Searches for Beyond SM Physics with ATLAS and CMS

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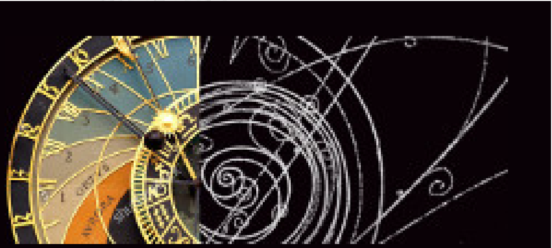
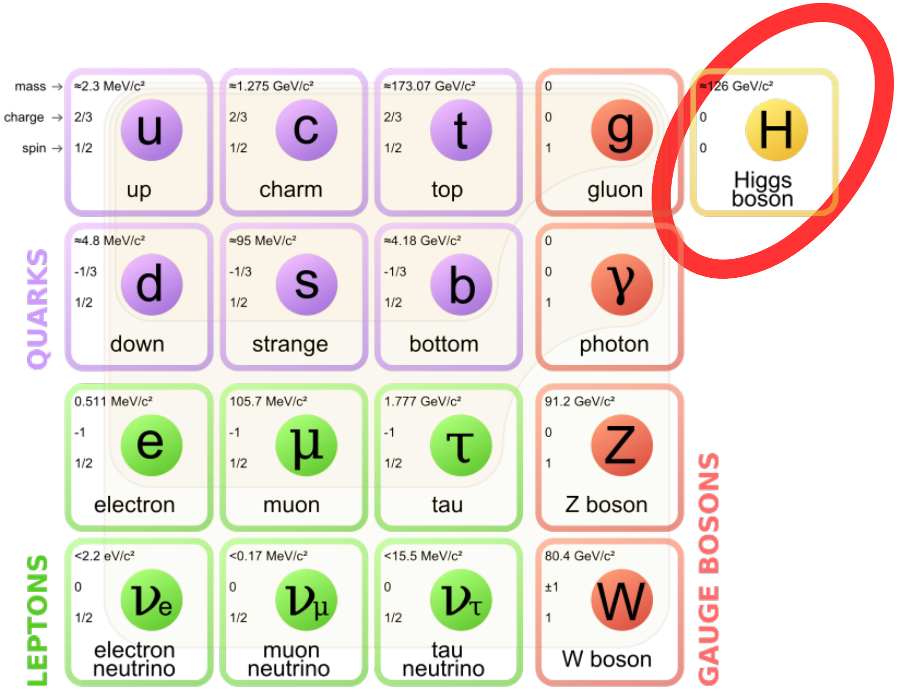
on behalf of the ATLAS and CMS collaborations

FPCP 2017 - Flavor Physics & CP Violation



Why beyond SM?

- In 2012 the Standard Model of Particle Physics (SM) particle content was completed with the discovery of the last missing piece of the puzzle – *the Higgs boson*



However, we know that the SM is not the final theory:

- Gravity not included
- Dark matter not included
- Dark energy not included
- Cannot generate the observed matter-antimatter asymmetry
- Neutrino masses not included

There is “hard” evidence that there is **new physics** beyond the SM

Why beyond SM at the LHC?

- There are very good reasons to look for beyond SM (BSM) physics at the LHC
  - LHC defines the energy frontier and it is the only place to look directly for heavy new particles
  - Some of the “hard evidence” BSM physics questions may be related
    - e.g. searches for weakly interacting massive particles (dark matter candidate); new CP violation sources; TeV scale gravity; seesaw scenarios for neutrino masses, ….
  - “Soft evidence” BSM physics questions directly point to the energy scale explored by the LHC
    - Force unification implying SUSY at TeV
    - Little hierarchy problem: fine tuning of the mass of the Higgs boson

Where to look for BSM physics at ATLAS/CMS

- Through the Higgs sector
  - No a priori reason for the Higgs sector to be minimal
- Supersymmetry (SUSY)
  - Highly motivated (unification, dark matter, little hierarchy,…) and phenomenology thoroughly studied
- Exotics
  - Non-SUSY or BSM Higgs that is "beyond the beaten path"

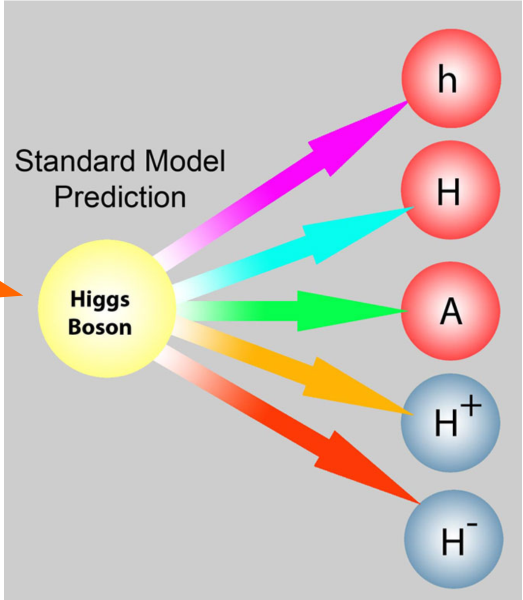
There is no clear boundary among these three categories, which are actually overlapping

Disclaimer: only a few highlights from each topic will be covered here due to time and space limitations!

BSM Higgs searches

- How to approach a BSM Higgs sector
  - Extended Higgs sector: more than one Higgs boson
    - Examples: singlet(s), 2HDM/MSSM, NMSSM (2 doublets+singlet), Georgi-Machacek (1 doublet + 2 triplets)
    - Charged scalars may be included as well

Example: 2HDM



- Exotic properties of the Higgs
  - Examples: composite Higgs, Higgs decaying to dark matter,…

Searching for Heavy Higgs bosons

- MSSM Higgs bosons
  - MSSM has a 2HDM Higgs sector

    plus some additional constraints from SUSY

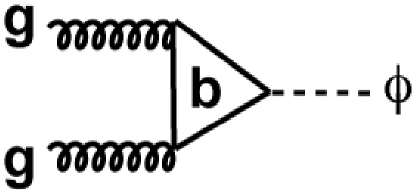
5 Higgs bosons:
3 neutral : h /H /A and
2 charged: $H^{+/-}$

Just 2 parameters at lowest order: mA and tanβ (= ratio of Higgs vevs)

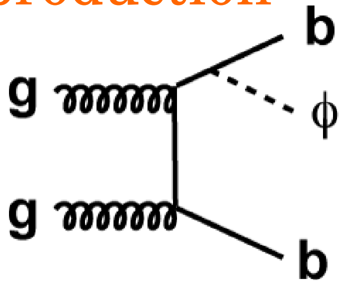
- Example: Neutral MSSM Higgs searches
  (charged Higgs searches exist but not covered here)
  - Production

Decay

Gluon-gluon fusion



"b-associated" production



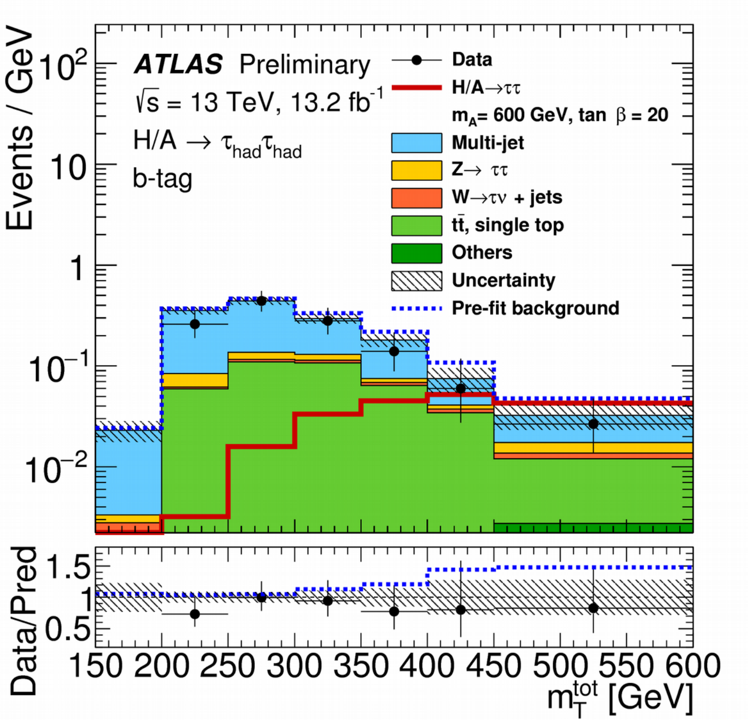
Higgs decays to ττ are favoured for large parts of the parameter space

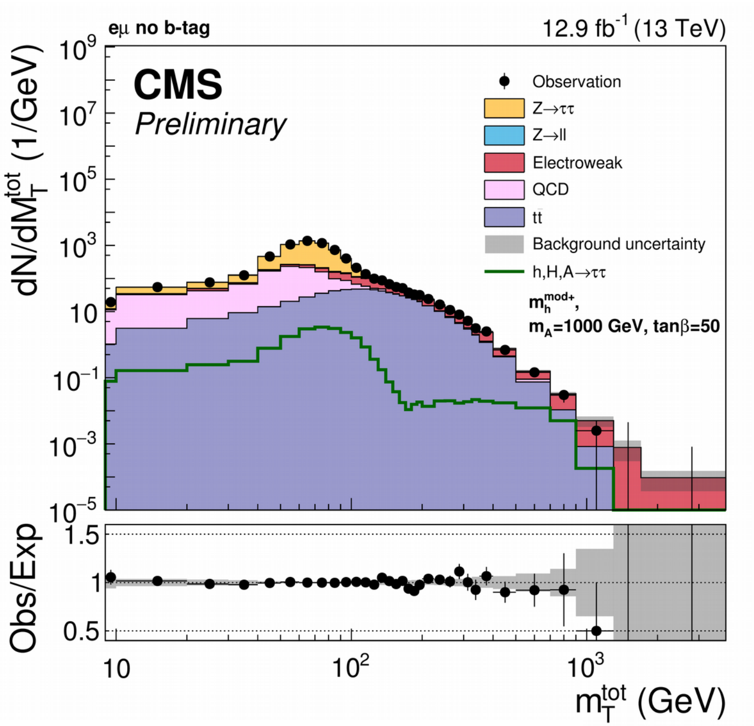
Searching for Heavy Higgs bosons

- Example of the neutral MSSM Higgs search

ATLAS-CONF-2016-085
CMS-PAS-HIG-16-037

Production mechanisms motivate the definition “b-tag” and “no b-tag” (b-veto) categories



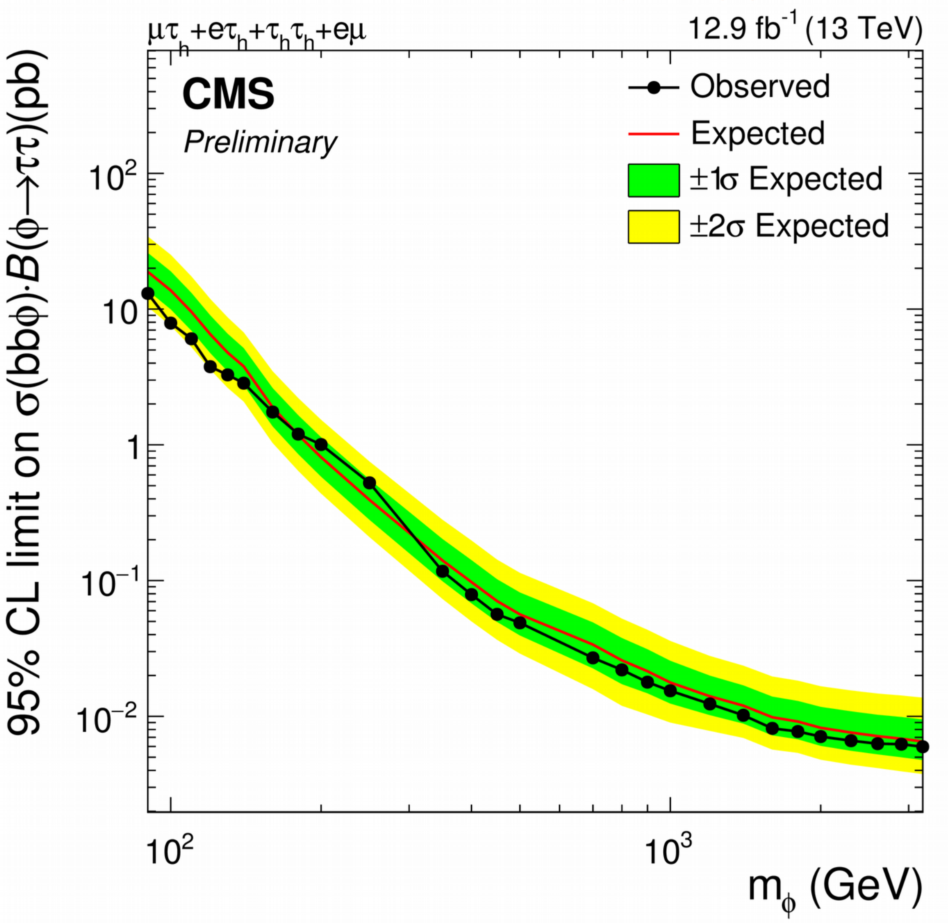


$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}.$$

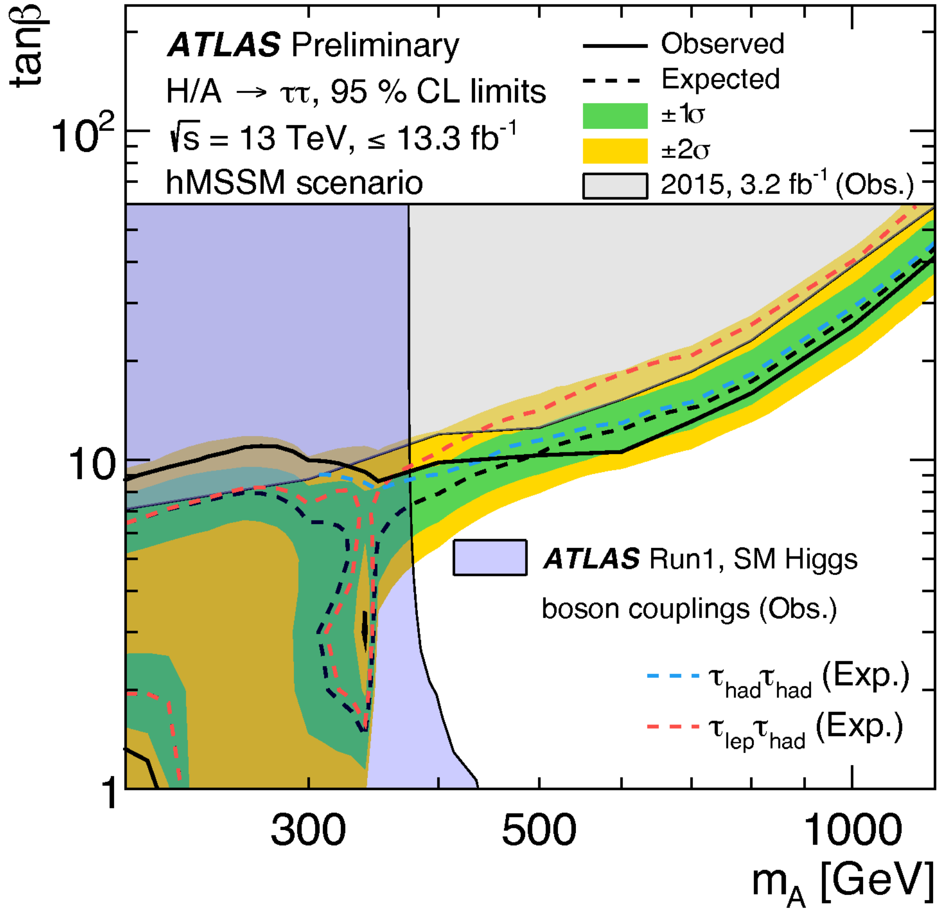
Searching for Heavy Higgs bosons

- Interpreting the search

as cross section limits for the production of a heavy Higgs



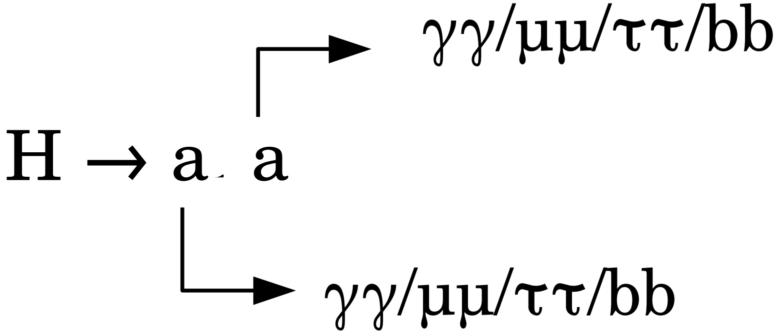
… or In various MSSM scenarios



Searching for light Higgs bosons

- In next-to-MSSM or various extensions with singlets there are light Higgs bosons to which the 125-GeV Higgs can decay to

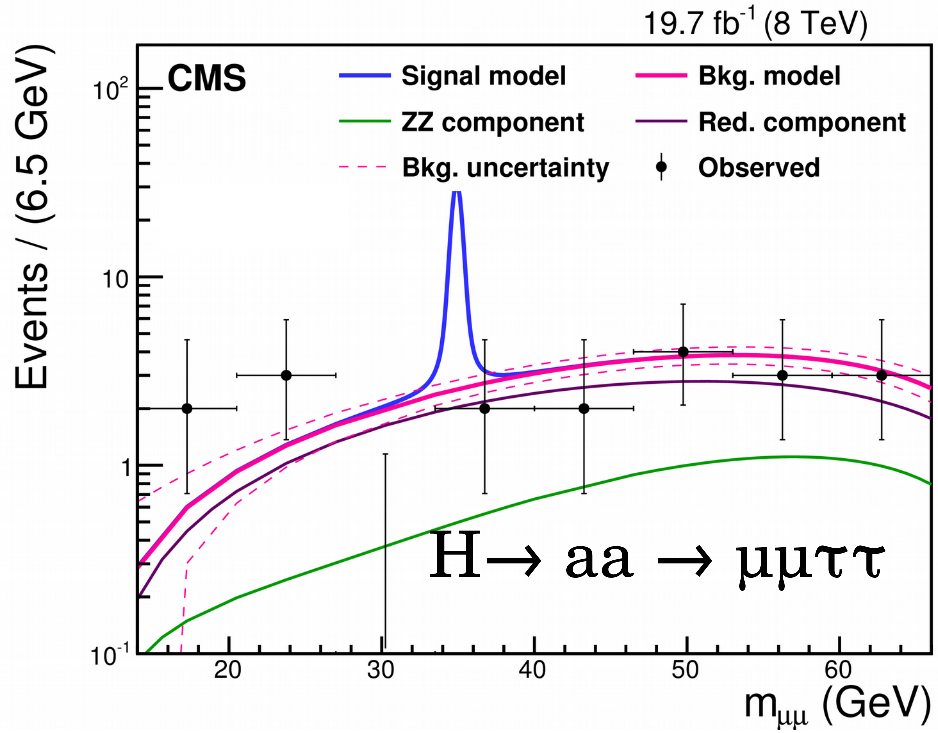
According to the mass of the light Higgs various decay channels are possible



