Beyond Standard Model searches at LHC
Status and Prospects

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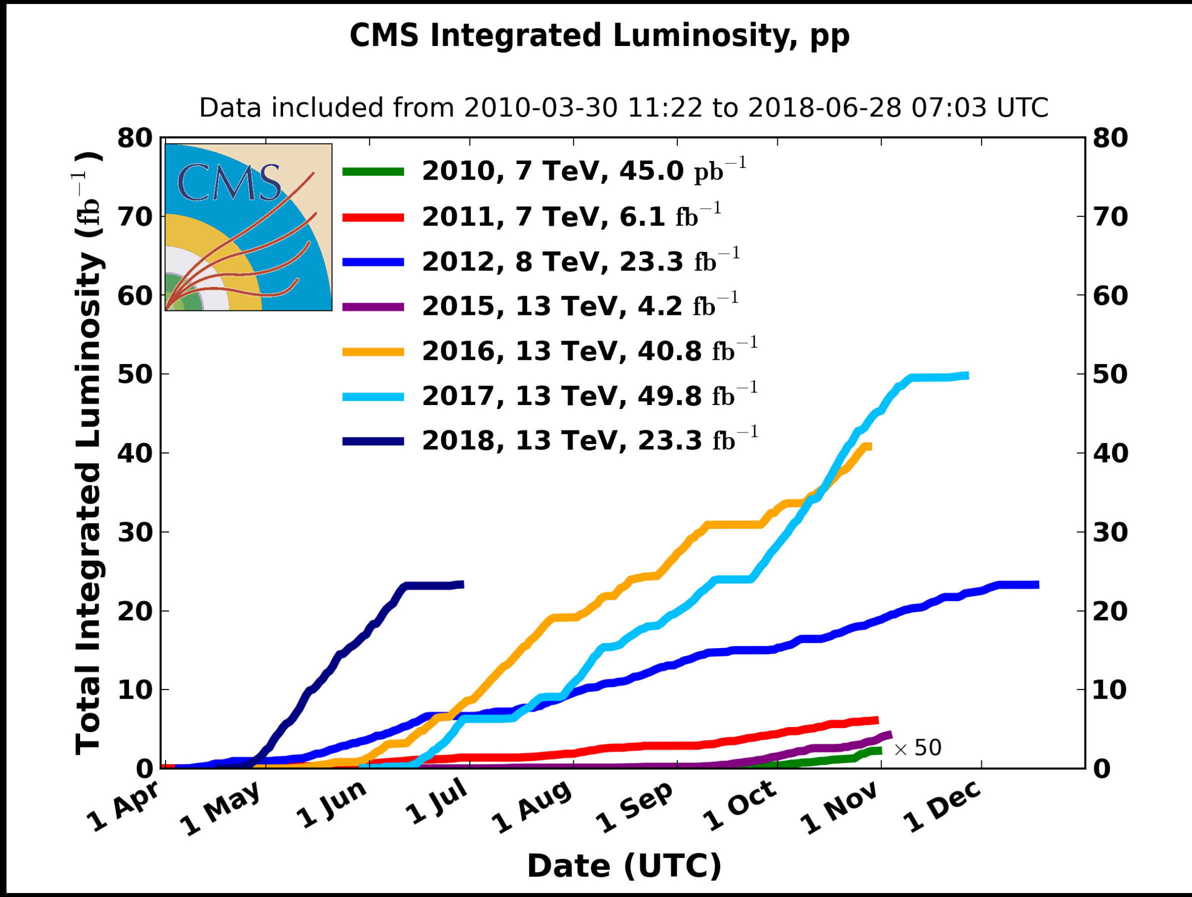
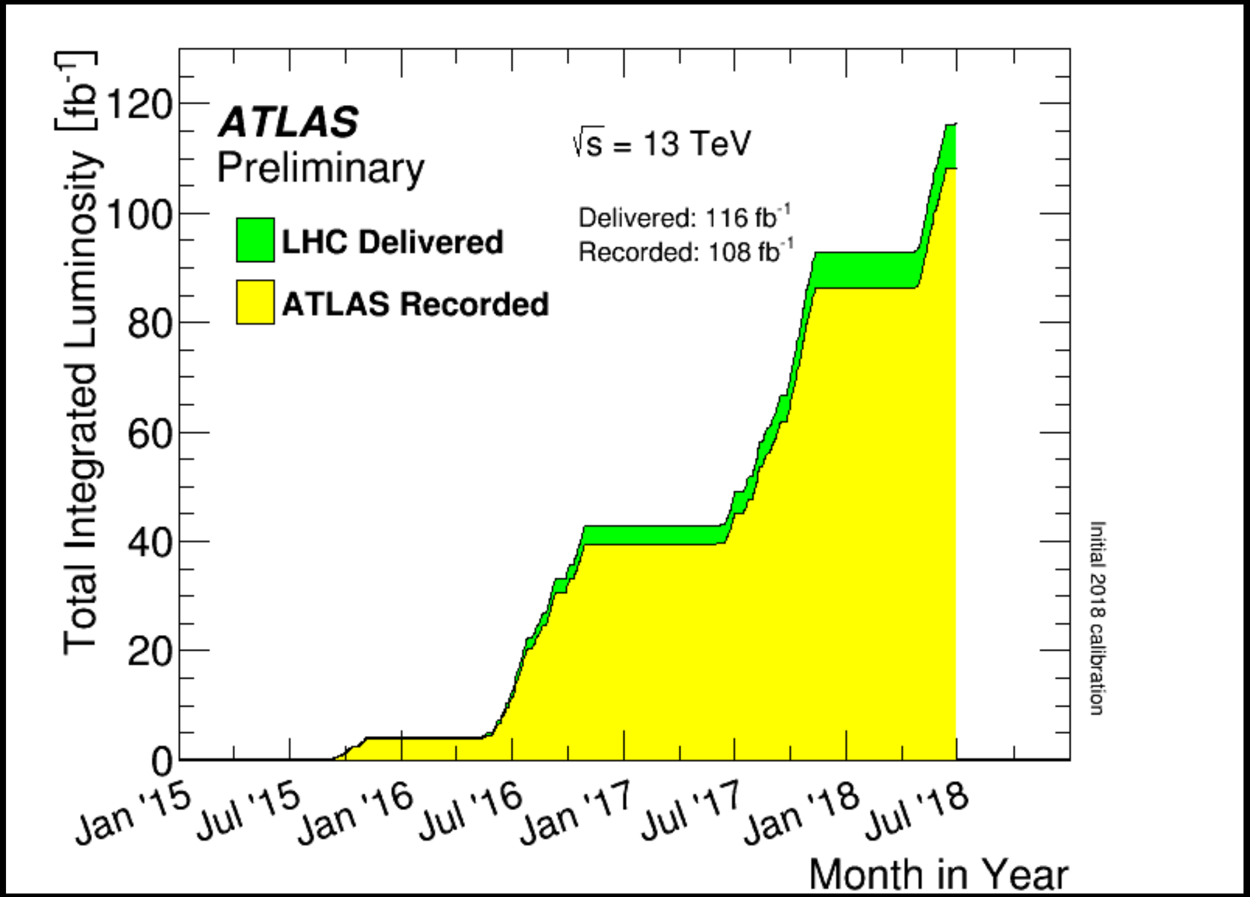
INFN Milano

Pushing the Boundaries of the energy and intensity frontiers
Durham, 2-4 July 2018

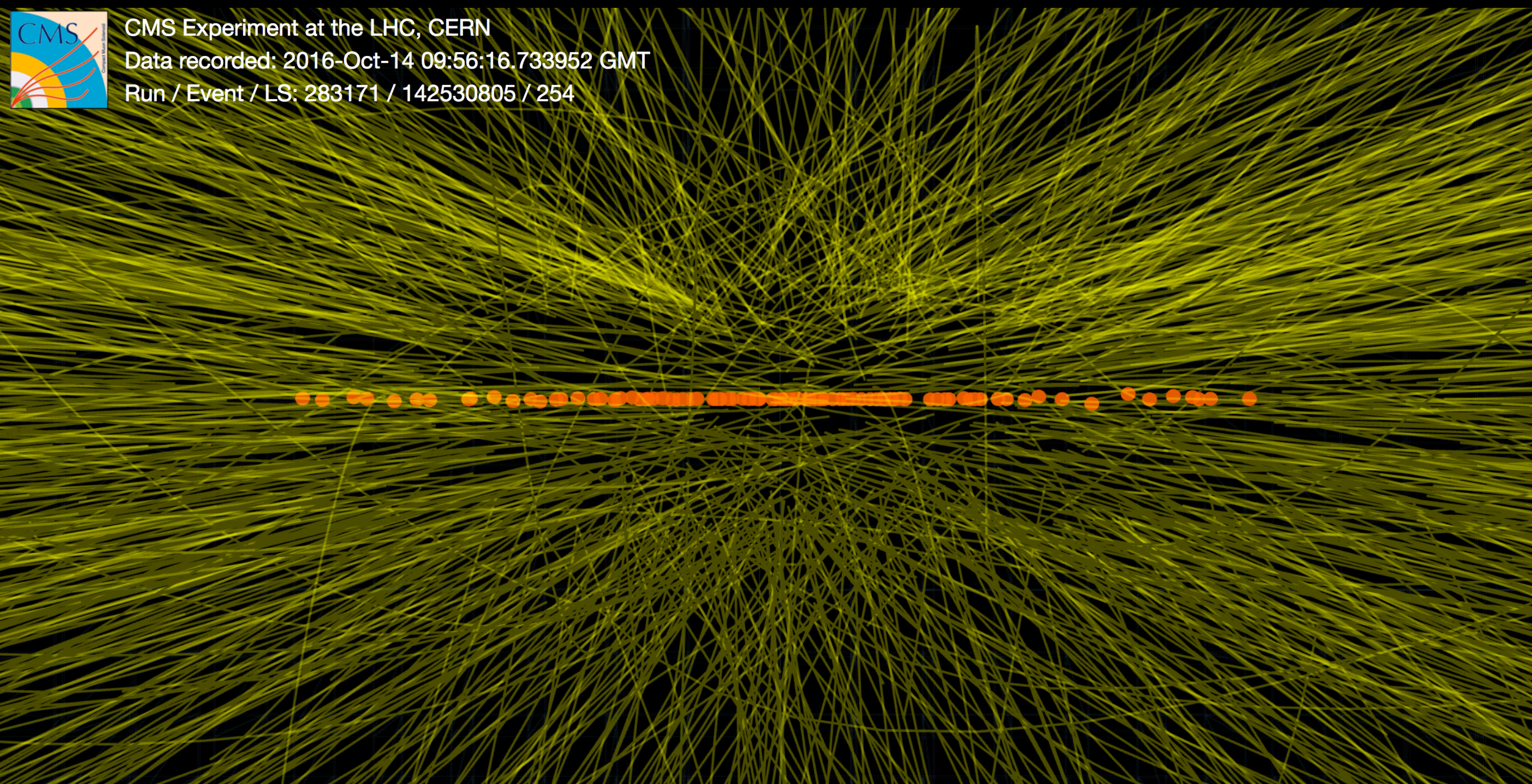
We got data

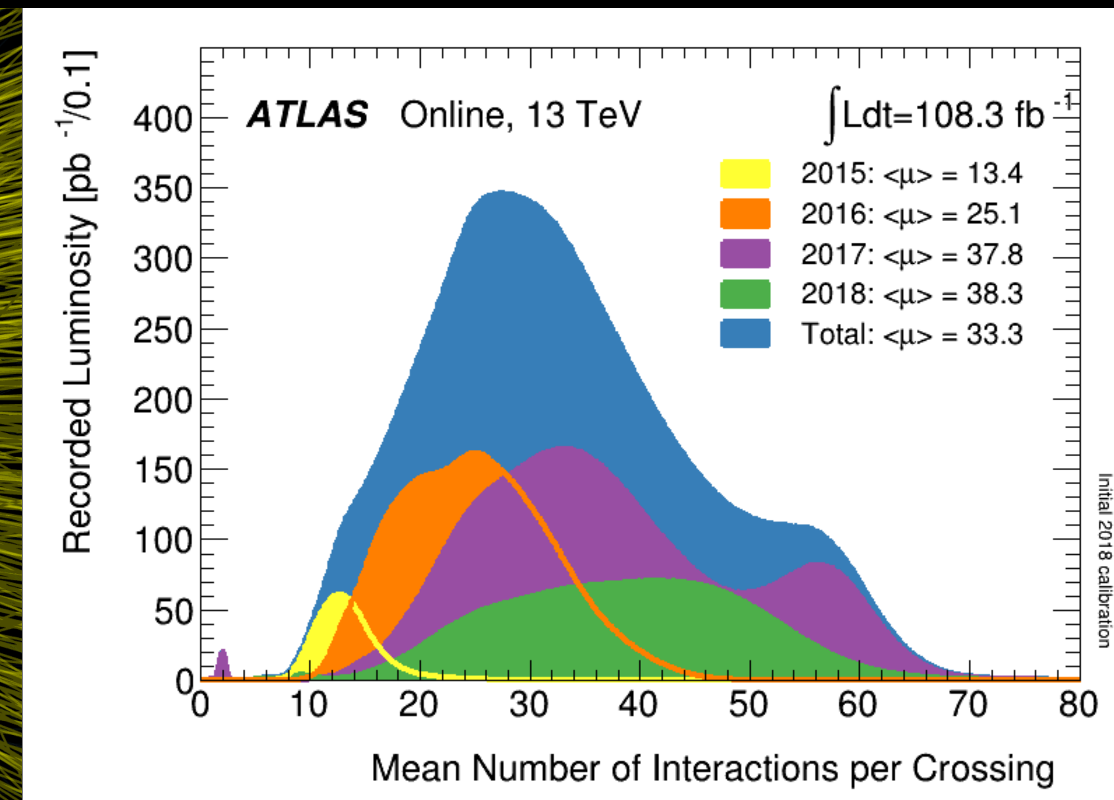




- Fantastic increase in sensitivity w.r.t. LHC run1

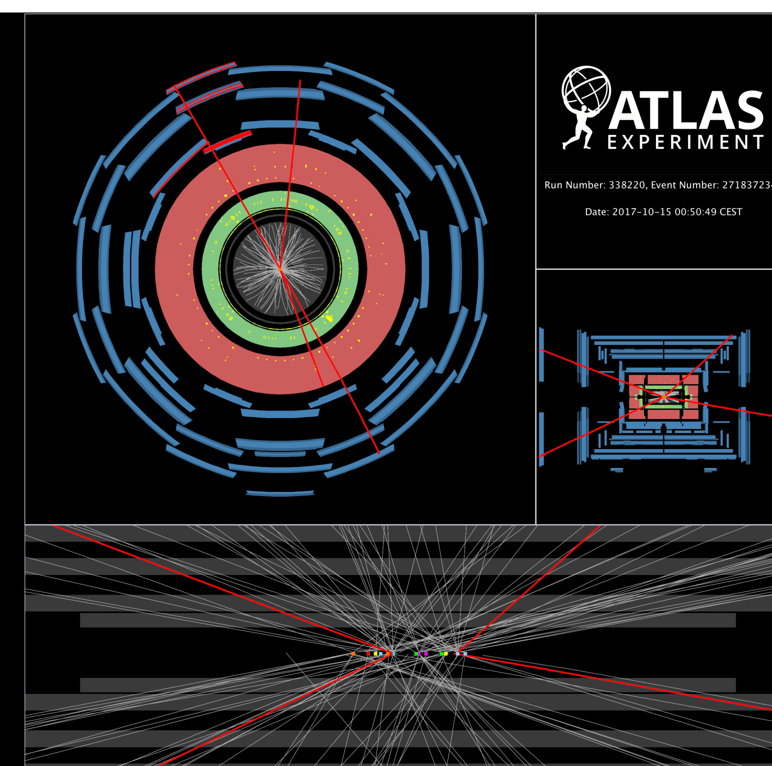
We also got pileup





This is from a special fill with <μ>=100

We are at twice the LHC design luminosity (and design pileup)

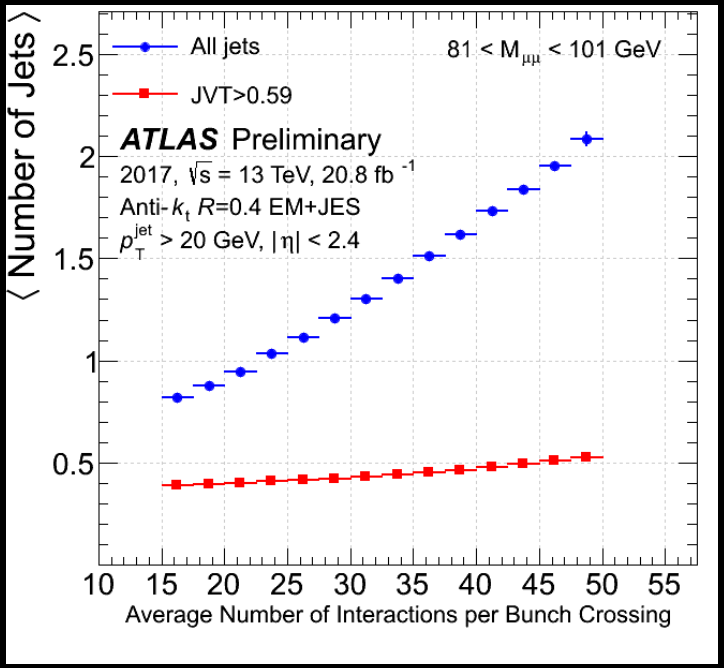


Two Z candidates from different vertices !

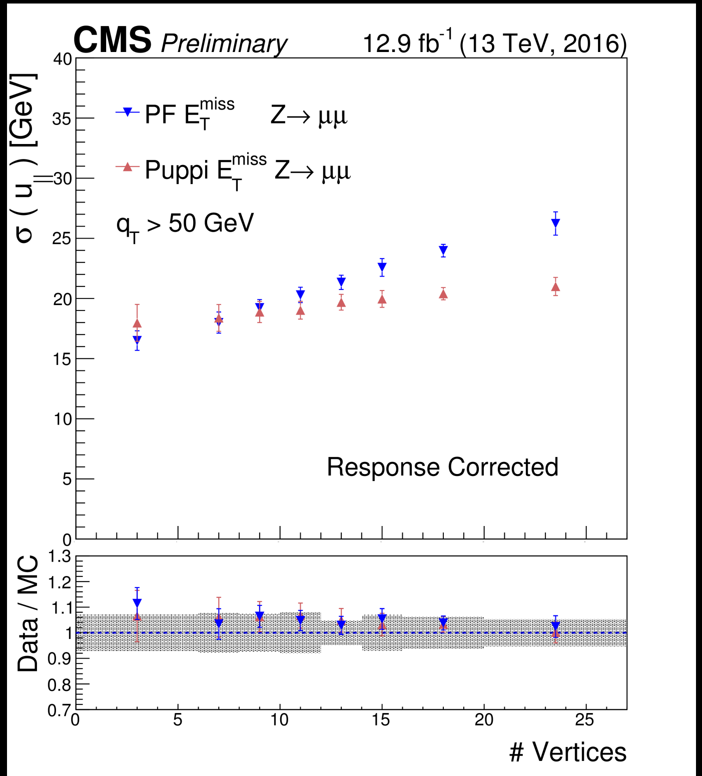
...but we can handle that

- Detectors, trigger, and computing are dealing well with the LHC performances
- In some cases, thanks to upgrades (for example, the ATLAS Pixel readout has been upgraded during run2 to cope with the high bandwidth)
- Combined Performance groups are constantly improving performances with smarter algorithms
- This talk focuses on physics results but **these wouldn't have been possible without the lower level work on detector and reconstruction software**

JETM-2017-009



CMS-PAS-JME-16-004



Is the best behind us ?

Increase in the mass reach of runX over runY, as a function of the mass reach of runX.
Numbers given for gluon fusion production.

system mass	100 GeV	1 TeV	4 TeV
run1 => run2	115%	87%	70%
run2=> run3	26%	19%	13%
run3 => run5	90%	50%	24%

Calculated with collider-reach.web.cern.ch

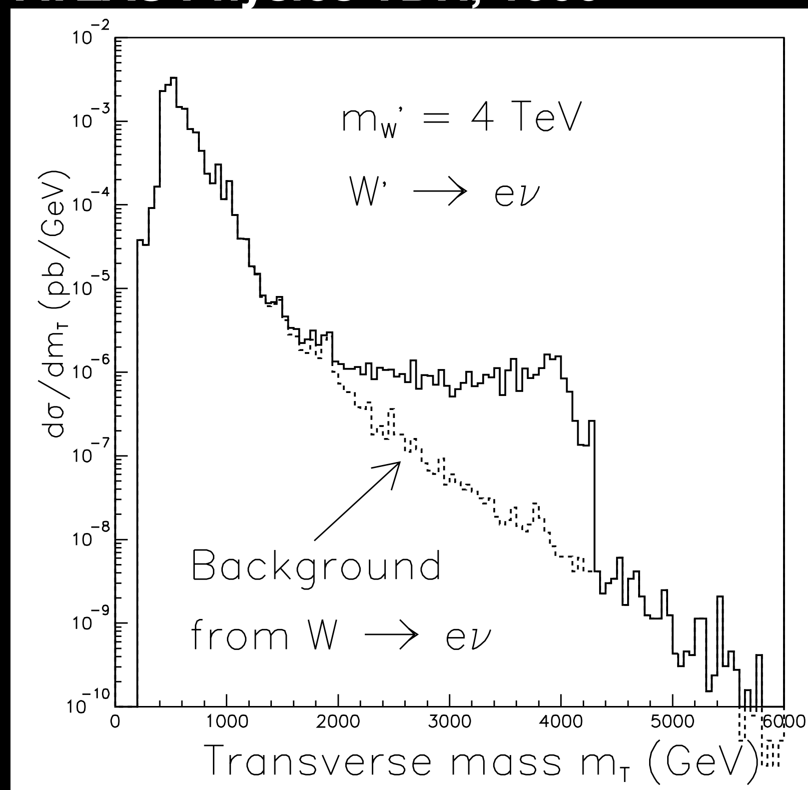
- With constant collision energy and constant luminosity, it takes increasingly more time to improve the reach with just more data
- Better prospects for low mass weakly coupled particles than heavy stuff.

not really…

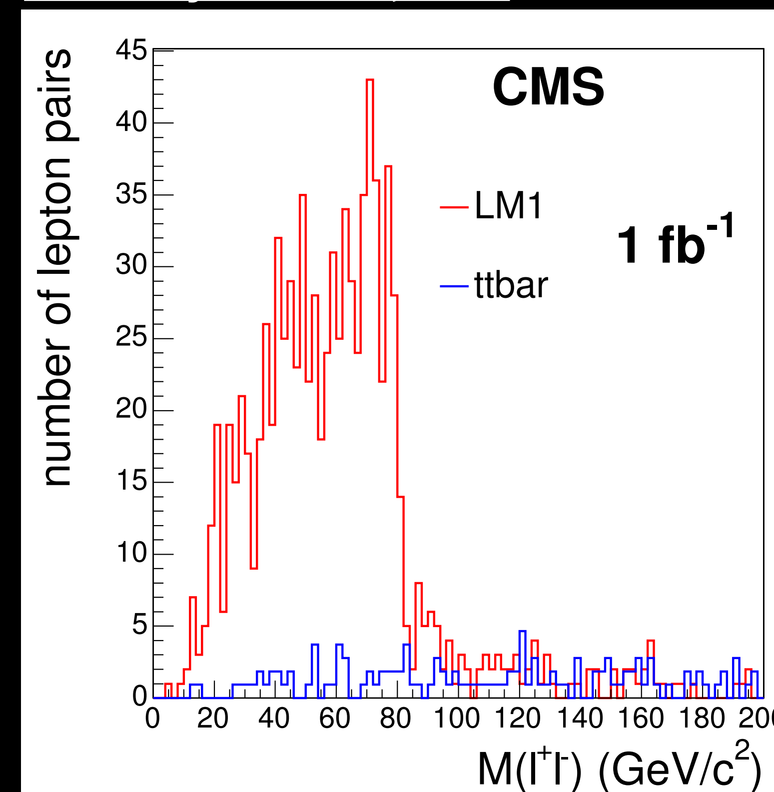
- most searches have exploited only a quarter of the anticipated run2 data
- reconstruction and analysis techniques are getting better
- emphasis is shifting from "analyze the new data as soon as possible" to “develop a smarter analysis". Not all searches are statistically limited
- new signatures : we have not looked everywhere. We only need one positive result.

where is the new physics ?

