Search for Lepton Flavor Violation with ATLAS

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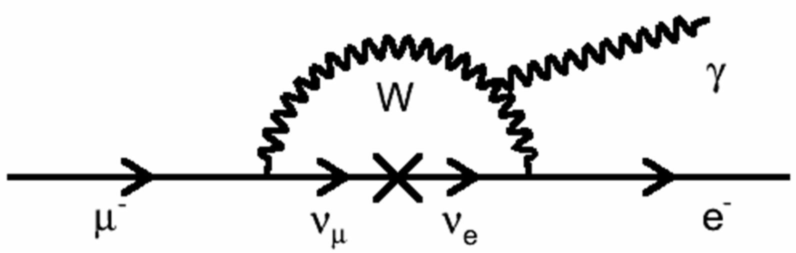
Outline

- Introduction
- LHC and the ATLAS detector
- Searches for LFV decays of Standard Model particles
- Beyond the Standard Model LFV searches
- Summary

Introduction

- Lepton Number and Flavor are not related to a gauge symmetry.
- $\Rightarrow$ Might not be conserved.
- Neutrino oscillations indeed show this.
- Important question is whether charged leptons violate lepton flavor conservation.
- Neutrino-induced lepton flavor violation for charged leptons is expected to be very small [e.g., BR($\mu \rightarrow e\gamma$) ~ 10^{-50}]. (Small but not as small for some τ decays.)



- Might manifest itself in
  - decays of Standard Model particles (e.g. $Z \rightarrow e\mu$).
  - decays of Beyond the Standard Model particles (e.g. $Z' \rightarrow e\mu$).
  - Quantum Black Holes (e.g., $QBH \rightarrow e\mu$).
  - other interactions.

RPV SUSY

SUSY allows superpotential term of the form

$$W = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_j\overline{D}_k + \frac{1}{2}\lambda''_{ijk}\overline{U}_i\overline{D}_j\overline{D}_k + \epsilon_iL_iH_2$$

Multiplets:

L and Q are lepton and quark doublets.
E, U, and D are charged lepton, up-like quark, and down-like quark singlets.
H is Higgs doublet (the one coupling to up-like quarks).
i, j, and k are summed over generations.

These terms violate R-parity, R = $(-1)^{3(B-L)+2S}$.

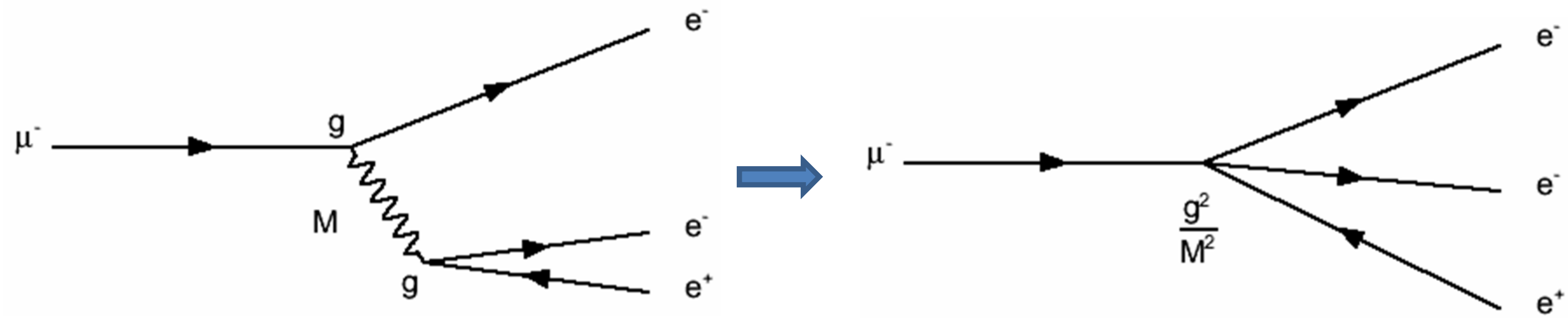
λ and λ' terms violate lepton number and flavor; λ'' terms violate baryon number.

Limits on proton decay mean either λ and λ' = 0 or λ'' = 0.

Usually require R-parity conversation, but this is not necessary.

Low Energy Constraints

- Low energy results (e.g., $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, μ-e conversion, τ decays, etc.) provide constraints (but there are often assumptions).
- **In general, limits on e-μ processes are more stringent.**
- Often limits are given in terms of an effective energy scale, which is a combination of mass/energy scales and coupling constants. For example, if $\mu \rightarrow eee$ proceeds through a massive, LFV particle with mass M and coupling g, the Feynman diagram essentially becomes a 4-point interaction proportional to g^2/M^2.



- **At the LHC, if the true mass scale is above a few TeV, then we are not sensitive. But if the effective scale is large because the mass scale is in the TeV range but the couplings are small, we may be able to see it. Also, LHC is almost as sensitive to eτ and $\mu\tau$ modes as to eμ modes.**

LHC and ATLAS

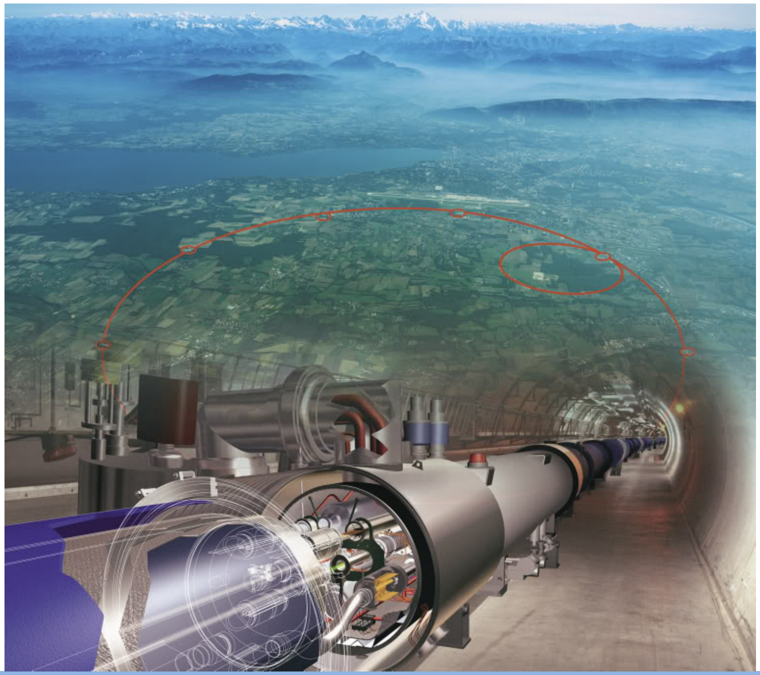
Large Hadron Collider (LHC) collides protons or heavy ions at high energy.

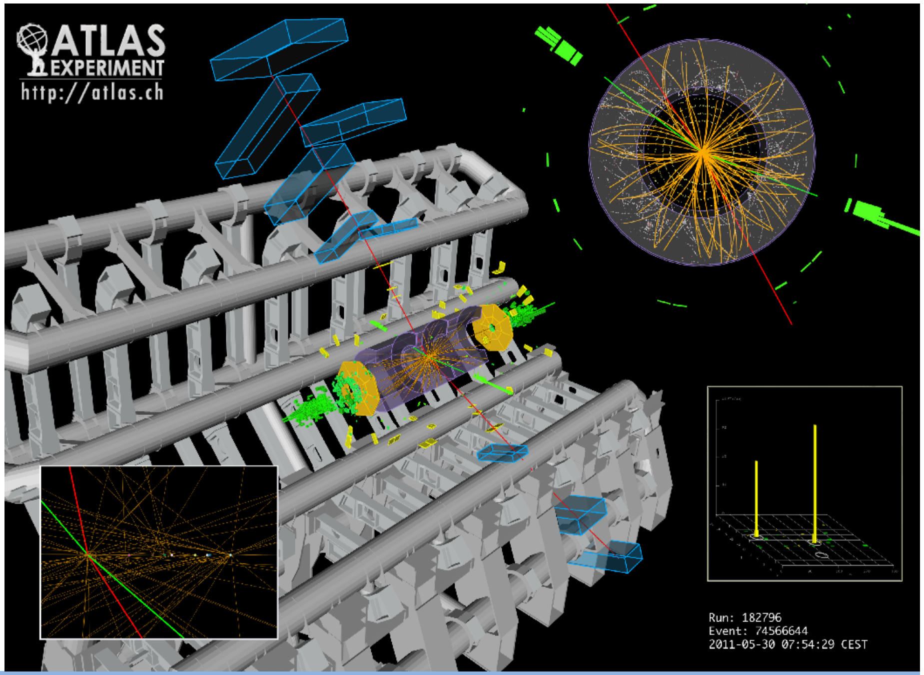
27 km ring near Geneva, Switzerland.

4 major detectors: ATLAS, CMS, LHCb, and ALICE

Results here from 8-TeV pp data taken in 2012 (~20 fb^{-1}) and 13-TeV pp data taken in 2015 (~3 fb^{-1}) .

Concentrate on leptons: e, μ, and τ, using both hadronic and leptonic τ decays





Higgs $\rightarrow \mu\tau$

JHEP 11 (2015) 211
arXiv: 1508.03372 and
Submitted to EPJC
arXiv: 1604.07730

Events with μ and τ decaying hadronically or leptonically.

Use τ kinematics and missing E_T vector to correct for undetected ν using Missing Mass Calculator (MMC).

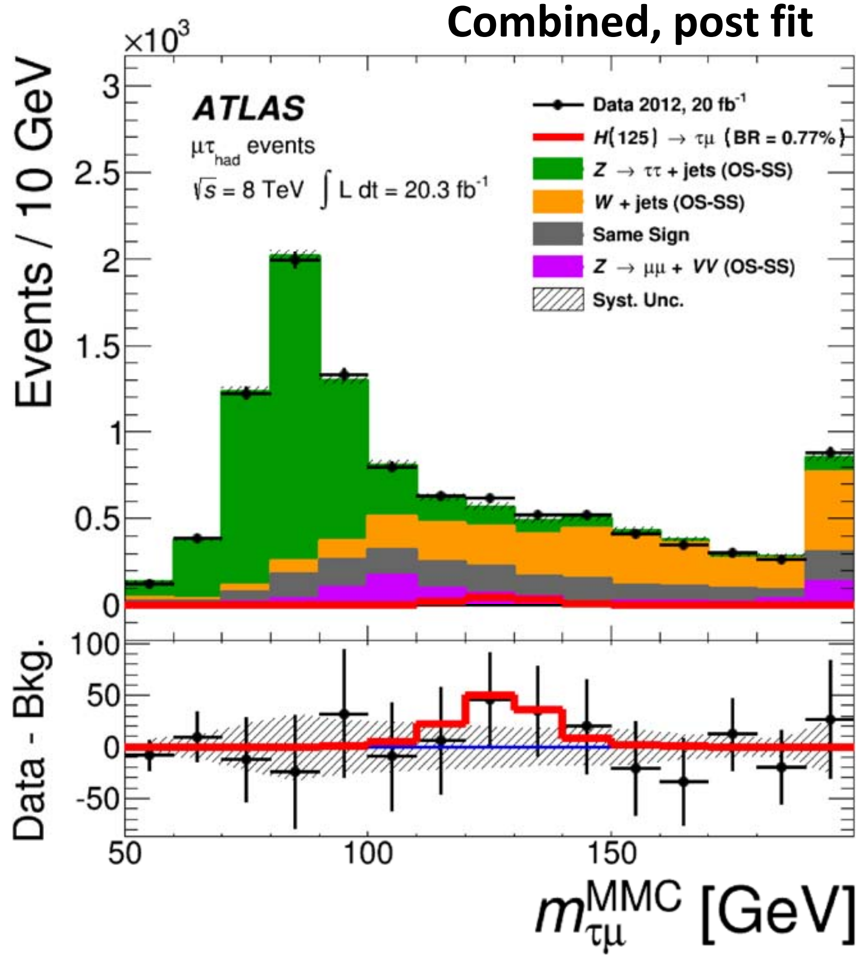
Two signal regions: one dominated by $Z/\gamma^* \rightarrow \tau\tau$ at lower $\mu\tau$ mass and one dominated by W + jets at higher mass.

Require moderate missing E_T to suppress $Z/\gamma^* \rightarrow \mu\mu$.

BR ($H \rightarrow \mu\tau$) < 1.43% (95% CL)

Theory: BR < ~10% from
$\tau \rightarrow \mu\gamma$ and $(g\text{-}2)_{e,\,\mu}$

Combined, post fit

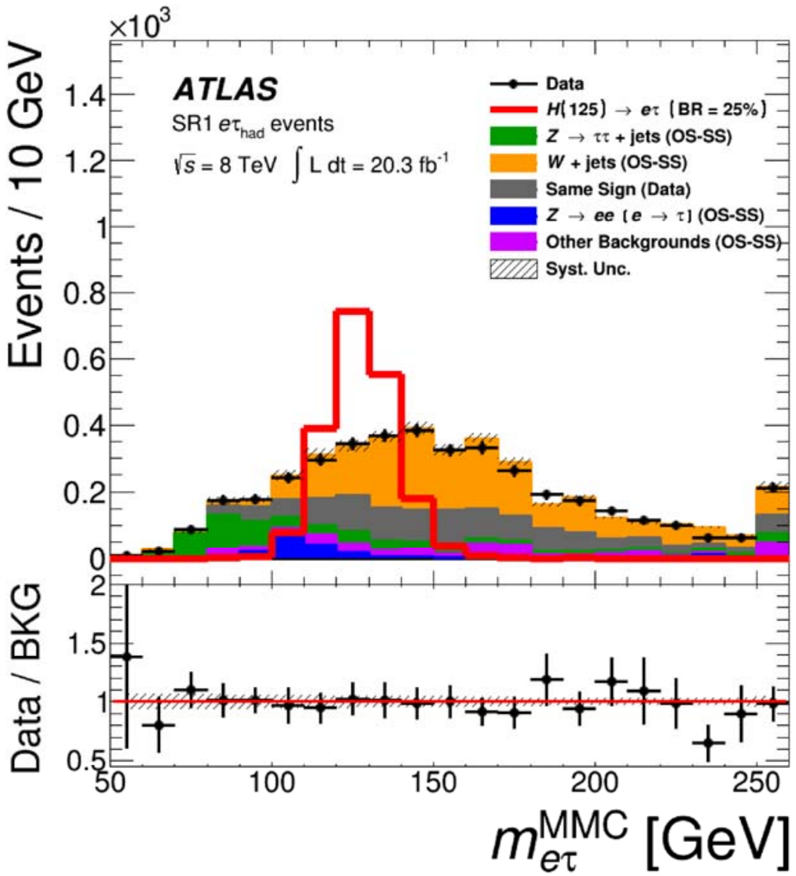


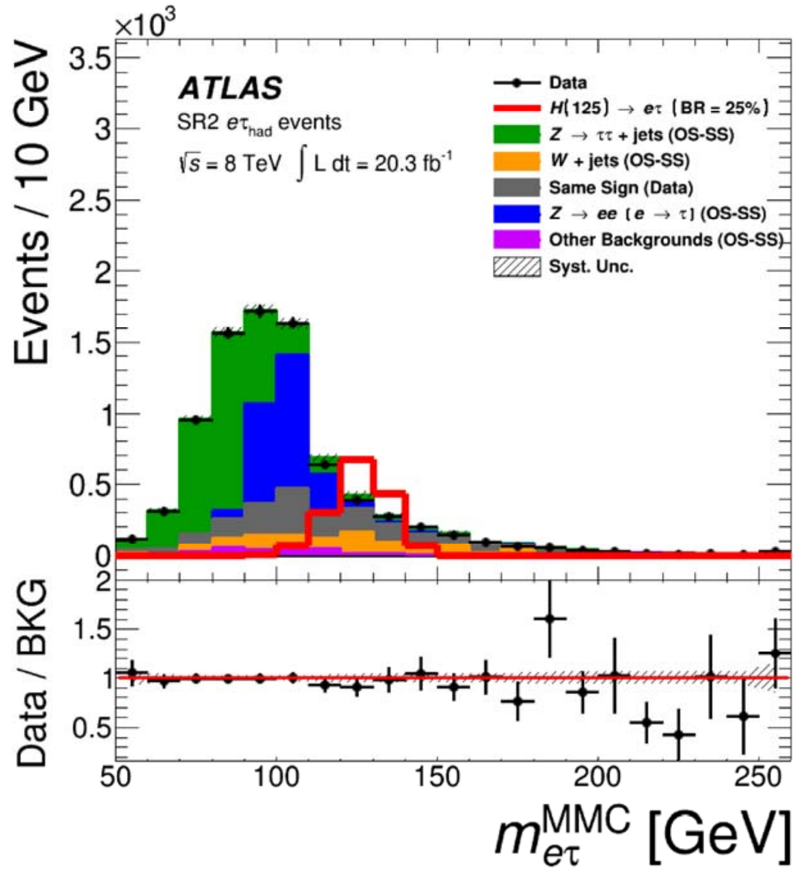
Higgs → eτ

Submitted to EPJC
arXiv: 1604.07730

Similar to μτ analysis, except μ → e.

