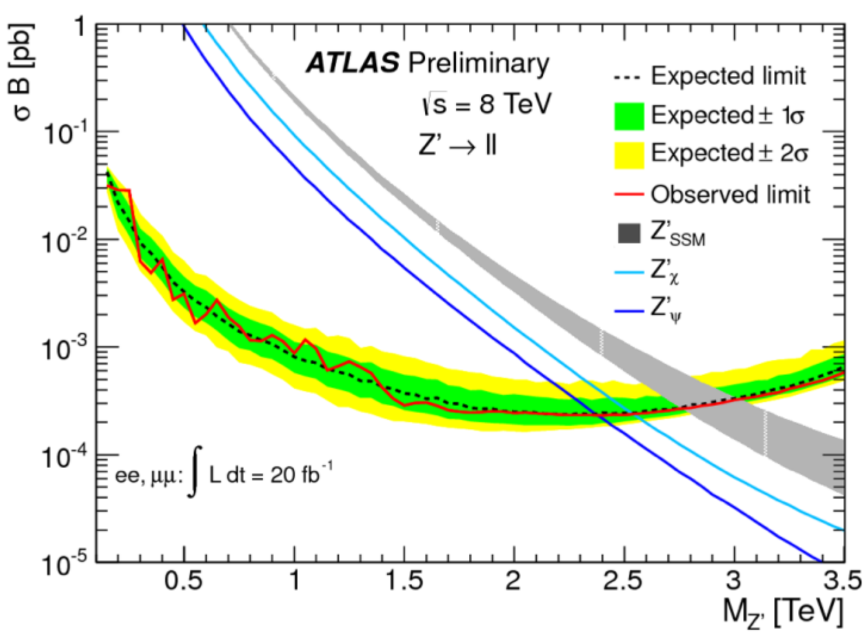


Negative interference

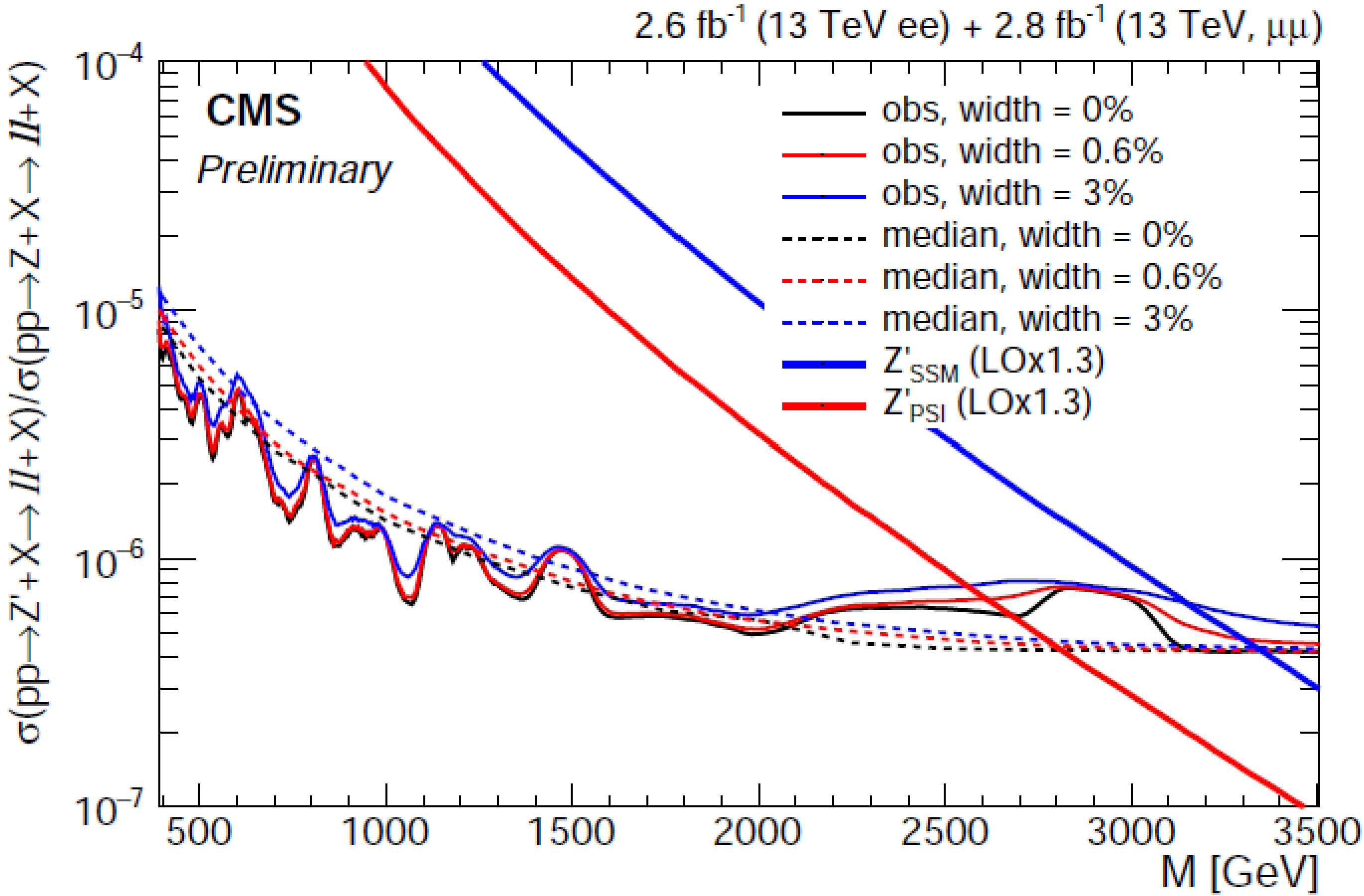
Searches for Z' in dileptons



$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$$

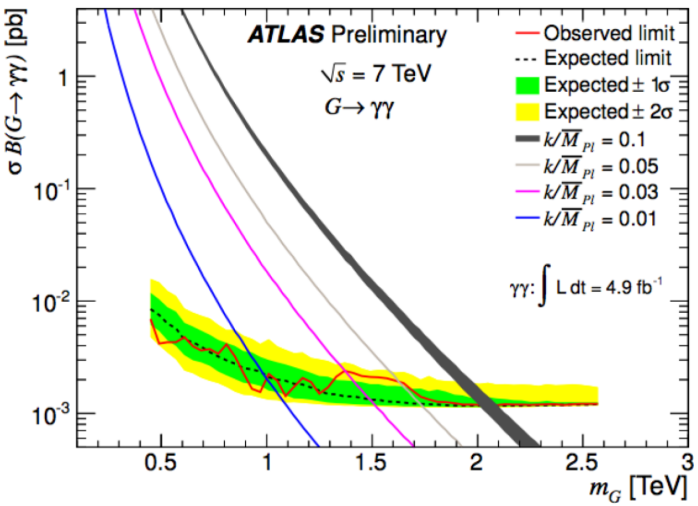


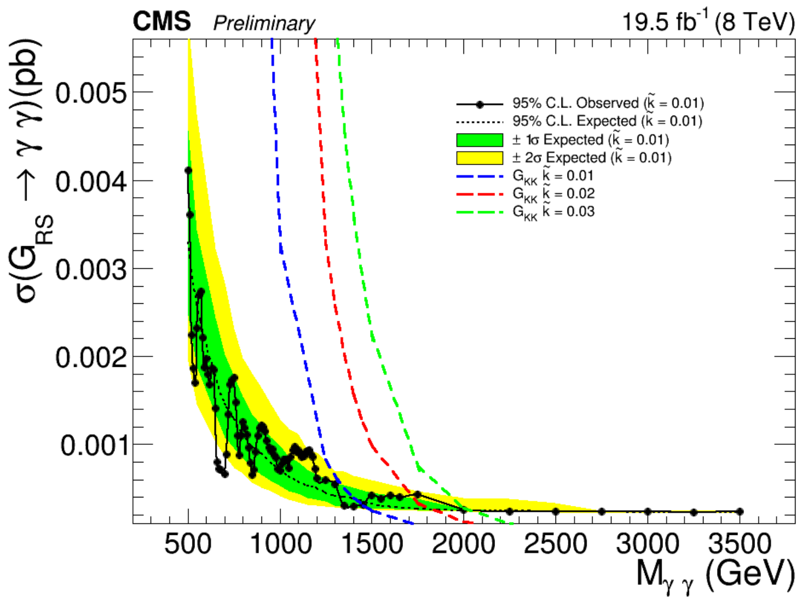