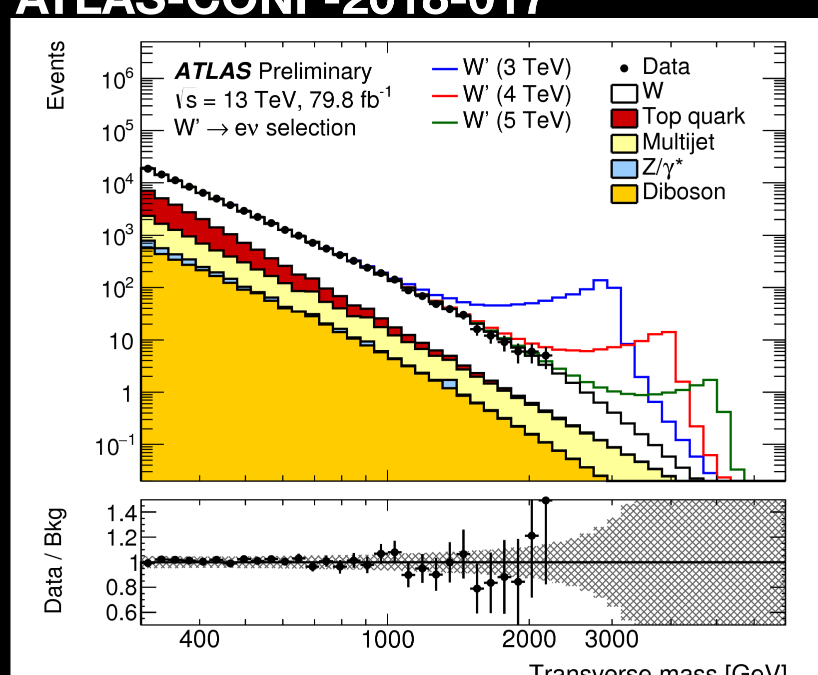
ATLAS Physics TDR, 1999



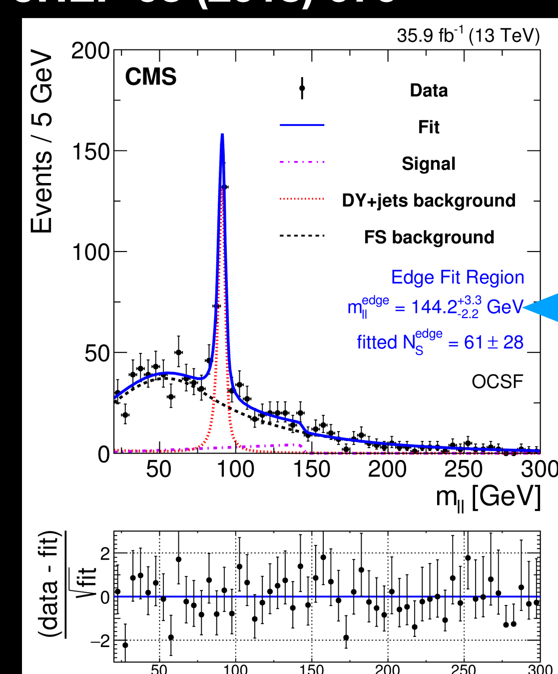
CMS Physics TDR, 2006



ATLAS-CONF-2018-017



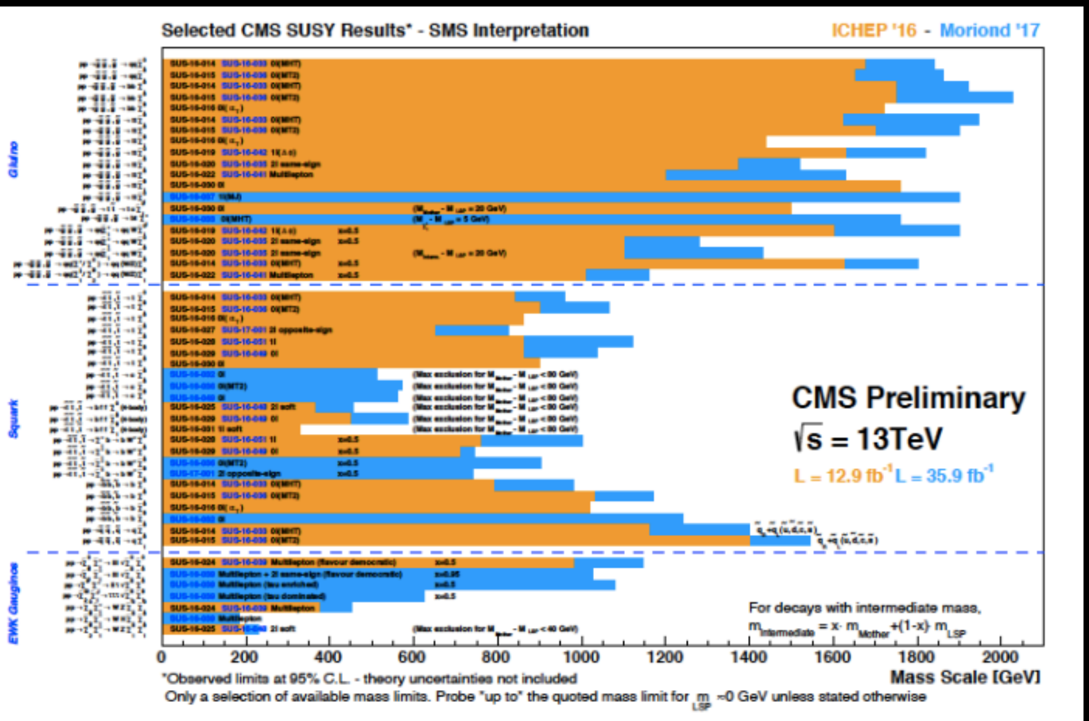
JHEP 03 (2018) 076

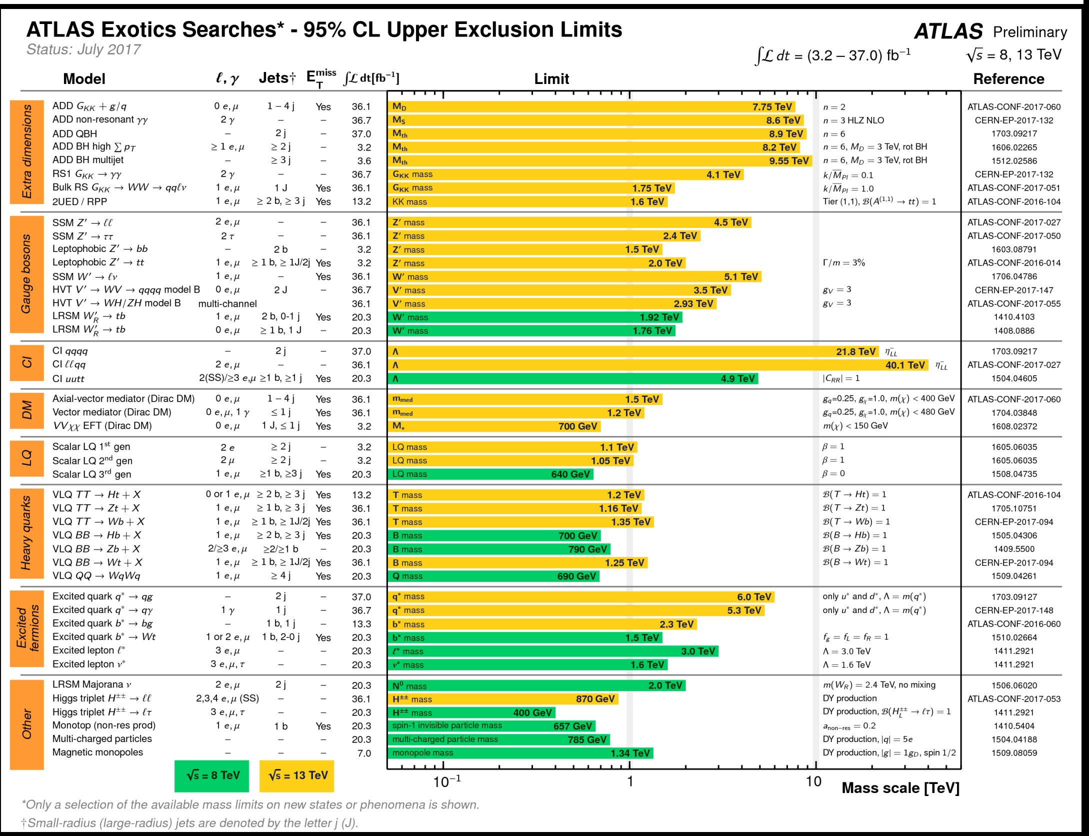


Fitted signal, with 2.3 (1.5) local (global) significance

now we have many searches…

(far more than I can talk about)





There are O(100) papers on direct BSM searches from ATLAS and CMS each in each iteration (i.e. without counting updates with more luminosity)

https://twiki.cern.ch/twiki/bin/view/AtlasPublic
http://cms-results.web.cern.ch/cms-results/public-results/publications/

so I need to choose

- Supersymmetry : still a major option to address naturalness and Dark Matter and I like it

- Dark Matter related searches (monoX and resonances) : motivated by Dark Matter and naturalness (which suggest weak scale Dark Matter)

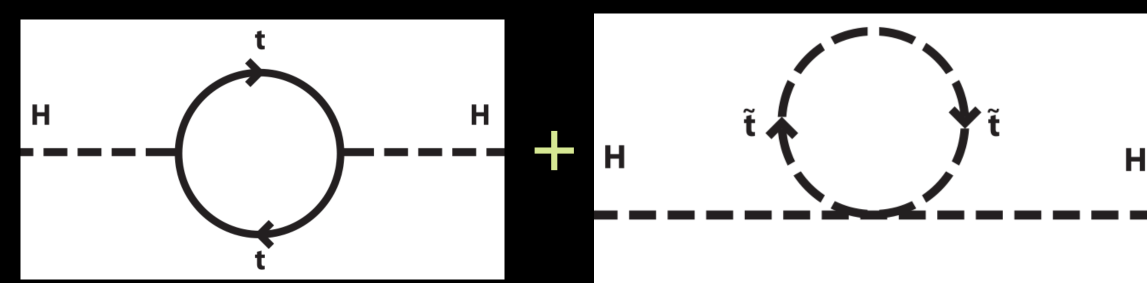
- Vector Like Quarks and W'/Z' (addressing naturalness though Higgs compositeness)

- leptoquarks (motivated by flavor anomalies)

Supersymmetry

why SUSY is cool ?

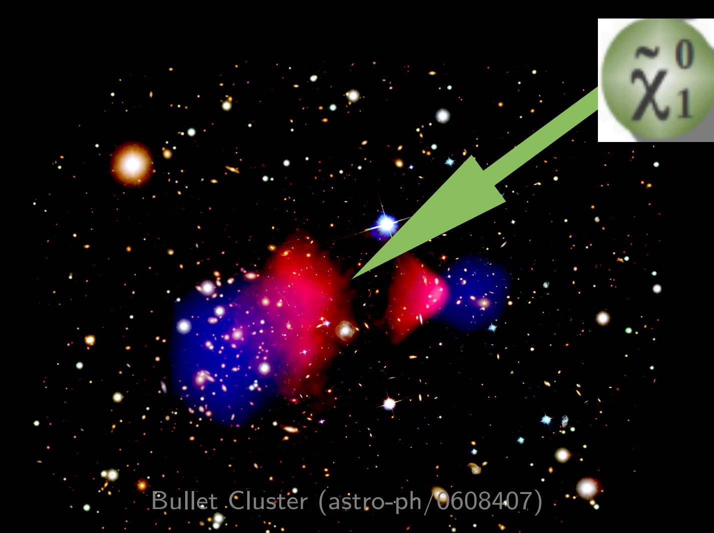
- Electroweak symmetry breaking predicted and natural



= 0

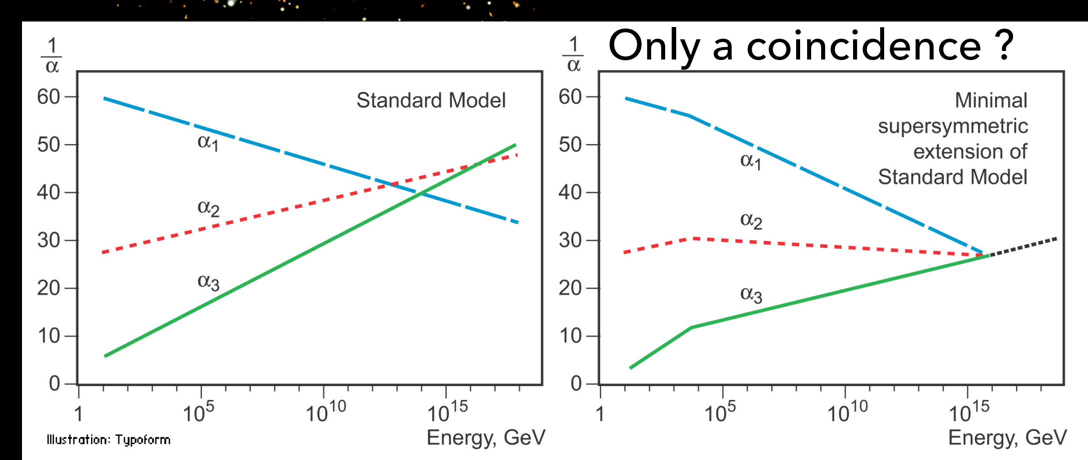
Only works if stop not much heavier than top and Higgs !

- Dark Matter candidate



- Requires R-parity conservation
- Constraints from relic density and direct detection limits

- Unification of forces



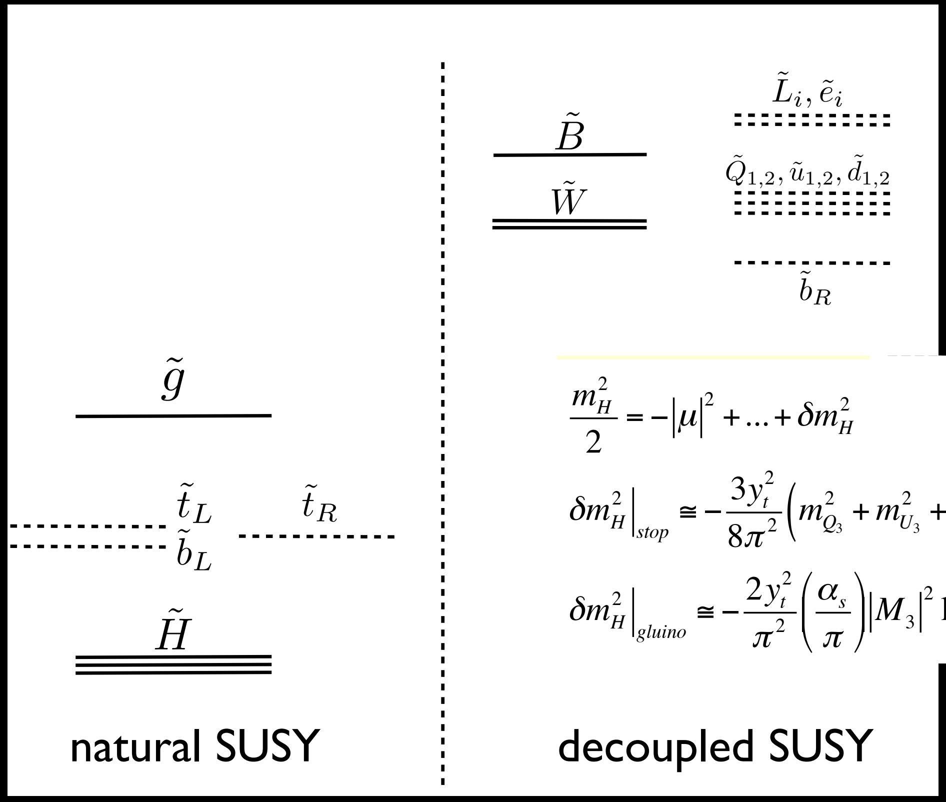
- SUSY gives a very rich variety of signatures and associated searches

Natural mass spectra

- Naturalness motivates searches of gluinos, third generation squarks, light higgsino-like LSP

- In principle one can compute fine-tuning from sparticle masses, but there are caveats (like masses not being independent parameters but generated by the unknown symmetry breaking mechanism)

- How much fine tuning are you prepared to accept ?



$$\frac{m_H^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right)$$

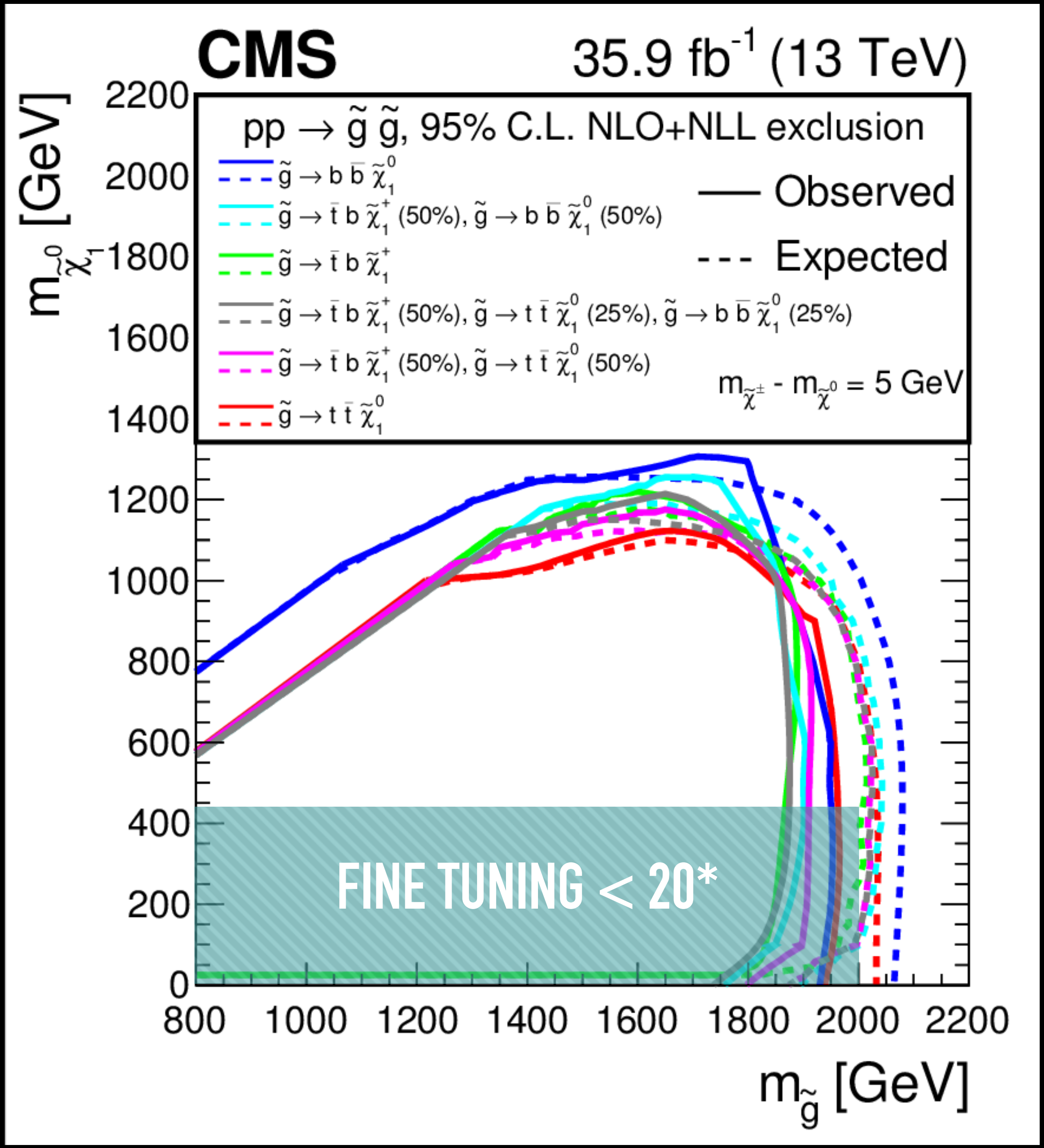
$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2\ln^2\left(\frac{\Lambda}{TeV}\right)$$

Mean apparent sizes (2% tuning):
Moon 31.5'
Sun 32.1'

gluino searches

- Colour octet, high cross section
- Relatively mild dependence of limits on decay mode.
- Limits will only improve slowly (factor 10 cross section between 2.0 and 2.5 TeV)

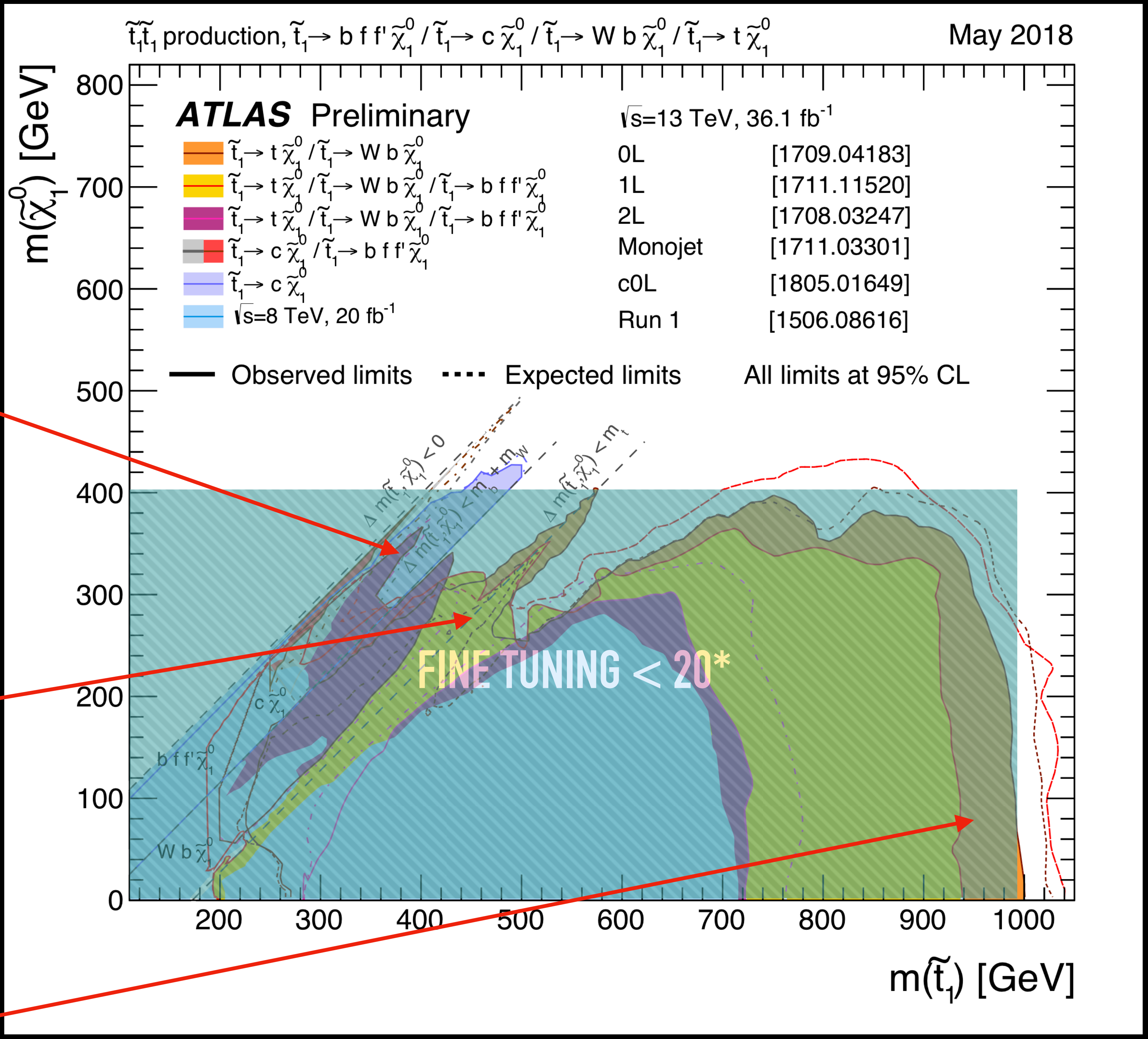
PRD 96, 0322003



* using formulas from Papucci et al., arXiv:1110.6926. Caveats apply !