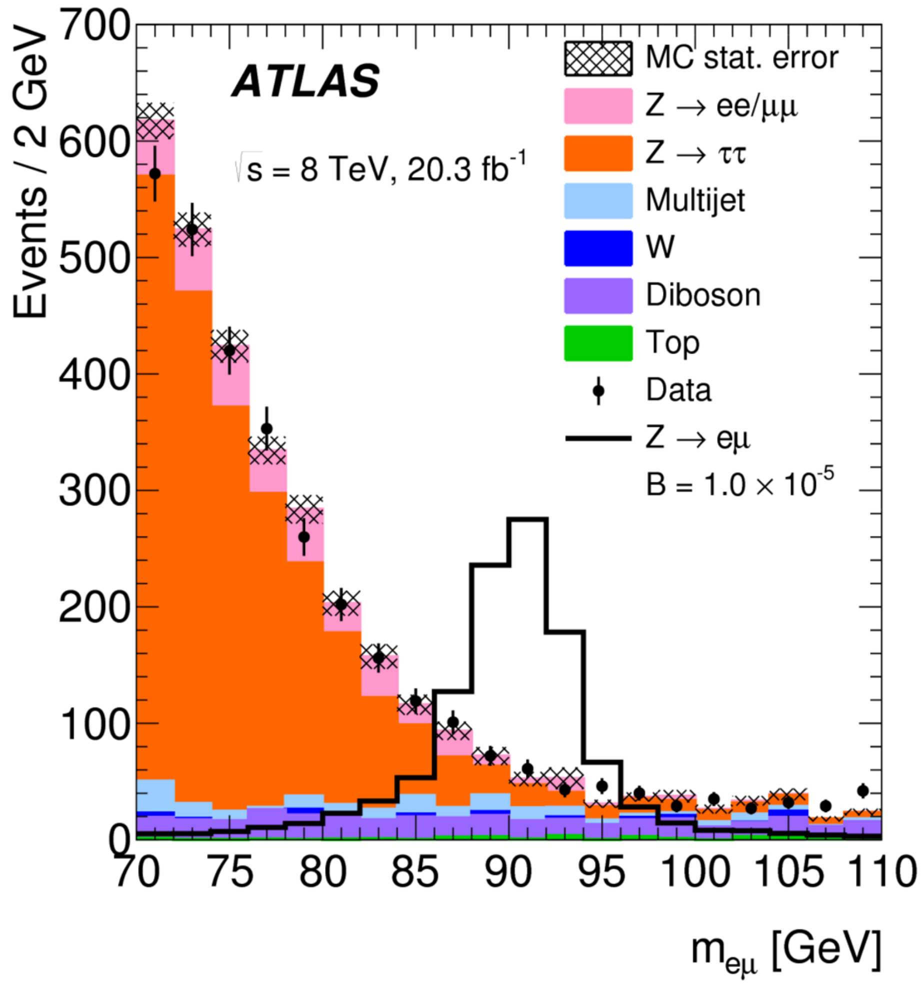
BR (H→eτ) < 1.04% (95% CL)





$Z \rightarrow e\mu$

PRD 90, 072010 (2014)
arXiv: 1408.5774

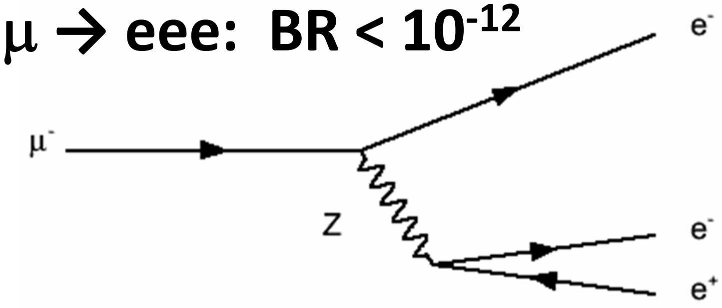


Fit to background + signal.

BR ($Z \rightarrow e\mu$) < 7.5×10^{-7} (95% CL)

LEP: BR < 1.7×10^{-6} (95% CL)

Limit inferred from
$\mu \rightarrow eee$: BR < 10^{-12}



$Z \to \mu\tau$

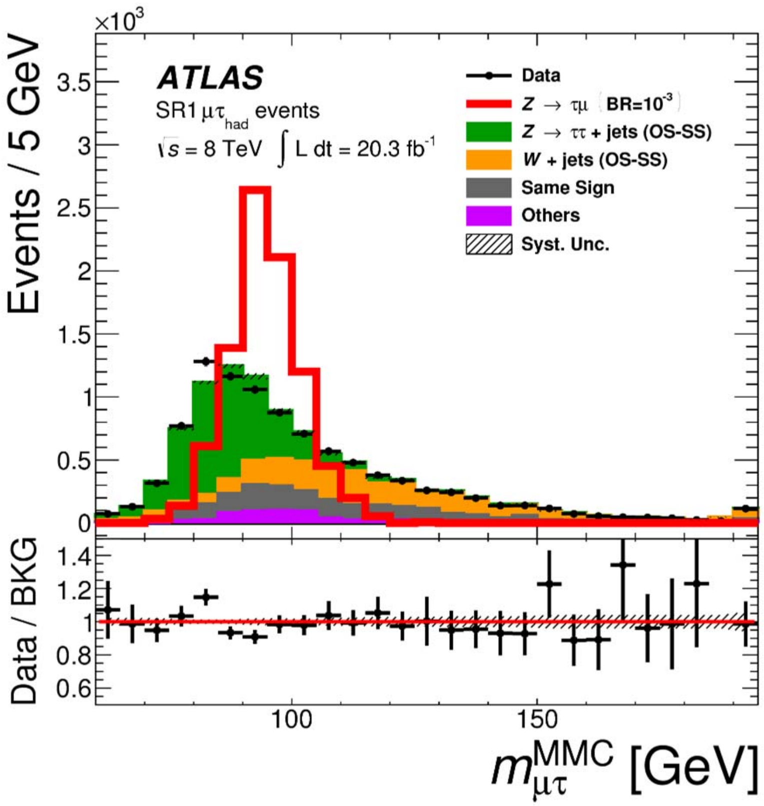
Submitted to EPJC
arXiv: 1604.07730

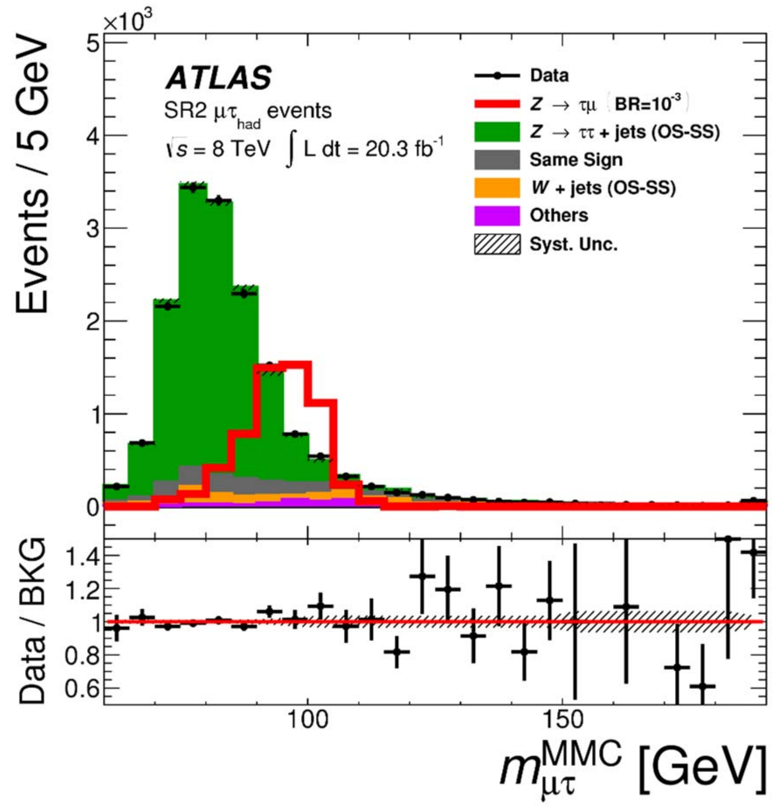
Use hadronic τ decays (similar analysis to $H \to \mu\tau_{had}$).

Use τ kinematics and missing E_T to correct for undetected ν.

BR ($Z \to \mu\tau$) < 1.7×10^{-5} (95% CL)

LEP: BR < 1.2×10^{-5} (95% CL)



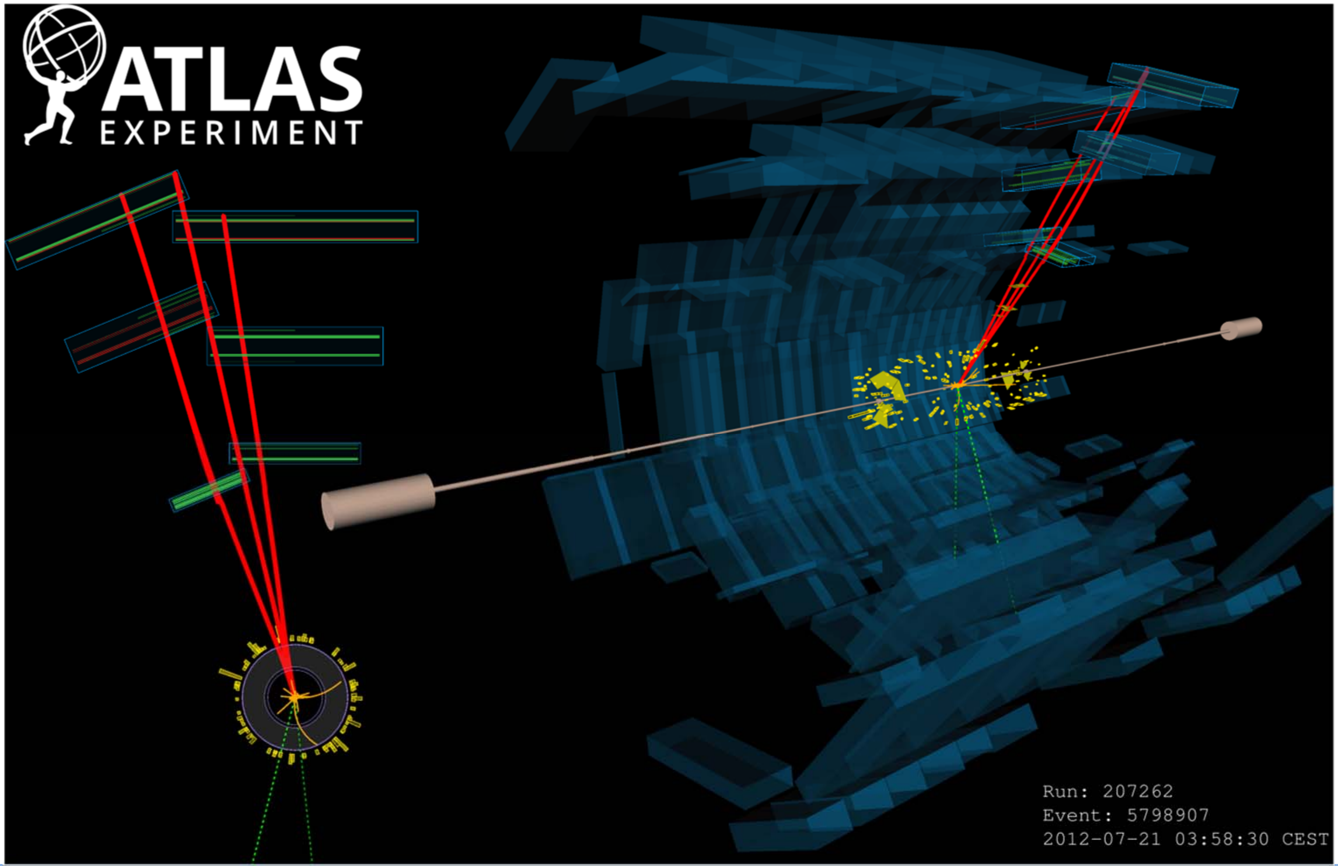


$\tau \rightarrow \mu\mu\mu$

EPJC (2016) 76
arXiv: 1601.03567

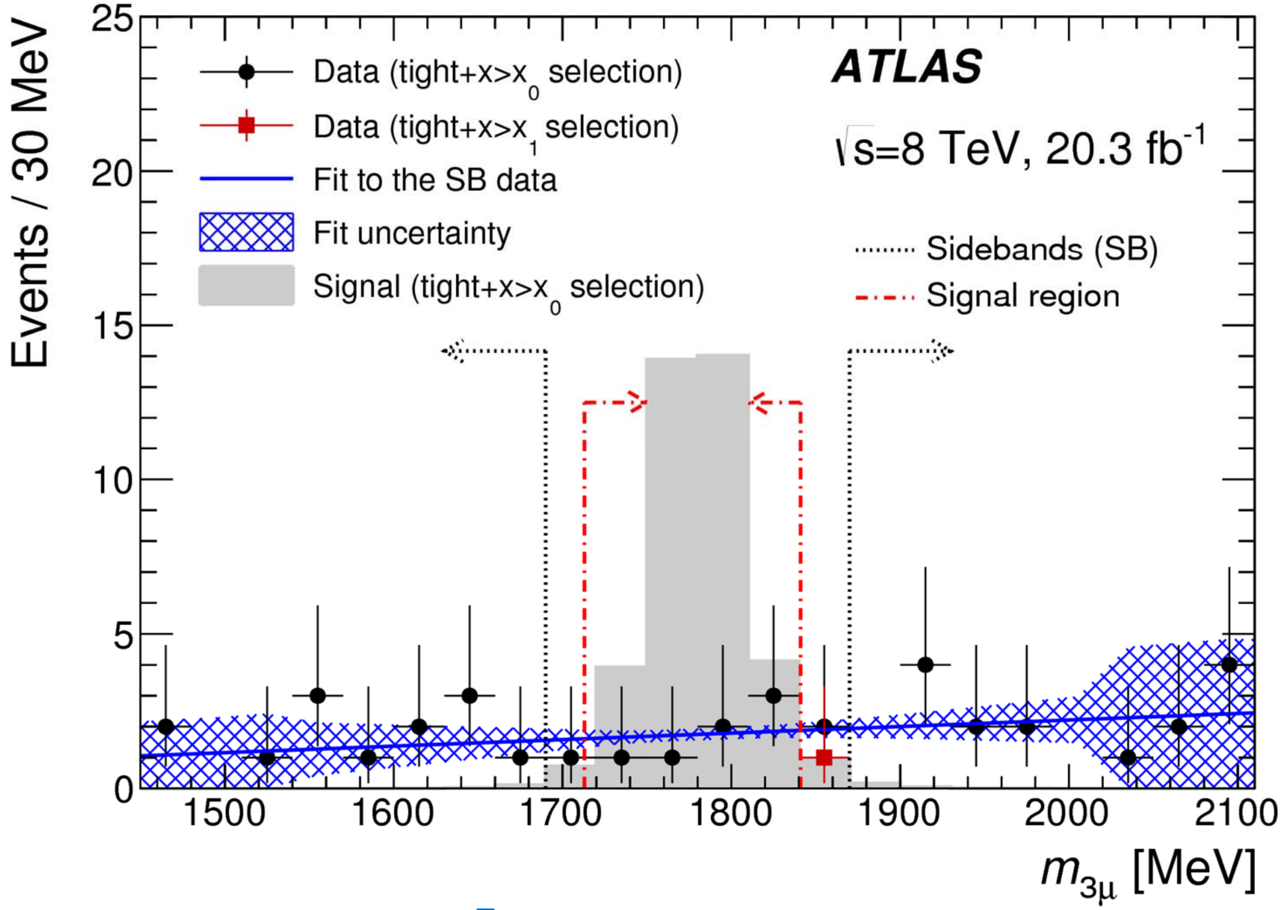
pp → W → $\tau\,\nu \rightarrow (\mu\mu\mu)\,\nu$

Use Boosted Decision Tree based on E_T^{miss} , muon momenta, track and vertex quality, W kinematics, etc.



τ → μμμ

EPJC (2016) 76
arXiv: 1601.03567

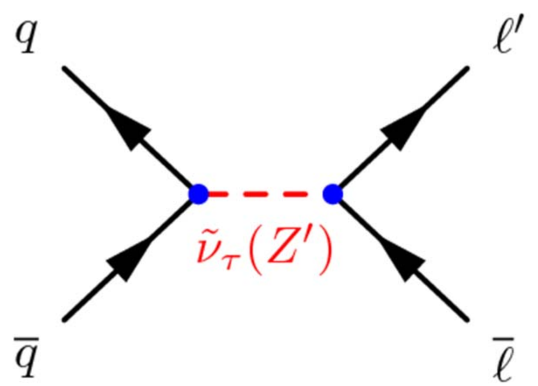


BR (τ → μμμ) < 3.8 × 10^{-7} (95% CL)

PDG: BR < 2.1 × 10^{-8} (90% CL) (primarily Belle)

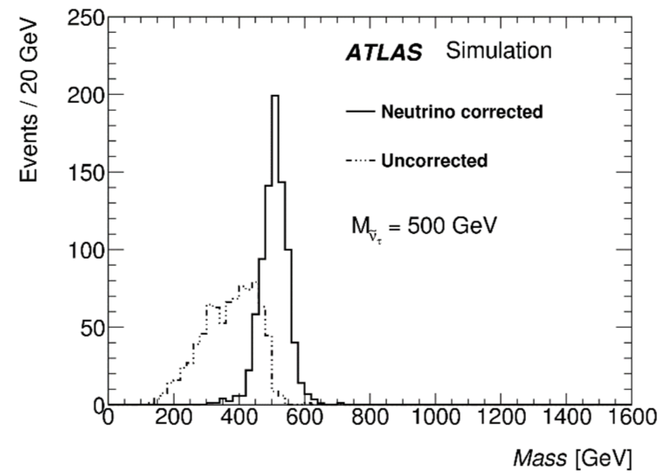
Z' or $\tilde{\nu} \rightarrow e\mu$, $e\tau$, or $\mu\tau$

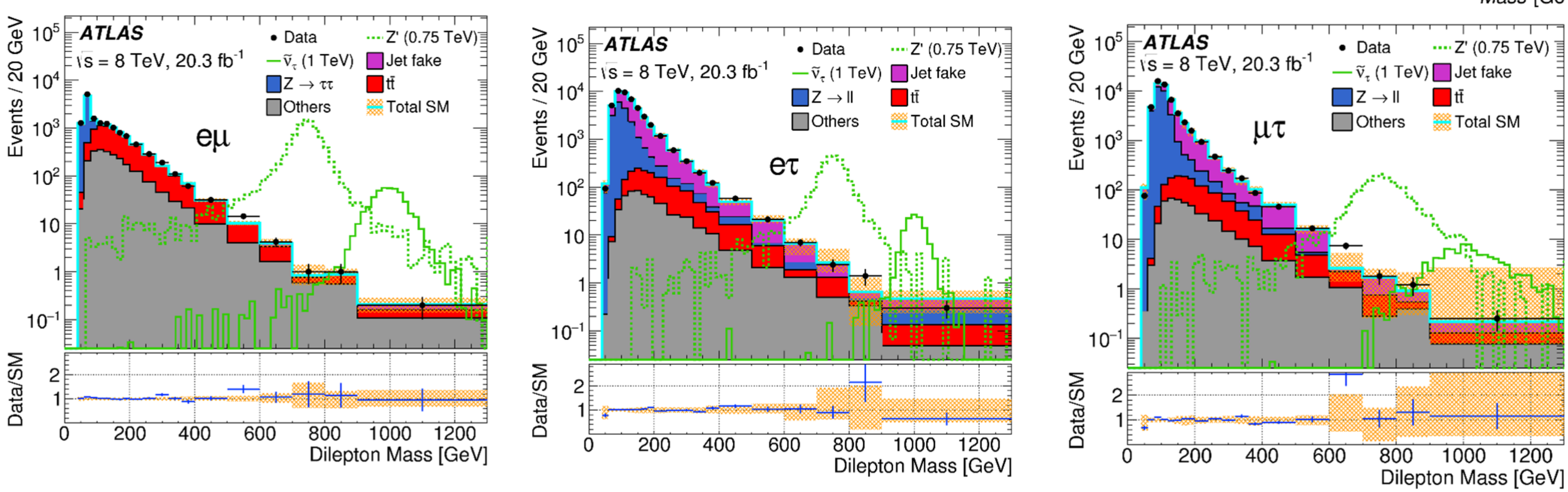
PRL 115, 031801 (2015), arXiv: 1503.04430



High Pt, back-to-back, opposite sign, different flavor.

