

Run 1 Searches for Beyond-SM Physics with the ATLAS Detector

Andy Haas (NYU)

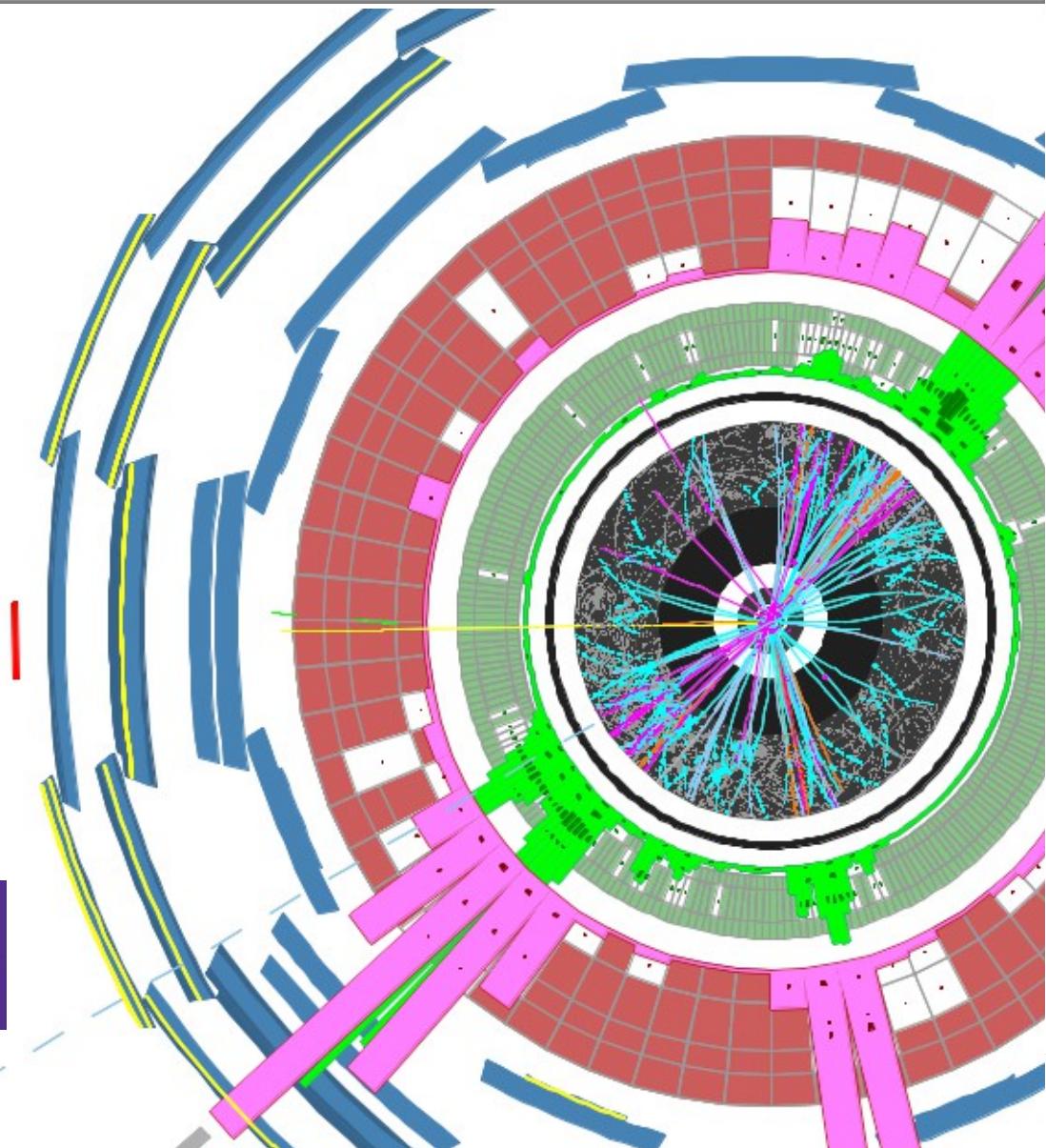
CERN PH LHC Seminar

April 21, 2015

<https://indico.cern.ch/event/360244/>

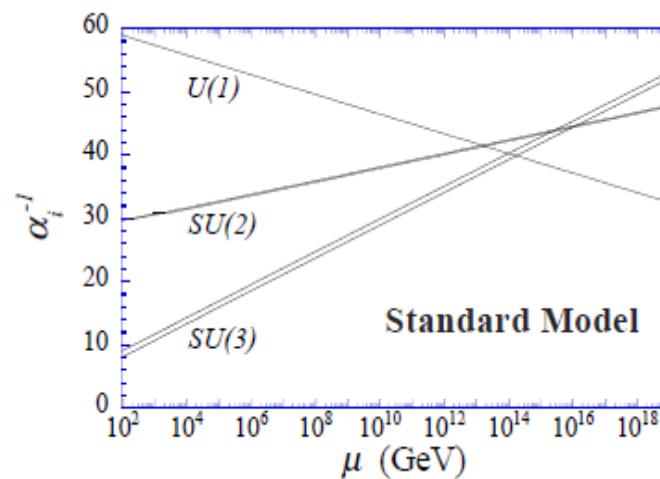
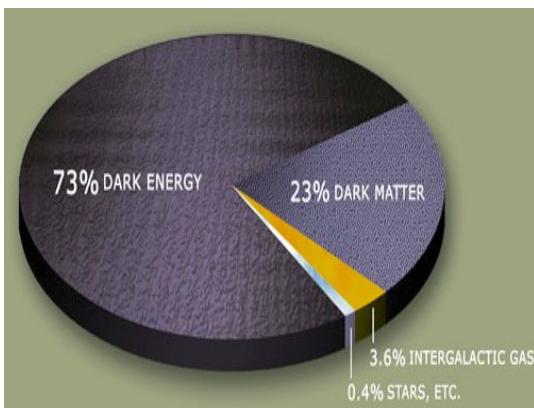


NEW YORK UNIVERSITY



Why Beyond-SM?

- SM was always considered just a “model”
 - low-energy approximation of the real “theory”
- BSM predictions nearly as old as SM itself!
- Some motivations for BSM at the EW scale
 - **Dark matter is WIMPs?**
 - **Gauge group unification?**
 - **Hierarchy problem?** (Assuming new physics at some high scale, fine tuning can be greatly reduced by BSM near the EW scale.)



1964: Higgs mechanism
 1967: SM formulated
 1971: SM renormalizable
 1973: Neutral currents found
 1974: Charm quark found
1974: SUSY predicted
 1983: W/Z found
 1995: Top quark found
 2012: Higgs found
2017: SUSY found?

QUARKS		GAUGE BOSONS	
mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$
charge →	2/3	2/3	0
spin →	1/2	1/2	1
up	c	t	g
down	charm	top	gluon
d	s	b	γ
strange	bottom	photon	Z boson
e	μ	τ	W boson
electron	muon	tau	
$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	
-1	-1	-1	
1/2	1/2	1/2	
electron neutrino	ν_μ	ν_τ	
$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<15.5 \text{ MeV}/c^2$	
0	0	0	
1/2	1/2	1/2	
muon neutrino	ν_τ	tau neutrino	
$80.4 \text{ GeV}/c^2$			
± 1			
1			
W			
Higgs boson			

Overview of BSM Searches

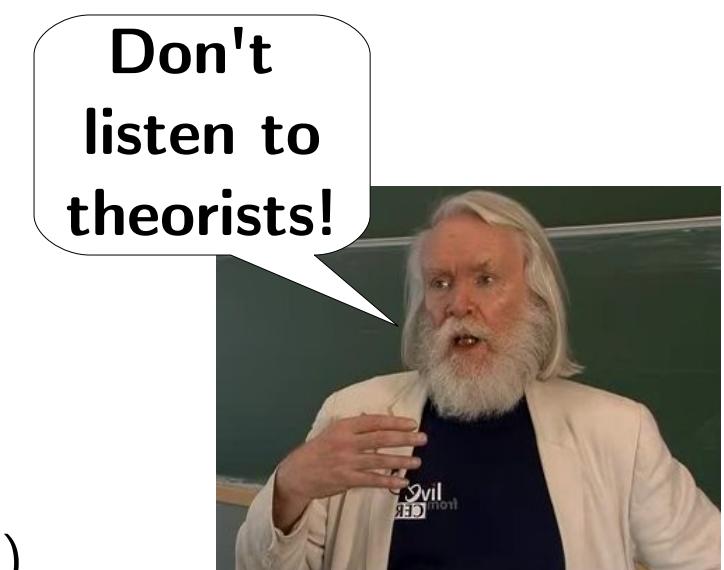
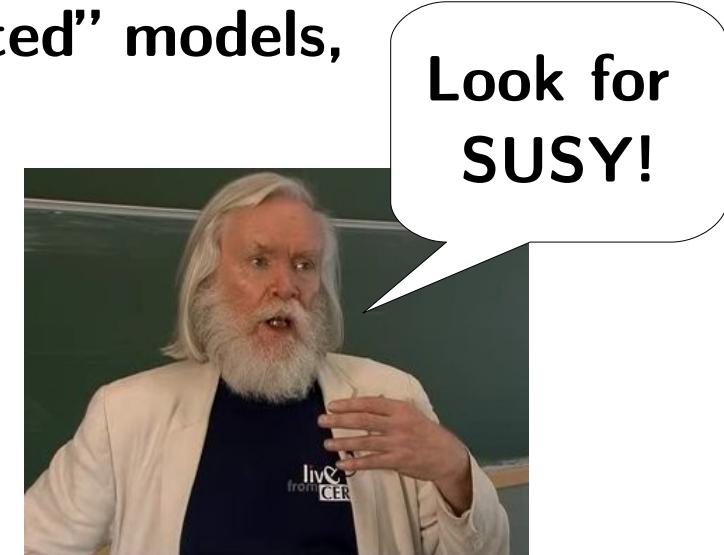
- Driven by some particularly “well-motivated” models, but also casting a wide net!
- Naturalness – solving the hierarchy problem
 - Supersymmetry
 - Gluinos, stops, etc.
 - Electroweak-inos
 - New Higgs boson decays
 - Other Higgs bosons
 - Vector-like quarks (other top partners)
 - Large Extra Dimensions
- Hidden sectors



Look for
SUSY!

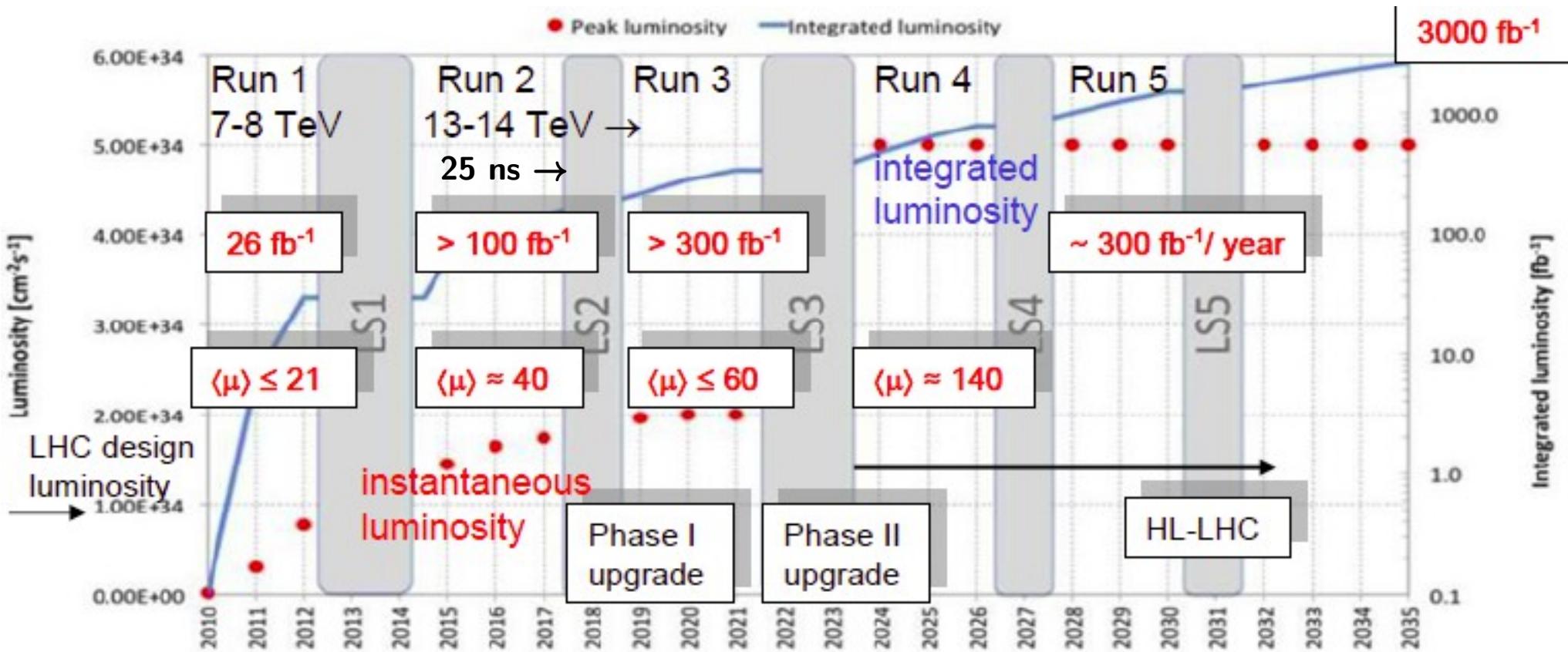
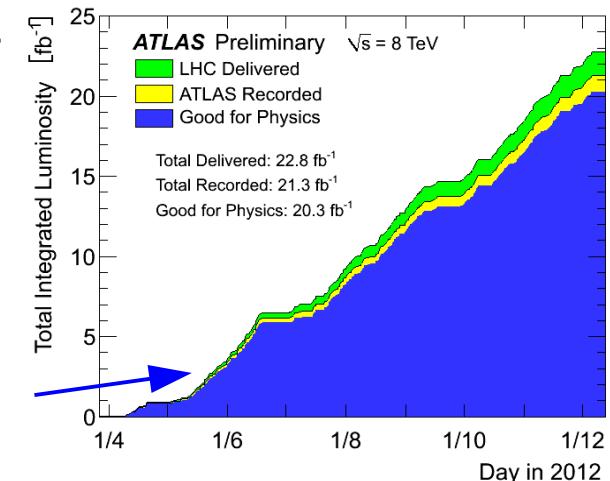
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- Naturalness – solving the hierarchy problem
 - Supersymmetry
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 - Large Extra Dimensions
- Hidden sectors
- Other – look everywhere you can!
 - Exotic new particles
 - General search for discrepancy with SM (in 697 final-states, for N_{event} , M_{eff} , M_{inv} , MET)



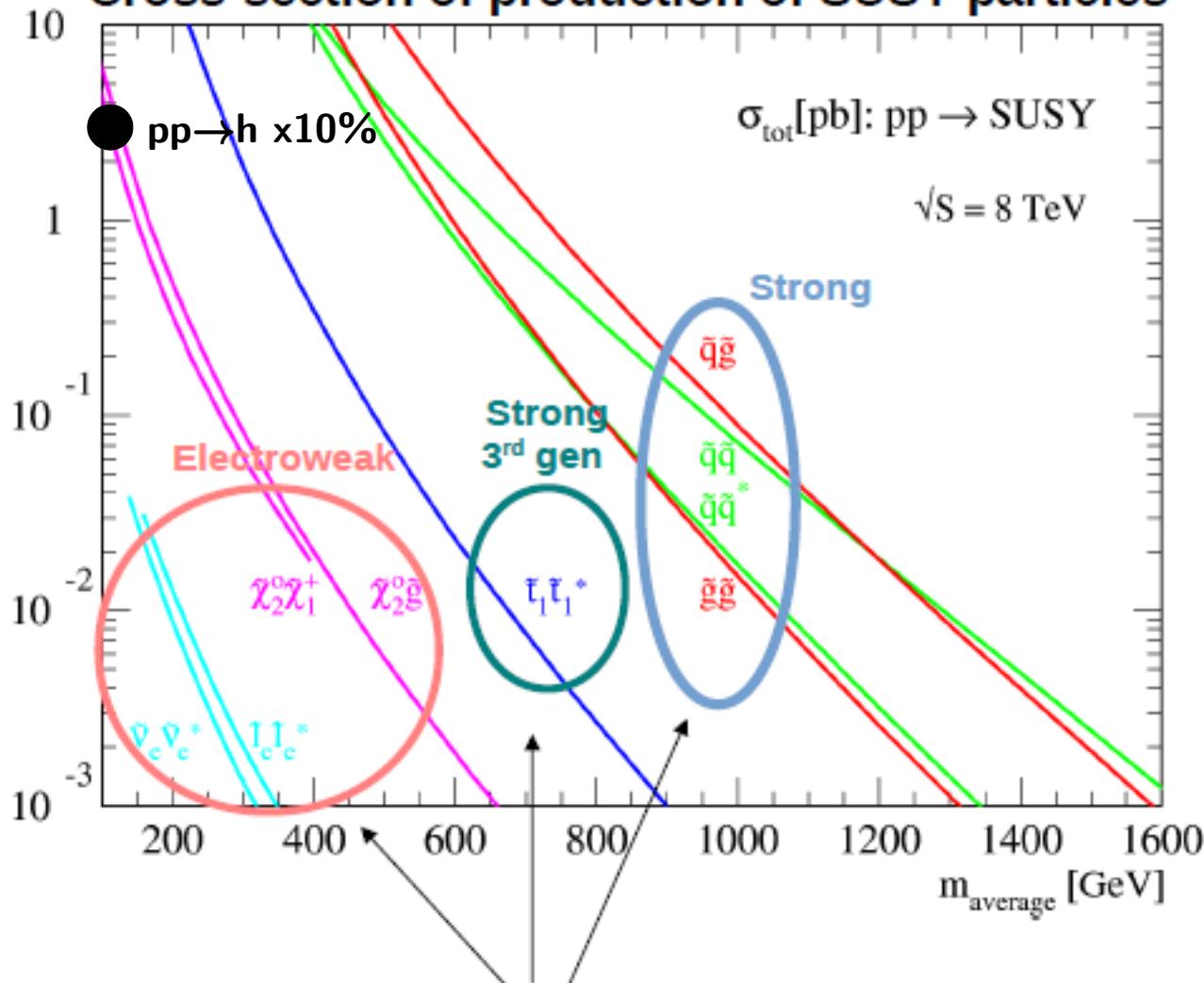
LHC Run 1

- pp collisions in 2010 – 2012 at 50ns spacing
- 7 TeV in 2010, 2011: 45/pb, 5.1/fb
- 8 TeV in 2012: 21.3/fb
 - Excellent data quality → 20.3/fb good!

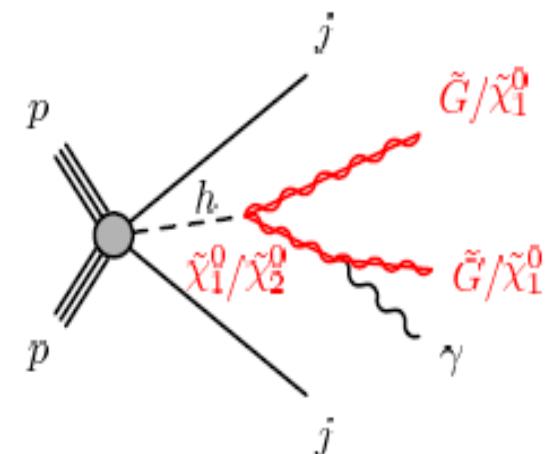


SUSY Production

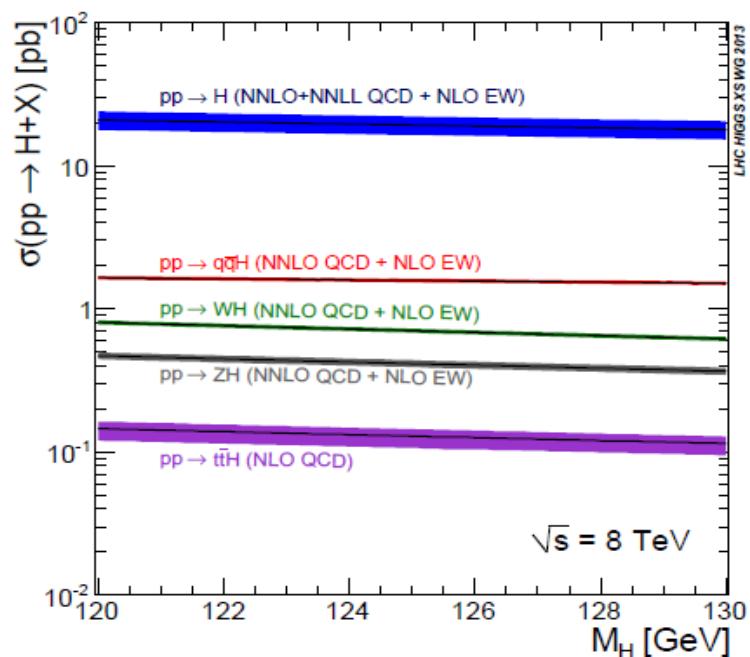
Cross-section of production of SUSY particles



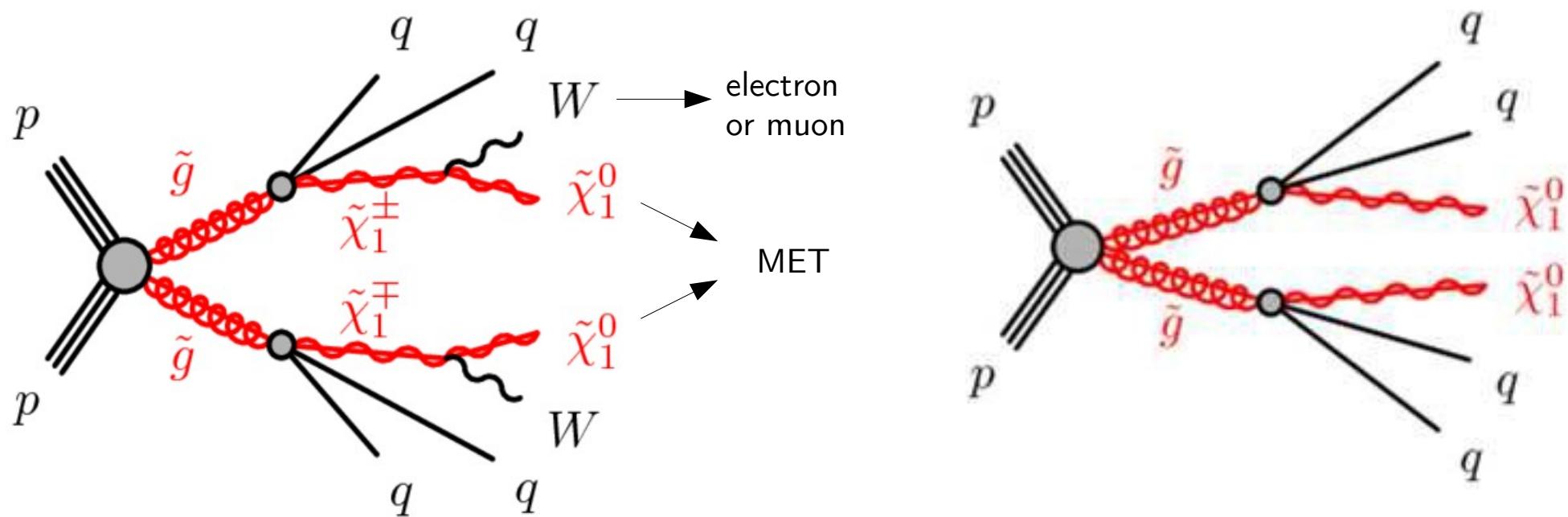
Search strategies developed by ATLAS target all these SUSY production modes



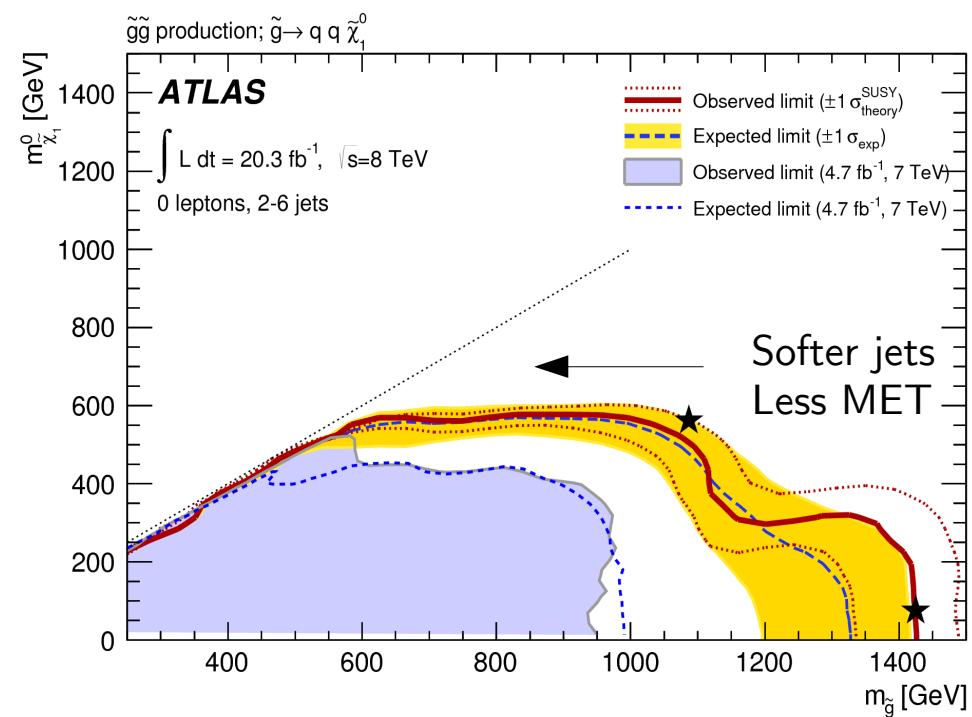
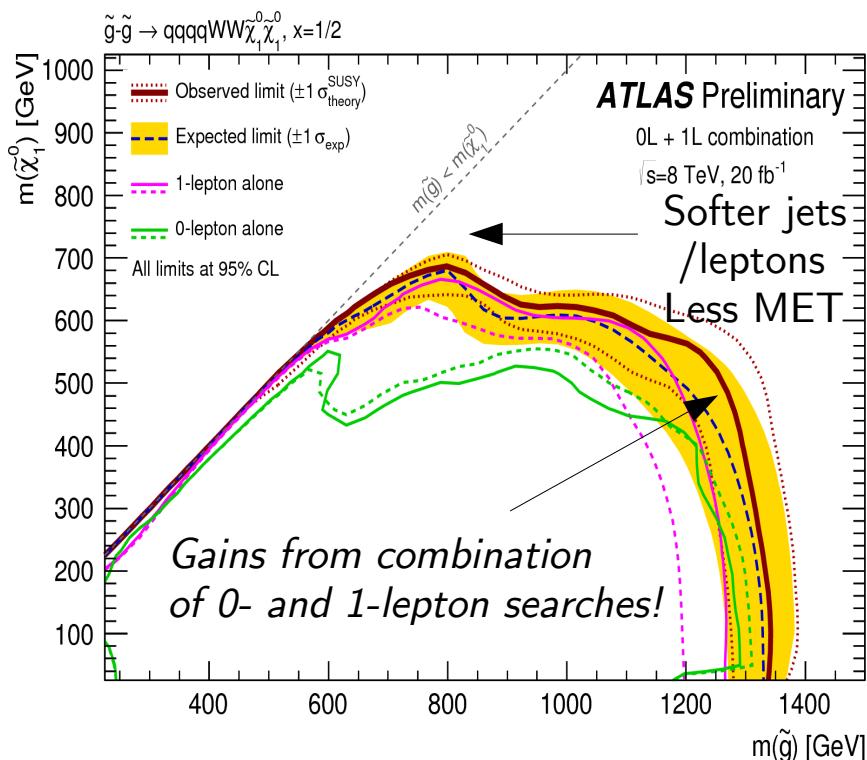
Also consider Higgs \rightarrow SUSY



- Gluinos are pair-produced, decay (promptly?) to **jets+MET** or...
 - possibly to jets+W+MET if chargino is available
jets+lepton(s)+MET
 - possibly to ttbar+MET if stop is lighter than other squarks
lepton(s), same-sign leptons, and/or b-jets+MET
- We often consider “*simplified models*”, just one main decay at a time
→ reality may have multiple competing decay channels...



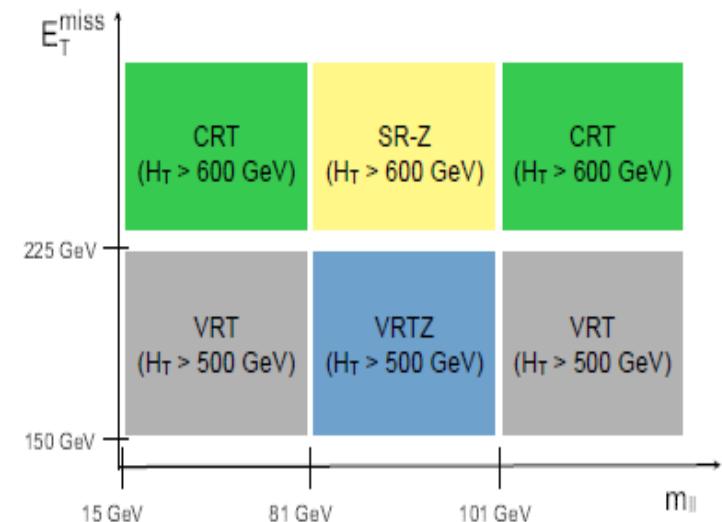
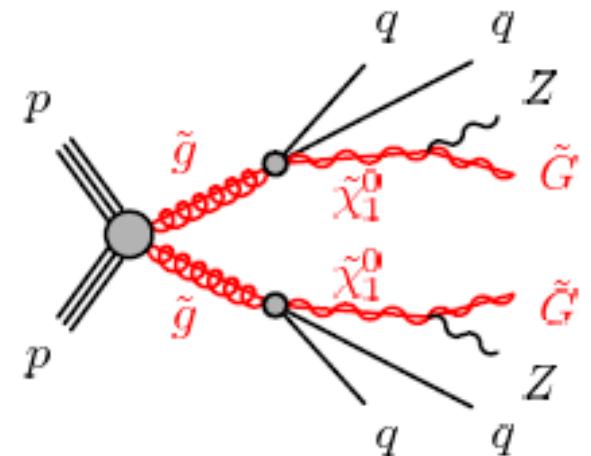
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lepton(s), same-sign leptons, and/or b-jets+MET
- Limits on gluino mass depend on decays and other sparticle masses*



Search for SUSY with 2l+jets+MET

arXiv:1503.03290

- Various decay chains can give 2l+jets+MET
- Look at events with a $Z \rightarrow l\bar{l}$ candidate
- $\text{MET} > 225\text{GeV}$ and $H_T > 600\text{GeV}$
(H_T is the sum of the jets' and leptons' pT)
- Main background ($t\bar{t}$) estimated from data using $e\mu$ events with the same cuts as the SR, cross checked using Z side-bands

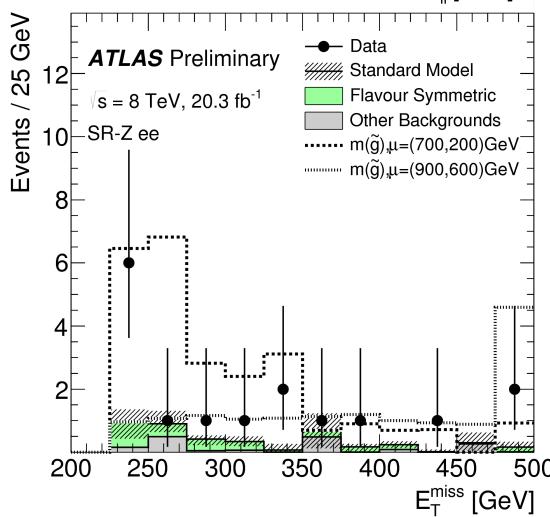
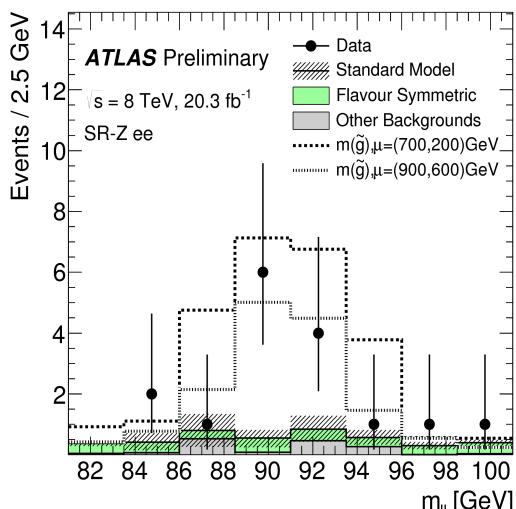


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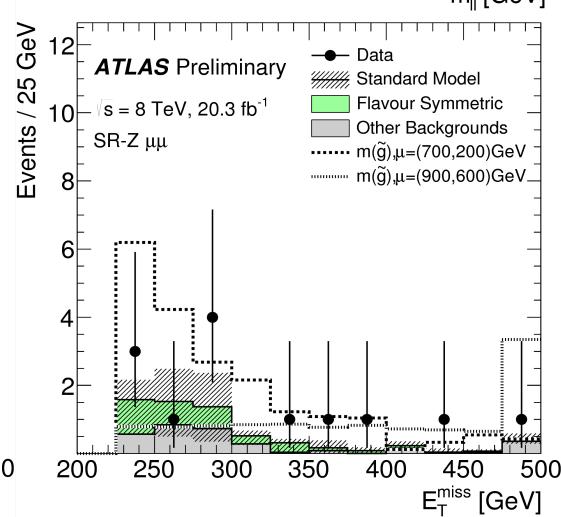
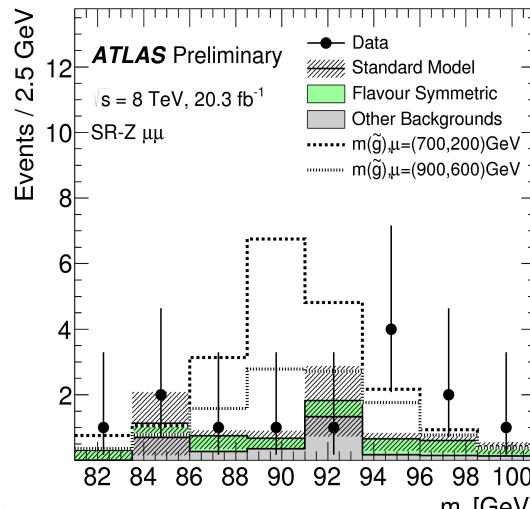
Electron

Data: 16
Bkgd: 4.2 ± 1.6
p-value: 3.0σ

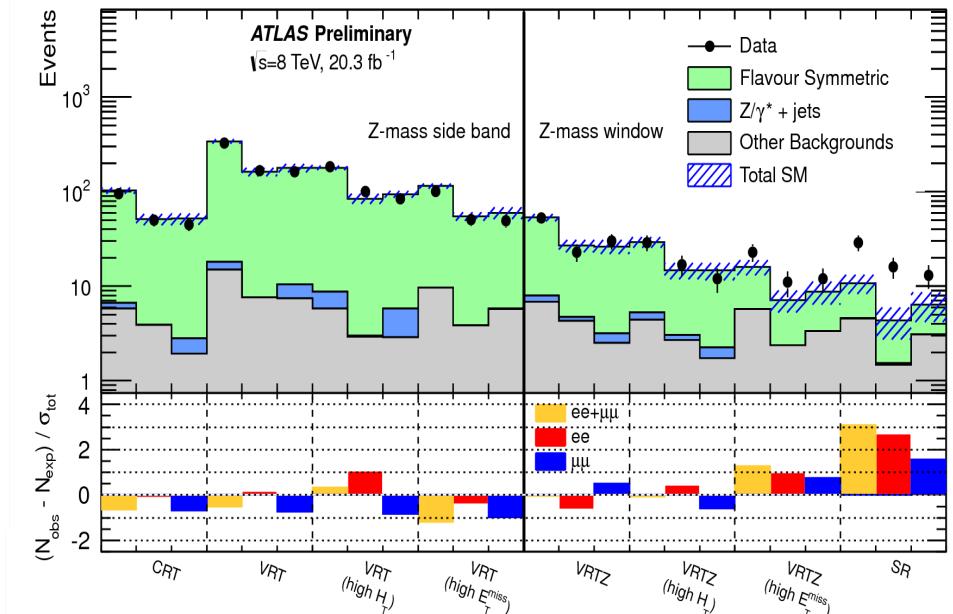


Muon

Data: 13
Bkgd: 6.4 ± 2.2
p-value: 1.7σ



3.0σ combined



Several theory interpretations on the arXiv,
usually favoring sbottom, e.g. arXiv:1504.04390, ...

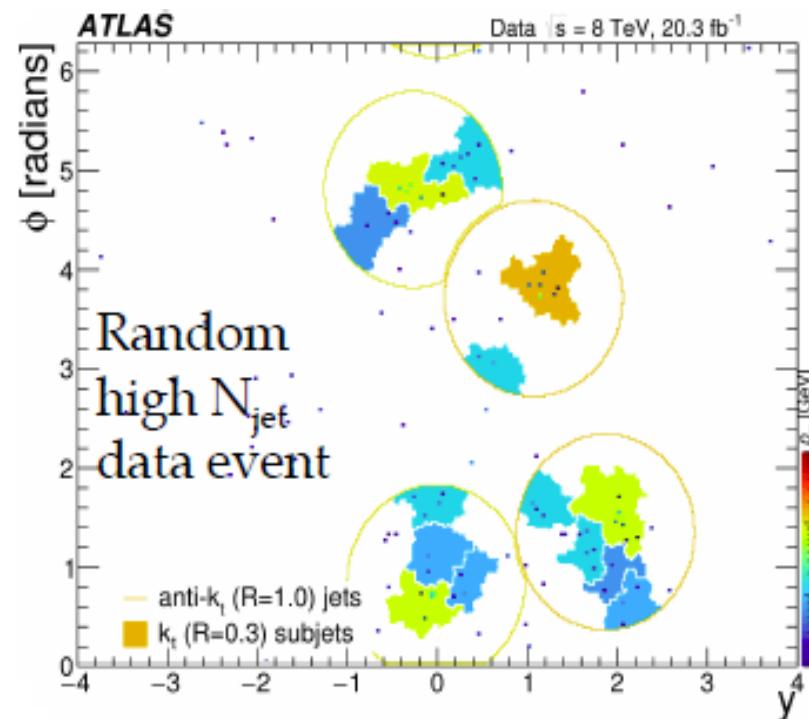
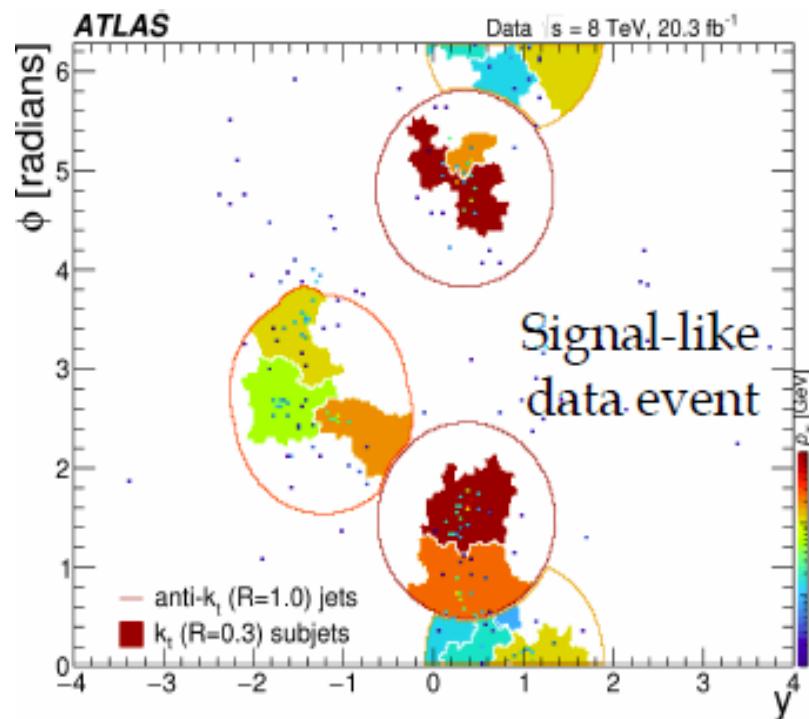
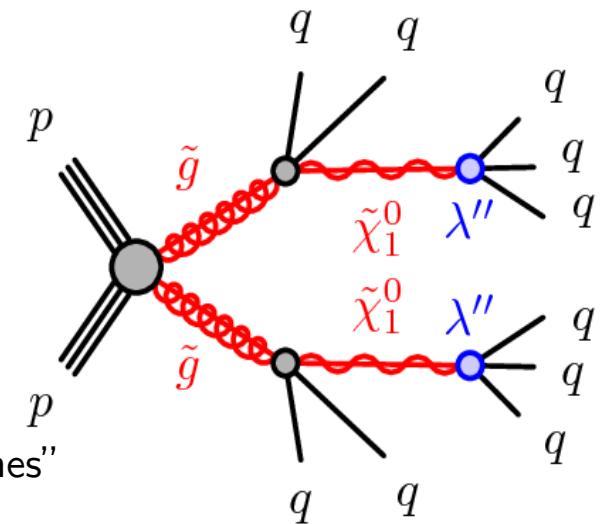
Follow up in Run 2

If LSP decays to jets (via R-parity-violation), **no MET**

Excess searched for with $\geq 6,7$ jets or large total (fat-)jet mass

New technique for data-driven QCD backgrounds!

"Jet Substructure Templates: Data-driven QCD Backgrounds for Fat Jet Searches"
JHEP 1405 (2014) 005, T. Cohen, et al.