top squark searches

Summary plot assuming direct decay to the lightest neutralino



ISR+MET, soft leptons, soft b-jets

ISR + tt +MET

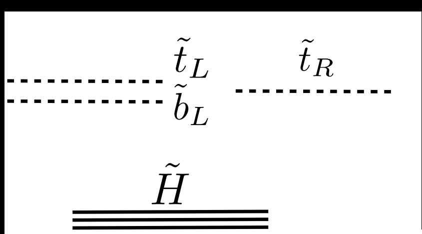
boosted top, large MET

*** using formulas from Papucci et al., arXiv:1110.6926. Caveats apply !**

For CMS equivalent see https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsSUS/T2tt_limits_summary_cms_Moriond17.pdf

top squark, less simplified

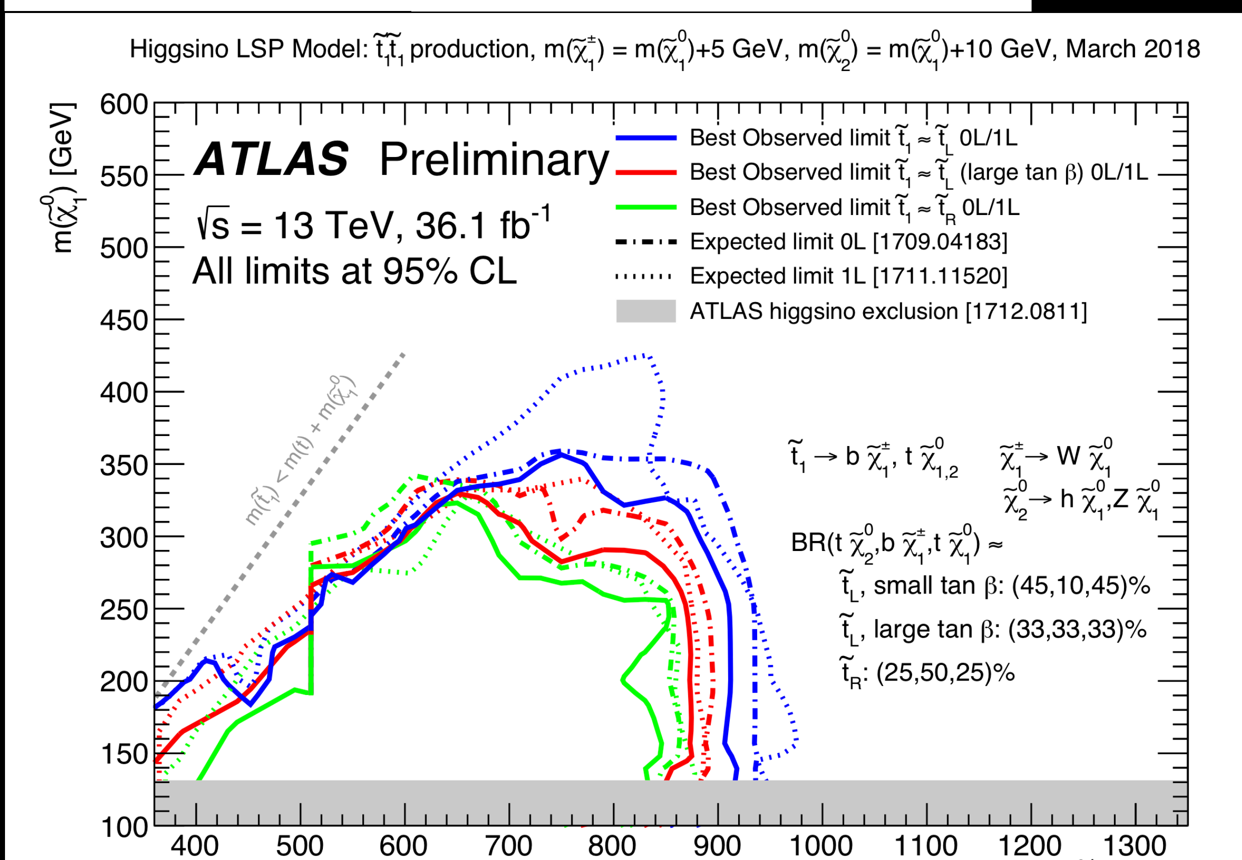
- stop limits gets weaker for more complex (realistic?) decays
- Searches were optimized on simplified models and only interpreted in the more complex ones



natural SUSY

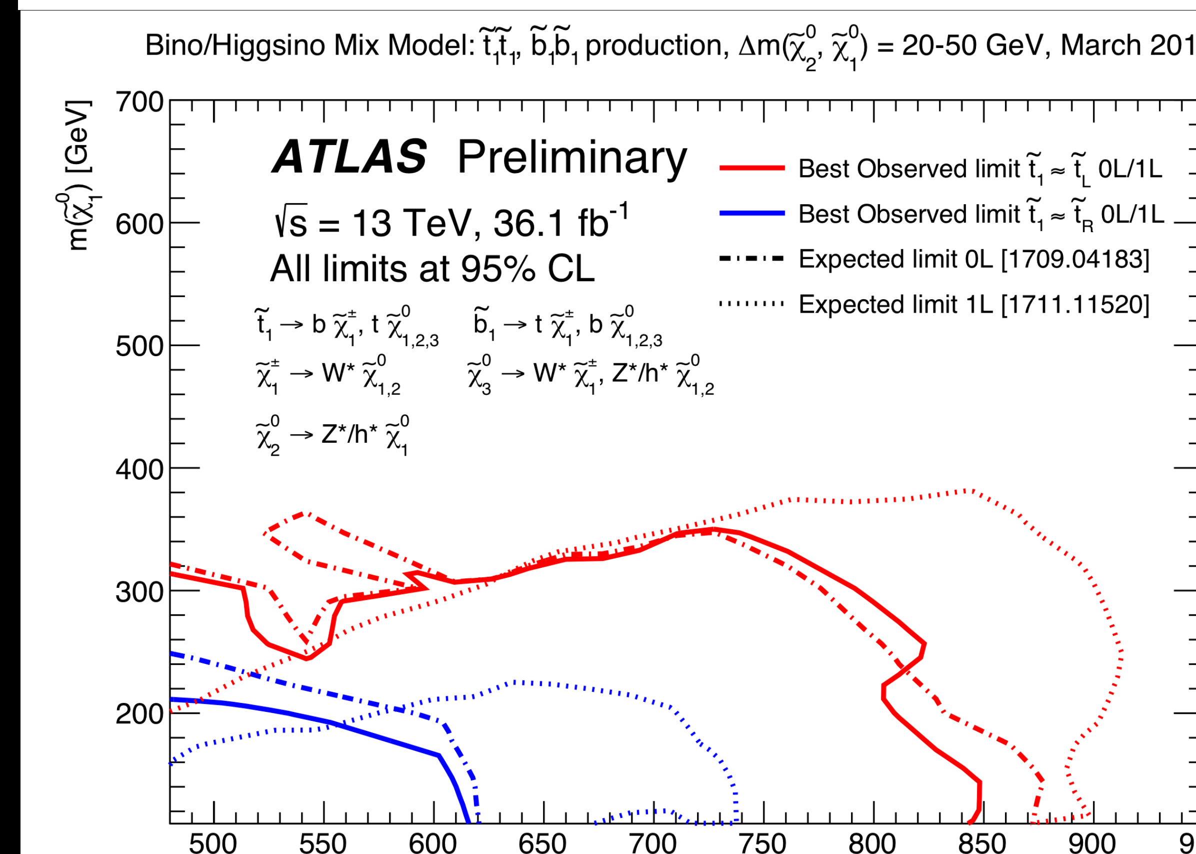
Still it seems difficult to have a stop below 400 GeV. Do we have any holes in low mass coverage ?

green curve : tR production
blue and red : t_L/b_L production



ATLAS stop higgsino

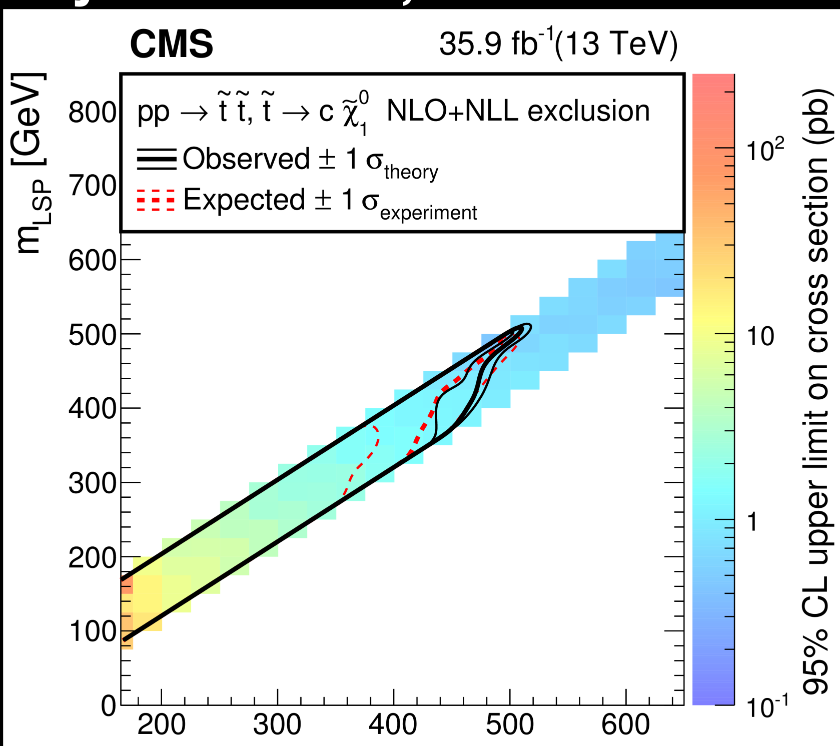
Several EWKinos (higgsino-bino mix) in a few tenths of GeV



ATLAS stop well tempered

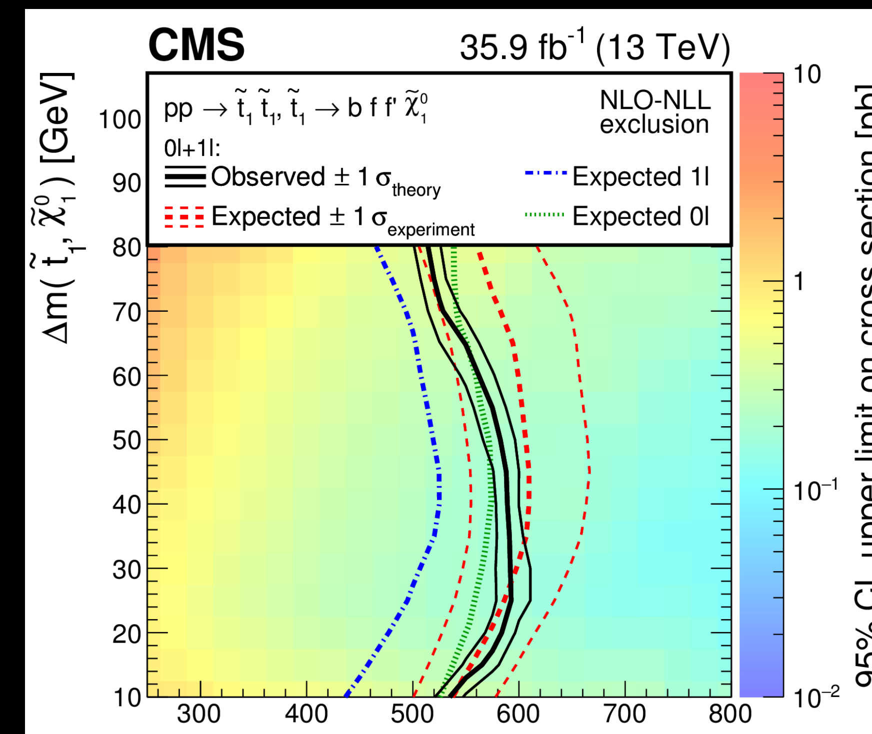
compressed stops

Phys Lett B 778, 263

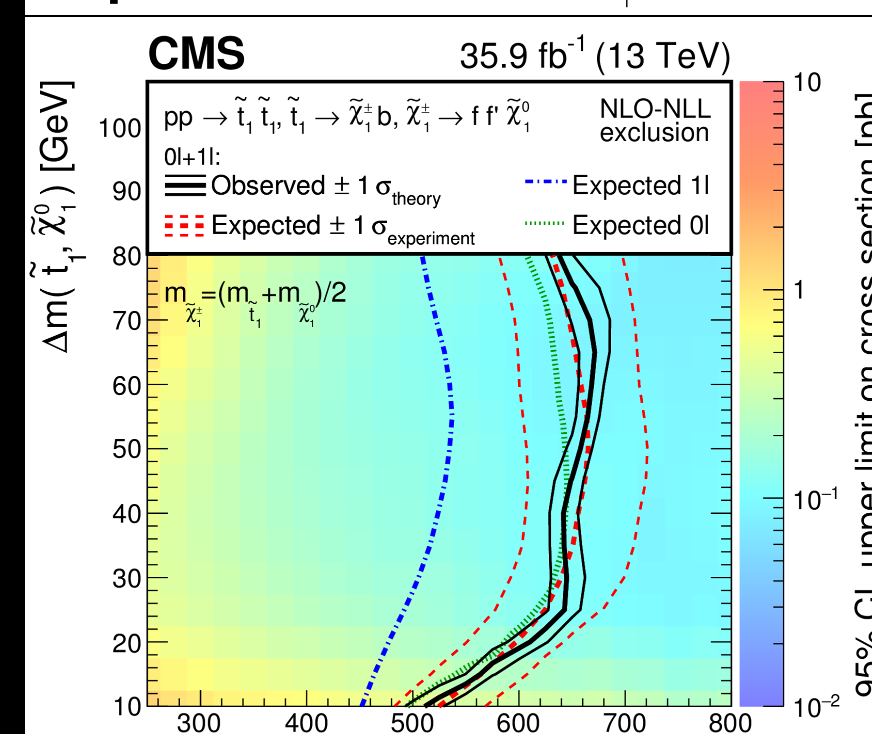


stop to c N$_1$

arXiv:1805.05784



stop to b f f' N$_1$



stop to b f f' N$_1$ via C$_1$

- Small Δm motivated by Dark Matter (stop-bino coannihilation)
- Signature is ISR+bb+MET and ISR+cc+MET, relatively strong limits set by CMS
- Mixtures of 4-body and charm decay modes might be less constrained ?

electroweak simplified

- bino LSP, wino NLSP is the benchmark signal model.
- Very tight limits if sleptons are between bino and wino. Otherwise :
- $C_1 N_2 \Rightarrow N_1 W N_1 Z$
- $C_1 N_2 \Rightarrow N_1 W N_1 h$
- $C_1 C_1 \Rightarrow W N_1 W N_1$ (more difficult, weaker limits than from either C_1N_2 final state)
- The figures are a statistical combination of relevant searches, interpreted in each model. It's nice to see that the 50-50% BR case has a similar sensitivity (expected limit) than the pure higgs decay !
- Is m(LSP) < 100 GeV and m(NLSP) < 500 GeV excluded ? Only for wino cross sections…

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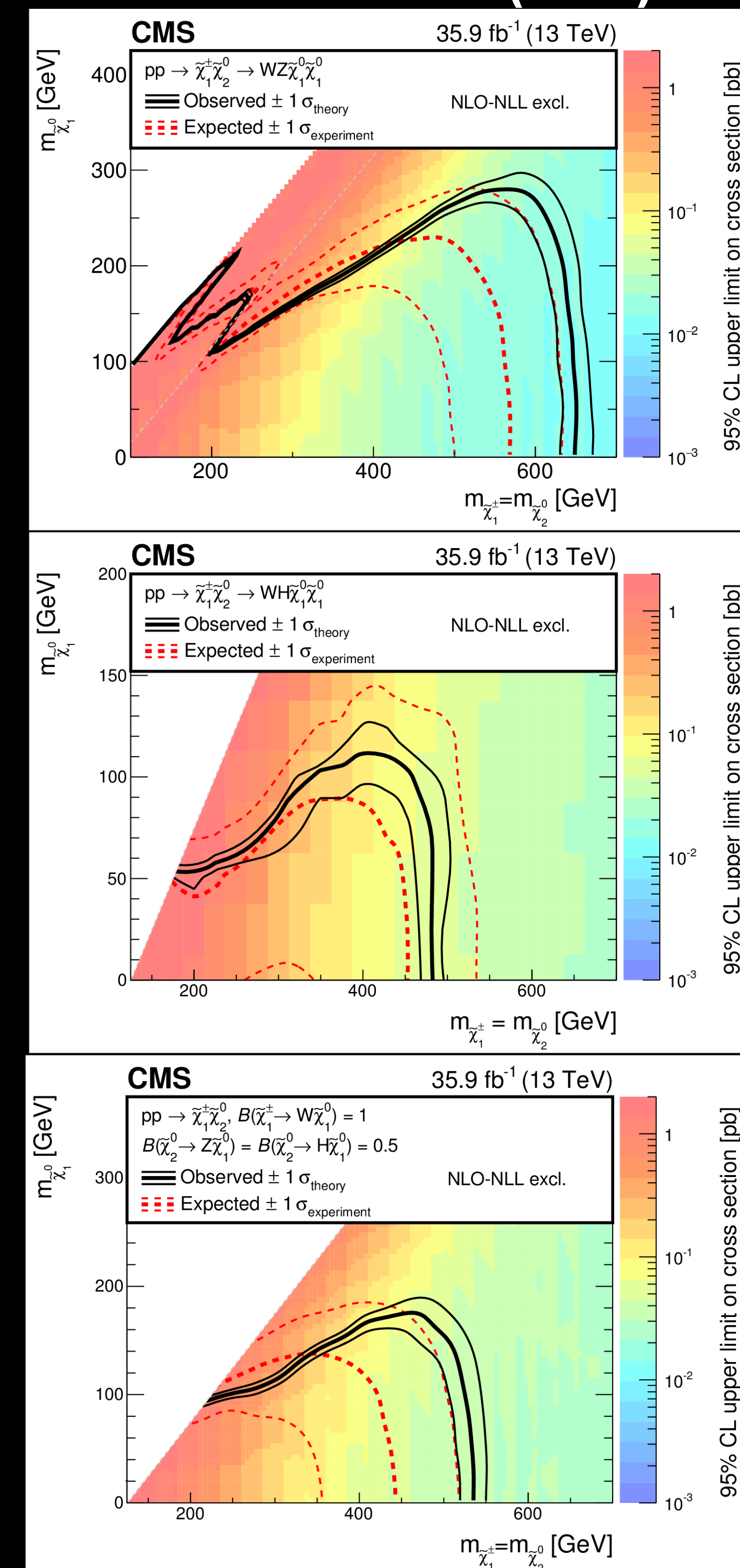
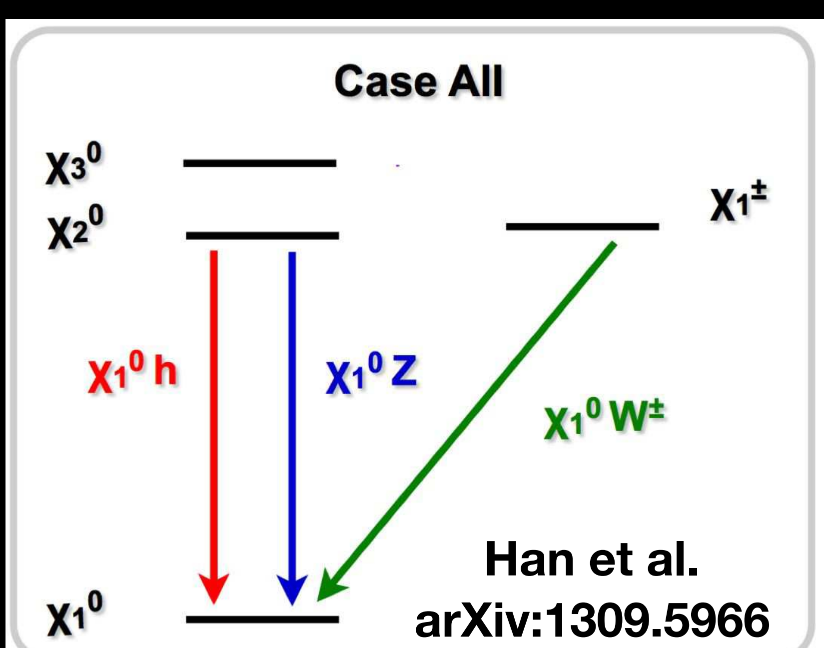
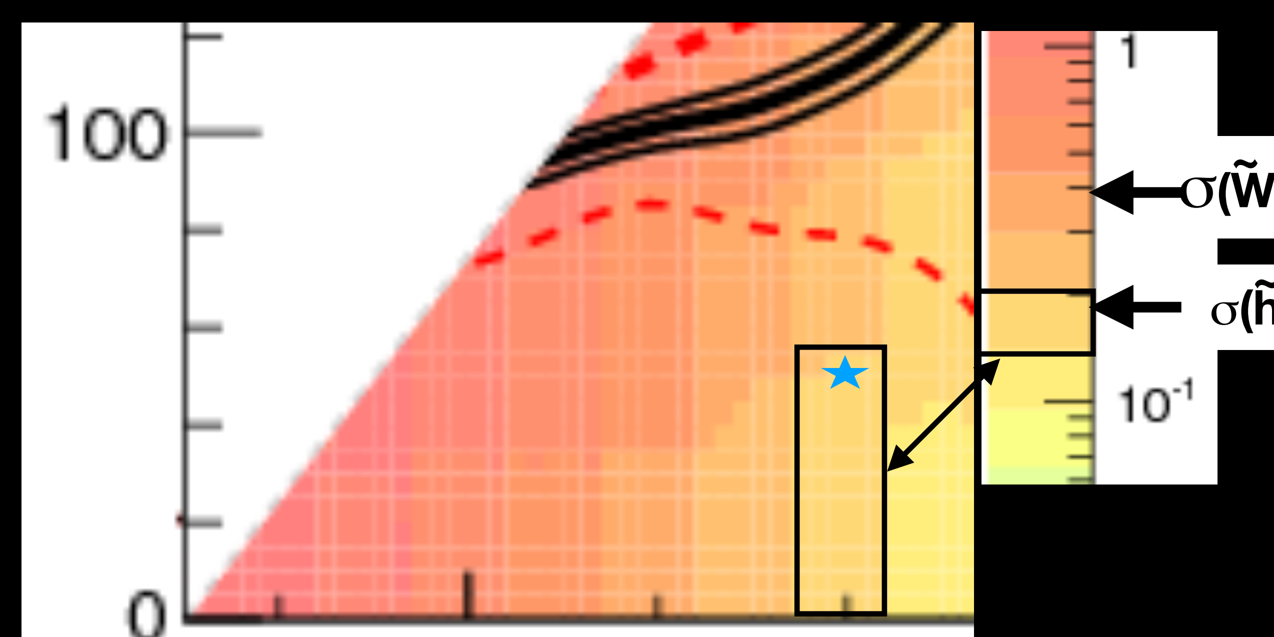


robust limits ?

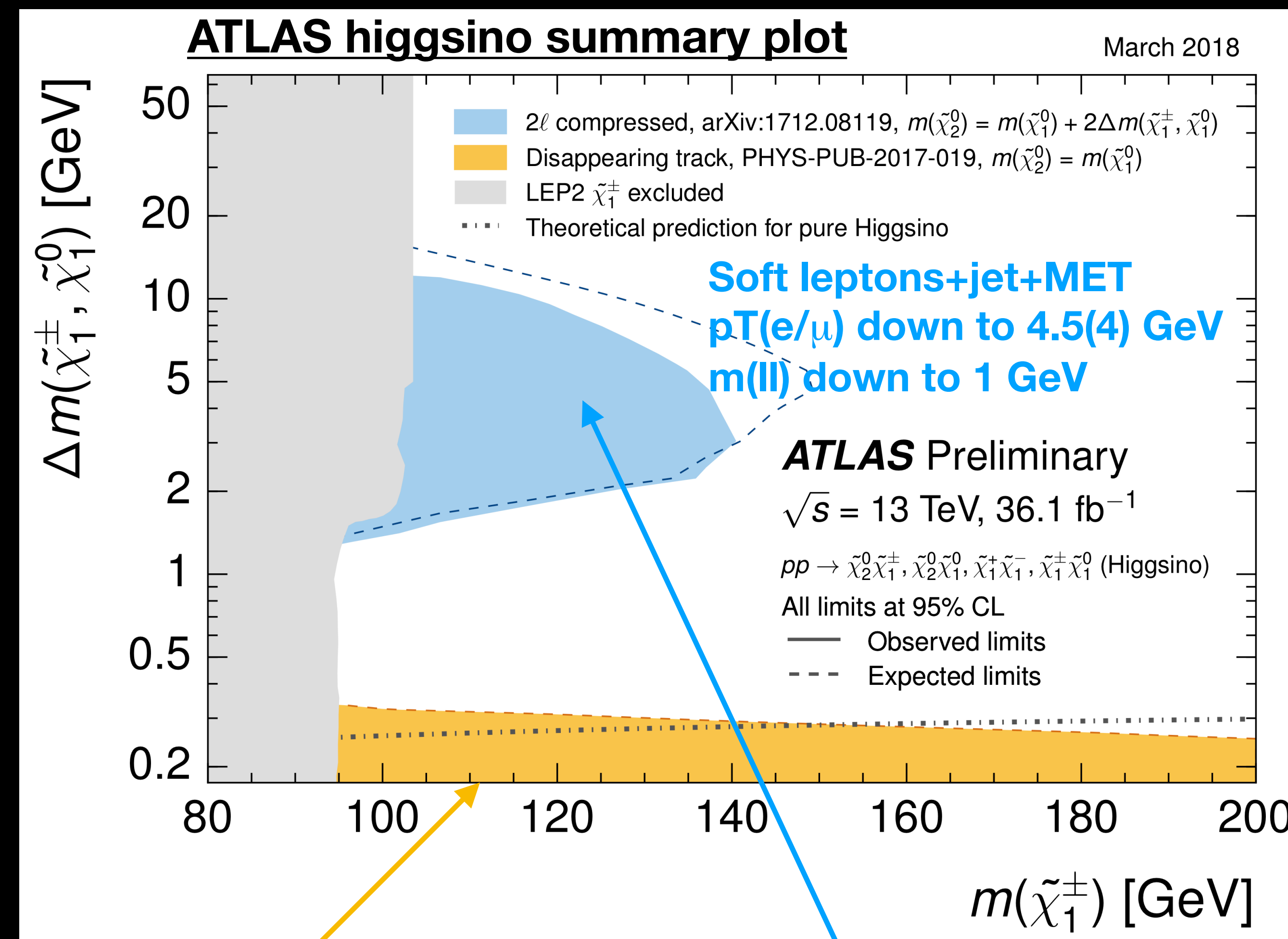
- Let's take μ=300 GeV, M_1=50 GeV (heavy winos). More natural than the wino NLSP model (neither is a good choice for relic density)
- N_2C_1 + N_3C_1 cross section is 180 fb (the wino cross section is 386 fb)
- $N_2(N_3)$ decays mostly to ZN_1 (hN_1) so WZ+MET and WH+MET final states are roughly equally likely
- The CMS cross section limit is about 200 fb, so this mass is well inside the wino exclusion contour, but an higgsino-like N_2,N_3,C_1 triplet is allowed