$\gamma\gamma/\mu\mu/\tau\tau/bb$

$H \rightarrow a\ a$

$\gamma\gamma/\mu\mu/\tau\tau/bb$



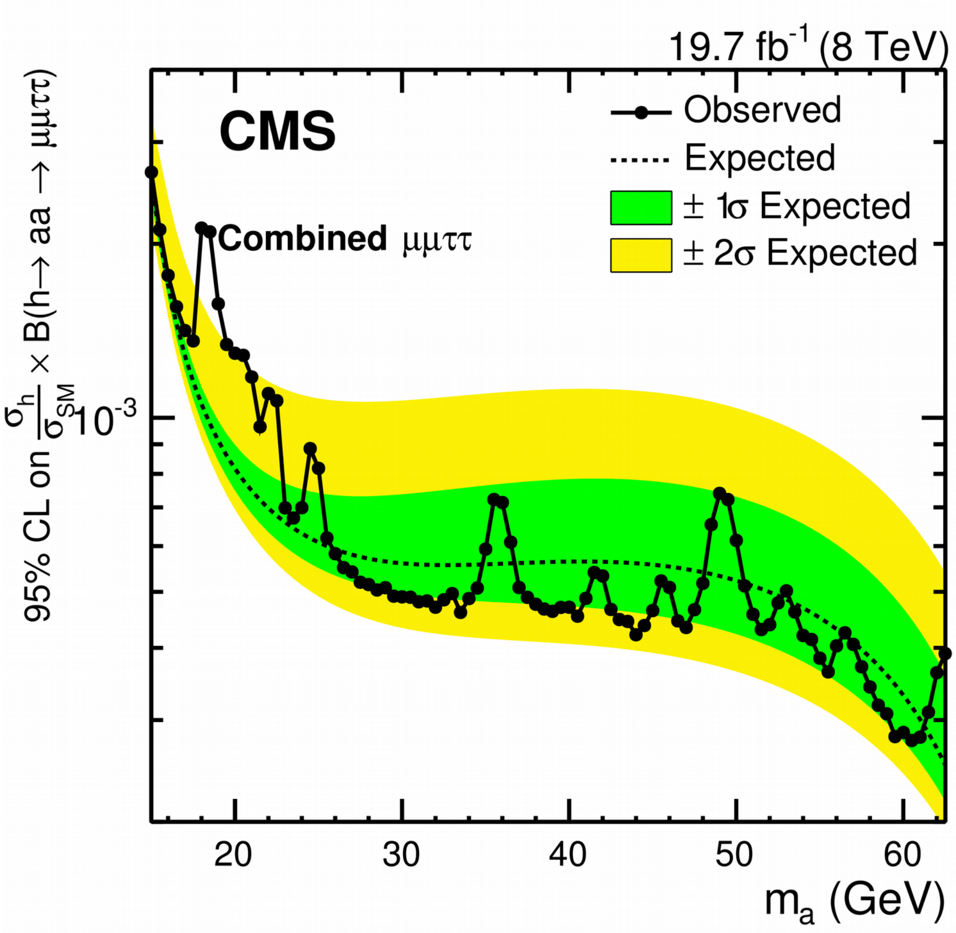
CMS has recently submitted a search on 8 TeV data for

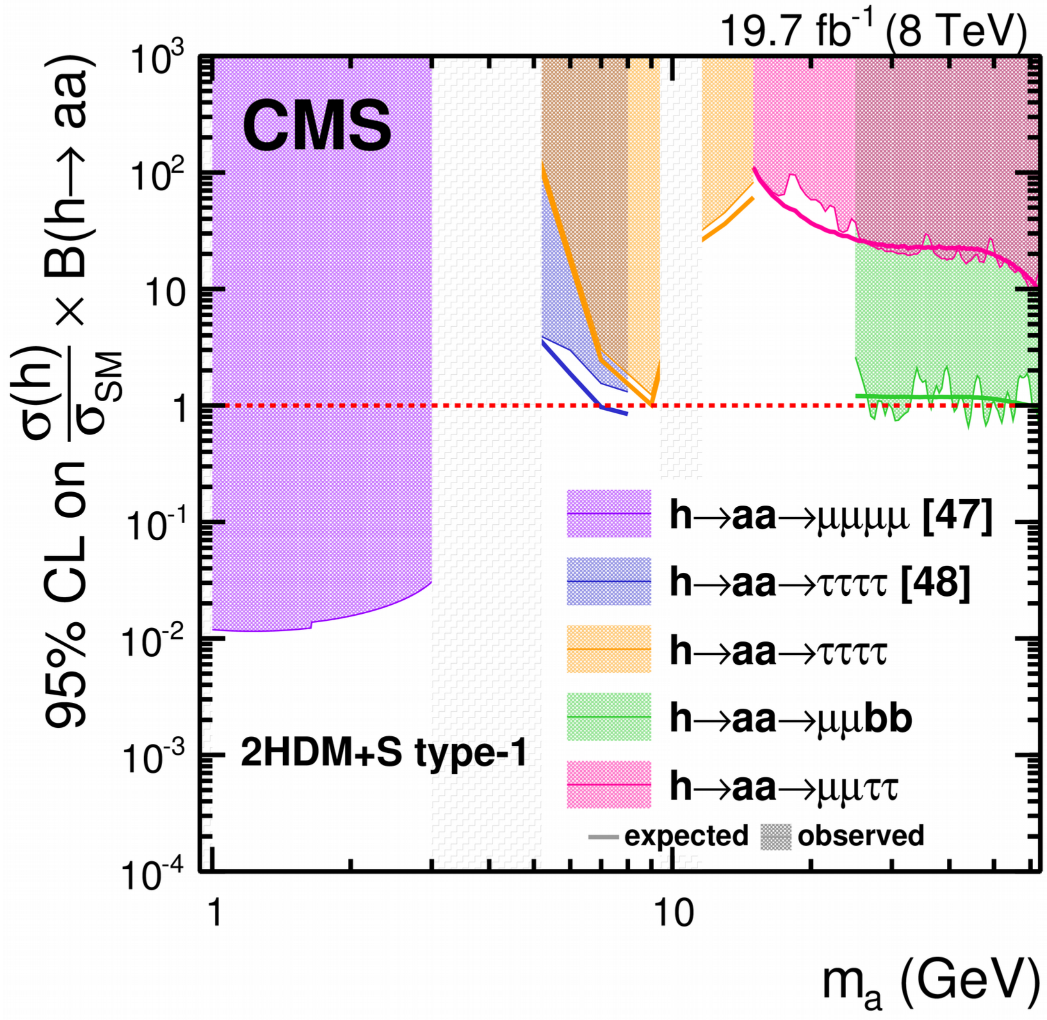
H(125) → aa→ $\tau\tau\tau\tau$/ $\mu\mu\tau\tau$/ $\mu\mu bb$

arXiv:1701.02032

Searching for light Higgs bosons

- Results of the search

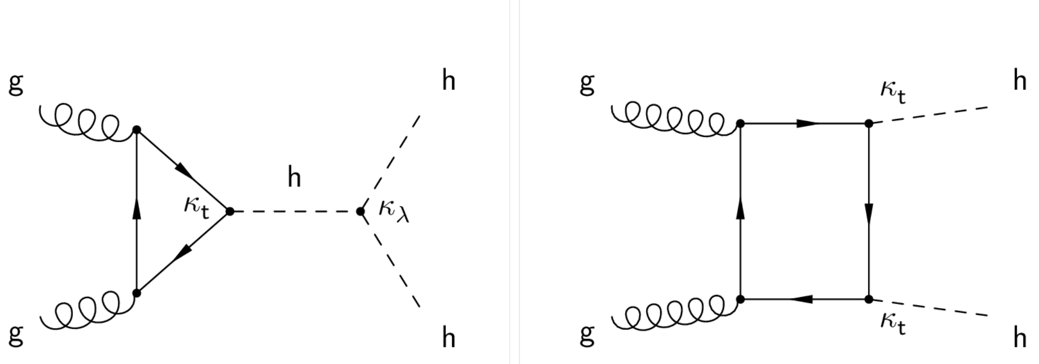


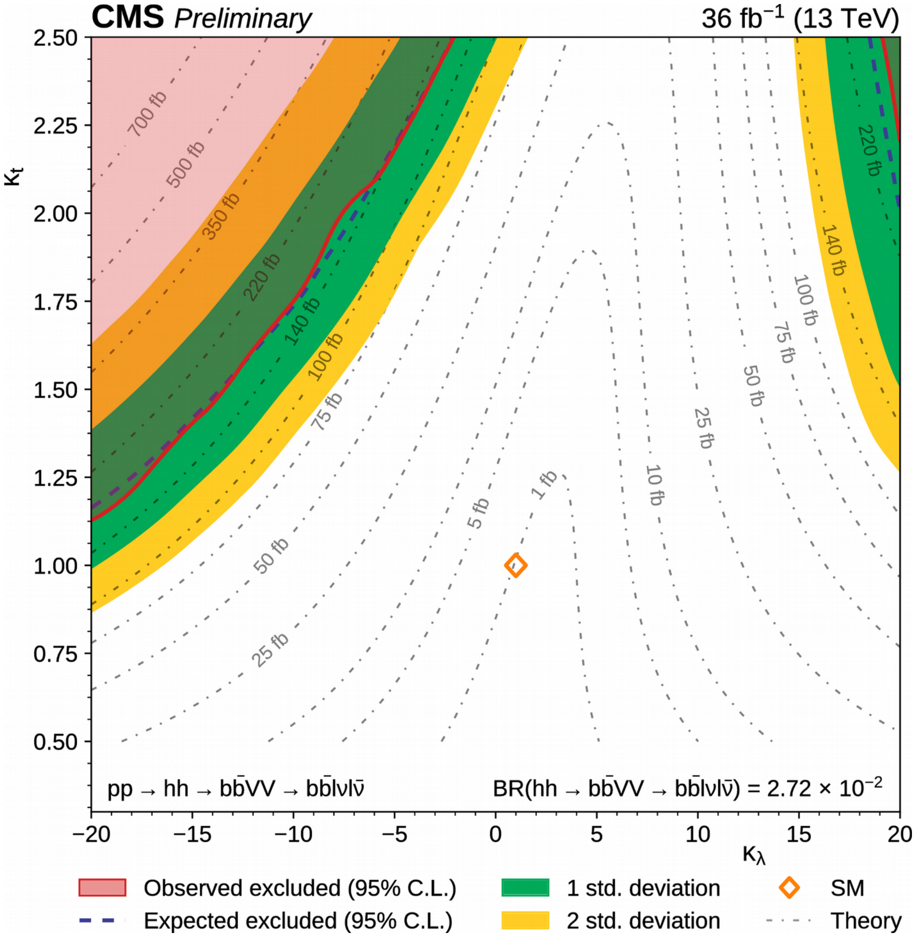


Searching for exotic properties

- Di-Higgs production is rare in the SM, however, an anomalously large rate can be evidence of a composite 125-GeV Higgs boson

CMS search for
hh → bb WW/ZZ → bb lvlv





$\sigma(pp \to hh) < 72$ fb (exp. 81^{+42}_{-25} fb)
which is about 80 times the SM cross section

CMS-PAS-HIG-17-006

Supersymmetry (SUSY)

- SUSY is the most studied individual framework for BSM physics at colliders
- Basic concepts for SUSY searches: **A very rough guide**

R-parity violated → Signatures without MET

R-parity conserved → Signatures with MET

Strong production → MET + jets:
- gluino production
- squark production
- …

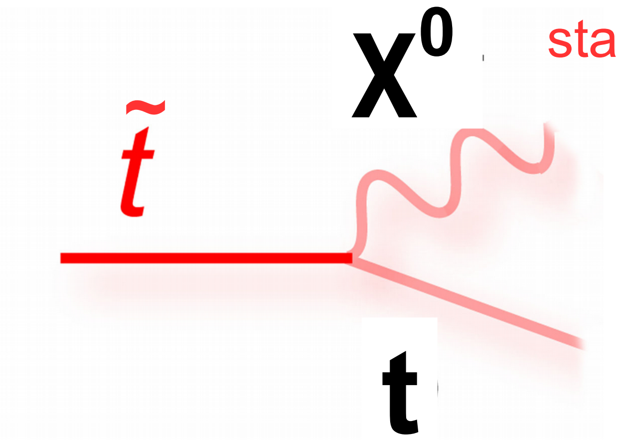
Weak production → Multileptons, MET, Higgs:
- sleptons
- gauginos
- …

Breaking news: SUSY to be found soon!

ATLAS and CMS representative makes an official wish for supersymmetry discovery in Charles Bridge Prague.

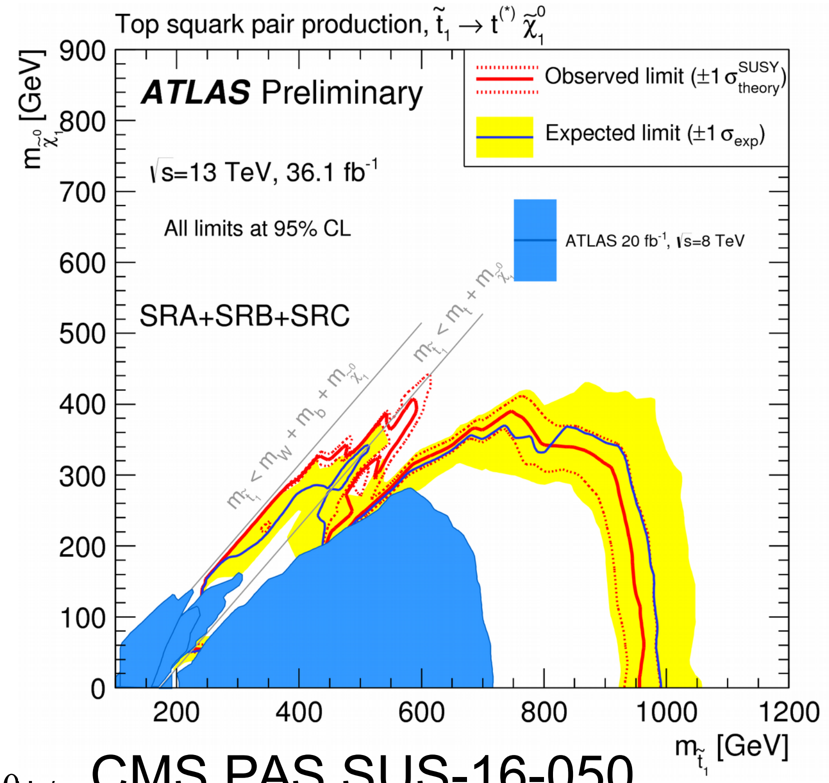
Top and SUSY

- Top quarks are very important in SUSY searches:
  - Related to *top squark* search, which is the quintessential SUSY search:
    stops have to be light for a natural Higgs boson mass



Neutralino:
stable → missing ET

Top quark:
fully hadronic to maximize BR



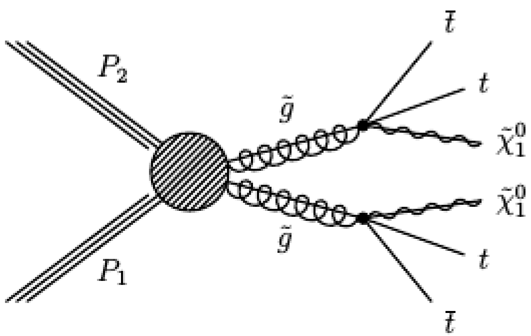
CMS PAS SUS-16-050

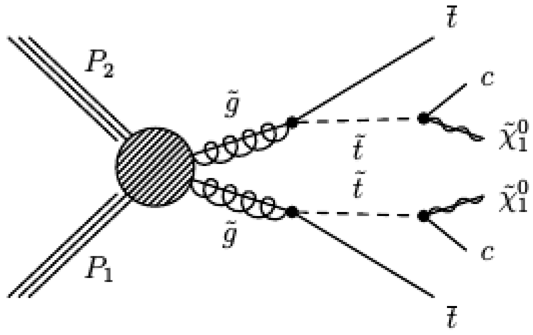
ATLAS-CONF-2017-020

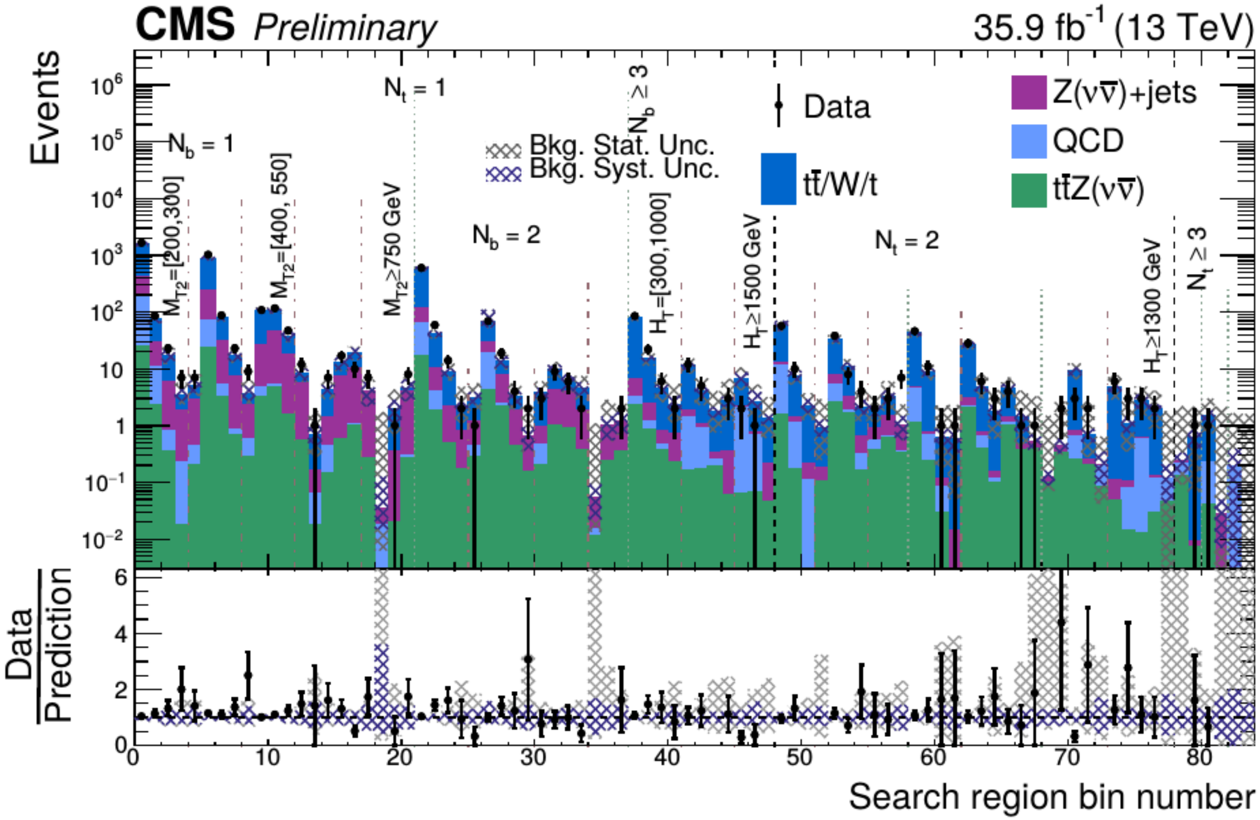
Top-tagging for SUSY

- Final states with top can be also used to look for other SUSY particles
  - This CMS search has defined a dedicated top tagger to improve sensitivity

