Status and prospects of BSM models after the first years of LHC

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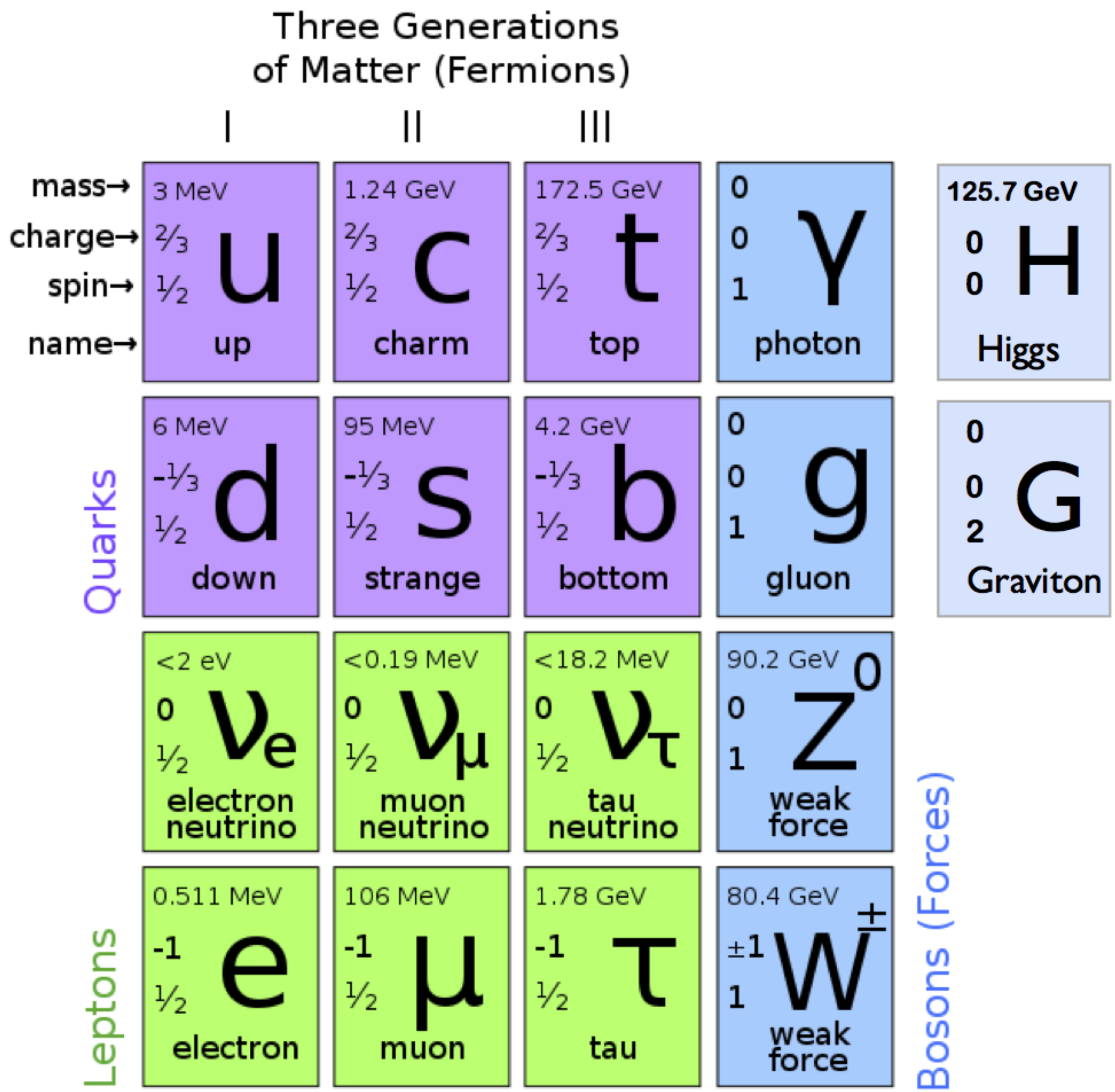
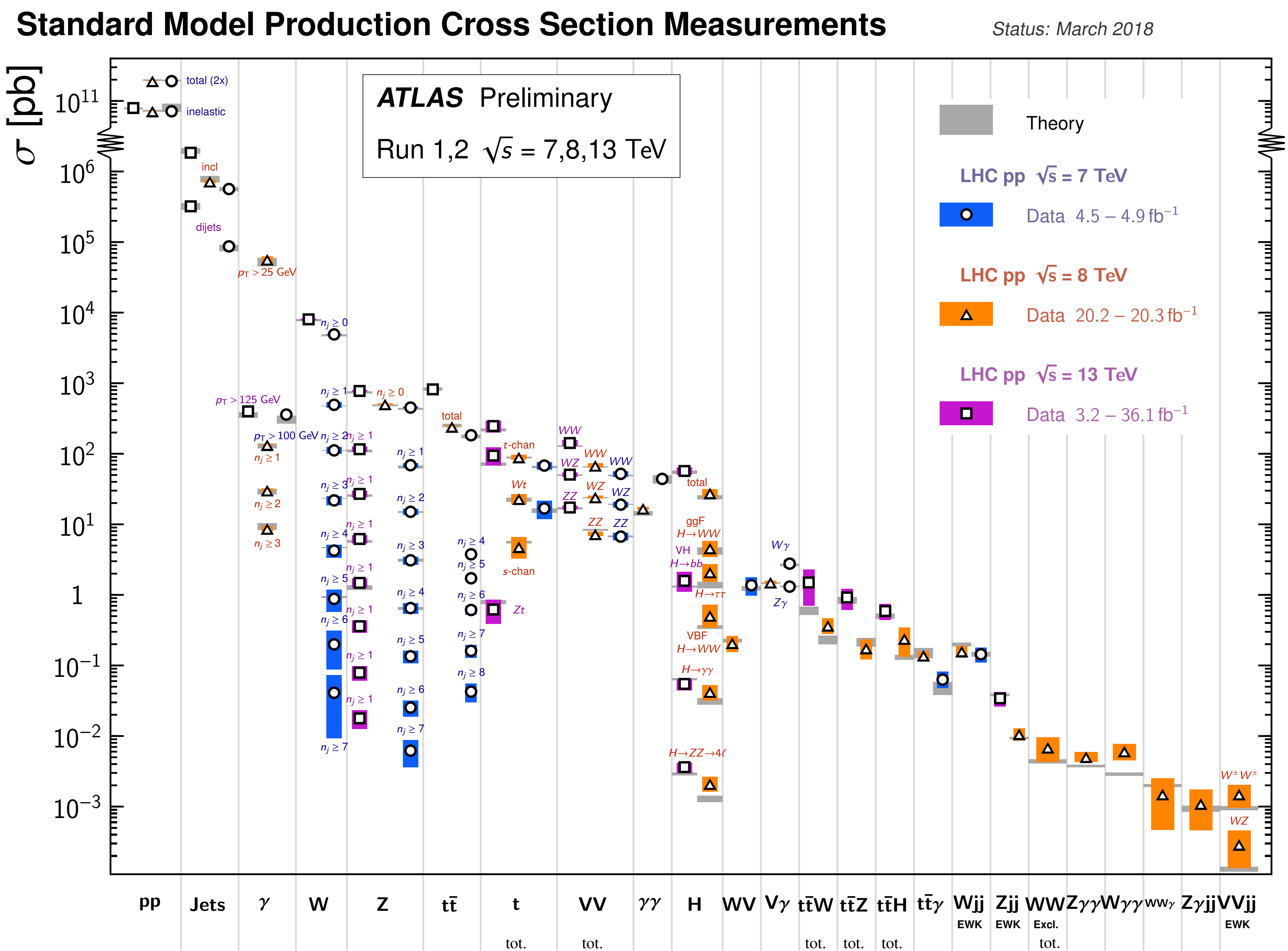
Overview

- Standard Model: where do we stand
- Why do we want to extend the Standard Model
- Prinicple ways to extend the Standard Model
- LHC searches with some focus Dark Matter
- Concluding remarks