$M(Z'_{SSM})$	expected	observed
CMS	> 2.96 TeV	> 2.96 TeV
ATLAS	> 2.85 TeV	> 2.86 TeV

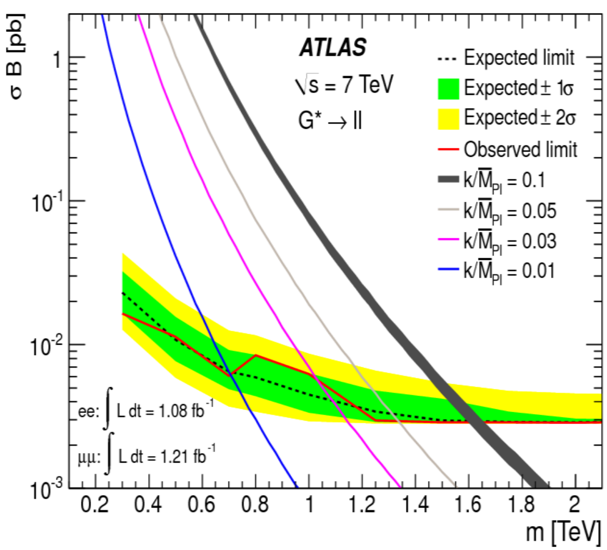


channel	Z'_ψ obs (TeV)	Z'_ψ expected (TeV)	Z'_{SSM} obs (TeV)	Z'_{SSM} expected (TeV)
ee	2.40	2.45	2.75	2.95
$\mu^+\mu^-$	2.40	2.55	3.00	3.05
$ee+\mu^+\mu^-$	2.60	2.80	3.15	3.35