CMS PAS SUS-16-050



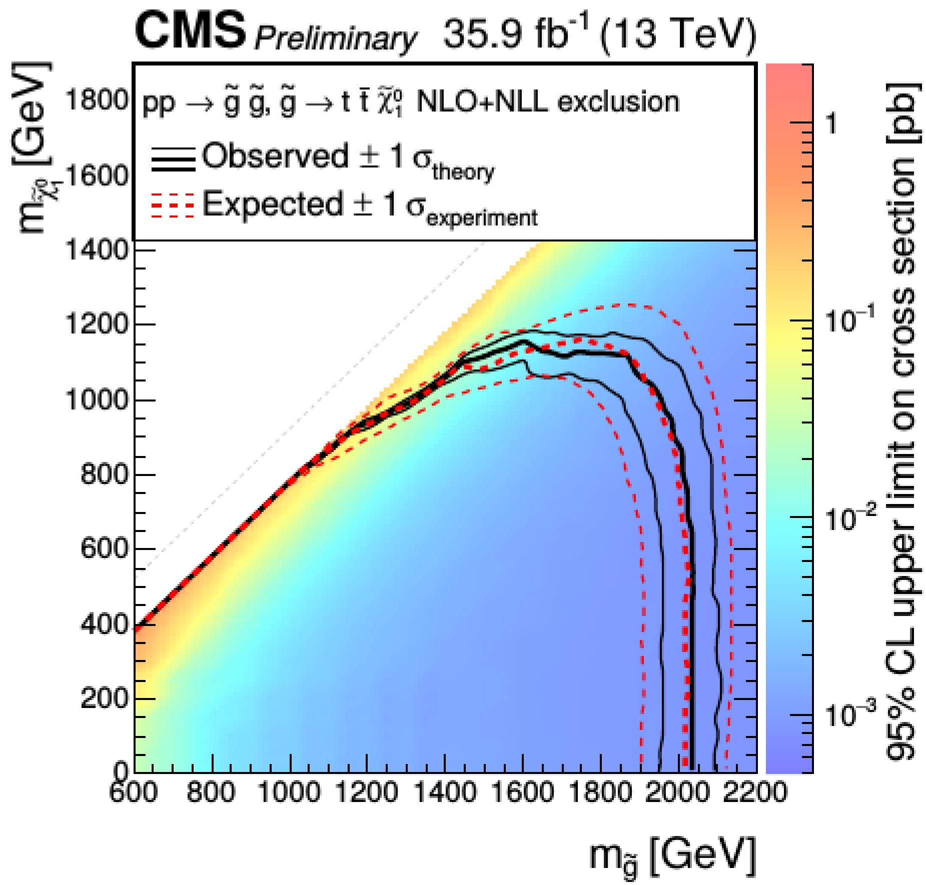


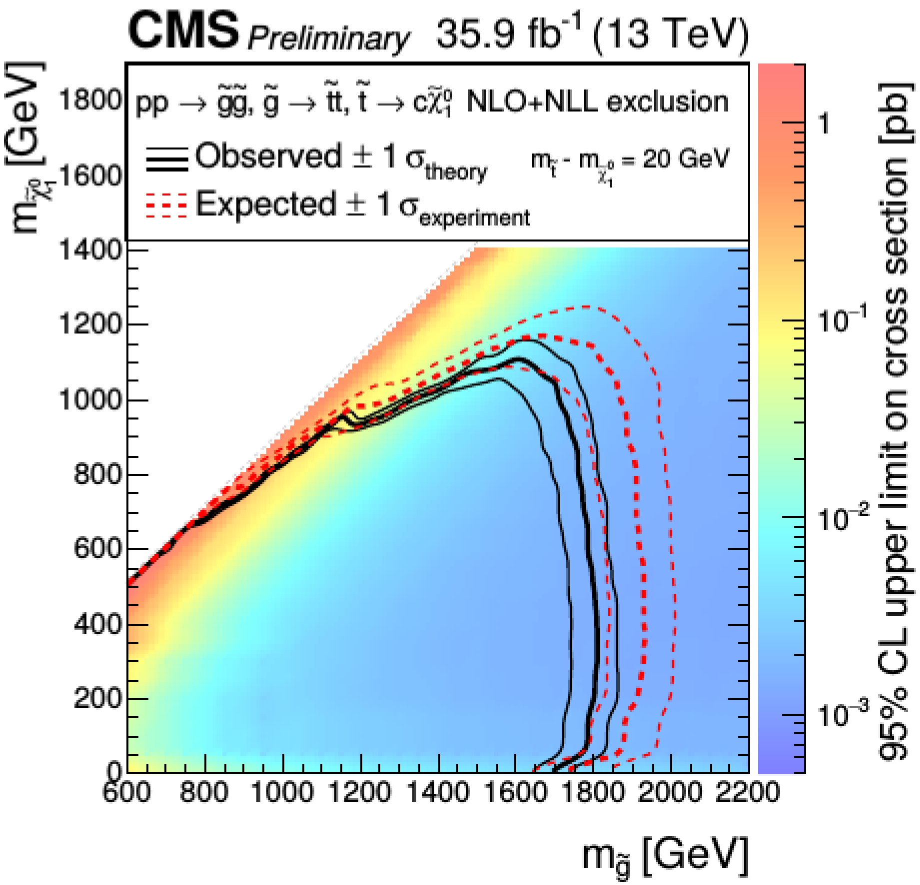


Top-tagging for SUSY

- Similar exclusion plots for gluinos are produced (in addition to stop quark vs χ_0):

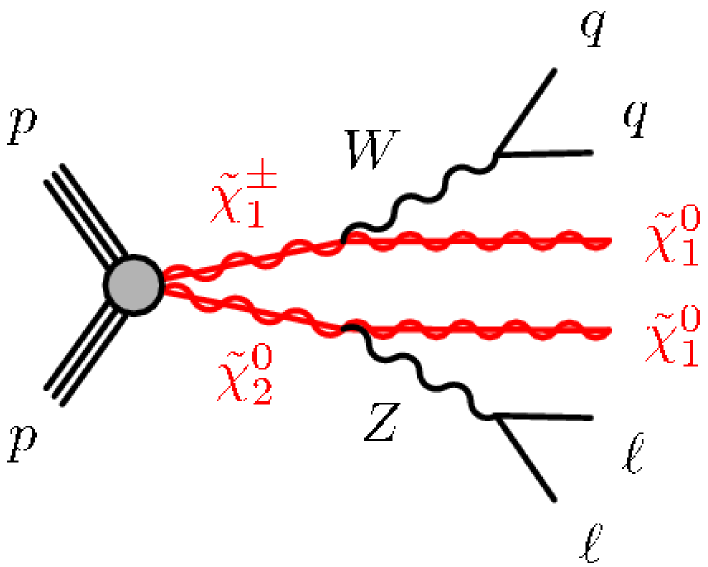
CMS PAS SUS-16-050



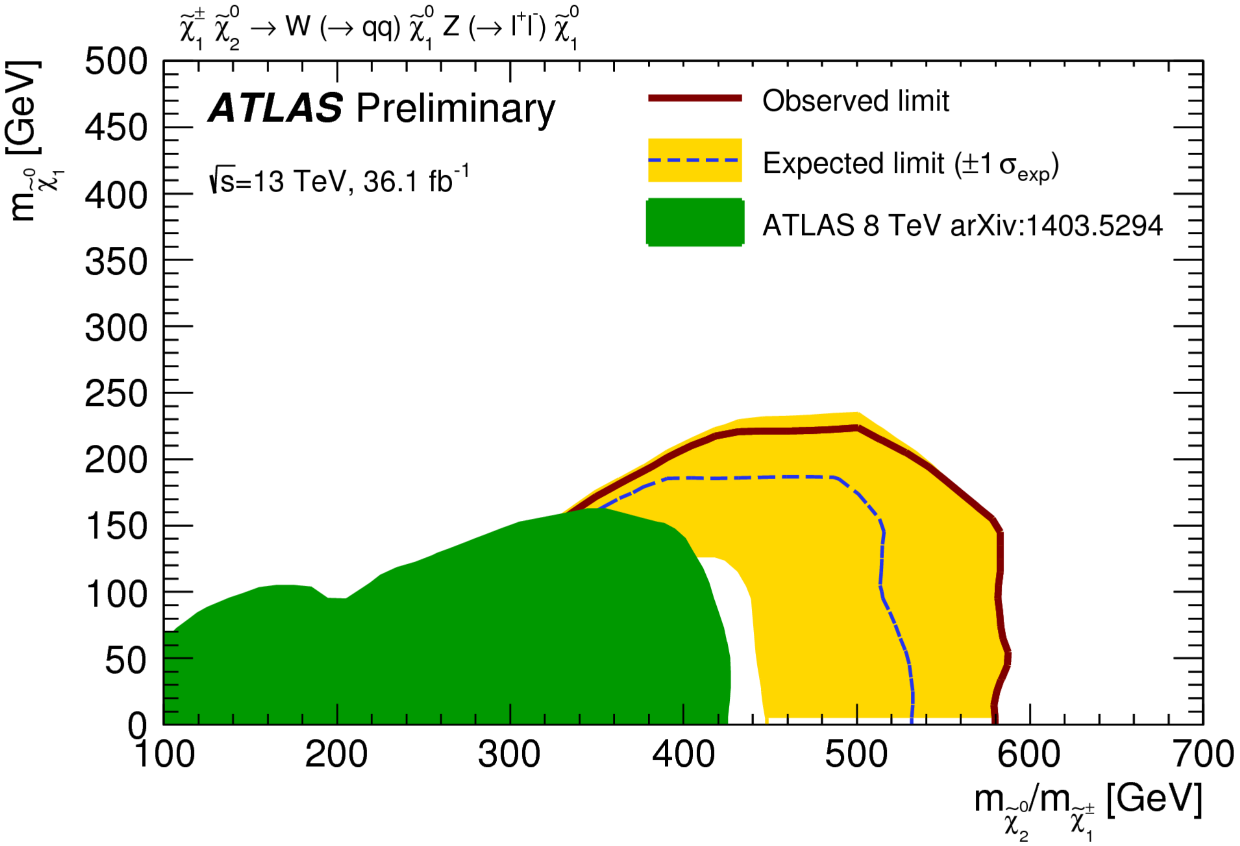


Weak SUSY production examples

Electroweak SUSY searches: suppressed due to small couplings, but much usually cleaner due to the leptons in final state



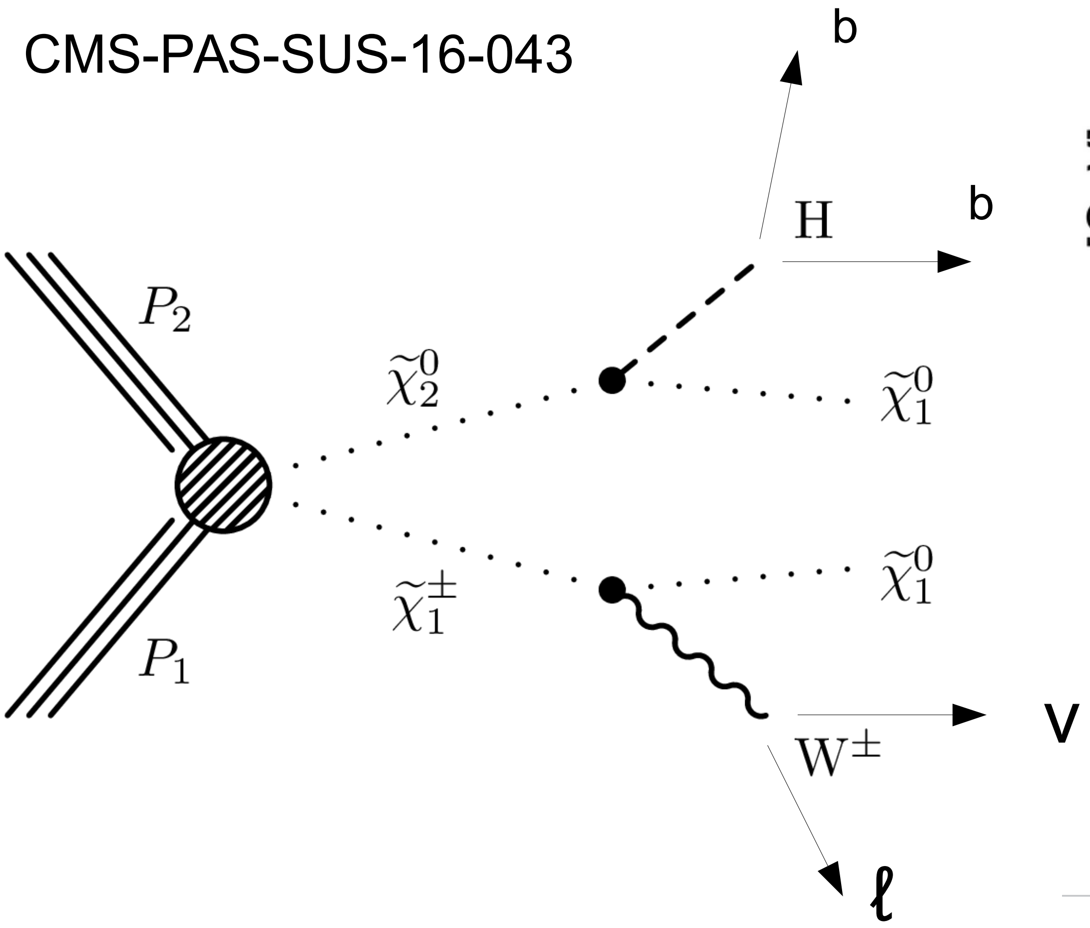
ATLAS-CONF-2017-039

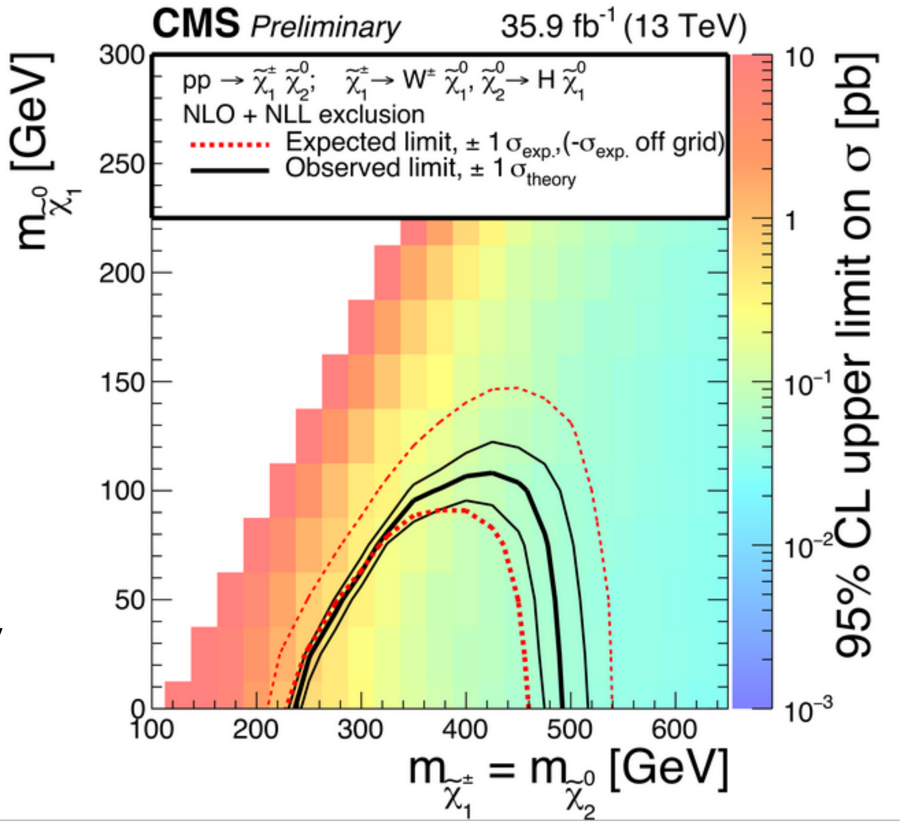


Weak SUSY production examples

Electroweak SUSY searches: suppressed due to small couplings, but much usually cleaner due to the leptons in final state

CMS-PAS-SUS-16-043

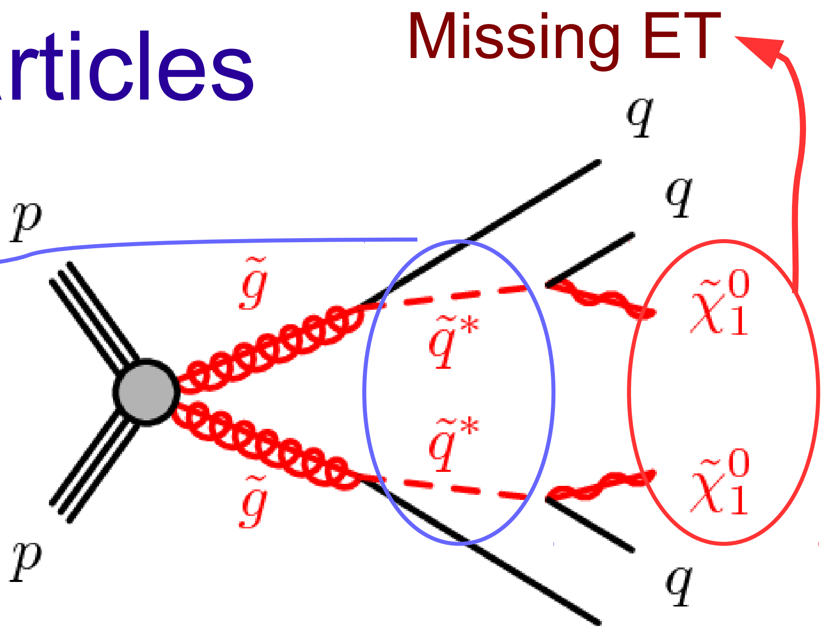




Long-Lived particles

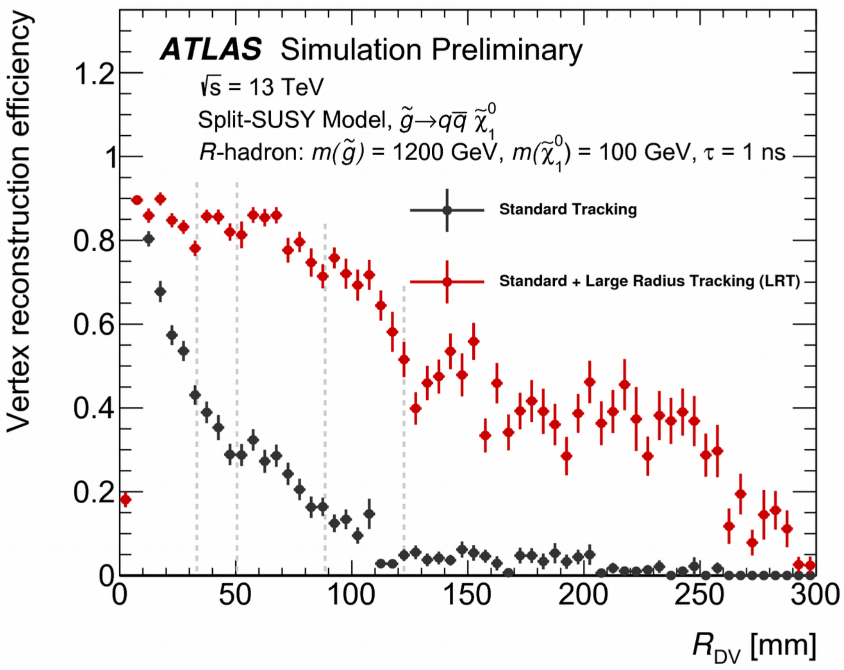
- Very interesting
  - Many theories, not just SUSY, have models with long-lived particles (e.g. hidden valley models): SUSY/Exotics boundary
- … but very challenging
  - The LHC experiments are designed to look for objects produced close to the interaction point and within a small time window

