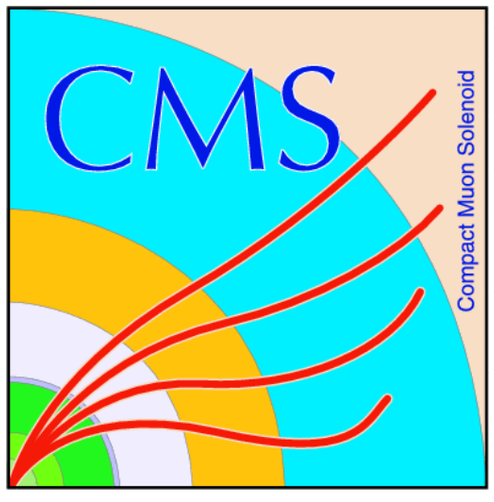
Highlights on SUSY and Exotics at the LHC

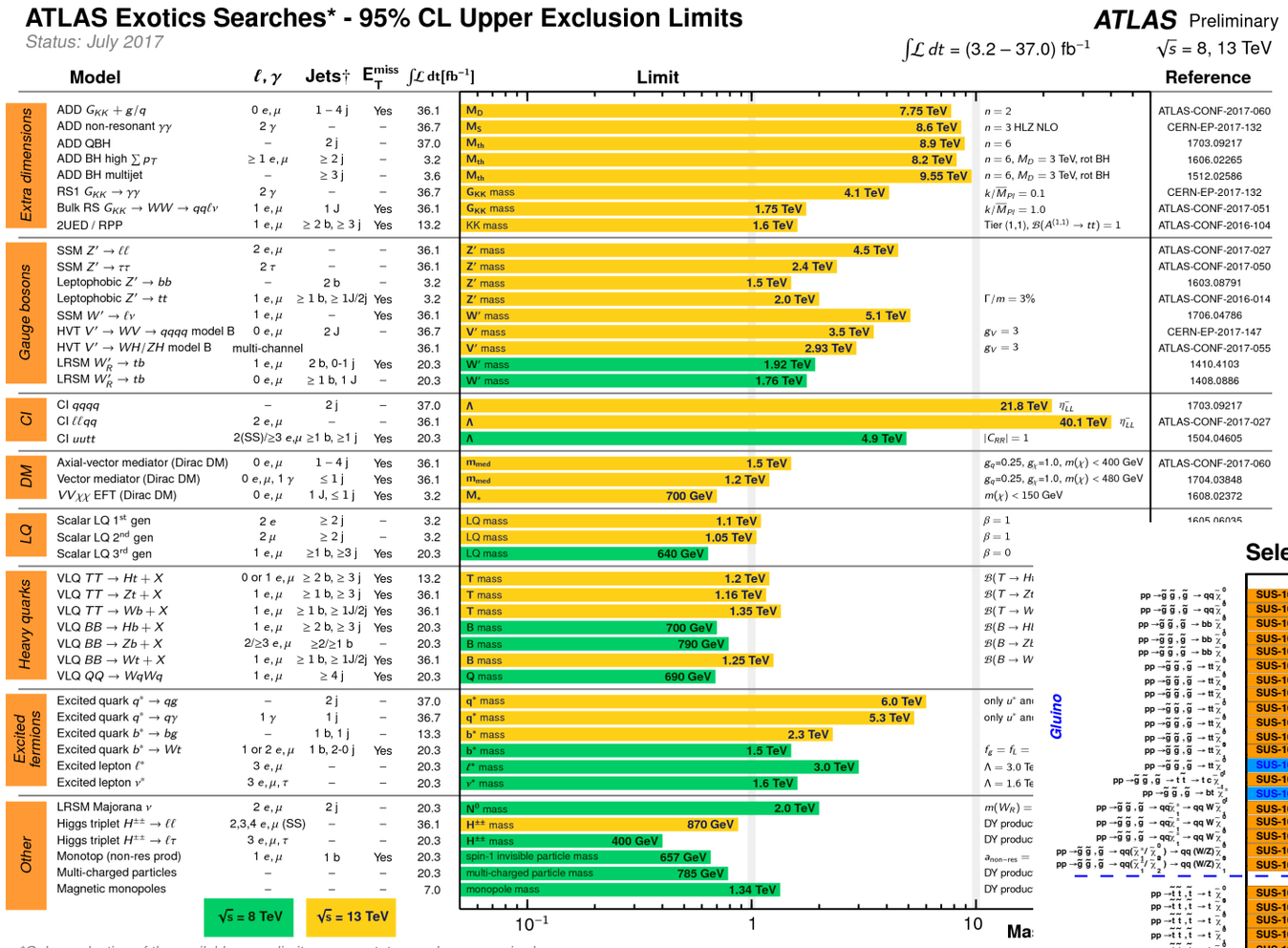
Nadja Strobbe (FNAL)
on behalf of the ATLAS and CMS collaborations

Blois 2018

June 5, 2018

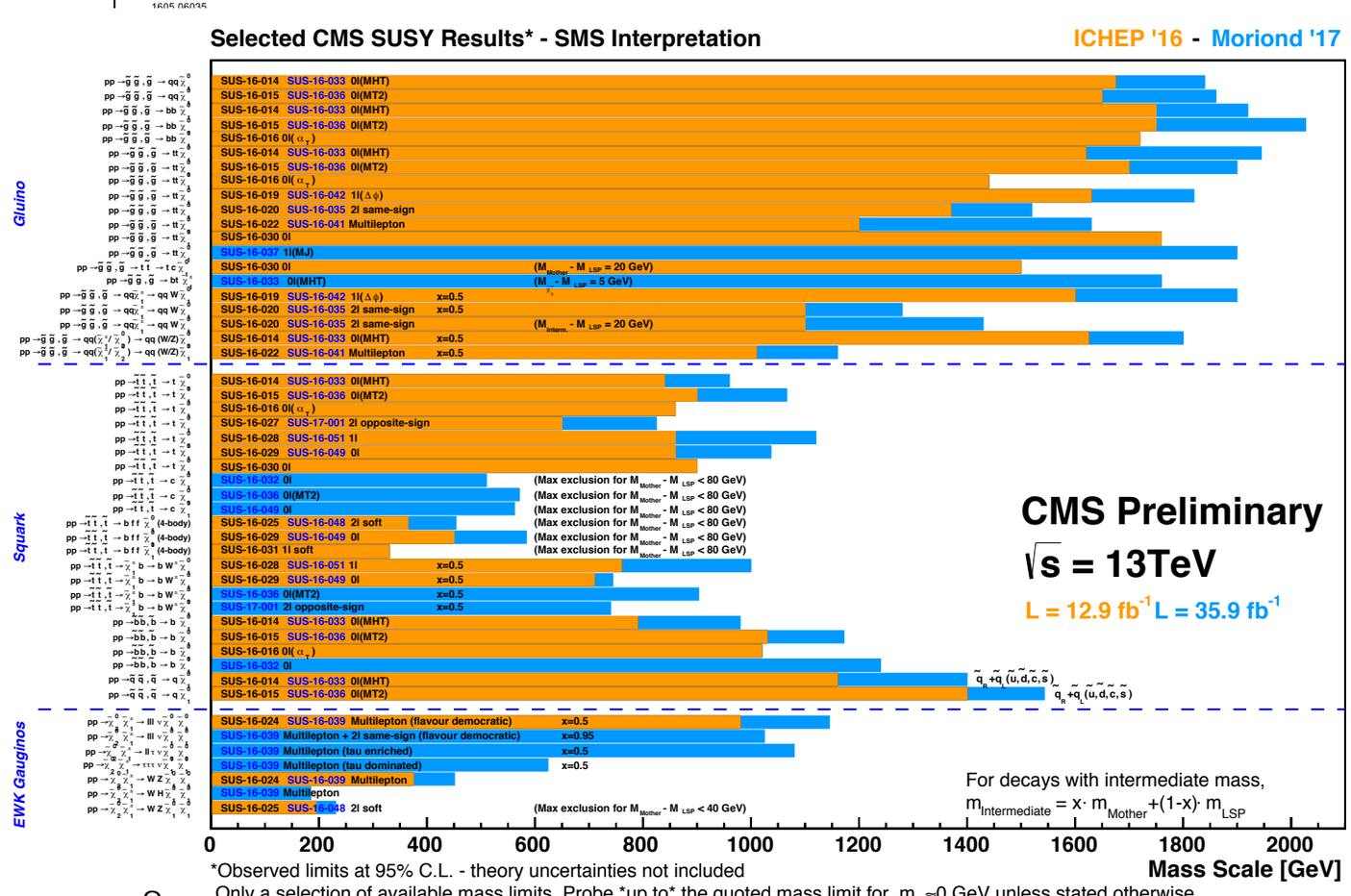


BSM physics at the LHC



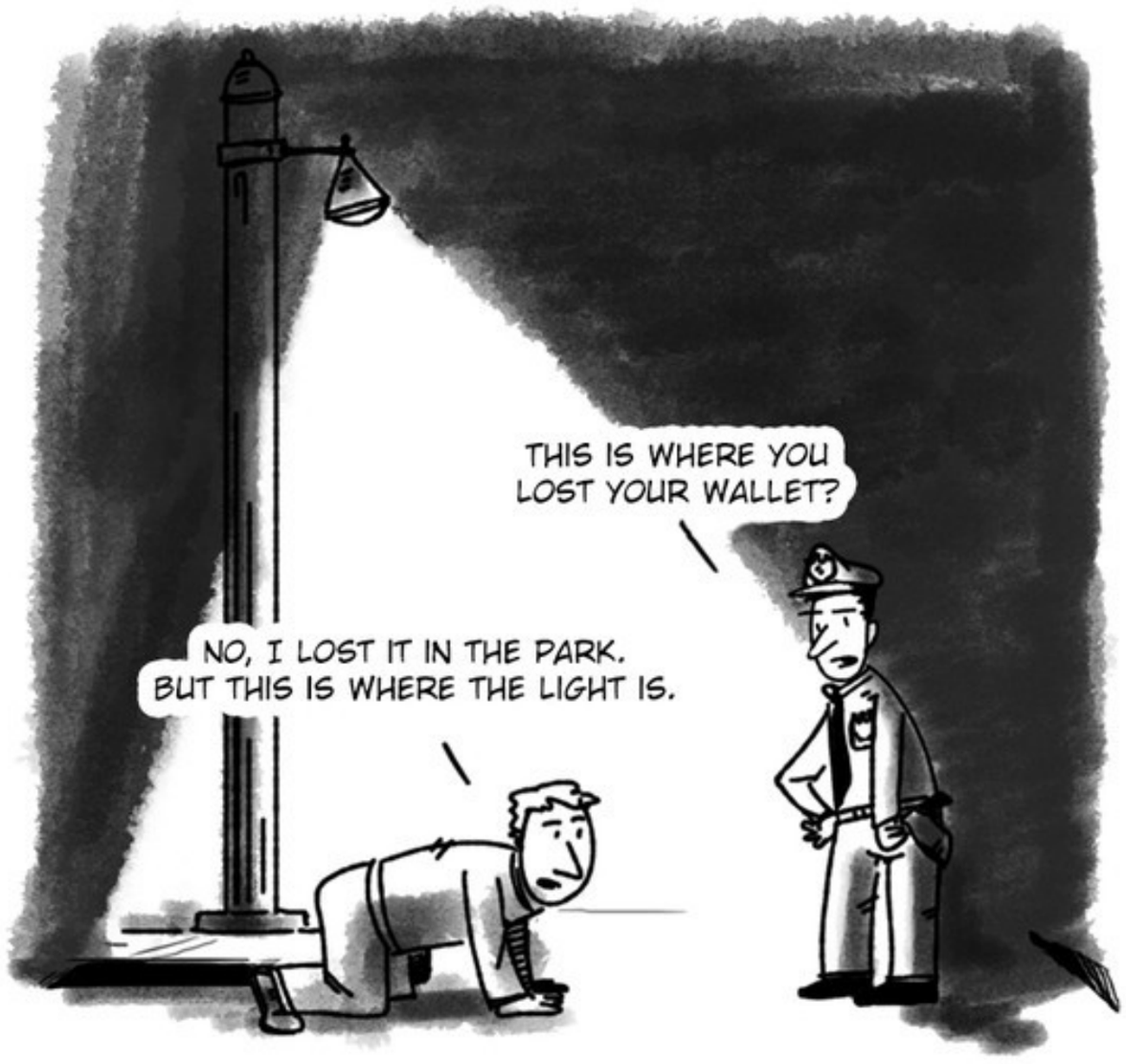
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

MANY searches performed!



No new physics found (yet?)

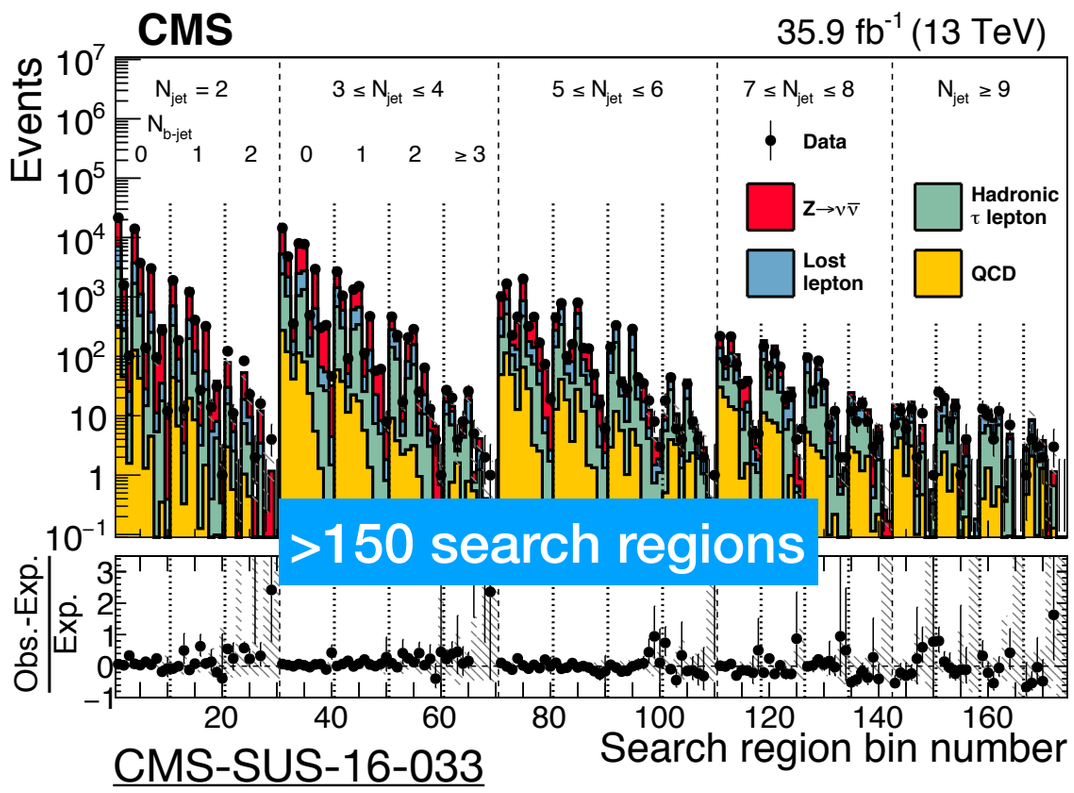
Expanding the search

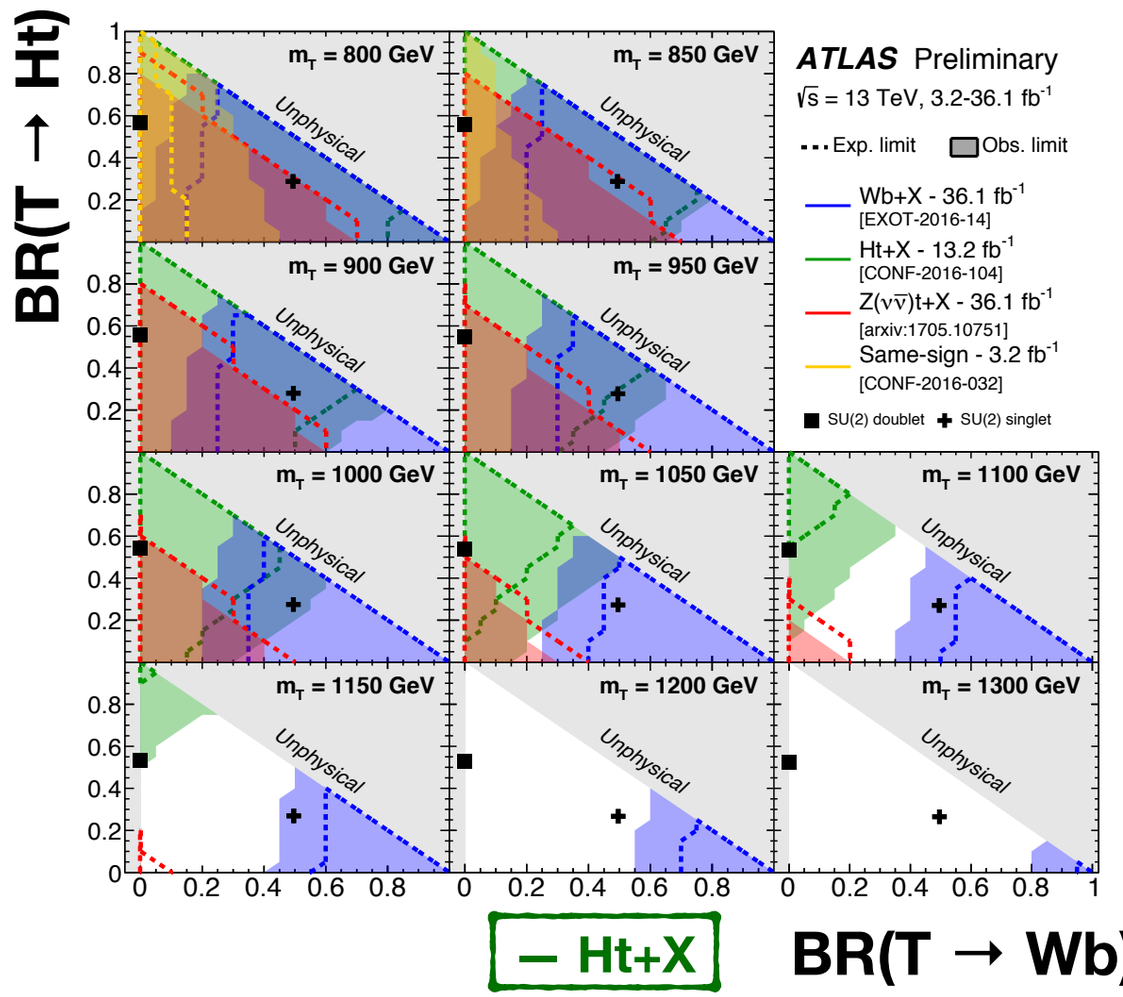


Nigel Henderson, ‘Photograph of two unidentified children, one of which is climbing a lamp-post’ [c.1949–c.1956] Tate Archive, © Nigel Henderson Estate

New analysis strategies

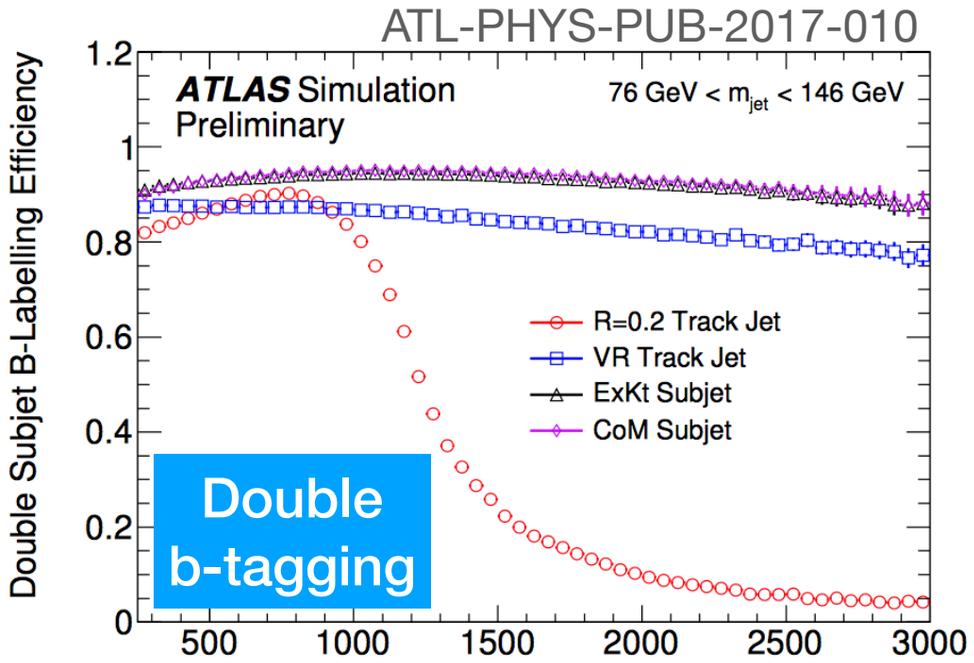
- Combine analyses for enhanced sensitivity or expand single analysis to have many search regions (e.g. many CMS SUSY searches)
- Discovery of the **Higgs boson** opened up new search avenues
  - Expand searches to include final states with Higgs bosons
  - Search for BSM in precision measurements of Higgs sector: couplings, branching fractions, cross sections

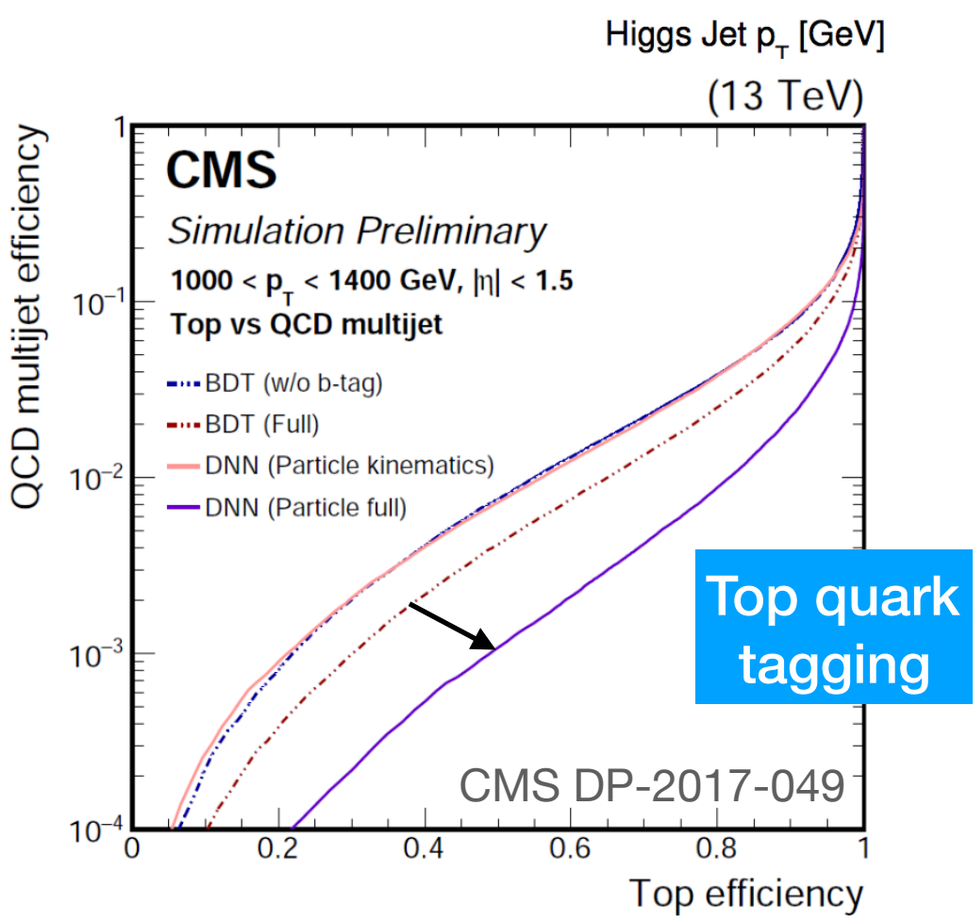




Fancier techniques

- Design/improve taggers for more **complicated objects**
  - (double) b-tagging
  - charm jets
  - top jets
    - boosted W/Z/H bosons
- More extensive use of **jet substructure**
- Move towards using novel **machine learning** techniques, e.g. from Boosted Decision Trees to Deep Neural Networks