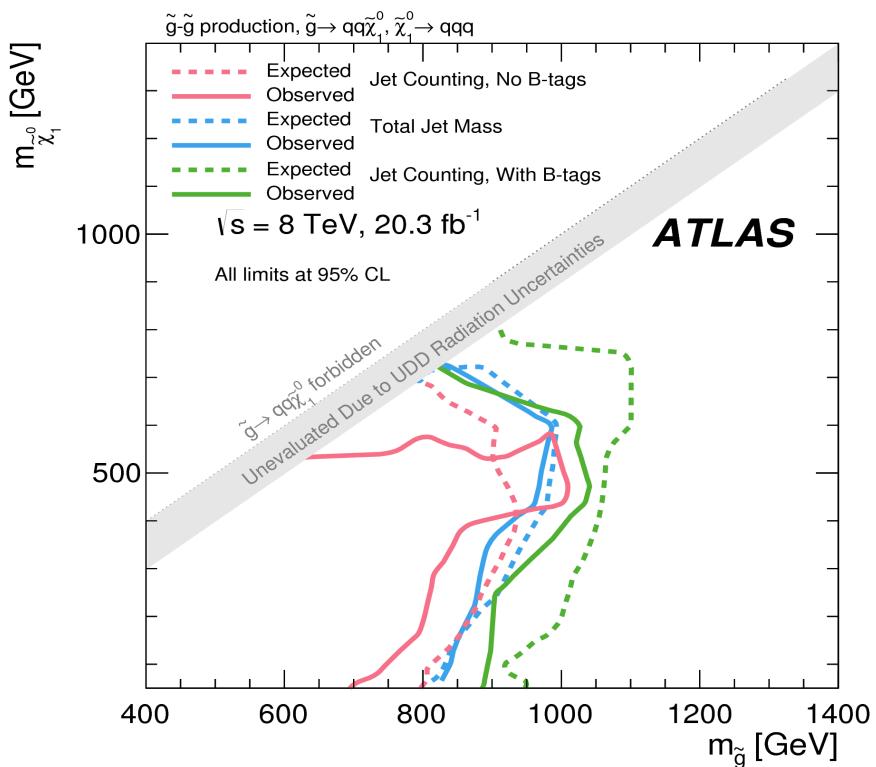
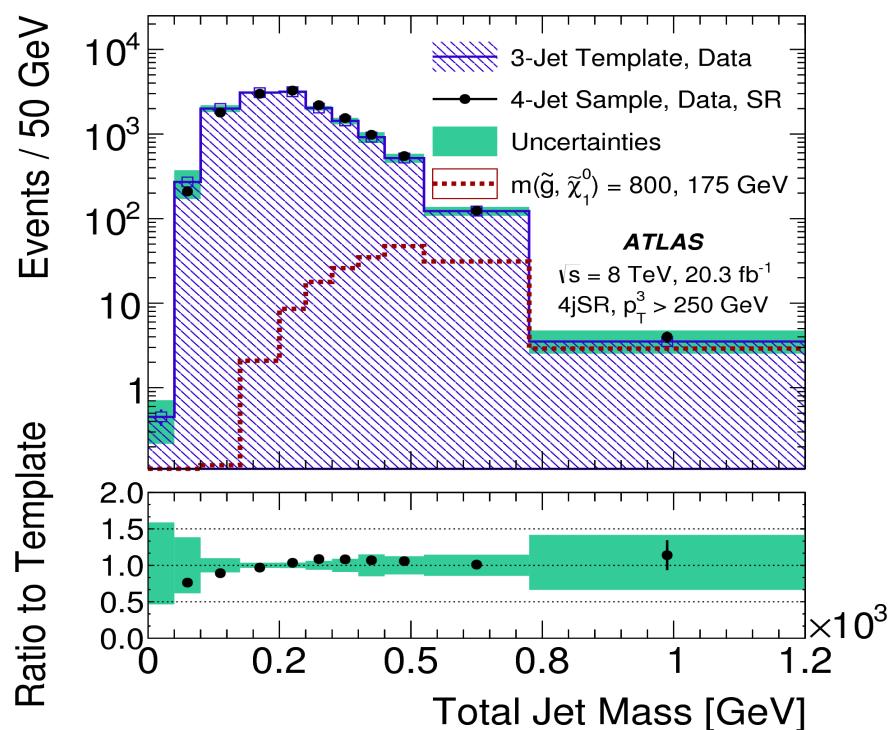
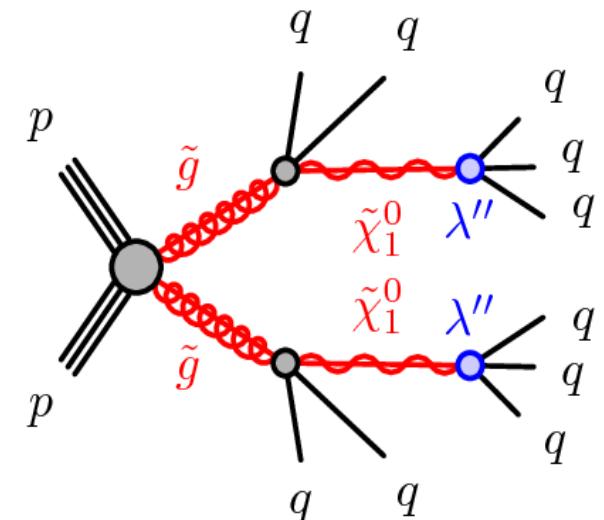
Gluino \rightarrow multi-jets

arXiv:1502.05686

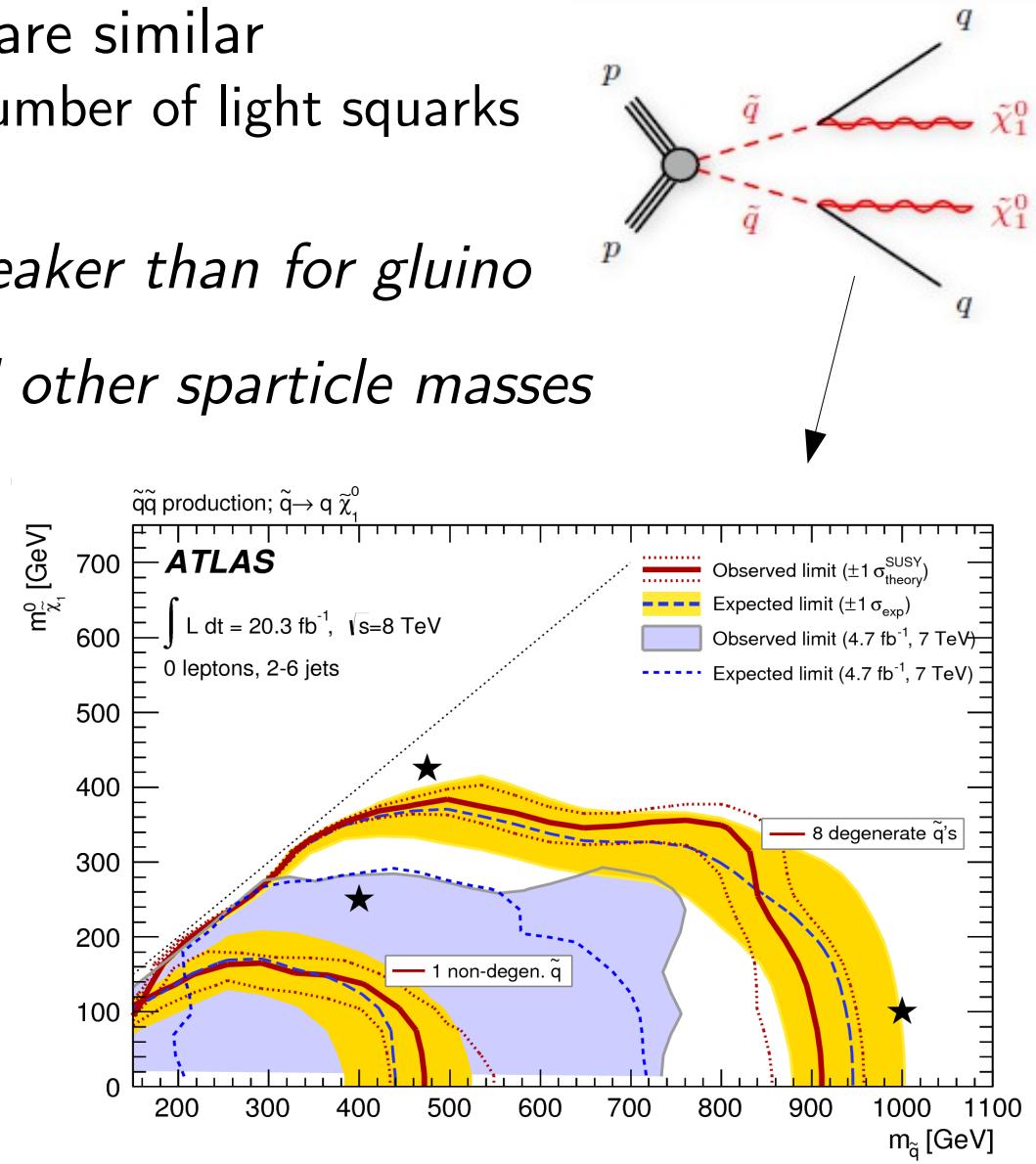
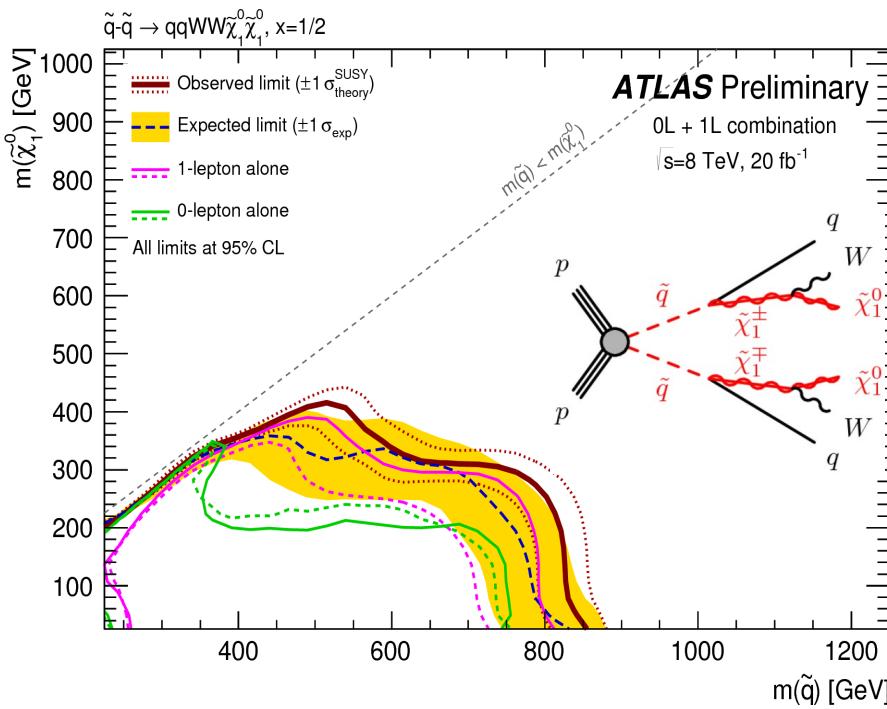
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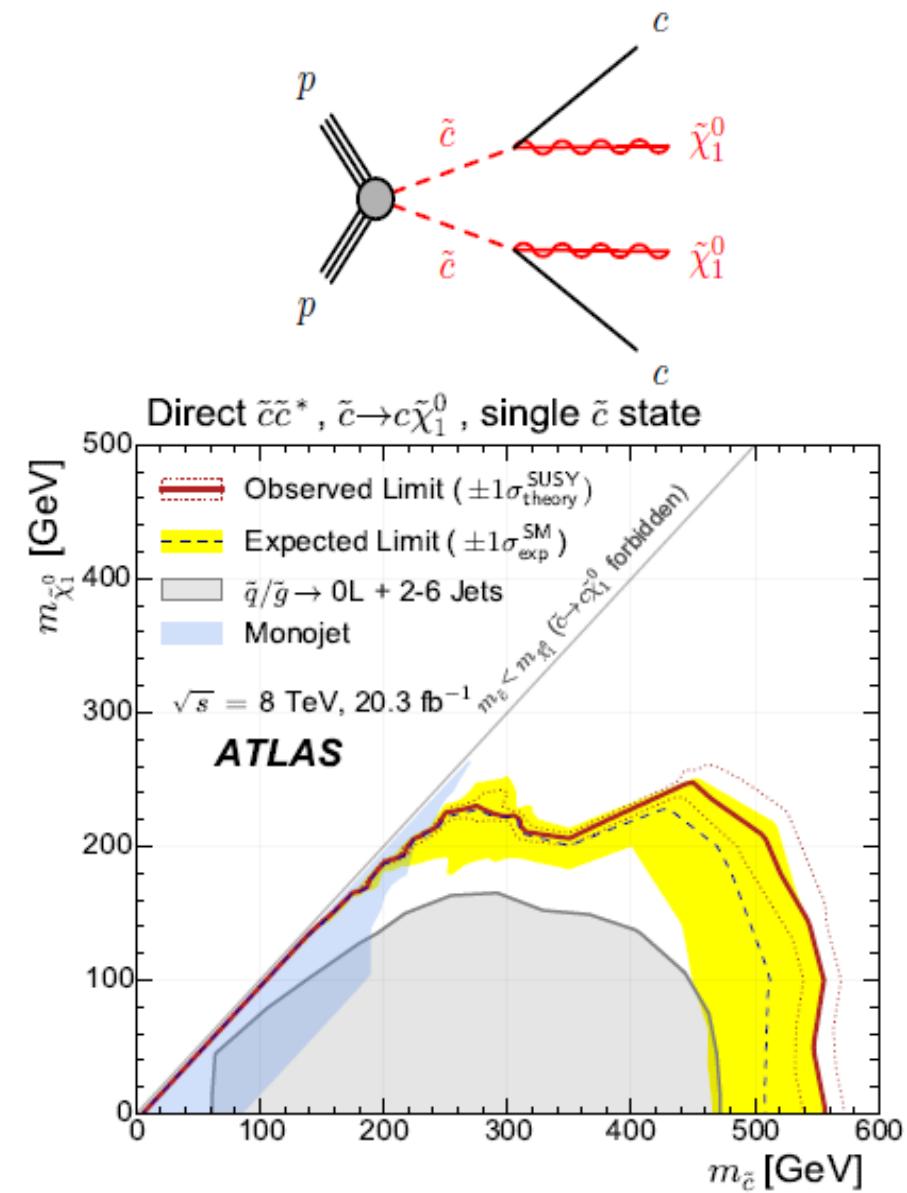
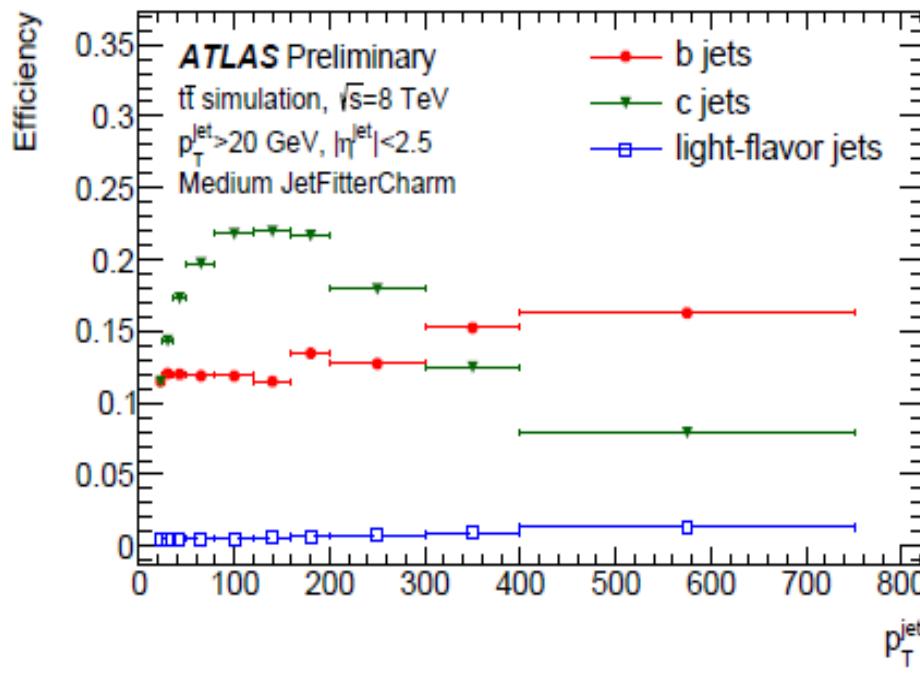
Gluino excluded up to ~ 900 GeV in this case!



- Squark production and decays are similar
 - Production rate depends on number of light squarks
- *Limits on squark masses are weaker than for gluino (lower prod. rate) and also depend on decays and other sparticle masses*



- Could also be a charm squark
- Use **charm tagging!**
 - Developed for this analysis
 - Rejects light jets and also b-jets



- ~ 100 GeV improvement in exclusion over inclusive \tilde{q}/\tilde{g} (grey)

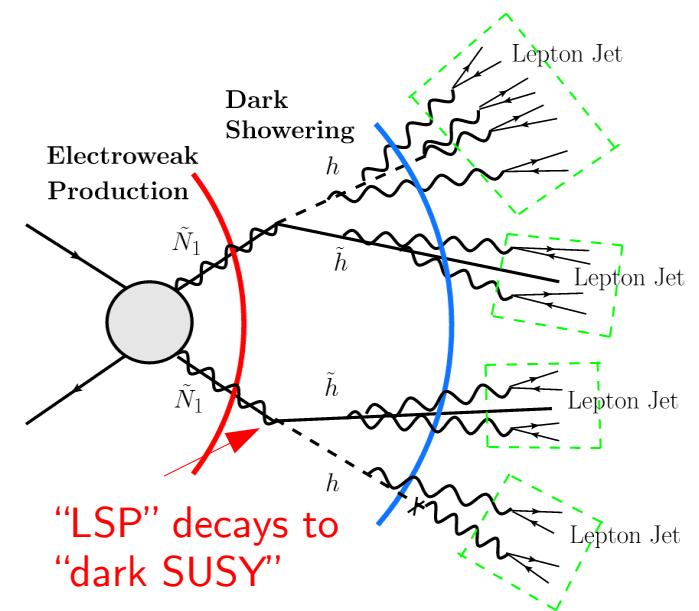
SUSY LSP Decays to “Lepton-Jets”

PLB 719, 299 (2013)

- Hidden-sector \rightarrow “dark photon” \rightarrow lepton jets: muon/electron jets
- **LSP may always decay to dark sector \rightarrow lepton-jets**
- Custom lepton-jet identification used to separate from QCD jets
- Searched for events with:
 - 2 prompt muon lepton-jets
 - 2 prompt electron lepton-jets
 - 1 prompt 4-muon lepton-jet
- No excess observed
- *Constrains squark-production up to \sim TeV and EW-production up to \sim 400 GeV*

	Electron LJ	1 Muon LJ	2 Muon LJ
Data	15	7	3
All background	15.2 ± 2.7	3.0 ± 1.0	0.5 ± 0.3

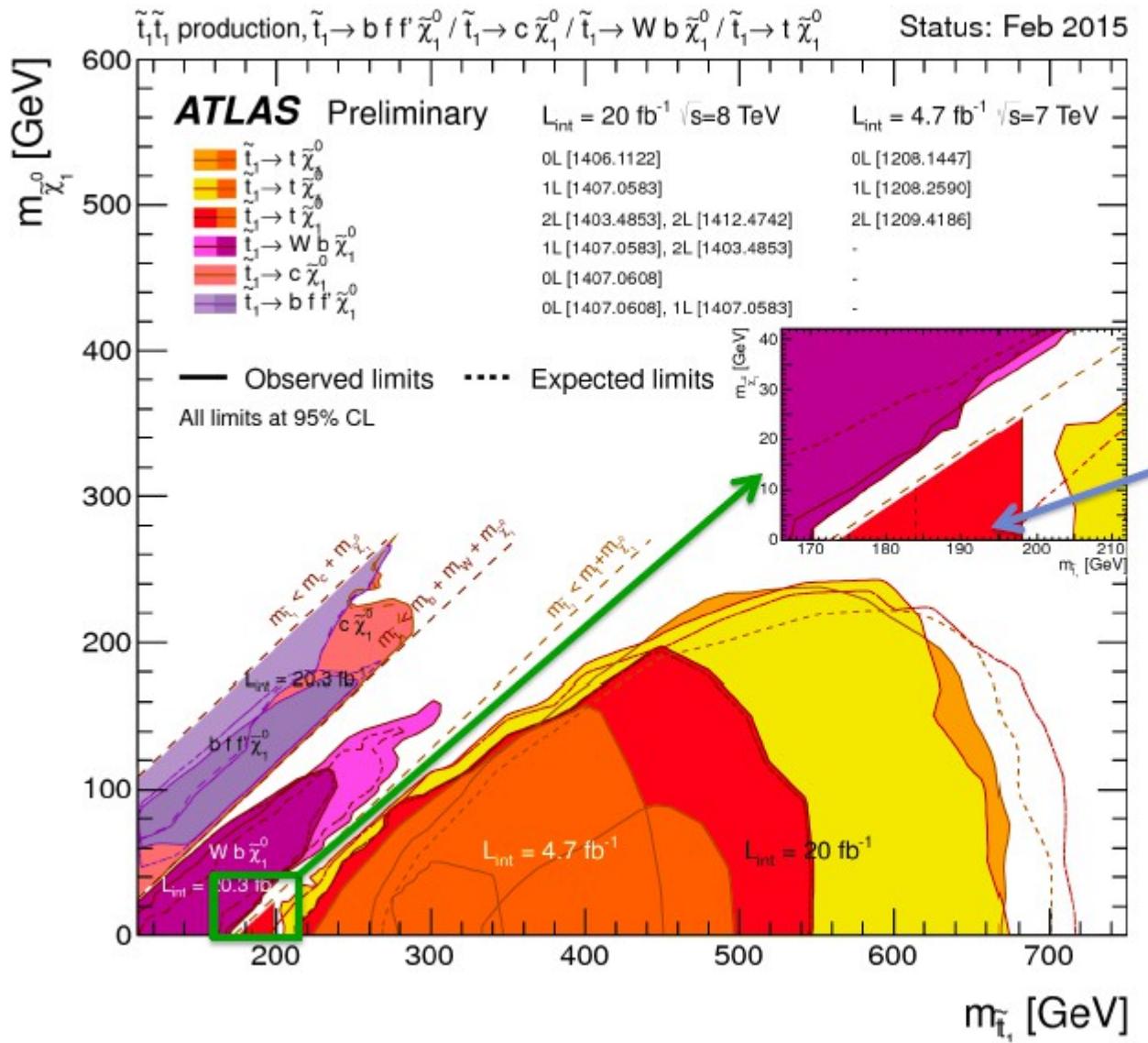
Jet prob bkgd method: 2.2 ± 0.9



arXiv:0909.0290, et. al

Stop Searches

- Stop is special for “naturalness” → directly cancels the top loop
- Search depends on stop mass and decay channels – broad program...



Filling up the **holes** with new ideas.

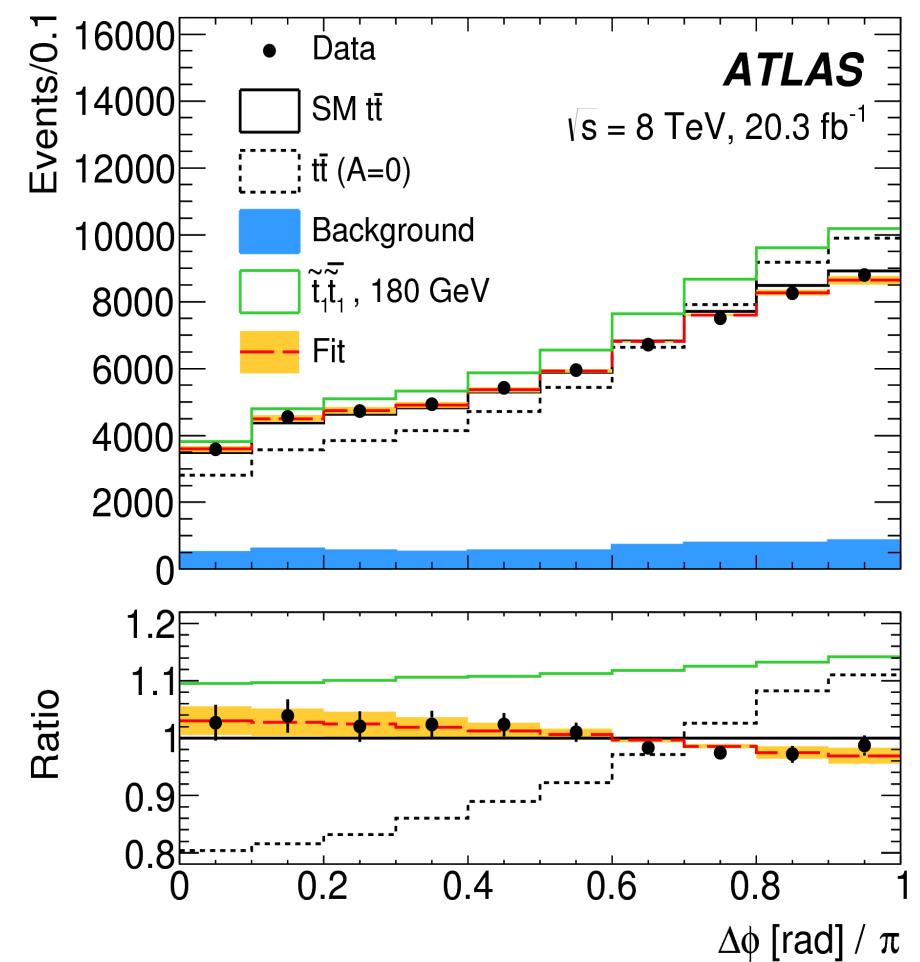
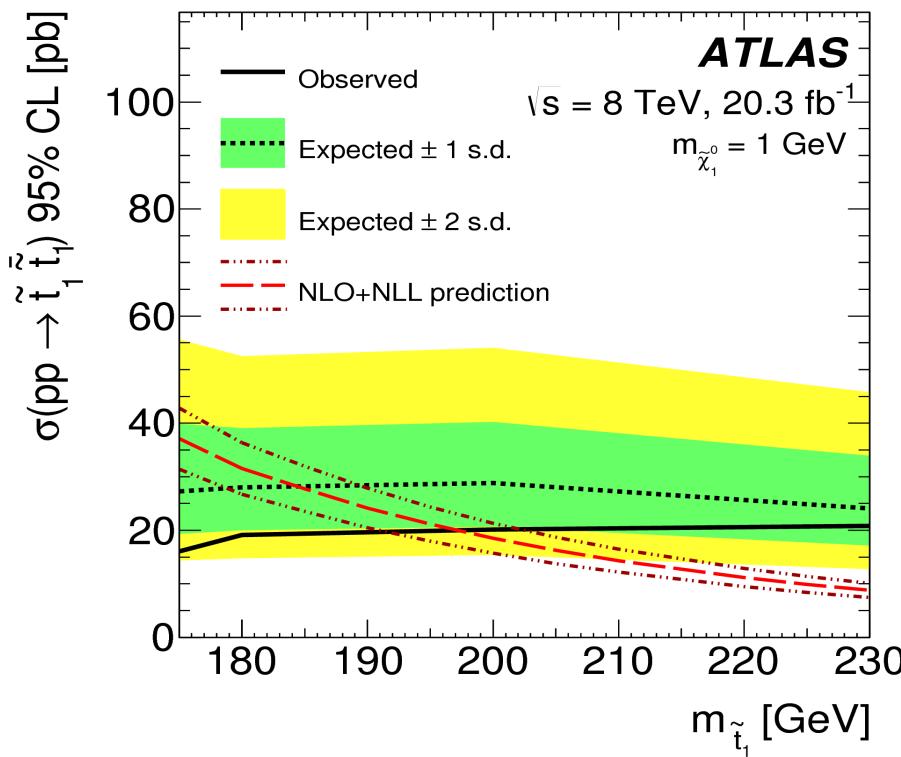
Run 2 will continue to fill in holes

Only weak region will continue to be for heavy neutralino

“Stealth” Stop

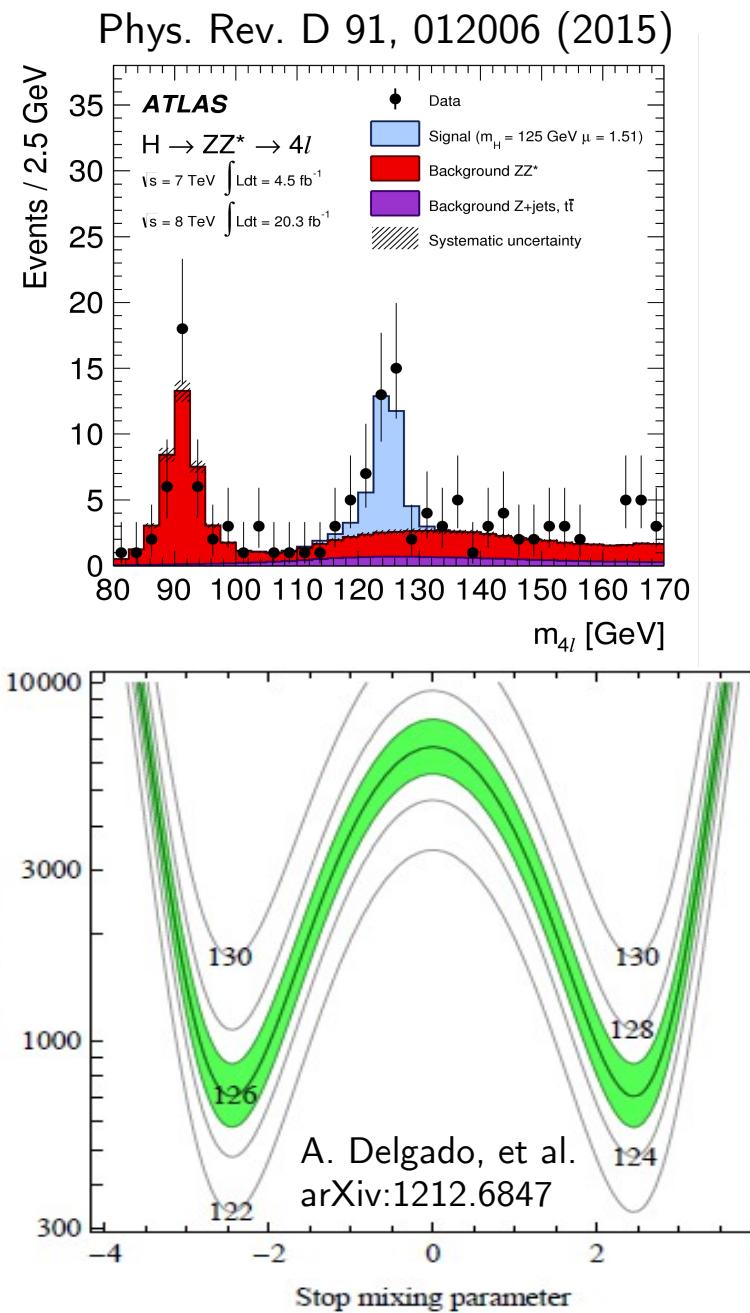
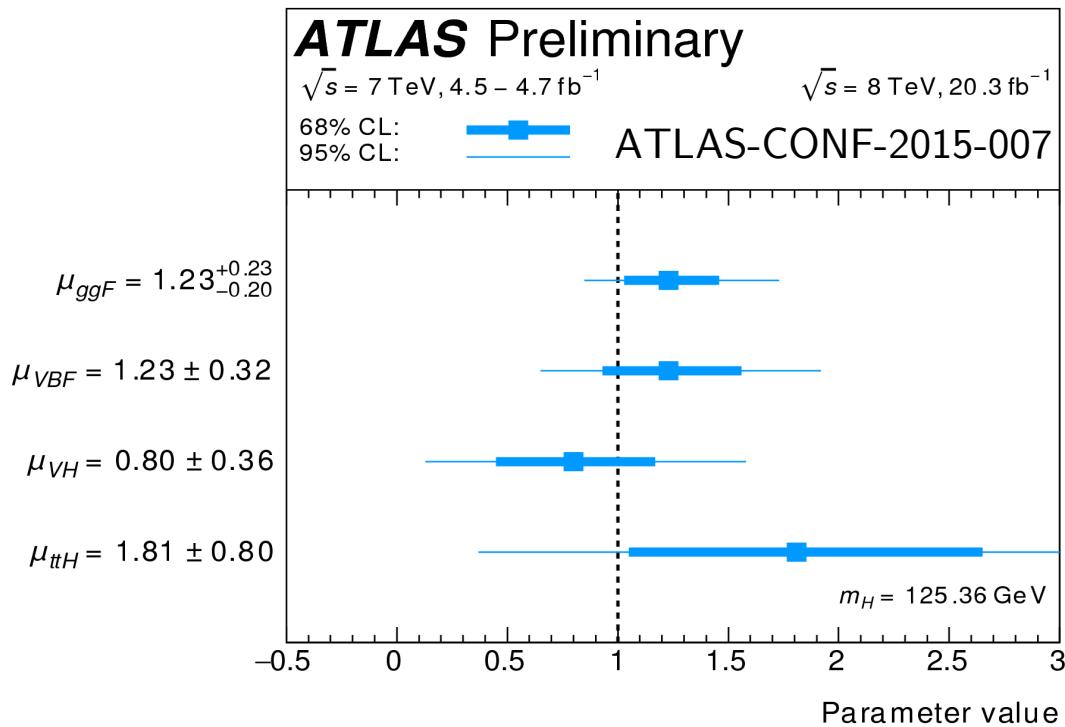
Phys. Rev. Lett. 114, 142001 (2015)

- Stop just above top mass is hard to find – hidden by top!
 - Top theory xs uncertainty is comparable to stop xs
 - Precision ATLAS ttbar xs measurement (Eur.Phys.J. C74 (2014) 3109) constrained stop <177 GeV
- Use ***spin*** to separate top / stop in di-lepton “top” sample
- *Exclude stop<191 GeV*

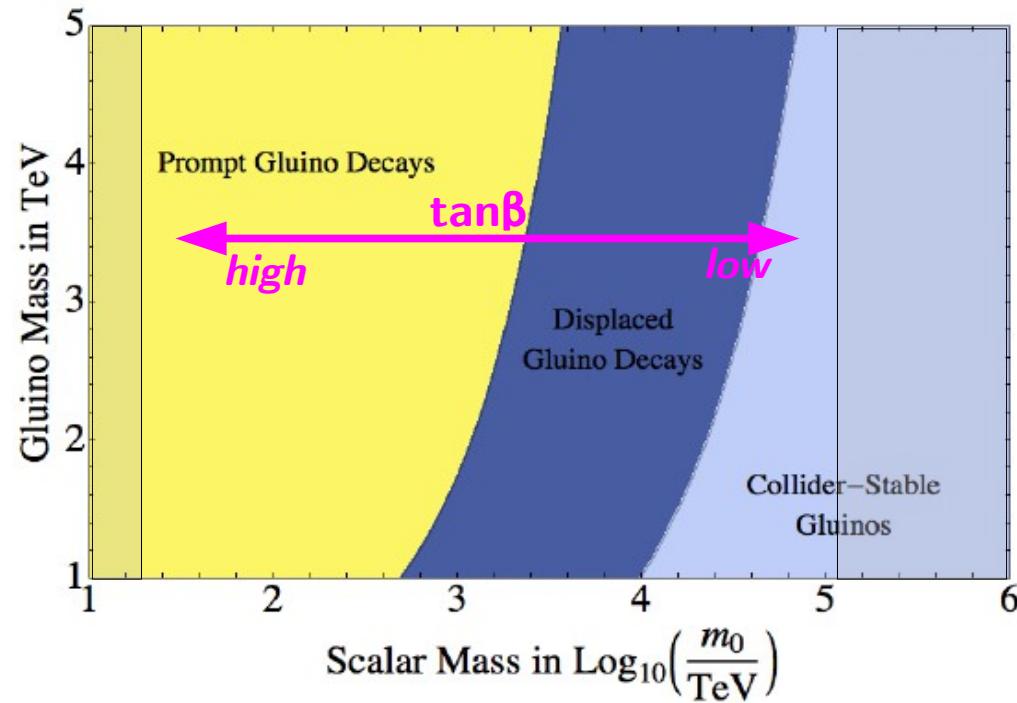
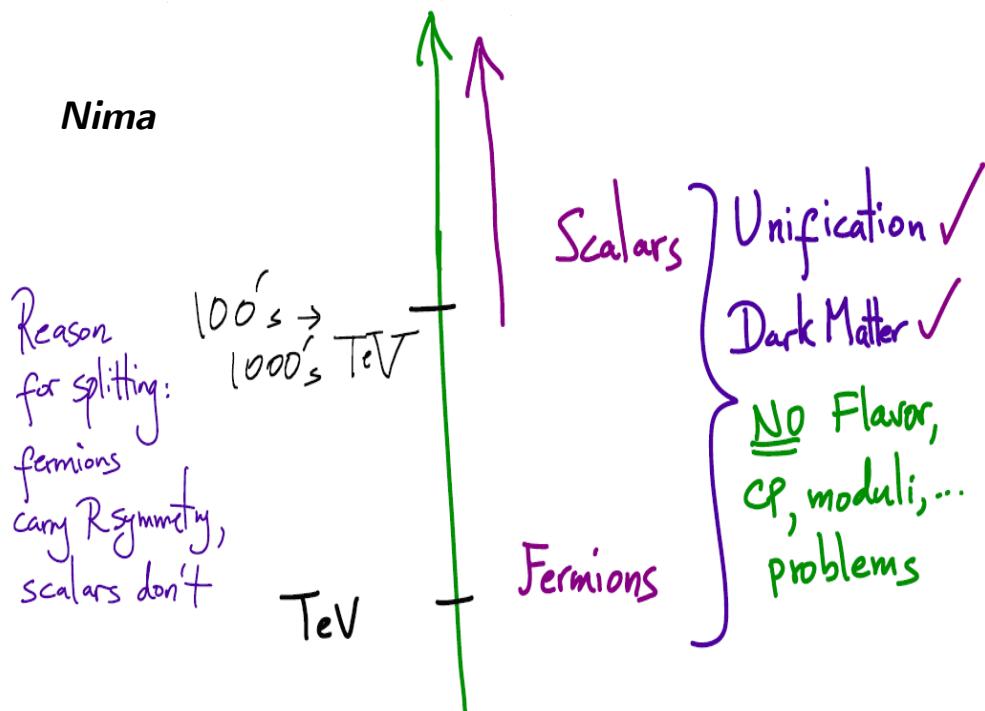


SM-like Higgs at 125 GeV ?!

- Higgs boson was finally discovered!
- But the mass was not great news for SUSY at the LHC... stop at ~ 3 TeV?
- Couplings have now also been shown to be very SM-like...



Mini-Split SUSY → Displaced gluino decays



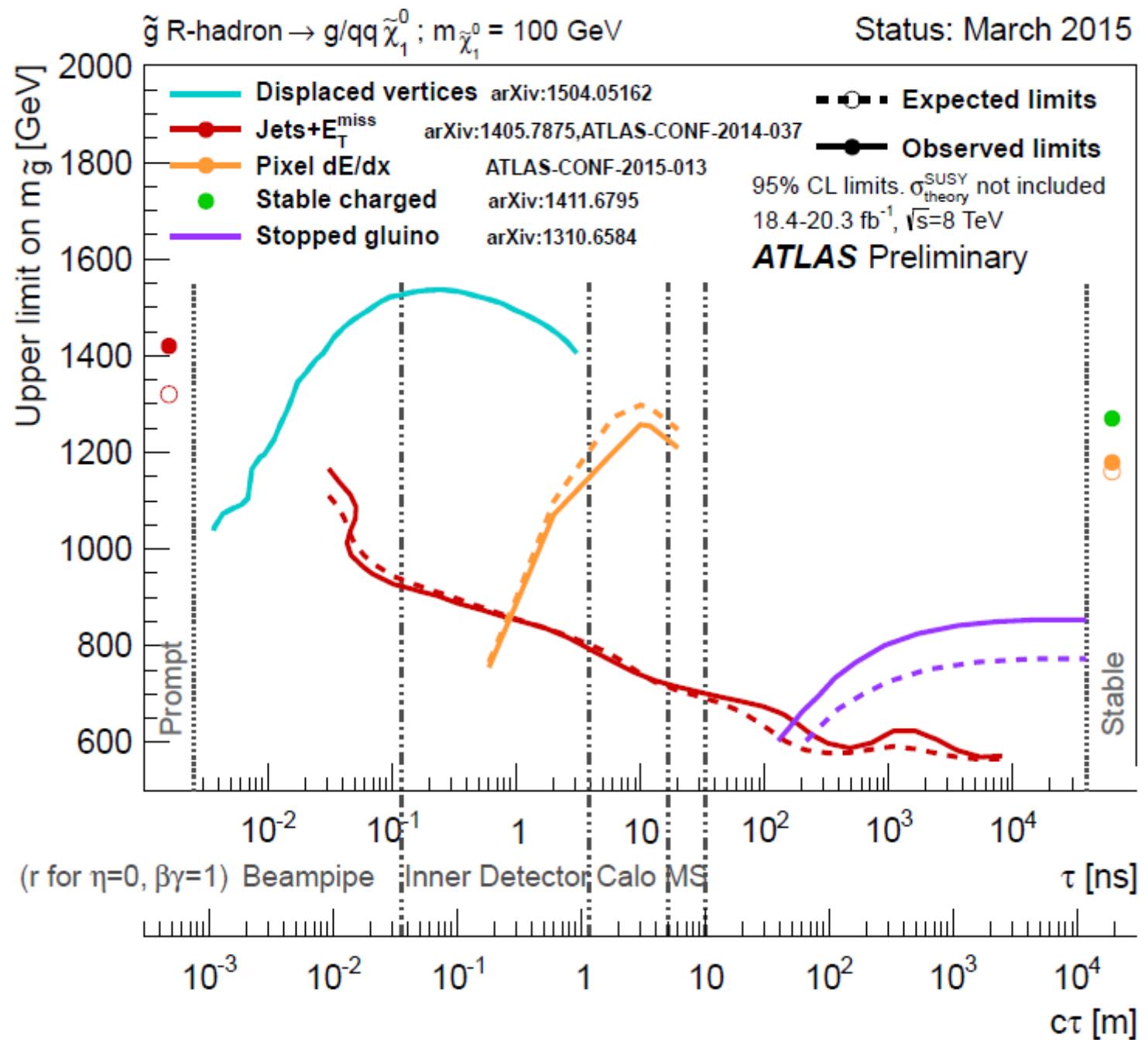
- Only the sfermions are within LHC reach
 - Can go after **gluinos or EW-inos**
- Gluino lifetime depends on the squark masses (m_0) **Mini-unnatural!**

“*Mini-split*”, arXiv:1210.0555, A. Arvanitaki, N. Craig, S. Dimopoulos, G. Villadoro

“*Simply Unnatural SUSY*”, arXiv:1212.6971, N. Arkani-Hamed, A. Gupta, D.E. Kaplan, N. Weiner, T. Zorawski

Long-lived Gluino Summary

**Robust exclusion
up to ~1.3 TeV
across all lifetimes
(for light neutralino)**



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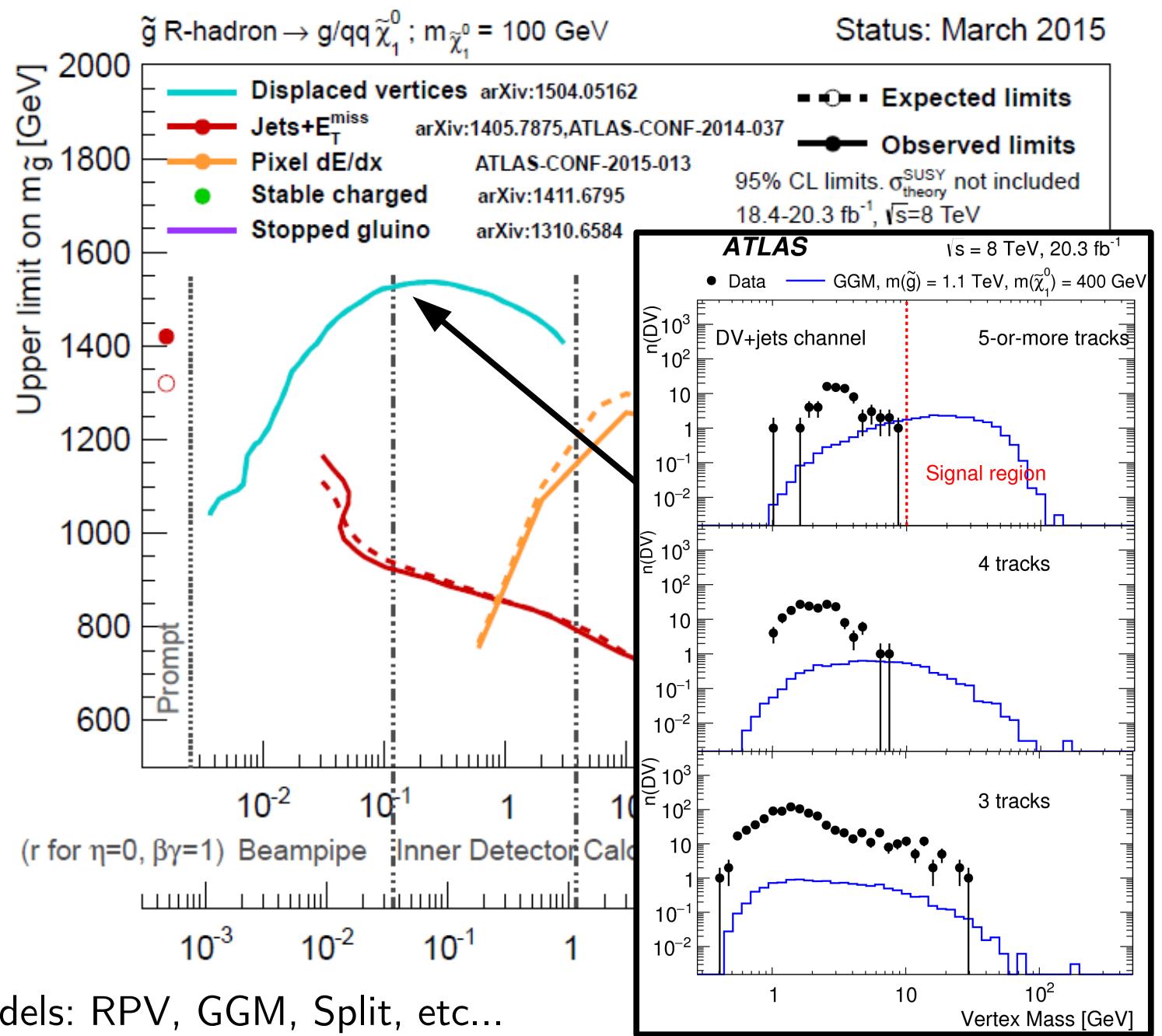
Best sensitivity at
~10 cm, from DV
on arXiv today!

