Beyond the Standard Model at LHC

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Why physics beyond the SM

- The Standard Model describes fundamental particles and interaction
- The SM is a very well verified theory
- But it does not describe all known phenomena, so can’t be considered a “theory of everything”
- Does not include:
  - Gravity
  - Dark matter

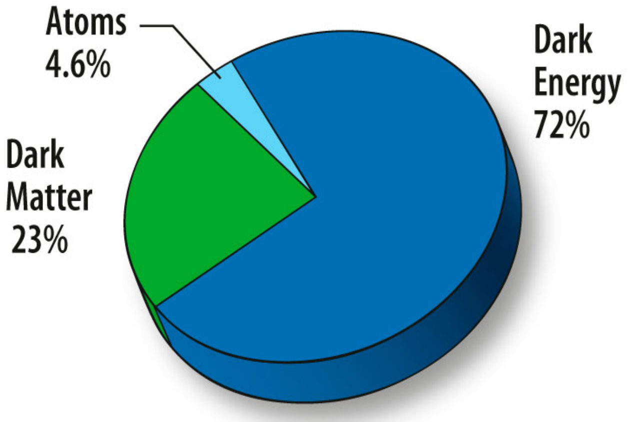
Gravity

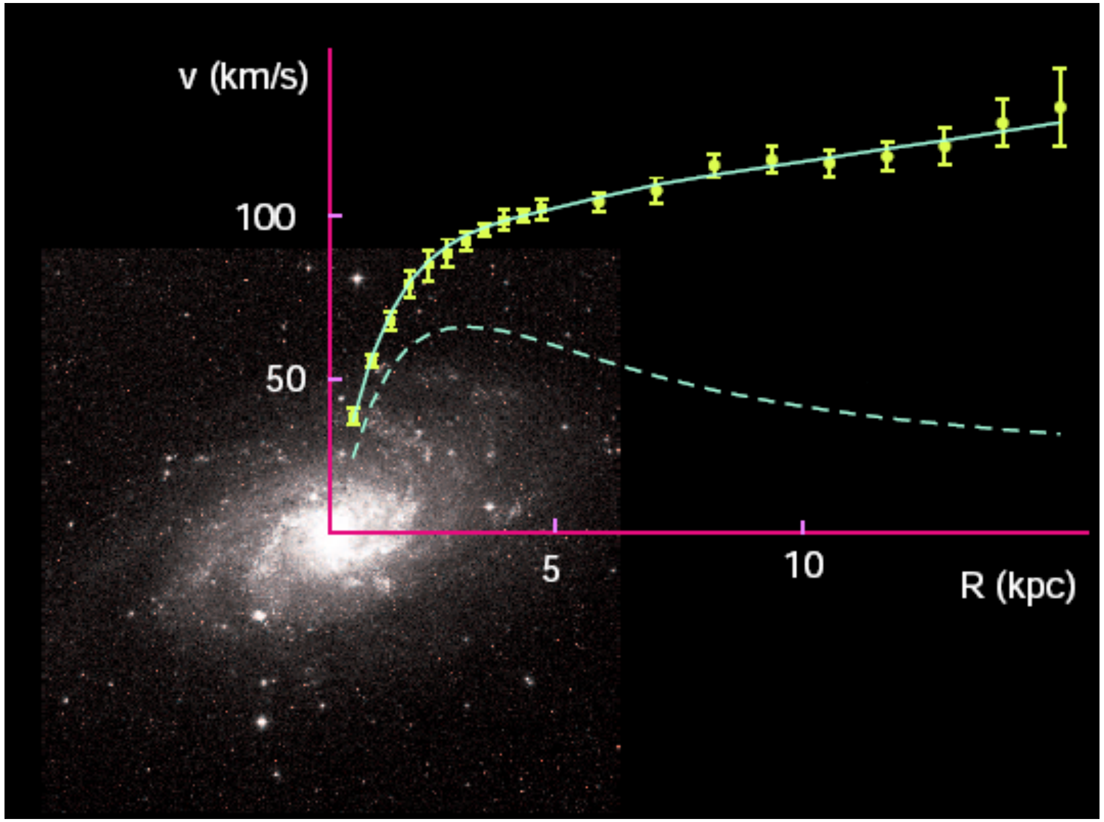
- No consistent (=renormalizable) quantum description of Einstein's General Relativity equations
  - Graviton (spin=2)?
- Scale problem: $G_F/G_N \sim 10^{32}$, or, in term of mass scale: $m_{Plank}/m_{EWK} \sim 10^{16}$

- Why so many orders of magnitude?
- Underlying physics reason, or "Anthropic principle"?
- Hides higher space dimensionality?

Dark matter

- Ordinary matter constitutes only 5% of the universe content
  - A small fraction of it makes stars and planets
- A much larger "dark" fraction manifests its presence only via its gravitational effects
  - Galactic rotation curves
- Dark energy is needed in the universe to explain the expansion acceleration

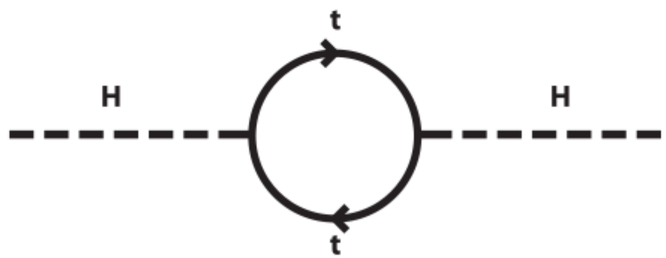




Rotational curve of galaxy M33

Theoretical arguments

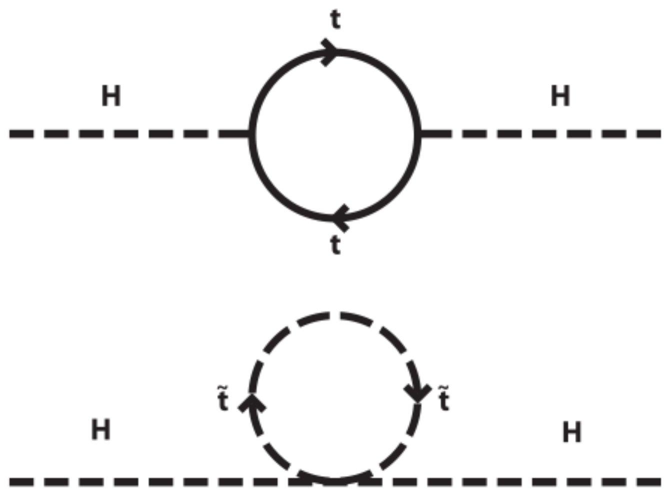
- Theoretical arguments suggest physics beyond the SM to guarantee the "hierarchy" of Higgs mass corrections
  - $\Delta m_H^2 \approx k\, \Lambda^2$



- k is a numerical constant
  - Computable from Feynman loops
- Λ is a cutoff scale (where new physics occurs, could be the Plank scale)
- Higgs physics mass very different from the SM mass parameter via quantum loop corrections
  - "Instability" w.r.t. new physics scale
  - Requires fine tuning of many orders of magnitude
- New particles could run in the loop and provide the proper cancelation without ad hoc fine tuning
  - Supersymmetry?

Super symmetry

- New scalar partners can enter in the loop
- Quantum corrections have opposite sign and cancel perfectly, solving the hierarchy problem
- The particle spectrum would be duplicated
- As we don't see s-partners with the same mass as ordinary particles, SuSy must be broken



- Super symmetry has an elegant mathematical formulation and also arises from string-inspired models

Susy mathematical model

- A new symmetry operator transforms fermions to bosons and vice versa

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

- Special commutation relations

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = -2\sigma^\mu_{\alpha\dot\alpha} P_\mu,$$

$$\{Q_\alpha, Q_\beta\} = 0, \qquad \{Q^\dagger_{\dot\alpha}, Q^\dagger_{\dot\beta}\} = 0$$

$$[Q_\alpha, P^\mu] = 0, \qquad [Q^\dagger_{\dot\alpha}, P^\mu] = 0$$

- Superspace: extensio of 4D space-time with the addition of anticommutating coordinates

$$x^\mu \Rightarrow x^\mu,\ \theta^\alpha,\ \theta^\dagger_{\dot\alpha} \qquad \hat{Q}_\alpha = i\frac{\partial}{\partial\theta^\alpha} - (\sigma^\mu\theta^\dagger)_\alpha\partial_\mu$$

Q = translation in the superspace!

- Superfield can be decomposed by series expansion in θ (no more than 2nd degree) into ordinary fermion and boson fields + an auxiliary field F (Wess-Zumino)

$$\Phi = \phi(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$

Susy phenomenology

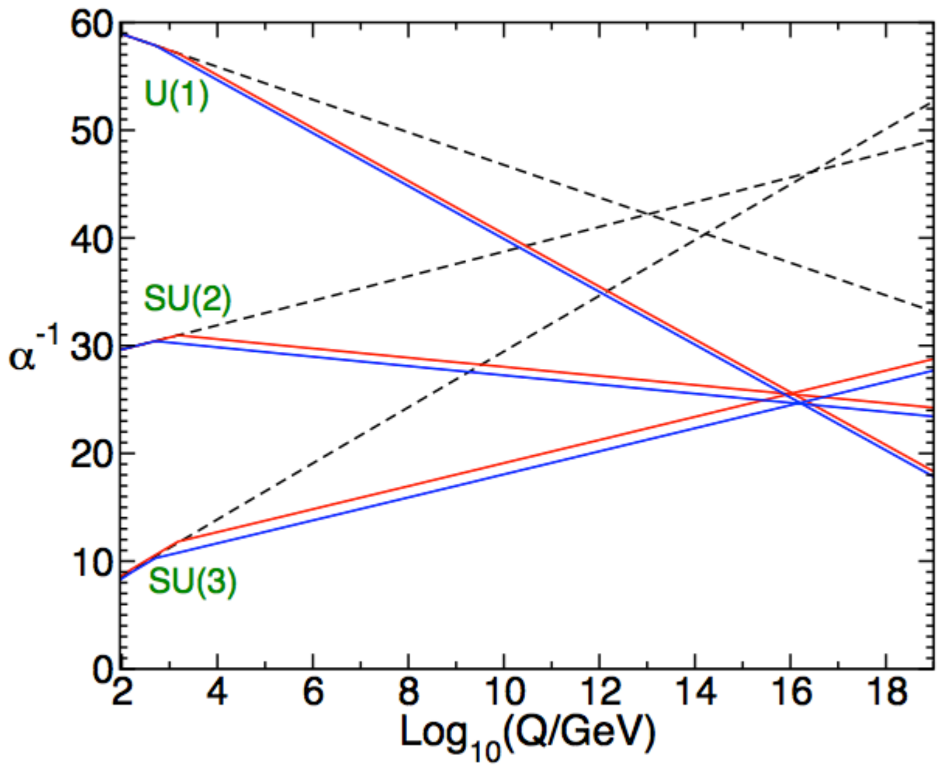
- R-parity conservation?
  - $R = (-1)^{3(B - L) + 2S}$, R=1 for ordinary particles, R=−1 for Susy partners
  - Violation of R-parity would result in most of the models in short proton lifetime
  - The lightest particle with R=−1 (LSP) can't decay (DM candidate!)
- Two (or more…) Higgs doublets (MSSM)
  - a single doublet can't form Susy-invariant terms

$$H_u = (H_u^+ \, H_u^0),\; H_d = (H_d^0 \, H_d^-)$$

  - Ratio of v.e.v: $\tan\beta \equiv v_u/v_d$, also related to m_t/m_b
  - Higgs bosons mass pattern predicted at tree level ($m_{h^0} < m_Z$!), but loop corrections may change the pattern (up to 135 GeV still allowed)

Susy and GUT

- Susy could be an intermediate step toward a grand unification
- Adding more degrees of freedom would allow the running couplings to meet at a common (GUT) scale



SuSy zoology

- Higgsinos and gauginos mix states introducing EWK breaking into two charginos and four neutralinos
- If the LSP is the lightest neutralino, would be a good DM candidate
  - Some models also propose the gravitino as LSP

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \ \widetilde{d}_L)$	$(u_L \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\bar{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \ \widetilde{e}_L)$	$(\nu \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\bar{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ H_u^0)$	$(\widetilde{H}_u^+ \ \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \ H_d^-)$	$(\widetilde{H}_d^0 \ \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \ \widetilde{W}^0$	$W^\pm \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