Where do we stand: Standard Model, particle content

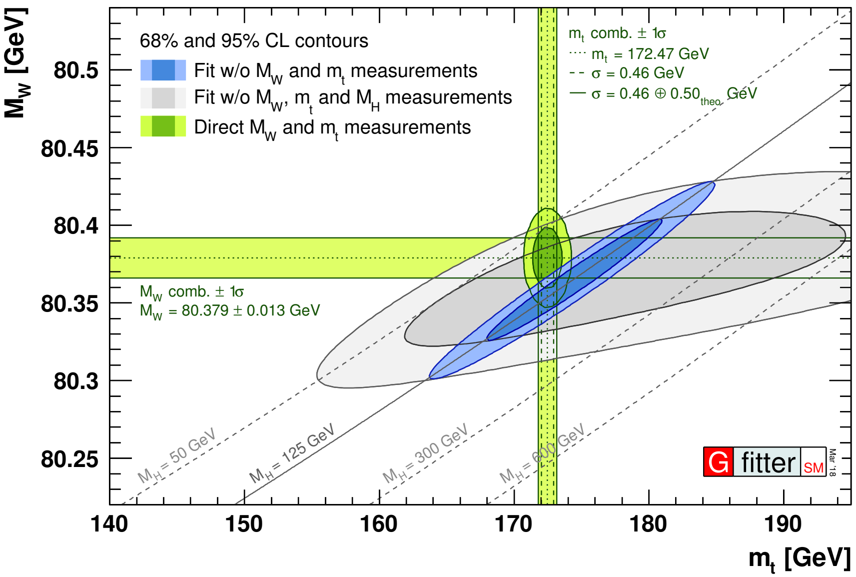


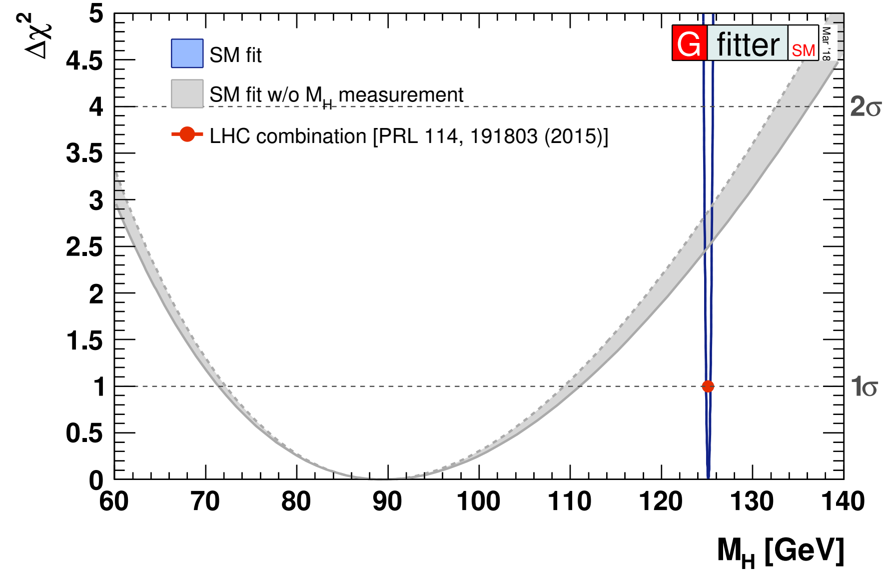
Where do we stand: LHC



Where do we stand: precision physics

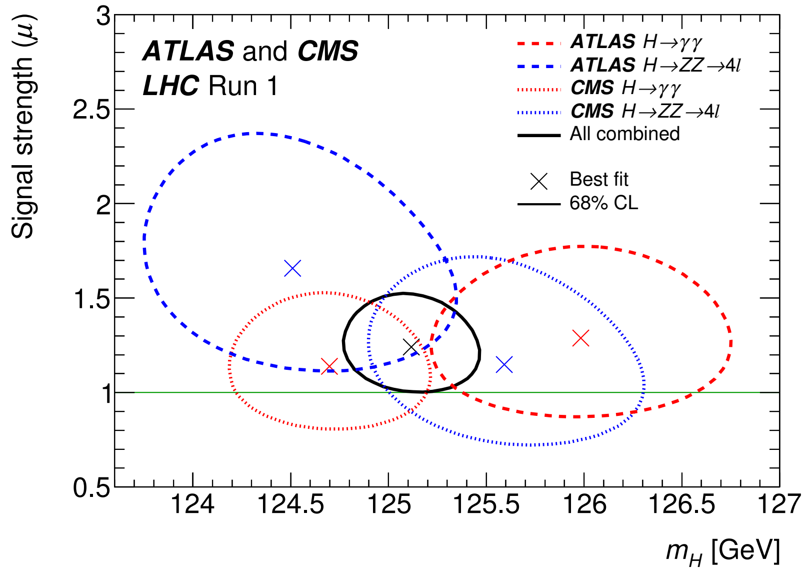
basic idea: consistency tests using precision observables, where t, W, H enter via quantum effects

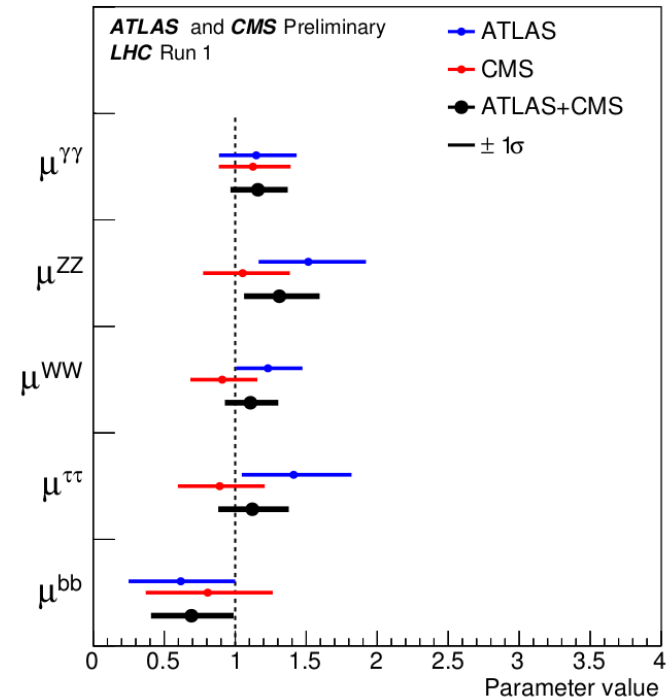




http://project-gfitter.web.cern.ch/project-gfitter

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





$m_H = 125.09 \pm 0.21$ (stat) ± 0.11 (sys) GeV

run 1, PRL **114** (2015) 191803

ATLAS-CONF-2015-044

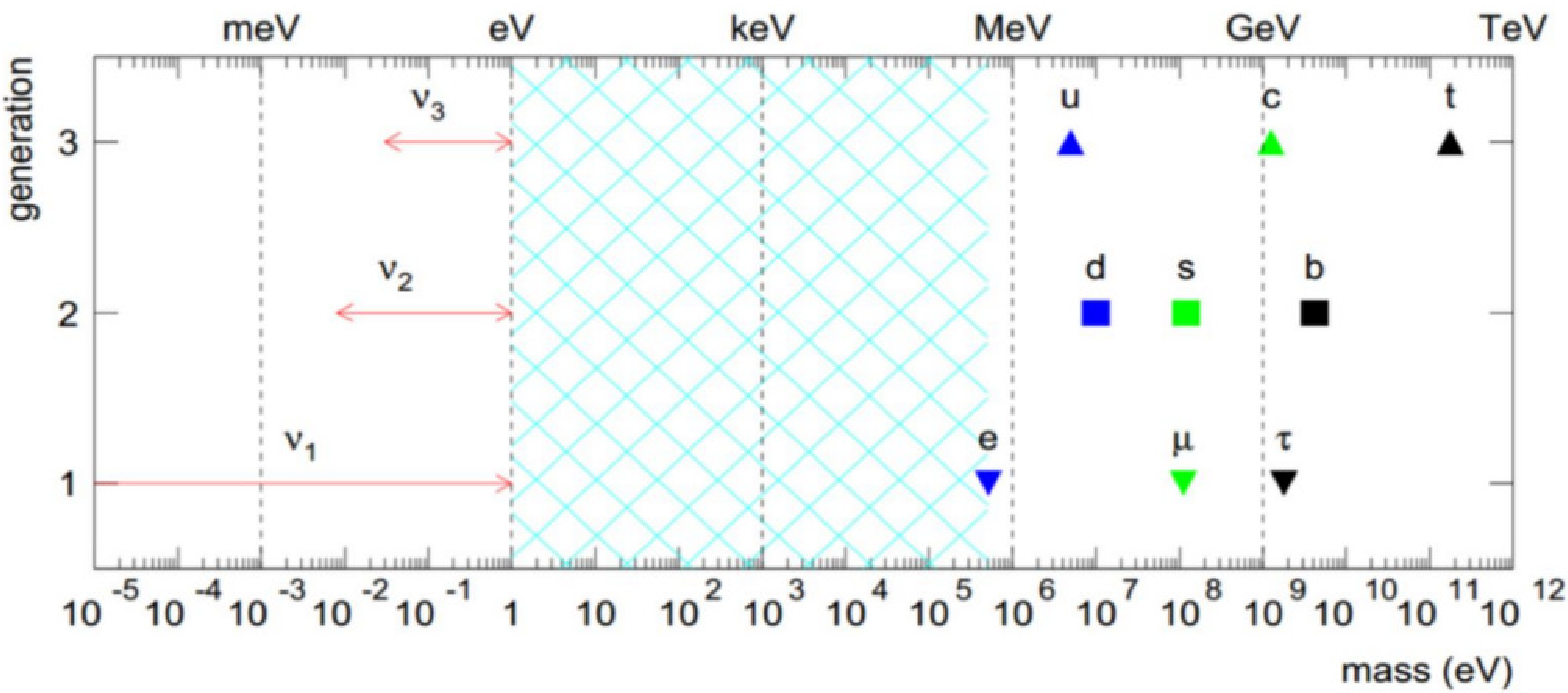
CMS-PAS-HIG-15-002

ATLAS: $m_H = 124.98 \pm 0.19$ (stat) ± 0.21 (sys) GeV

CMS: $m_H = 125.26 \pm 0.20$ (stat) ± 0.08 (sys) GeV

talk by A.-M. Magnan @ ALPS 2018

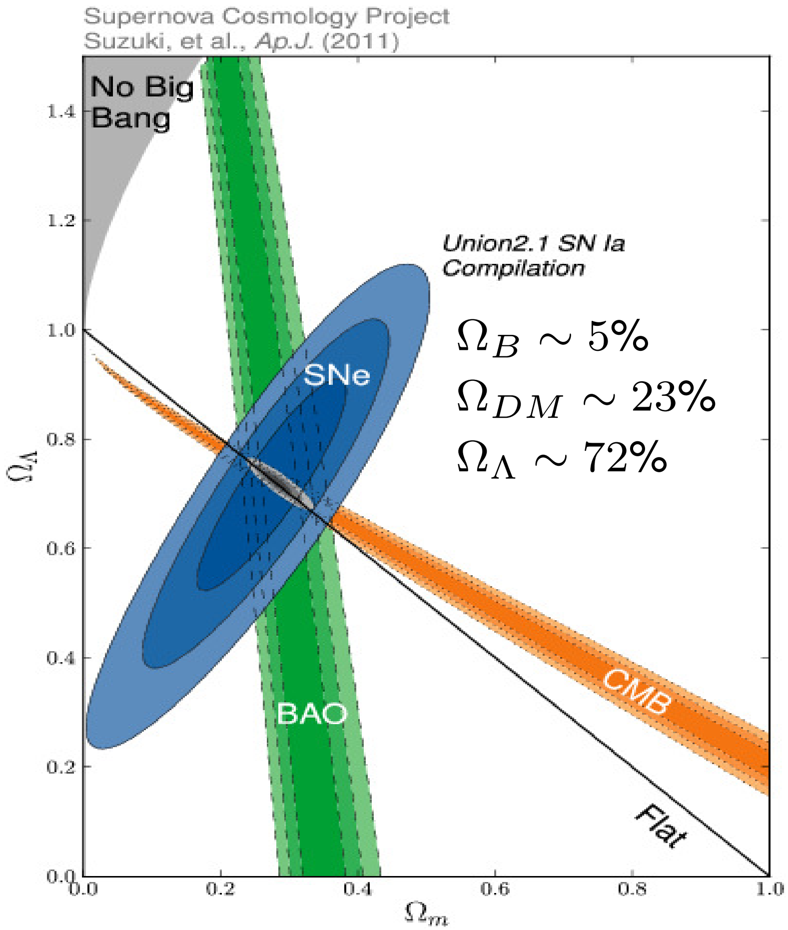
Why extending the SM: fermion mass spectrum



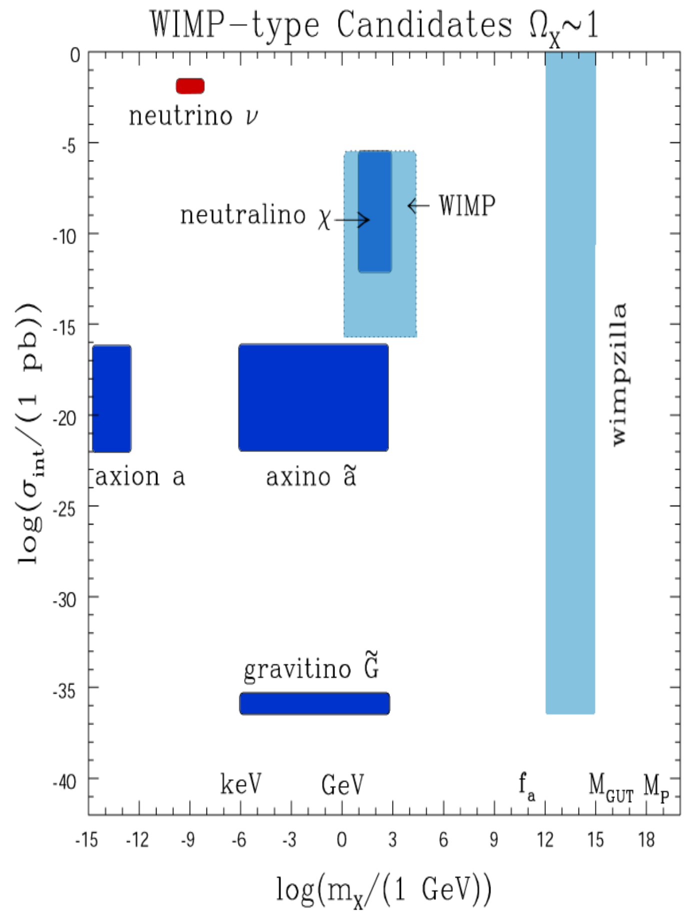
- hierarchy of fermion masses, in particular ν
- mixing pattern: small mixing for q versus large mixing for ν

Why extending the SM: cosmology

- What is the nature of dark matter ?