Many channels:

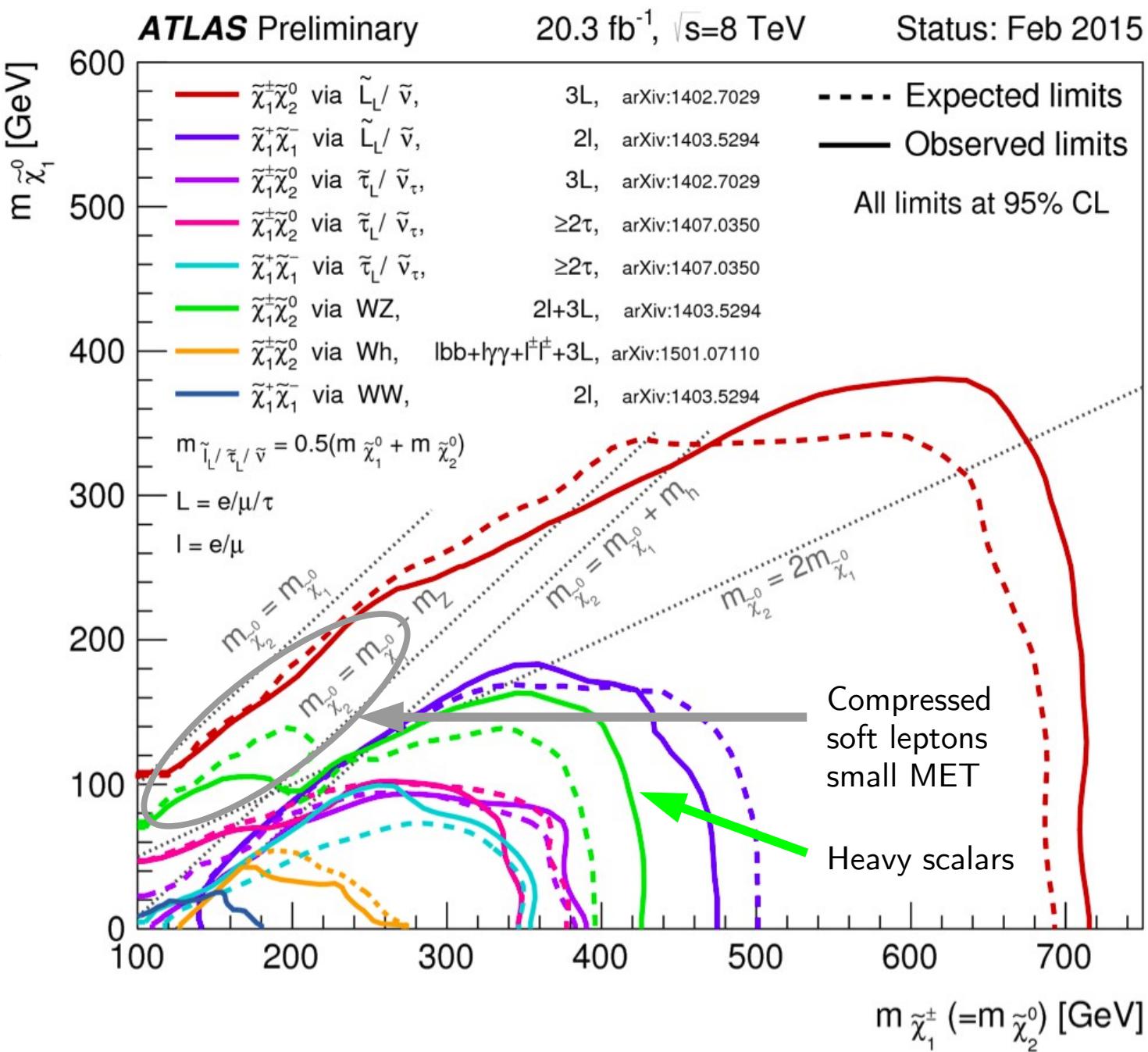
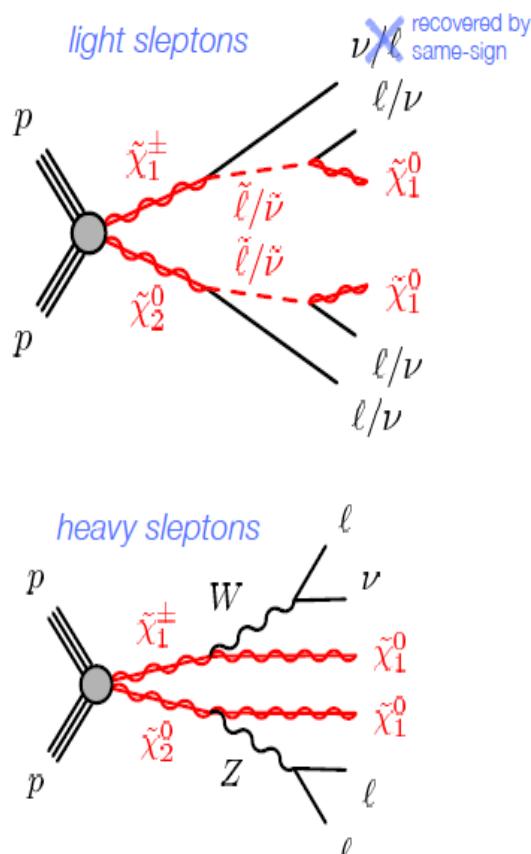
- DV+jet
- DV+ E_T^{miss}
- DV+muon
- DV+electron
- e^+e^-
- $\mu^+\mu^-$
- $e^\pm\mu^\mp$

No events pass
signal selections

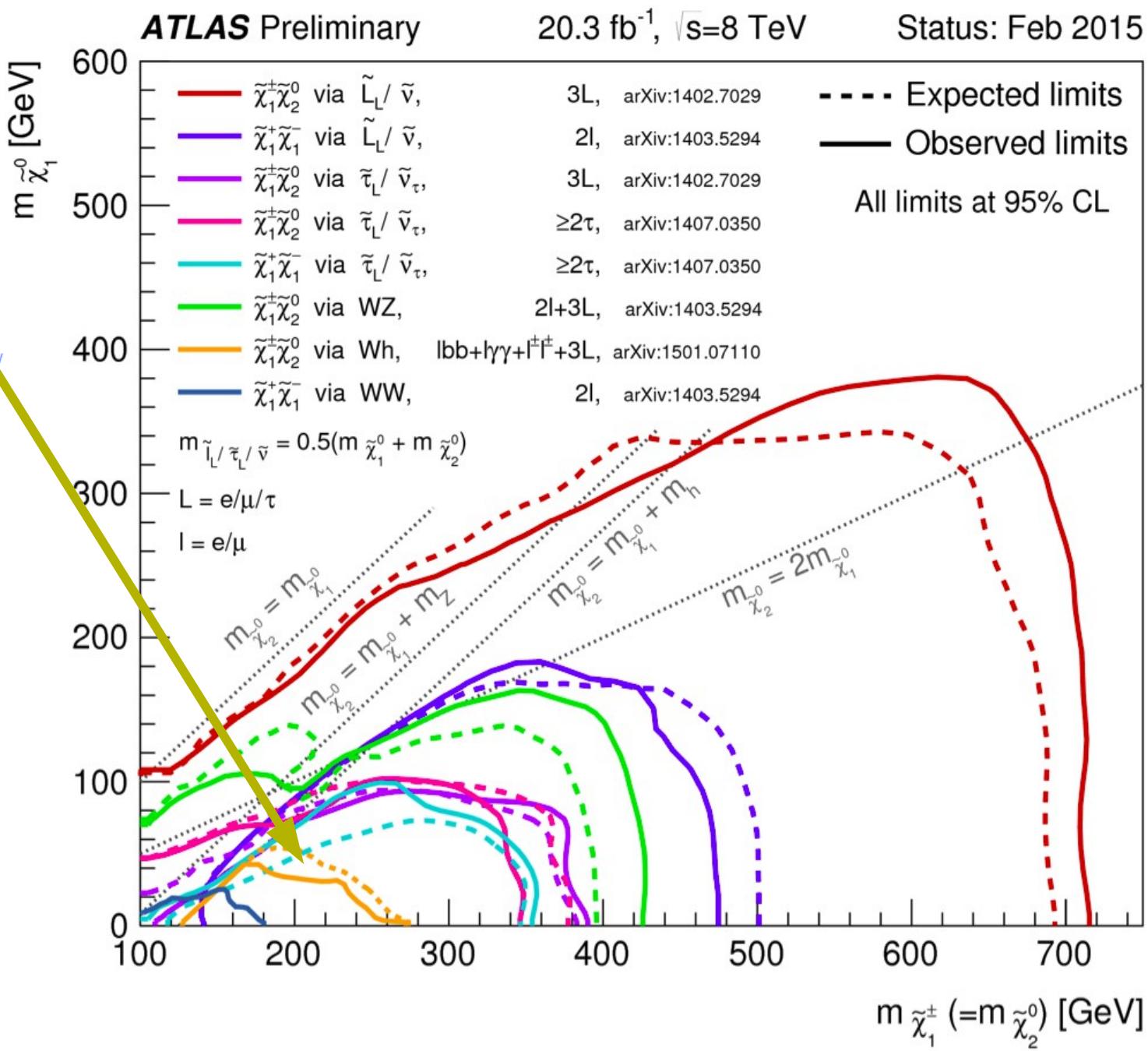
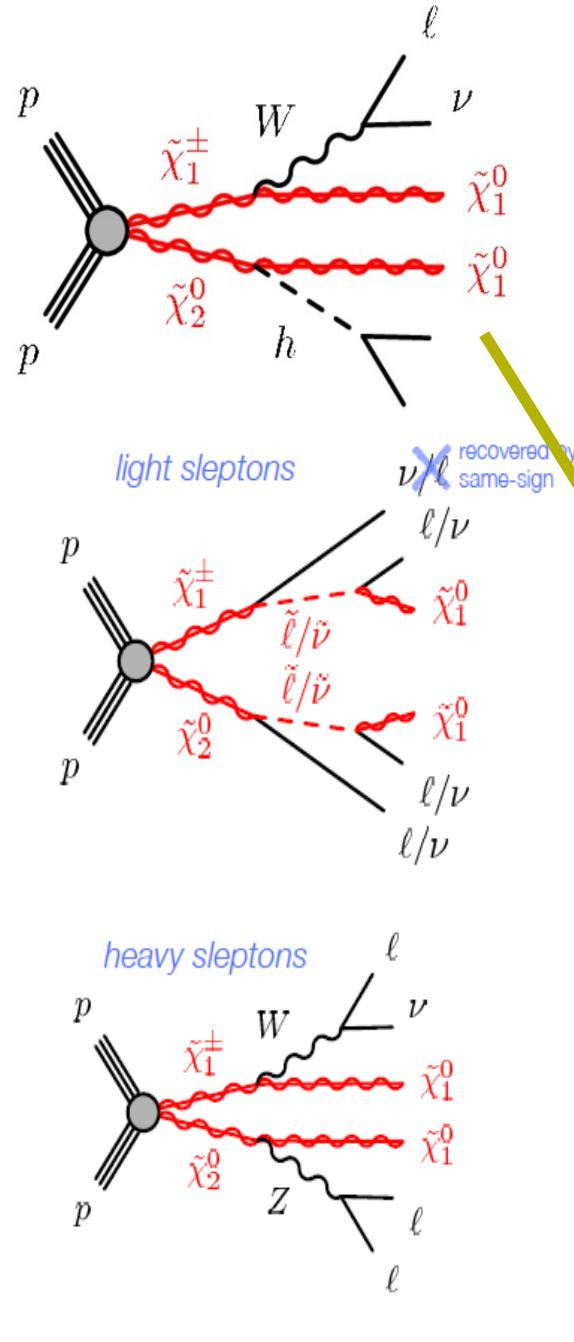
Interpreted in many models: RPV, GGM, Split, etc...



Chargino/Neutralino Searches



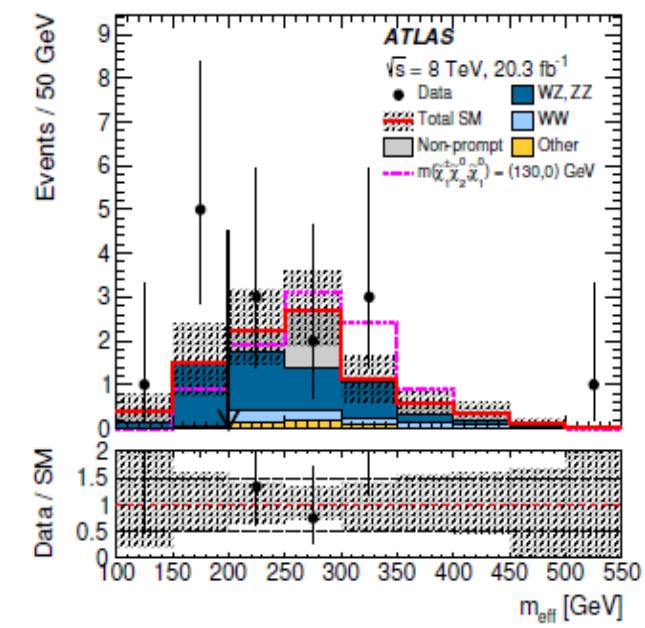
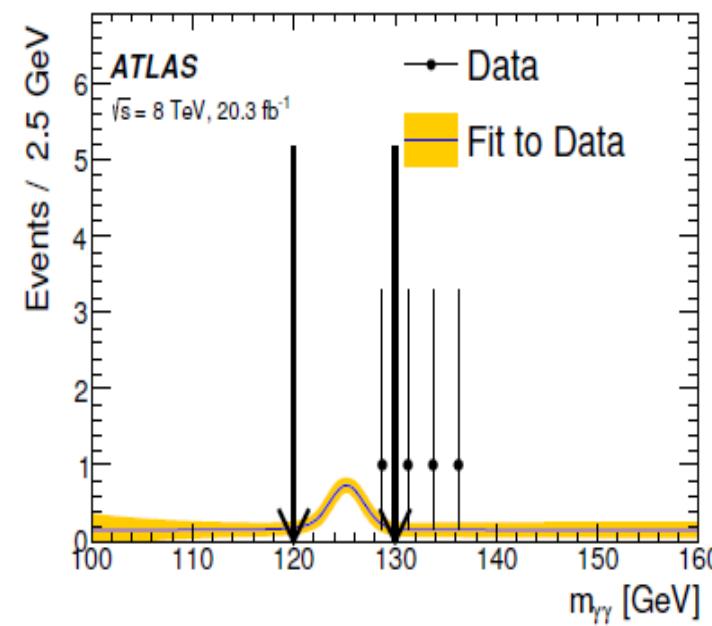
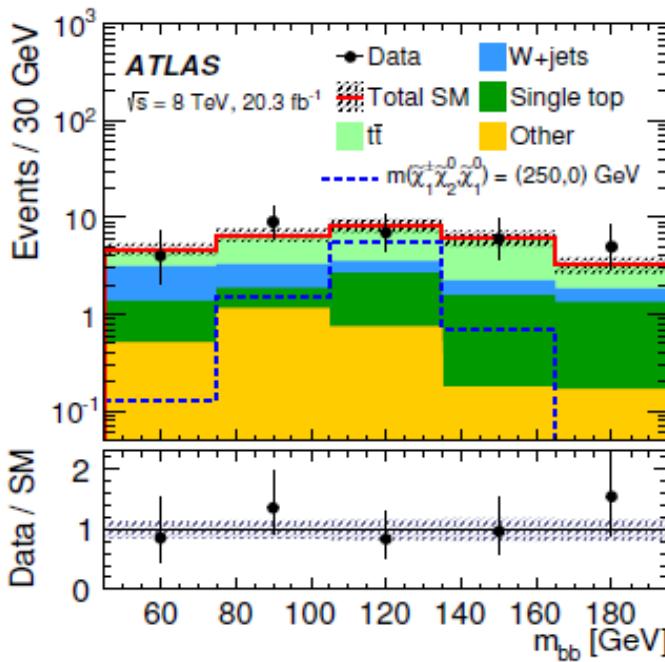
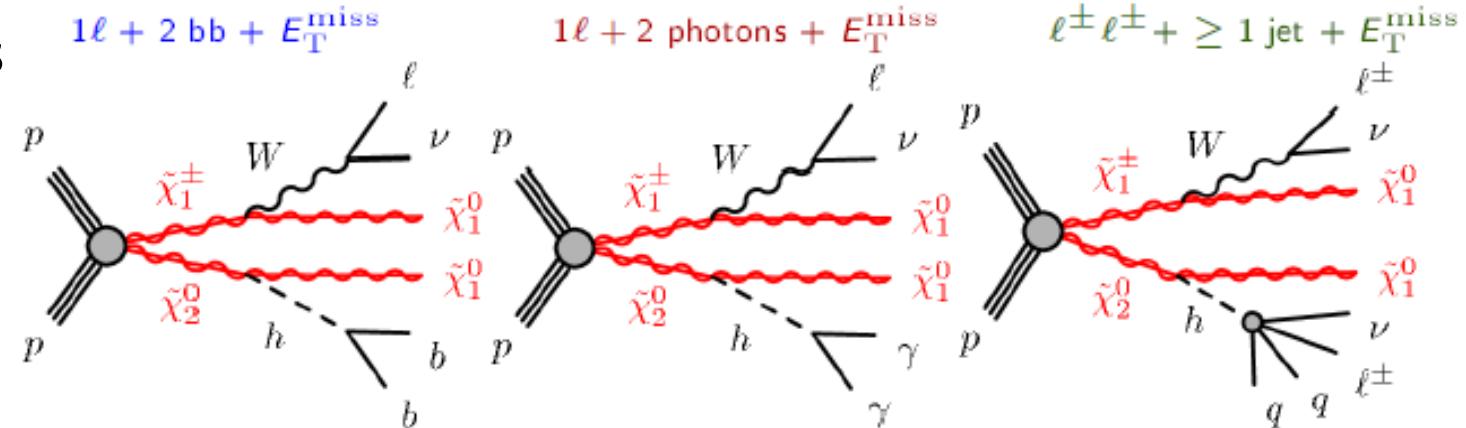
Chargino/Neutralino Searches



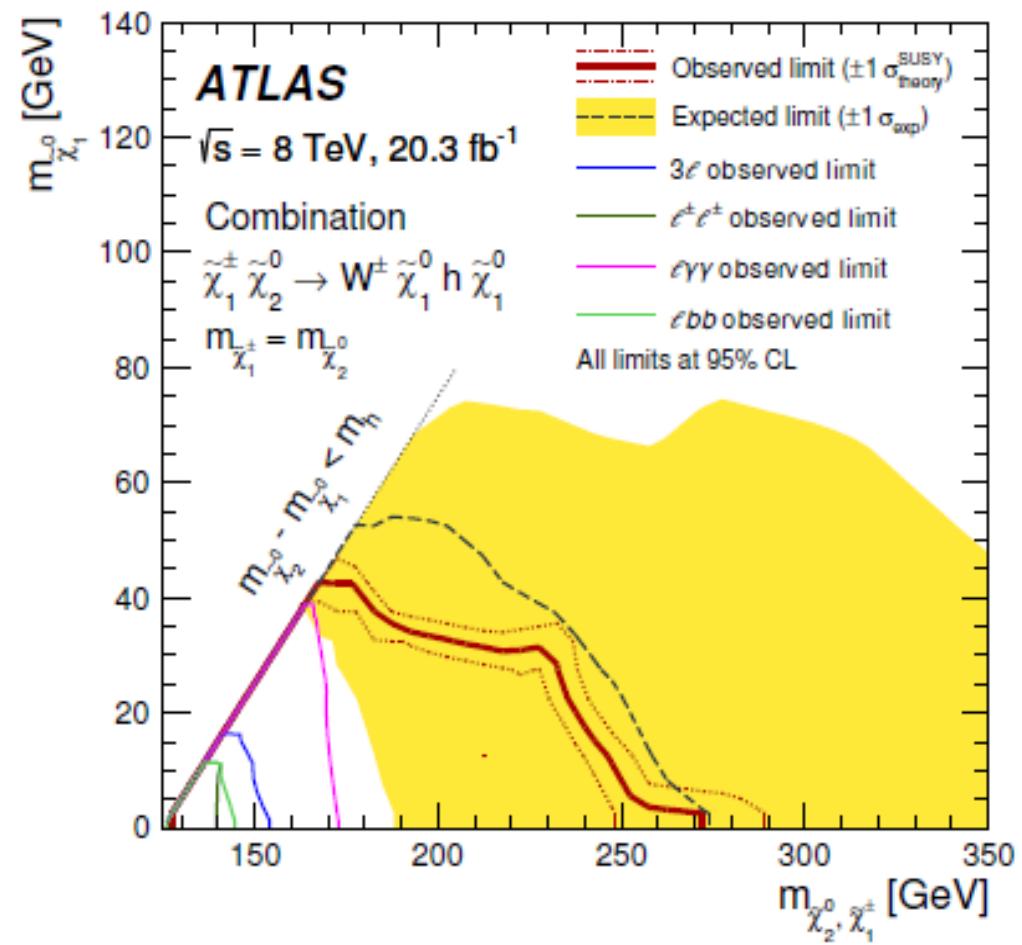
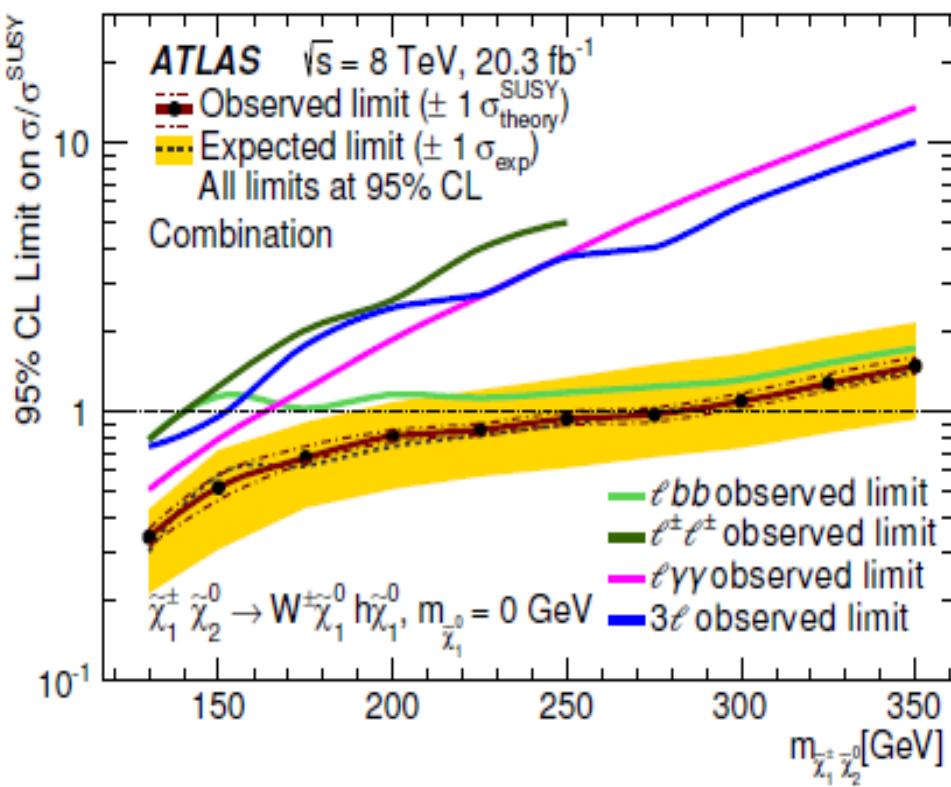
Chargino/Neutralino \rightarrow Wh+MET

arXiv:1501.07110

- Now that we've found a SM-like Higgs boson, use in BSM searches!
- Combine various SM Higgs boson decay channels



- Now that we've found a SM-like Higgs boson, use in BSM searches!
- Combine various SM Higgs boson decay channels
- Will be powerful in Run 2*

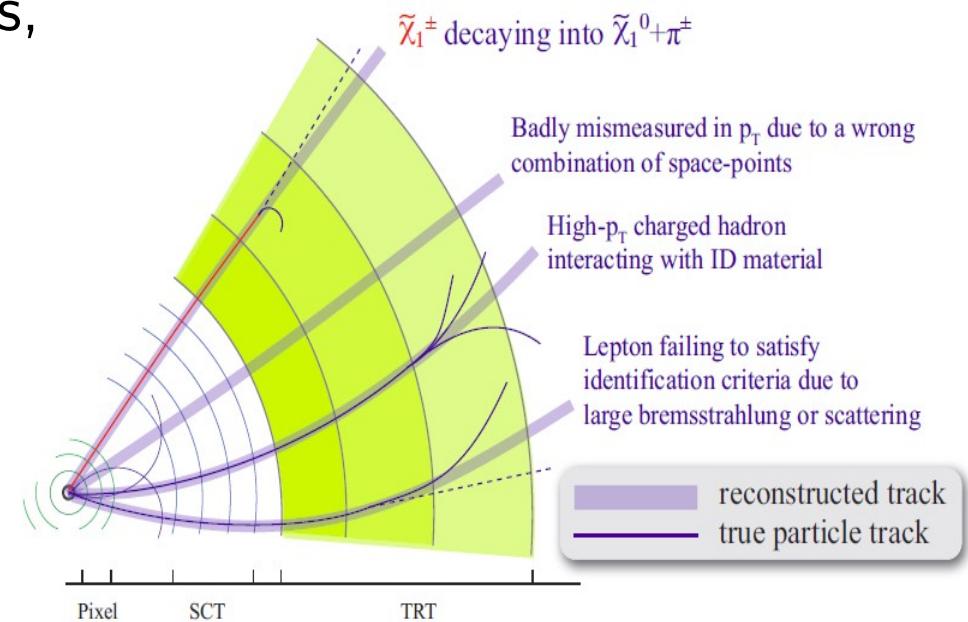
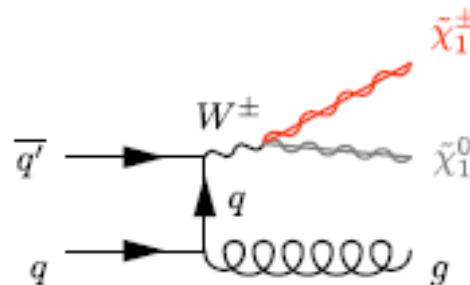


Long-lived Chargino → Disappearing Track Search

Phys. Rev. D 88, 112006 (2013)

- Chargino becomes long-lived when nearly-degenerate with the LSP
- Light Wino and Bino, heavy Higgsinos, Wino LSP
 - Lifetime ~ 50 mm, $\Delta m \sim 165$ MeV from EW contribution
- Higgsino LSP, only light Higgsinos
 - Lifetime ~ 5 mm, $\Delta m = \frac{1}{2} \alpha m_Z = \sim 355$ MeV
- Chargino travels through some layers, decays to a soft pion + MET
- *Look for high-pt isolated track without hits in outer tracking layers*

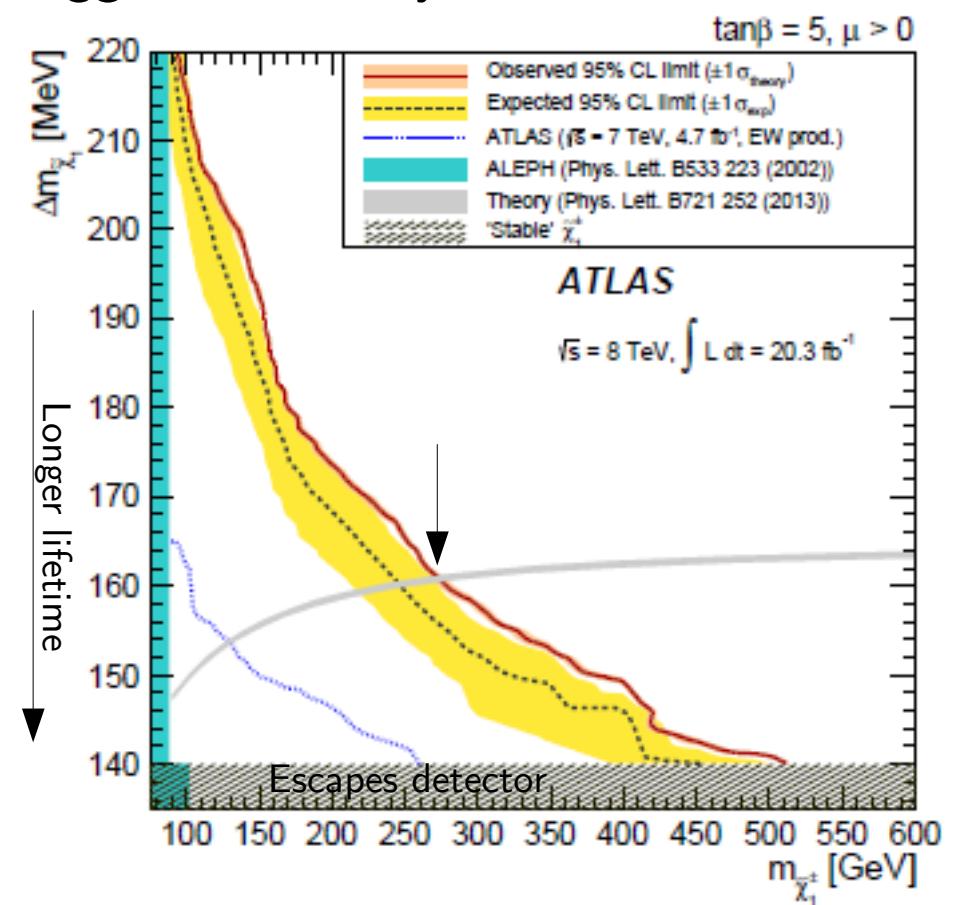
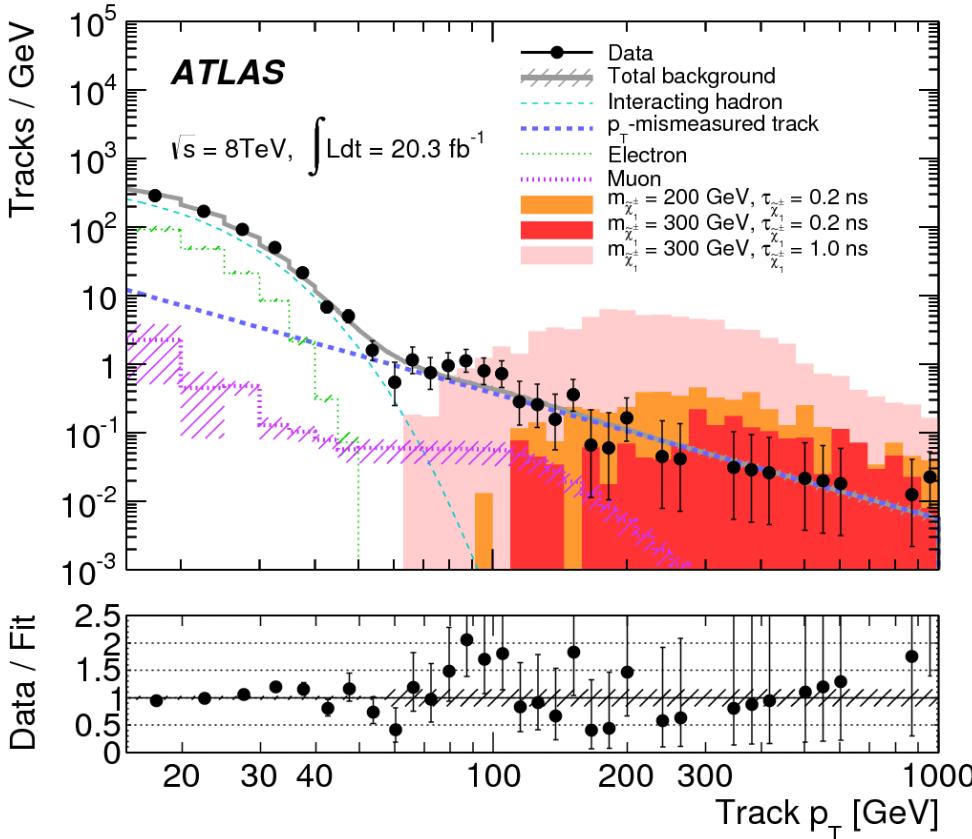
Need $p_T > 90$ GeV ISR
for MET trigger:
 $\sim 15\%$ of cross-section



Long-lived Chargino \rightarrow Disappearing Track Search

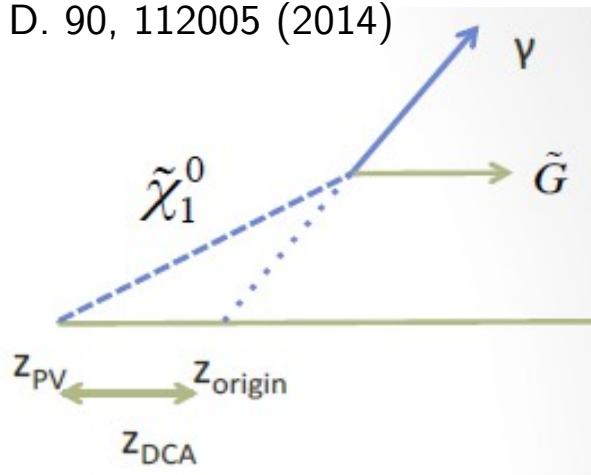
Phys. Rev. D 88, 112006 (2013)

- Background track p_T shapes fit to data ...
- *Exclude chargino < 270 GeV in AMSB with lifetime ~ 50 mm*
- Critical to increase sensitivity for shorter tracks in Run 2 (IBL+pixel?)
– Would finally extend sensitivity for Higgsino LSP beyond LEP limit!

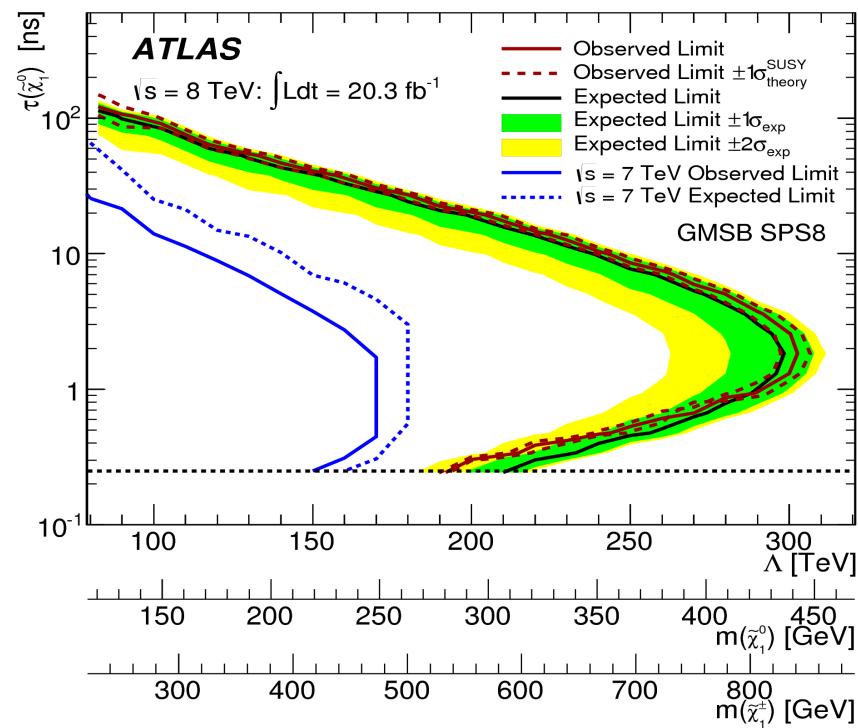
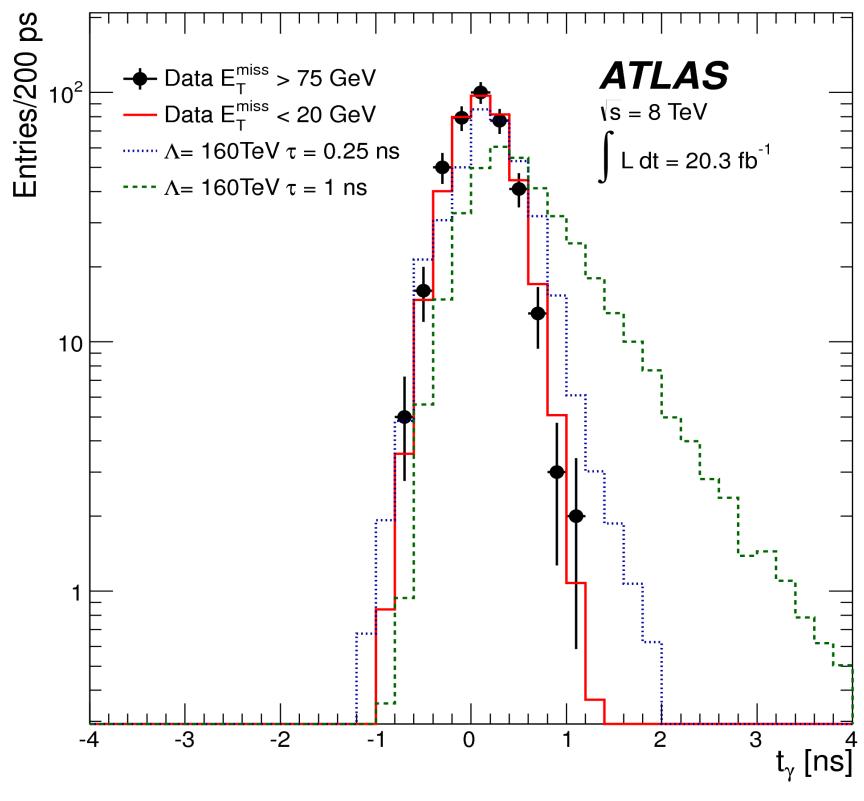


Long-lived Neutralino \rightarrow Displaced/Late Photons

Phys. Rev. D. 90, 112005 (2014)



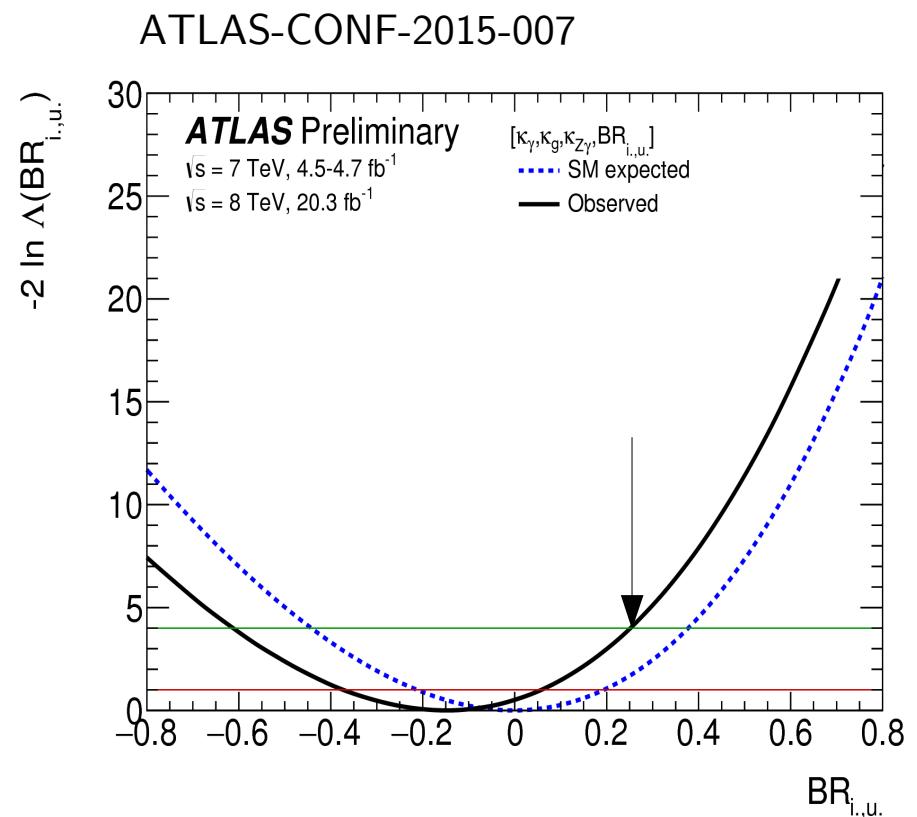
- Well-motivated, small gravitino coupling
- Two displaced/late photons and MET
 - Require photons to not point to PV or arrive at calorimeter late (t_γ)
- Calibrated with $Z \rightarrow ee$ decays
- *Excludes up to ~ 800 GeV chargino / ~ 400 GeV neutralino in GMSB model*



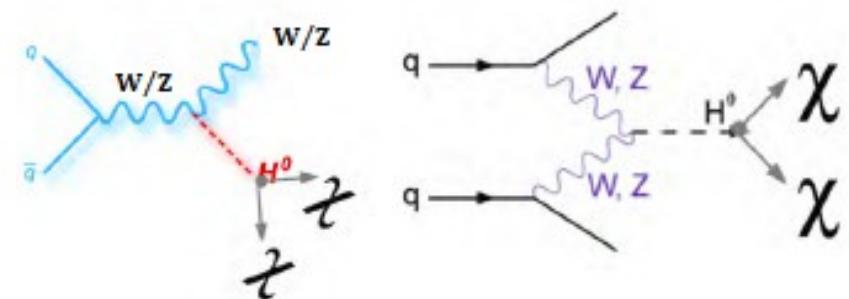
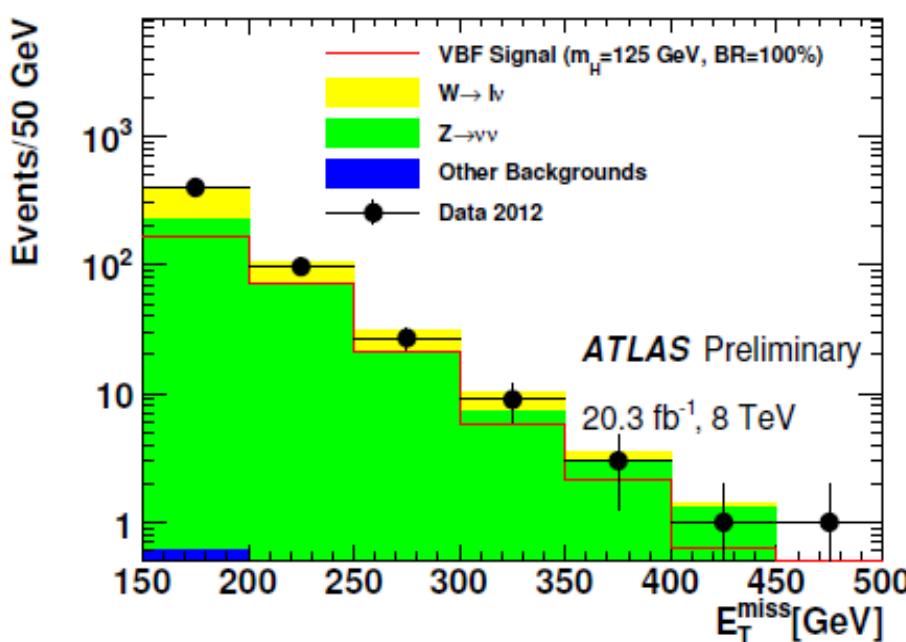
New decays of the “SM-like” Higgs boson

- Higgs boson is very narrow – small couplings can give large BR !
- BR $h \rightarrow \text{BSM} < 27\%$ at 95% CL from fits to observed Higgs decays
 - Still plenty of room for new BSM decays, even after Run 2
- Lots of possibilities for $h \rightarrow \text{BSM}$
 - $h \rightarrow \text{invisible} (\text{MET})$
 - $h \rightarrow \gamma + \text{MET}$
 - $h \rightarrow \gamma\gamma, l\bar{l}, b\bar{b} + \text{MET}$
 - $h \rightarrow aa (\text{ss}) \rightarrow xx yy$
 - $h \rightarrow aa (\text{ss}) \rightarrow xx + \text{MET}$
 - $h \rightarrow \text{lepton-jet(s)} (+\text{MET})$
 - ...
- All can be prompt or long-lived!