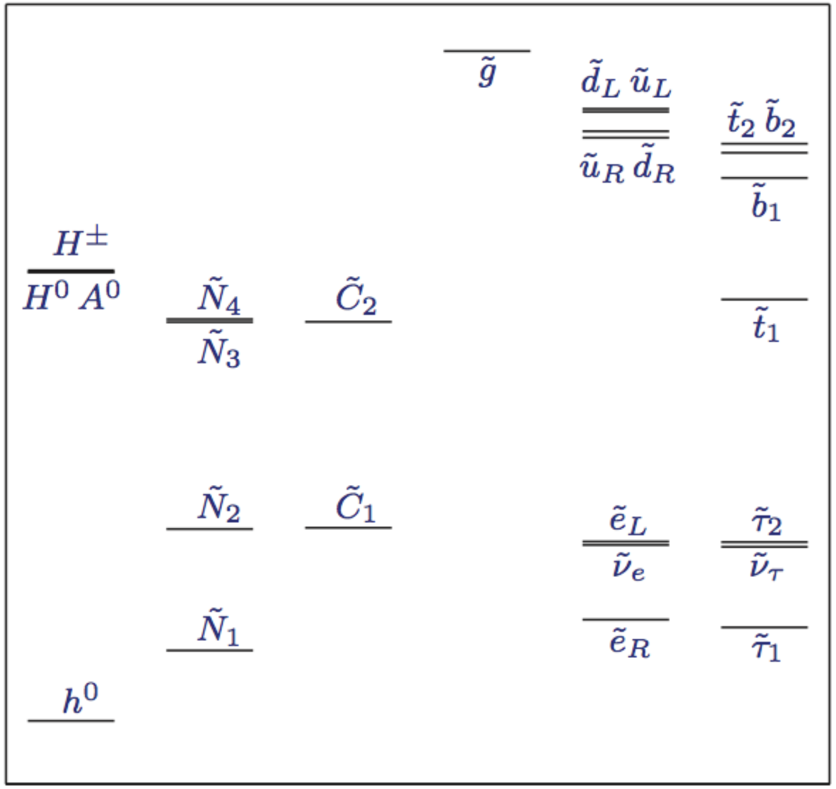
Susy mass spectrum

- Assuming all mass are degenerate at a given (large) scale, the mass parameter pattern may become simplified
  - mSUGRA (supergravity-inspired):
    - m_0: scalar mass
    - $m_{1/2}$: gaugino mass
    - A_0: trilinear coupling (higgs-sfermion-sfermion), soft-breaking
  - Other schemes have also been proposed

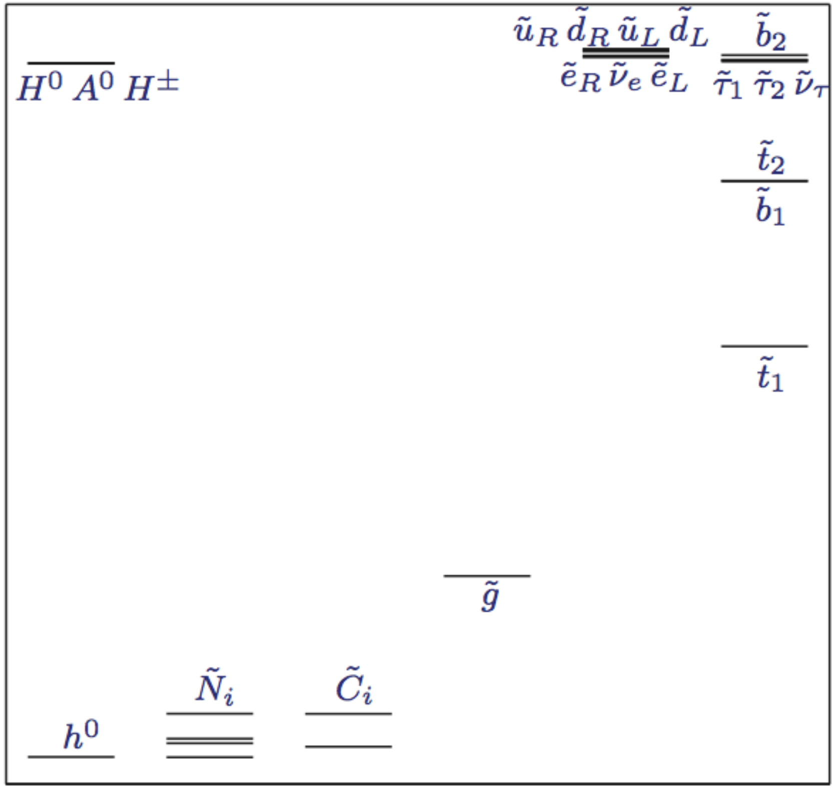
Possible mass spectra

- Mass spectra are not predicted by theory, depend on the model

mSUGRA



$m_0^2 \ll m_{1/2}^2$



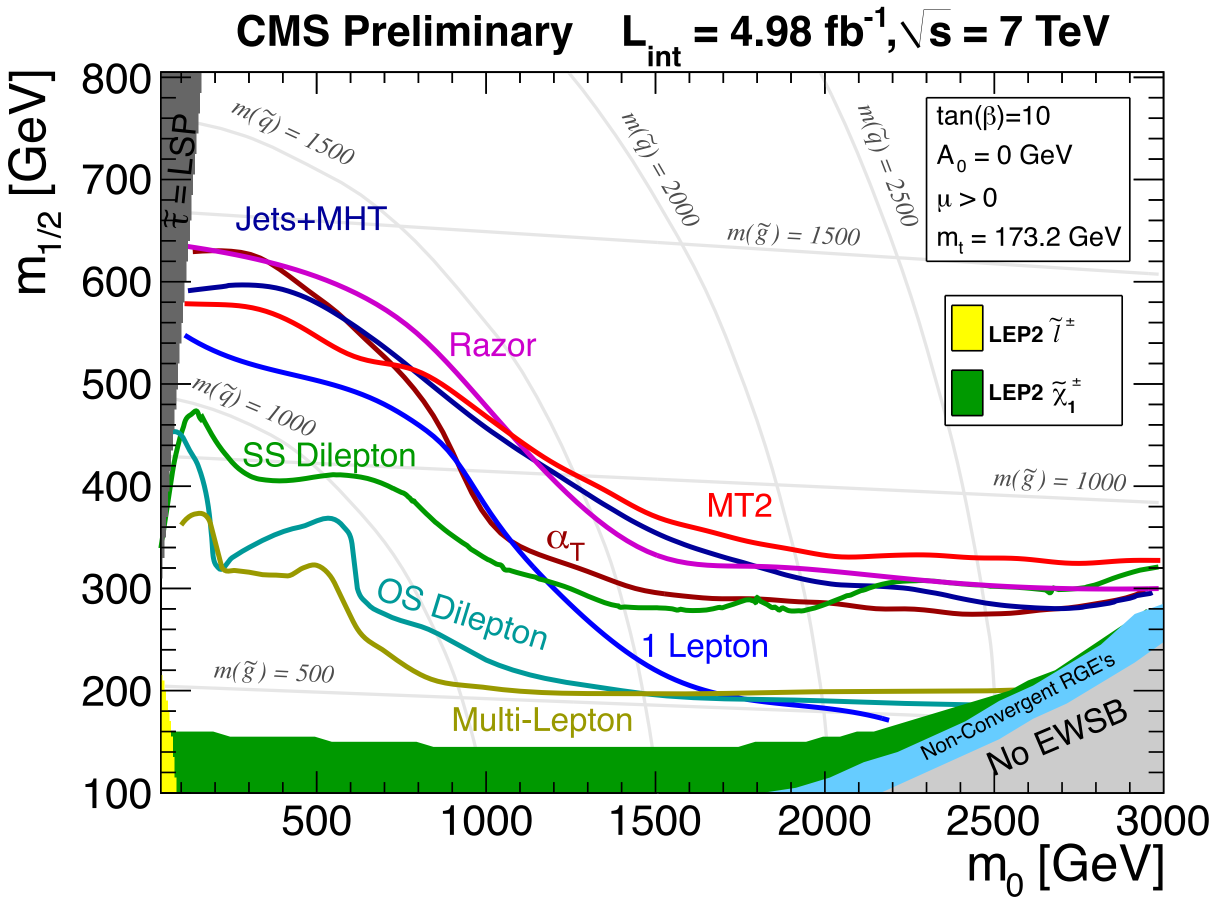
$m_0^2 \gg m_{1/2}^2$

Experimental signatures

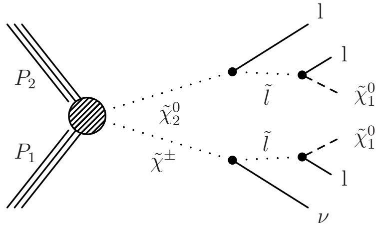
- Susy particles produced in pair (R-parity conservation)
- Decay chains via s-particles + ordinaly particles
- LSP escape undetected (→ MET!)
- Signatures with leptons are easier to detect

Search for Susy

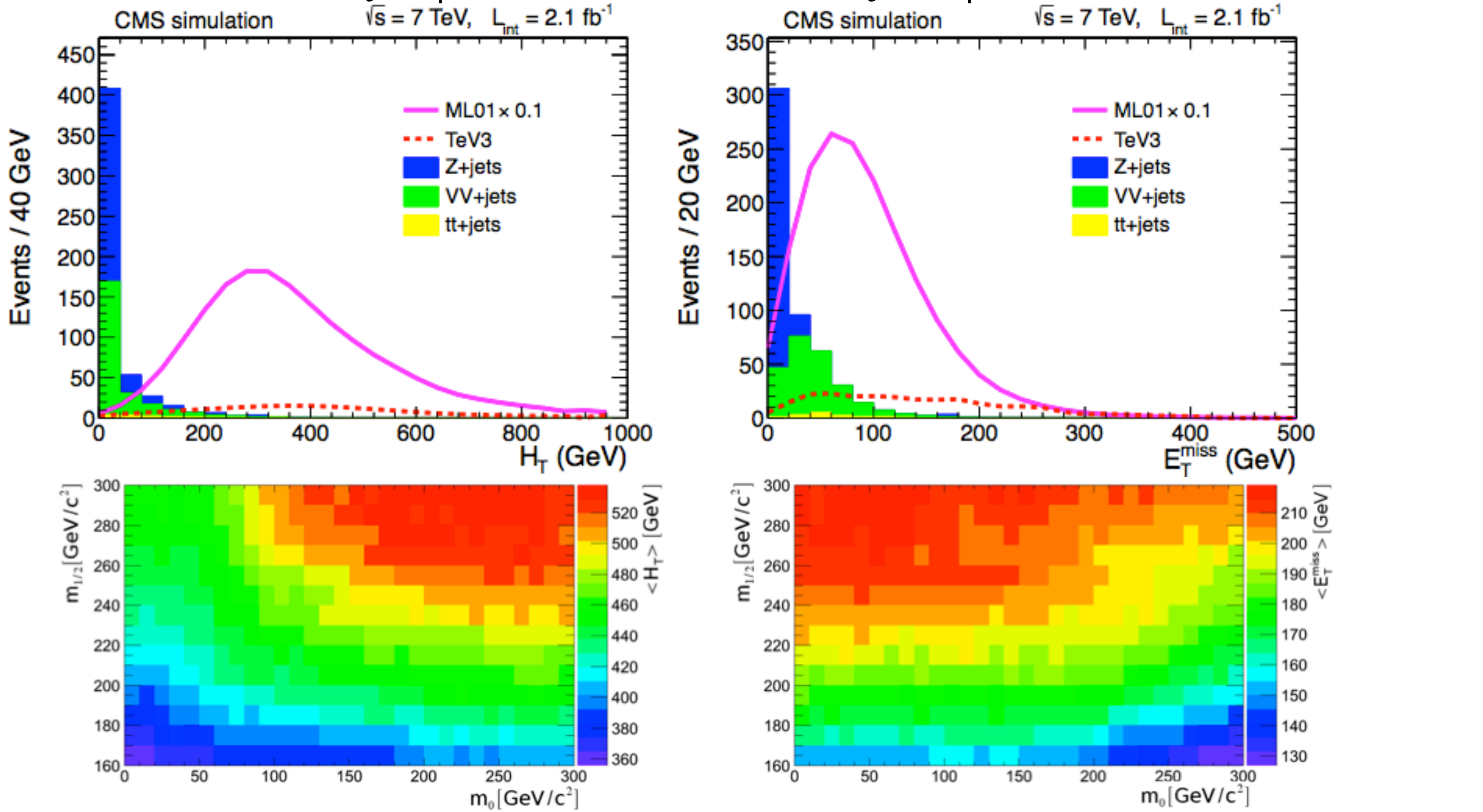
- So far no evidence for Susy particles
  - Limits have been set in the $m_0/m_{1/2}$ plane