Assume neutrino in same direction as τ.





Z' or $\tilde{\nu} \to e\mu$, $e\tau$, or $\mu\tau$

Limits on cross sections times branching ratio (95% CL).

Sneutrino coupling limits better or comparable to low energy limits for τ modes and $s\bar{s} \to e\mu$. Within order of magnitude for $d\bar{d}$, $d\bar{s}$, or $s\bar{d} \to e\mu$.

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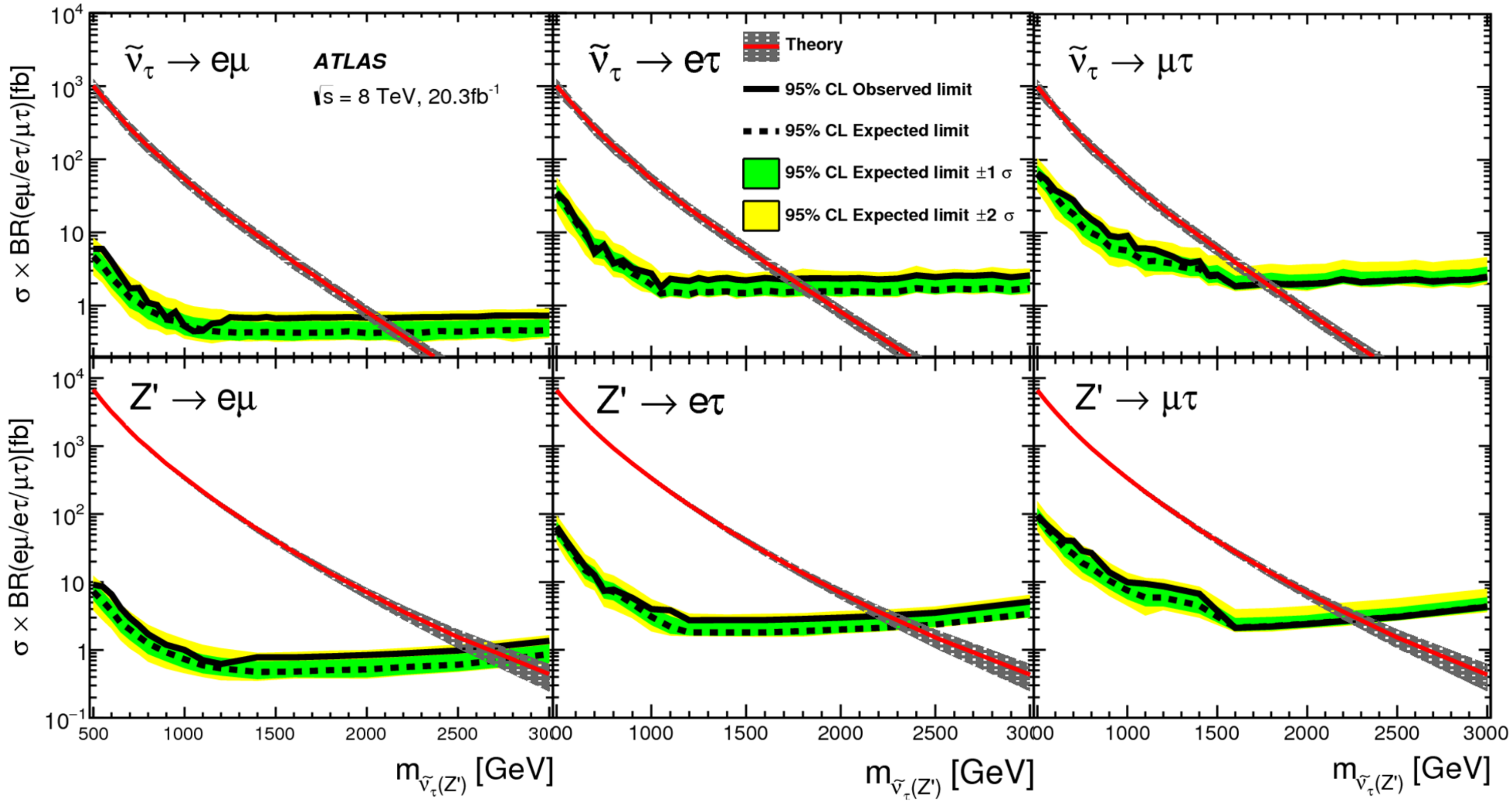


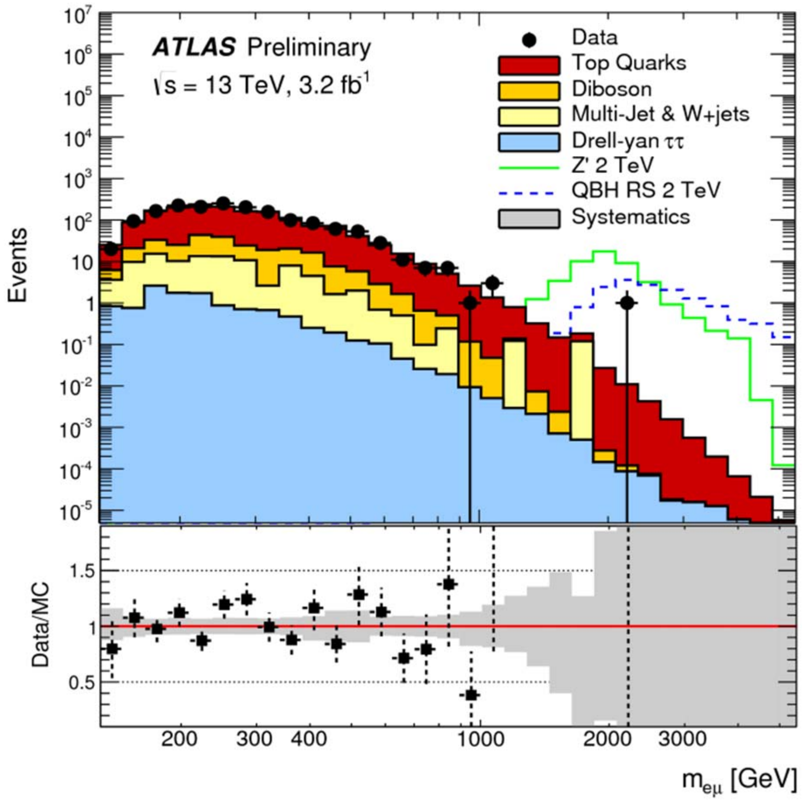
Z' or QBH → eμ

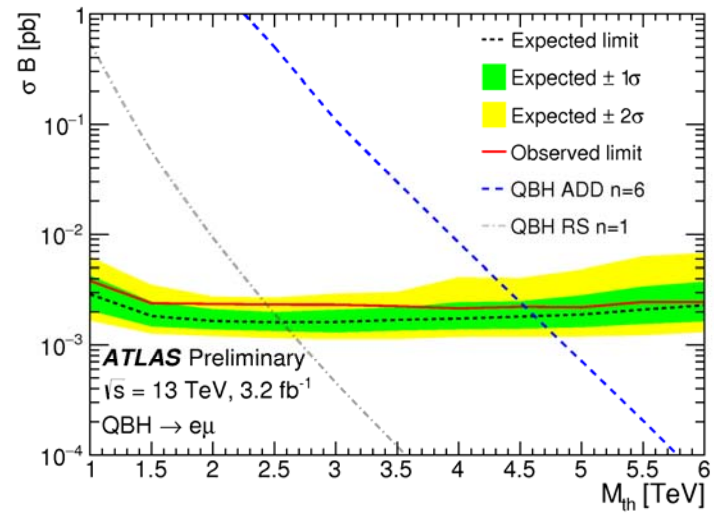
ATLAS-CONF-2015-072
cds.cern.ch/record/214844

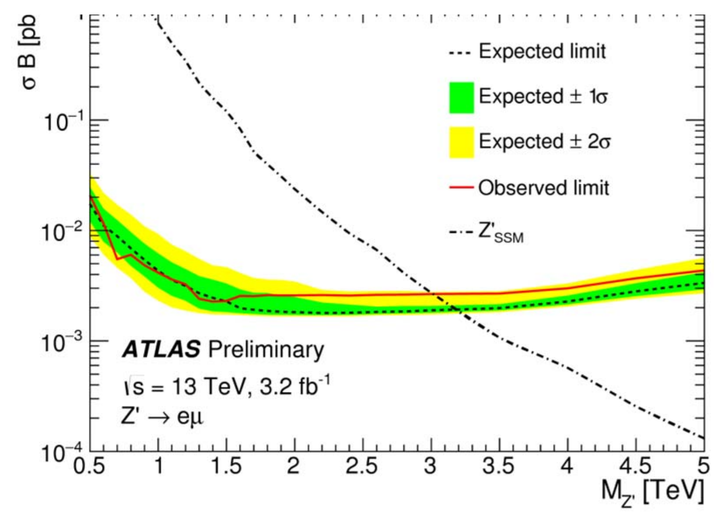
13-TeV analysis. **Similar to 8-TeV eμ search.**

Look for high p_T e and μ of opposite sign.

Quantum Black Holes (QBH) might be produced in theories with large extra dimensions and are expected to not conserve lepton flavor.

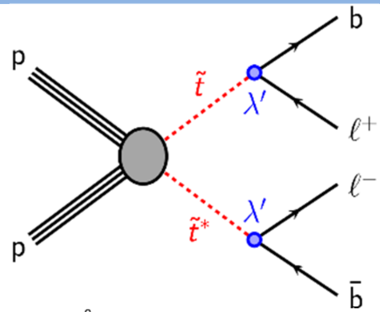






B-L top squark

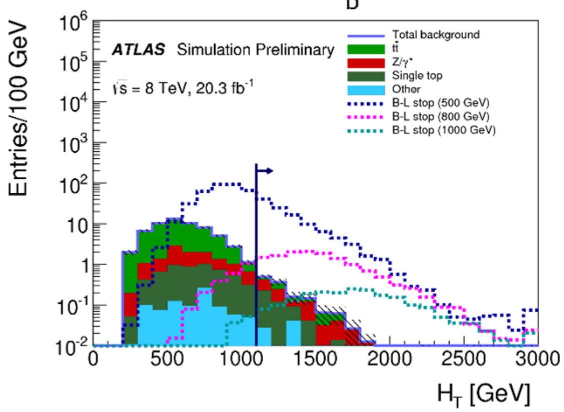
cds.cern.ch/record/2002885

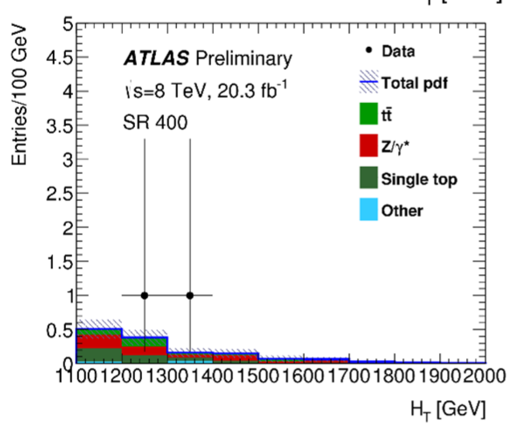


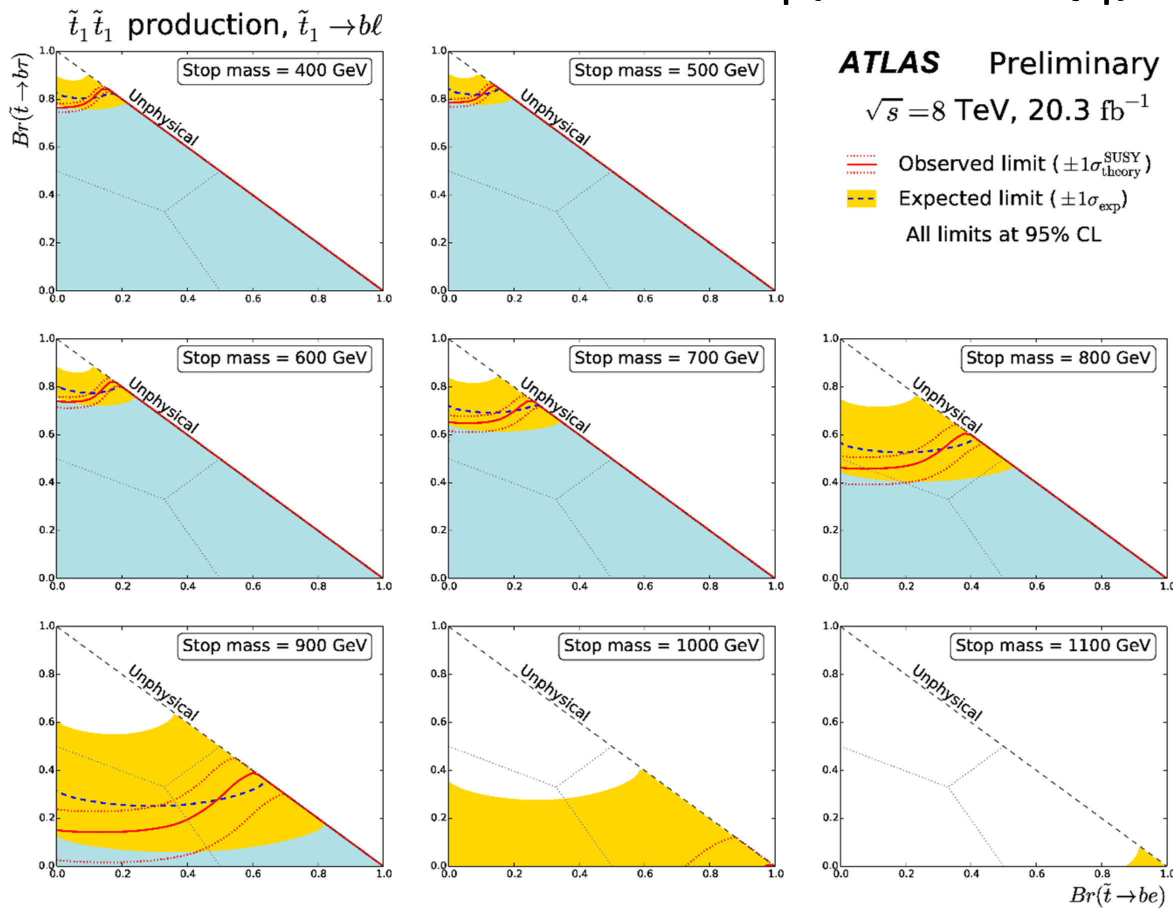
RPV SUSY with extra U(1) symmetry.

Search for $ee b\bar{b}$, $\mu\mu b\bar{b}$, and $e\mu b\bar{b}$ (b-tag jets).

Discriminate on bℓ mass, bℓ mass difference, H_T (scalar sum p_T).