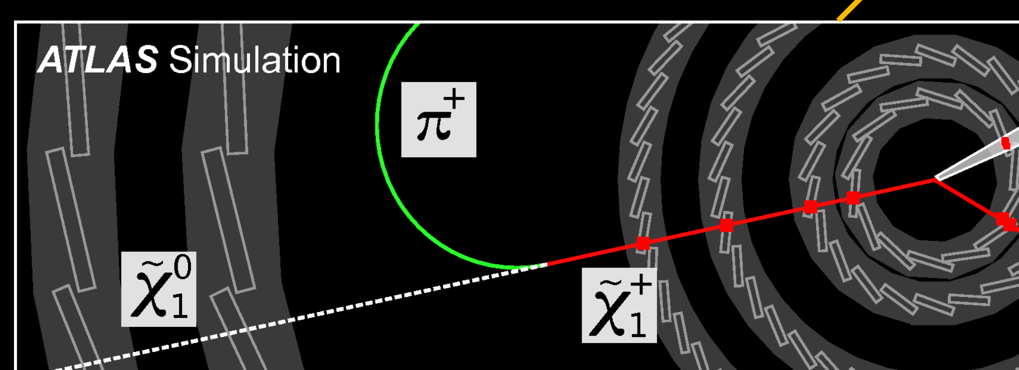


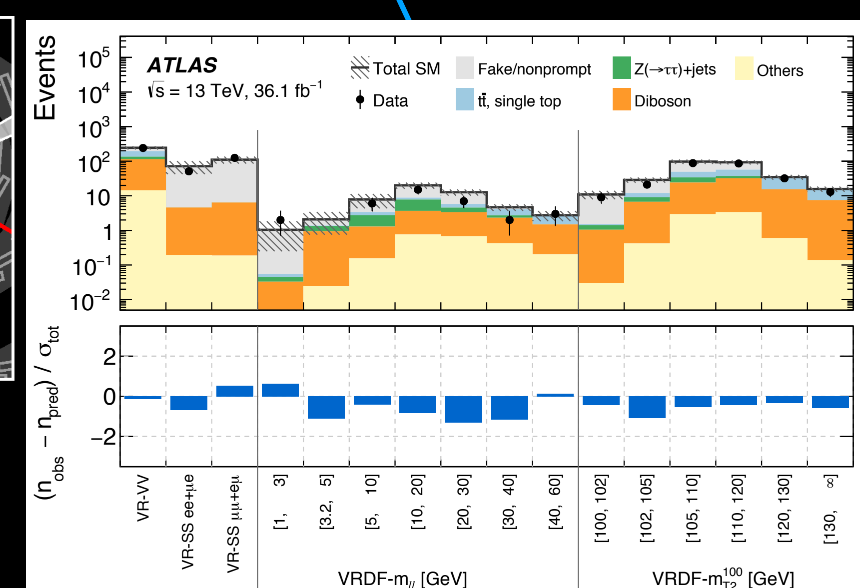


higgsino searches

- If an higgsino-like N_1 is the LSP and everything else is heavy, a mass-degenerate triplet of states is left - the ultimate challenge !
- Since the higgsino mass m drives fine tuning it's a very motivated scenario
- First limits from ATLAS and CMS now available
- Still a gap for $0.3 < \Delta M < 2$ GeV



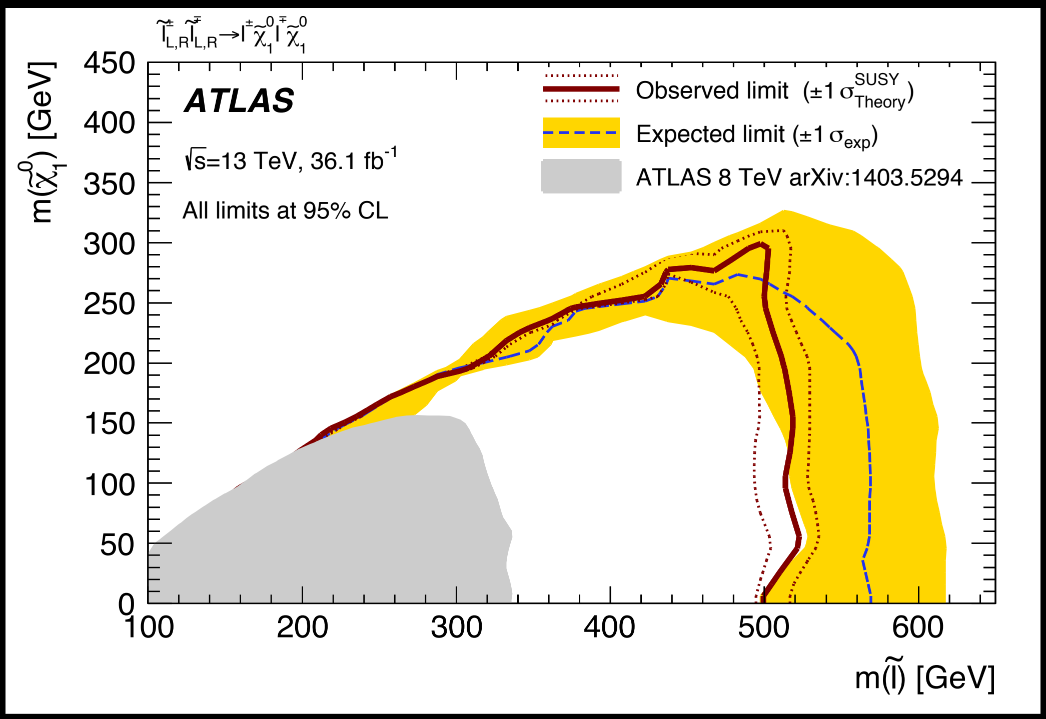




CMS compressed higgsino : PLB 782, 440
CMS disappearing track : arXiv:180407321

g-2 and sleptons

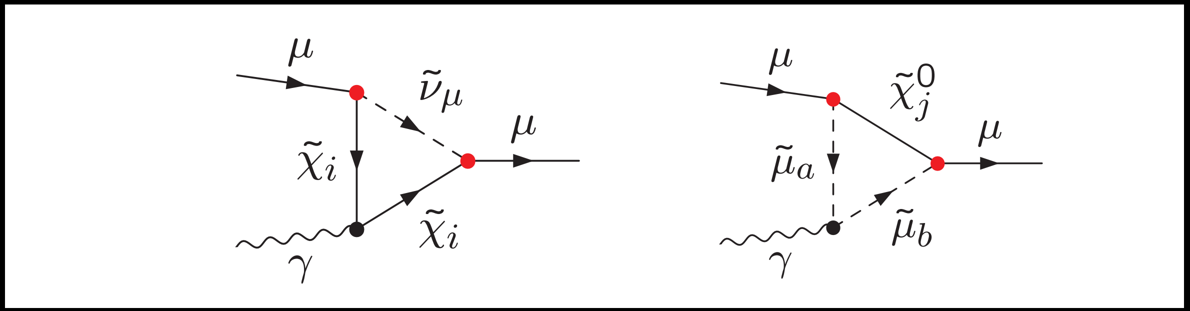
arXiv:1803.02762

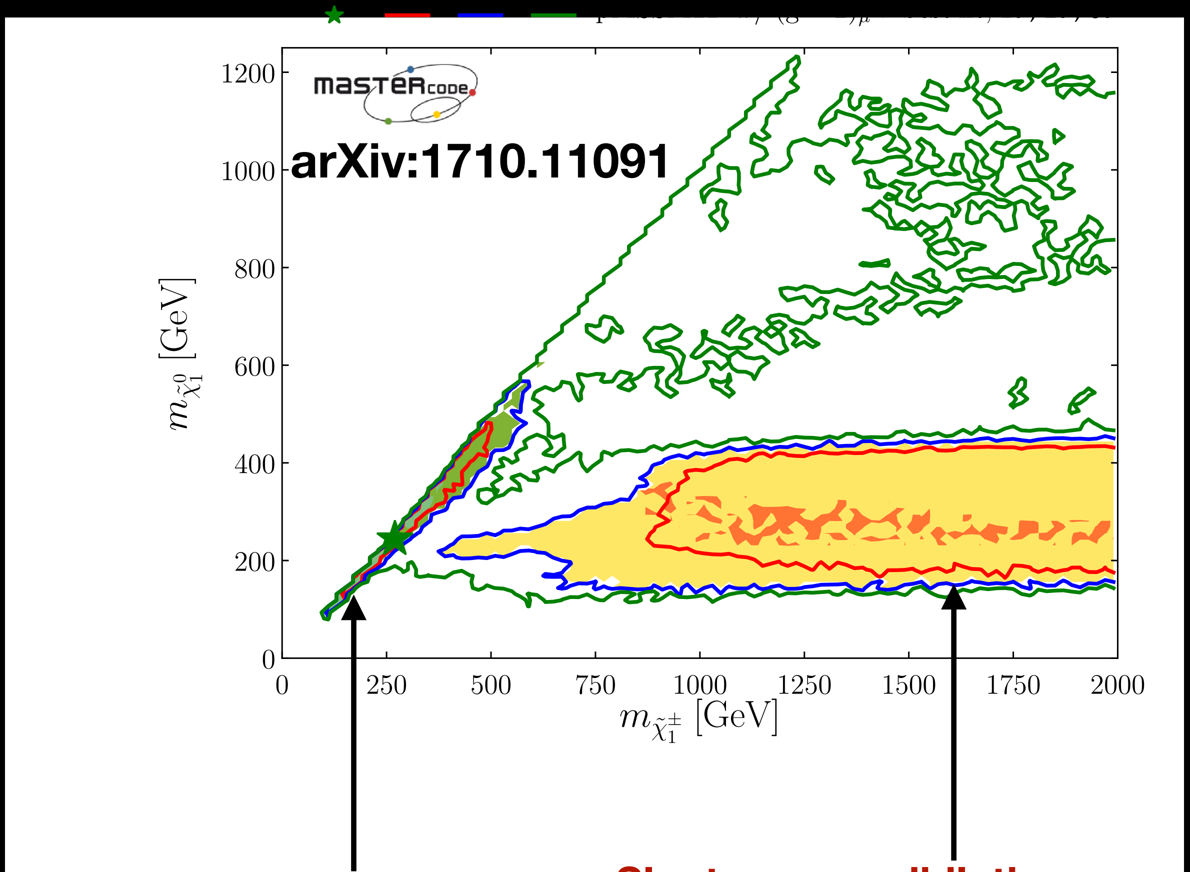


Direct slepton limits not yet covering

- mass differences 20 < ΔM(l,N_1) < 50 GeV
- beware of simplified model assumptions ! The N_1 l decay might easily compete with C_1 v => N_1 v+soft
- still need to probe direct *stau* production

Light charginos and sleptons ?

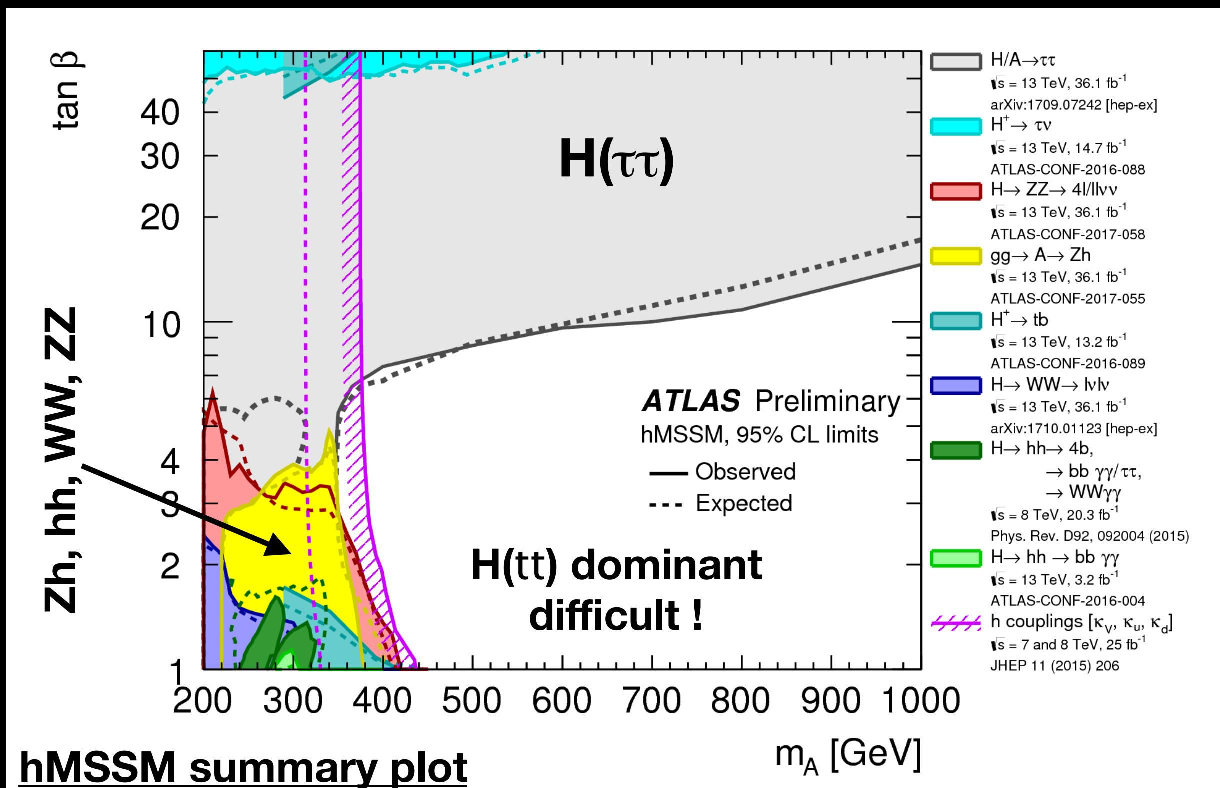




Chargino coannihilation (sleptons below 750 GeV)

Slepton coannihilation (nearly degenerate slepton and bino like neutralino)

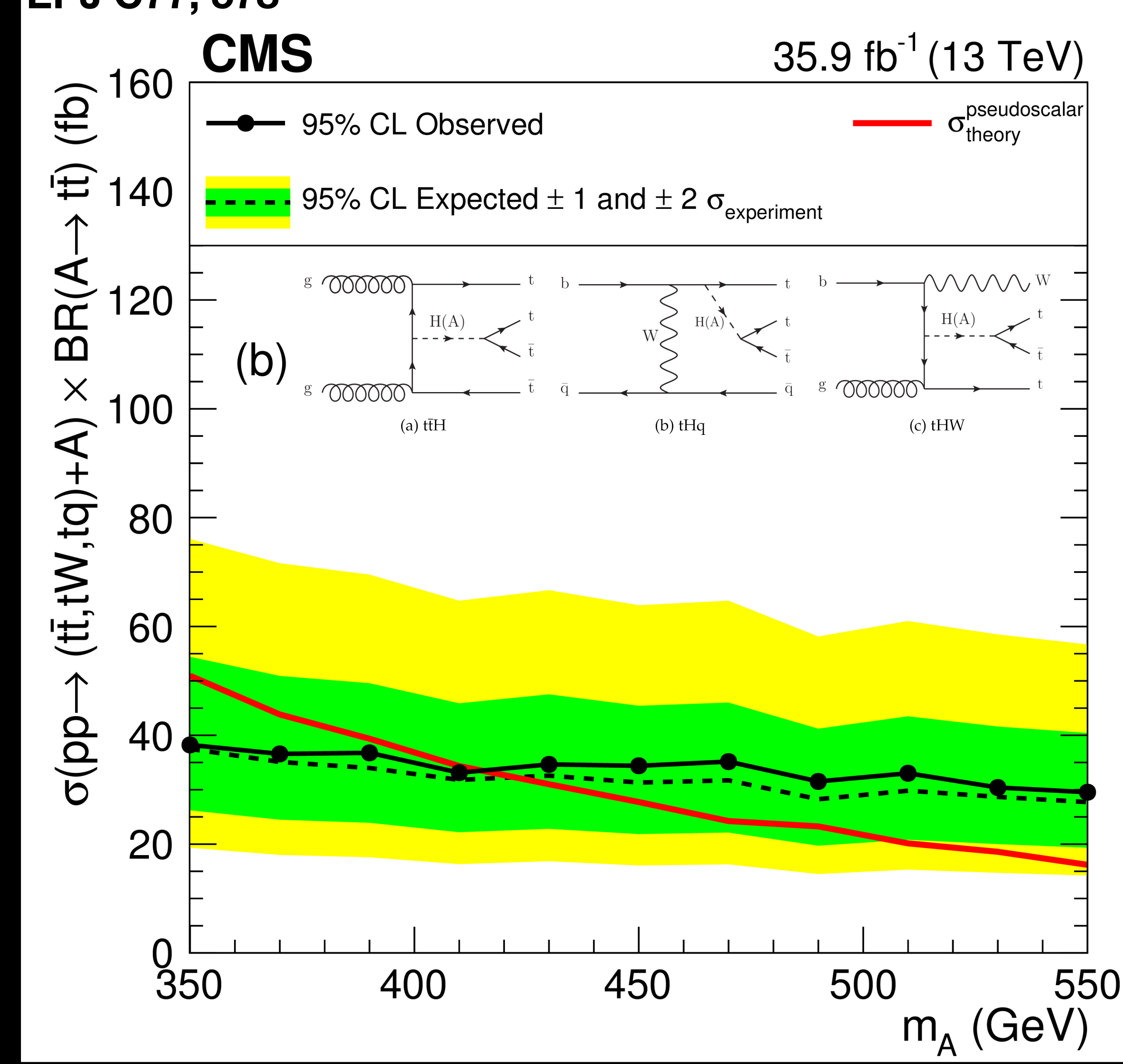
Supersymmetric Higgs sector



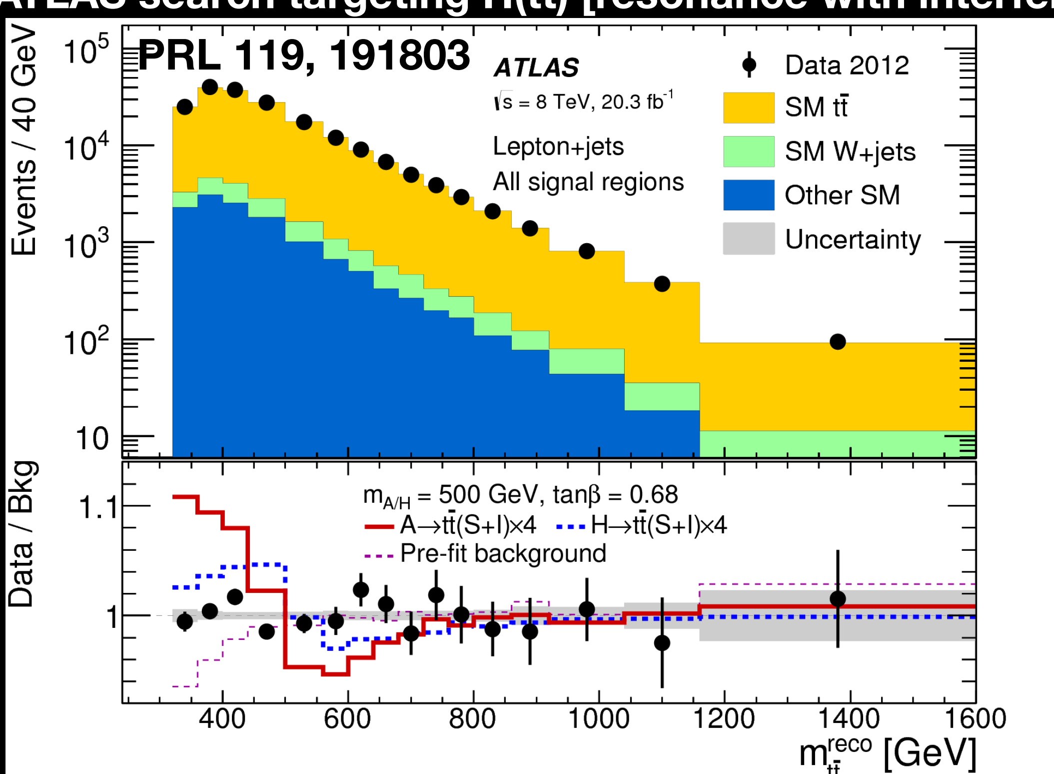
Higgs decays to SUSY particles can be large in some regions of parameter space (see for example R.K. Barman et al., arXiv:1607.00676)

CMS search with SS leptons targeting 4-top production

EPJ C77, 578



ATLAS search targeting H(tt) [resonance with interference]



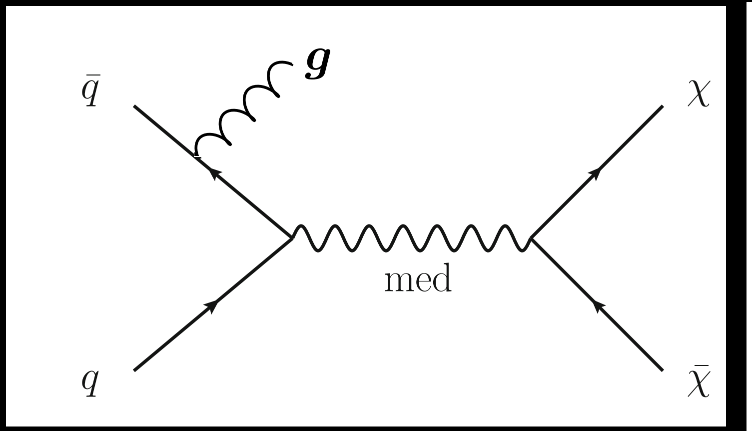
SUSY - summary

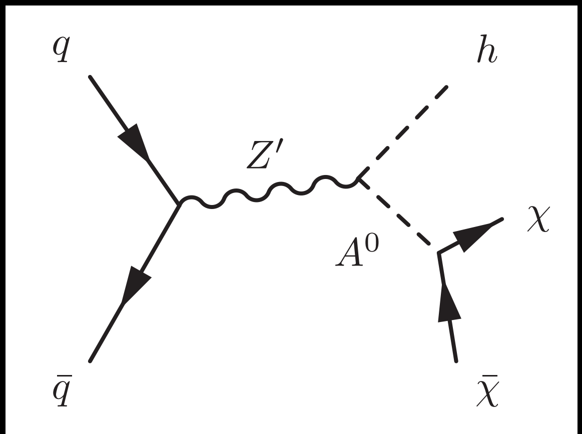
- gluino searches : good coverage, ~2 TeV limits for light LSP, will improve by a few hundred GeV by the end of run3
- stop searches : rich phenomenology, masses in 400-1000 GeV still possible for non trivial decay chains.
- EWKinos : light non compressed spectrum still possible with higgsino cross section, but will be probed with current data. Compressed EWKinos and direct slepton searches also well motivated.