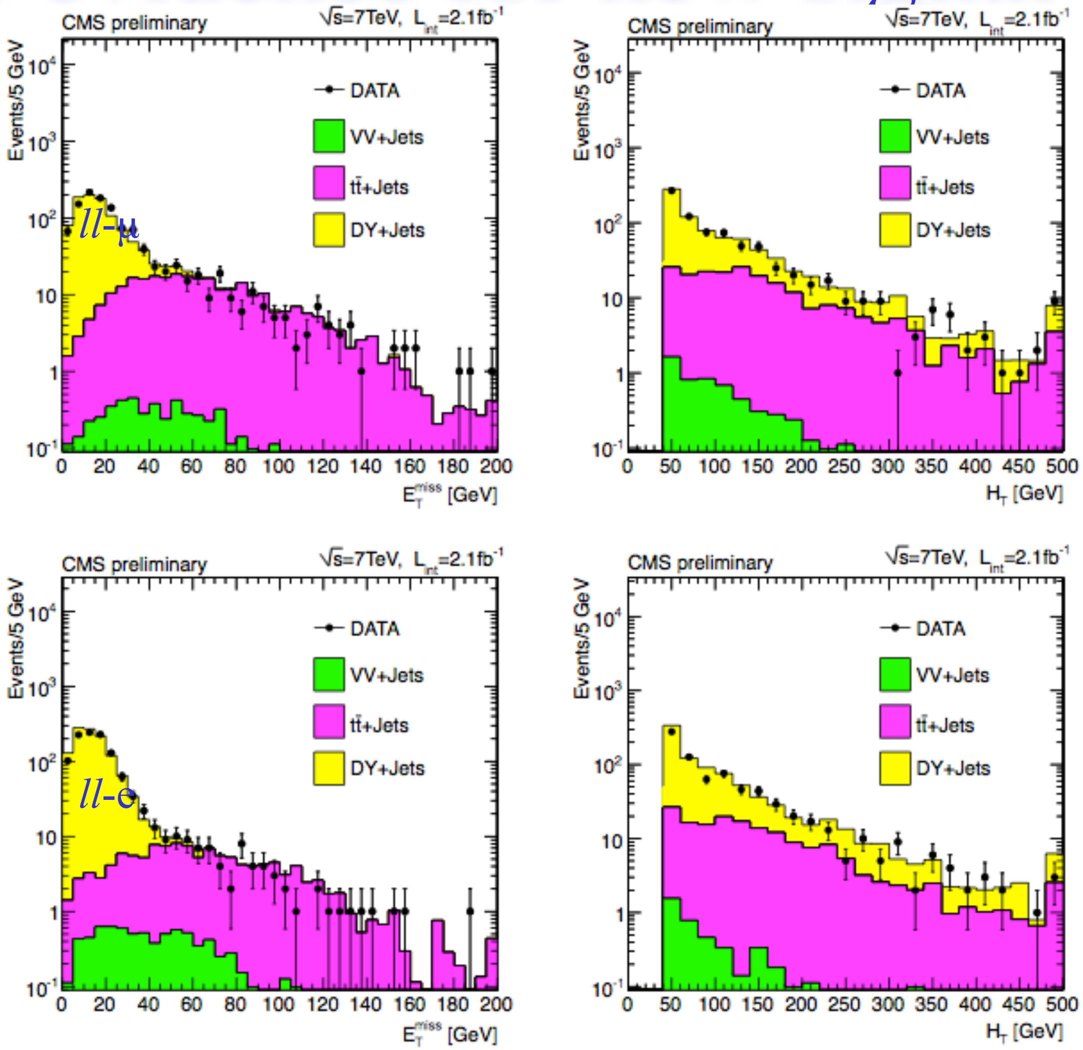
Easy case: multileptons



- Search for at least three leptons (e, μ, τ) plus MET or transverse hadronic activity H_T = sum of transverse jet E_T

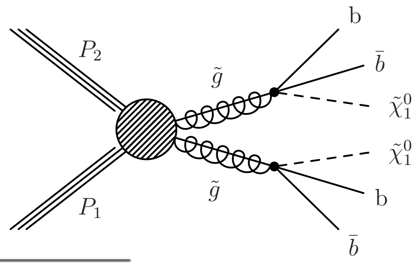


No evidence for new signal



- → Limits can be set in the $m_0/m_{1/2}$ plane

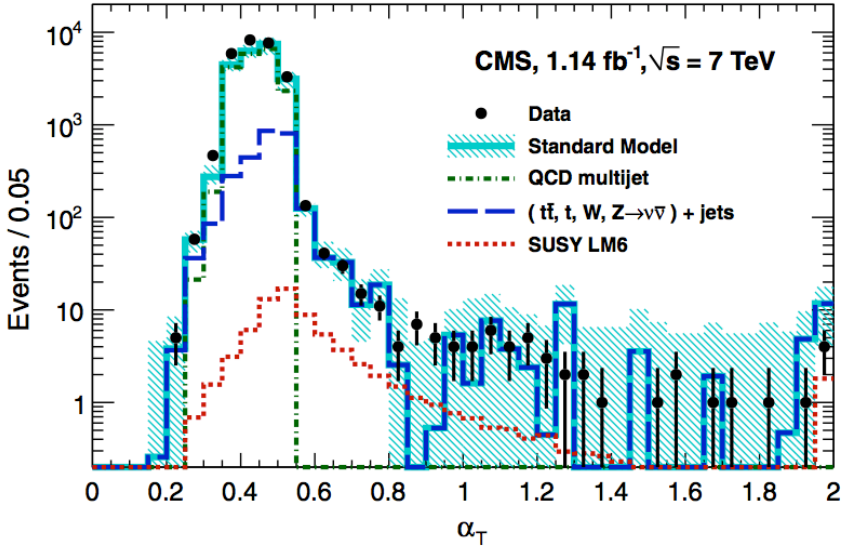
α_T variable (multijet)



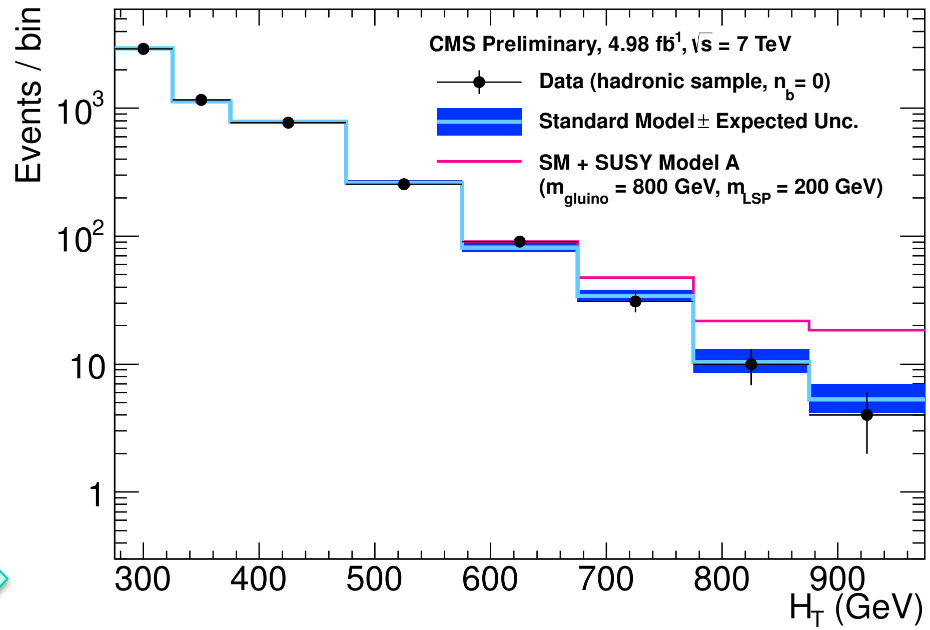
- In case of a two-jet event:

$$\alpha_T = \frac{E_T^{j_2}}{M_T} \quad , \quad M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2}$$

- Otherwise: cluster jets in order to minimize the E_T difference of the two



$\alpha_T > 0.55$



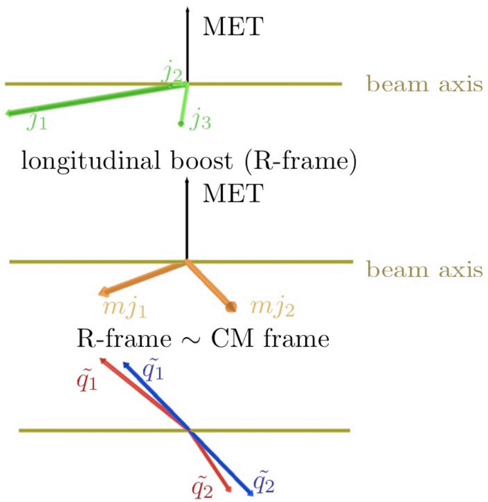
Razor variable (multijet)

- Heavy → LSP + jets
- Cluster entire event in two “megajets”
- Exploits kinematics differences with proper boost (CMS-SUS-11-008)

$$R \equiv \frac{M_T^R}{M_R}$$

$$M_R \equiv \sqrt{(p_{j_1} + p_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$