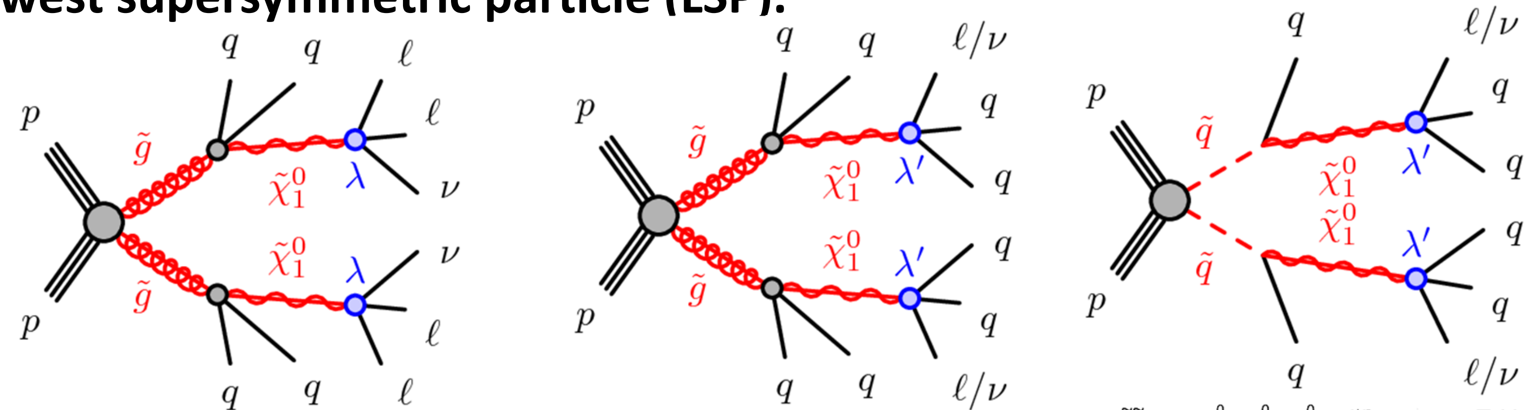




Multileptons in RPV SUSY

cds.cern.ch/record/2017303

ATLAS has reinterpreted SUSY searches in terms of RPV SUSY with an unstable lowest supersymmetric particle (LSP).



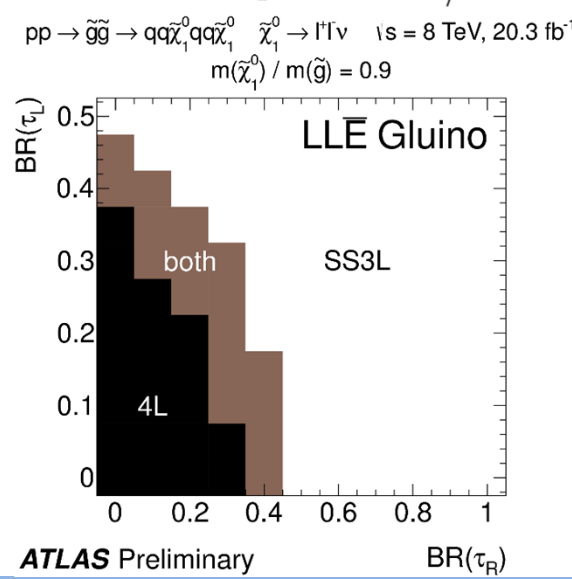
Define 2 types of signal regions:

- **4L: 4ℓ, 3$\ell\tau$, or 2ℓ2τ, where ℓ is e or μ.**
- **SS/3L: $\ell^{\pm}\ell^{\pm}$ or $\ell\ell\ell$.**

Include requirements on number of jets and reject Z → $\ell\ell$, $\ell\ell\gamma$, and $\ell\ell\ell\ell$.

Expect 1.4 to 3 events in various categories.

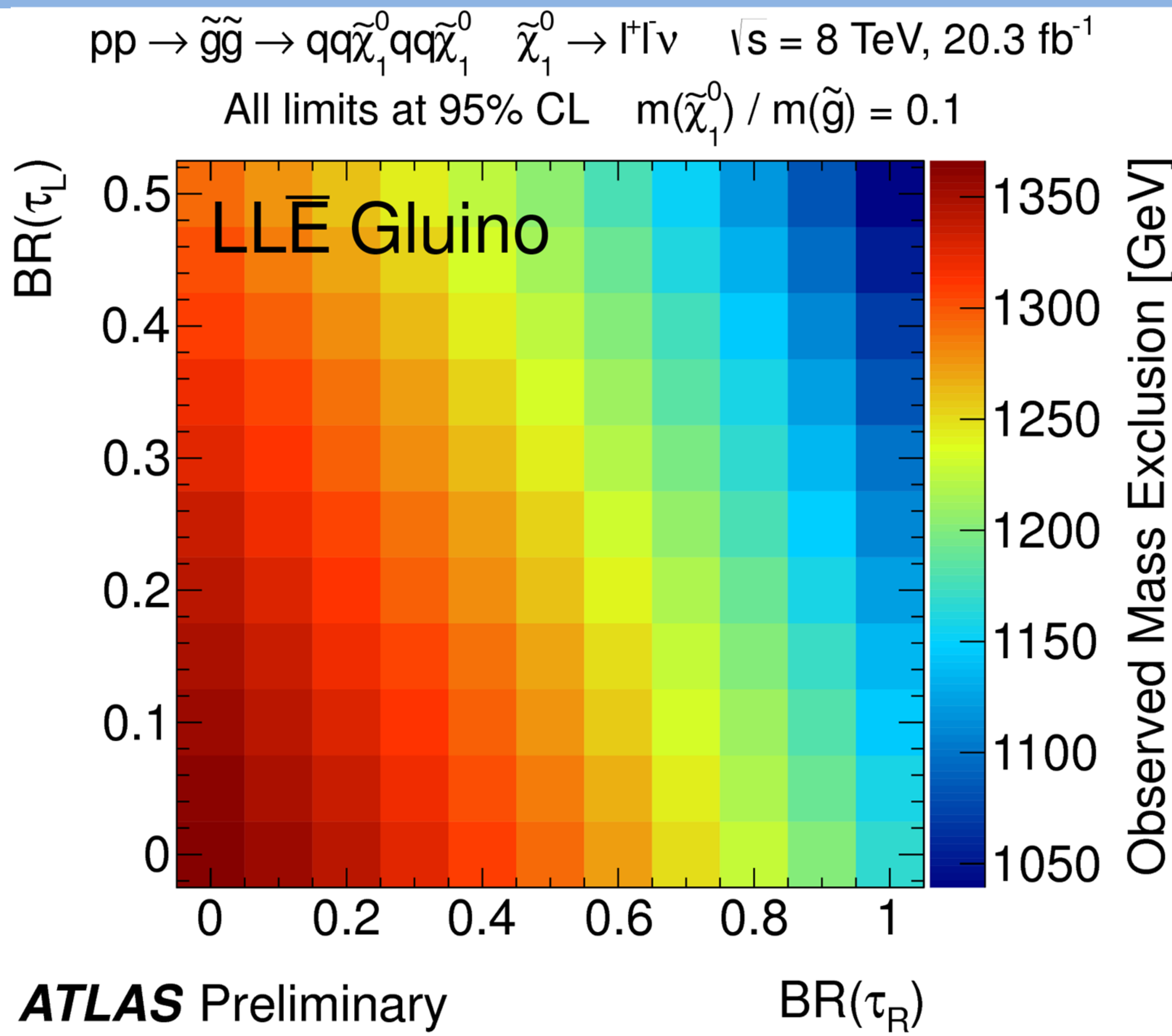
Observe compatible numbers.



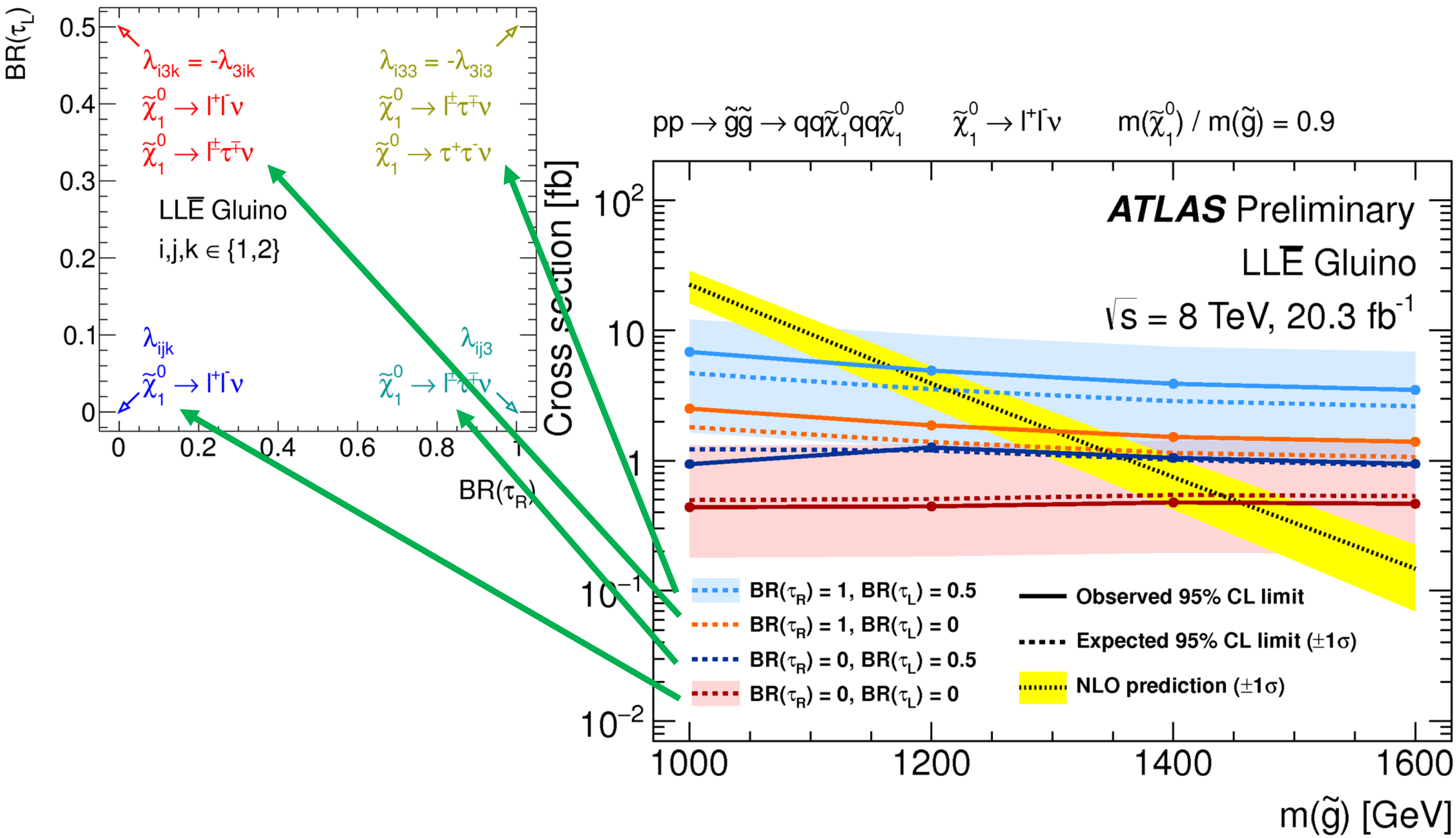
Multileptons in RPV SUSY

Limits depend on many parameters, including SUSY masses and which mode.

Example limit plot shown here.

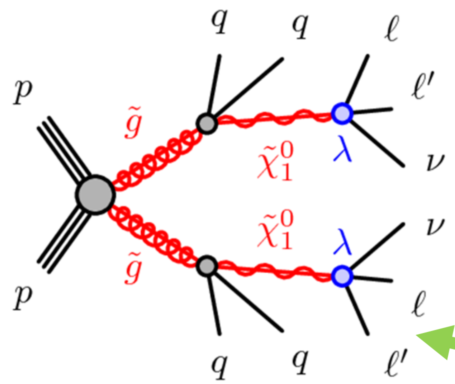


Multileptons in RPV SUSY



Displaced Vertices in RPV SUSY

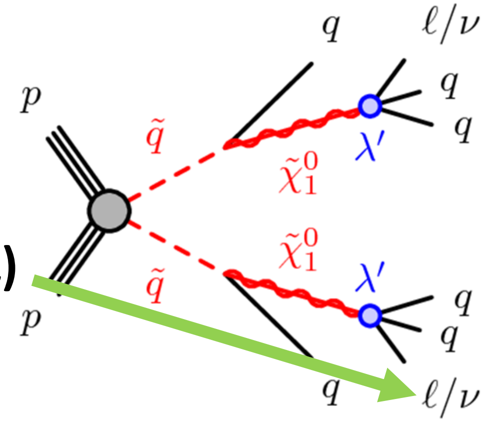
PRD 92 (2015) 072004, arXiv: 1504.05162

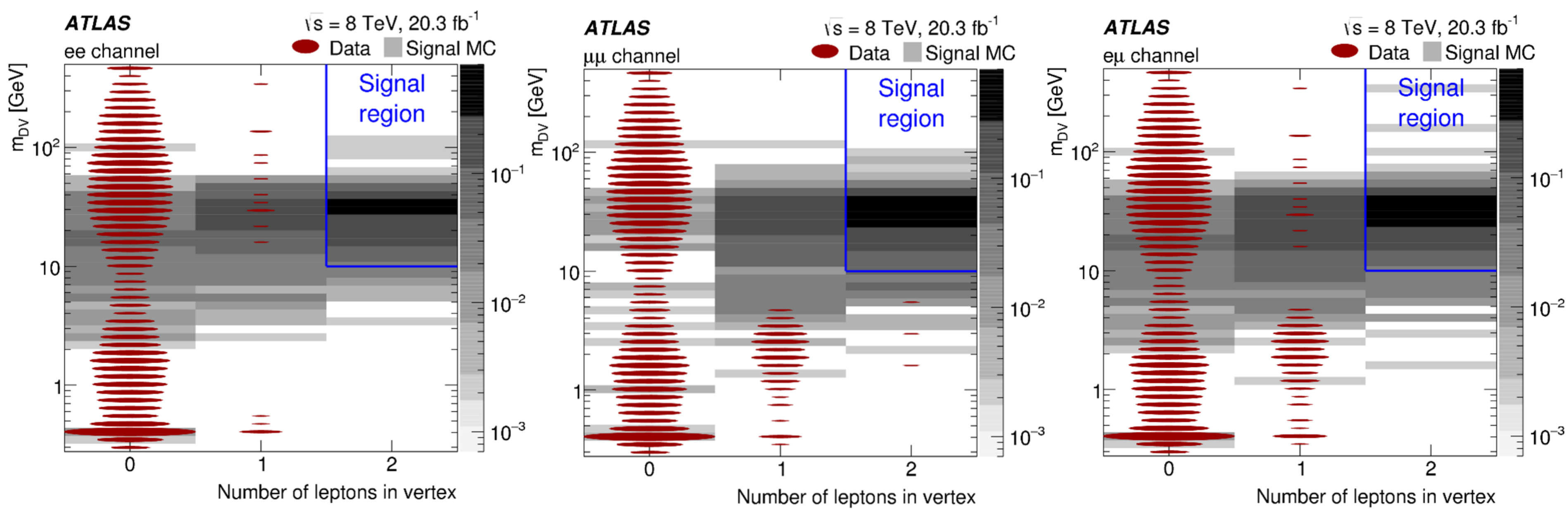


In RPV SUSY, lowest supersymmetric particle (LSP) is not stable.

If couplings are small, the LSP may give a displaced vertex.

Look for displaced vertices with 1ℓ (e or μ) or 2 leptons (ee, eμ, or μμ).

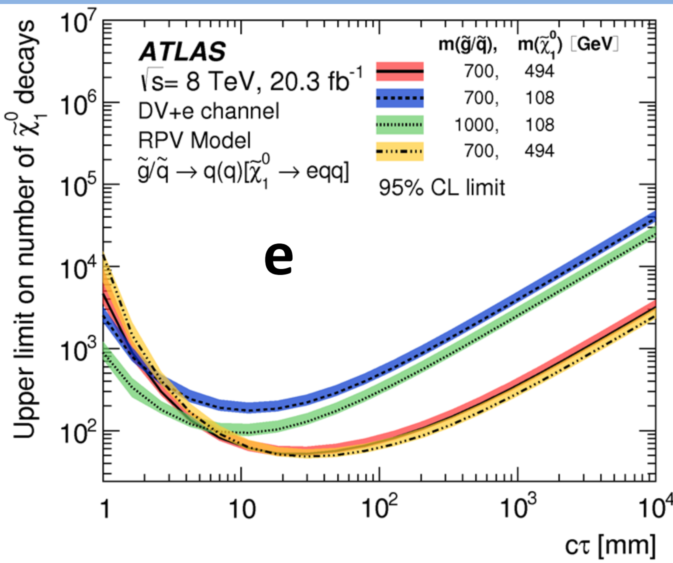


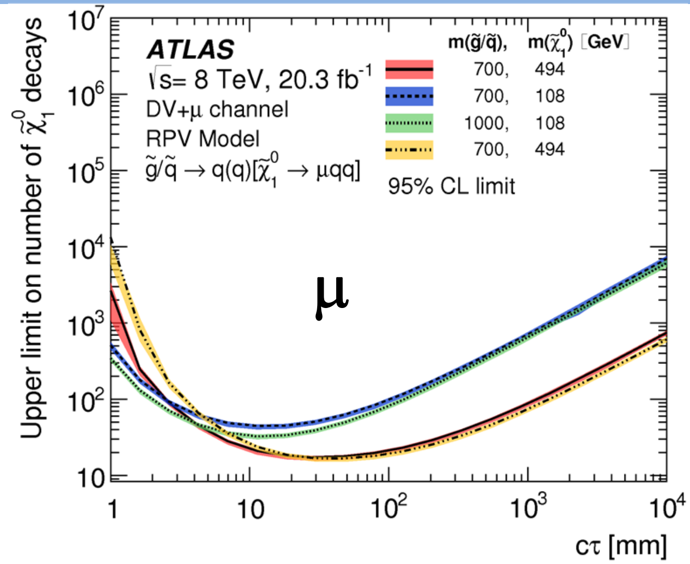


Displaced Vertices in RPV SUSY

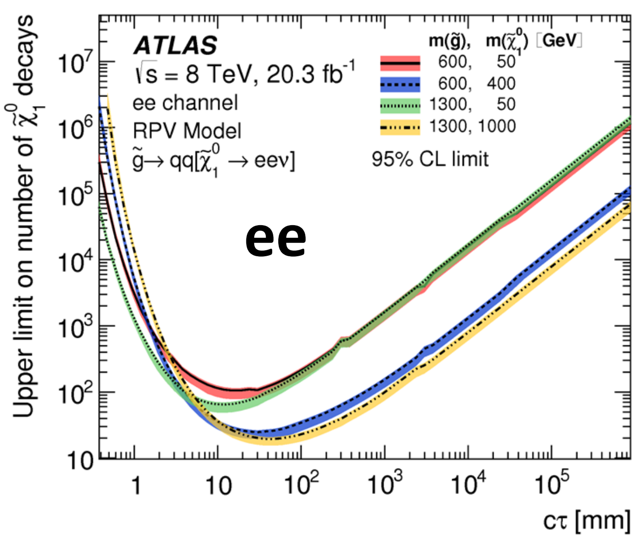
DV + 1ℓ

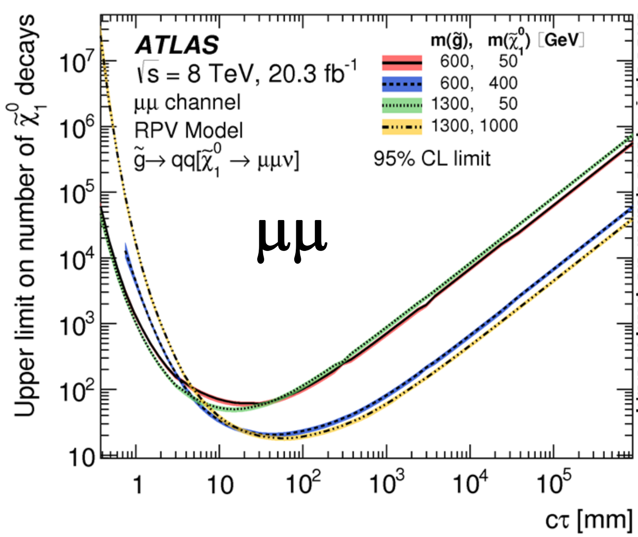
Limits on number vs cτ are most model-independent