$\Omega_B \sim 5\%$
$\Omega_{DM} \sim 23\%$
$\Omega_\Lambda \sim 72\%$



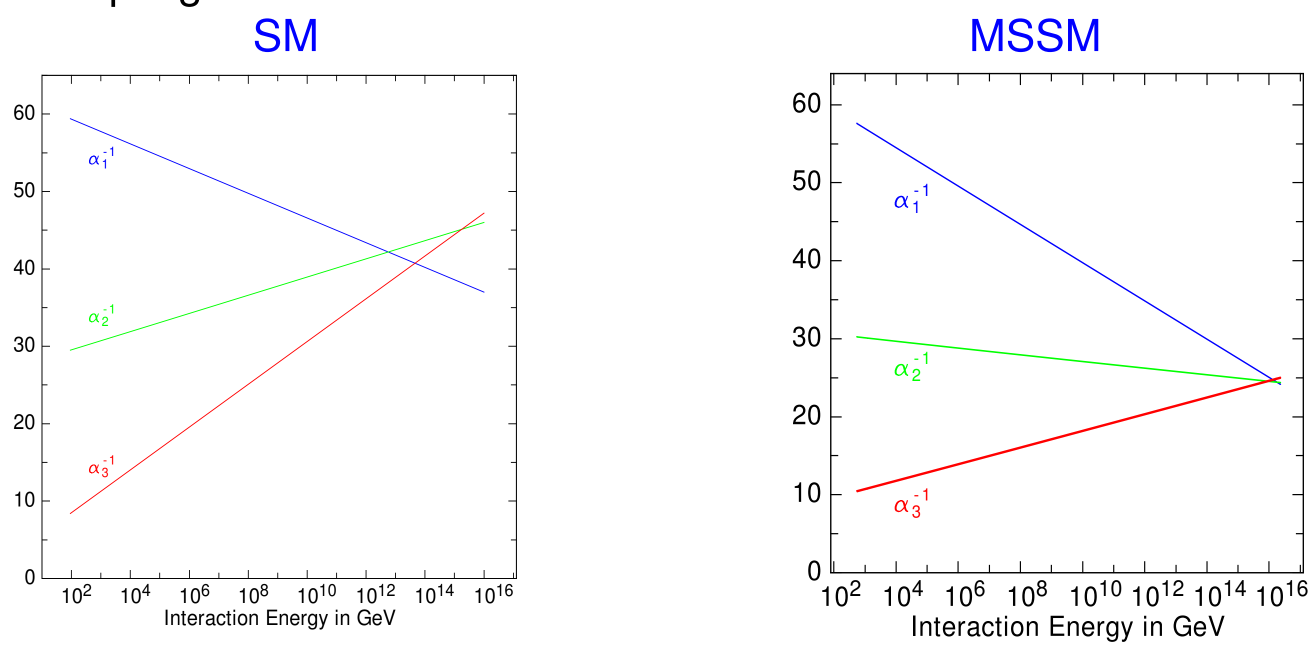
L. Roszkowski, astro-ph/0404052

- What is the origin of the observed baryon asymmetry?

Why extending the SM

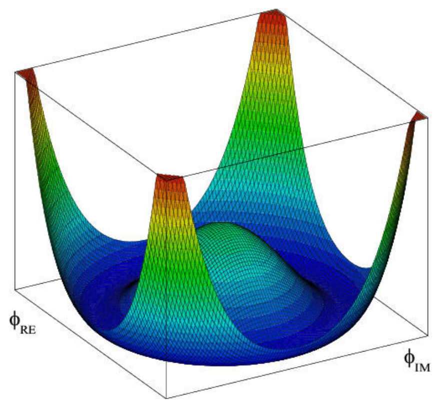
- How to combine gravity with the SM?
  possible way: local Supersymmetry (SUSY) implies gravity
- SM particles can be put in multiplets of larger gauge groups
  - in $SU(5)$: $1 = \nu^c_R$, $5 = (d^c_{\alpha,R}, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, l_R)$
  - in $SO(10)$: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

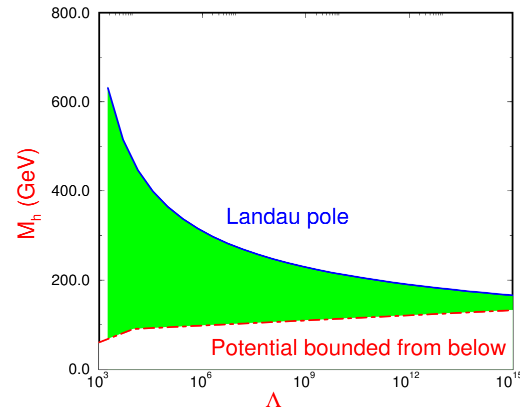
  However there are two problems in the SM but not in SUSY:
  - proton decay (also in SUSY $SU(5)$ a problem)
  - gauge coupling unification



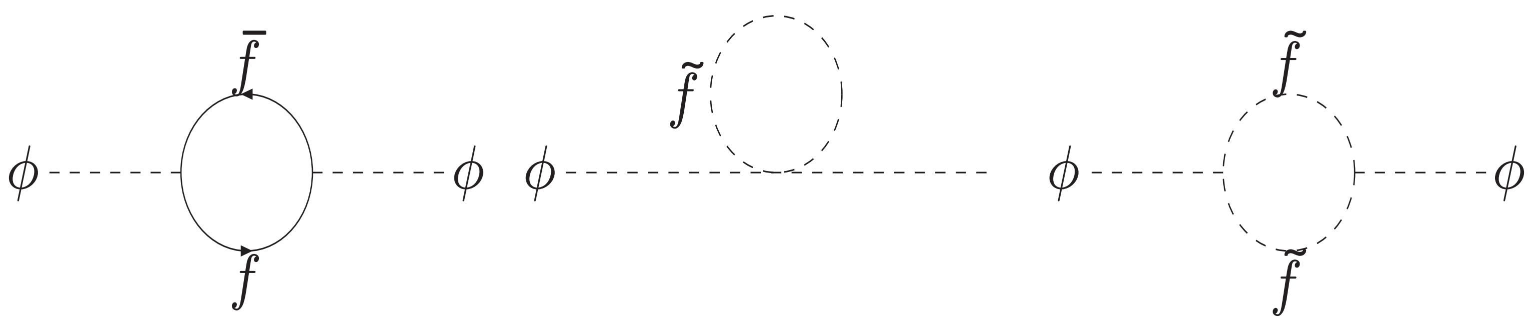
Why extending the SM?

- SM & $m_h = 125.1$ 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 (?)



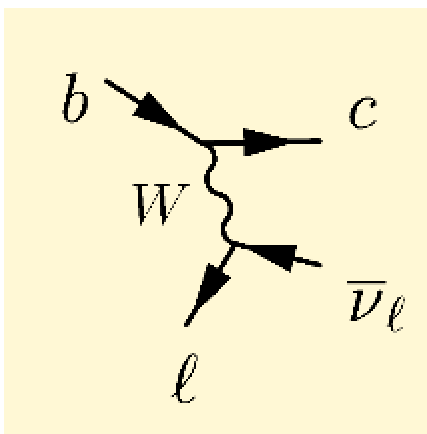
$\delta m_h^2 \propto \Lambda^2$: Sensitivity to highest mass scale of unknown physics

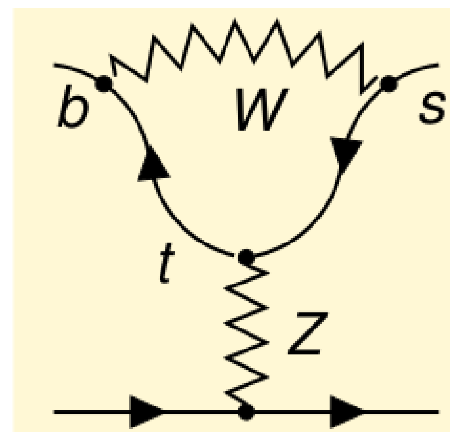
Why extending the SM

Most of the data can be explained (extremely well) by the SM, but there are anomalies

- $(g-2)_\mu$
- b-physics:

$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}l\bar{\nu})} \; (l = e, \mu) \qquad , \; R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$





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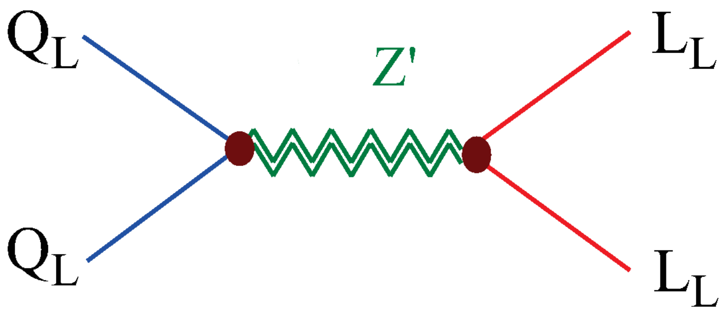
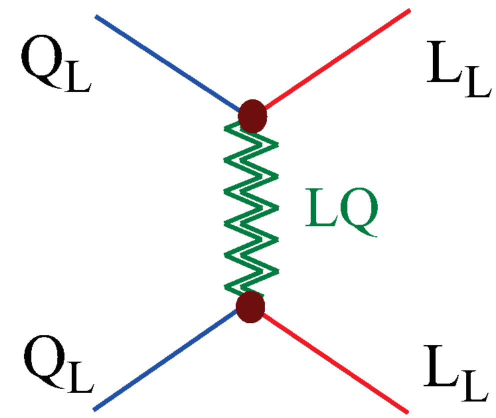
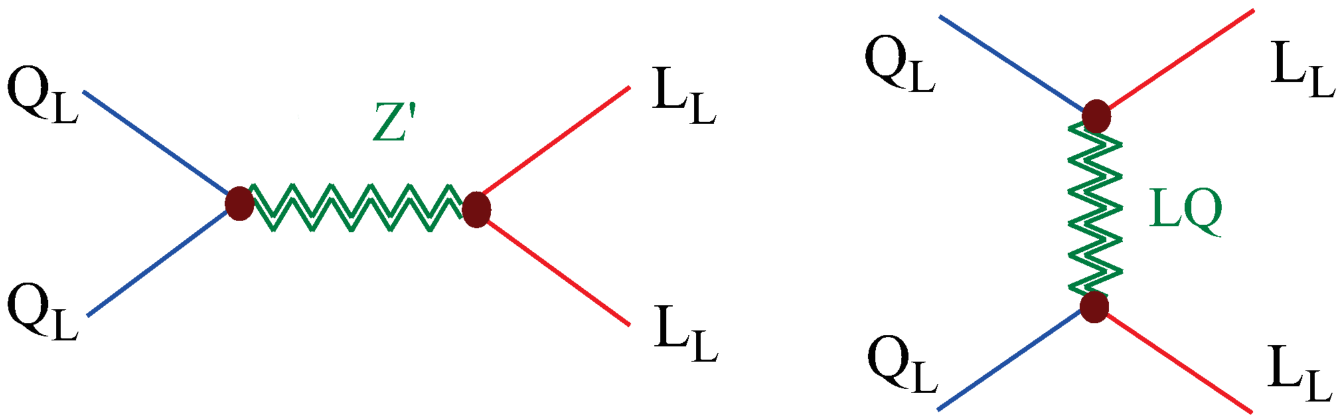