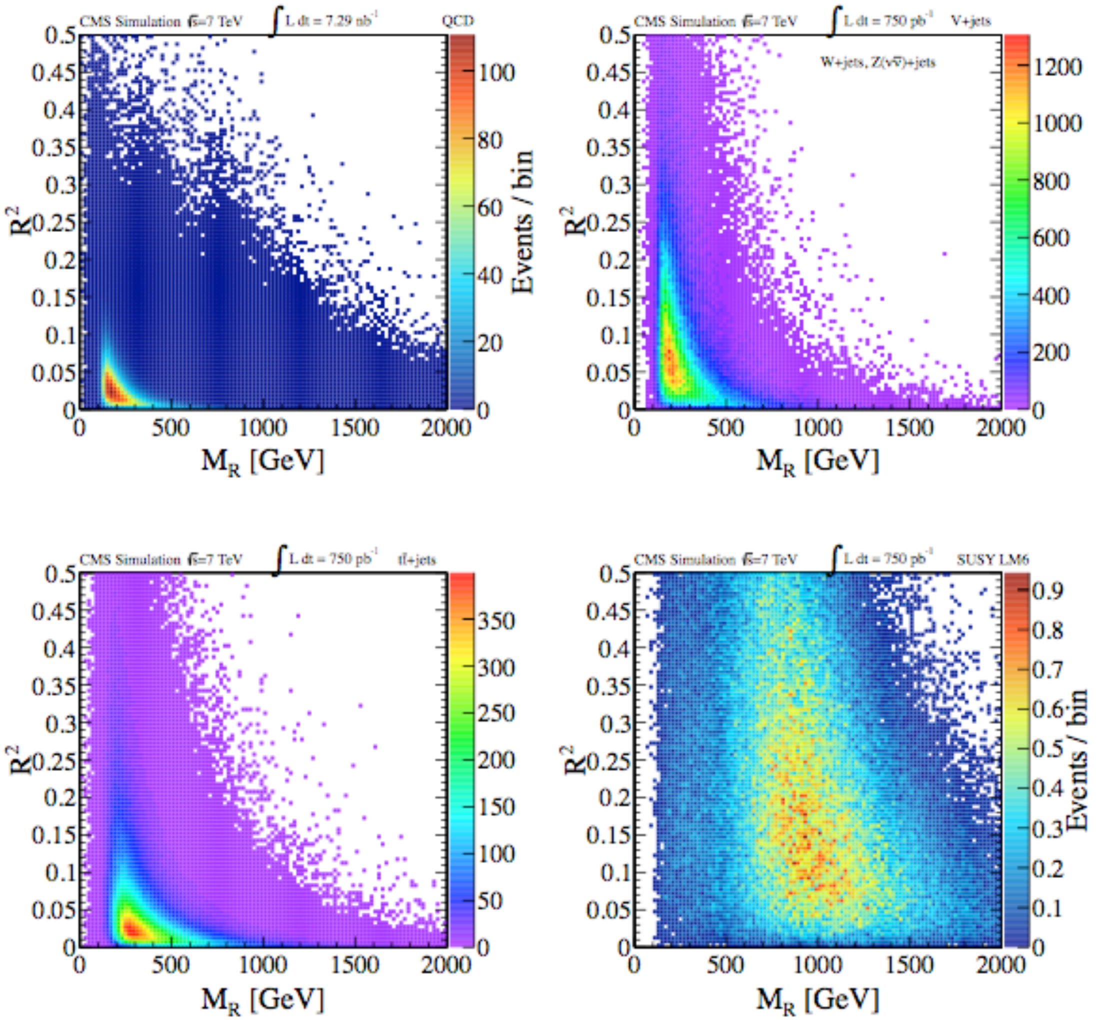
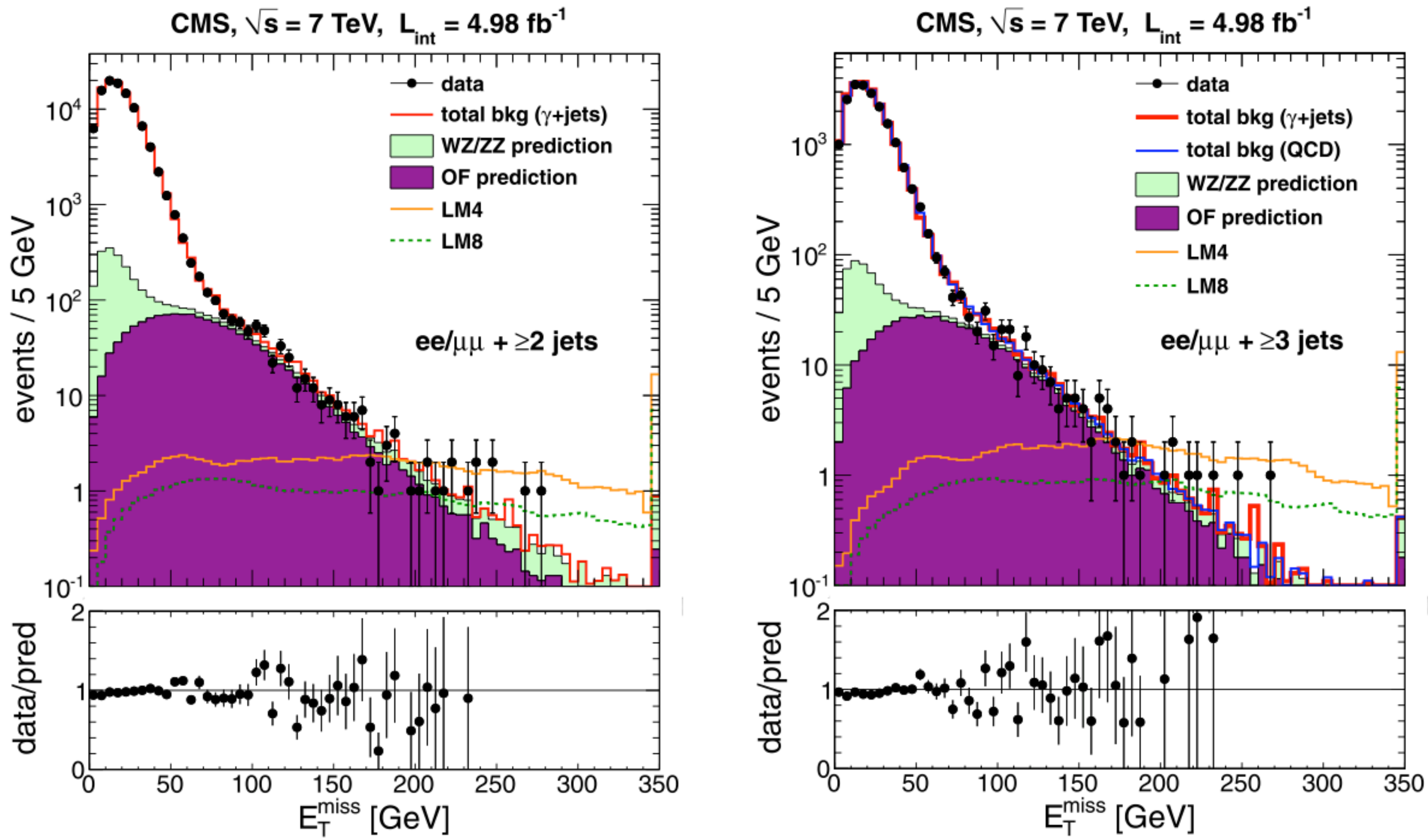


Figure 1: Scatter plot in the (M_R, R^2) plane for simulated events: (top left) QCD multijet, (top right) W+jets and $Z(\nu\bar{\nu}$+jets, (bottom left) $t\bar{t}$+jets, and (bottom right) the SUSY benchmark model LM6 [12] with M_Δ = 831 GeV. The yields are normalized to an integrated luminosity of $\sim$ 800 pb^{-1}, except in the QCD multijet case where we use the corresponding generated luminosity. The bin size is (20 GeV × 0.005).

JBZ

$$JZB = \left|\sum_{\text{jets}} \vec{p}_T\right| - |\vec{p}_T^{(Z)}| \approx |-\vec{E}_T^{\text{miss}} - \vec{p}_T^{(Z)}| - |\vec{p}_T^{(Z)}|$$

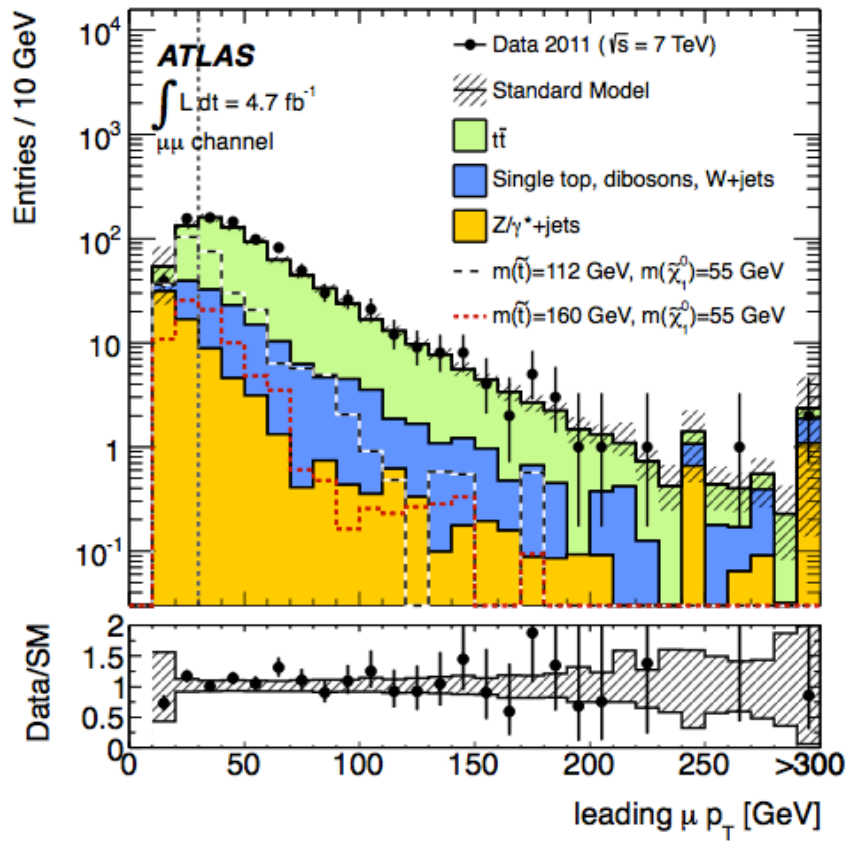
- Susy search in Z+jets+MET, e $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0$ Z



Stop search

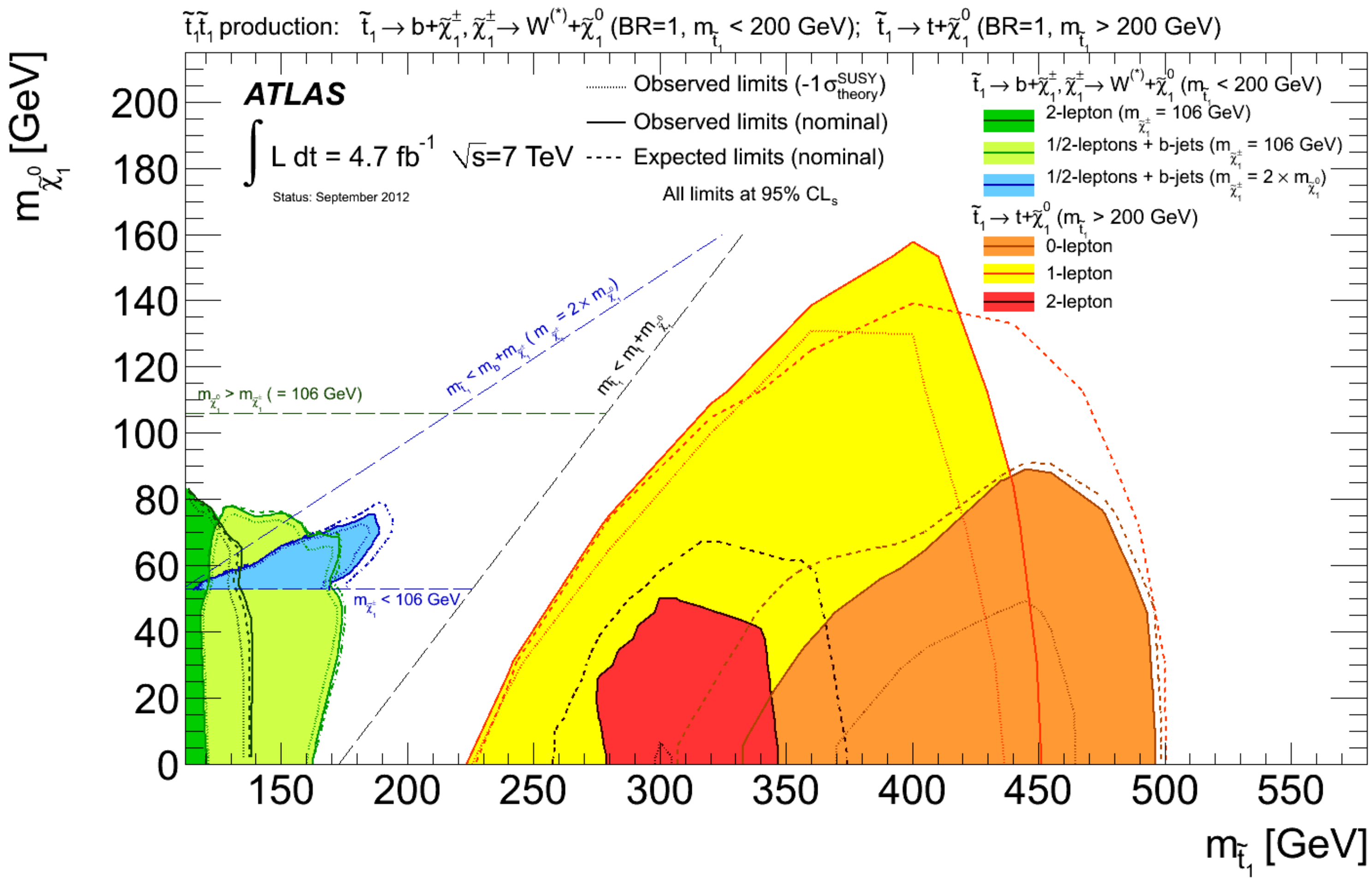
- Stop could be the lightest squark due to large mixing effect in the 3rd generation
- Stop can be produced in pairs, decaying in a tt pair plus neutralinos (LSP) with a sizeable cross section