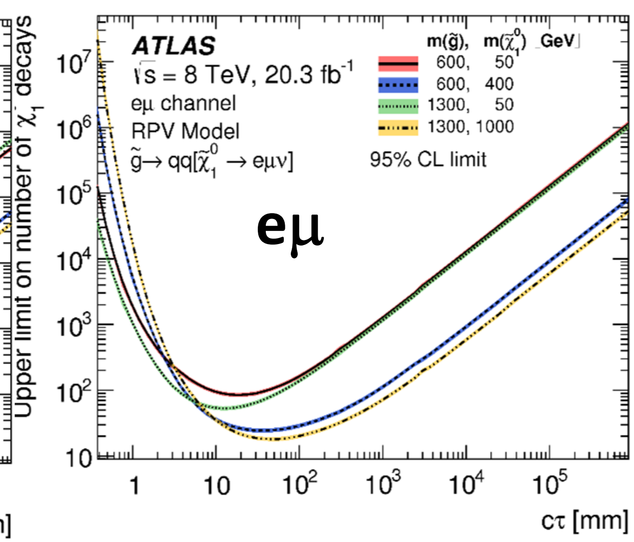




DV + 2ℓ



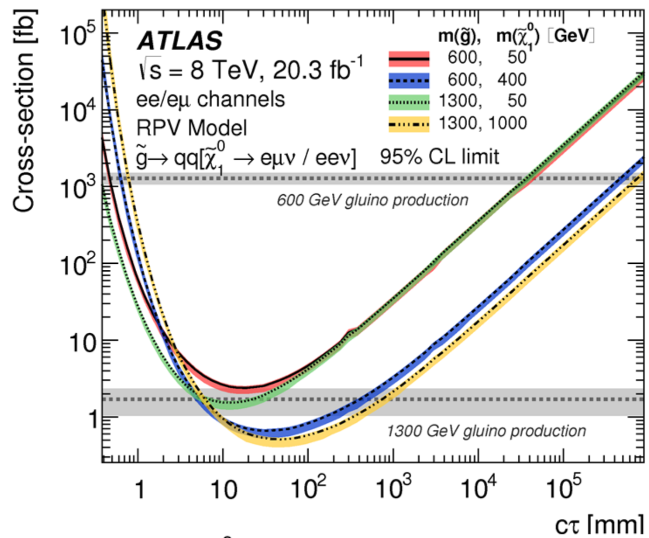


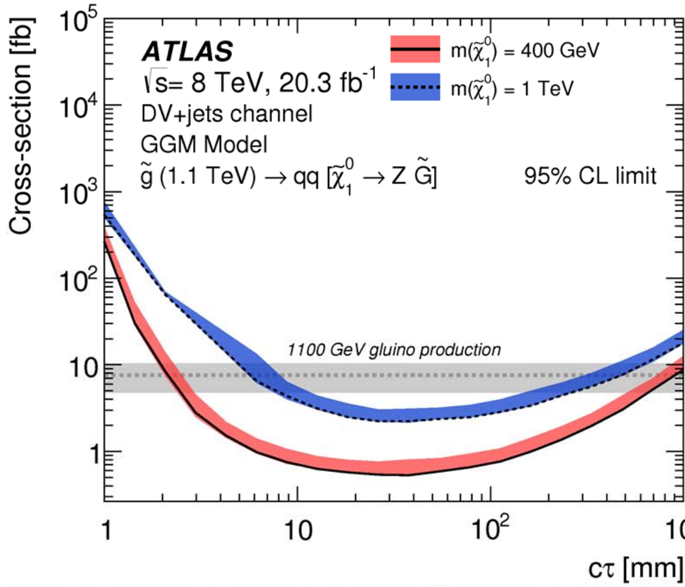


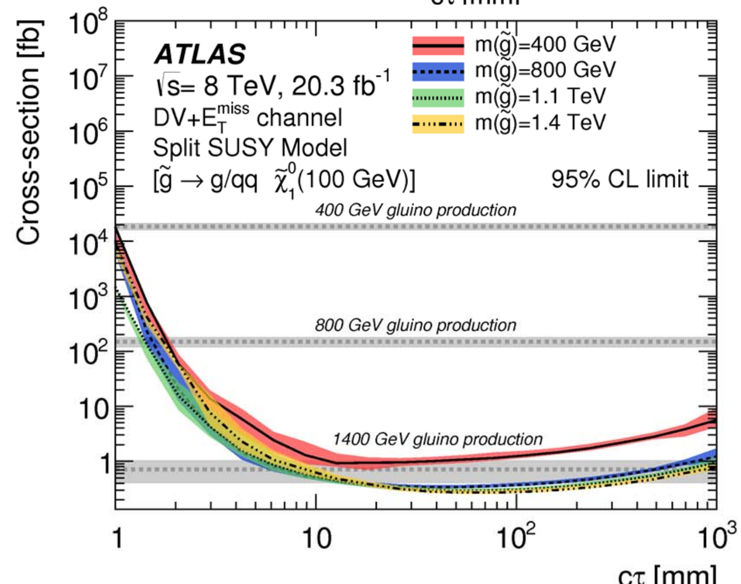
Displaced Vertices in RPV SUSY

Can convert to cross section and mass limits in various models.

Here is a small sample of the available plots.

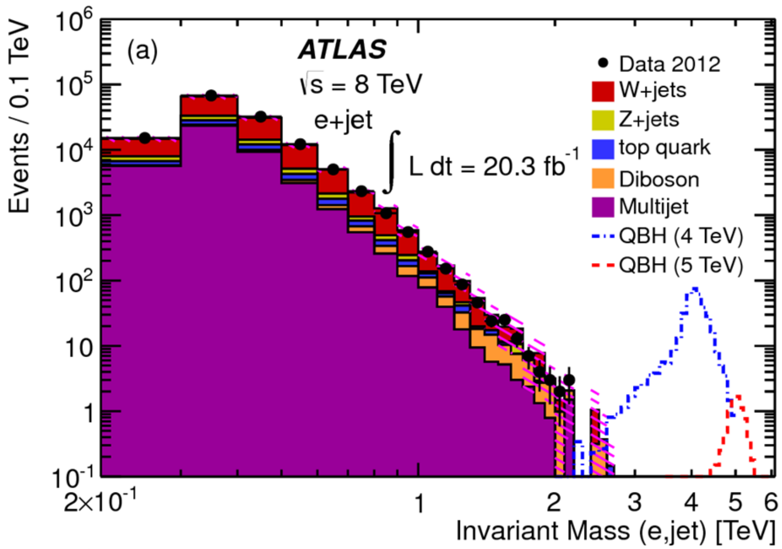


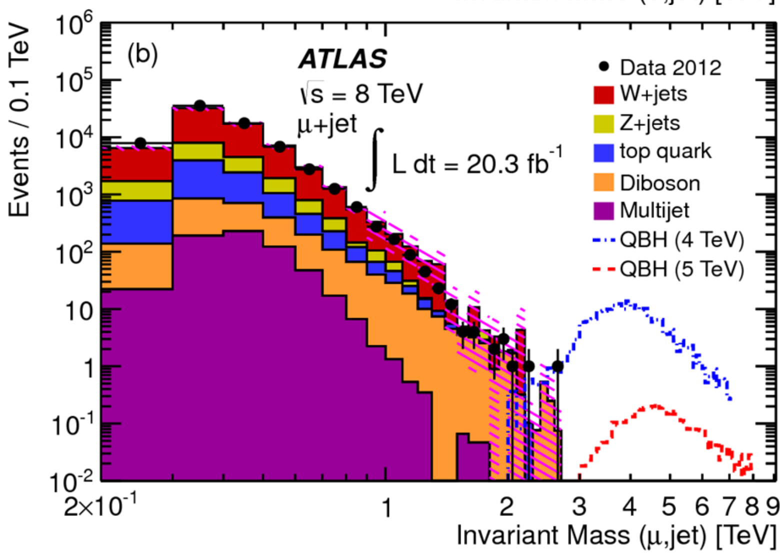




Black Hole → lepton + jet

PRL 112, 091804 (2014)

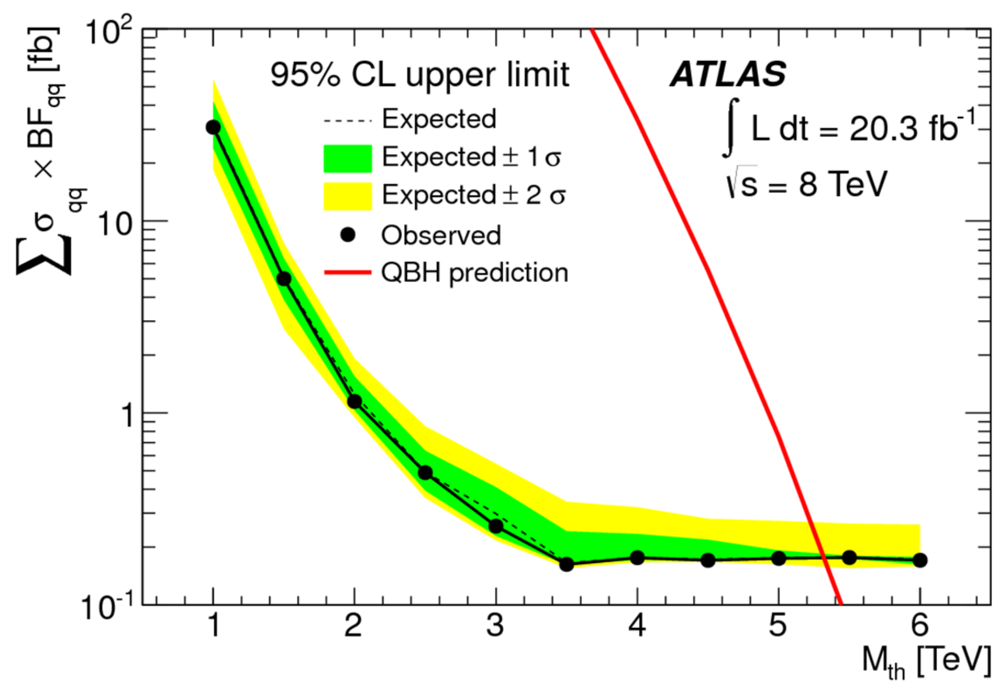




Quantum black holes predicted in low-scale gravity theories.

Expected to conserve angular momentum, charge, color but not other SM quantities.

Search for BH → ℓ + jet.



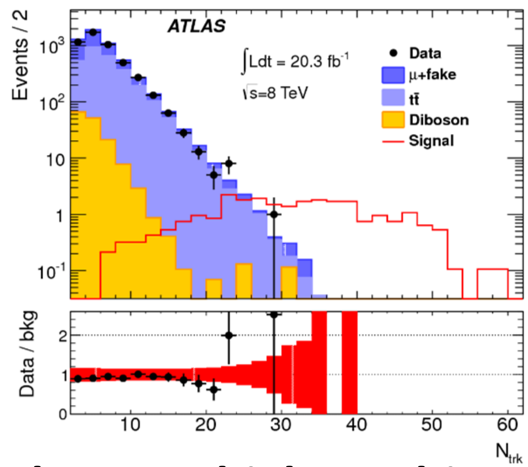
Other Black Hole Modes

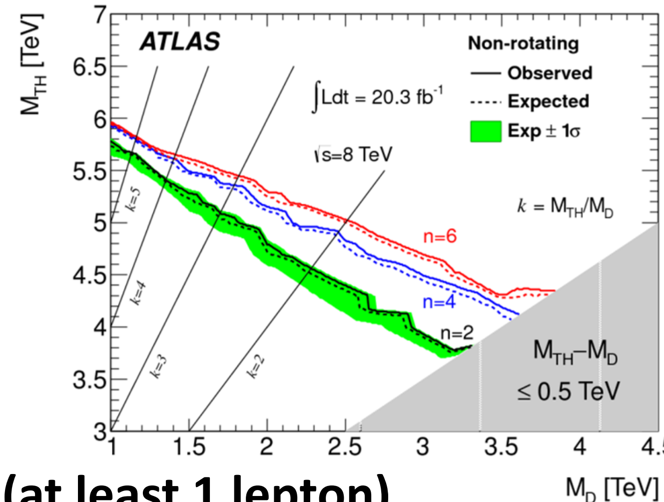
PRD 88 (2013) 072001, arXiv:1308.4075 JHEP08 (2014) 103, arXiv:1405.4254

Black holes are expected to violate lepton flavor.

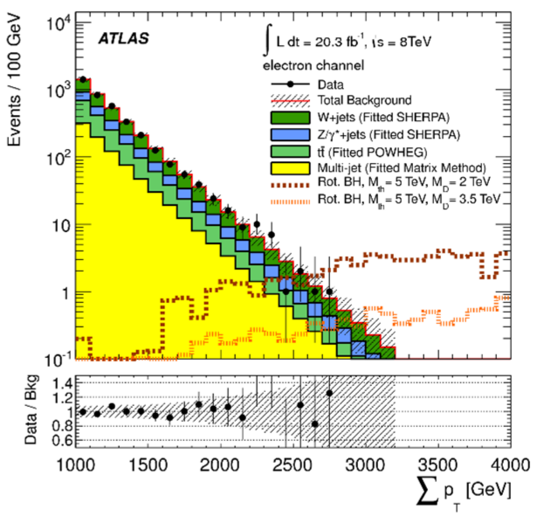
These modes have LFV but do not explicitly show it.