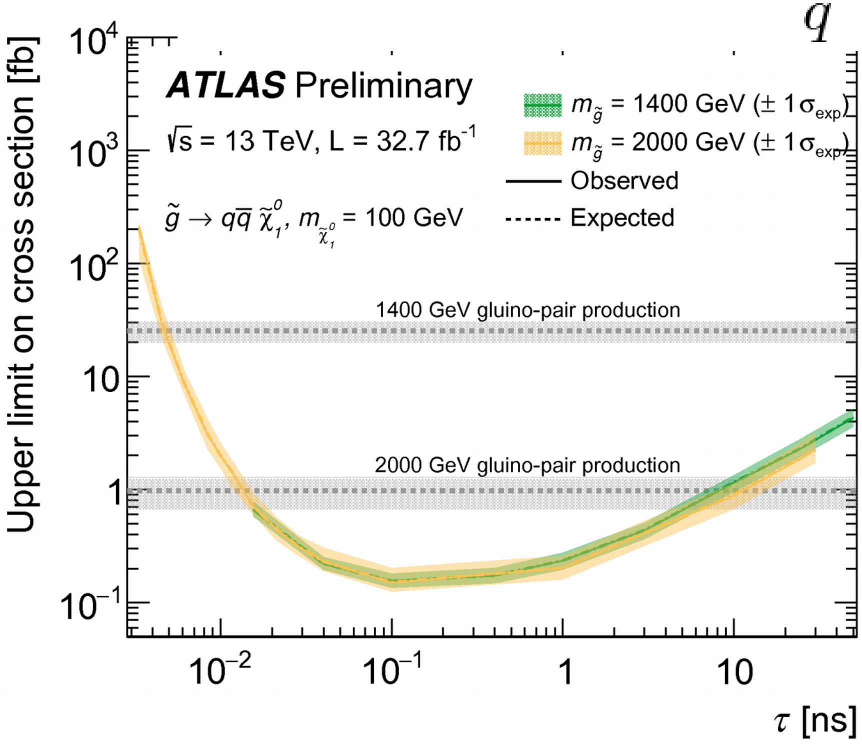
Long-Lived particles



Long-lived gluinos leading to *displaced vertices*

ATLAS-CONF-2017-026





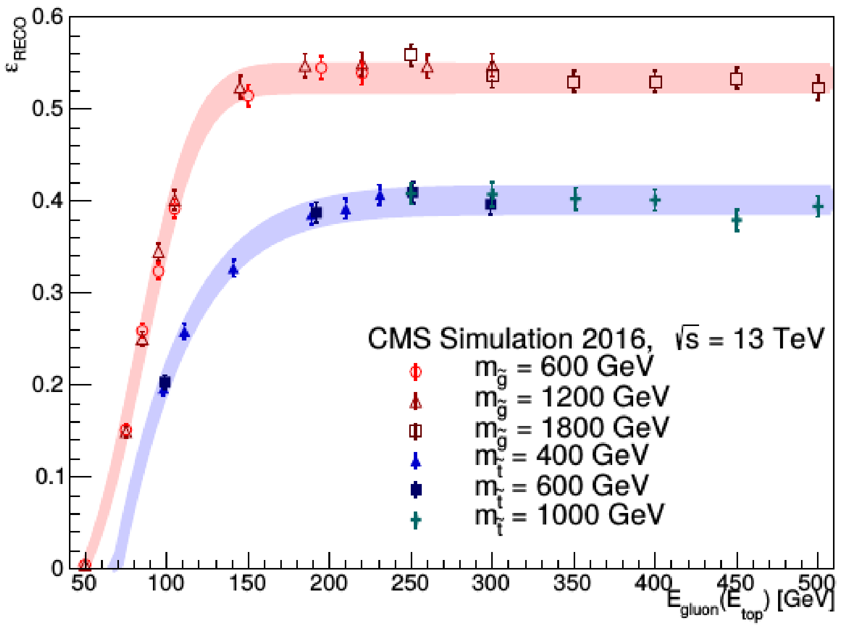
Innovations in tracking algorithms are needed to efficiently deal with displaced vertices

Long-Lived particles

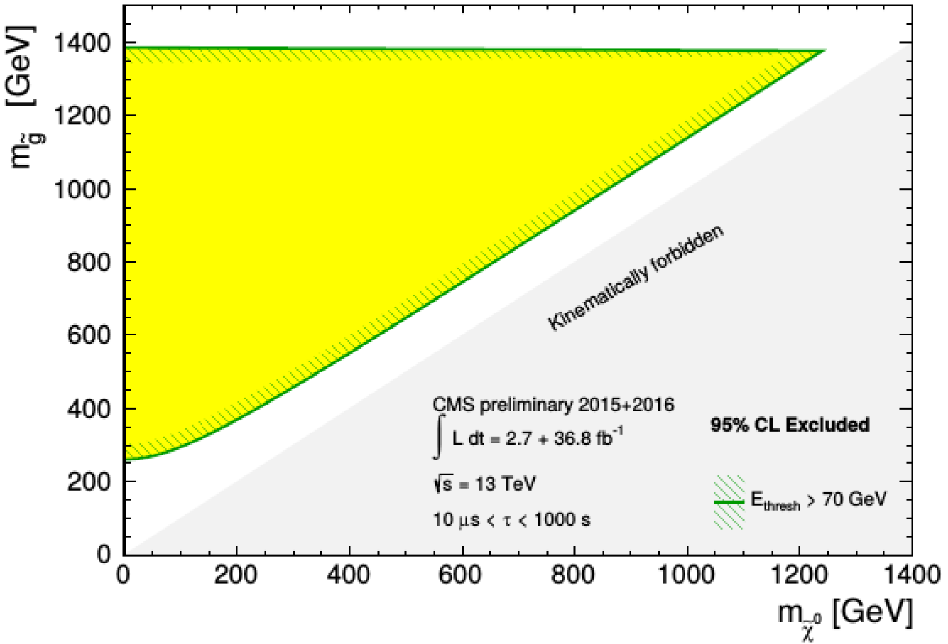
CMS-PAS-EXO-16-004

Search for long-lived SUSY partners that decay in the calorimeters

$$\tilde{g} \rightarrow g\tilde{\chi}^0$$
$$\tilde{t} \rightarrow t\tilde{\chi}^0$$

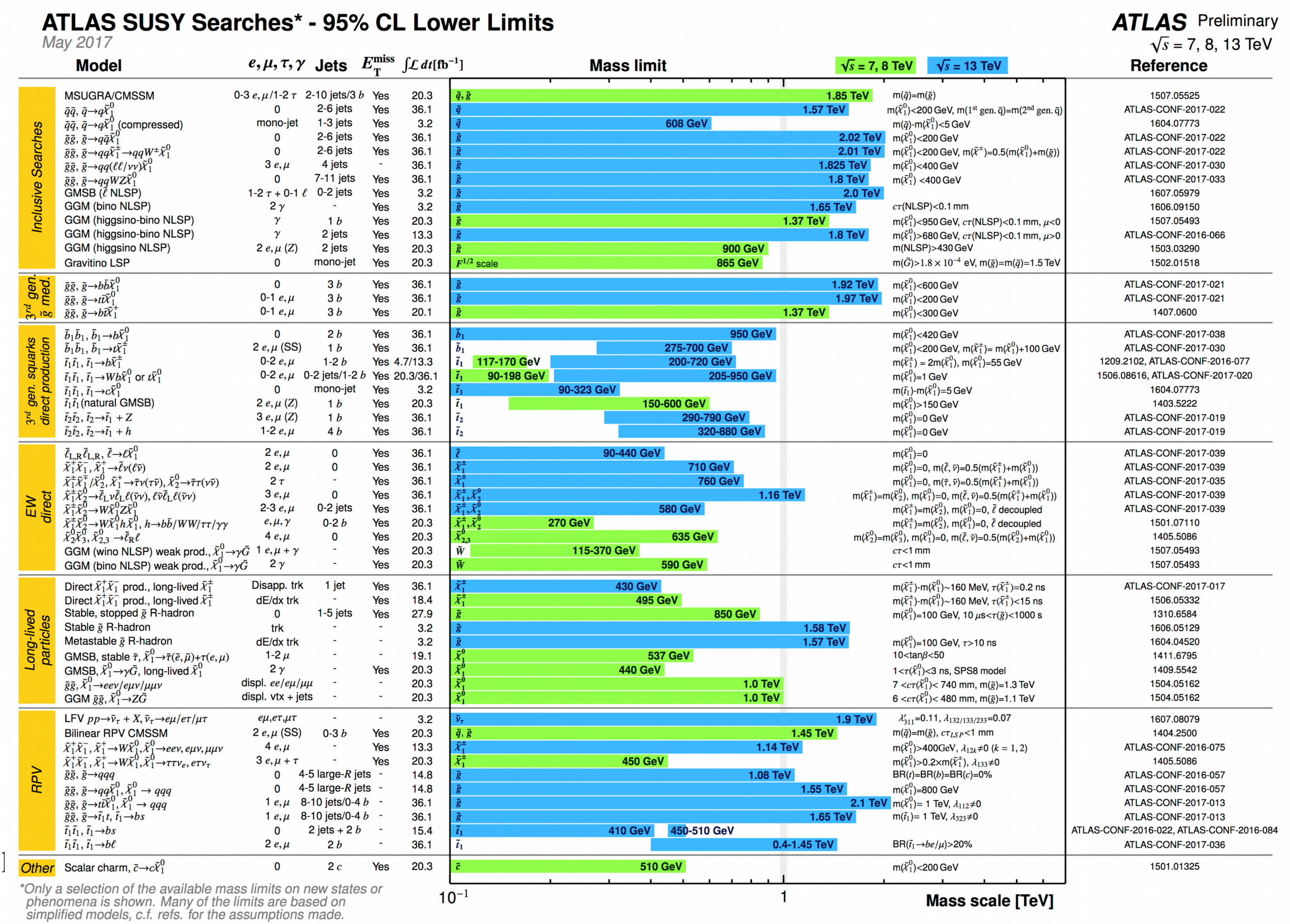


Efficiency to reconstruct the original gluino/top squark vs gluon/top energy



Limits example: long-lived gluinos with lifetimes between 10 μs and 1000 s

LHC SUSY searches at a glance



ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

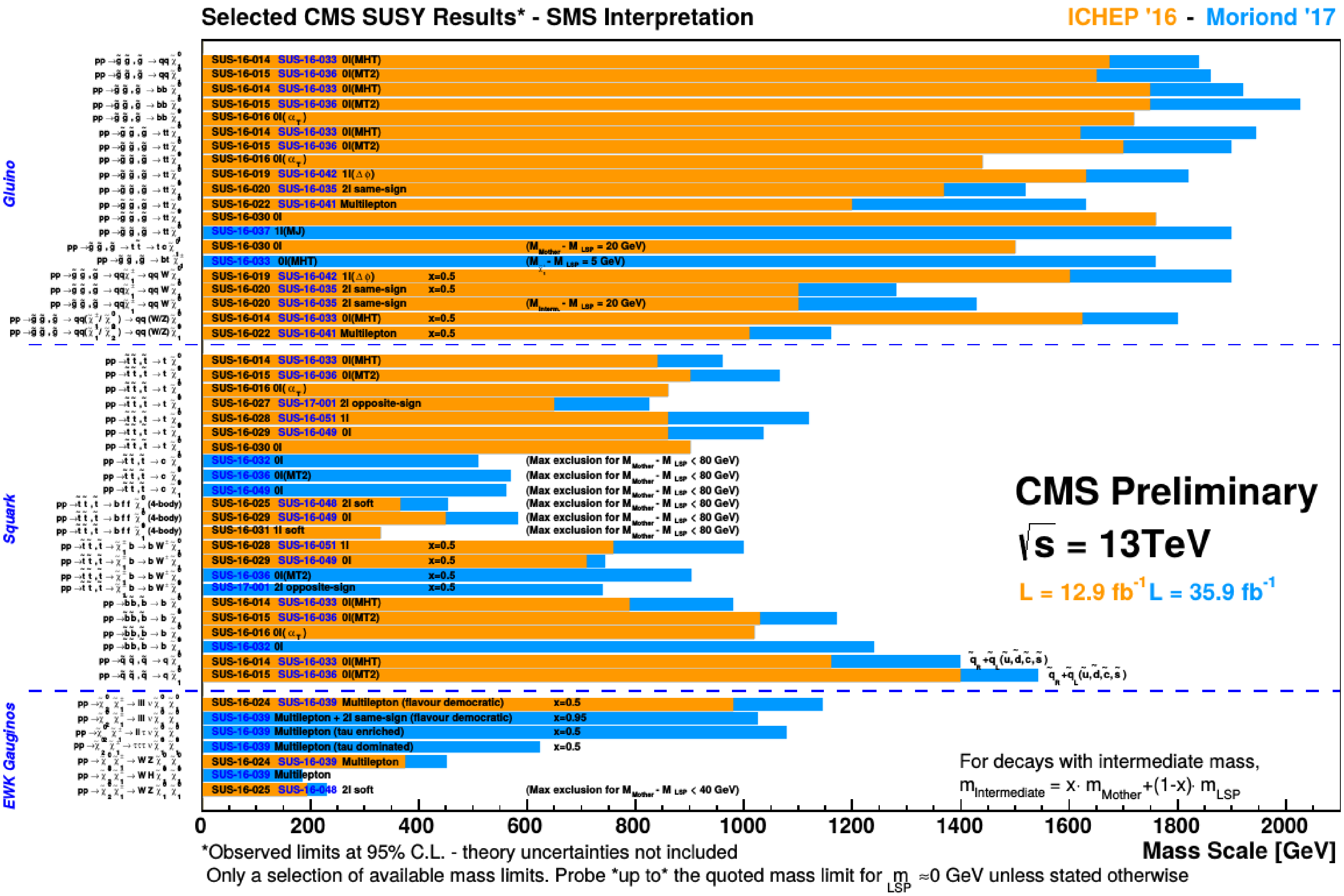
$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 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	🟩 $\tilde{q},\tilde{g}$ 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{q}$ 1.57 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.02 TeV	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}^{\pm}_1\rightarrow qqW^{\pm}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.01 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	36.1	🟦 $\tilde{g}$ 1.825 TeV	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	🟦 $\tilde{g}$ 1.8 TeV	m($\tilde{\chi}^0_1$) <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	🟦 $\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}^0_1$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde{g}$ 1.8 TeV	m($\tilde{\chi}^0_1$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 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
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.92 TeV	m($\tilde{\chi}^0_1$)<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.97 TeV	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}^0_1$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}^0_1$	0	2 b	Yes	36.1	🟦 $\tilde{b}_1$ 950 GeV	m($\tilde{\chi}^0_1$)<420 GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}^{\pm}_1$	2 e,μ (SS)	1 b	Yes	36.1	🟦 $\tilde{b}_1$ 275-700 GeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^{\pm}_1$)= m($\tilde{\chi}^0_1$)+100 GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\tilde{\chi}^{\pm}_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}^{\pm}_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 205-950 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}^0_1$	0	mono-jet	Yes	3.2	🟦 $\tilde{t}_1$ 90-323 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	🟦 $\tilde{t}_2$ 290-790 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	🟦 $\tilde{t}_2$ 320-880 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	36.1	🟦 $\tilde{\ell}$ 90-440 GeV	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	🟦 $\tilde{\chi}^{\pm}_1$ 710 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_2$, $\tilde{\chi}^+_1\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\rightarrow\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	🟦 $\tilde{\chi}^{\pm}_1$ 760 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-035
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	🟦 $\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_2$ 1.16 TeV	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($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\rightarrow W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	36.1	🟦 $\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_2$ 580 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\rightarrow W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_2$ 270 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\rightarrow\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}^0_{2,3}$ 635 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., $\tilde{\chi}^0_1\rightarrow\gamma\tilde{G}$	1 e,μ + γ	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}^0_1\rightarrow\gamma\tilde{G}$	2 γ	-	Yes	20.3	🟩 $\tilde{W}$ 590 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	36.1	🟦 $\tilde{\chi}^{\pm}_1$ 430 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}^{\pm}_1$ 495 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	m($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}^0_1$ 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\rightarrow eev/e\mu\nu/\mu\mu\nu$	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 $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\rightarrow Z\tilde{G}$	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 $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}^{\pm}_1$ 1.14 TeV	m($\tilde{\chi}^0_1$)>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\rightarrow W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	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
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.55 TeV	m($\tilde{\chi}^0_1$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\rightarrow qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 2.1 TeV	m($\tilde{\chi}^0_1$)= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow\tilde{t}_1t$, $\tilde{t}_1\rightarrow bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	15.4	🟦 $\tilde{t}_1$ 410 GeV 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\ell$	2 e,μ	2 b	-	36.1	🟦 $\tilde{t}_1$ 0.4-1.45 TeV	BR($\tilde{t}_1\rightarrow be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 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. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

LHC SUSY searches at a glance



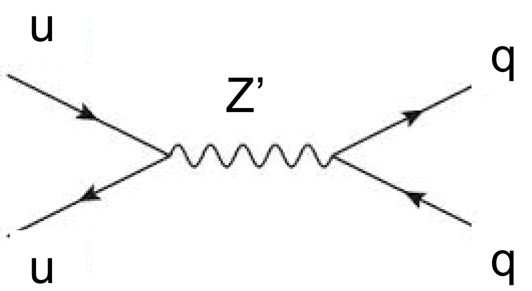
Exotic searches

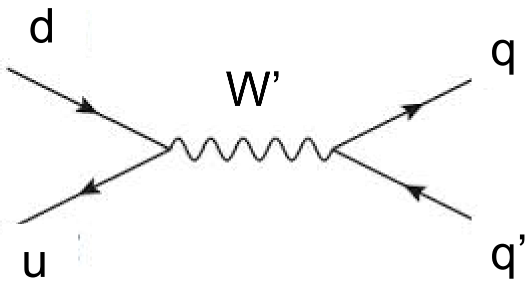
- Exotic searches include those extreme enough not to be included in BSM Higgs/SUSY
  - Often signature driven
  - Many of them inspired by Grand Unified Theories or related topics
    - e.g. search for heavy vector bosons, see-saw models etc, but at TeV (and not GUT) scale

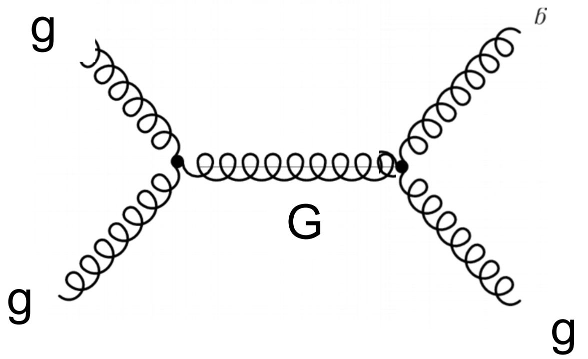
Di-jet spectrum

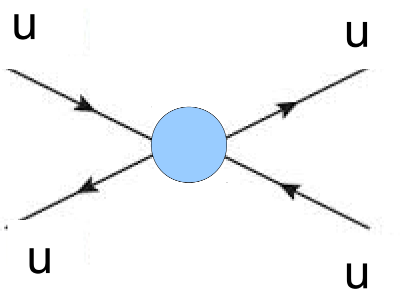
CMS PAS-EXO-16-056
CMS PAS-EXO-17-001
ATLAS arxiv:1703.09127

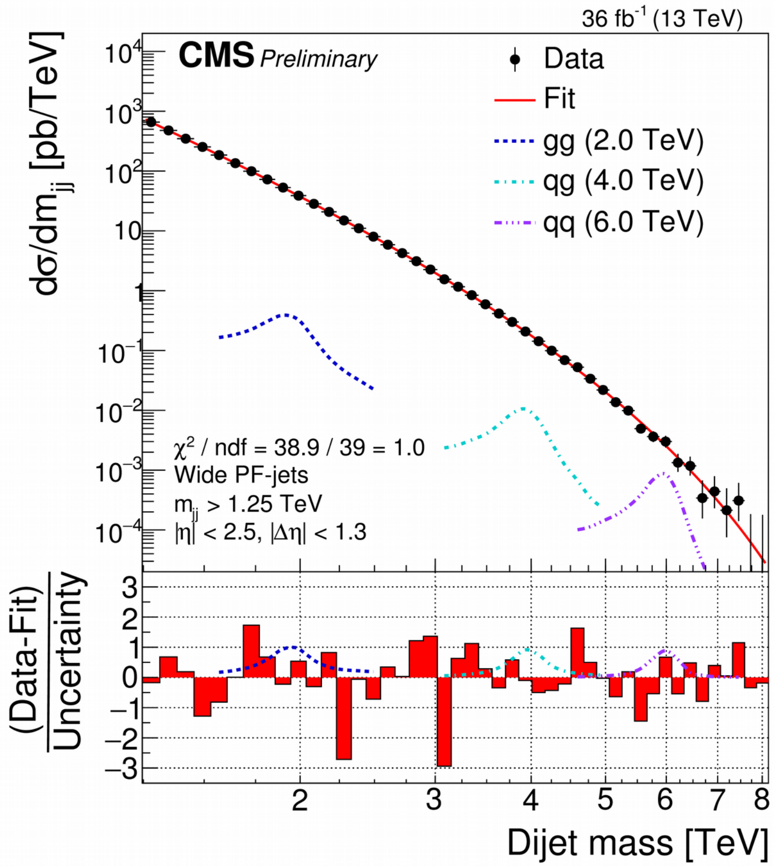
- Examining the tail of the di-jet mass distribution
  - Many BSM theories include resonances that decay to di-jets
  - Non-resonant phenomena (e.g. quark substructure)