Searches for RS gravitons

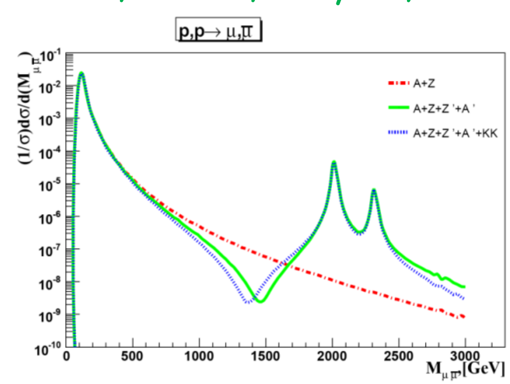




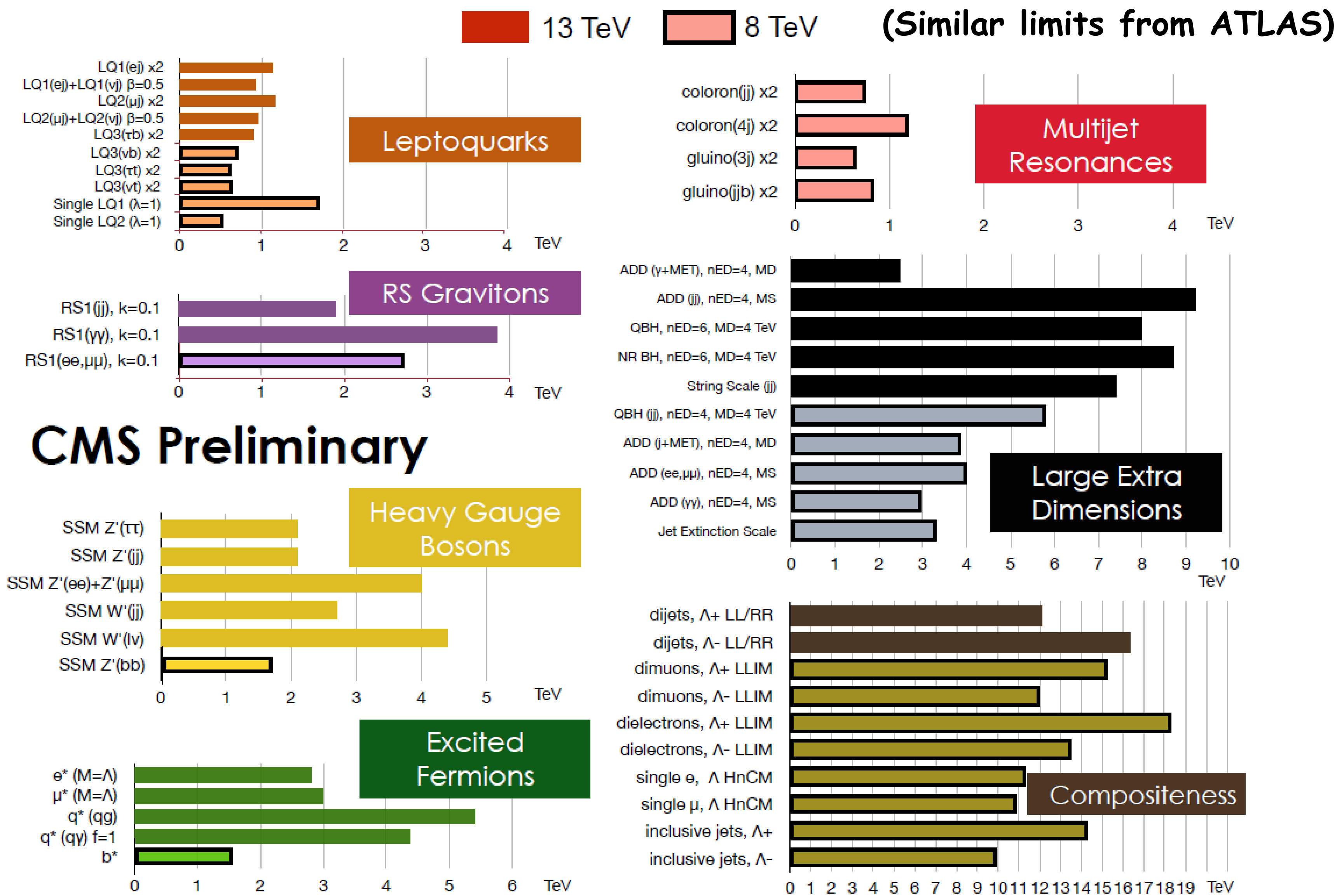


Interferences

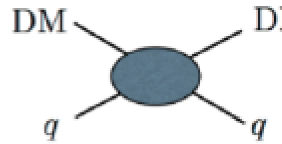
E.B., Bunichev, Smolyakov, Volobuev



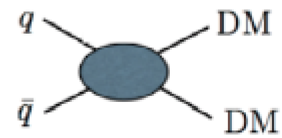
Excluding Dark Matter and Long Lived particles searches



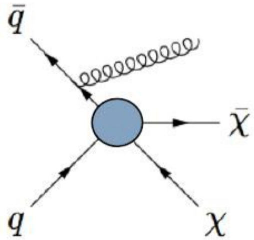
Dark Matter searches



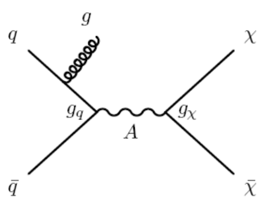
Direct Detection (t-channel)

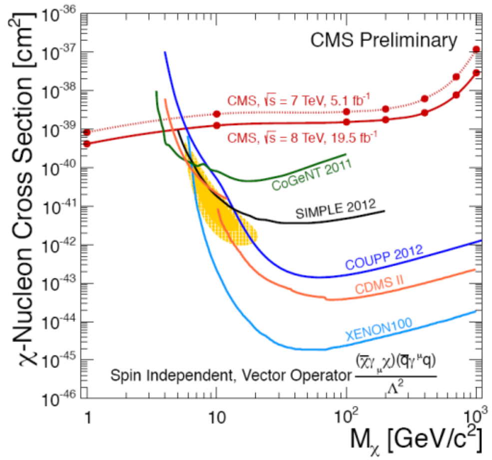


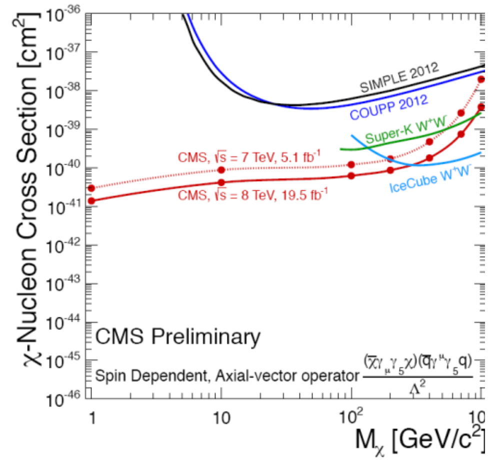
Collider Searches (s-channel)