Dark Matter

Dark Matter searches

- Looking for Dark Matter particles recoiling from SM objects => mono-X
- Mostly using simplified models with a mediator
    - Plenty of parameters : at least mediator mass, spin/parity and couplings to SM and DM, and DM mass
- mono-jet is the more powerful channel for simplest diagrams
- full theory can be more complicated (with additional particles, etc.), mono-X signatures can arise from decay of heavy particles
- qq => mediator => qq diagram : link with resonance searches





	ATLAS	CMS
mono-jet	JHEP 01 (2018) 126	PRD 97, 092005
mono-γ	EPJ C77, 293	JHEP10 (2017) 073
mono-V	PLB 776, 318 [ll] ATLAS-CONF-2018-005 [had]	PRD 97, 092005 [had] EPJ C52, xxx [ll]
mono-H	PRL 119, 181804 [bb] PRD 96, 112004 [γγ]	arXiv:1806.04771 [bb,ττ]
tt+MET	arXiv:1711.11520 EPJ C78, 18	JHEP 06 (2018) 027

Full 2015+2016 data

monojet search

- Signature is an excess at large MET
- Main background is Z(νν)+jets, constrained with Z(ll)+jets and W(lν)+jets
- Limited by systematics over much of the MET range (~2% at low MET)
- It's an example of a precision search, future sensitivity will depend on control of systematics

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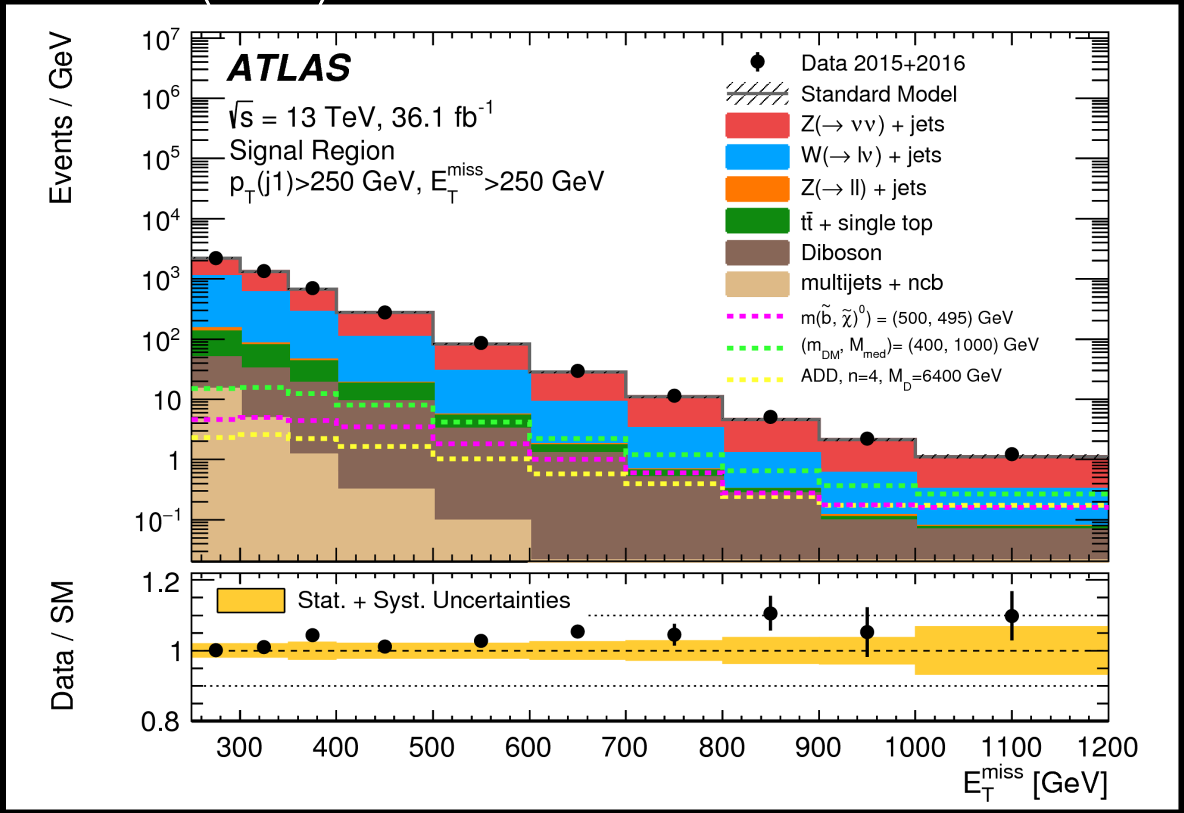

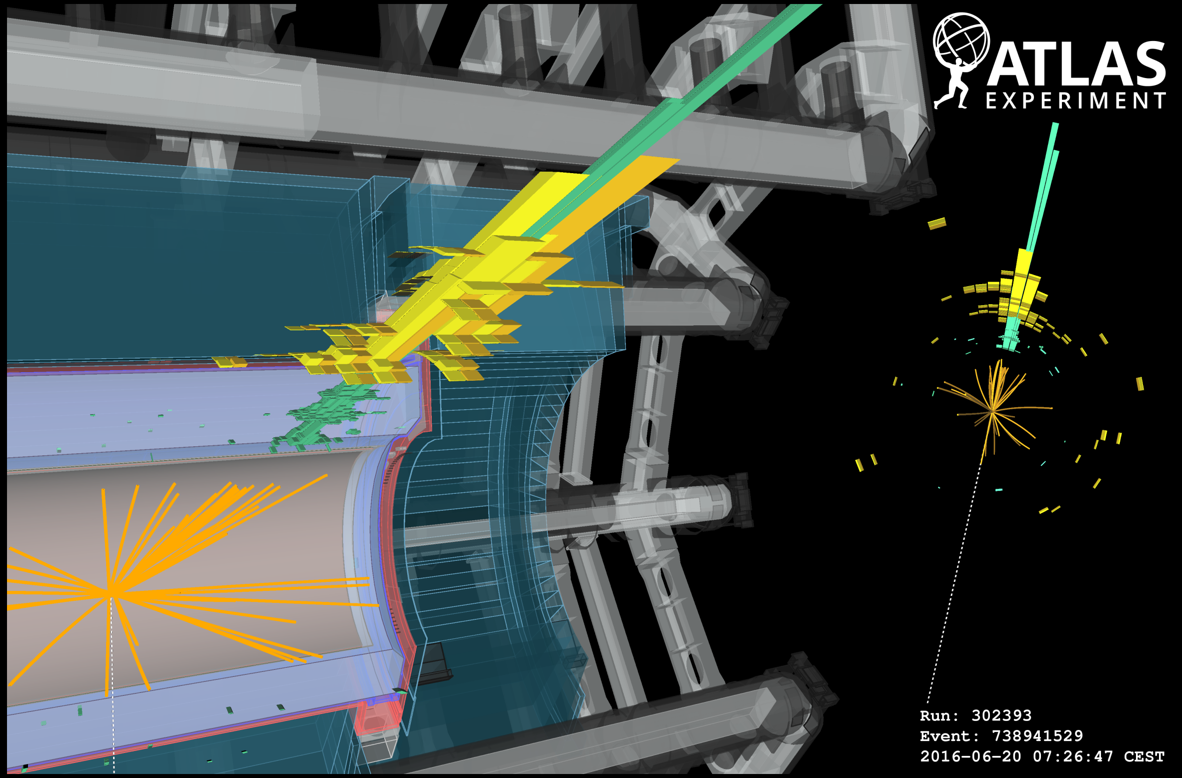

simplified model limits

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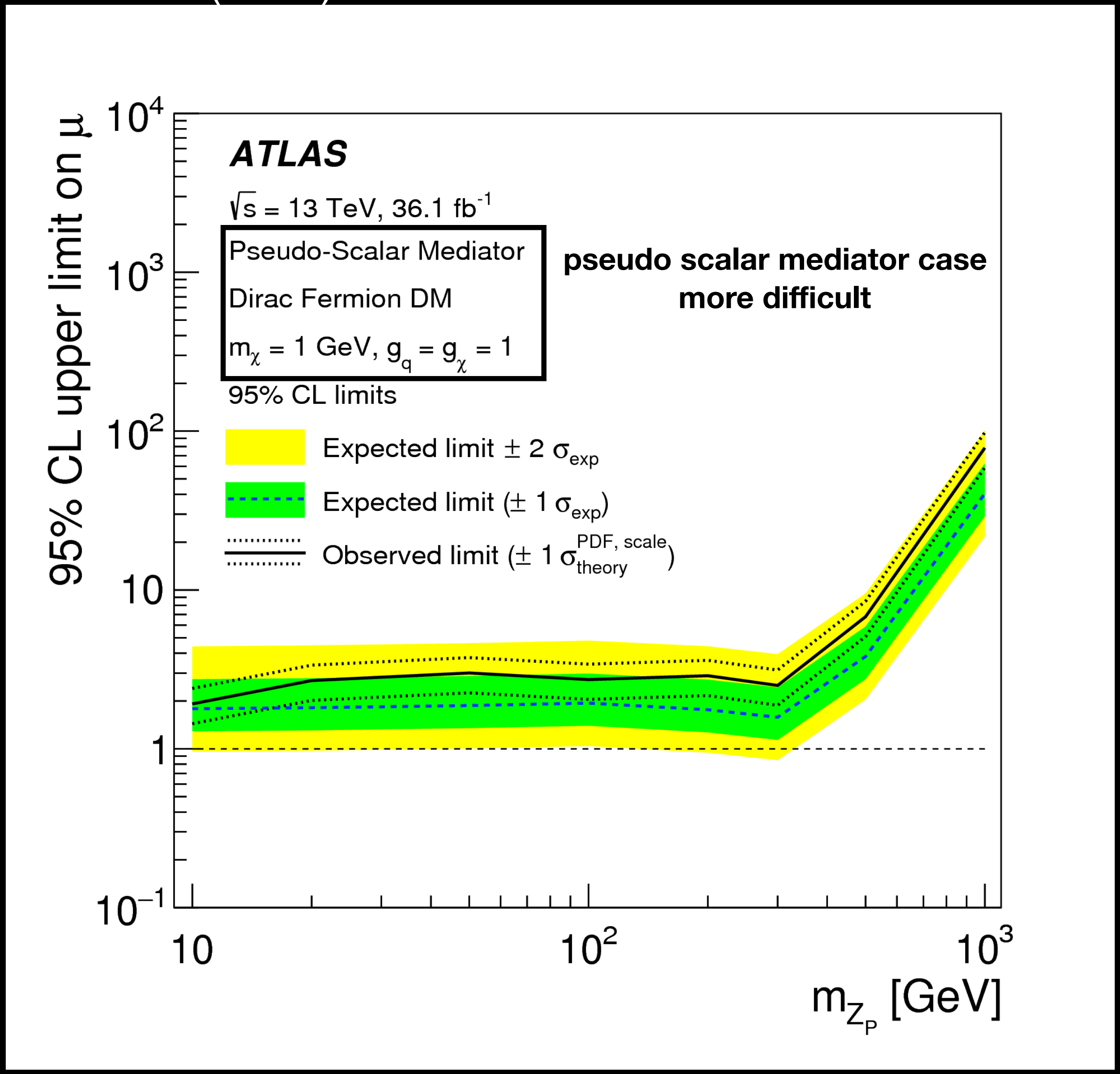

pseudo scalar mediator case more difficult

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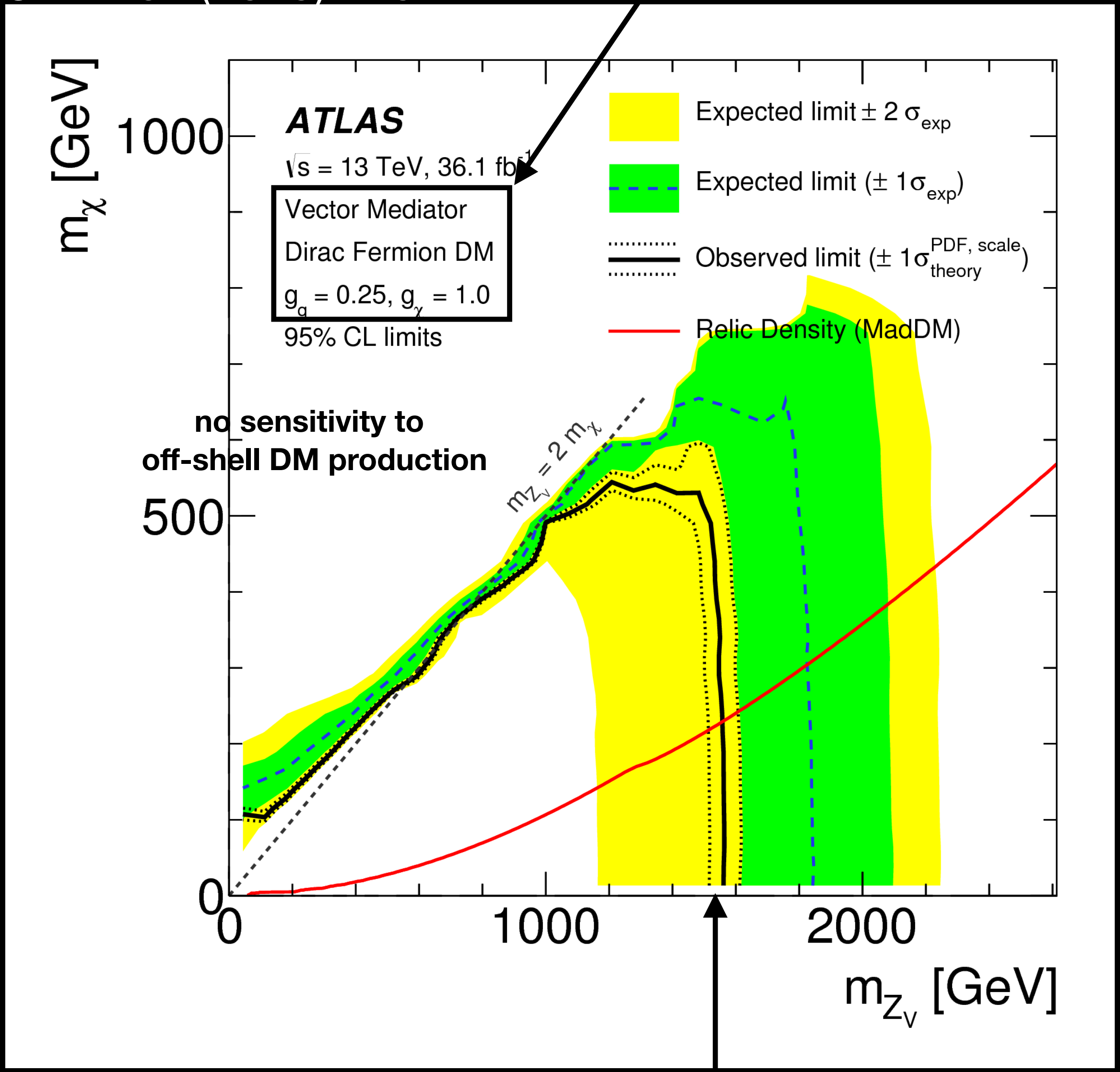
choice of parameters other than mass

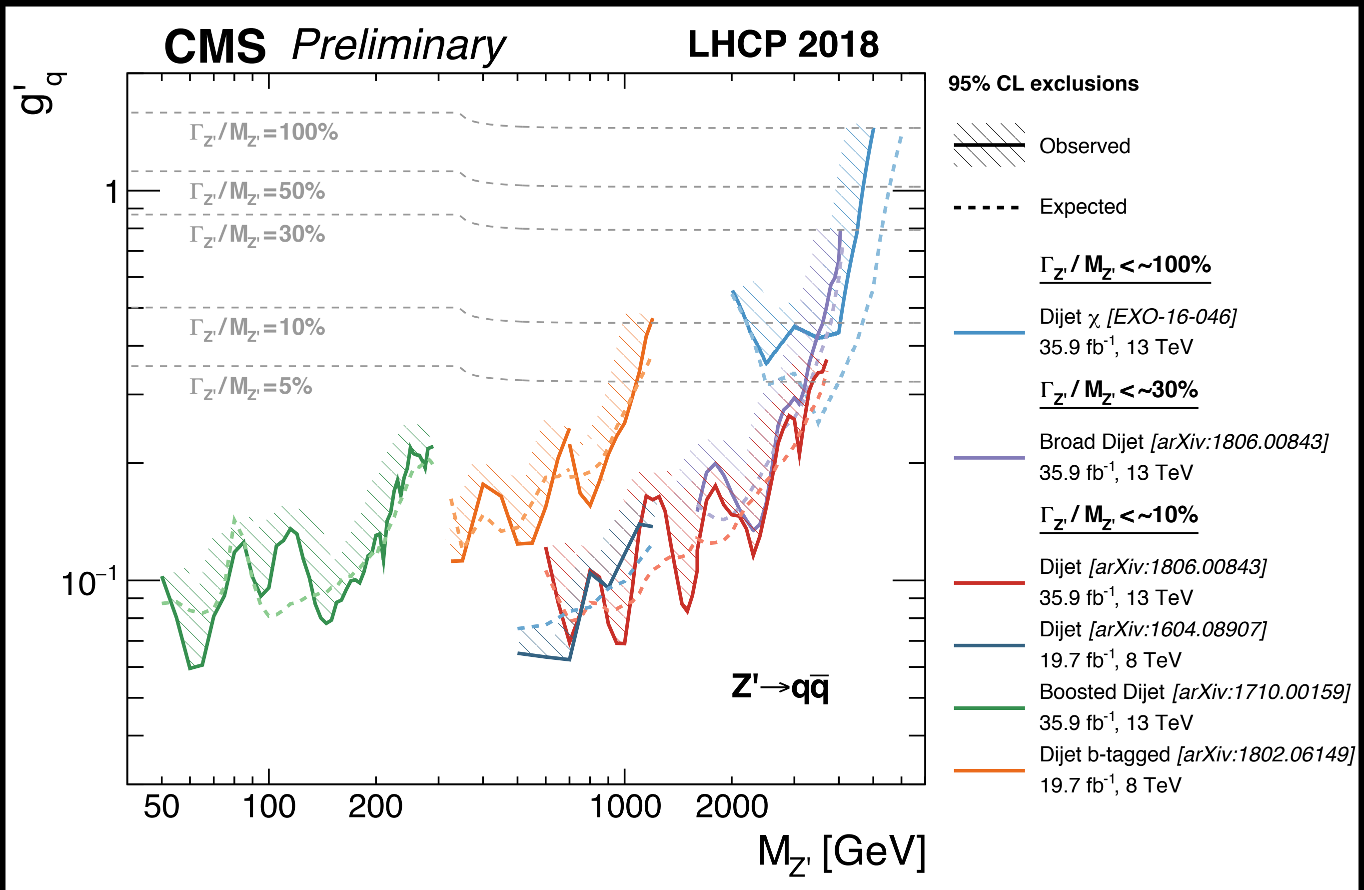
$g_q g_{DM} = 0.25$



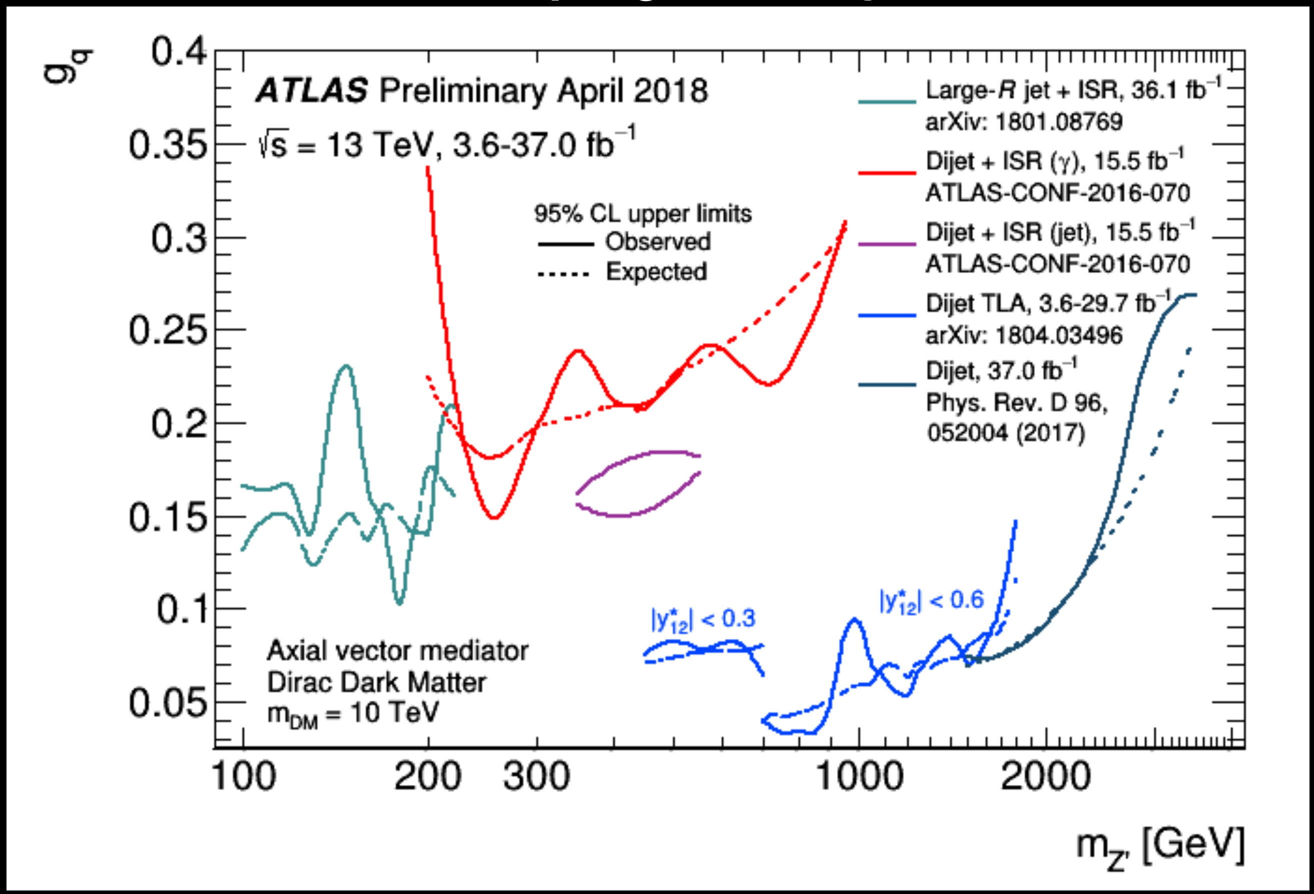
no sensitivity to off-shell DM production

vertical lines = no dependence on m_{DM} until close to diagonal

di-jet resonant search



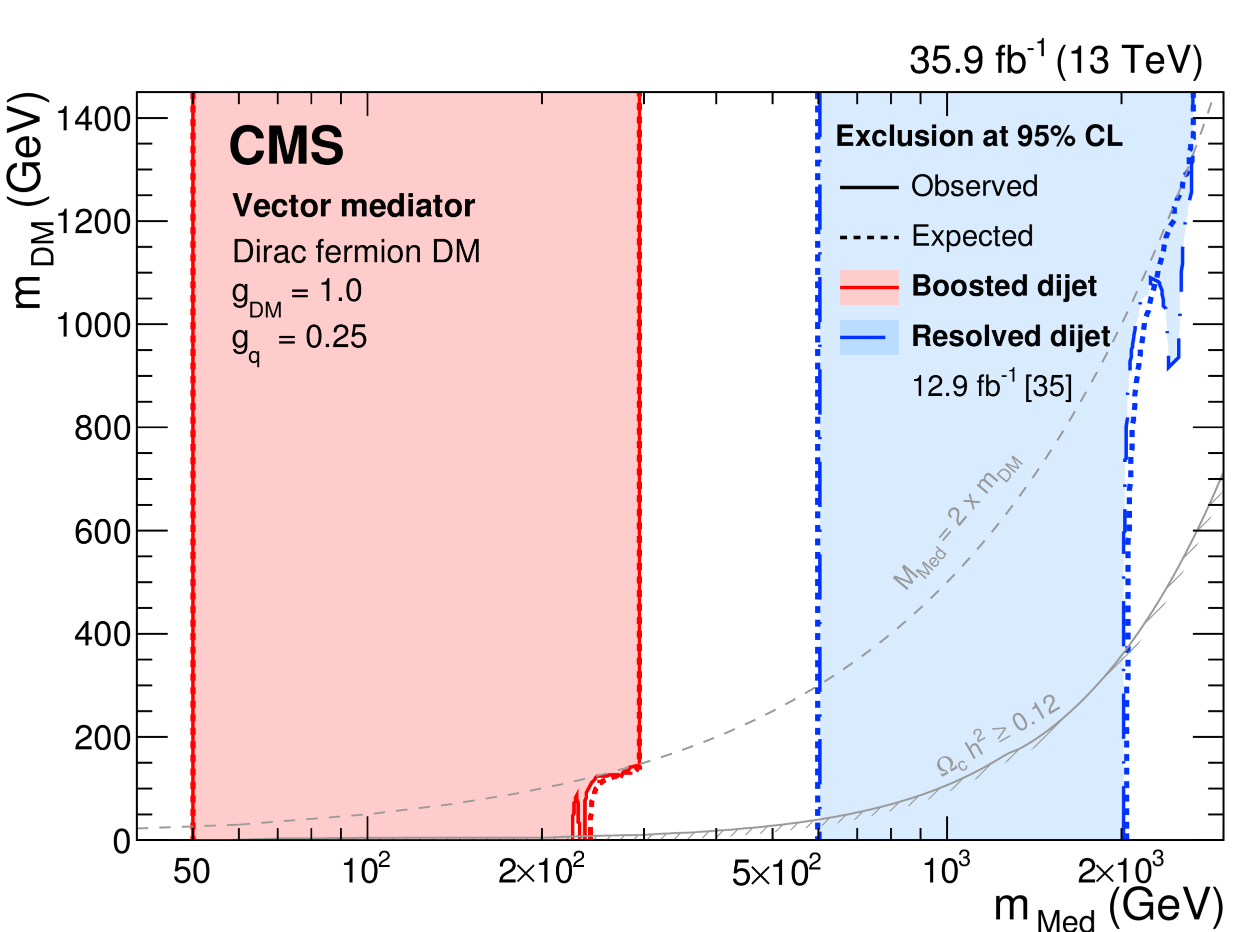
ATLAS Dark Matter coupling summary

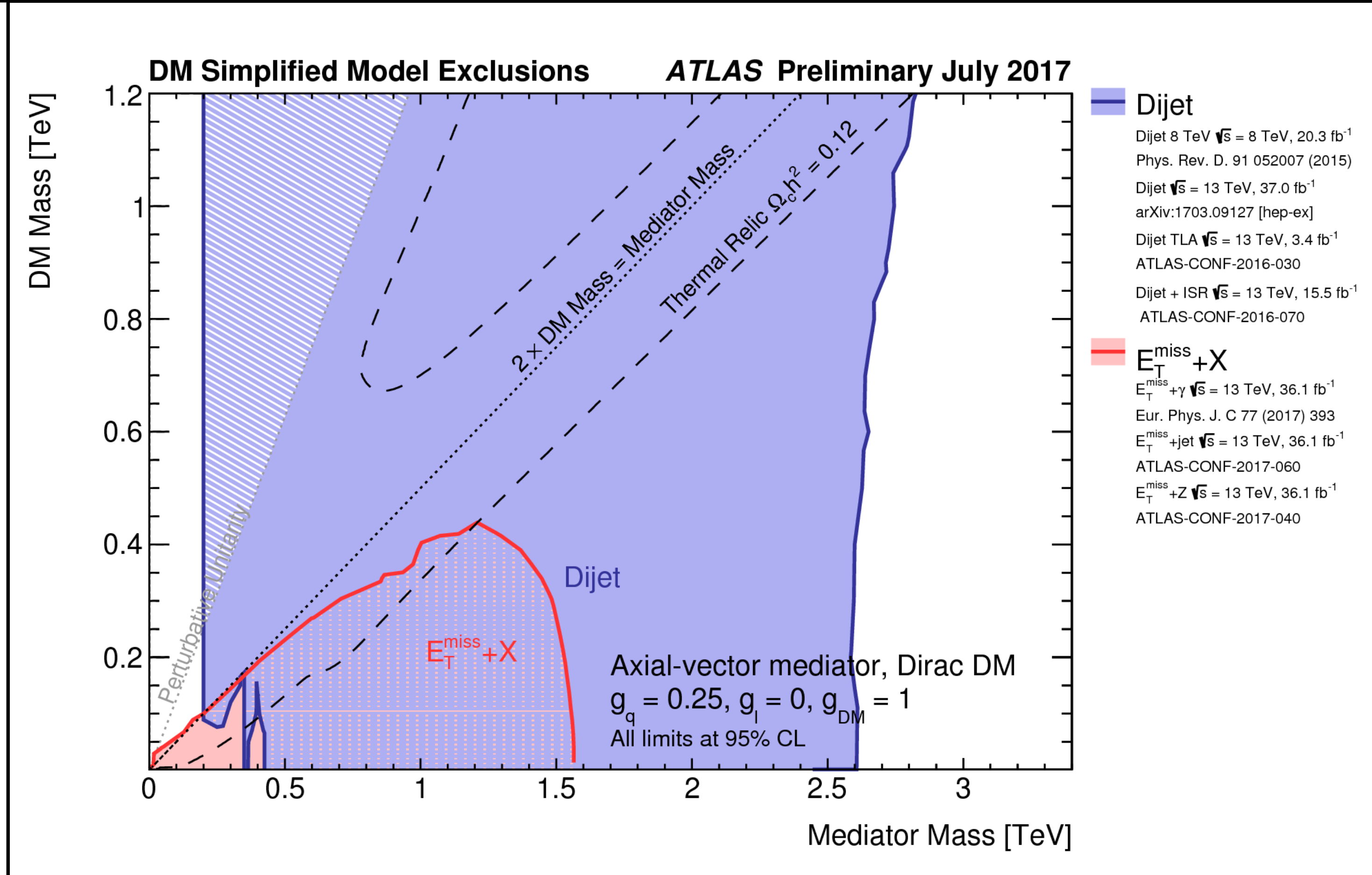


Various techniques (and triggers!) are used to probe the mass range from 50 to 4000 GeV