Q$_L$
Q$_L$
Z'
L$_L$
L$_L$


Q$_L$
Q$_L$
LQ
L$_L$
L$_L$

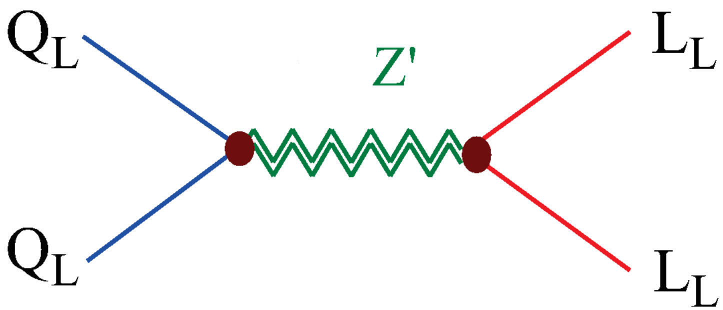


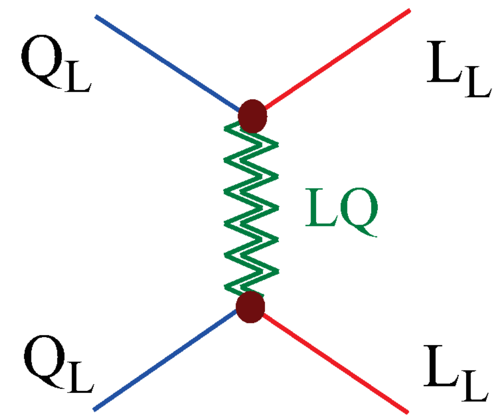
Roads to UV completions

non-perturbative TeV-scale dynamics (non-renormalizable models)

- breaking of a global symmetry:scalar leptoquark (LQ) as pseudo-Nambu-Goldstone-boson (Gripaios, ’10; Gripaios, Nardecchia, Renner, ’14, . . .)
- new strong interactions: vector LQ (or W',Z') as technifermion resonances (Barbieri et al. ’15; Buttazzo et al. ’16; Barbieri et al. ’17, . . .)
- extra space dimensions: W', Z' as Kaluza-Klein excitations (Megias, Quiros, Salas ’17; Megias, Panico, Pujolas, Quiros ’17, . . .)

b-physics: ‘simplified models’ + roads to UV completions



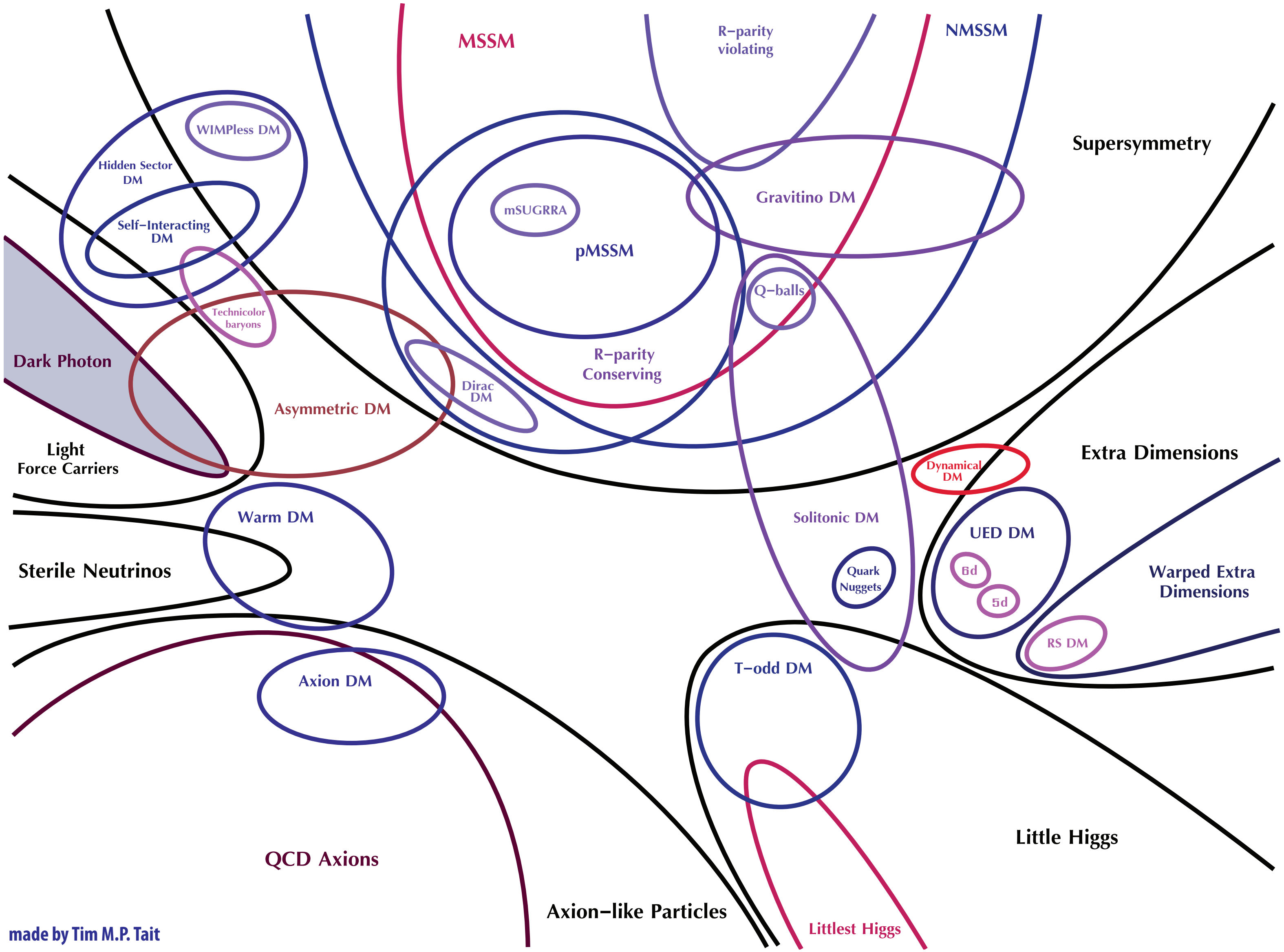


Roads to UV completions

perturbative TeV-scale dynamics (renormalizable models)

- extend Standard Model gauge group, e.g.
  $SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times SU(3)_L \times SU(2)_R$ or
  $SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(4) \times SU(2)_L \times SU(2)_R$
  (Buras et al., ’13; Calibbi, Crivellin, Li, ’17; Assad, Fornal, Grinstein, ’17, . . .)
- supersymmetry, with/without R-parity (Hiller, Schmaltz, ’14; Becirevic et al. ’16; Kitahara, Nierste, Tremper, ’16, . . .)

Model space & dark matter



J.L. Feng et al., arXiv:1401.6085

	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

requirements

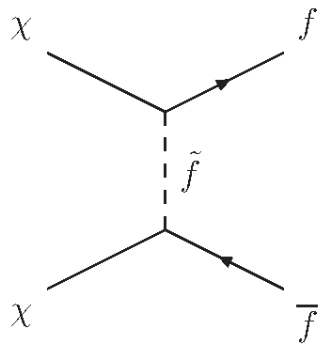
- electrically neutral ('dark')
- either stable: usually via discrete symmetry: R-parity, KK-parity, Z_n, ...
  or life-time larger than age of universe
- massive and weakly interacting as $\Omega_{DM} h^2 \simeq 0.1$

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

generic signal at high energy colliders

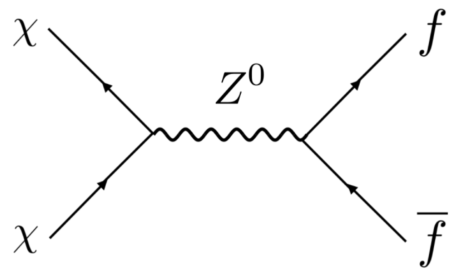
- large missing transvers momentum / transverse energy

Dark matter, annihilation processes



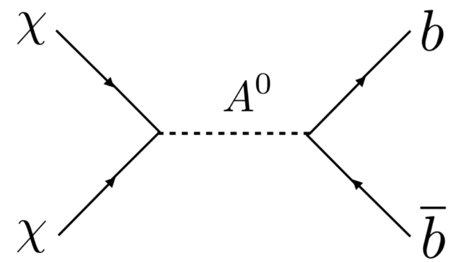
bino

bulk region

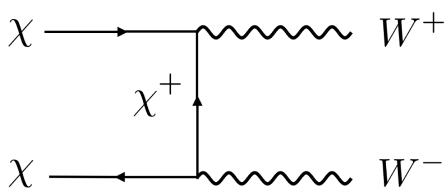


wino, higgsino

focus-point region

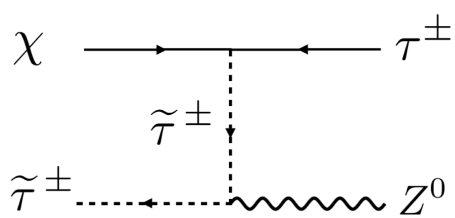


funnel region

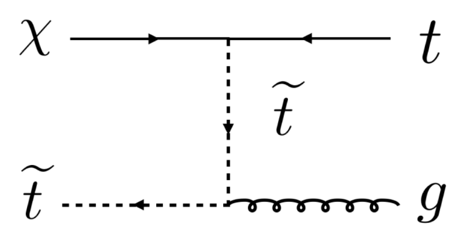


wino, higgsino

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-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