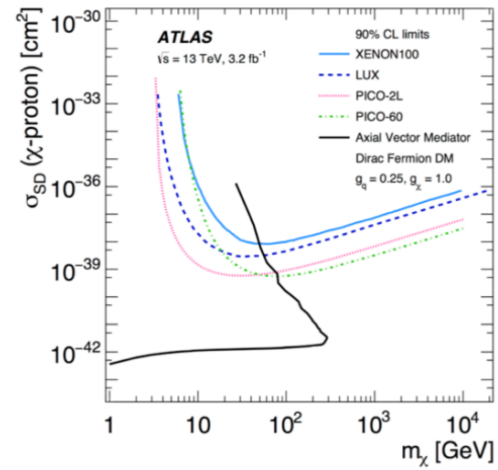
monojet +MET



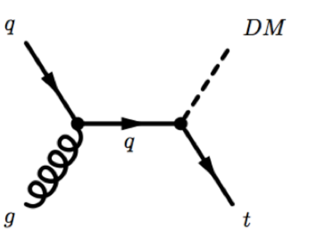


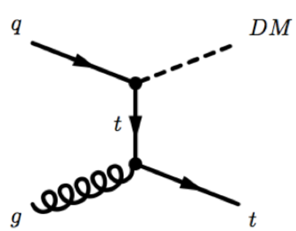


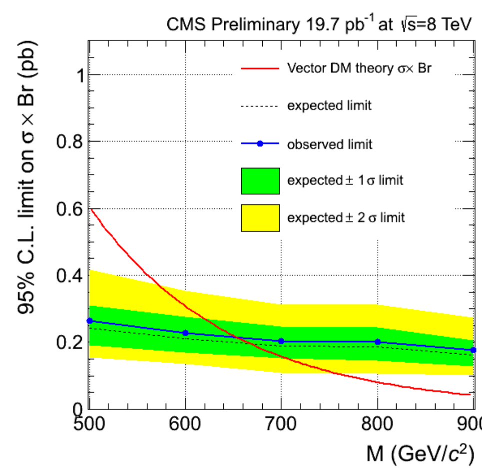
1604.07773

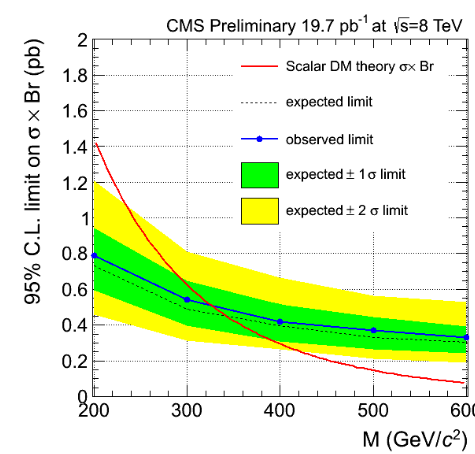


Dark Matter searches in association with single top

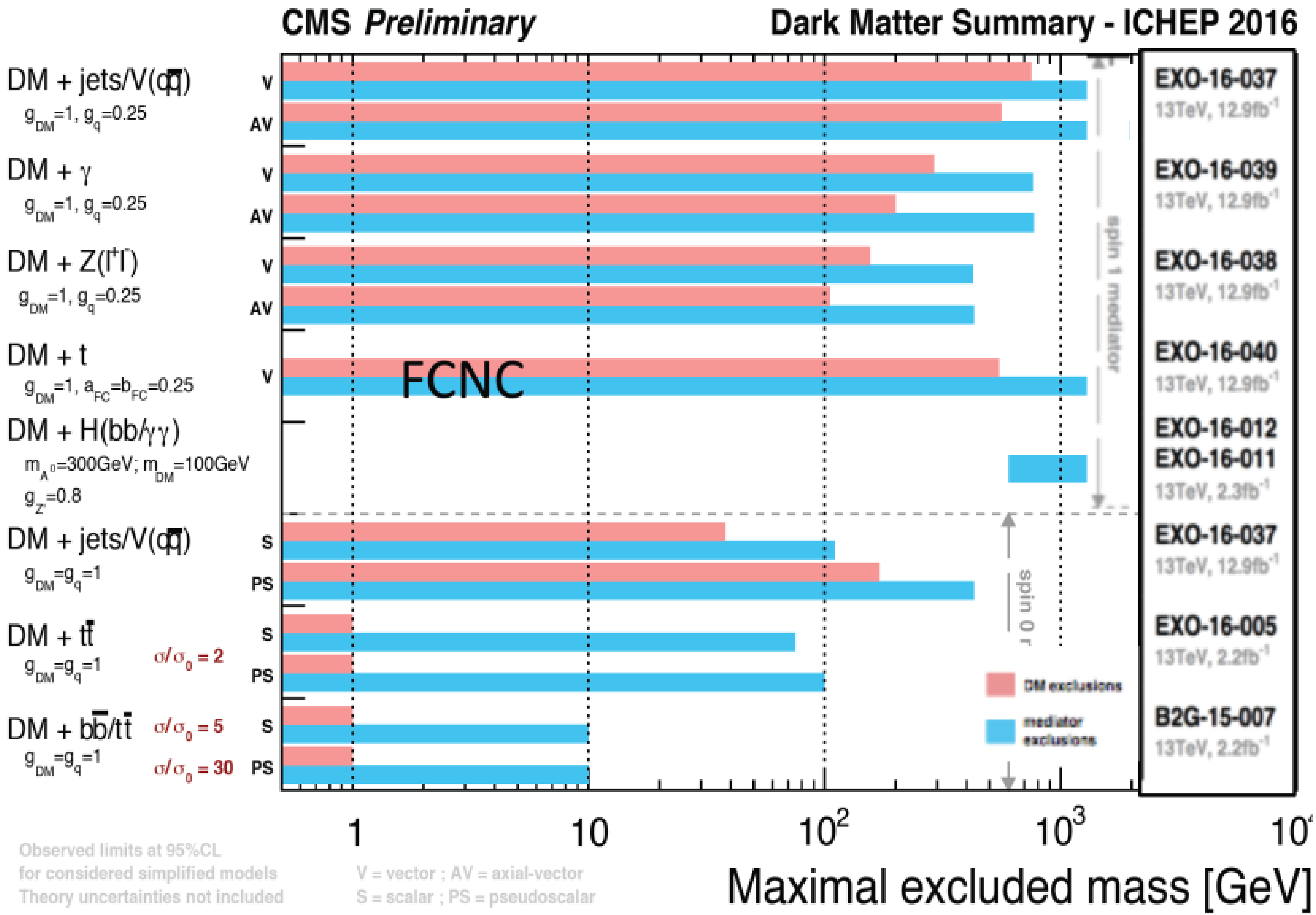








Mass of vector (scalar) DM candidate less that 655 (327) is excluded at 95% C.L.



CMS Preliminary
Dark Matter Summary - ICHEP 2016
DM + jets/V(qq̄)
g_{DM}=1, g_q=0.25
V
AV
DM + γ
g_{DM}=1, g_q=0.25
V
AV
DM + Z(l+l-)
g_{DM}=1, g_q=0.25
V
AV
DM + t
g_{DM}=1, a_{FC}=b_{FC}=0.25
V
FCNC
DM + H(bb/γγ)
m_{A^0}=300GeV; m_{DM}=100GeV
$g_{Z'}$=0.8
DM + jets/V(qq̄)
g_{DM}=g_q=1
S
PS
DM + tt̄
g_{DM}=g_q=1
σ/σ_0 = 2
S
PS
DM + bb̄/tt̄
g_{DM}=g_q=1
σ/σ_0 = 5
σ/σ_0 = 30
S
PS
spin 1 mediator
spin 0 r
DM exclusions
mediator exclusions
EXO-16-037
13TeV, 12.9fb-1
EXO-16-039
13TeV, 12.9fb-1
EXO-16-038
13TeV, 12.9fb-1
EXO-16-040
13TeV, 12.9fb-1
EXO-16-012
EXO-16-011
13TeV, 2.3fb-1
EXO-16-037
13TeV, 12.9fb-1
EXO-16-005
13TeV, 2.2fb-1
B2G-15-007
13TeV, 2.2fb-1
m_{DM} [GeV]
1
10
10^2
10^3
10^4
Maximal excluded mass [GeV]
Observed limits at 95%CL
for considered simplified models
Theory uncertainties not included
V = vector ; AV = axial-vector
S = scalar ; PS = pseudoscalar

Searches below threshold

Effective field theory approach

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \cdots$$

c_i - dimensionless coefficients
O_i – operators constructed from SM fields preserving
SM gauge invariance