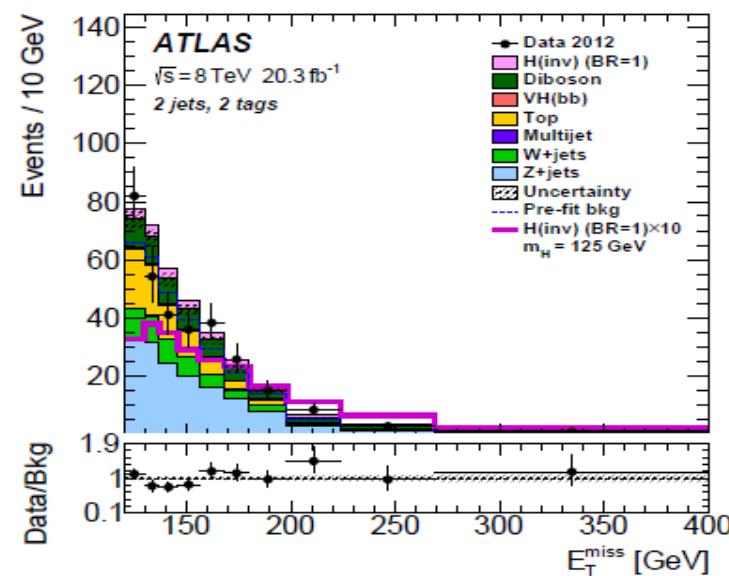
“Exotic Decays of the 125 GeV Higgs Boson”
D. Curtin, et al., arXiv:1312.4992



- Higgs decays to light neutralinos are well-motivated
- Use VBF production to enhance Higgs boson S/B ratio (assumes SM production)
- *Exclude BR h \rightarrow MET < 29%*



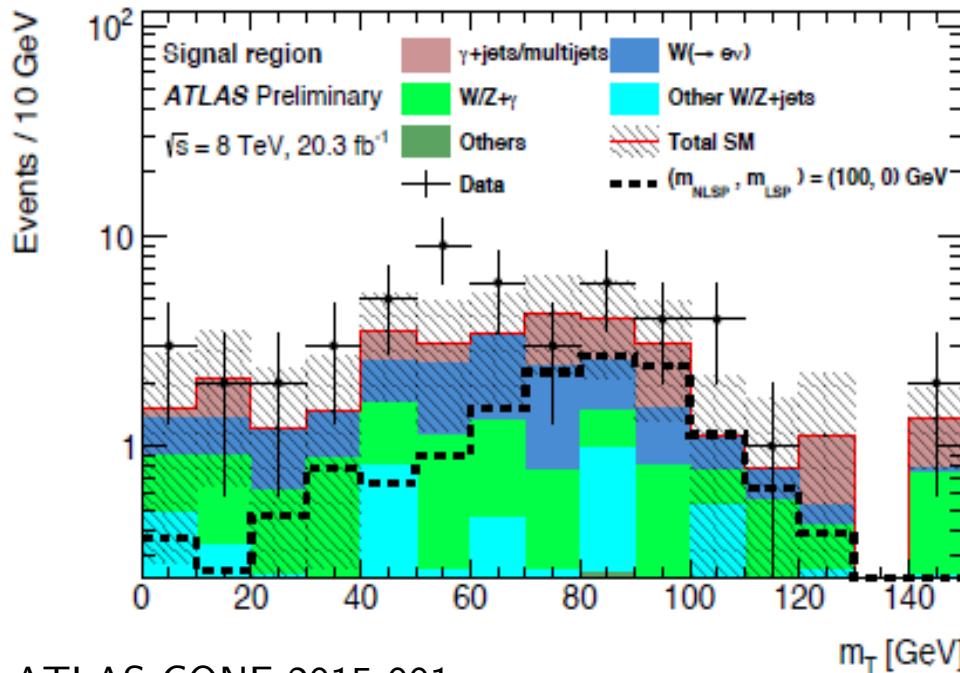
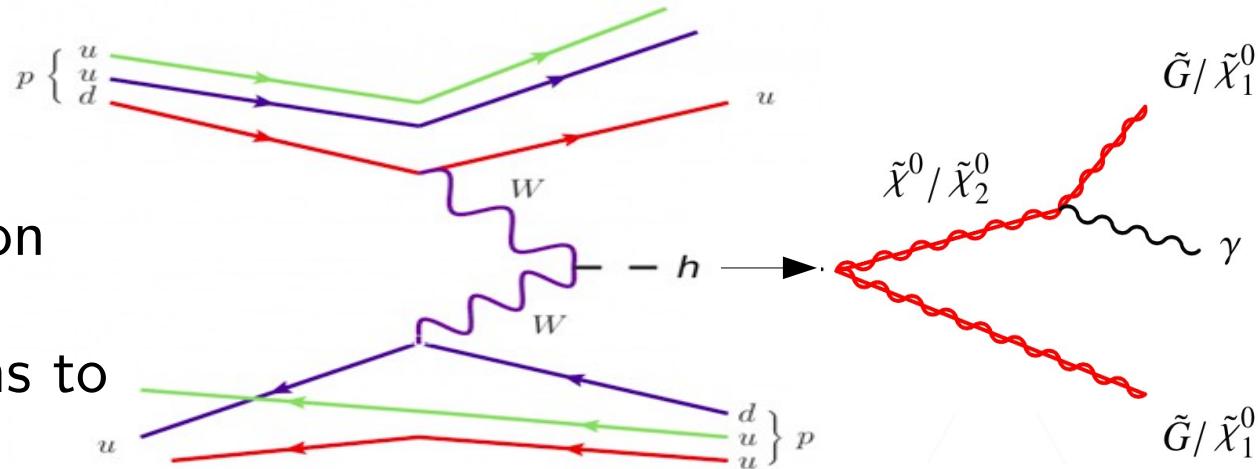
- Also look in the Vh channel using hadronic V decays
- *Excludes BR h \rightarrow MET < 78%*



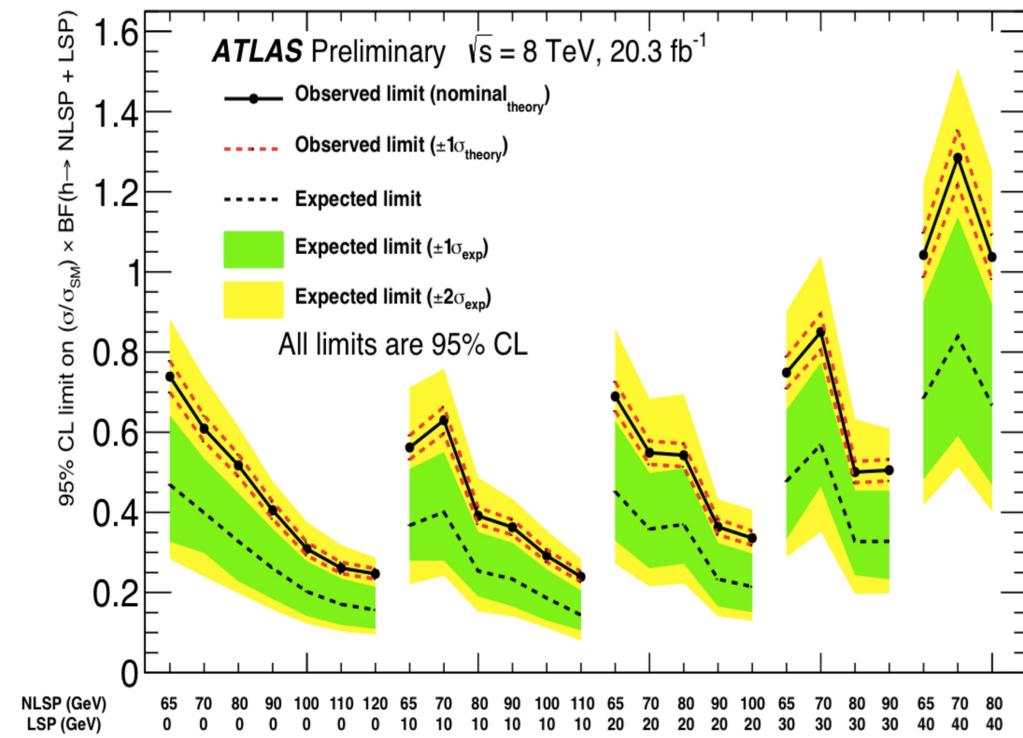
Will combine these with Z \rightarrow ll + h \rightarrow MET ...

Higgs \rightarrow Neutralino/Gravitino $\rightarrow \gamma + \text{MET}$

- Challenging due to soft photon and MET
- Use VBF Higgs production to increase sensitivity
- Only unconverted photons to reduce fake $e \rightarrow \gamma$ bkgd.
- *Exclude BR* $h \rightarrow \gamma + \text{MET} \sim 25\%$

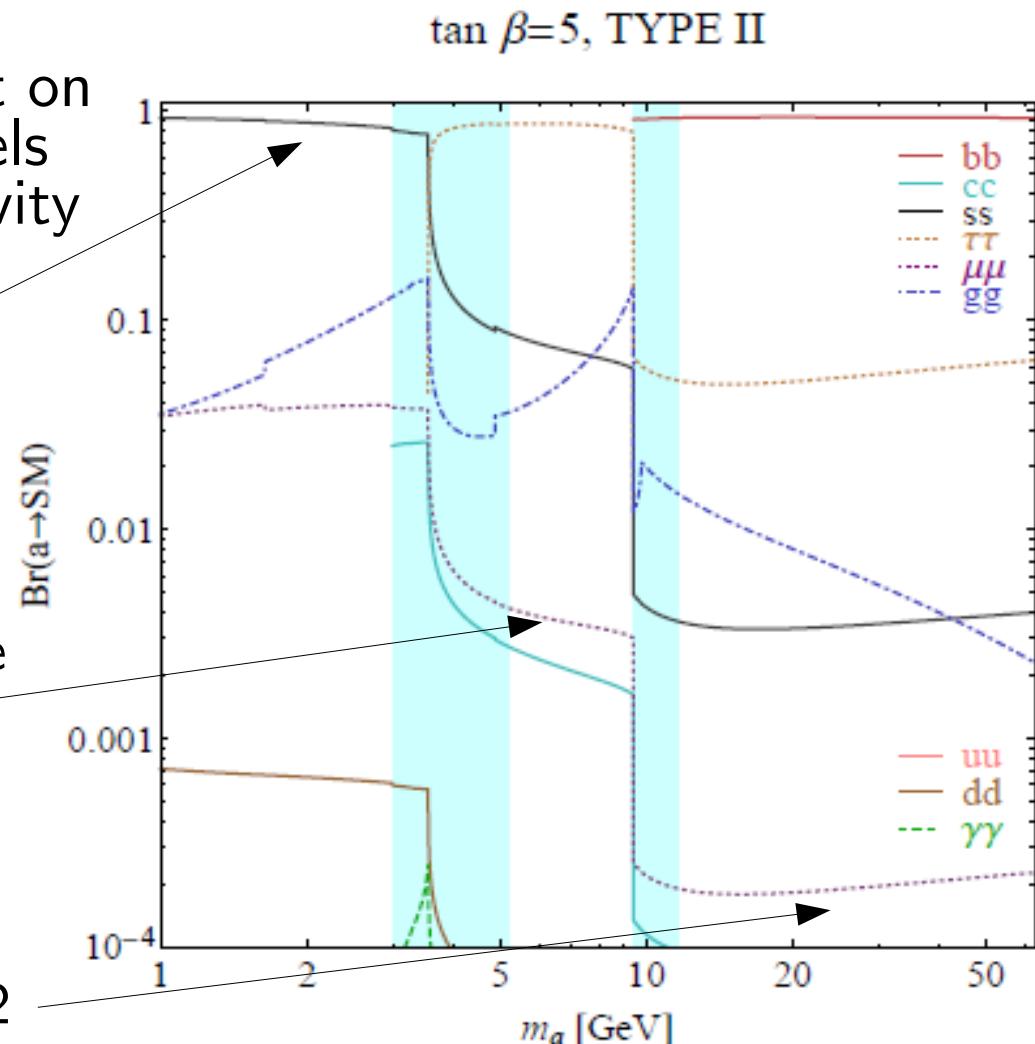


ATLAS-CONF-2015-001

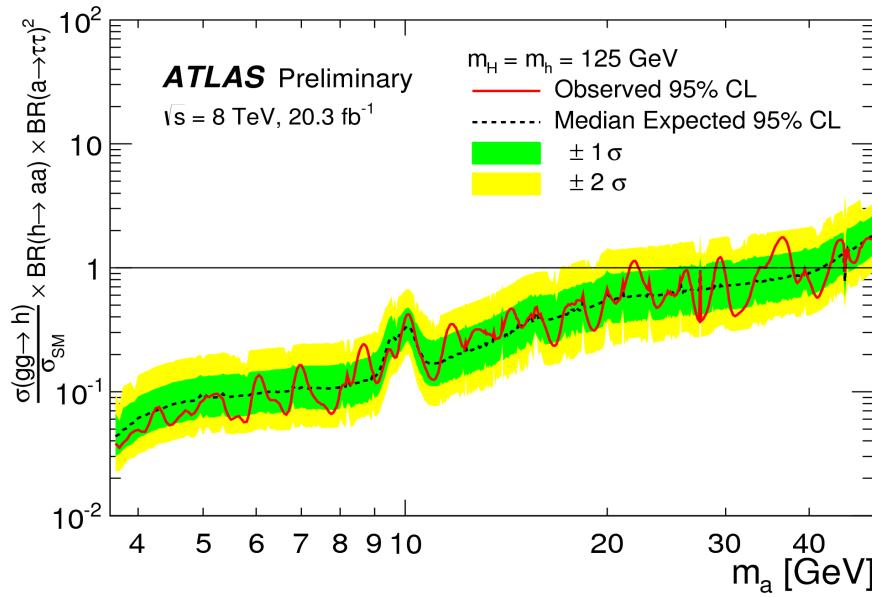
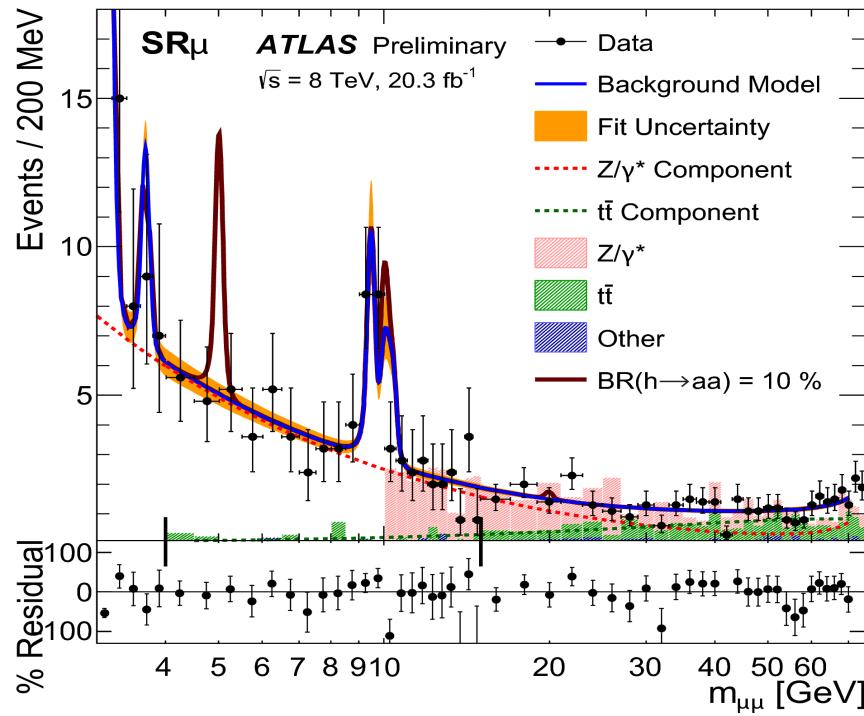


$$h \rightarrow aa \text{ (ss)} \rightarrow xx \text{ yy}$$

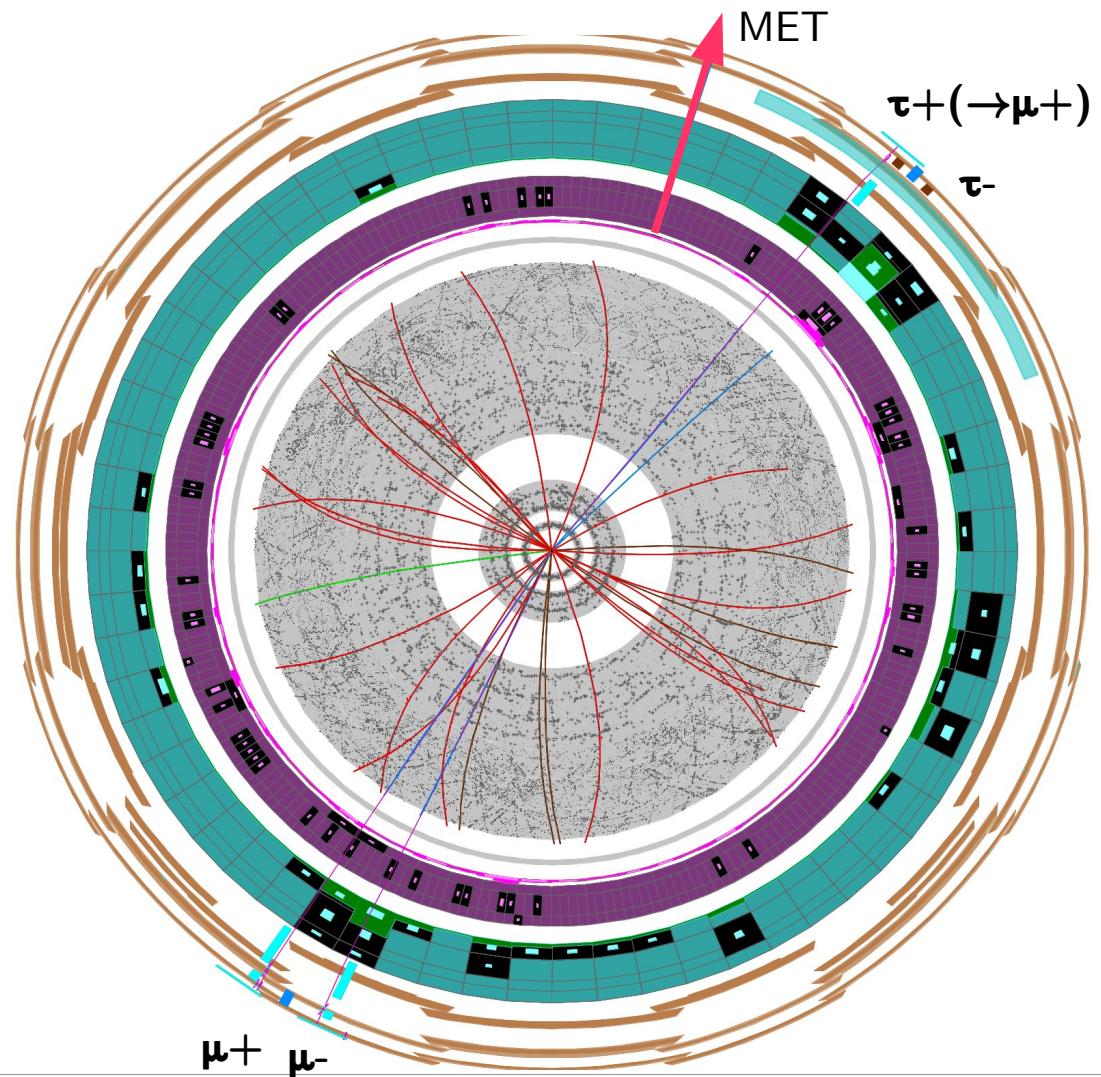
- Many possibilities, but focus first on well-motivated channels where possible to achieve sensitivity
- $a \rightarrow ee$ or $\mu\mu$ covered by lepton-jet searches
- $aa \rightarrow 4\tau$ is difficult
 - We accept a 1% BR and require at least one $a \rightarrow \mu\mu$ decay:
 $h \rightarrow aa \rightarrow \mu\mu \tau\tau$
- $aa \rightarrow 4b$ is impossible
 - Perhaps $\mu\mu$ bb possible in Run 2
- Other channels with photons or MET are also being studied



"Exotic Decays of the 125 GeV Higgs Boson"
D. Curtin, et al., arXiv:1312.4992

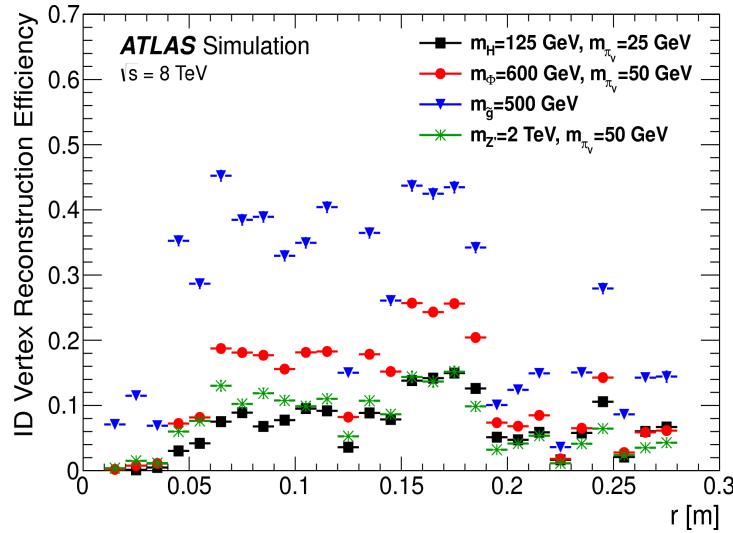


- Select $\mu\mu$ and collinear $\tau\tau (\rightarrow e/\mu)$
- Search for a bump in $\mu\mu$ mass
- *Exclude $BR(h \rightarrow aa)$ as low as 3.5%*

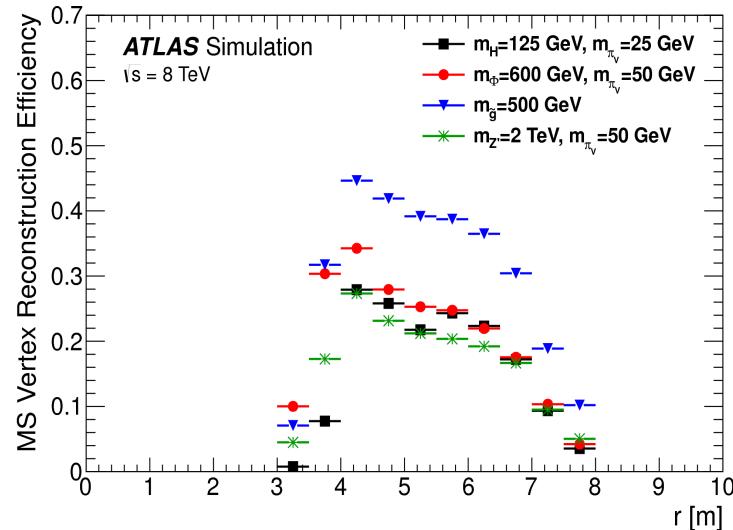


Higgs \rightarrow Long-lived Decays (Hidden Valley)

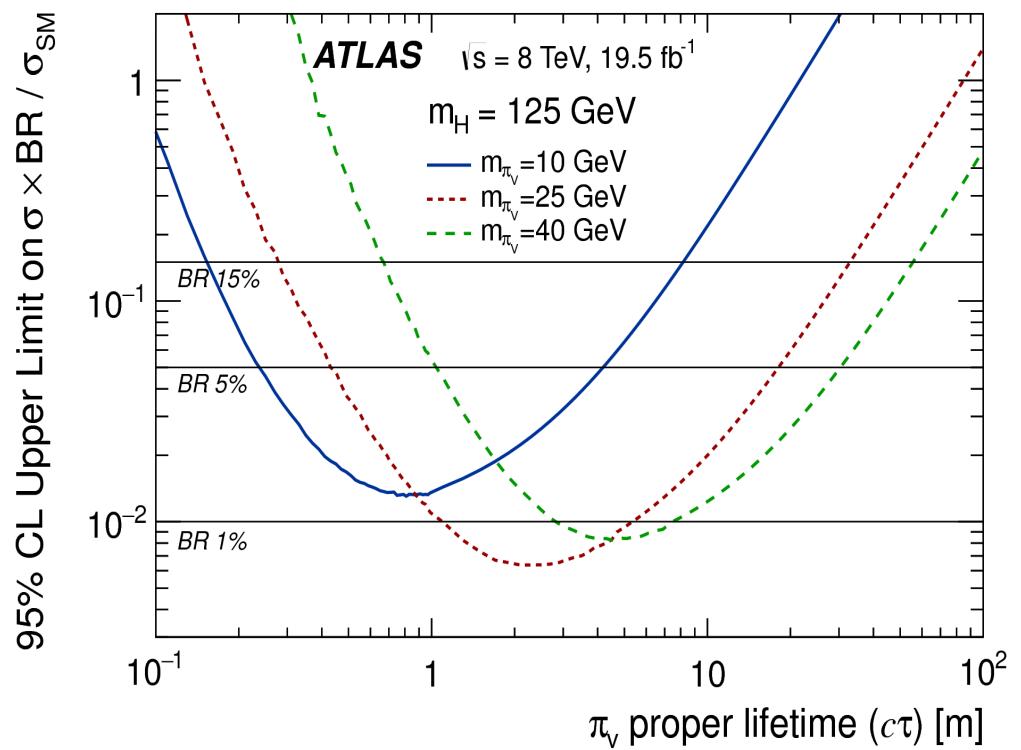
Vertex in inner tracker near a jet
with at least 5 tracks and large mass



OR a vertex in muon system using
special reco algorithm and trigger



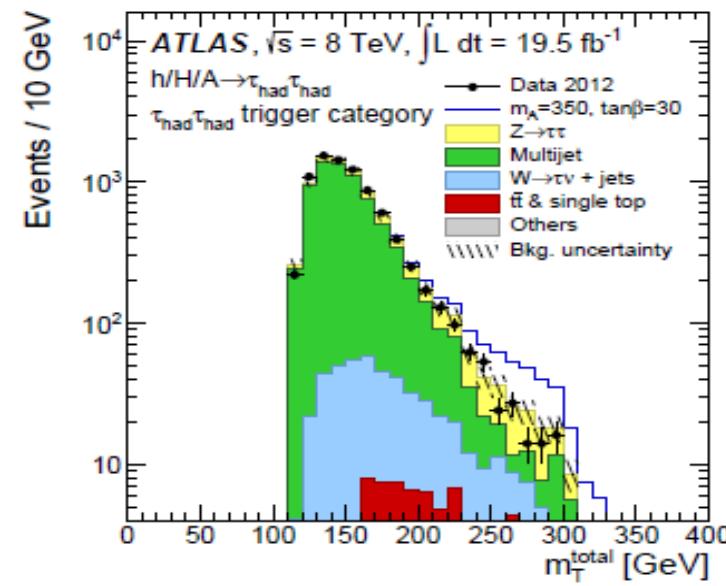
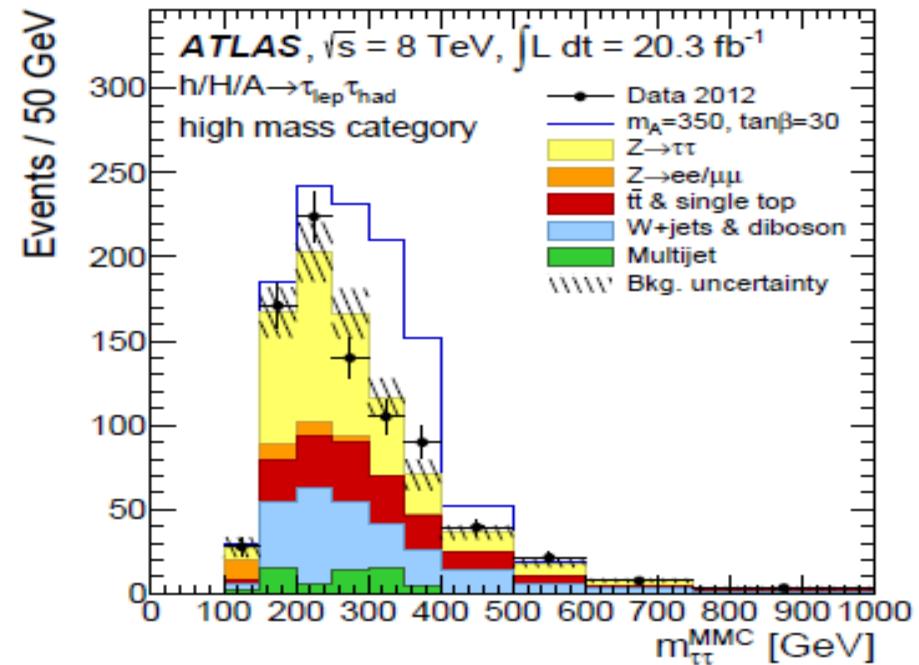
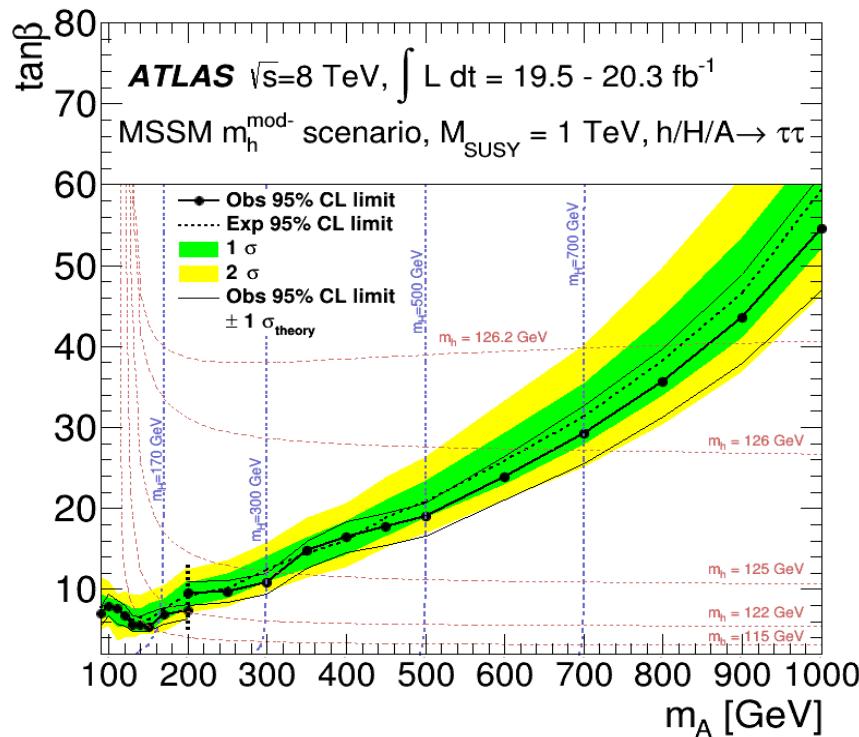
- Combination of searches for DV's in **Inner Detector or Muon System**
- Also searched for decays in the **Hadronic Calorimeter** using low EM fraction jets
- Excludes $h \rightarrow HV \ BR < 15\%$ for a broad range of HV lifetimes (also Stealth SUSY and Z' interpretations)*



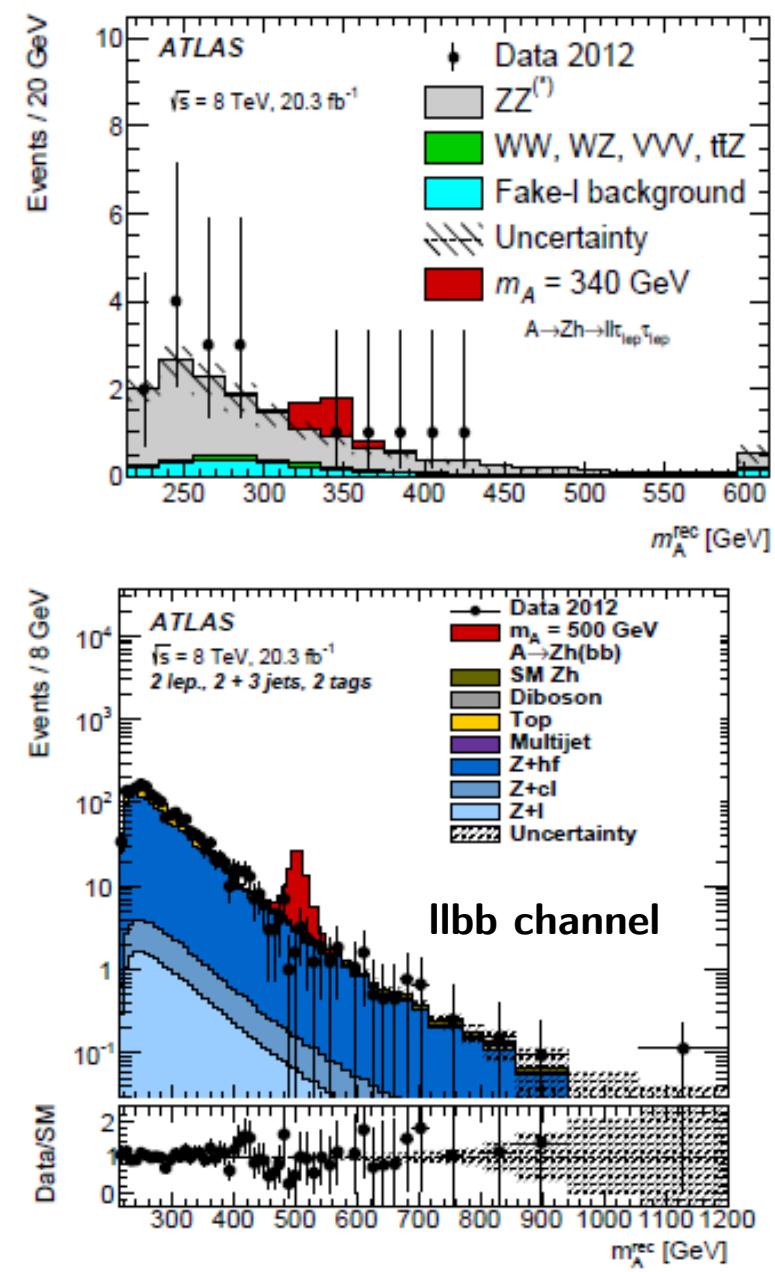
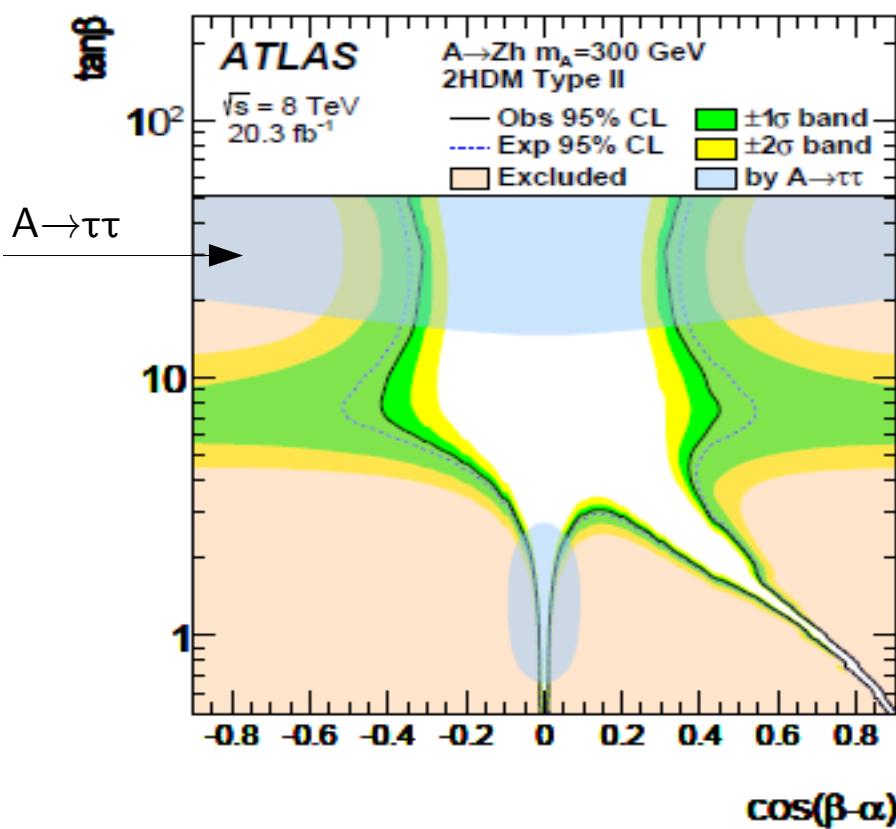
Other Higgs Bosons: A/H $\rightarrow \tau\tau$

arXiv:1409.6064

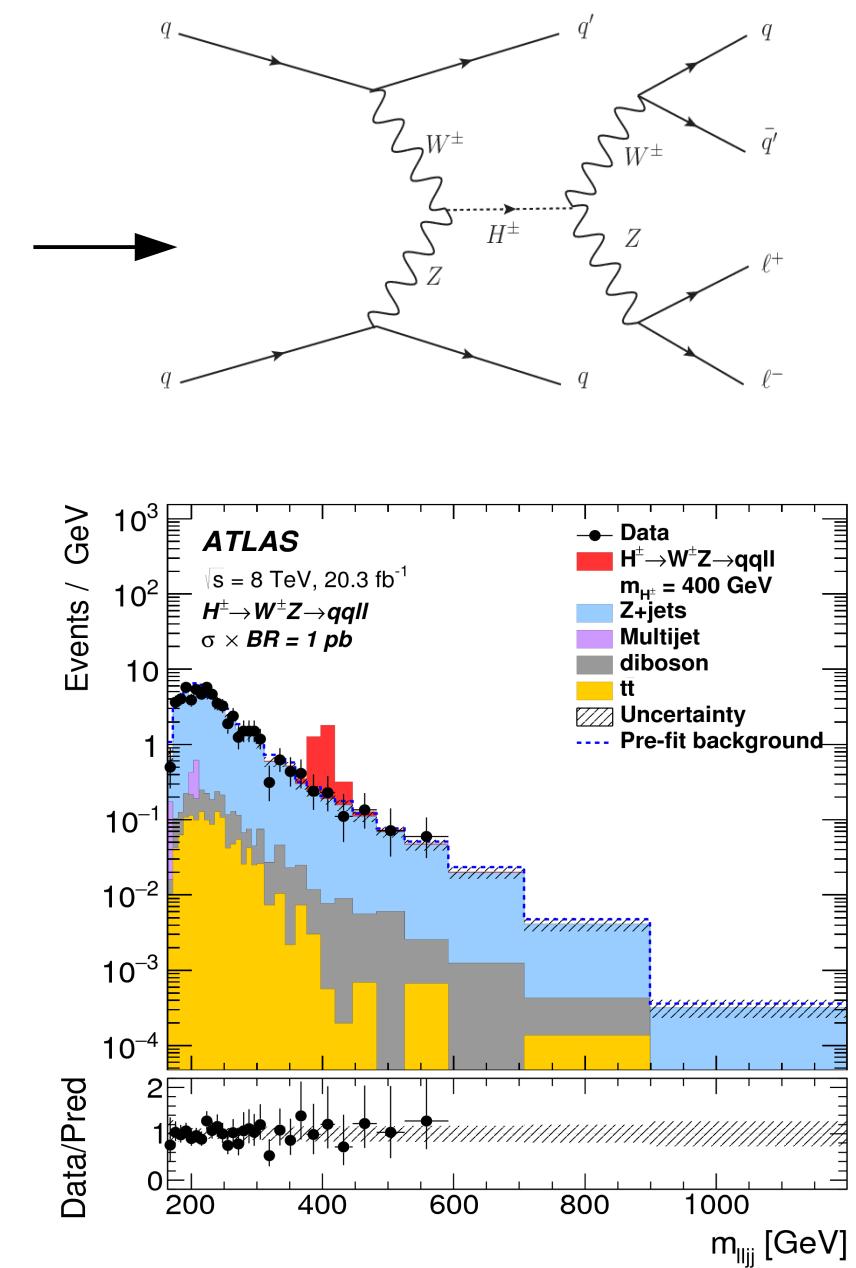
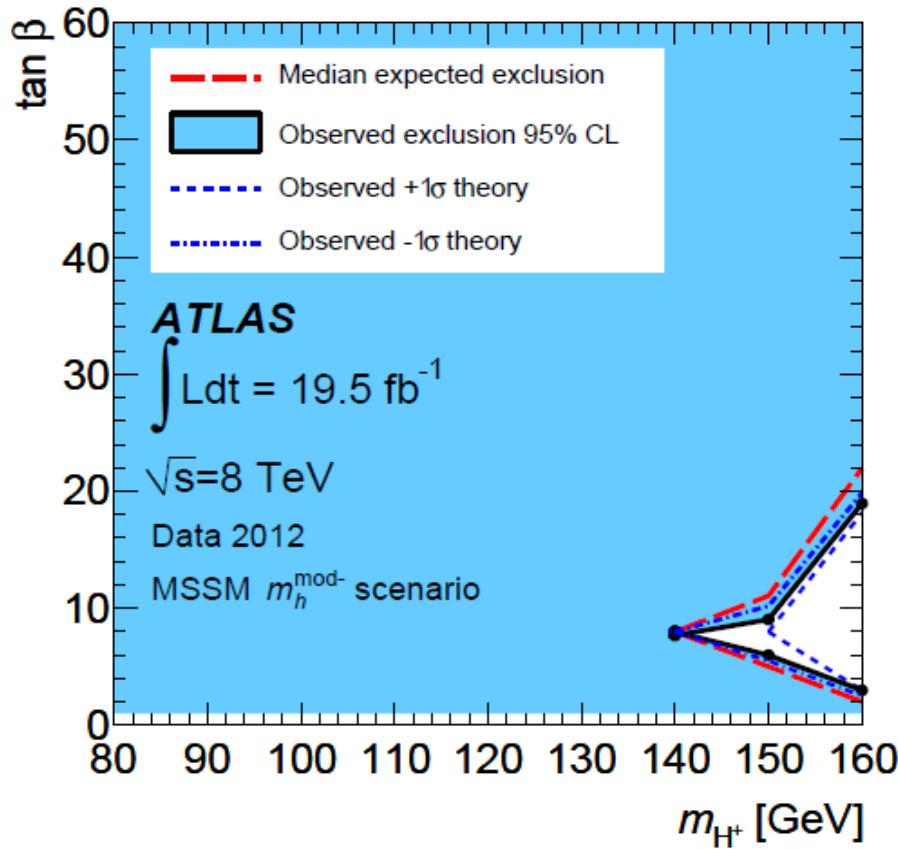
- **Several searches for A, H, H $^\pm$**
- At large $\tan\beta$, mostly H/A $\rightarrow bb$, but H/A $\rightarrow \tau\tau$ usually more sensitive
- Combine several channels, with leptonic and hadronic tau decays
- *Strong constraints on large $\tan\beta$ scenarios, for mA < ~1 TeV*