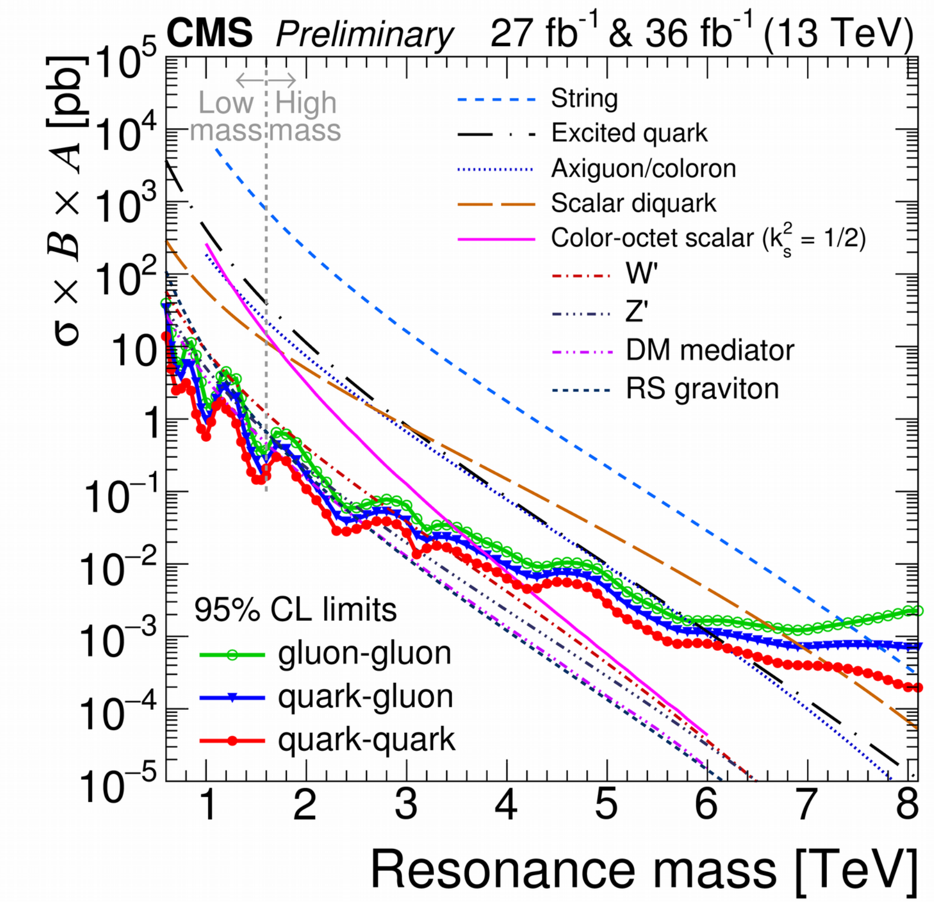




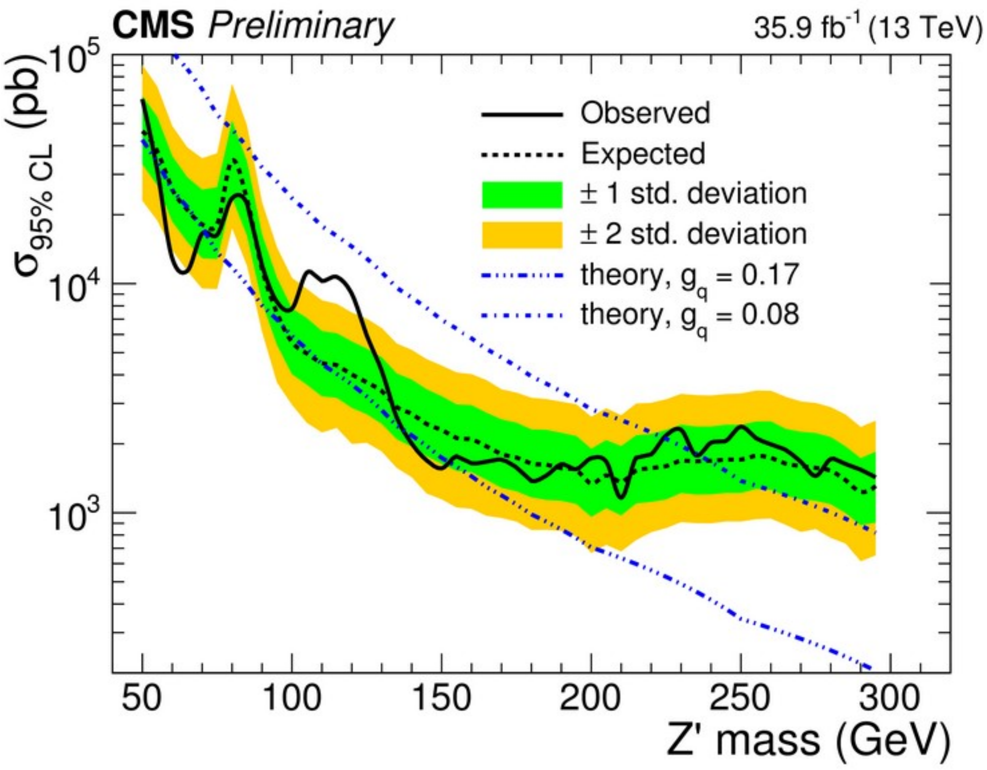
Di-jet spectrum

CMS PAS-EXO-16-056
CMS PAS-EXO-17-001
ATLAS arxiv:1703.09127

Generic limits compared to predictions for various models

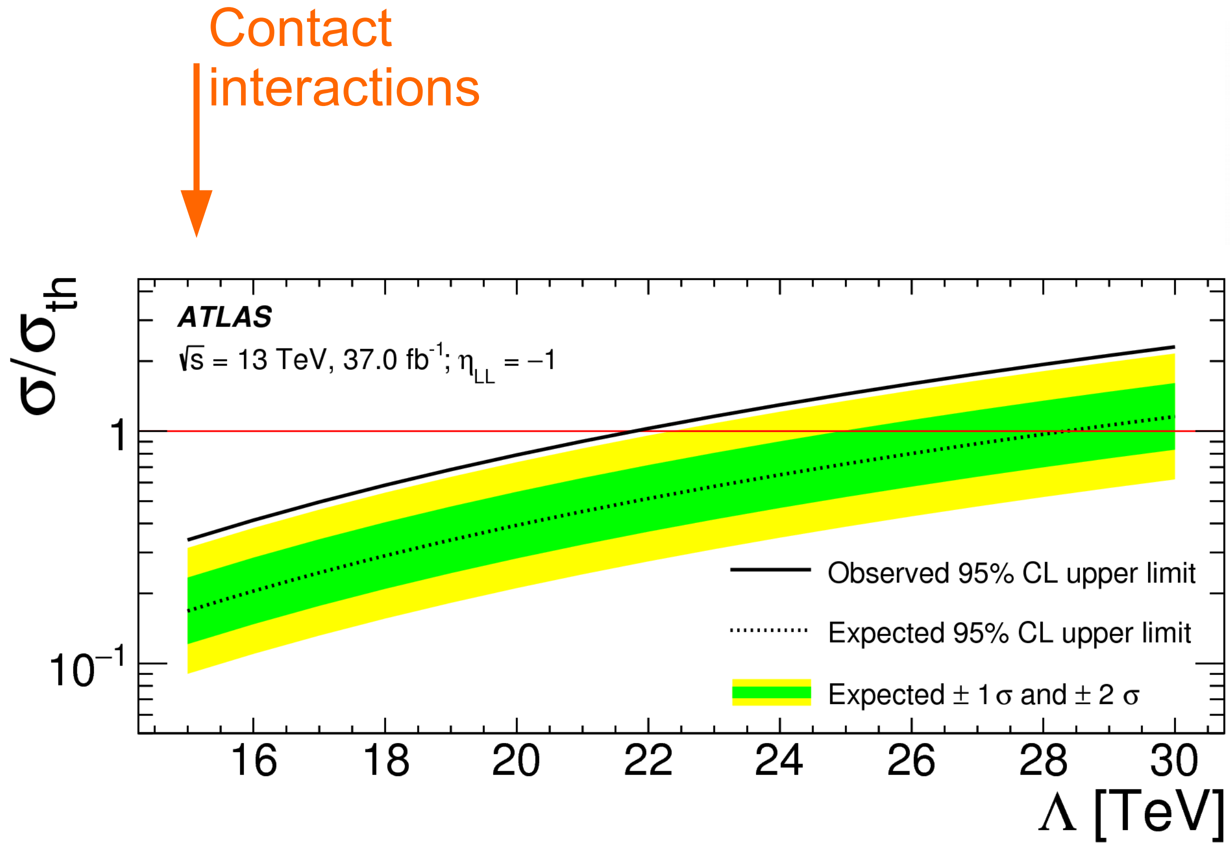


CMS extension of the search in the low mass region

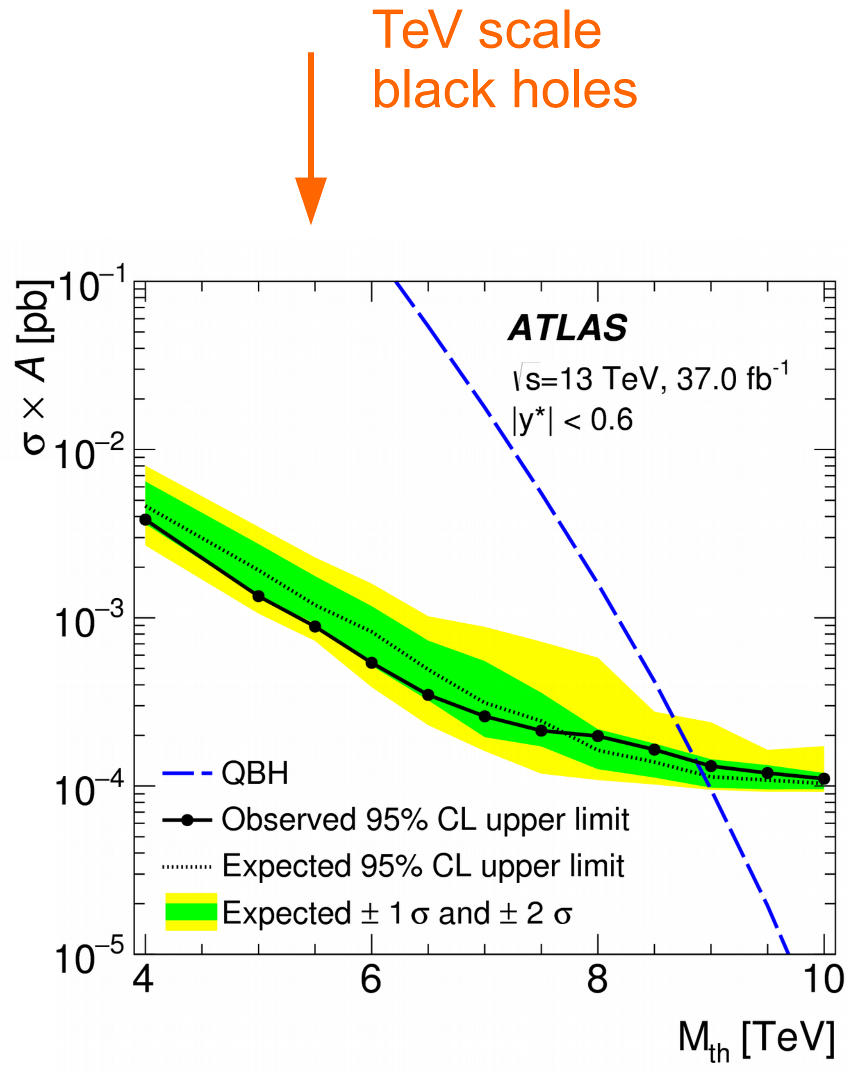


Di-jet spectrum

- Model dependent interpretations



Contact interactions

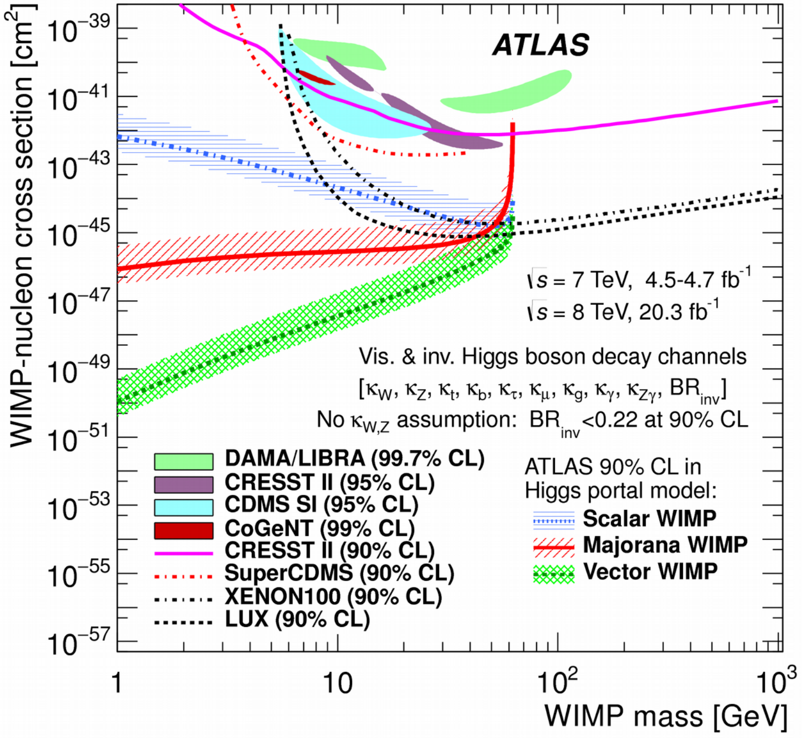


TeV scale black holes

Dark matter searches

- A new weakly interacting massive particle that may explain the “WIMP miracle” in cosmology has been searched for at the LHC in many different channels
- Example:
  - Higgs boson to dark matter decays, *directly* or *indirectly* (though precision measurements of the couplings)

JHEP11(2015)206

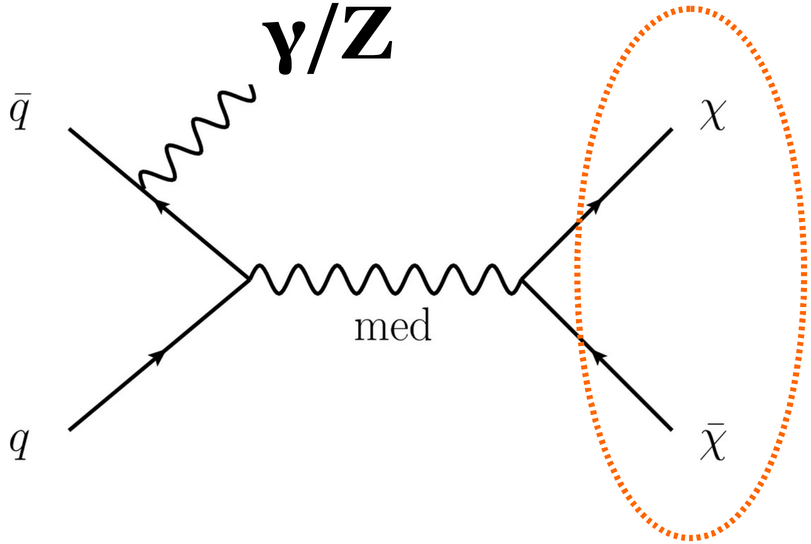


Example from ATLAS Run-I Higgs couplings; similar results from CMS as well

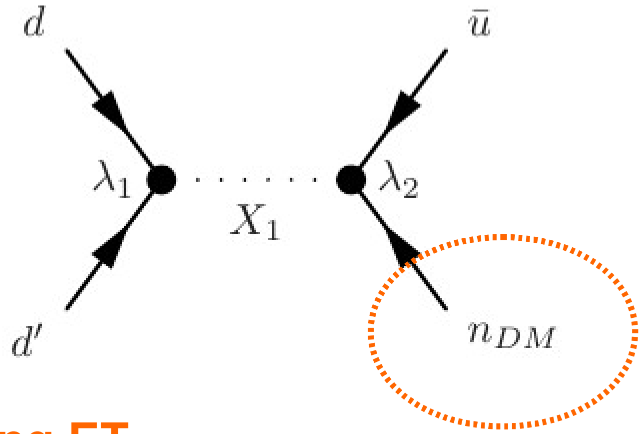
Dark matter searches

- One direct way to look for Dark Matter (DM) is to look for mono-X production, where X = a usual object
    - Dark matter recoils against the “mono-object”

Examples: mono-photon or mono-Z



mono-jet



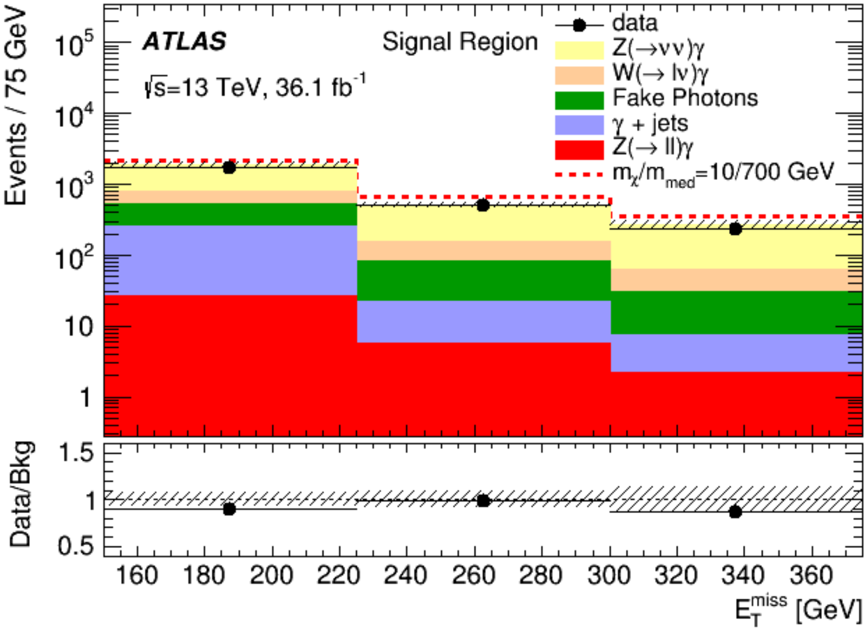
Missing ET

Dark matter searches

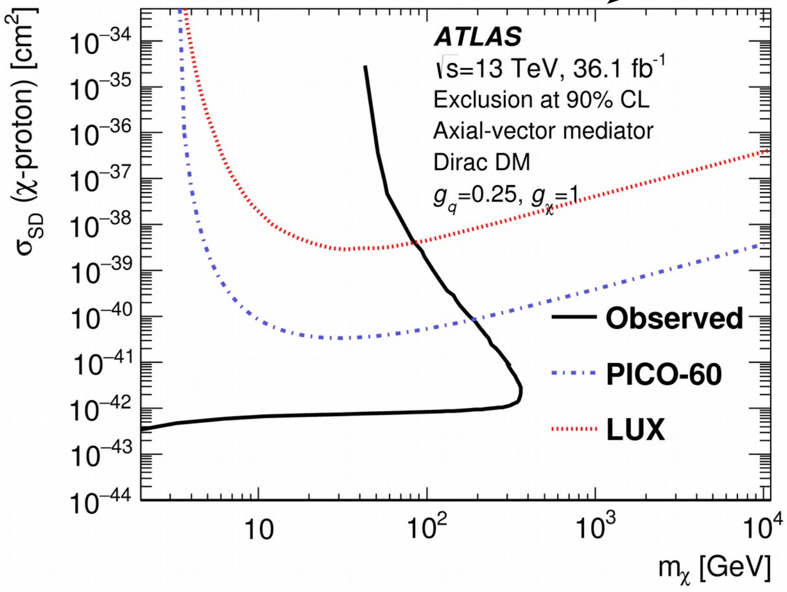
arXiv:1704.03848

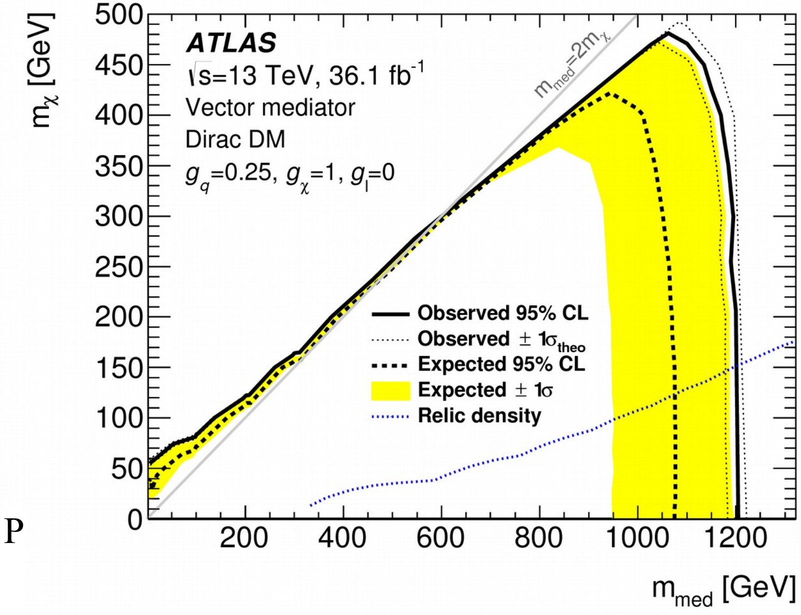
- Mono-photon example from ATLAS

Number of events in the various signal regions of the search



Various interpretations of the results:

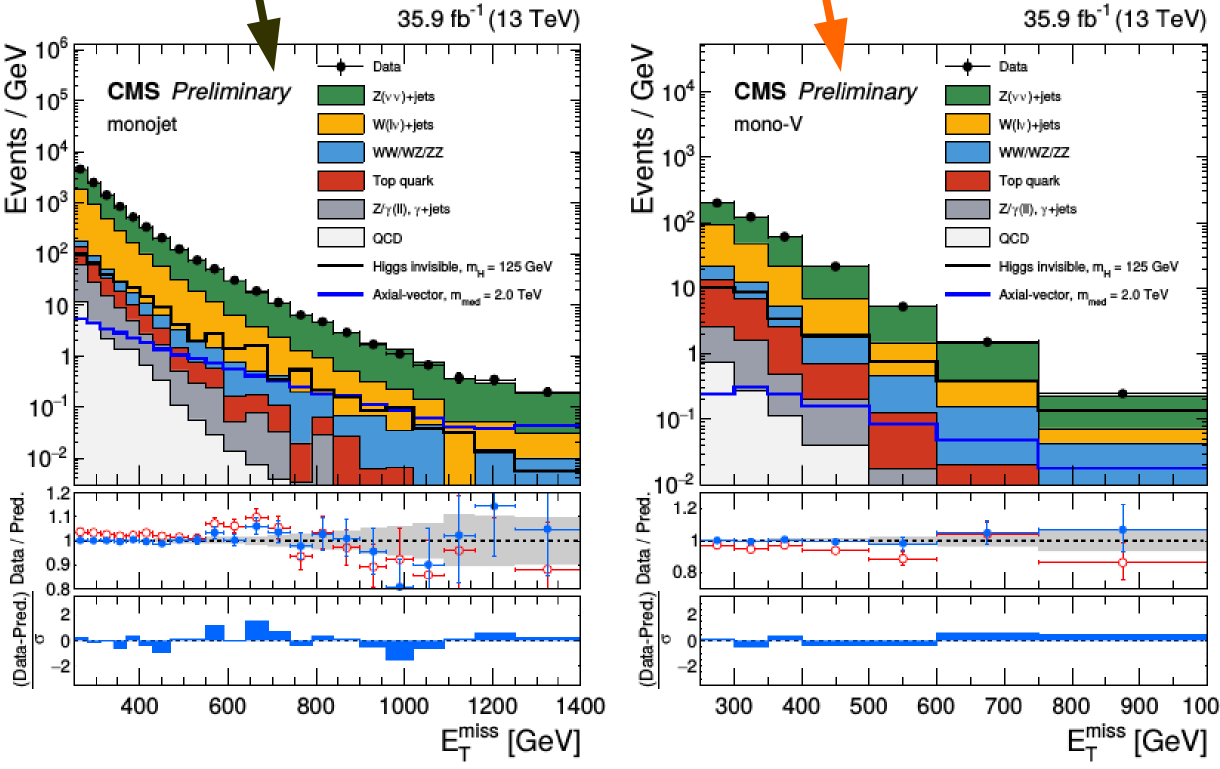




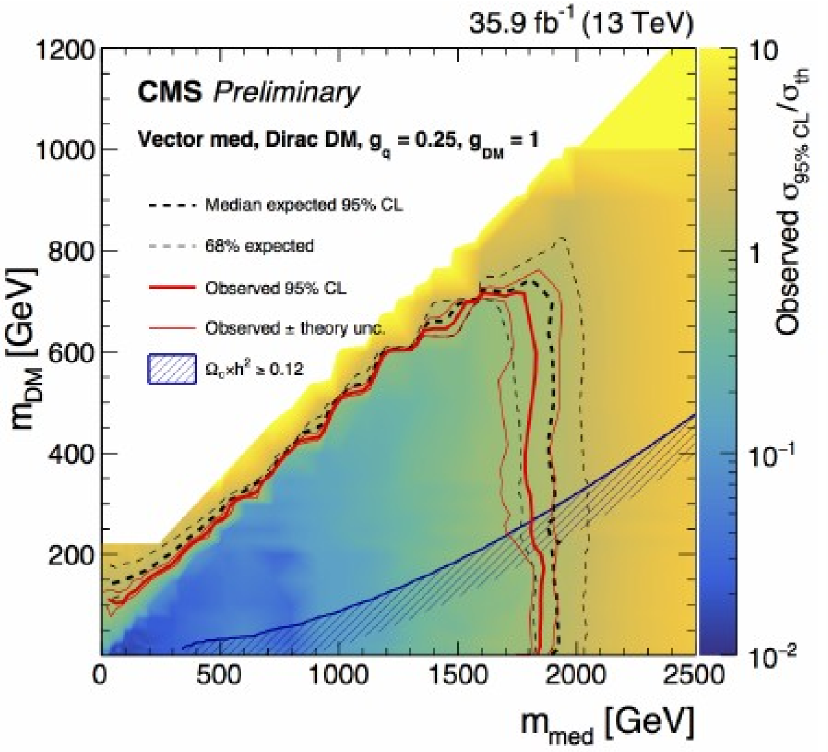
Dark matter searches

CMS-PAS-EXO-16-048

- *Mono jet* / *mono vector boson* example from CMS

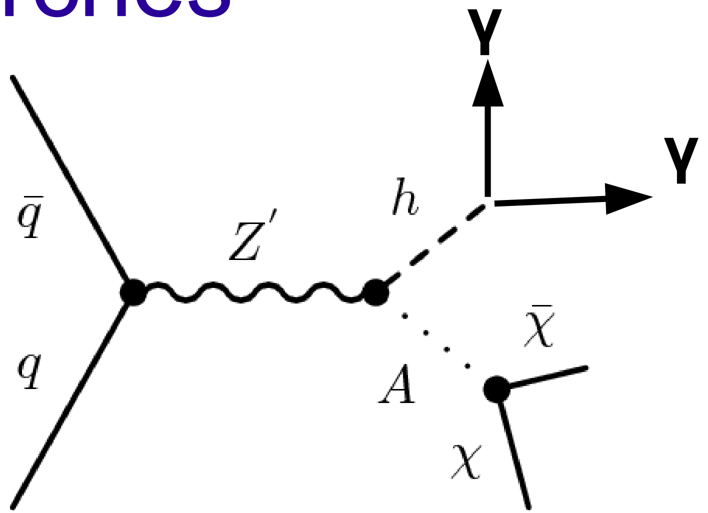


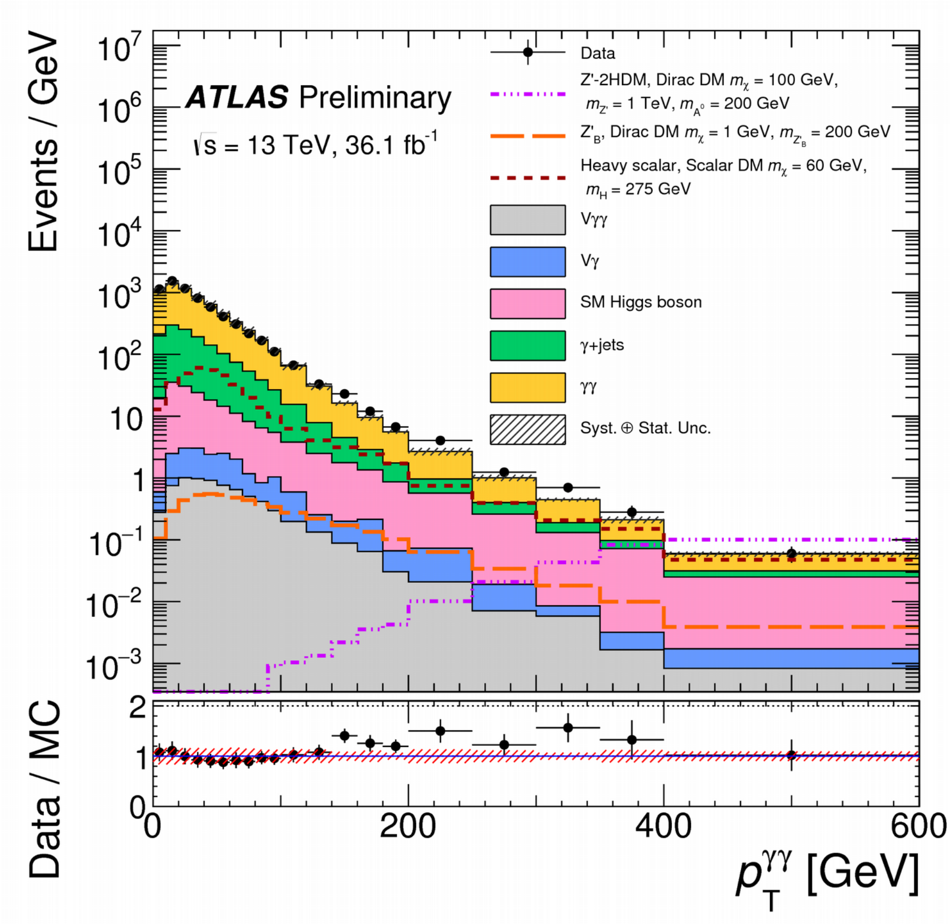
Missing ET distributions for the two different final states



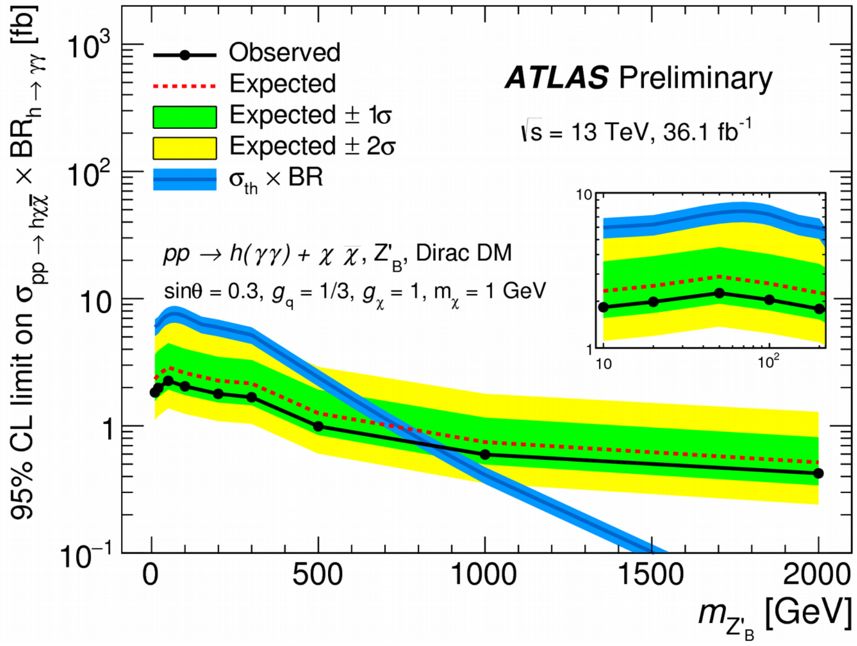
Dark matter searches

- Dark matter produced in association with a Higgs boson



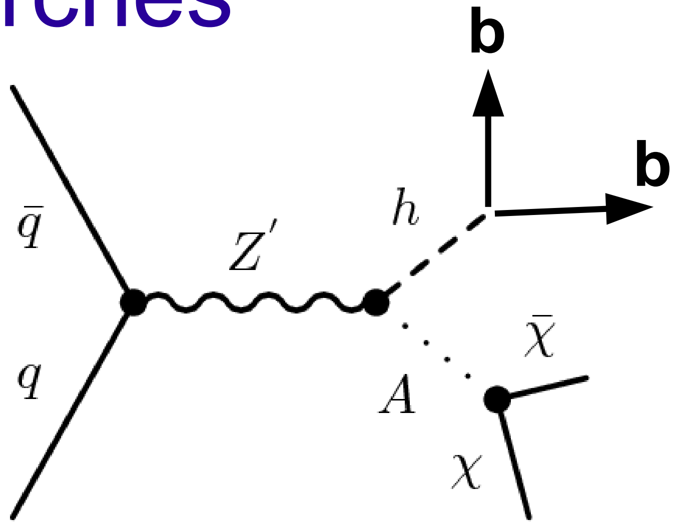


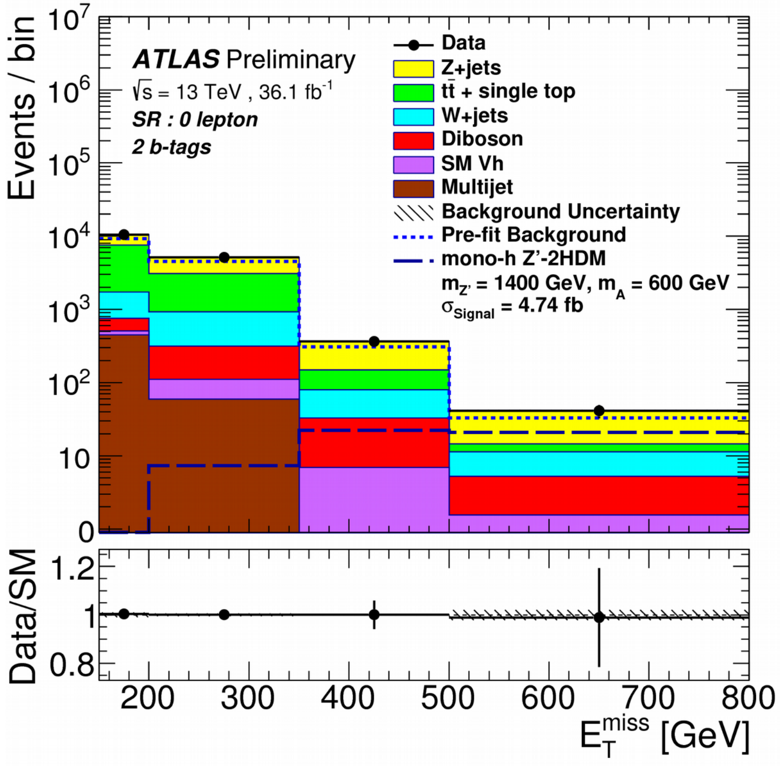
ATLAS-CONF-2017-024

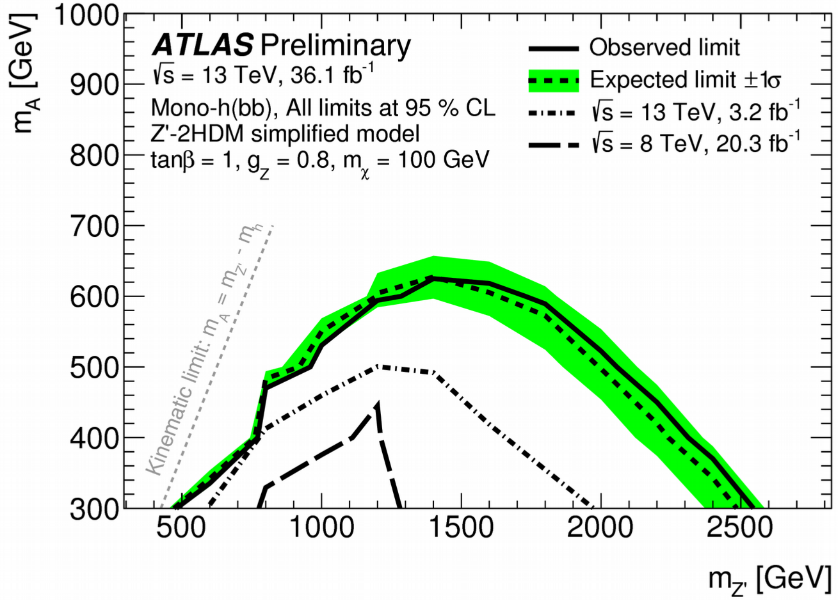


Dark matter searches

- Dark matter produced in association with a Higgs boson



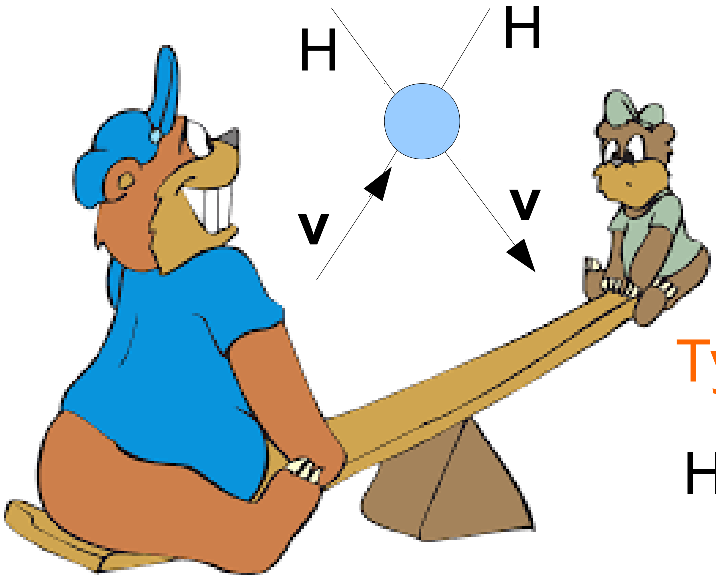




ATLAS-CONF-2017-028

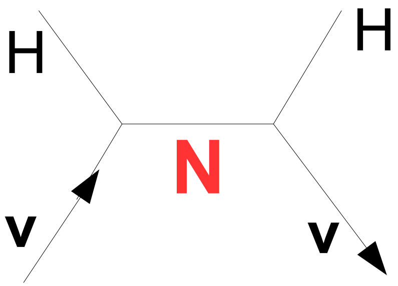
See-saw inspired searches

- Massive neutrinos are direct evidence for BSM physics!
  - Neutrino mass generation is an open question



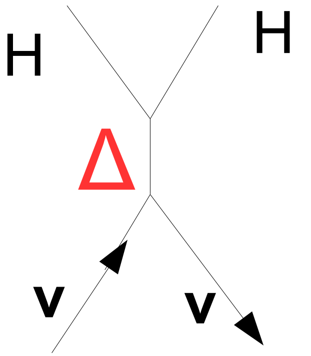
See-saw mechanism is the most popular mechanism for neutrino mass: the neutrino mass is small because it is driven by new heavy particles

Type-I see saw



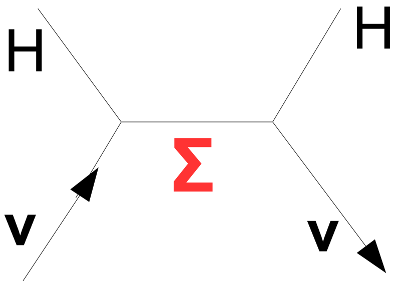
Heavy right-handed neutrino

Type-II see saw



Triplet (scalar)

Type-III see saw



Triplet (fermionic)

See-saw inspired searches

- CMS type-III inspired search

Triplet with heavy fermions that are produced in pairs weakly and decay to various multi-lepton final states