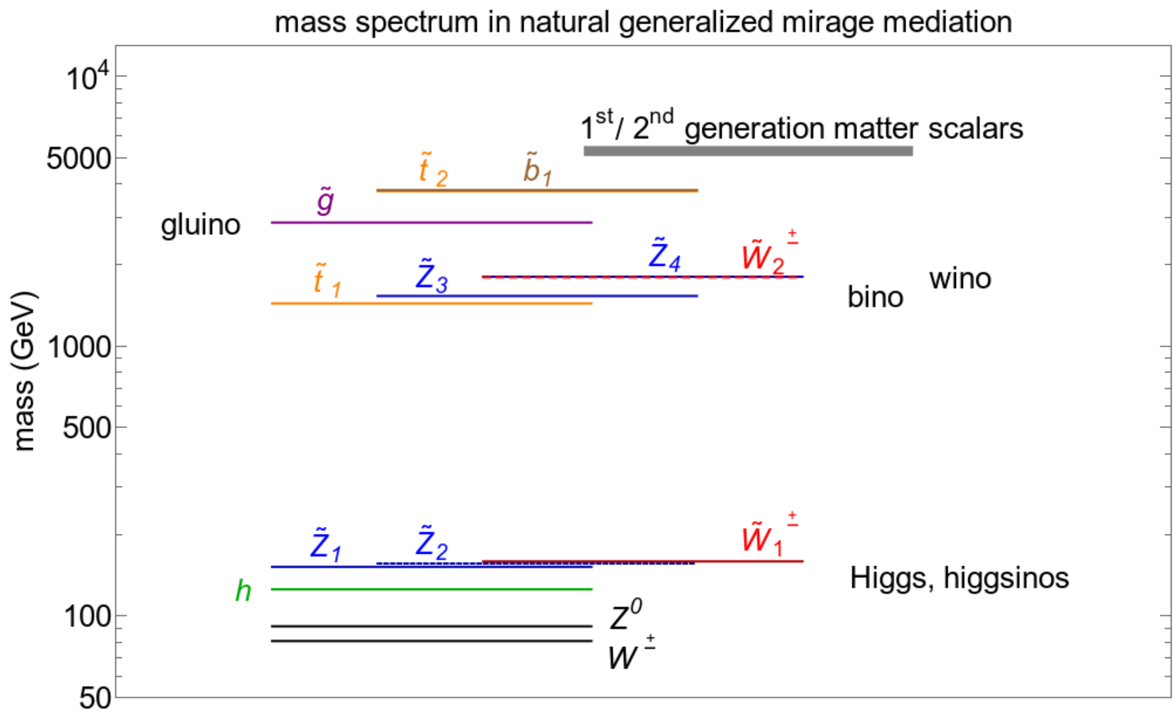
SUSY models give examples of all of these, so this is a good place to start with, even if DM has nothing to do with SUSY

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

Example: general Mirrage Mediation

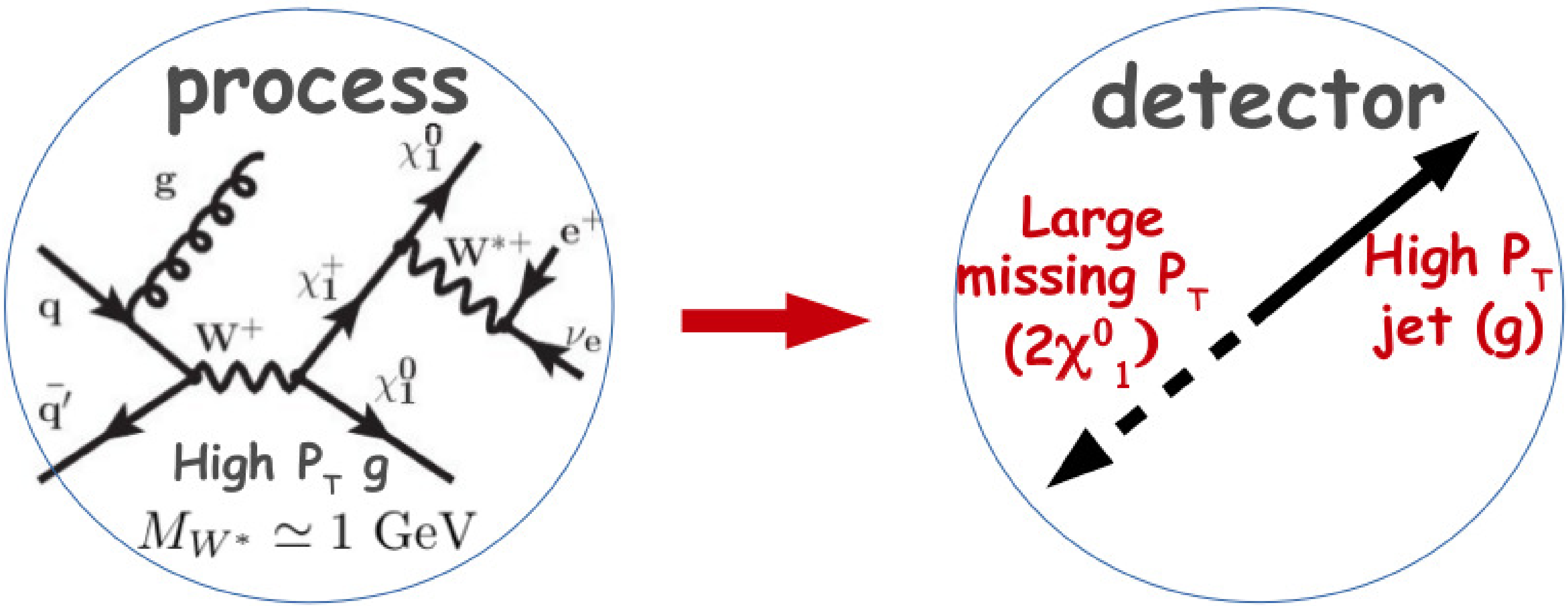
Different sources for soft SUSY breaking: moduli & AMSB

main consequence: gaugino masses unify at a (vastly) different scale then gauge couplings



H. Baer, V. Barger, H. Serce and X. Tata, arXiv:1610.06205

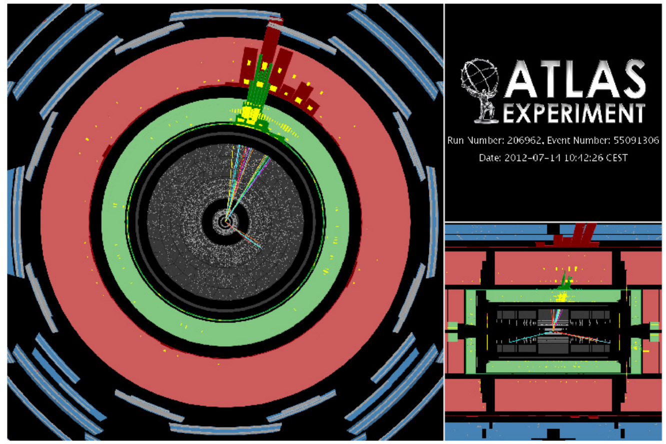
Most challenging case: only higgsinos accessible but nothing else and ΔM to small for any leptonic signature



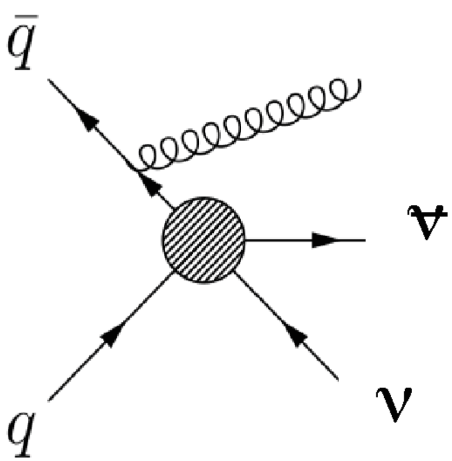
The only way to probe compressed higgsinos is a mono-jet signature:
'Where the Sidewalk Ends? ...' Alves, Izaguirre,Wacker 2011

related work C. Han et al., arXiv:1310.4274; P. Schwaller, J. Zurita, arXiv:1312.7350; Z. Han et al, arXiv:1401.1235; H. Baer et al.,arXiv:1401.1162, ...

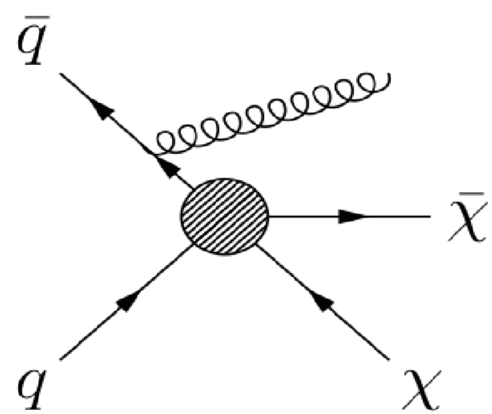
Monojets



$p_{\mathrm{T}}^{\mathrm{jet1}} = 852\,\mathrm{GeV},\ \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} = 863\,\mathrm{GeV}$