This talk

- Aim to give you a feeling of the breadth of the LHC search program, focusing on new results since Moriond
- Topics covered:
  - Supersymmetry
  - Lepto-quarks
  - Heavy resonances
  - Vector-like quarks

See also parallel talks by
O. Brandt, A. Zucchetta, N. Abraham,
T. Golling, A. Reimers, G. Pasztor

- Covered elsewhere: Dark Matter (S. Meehan), Long Lived Particles (R. Sawada)

All results and documentation:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html

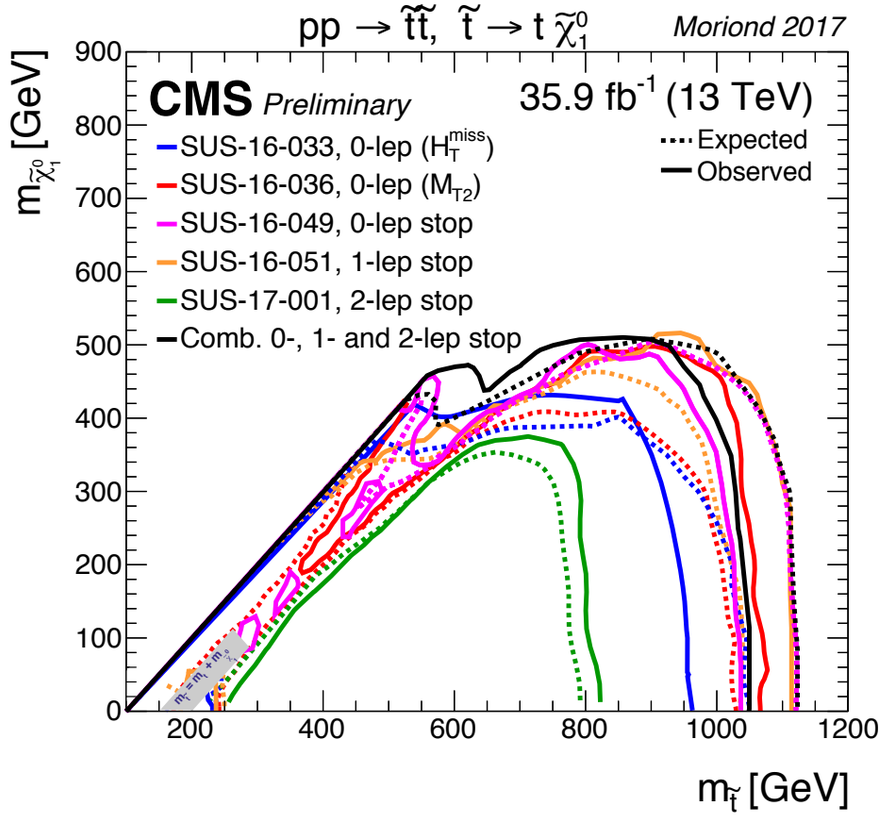
SUSY searches

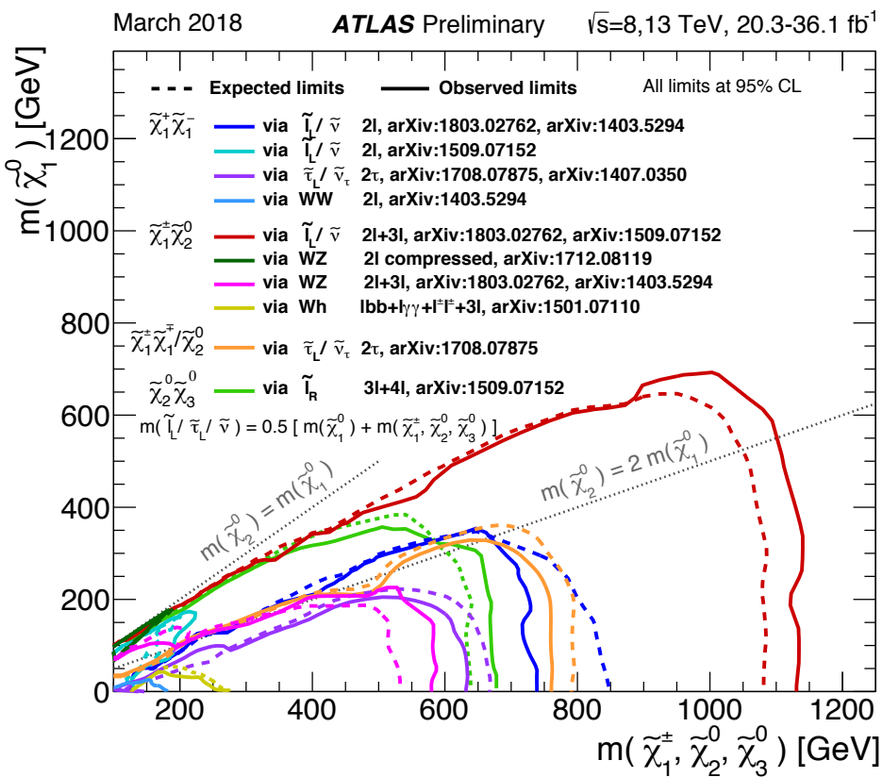
Started with few relatively simple and robust analyses, e.g. jets+MET, 1-lepton, dilepton

Evolution over the years:

- Focus shifted towards **heavy flavor**, e.g. top squarks (naturalness arguments)
- Different signal models:
  mSUGRA → simplified models → pMSSM
- **EWKinos** more prominent as luminosity increases
- Dedicated analyses to close gaps in coverage, e.g. very compressed top squarks

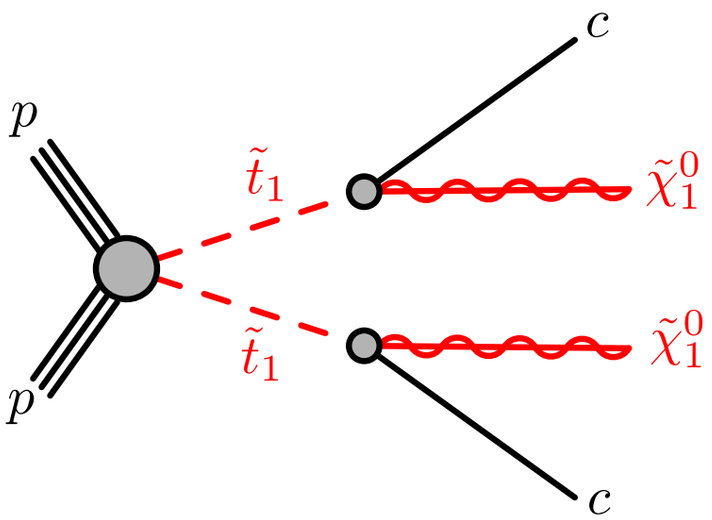
Not many new results this year, most searches waiting for Full Run 2 statistics



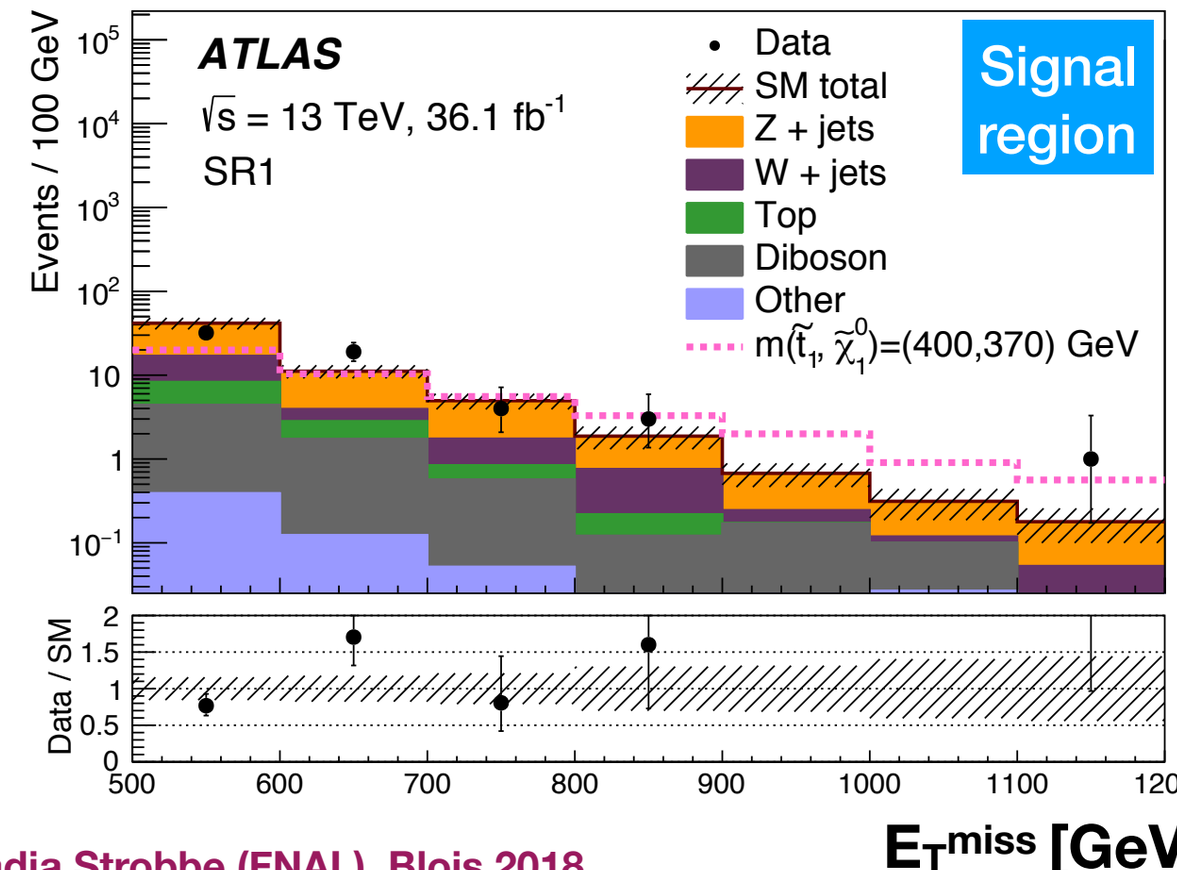


Search for supersymmetry with charm tagging

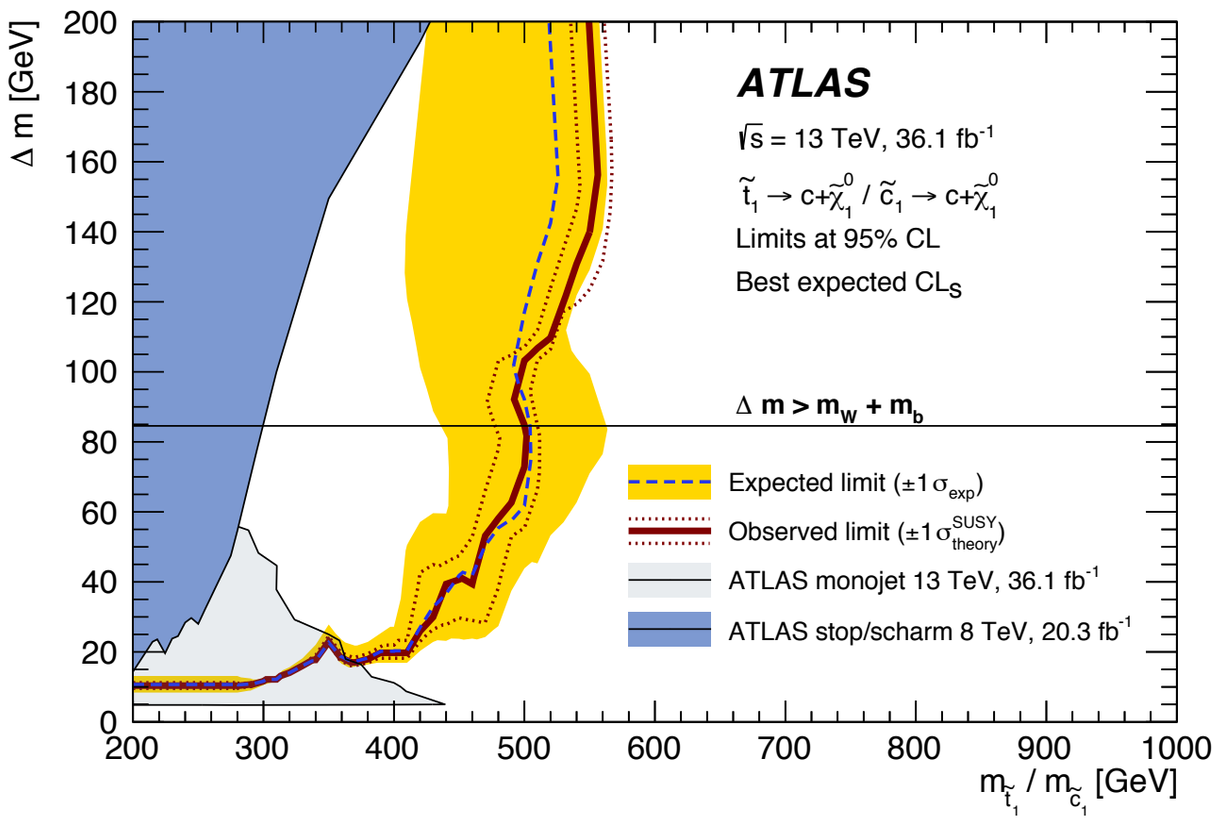
arXiv:1805.01649
CMS: PLB 778 (2018) 263



- Require ≥1 charm-tagged jet, and large MET
- Main backgrounds: Z+jets, W+jets, ttbar
- Backgrounds from simulation, normalized in data control regions, tested in validation regions



Exclude top squarks up to ~500 GeV for small mass differences with the LSP

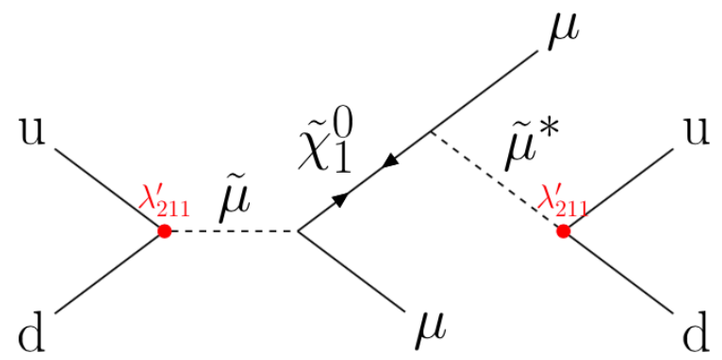


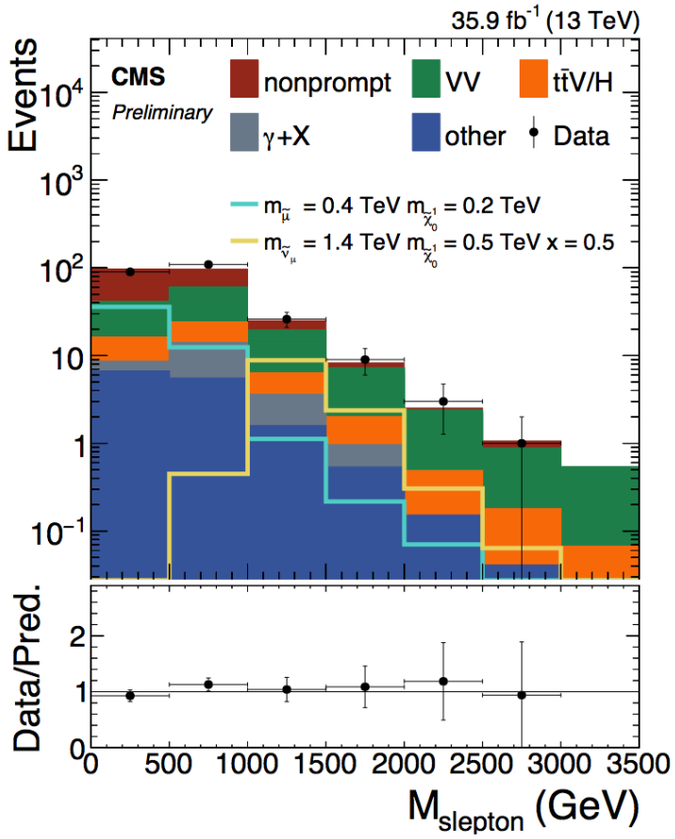
NEW

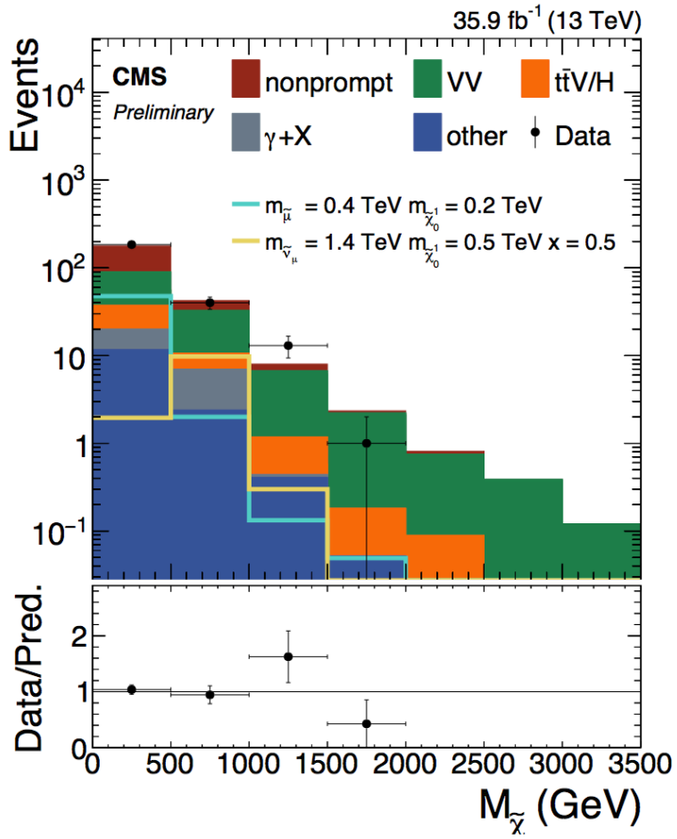
RPV smuon

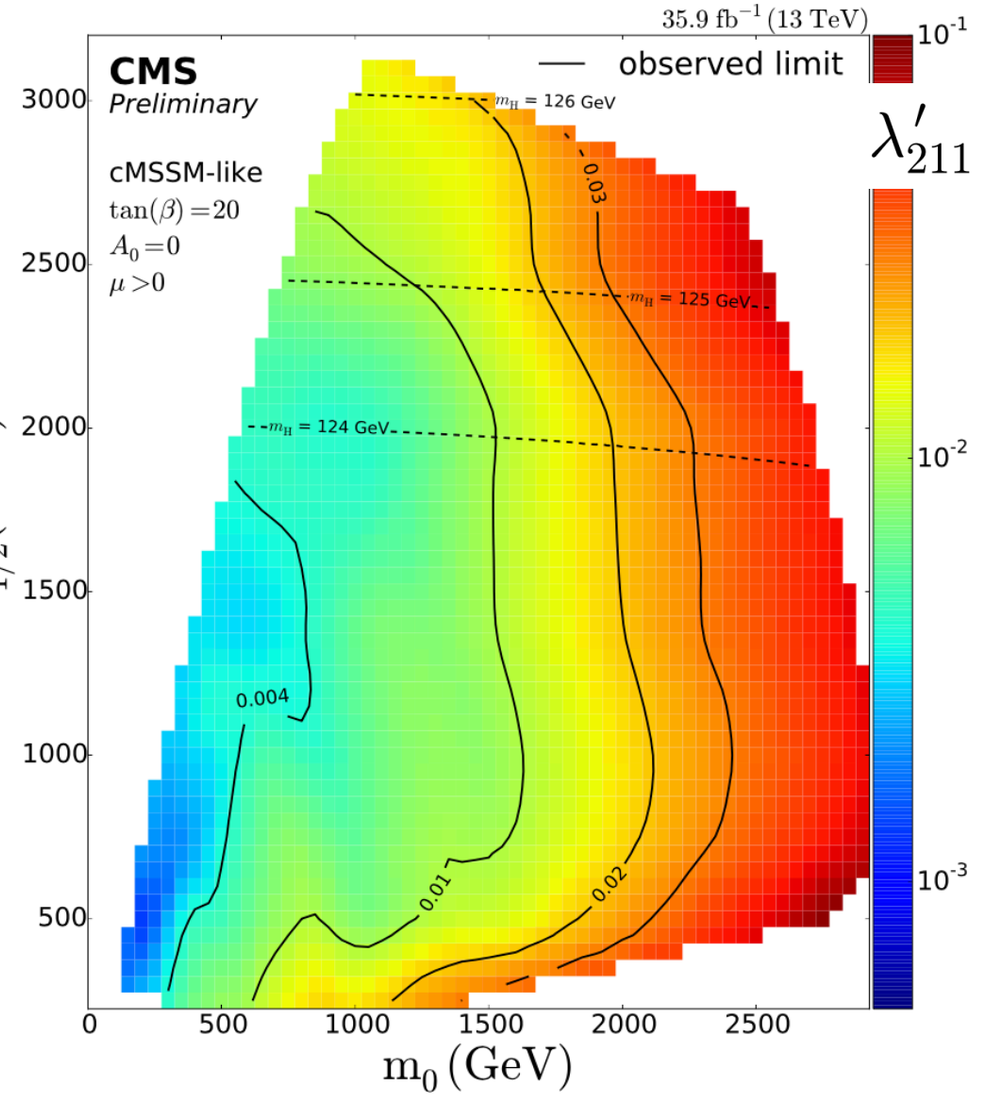
SUS-17-008

- Resonant smuon production via RPV coupling
- Final state contains exactly 2 same-charge muons & at least 2 jets
- Define search regions based on
  - $M_{slepton} = M(l_1,l_2,jets)$
  - $M_{chi} = M(l_2,j_1,j_2)$









