Models of Dark Matter and constraints from the Large Hadron Collider

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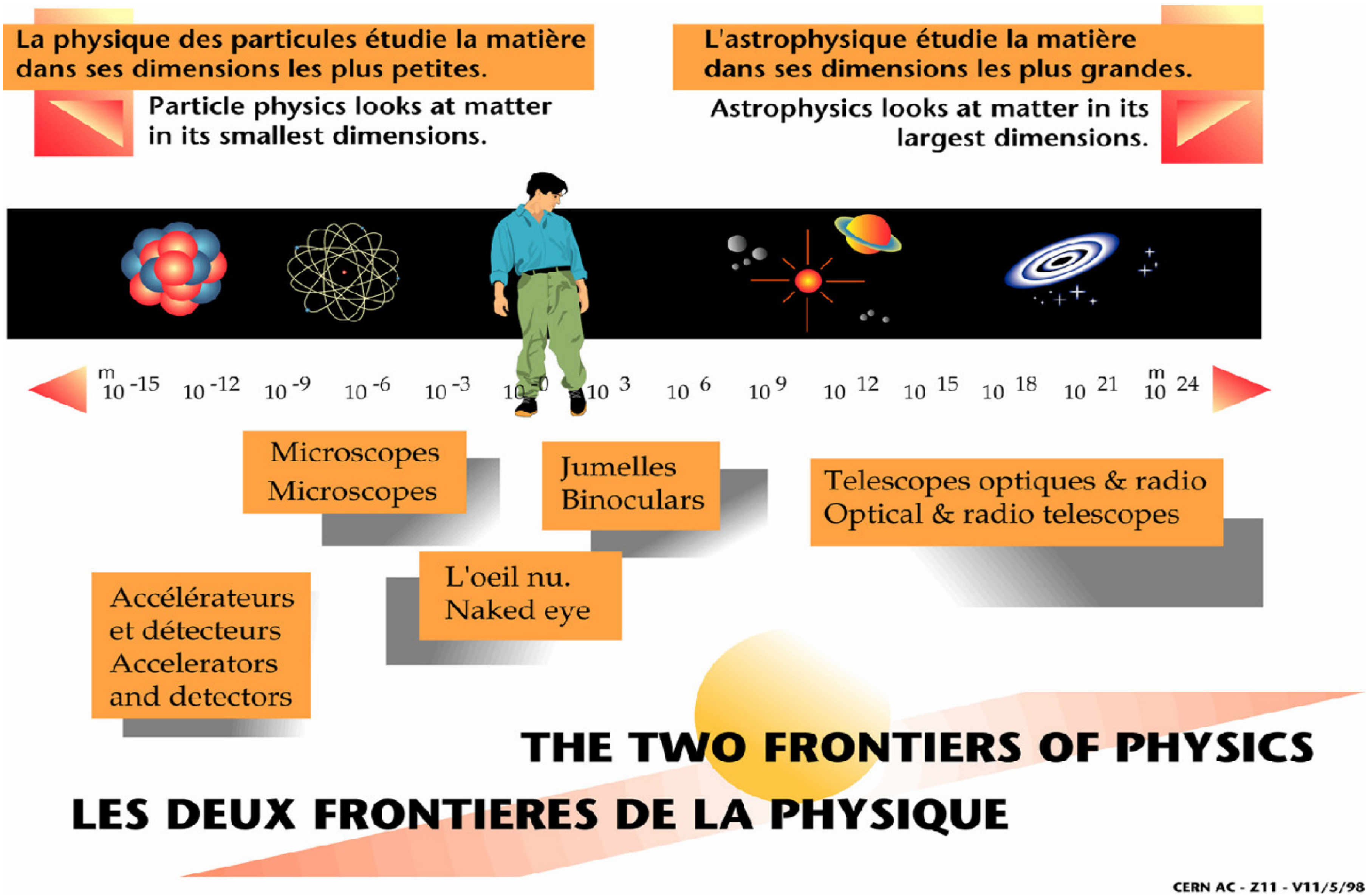
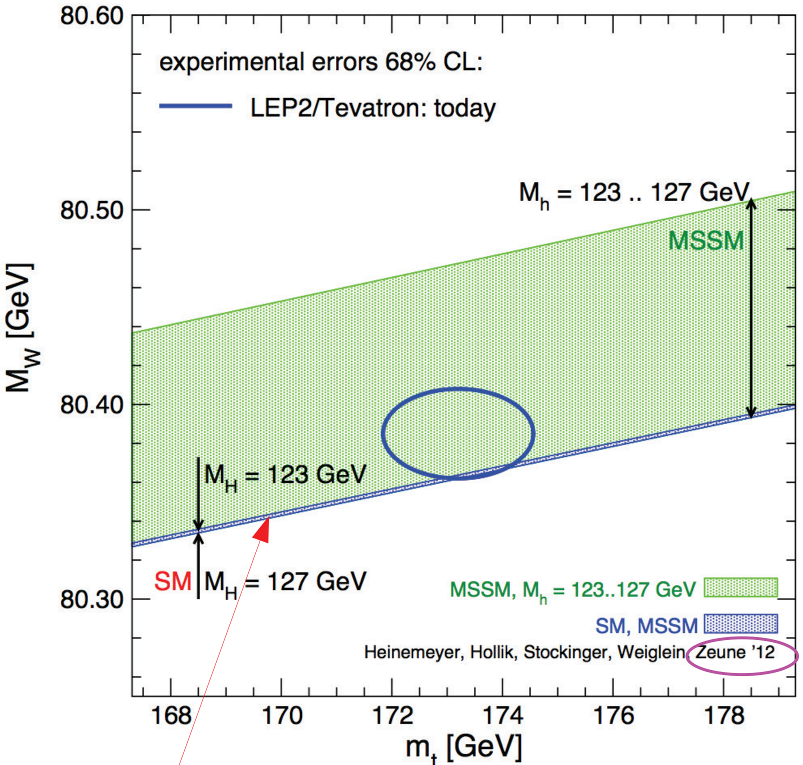
Overview

- Where do we stand and why do we want to extend the Standard Model
- Example: supersymmetry
- Dark Matter at the LHC
  - Monojet and monophoton searches
  - SUSY searches and implications for model building
- Conclusions

Where do we stand

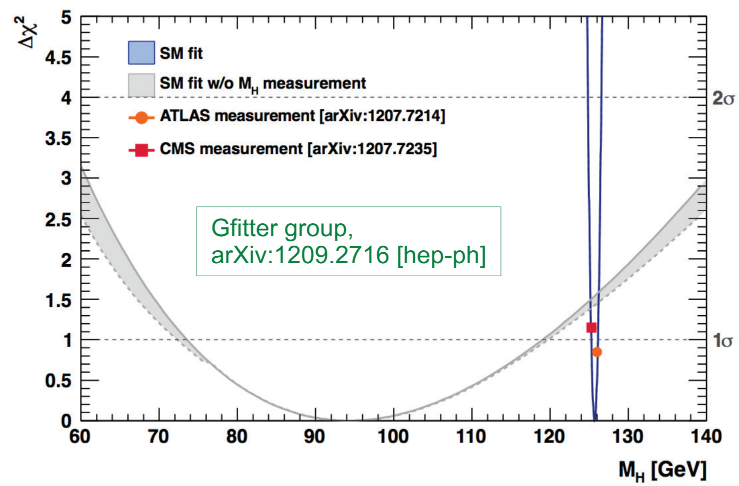


W boson mass



In the context of the standard model, the mass of the new boson discovered by ATLAS+CMS is inside this blue band.

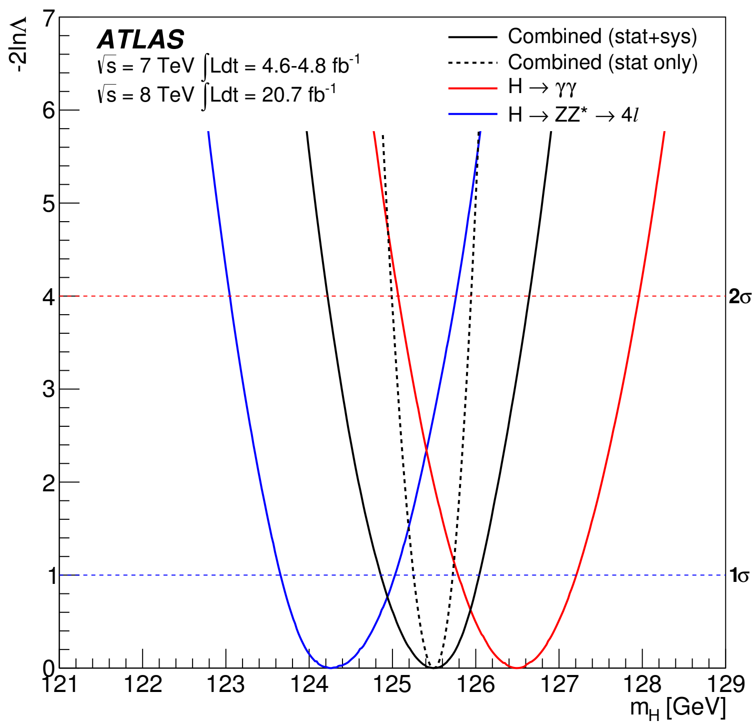
Comparison of indirect constraints on the Standard Model Higgs boson and the direct measurements of the mass of the new boson discovered by ATLAS and CMS:



Consistent at the 1.3 σ level.