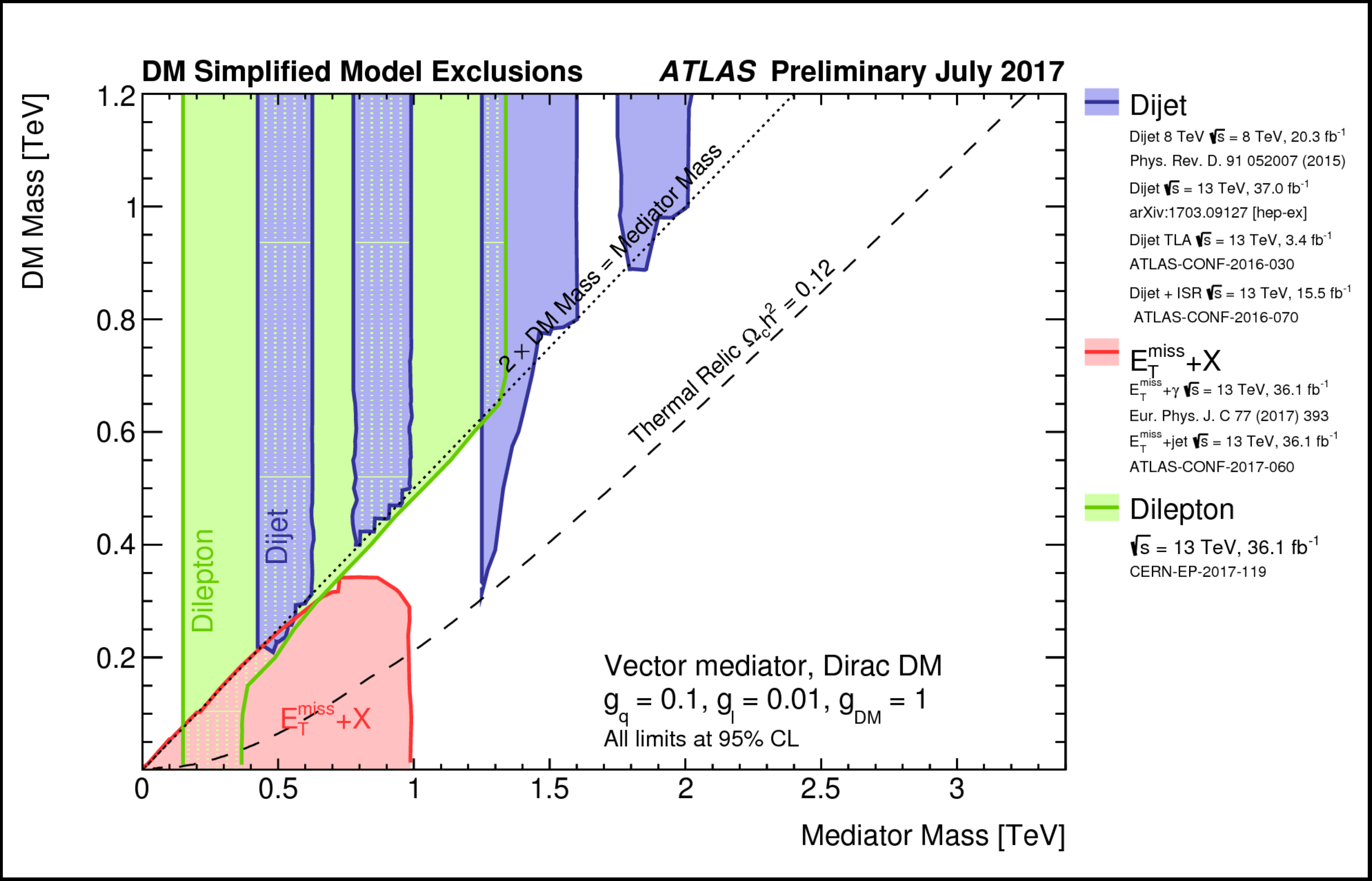
Sensitivity to g_q between 0.05 and 0.2 depending on mass (for leptophobic scenario)

mono-X vs di-jet



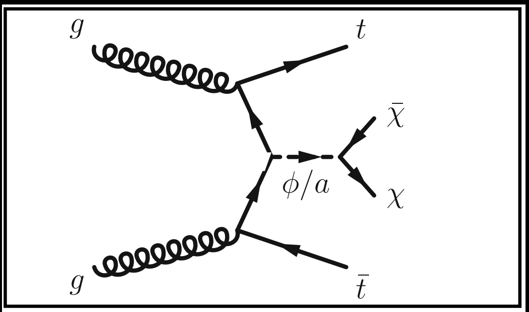


- if the mediator couples to lepton, strong limits from ee/μμ resonant search
- Otherwise, dijet resonance search complementary to mono-jet

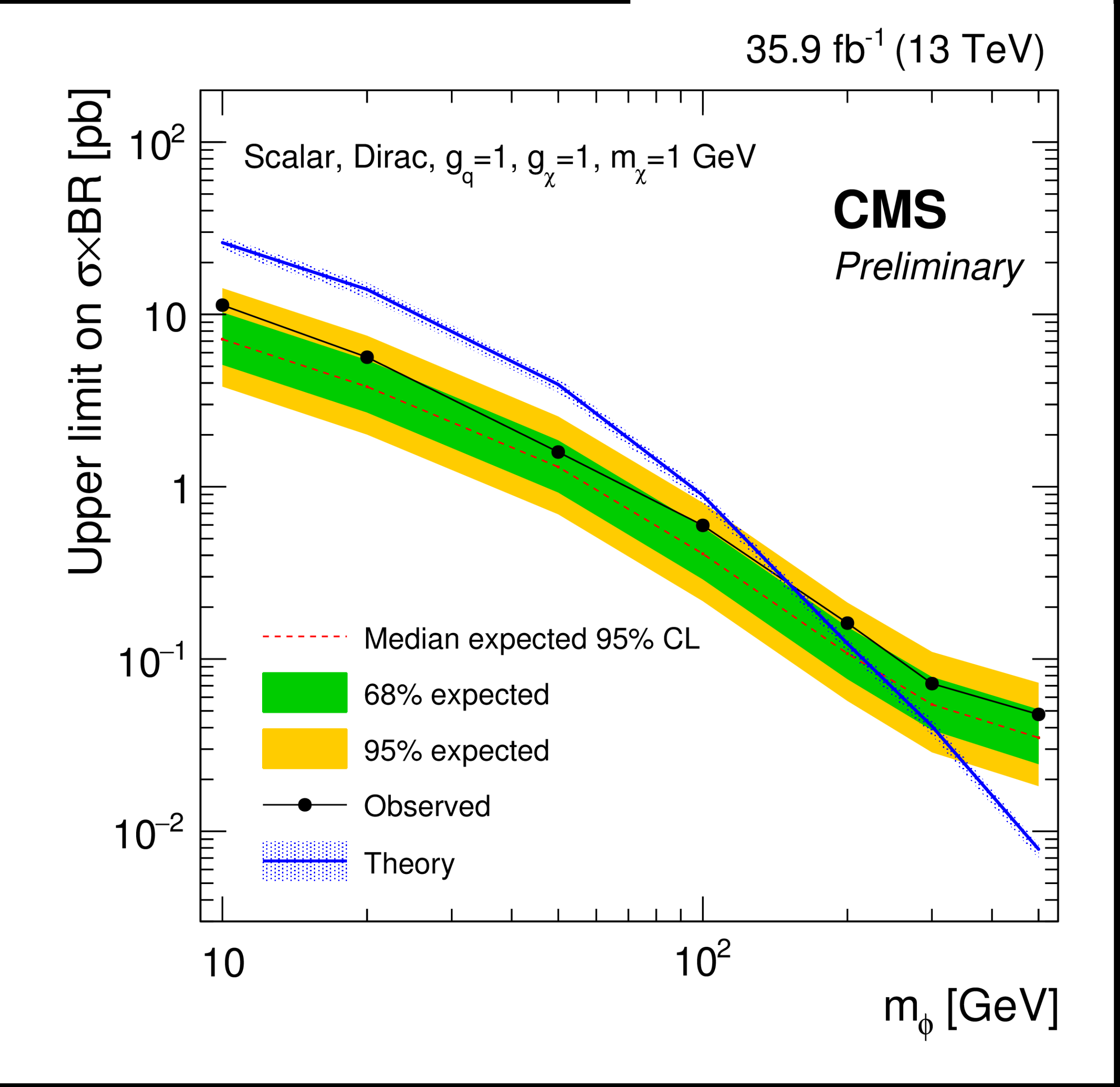


Since three different couplings are involved, ll, jj, and mono-jet are really complementary !

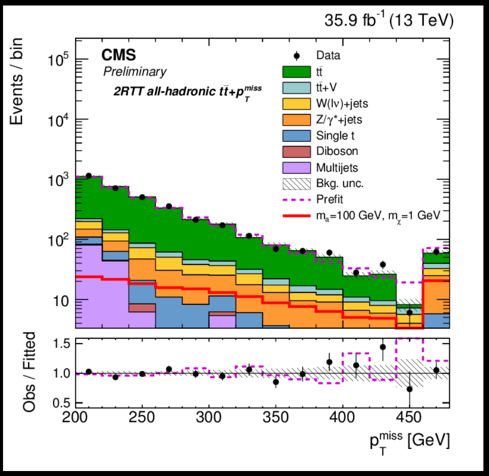
heavy flavour

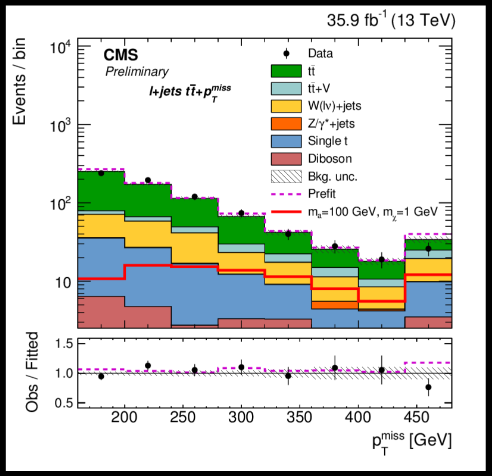


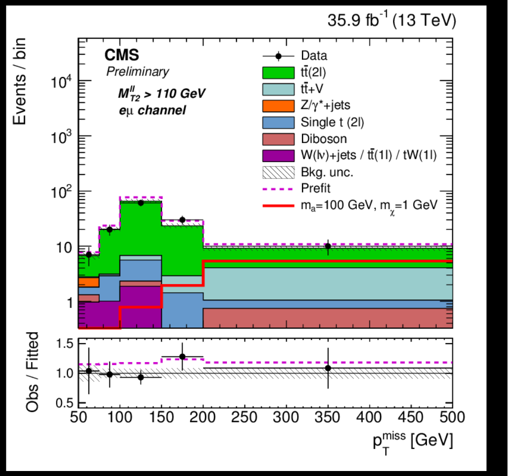
CMS-PAS-EXO-16



- scalar mediators Yukawa couplings enhances top final states
- The last result from CMS combines 0,1,2 lepton channels



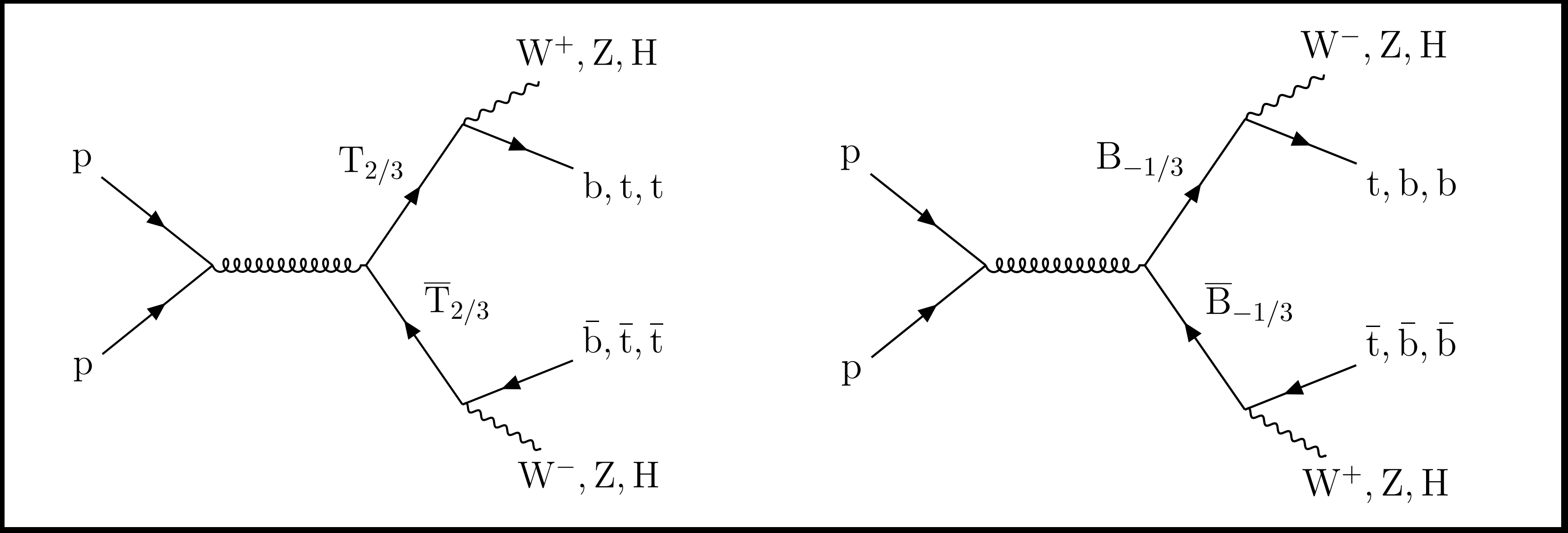




0-lepton | **1-lepton** | **2-lepton**

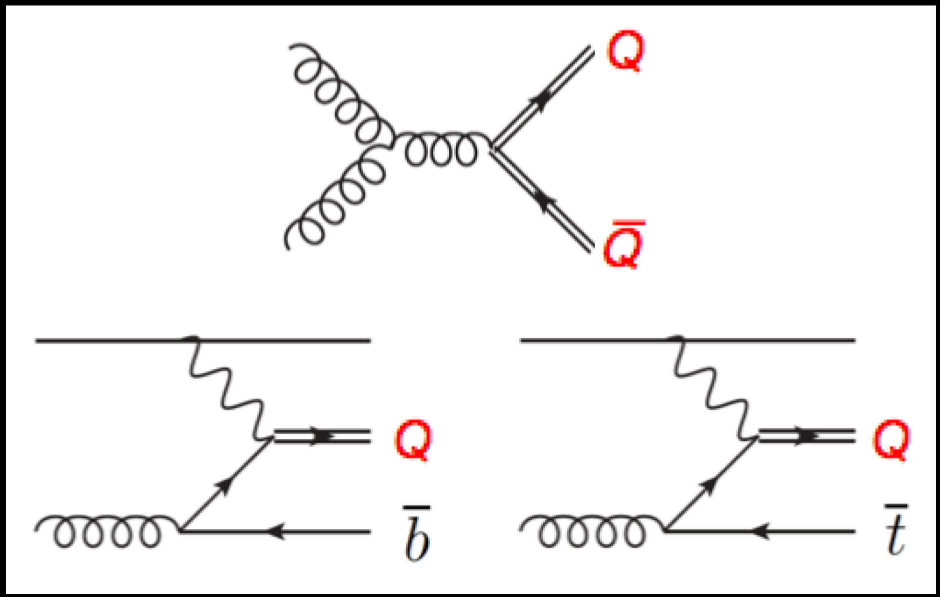
top-tagging jet triplets | **Large M_T, M_{T2}^W** | **Large M_{T2}^{ll}**

vector like quarks



VLQ - introduction

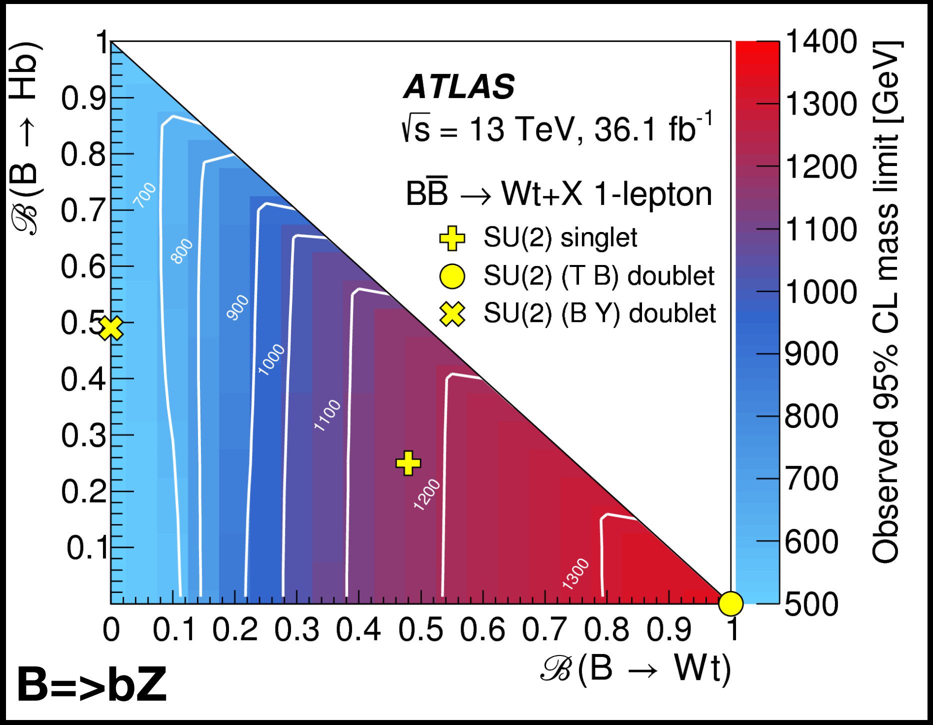
- Present in many BSM models (extra dimensions, composite Higgs, …)
- Link to hierarchy problem
- Nice set of final states to explore



B can decay to bH, bZ, tW
T can decay to tH, tZ, tW
X (Q=5/3e) => tW, Y (Q=-4/3) => bW

- **Pair production via strong production, model independent cross section, 6 final states for B,T each**
- **Single production depends on coupling, potentially dominant at high mass**

arXiv:1806.07162



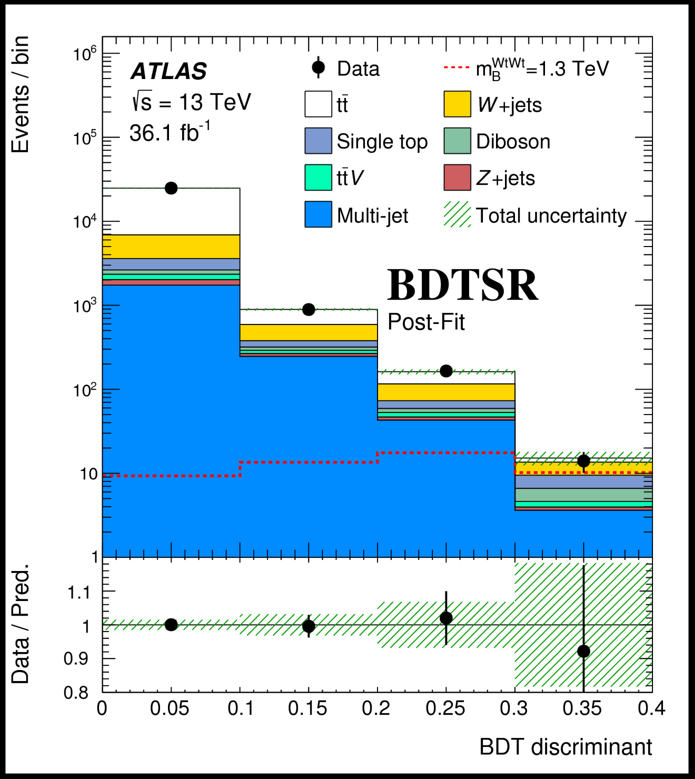
Scan of the three BRs shown in triangle plots

VLQ pair production

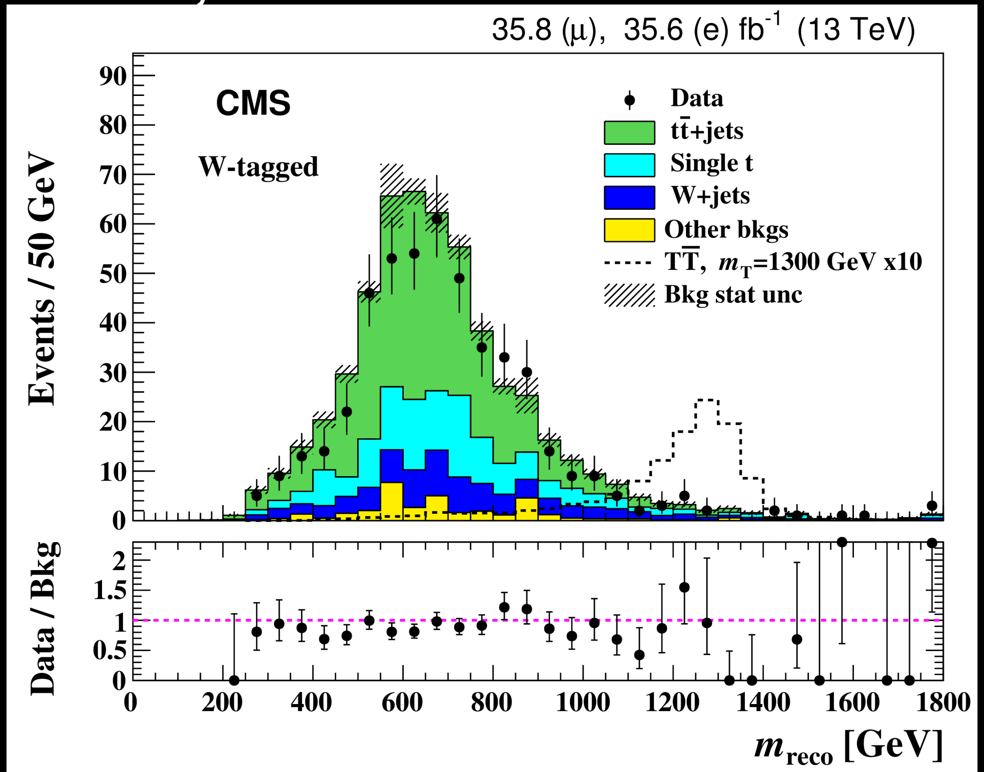
CMS and ATLAS searches with 36 fb-1 :
arXiv:1805.04758 : Inclusive 1,2,3 lepton search
PLB 779, 82 : WbWb in 1 lepton+jets
B2G-17-008 : WtWt in 2SS and 1 lepton+jets
JHEP 08(2017)052 : Zt+X in 1l+jets+MET
JHEP 10(2017)141 : Wb+X in 1l+jets
arXiv:1803.09678 : tH and tZ in 0/1 lepton + multiple b-jets
arXiv:1806.01762 : Wt+X in 1l+jets