Anomalous Top Couplings

The top quark interactions of dimension 4:

$$\mathcal{L}_4 = -g_s \bar{t}\gamma^\mu T^a t G^a_\mu - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \bar{t}\gamma^\mu (v^W_{tq} - a^W_{tq}\gamma_5) q W^+_\mu$$
$$-\frac{2}{3} e \bar{t}\gamma^\mu t A_\mu - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \bar{t}\gamma^\mu (v^Z_{tq} - a^Z_{tq}\gamma_5) q Z_\mu$$

The dimension 5 couplings have the generic form:

$$\mathcal{L}_5 = -g_s \sum_{q=u,c,t} \frac{\kappa^g_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f^g_{tq} + i h^g_{tq}\gamma_5) q G^a_{\mu\nu} - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \frac{\kappa^W_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^W_{tq} + i h^W_{tq}\gamma_5) q W^+_{\mu\nu}$$
$$-e \sum_{q=u,c,t} \frac{\kappa^\gamma_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^\gamma_{tq} + i h^\gamma_{tq}\gamma_5) q A_{\mu\nu} - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \frac{\kappa^Z_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^Z_{tq} + i h^Z_{tq}\gamma_5) q Z_{\mu\nu}$$

Natural size k ~ v/Λ

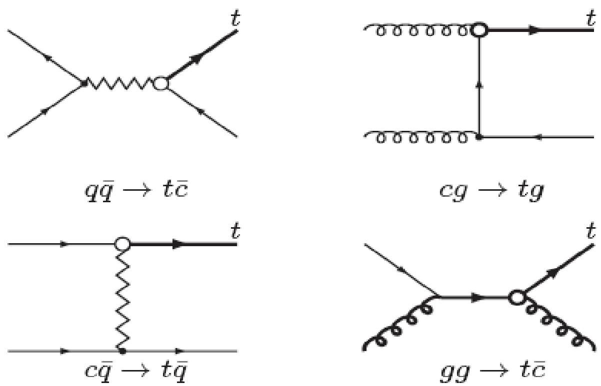
Present constrains come from

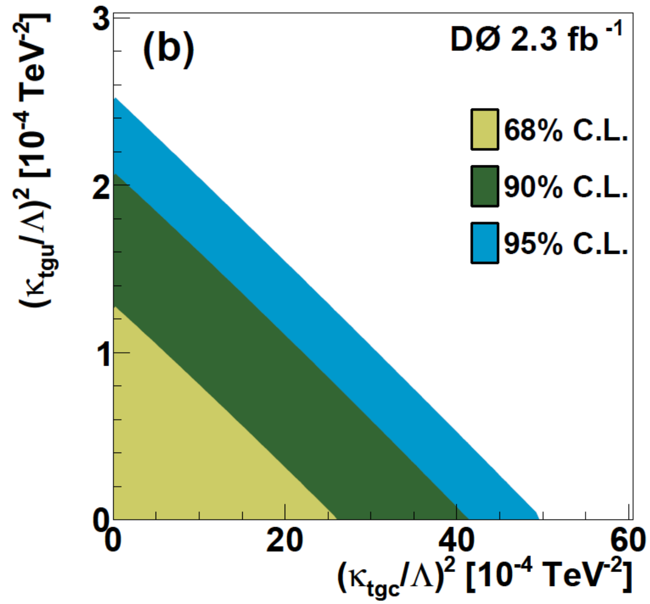
- Low energy data via loop contributions
  $K_L \to \mu^+\mu^-$, $K_L - K_S$ mass difference, $b \to l^+ l^- X$, $b \to s\gamma$
- LEP2
- Tevatron Run**1,2**
- HERA
- Unitarity violation bounds

FCNC anomalous top couplings

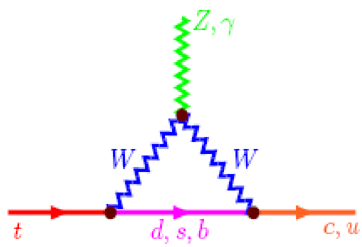
- Couplings: tqg, $tq\gamma$, tqZ, where $q = u, c$

$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\left[\kappa_{tq}^{\gamma,Z} e\bar{t}\sigma_{\mu\nu} q F^{\mu\nu}_{\gamma,Z} + \kappa_{tq}^{g} g_s \bar{t}\sigma_{\mu\nu}\frac{\lambda^i}{2} q G^{i\mu\nu}\right] + h.c.$$





W' boson and FCNC MC event samples from SingleTop (CompHEP) generator



	SM	two-Higgs	SUSY
$BR(t \to cg)$	$5 \cdot 10^{-11}$	10^{-6}	10^{-3}
$BR(t \to c\gamma)$	$5 \cdot 10^{-13}$	10^{-6}	10^{-5}
$BR(t \to cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}

FCNC decays are highly suppressed in SM $t \to qg,\quad t \to q\gamma,\quad t \to qZ$

To compare FCNC limits from top decays and top production one can express limits on FCNC couplings in term of Br fractions

$$\Gamma(t \to qg) = \left(\frac{\kappa^g_{tq}}{\Lambda}\right)^2 \frac{8}{3}\alpha_s m_t^3 \quad , \quad \Gamma(t \to q\gamma) = \left(\frac{\kappa^\gamma_{tq}}{\Lambda}\right)^2 2\alpha m_t^3,$$

$$\Gamma(t \to qZ)_\gamma = \left(|v^Z_{tq}|^2 + |a^Z_{tq}|^2\right) \alpha\, m_t^3 \frac{1}{4M_Z^2 \sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_Z^2}{m_t^2}\right),$$

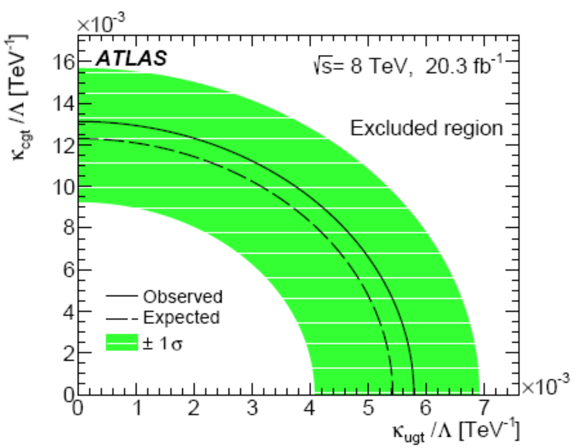
$$\Gamma(t \to qZ)_\sigma = \left(\frac{\kappa^Z_{tq}}{\Lambda}\right)^2 \alpha\, m_t^3 \frac{1}{\sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(2 + \frac{M_Z^2}{m_t^2}\right)$$