Requirement	ee channel	$\mu\mu$ channel	$e\mu$ channel
		Signal Region	
lepton p_T	> 17 GeV	> 12 GeV	$> 17(12)$ GeV for $e(\mu)$
leading lepton p_T		< 30 GeV	
m_{ll}	> 20 GeV and Z veto		> 20 GeV
jet p_T		≥ 1 jet, $p_T > 25$ GeV	
E_T^{miss}		> 20 GeV	
$E_T^{miss,sig}$		> 7.5 GeV$^{1/2}$	
		Top Control Region	
lepton p_T	> 17 GeV	> 12 GeV	$> 17(12)$ GeV for $e(\mu)$
leading lepton p_T		> 30 GeV	
m_{ll}	> 20 GeV and Z veto		> 20 GeV
jet p_T		≥ 2 (b)jets, $p_T > 25$ GeV	
b-jet p_T		≥ 1 b jet, $p_T > 25$ GeV	
E_T^{miss}		> 20 GeV	
$E_T^{miss,sig}$		> 7.5 GeV$^{1/2}$	
		Z Control Region	
lepton p_T	> 17 GeV	> 12 GeV	n/a
leading lepton p_T	< 30 GeV		n/a
m_{ll}	> 81 GeV and < 101 GeV		n/a
jet p_T	≥ 1 jet, $p_T > 25$ GeV		n/a
E_T^{miss}	> 20 GeV		n/a
$E_T^{miss,sig}$	> 4.0 GeV$^{1/2}$		n/a



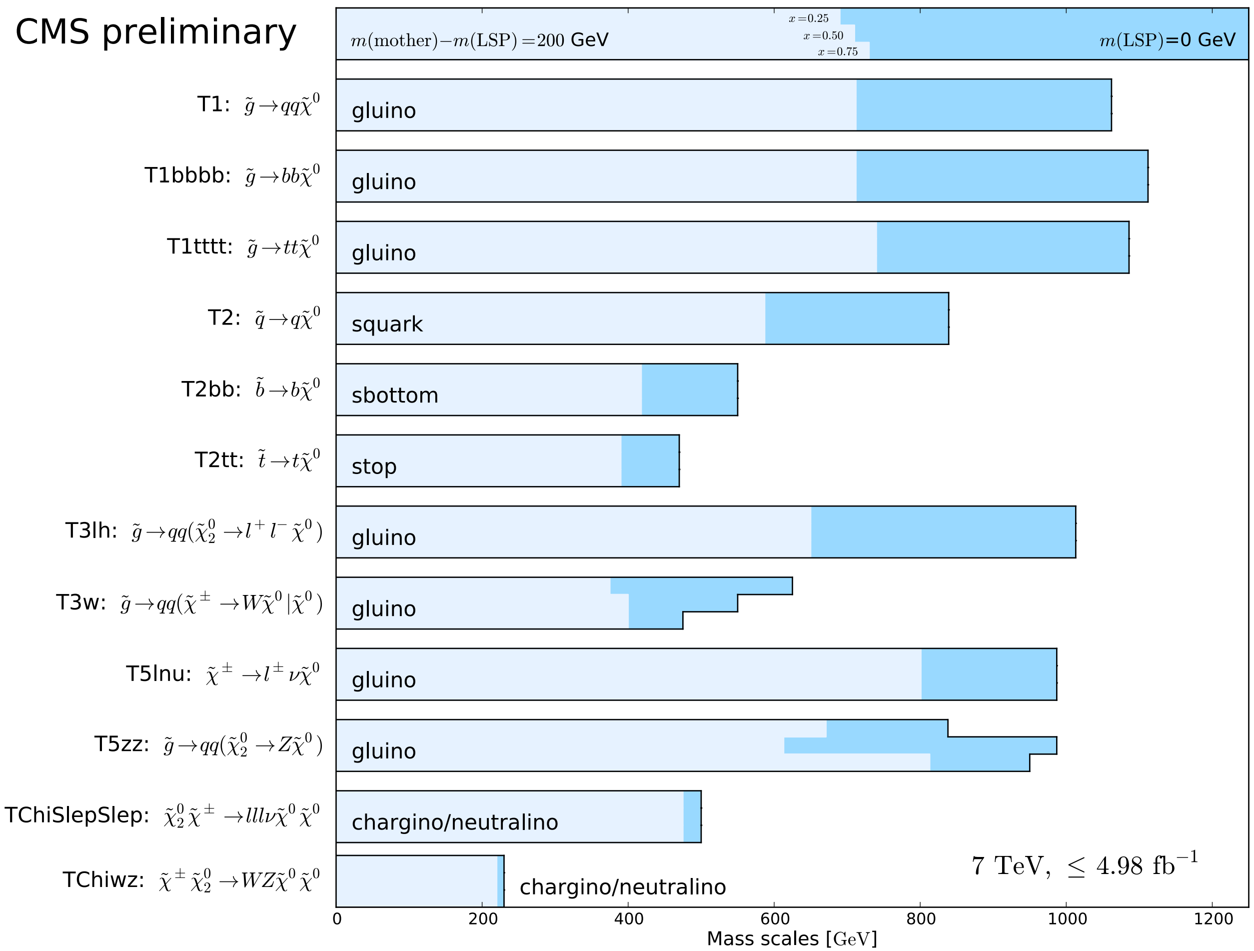
Direct searches

- Direct limits on stop

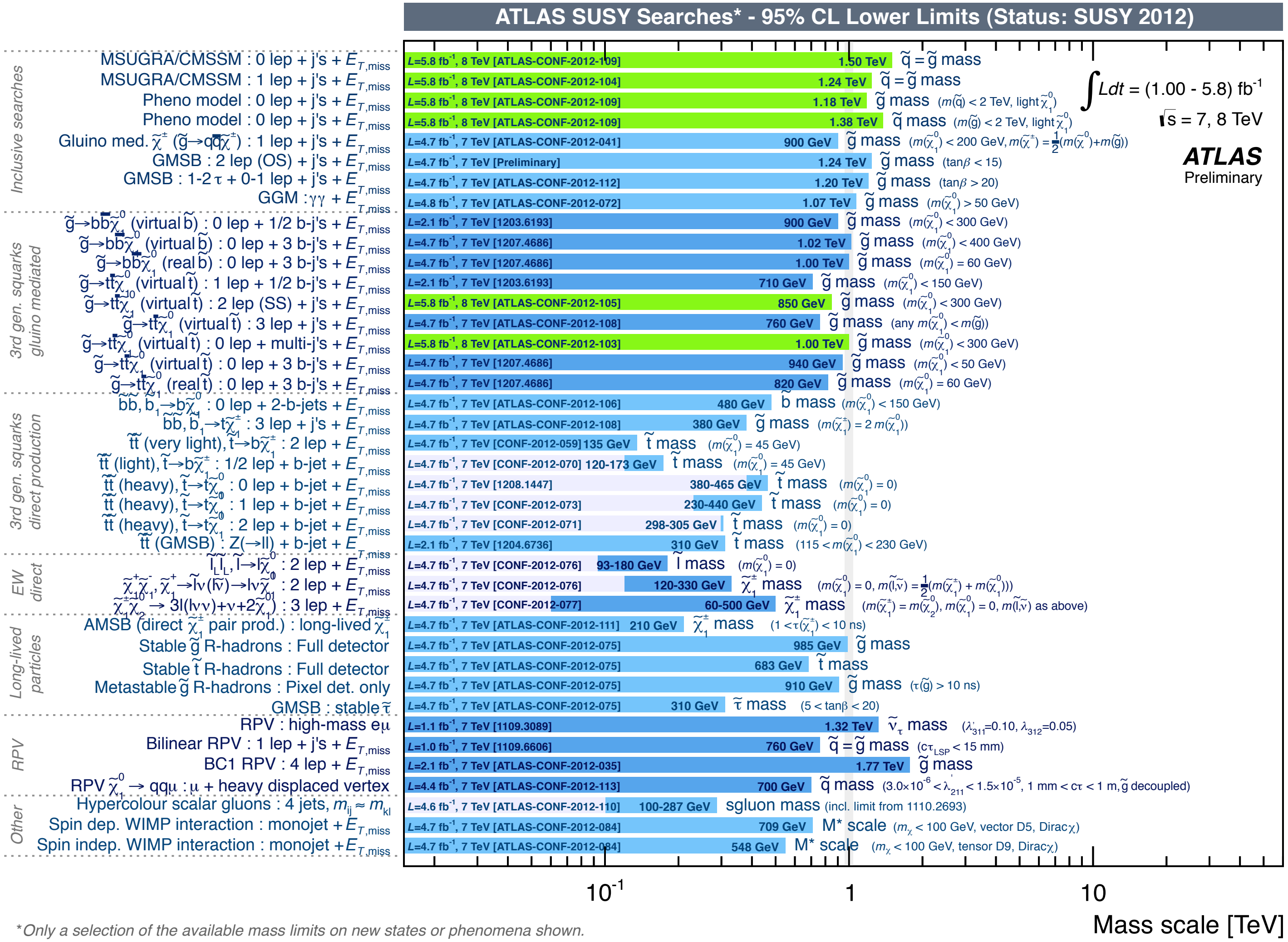


Sparticle mass limits (CMS)

- Exact values depend on various assumptions



Sparticle mass limits (ATLAS)



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Susy summary

- No evidence of Susy particles so far
- No hint of either a second neutral Higgs or charged Higgs
- If Susy exists:
  - either it hides on some special corner of its parameters “phase space”
  - Or it should be less trivial than the assumed MSSM/mSUGRA

Extra dimensions

- During ’20s Kaluza and Klein proposed a model to unify gravity and elecromagnetism by adding fifth space dimension

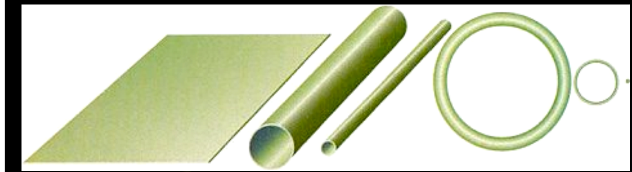
4x4: Einstein’s equations

4x1: Maxwell’s equations

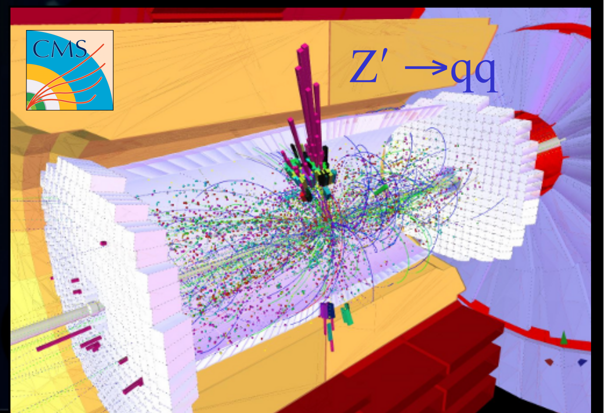
$$\hat{g}^{\hat{\mu}\hat{\nu}} = \begin{pmatrix} g^{\mu\nu} & -A^{\mu} \\ -A^{\nu} & -\frac{1}{\phi} + A^2 \end{pmatrix}$$

- If the fifth dimension is “compactified”, it would no longer be visibiel
- Byproduct of compactification: the electric charge is quantified!
- The model was abandoned because of difficulties with quantum description, now revisited in more complex contexts