NEW

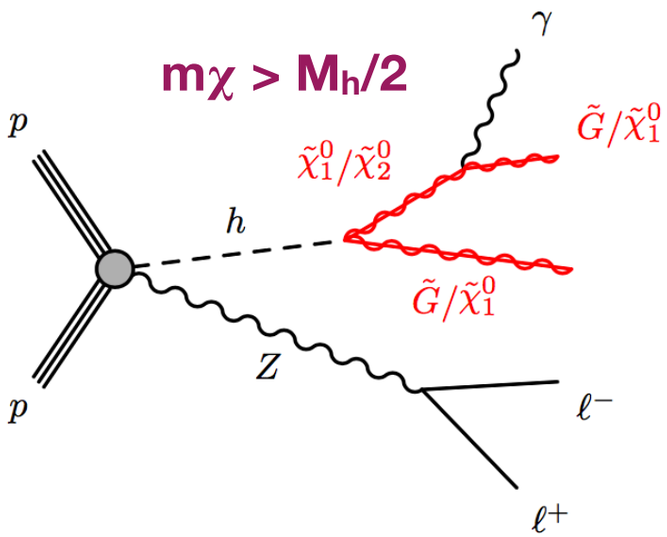
Higgs → photon(s) + E_T^{miss}

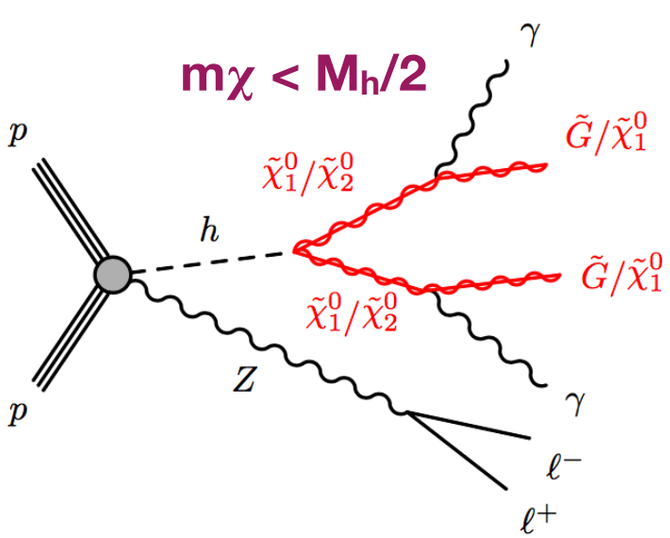
ATLAS EXPERIMENT

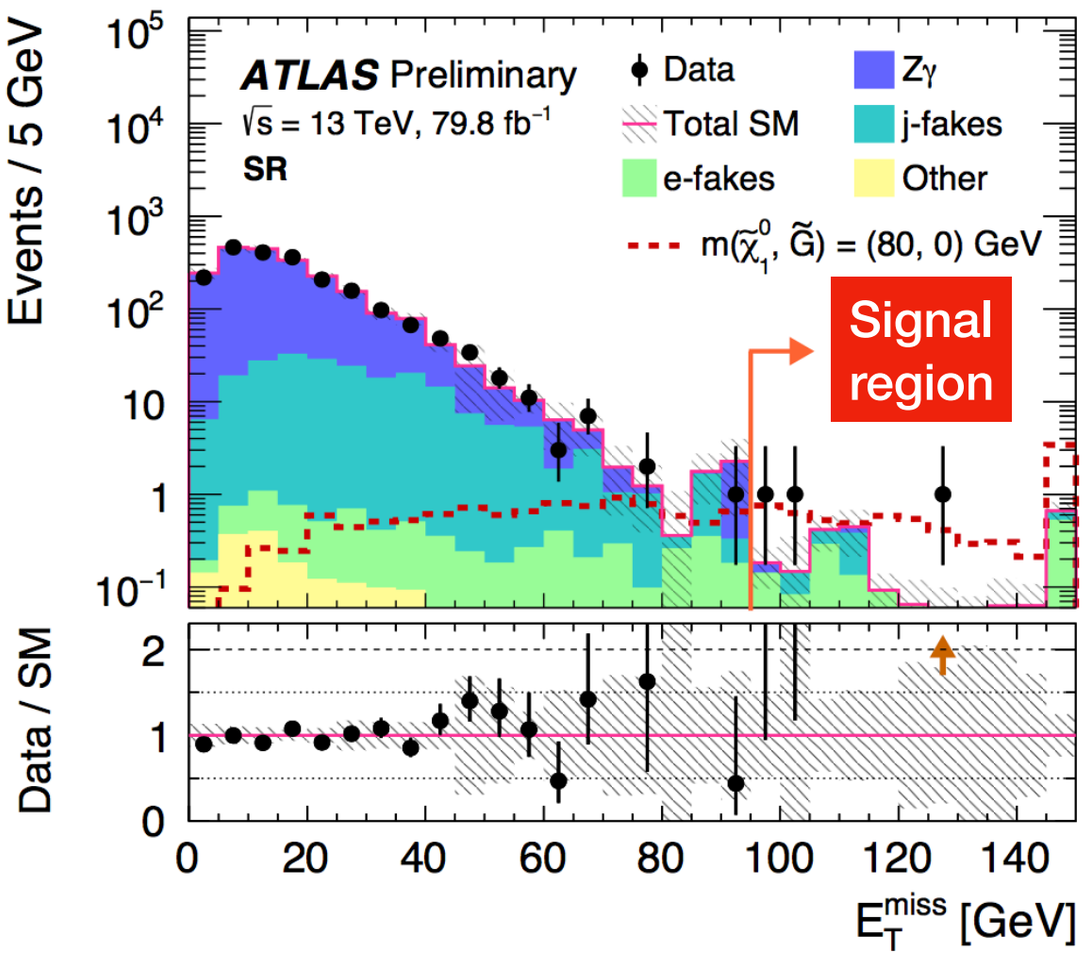
CONF-2018-019

2015+2016+2017

- GMSB or nMSSM SUSY decays of the Higgs can produce 1 or 2 photons and E_T^{miss}
  - Consider ZH production with Z → ee/μμ to reduce backgrounds
  - Exploit balance of Z and γ(γ) + E_T^{miss} systems
- 3 events observed (2.1 ± 0.5 expected) in **79.8 fb^{-1}** of data!
- UL on visible cross section = 0.06 fb
- **B[H→γ(γ) + E_T^{miss}] < 5—18%** depending on (N)LSP masses



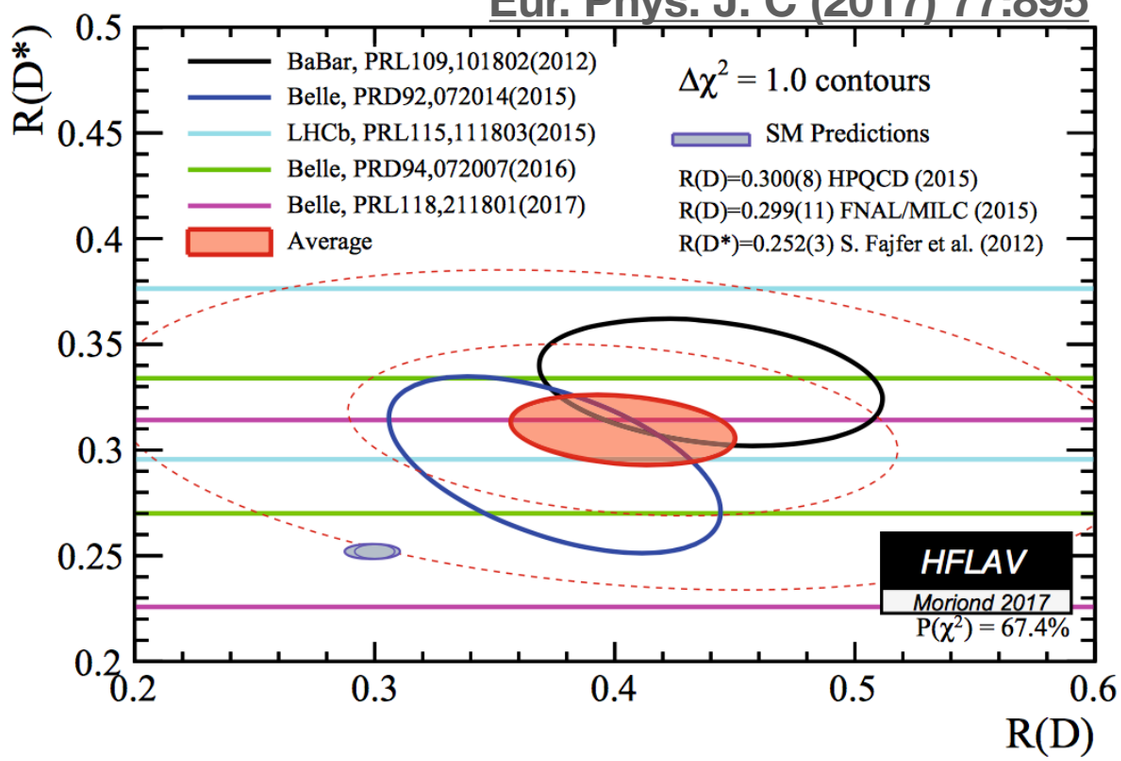


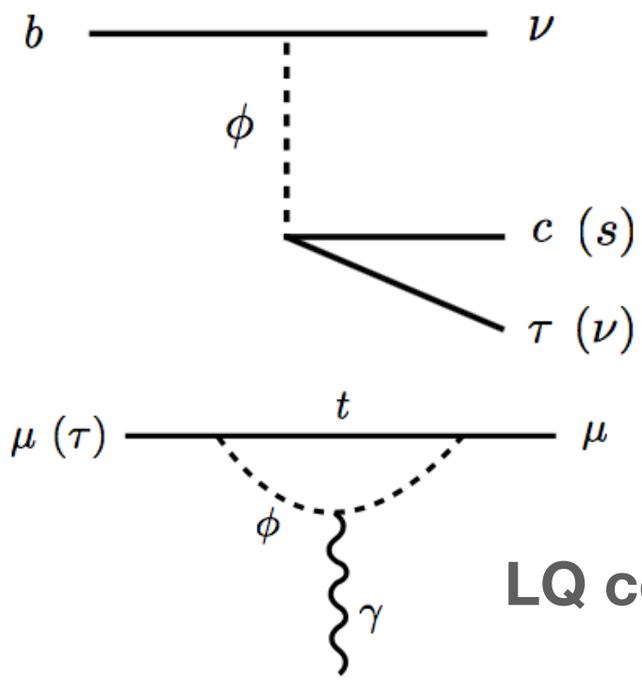


Lepto-quarks

- Renewed interested
- Anomalies in rare b decays confirmed by LHCb
  - $R_{D^{(*)}} = \frac{\mathcal{B}(\overline{B^0} \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\overline{B^0} \to D^{(*)}\mu\bar{\nu})}$ (4σ)
  - $R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$ (2.5σ)
- Long standing discrepancy in anomalous magnetic moment of the muon, a_μ (3.5σ)
- TeV-scale lepto-quarks with strong 3rd generation couplings could explain these deviations!

Eur. Phys. J. C (2017) 77:895





LQ contrib to b-decay

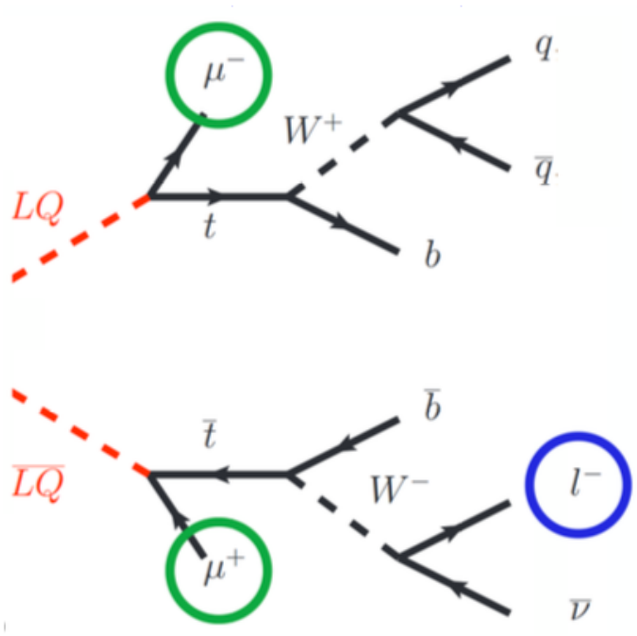
LQ contrib to a_μ

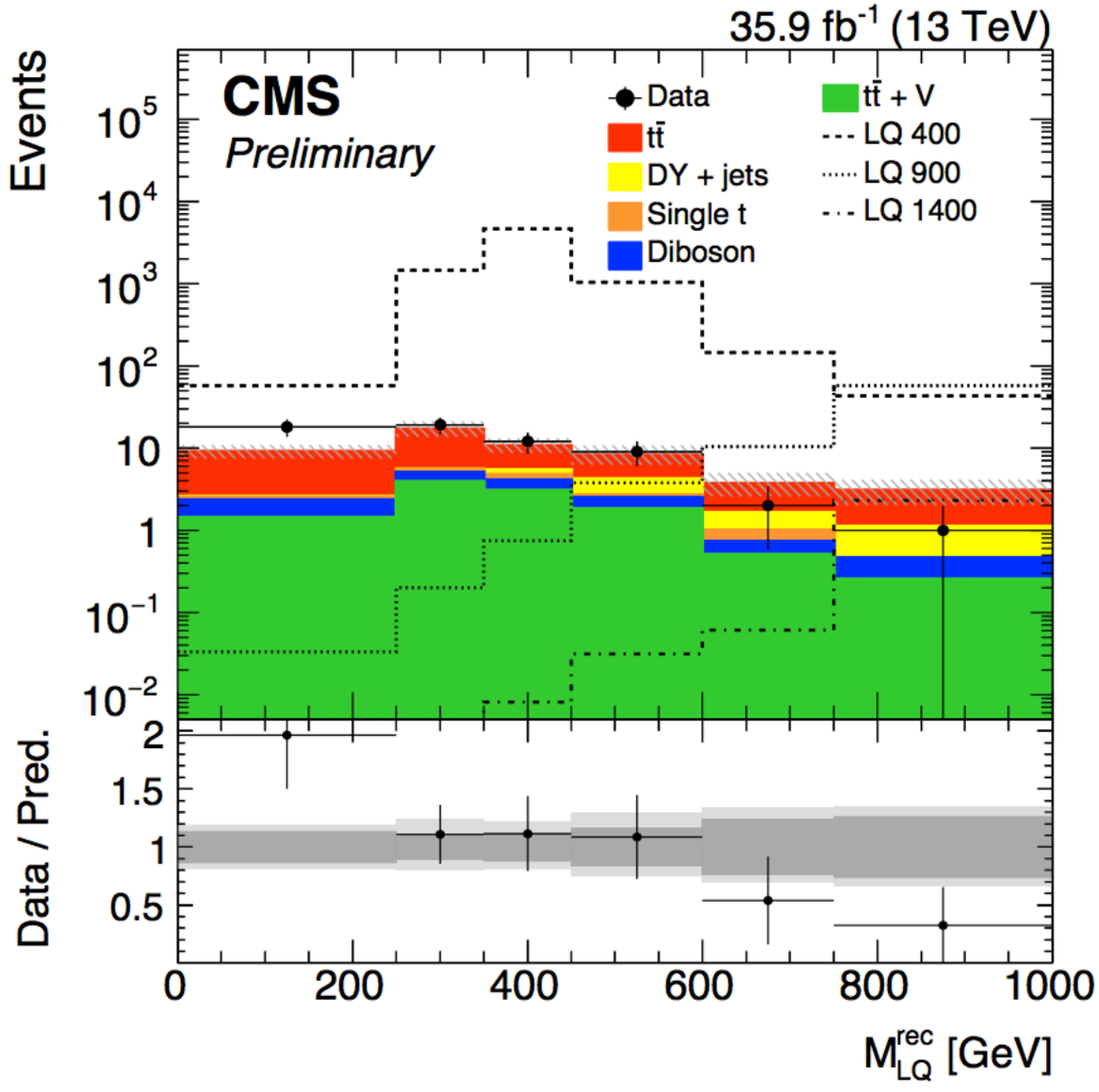
NEW

LQ → top + muon

B2G-16-027

- Especially important to explain a_μ and R_K
- 2 search categories
  - General purpose 2-muon category, predicted from 2-electron region using $S_T = \sum$(jets, leptons, E_T^{miss})
  - Category with 3 leptons, which allows for LQ mass reconstruction using χ^2 fit





- No deviations from SM observed

NEW

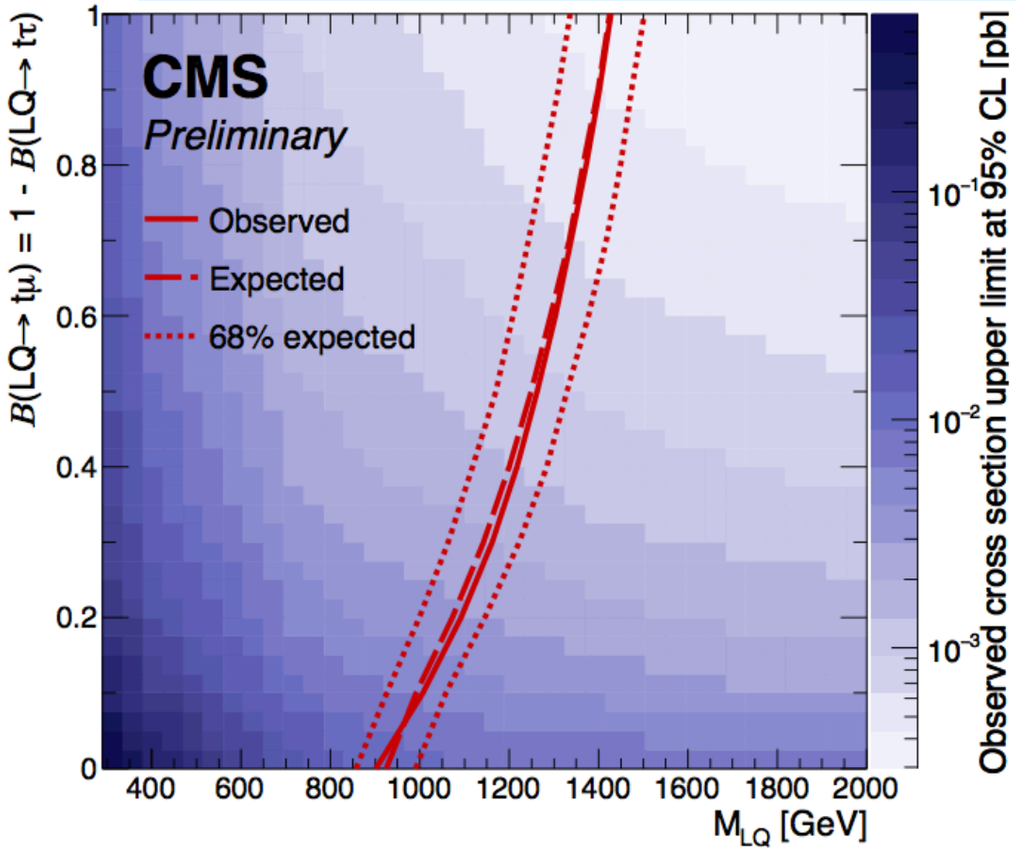
3rd gen lepto-quarks

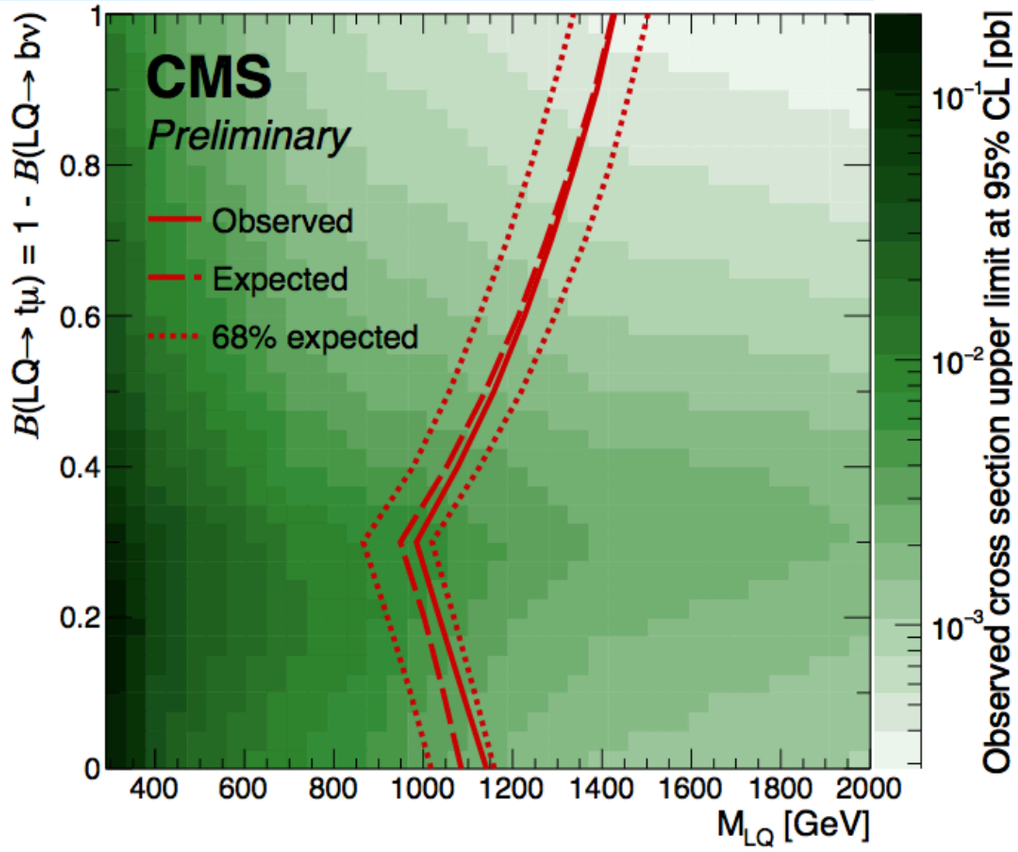
B2G-16-027

Combine top + muon search with 2 orthogonal searches

- LQ → top + tau (B2G-16-028) to set limits on σ(LQLQ→ tltl) (with l = μ, τ)
- LQ → b + neutrino (SUS-18-001 reinterpretation) to set limits on σ(LQLQ→ tμtμ/bνbν)

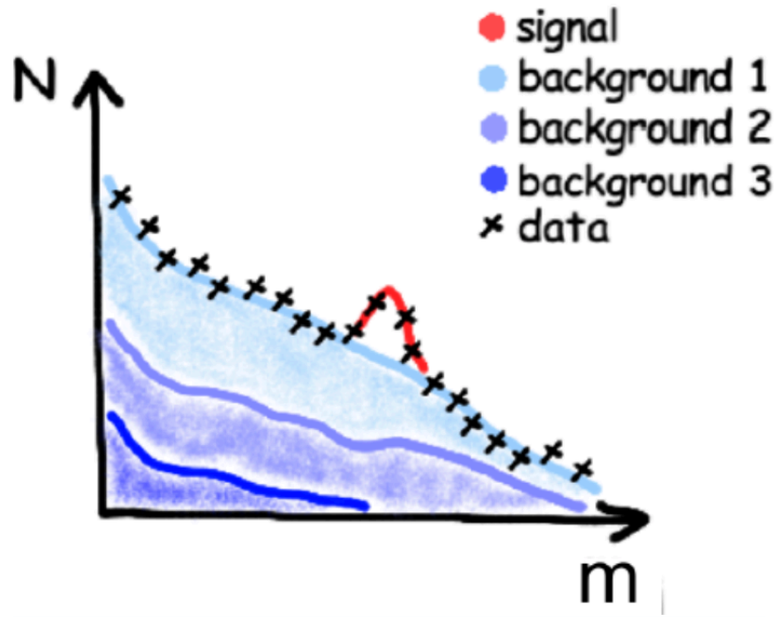
Exclude LQ below 900 GeV for any branching fraction!



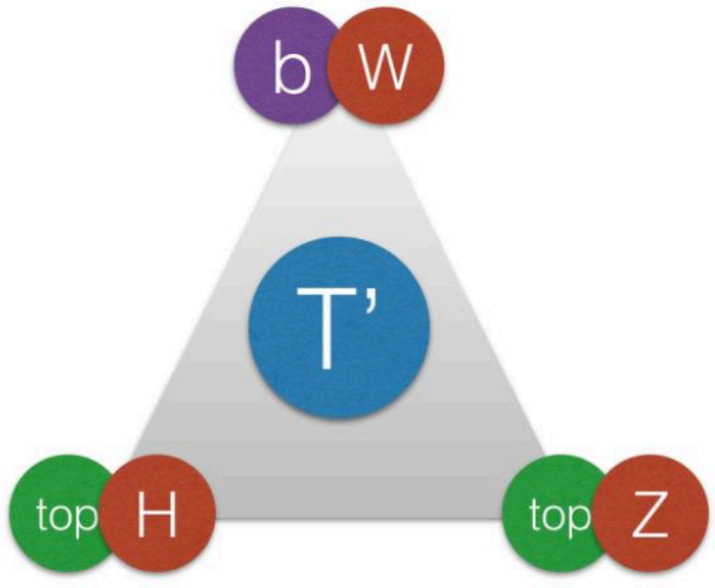


Other new particles

- **Heavy resonances:**
  - Directly probe mass scales up to the limit of the accelerator, i.e. multi-TeV
  - Present in many BSM theories (Z', W')
  - Multitude of decay modes possible
    - Classic: dilepton & dijet
    - **ttbar,** t+V**, VV, including Higgs**
  - Heavy → boosted object techniques
- Not always heavy, i.e. **low mass Z'**
- **Vector-like quarks**
  - Colored spin-1/2 fermions
  - Various possible electric charges (2/3, 5/3, -1/3, -4/3)
  - Many models favor **decays to vector bosons and 3rd generation quarks** (T → tH, tZ, bW and B → bH, bZ, tW)



Typical analysis strategy: "Bump hunt"



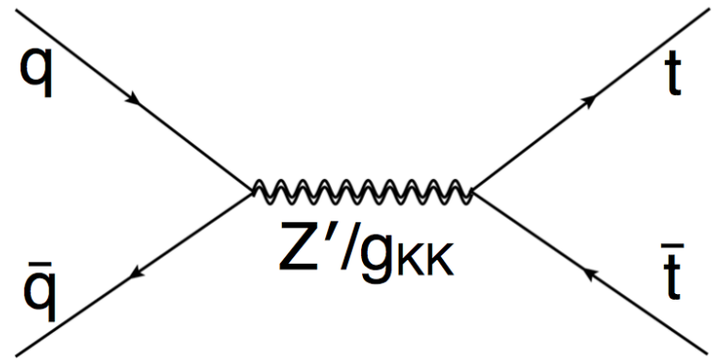
Note: Dijet resonances covered by S. Meehan

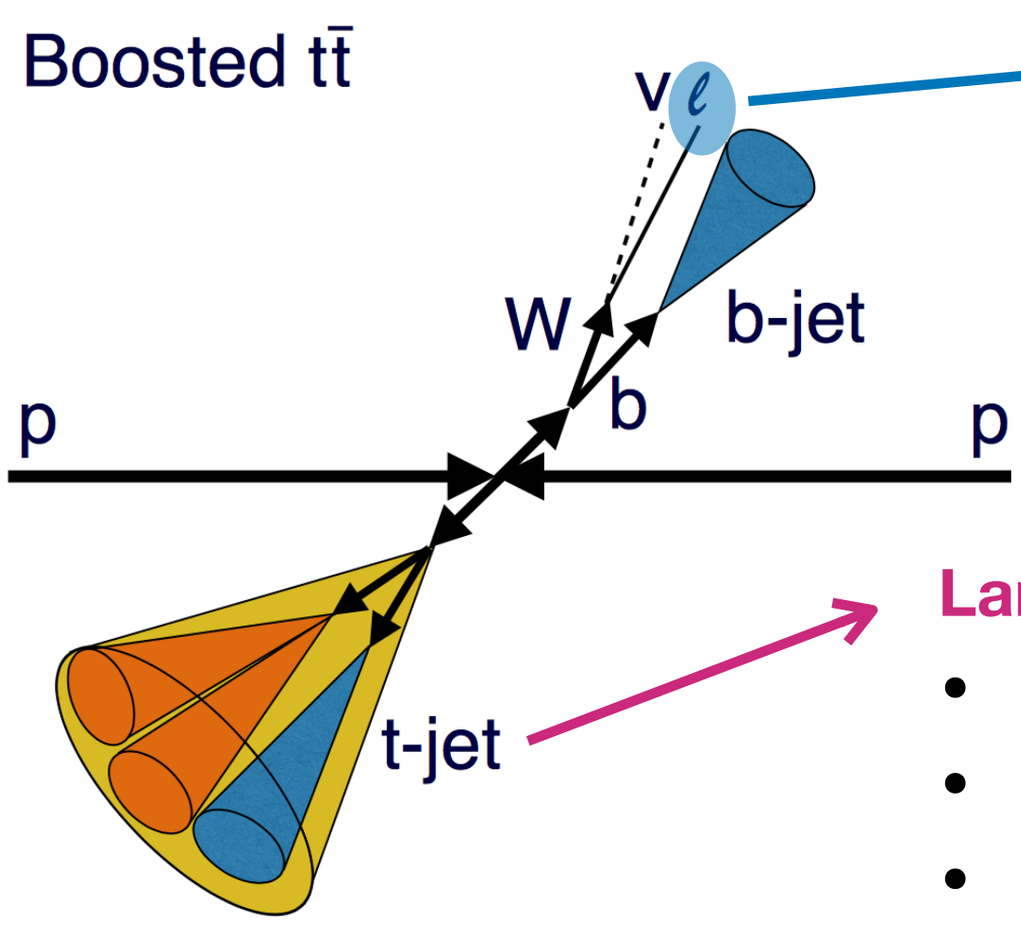
NEW

ttbar resonance search

B2G-17-017
36 fb^{-1} (2016)

- First combination of all-hadronic, single lepton, and dilepton channels
- Focus on resonances above 2 TeV





Non-isolated leptons

- Correct jet momentum to account for nearby lepton
- Require minimum relative p_T of lepton wrt axis of closest jet (in ΔR)

Large-radius jet with 3 subjets

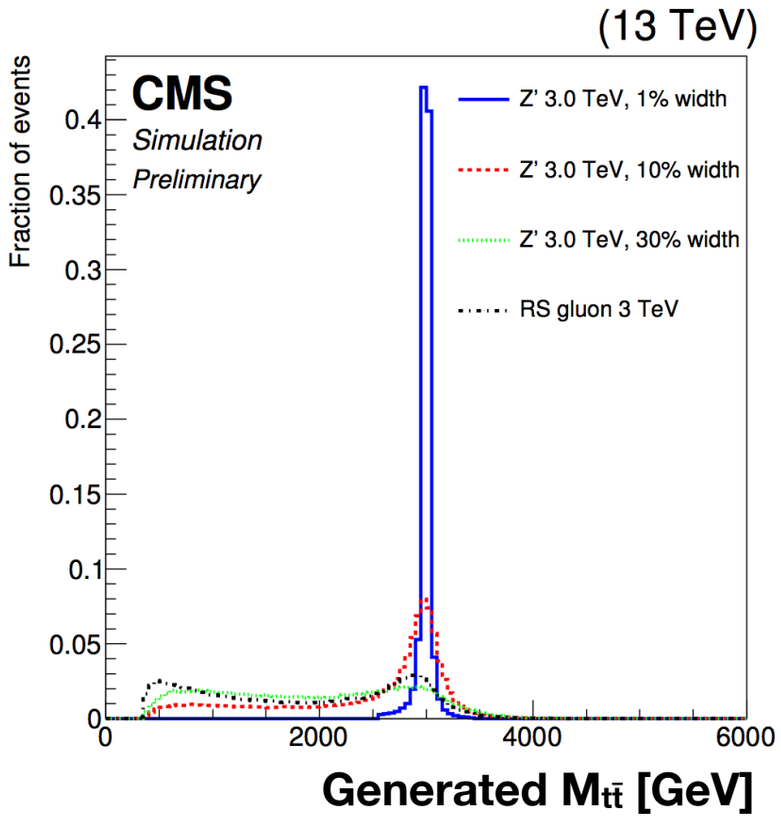
- Jet substructure techniques, i.e. N-subjettiness
- Use softdrop grooming for jet mass
- Use Puppi for pileup mitigation

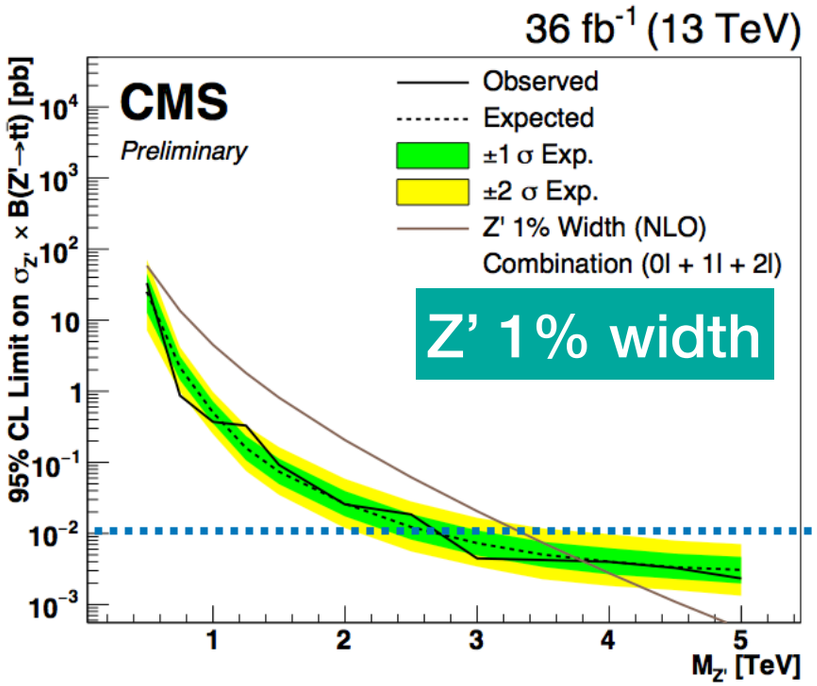
NEW

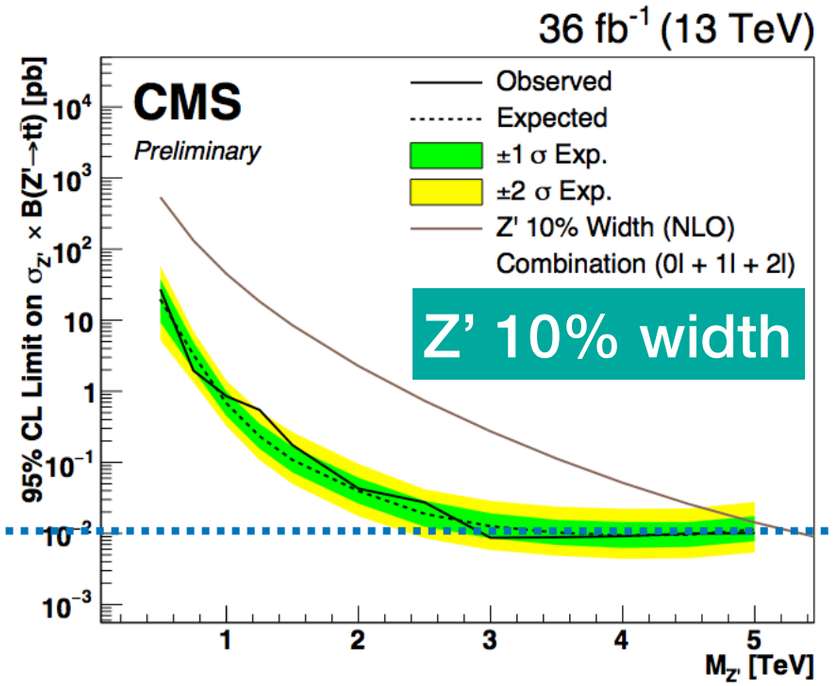
ttbar resonances

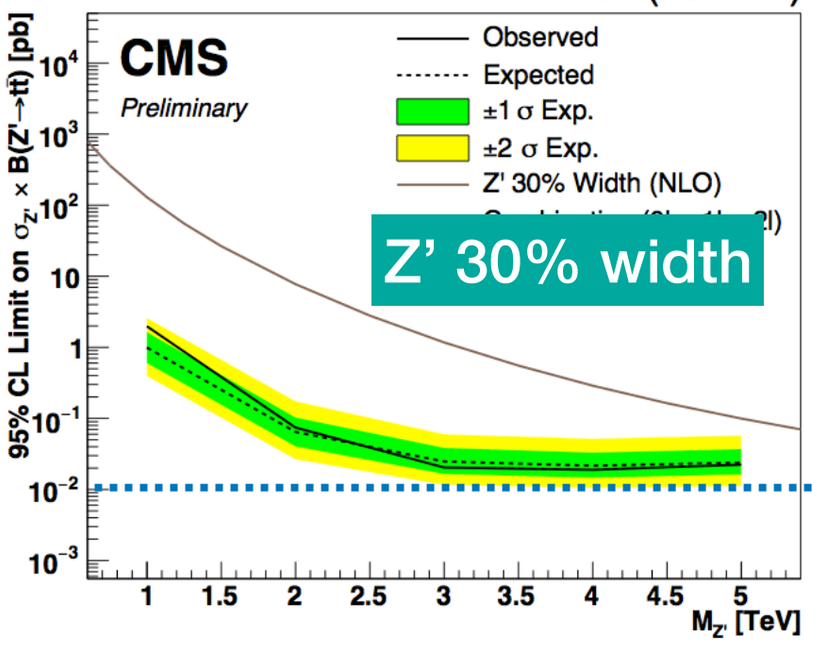
B2G-17-017
36 fb^{-1} (2016)

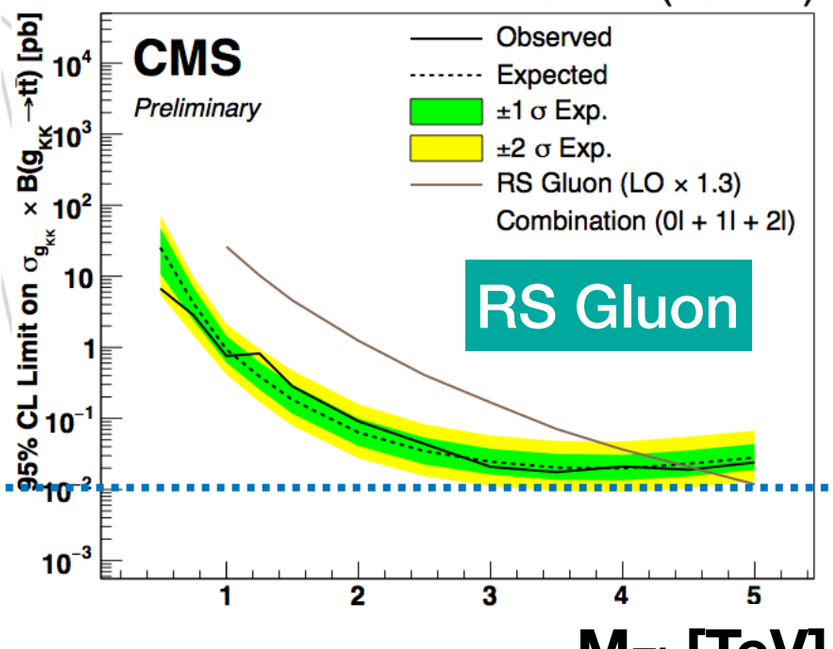
Signal shape depends on assumption of the relative width









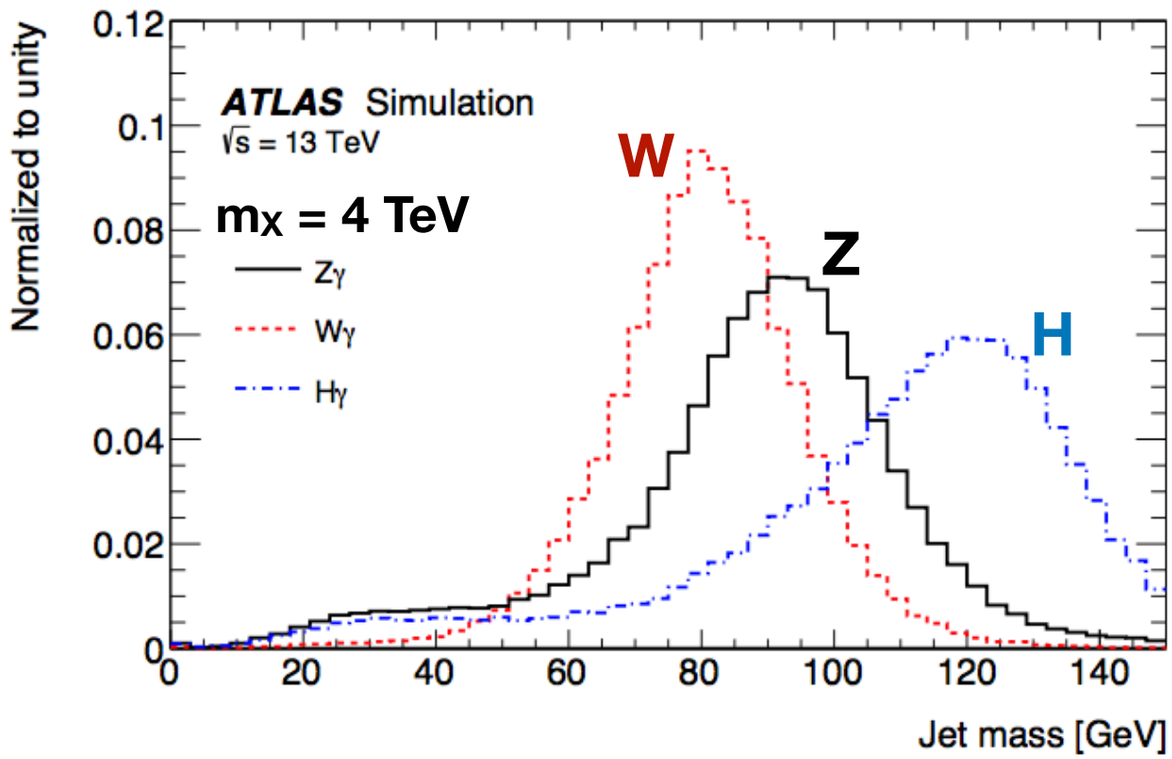


Limits up to 5 TeV!

γ + W/Z/H resonances

arXiv:1805.01908

- Select events with a high p_T photon and high p_T large-R jet
- Require consistency of large-R jet with W/Z or **Higgs** boson
- Multiple categories depending on whether jet is double-b-tagged, two-prong, or just passes mass window
- Bump hunt on falling spectrum

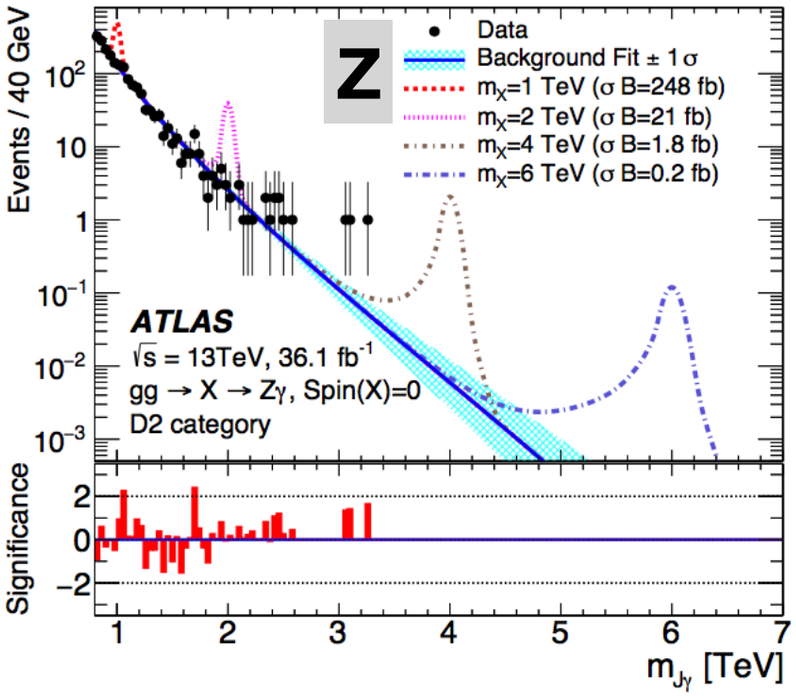


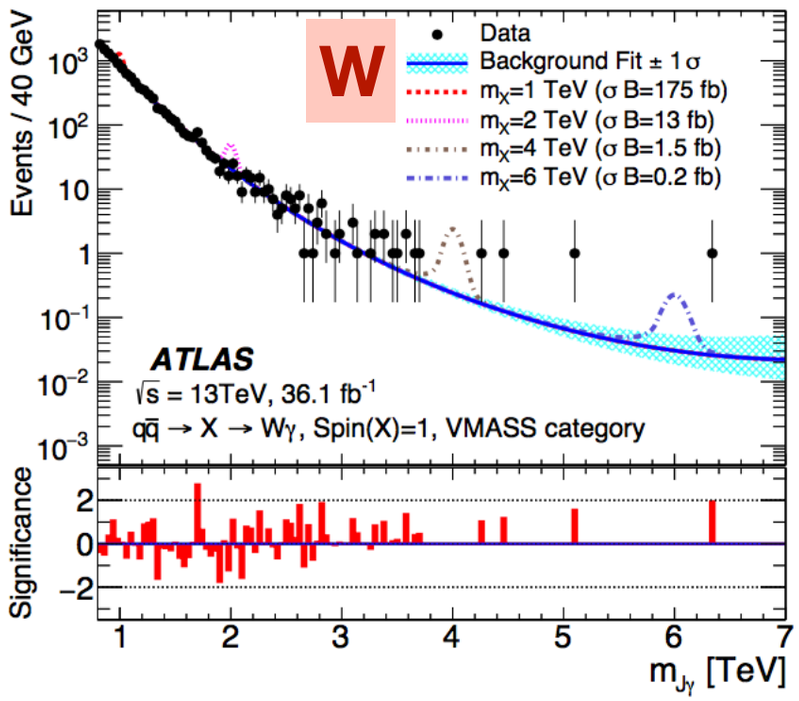
Selection	Event yield in each category ($m_{J\gamma} > 1$ TeV)				
	Baseline	BTAG	D2	VMASS	ELSE
$Z\gamma$ search	60,237	25	784	5,569	53,859
$W\gamma$ search	60,237	—	661	5,216	54,360
$H\gamma$ search	60,237	59	—	—	—

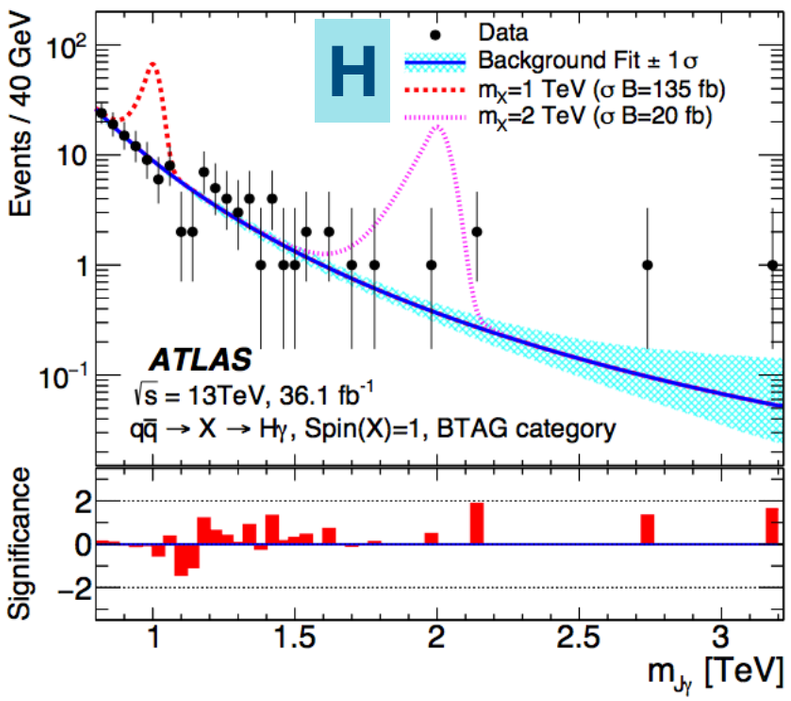
γ + W/Z/H resonances

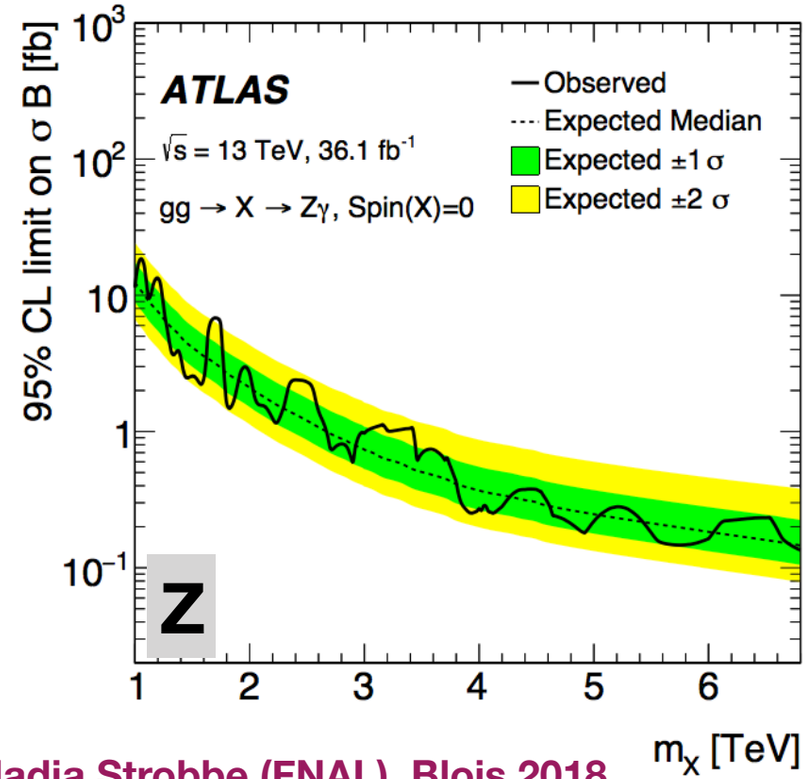
ATLAS EXPERIMENT

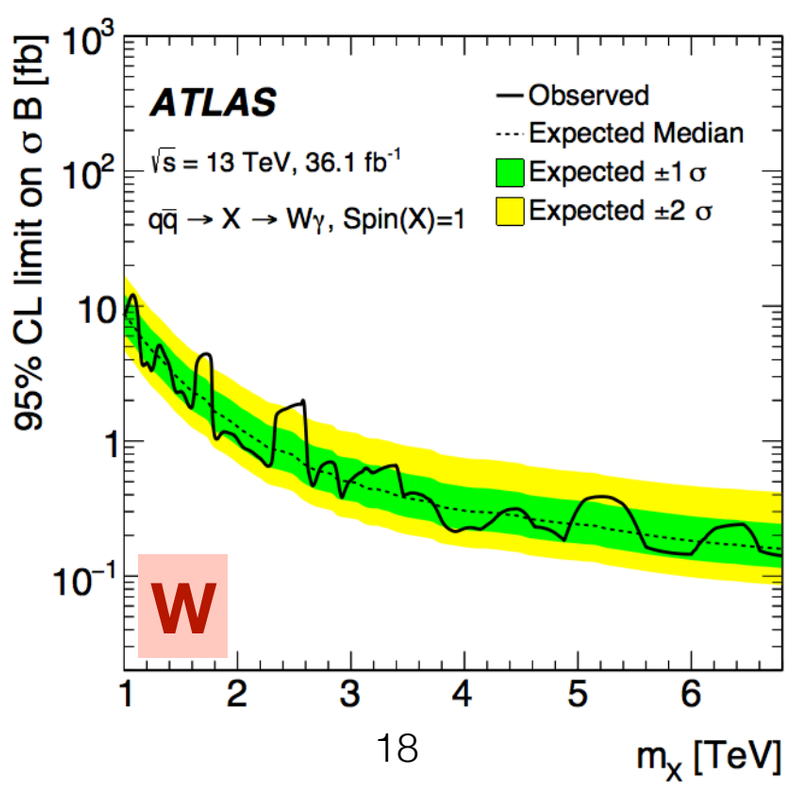
arXiv:1805.01908

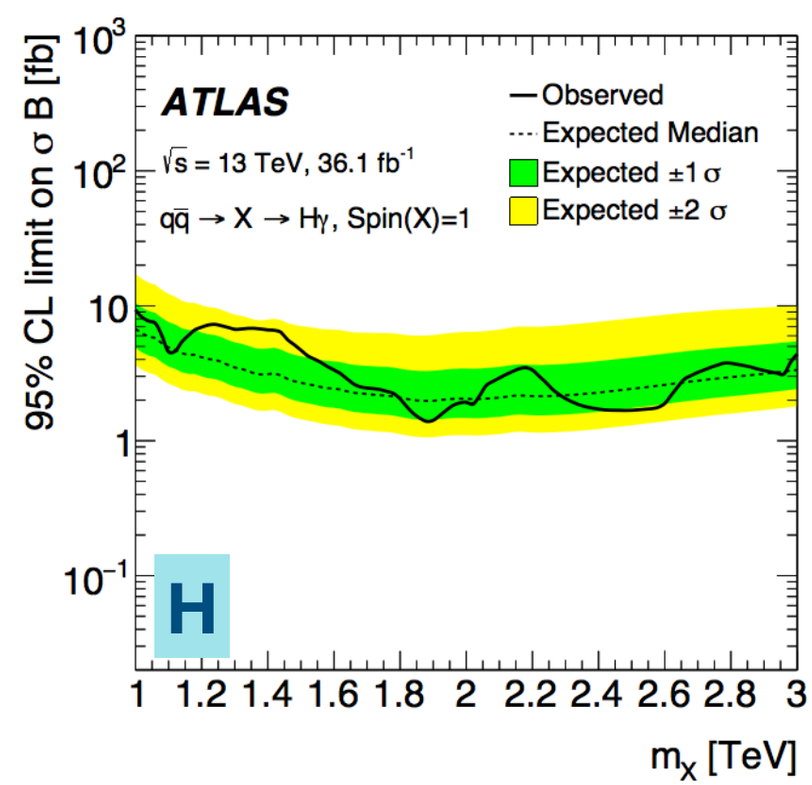






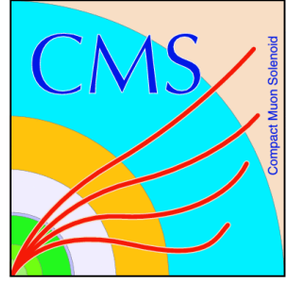






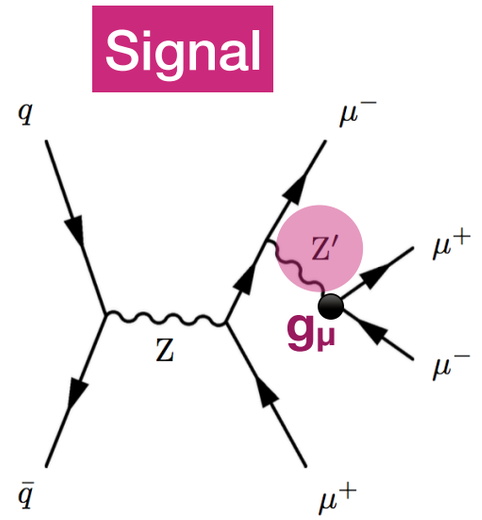
NEW

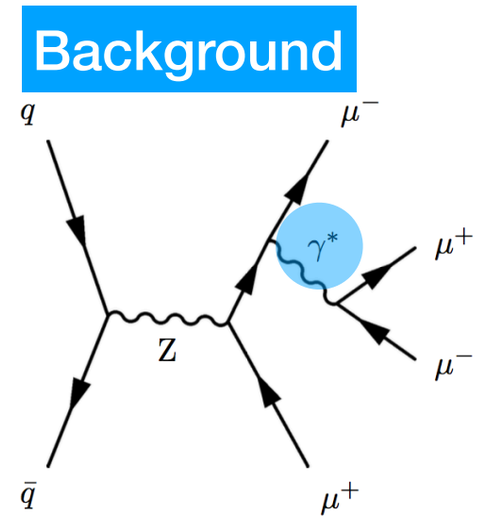
Search for an L_μ-L_τ gauge boson using $Z \to 4\mu$ events



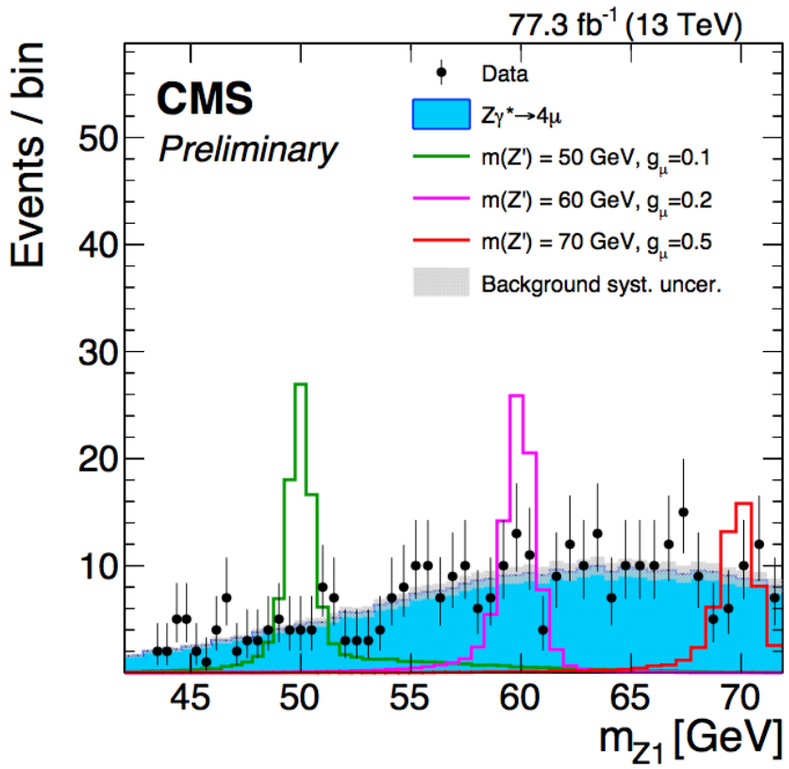
EXO-18-008
2016+2017

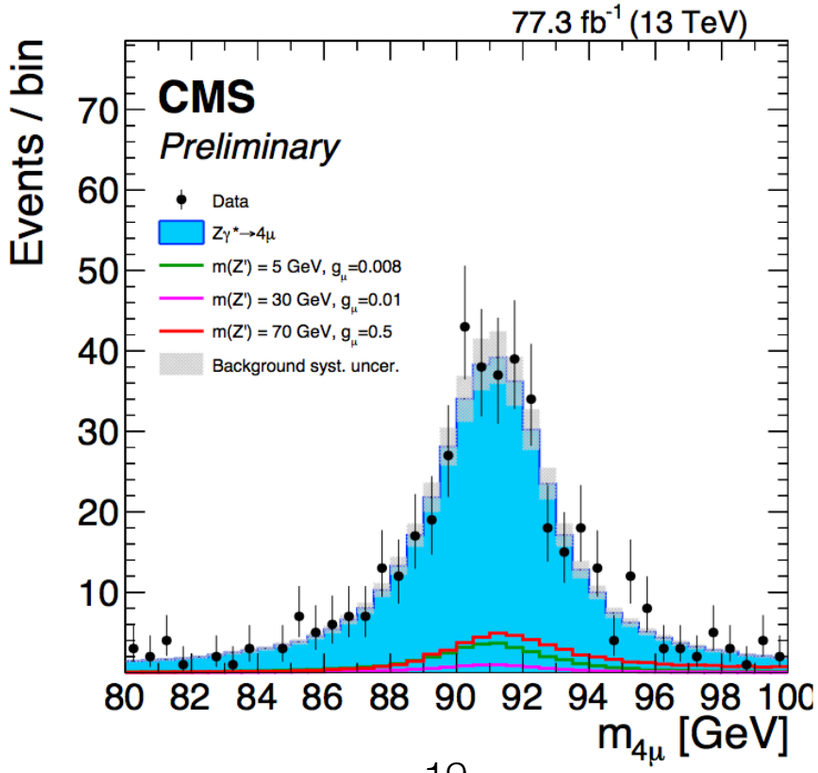
- 2016 & 2017 data sets, for total of **77.7 fb^{-1}**!
- Light Z' from extra U(1)' symmetry, motivated by a_μ and R_K anomalies
- Select events with **4 isolated muons** (down to 5 GeV in momentum)
- Reconstruct $Z' \to \mu^+\mu^-$ candidate mass

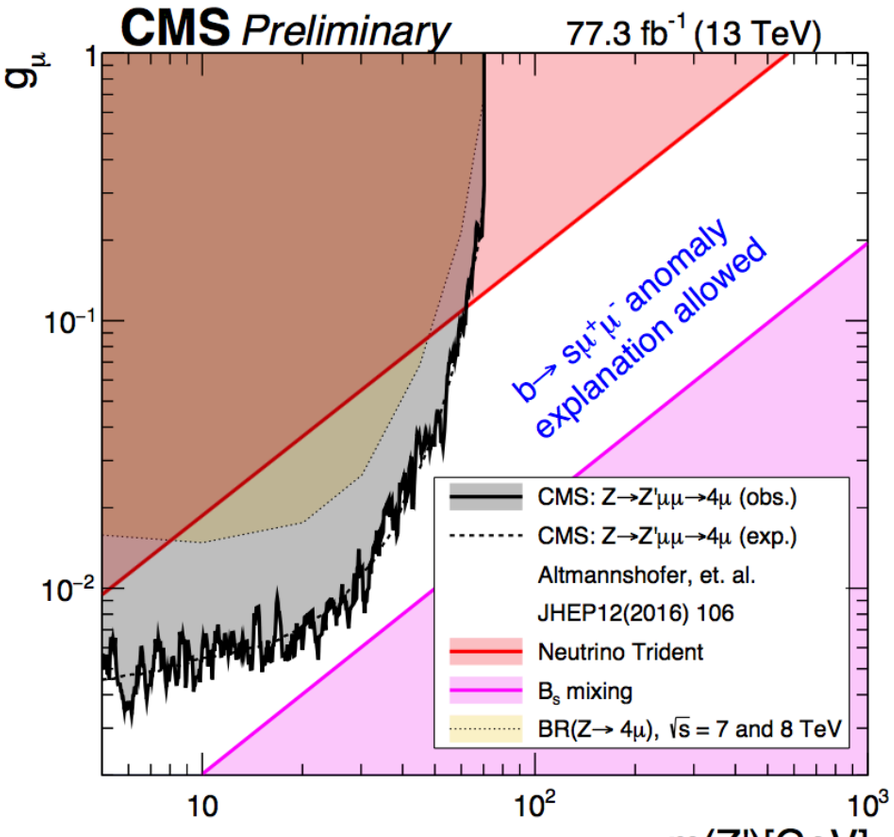




- Counting experiment with sliding mass window







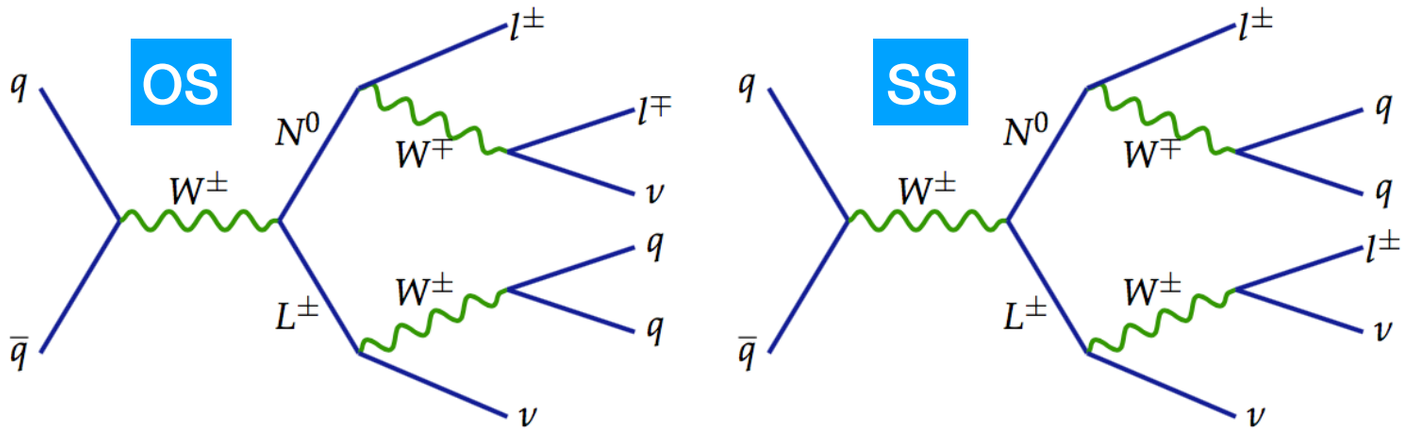
NEW

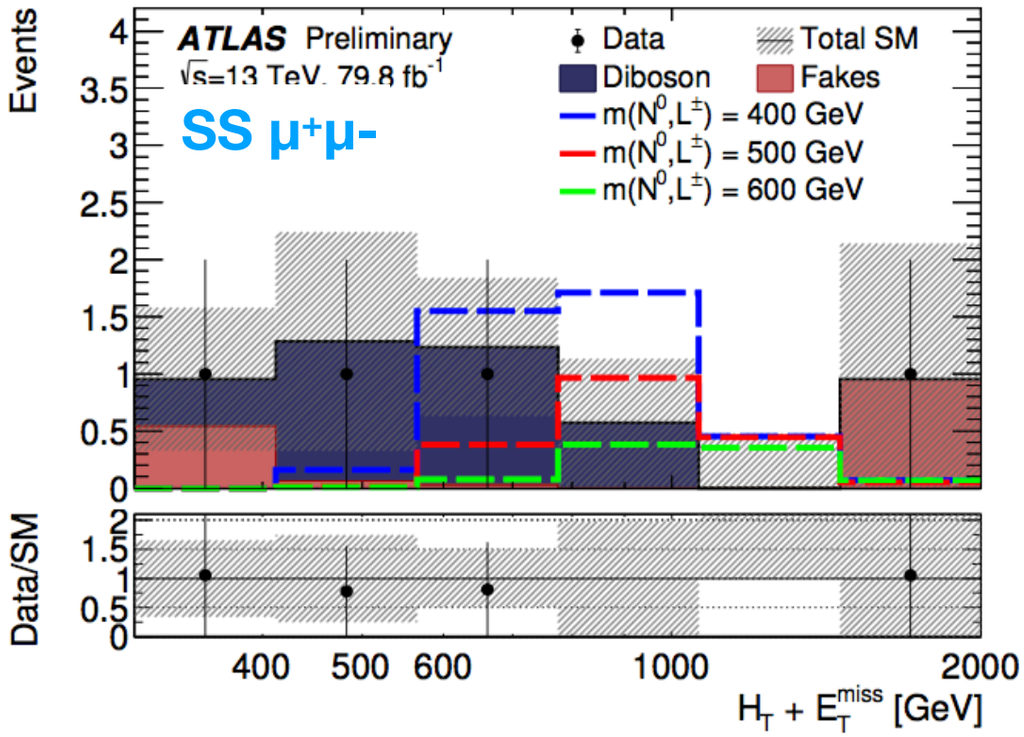
Type-III seesaw heavy leptons

ATLAS EXPERIMENT

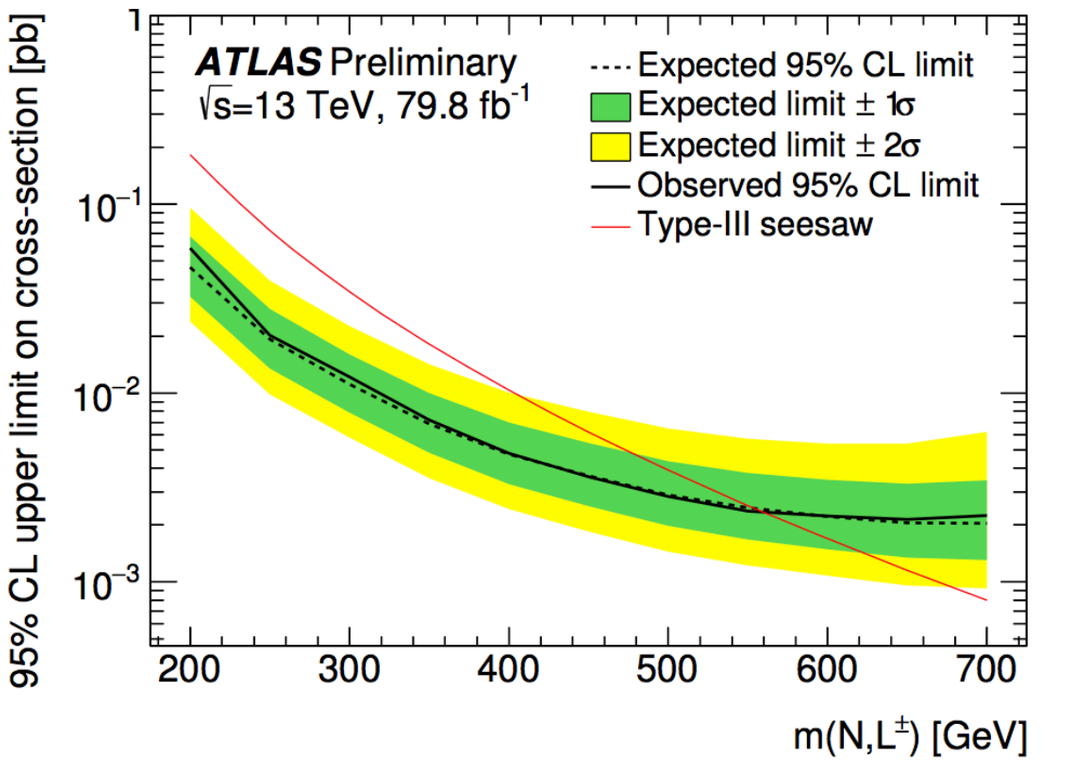
CONF-2018-020

2015+2016+2017





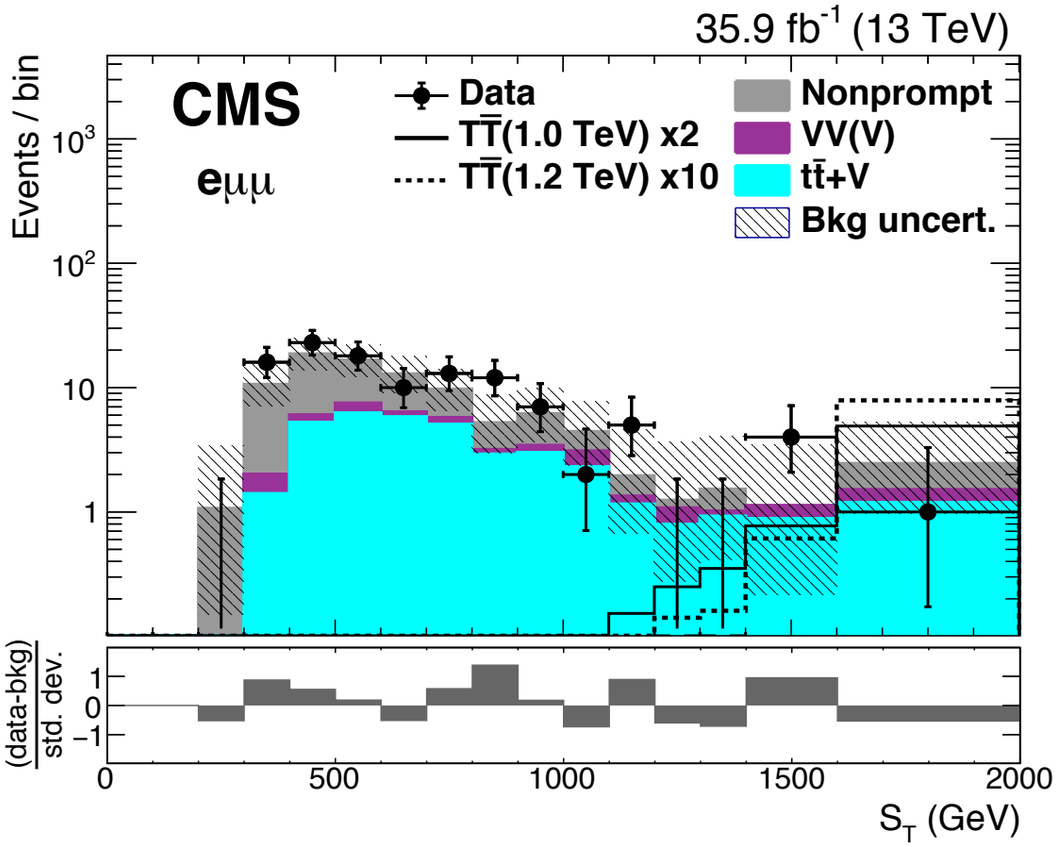
- Seesaw mechanism can explain very small neutrino masses, and predicts heavy leptons
- Search using **79.8 fb-1**, with final state: 2 leptons, 2 jets, E_T^{miss}
- Require large p_T(ll) and p_T(jj) to exploit boosted objects
- 6 categories (flavor, charge) with 6 bins of H_T+E_T^{miss} each

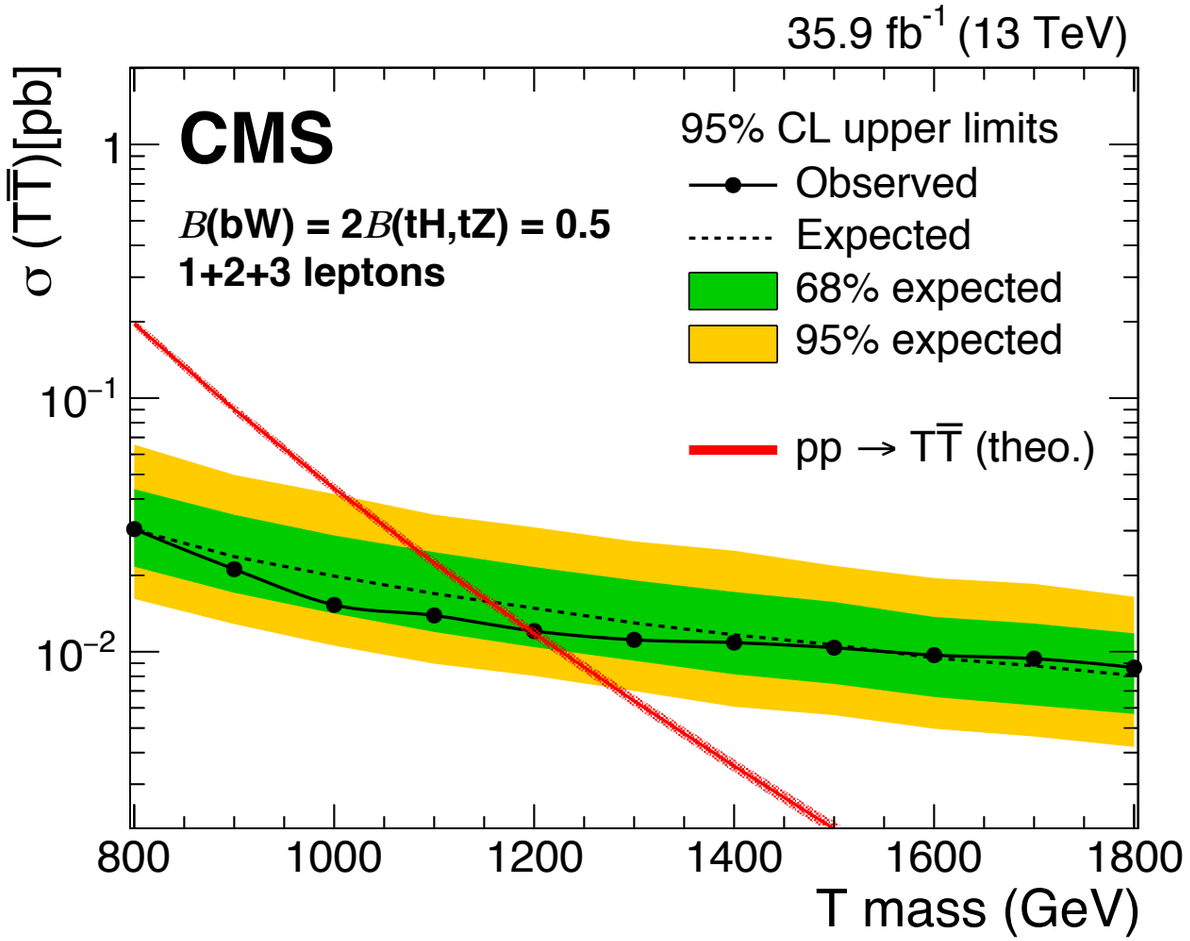


Search for vector-like T/B in final states with leptons

B2G-17-011

- Boosted topology means leptons can be close to jets → Use p_T-dependent isolation cone ("mini-isolation")
- W/H tagging using substructure techniques (N-subjettiness)
- 3 orthogonal categories
  - single lepton, use min[M(l,b)]
  - same-sign dilepton, use H_T^{lep}
  - trilepton, use S_T

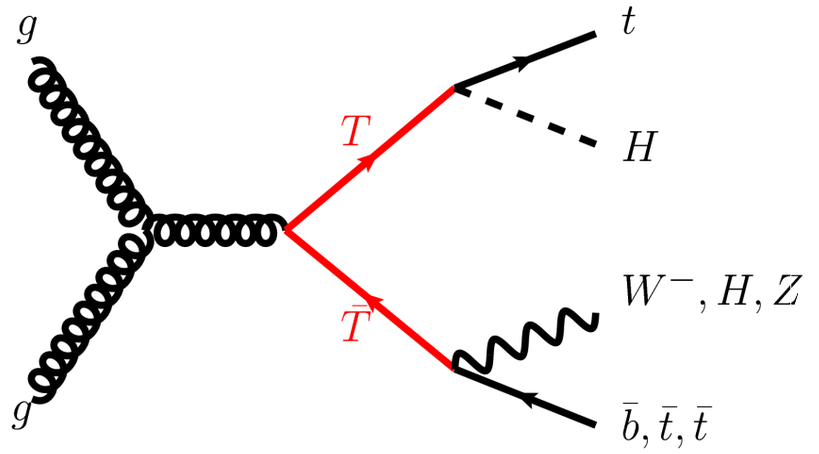


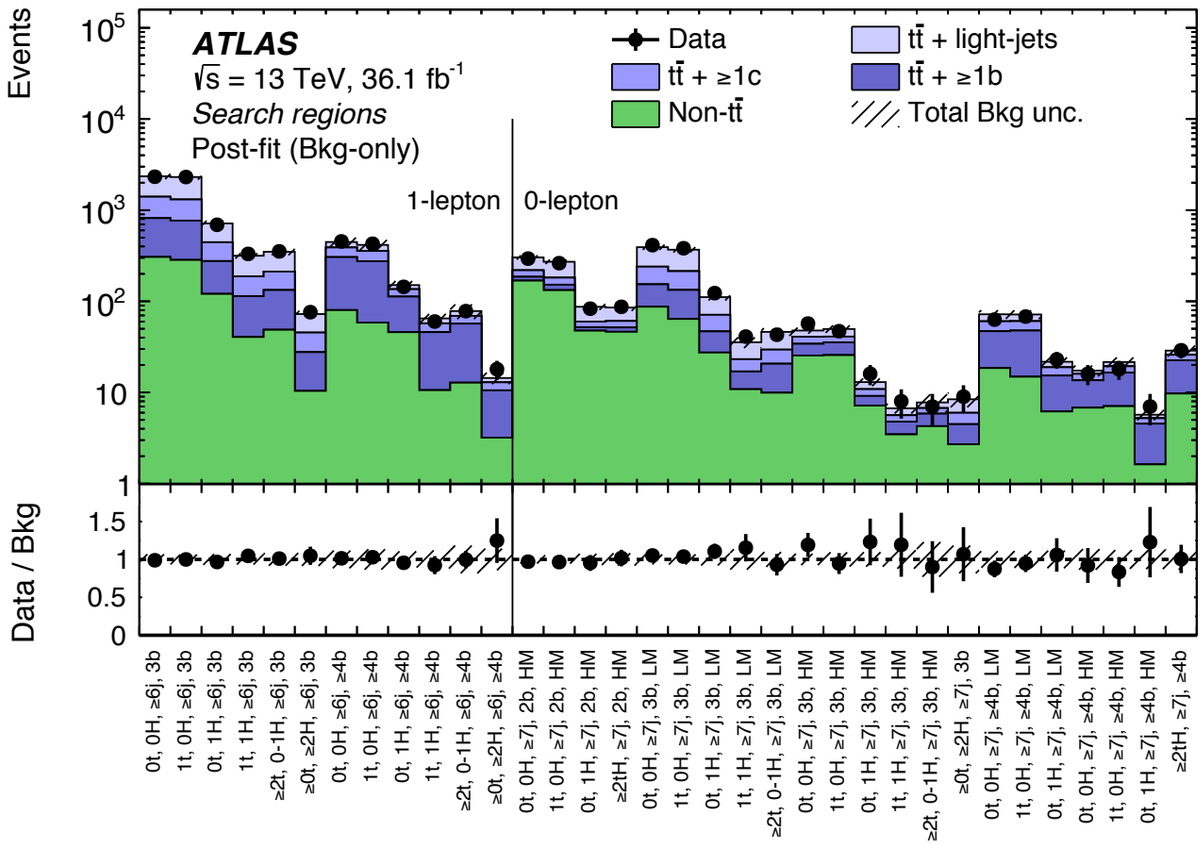


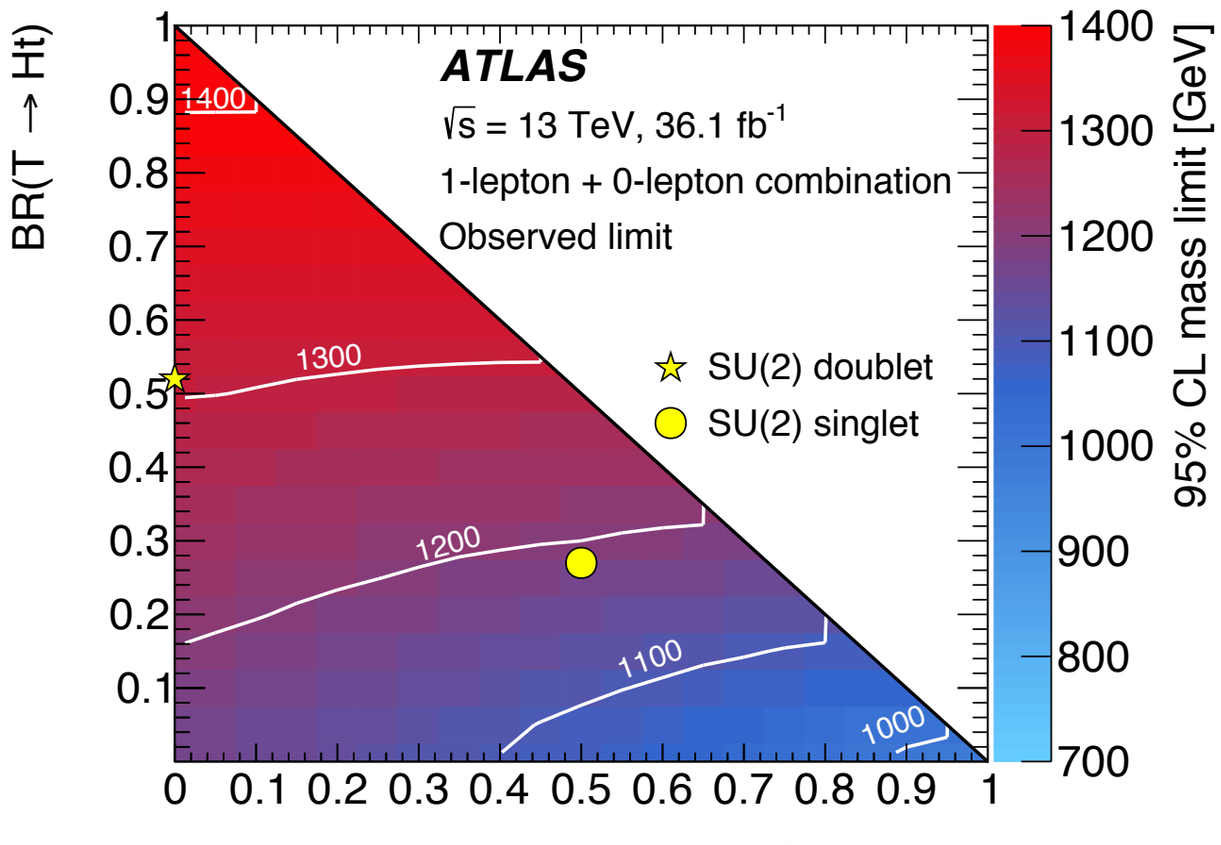
Search for vector-like T in final states with many b-jets

arXiv:1803.09678

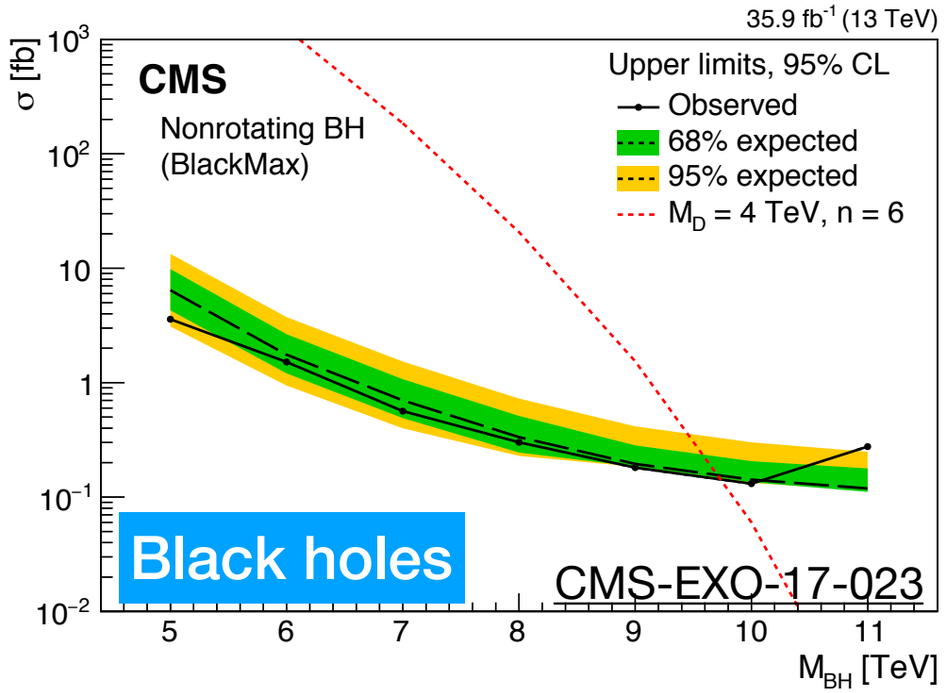
- Analysis in 0- and 1-lepton final state, focusing on models with large B(T → tH)
- Apply H and top tagging algorithms
- Define signal regions based on N_b, N_t, N_H
- Do binned likelihood fit using m_{eff}

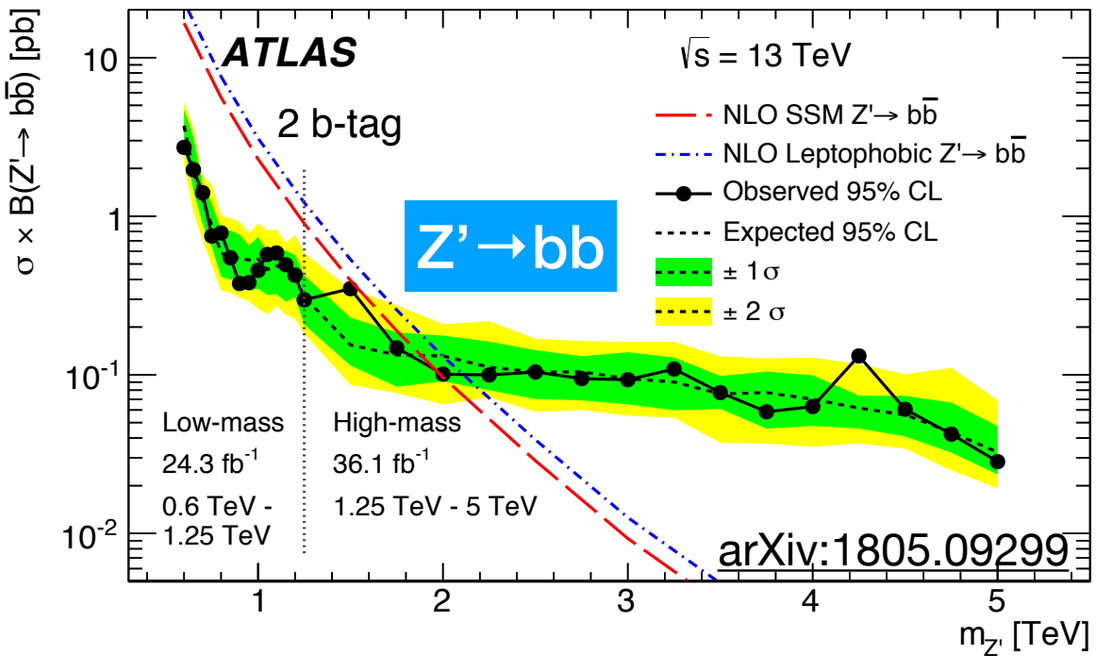


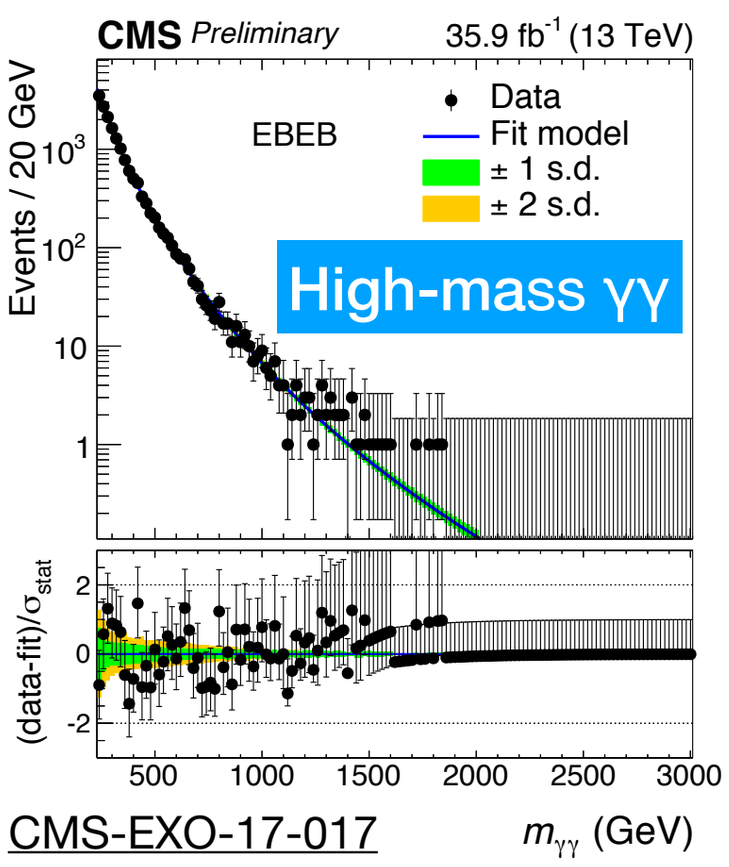


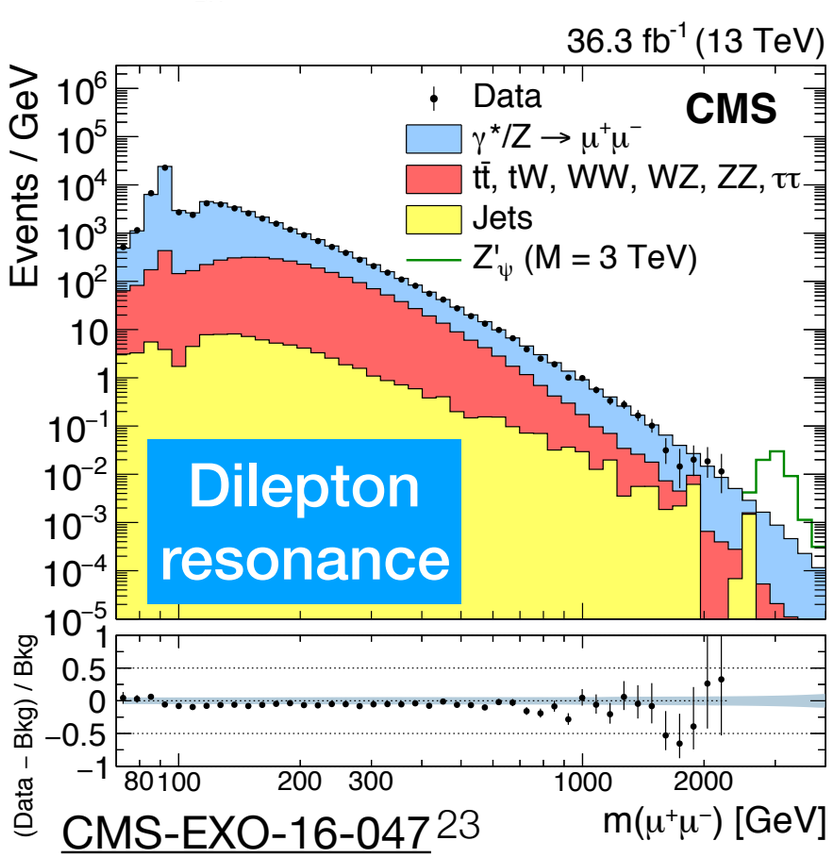


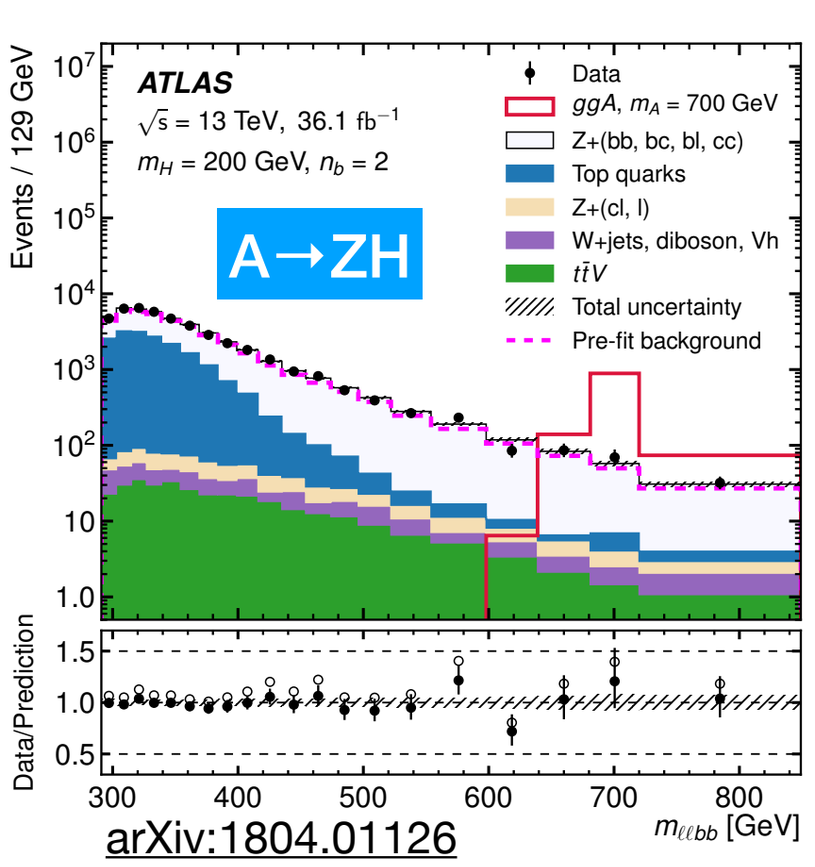
Other exotic searches





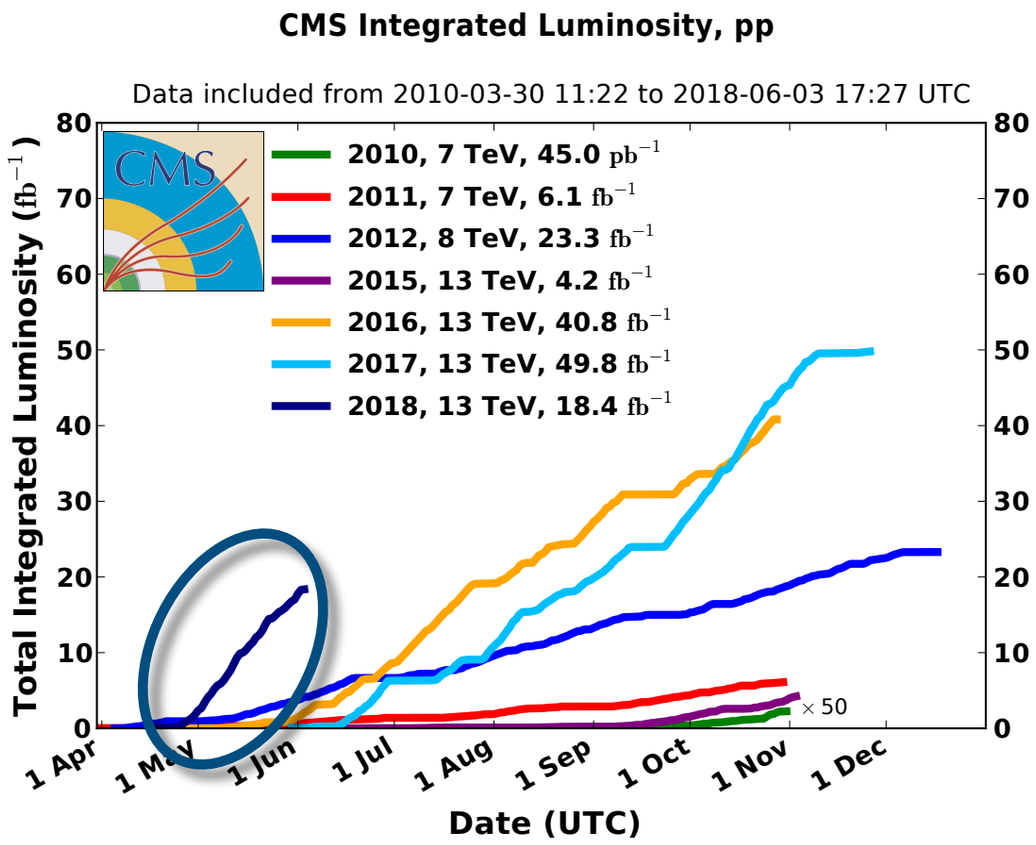


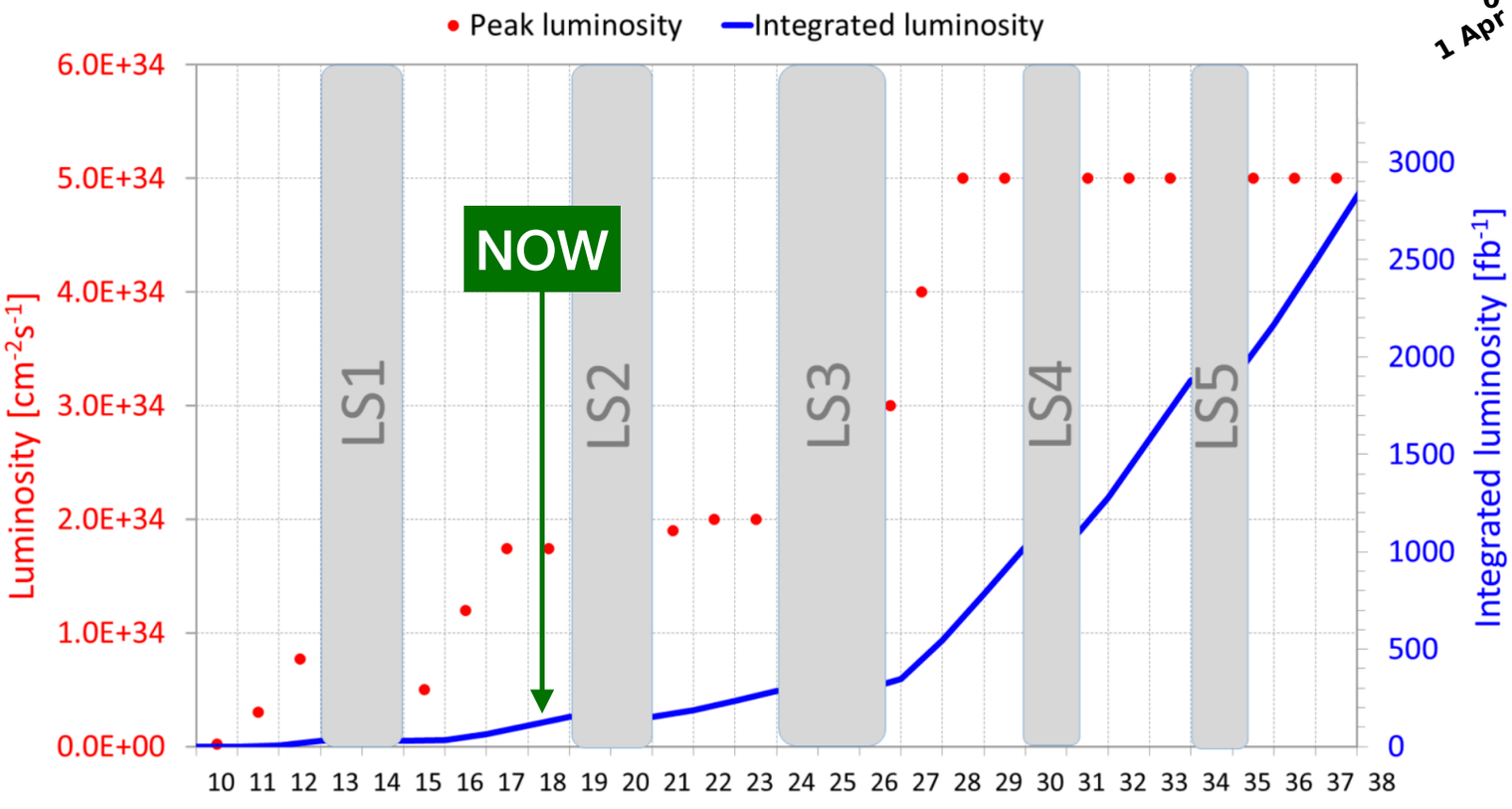


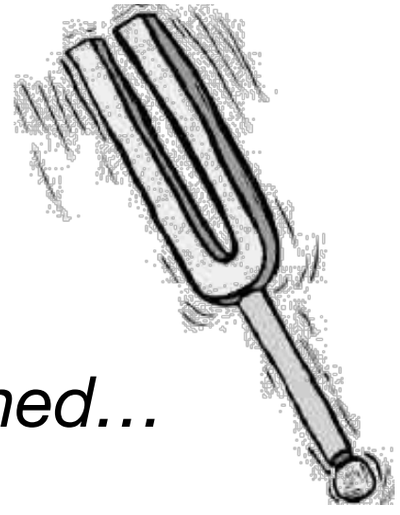


Outlook

- Very fast 2018 LHC ramp-up
- Results on Full Run 2 data (>120 fb^{-1}) coming next year!
- All this data is still only ~5% of what the LHC will deliver!





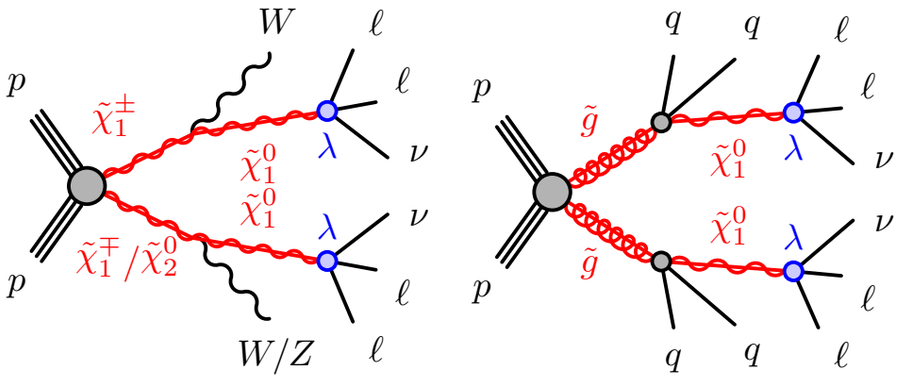


Stay tuned…

Backup

Search for SUSY in events with 4 or more leptons

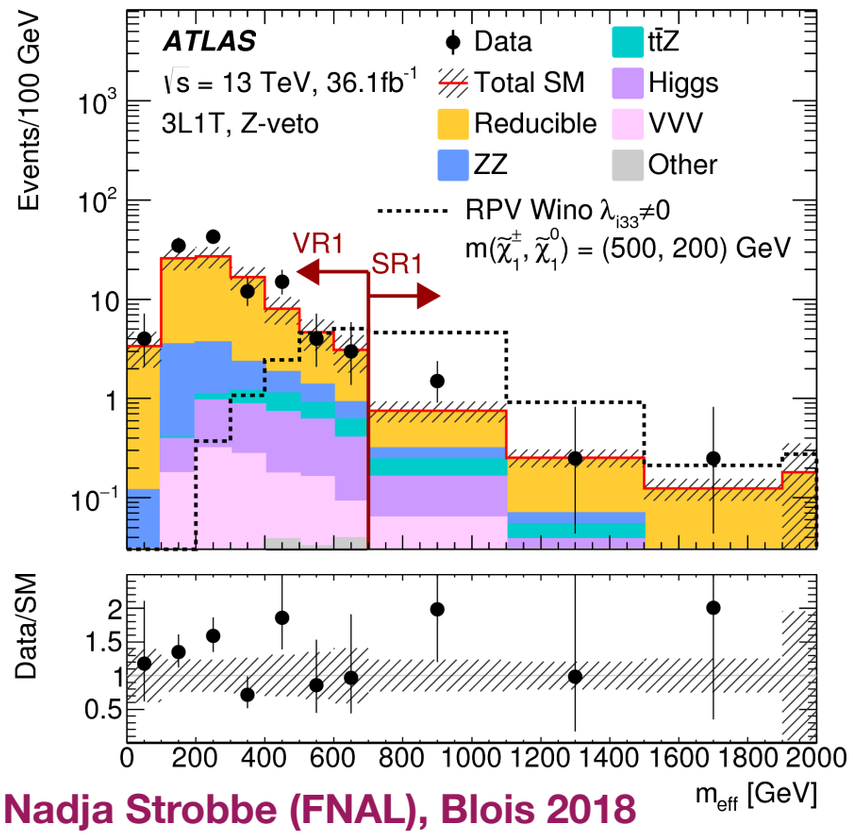
arXiv:1804.03602

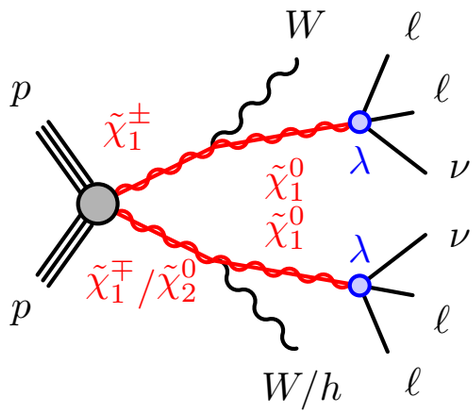


RPC production

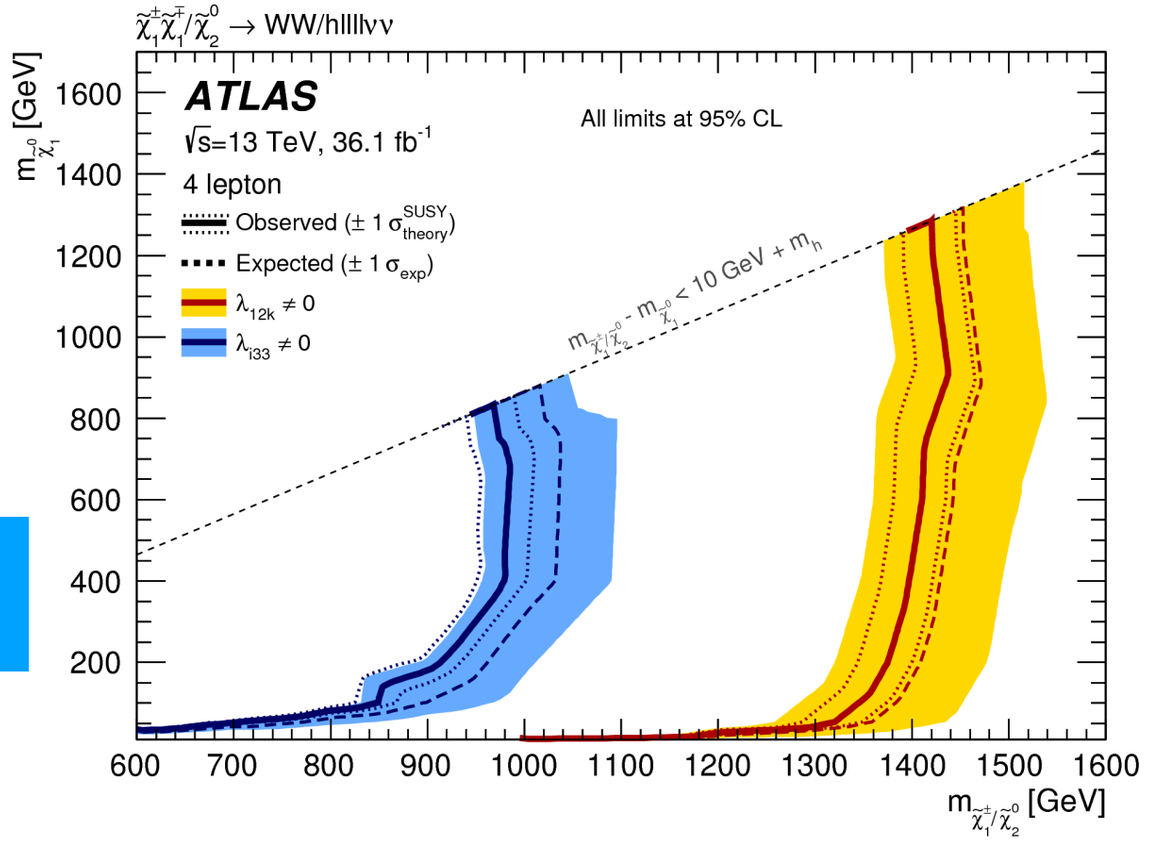
RPV decay

- ≥ 4 leptons (e, μ, τ) with up to 2 τ_{had}
- 6 signal regions defined by number of light leptons, m_{eff}, and MET
- Estimate reducible background from fake leptons using data control region
- No excess observed





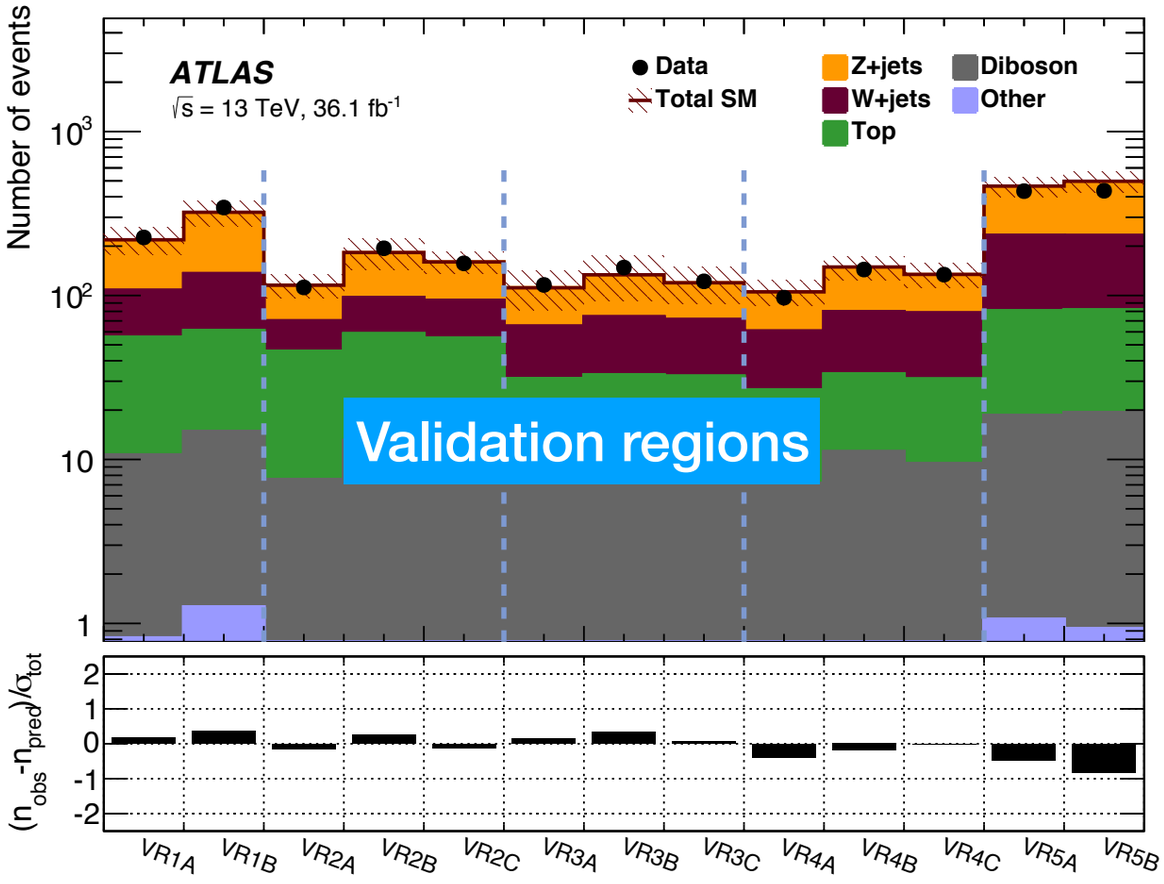
Winos excluded up to 1.0/1.4 TeV

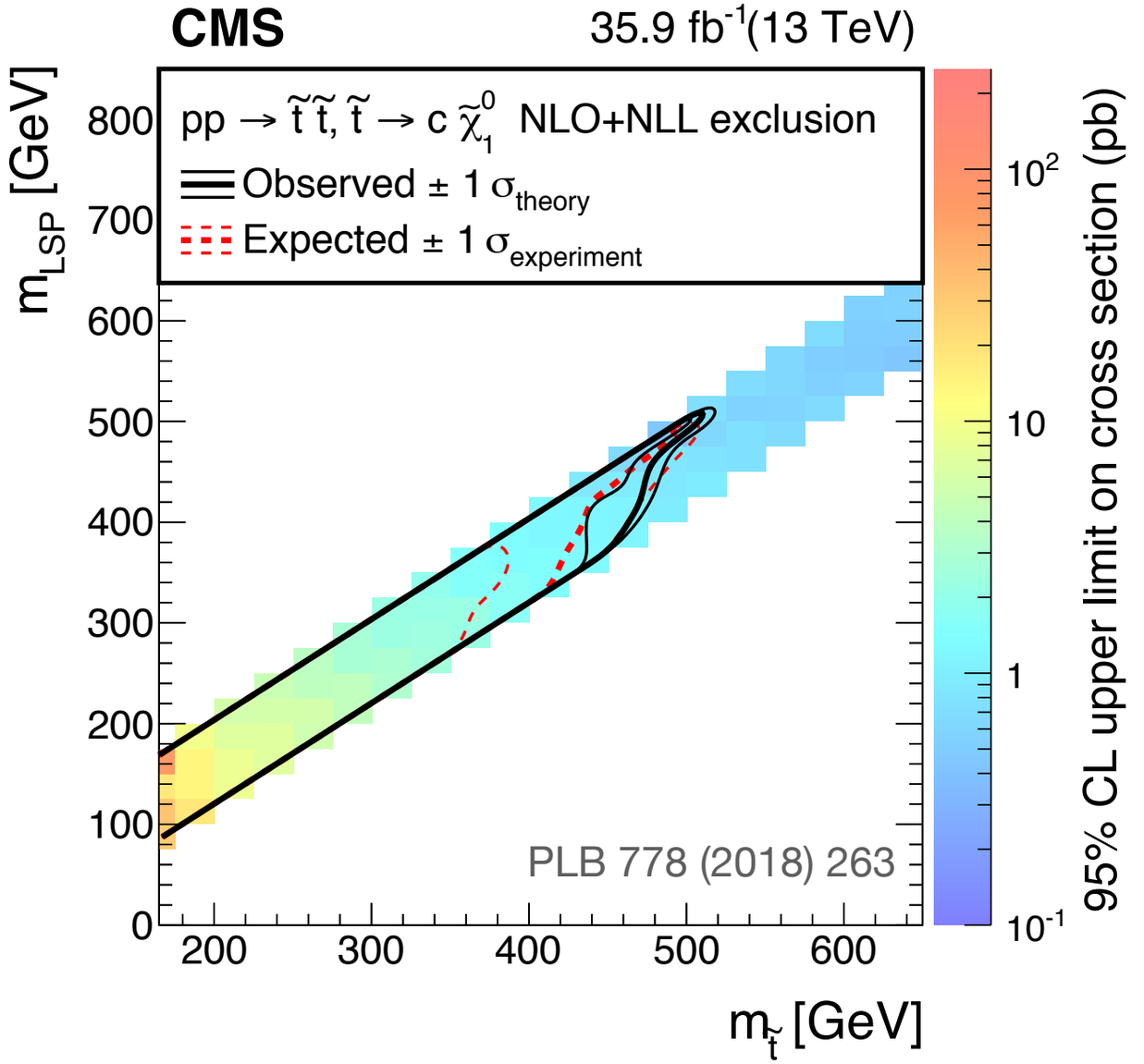


NEW

Search for supersymmetry with charm tagging

arXiv:1805.01649
CMS: PLB 778 (2018) 263





NEW

Higgs → photon + E_T^{miss}

ATLAS EXPERIMENT

CONF-2018-019

Cut	CR WZ	CR Zγ	VR Zγ	VR jets	SR
Pass triggers and vetos	✓	✓	✓	✓	✓
2 signal leptons	✓	✓	✓	✓	✓
At least 1 signal photon	> 25 GeV(electron)	> 25 GeV	> 25 GeV	> 25 GeV	> 25 GeV
$m_{\ell\ell}^{\text{win}}$	81-101 GeV	81-101 GeV	81-101 GeV	85-120 GeV	81-101 GeV
$E_{\text{T}}^{\text{miss}}$	> 95 GeV	20-35 GeV	35-70 GeV	> 35 GeV	> 95 GeV
$\text{Bal}_{p_{\text{T}}}$	< 0.2	< 0.2	< 0.2	-	< 0.2
$\Delta\phi_{\ell\ell,\gamma E_{\text{T}}^{\text{miss}}}$	> 2.8	-	-	< 2.2	> 2.8
$\Delta\phi(\ell,\ell)$	< 1.4	< 2.0	< 2.0	-	< 1.4

Observed events	3
Expected background events	2.1 ± 0.5
Expected signal events $m_{NLSP}, m_{LSP} = 80, 0$ GeV	8.1
$e \to \gamma$ fakes	1.5 ± 0.3
j $\to \gamma$ fakes	0.6 ± 0.3
SM $Z\gamma$	$0.03^{+0.15}_{-0.03}$
Other	$0.00^{+0.01}_{-0.00}$

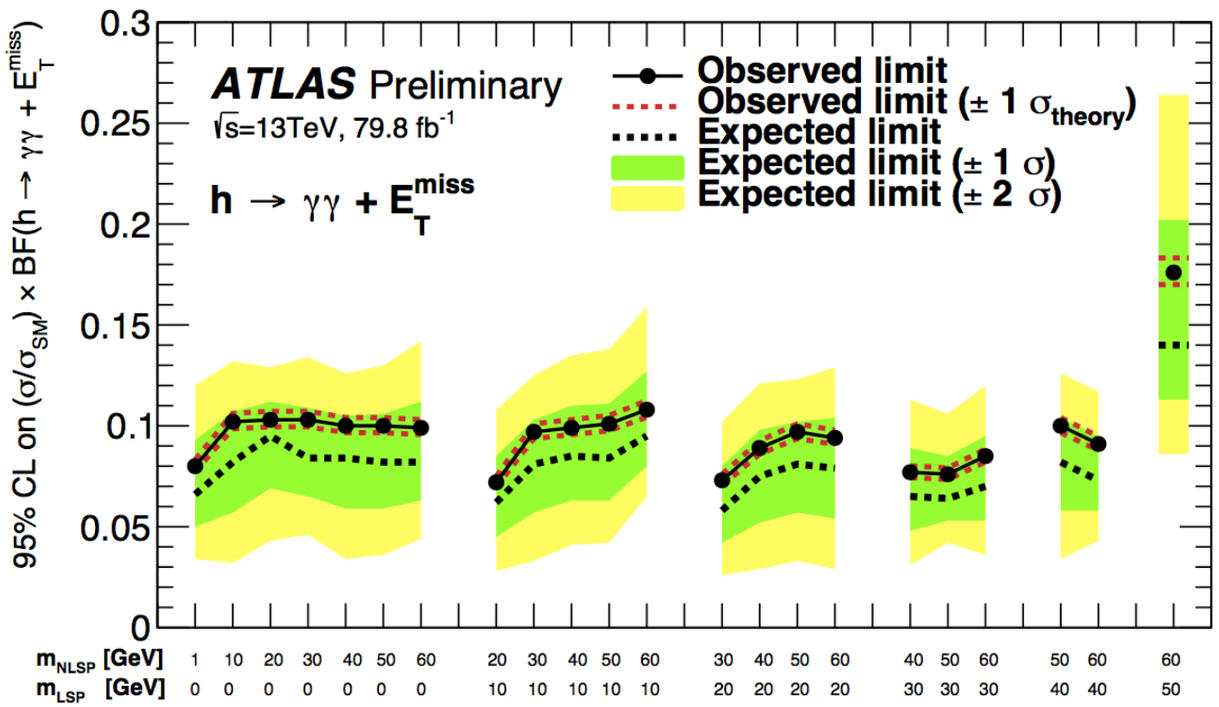
Total background expectation	2.1
Total systematic uncertainty	±0.5 [22%]
Uncertainty component	
CR WZ and jet fake sample size	±0.3 [15%]
Stat. error of $\kappa_{\text{tight}}^{\text{j}\to\gamma}$	±0.3 [12%]
$E_{\text{T}}^{\text{miss}}$ dependence of $\xi_{data}^{e\to\gamma}$	±0.1 [7%]
Jet energy resolution	±0.1 [6%]
$\xi_{MC}^{e\to\gamma}$ closure	±0.1 [5%]
$E_{\text{T}}^{\text{miss}}$ soft-term resolution	±0.1 [5%]
CR correlation $\kappa_{\text{tight}}^{\text{j}\to\gamma}$	±<0.1 [3%]
Pseudo photon scaling $\kappa_{\text{tight}}^{\text{j}\to\gamma}$	±<0.1 [2%]
Window dependence of $\xi_{data}^{e\to\gamma}$	±<0.1 [2%]
Photon/lepton energy scale	±<0.1 [2%]
Photon isolation	±<0.1 [2%]
$\langle\mu\rangle$ dependence of $\xi_{data}^{e\to\gamma}$	±<0.1 [1%]
Jet energy scale	±<0.1 [1%]