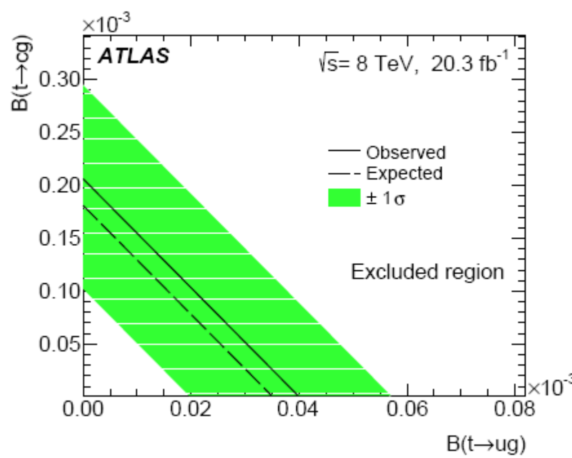
D0:

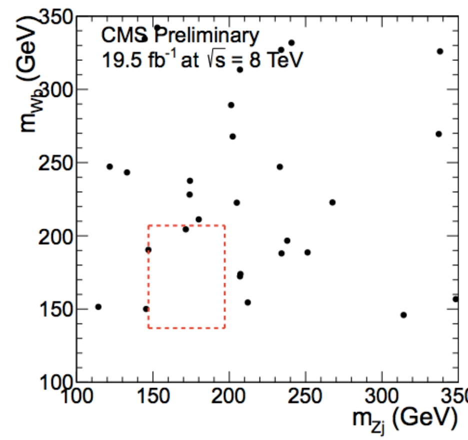
	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgf}/Λ	0.013 TeV^{-1}	0.057 TeV^{-1}
$\mathcal{B}(t \to qg)$	2.0×10^{-4}	3.9×10^{-3}

CDF:

$$\mathcal{B}(t \to u + g) < 3.9 \cdot 10^{-4}$$
$$\mathcal{B}(t \to c + g) < 5.7 \cdot 10^{-3}$$







CMS limit:

B(t -> Zq) < 0.07% @ 95%C.L.

Many interesting new results

Indirect search for BSM physics – the main goal of the LHCb experiment.

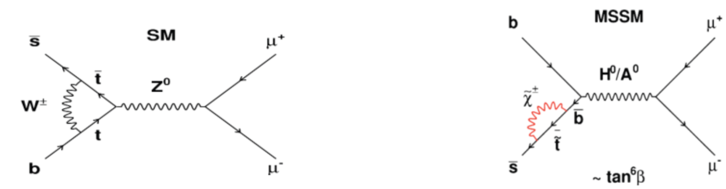
Rare $B^0_s \to \mu^+\mu^-$ decay

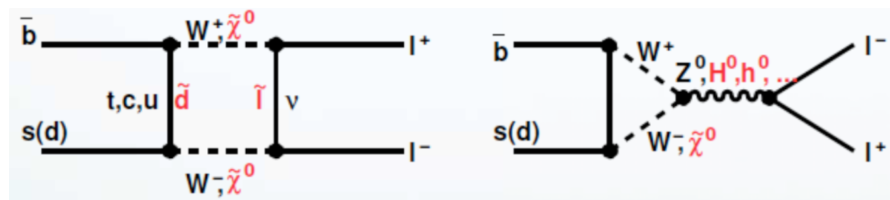
LHCb:

$$Br(B^0_s \to \mu\mu) = (3.2^{+1.4}_{-1.2}(\mathrm{stat})^{+0.5}_{-0.3}(syst)) \times 10^{-9}$$

CMS:

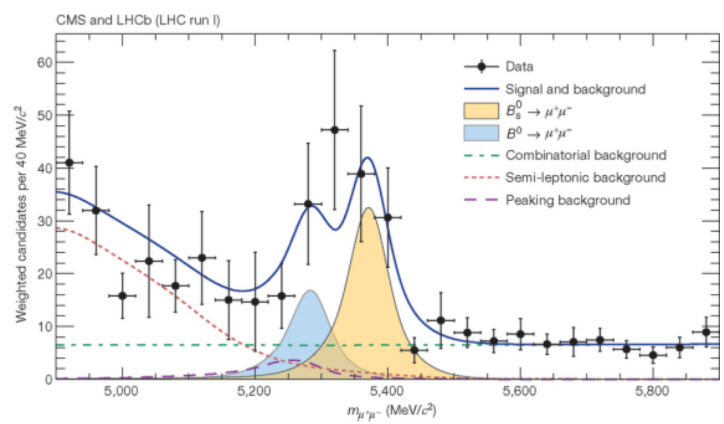
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$





Combined result (Nature 522 (2015) 68)