Other channels still with earlier datasets

arXiv:1806.07162



PLB 779, 82

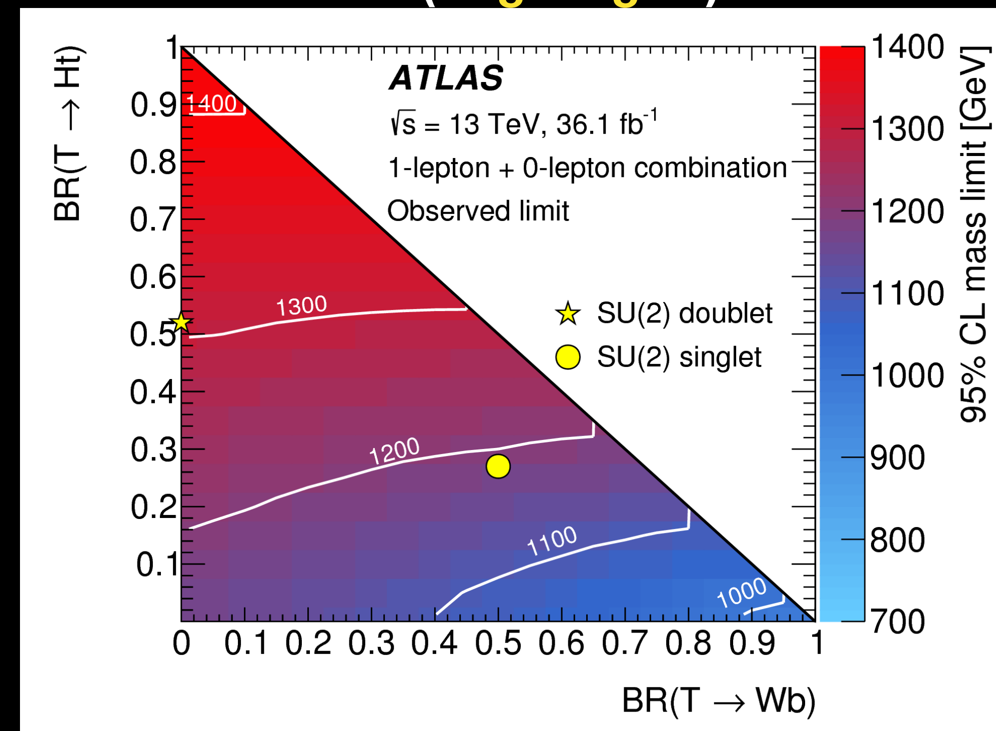


- Tagging hadronic W,Z,top,Higgs decays in many channels
- Observable ranges from inclusive discriminant to T,B mass peaks; analysis techniques ranging from cut and count to BDT

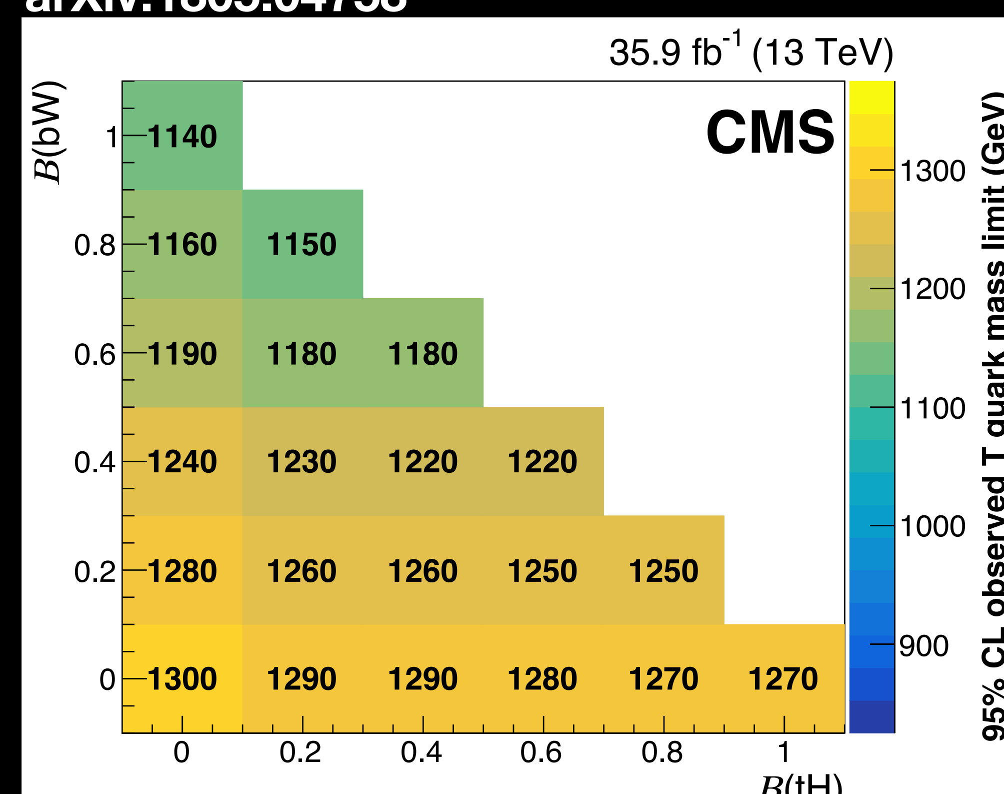
VLQ limits

- Limits on T quarks in the 1.1-1.4 TeV range depending on BR
- That assumes no non-SM decays

arXiv:1803.09678 (targeting tH)



arXiv:1805.04758

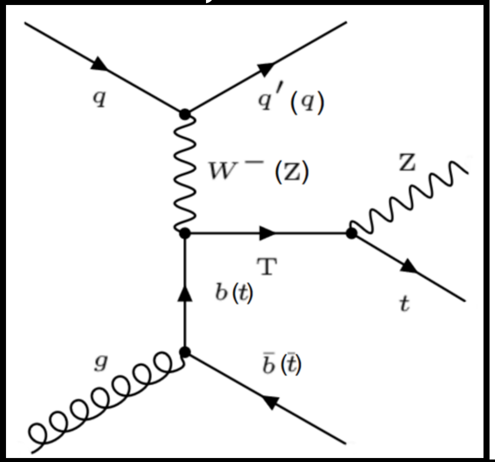


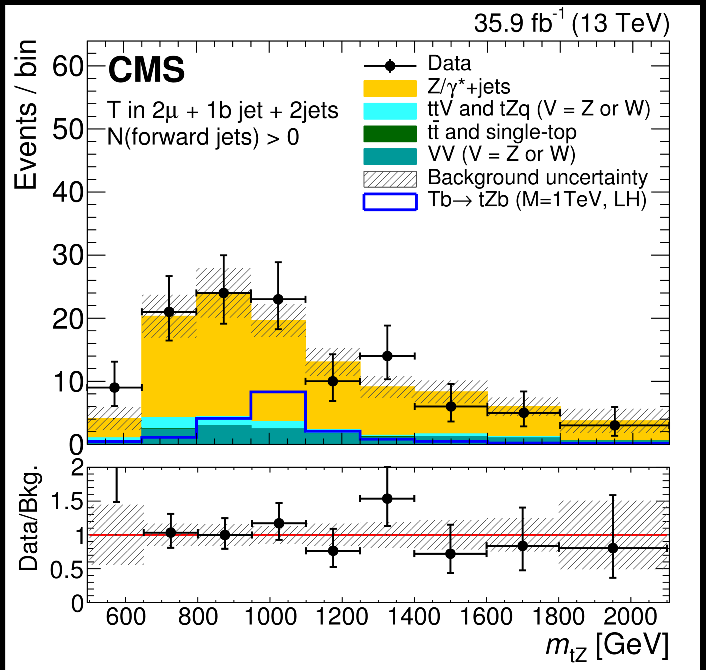
VLQ single production

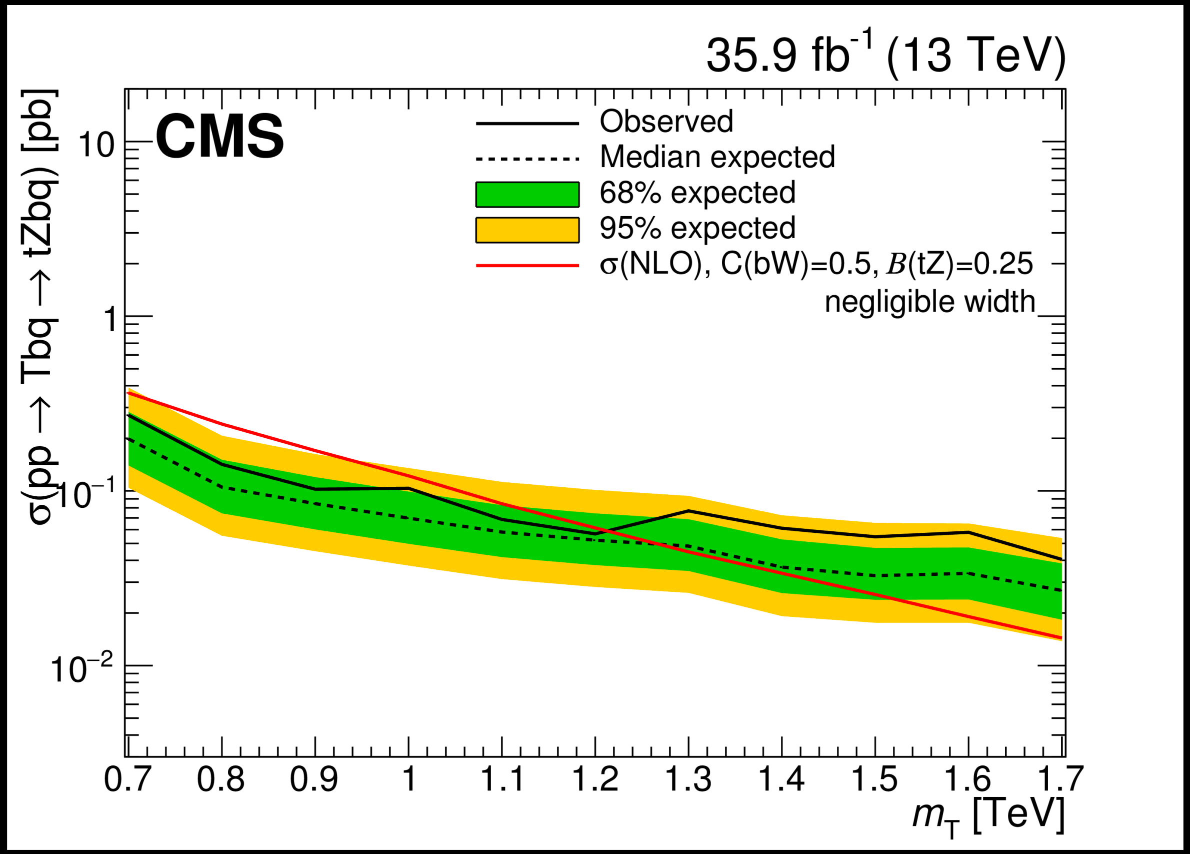
- Competitive at high mass, but model dependent cross section
- Easier reconstruction of mass peak
- Possibility of forward jet tagging

- **PL B781, 574 : target T to Zt (ll jjb) with fwd jet tagging**
- **arXiv:1802.01486 : target B to Hb, Higgs tagging, fwd jets, b-jet multiplicity**

PLB 781, 574







LeptoQuarks

LQ

- Flavour anomalies in $b \Rightarrow s\mu\mu$ and $b \Rightarrow c\tau\nu$ motivates leptoquark searches (exp. 2nd and 3rd generation)
- Some recent results :

New J. Phys. 18,093016 : eqeq, μqμq

PAS-EXO-16-043 : ee jj

PAS-EXO-17-003 : μμjj, μνjj

PAS-B2G-16-027 : tμ tμ

arXiv:1803.02864 : τt τt

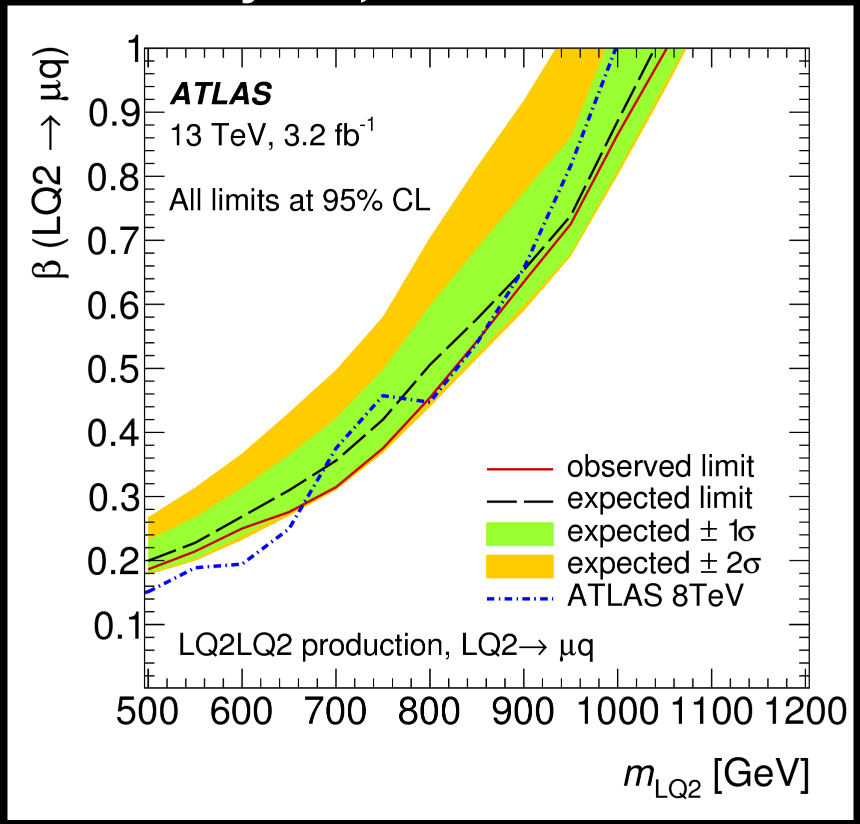
arXiv:1805.10228 : M_{T2} susy search reinterpreted for tν, bν, qν

arXiv:1806.03472 : τb single production

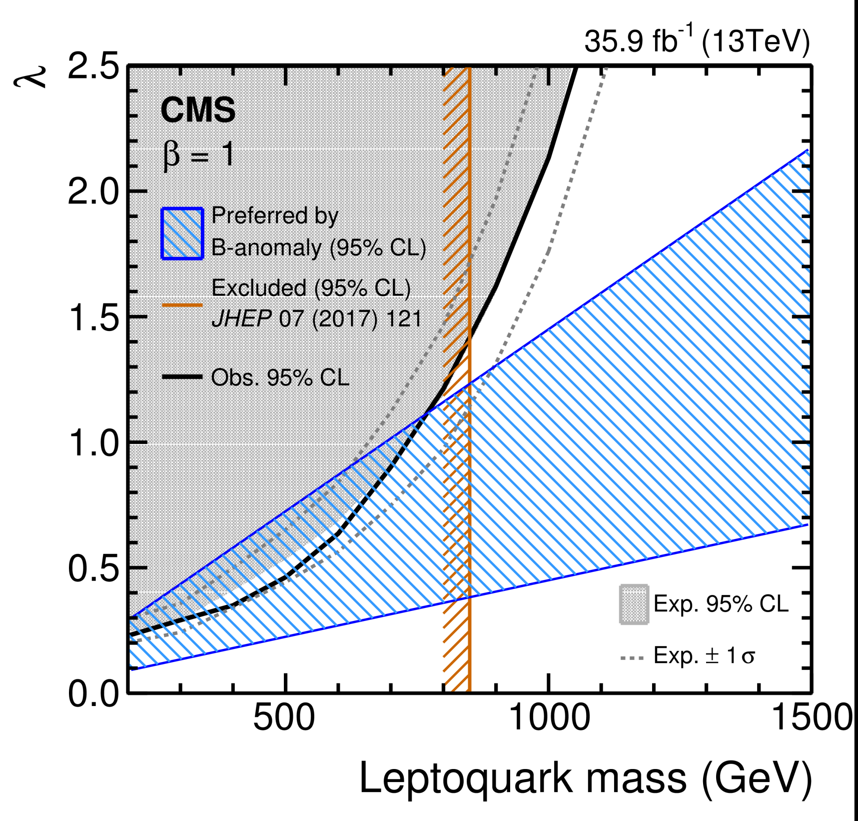
JHEP 07 (2017) 121 : τb τb pair production

- Can also reinterpret searches for scharm (cνcν), sbottom (bνbν), stop (tνtν), RPV stop (blbl) etc.
- With cross-generation combinations (eg. ebeb) and final states from BR~0.5 (eg. LQ LQ => bτ cν), lots of final states, not all covered by dedicated searches. Priorities ?

New J. Phys.18,093016



arXiv:1806.03472



Final remarks

- ATLAS and CMS are looking for new particles in a large variety of final states.

- Of course that's little comfort if we miss the one with a signal. Are we looking in the right places ?

- Analysis techniques are getting more sophisticated, as we build over the experience of early searches. The trend will continue, with more time between each doubling of integrated luminosity. Expect more BDTs, shape fits, machine learning, and also new ideas in physics object selections

- Are we over-optimizing on simplified models ? Would reinterpretations become more difficult ?

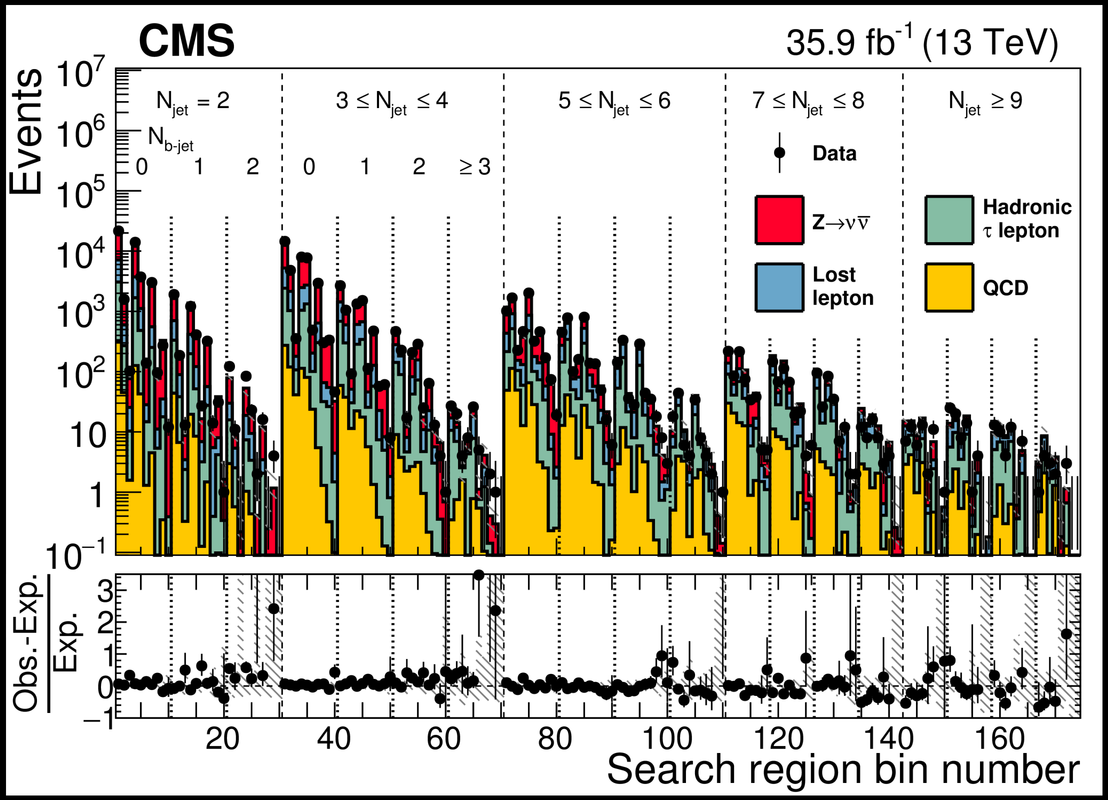
- New physics at the electroweak scale remains as motivated as ever. The hierarchy problem, Dark Matter, and hints of deviations from SM (lepton flavour universality anomalies, g-2) give reasons for hope

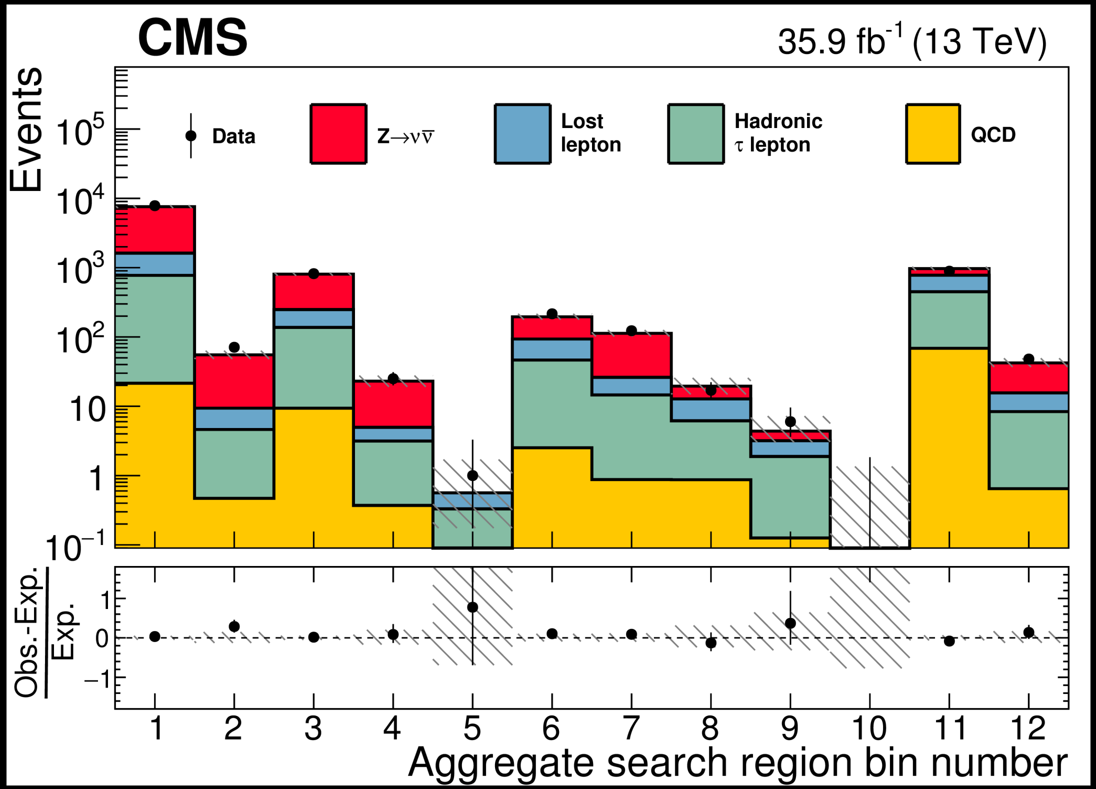
- Negative results so far just means there might be something just beyond the existing limits