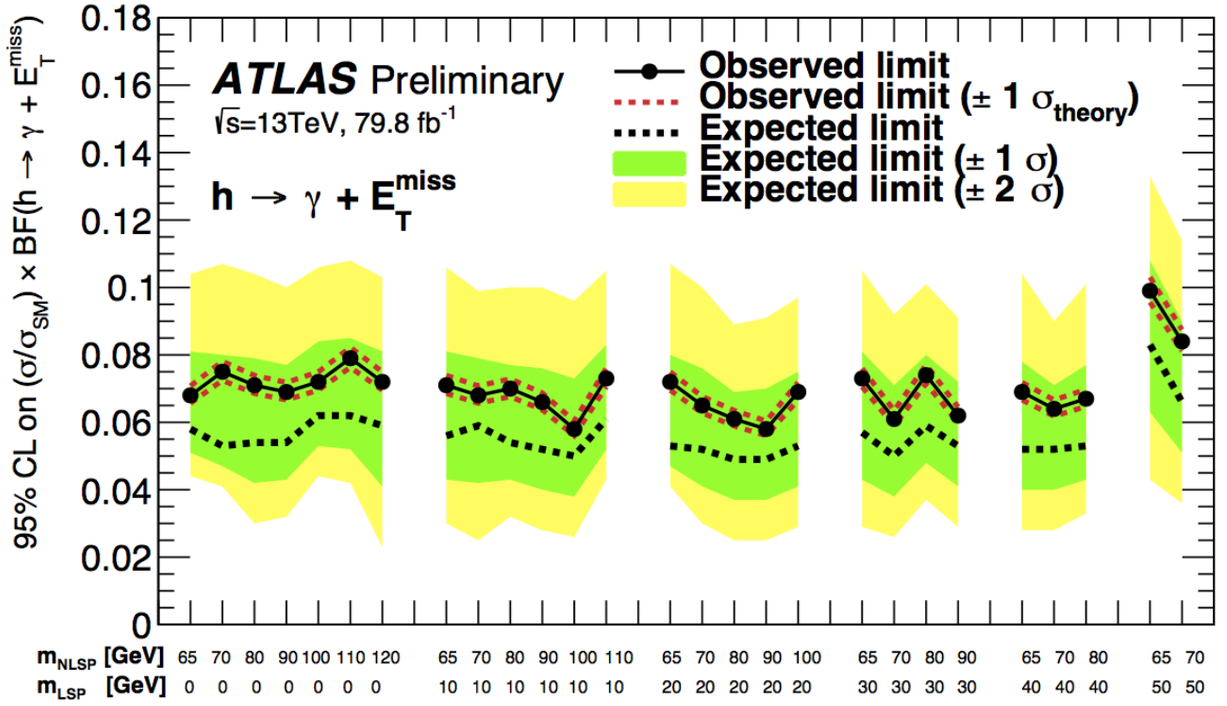
NEW

Higgs → photon + E_T^{miss}

ATLAS EXPERIMENT

CONF-2018-019





$\langle\epsilon\sigma\rangle^{95}_{obs}$[fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s=0)$
0.06	5.1	$4.5^{+1.9}_{-1.0}$	0.32

NEW

LQ → top + muon

B2G-16-027

- $S_T = \sum$(jets, leptons, MET)
- Use di-electron CR, and corrections from MC

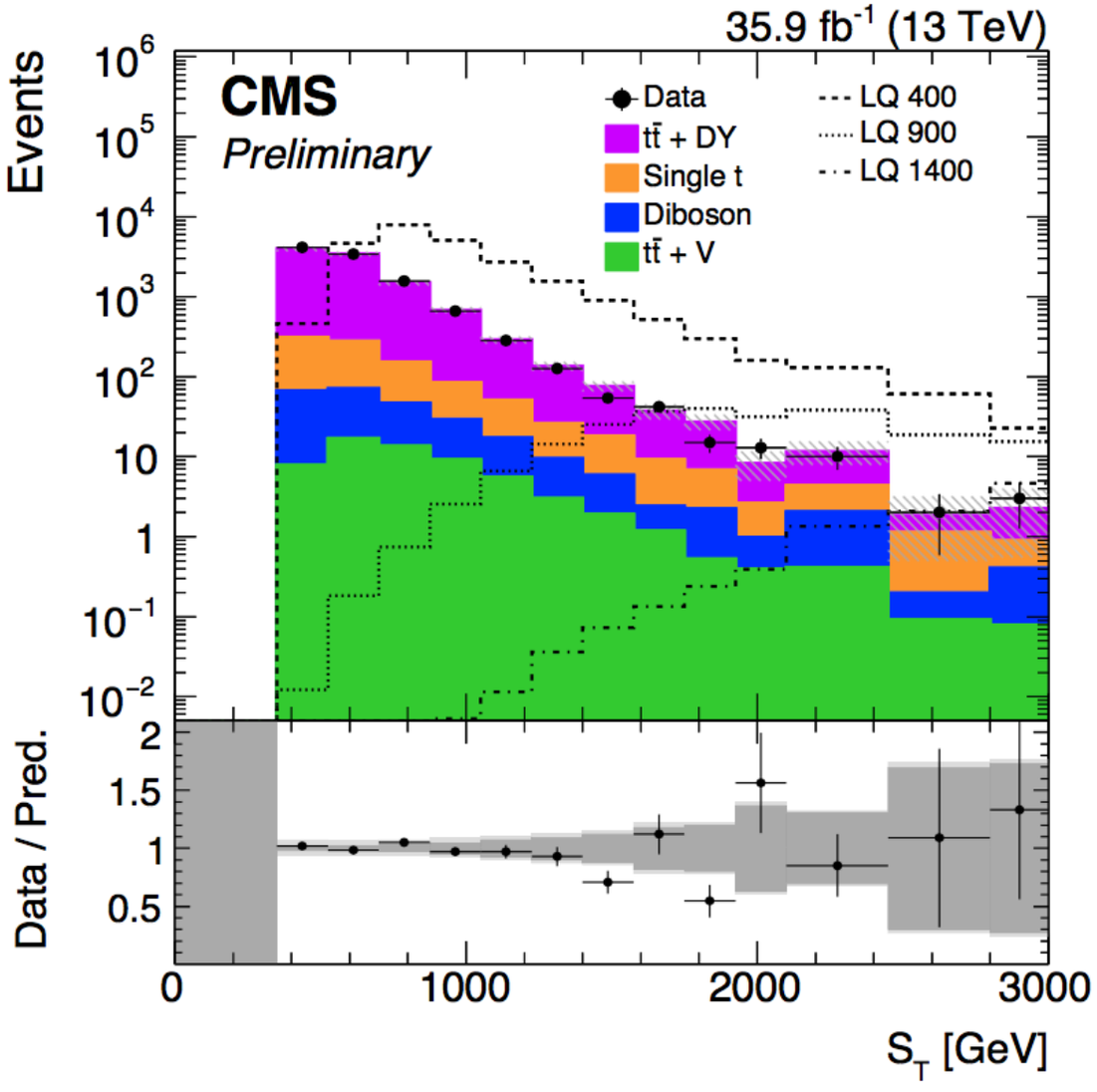


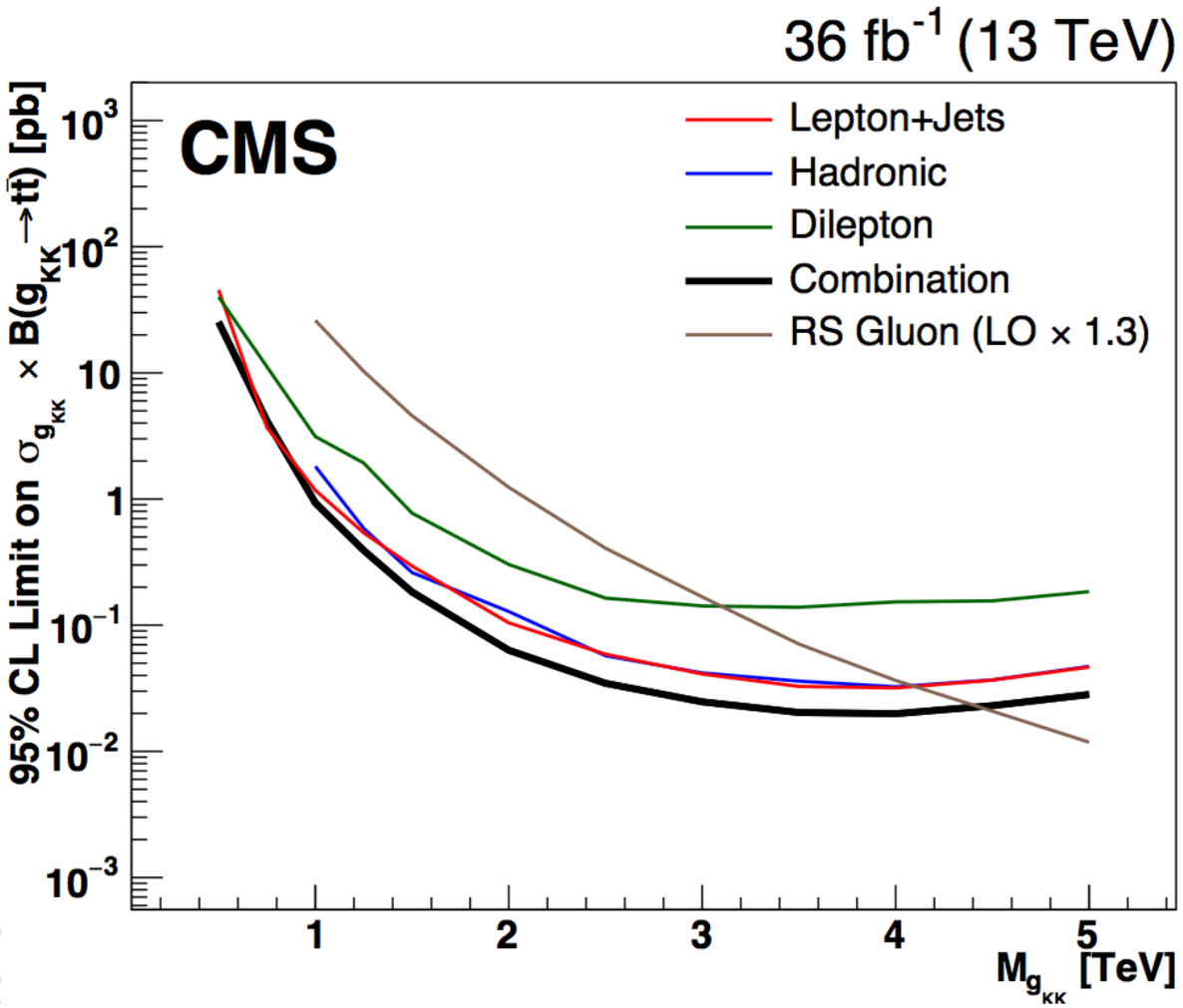
Table 1: Prior systematic uncertainties in the SM backgrounds and signal.

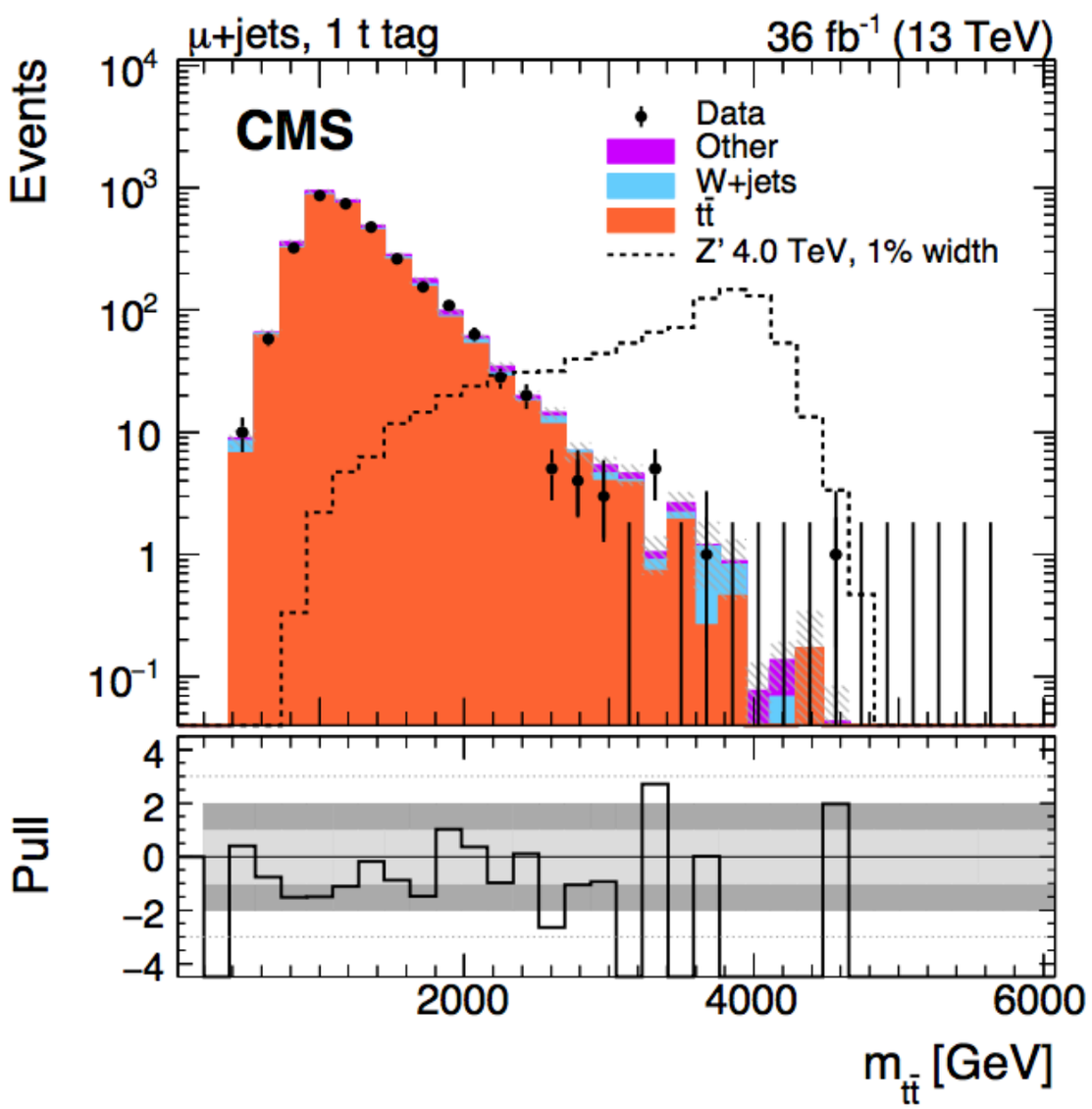
	Data-driven [%]	Simulated [%]	Signal [%]
Luminosity	—	2.5	2.5
$t\bar{t}$ rate	0.4	5.6	—
DY + jets rate	0.2	10	—
single t rate	0.7	10	—
Diboson rate	< 0.1	20	—
$t\bar{t}$ + V rate	0.1	25	—
Pileup	0.3	$< 0.1 - 6.3$	$< 0.1 - 1.8$
JEC	2.1	$0.1 - 8.9$	$0.1 - 2.3$
JER	0.5	$< 0.1 - 0.6$	< 0.1
b-tagging efficiency	< 0.1	$0.9 - 3.1$	$2.7 - 5.7$
b-tagging mis-ID	< 0.1	$2.6 - 7.4$	$3.2 - 4.7$
μ efficiencies	$0.9 - 3.2$	$0.7 - 3.6$	$0.6 - 4.9$
μ mis-ID rate	0.1	$0.4 - 63.1$	$0.2 - 2.7$
e efficiencies	$0.6 - 3.6$	$< 0.1 - 1.8$	$< 0.1 - 1.5$
e mis-ID rate	< 0.1	$0.4 - 21.6$	$< 0.1 - 0.8$
Ren. & fact. scales	$< 0.1 - 1.0$	$9.8 - 19.7$	—
PDF	< 0.1	$1.4 - 25.3$	$0.5 - 3.7$
$\alpha(S_T)$	1.9	—	—

NEW

ttbar resonance search

B2G-17-017
36 fb^{-1} (2016)





NEW

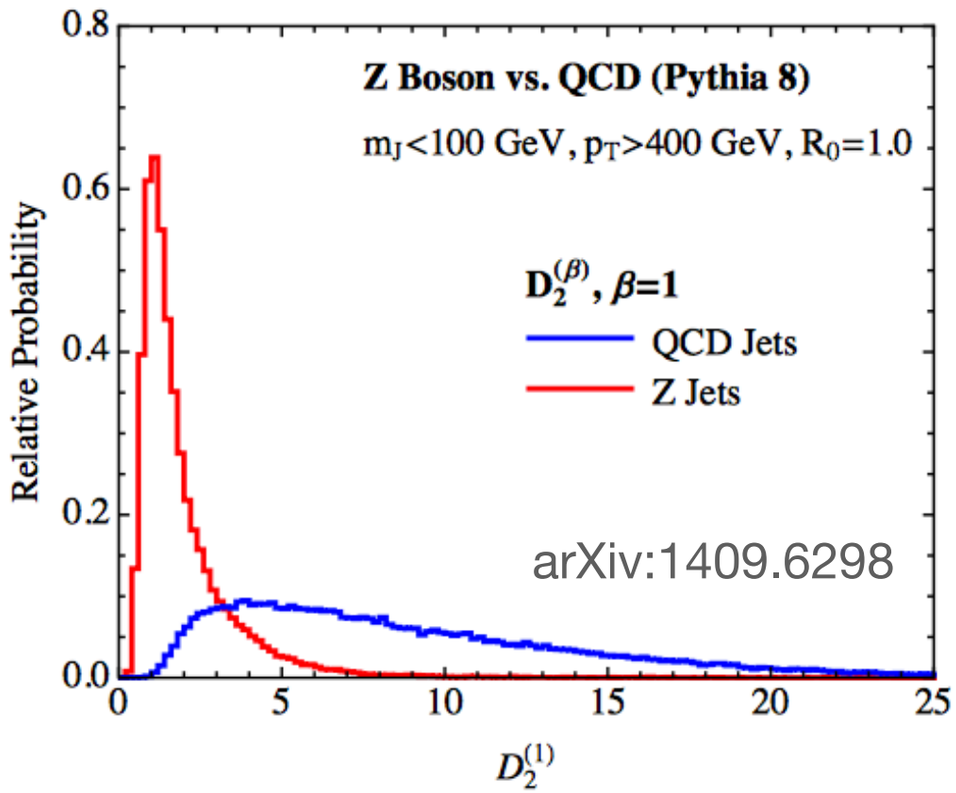
γ + W/Z/H resonances

arXiv:1805.01908

- Multiple categories depending on whether jet is double-b-tagged, two-prong (using energy correlation functions), or just passes mass window

Selection	Event yield in each category ($m_{J\gamma} > 1$ TeV)				
	Baseline	BTAG	D2	VMASS	ELSE
$Z\gamma$ search	60,237	25	784	5,569	53,859
$W\gamma$ search	60,237	—	661	5,216	54,360
$H\gamma$ search	60,237	59	—	—	—

	Impact on normalization and efficiency [%]
Luminosity	2.1
Jet energy scale	2–6
Photon identification and isolation	0.5–1.5
Flavor tagging	10–20
n_{trk} associated with the jet	6
Jet mass resolution	3–6
$D_2^{(\beta=1)}$ scale and resolution	< 1
Pileup modeling	1–2
	Impact on signal peak position [%]
Jet energy and mass scale	1–3
Photon energy scale	< 0.5
	Impact on signal peak resolution [%]
Jet energy resolution	5 (m_X < 2.5 TeV)–15 (m_X > 2.5 TeV)
Photon energy resolution	1–3
	Impact on acceptance [%]
PDF	2–12
Parton shower	2

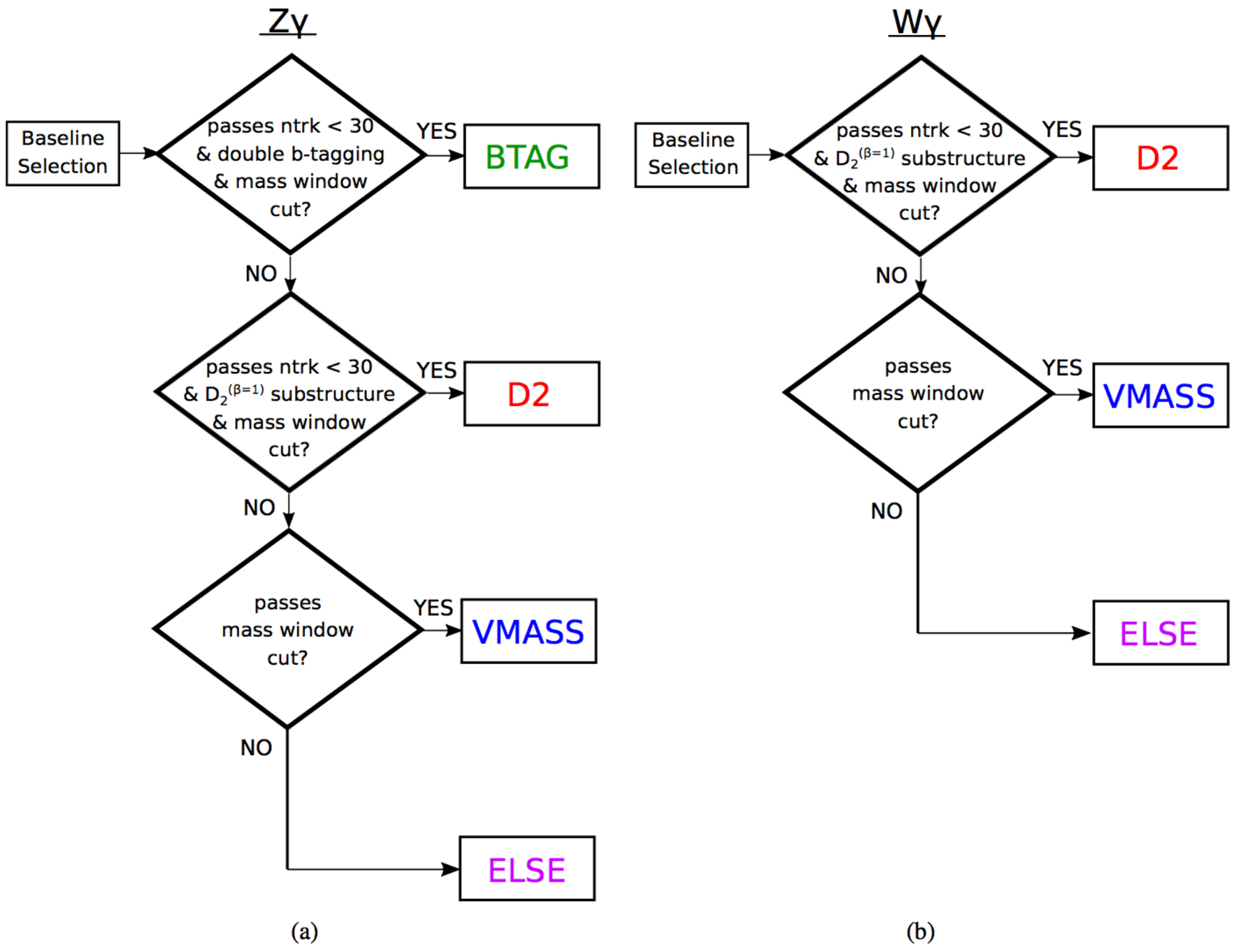


NEW

γ + W/Z/H resonances

ATLAS EXPERIMENT

arXiv:1805.01908



Vector-like quarks

- "Vanilla" 4th generation quarks are excluded
- Search for vector-like quarks instead
  - **Colored spin-1/2 fermions**
  - **Various possible electric charges** (2/3, 5/3, -1/3, -4/3)
  - L/R-handed components transform the same way under gauge transformations (bare mass term allowed)
  - Can play similar role to top squarks for solving hierarchy problem
  - Pair production or single production
  - Many models favor **decays to vector bosons and 3rd generation quarks** (T → tH, tZ, bW and B → bH, bZ, tW)