$$Br(B^0_s \to \mu^+\mu^-)_{exp} = (2.8^{+0.7}_{-0.8}) \times 10^{-9}$$

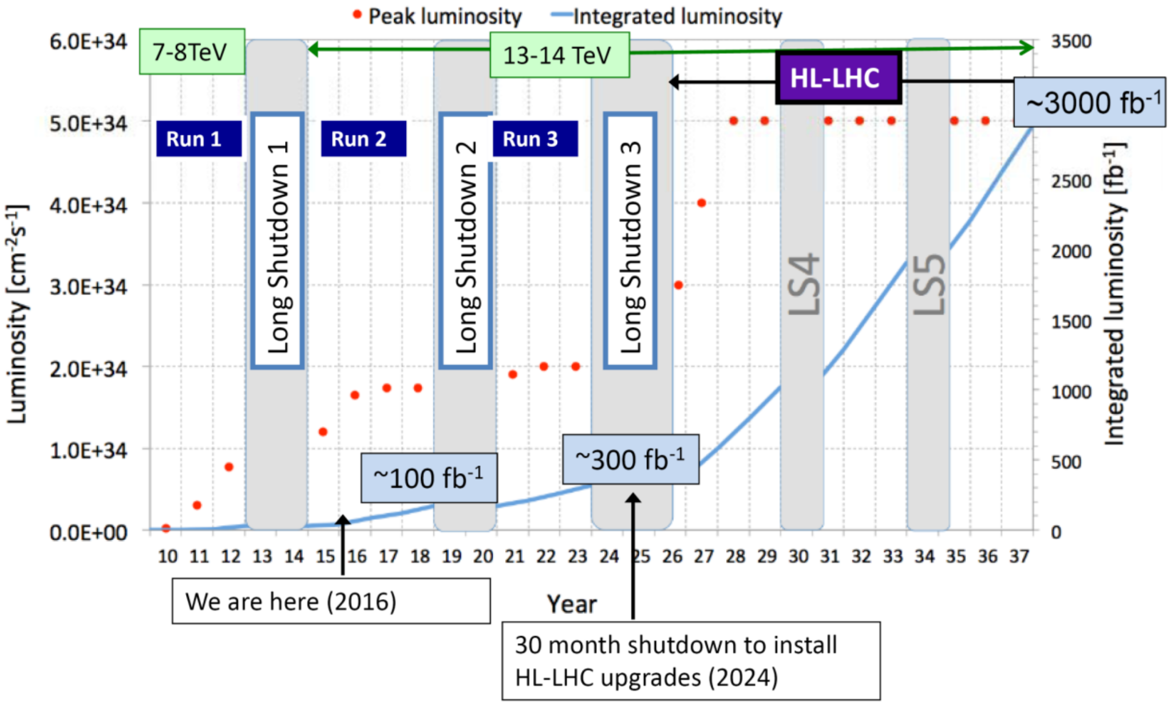


Observed decay rate is compatible with the SM expectation:

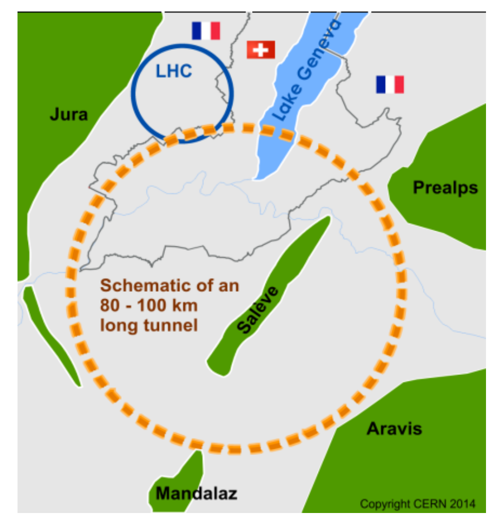
$$Br(B^0_s \to \mu^+\mu^-)_{theory} = (3.66 \pm 0.23) \times 10^{-9}$$

LHC and HL-LHC

Fabiola Gianotti



Future Circular Colliders (FCC)



International conceptual design study ~100 km ring:

- ❑ **pp collider (FCC-hh)**

  $\sqrt{s}$ ~ 100 TeV, L~2x10^{35}

- ❑ **e^+e^- collider (FCC-ee)**

  $\sqrt{s}$ = 90-350 GeV, L~200-2 x 10^{34} **-1**

- ❑ **pe collider (FCC-he): option**

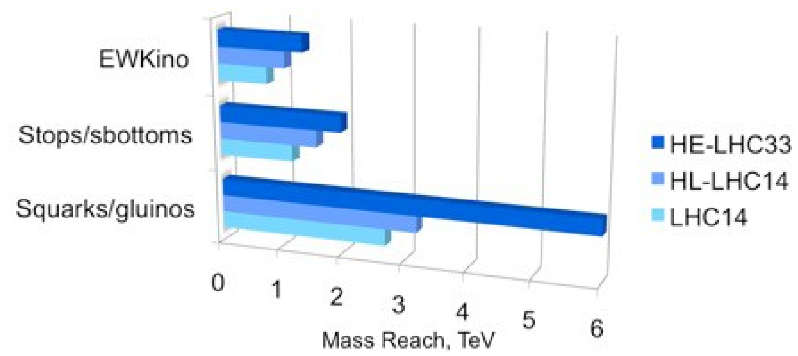
  $\sqrt{s}$ ~ 3.5 TeV, L~10^{34}

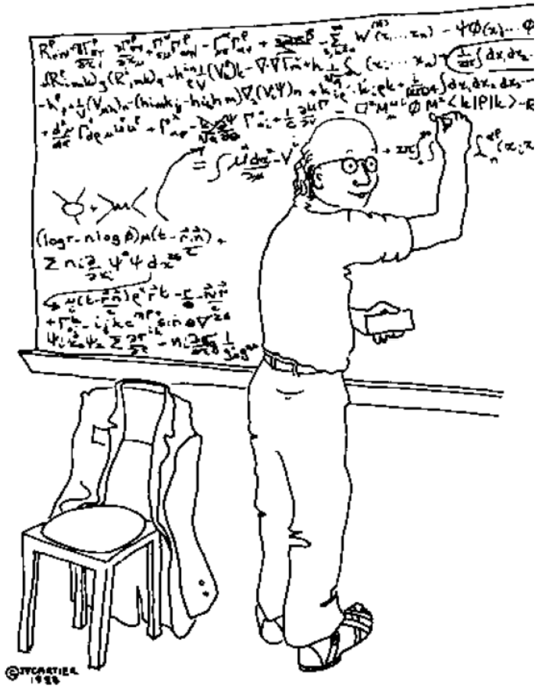
Expected precisions for Higgs couplings

Snowmass Higgs working group 2013

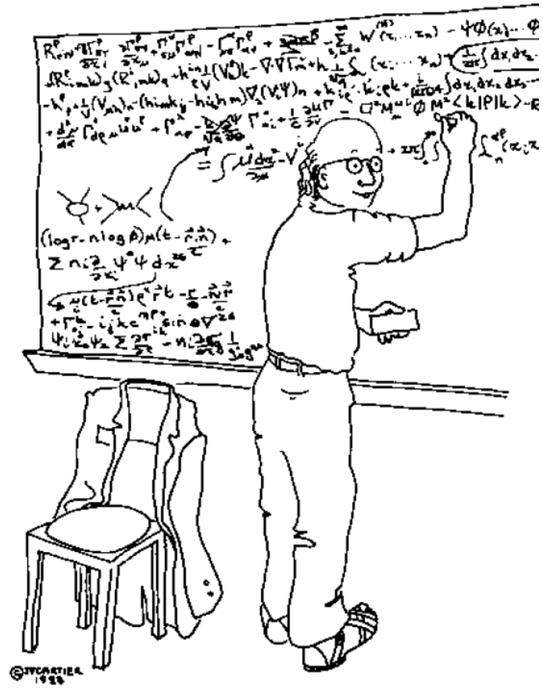
Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 − 7%	2 − 5%	8.3%	4.4%	3.8%	2.3%	−/5.5/<5.5%	1.45%
κ_g	6 − 8%	3 − 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 − 6%	2 − 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 − 6%	2 − 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 − 8%	2 − 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 − 13%	4 − 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 − 15%	7 − 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$





"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."