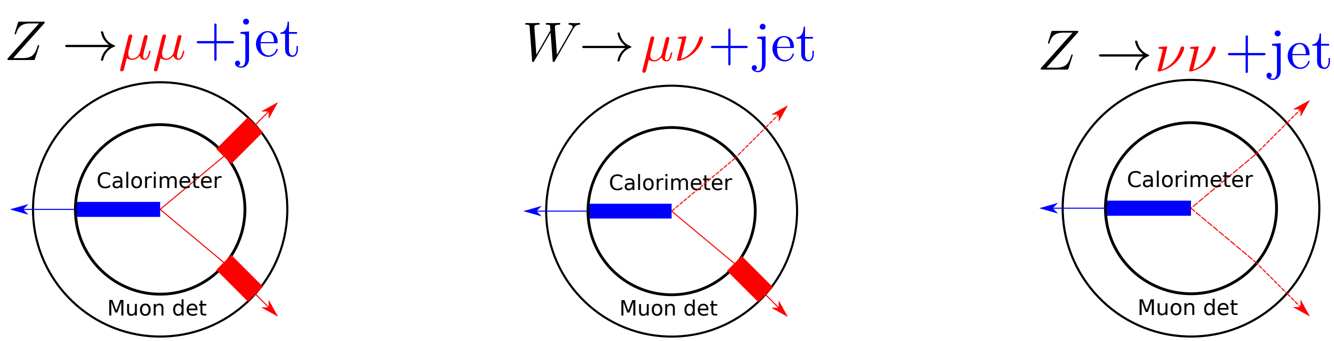
$Z \to \nu\nu$ background



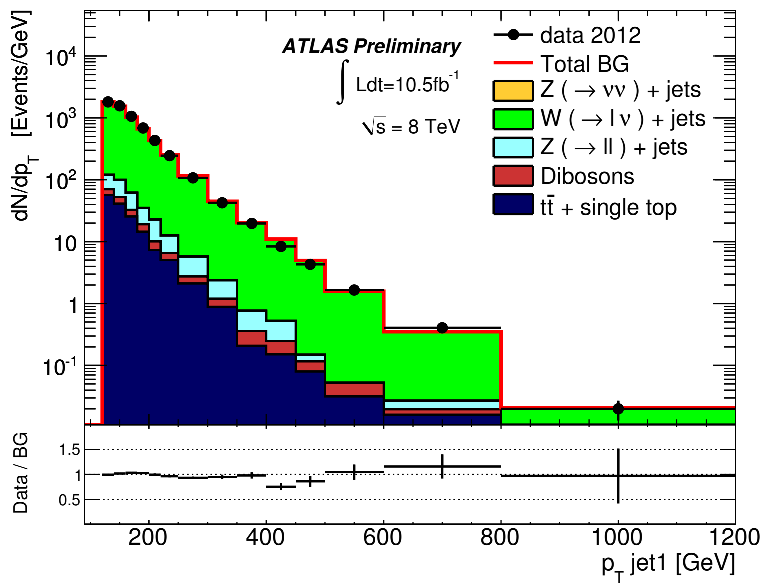
DM Signal

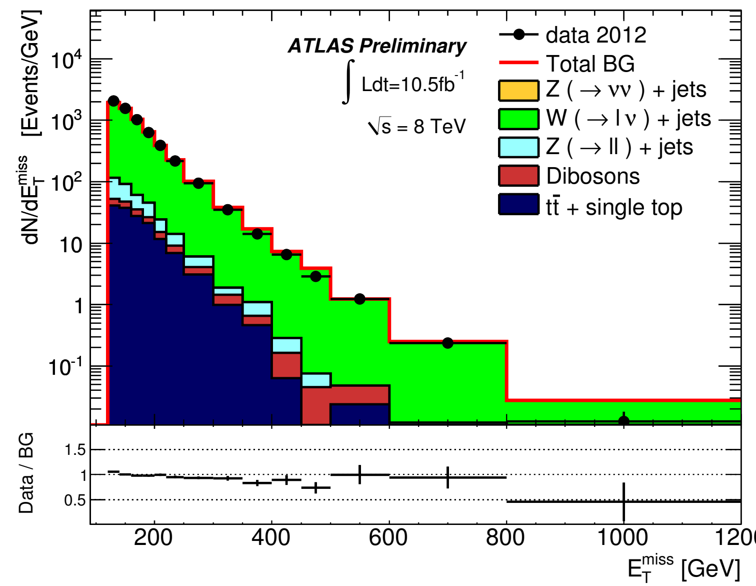
Estimating the $Z \to \nu\nu$ background

- 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 $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$: 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



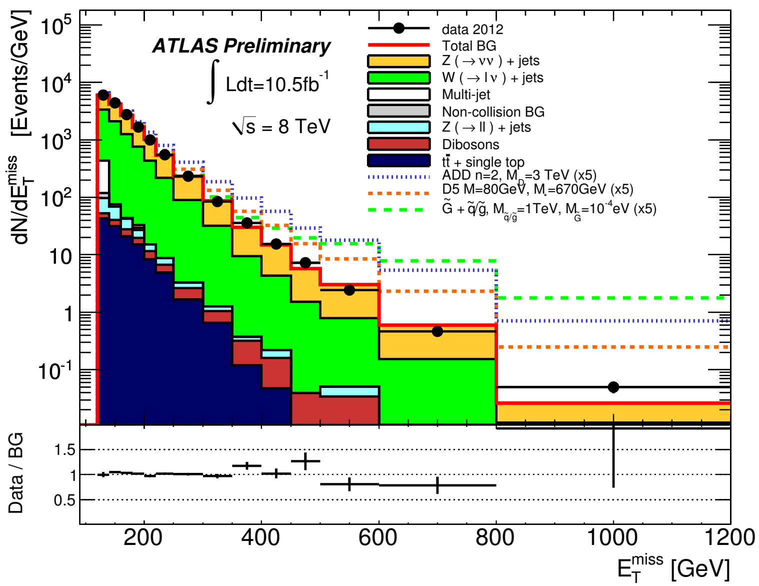
Monojets

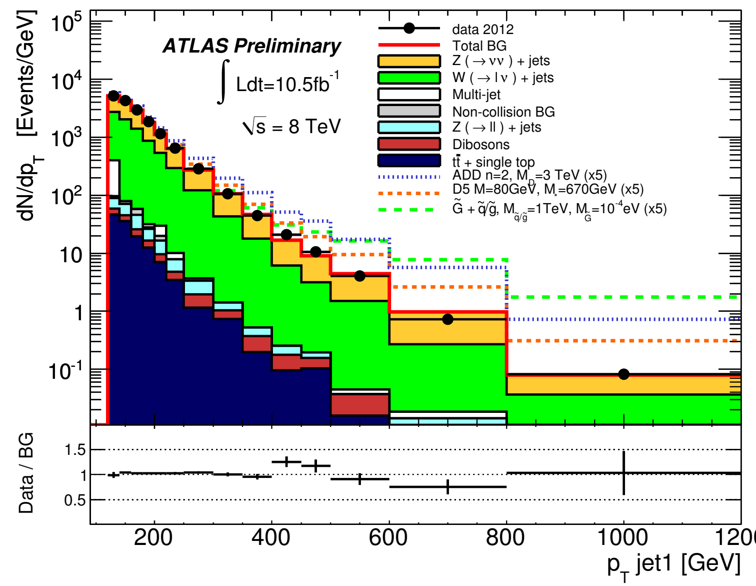




control region (ATLAS-CONF-2012-147)

Monojets



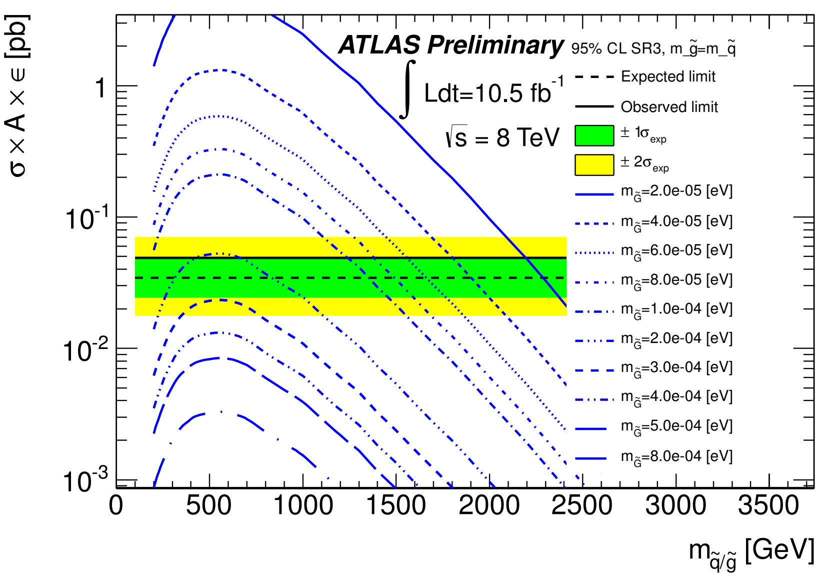


signal region SR1 (ATLAS-CONF-2012-147)

Monojets, 8 TeV

SUSY

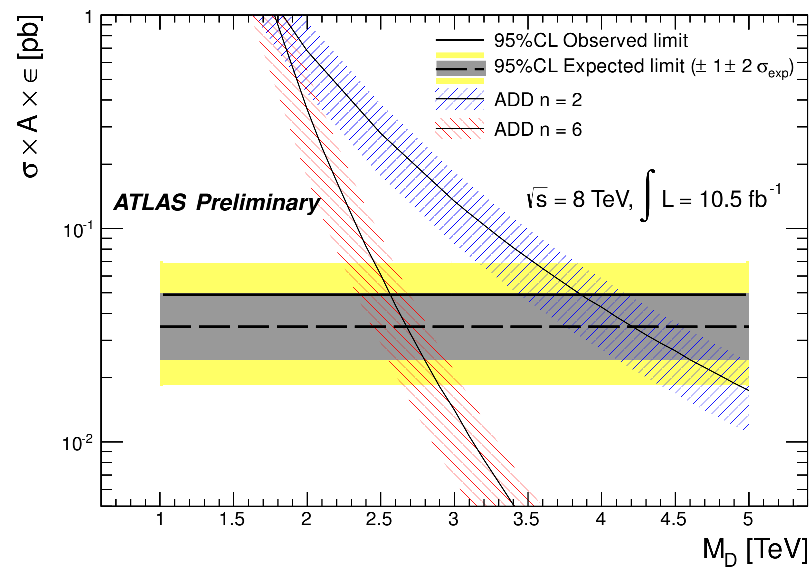
$\sigma(pp \to \tilde{G} + \tilde{q}/\tilde{g}) \propto \frac{1}{m^2_{\tilde{G}}}$



extra dimensions

$M^2_{Planck} \sim M_D^{2+n} R^n$

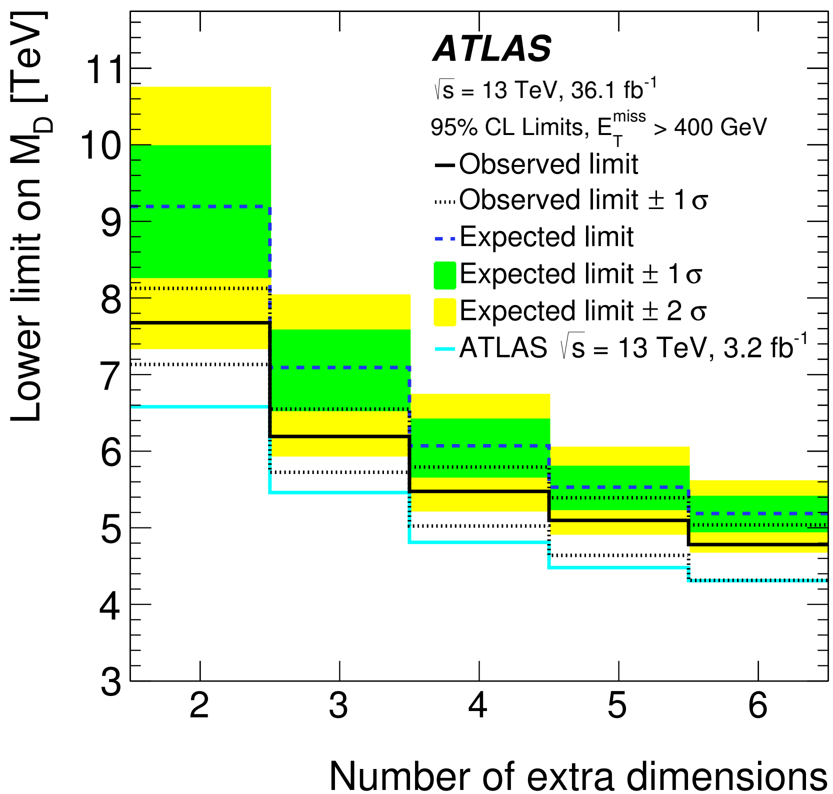
$\sigma(pp \to G^1 + j)$



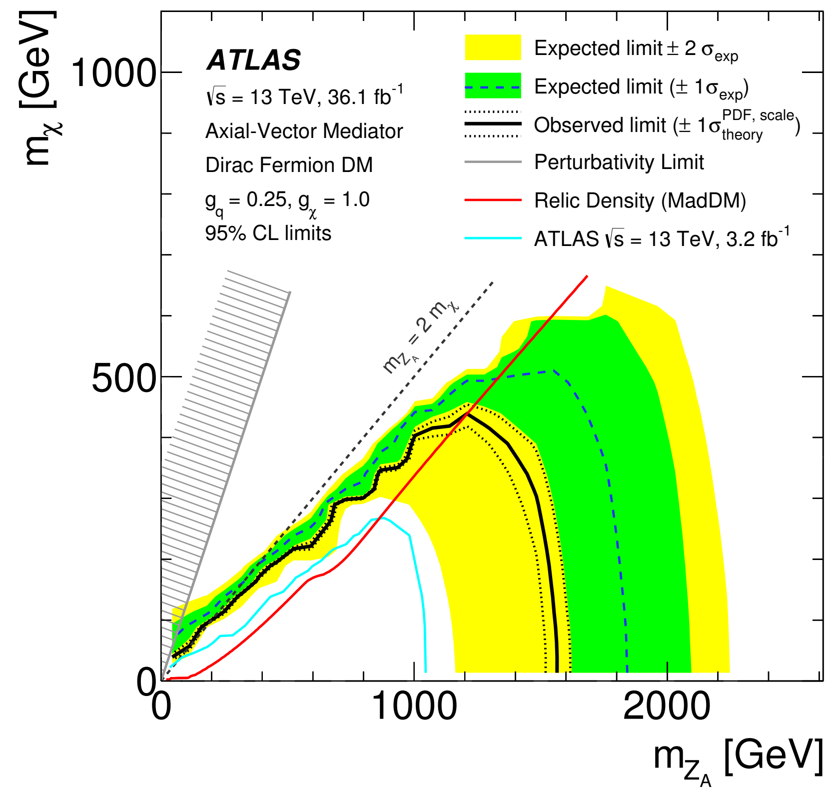
(ATLAS-CONF-2012-147; similar results by CMS, see arXiv:1408.3583)

Monojets, 13 TeV

extra dim.