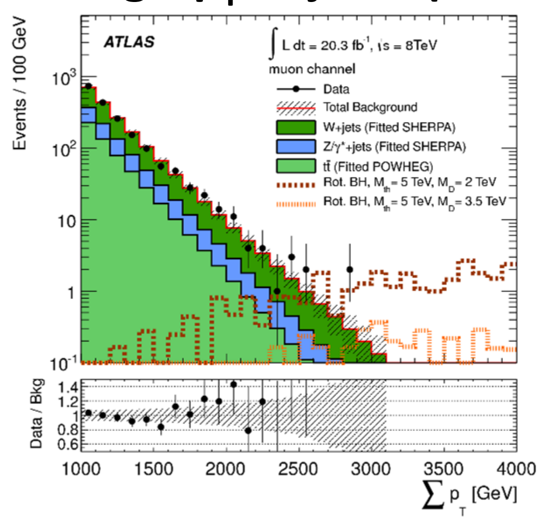
Black hole -> $\mu^{\pm}\,\mu^{\pm}$ + tracks

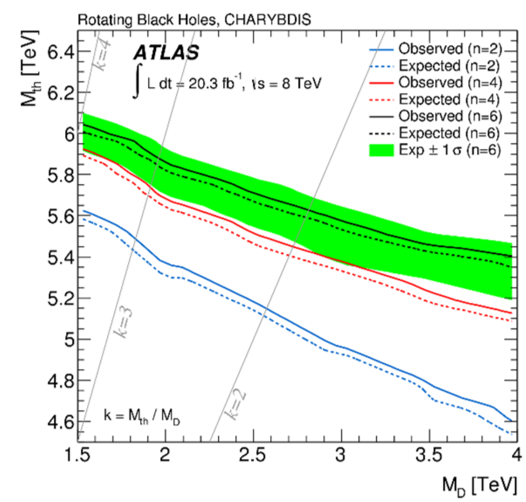




Black hole -> ≥ 3 high-p_T objects (at least 1 lepton)



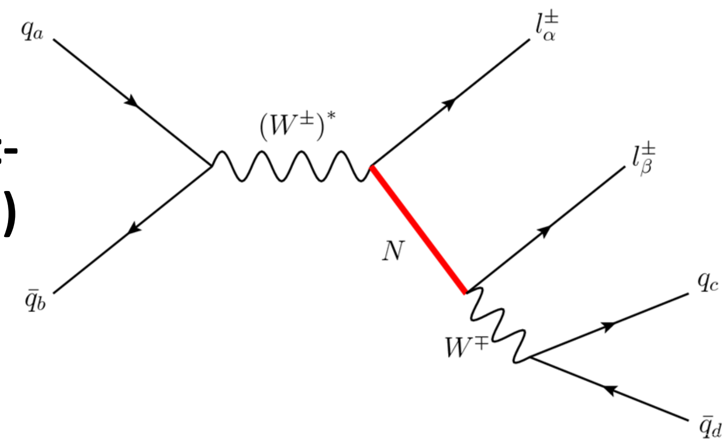


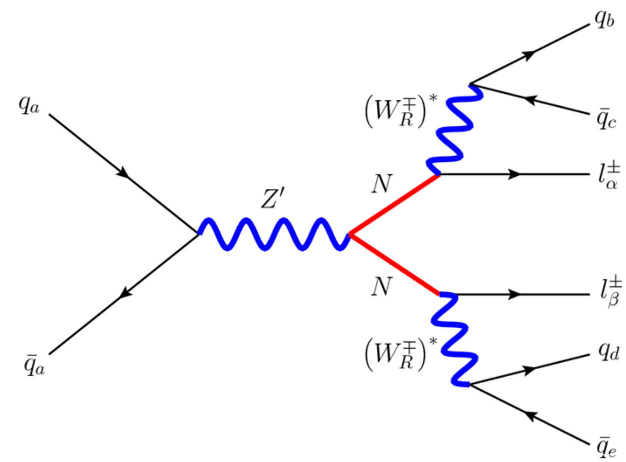


Majorana Neutrinos

JHEP07 (2015) 162
arXiv:1506.06020

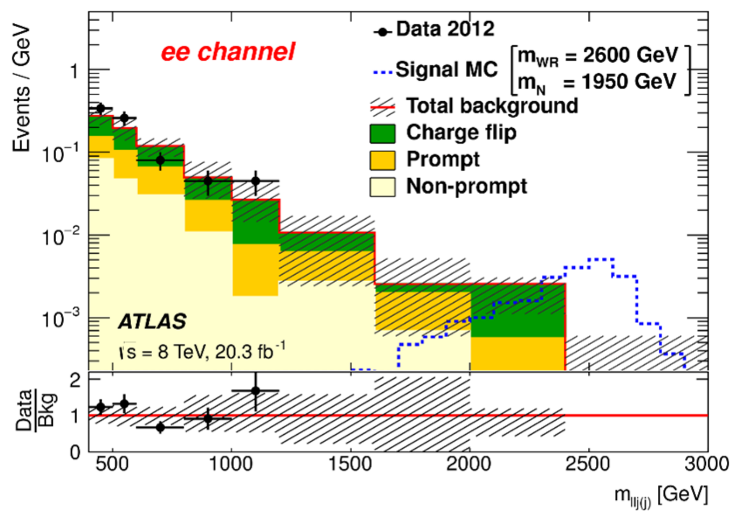
Theories with heavy neutrinos (such as Seesaw models and left-right symmetric models) may have lepton flavor and number violation.

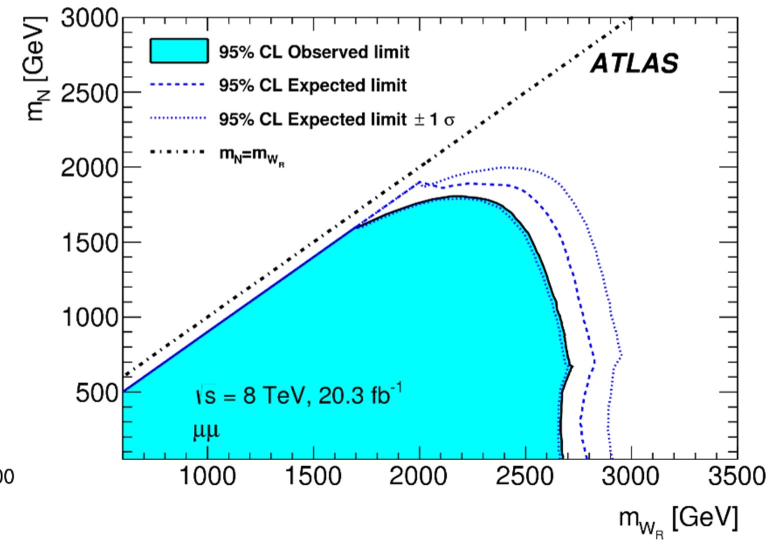




Search for events with like-sign dileptons ($e^\pm e^\pm$ or $\mu^\pm\mu^\pm$) and at least two jets.

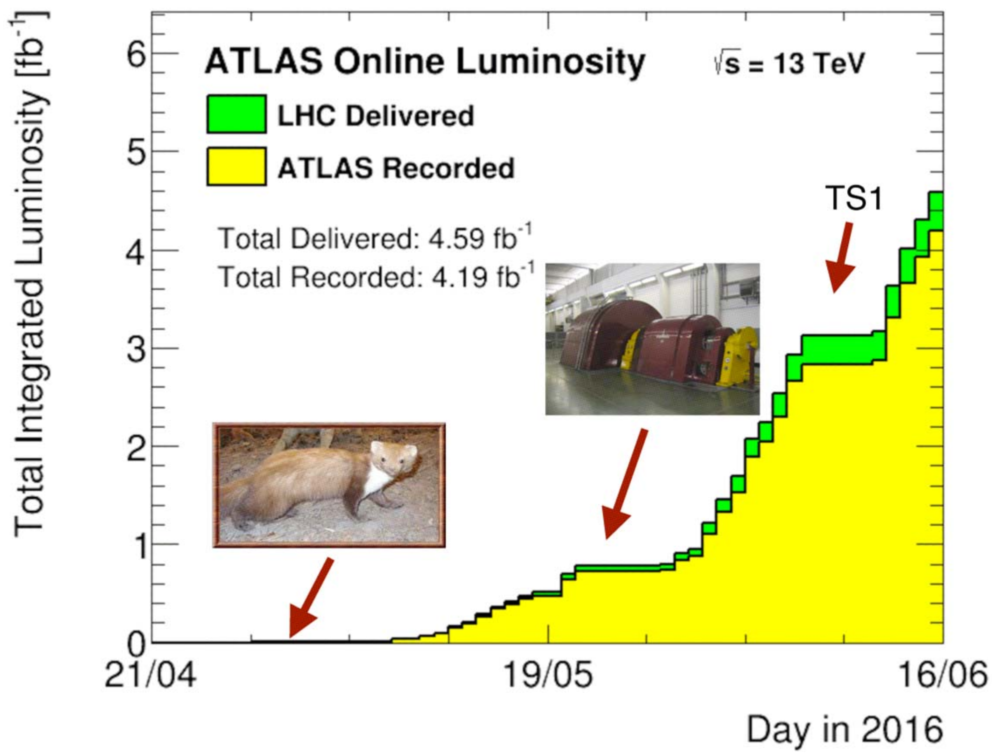
No excess seen.





Summary

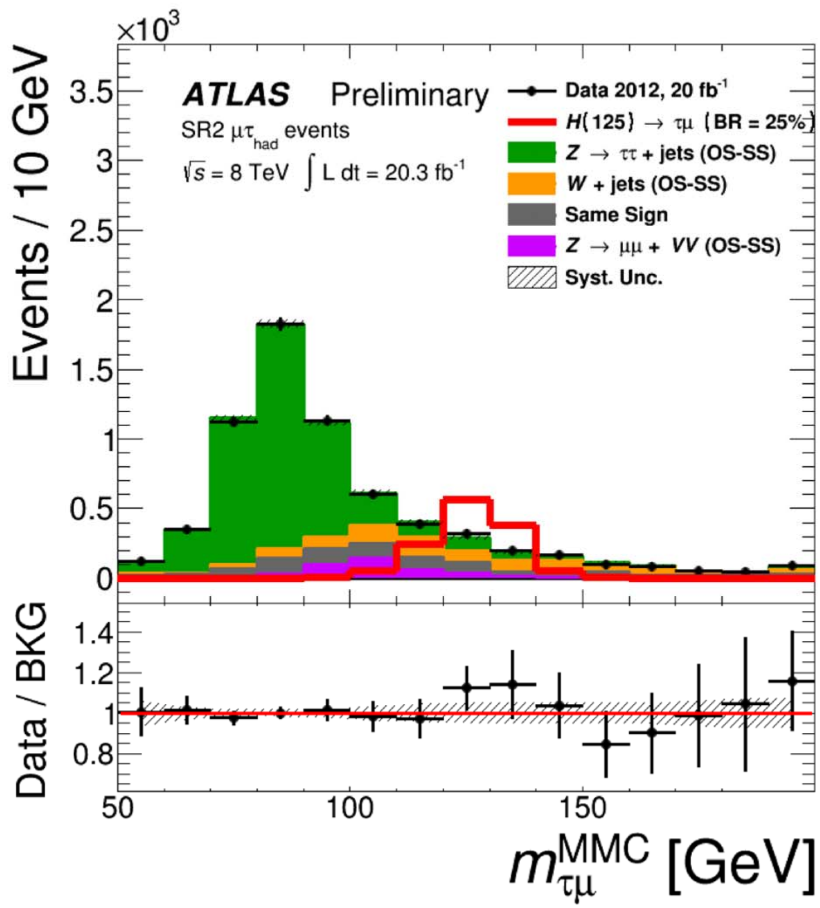
- **ATLAS has searched for lepton flavor violation in the 8-TeV and 13-TeV data via**
  - **decays of Standard-Model particles (Z, H)**
  - **decays of possible new particles ($\tilde{\nu}$, Z', $\tilde{\chi}$)**
  - **decays of Quantum Black Holes.**
- **No excess over the Standard Model expectations is seen.**
- **Limits are placed on various production and decay mechanisms.**
- **LHC is running at 13 TeV, and we look forward to studying the increased data sets.**



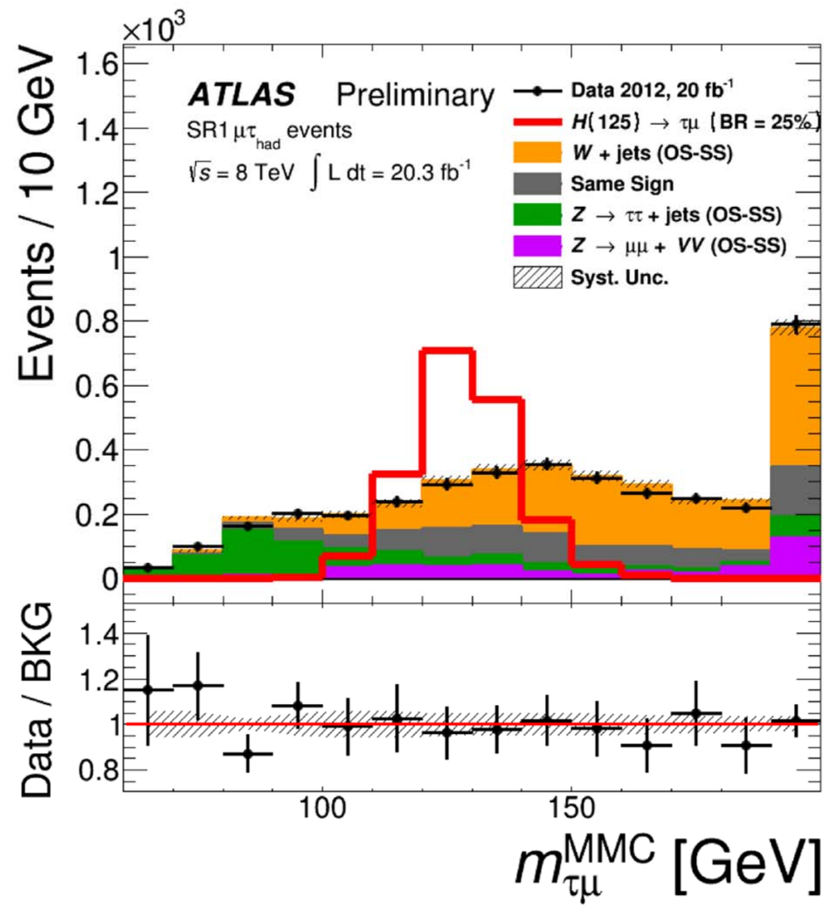
Backup Slides

Higgs → μτ

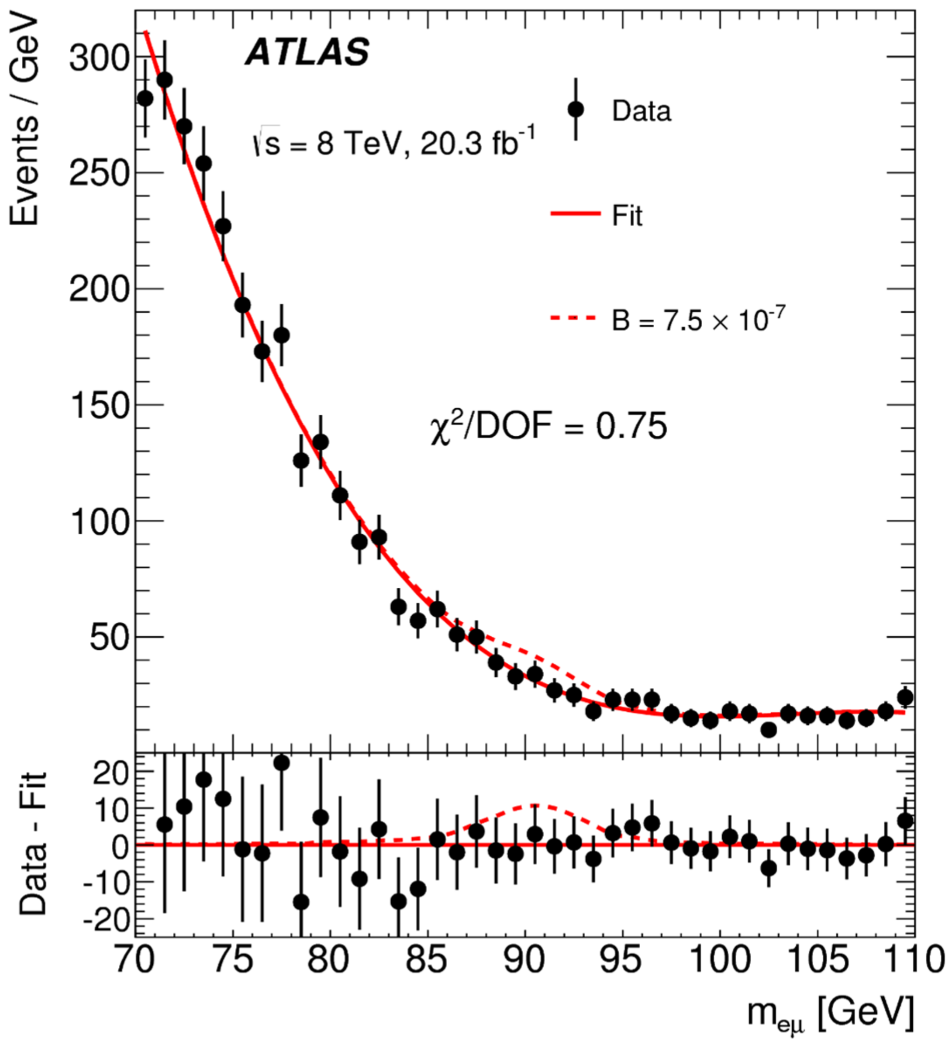
SR1



SR2



$Z \to e\mu$



ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Data
Fit
B = 7.5 × 10^{-7}
χ^2/DOF = 0.75
Events / GeV
Data - Fit
$m_{e\mu}$ [GeV]

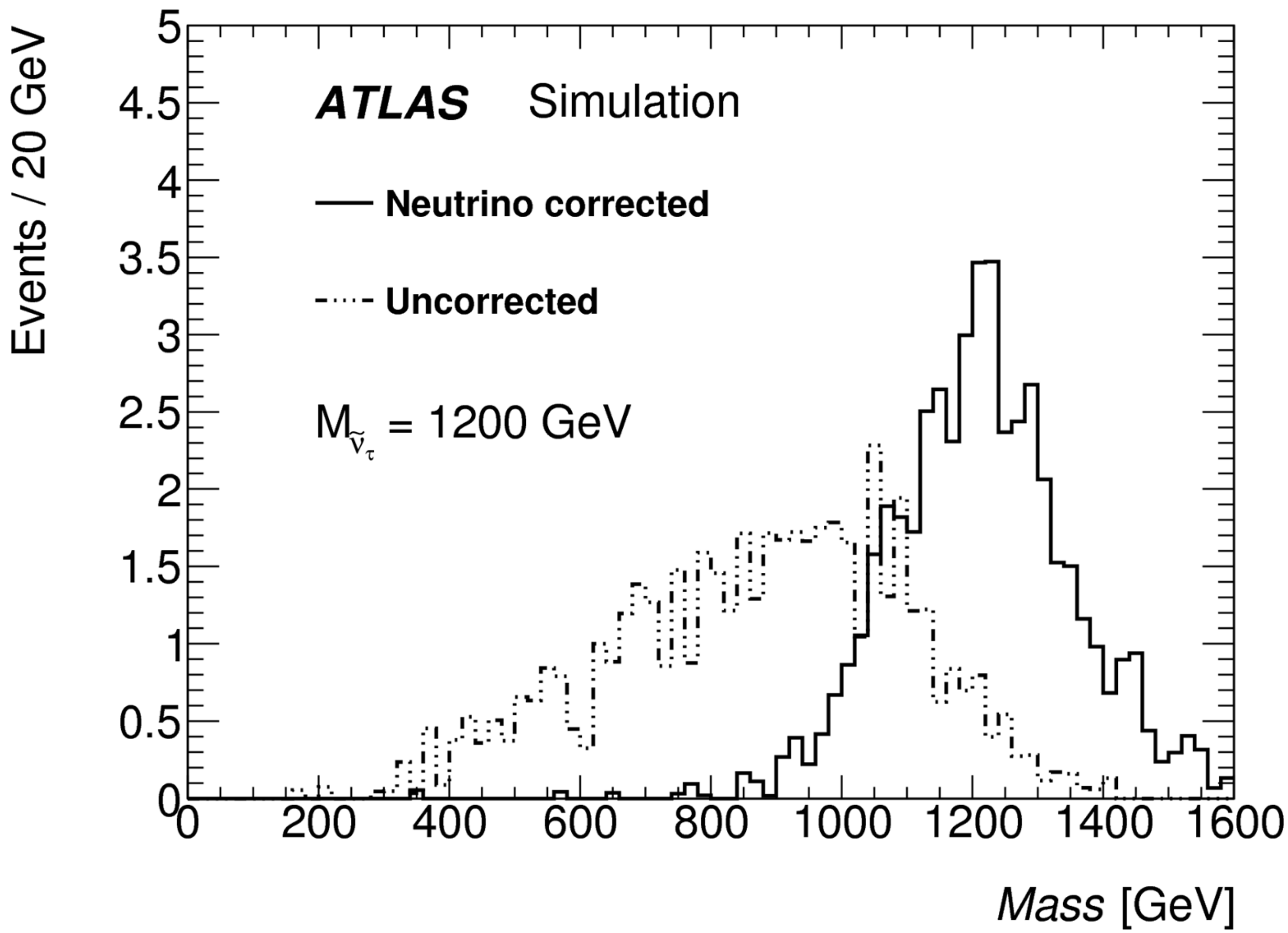
$Z \to e\mu$

Z decay	Acceptance (%)	Efficiency (%)
ee	37.6	28.7
$\mu\mu$	43.3	41.2
$e\mu$	38.9	36.5

