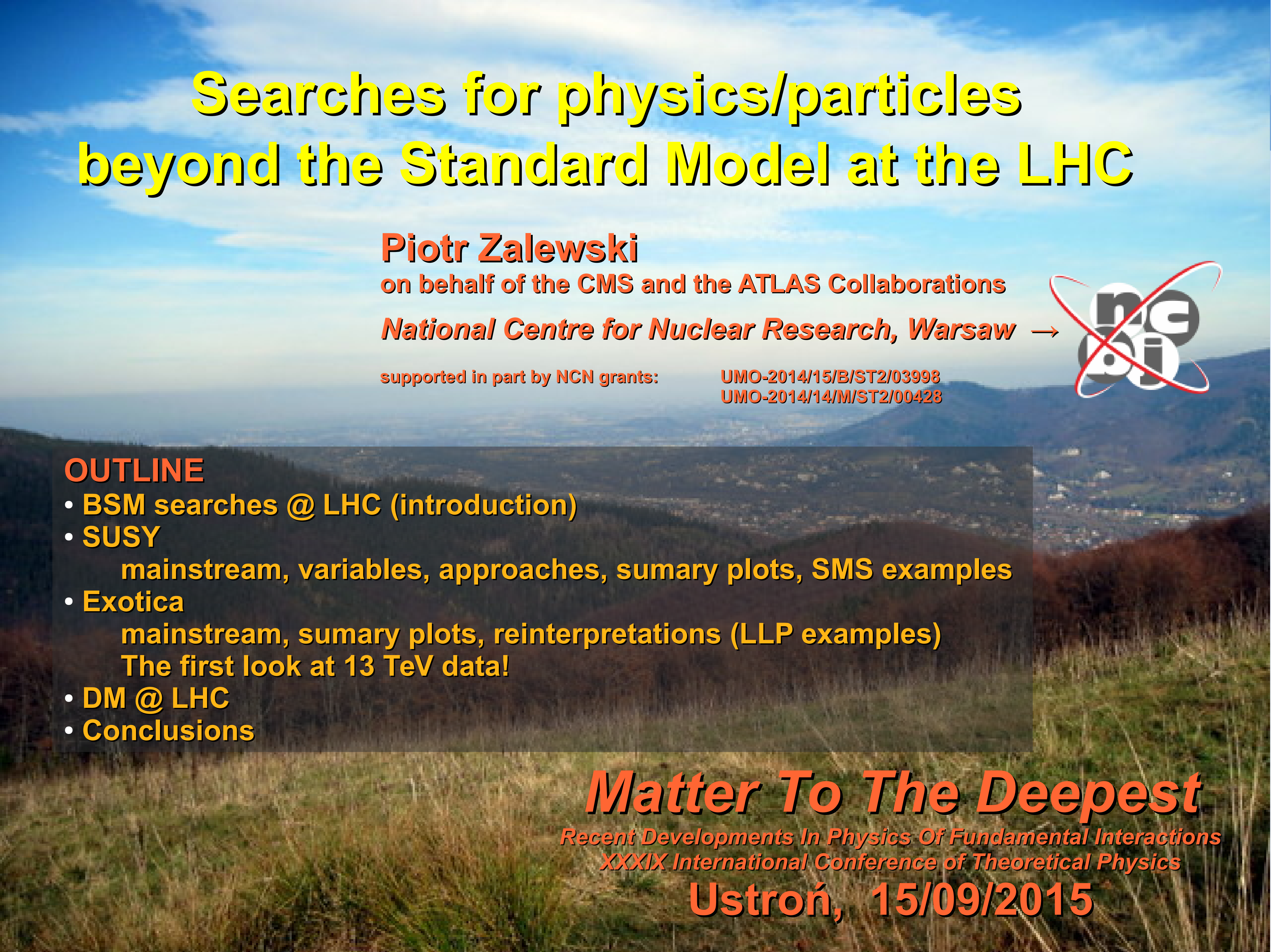


Searches for physics/particles beyond the Standard Model at the LHC

Piotr Zalewski
on behalf of the CMS and the ATLAS Collaborations
National Centre for Nuclear Research, Warsaw →

supported in part by NCN grants: UMO-2014/15/B/ST2/03998
UMO-2014/14/M/ST2/00428

OUTLINE

- BSM searches @ LHC (introduction)
- SUSY
  mainstream, variables, approaches, sumary plots, SMS examples
- Exotica
  mainstream, sumary plots, reinterpretations (LLP examples)
  The first look at 13 TeV data!
- DM @ LHC
- Conclusions

Matter To The Deepest

Recent Developments In Physics Of Fundamental Interactions
XXXIX International Conference of Theoretical Physics

Ustroń, 15/09/2015

Searches for BSM @ LHC (an introduction)

At the LHC BSM searches are organized into two big subgroups: SUSY and Exotic(a).
The later is a short name for all non - (mainstream) SUSY.
In the CMS, Exotica was divided further to establish Beyond 2 Generation (B2G) subgroup.

What is needed to perform searches for direct BSM phenomena?

- Well performing collider + efficient & precise multi-purpose detectors (ATLAS & CMS).
- A choice of a search topology (several topologies for one phenomenon are possible and *vice versa:* several phenomena could be searched for in a given topology).
- Trigger: high level HLT (software) but not forgeting level one L1 (instrumental).
- Physics objects (jet, E_T^{miss}, leptons, photon): definition, performance, validation, time stability *etc.*

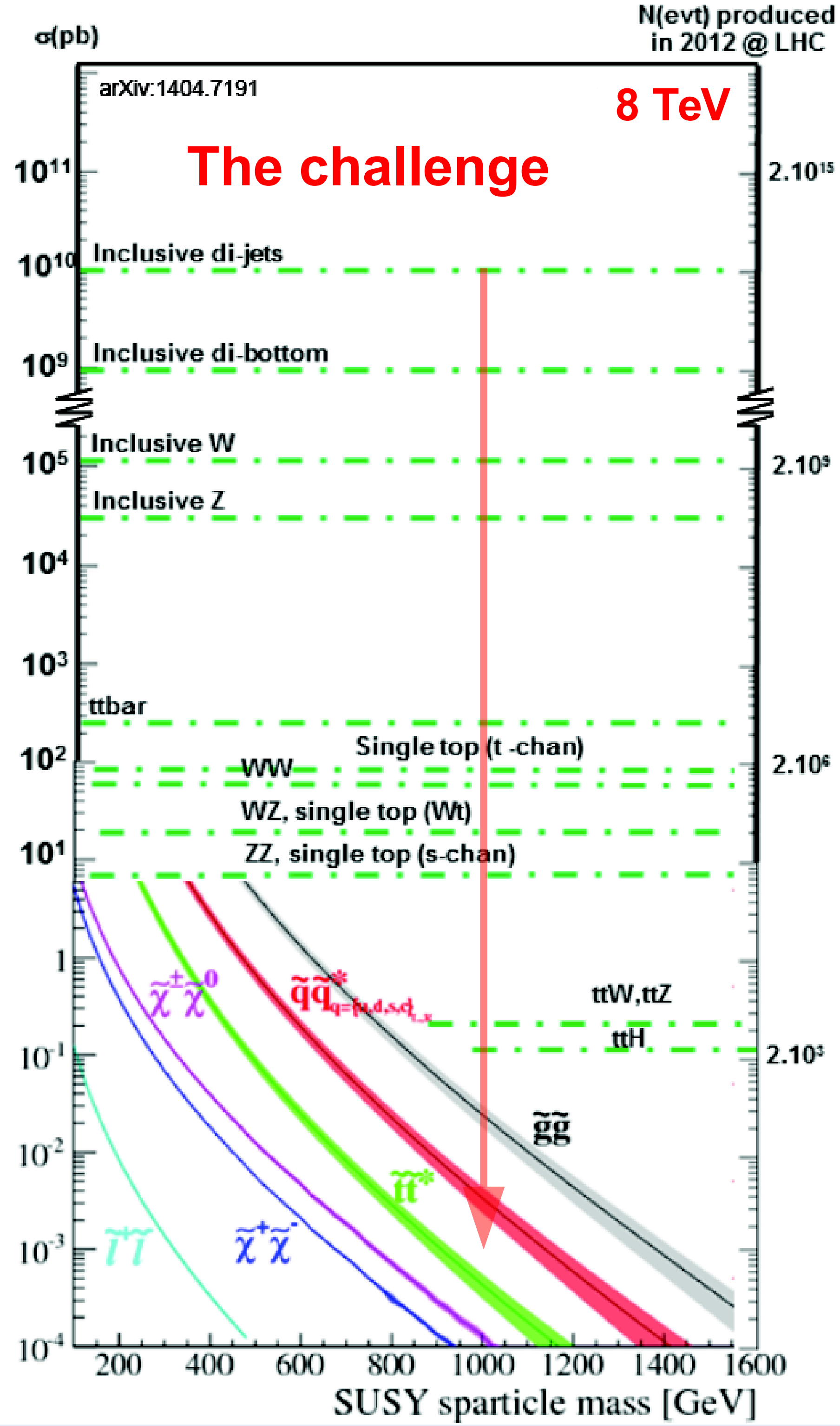
  It is done for all analyses, but some searches need custom objects (long-lived, monopoles …).

- Preselection: to assure homogeneous trigger efficiency (and suppress background).
- A choice of signal sensitive variables (at least two).

  Definition of one (or several) Signal enriched Regions SR (both criteria satisfied).
  What rest form Control Regions CR in which at least one criterion is not satisfied.
  Use data driven methods to find out and validate transfer factors from CR to SR to obtain a data driven estimate of background level in the SR (including background systematics – not explained here), however, while data driven methods are preferred, sometimes it is necessary to use MC to estimate the level of background.
  It could be more complicated if ”shape analysis” is used instead of ”counting experiment”.

- Claim discovery if statistically significant excess is found or, if not, interpret the result in term of constraints on selected models.

SUSY



The challenge

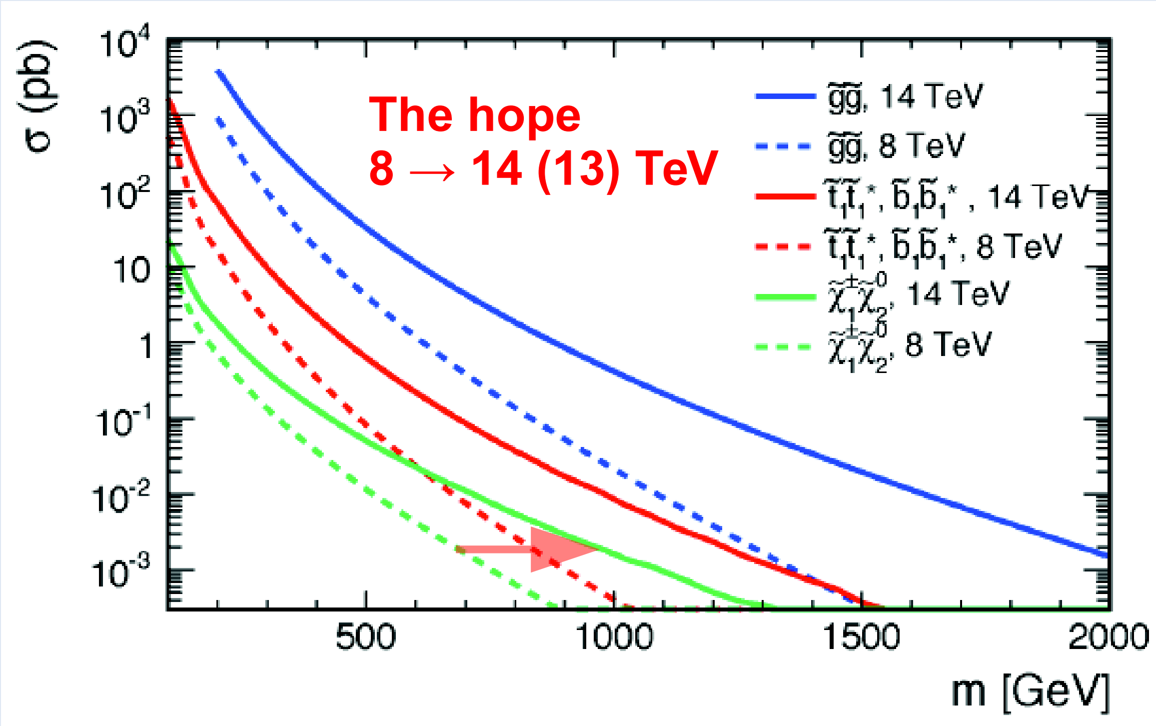
8 TeV

SUSY is the benchmark for general BSM searches
(many SUSY searches could be reinterpreted in other models)

From inclusive searches for missing transverse energy E_T^{miss}
and given number of jets, leptons (SS, OS *etc.*), photons

via targeted searches for specific scenarios

to exploration of challenging (*eg.* compressed spectra)
or "less standard" (RPV, non-prompt decays *etc.*) ones.



The hope
8 → 14 (13) TeV

Searching for SUSY

What makes our (experimentalists) life hard?

- Triggering on soft signals
- Background estimation (using data driven methods whenever possible)
- Background systematics (which limits sensitivity for challenging scenarios)

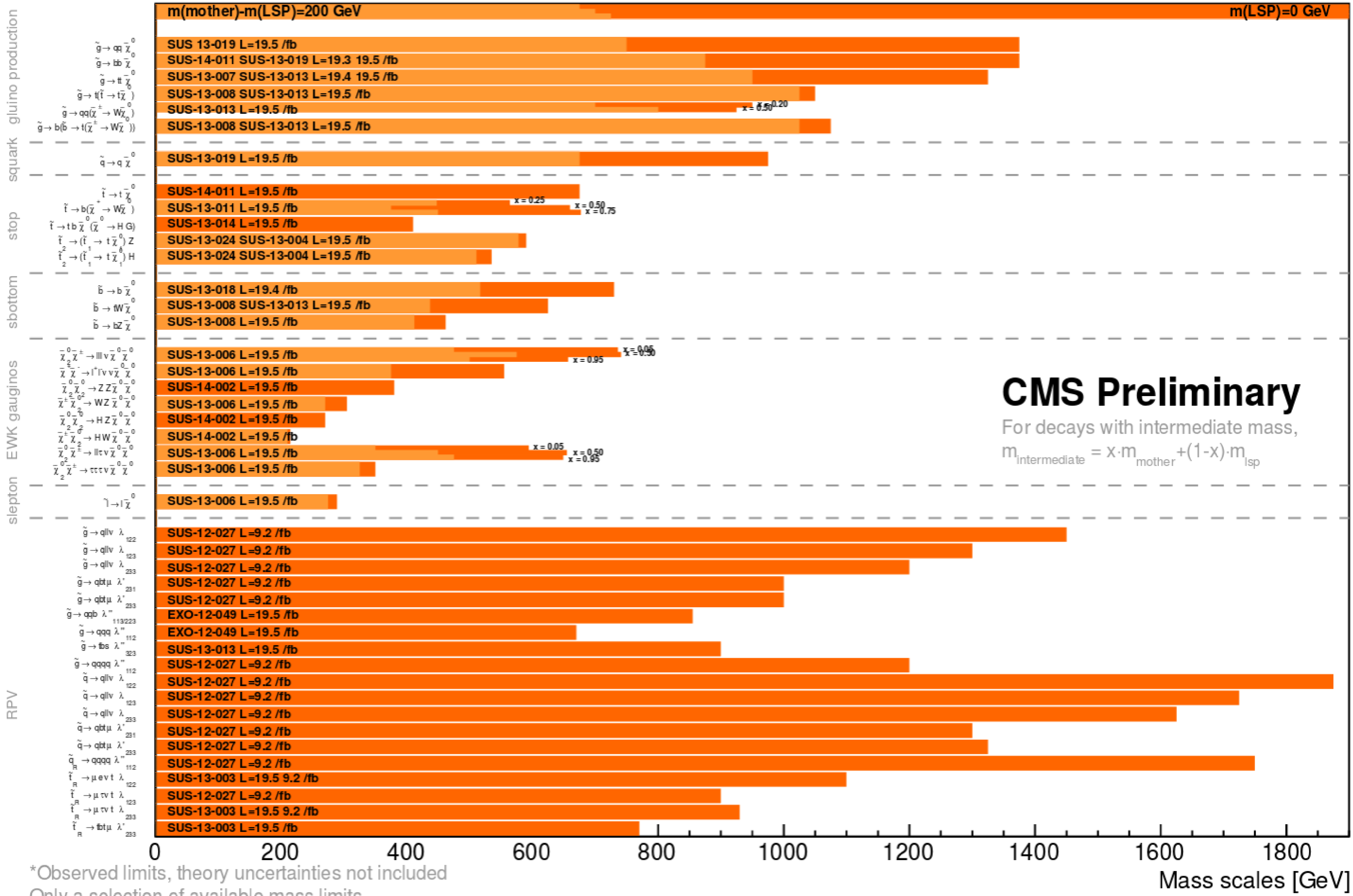
What help us?