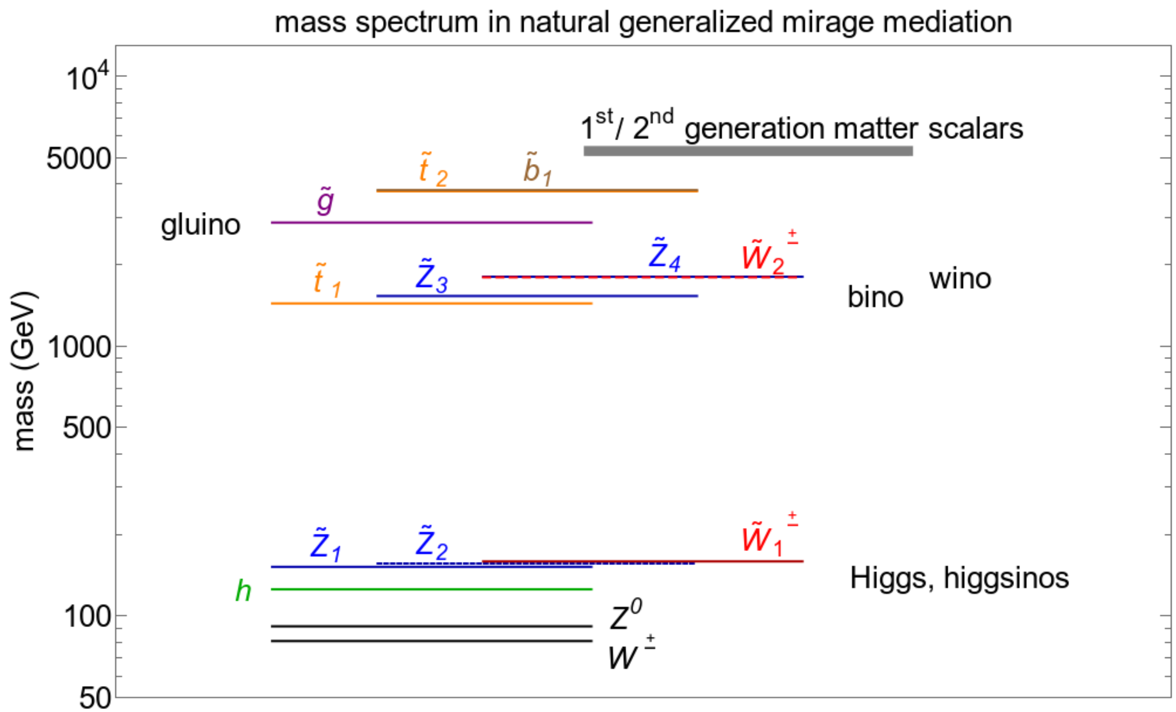
Z'-model



ATLAS arXiv:1711.03301

Example: general Mirrage Mediation

Different sources for soft SUSY breaking: moduli & AMSB
main consequence: gaugino masses unify at a (vastly) different scale then gauge couplings

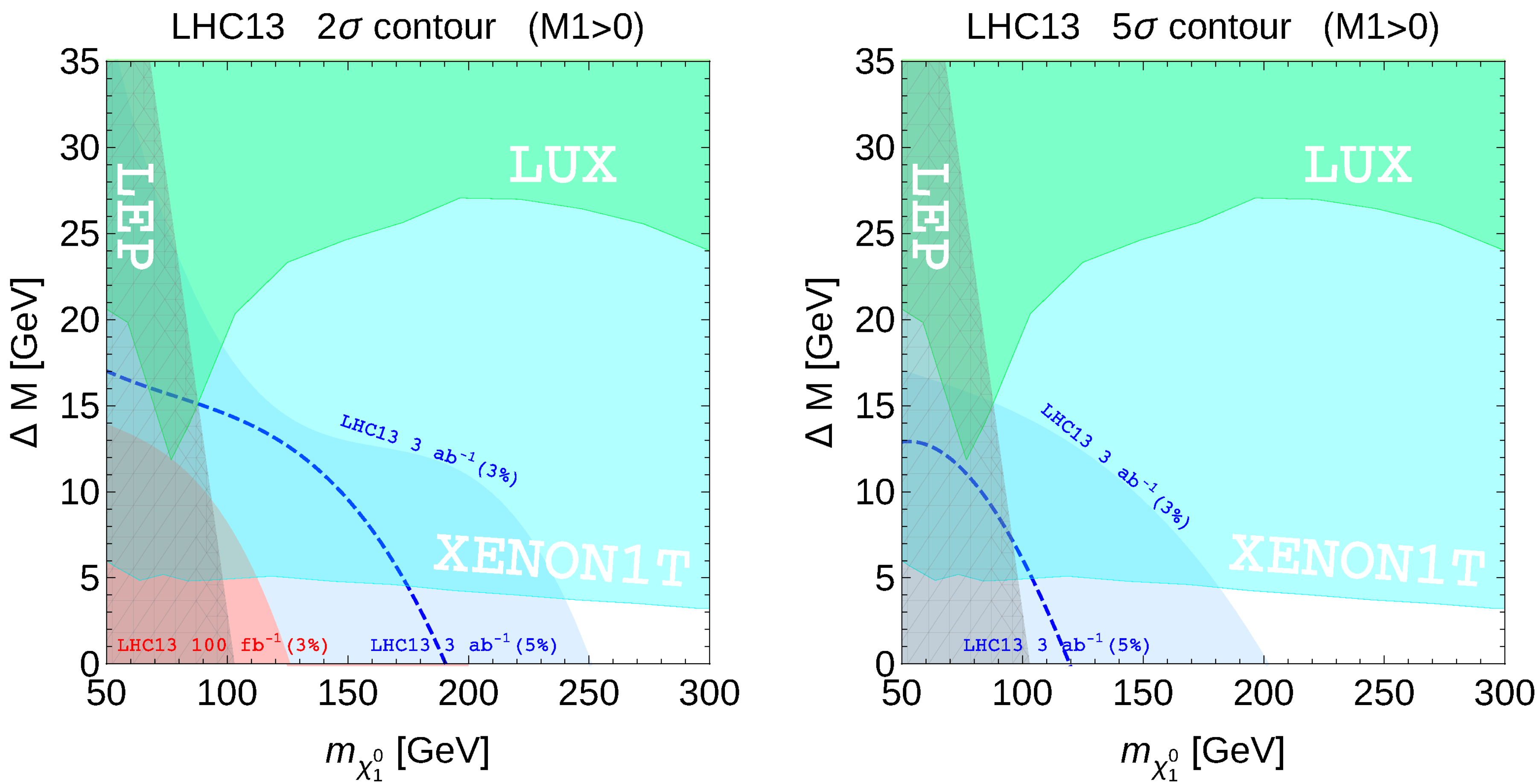


H. Baer, V. Barger, H. Serce and X. Tata, arXiv:1610.06205

Dark matter: extra ingredient needed, e.g. singlino of NMSSM

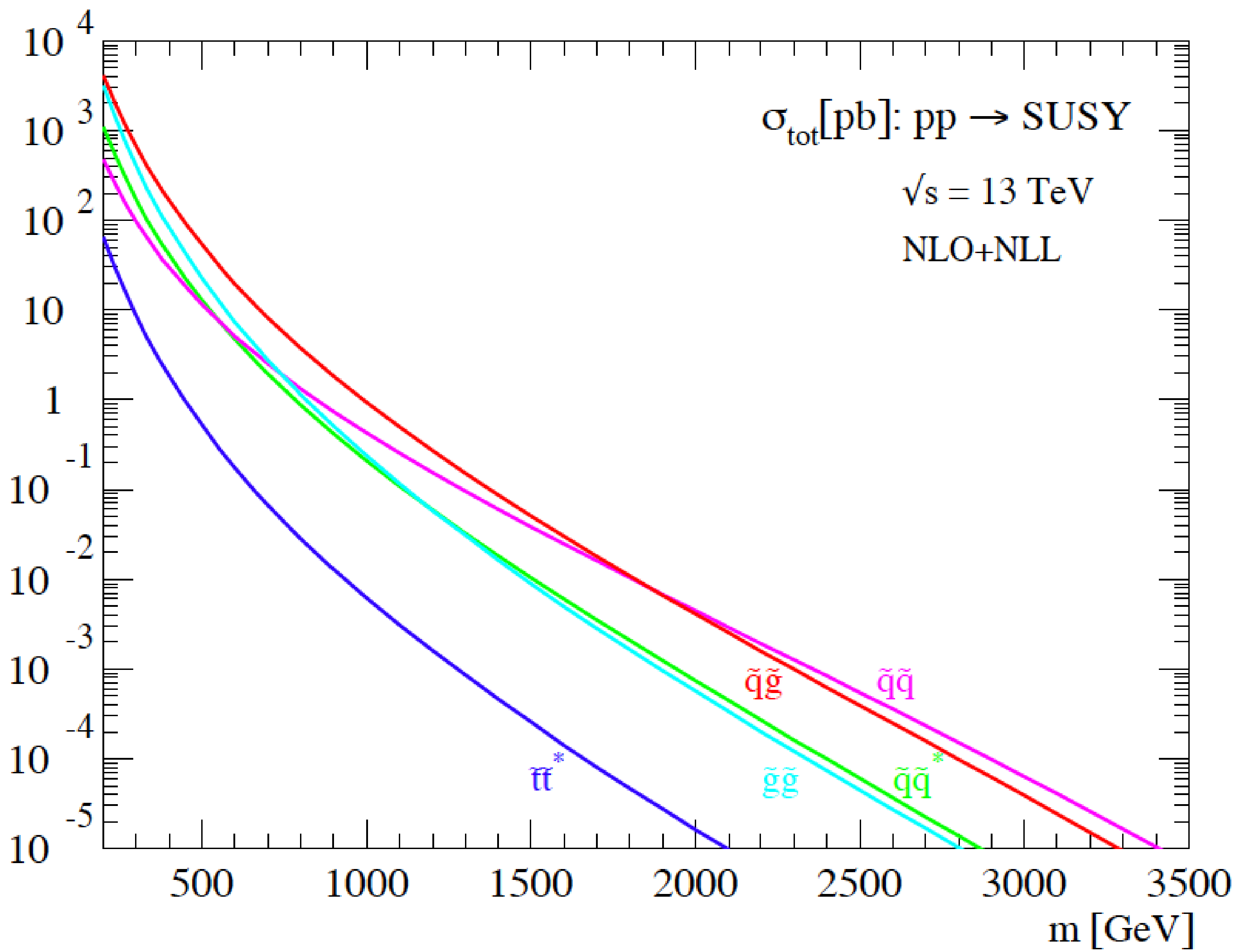
Complementarity: LHC @ 13 TeV versus DM direct detection