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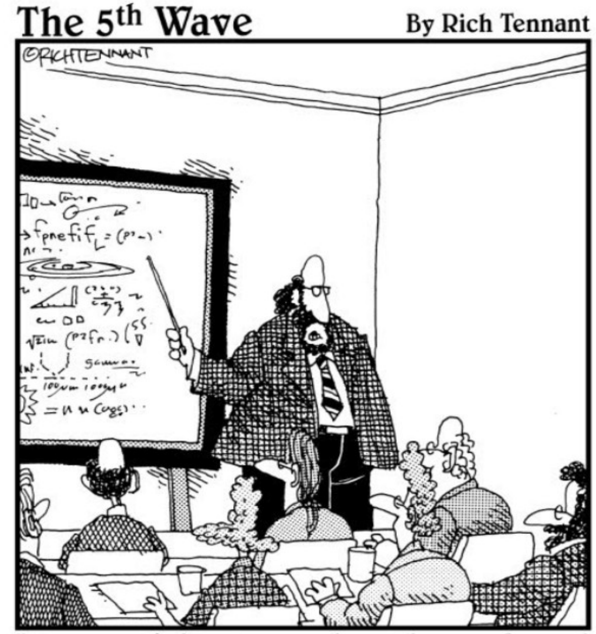
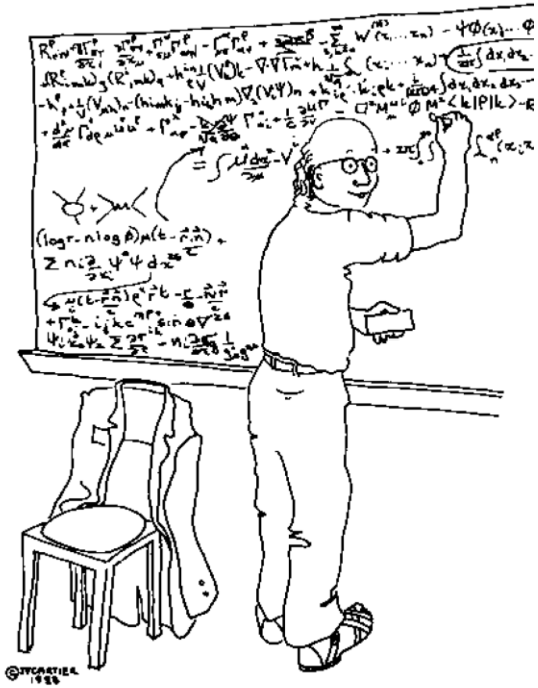


"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."



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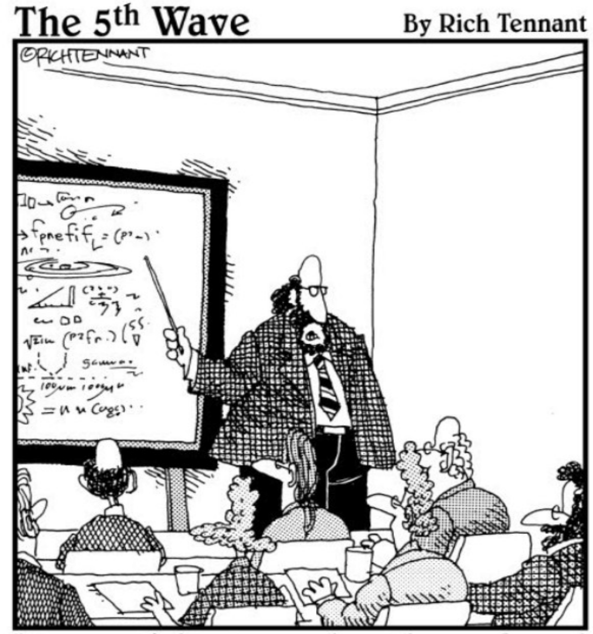

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**"It doesn't matter how beautiful your theory is,
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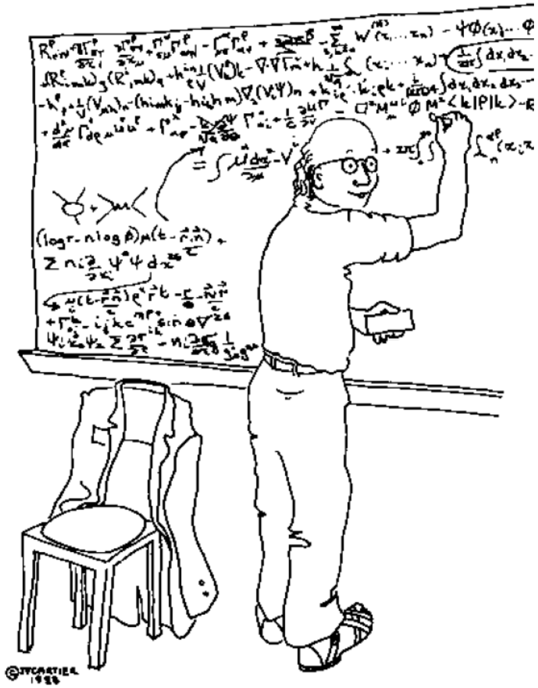
If it doesn't agree with experiment, it's wrong".**

Richard P. Feynman



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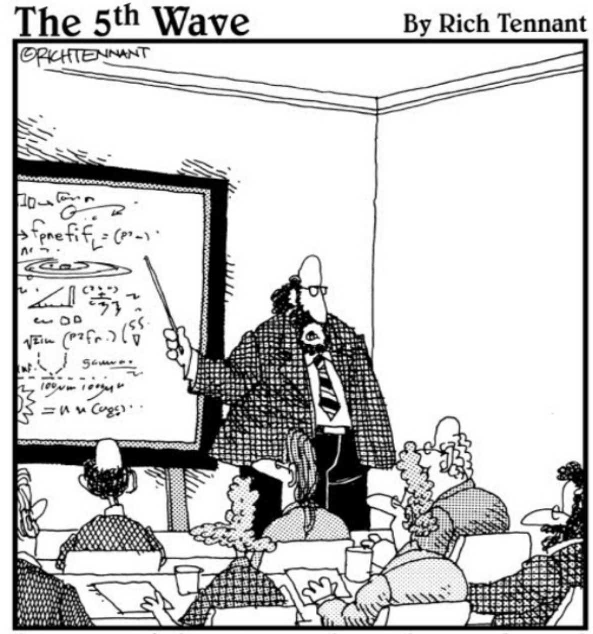

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But with correct (confirmed) experiment….