Z decay	Efficiency (%)	N_Z (10^8)
ee	10.8 ± 0.3	7.85 ± 0.24
$\mu\mu$	17.8 ± 0.4	7.79 ± 0.17
$\langle ee, \mu\mu \rangle$		7.80 ± 0.15
$e\mu$	14.2 ± 0.4	

Sources	MC			Data					
Channels	ee	$\mu\mu$	$e\mu$	ee		$\mu\mu$		$e\mu$	
—	Eff. (%)	Eff. (%)	Eff. (%)	Events	Eff. (%)	Events	Eff. (%)	Events	Eff. (%)
Initial	—	—	—	242,852,345	—	242,852,345	—	242,852,345	—
Triggered	62.5	65.7	64.8	76,840,946	31.6	76,840,946	31.6	76,840,946	31.6
Two Lepton, η and p_T cuts	31.1	51.6	40.6	4,908,037	6.4	8,129,937	10.6	76,657	0.1
$E_T^{miss} < 17$ GeV	67.9	66.9	68.0	3,384,179	69.0	5,547,293	68.2	12,189	15.9
$p_{T}{}^{jet}_{max} < 30$ GeV	84.9	81.7	81.8	2,965,933	87.6	4,869,110	87.8	8,744	71.7
$70 < m_{\ell\ell} < 110$ GeV	96.4	96.3	97.1	2,847,689	96.0	4,670,014	95.9	3,163	36.2
$85 < m_{\ell\ell} < 95$ GeV	81.8	86.5	86.2	2,248,034	78.9	3,702,598	79.3	362	11.4

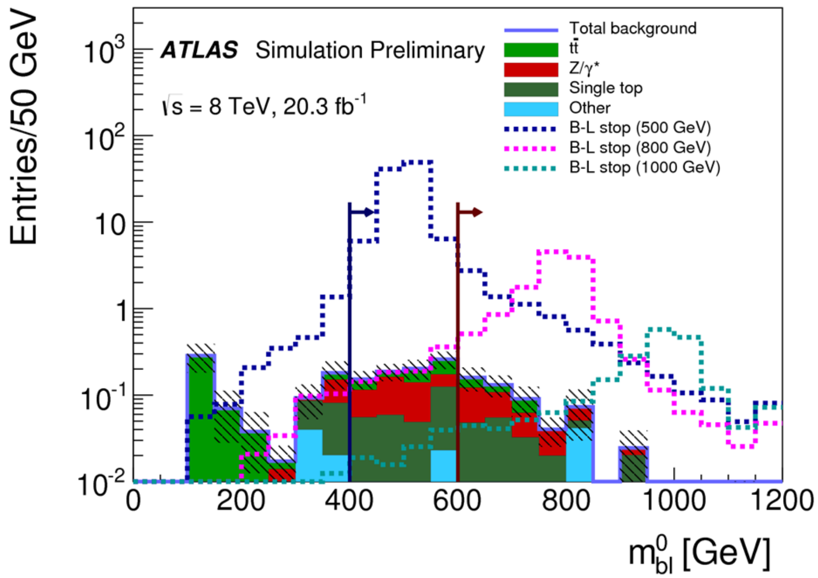
Z' or $\tilde{\nu} \rightarrow e\mu$, $e\tau$, or $\mu\tau$

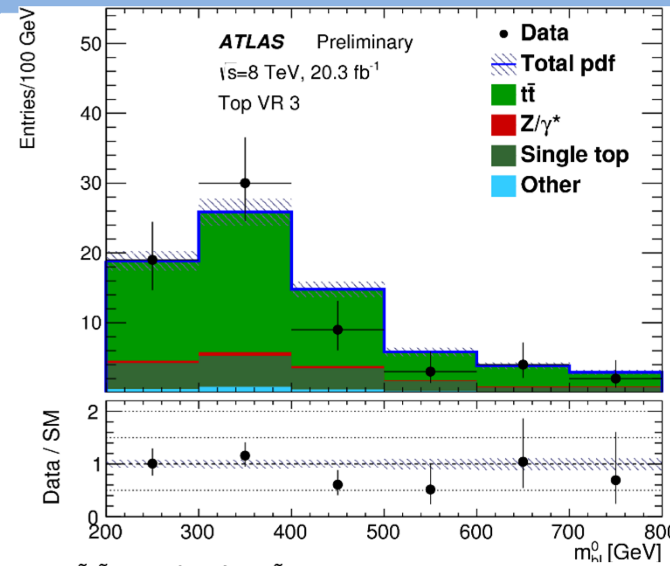


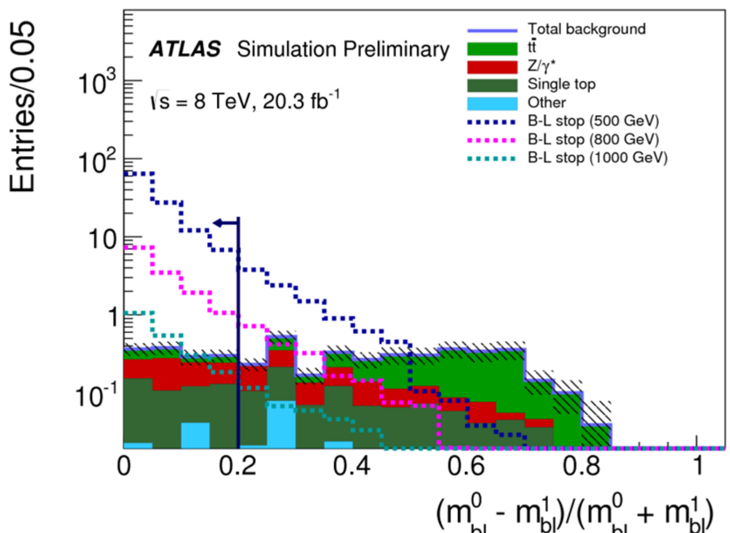
Z' or $\tilde{\nu} \rightarrow$ eμ, eτ, or μτ

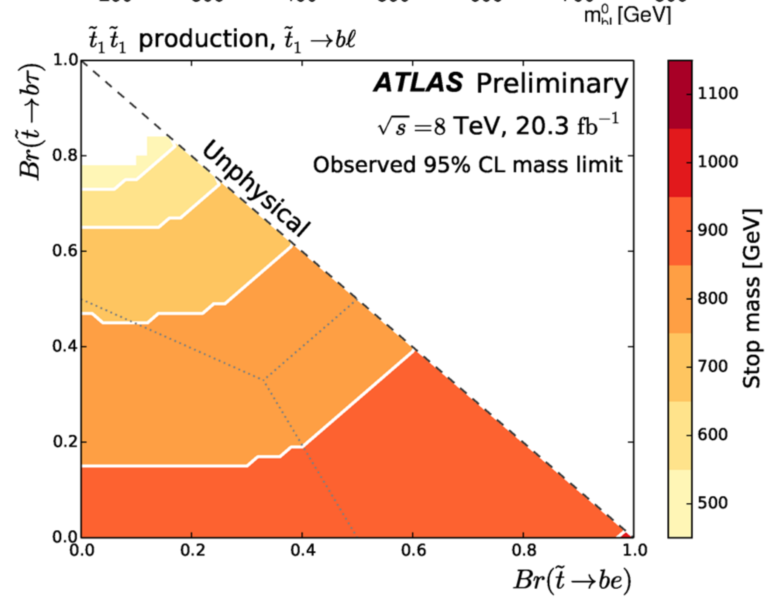
	$m_{\ell\ell'} < 200$ GeV			$m_{\ell\ell'} > 200$ GeV		
Process	$N_{e\mu}$	$N_{e\tau_{\text{had}}}$	$N_{\mu\tau_{\text{had}}}$	$N_{e\mu}$	$N_{e\tau_{\text{had}}}$	$N_{\mu\tau_{\text{had}}}$
$Z/\gamma^* \rightarrow \tau\tau$	6000±400	11000± 900	11200± 700	28± 12	72± 21	99± 33
$Z/\gamma^* \rightarrow ee$	—	6100±1100	—	—	430± 70	—
$Z/\gamma^* \rightarrow \mu\mu$	—	—	19500±1300	—	—	410± 80
$t\bar{t}$	4220±290	690± 60	580± 50	1640±120	700± 60	550± 40
Diboson	1440± 80	321± 29	258± 17	474± 30	197± 17	141± 11
Single top quark	470± 40	87± 11	60± 7	202± 17	90± 10	73± 8
W+jets	54± 18	17000±4000	14000±4000	8± 4	3600±700	2800±600
Multijet	227± 32	4800±1000	700± 800	58± 12	340±210	100±190
Total	12400±600	40400±2900	46000±4000	2400±130	5400±500	4200±400
Data	12954	41304	48304	2474	5336	4184