exclusion reach | discovery reach



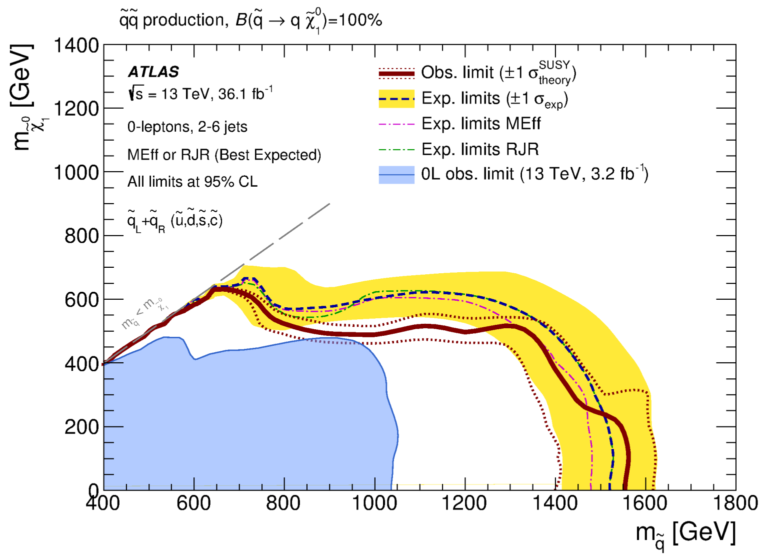
D. Barducci, A. Belyaev, A. Bharucha, WP, V. Sanz, arXiv:1504.02472

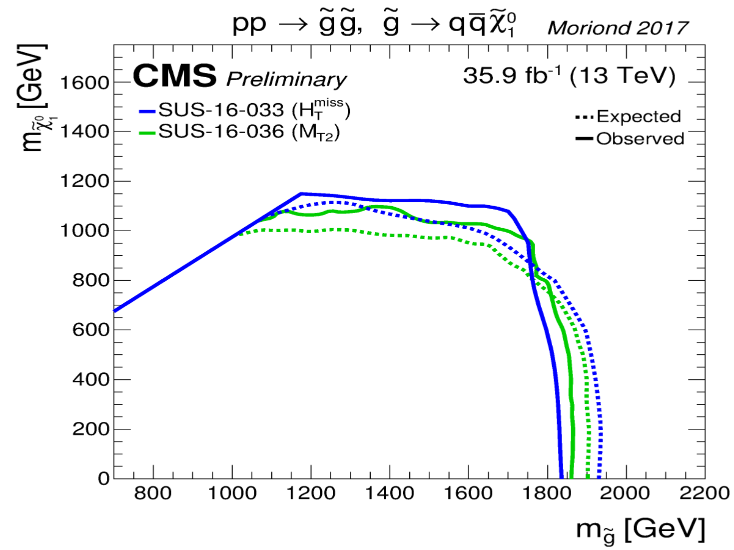
Pair production of SUSY particles

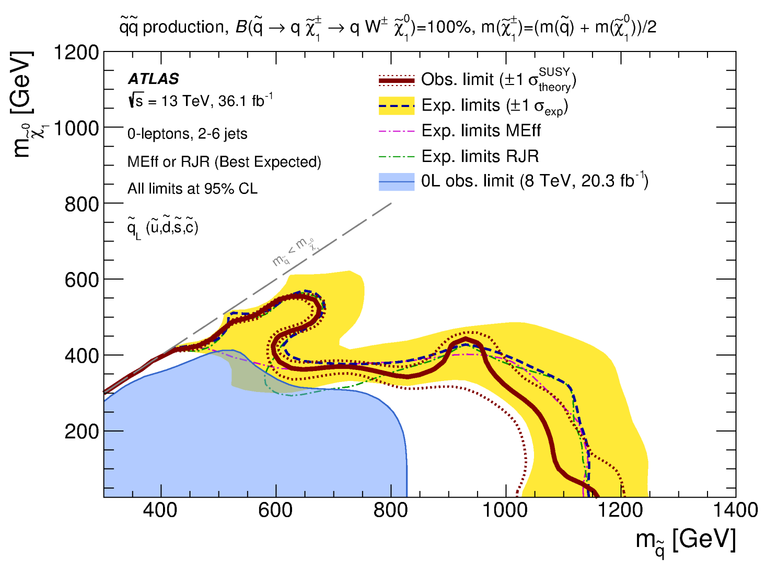


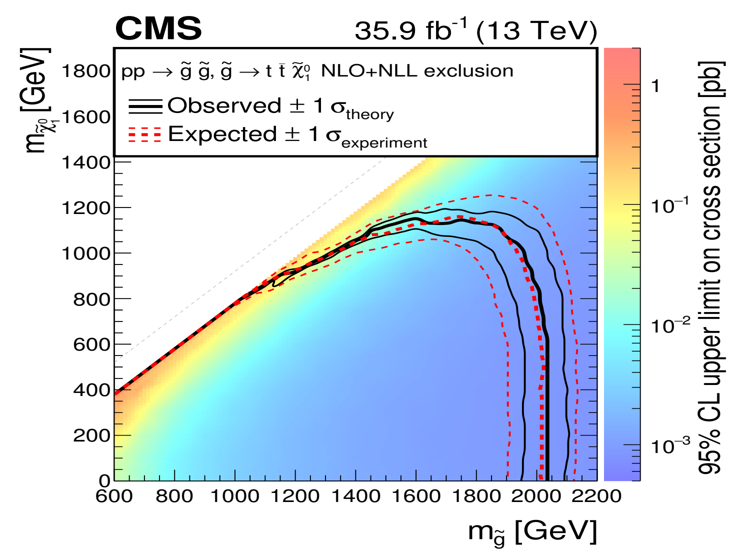
M. Krämer, M. Mühlleitner, arXiv:1501.06655

Examples for SUSY searches 13 TeV data





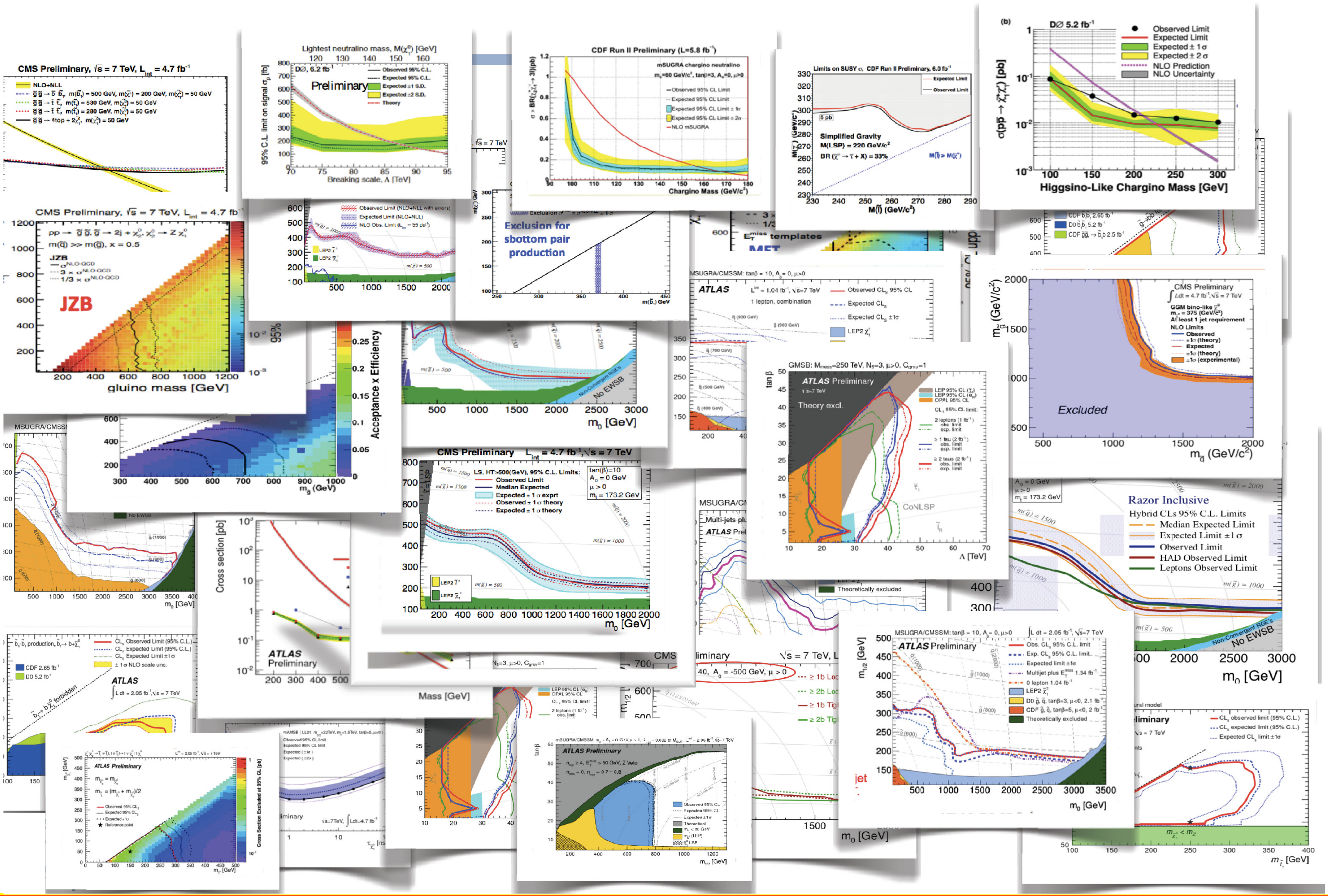




arXiv:1712.02332

arXiv:1710.11188

also other BSM searches, so far nothing ...



Concluding remarks

- Standard Model agrees very well with data so far
- Several reasons for extensions: fermion masses & mixings, dark matter, unification of forces . . .
- LHC severely constrains BSM extension, in particular
  - heavy resonances in the s-channel like Z'
  - DM-models leading signals with hard jets/leptons + missing energy
- no conclusive BSM signal so far, but might still be hidden in the data
  $\Rightarrow$ need good knowledge of tails of distributions
  $\Rightarrow$ requires still much more work