- Growing set of kinematical variables E_T^{miss}, H_T, S_T ($\rightarrow S_T^{lept.}$), razor (→ super-razor) *etc.*
- Multivariate analyses
- New models/signatures, analysis methods, background suppression ideas, *etc.*

What guide us?

- Searches are inspired and/or interpreted
  - → in specific models (CMSSM, NUHM, NMSSM *etc.*)
  - → phenomenological pMSSM
  - → simplified models SMS
- Our desire for discovery of BSM physics

Summary of CMS SUSY Results* in SMS framework



*Observed limits, theory uncertainties not included

Only a selection of available mass limits

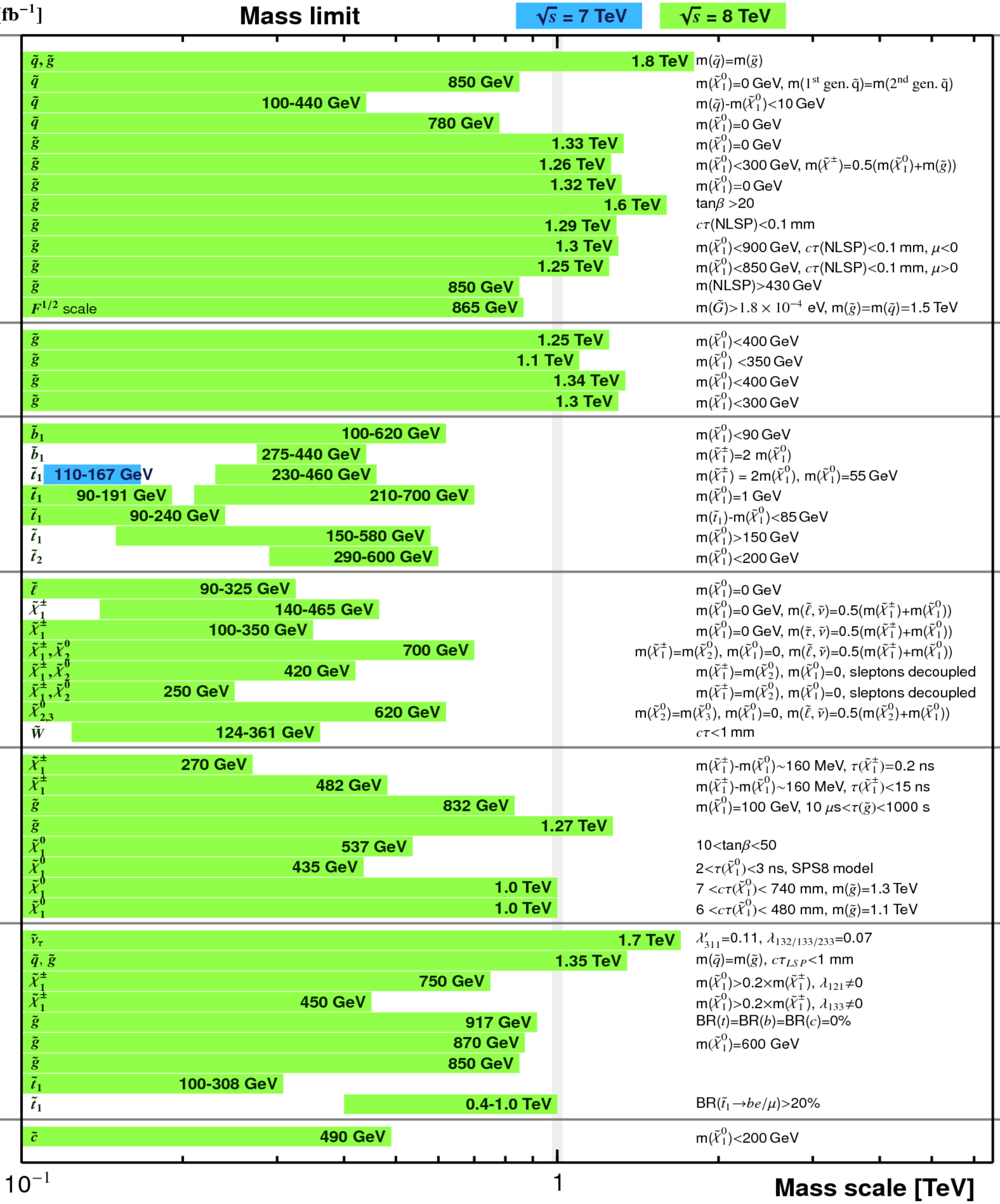
Probe *up to* the quoted mass limit

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV



	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.8 TeV	$m(\tilde{q})$=$m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$ 100-440 GeV	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$<10 GeV	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 780 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$ 1.26 TeV	$m(\tilde{\chi}^0_1)$<300 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}^0_1)$+$m(\tilde{g})$)	1507.05525
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}^0_1)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}^0_1)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})$>1.8×10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}^0_1)$ <350 GeV	1308.1841
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}^0_1)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}^0_1)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}^\pm_1)$=2 $m(\tilde{\chi}^0_1)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$ 🟦 110-167 GeV 230-460 GeV	$m(\tilde{\chi}^\pm_1)$ = 2$m(\tilde{\chi}^0_1)$, $m(\tilde{\chi}^0_1)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 90-191 GeV 210-700 GeV	$m(\tilde{\chi}^0_1)$=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}^0_1)$>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	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}^0_1)$=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	$\tilde{\chi}^\pm_1$ 140-465 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 100-350 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1407.0350
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 700 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 420 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 250 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$ 620 GeV	$m(\tilde{\chi}^0_2)$=$m(\tilde{\chi}^0_3)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^0_2)$+$m(\tilde{\chi}^0_1)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$ 124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^\pm_1$ 270 GeV	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$~160 MeV, $\tau(\tilde{\chi}^\pm_1)$=0.2 ns	1310.3675
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}^\pm_1$ 482 GeV	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$~160 MeV, $\tau(\tilde{\chi}^\pm_1)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 435 GeV	2<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$ 1.0 TeV	7 <$c\tau(\tilde{\chi}^0_1)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}^0_1$ 1.0 TeV	6 <$c\tau(\tilde{\chi}^0_1)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 750 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 450 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 870 GeV	$m(\tilde{\chi}^0_1)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$ 100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	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, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1501.01325

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

An example of multi-object SUSY searches

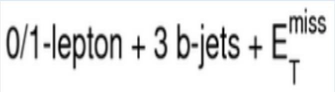
SUSY scenarios with the top squark as the lightest quark partner

SMS: simplified model spectra →

Gluino pair production, with subsequent decays to two top quarks and the LSP through either an on-shell (the upper diagram) or a virtual (the lower) top squark.

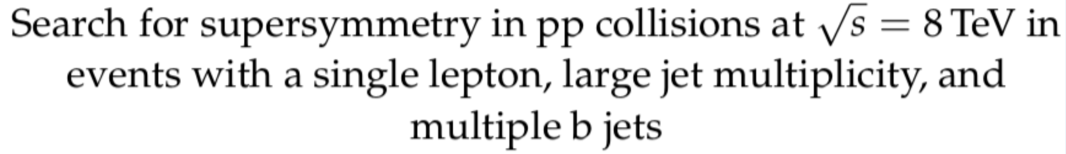
Summary of the searches for squarks and gluinos using $\sqrt{s} = 8$ TeV pp collisions with the ATLAS experiment at the LHC

arXiv:1507.05525



0/1-lepton + 3 b-jets + E_T^{miss}

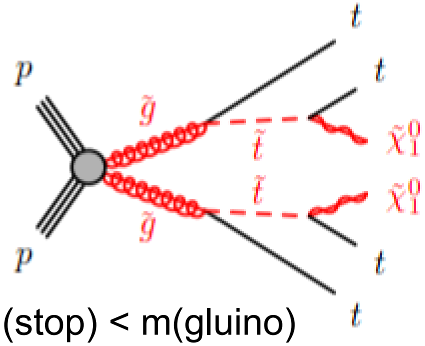
arXiv:1407.0600; JHEP 1410 (2014) 24



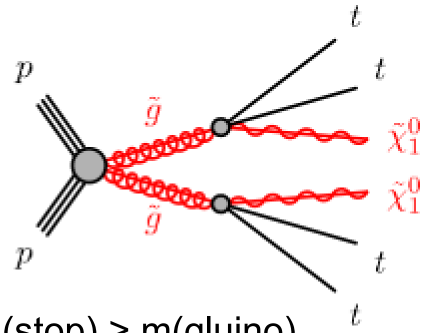
Search for supersymmetry in pp collisions at $\sqrt{s} = 8$ TeV in events with a single lepton, large jet multiplicity, and multiple b jets

CMS-SUS-13-007

arXiv:1311.4937
PLB 733 328 (2014)



m(stop) < m(gluino)



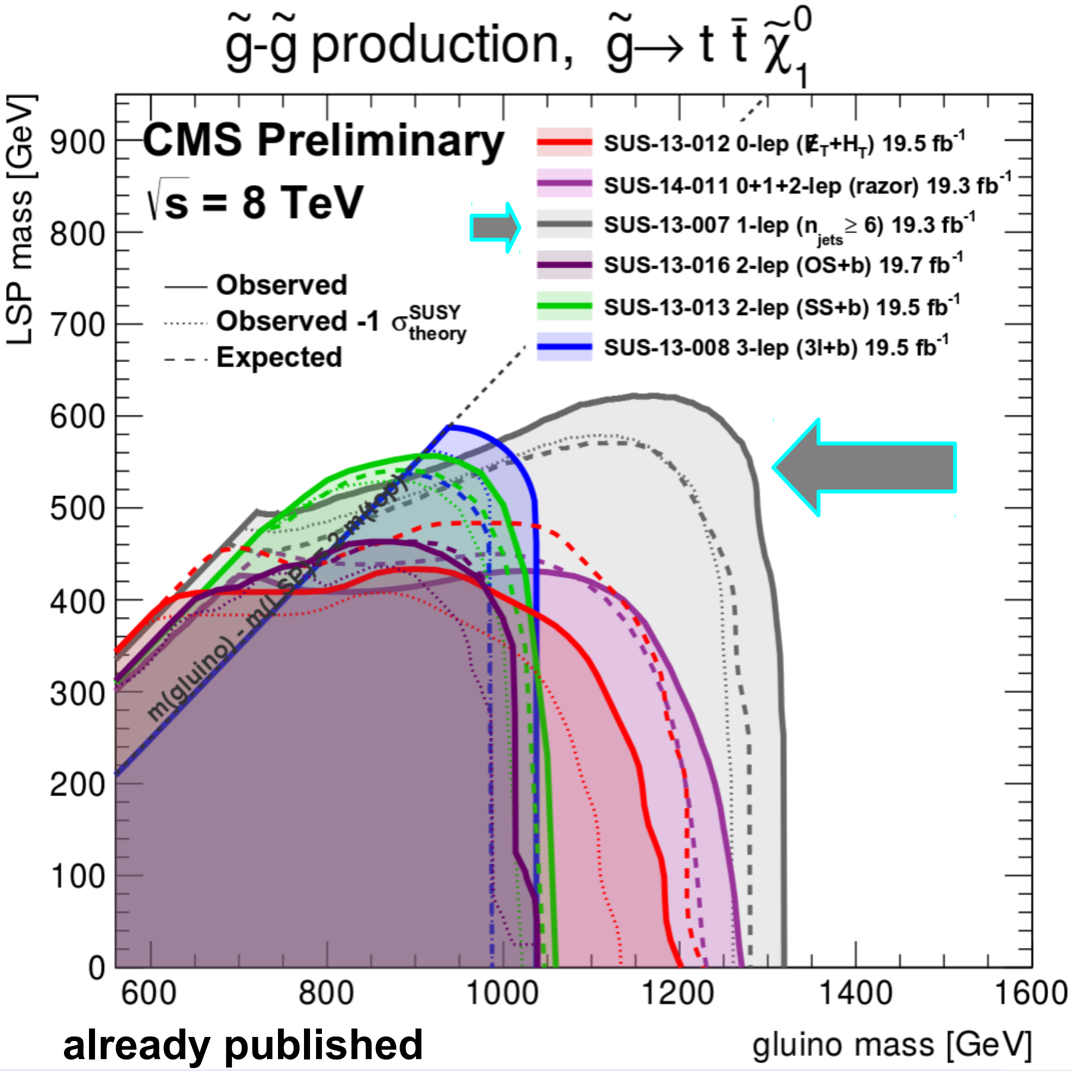
m(stop) > m(gluino)

Signature: 1 lepton (also 0 for ATLAS), E_T^{miss}, many jets of which multiple are b-tagged