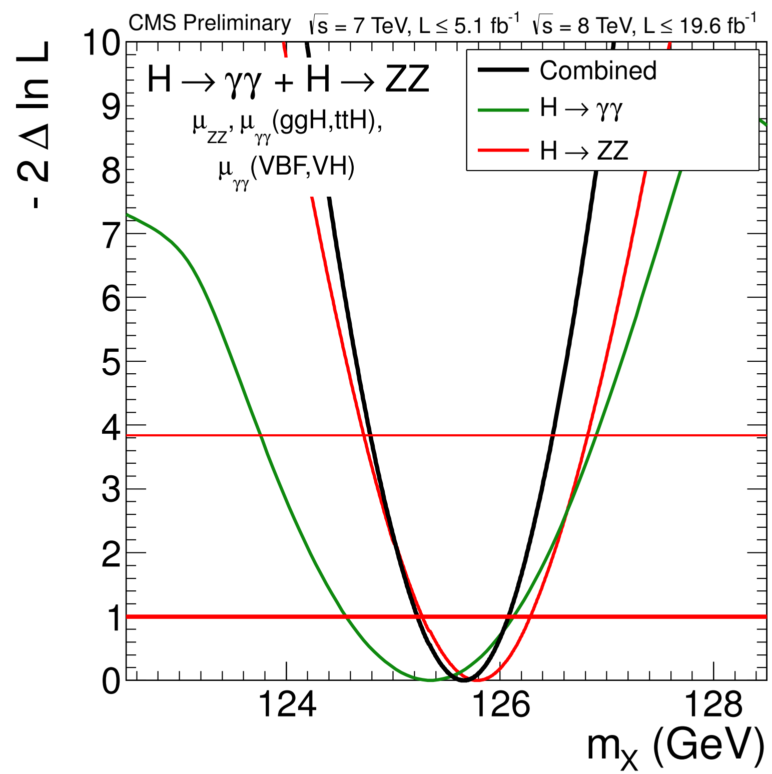
Where do we stand: Higgs results in a nut-shell, I

ATLAS, arXiv:1307.1427



$$M_H = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{sys}}\ \text{GeV}$$

CMS, CMS-PAS-HIG-13-005

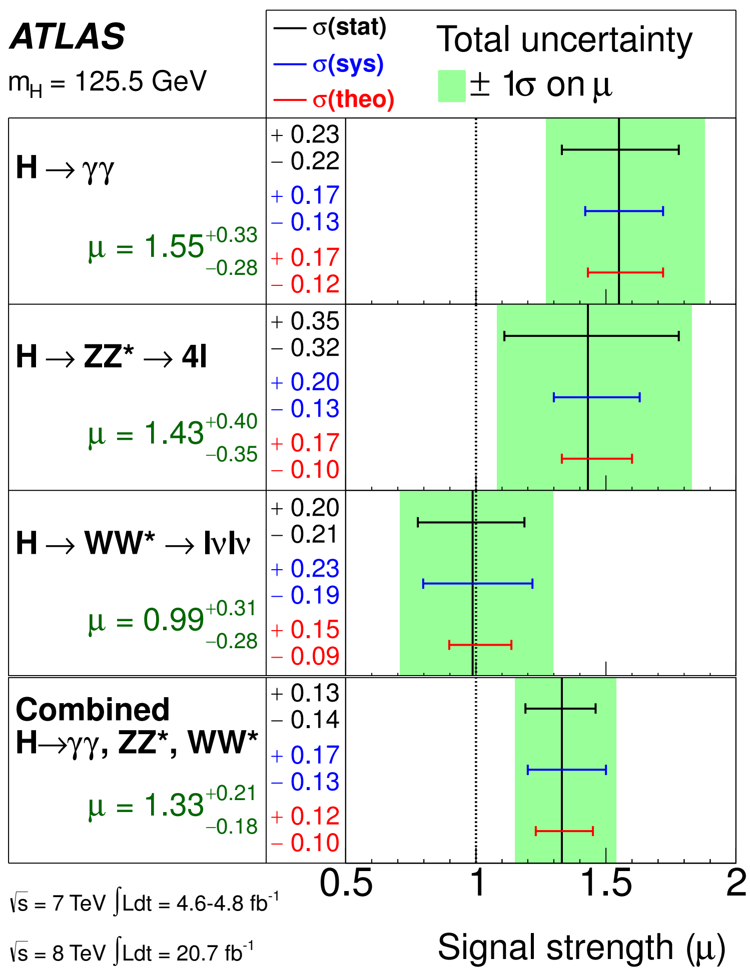


$$M_H = 125.7 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}\ \text{GeV}$$

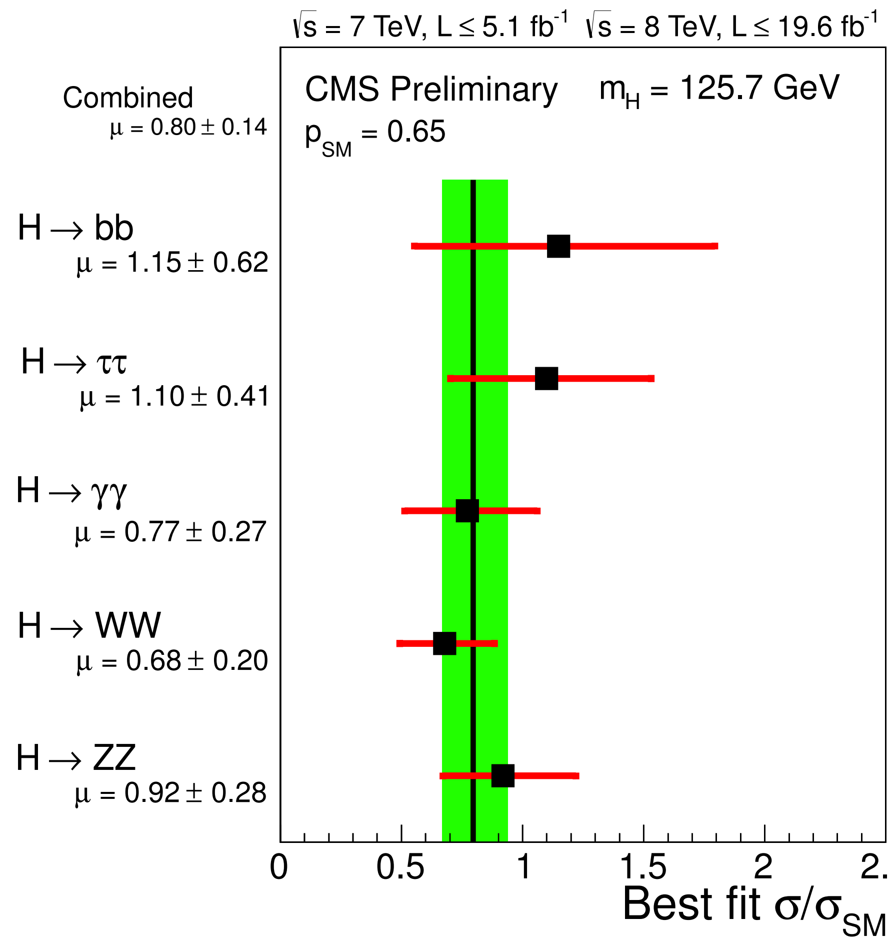
for details see e.g. talks by G. Landsberg and F. Cerutti @ EPS-HEP, Stockholm, 2013

Where do we stand: Higgs results in a nut-shell, II

ATLAS, arXiv:1307.1427

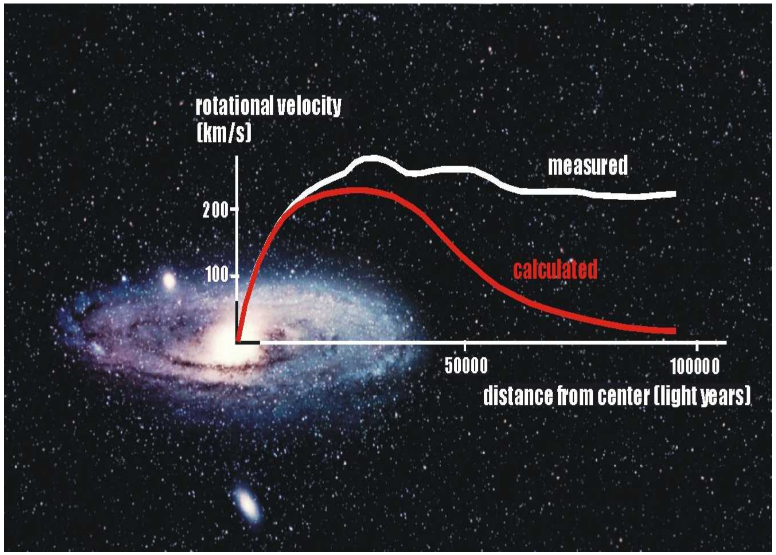


CMS, CMS-PAS-HIG-13-005



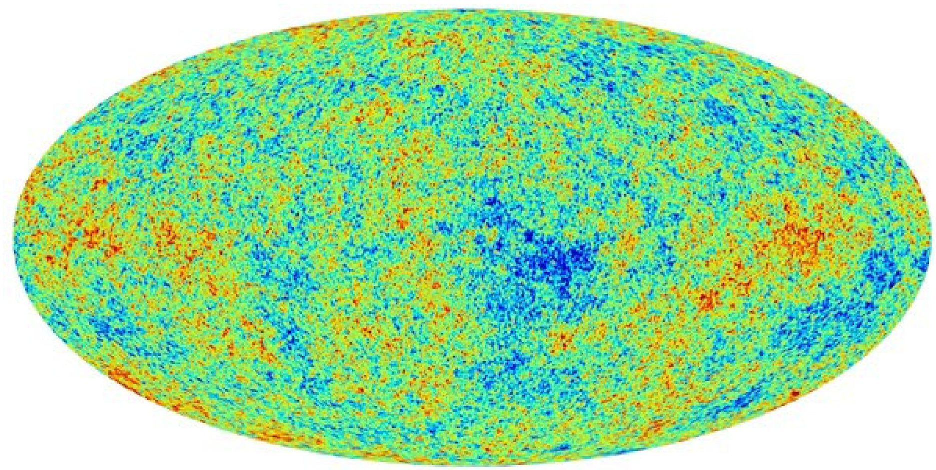
for details see e.g. talk F. Cerutti @ EPS-HEP, Stockholm, 2013