- The full run2 dataset gives a large potential for improvements

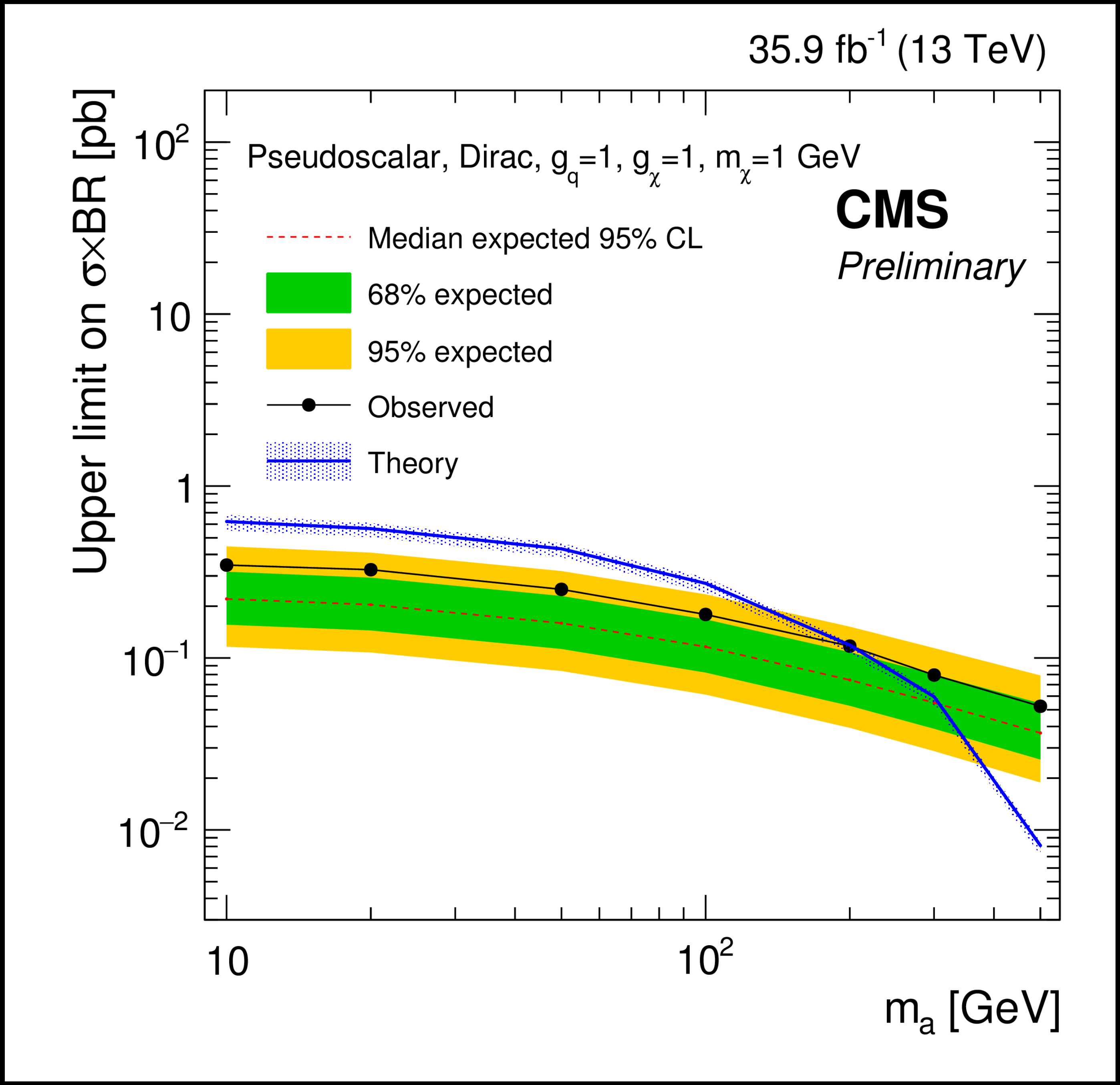
Backup

SUS-16-033 search



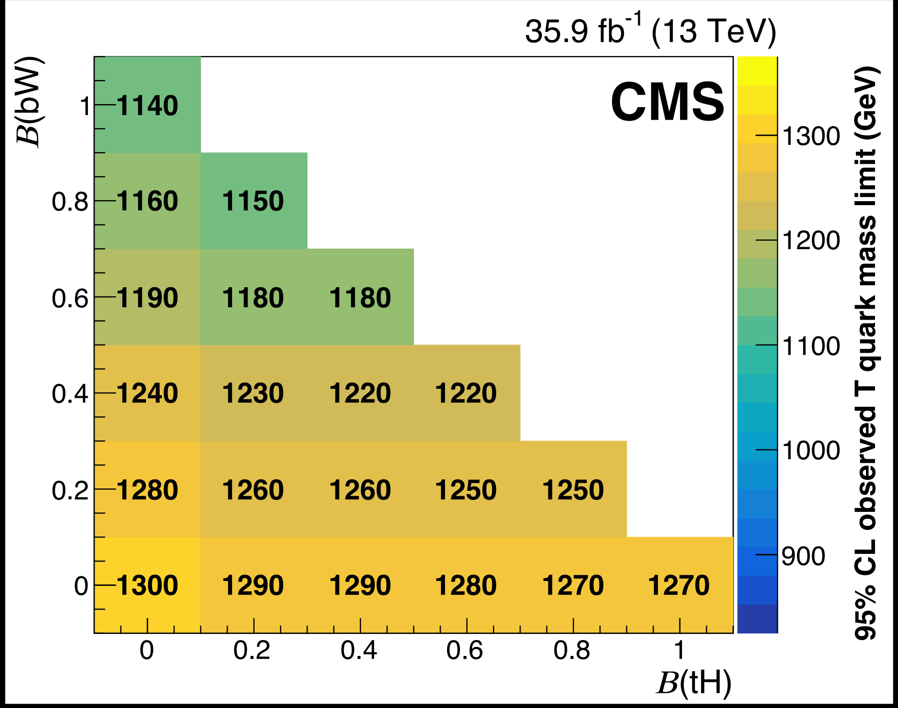


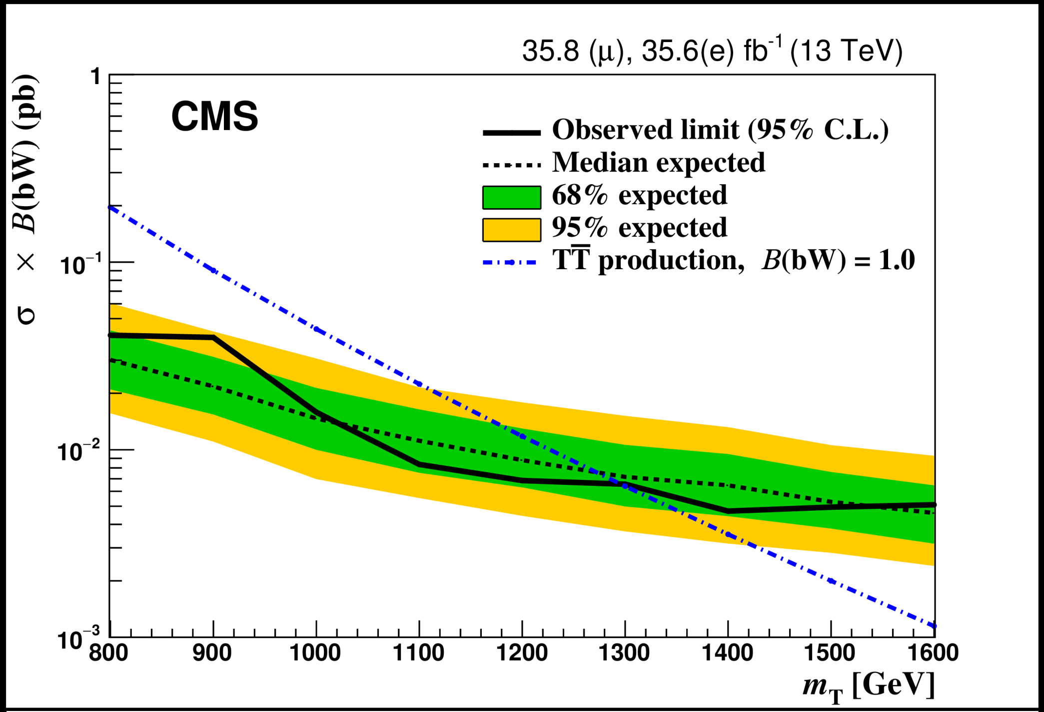
- Search regions binned in number of jets, b-jets, missing momentum, HT
- 173 bins for optimal exclusion
- 12 aggregate signal regions

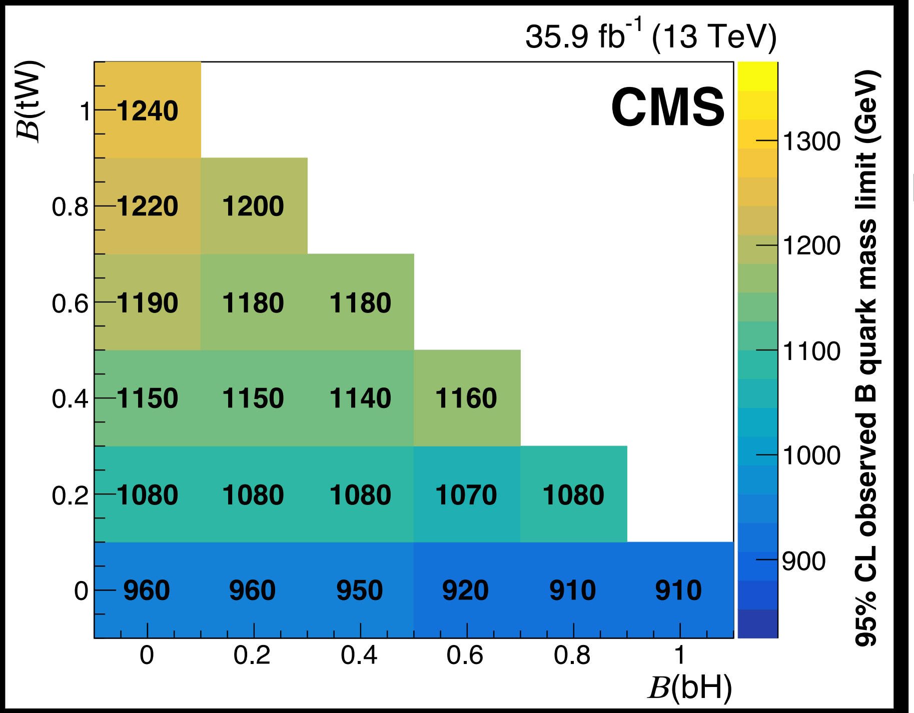


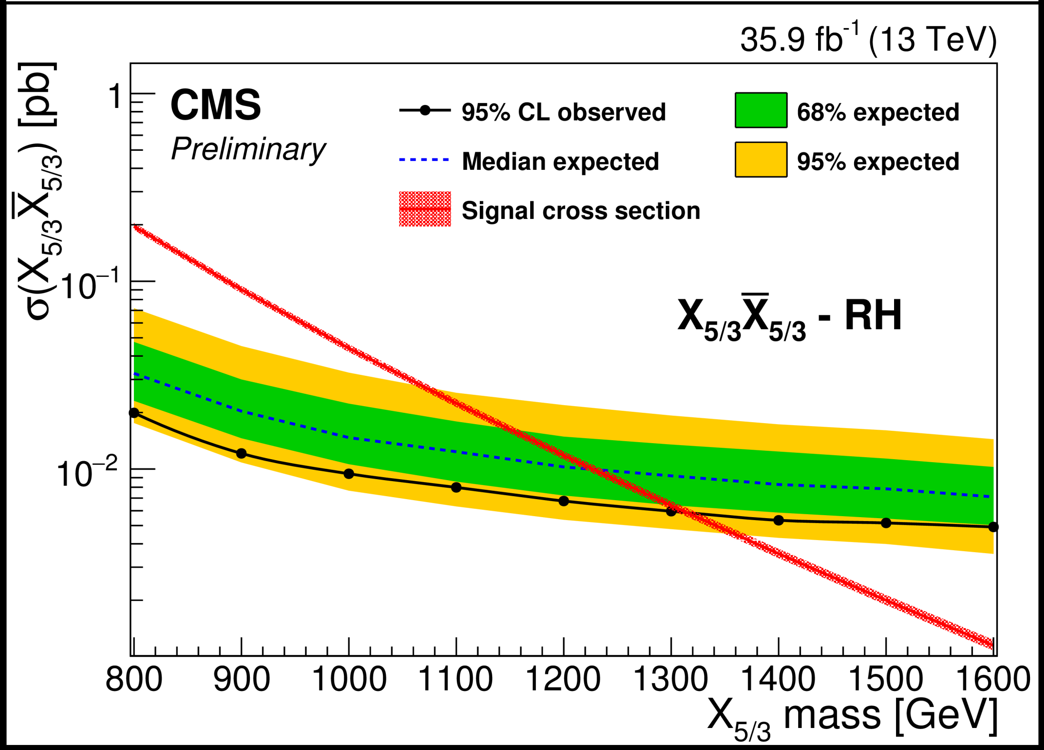
35.9 fb^{-1} (13 TeV)
Pseudoscalar, Dirac, g_q=1, g_χ=1, m_χ=1 GeV
CMS
Preliminary
Median expected 95% CL
68% expected
95% expected
Observed
Theory
Upper limit on σ×BR [pb]
10^2
10
1
10^{-1}
10^{-2}
10
10^2
m_a [GeV]

VLQ CMS limits



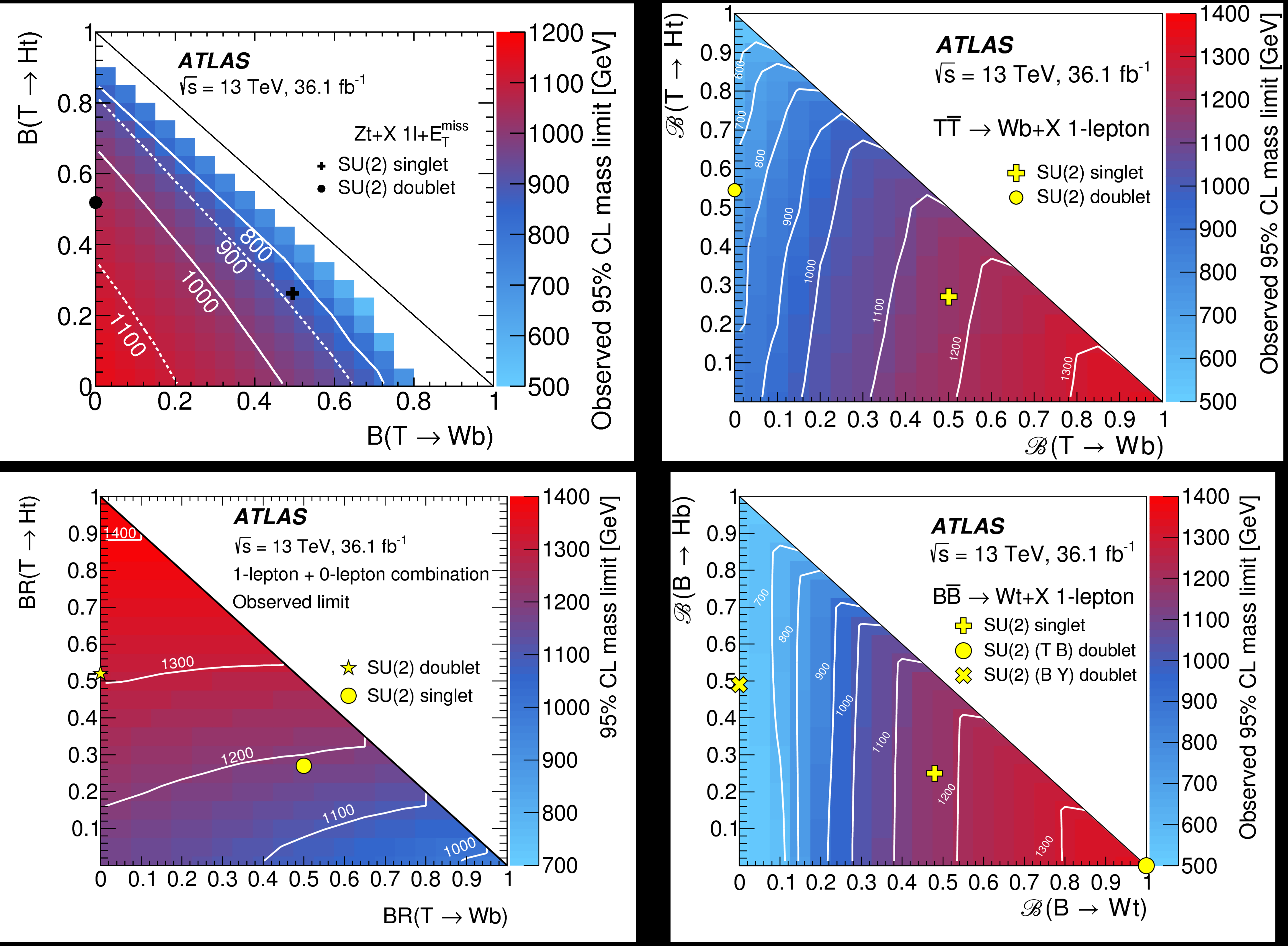




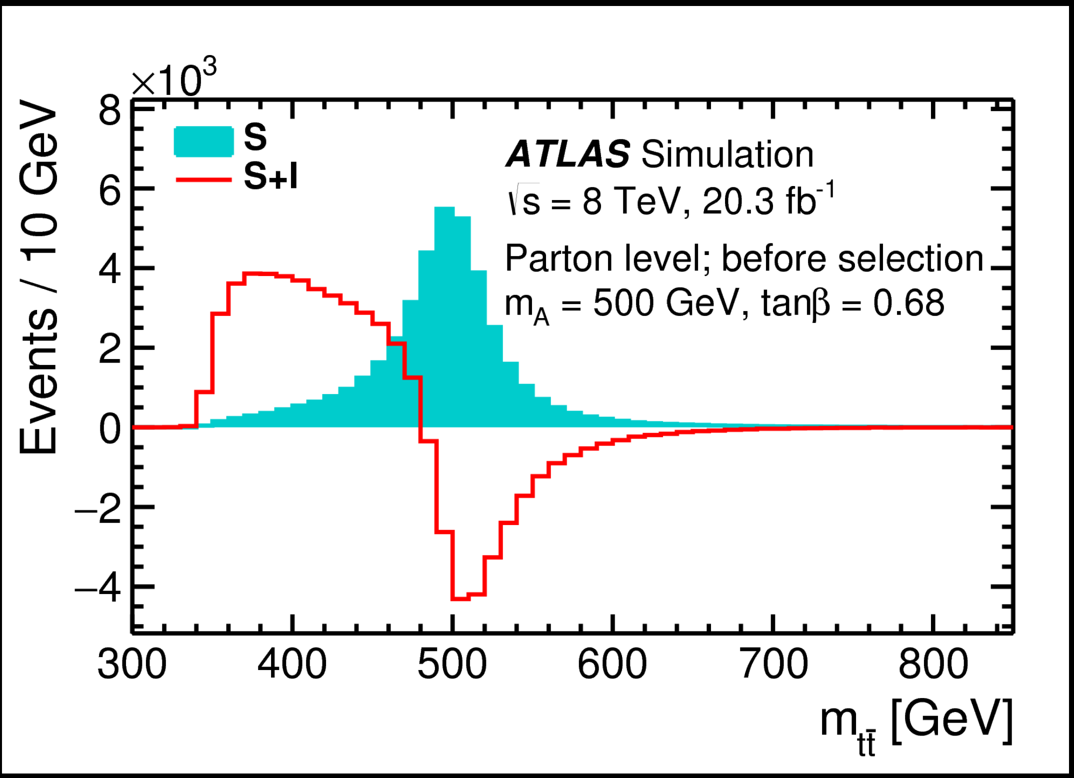


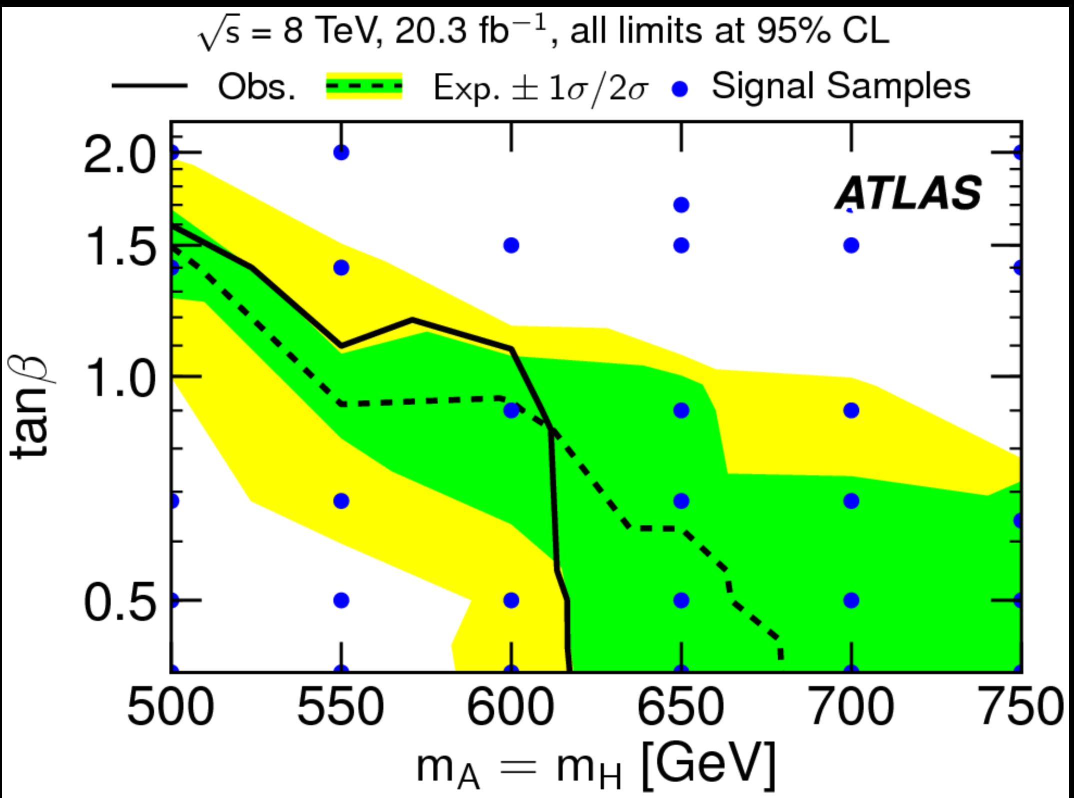
VLQ CMS single production

VLQ ATLAS limits



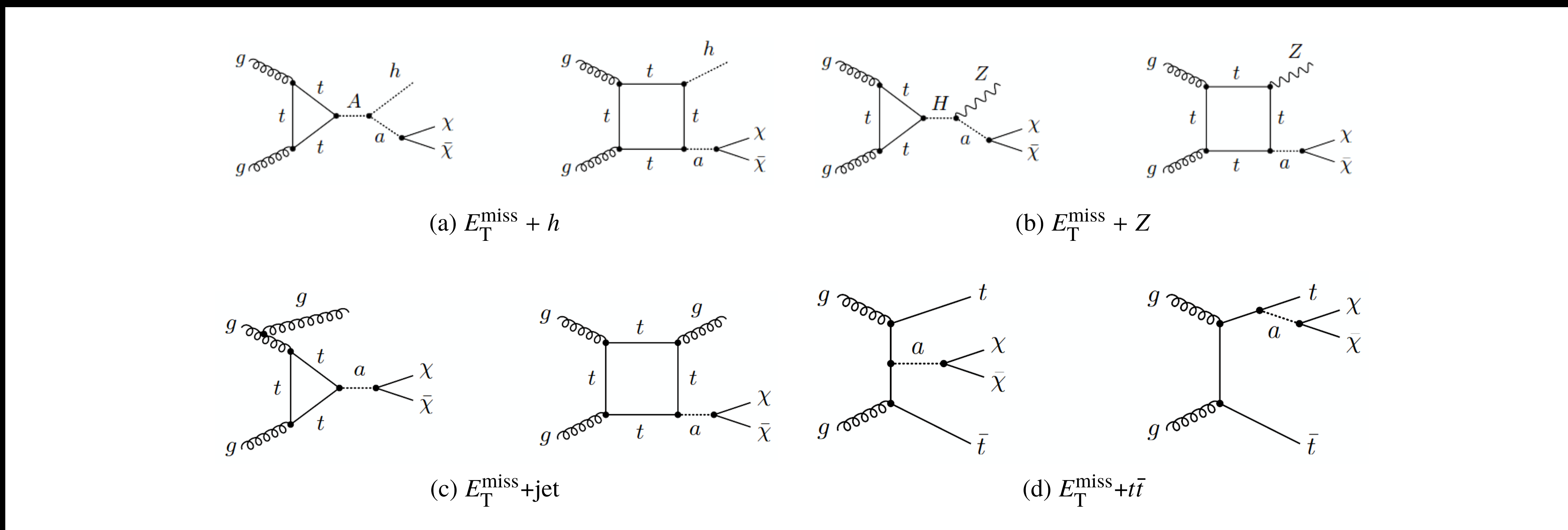
Backup material on EXOT-2016-04





Systematic uncertainties [%]	Total bkg	S	$S+I$
Luminosity [55]	1.7	1.9	1.9
PDF	2.5	2.1	12
$t\bar{t}$ initial-/final-state radiation	3.2	–	–
$t\bar{t}$ parton shower + fragmentation	4.9	–	–
$t\bar{t}$ normalization	5.7	–	–
$t\bar{t}$ event generator	0.5	–	–
Top quark mass	0.5	2.2	13
Jet energy scale	6.4	4.9	9.3
Jet energy resolution	1.3	1.6	1.7
b-tagging: b-jet efficiency	1.5	1.3	1.1
b-tagging: c-jet efficiency	0.2	0.2	0.8
Electron efficiency	0.3	0.4	0.7
Muon efficiency	0.9	1.0	1.0
Signal MC scales	–	7.3	7.3
Reweighting	–	–	5.0
MC statistical uncertainty	0.5	2.4	11
Total uncertainty	11	10	25

2HDM+pseudoscalar model



(a) $E_{\mathrm{T}}^{\mathrm{miss}} + h$ (b) $E_{\mathrm{T}}^{\mathrm{miss}} + Z$

(c) $E_{\mathrm{T}}^{\mathrm{miss}}$+jet (d) $E_{\mathrm{T}}^{\mathrm{miss}}$+$t\bar{t}$

Benchmark from the LHC Dark Matter working group

Rich phenomenology, complementary to that provided by simplified models