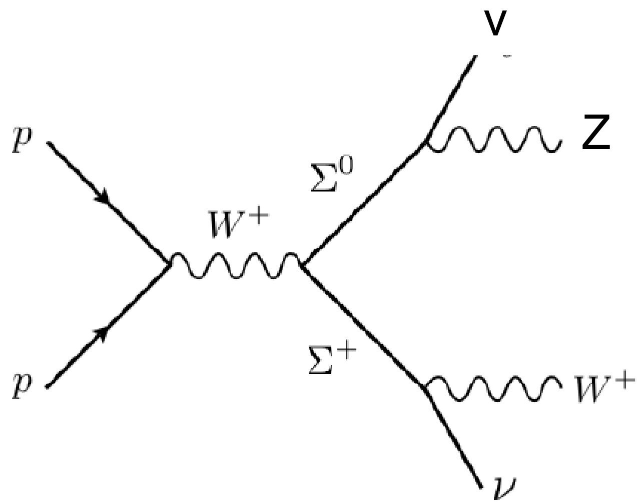
$$\Sigma = \begin{pmatrix} \Sigma^+ \\ \Sigma^0 \\ \Sigma^- \end{pmatrix}$$

$\Sigma^+ \rightarrow$ $W^+\nu$, Zl^+, Hl^+

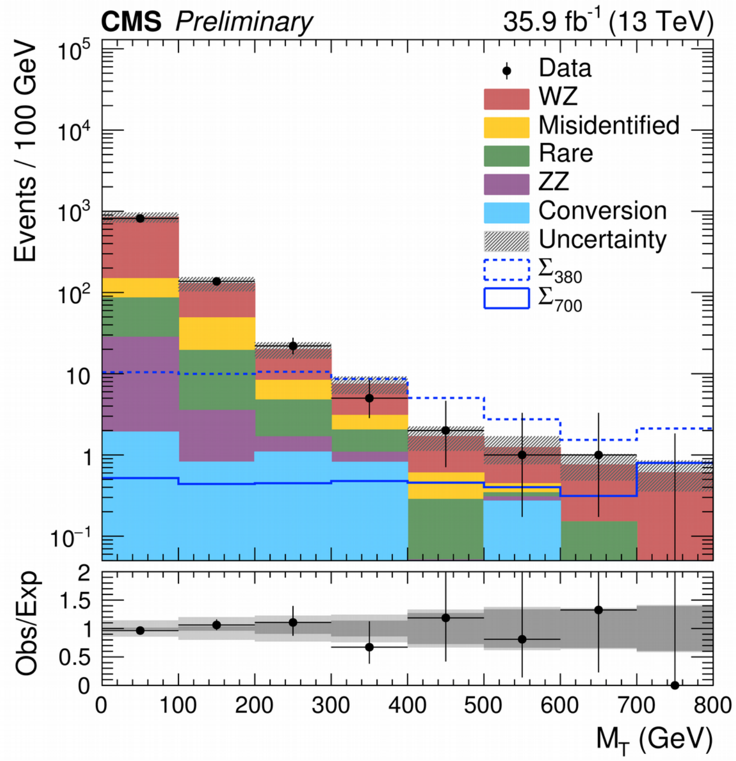
$\Sigma^0 \rightarrow$ W^+l^-, $Z\nu$, $H\nu$

CMS-PAS-EXO-17-006

Example of a final state considered:



3 leptons with 2 of them compatible with a Z→ ll decay and MET > 100 GeV



See-saw inspired searches

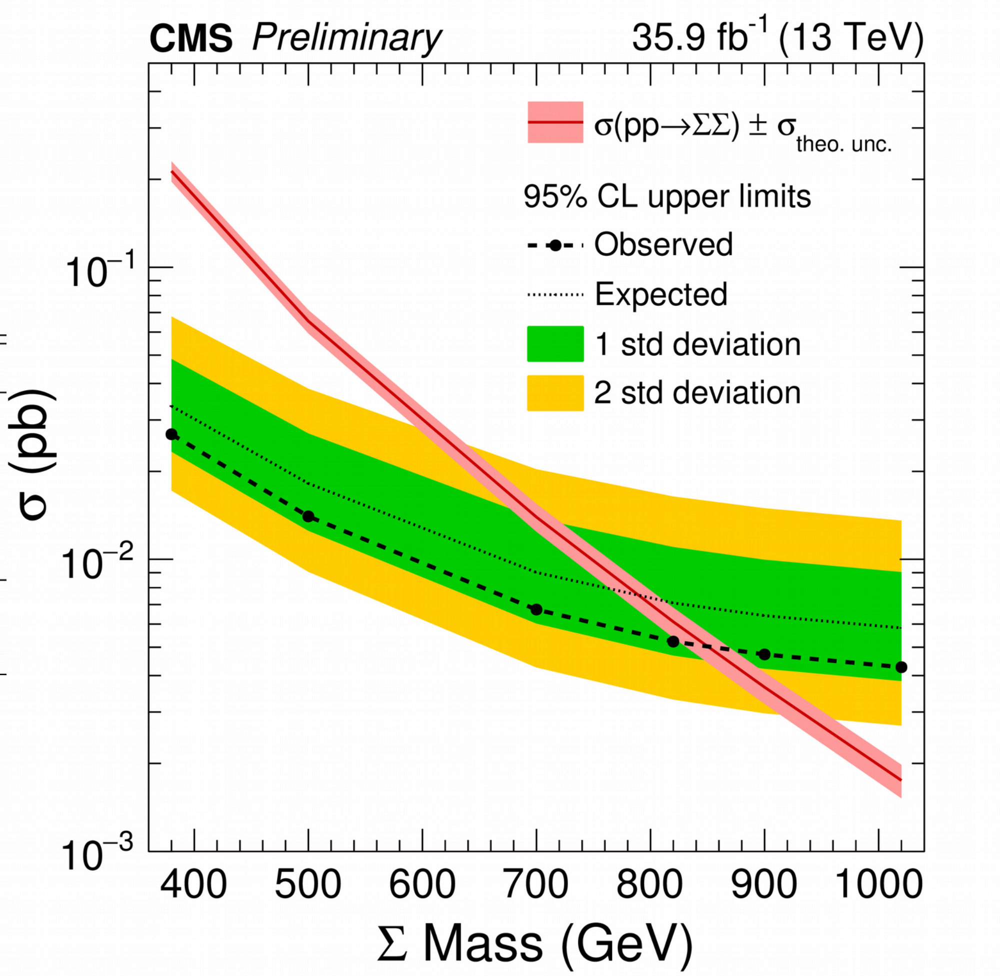
CMS-PAS-EXO-17-006

In total 6 multi-lepton cateogories have been examined and the results are interpreted in a flavour-democratic fermion triplet model

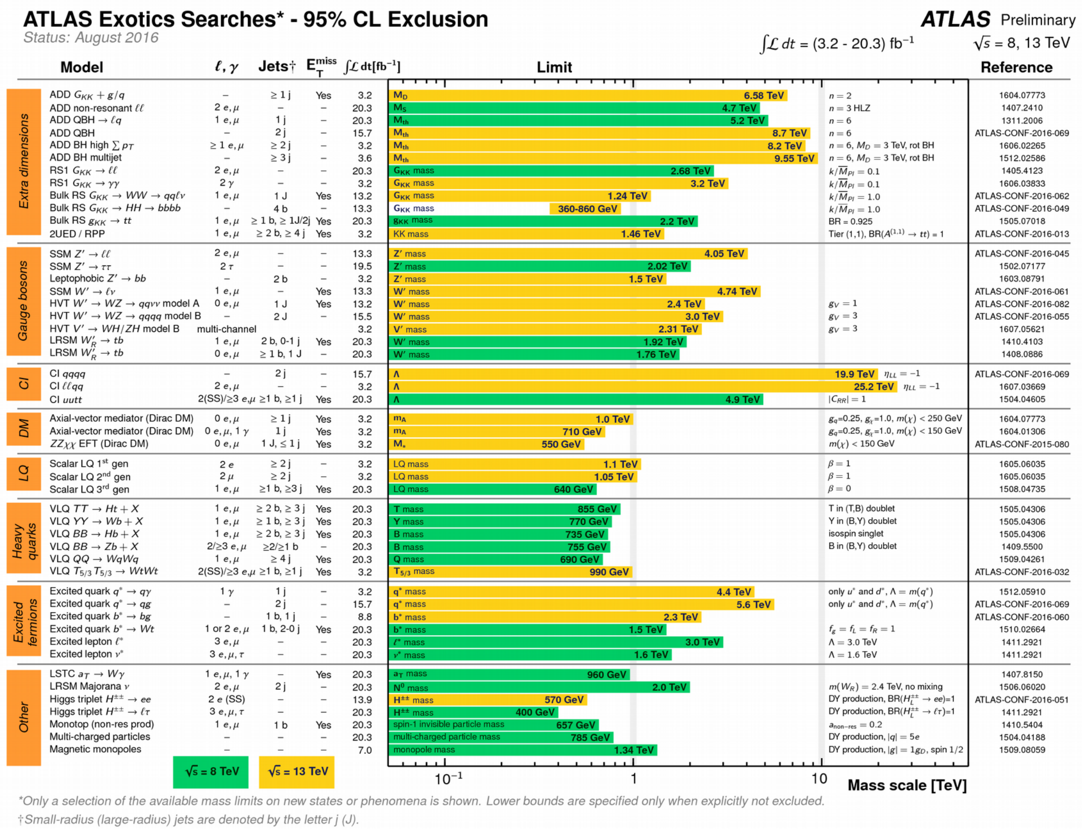
N_{leptons}	OSSF	Kinematic Variable	CR-veto
3	on-Z	M_{T}	$E_{\text{T}}^{\text{miss}} > 100\,\text{GeV}$
	above-Z	$L_{\text{T}} + E_{\text{T}}^{\text{miss}}$	-
	below-Z	$L_{\text{T}} + E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 50\,\text{GeV}$
	none	$L_{\text{T}} + E_{\text{T}}^{\text{miss}}$	-
≥ 4	1 pair	$L_{\text{T}} + E_{\text{T}}^{\text{miss}}$	-
	2 pairs	$L_{\text{T}} + E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 50\,\text{GeV}$ if on-Z

L_T = scalar sum of all lepton pT

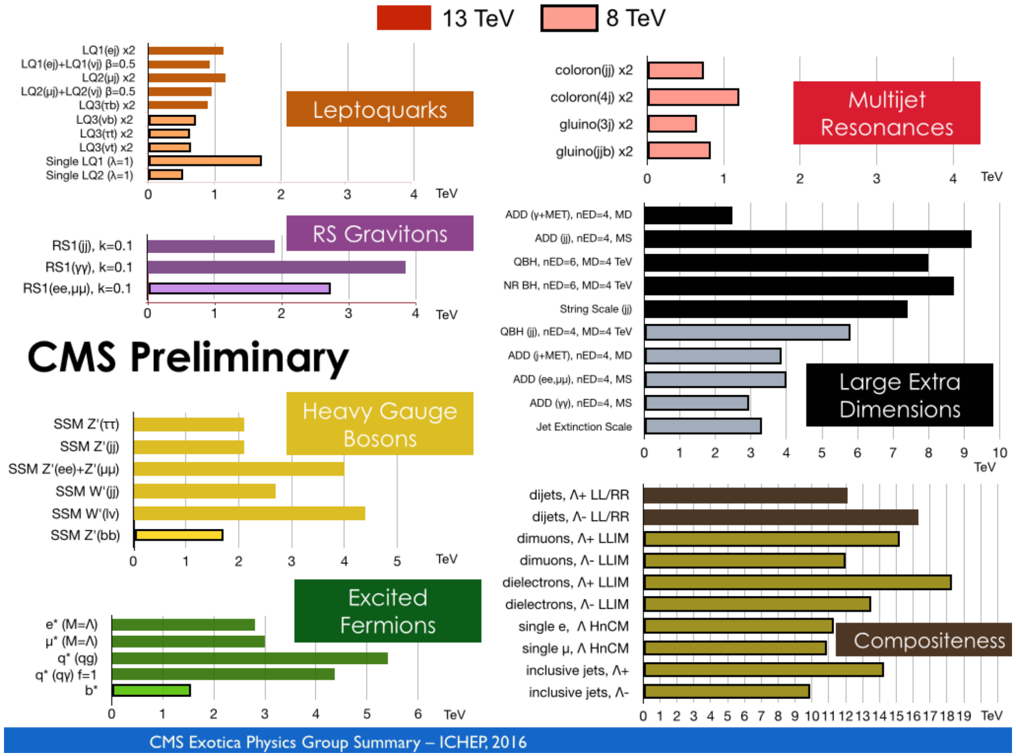
OSSF = opposite-sign same flavour



LHC exotics at a glance



*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.
†Small-radius (large-radius) jets are denoted by the letter j (J).



See the links below for more summary plots!

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#ATLAS_Exotics_Summary

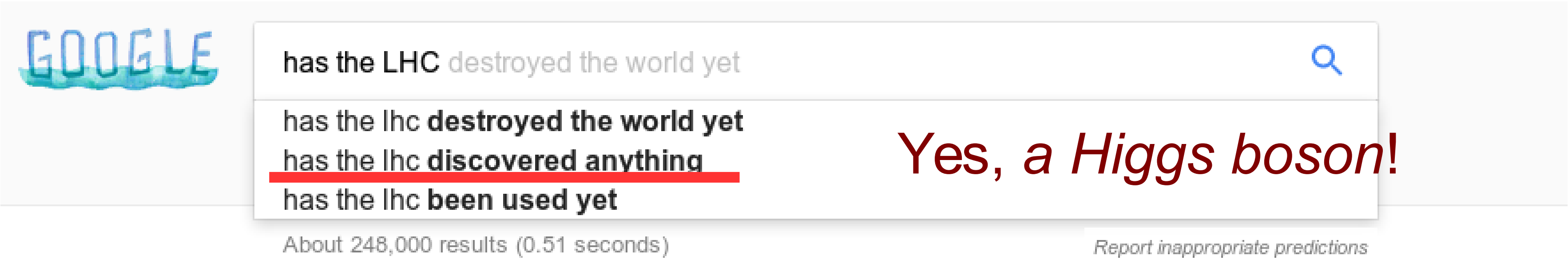
http://cms-results.web.cern.ch/cms-results/public-results/publications/

Summary

- Only very few results could be presented here: there is a wealth of ATLAS and CMS results:

http://cms-results.web.cern.ch/cms-results/public-results/publications/

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



has the LHC destroyed the world yet

has the lhc **destroyed the world yet**

has the lhc **discovered anything**

has the lhc **been used yet**

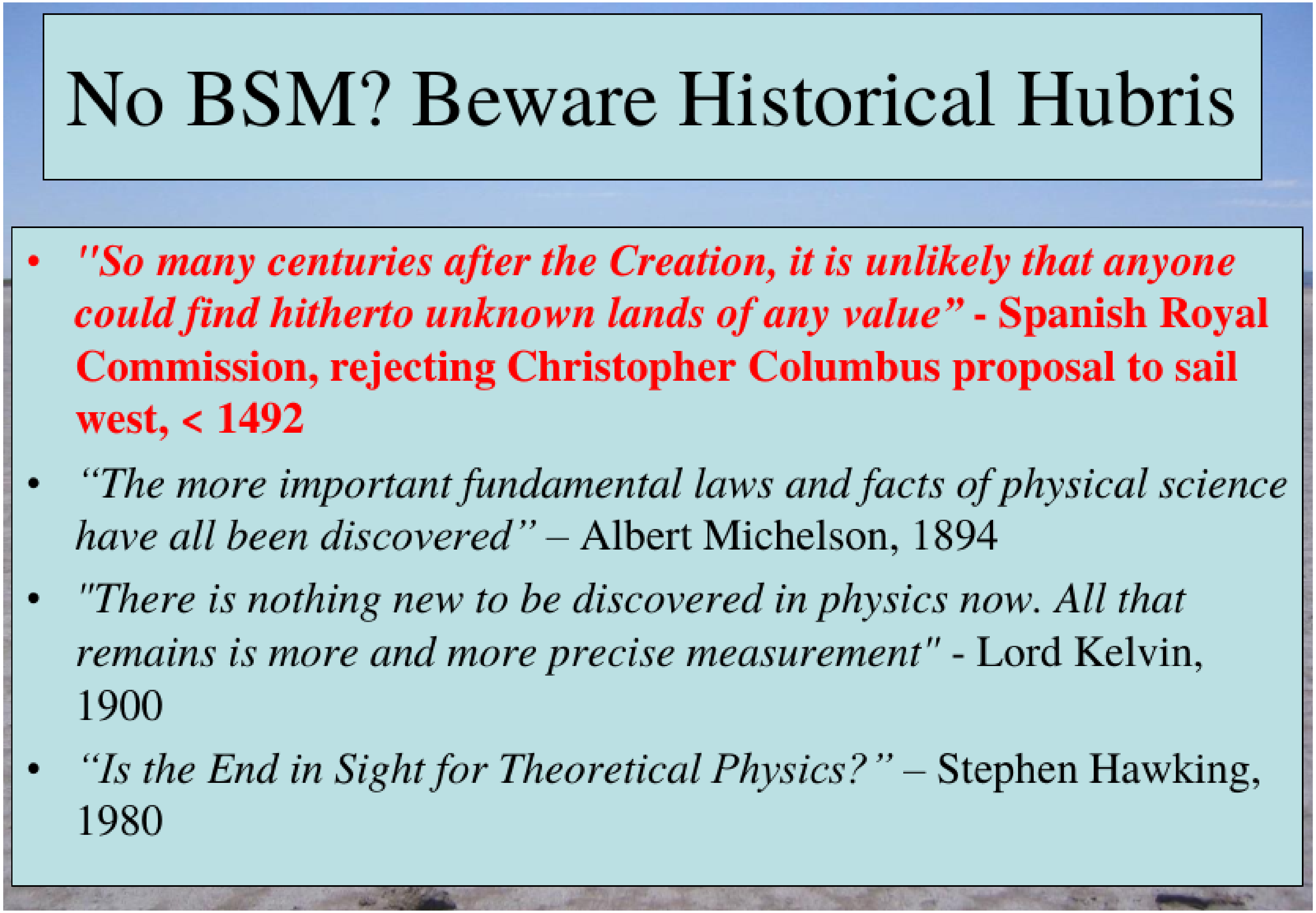
About 248,000 results (0.51 seconds)

Report inappropriate predictions

Yes, *a Higgs boson*!

No discovery *yet* beyond that, but do not rush into making conclusions!