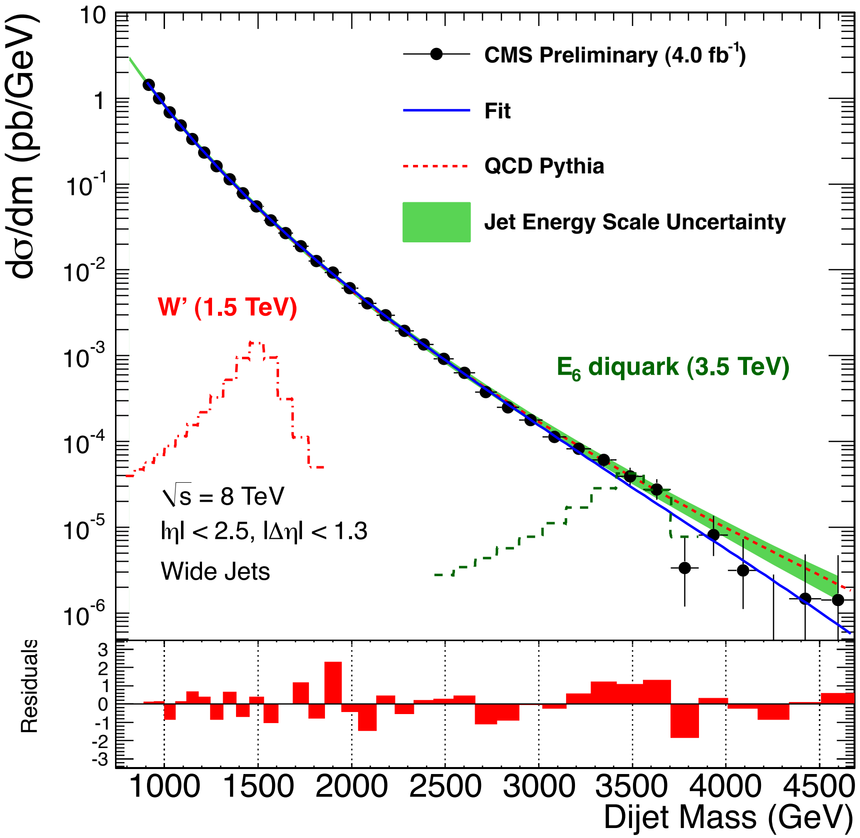
Extra dimensions

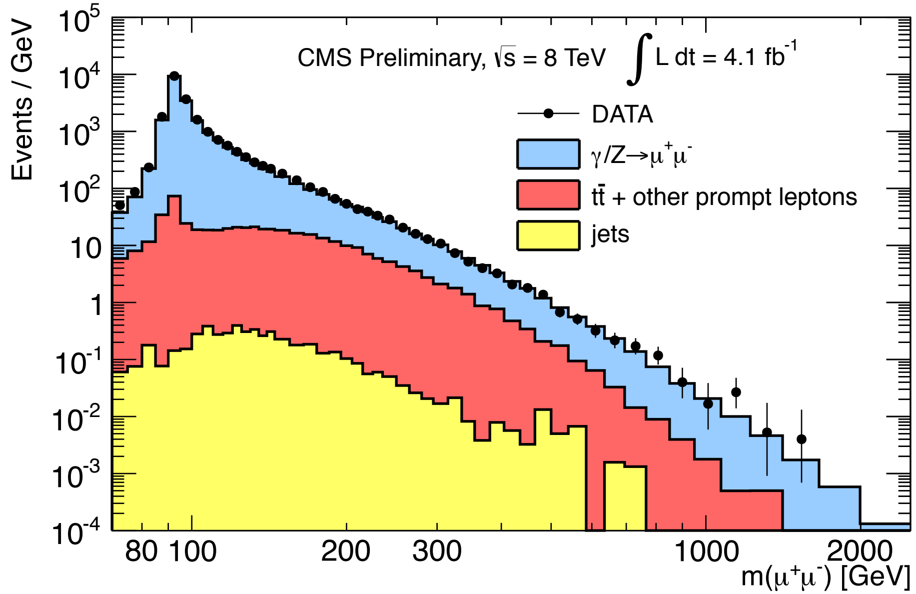


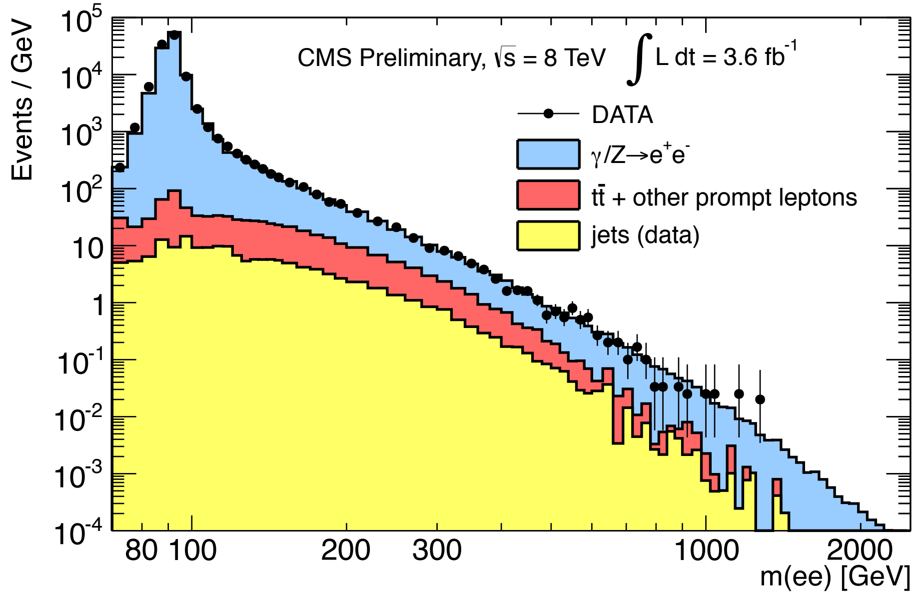
- Particles excitation by “curling” around the compactified dimension give raise to a spectrum of new particles
- Search for heavy resonances decaying into pairs of leptons or jets
- $m_n^2 = m_0^2 + n^2/R^2$
- DM candidates could be excitations of a standard particle?



Search for dijet/dilepton res.

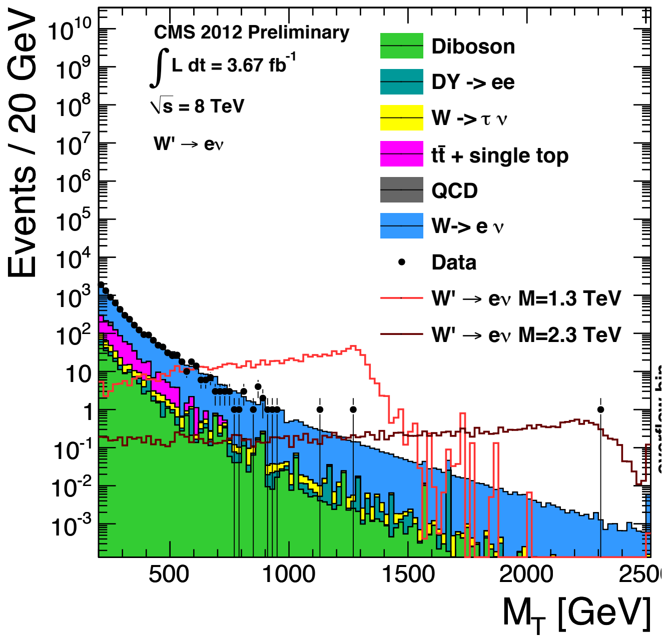


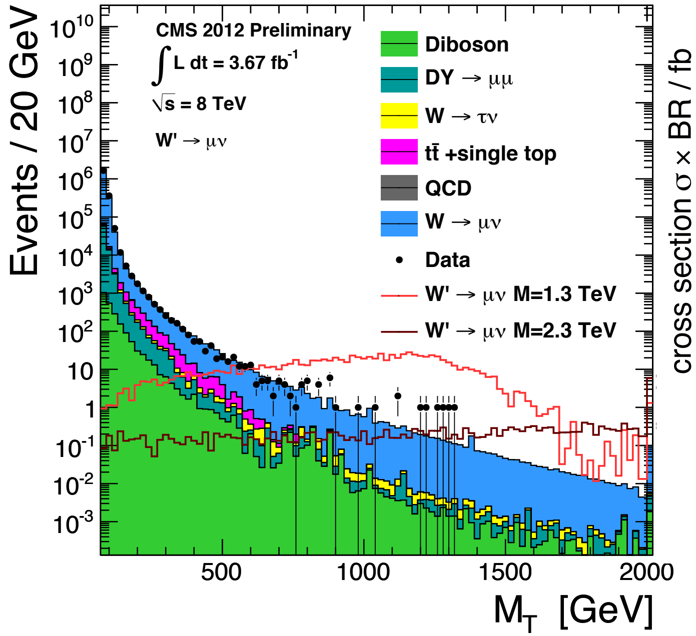


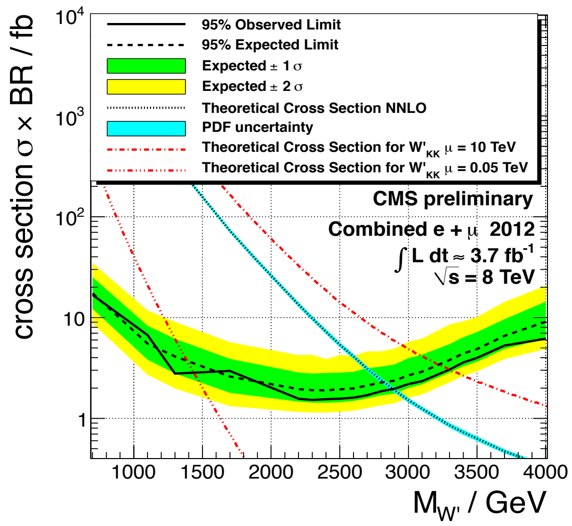


- Nothing found at LHC so far

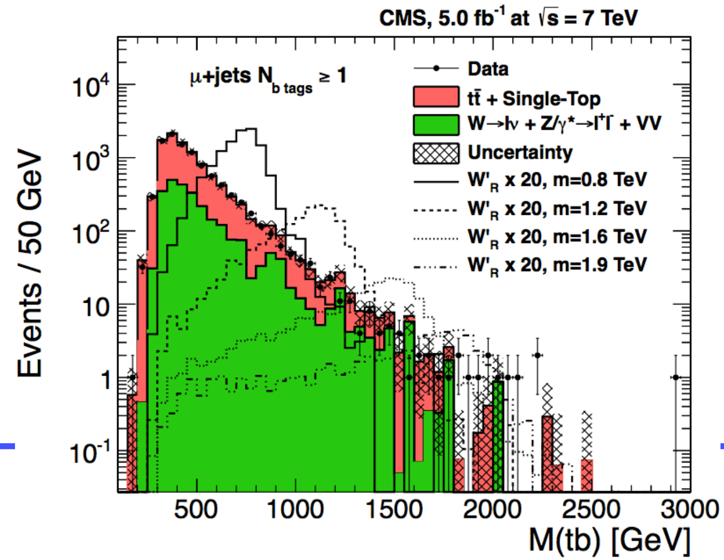
Search for heavy W'







Also searched for in W'→tb,
Similar to SM single-top production
in the s channel

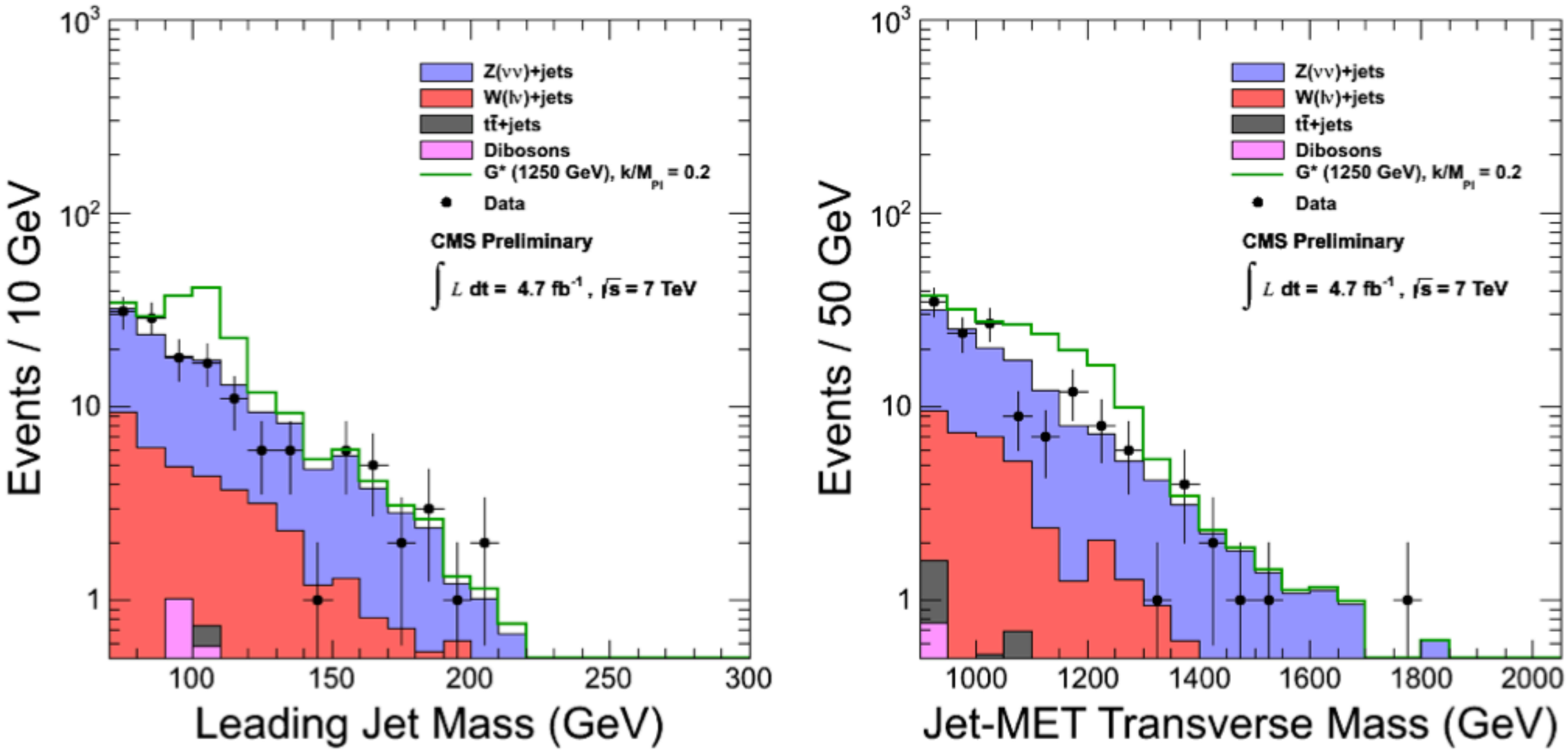


Extra dimensions and gravity

- Extra dimension could also explain the hierarchy of plank scale vs EWK scale
- Gravity weaker because it propagates in more dimensions
- EWK world = a brane in a higher dimensional space (Arkani-Hamed, Dimopolous, and Dvali (ADD))
  - Gauss law: Planck scale of gravity in four dimensions (M_{Pl}) related to a fundamental Planck scale in $4 + n_{ED}$ dimensions (M_D) according to the following relation: $M_{Pl}^2 \approx M_D^{2+n_{ED}} \times R^{n_{ED}}$
- Randall-Sundrum (RS) model (5D) predicts a detectable graviton KK excitation with several possible decays (e.g.: $G^* \rightarrow ZZ$, ff, …)