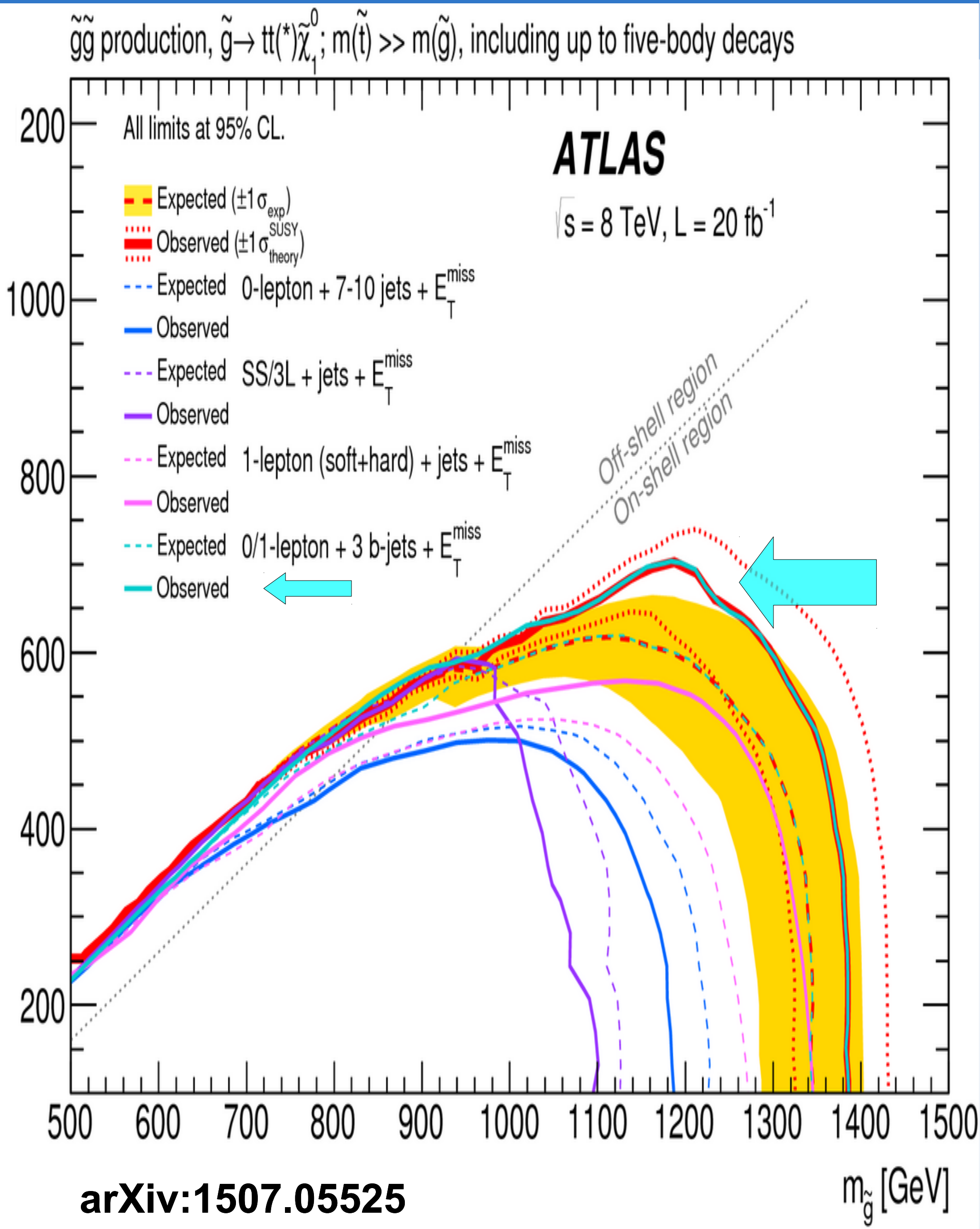
Dozens of different analyses performed by ATLAS and CMS to search for squarks and gluino production. Interpretation in several models including phenomenological pMSSM framework and SMS.

An example of multi-object SUSY searches

Results of analyses highlighted in the previous slide are depicted with arrows.



already published



arXiv:1507.05525
accepted by JHEP

2nd example: direct electroweakinos

Direct electroweak production of charginos and neutralinos (or sleptons) may dominate at the LHC if the strongly interacting SUSY particles are heavy.

The corresponding final states do not necessarily contain much hadronic activity and thus may have eluded detection.

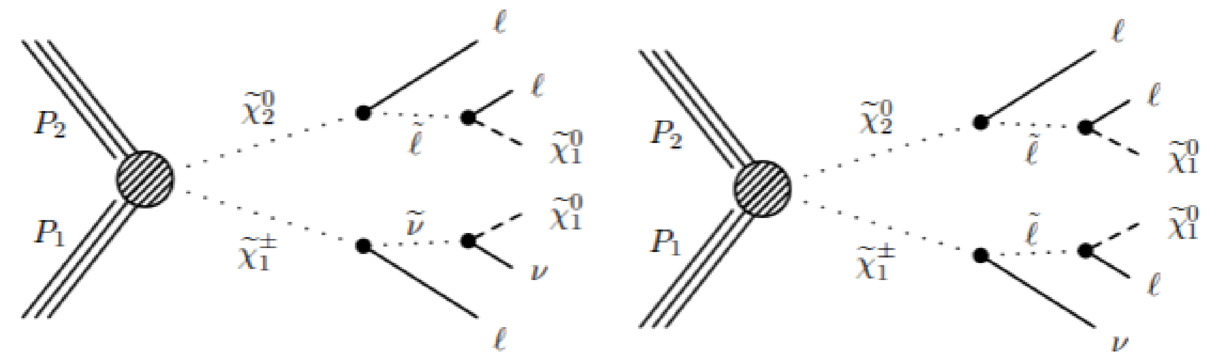
X-sections are much smaller than in the case of production *via* strong interaction.

The CMS Collaboration;

Searches for electroweak production of charginos,neutralinos, and sleptons decaying to leptons and W, Z, and Higgs bosons in pp collisions at 8 TeV;

arXiv:1405.7570, CMS-SUS-13-006

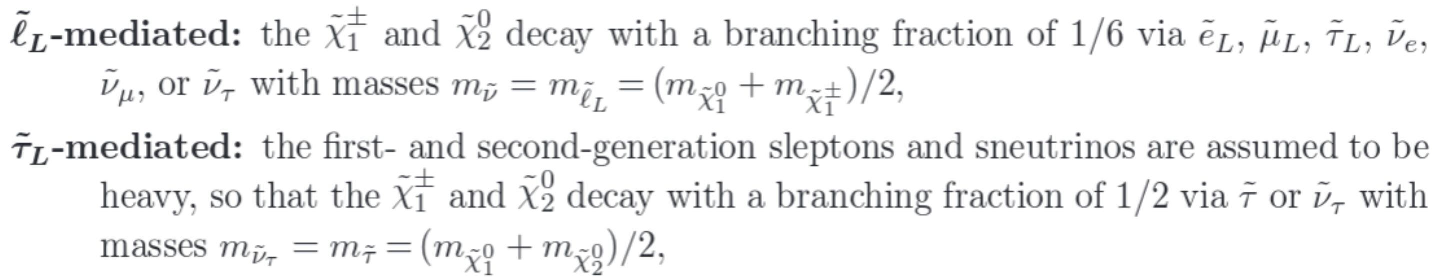
Eur. Phys. J. C (2014) 74:3036



The ATLAS Collaboration;

Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum in √s=8TeV pp collisions with the ATLAS detector;

arXiv:1402.7029;
(so called, 3L analysis);
JHEP 04 (2014)169



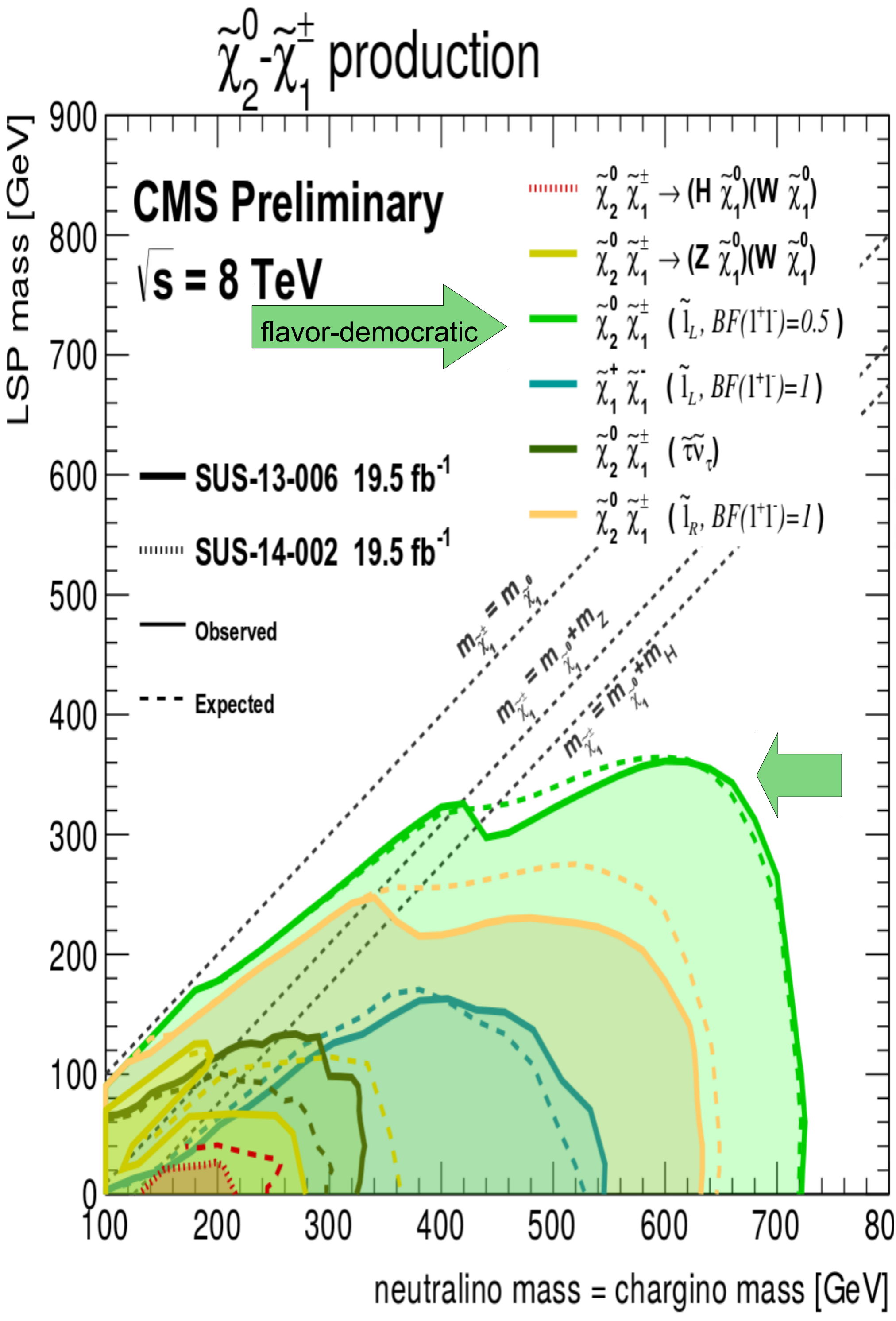
$\tilde{\ell}_L$-mediated: the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay with a branching fraction of 1/6 via $\tilde{e}_L$, $\tilde{\mu}_L$, $\tilde{\tau}_L$, $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, or $\tilde{\nu}_\tau$ with masses $m_{\tilde{\nu}} = m_{\tilde{\ell}_L} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^\pm})/2$,

$\tilde{\tau}_L$-mediated: the first- and second-generation sleptons and sneutrinos are assumed to be heavy, so that the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay with a branching fraction of 1/2 via $\tilde{\tau}$ or $\tilde{\nu}_\tau$ with masses $m_{\tilde{\nu}_\tau} = m_{\tilde{\tau}} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0})/2$,

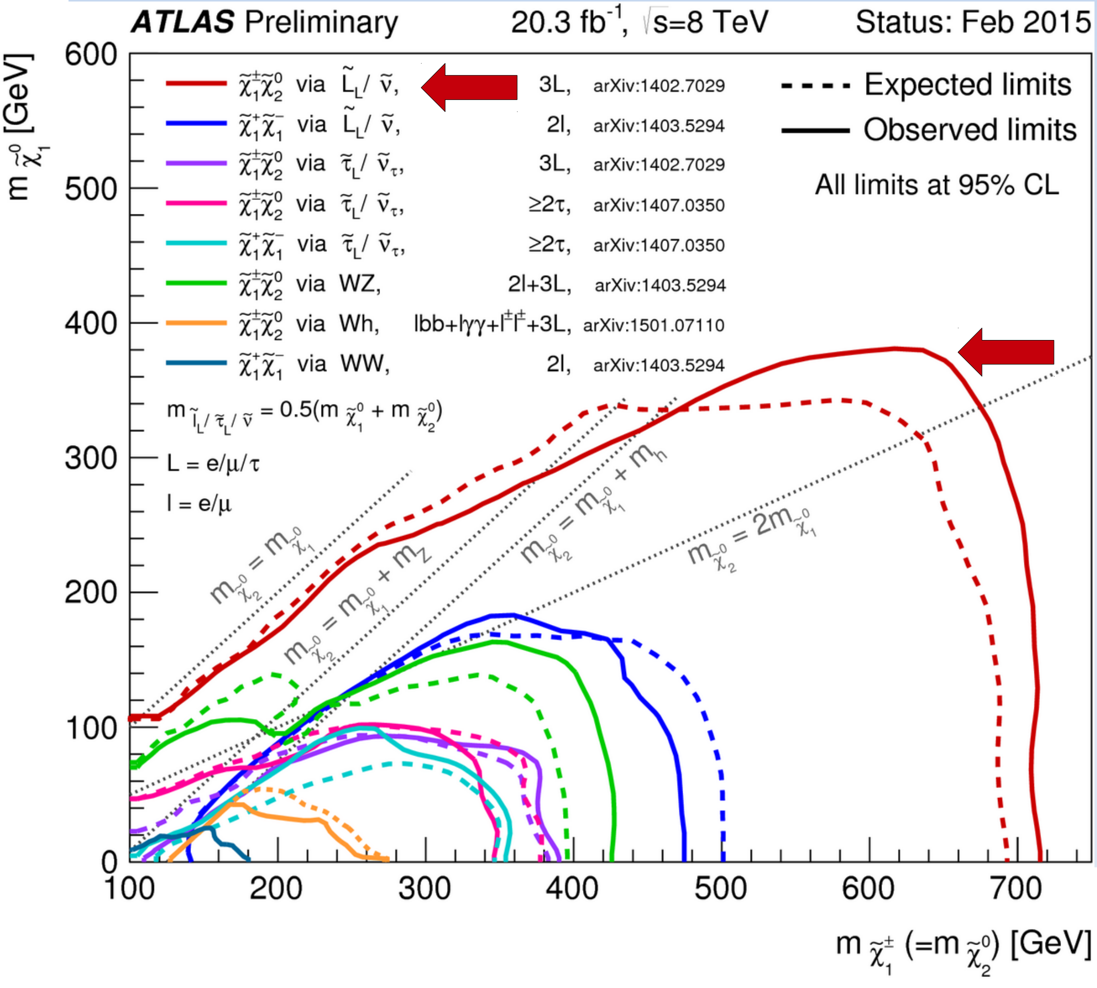
Many more scenarios taken into account by ATLAS and CMS

direct electroweakinos

different lines show constraints on different scenarios



flavor-democratic



All BSM searches not classified as SUSY falls into Exotic(a) (or B2G in the CMS).