One of the big questions: dark matter



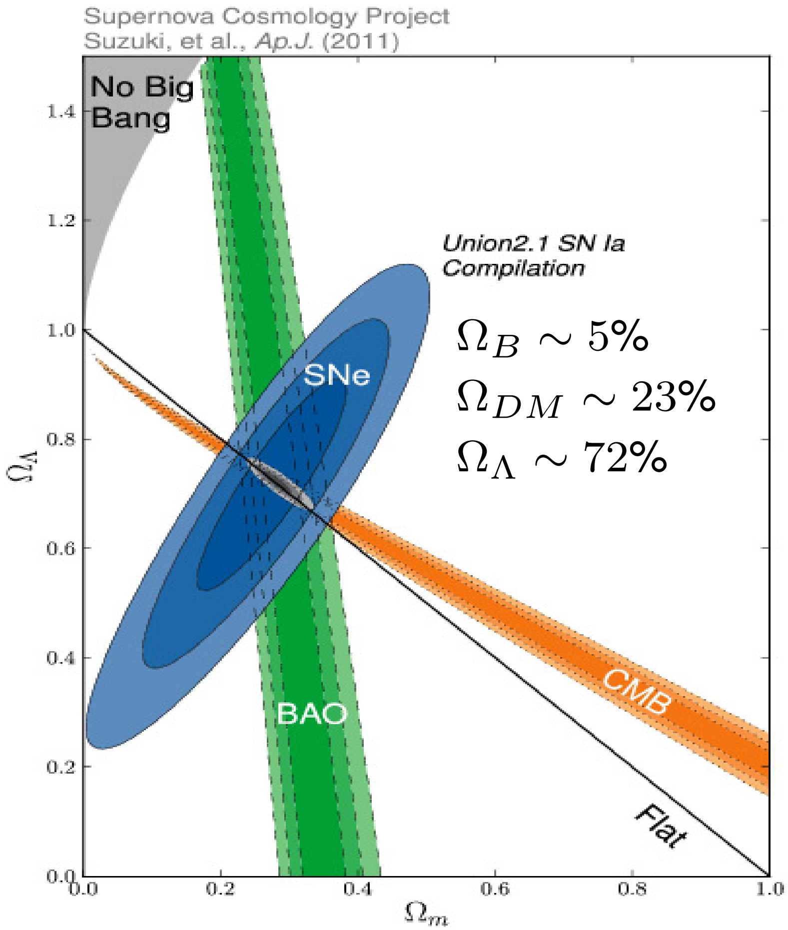
Zwicky: galaxies rotate to fast
in comparision to the observed mass

The universe at the age of $\simeq 4{\cdot}10^5$ years



CMB $\simeq 13.7{\cdot}10^9$ years later
(WMAP and Planck satellites)

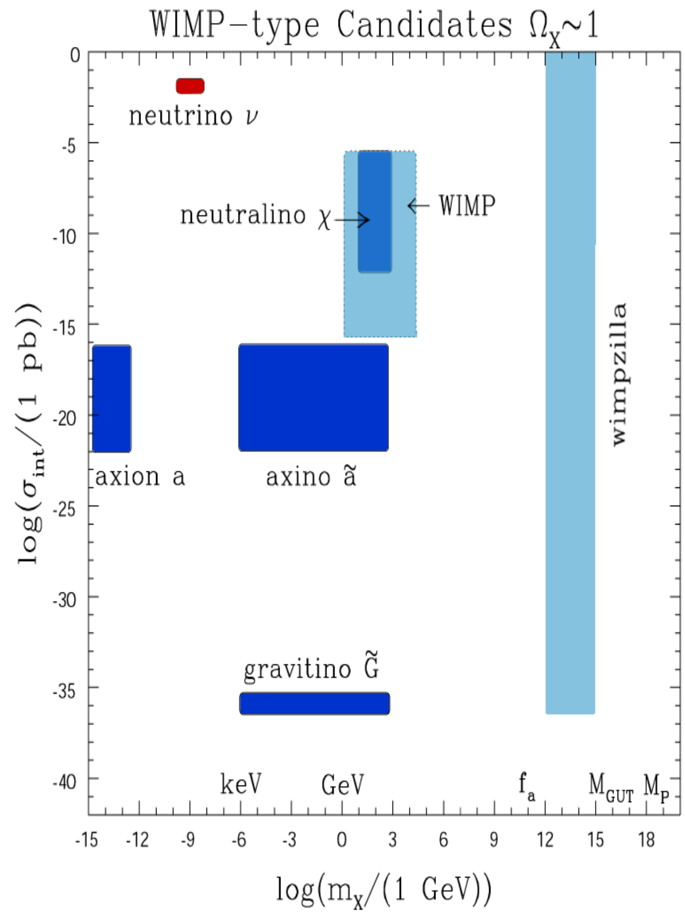
- What is the nature of dark matter ?



$\Omega_B \sim 5\%$

$\Omega_{DM} \sim 23\%$

$\Omega_\Lambda \sim 72\%$



L. Roszkowski, astro-ph/0404052

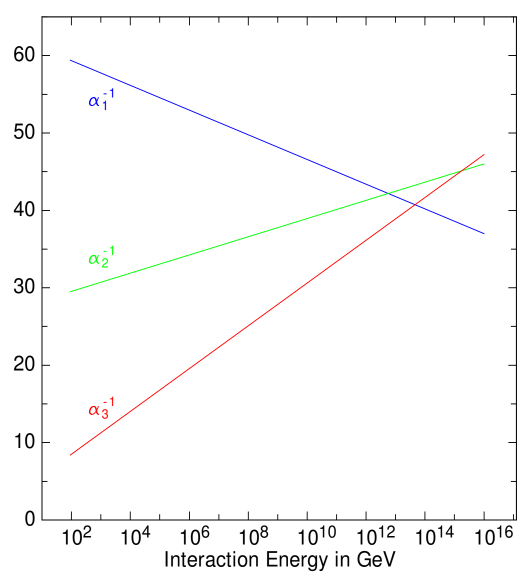
- What is the origin of the observed baryon asymmetry?

Why do we want to extend the SM

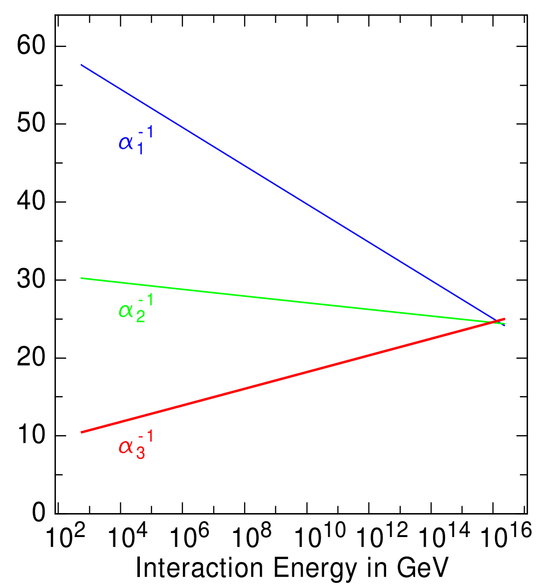
- How to combine gravity with the SM?
  $\Rightarrow$ local Supersymmetry (SUSY) implies gravity
- SM particles can be put in multiplets of larger gauge groups
  - in $SU(5)$: $1 = \nu^c_R$, $5 = (d^c_{\alpha,R}, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, l_R)$
  - in $SO(10)$: $16 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, d^c_{\alpha,R}, l_L, l_R, \nu_{l,L}, \nu^c_R)$

  However there are two problems in the SM but not in SUSY:
  - proton decay (also in SUSY $SU(5)$ a problem)
  - gauge coupling unification

SM

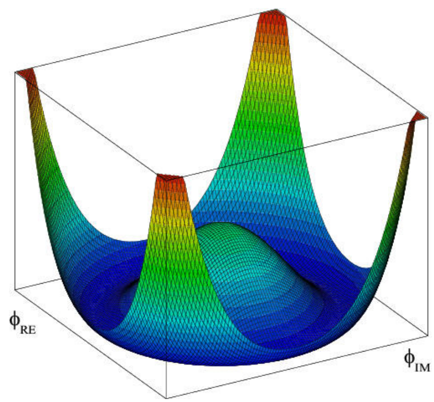


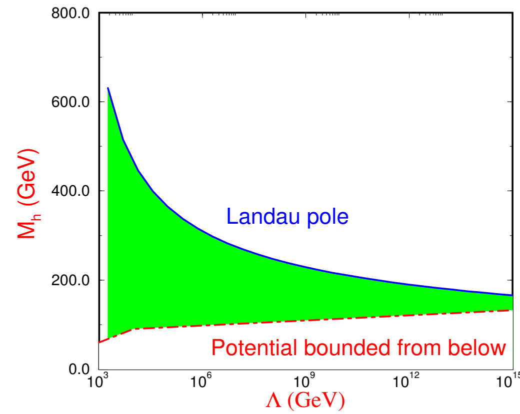
MSSM



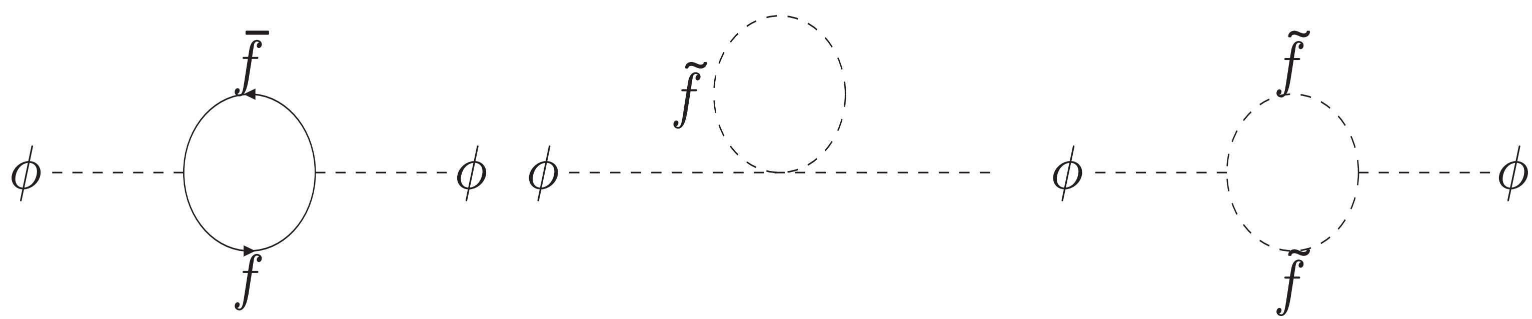
Why do we want to extend the SM

- SM & $m_h = 125.5$ GeV: potentially meta-stable (G. Degrassi *et al.*, arXiv:1205.6497)





- "Why does electroweak symmetry break?" or "Why is $\mu^2 < 0$ in the SM?"
- Hierarchy problem



$\delta m_h^2 \propto \Lambda^2$: Sensitivity to highest mass scale of unknown physics

Supersymmetry, MSSM

	Standard Model		MSSM
matter:	e d d d	$\Leftrightarrow$	$\tilde{e}$ $\tilde{d}$ $\tilde{d}$ $\tilde{d}$
	ν_e u u u		$\tilde{\nu}_e$ $\tilde{u}$ $\tilde{u}$ $\tilde{u}$
gauge sector:	γ Z^0 $W^\pm$ g	$\Leftrightarrow$	$\tilde{\gamma}$ $\tilde{z}^0$ $\tilde{w}^\pm$ $\tilde{g}$
Higgs sector:	h H A $H^\pm$	$\Leftrightarrow$	$\tilde{h}^0_d$ $\tilde{h}^0_u$ $\tilde{h}^\pm$

R-Parity: $(-1)^{(3(B-L)+2s)}$

$(\tilde{\gamma}, \tilde{z}^0, \tilde{h}^0_d, \tilde{h}^0_u) \to \tilde{\chi}^0_i$, $(\tilde{w}^\pm, \tilde{h}^\pm) \to \tilde{\chi}^\pm_j$

DM particle: $\tilde{\chi}^0_1$

Dark Matter candidates

- neutrinos: $\Omega_\nu h^2 < 0.0067$ @ 95% CL
- sterile neutrinos (with respect to $SU(3)_C \times SU(2)_L \times U(1)_Y$)
- axions
- SUSY
  - neutralino $\tilde{\chi}_1^0$
  - gravitinos
  - $\tilde{\nu}_R$ (in models with sterile neutrinos)
  - axinos
- models with extra dimensions: KK-states
  - first vector boson KK state V_Y^1
  - first graviton KK state G^1
- ...

Dark Matter candidates

requirements

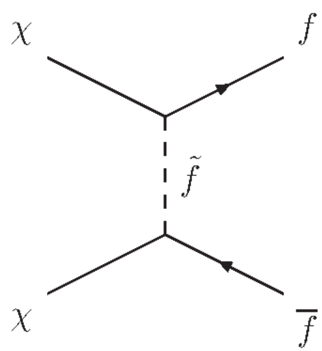
- electrically neutral ('dark')
- either stable: usually via discrete symmetry: R-parity, KK-parity, Z_n, ...
  or life-time larger than age of universe
- massive and weakly interacting as $\Omega_{DM} h^2 \simeq 0.1$

Note: there might be more than one component, we have at least neutrinos

generic signal at high energy colliders

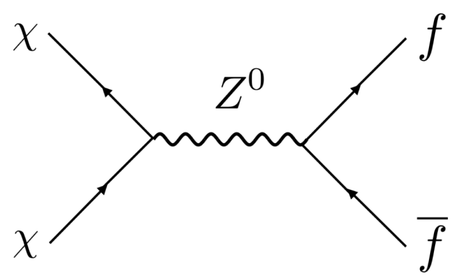
- large missing transvers momentum / transverse energy

Dark matter, annihilation processes



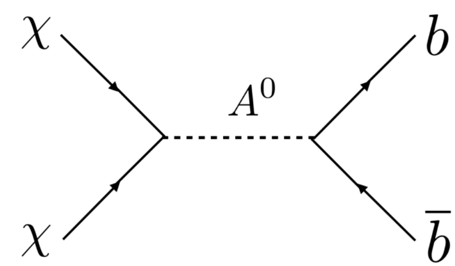
bino

bulk region

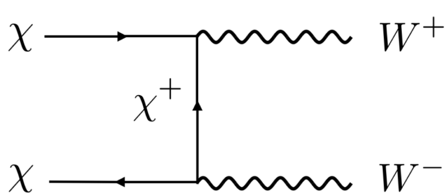


wino, higgsino

focus-point region

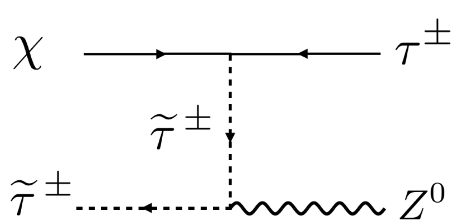


funnel region

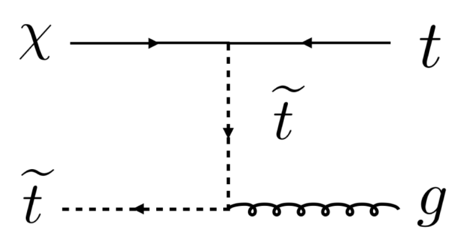


wino, higgsino

focus-point region



stau co-annihilation



stop co-annihilation

How to produce DM particles at the LHC

- Direct production: $\chi\chi$ + SM particles
  - includes monojet, monophoton, mono-b, mono-Z, mono-W, mono-H
- Associated production with a heavier exotic E: $\chi + E$, then $E \to \chi+$ SM
- Pair of heavier exotics $E + E$, then both $E \to \chi+$ SM
- SM decays to χ: $Z \to \chi\chi$, $h \to \chi\chi$, $t \to c\chi\chi$
- Exotic resonance decays: $E \to \chi\chi$
- Heavier metastable exotic, decay of $E \to \chi$ not seen in the detector

SUSY give a lots of examples of all of these, so this is a good place to start with, even if DM has nothing to do with SUSY

Moreover: usually exotics of other BSM extensions have large cross sections at LHC due to higher spin

Mediators at the LHC ?

- Besides heavier unstable relatives of the DM particle, one is also interested in the particle(s) which mediate the non-gravitational interactions of the DM-particle with SM particles

- SM: the only s-channel mediators are Z and h

- exotic mediators may be very heavy $\Rightarrow$ DM-SM interactions described by contact interactions

- if mediators are lighter, produce and identify them at LHC, not necessarily in association with with DM-particles, e.g. the heavy Higgs-boson in SUSY

Dark Matter @ LHC, results

- A very broad and powerful program of MET-related searches at ATLAS and CMS.

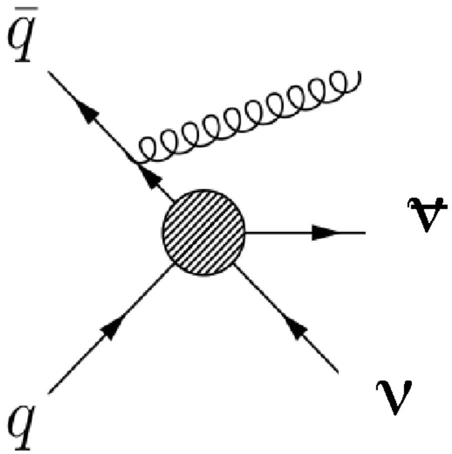
  These are the 'SUSY' searches.

- Strong results from monojet and monophoton searches.

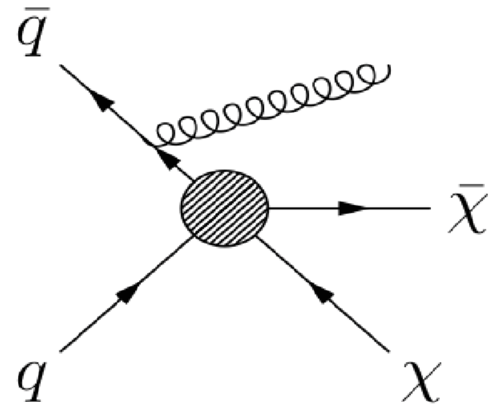
  These are 'Exotic searches'

- Weak constrains on invisible decays of the Higgs boson

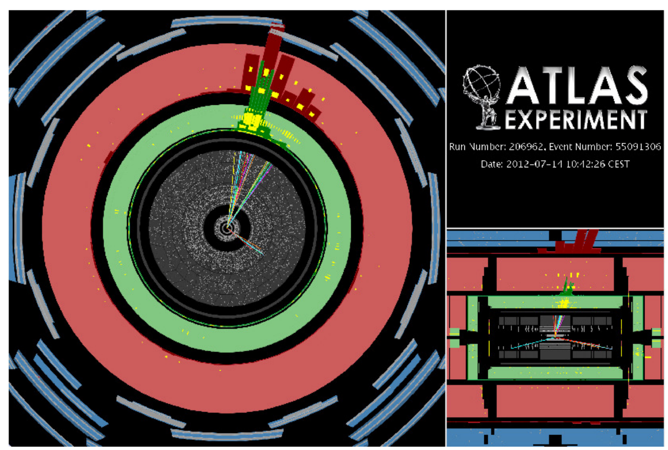
Monojets



$Z \to \nu\nu$ background



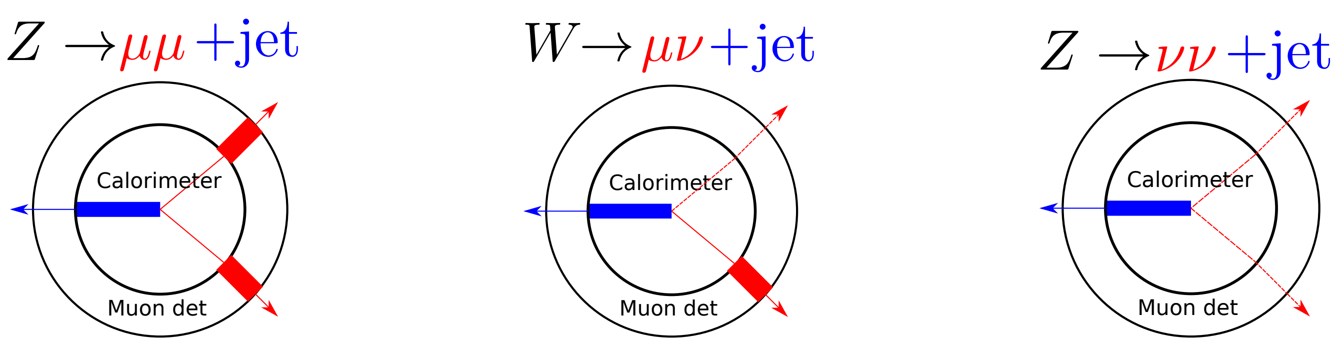
DM Signal



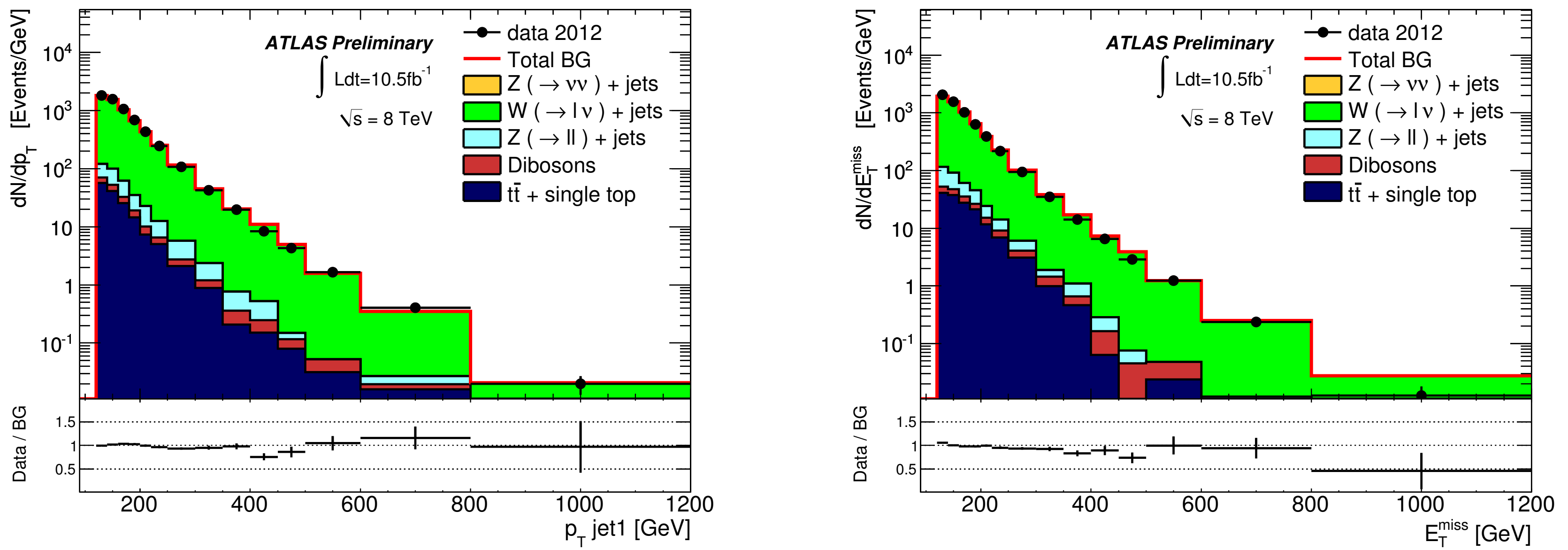
$p_T^{\mathrm{jet1}} = 852\,\mathrm{GeV},\ E_T^{\mathrm{miss}} = 863\,\mathrm{GeV}$

Estimating the $Z \to \nu\nu$ background

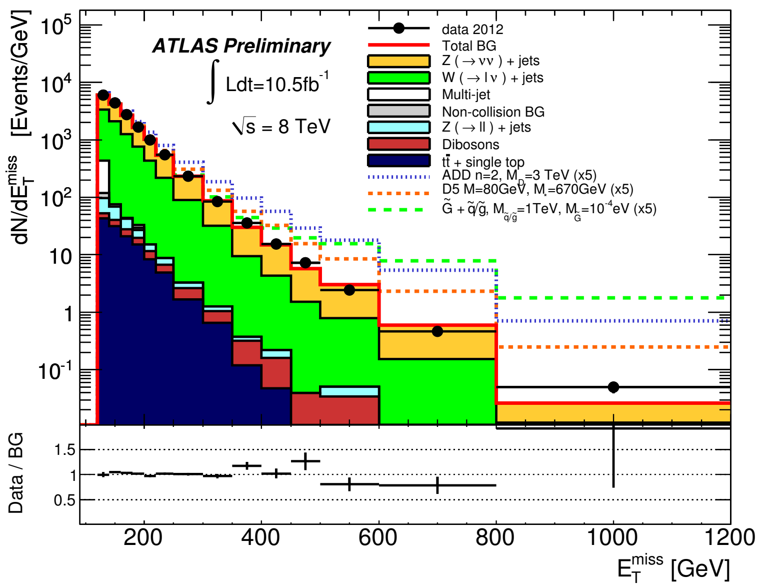
- Muons are minimum ionizing particles
  - They leave almost no energy in the calorimeter
  - Instead, they are measured by the muon spectrometer
- Neutrinos leave no energy in the calorimeter or spectrometer
- Consider a calorimeter-based $\mathrm{E_T^{miss}}$: muons and neutrinos are similar
- Identify $Z \to \mu\mu$ and $W \to \mu\nu$ events in data with the spectrometer
  - Use MC ratios to "transfer" to $Z \to \nu\nu$ estimate in data

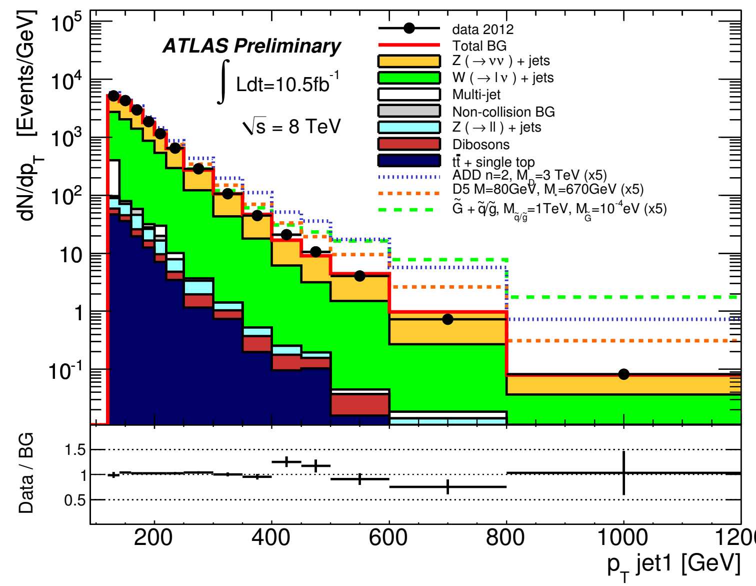


Monojets



control region (ATLAS-CONF-2012-147)

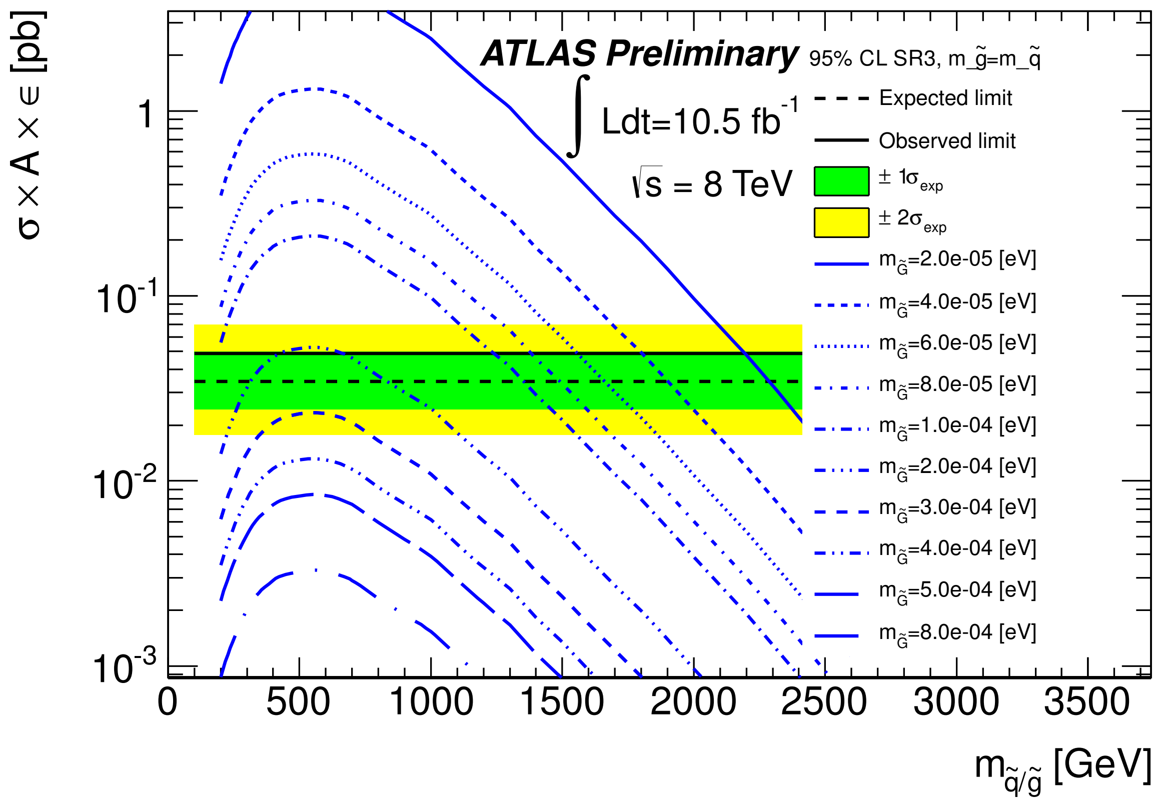




signal region SR1 (ATLAS-CONF-2012-147)

Monojets, SUSY interpretation

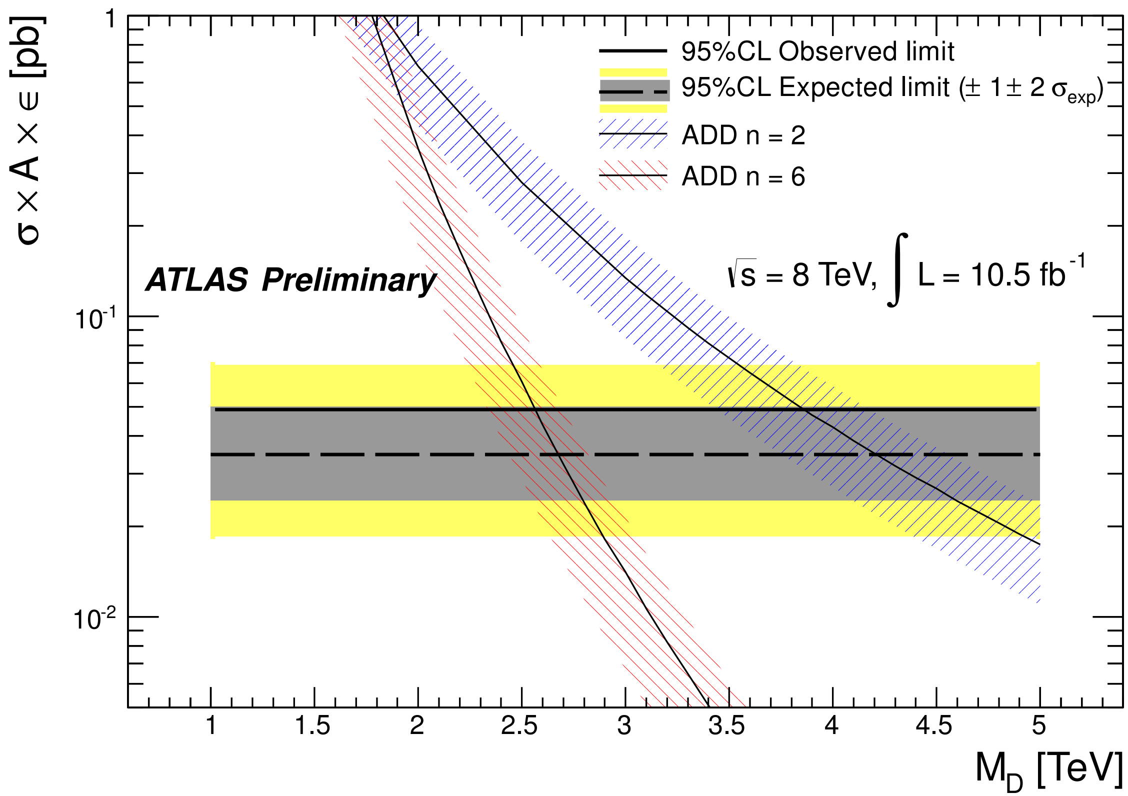
$$\sigma(pp \to \tilde{G} + \tilde{q}/\tilde{g}) \propto \frac{1}{m_{\tilde{G}}^2}$$



(ATLAS-CONF-2012-147; similar results by CMS, see arXiv:1408.3583)

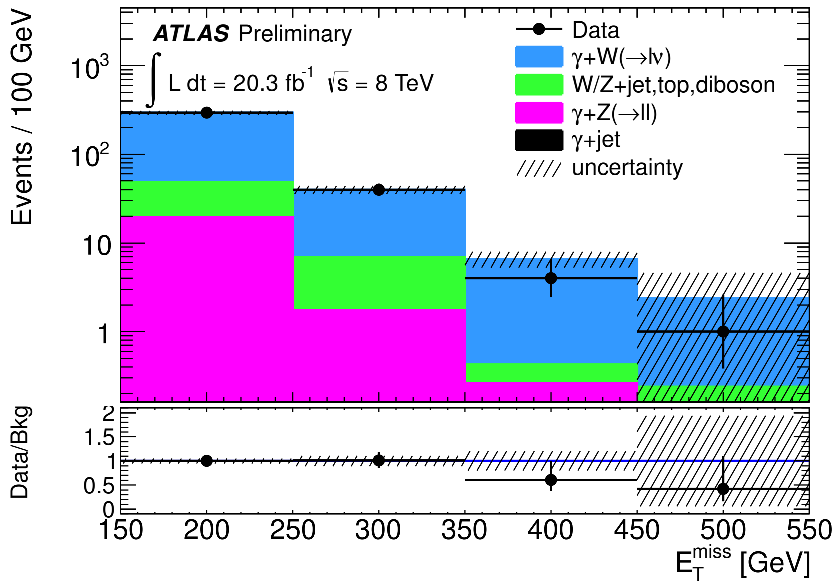
Monojets, extra dimensions

$\sigma(pp \to G^1 + j)$ $M^2_{Planck} \sim M_D^{2+n} R^n$

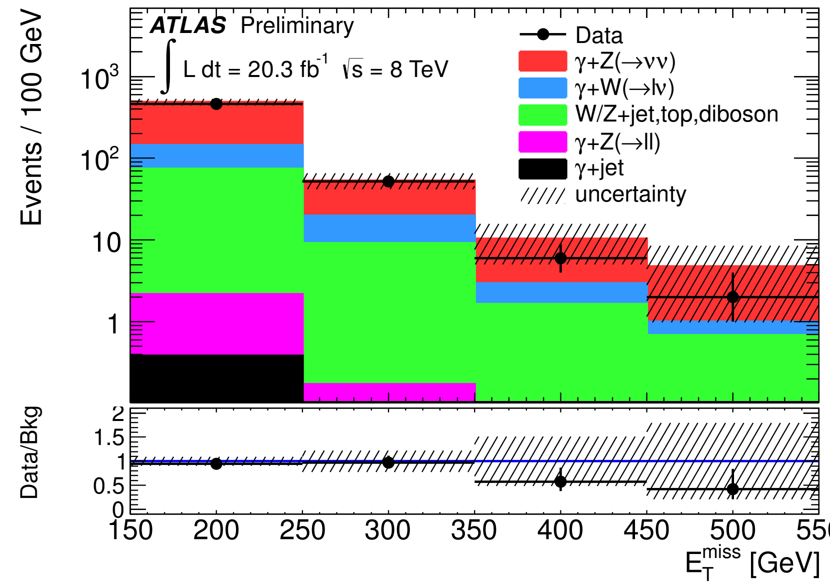


(ATLAS-CONF-2012-147; similar results by CMS see arXiv:1408.3583)

Monophotons



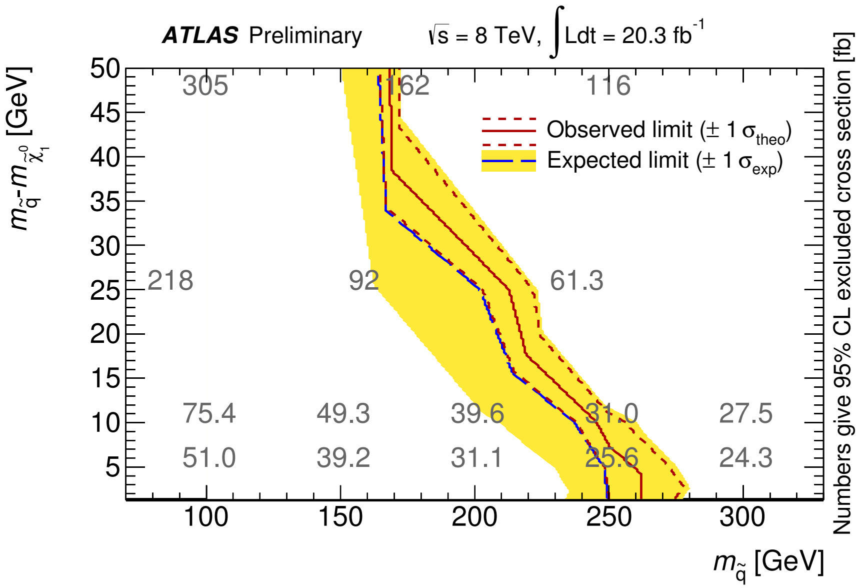
control region



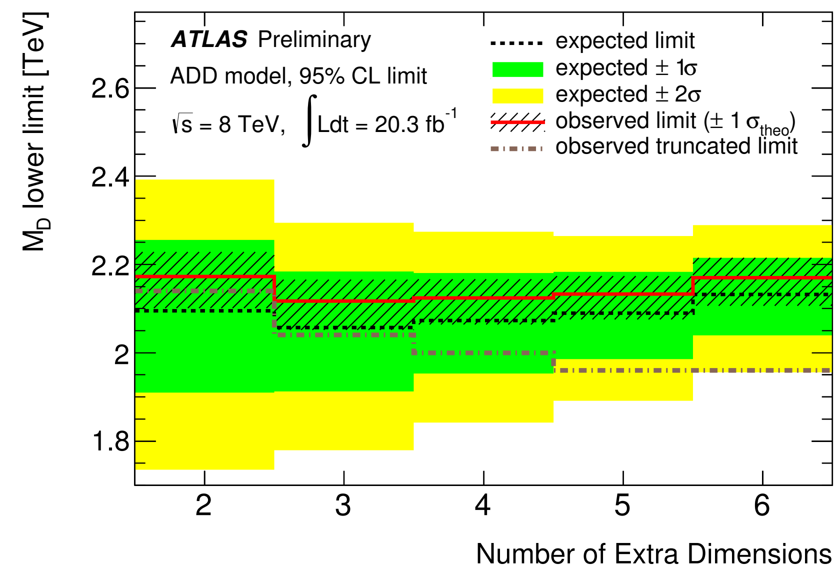
signal region

(ATLAS-CONF-2014-151)

Monophotons



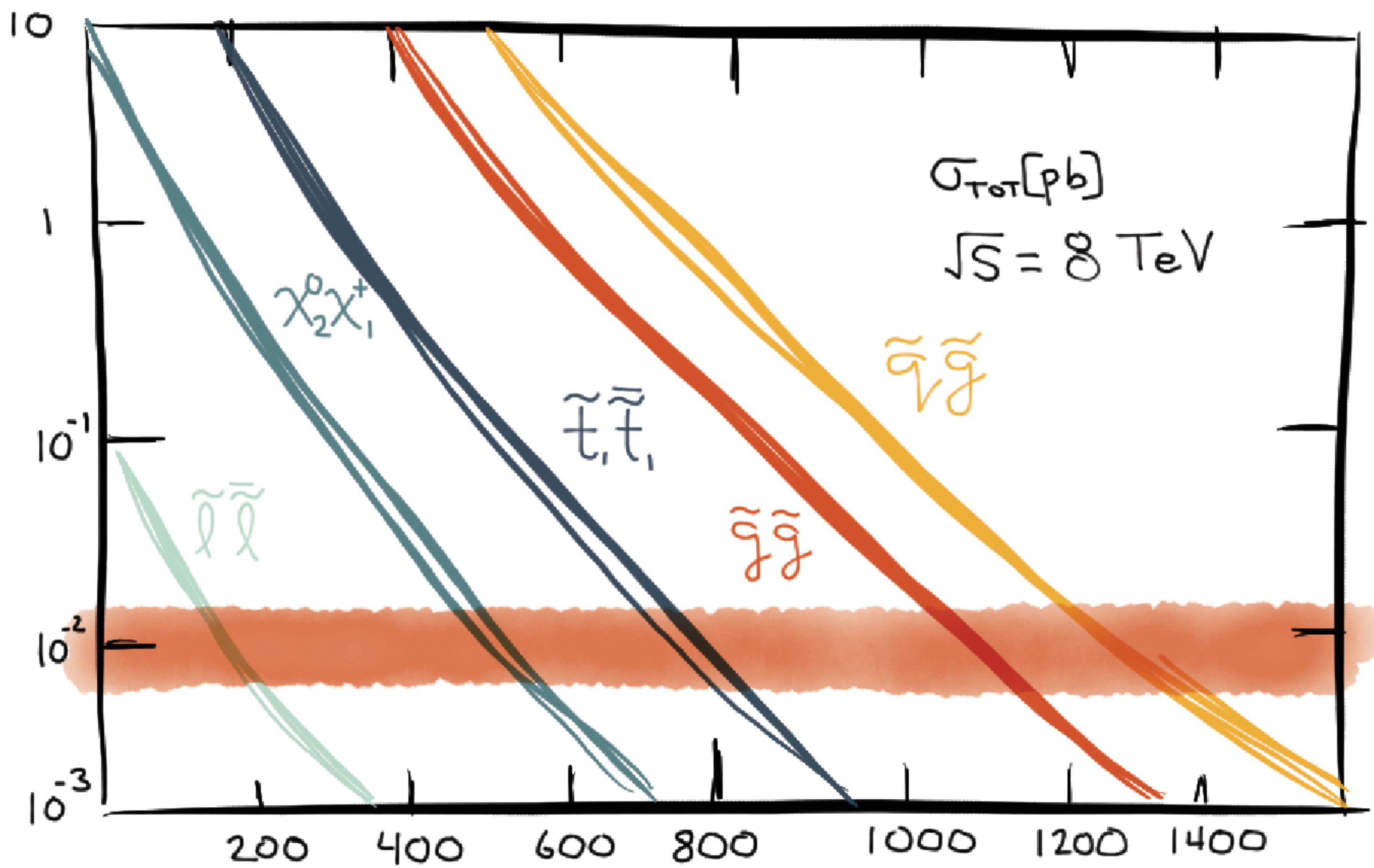
SUSY



ADD

(ATLAS-CONF-2014-151)

Pair production of SUSY particles



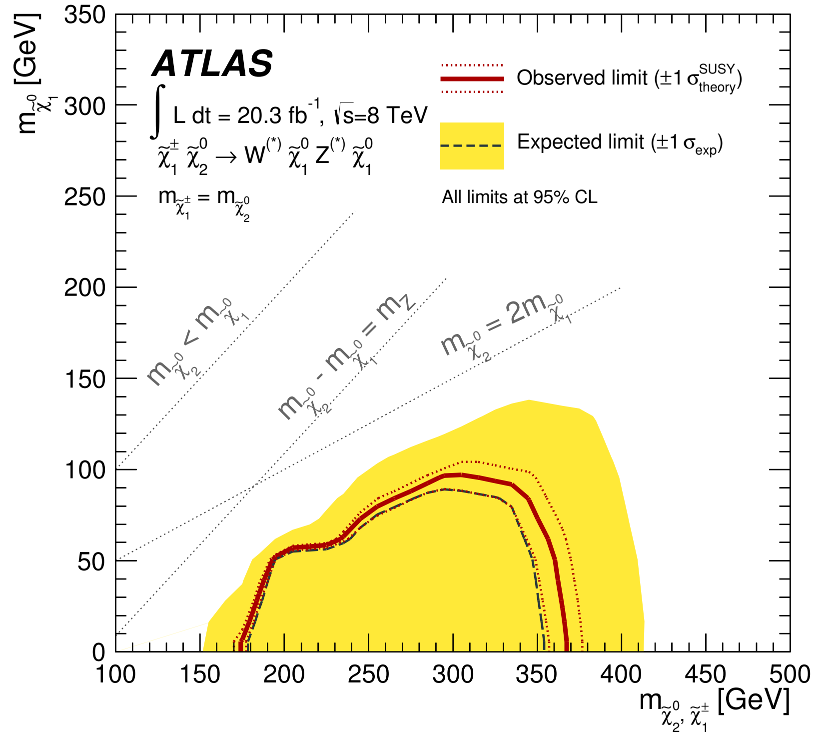
Nathaniel Craig, arXiv 1309.0528

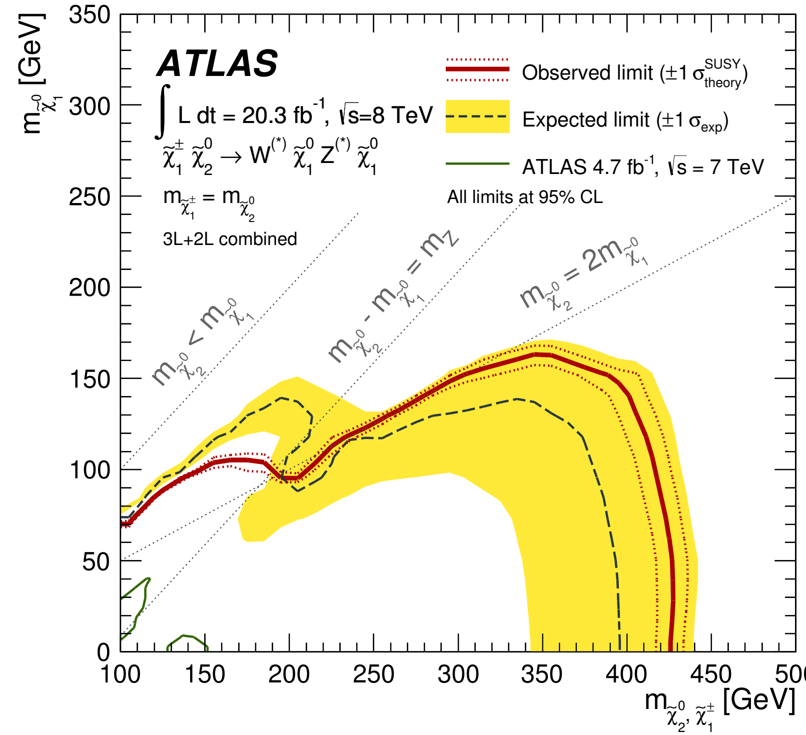
Bounds on charginos and neutralinos

ATLAS arXive:1403.5294

$$pp \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 + X$$

Observed and expected 95% CL exclusion regions



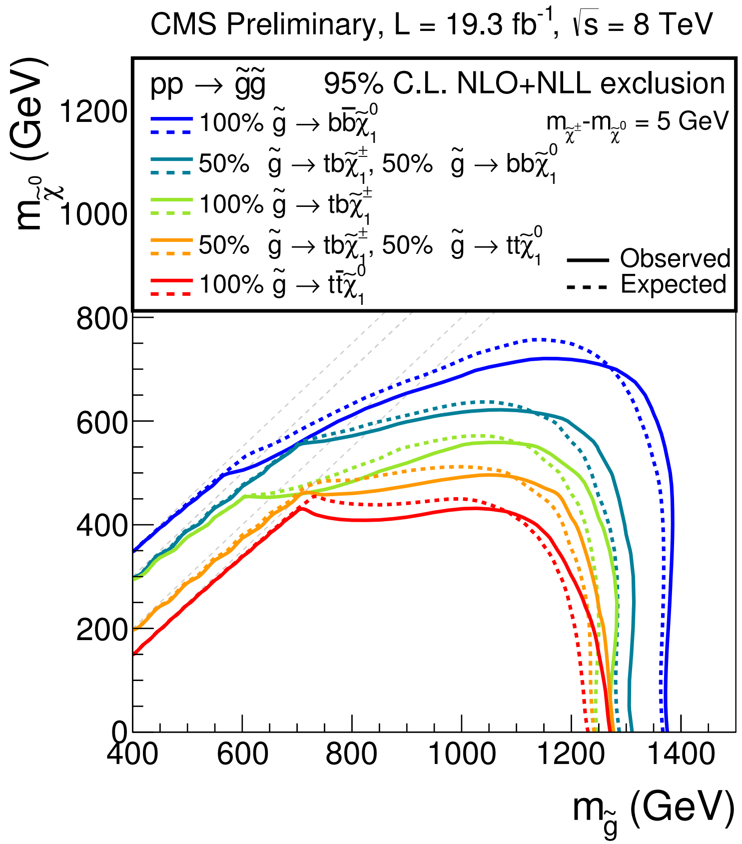


followed by W and Z-mediated decays

combine with three-lepton of arXiv:1402.7029

assumption: specific nature of $\tilde{\chi}_1^+$, $\tilde{\chi}_i^0$ and mass hierarchies

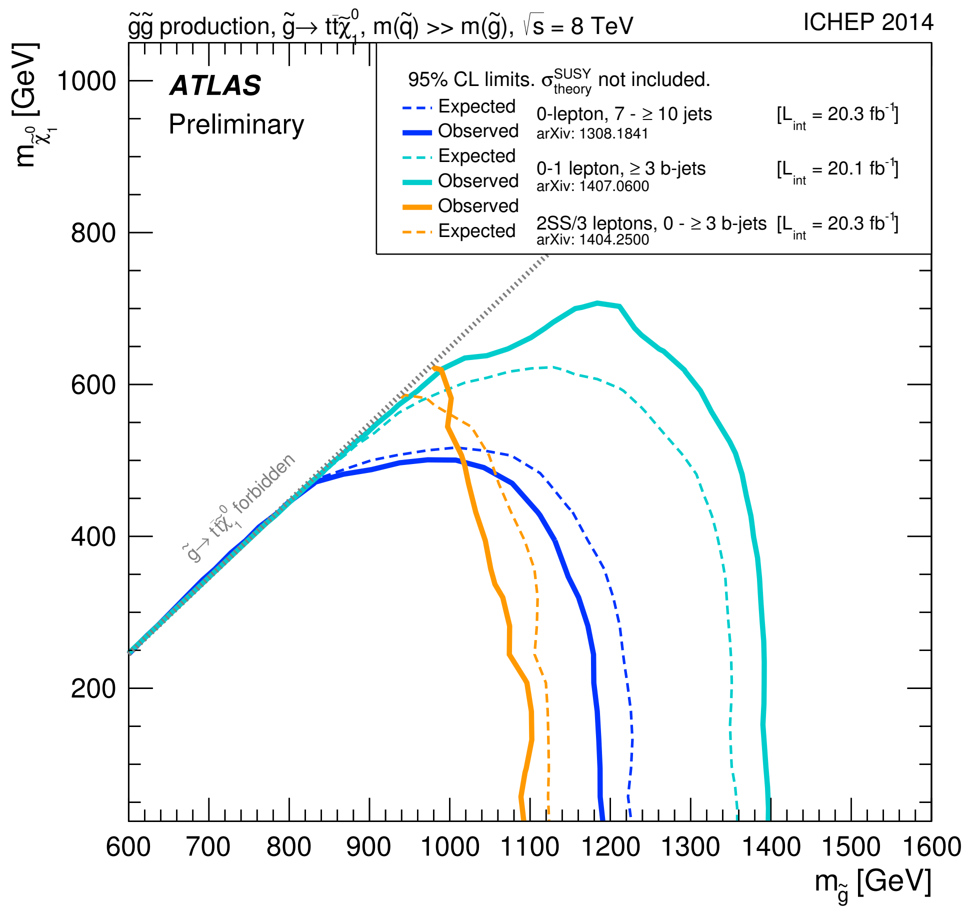
Very sensitive SUSY searches



- fully inclusive except of for requirement of ≥ 1 b-tag
- the exclusion of $m_{\tilde{g}} = 1.35$ TeV corrsponds to only 8 signal events after a 30% efficient selection
- this corresponds cross section $\times$ BR of 1.3 fb
- for comparision: Higgs boson cross section $\times BR(h \to \gamma\gamma)$ is about 10 fb

(CMS-SUS-14-011-pas)

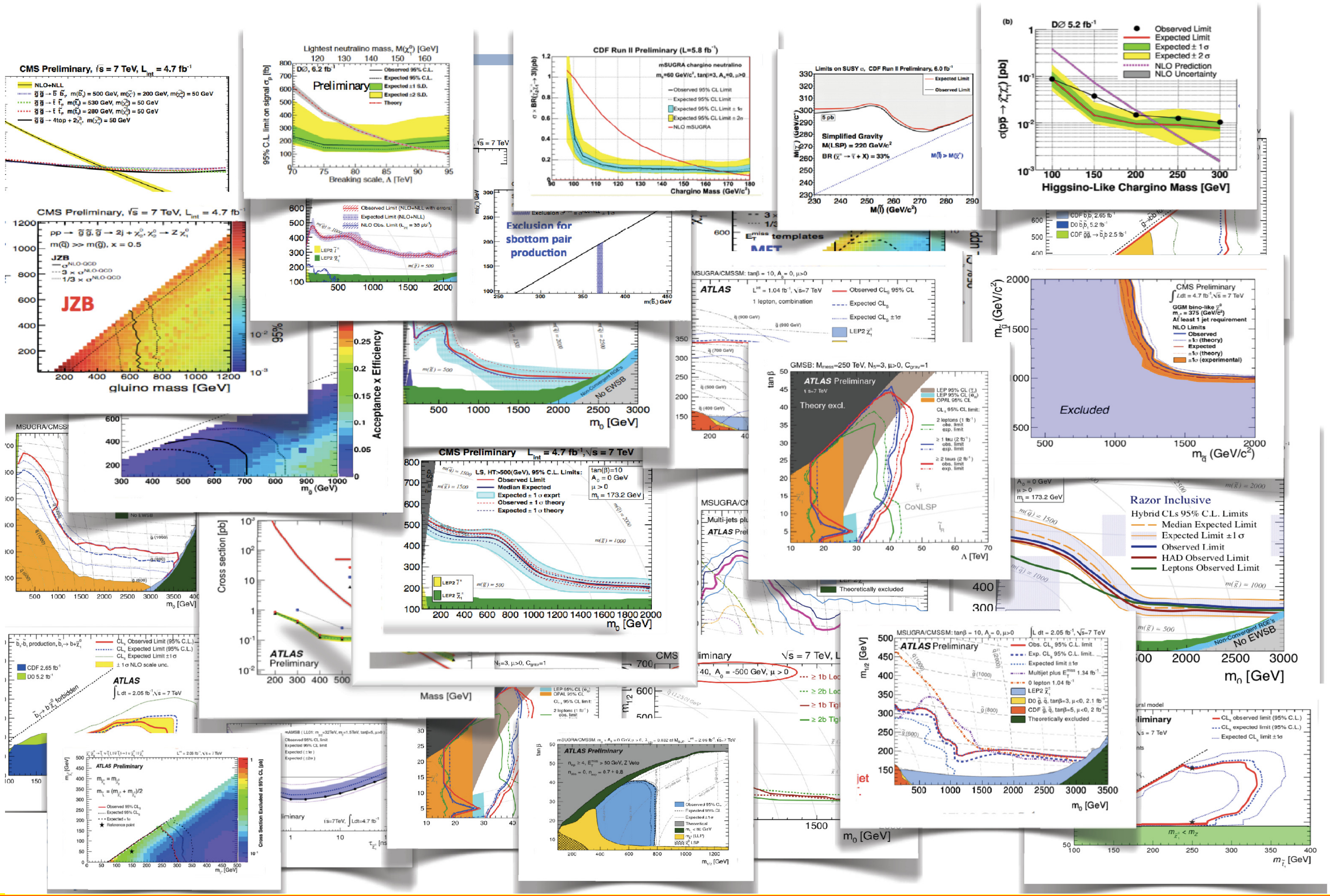
Very sensitive SUSY searches



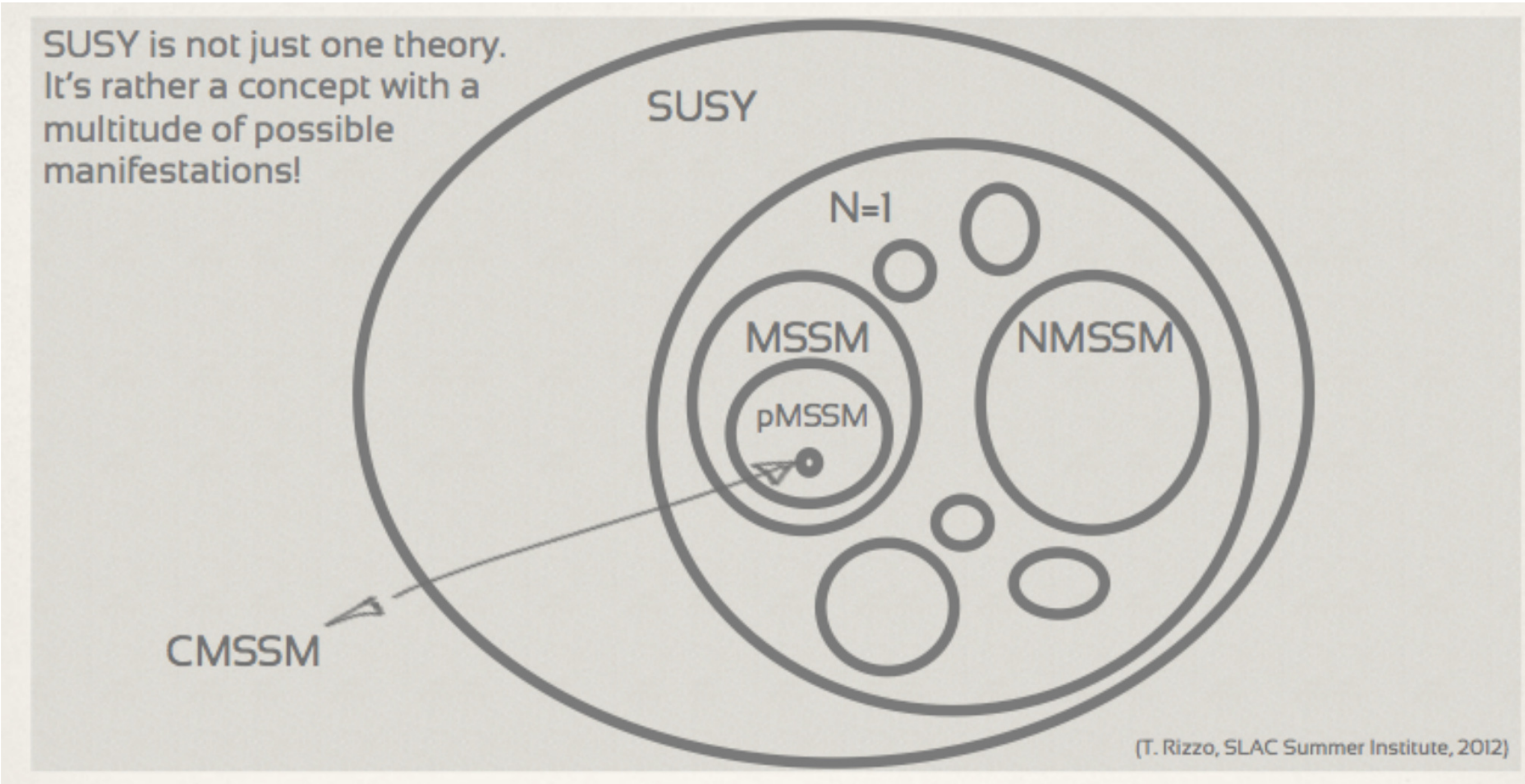
exclusive search with small backgrounds

but also excludes cross section $\times$ BR as small as 1.3 fb

also other BSM searches, so far nothing . . .



SUSY parameter sapce



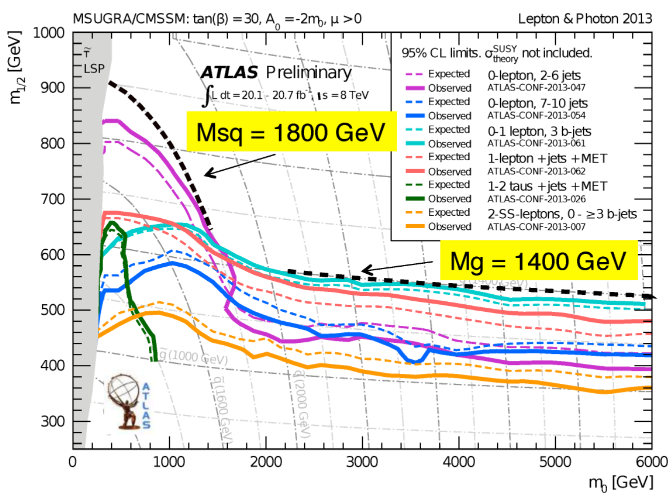
LHC searches at 7 and 8 TeV have so far excluded a sizable part of the pMSSM and a small fraction of the NMSSM

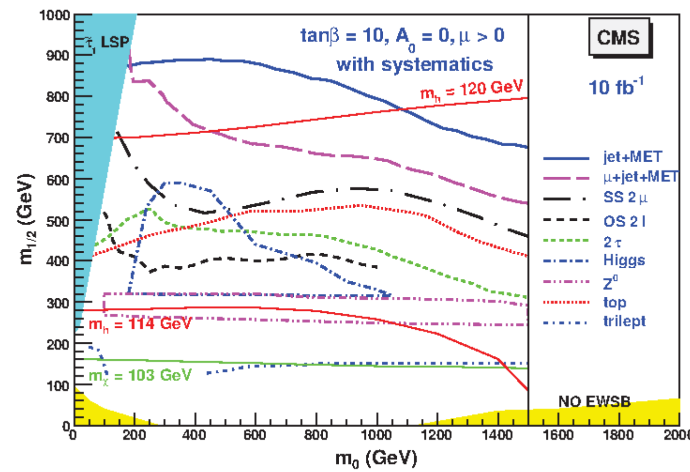
too soon to tell from LHC exclusions if SUSY (or also other BSM extensions) is related to electroweak scale and dark matter

Concluding remarks

Puzzling situation

- collider data agree very well with SM expectations
- cosmological and astrophysical observations as well as theory arguments point to new physics in the TeV range
- I do not expect significant SUSY signals at LHC@13/14TeV before $L \simeq 10$ fb^{-1} but potentially an s-channel resonance such as a Z'





- despite servere bounds: huge model parameter space in various BSM models still open