- In 2HDM, A \rightarrow Zh can be dominant decay, especially below ttbar threshold
- A is a narrow resonance in 220 – 1000 GeV
- Look for Z \rightarrow ll + h \rightarrow bb or $\tau\tau$
and Z \rightarrow vv + h \rightarrow bb
- *Excludes complimentary lower tan β space*

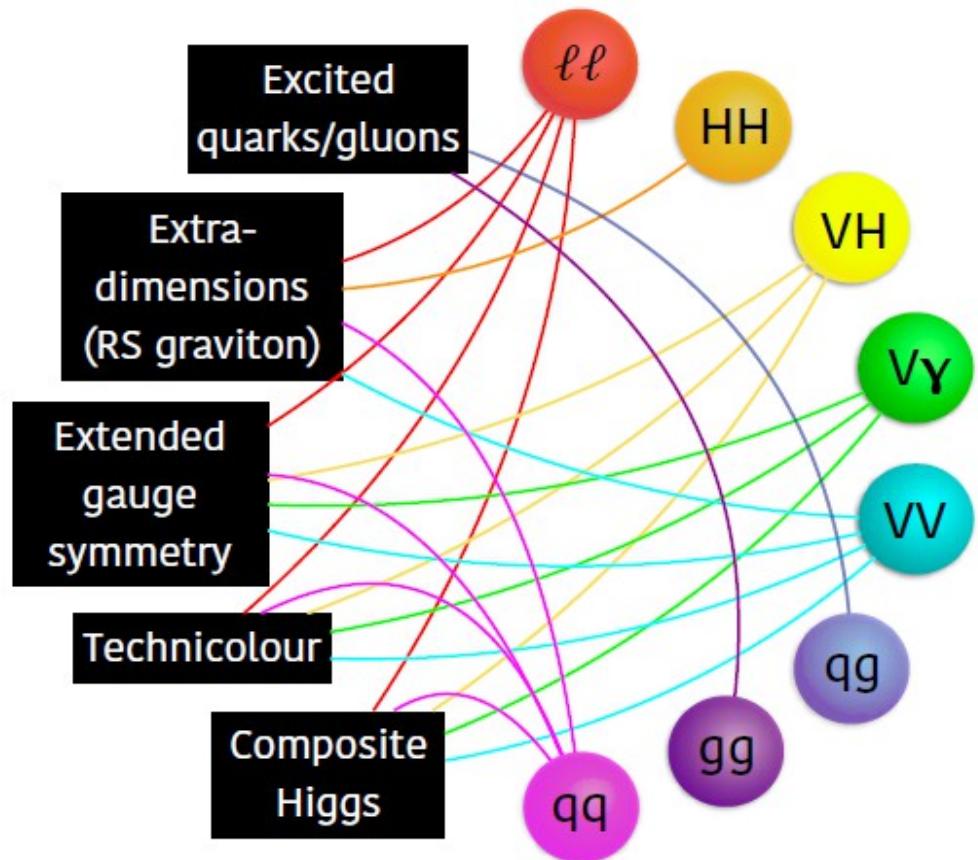


- $t \rightarrow H^\pm b$, $H^\pm \rightarrow \tau \nu$
 - Rules out much of MSSM for H^\pm mass < 160 GeV
- Also search for $H^\pm \rightarrow WZ$ with VBF, for Georgi-Machacek Higgs Triplet model

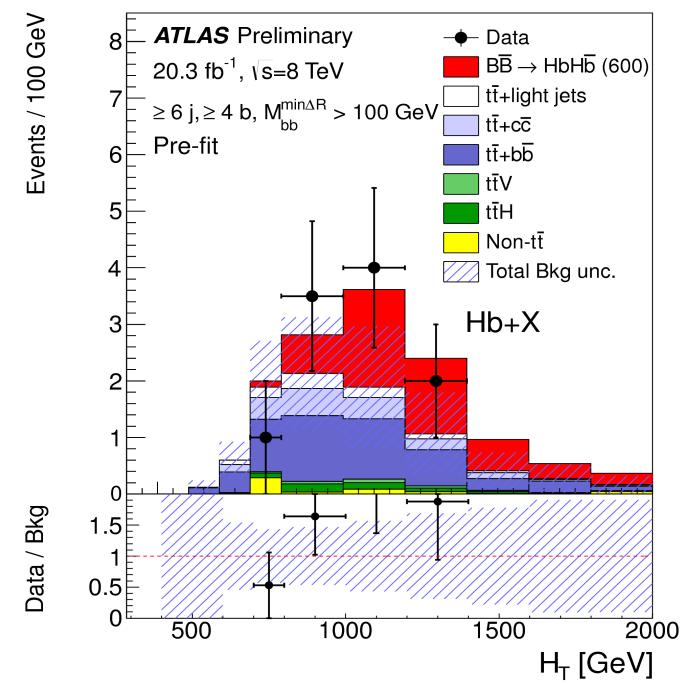
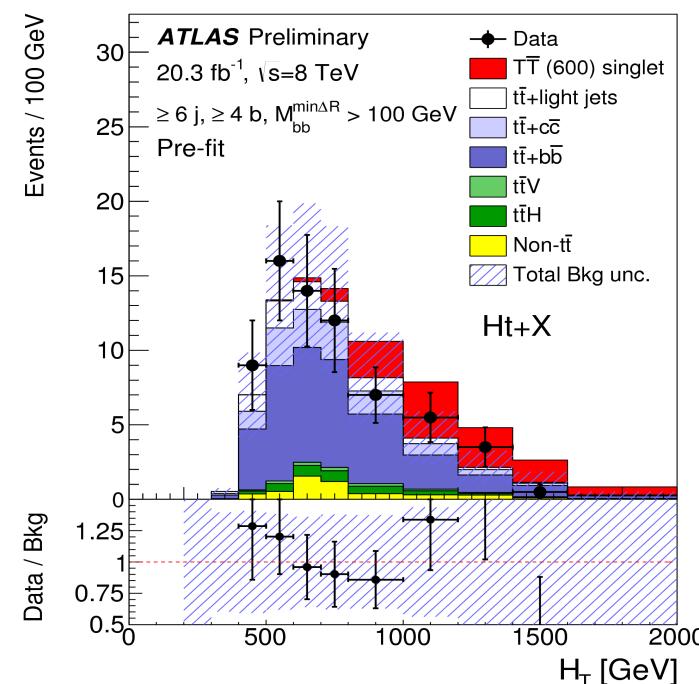
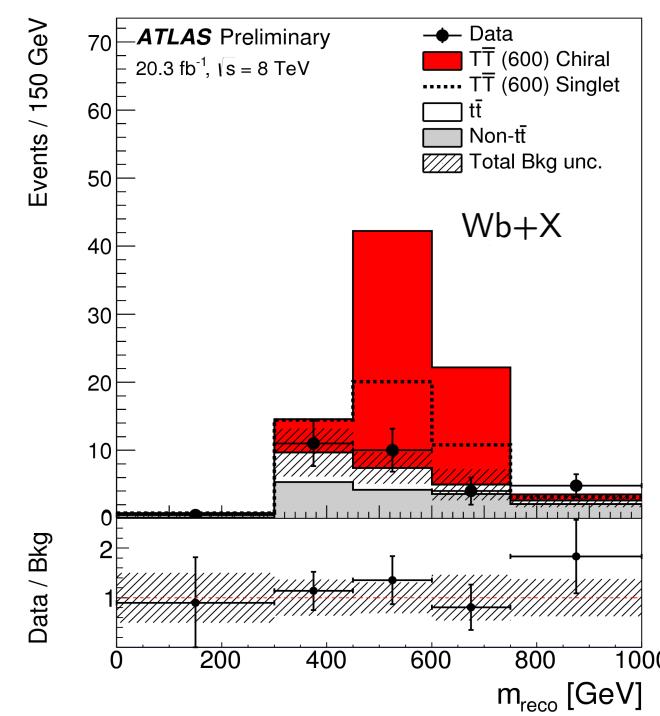
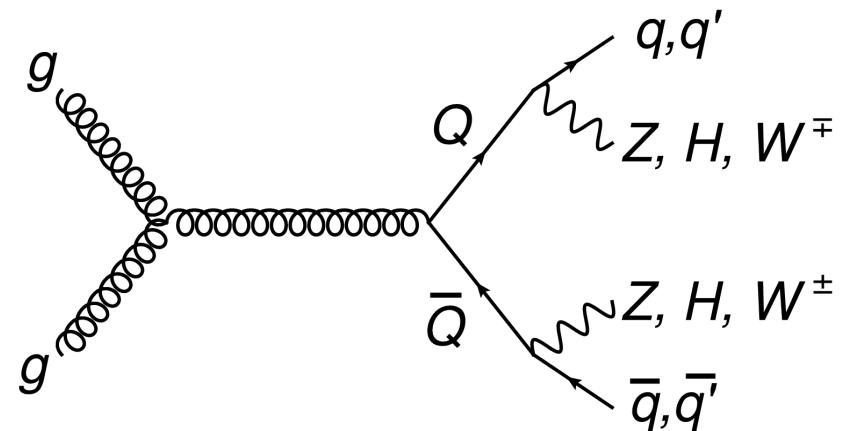


Other Solutions to the Hierarchy Problem

- Composite Higgs / Little Higgs \rightarrow **Vector-like quarks (T,B)**
 - Can cancel Higgs mass divergences from top loops
 - Color-triplet spin-1/2 fermions
 - Left and right handed under SU(2)
- These and other models can also predict **new resonances**
- Great way to find BSM!

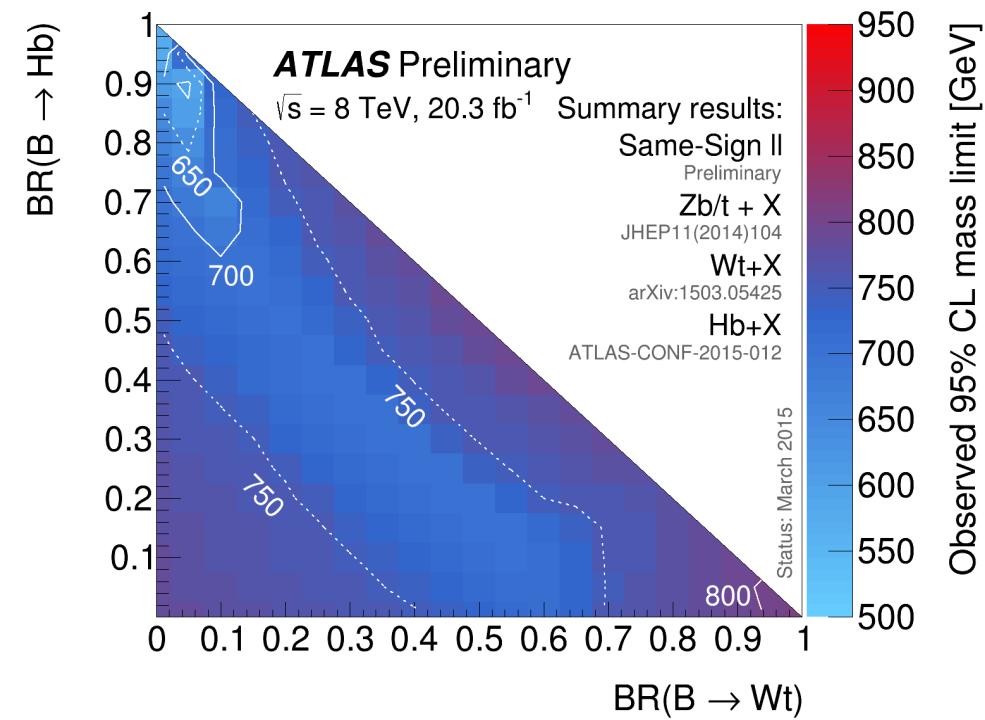
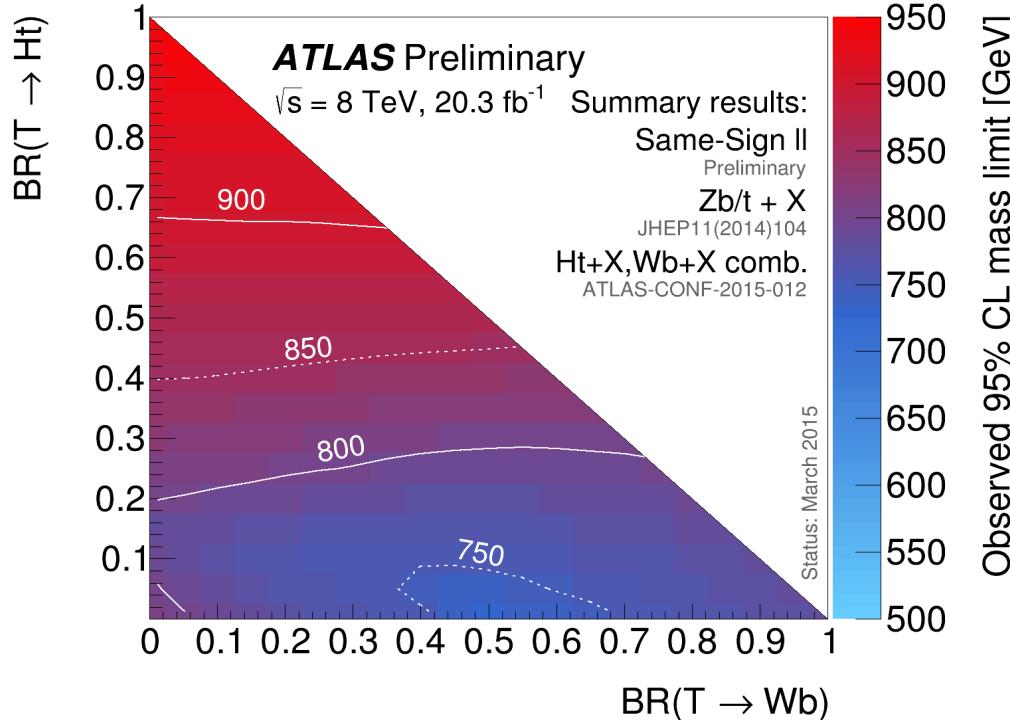
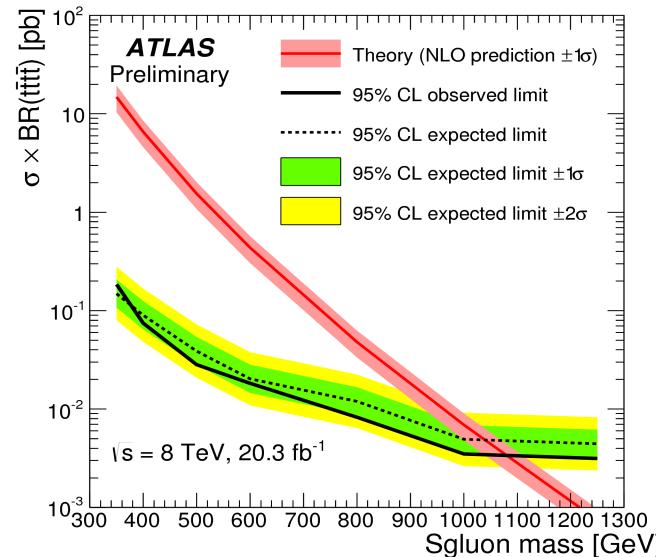


- Look for the possible VLQ decays, all of which give **lepton+jets+MET**
- Optimized searches for:
 - $T\bar{T} \rightarrow Wb+X$
 - $T\bar{T} \rightarrow Ht+X$
 - $BB \rightarrow Hb+X$



Vector-like quarks

- Combined with other VLQ searches
 - Excludes T below 715-950 GeV
 - Excludes B below 575-813 GeV
- Also constrains 4t production

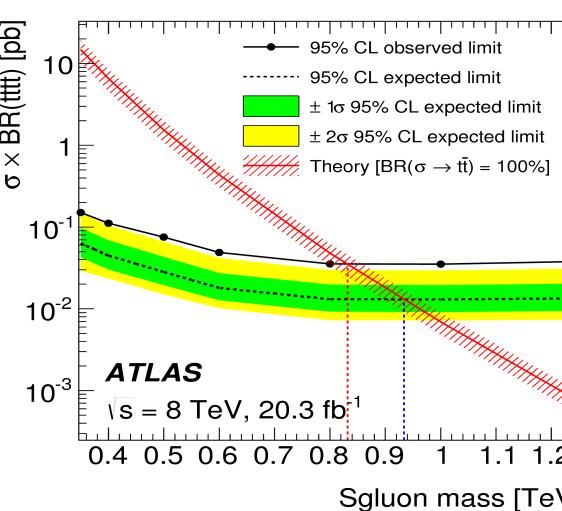
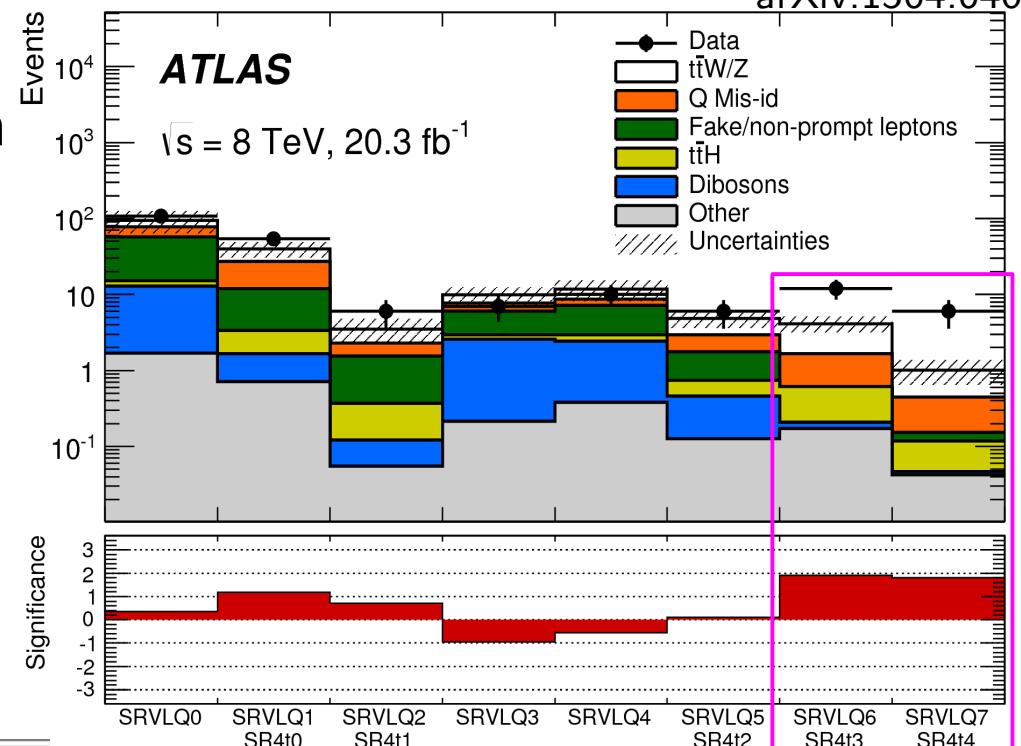


NEW! B-jet(s) with Same-sign Leptons and MET

arXiv:1504.04605

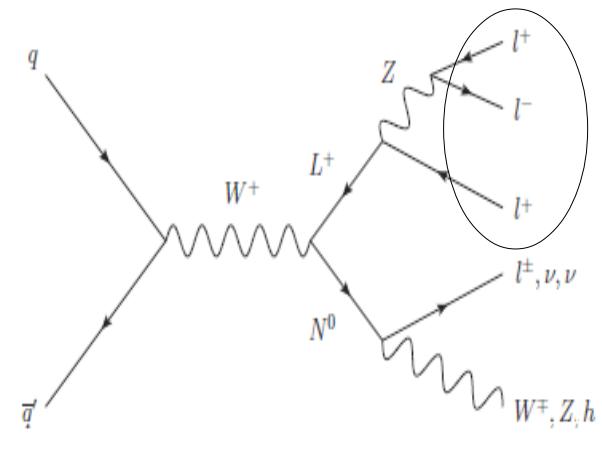
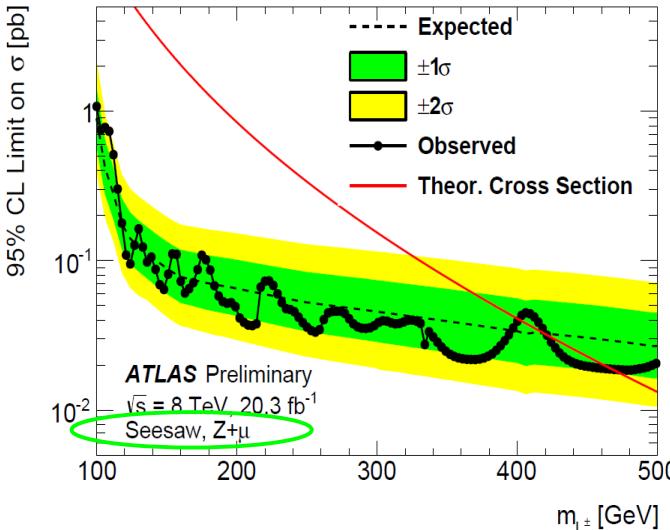
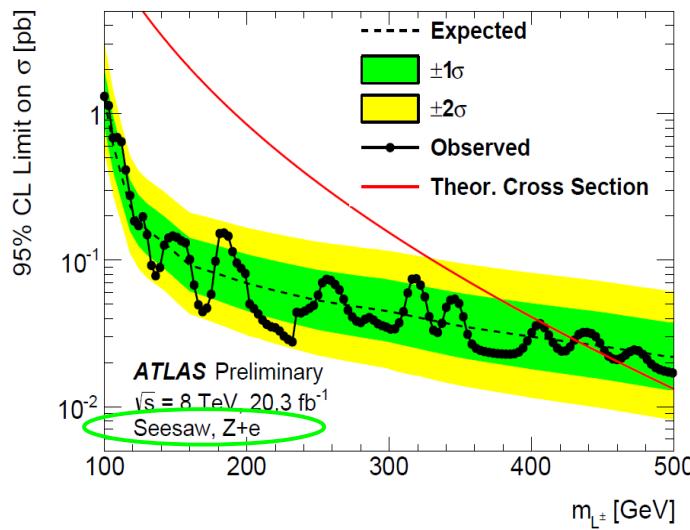
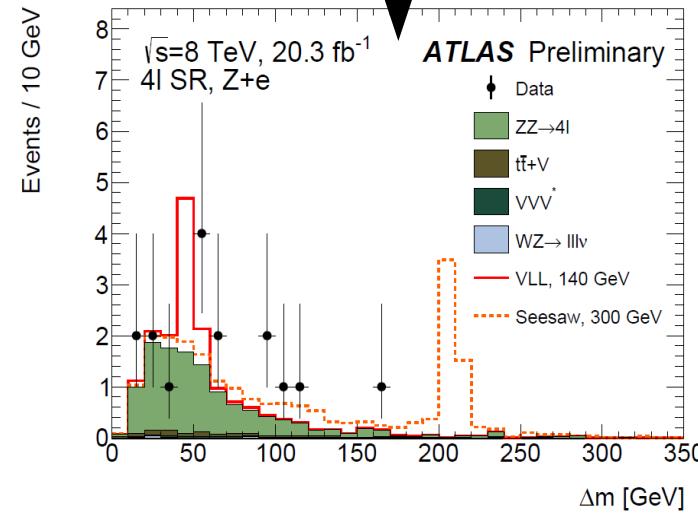
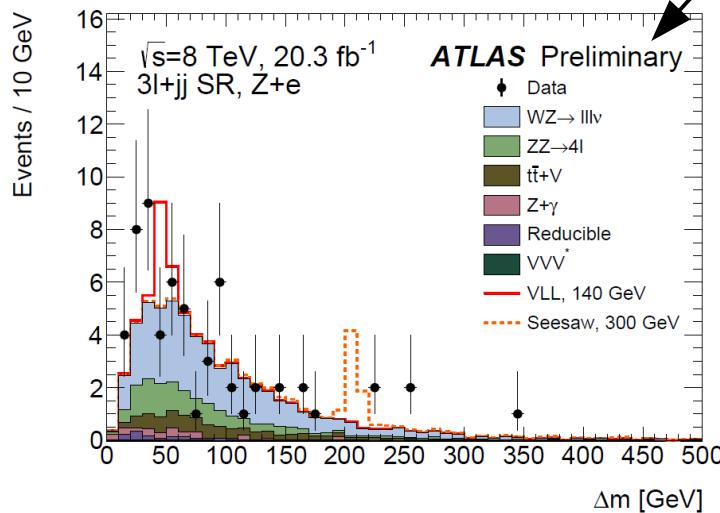
- Also sensitive to vector-like quarks, chiral b', 4-top production
- 2.5 σ excess with 2/3 b-jets and large MET and large H_T
 - Main background is tt+X, taken from simulation
 - tt+X cross-checked with several generators, scaled to NLO
- Will follow up in Run 2

Definition		Name	
$e^\pm e^\pm + e^\pm \mu^\pm + \mu^\pm \mu^\pm + eee + ee\mu + e\mu\mu + \mu\mu\mu, N_j \geq 2$			
$400 < H_T < 700 \text{ GeV}$	$N_b = 1$	$E_T^{\text{miss}} > 40 \text{ GeV}$	SRVLQ0
	$N_b = 2$		SRVLQ1
	$N_b \geq 3$		SRVLQ2
$H_T \geq 700 \text{ GeV}$	$N_b = 1$	$40 < E_T^{\text{miss}} < 100 \text{ GeV}$	SRVLQ3
		$E_T^{\text{miss}} \geq 100 \text{ GeV}$	SRVLQ4
	$N_b = 2$	$40 < E_T^{\text{miss}} < 100 \text{ GeV}$	SRVLQ5
		$E_T^{\text{miss}} \geq 100 \text{ GeV}$	SRVLQ6
		$E_T^{\text{miss}} > 40 \text{ GeV}$	SRVLQ7
$e^+e^+, e^+\mu^+, \mu^+\mu^+, N_j \in [2, 4], \Delta\phi_{\ell\ell} > 2.5$			
$H_T > 450 \text{ GeV}$	$N_b \geq 1$	$E_T^{\text{miss}} > 40 \text{ GeV}$	SRttee, SRtte μ , SRtt $\mu\mu$



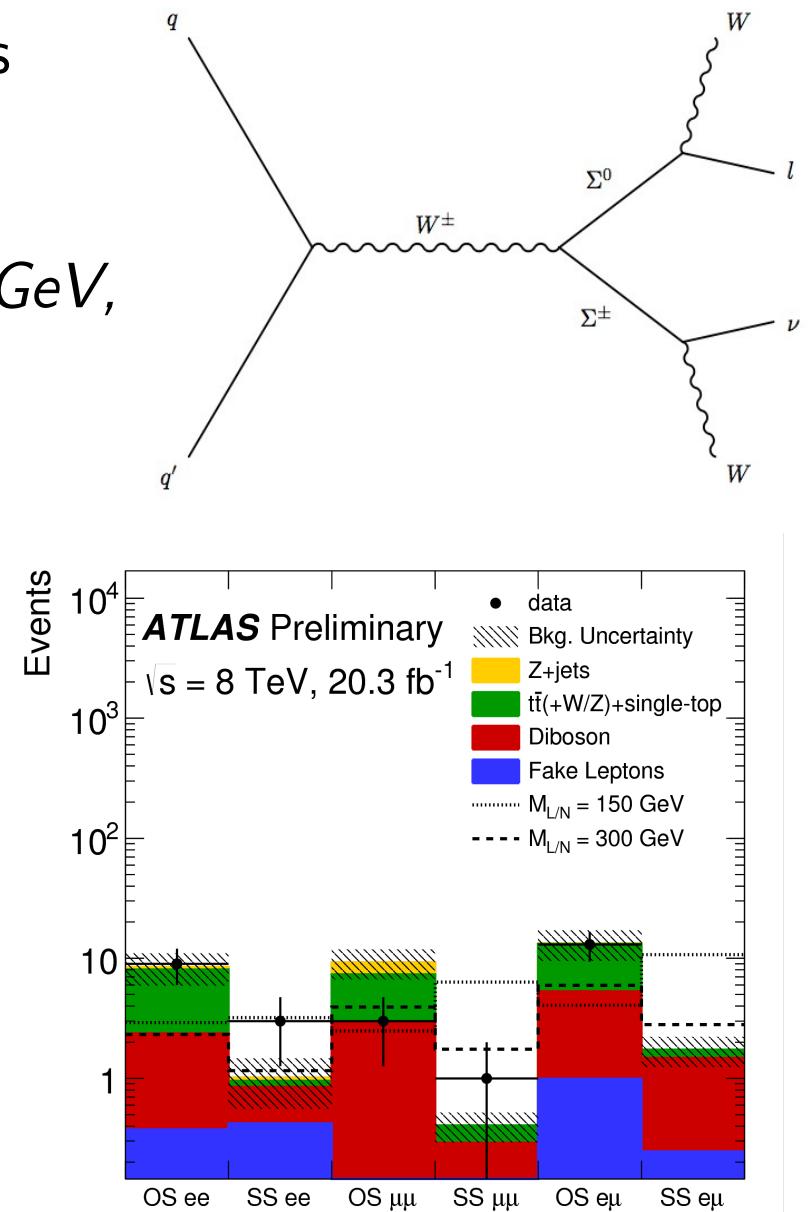
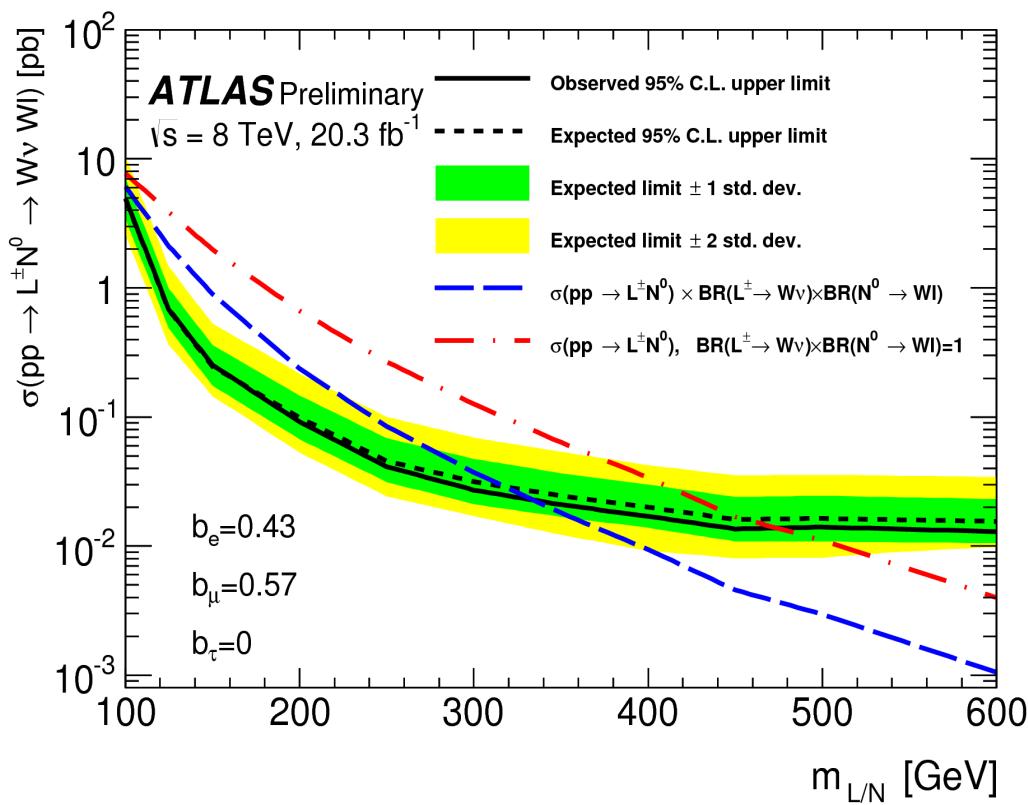
p-value: 2.5 σ

- Search for $Z+e$ or $Z+\mu$ resonance
 - Also look for **additional jets** or **4th lepton**



- Interpretations:
- Vector-like Leptons**
 - Type-III Seesaw Lepton model of ν mass
 - Model independent limit on cross-section

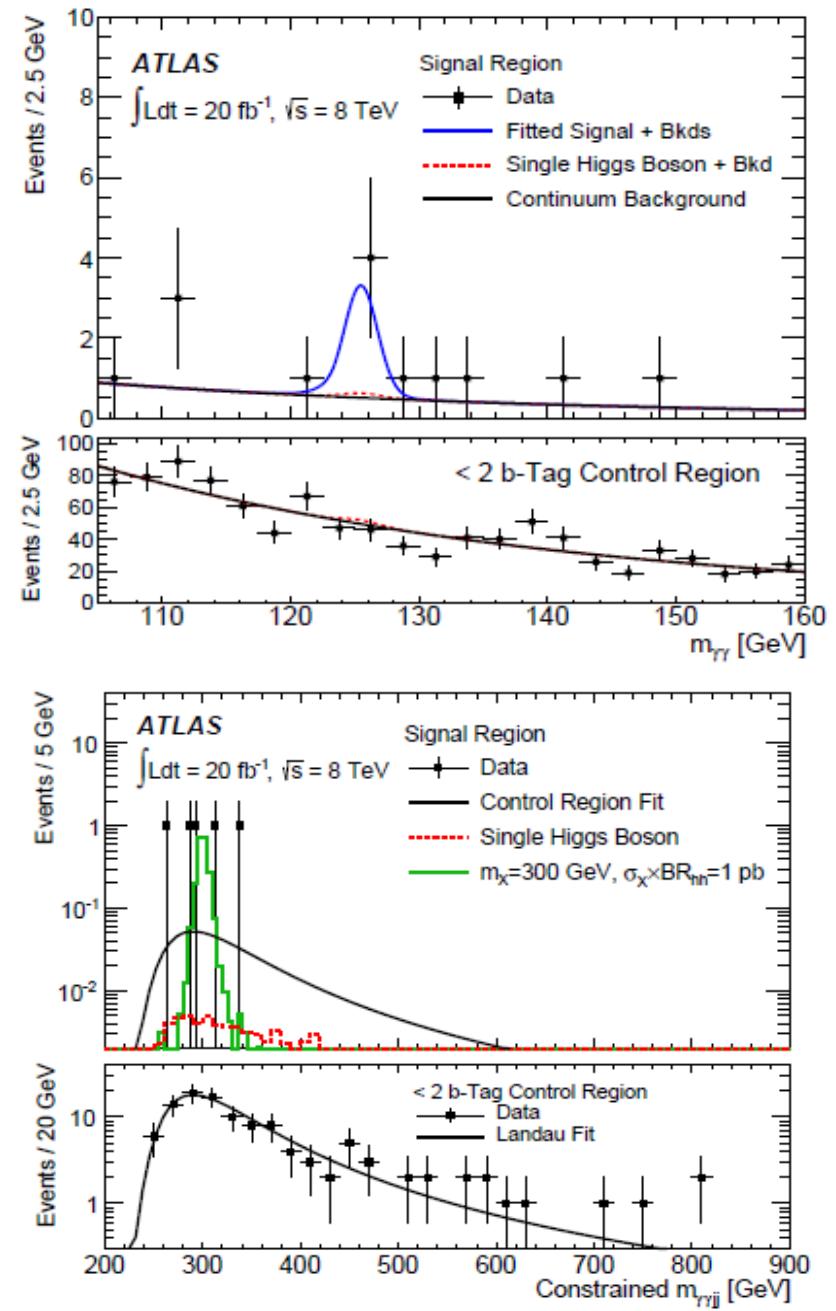
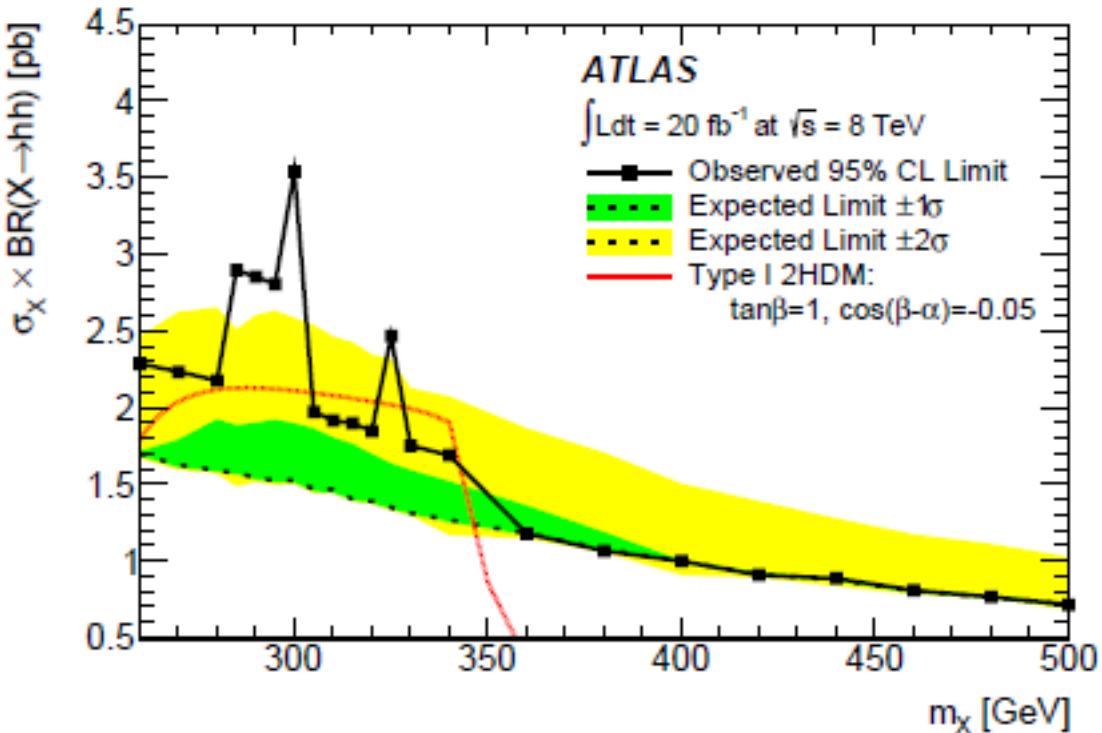
- Also sensitive to Type III Seesaw leptons
- Non-resonant, look for excess of events
- *Excludes Heavy Leptons up to 325-540 GeV, depending on theoretical parameters*



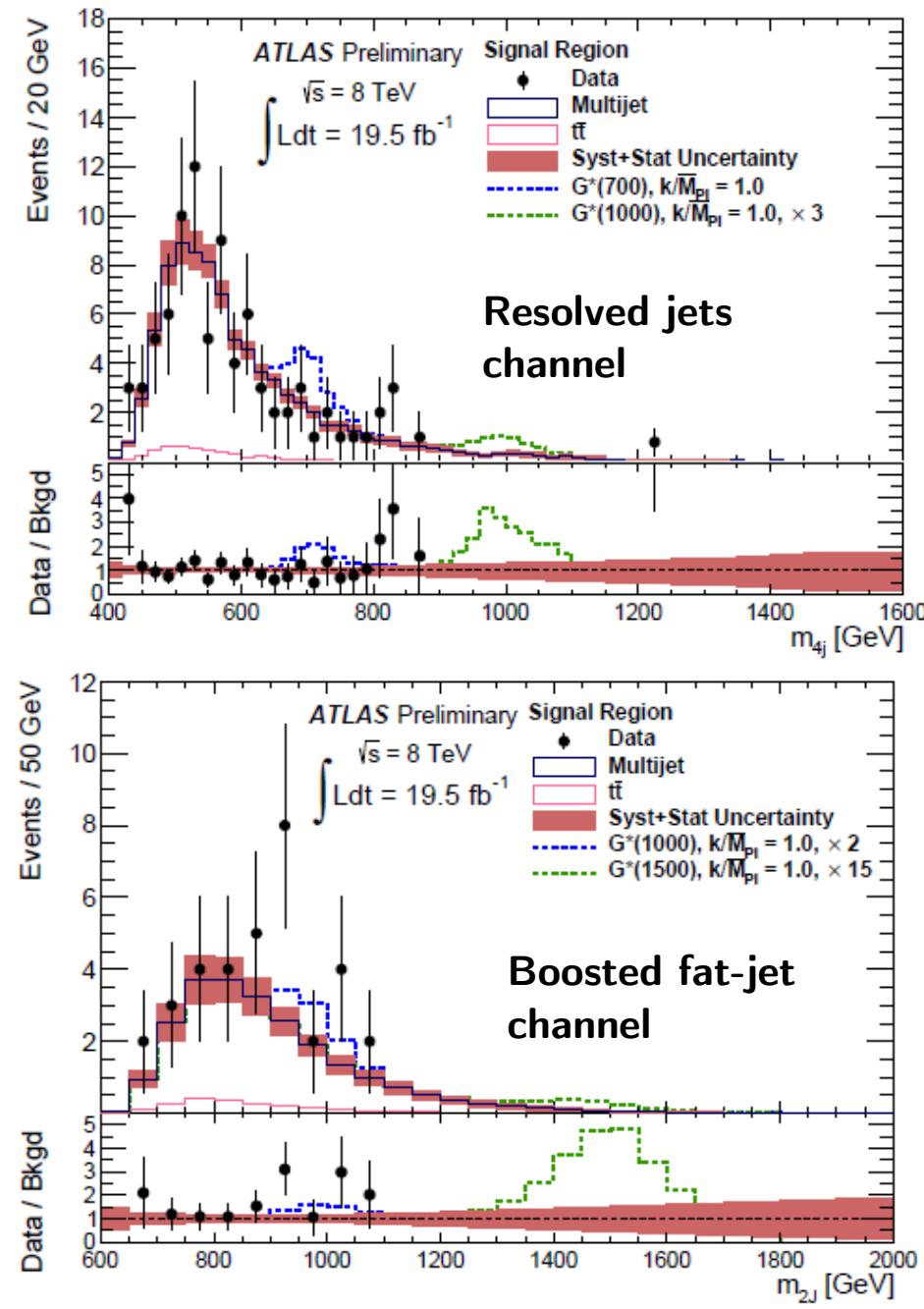
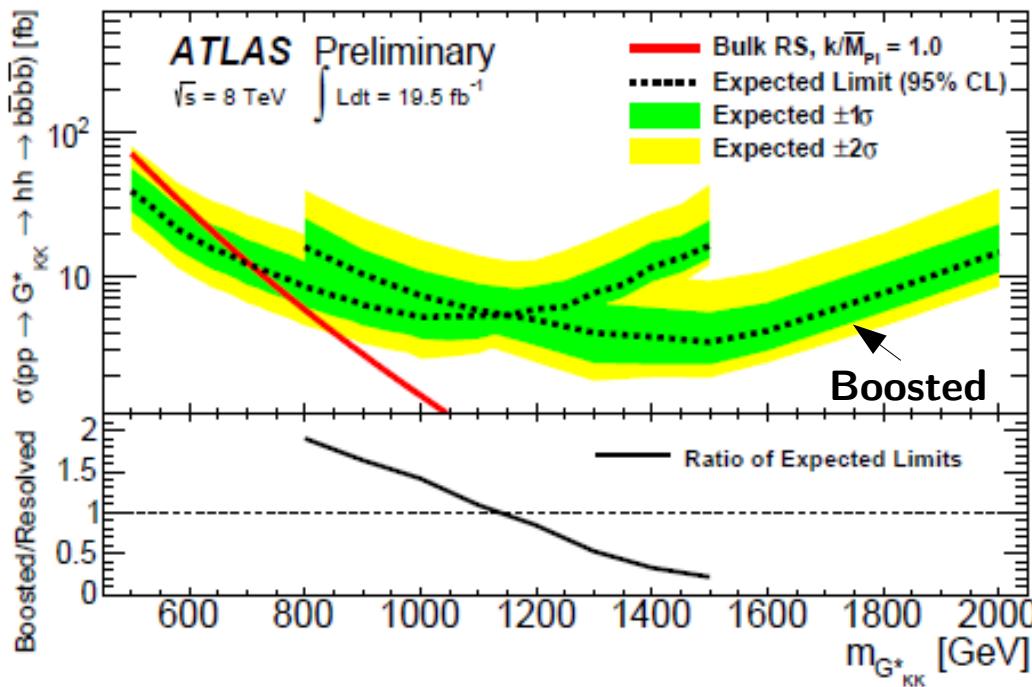
hh resonances in the bb $\gamma\gamma$ channel

arXiv:1406.5053

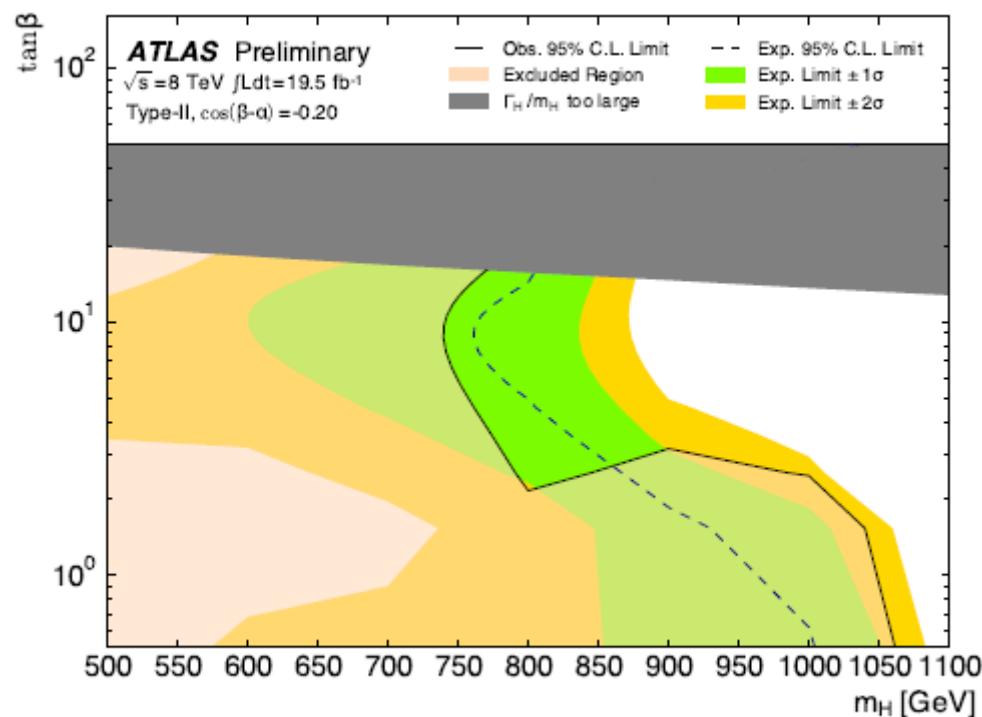
- Narrow $X \rightarrow hh$ resonance
- Look in the clean $bb + \gamma\gamma$ final-state
- Small excess (2.4σ) at $X \sim 300$ GeV
- *Important search for Run 2*



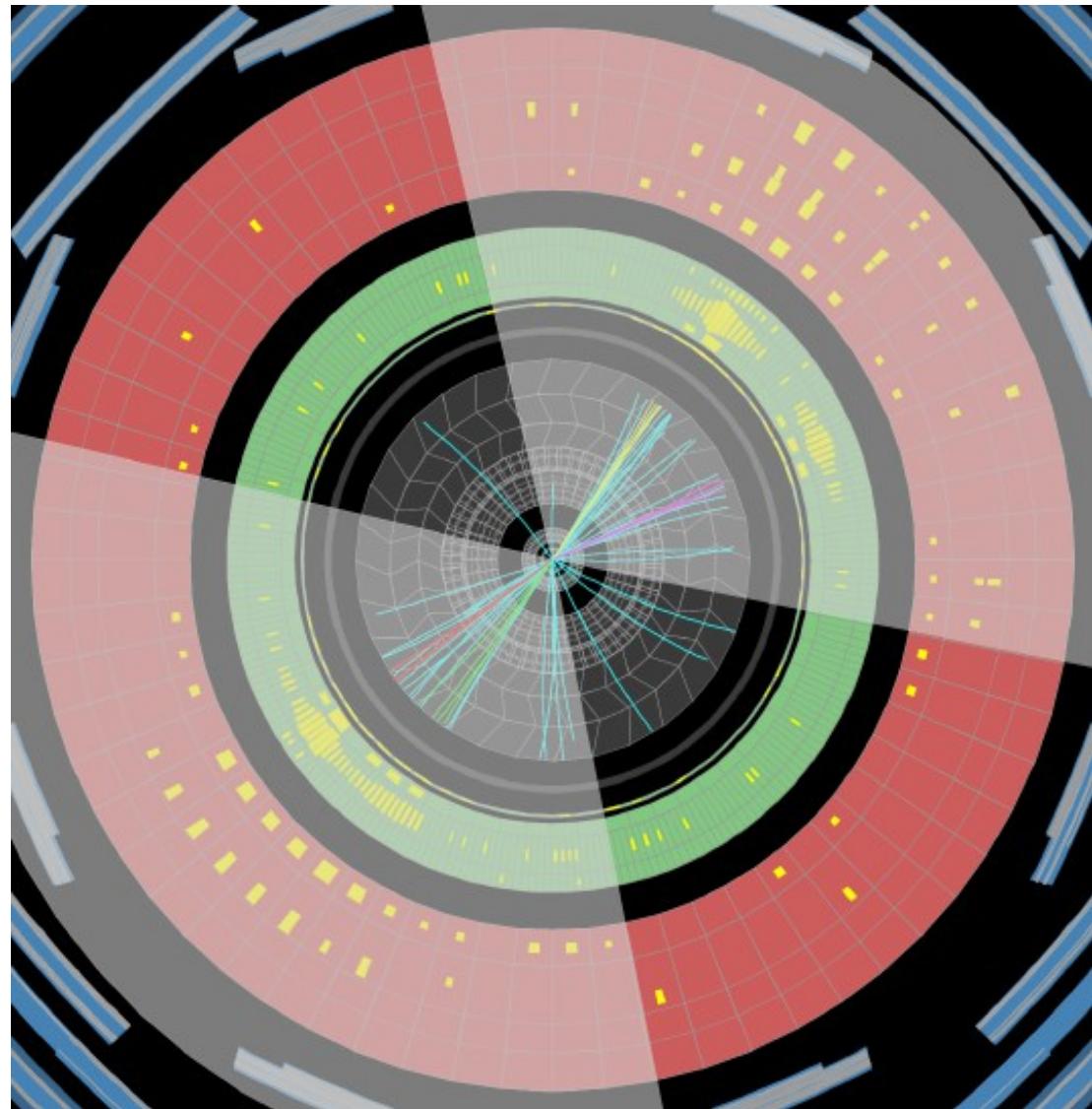
- Narrow $G^* \rightarrow hh$ resonance
- h can be ***boosted***
 - reco as single fat-jet
 - b-tag using track-subjets
 - Adds sensitivity at large mass
- *Important search for Run 2*



- $G^* \rightarrow hh$ excluded up to 990 GeV ($k/M_{Pl}=2$)
- *Also interpreted in 2HDM as $H \rightarrow hh$*



Type-II 2HDM, $\cos(\beta - \alpha) = -0.2$

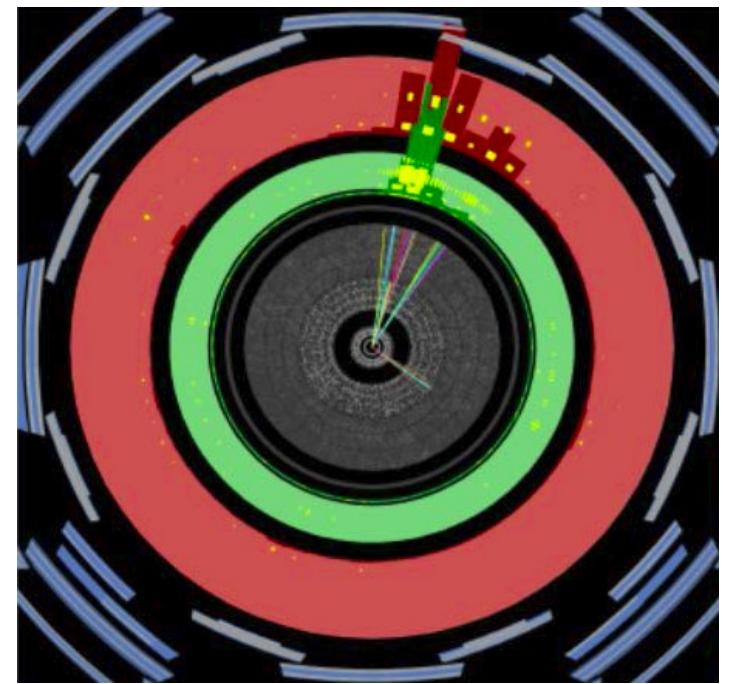
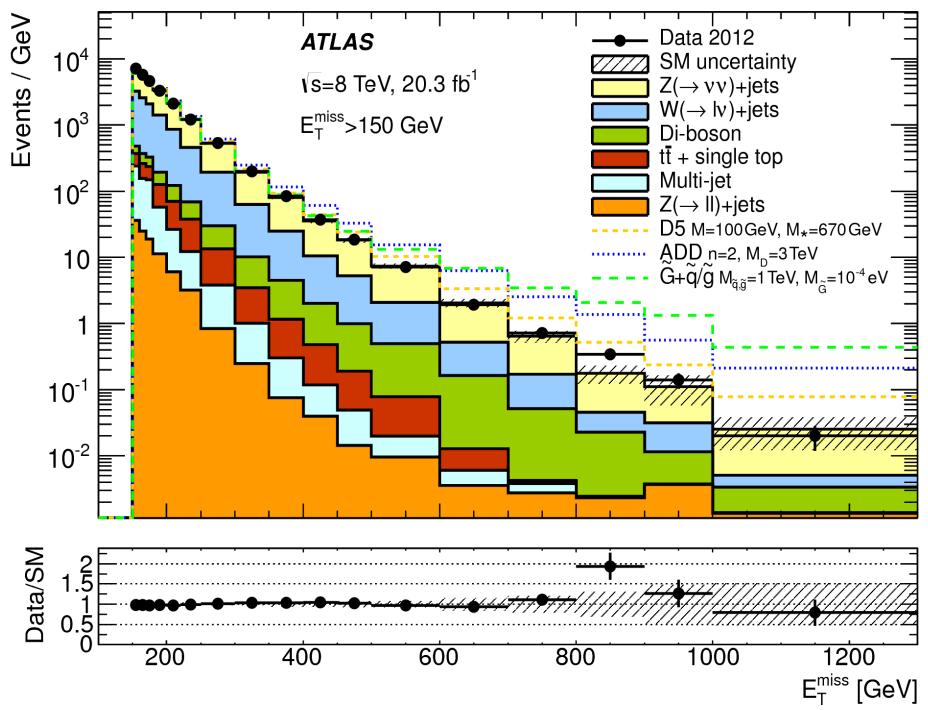
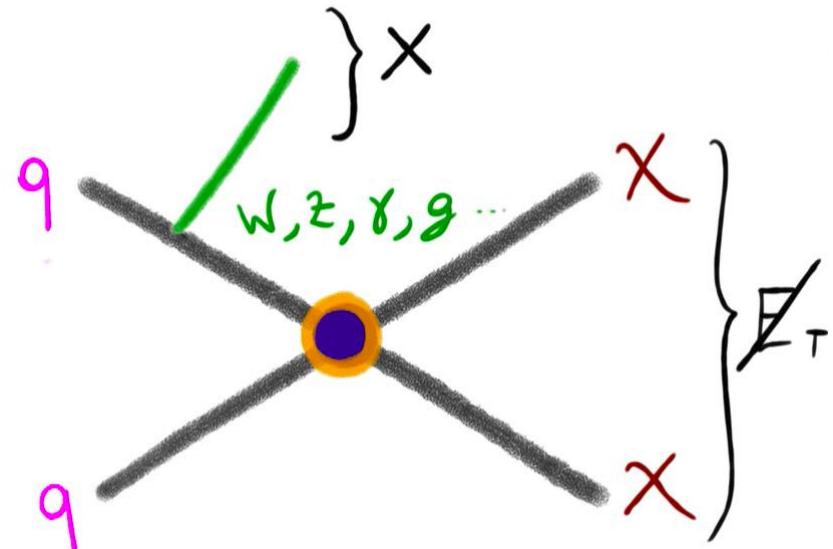


Event selected by boosted analysis

Direct Searches for Dark Matter

arXiv:1502.01518

- Look for MET along with jet, photon, W/Z, Higgs, heavy quark, ...
 - Example: **mono-jet search**
 - Lepton and isolated track vetos
 - Jet p_T / MET > 0.5
 - $Z \rightarrow v\bar{v} + \text{jet(s)}$ constrained using W and $Z \rightarrow ll$ control regions

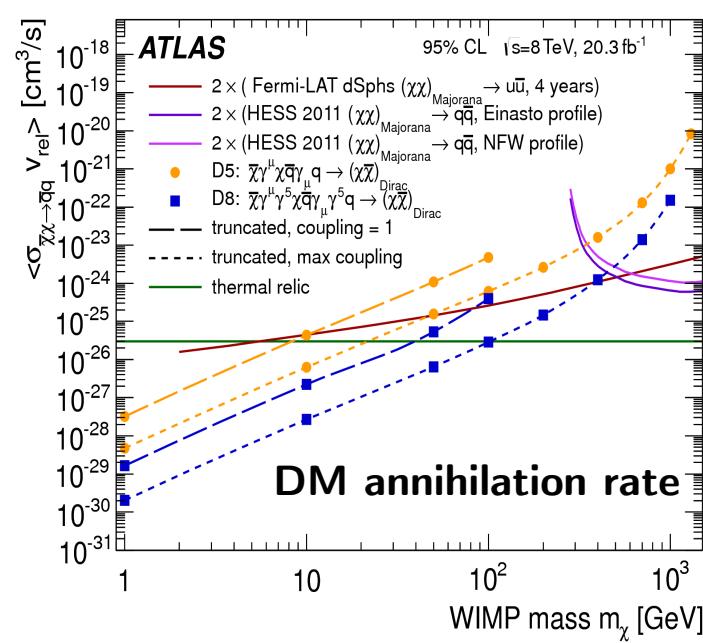
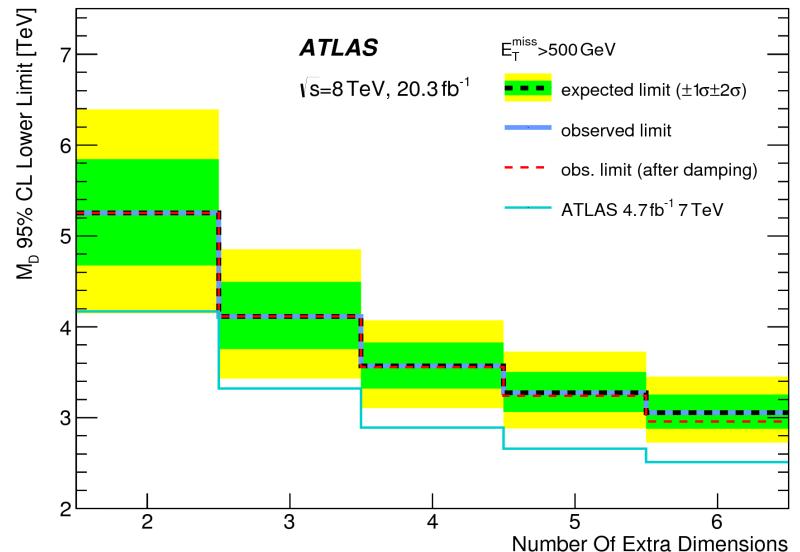
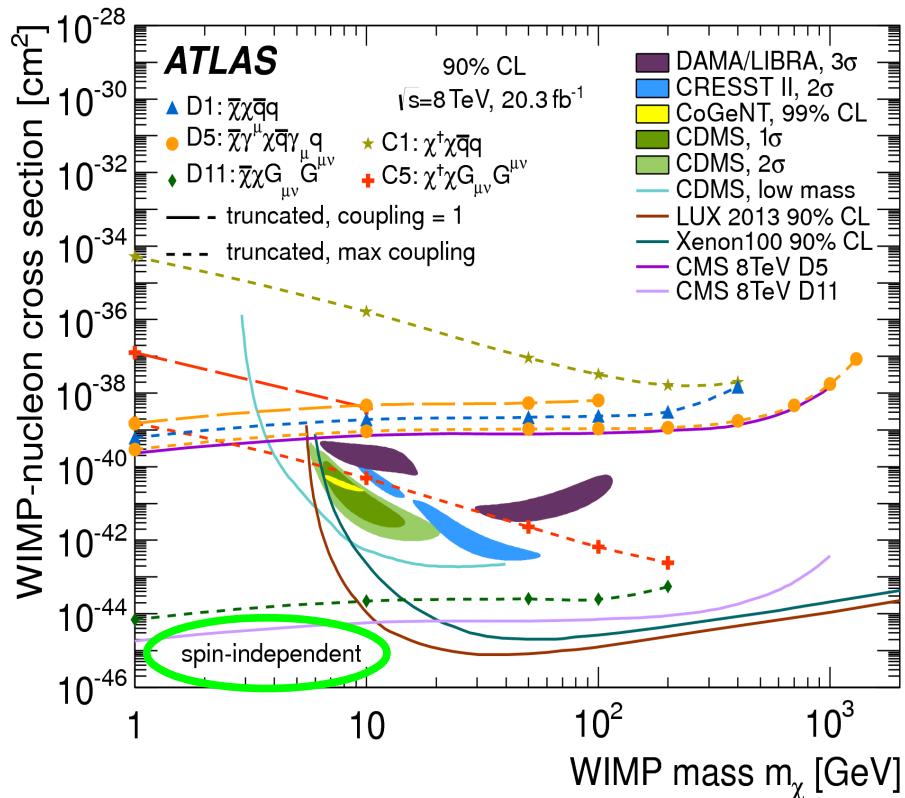


Direct Searches for Dark Matter

arXiv:1502.01518

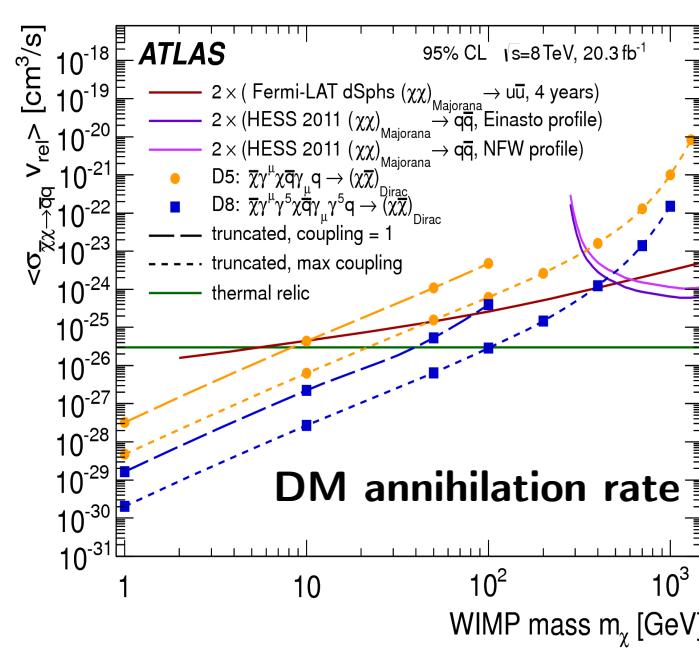
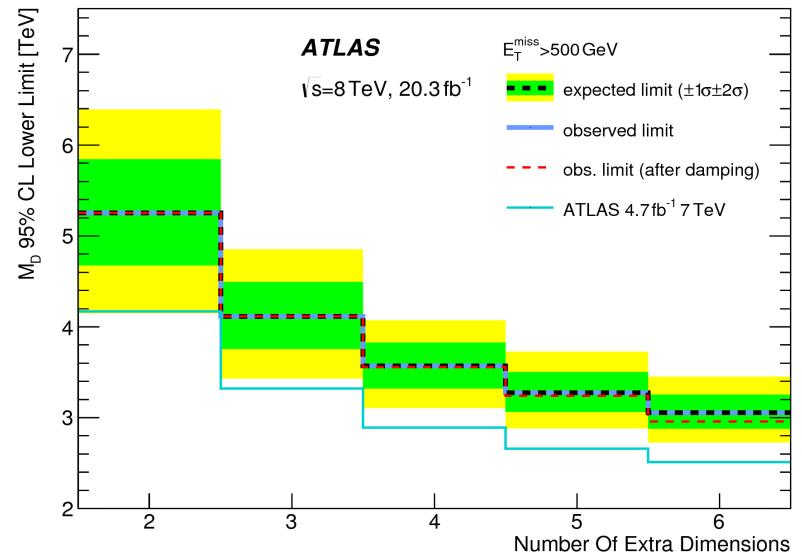
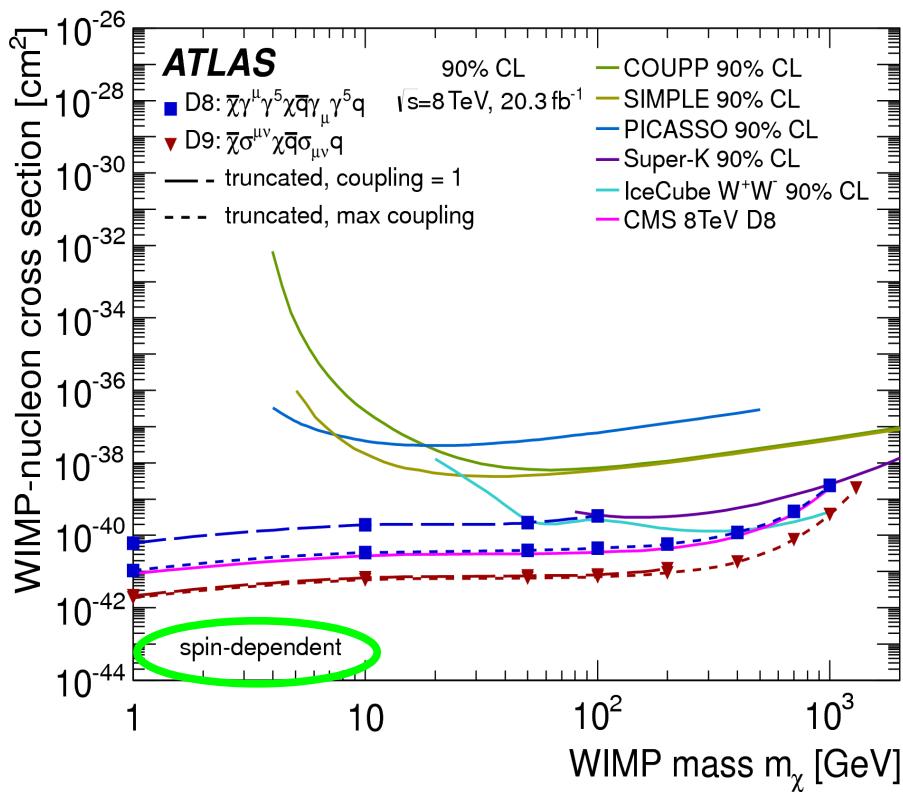
- Mono-jet search interpretations**

- Large extra dimensions
- Dark matter production (effective operators)
- Gravitino + squark/gluino
- Invisible Higgs decay

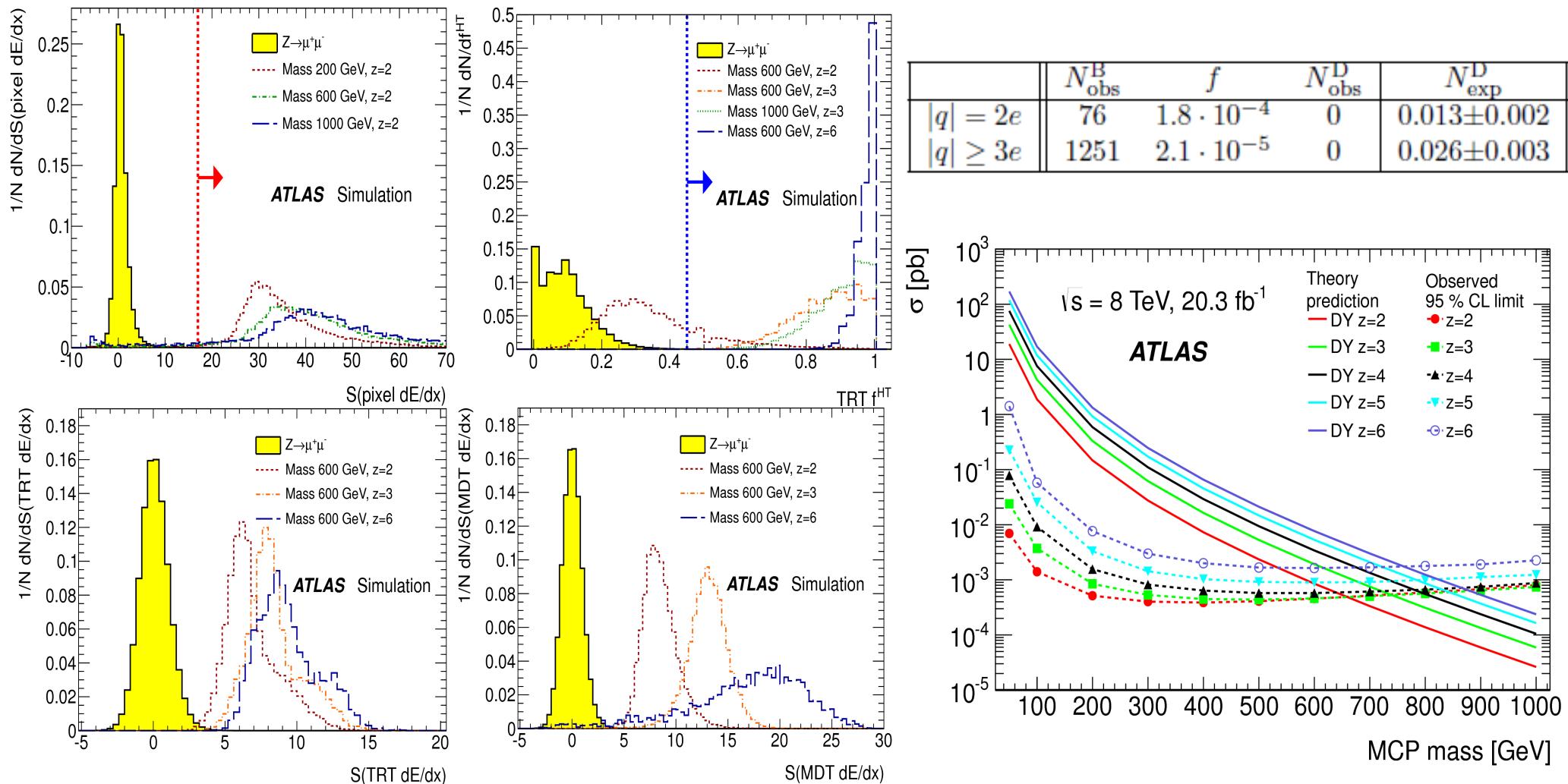


- Mono-jet search interpretations**

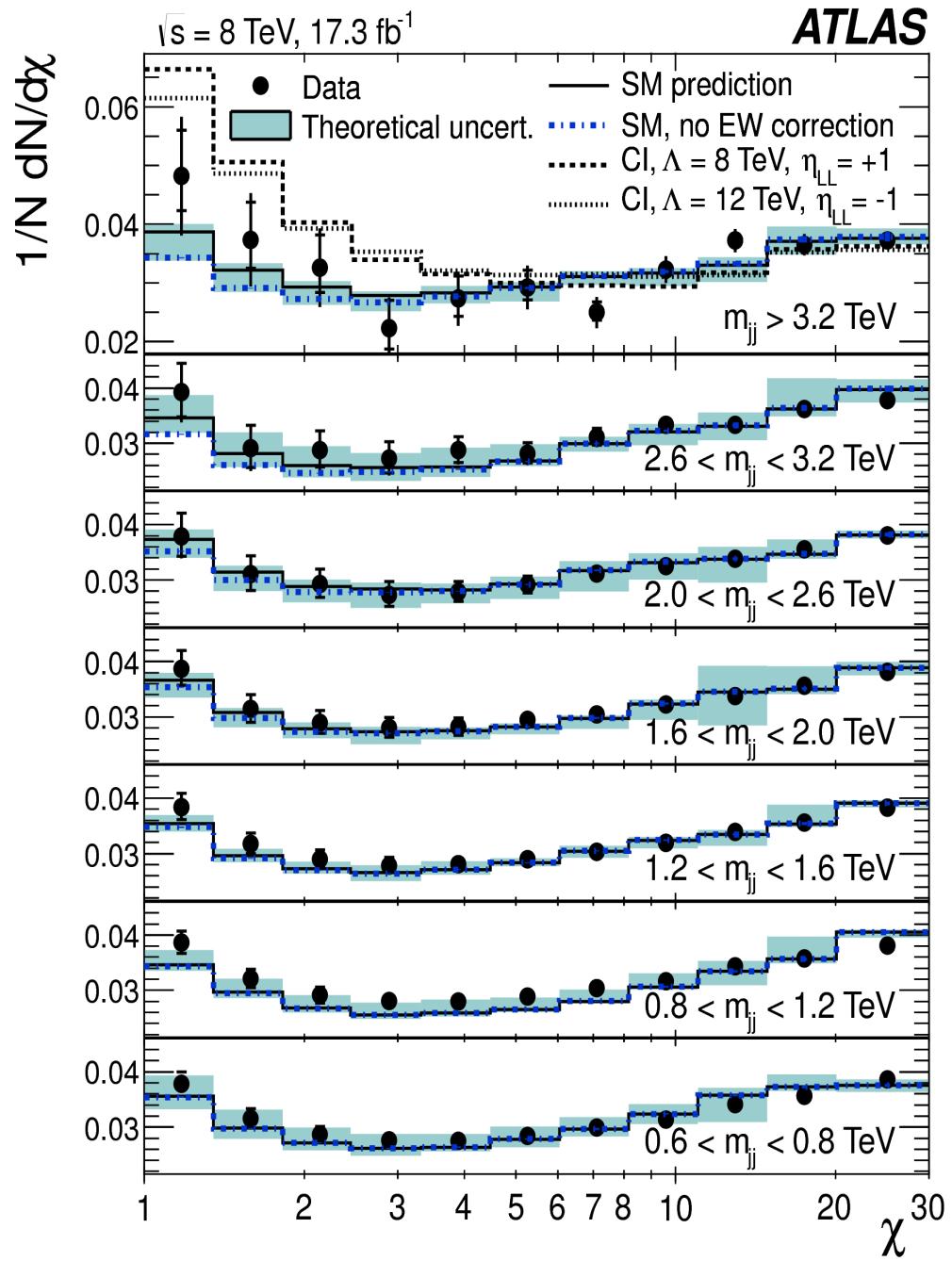
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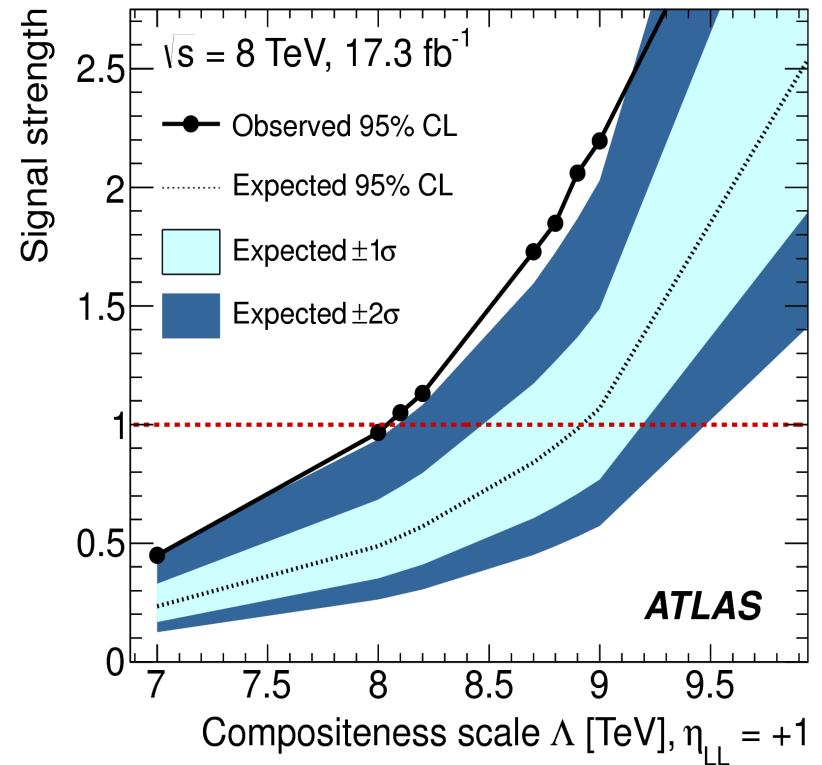
- Look for particles with $|q|=2,3,4,5,6$ electron charge
- Large dE/dx in pixel, straw tracker, and muon system
- *Excludes DY production of multi-charge particles up to ~ 800 GeV*



- LHC di-jet production dominated by t-channel gluon exchange
 - steeply falling di-jet mass
 - angular distributions peaked at $|\cos \theta^*|=1$
- Sensitive to new contact interactions, quark compositeness, ...
- $\chi = e^{|y_1 - y_2|}$ in bins of m_{jj}
- QCD prediction reweighted to NLO, with EW corrections
- Amazing agreement with theory, small $\sim 2\sigma$ excess at large mass...



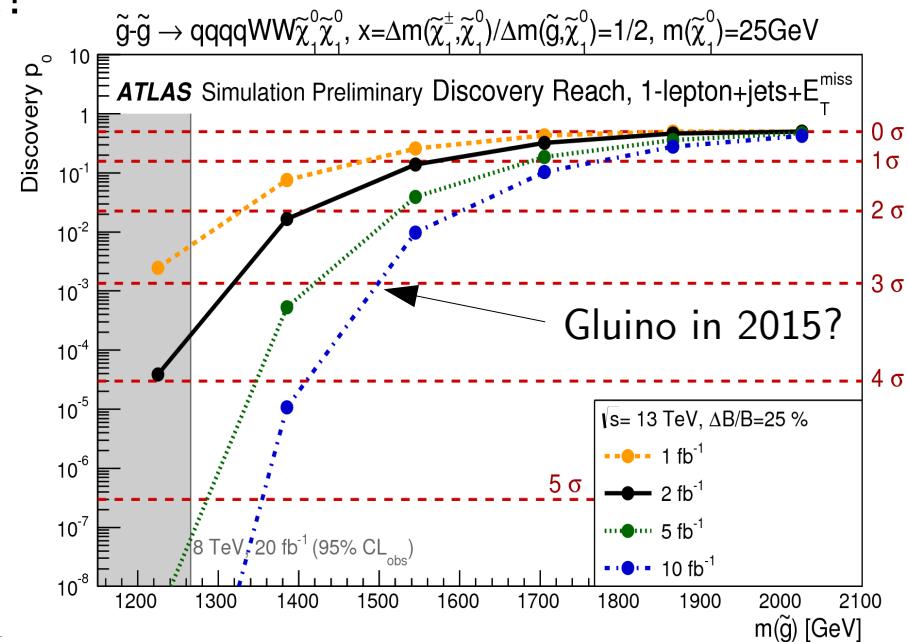
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Follow up quickly in Run 2!

Summary of Run 1 Searches

- Huge leap forward in BSM limits, both in variety and sensitivity
 - Only had time to highlight some of our many many searches!
- Great progress in addressing “holes” as well as new models
 - Clever new ideas can help cover new territory
 - Always more to do... continue to expand in Run 2
- General feeling of "Higgs and no BSM"?
 - Very unexpected! Unnatural? Anthropic?
 - Of course disappointing, but would be *amazing* outcome!
- LHC just now nearing design energy
 - Run2 will be exciting!
 - New heavy states could be discovered this year!

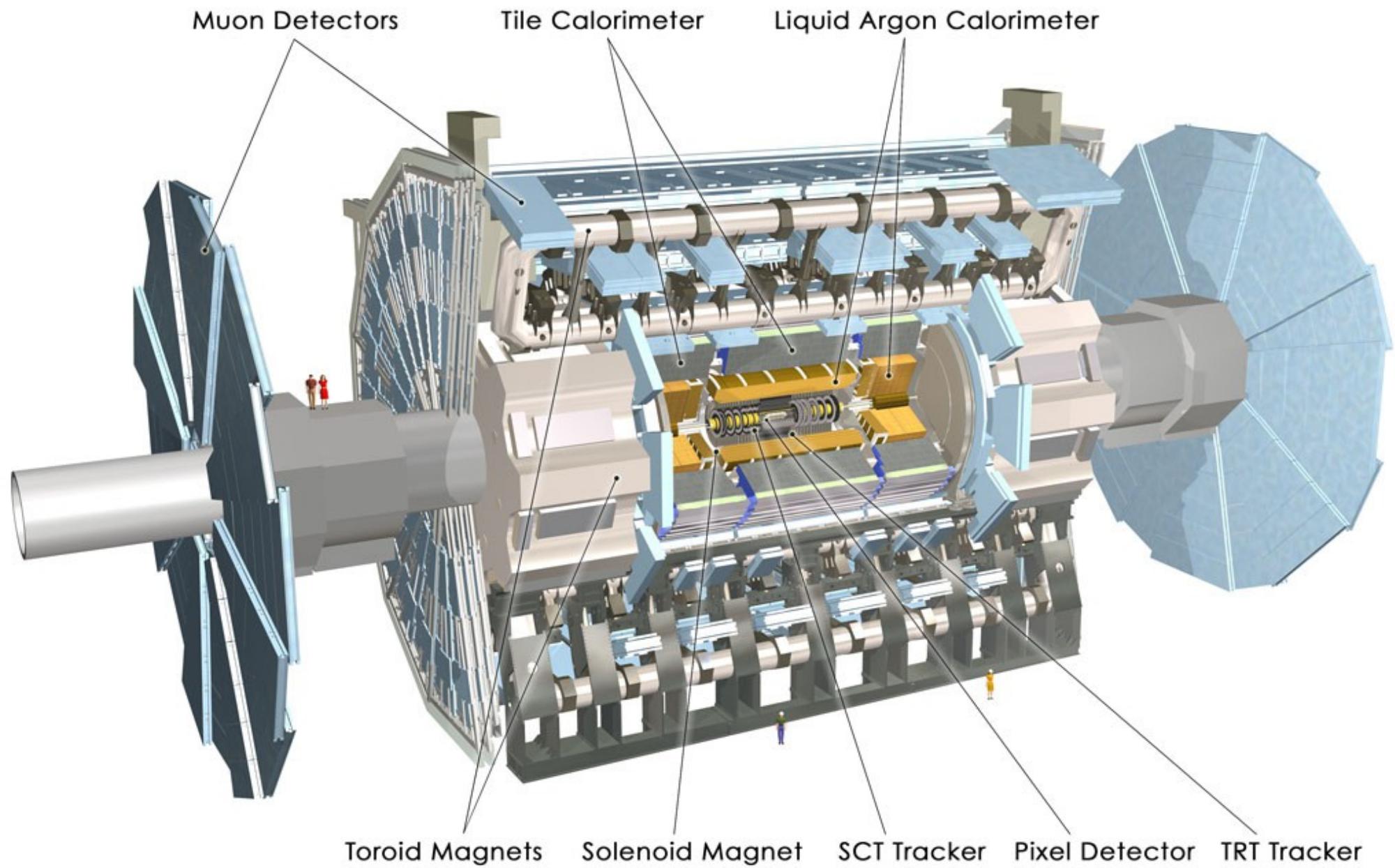


- ... the studios are pushing for a sequel!



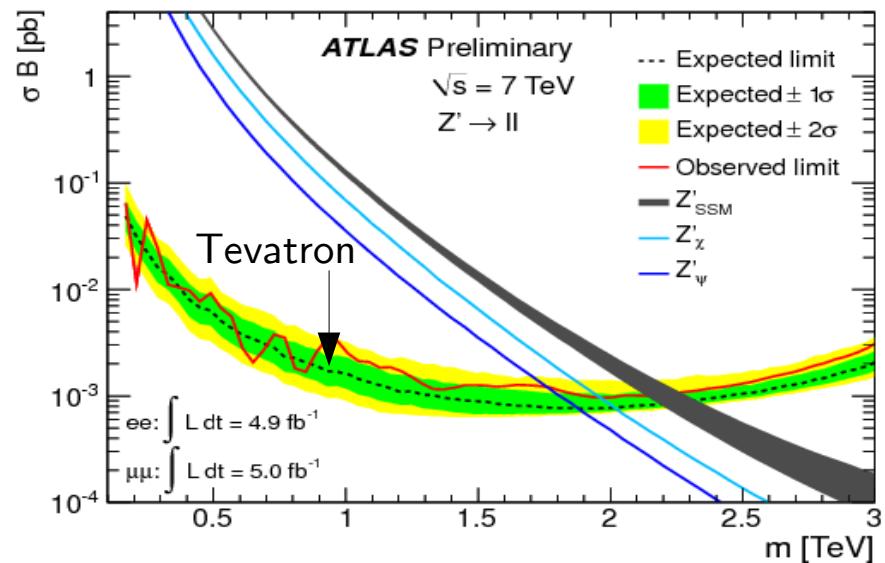
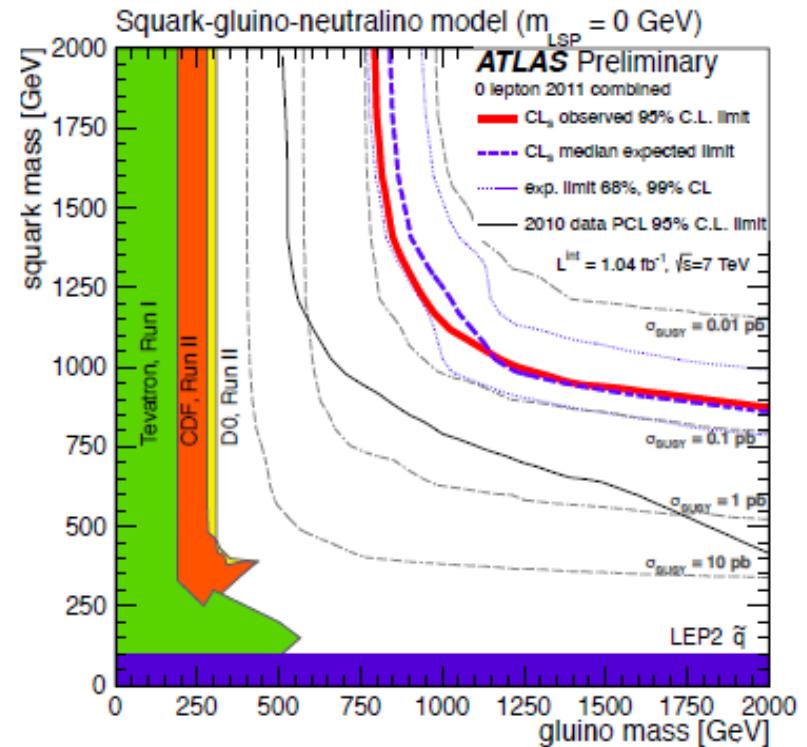
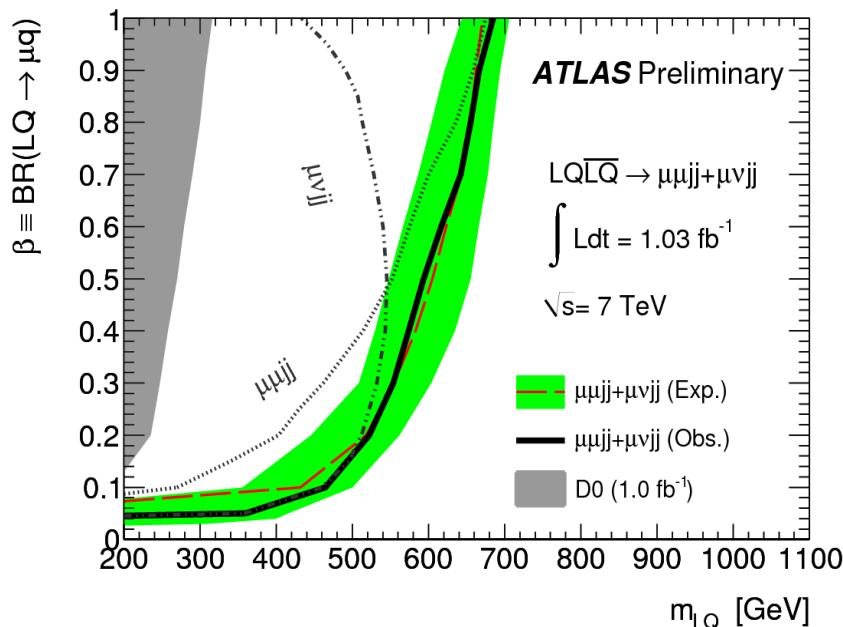
Backup

ATLAS



Early ATLAS BSM Searches

- Searches with 2010 and 2011 data were performing well!
 - Backgrounds understood
 - Systematics under good control
- Quickly became clear that nature was not giving up secrets easily...
- **Dig in and look harder!**



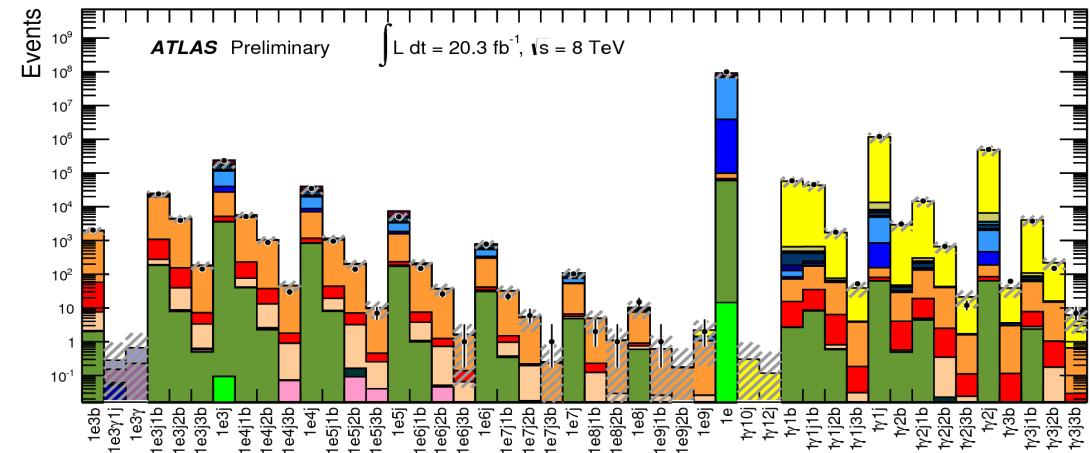
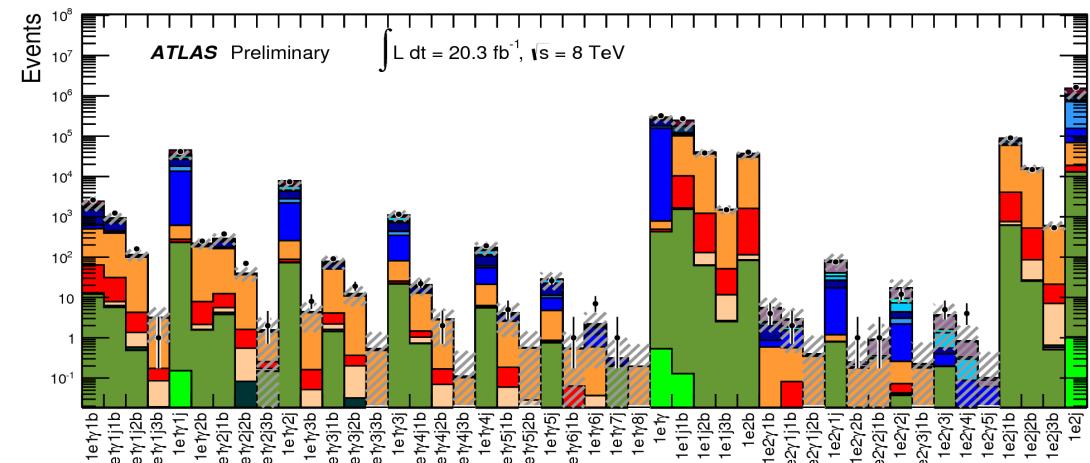
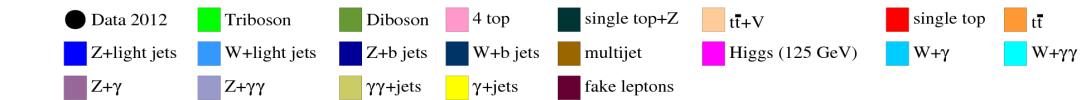
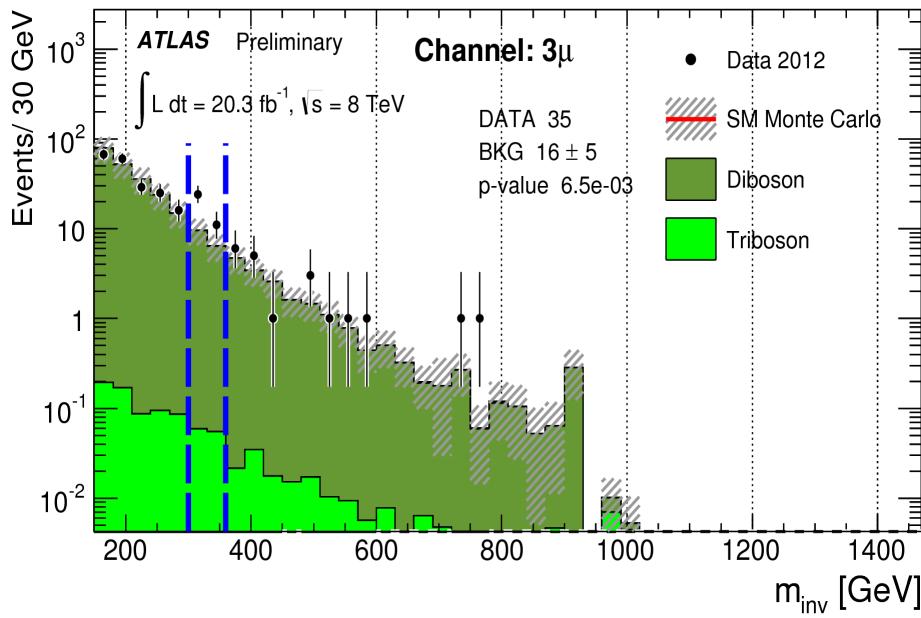
Search for SUSY with 2l+jets+MET

arXiv:1503.03290

Channel	SR-Z ee	SR-Z $\mu\mu$	SR-Z same-flavour combined
Observed events	16	13	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
Z/γ^* + jets (jet-smearing)	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
Rare Top	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

General Search Methods

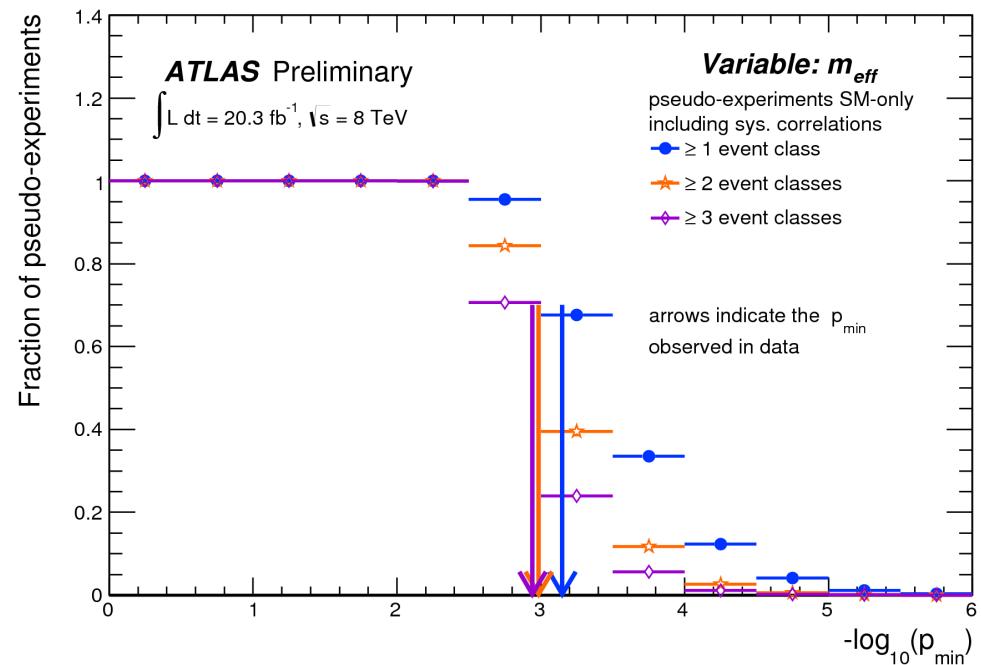
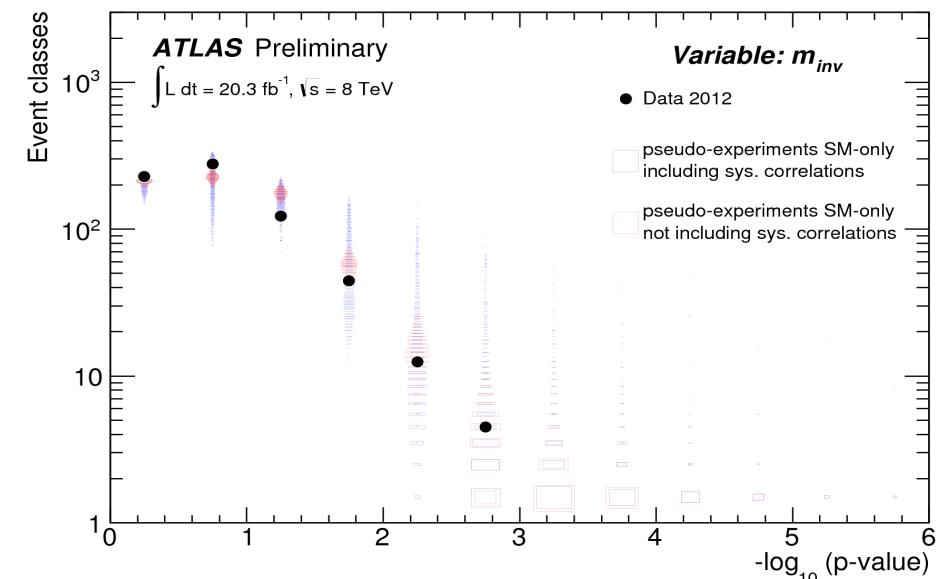
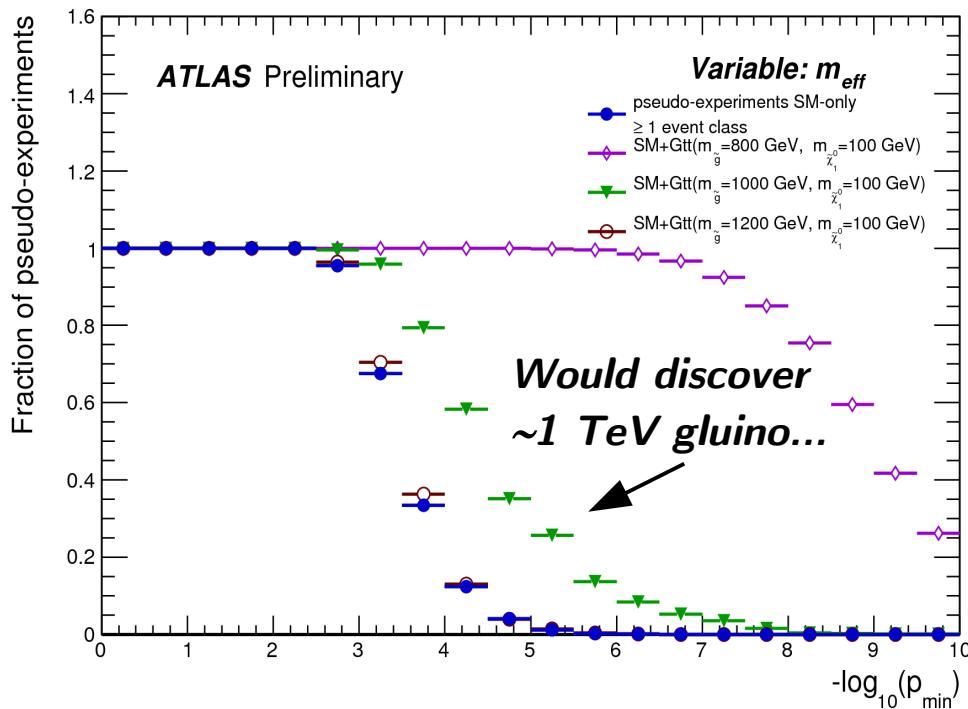
- Look in every final-state possible...
as theory-blind (*theorist-deaf?*)
as possible
- Compare data to backgrounds*
 - Number of events
 - Excesses in M_{eff} , M_{inv} , or MET distributions
- ***697 final-states...***



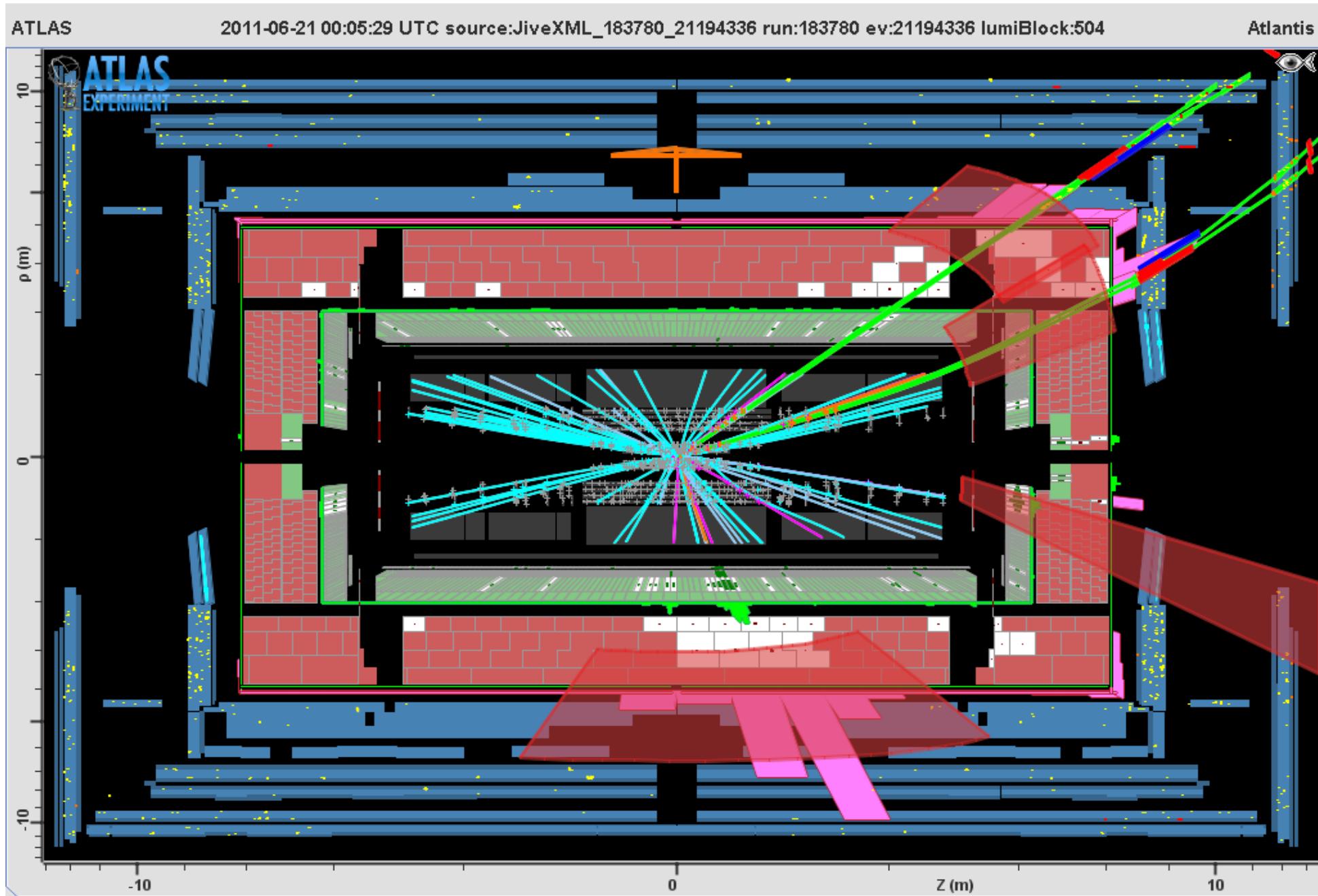
* Background mostly taken from MC, with some correction factors, unlike dedicated searches...

General Search Methods

- Compare to “look-elsewhere” effect
- Sensitive to new physics...
- Good way to search when you don't know what to look for!
- ***How to improve for Run2?***



Candidate Lepton-jet in Data





LHC

Summer 2008....

$\sqrt{s} = 14 \text{ TeV}$



ATLAS

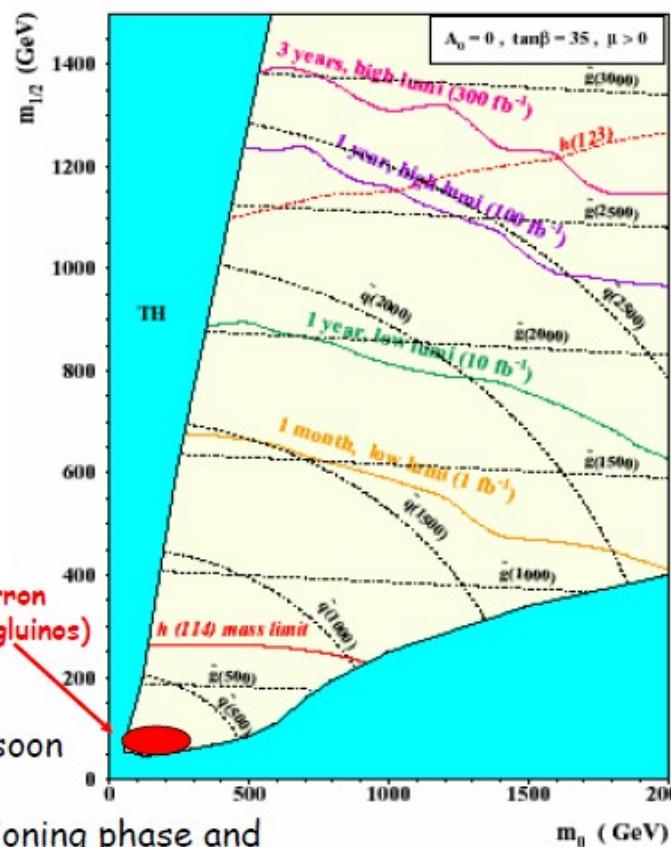
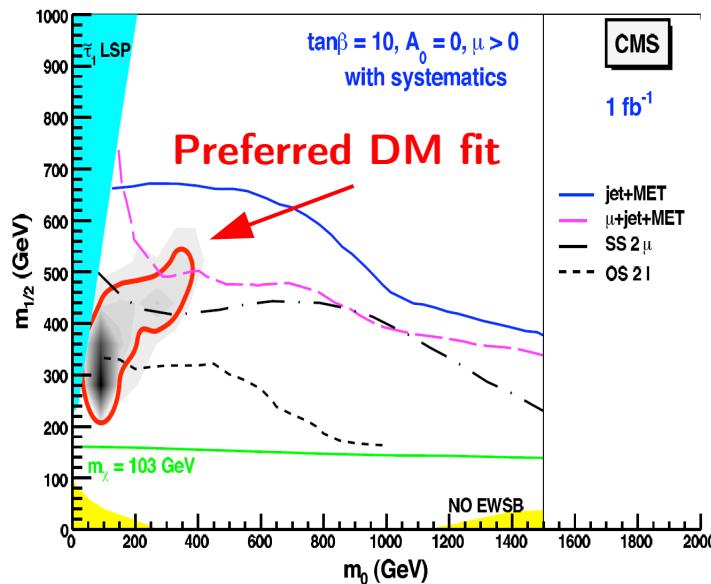
CMS



LEPTON-PHOTON 2007

XXIII International Symposium on Lepton and Photon Interactions
at High Energy Aug 13-18, Daegu, Korea

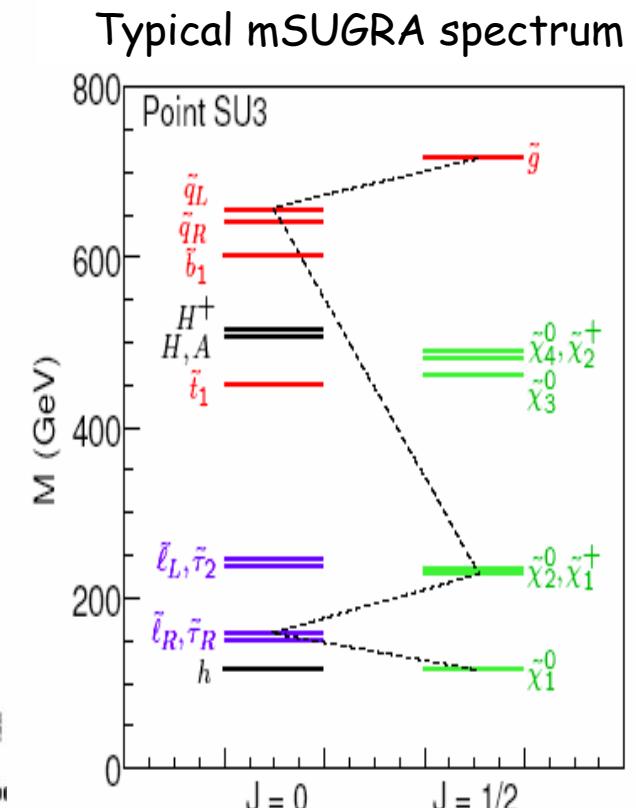
LHC Expectations for BSM



The LHC is built to discover SUSY
If it is there, we will find it relatively soon

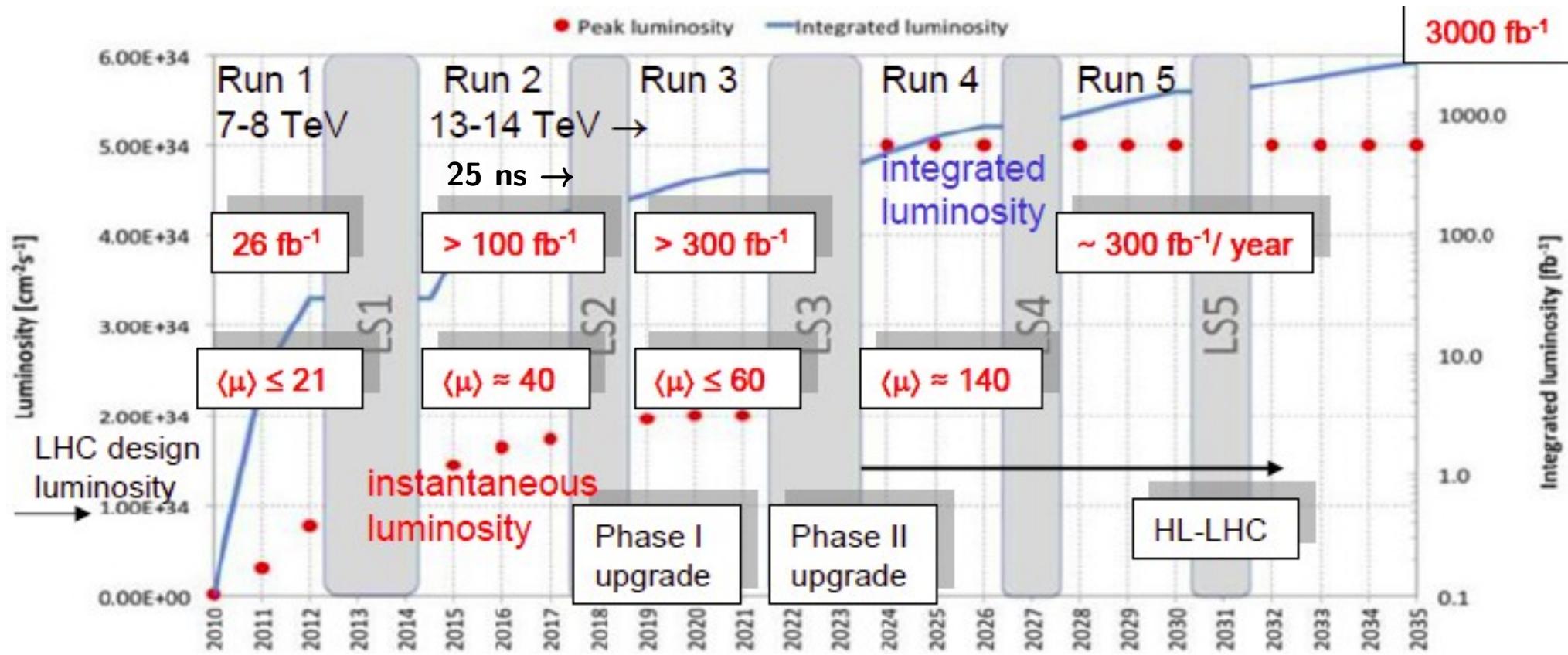
But...do not underestimate the commissioning phase and
the work needed to understand the SM backgrounds....

(First SUSY discovery by LP'09 ?!)



- Discovery up to $m \sim 750$ GeV with 200 pb^{-1} at $\sqrt{s} = 10 \text{ TeV}$
- With 200 pb^{-1} , ATLAS discovery reach beyond expected Tevatron exclusion (~ 400 GeV) if $\sqrt{s} \geq 7 \text{ TeV}$
- However: understanding the (tricky) backgrounds, in particular fake missing transverse energy coming from instrumental effects (cracks, noise, ...), will take time
- Ultimate LHC reach: $\sim 3 \text{ TeV}$

LHC Upgrades



- 13 TeV collisions at 25 ns to start in May 2015
- ~100/fb at 13-14 TeV expected by 2018!

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

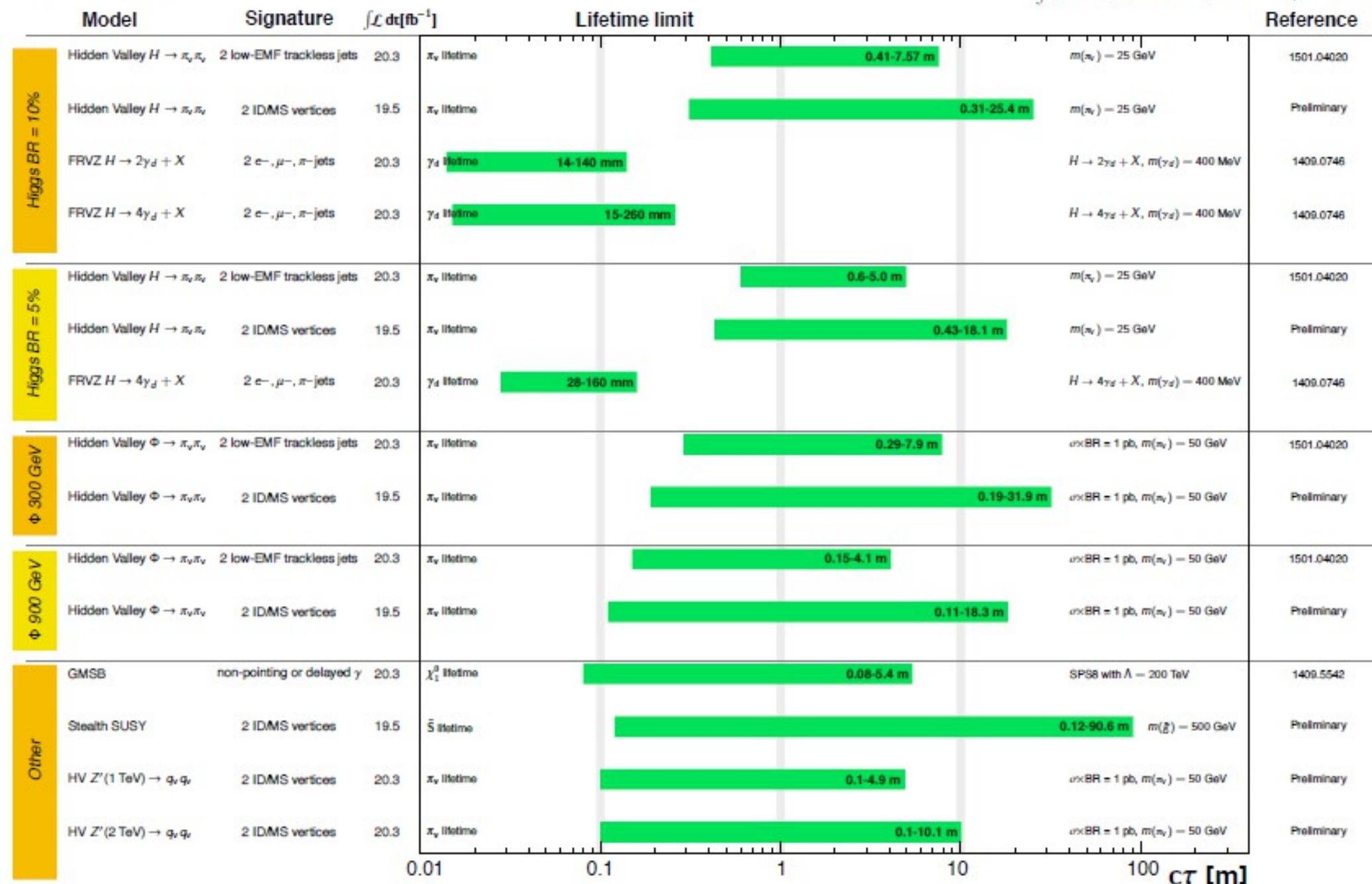
ATLAS Preliminary

Status: March 2015

$\int \mathcal{L} dt = (19.5 - 20.3) \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

Reference



CMS Search for SUSY with 2l+jets+MET: on Z

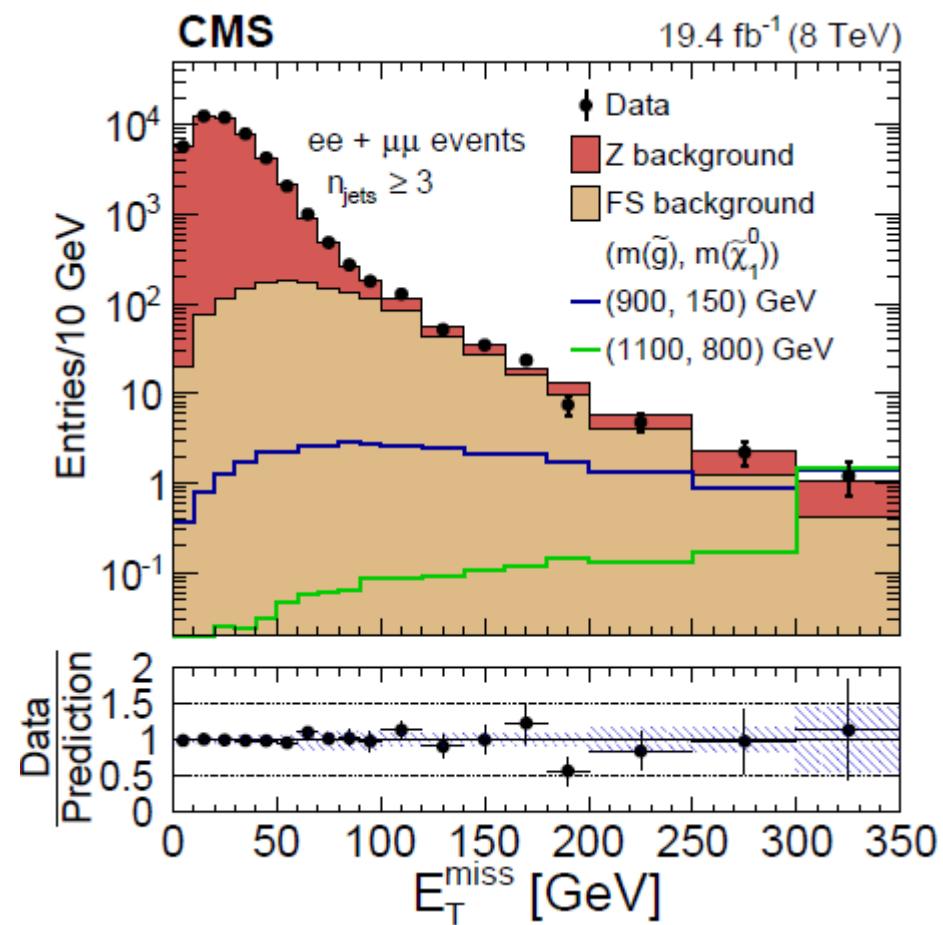
Recall ATLAS Signal Region: MET>225GeV and HT>600GeV

arXiv:1502.06031

CMS has new Signal Region with Njets>2 and large MET

- No excess seen
- More DY background than ATLAS (from looser H_T)
- ~30% overlap with ATLAS selection

E_T^{miss} (GeV)	100–200	200–300	>300
DY background	124 ± 33	12.7 ± 3.8	3.2 ± 1.8
FS background	354 ± 28	26.5 ± 5.4	2.0 ± 1.4
Total background	478 ± 43	39.2 ± 6.6	5.3 ± 2.3
Data	490	35	6
GMSB signal yields			
$m_{\tilde{g}} = 900, m_{\tilde{\chi}_1^0} = 150$	22.0 ± 0.4	11.0 ± 0.3	7.1 ± 0.2
$m_{\tilde{g}} = 1100, m_{\tilde{\chi}_1^0} = 800$	1.1 ± 0.04	1.5 ± 0.05	7.4 ± 0.1

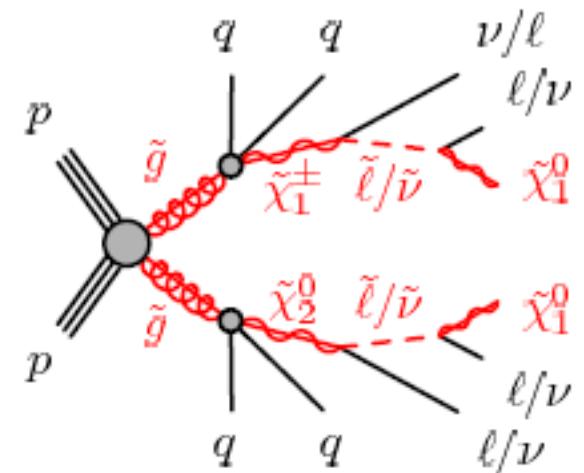
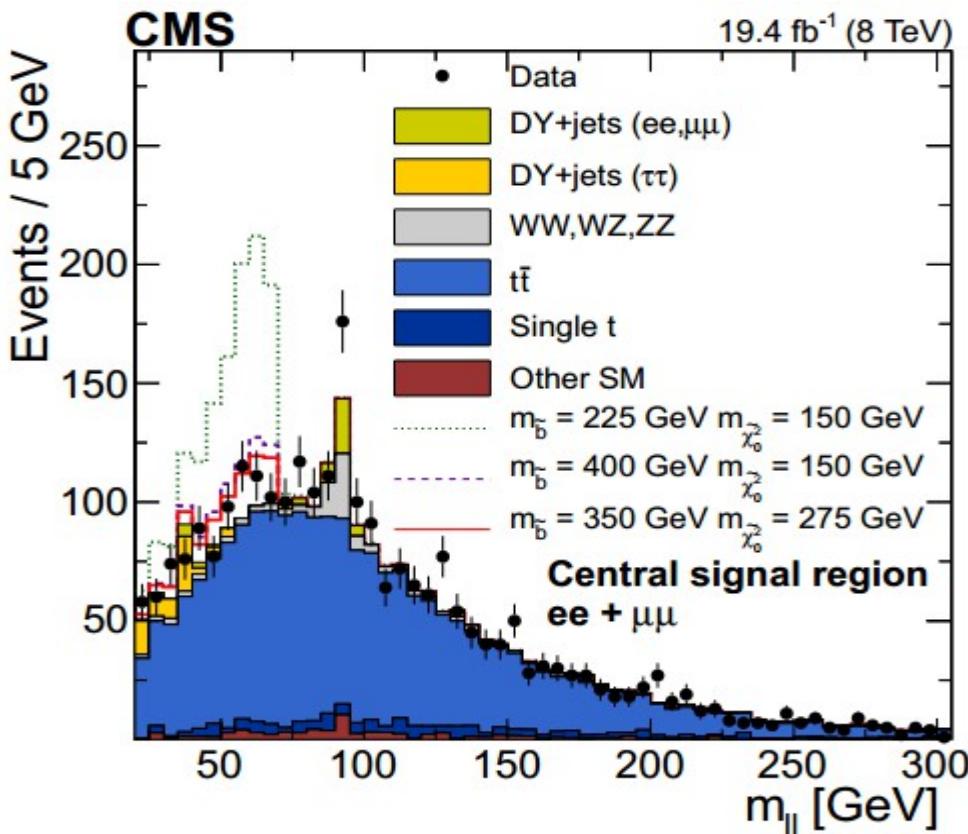


Search for SUSY with 2l+jets+MET

Various SUSY decay chains can give 2l+jets+MET

Also study off-Z-peak range, with 2 or 4 jets, with or without b-tags, and CMS-like selection

Recall CMS 2.6 σ excess $20 < m(l\bar{l}) < 70$ GeV with 2/3 jets
[arXiv:1502.06031](https://arxiv.org/abs/1502.06031)



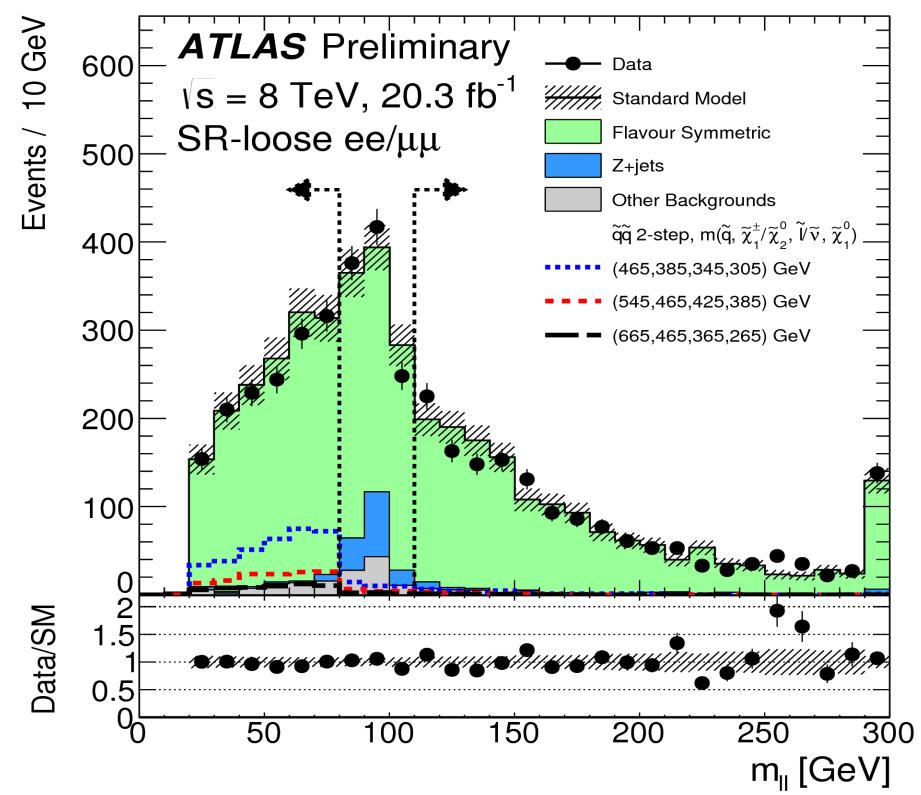
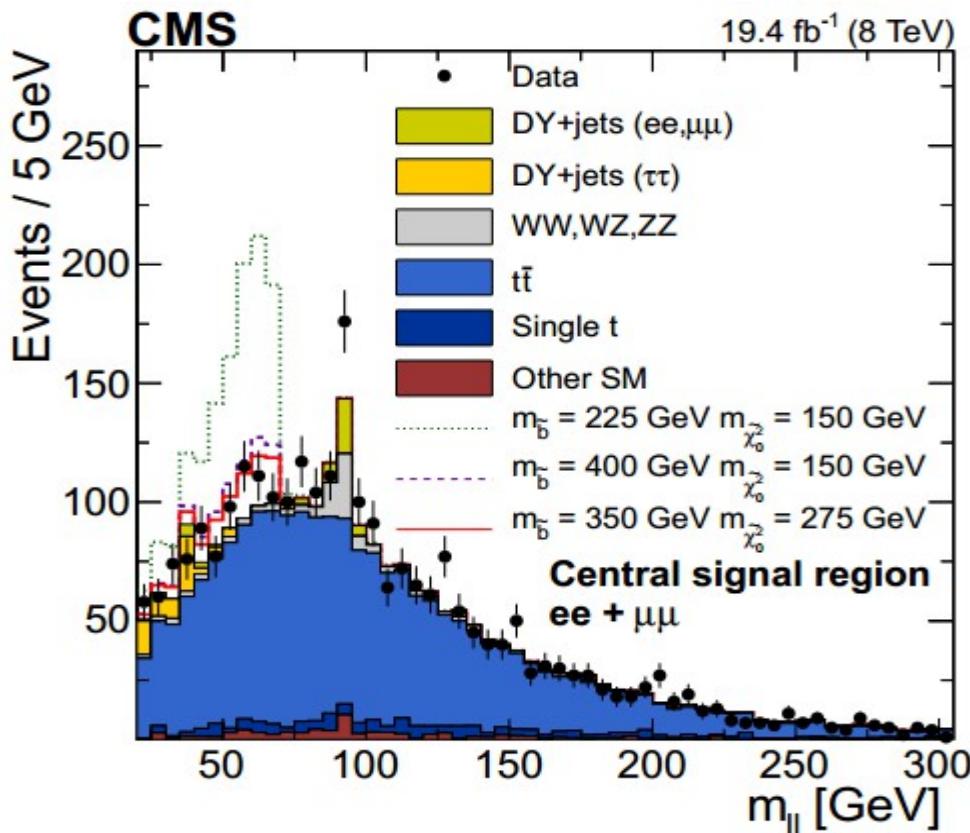
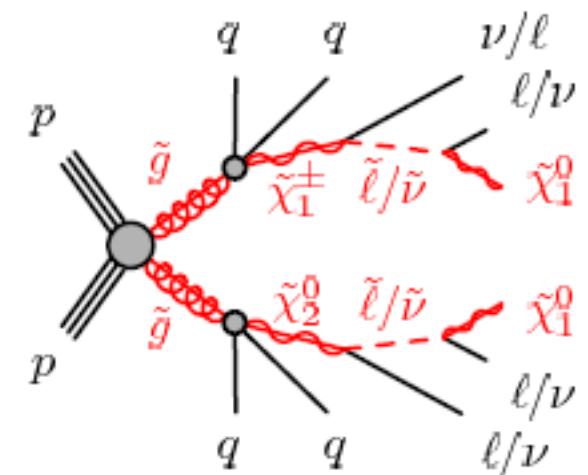
CMS-like selection

Search for SUSY with 2l+jets+MET

Various SUSY decay chains can give 2l+jets+MET

Also study off-Z-peak range, with 2 or 4 jets, with or without b-tags, and CMS-like selection

No excess seen in similar ATLAS selection



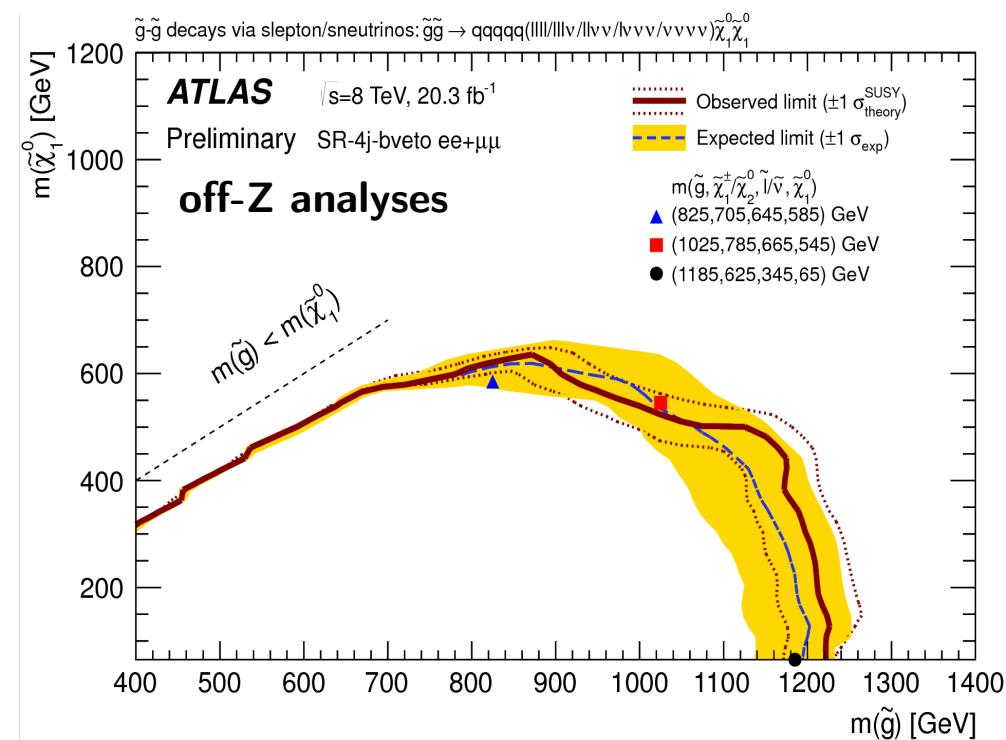
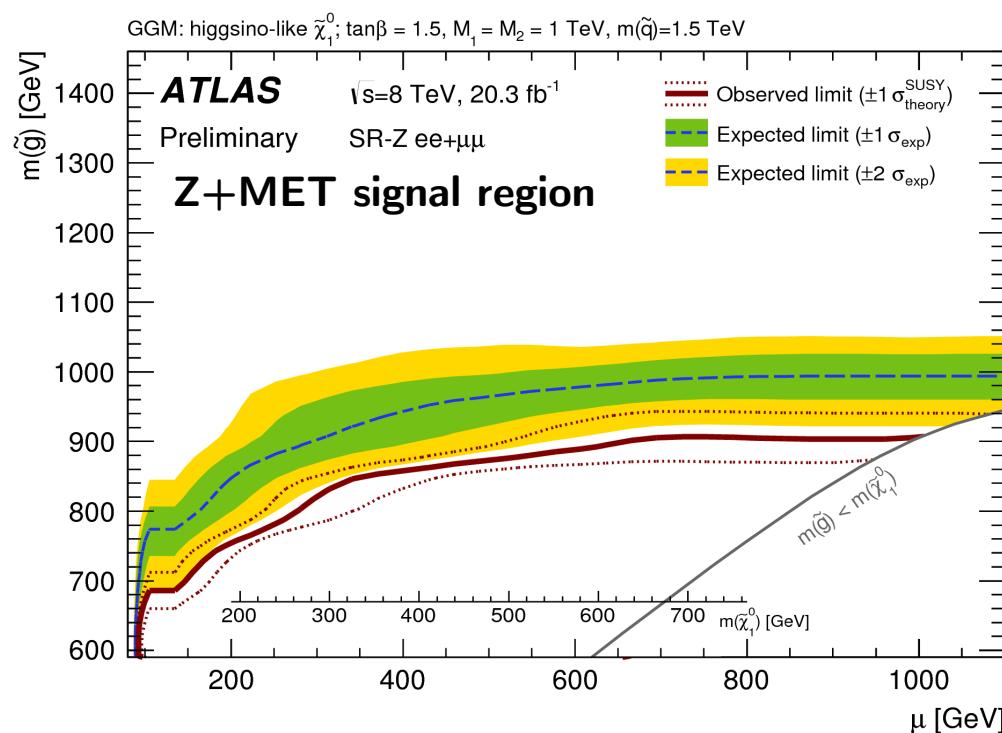
Search for SUSY with 2l+jets+MET

Set limits in GGM models,
as well as squark/gluino decays chains
with neutralinos

3.0 sigma excess in Z+MET at
large HT weakens limits

	Dilepton edge	Z+MET
ATLAS	No excess	3.0 σ
CMS	2.6 σ	No excess

The ATLAS and CMS edge selections are the same (by design) but the Z+MET are different, only $\sim 30\%$ of our events enter the CMS selection



Jet Substructure



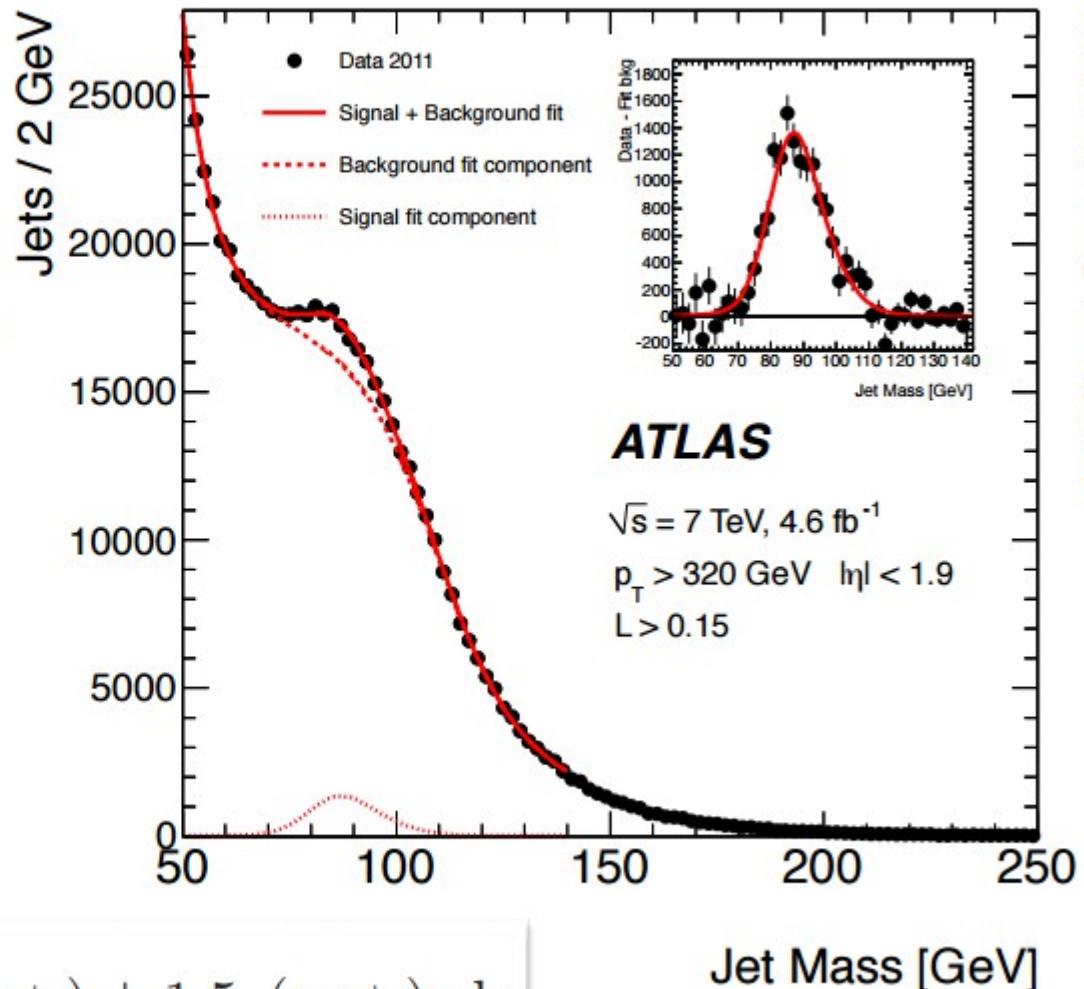
W/Z cross sections measurement

- binned maximum likelihood fit to the jet mass distribution used to extract the W/Z signal
- cross section calculated from:

$$\sigma_{W+Z} = \frac{N^{W+Z}}{\mathcal{L} \cdot \varepsilon}$$

- NLO CDQ calculation:
 $\sigma_{W+Z} = 5.1 \pm 0.5 \text{ pb}$
- measurement agrees within 2σ

$$\sigma_{W+Z} = 8.5 \pm 0.8 \text{ (stat.)} \pm 1.5 \text{ (syst.) pb}$$

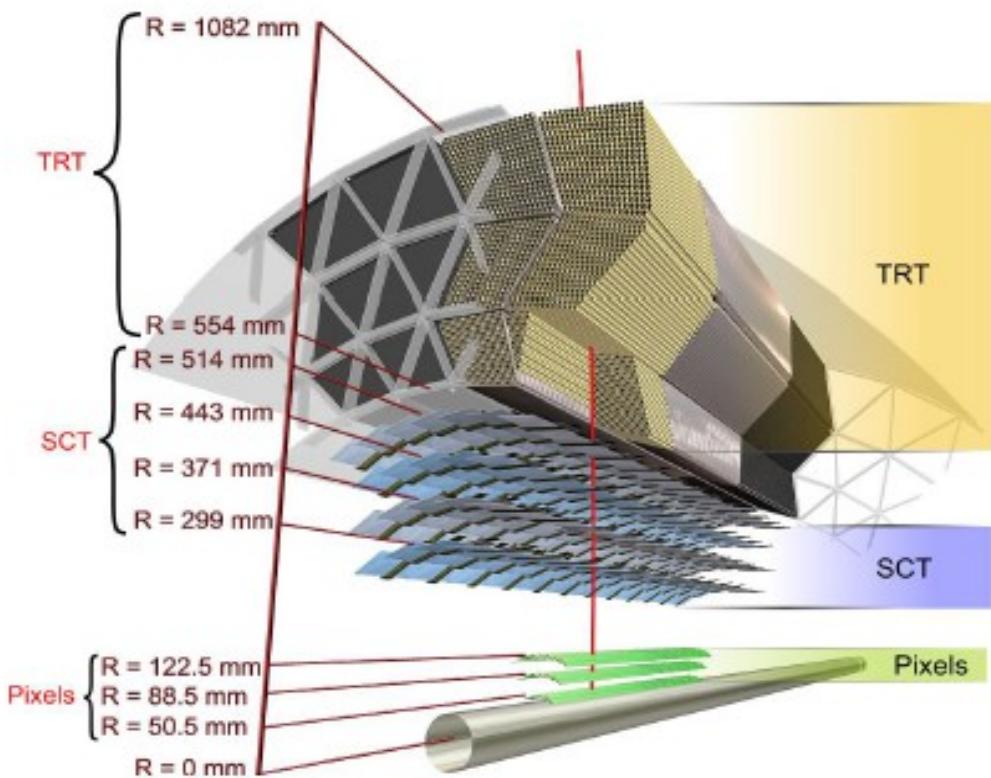


2014 New J. Phys. 16 113013

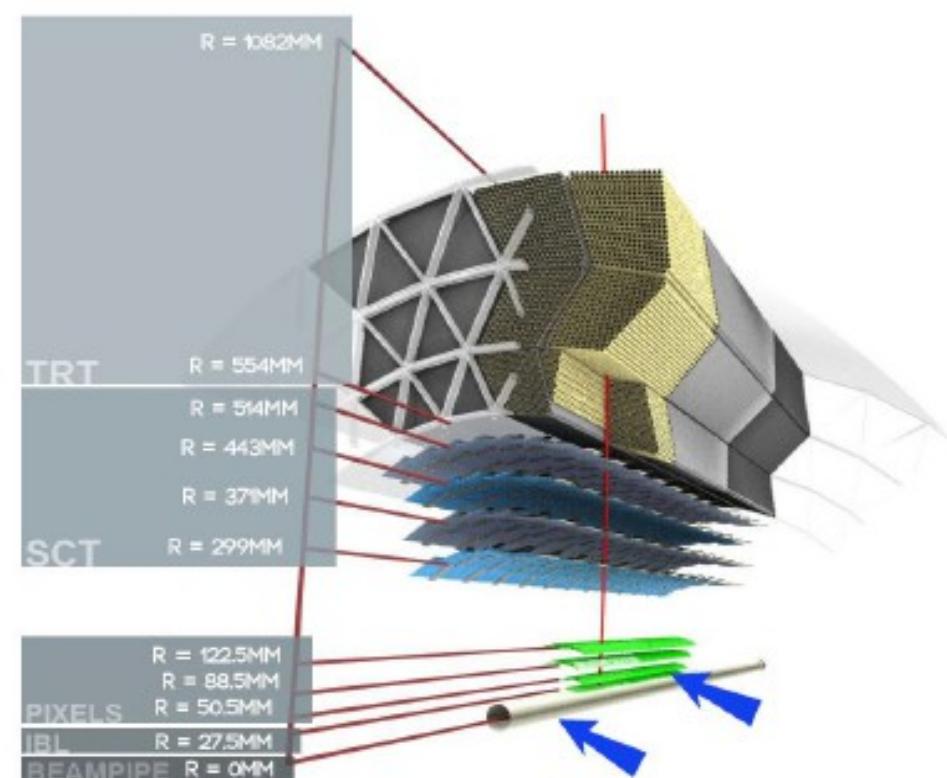
Detector Upgrades

- New silicon layer installed!
- Many trigger upgrades installed... (including L1 VBF trigger)
- ...

Original



Updated



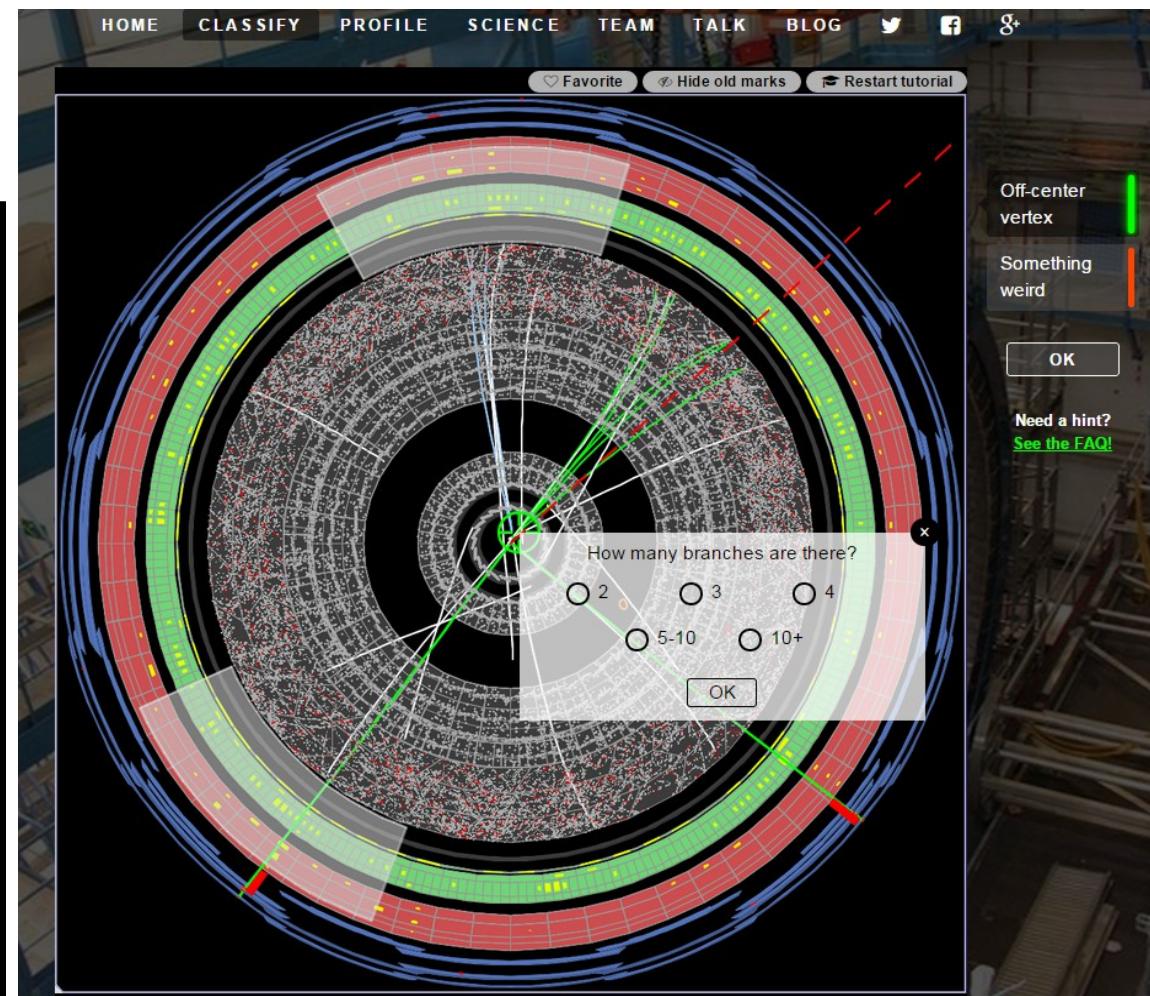
You can look for DV's at home!

- Shameless plug: <http://HiggsHunters.org> - a Zooniverse project
- Look for DV's on ATLAS data (and simulated) images
- Preselected with $Z \rightarrow \mu\mu$ ($pT > 60$ GeV), $MET > 40$ GeV
- Over 6k users and 700k images classified so far

Working with Zooniverse

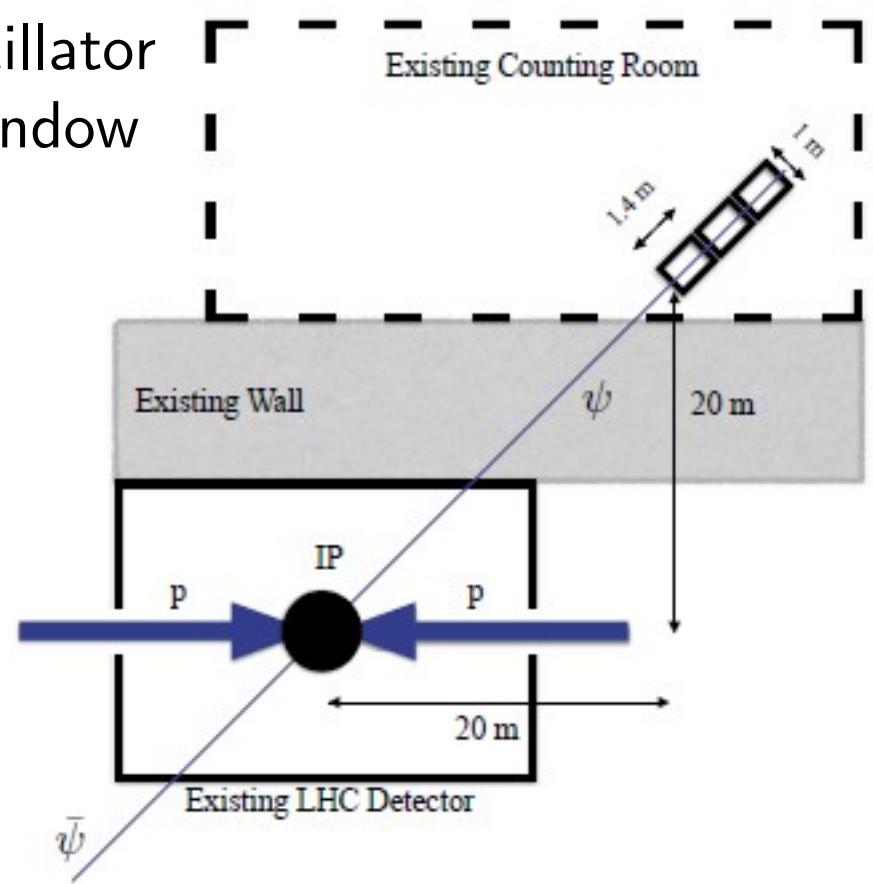
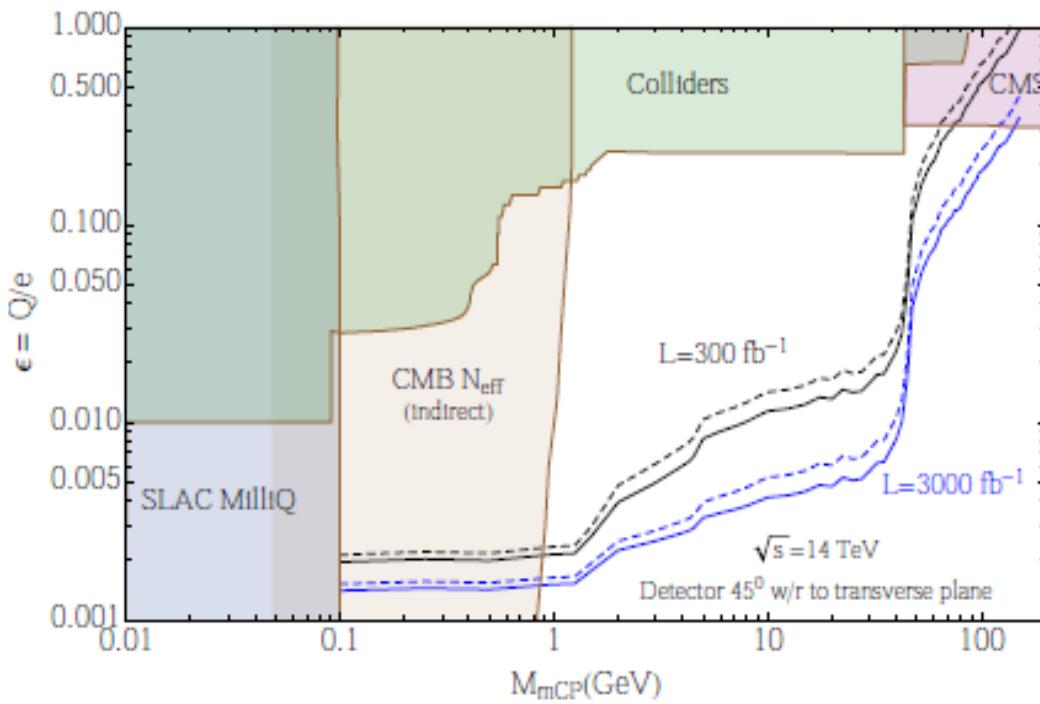
The screenshot shows the Zooniverse homepage with a world map in the background. Several project cards are displayed:

- Study explosions on the Sun**: An image of a solar flare.
- How do galaxies form?**: An image of a spiral galaxy.
- "Citizen Science": public participates in real science research projects**: A list of statistics:
 - >1 million users worldwide
 - 20 Projects
 - 60 papers
- Help explore the ocean floor**: An image of a starfish.



Exploring other possibilities: *mCP@LHC*

- Milli-charged particles = new particles with electric charge $\sim 10^{-3}$
- Easy to add to SM: “dark U(1)” (with massless dark photon) mixing through kinetic term \rightarrow dark fermion milli-charged under SM
- Currently weak direct limits for fermion mass > 100 MeV
- Would need new detector to see them at LHC... [arXiv:1410.6816](https://arxiv.org/abs/1410.6816)
- ~ 1 photo-electron in 1.4m long scintillator
- Require triple coincidence in time window



What BSM to look for?

Hitoshi Murayama
Lepton Photon '03



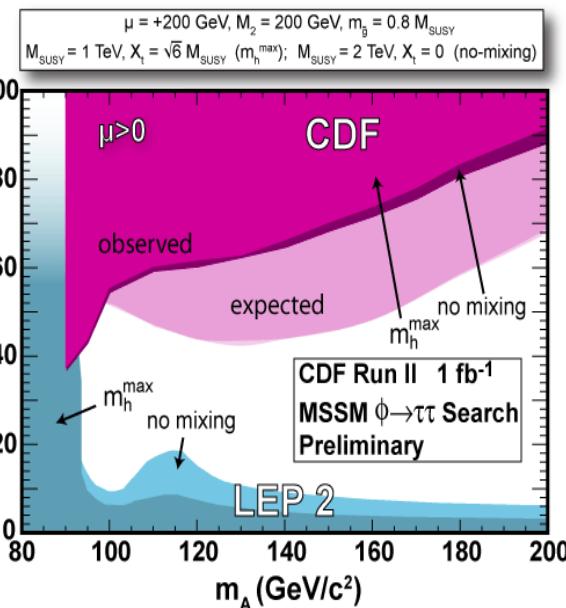
What BSM to look for?

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Lepton Photon '03

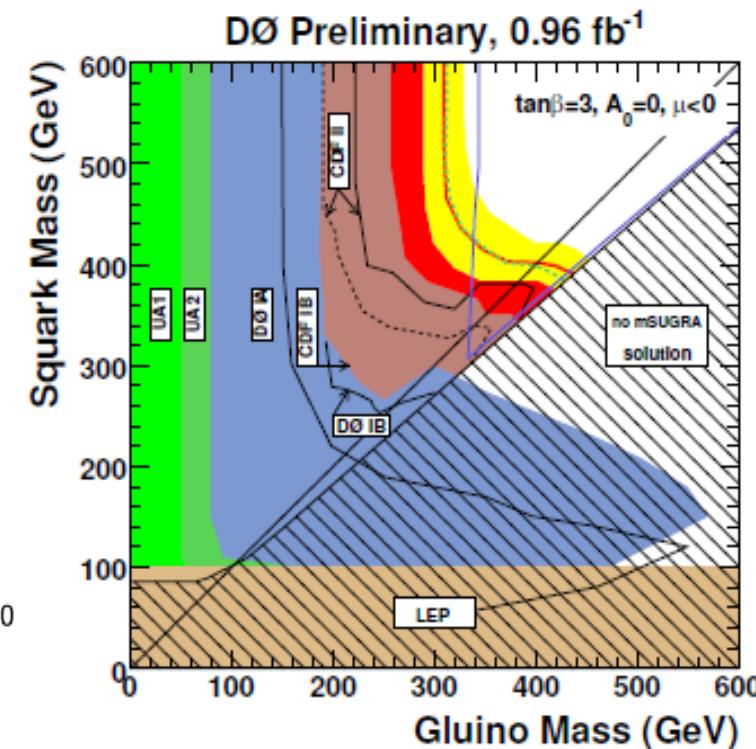
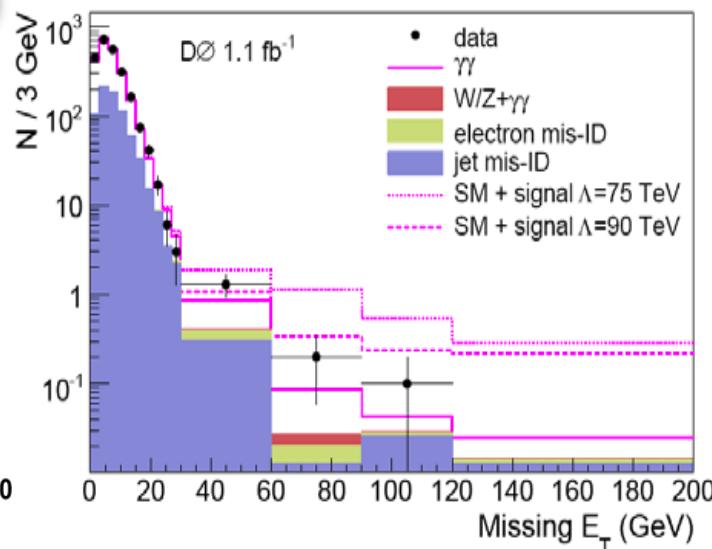


Some Pre-LHC Searches for BSM

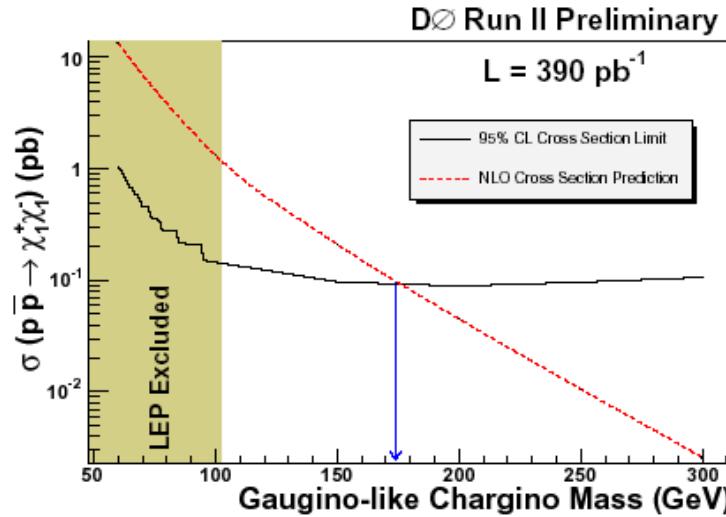
Heavy Neutral Higgs



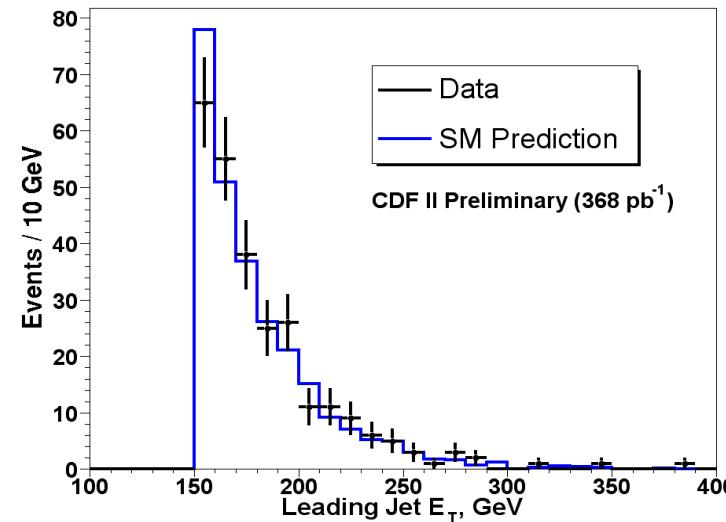
Two-photon + MET



Long-lived chargino (slow muon)



Mono-jet + MET

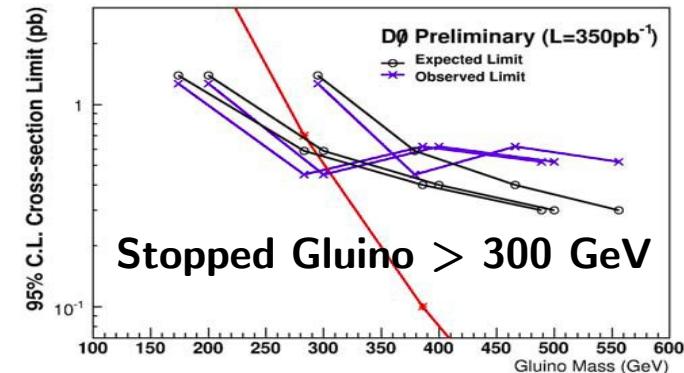
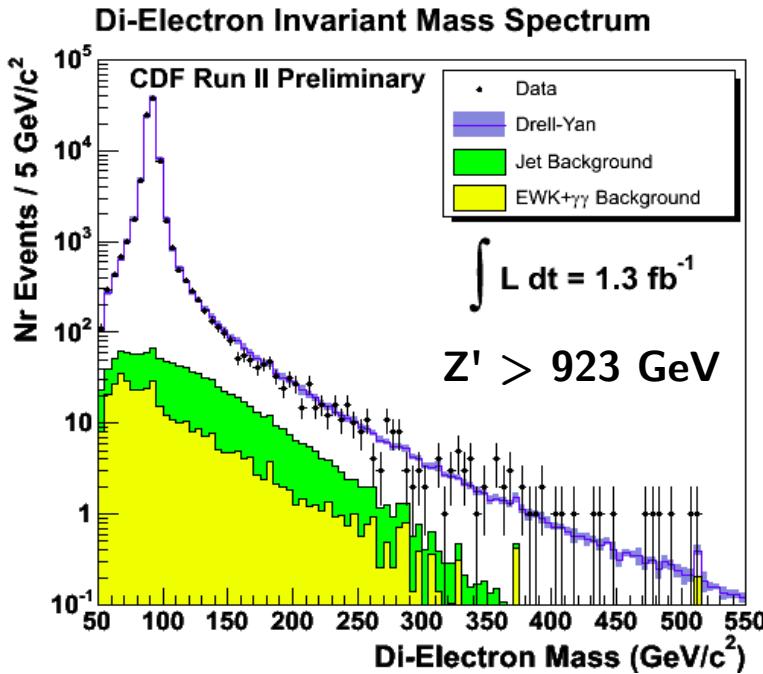
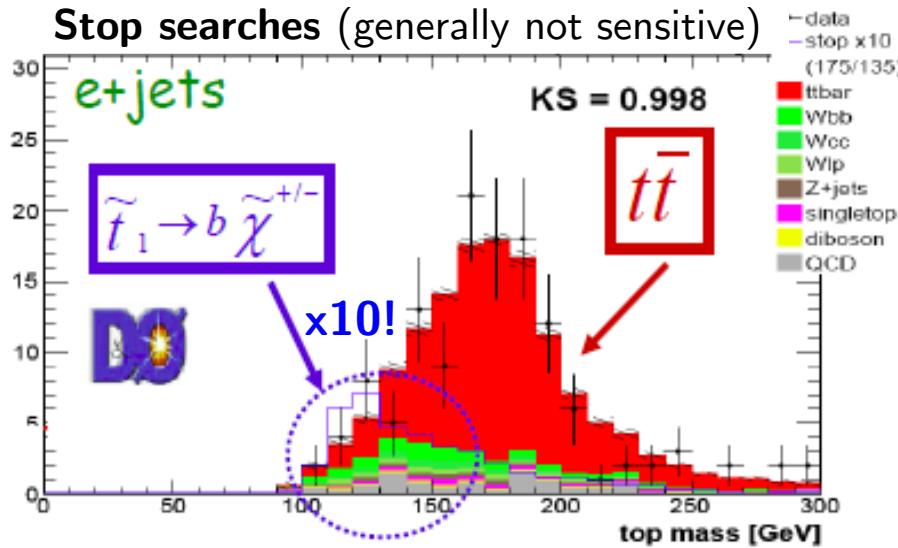


Squarks and Gluinos

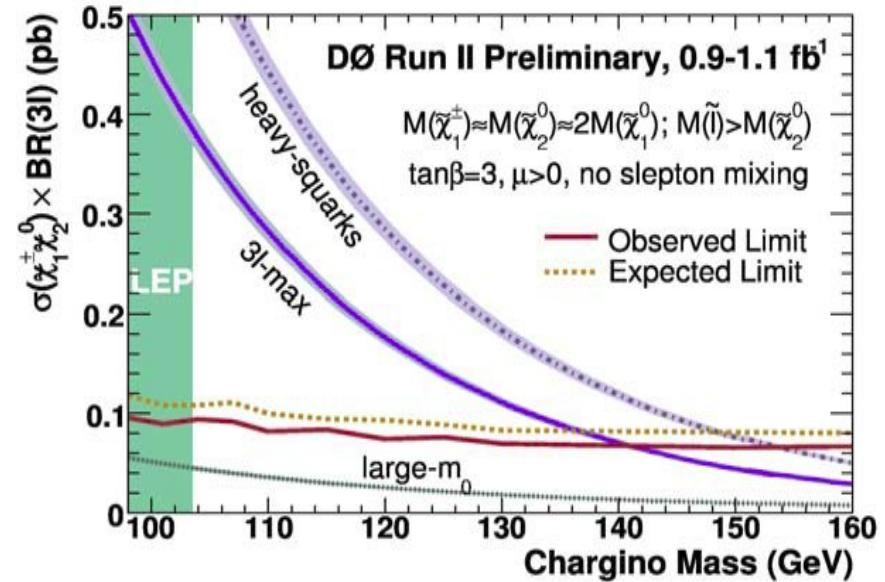
$m(\tilde{q}) > 385$ GeV
 $m(\tilde{g}) > 302$ GeV

Some Pre-LHC Searches for BSM

Stop searches (generally not sensitive)



Chargino/Neutralino $\rightarrow 3$ leptons +MET



Chargino mass limit in mSUGRA inspired models considerably improved

3l-max: M_{sl} slightly above $M_{\chi_2^0}$ and M_{sl} degenerate: $M_{\chi_1^+} > 140 \text{ GeV}$

heavy-sq: destructive t-channel contribution minimal: $M_{\chi_1^+} > 155 \text{ GeV}$

For large m_0 : sl's are heavy and small BR into leptons