Topological searches:

- Heavy narrow resonances (dijets, dileptons, diphotons)
  → Z', RS gravitons, compositness …
- Single lepton + E_t^{miss} → leptonic decays of W'
- Leptons and jets → leptoquarks
- Multiobject topologies → microscopic black holes
- Mono - ”something visible” → dark matter
- ...

At the SUSY – Exotica border

- RPV SUSY (more on the SUSY side)
- Long-Lived Particles (LLP)
- Many topologies with jets and leptons are also common for SUSY and Exotica
- ...

EXOTICA *par excellence*

- Monopoles
- Multi-charged or fractionally charged particles
- Jet extinction scale
- …

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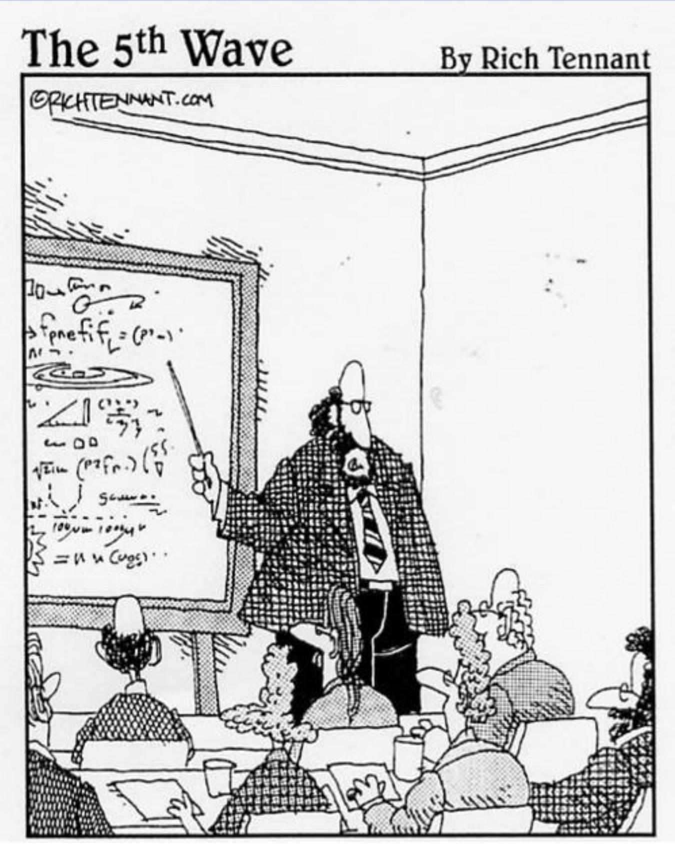
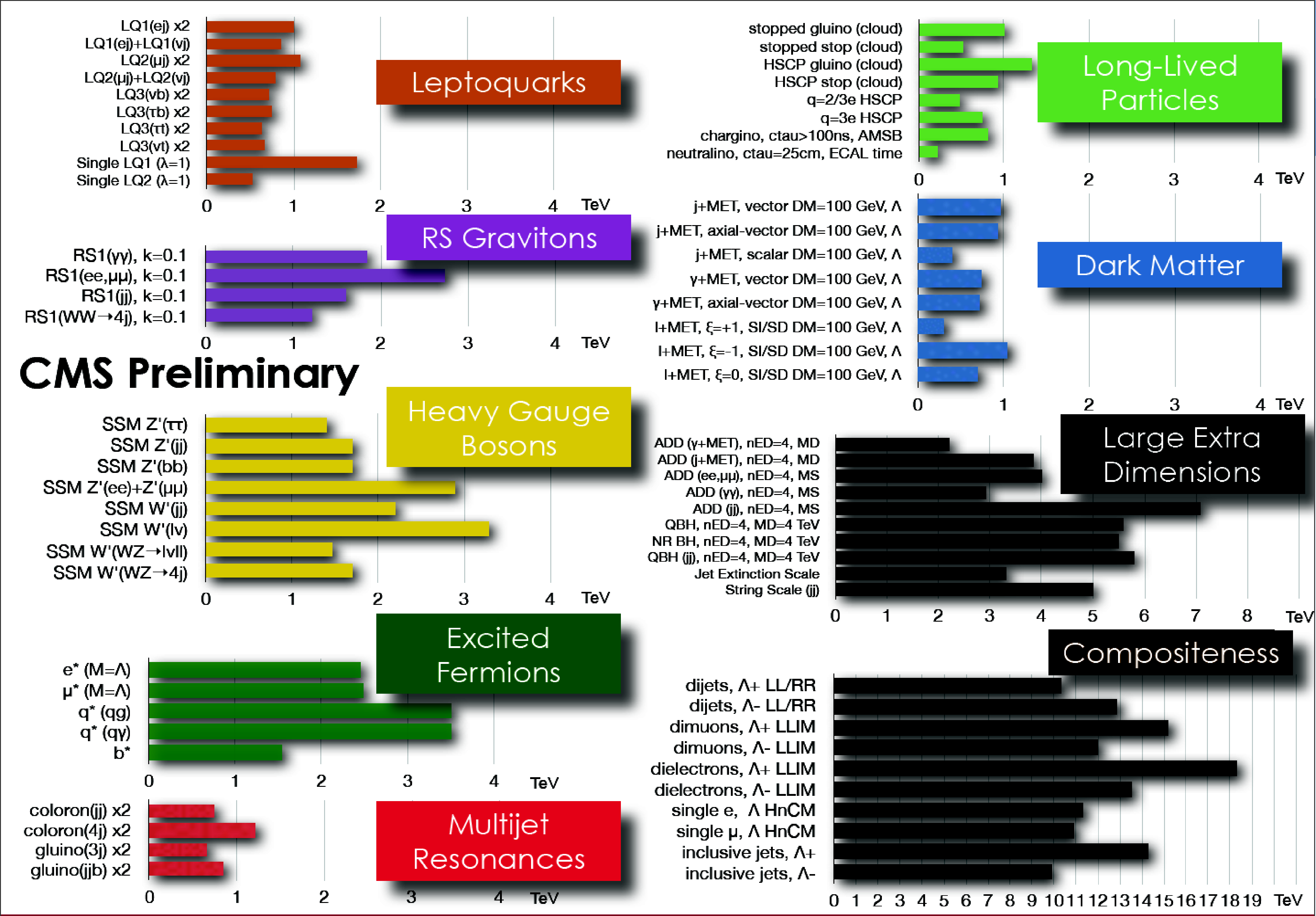
- …

In short: we search for everything except 'doesn't matter' particles.



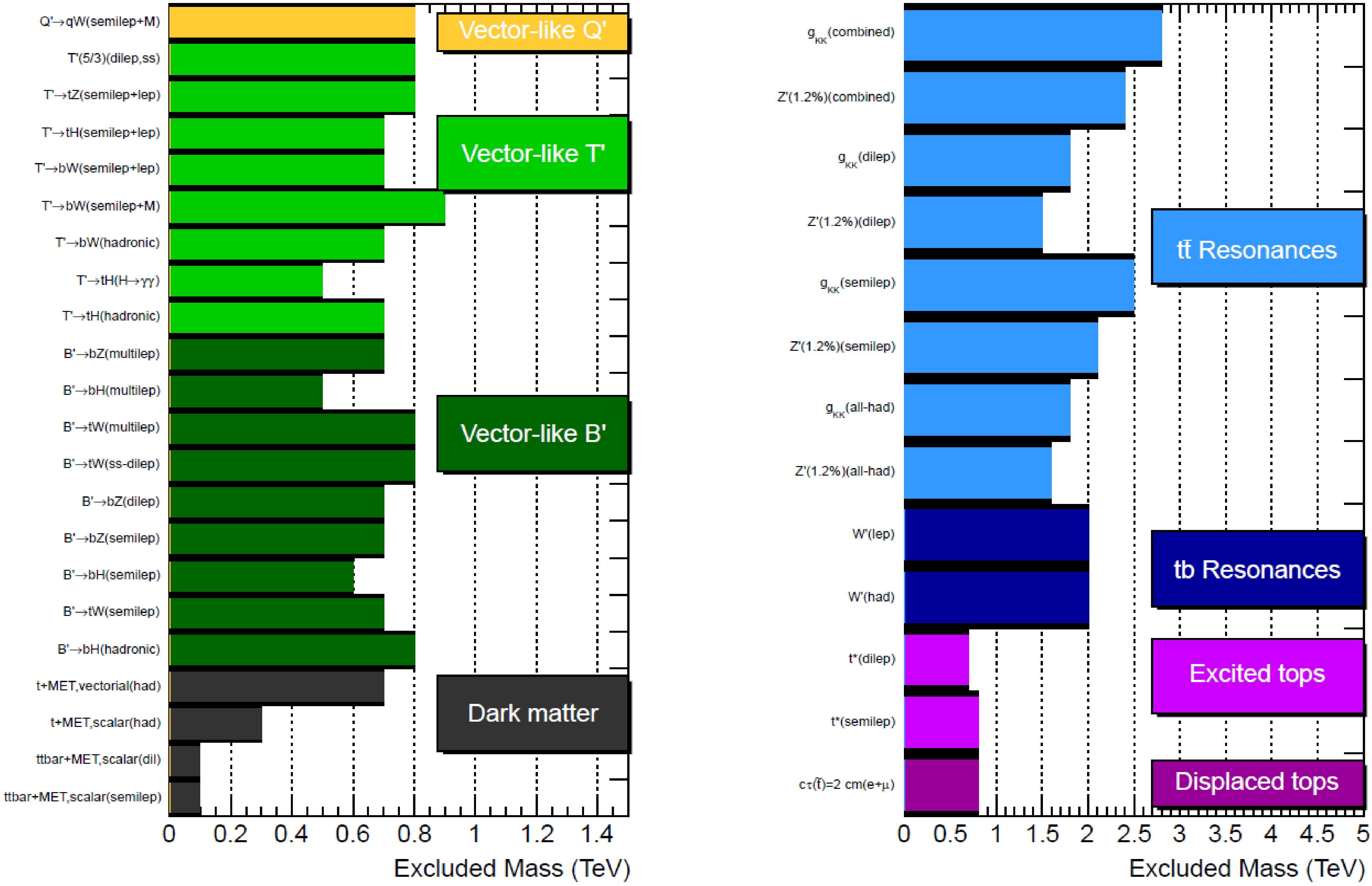
”After the discovery of 'antimatter' and 'dark matter, we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever.”



CMS Exotica Physics Group Summary – Moriond, 2015

CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)

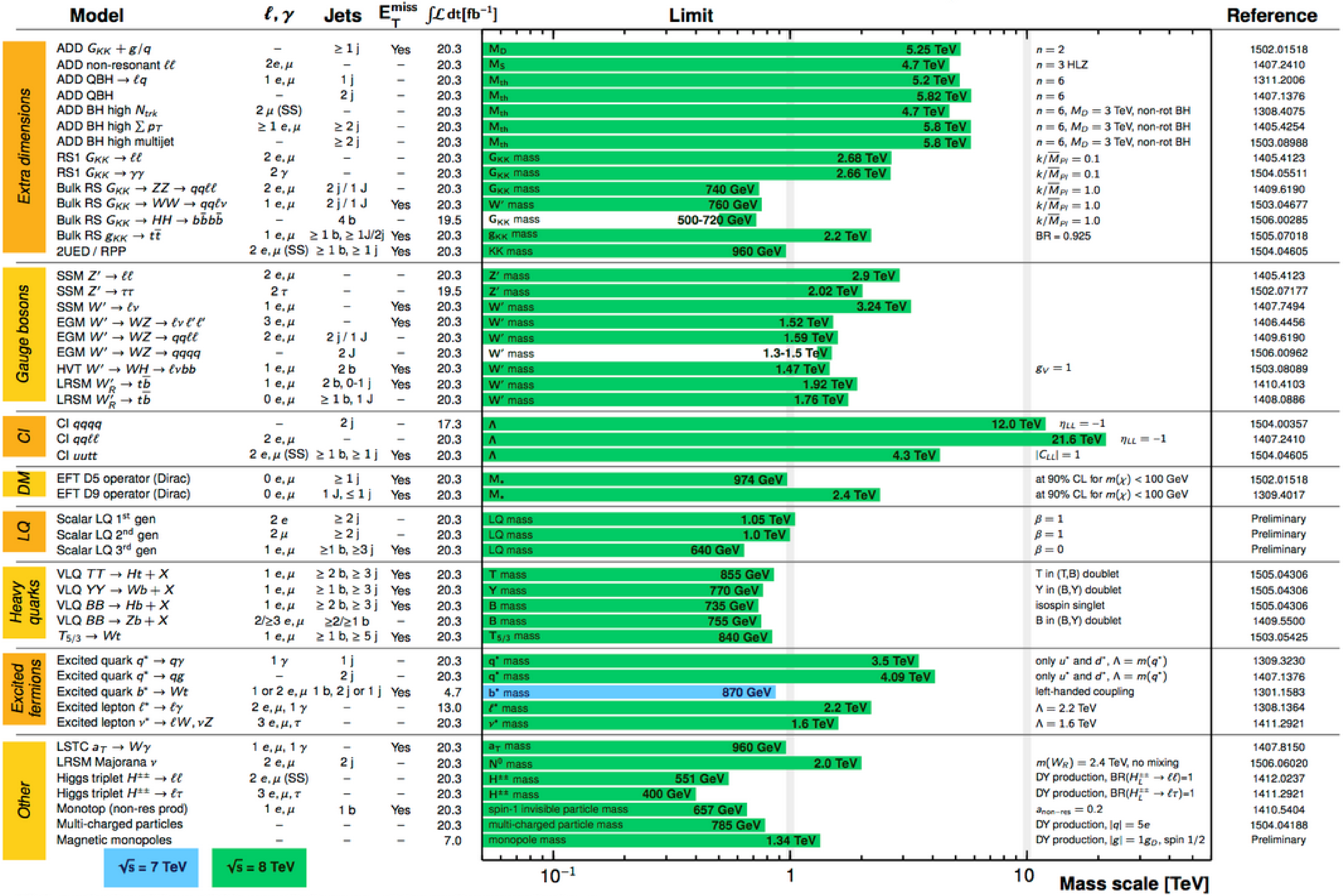


ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int\mathcal{L}\,dt = (4.7 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV



	Model	ℓ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D	5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	2e, μ	–	–	20.3	M_S	4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH → ℓq	1 e, μ	1 j	–	20.3	M_{th}	5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th}	5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th}	4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th}	5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th}	5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1503.08988
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass	2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass	740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W' mass	760 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass	500-720 GeV	$k/\overline{M}_{Pl} = 1.0$	1506.00285
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass	2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass	960 GeV		1504.04605
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z' mass	2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass	2.02 TeV		1502.07177
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W' mass	3.24 TeV		1407.7494
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass	1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass	1.59 TeV		1409.6190
	EGM $W' \to WZ \to qqqq$	–	2 J	–	20.3	W' mass	1.3-1.5 TeV		1506.00962
	HVT $W' \to WH \to \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W' mass	1.47 TeV	$g_V = 1$	1503.08089
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass	1.92 TeV		1410.4103
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass	1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ	12.0 TeV	$\eta_{LL} = -1$	1504.00357
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ	21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ	4.3 TeV	$\lvert C_{LL}\rvert = 1$	1504.04605
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	M_*	974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_*	2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	20.3	LQ mass	1.05 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	20.3	LQ mass	1.0 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass	640 GeV	$\beta = 0$	Preliminary
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass	855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass	770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass	735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass	755 GeV	B in (B,Y) doublet	1409.5500
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass	840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q* mass	3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q* mass	4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b* mass	870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass	2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \to \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass	960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass	551 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass	657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass	785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass	1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	Preliminary

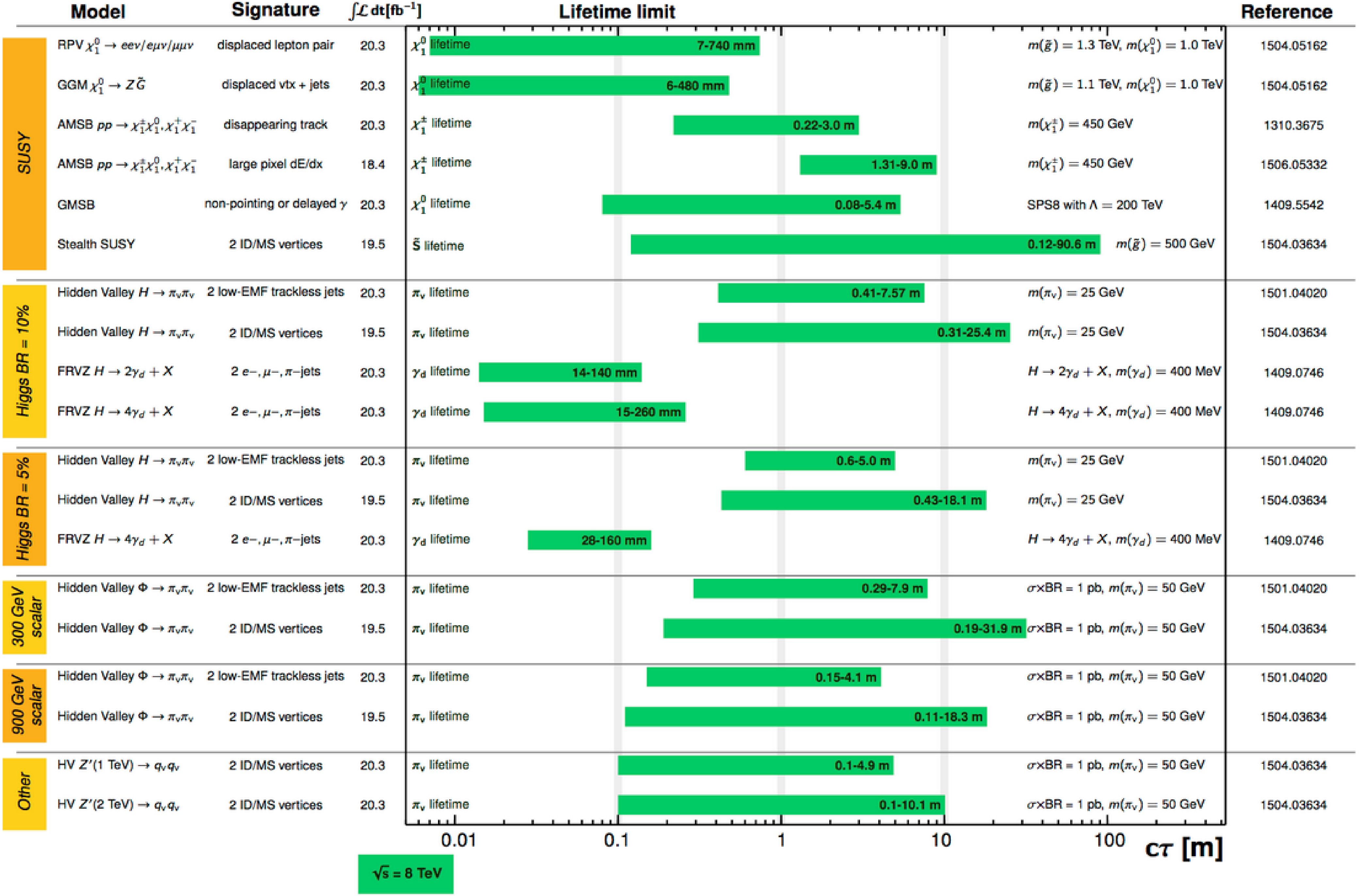
*Only a selection of the available mass limits on new states or phenomena is shown.

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int\mathcal{L}\,dt = (18.4 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8$ TeV



*Only a selection of the available lifetime limits on new states is shown.

LLP @ CMS an example of a reinterpretation

arXiv:1502.02522; CMS-EXO-13-006; Eur.Phys.J. C75 (2015) 7, 325

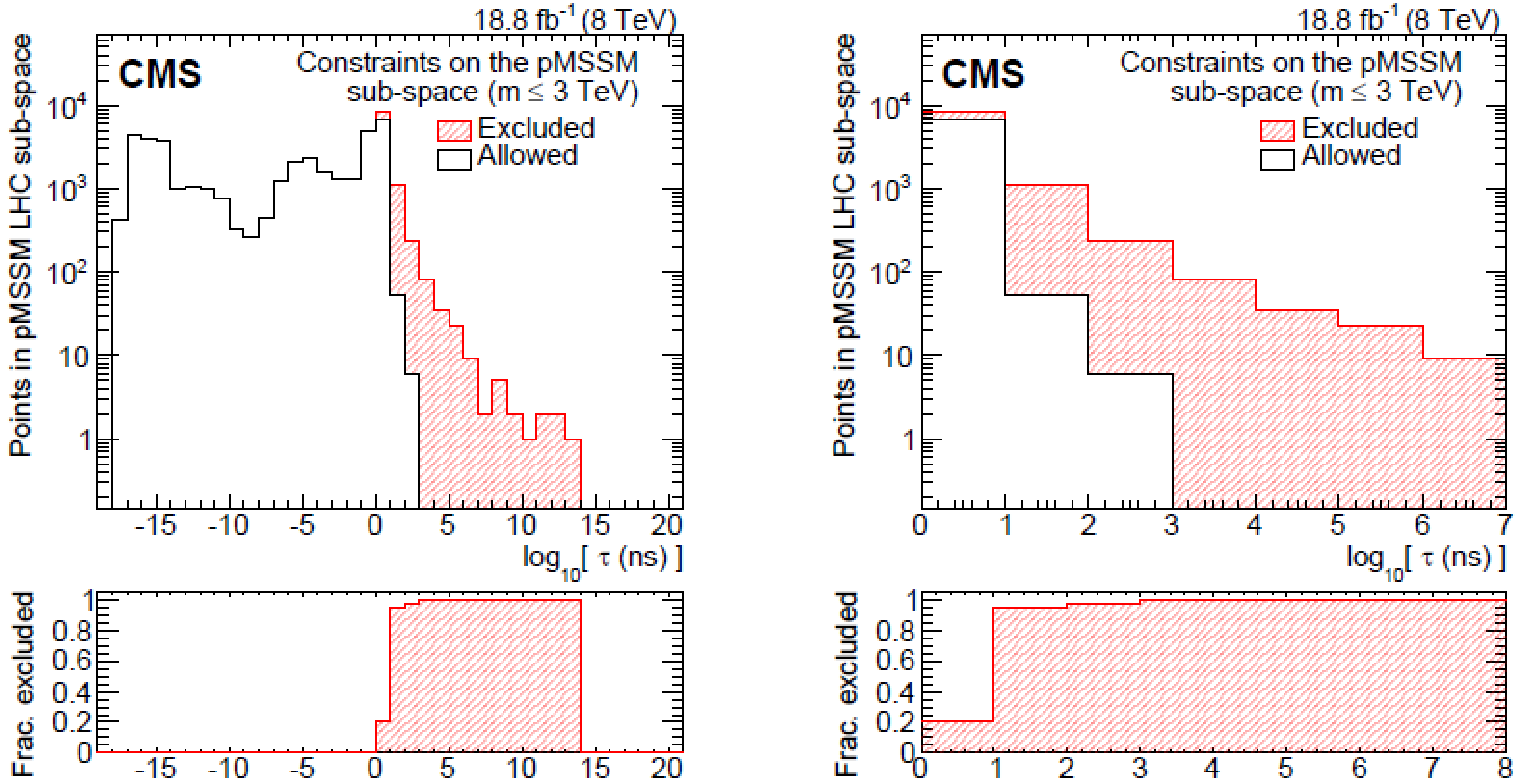


Figure 3: (left) Number of pMSSM points, in the sub-space covering sparticle masses up to about 3 TeV, that are excluded at a 95% CL (hatched red) or allowed (white) as a function of the chargino lifetime. (right) Enlargement of the long-lived region. The bottom panel shows the fraction of pMSSM points excluded by the analysis based on the results from the HSCP search [arXiv:1305.0491; CMS-EXO-12-026; JHEP07(2013)122].

HSCP → Heavy Stable Charged Particles

LLP @ ATLAS

an example of complementarity: 3 different analyses to cover wide lifetime range

LLP → Long-Lived Particles
SMP → Stable Massive Particles

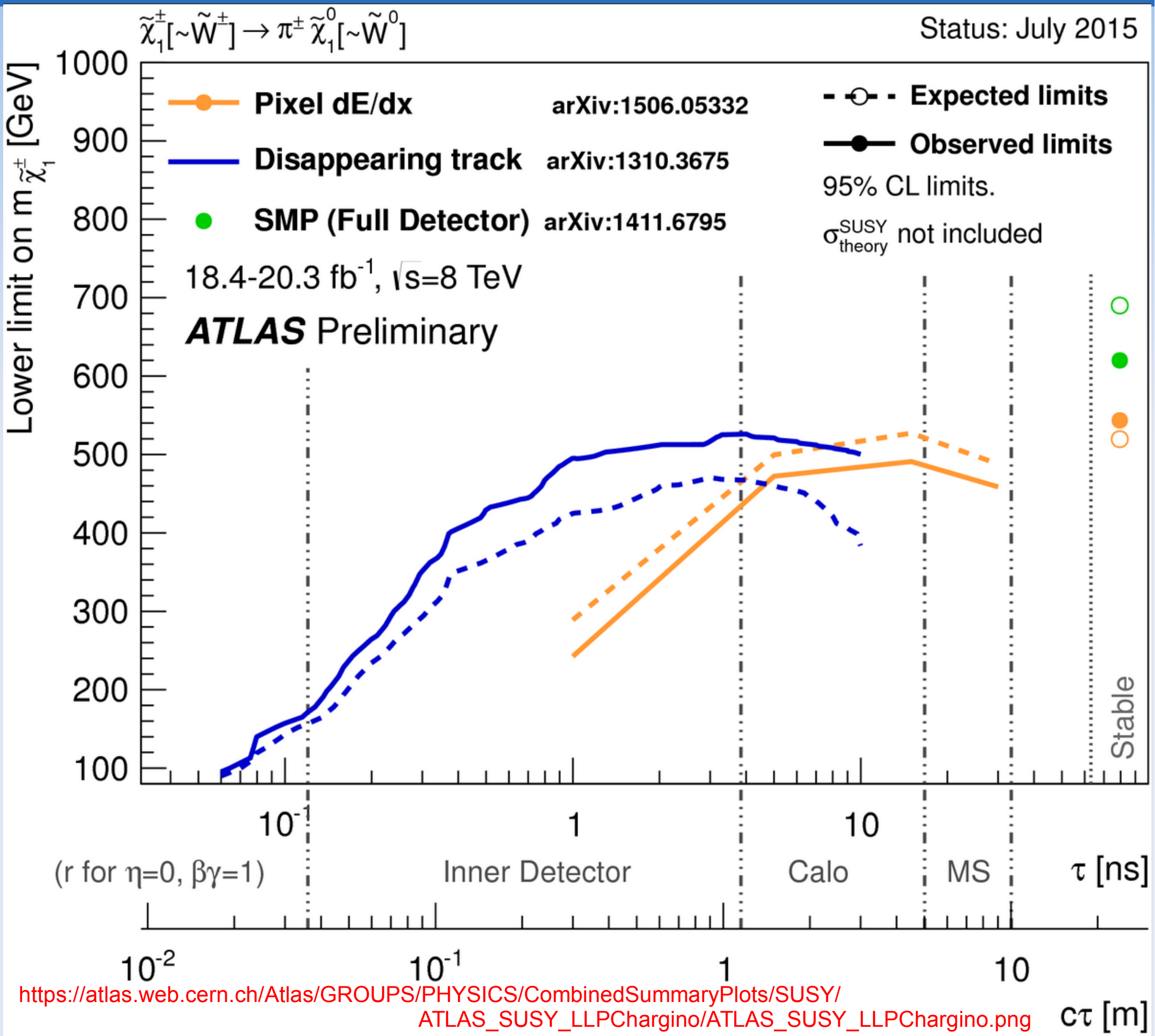
Constraints on the chargino mass-vs-lifetime plane for an AMSB model with tan(β)=5 and μ>0.

The wino-like chargino is pair-produced and decays to the wino-like neutralino and a very soft charged pion.

The solid lines indicate the observed limits, while the dashed lines indicate the expected limits.

The area below the curves is excluded.

The analyses have sensitivity at lifetimes other than those shown, but only the limits at tested lifetimes are shown.



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_LLPChargino/ATLAS_SUSY_LLPChargino.png

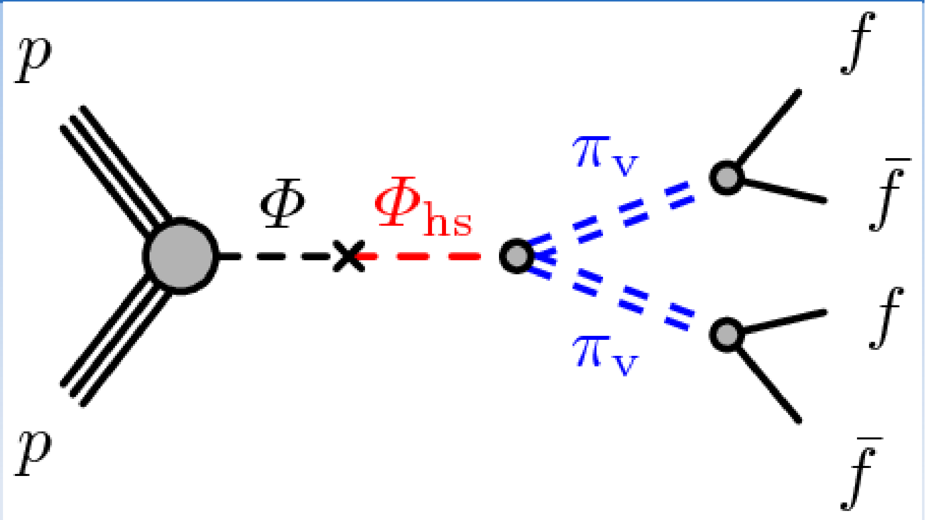
The dots represent results for which the particle is assumed to be stable. In this context, stable means escaping the detector.