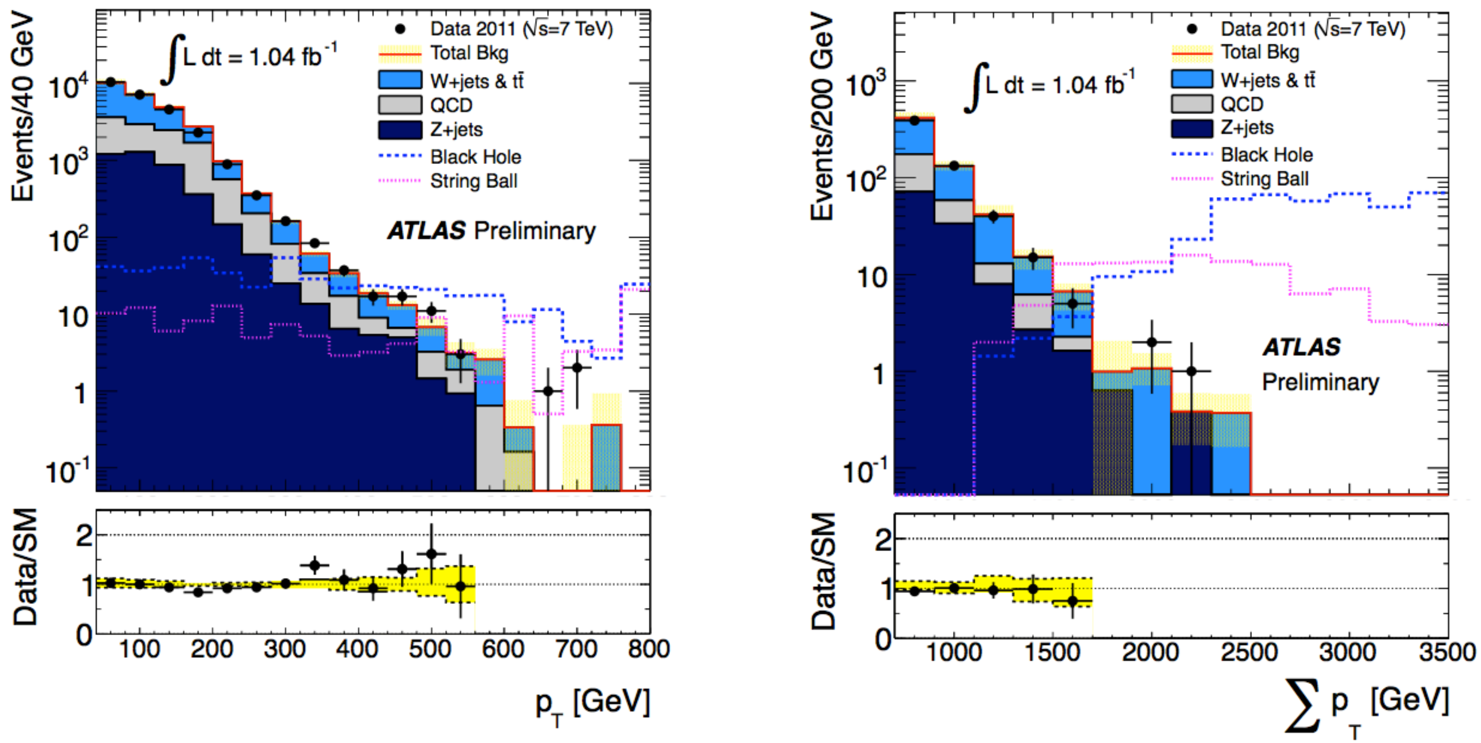
RS graviton* (G*→ZZ→qqνν)

- Signal = excess peaking at Z mass (jj) and G* mass (ll + MET)



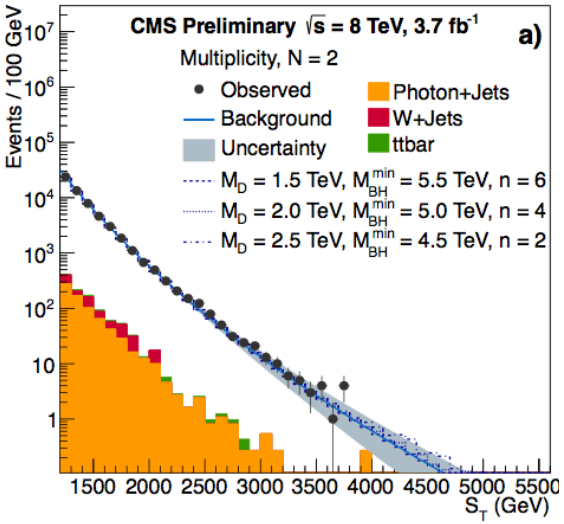
Black holes

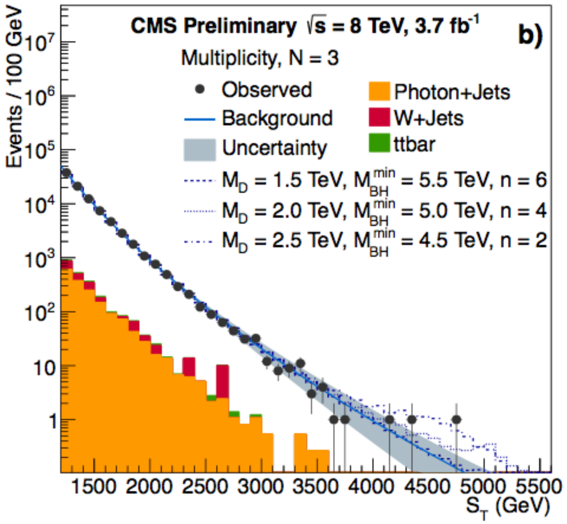
- BH/string balls may be produced, according to some models, at LHC
- Evaporation (Hawking's radiation) results in emission of SM particle with a "democratic" distribution
- Signature: events with jets and leptons
- No signal found, limits set in the parameter space

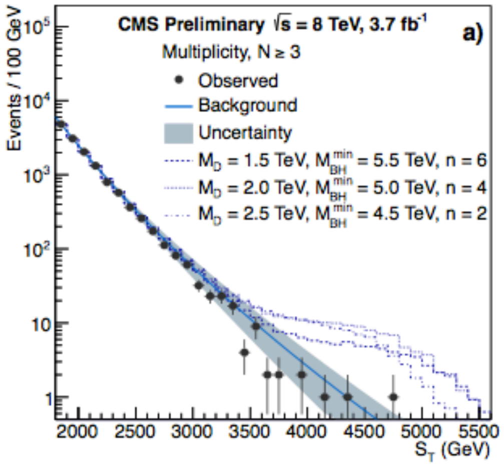


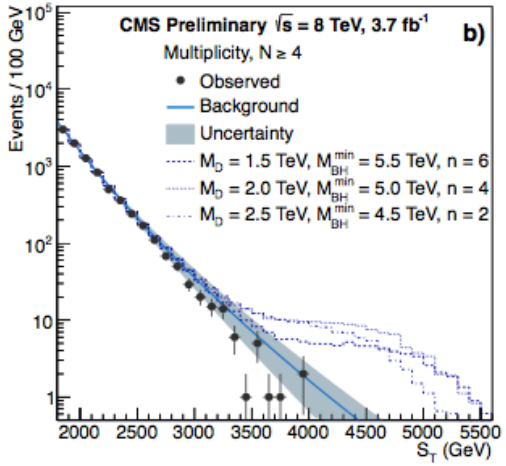
CMS: S_T

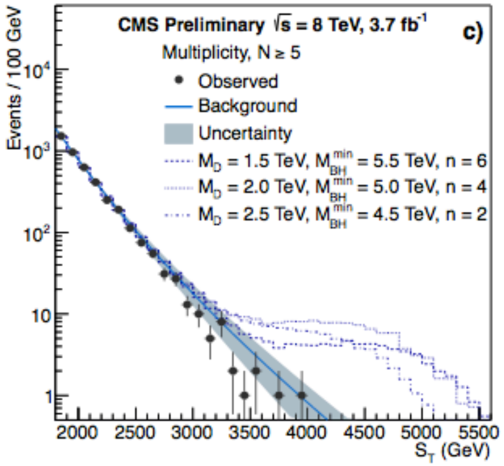
- S_T = scalar sum of p_T of individual selected objects:

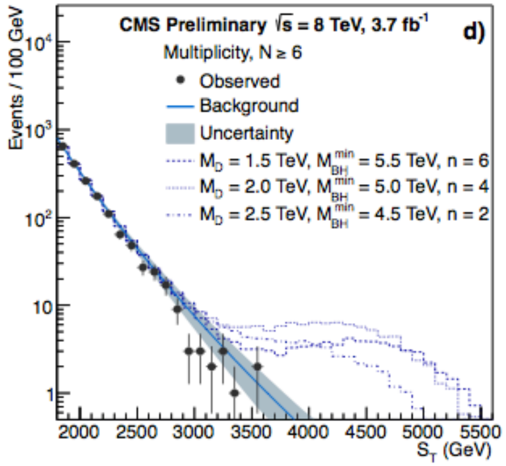


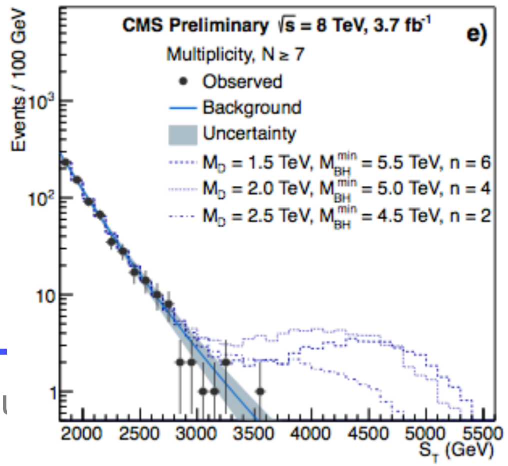


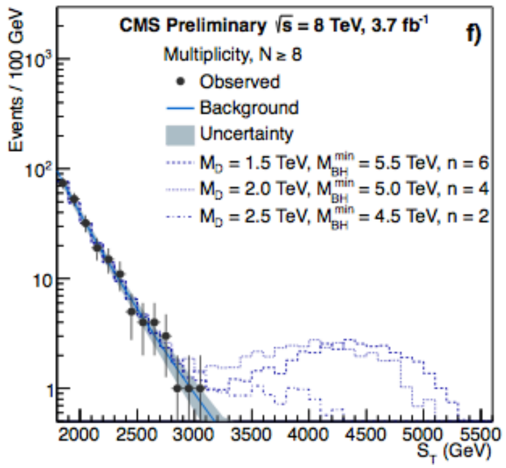






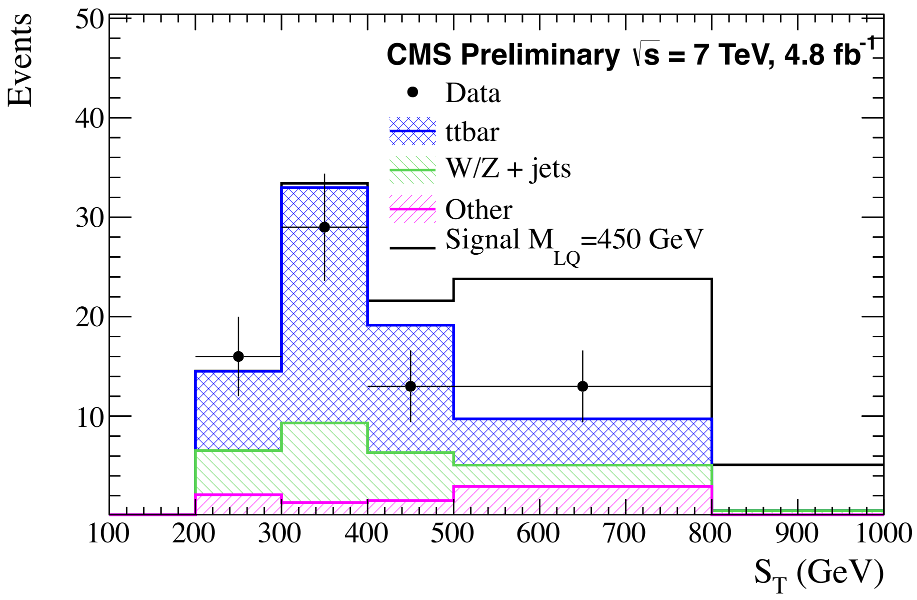


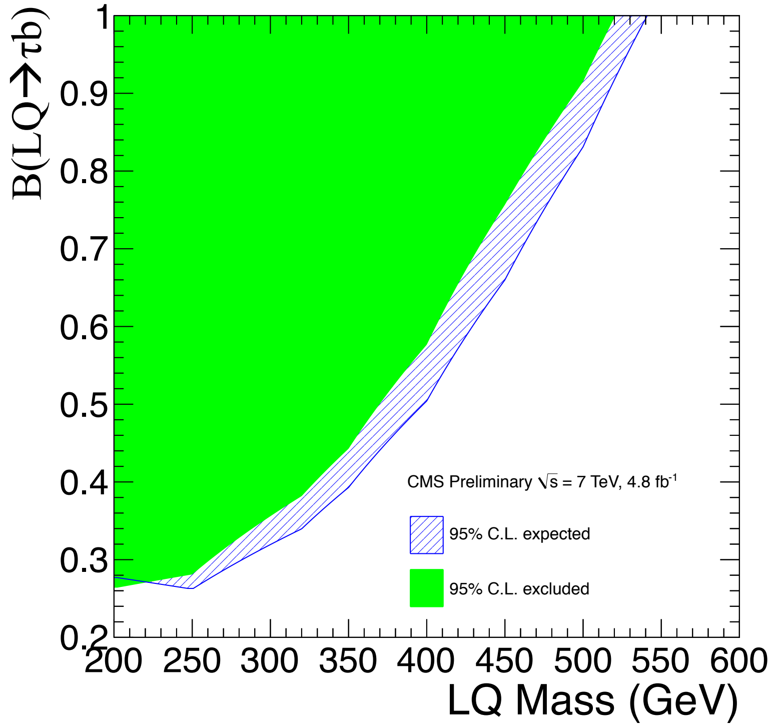




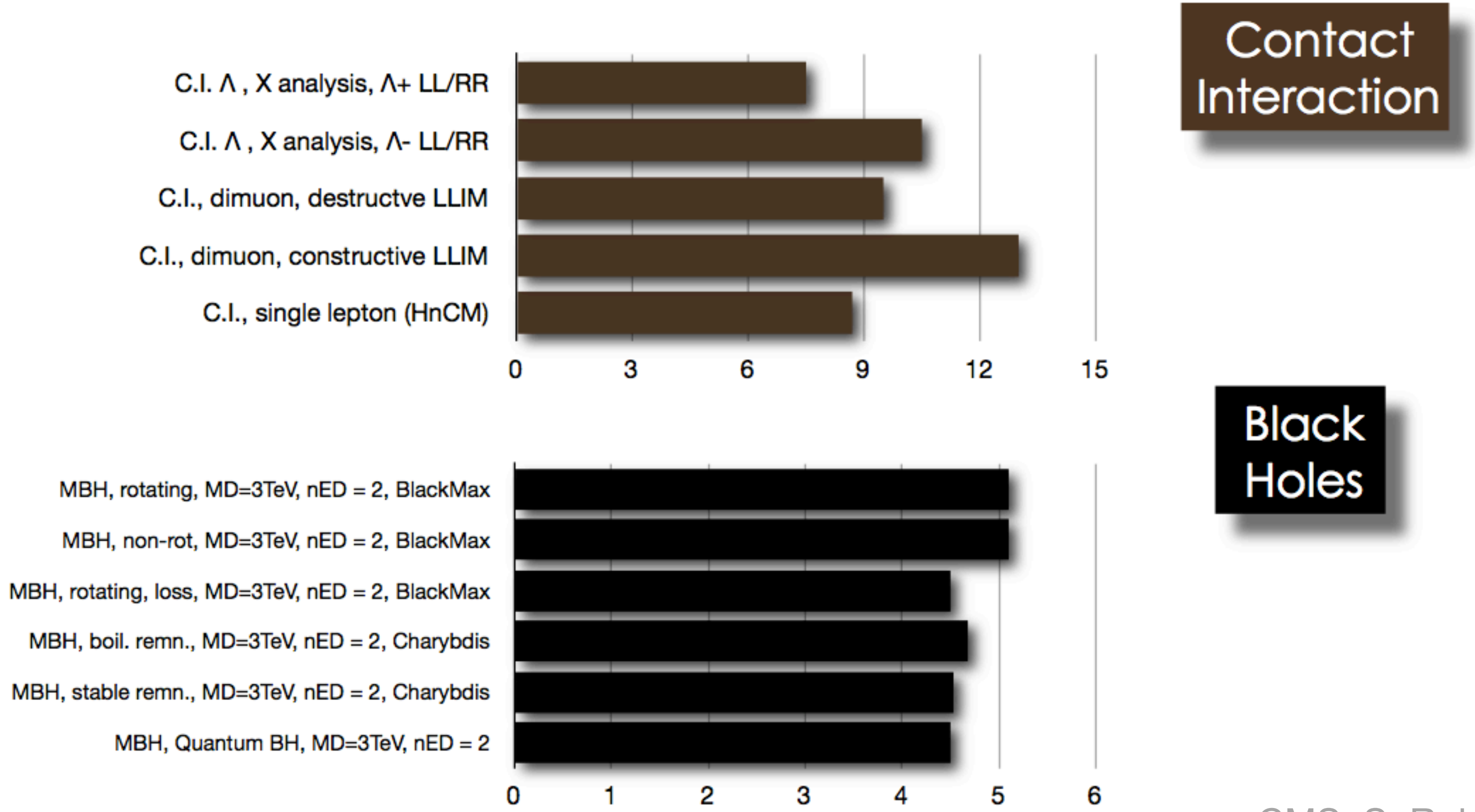
Leptoquarks

- GUT models (SU(5), SO(10)) and technicolor-composite models predict new bosons that couple to both leptons and quarks
- Produced in pairs via gg fusion or qq annihilation
- Search performed in the 3rd generation: LQ → τb (one tau decys to e or μ, the other to hadrons)

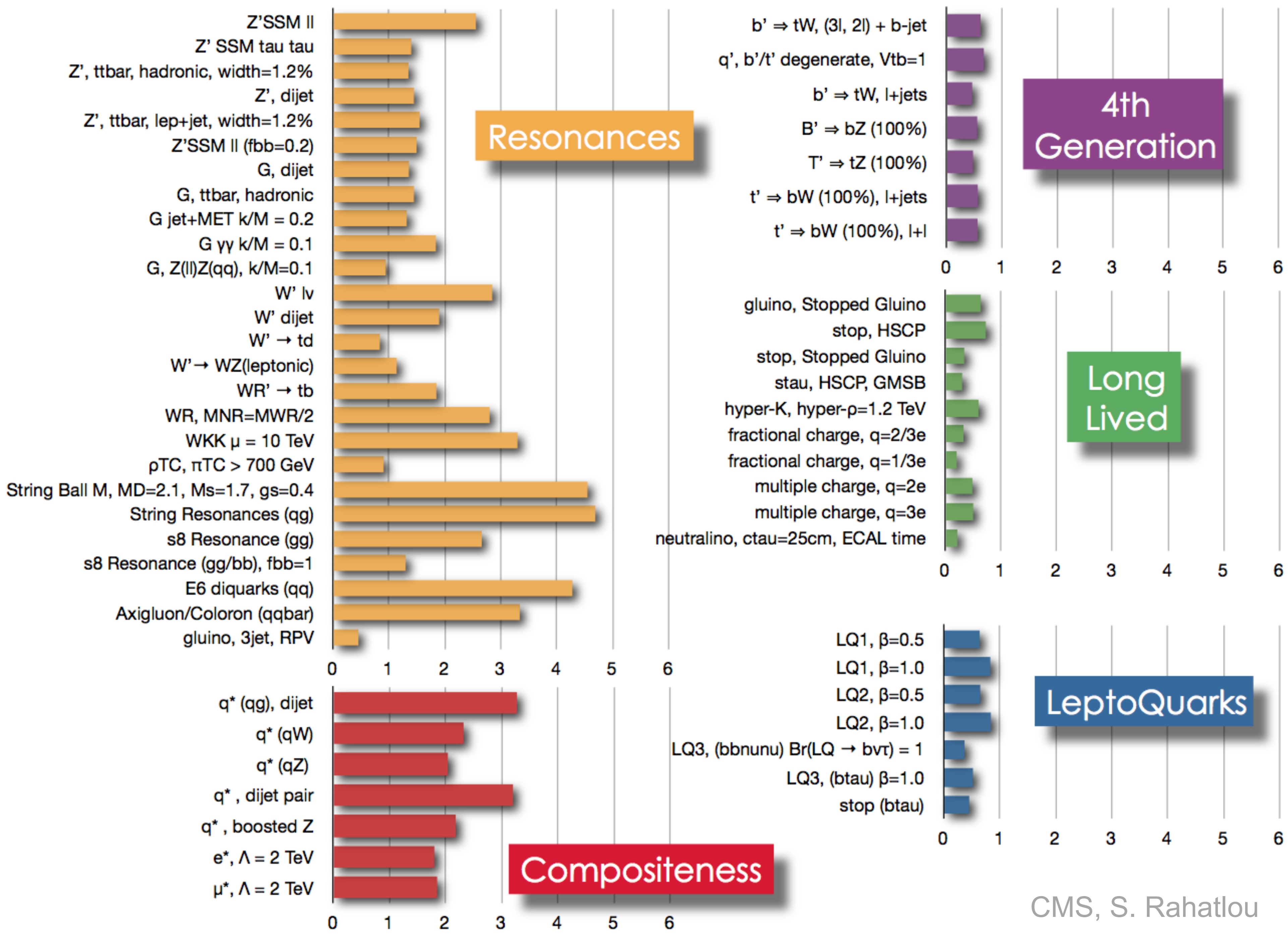




Exotica mass limits (CMS)



CMS, S. Rahatlou



Resonances
Z'SSM ll
Z' SSM tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(ll)Z(qq), k/M=0.1
W' lν
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Ball M, MD=2.1, Ms=1.7, gs=0.4
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
0 1 2 3 4 5 6
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0 1 2 3 4 5 6
4th Generation
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t' ⇒ bW (100%), l+jets
t' ⇒ bW (100%), l+l
0 1 2 3 4 5 6
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
0 1 2 3 4 5 6
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbnunu) Br(LQ → bντ) = 1
LQ3, (btau) β=1.0
stop (btau)
0 1 2 3 4 5 6
CMS, S. Rahatlou

Exotica mass limits (ATLAS)

Conclusions

- No hint of new physics found at LHC
- Simple Susy model excluded in a large fraction of the parameter space
  - … though "large fraction" depends on a "metrics" of the parameter space
- The search goes on, improvements are expected with larger data samples and, in next future, with the increase in center-of-mass energy

References

- A Supersymmetry primer, S. P. Martin, http://arxiv.org/abs/hep-ph/9709356