Concluding remark



No BSM? Beware Historical Hubris

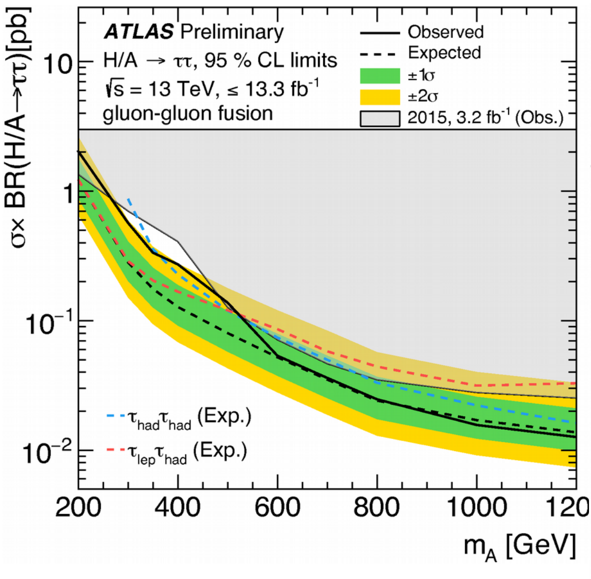
- ***"So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value"* - Spanish Royal Commission, rejecting Christopher Columbus proposal to sail west, < 1492**
- *"The more important fundamental laws and facts of physical science have all been discovered"* – Albert Michelson, 1894
- *"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"* - Lord Kelvin, 1900
- *"Is the End in Sight for Theoretical Physics?"* – Stephen Hawking, 1980

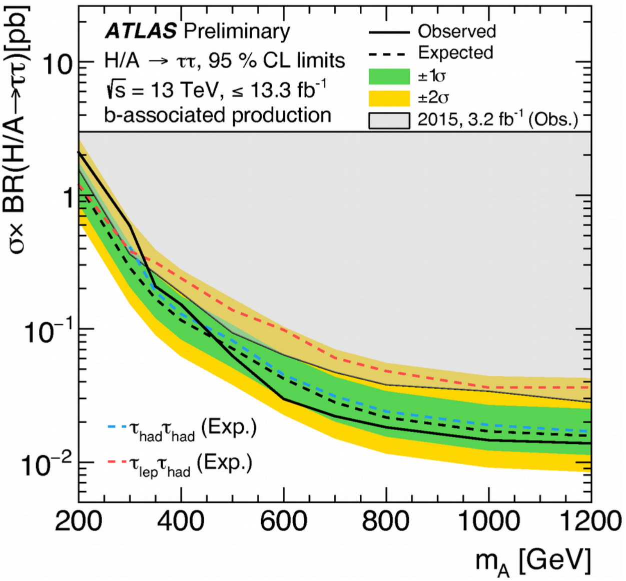
From the theory summary talk in LHCP 2014 by J. Ellis

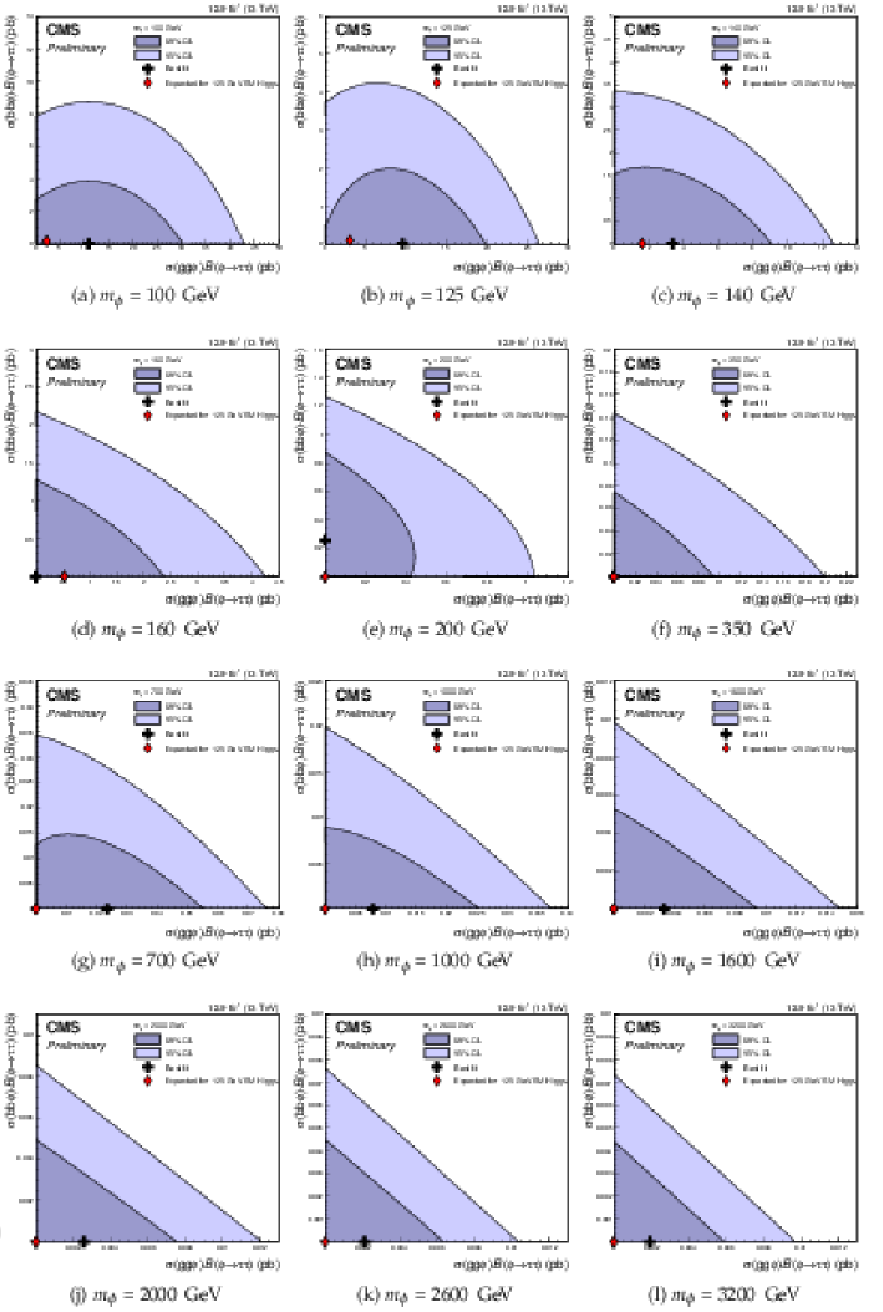
Additional slides

More on MSSM ττ result

Likelihood scan and cross section limits



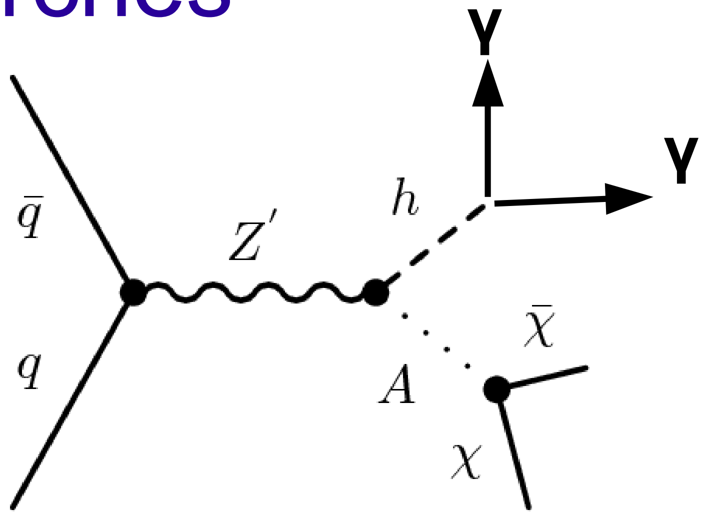




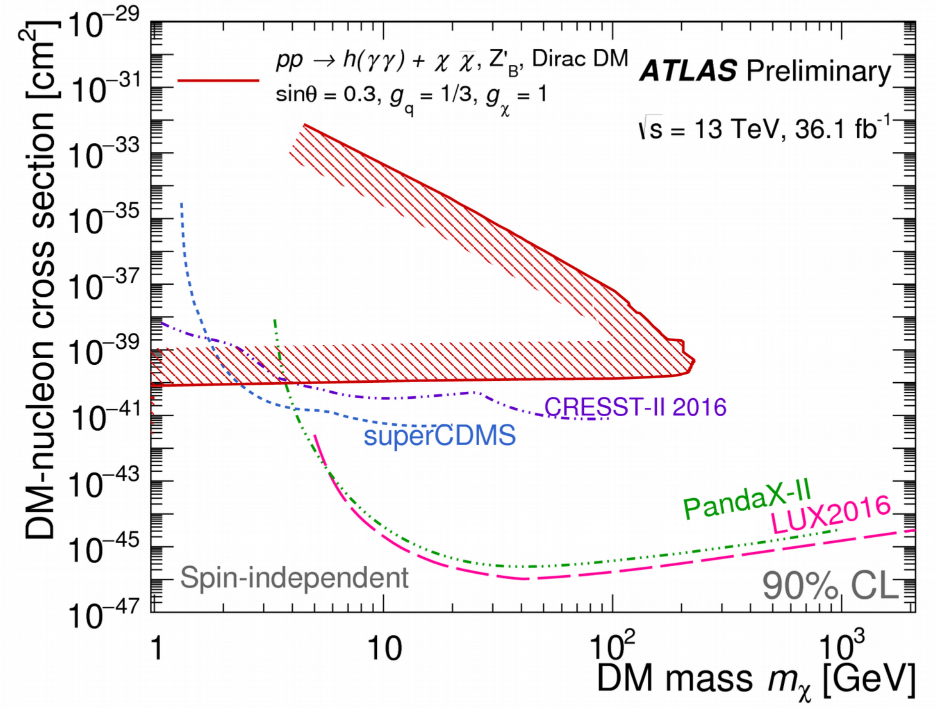
(a) m_ϕ = 100 GeV
(b) m_ϕ = 125 GeV
(c) m_ϕ = 140 GeV
(d) m_ϕ = 160 GeV
(e) m_ϕ = 200 GeV
(f) m_ϕ = 350 GeV
(g) m_ϕ = 700 GeV
(h) m_ϕ = 1000 GeV
(i) m_ϕ = 1600 GeV
(j) m_ϕ = 2000 GeV
(k) m_ϕ = 2600 GeV
(l) m_ϕ = 3200 GeV

Dark matter searches

- Dark matter produced in association with a Higgs boson



Interpretation in a Z'-2HDM scenario



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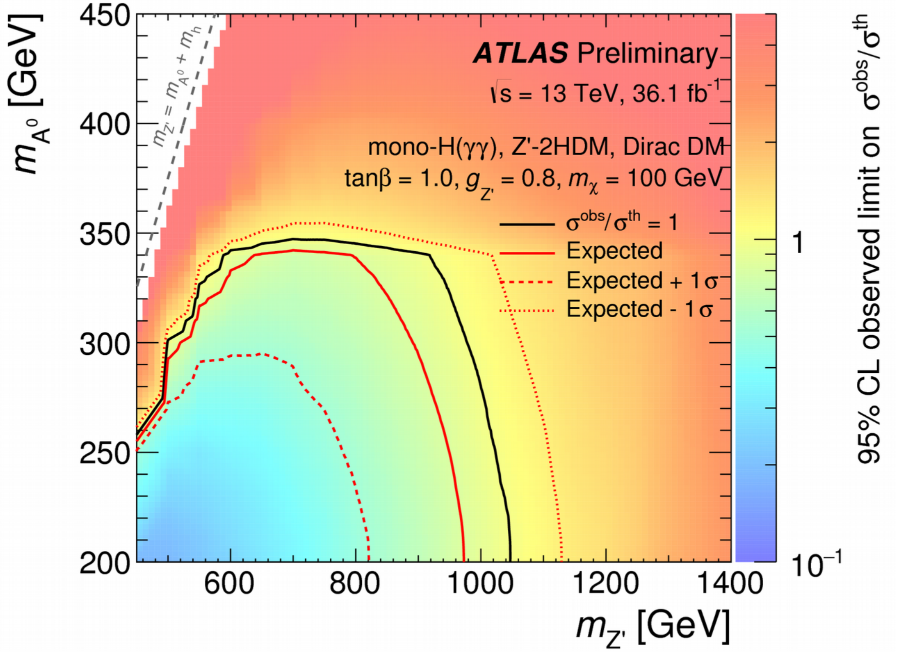
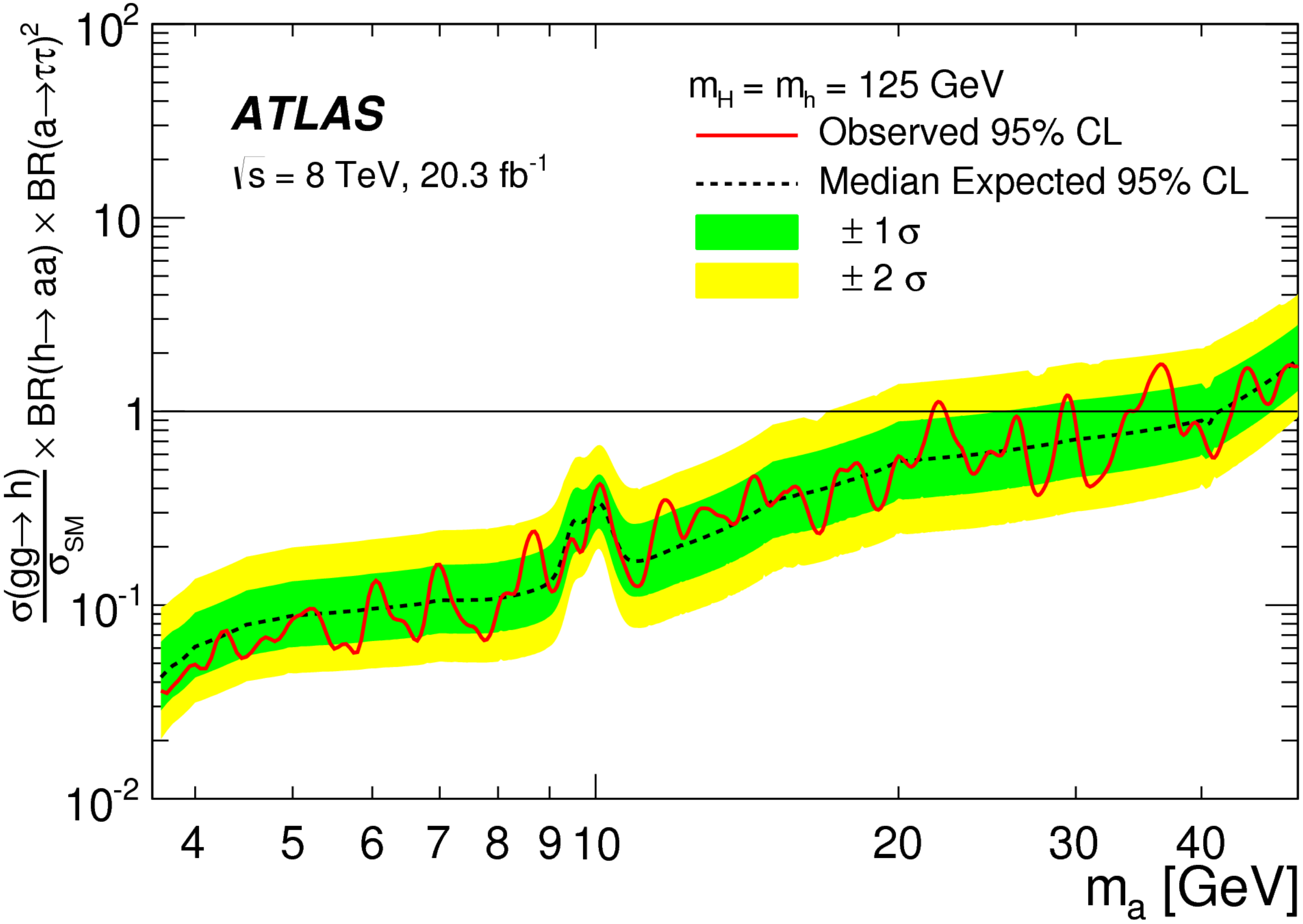


ATLAS Run-I h→aa→ μμττ result



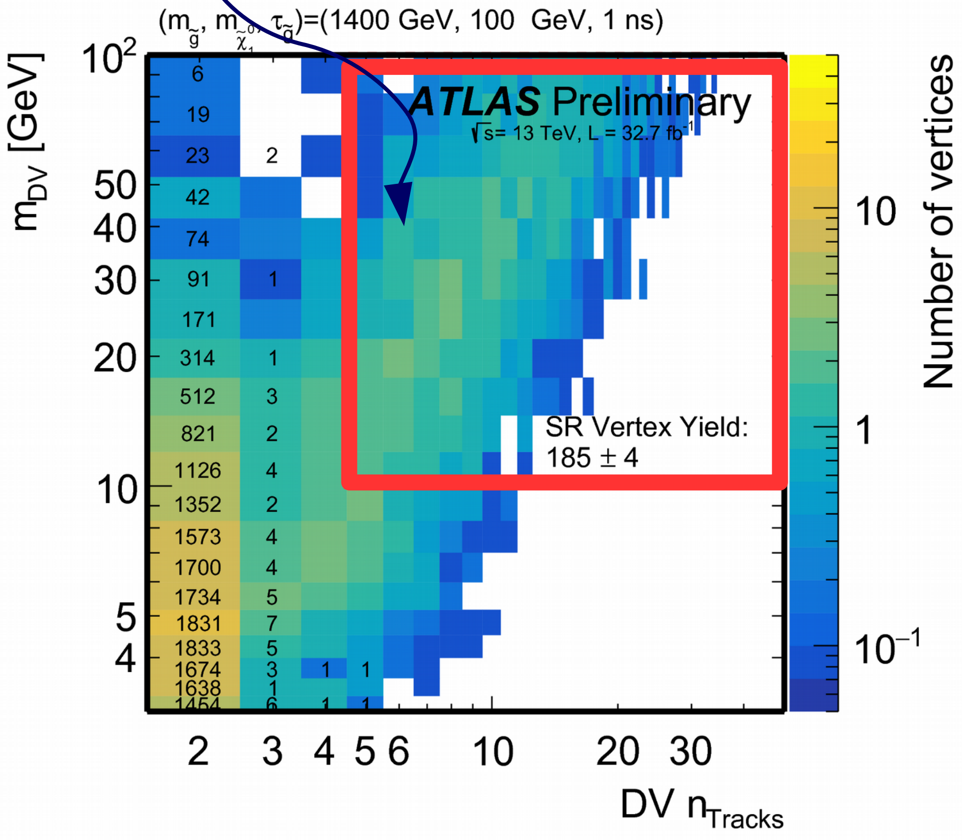
arXiv:1505.01609

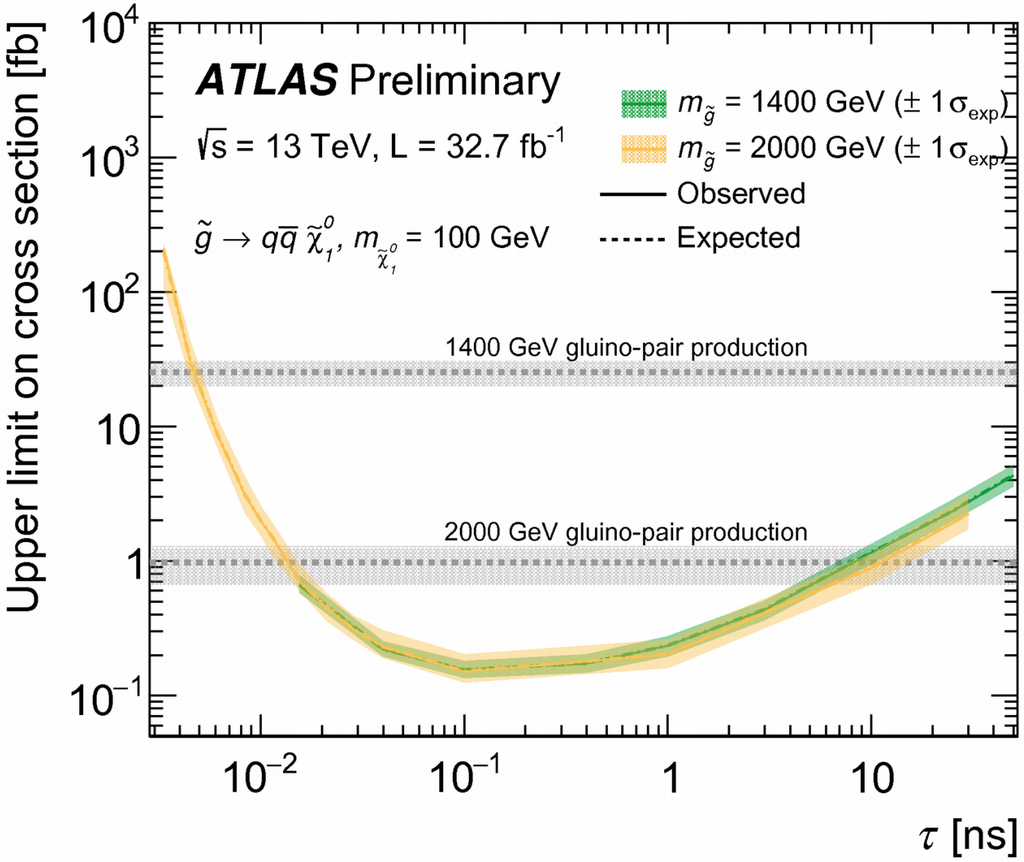
Long-Lived particles

ATLAS-CONF-2017-026

Color code: example of signal

Signal region





Observed data events with numbers