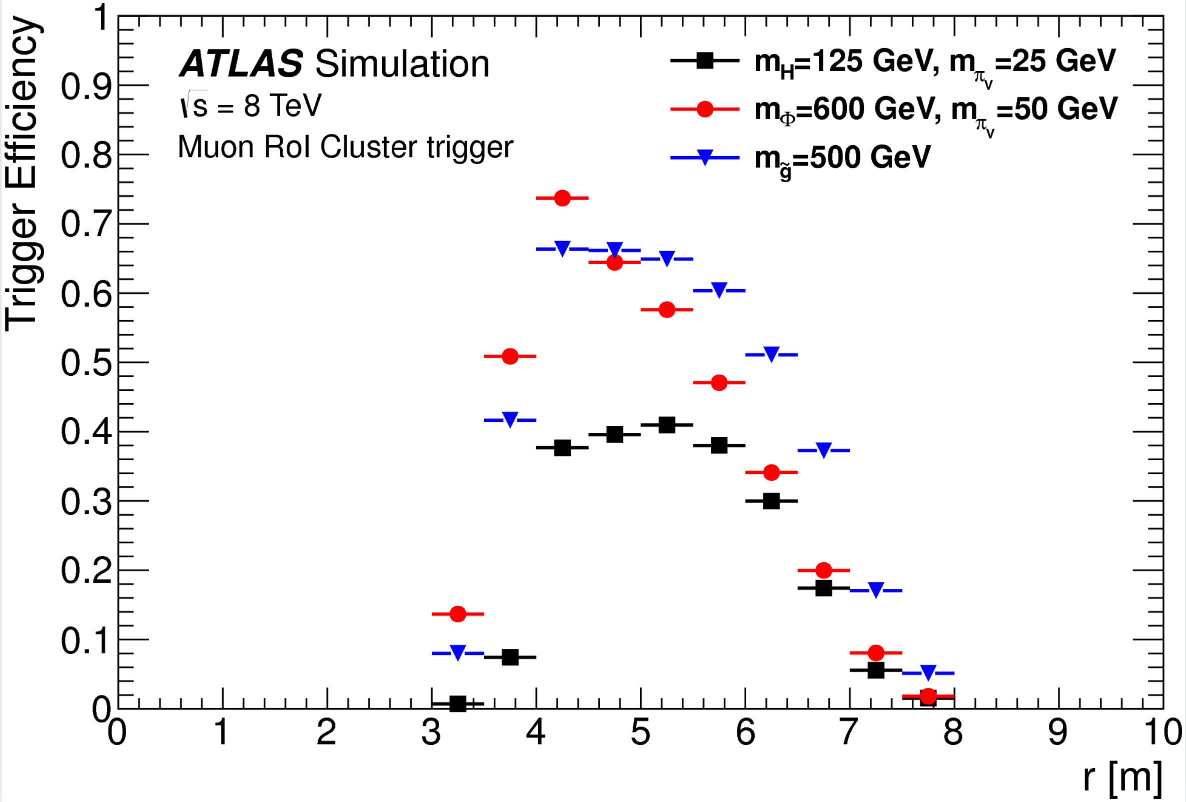
arXiv:1506.05332; accepted by EPJC
arXiv:1411.6795; JHEP 1501 (2015) 068
arXiv:1310.3675; Phys.Rev. D88 (2013) 11, 112006

LLP: displaced jets

Search for long-lived, weakly-interacting particles that decay to displaced hadronic jets in proton-proton collisions at √s=8TeV with the ATLAS detector

arXiv:1504.03634,
Phys. Rev. D 92, 012010 (2015)





Custom Muon RoI Cluster trigger: it is a signature-driventrigger that selects decays of neutral particles in the muon system (MS).

It is effcient for hadronic decays occurring in the region from the outer radius of the HCal to the middle of the MS.

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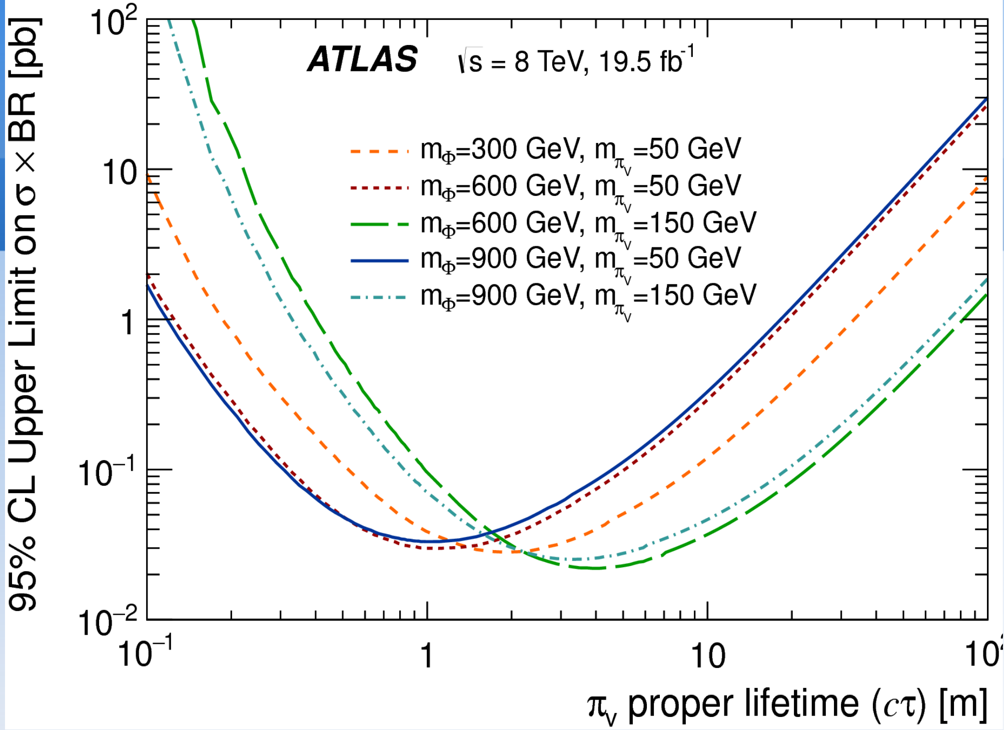
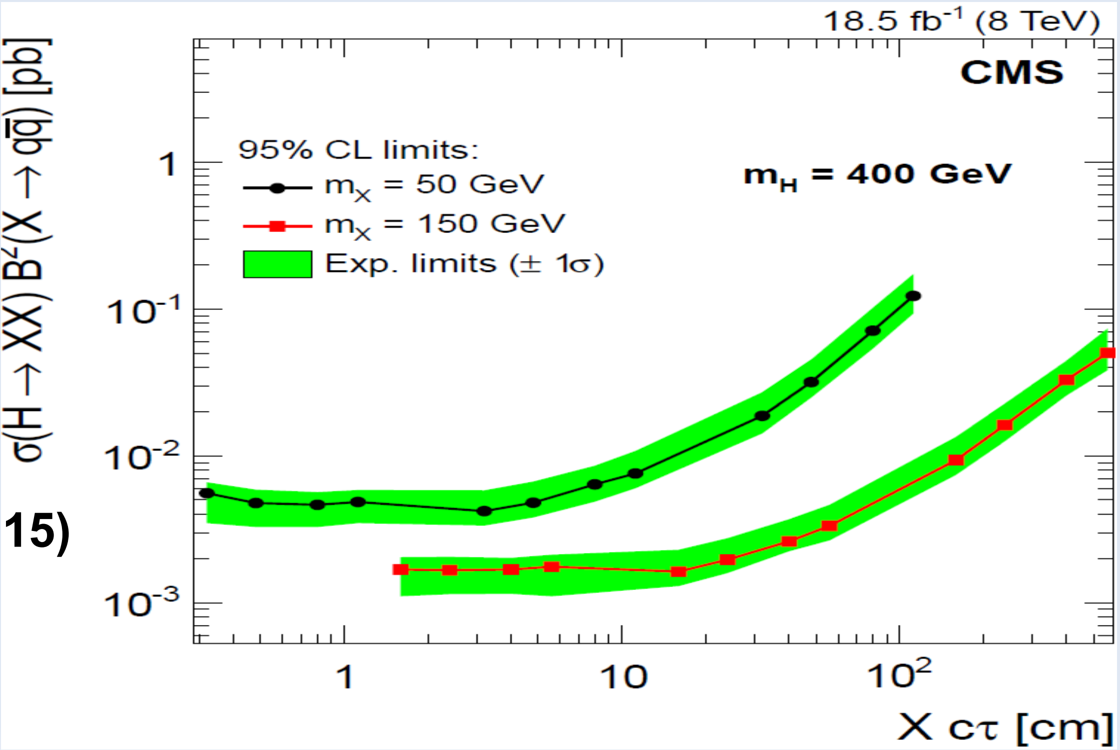


Search for long-lived neutral particles decaying to quark-antiquark pairs in proton-proton collisions at sqrt(s) = 8 TeV

arXiv:1411.6530,
Phys. Rev. D 91, 012007 (2015)

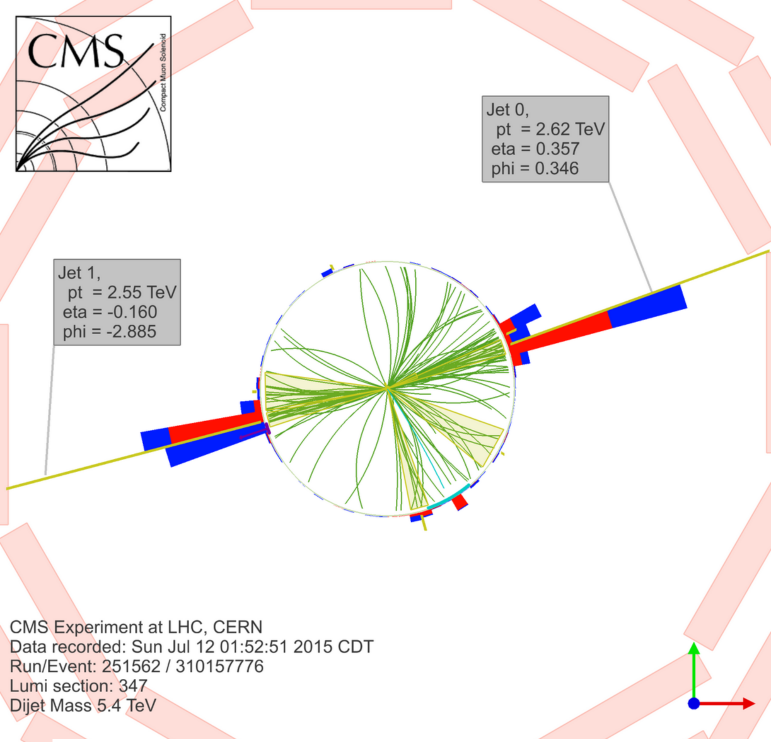
CMS

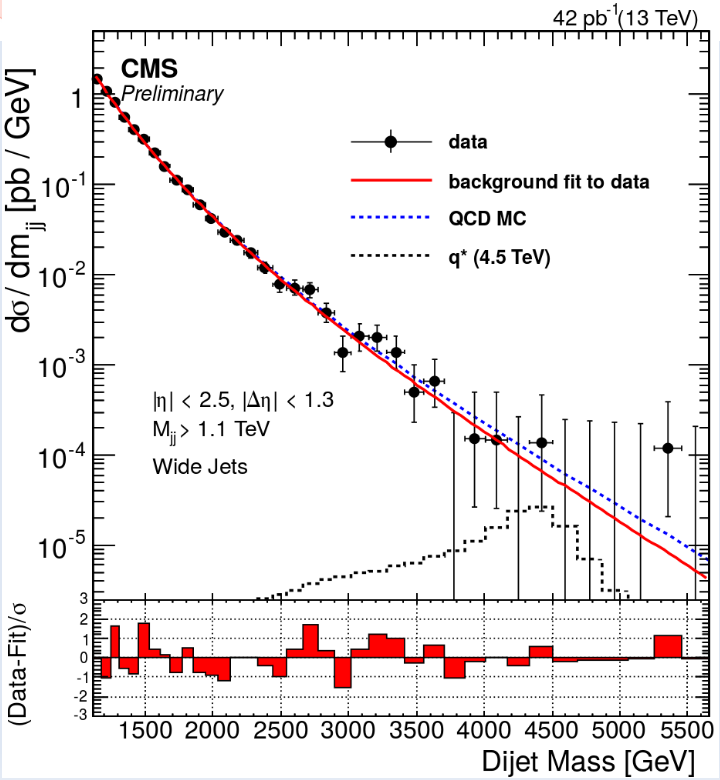


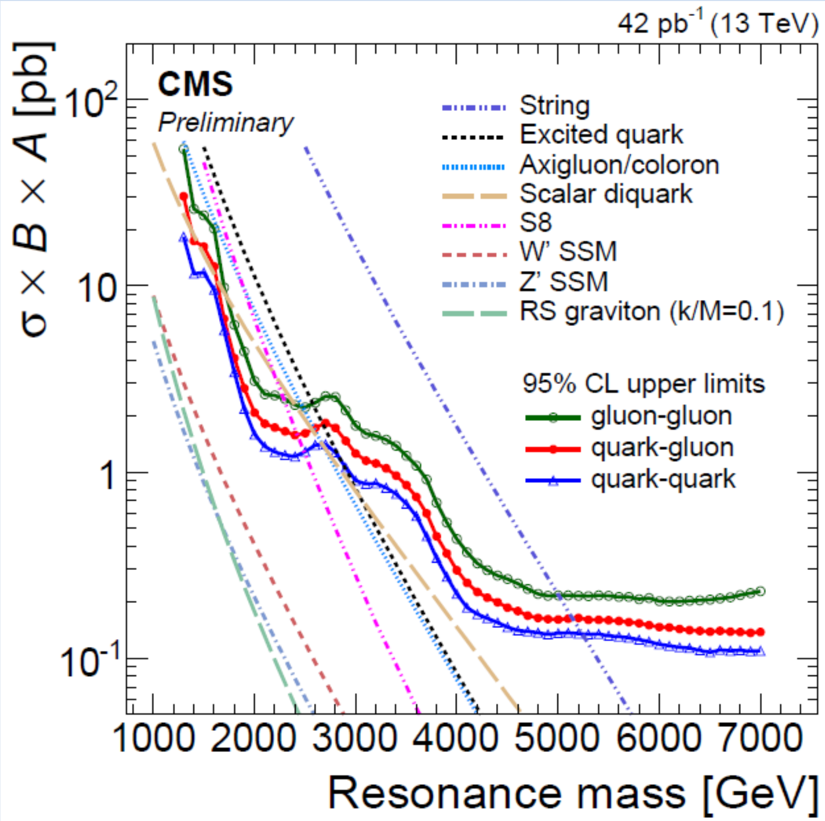
CMS @ 13 TeV

Search for narrow resonances using the dijet mass spectrum with 42 pb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV

CMS PAS EXO-15-001

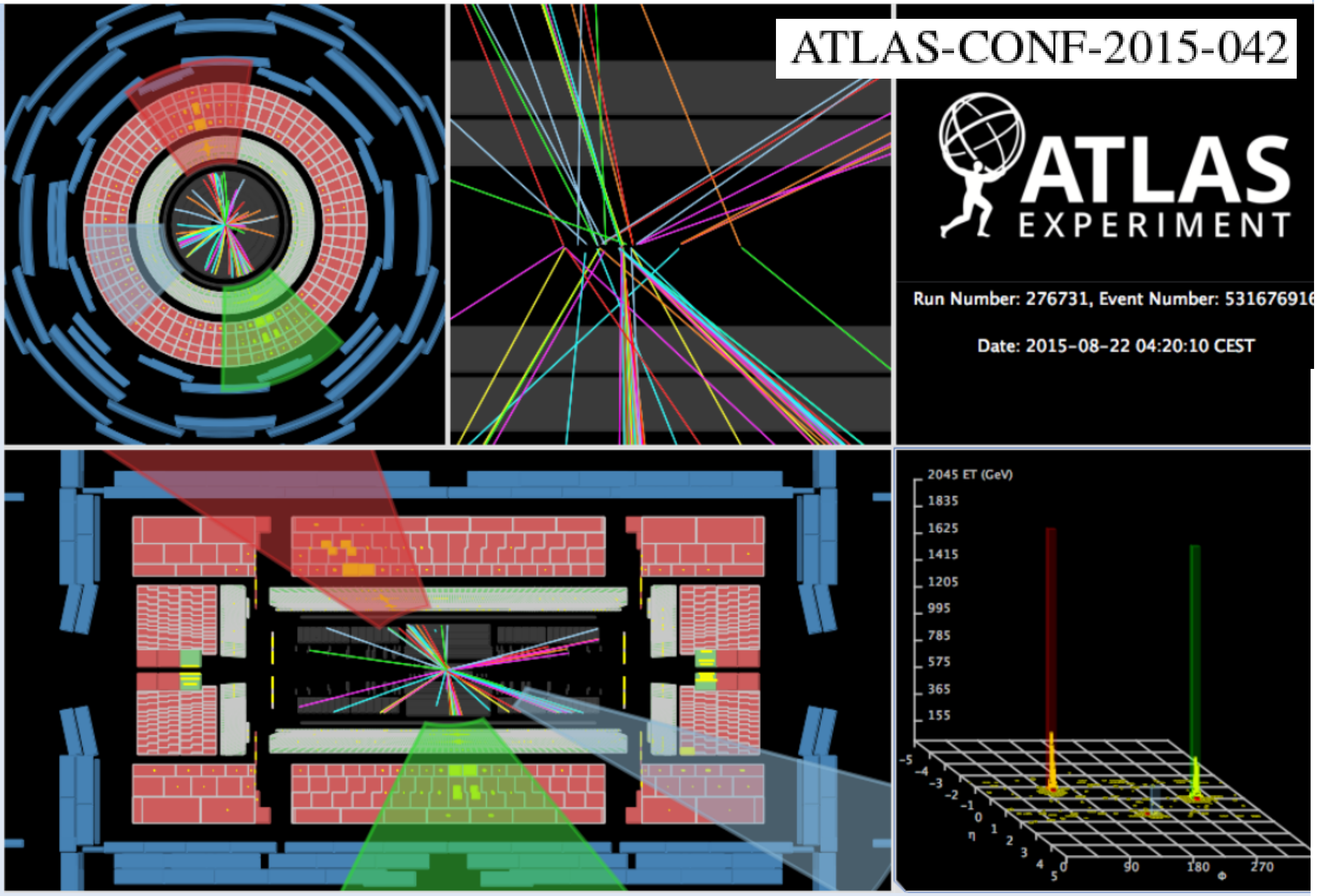


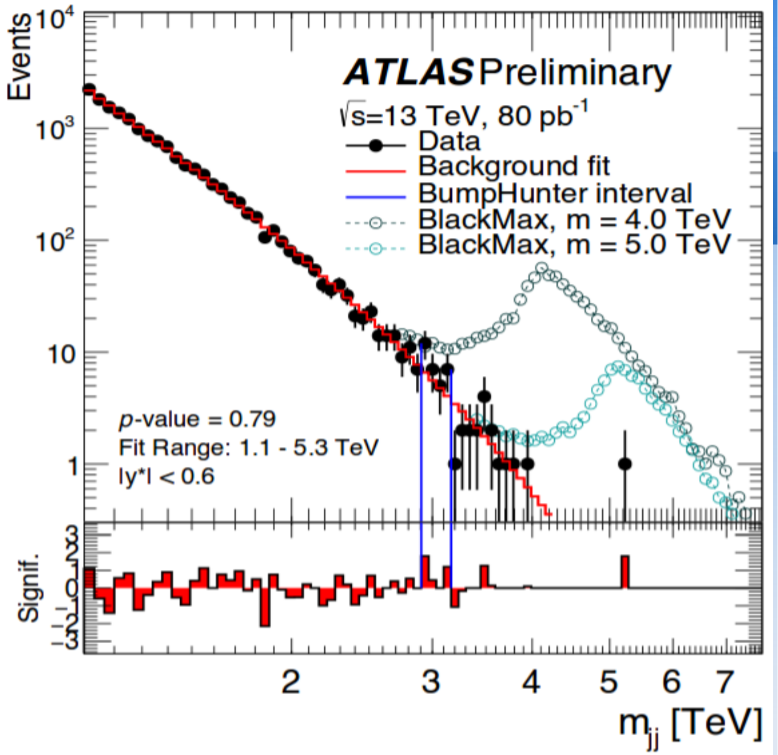


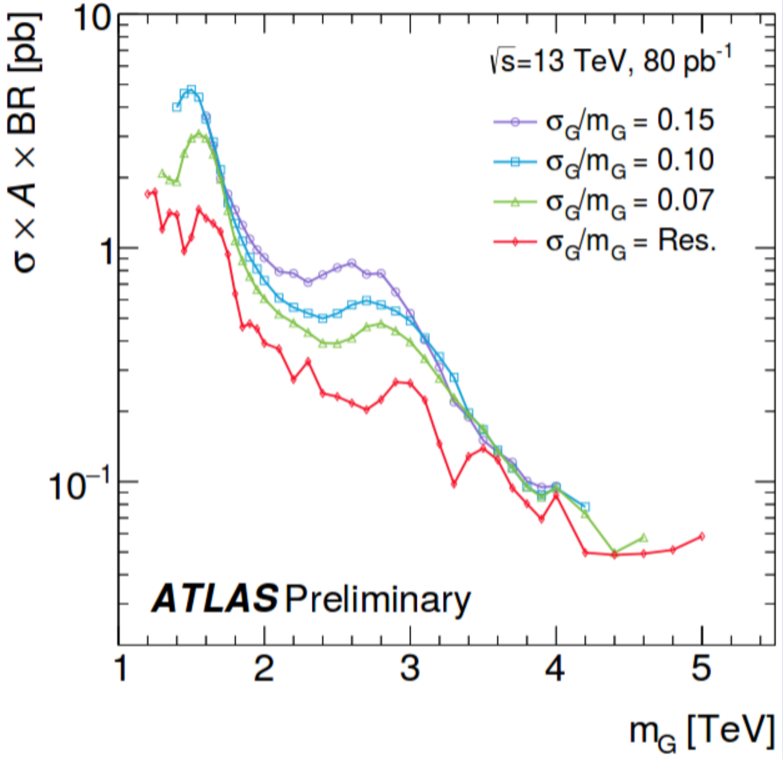


ATLAS @ 13 TeV

Search for New Phenomena in Dijet Mass and Angular Distributions with the ATLAS Detector at $\sqrt{s} = 13$ TeV


ATLAS-CONF-2015-042





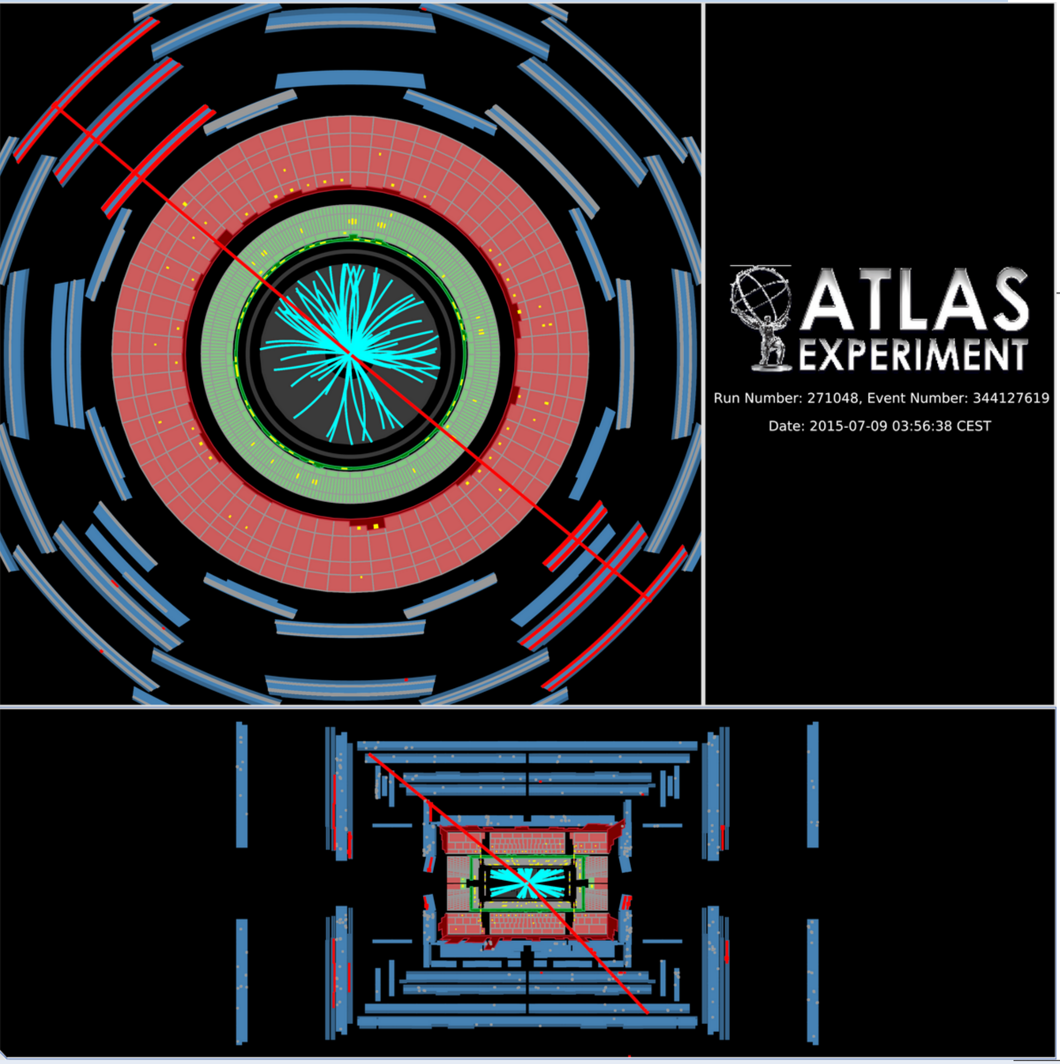
Other ATLAS @ 13 TeV Exotica:

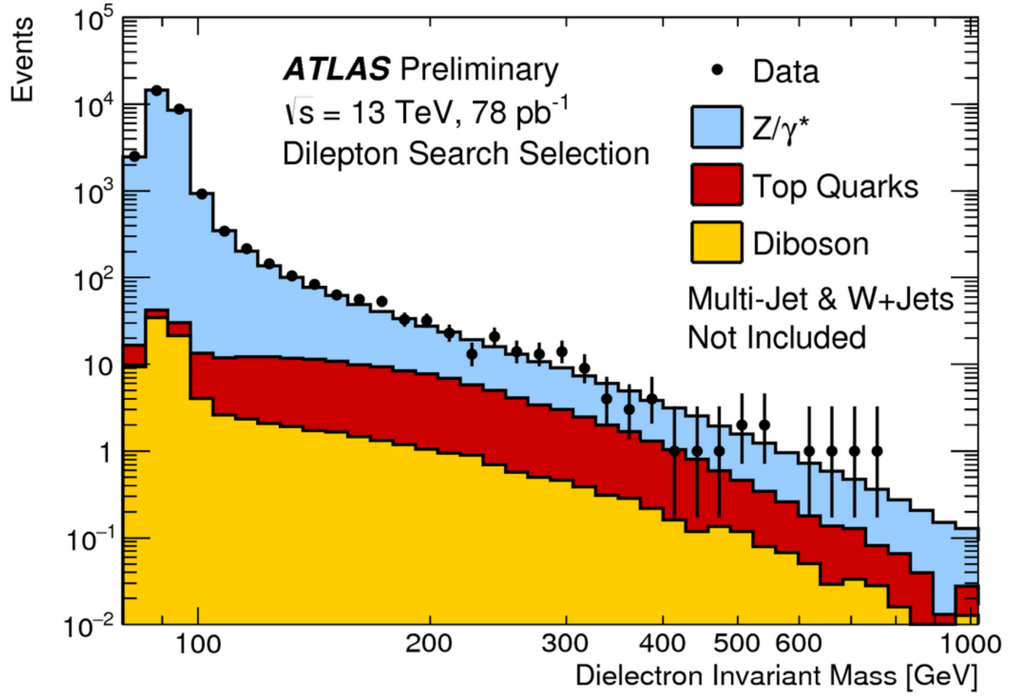
"Search for evidence for strong gravity in jet final states ...", ATLAS-CONF-2015-043