B-L top squark

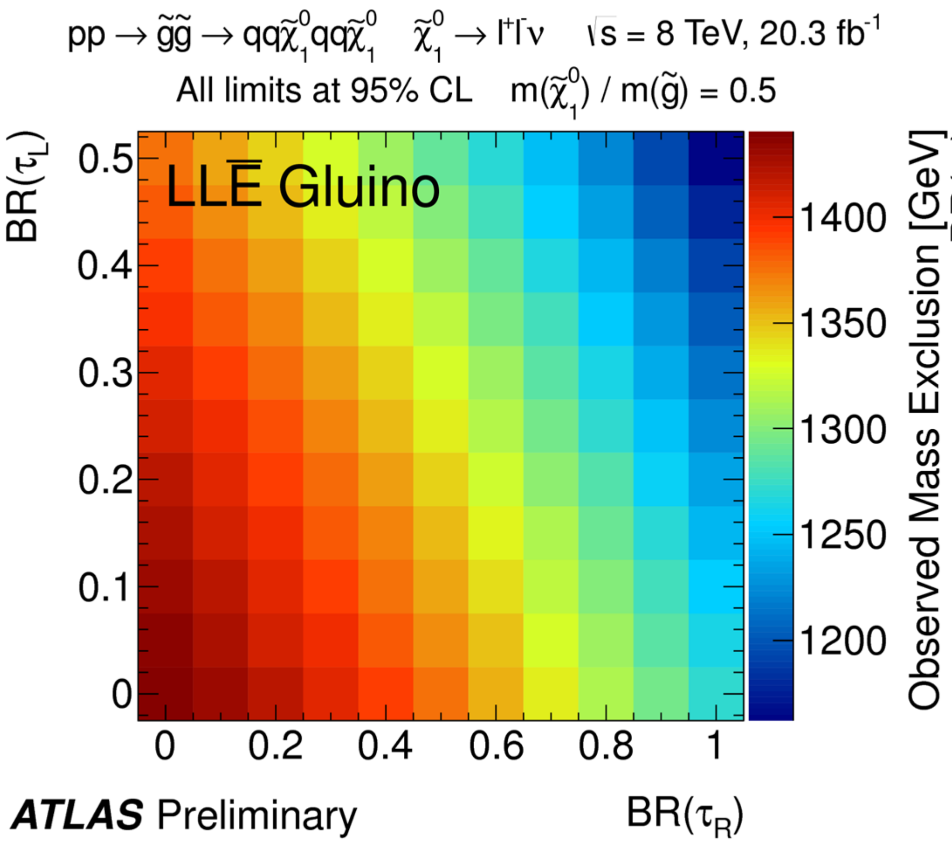


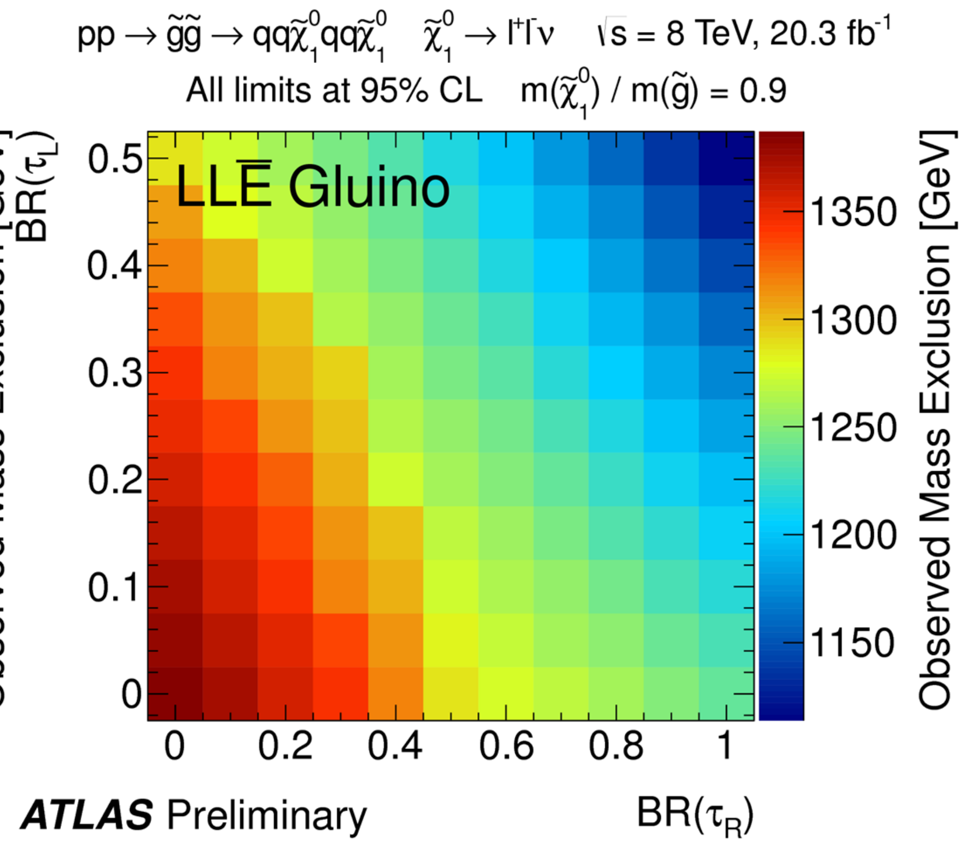




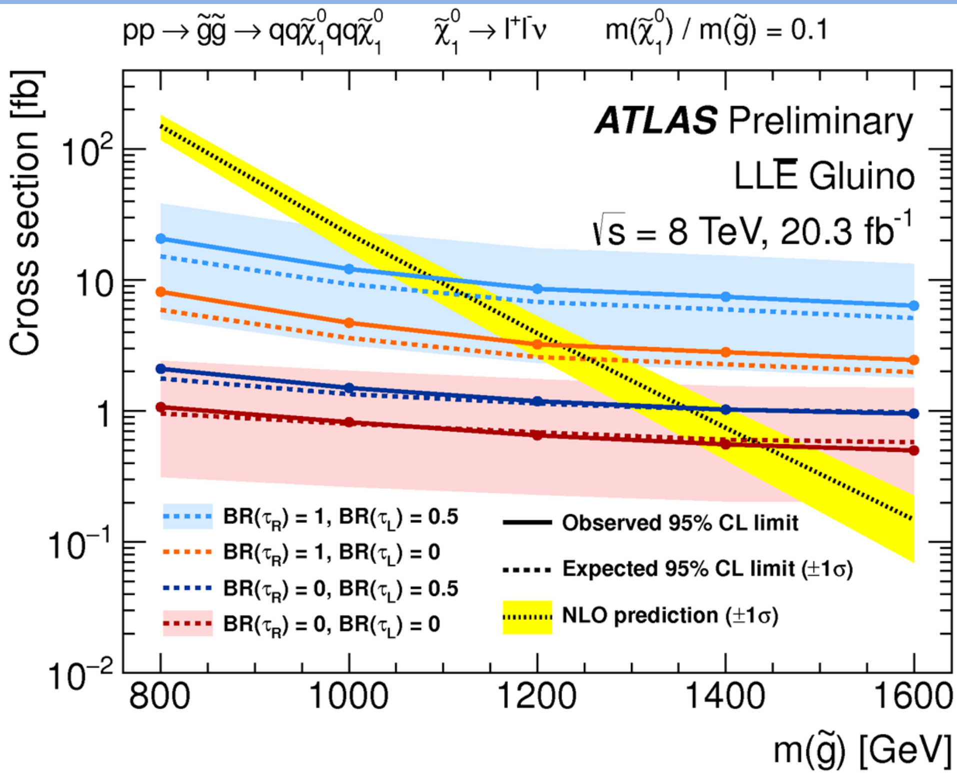


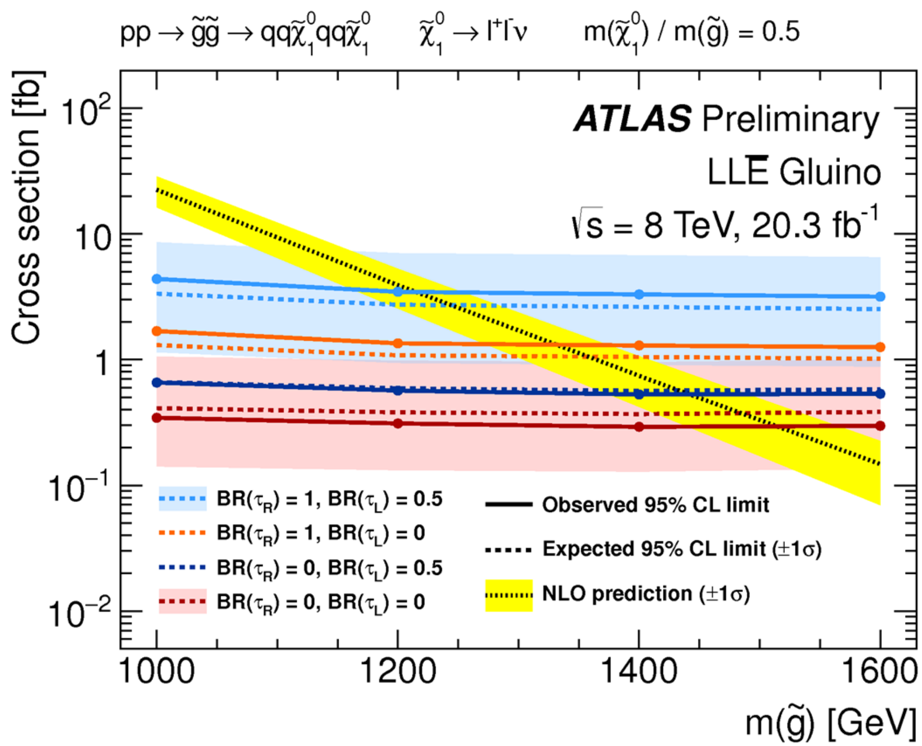
Multileptons in RPV SUSY





Multileptons in RPV SUSY

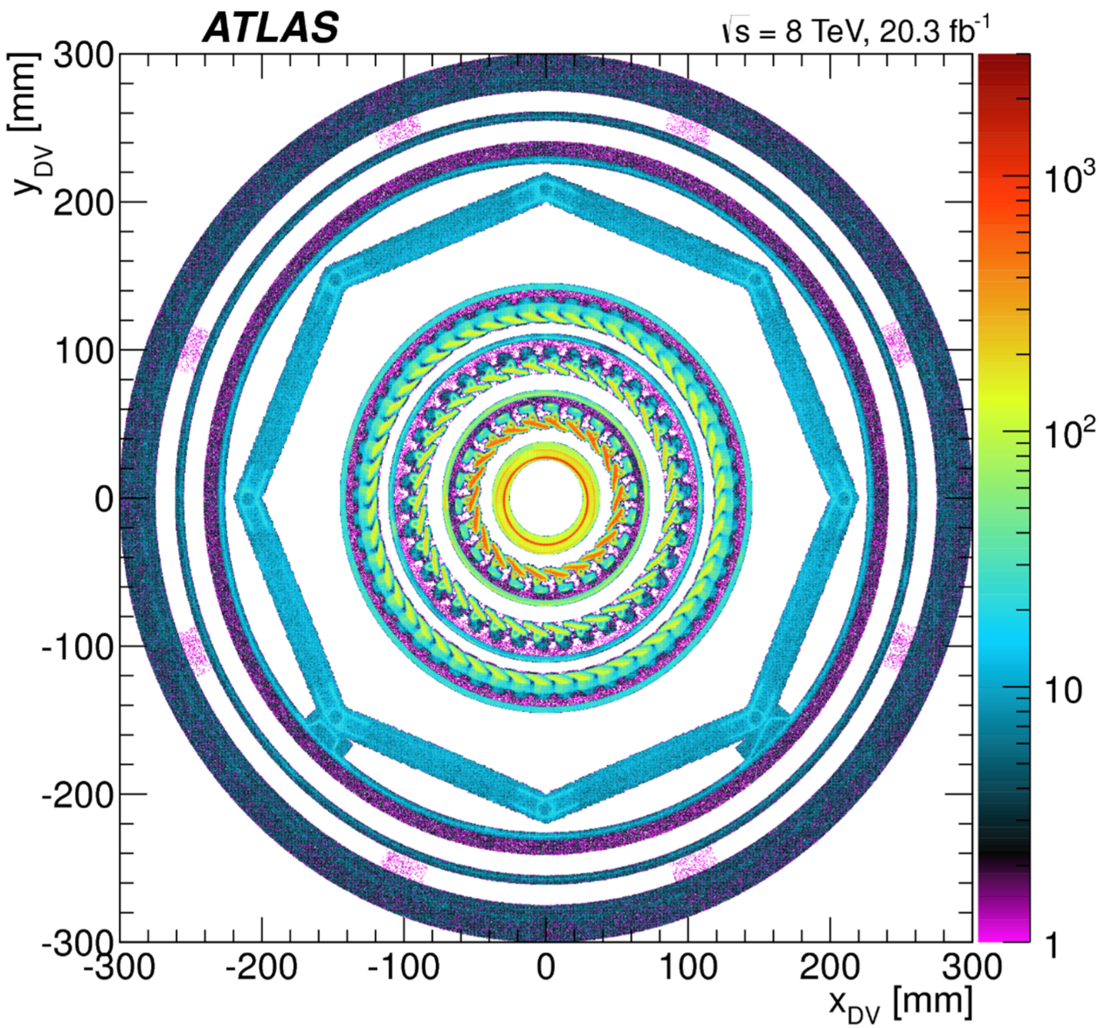




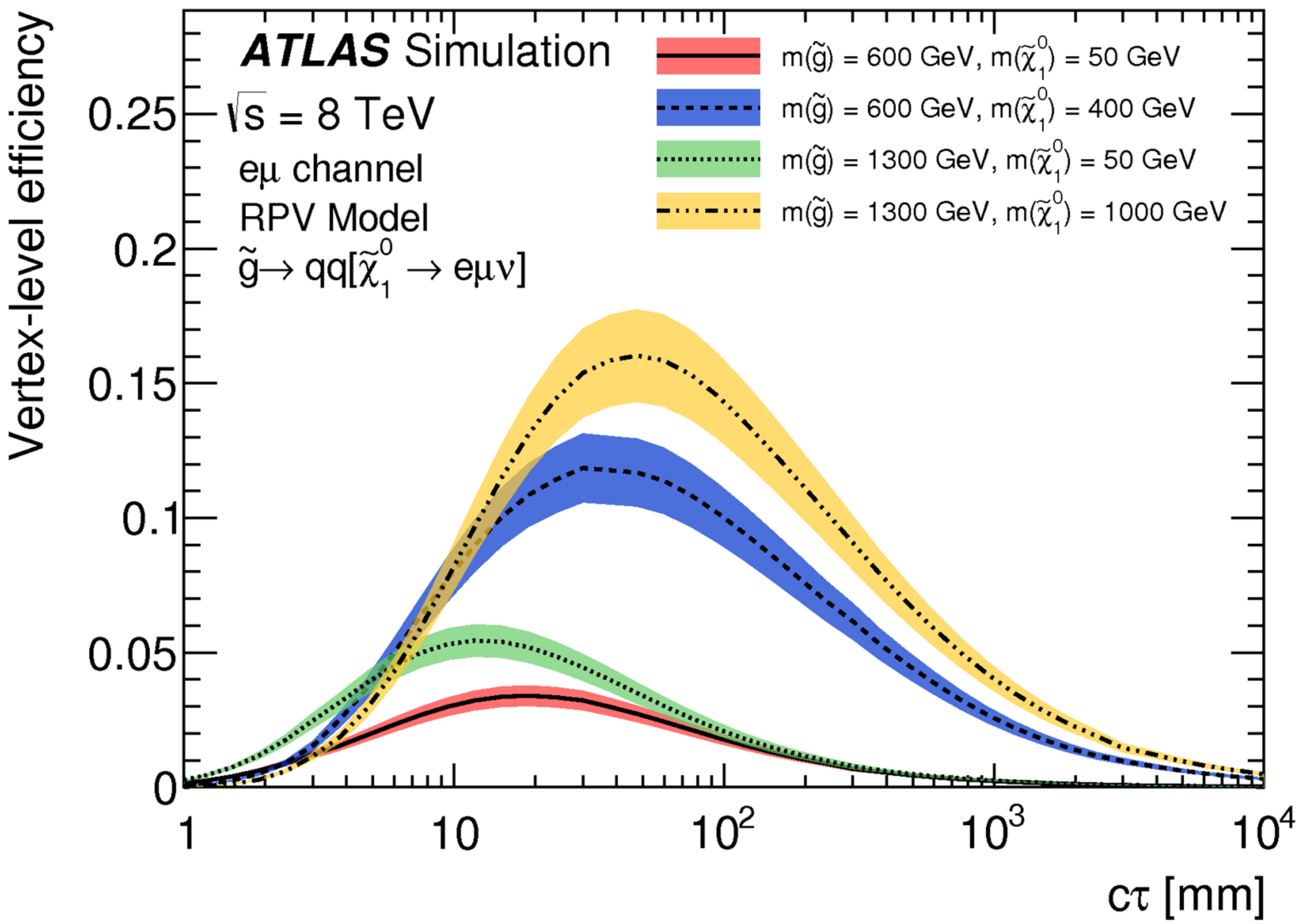
Displaced Vertices in RPV SUSY

Displaced vertices with less than 5 tracks.

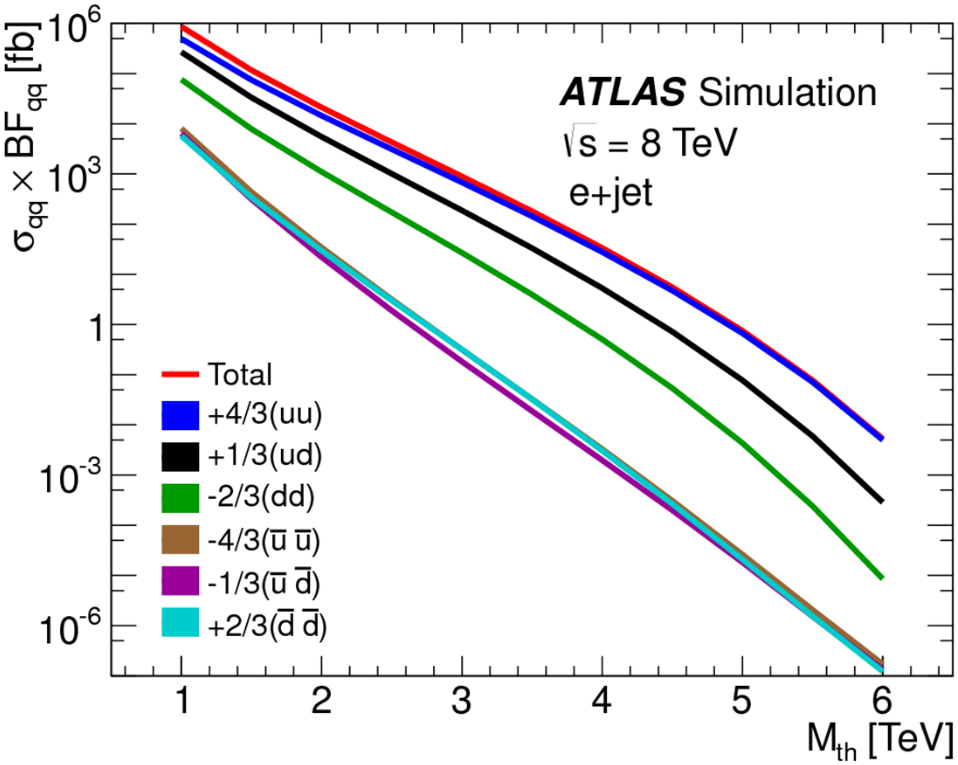
These regions are excluded from the signal search.



Displaced Vertices in RPV SUSY

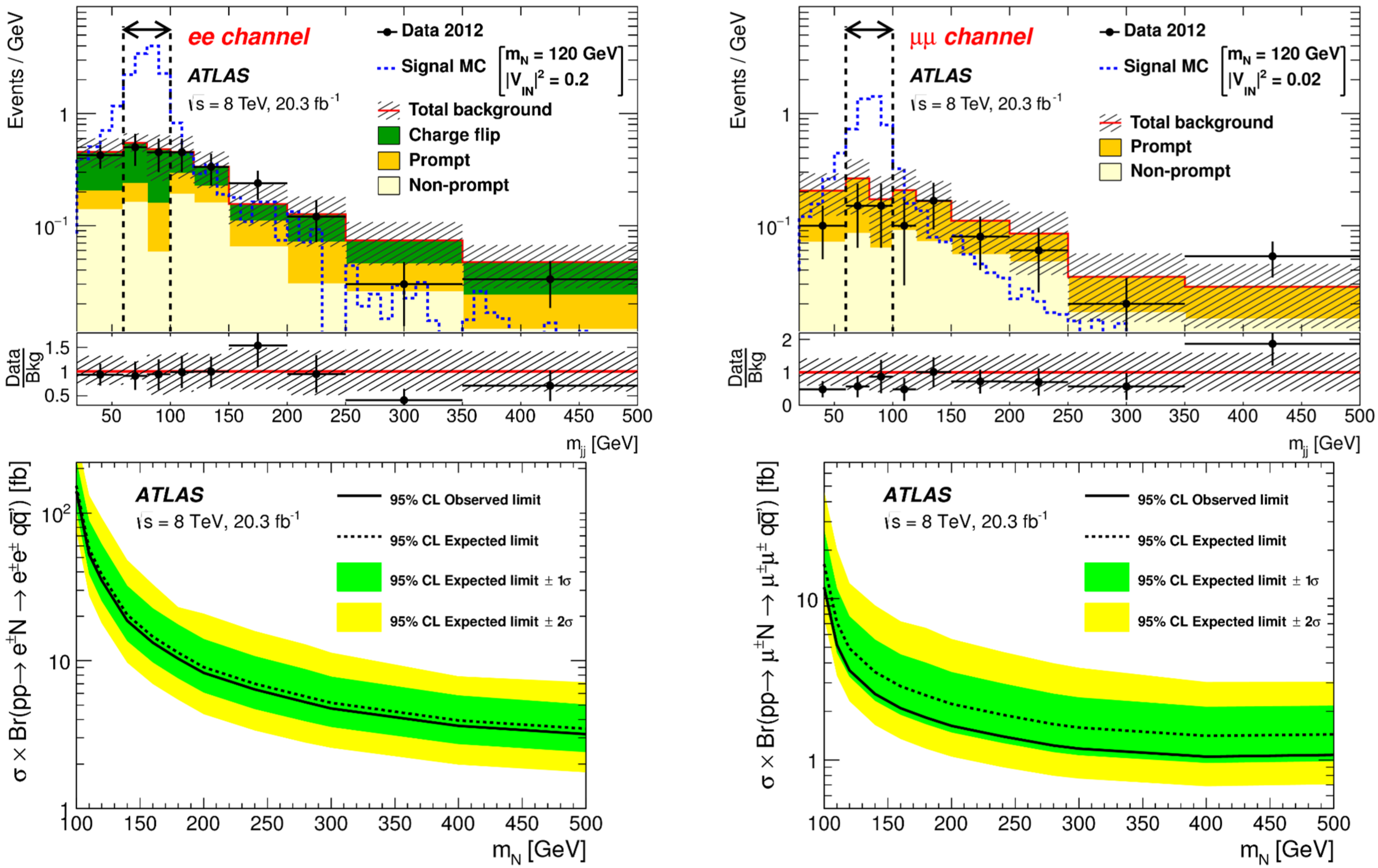


Black Hole → lepton + jet



M_{th}	Electron+jet Obs.	Electron+jet Exp.	Electron+jet Eff.	Muon+jet Obs.	Muon+jet Exp.	Muon+jet Eff.
TeV			%			%
1.0	1200	1210^{+230}_{-220}	57 ± 4	620	550 ± 280	38 ± 4
1.5	100	110 ± 40	57 ± 4	49	65^{+45}_{-40}	36 ± 4
2.0	12	19^{+13}_{-12}	56 ± 4	8	14^{+16}_{-14}	36 ± 4
2.5	0	$5.3^{+4.5}_{-3.9}$	55 ± 4	3	5^{+6}_{-5}	34 ± 4
3.0	0	$1.8^{+1.8}_{-1.6}$	54 ± 4	1	$2.1^{+2.9}_{-2.1}$	34 ± 4
3.5	0	$0.76^{+0.79}_{-0.67}$	54 ± 4	0	$1.0^{+1.6}_{-1.0}$	33 ± 4
4.0	0	$0.35^{+0.38}_{-0.34}$	53 ± 4	0	$0.57^{+0.94}_{-0.57}$	33 ± 5
5.0	0	$0.09^{+0.10}_{-0.09}$	52 ± 4	0	$0.24^{+0.39}_{-0.24}$	32 ± 5
6.0	0	$0.03^{+0.04}_{-0.03}$	52 ± 4	0	$0.13^{+0.22}_{-0.13}$	32 ± 6

Majorana Neutrinos



Majorana Neutrinos