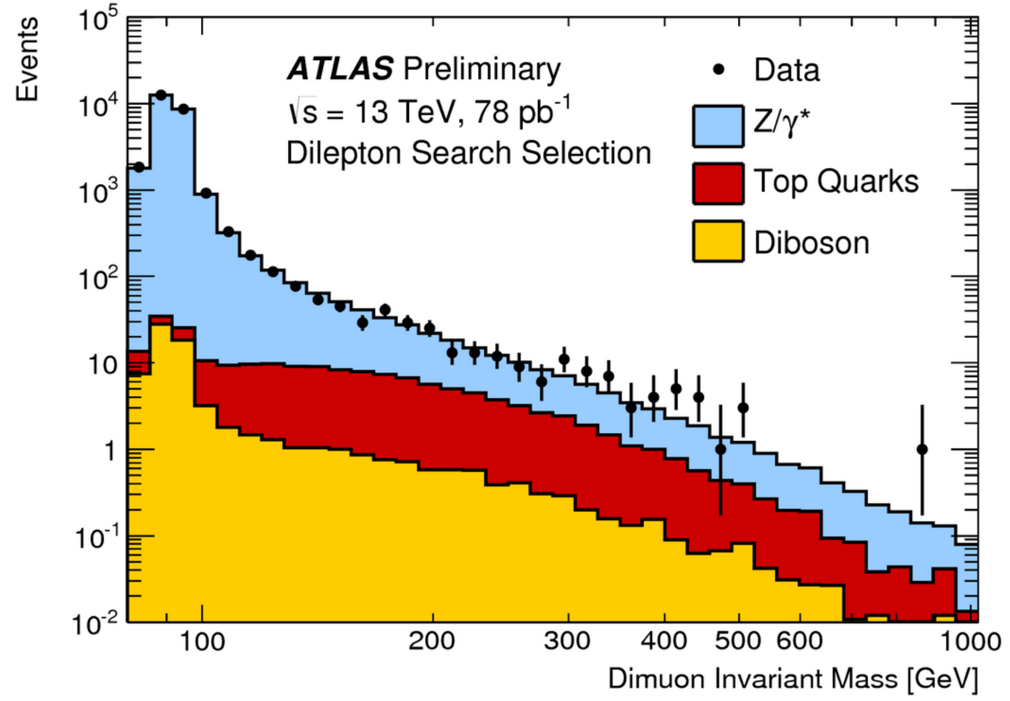
"Search for TeV-scale gravity signatures in high-mass final states with leptons and jets ...", ATLAS-CONF-2015-046

ATLAS @ 13 TeV

dilepton mass spectra →







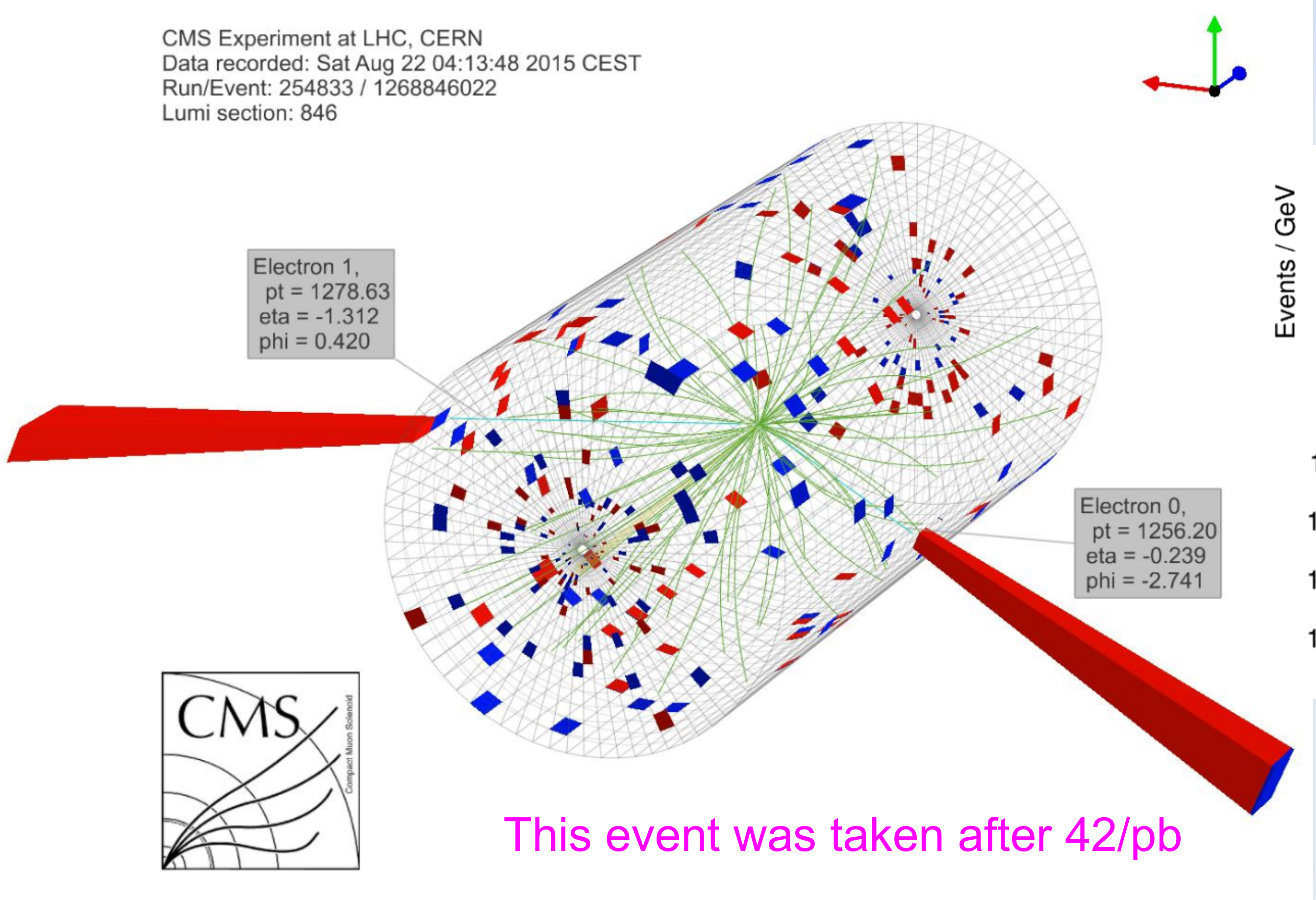
Event Display of a Candidate Electron-Positron Pair with an Invariant Mass of 2.9 TeV

CMS @ 13 TeV

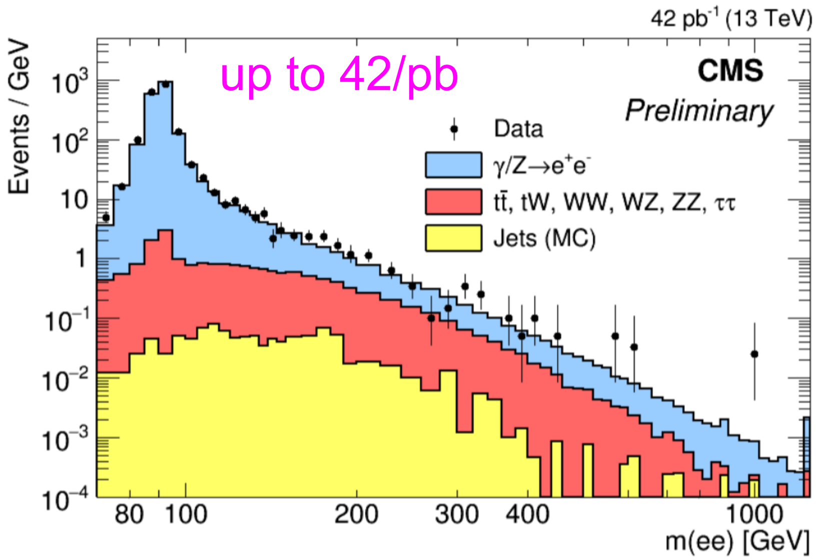
CMS DP -2015/039

This performance note shows the event display together with some kinematic quantities for a candidate electron-positron pair with an invariant mass of 2.9 TeV. The background expected from the SM above m(ee) = 1 TeV, 2 TeV and 2.5 TeV for an integrated luminosity of 65 pb-1 is also stated.

mass range	SM Bkg. Expectation
>1 TeV	0.21
> 2 TeV	0.007
> 2.5 TeV	0.002



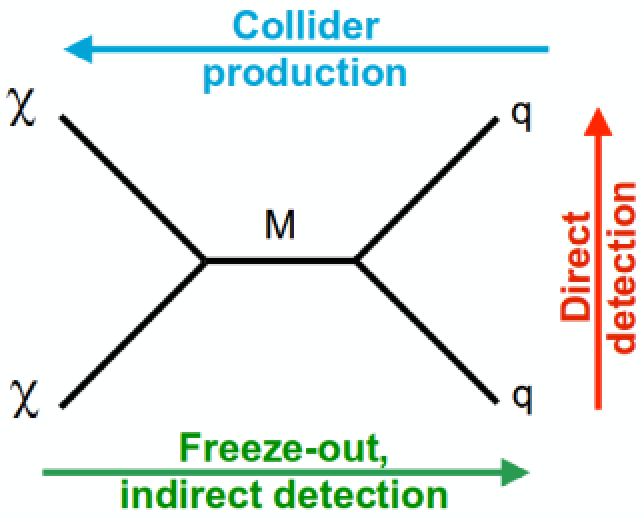
This event was taken after 42/pb



up to 42/pb

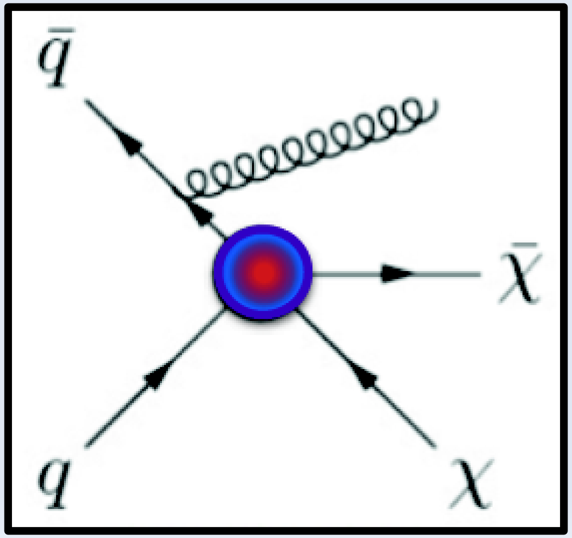
Dark matter @ LHC

- There are three main approaches to detect DM:
  - DM-nucleon scattering (direct detection)
  - Indirect detection (coannihilation)
  - Pair production at colliders
- All three processes are nothing but topological permutations of one and the same Feynman diagram:
  - But: how to trigger on a pair of DM particles at colliders?



Majority of BSM searches @ LHC could be interpreted as searches for dark matter because almost all BSM models contain some DM candidate.

mono –
something detectable & triggerable

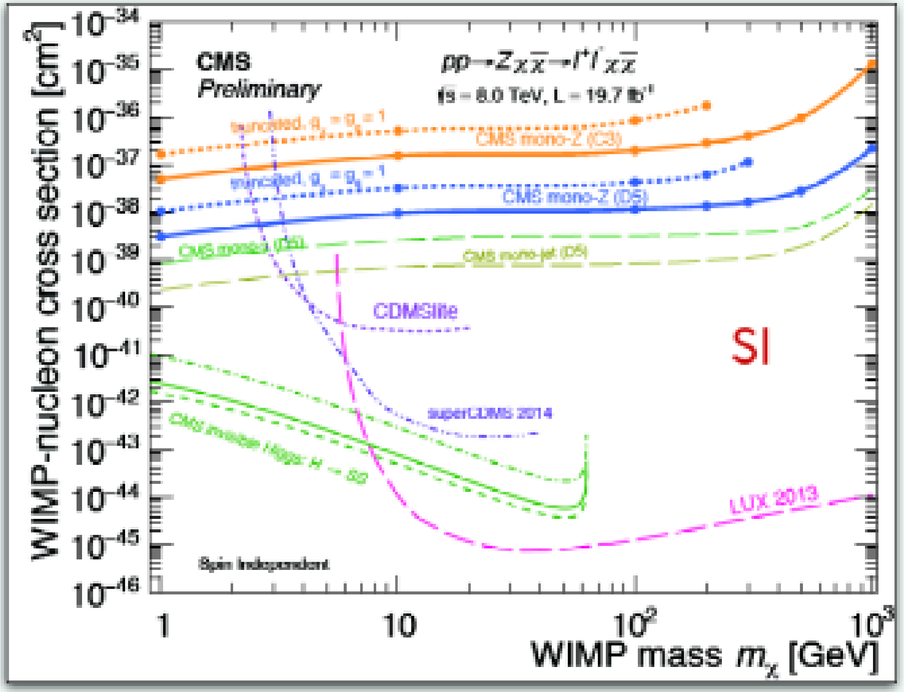


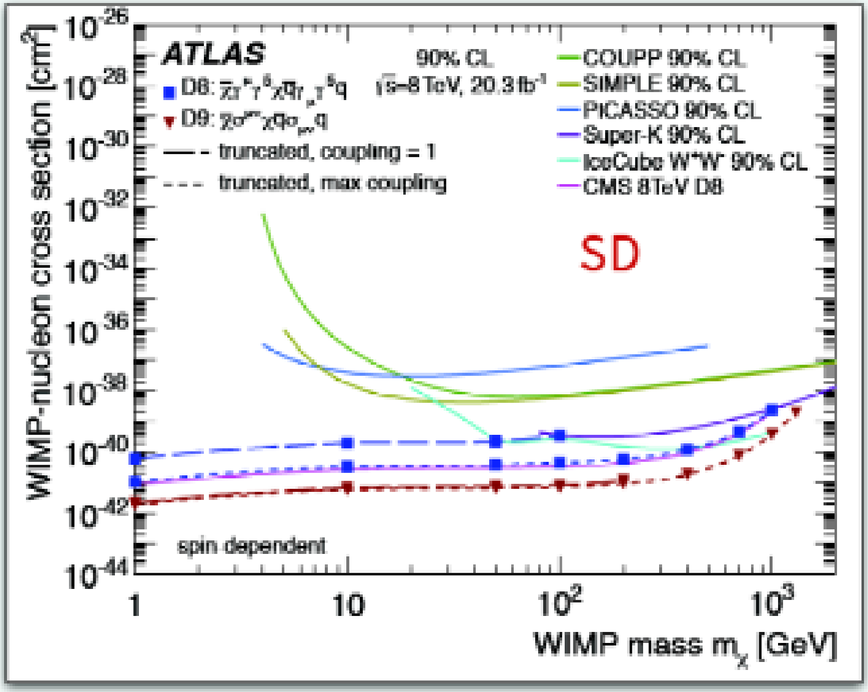
Dark matter @ LHC

Translate collider limits to bounds on σ_X-N

- Lower limit on M* translated to limits on σ_X-N
  - Phys.Rev.D82:116010,2010
- **Collider searches more sensitive at low M_X**
  - And up to medium M_X for spin-dependent interactions
- **Complementarity to direct searches**

But if DM particles are superweakly interacting eg. gravitino than the LHC is the only device that could provide a hint for DM in near future!





Conclusions

- A detailed search for almost every imaginable sympthom of BSM physics was performed on 7 & 8 TeV data by ATLAS and CMS.

- No signal of BSM phenomenon of any kind has been found yet.

- LHC run 2 at 13 TeV has just started.
- The amount of integrated luminosity at 13 TeV is limited but we expect an order of magnitude more up to the end of the year.
- Physics object are being validated for 13 TeV run.
- Cross sections for BSM physics significantly grow with pp energy.
- More search results are to be expected already this year.

- We have found nothing at 8 TeV, but we will keep searching at 13 TeV!

- LHC is a unique tool to search for DM.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults