



Searches for RPV SUSY and long-lived particles at the LHC

Minghui Liu

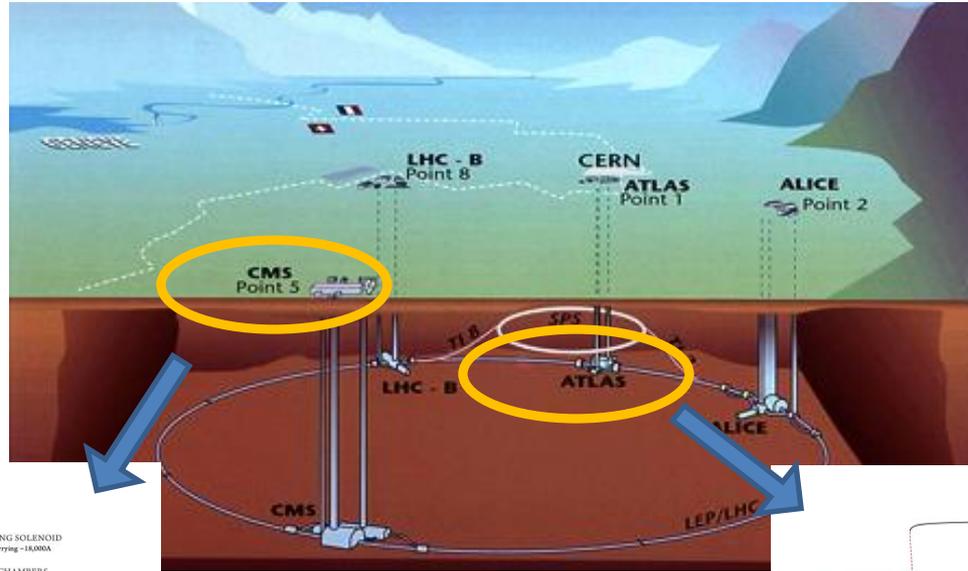
University of Science and Technology of China (USTC)

On behalf of the ATLAS and CMS collaboration



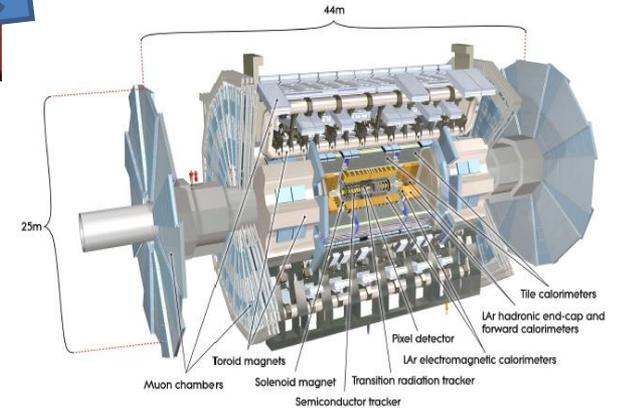
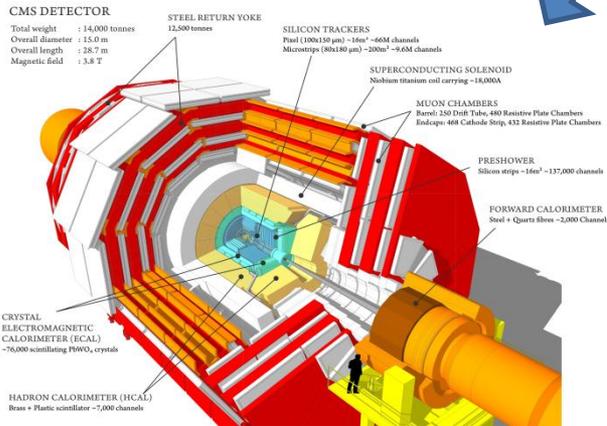
The Large Hadron Collider

2 General purpose detectors



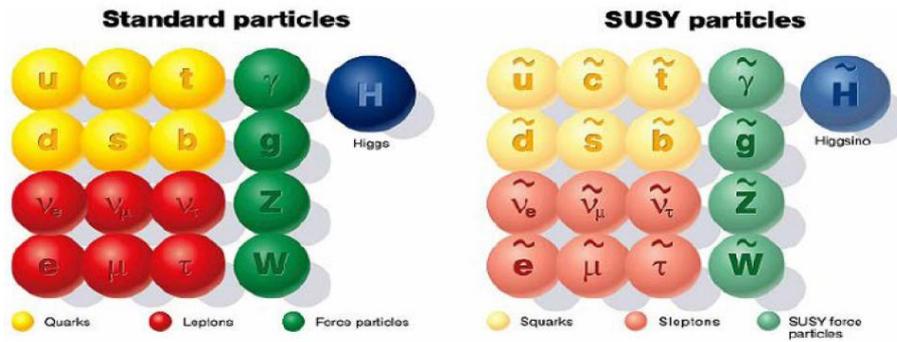
CMS

ATLAS



Validate the SM theory
Search for **new physics**

R-parity and Long-lived Particles (LLP)



- Hierarchy problem
- Dark matter/Energy
- neutrino mass

The last possible space-time symmetry

• R-Parity

$$R = (-1)^{3B+L+2S}$$

- For SM particle: $R = +1$
- For SUSY particle: $R = -1$

R-Parity violating (RPV)

- Both "B" and "L" are conserved in SM, but not necessary in SUSY

LLP:

Several New Physics models could give rise to LLP

LLPs can arise in a model if:

- ✓ Small coupling in decay chain.
- ✓ Strong virtuality (decay to heavy particles).
- ✓ Small mass differences in decay chain
- ✓ Pair production of particles with conserved quantum number.

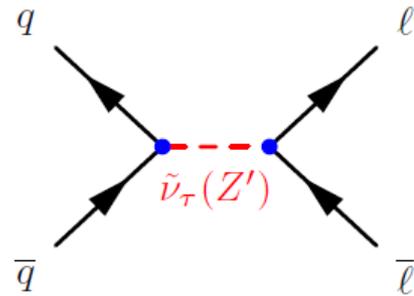
RPV search: 2 lepton final states

$\tilde{\nu}_\tau / Z' \rightarrow e\mu / e\tau / \mu\tau$ @ATLAS ([arXiv:1503.04430](https://arxiv.org/abs/1503.04430))

$Z \rightarrow e\mu$ @ATLAS (Phys. Rev. D 90, 072010 (2014))

Stop \rightarrow l+b@ATLAS (ATLAS-CONF-2015-015)

SS dilepton+jets@CMS (JHEP 01 (2014) 163)



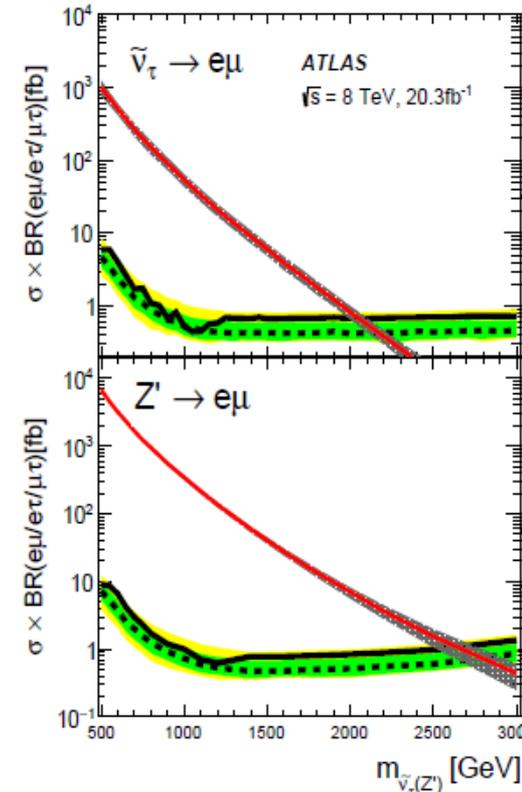
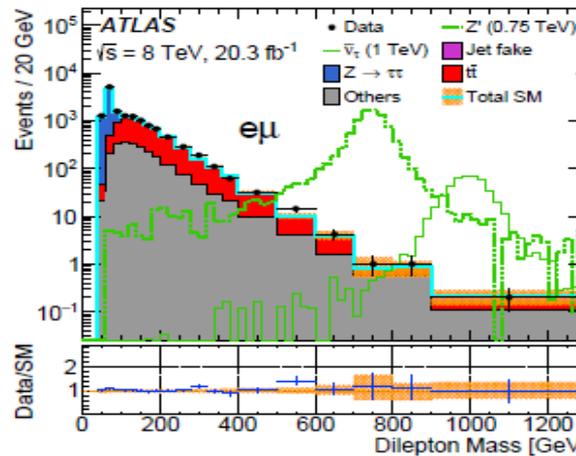
2 isolated leptons with:
different flavor
different charge
back to back

Backgrounds:

- ✓ Process with 2 real leptons:
 WW, ttbar, single top, $Z \rightarrow ll$ (MC simul)
- ✓ ≥ 1 lepton is misidentified from a jet:
 W+jet, QCD (data-driven method)

Systematics are mainly from:

- ✓ MC x-section theory uncertainty
- ✓ MC statistics
- ✓ Luminosity



channel	$\tilde{\nu}_\tau$ is excluded	Z' is excluded	Z Br($Z \rightarrow e\mu$)
emu	2.0TeV	2.5TeV	$< 7.5 \times 10^{-7}$
etau	1.7TeV	2.2TeV	
mutau	1.7TeV	2.2TeV	

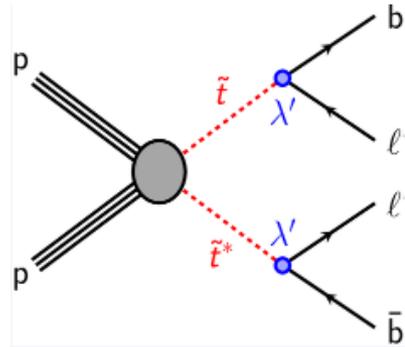
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SS dilepton+jets @ CMS (JHEP 01 (2014) 163)



◆ 2 OS isolated leptons
($ee/e\mu/\mu\mu$)

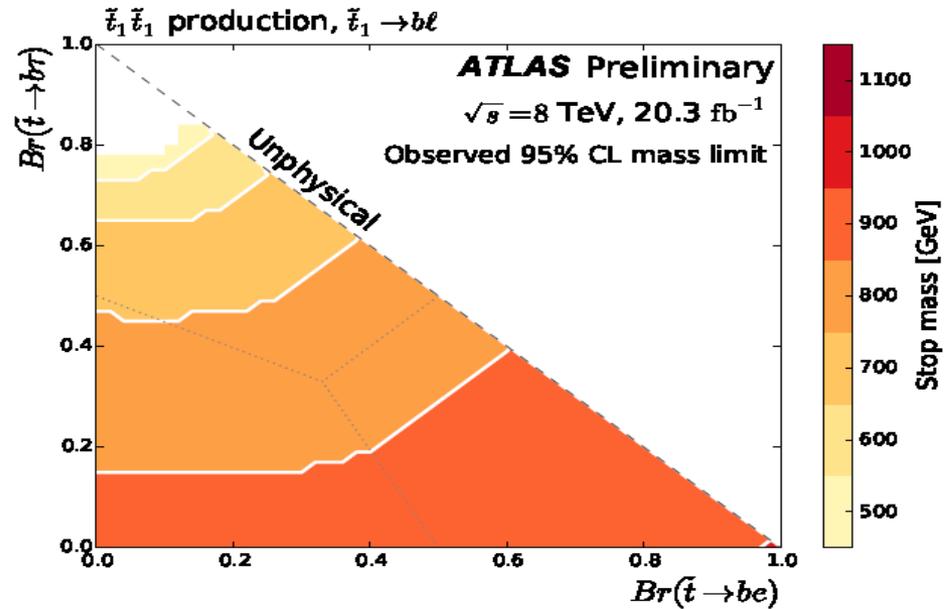
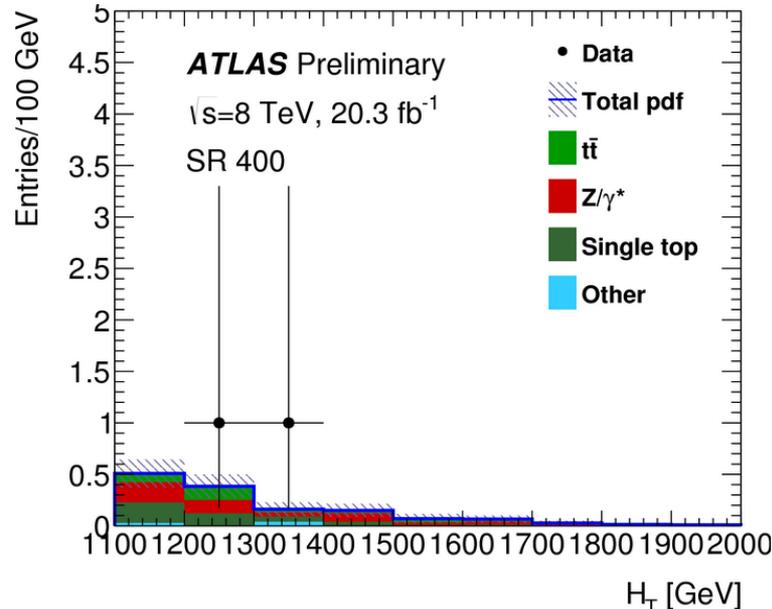
◆ 2 b-tagged jets

◆ No obvious MET

◆ 2 lb pairs with large, similar M_{lb}

Backgrounds:

- ✓ Ttbar, Wt
- ✓ Z+jet



Limits on Stop mass are placed between 500 GeV and 1 TeV with $Br(\text{stop} \rightarrow e/\mu+b) > 20\%$

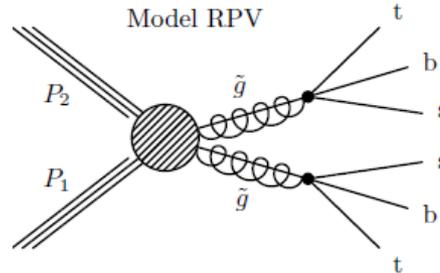
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Stop $\rightarrow l+b$ @ATLAS (ATLAS-CONF-2015-015)

SS dilepton+jets@CMS (JHEP 01 (2014) 163)



◆ 2 SS isolated leptons
(ee/eμ/μμ)

◆ A number of jets/bjets

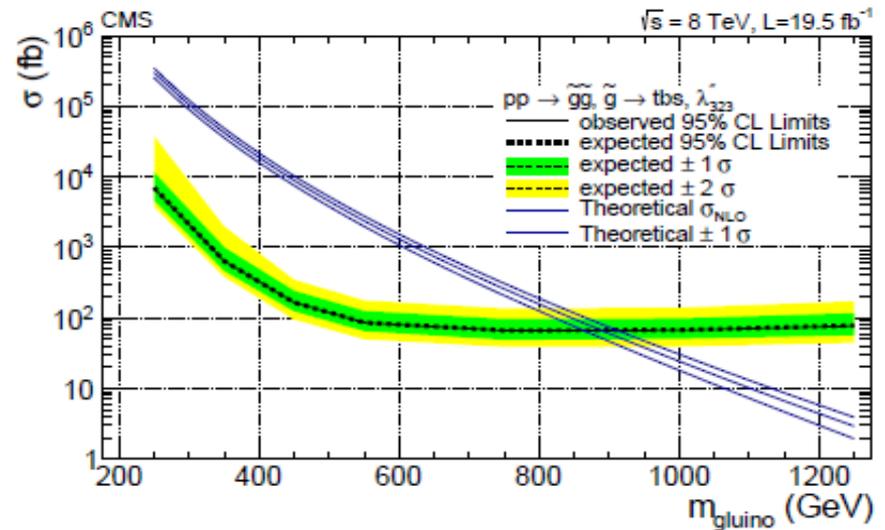
◆ Large Scalar sum of jet pT

Backgrounds:

- ✓ leptons from heavy flavor or jet misid
WW, ttbar
- ✓ rare SM processes with SS lepton pair
ttbar+W, ttbar+Z
- ✓ Charge misid

Systematics are mainly from:

- ✓ Modeling of lepton selection
- ✓ JES/JER
- ✓ b-jet identification



95% CL upper limit on the gluino production cross section

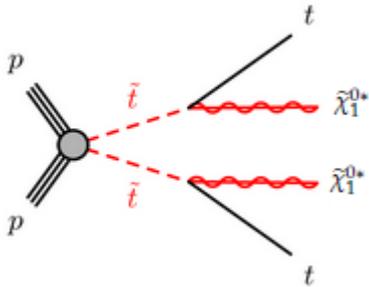
$$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow tbs(\bar{t}\bar{b}\bar{s}).$$

ATLAS has a similar result in: [JHEP06\(2014\)035](https://arxiv.org/abs/1406.035)

Gluino with mass < 900 GeV is excluded

RPV search: multilepton final states

3 leptons+b@CMS (Phys. Rev. Lett. 111 (2013) 221801)



$$\tilde{\chi}_1^{0*} \rightarrow l_i + \nu_j + l_k$$

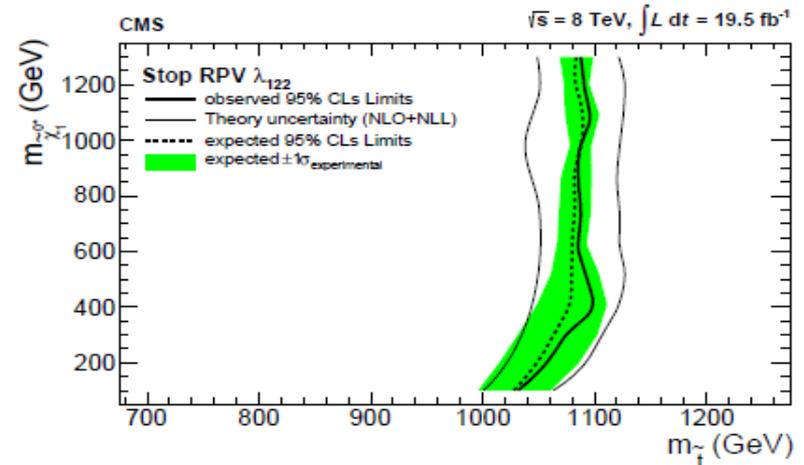
$$\tilde{\chi}_1^{0*} \rightarrow l_i + q_j + q_k$$

- ◆ At least 3 leptons
e/ μ / τ
- ◆ 2 bjets
- ◆ MET

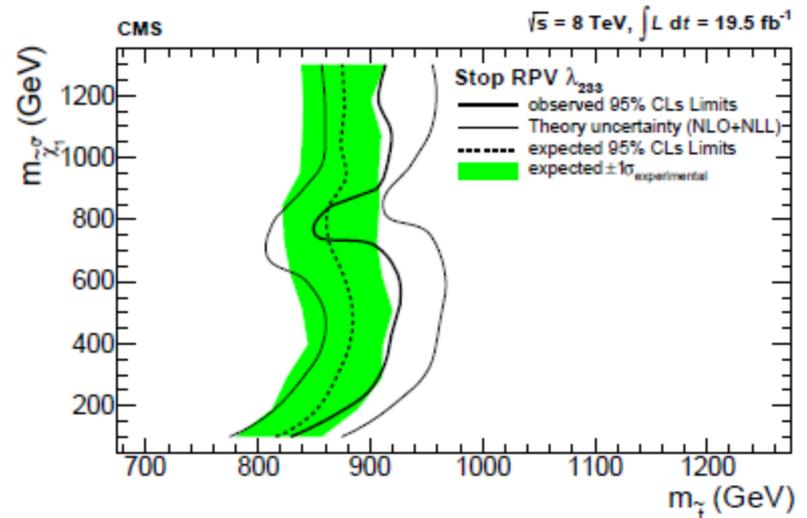
Backgrounds:

- ✓ irreducible (≥ 3 real leptons)
WZ, ZZ, ttbar+W, ttbar+Z...
- ✓ reducible (<3 real leptons)
Z+jet, ttbar, Wt, WW...

ATLAS has a similar RPV multi-lepton paper:
Phys. Rev. D. 90, 052001 (2014)



Stop <1020GeV is exclude @ $m_{\tilde{\chi}_1^0}=200\text{GeV}$



Stop <820GeV is exclude @ $m_{\tilde{\chi}_1^0}=200\text{GeV}$

RPV search: multijet final states

gluino pair to multijets @ATLAS

[arXiv:1502.05686](https://arxiv.org/abs/1502.05686)

- ◆ 6 or more high pT jets
- ◆ can have b-jet
- ◆ Large 3-jet invariant mass

Backgrounds:

- ✓ QCD multijet process dominant
- ✓ ttbar, W/Z+jet, Wt...

2background analysis strategy:

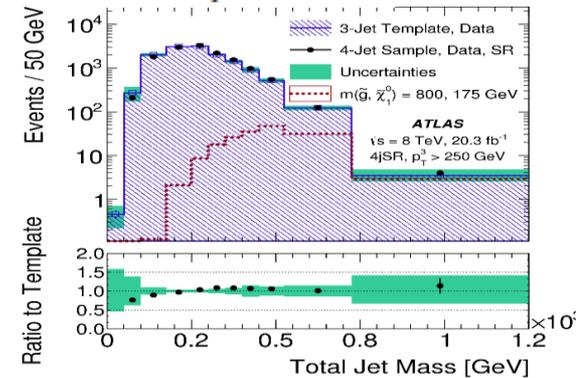
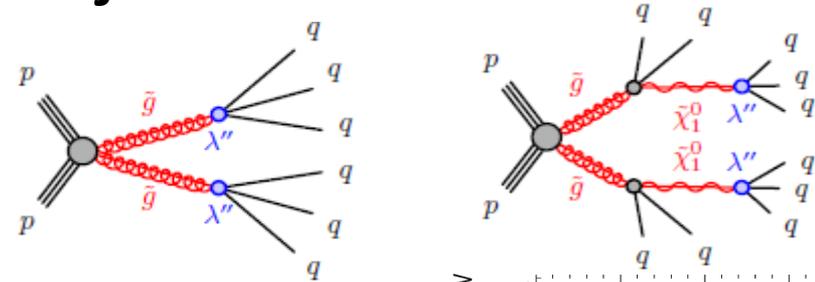
Jet-counting: for ≥ 6 jets scenario

Control region extrapolation method

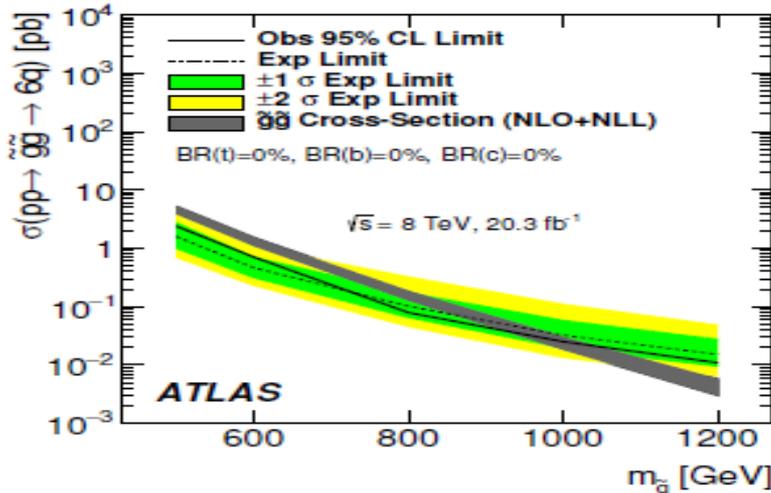
Total-jet-mass: for 10 jets scenario

$$M_J^\Sigma = \sum_{\substack{p_{Tj} > 100 \text{ GeV} \\ |\eta_j| \leq 2.5}}^4 m_j^{\text{jet}}$$

template fit method

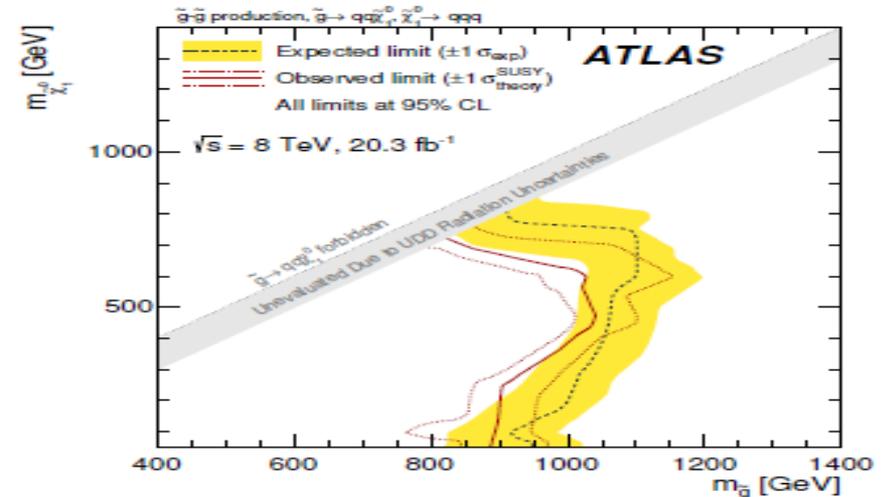


used to separate S from B



6 light (with b) quark model:

Glauino $m < 917$ (929) GeV is excluded

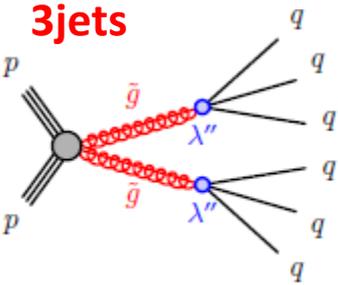


10 quark model: (with b)

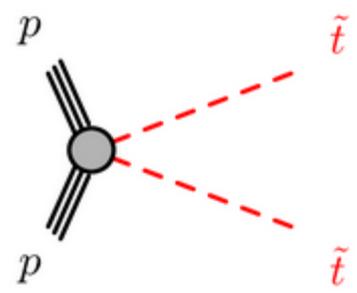
Glauino $m \sim 900$ GeV is excluded with $m_{\text{neutrino}} = 100$ GeV

RPV search: multijet final states

3jets resonance@CMS
 Phys. Lett. B 730 (2014) 193
Stop to multijets@CMS
 Phys. Rev. Lett. 111 (2013) 221801



- ◆ 6 or more high pT jets
- ◆ can have b-jet
- ◆ Large 3-jet invariant mass



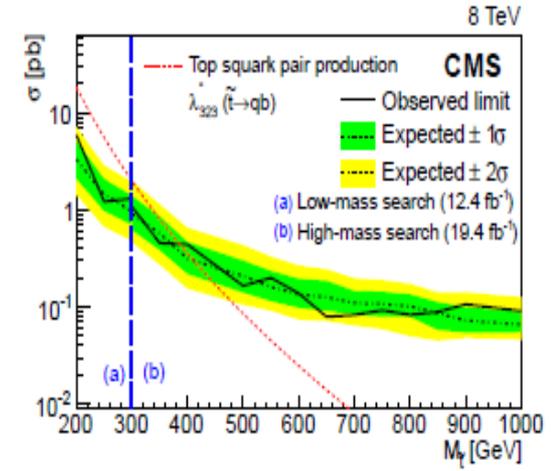
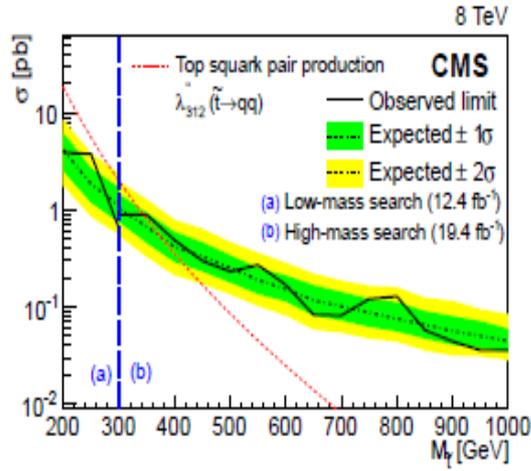
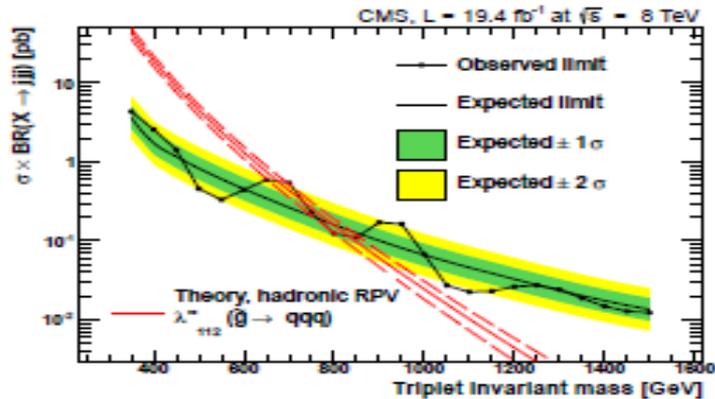
- $\tilde{t} \rightarrow b+q$
- $\tilde{t} \rightarrow q+q$

stop

- ◆ ≥ 4 high pT jets
- ◆ can have b-jet
- ◆ jet pairs : well separated

Backgrounds:
 ✓ QCD multijet process dominant
 ✓ $t\bar{t}$, W/Z+jet, Wt...

Backgrounds:
 ✓ QCD multijet process dominant
 ✓ $t\bar{t}$, W/Z+jet, Wt...



Low mass: 200-300GeV High mass: >300GeV

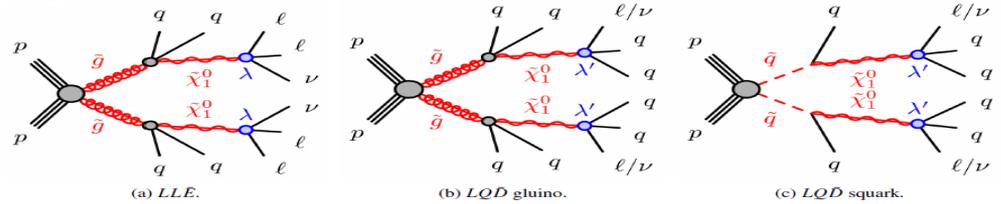
6 light (with b) quark model:
 Gluino $m < 650$ (835) GeV is excluded

From $\text{Stop} \rightarrow qq$, stop are excluded :
 M [200GeV, 350GeV]

From $\text{Stop} \rightarrow qb$, stop are excluded :
 M [200GeV, 385GeV]

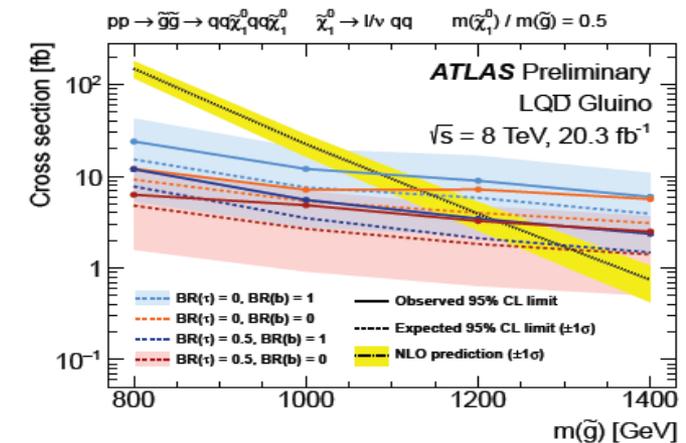
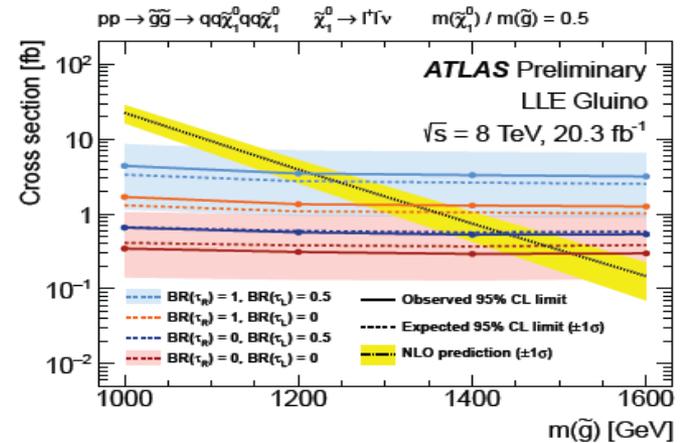
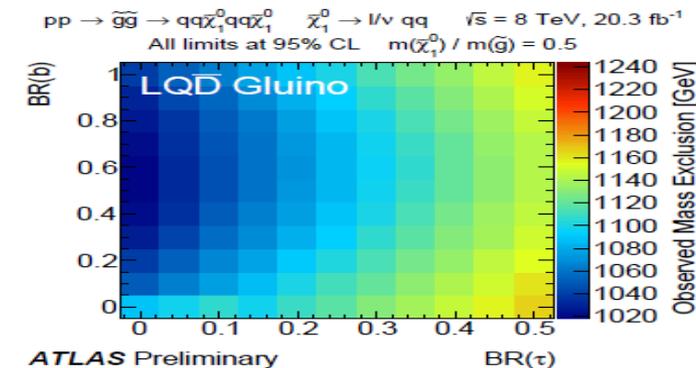
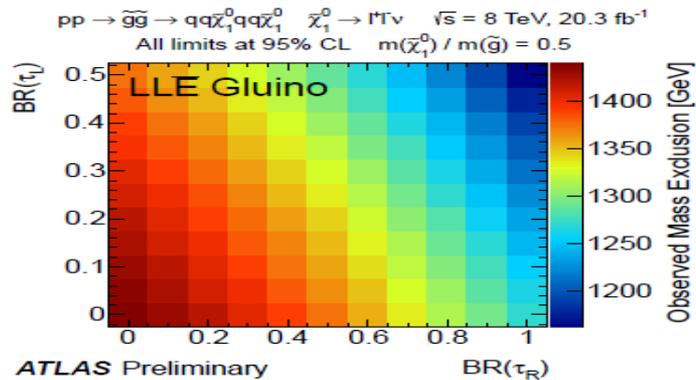
RPV search: summary search \rightarrow reinterpretation

4leptons, SS/3L, 0/1lepton+jets@ATLAS
ATLAS-CONF-2015-018



A comprehensive summary of re-interpreting a number of ATLAS searches in LLE and LQD SUSY models (varying kinematics and branching ratios to b-jets and taus)

LL \bar{E} and LQ \bar{D} simplified models



LLE RPV: gluino mass <1040 GeV is excluded

LQD RPV: gluino mass is excluded between 910 and 1220 GeV according to different coupling plan

LQD RPV: squark mass $i < 910$ GeV is excluded at large neutrino mass ($M_{\text{neu}}/M_{\text{sq}} = 0.9$)

LLP search: $\tilde{\chi}^\pm$ search

Particle with large ionisation energy loss

ATLAS-CONF-2015-013

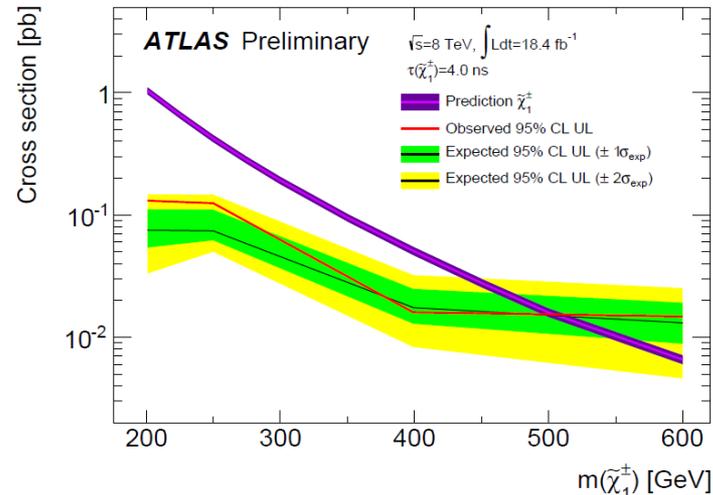
Disappearing track@CMS

(JHEP 01 (2015) 096)

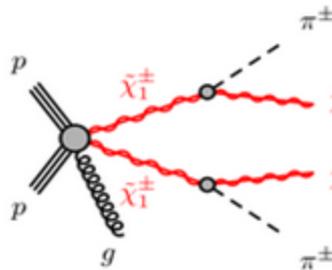
Particle with large dE/dx

Chargino $\rightarrow \pi + \text{neutrino}$

- ◆ move non-relativistically
- ◆ large dE/dx in pixel detector
- ◆ large MET



Chargino with $\tau = 4\text{ns}$ is excluded with $M < 496\text{GeV}$

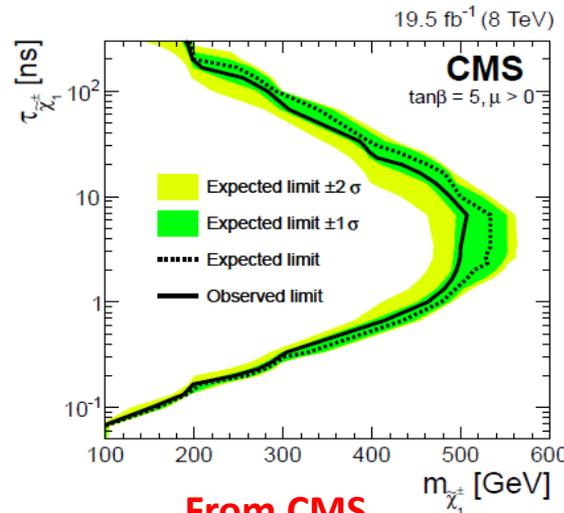


Disappearing track

- ◆ an isolated track, few hits in the outer ID, few associated Calo energy
- ◆ large MET
- ◆ an associated jet, well separated with MET
- ◆ soft pi, can not be reconstructed

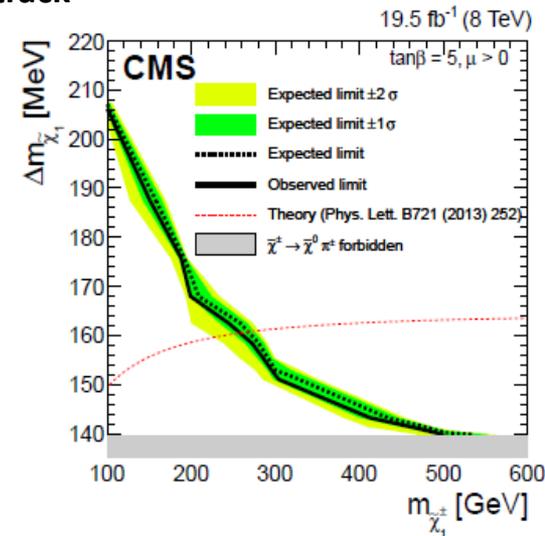
Backgrounds:

- ✓ hadrons interacting with material in ID
- ✓ e/μ fails id criteria
- ✓ p_T mis-measured track



From CMS

For $m_{\tilde{\chi}_1^\pm} = 505\text{GeV}$, life time is up to $\sim 7\text{ns}$
 Chargino with mass $< 260\text{GeV}$ is excluded



LLP search: $\tilde{\chi}_1^0$ search

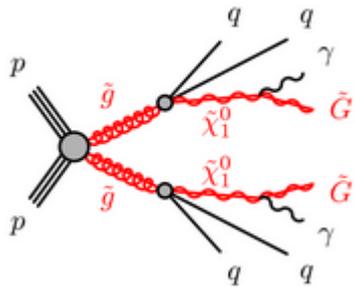
Non-pointing γ @ATLAS

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

Neutral particle to dijet@CMS

(Phys. Rev. D 91, 012007 (2015))

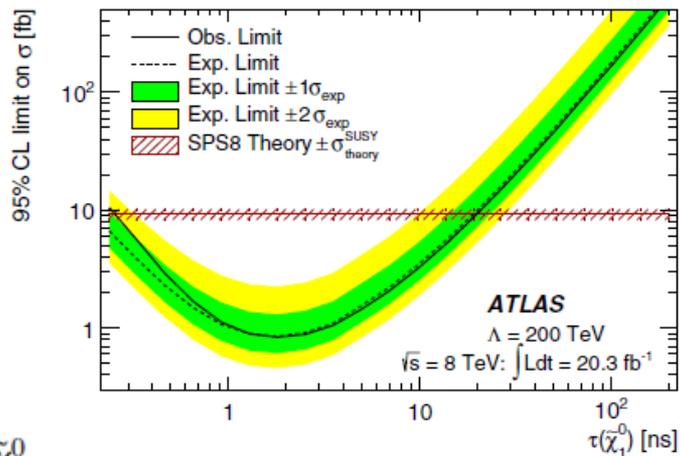
ATLAS



- ◆ 2 isolated high pT γ non-pointing/delayed
- ◆ large MET

Backgrounds:

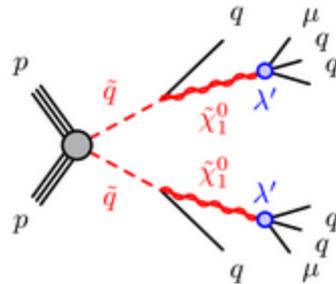
- ✓ dijet
- ✓ γ +jet
- ✓ di-photon



$\tilde{\chi}_1^0$

life time [0.3, 20ns] are excluded

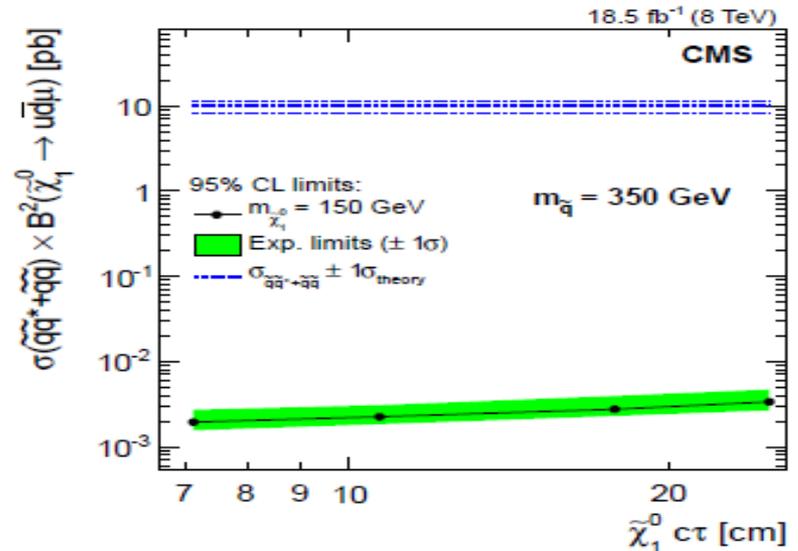
CMS



- ◆ 2 displaced di-jet vertex
- ◆ 2 displaced muons
- ◆ large H_T

Backgrounds:

- ✓ SM QCD process dominated



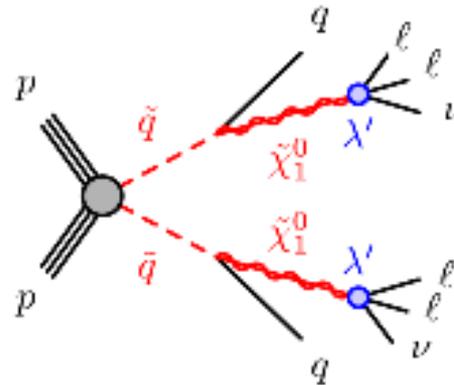
Decay length 7-30cm

X-section 2-3 fb

LLP search: $\tilde{\chi}_1^0$ search

Displaced dilepton search@CMS

Phys. Rev. D 91 (2015) 052012



- ◆ 2 displaced dilepton vertices
- ◆ MET

Backgrounds:

Drell-Yan $\rightarrow l^+l^-$ (dominate)

$t\bar{t}$ or Wt

W+jet/WW

QCD multijet

Systematics are mainly from:

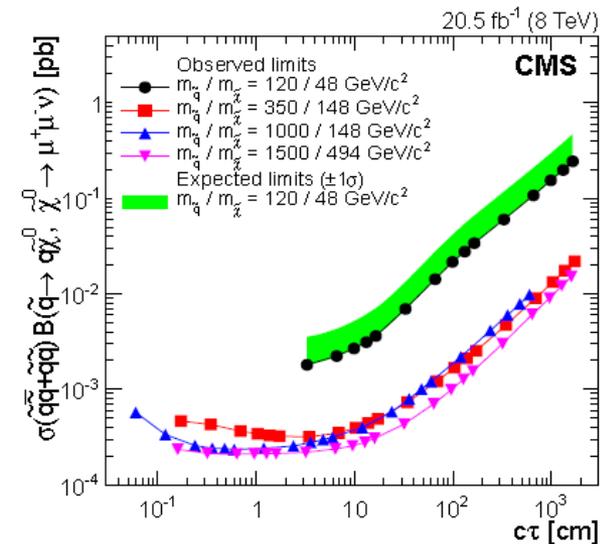
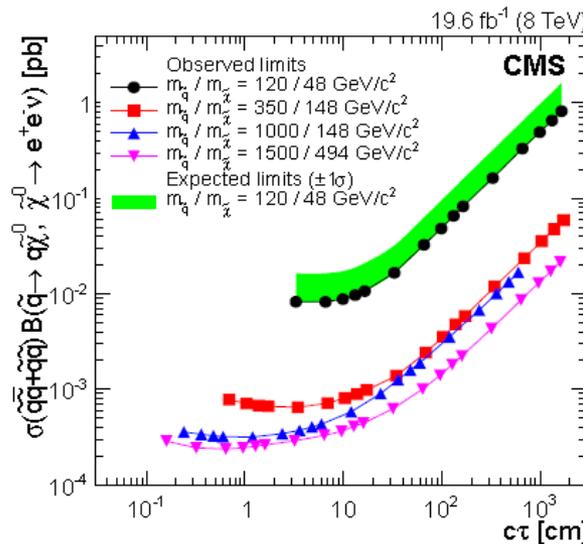
Theory uncertainty for SM process

Track finding efficiency

Trigger efficiency

Pileup modeling

Luminosity



For $M_{\text{squark}} > 350\text{GeV}$:

Upper limits on neutralino typically 0.2-5fb

Decay length at 0.1-100cm

LLP search: $\tilde{\chi}_1^0$ search

Displaced vertex@ATLAS

[arXiv:1504.05162](https://arxiv.org/abs/1504.05162)

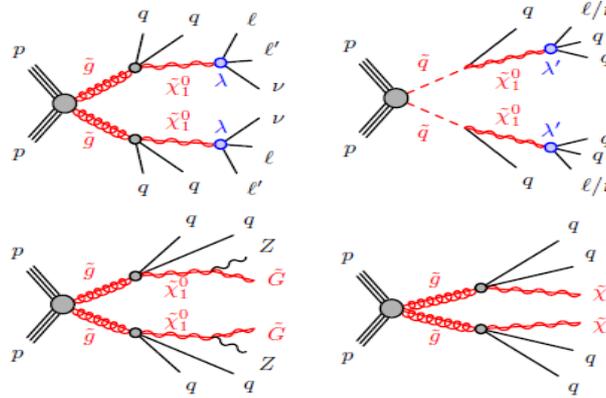
Backgrounds:

➤ Multitrack-vertex

accidental vertex-track crossings
merged vertices

➤ dilepton-vertex

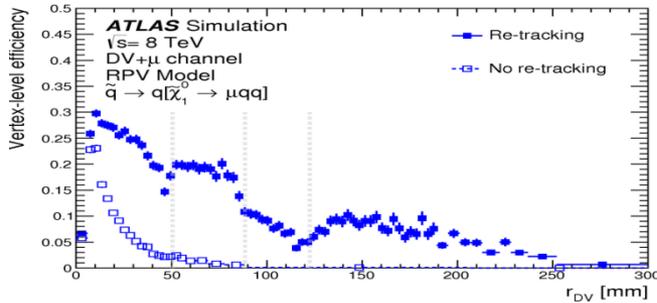
accidental lepton crossing, $Z \rightarrow \ell\ell$



- ◆ ≥ 1 displaced vertices
- ◆ a number of leptons
- ◆ a number of jets
- ◆ MET

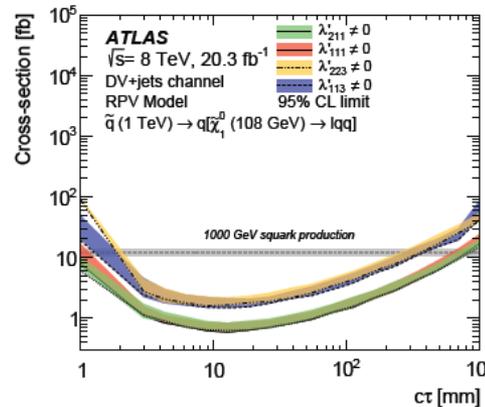
❑ vertices in regions of high density material are vetoed: avoid vertices from material interactions

❑ special high d0 tracking is run to improve the efficiency for DV at large radius



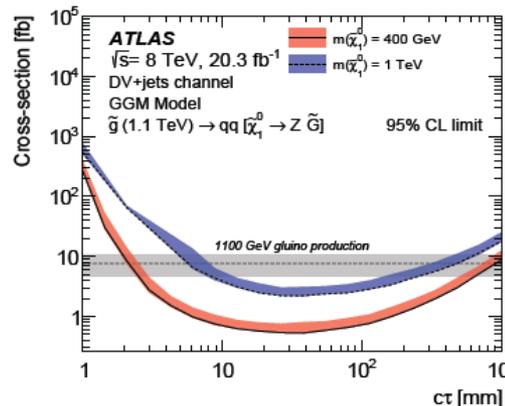
expected background is very small

Channel	No. of background vertices ($\times 10^{-3}$)
DV+jet	$410 \pm 7 \pm 60$
DV+ E_T^{miss}	$10.9 \pm 0.2 \pm 1.5$
DV+muon	$1.5 \pm 0.1 \pm 0.2$
DV+electron	$207 \pm 9 \pm 29$



●RPV scenario is excluded for gluino=600GeV, neutrino=400GeV, and $0.7 < c\tau < 3 \times 10^5$ mm with dilepton-DV

●RPV scenario with 1TeV squark for neutrino=108GeV, and $2.5 < c\tau < 200$ mm is excluded with multitrack-DV search

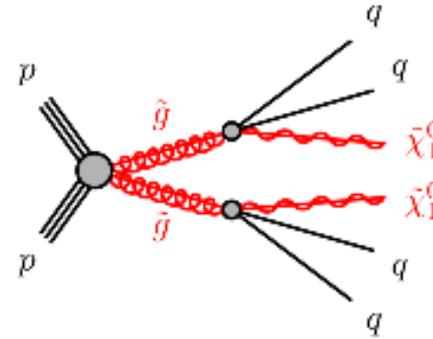


●GGM scenario with 1.1TeV gluino for neutrino=400GeV, and $3 < c\tau < 500$ mm is excluded with multitrack-DV search

●Split-SUSY scenario with 1.4TeV gluino and $15 < c\tau < 300$ mm is excluded with DV+jet/MET search

LLP search: \tilde{g} search

Glino with large ionisation energy loss
 ATLAS-CONF-2015-013
Stopped gluino search @CMS
 Eur. Phys. J. C 75 (2015) 151



Stopped gluino

- ◆ high energy jet
- ◆ high MET
- ◆ energy deposit in Calo
- ◆ random time
- ◆ neutrino is LSP

Glino with large dE/dx

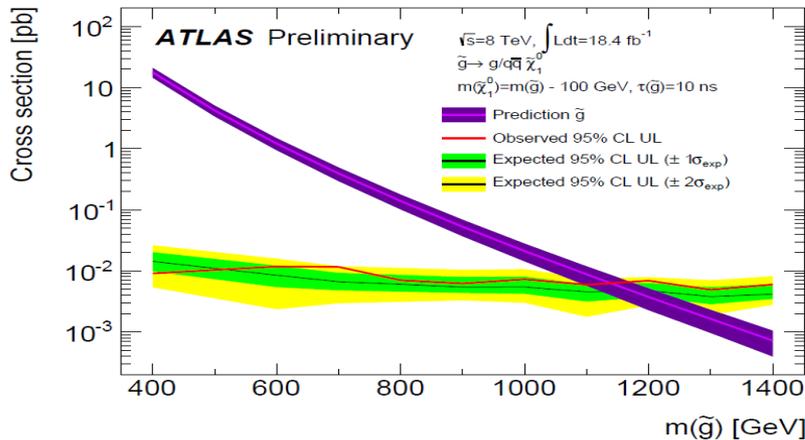
Glino \rightarrow neutrino + qq/g

- ◆ move non-relativistically
- ◆ large dE/dx in pixel detector
- ◆ large MET

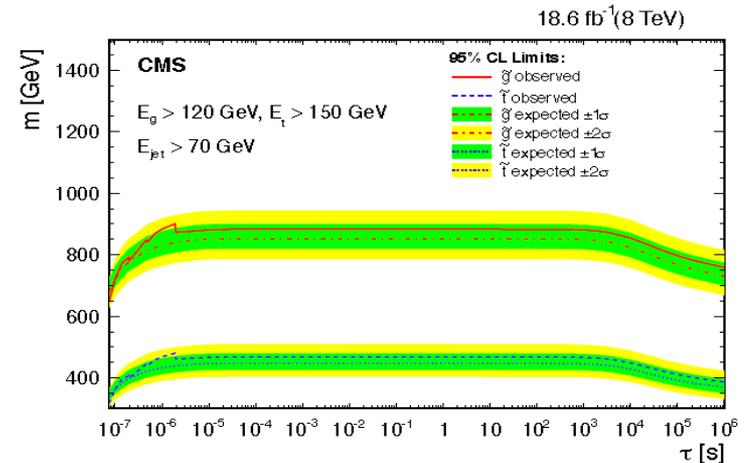
Backgrounds:
 High pT elec from W
 High pT muons

\tilde{g} stopped in the detector, and then decay after a while

Backgrounds:
 Beam halo backgrounds
 Cosmic ray muon background



Glino with $\tau = 10\text{ns}$ is excluded with $M < 1183\text{GeV}$



$E_g > 120\text{GeV}$, and $B(\tilde{g} \rightarrow g\tilde{\chi}^0) = 100\%$,
 Gluinos with lifetimes $1\mu\text{s}-1000\text{s}$,
 and $M < 880\text{GeV}$ are excluded.

LLP search: \tilde{t} search

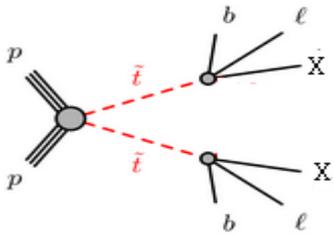
Stopped stop search @CMS

Eur. Phys. J. C 75 (2015) 151

Displaced $e+\mu$ @CMS

Phys. Rev. Lett. 114, 061801 (2015)

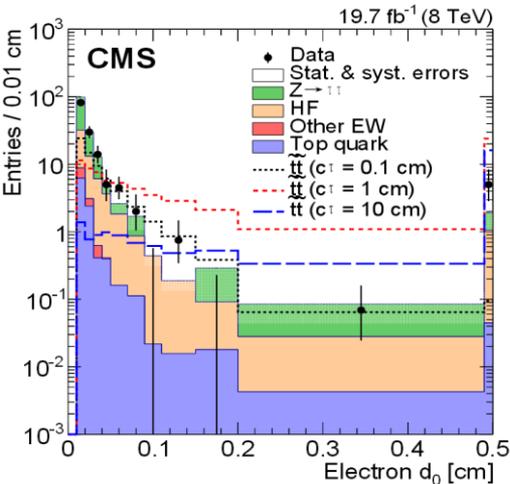
Displaced $e+\mu$



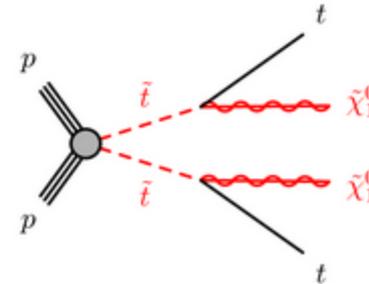
- ◆ 2 leptons of OS, different flavor
- ◆ away from PV
- ◆ back-to-back in phi
- ◆ stop is LSP

Backgrounds:

Ttbar, Wt, WW, W+jet, Z+jet
Heavy flavor(HF) QCD



$c\tau = 2$ cm, top squark masses up to 790 GeV are excluded



Stopped stop

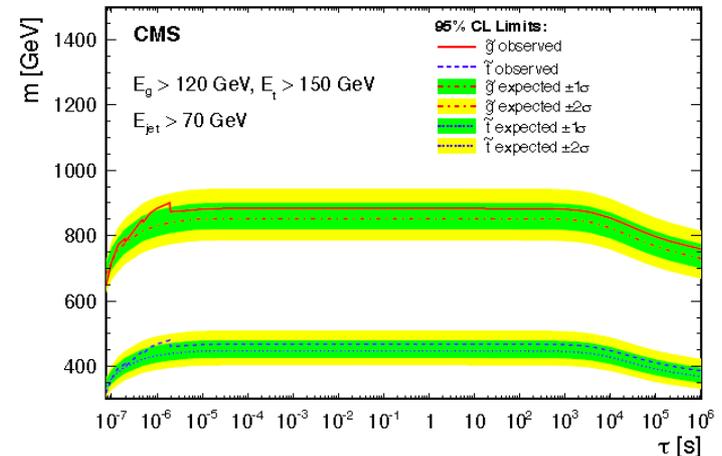
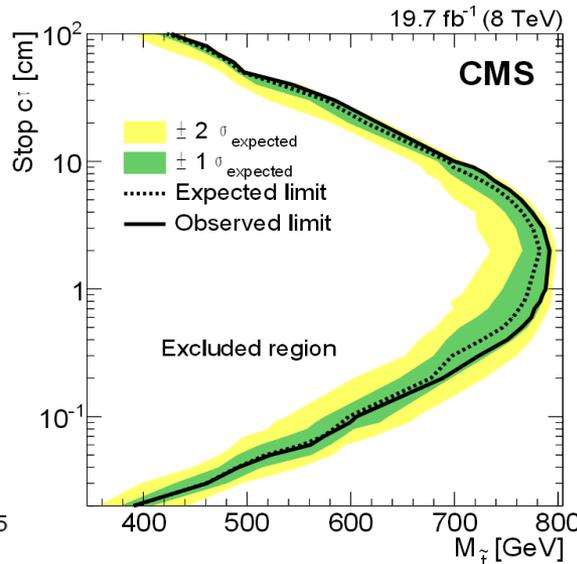
- ◆ energy deposit in Calo
- ◆ random time
- ◆ high MET
- ◆ neutrino is LSP

\tilde{t} stopped in the detector, and then decay after a while

Backgrounds:

Beam halo backgrounds

Cosmic ray muon background



$E_t > 150$ GeV, and $B(\tilde{t} \rightarrow t\tilde{\chi}^0) = 100\%$
stops with lifetimes $1\mu\text{s}-1000\text{s}$,
and $M < 470$ GeV are excluded.

LLP search: Scalar Boson search

Φ Boson search@ATLAS

[Physics Letters B 743 \(2015\) 15-34](#)

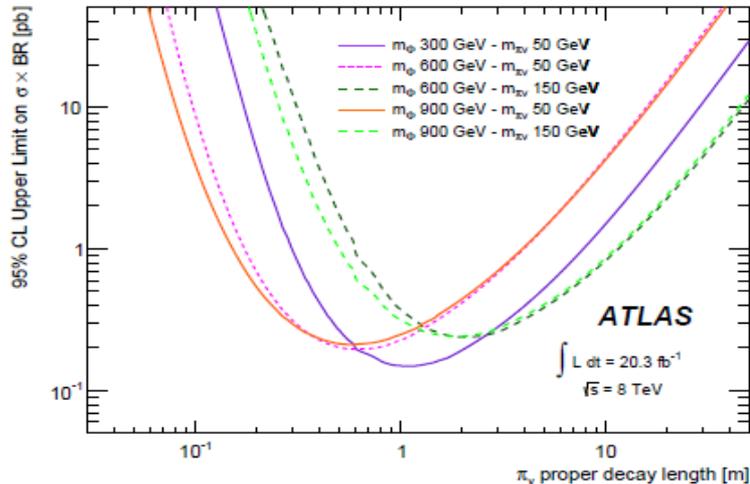
$\Phi \rightarrow \pi_\nu \pi_\nu$ ($\pi_\nu \rightarrow qq\bar{q}$)

Displaced jets final states with:

- ◆ in HadCalo
- ◆ narrow R and no charged track match
- ◆ no (little) energy deposit in EMCalo

Backgrounds:

- ✓ SM QCD process dominated
- ✓ cosmic ray



For $\Phi=900\text{GeV}$, $\pi_\nu=150\text{GeV}$ and decay length 1m, $\sigma(\Phi)\times\text{Br}$ upper limits $\sim 0.3\text{pb}$

Heavy $H \rightarrow XX$ @CMS

(Phys. Rev. D 91, 012007 (2015))

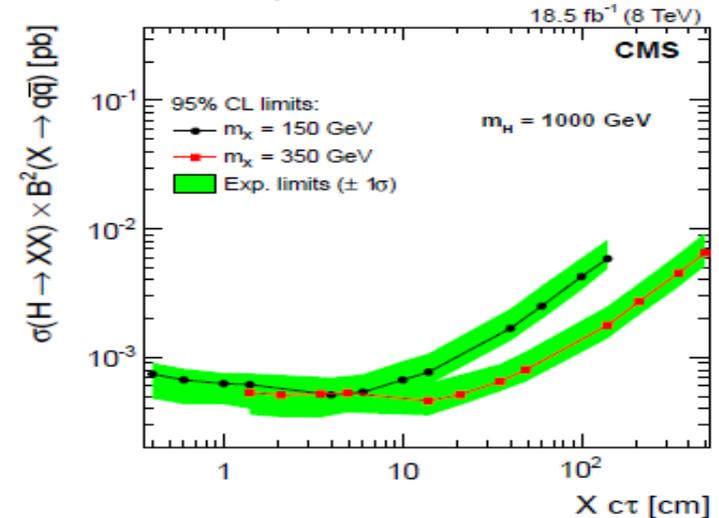
$H \rightarrow XX$ ($X \rightarrow qq\bar{q}$)

Two displaced dijet vertices

- ◆ in CMS tracker
- ◆ at least 2 tracks

Backgrounds:

- ✓ SM QCD process dominated

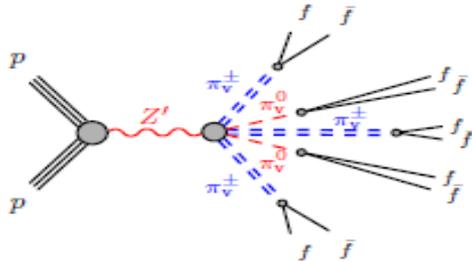


For X decay length 0.4-200cm, $\sigma(X)\times\text{Br}$ upper limits $\sim 0.5\text{-}70\text{fb}$

LLP search: Z' (& Stealth SUSY \tilde{S}) search

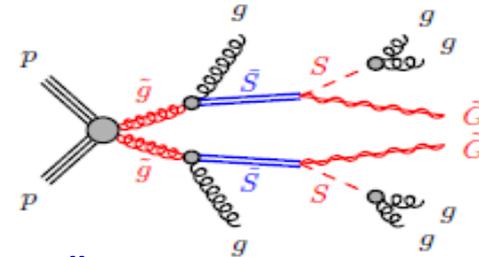
Z' search@ATLAS

[arXiv:1504.03634](https://arxiv.org/abs/1504.03634)



Stealth SUSY search@ATLAS

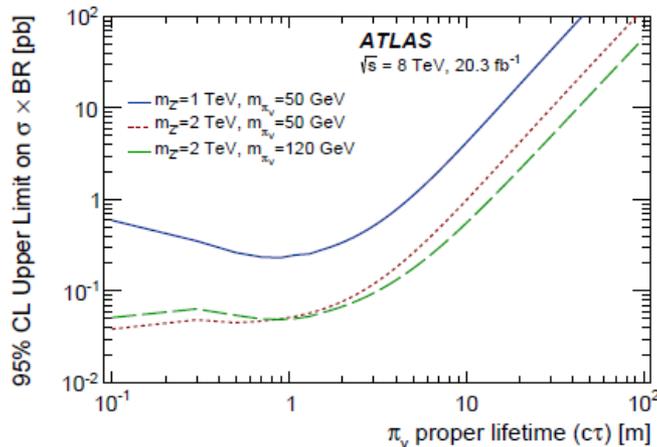
[arXiv:1504.03634](https://arxiv.org/abs/1504.03634)



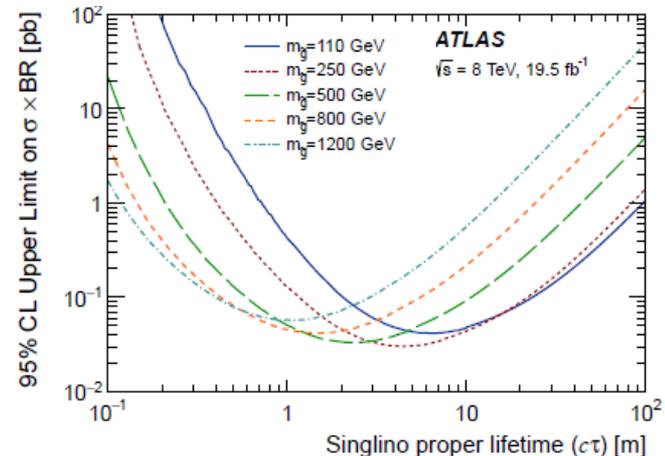
expected background is very small

Trigger	Topology	Predicted
Jet + E_T^{miss}	2IDVx	$(1.8 \pm 0.4) \times 10^{-4}$
Jet + E_T^{miss}	IDVx+MSVx	$(5.5 \pm 1.4) \times 10^{-4}$
Jet + E_T^{miss}	2MSVx	$(0.0^{+1.4}_{-0.0}) \times 10^{-5}$
Muon RoI Cluster	IDVx+MSVx	2.0 ± 0.4
Muon RoI Cluster	2MSVx	$0.4^{+0.3}_{-0.2}$

- ◆ Muon RoI trigger
- ◆ two displaced vertices (≥ 1 MS DV)
- ◆ back to back
- ◆ low MET



For $Z'=1\text{TeV}$, $\pi_v=50\text{GeV}$ and decay length 1m, $\sigma(Z') \times \text{Br}$ upper limit $\sim 0.2\text{pb}$



For gluino=500GeV, singlino decay length 1m, $\sigma(\text{gluino}) \times \text{Br}$ upper limit $\sim 0.1\text{pb}$

LLP search: MCP (multi-charged particle) search

MCPs search@ATLAS

[arXiv:1504.04188](https://arxiv.org/abs/1504.04188)

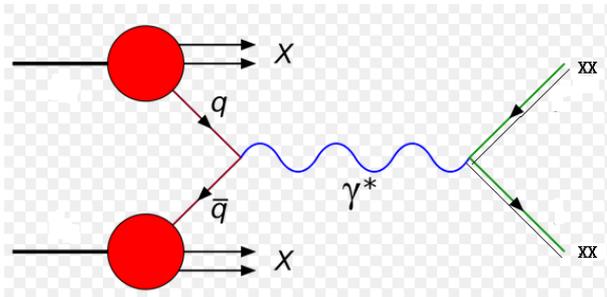
Several BSM predict MCP:

- almost-commutative model
- walking technicolor model
- left-right symmetric model

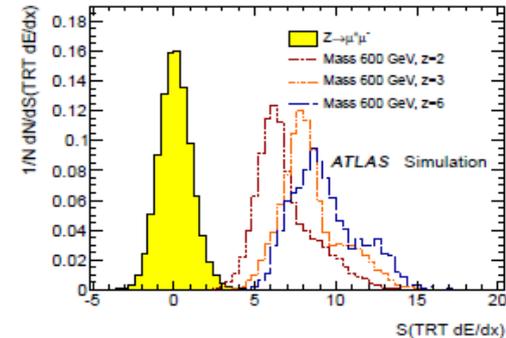
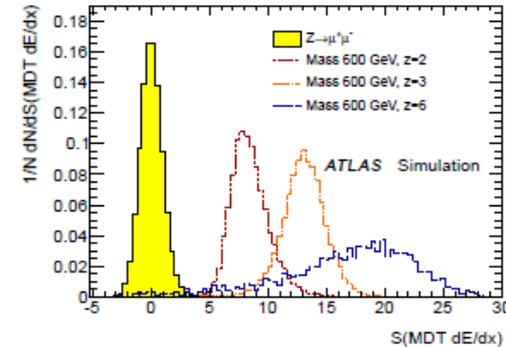


Doubly charged Higgs

Suppose MCPs are pair produced with Drell-Yan process

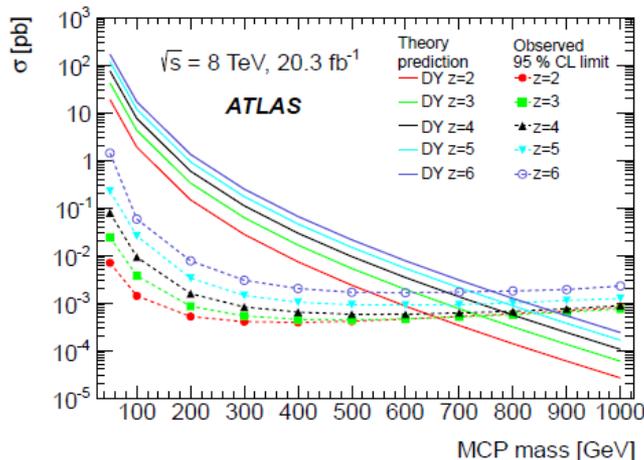


- ◆ Traverse ATLAS detector
- ◆ Leaving track in ID and MS
- ◆ Highly ionising: abnormally large dE/dx



Backgrounds are estimated with 2d sidebands method, and find to be negligible

	N_{exp}^D	N_{obs}^D
$z = 2$	0.013 ± 0.002	0
$z \geq 3$	0.026 ± 0.003	0



Mass exclusion limits for a Drell-Yan production model

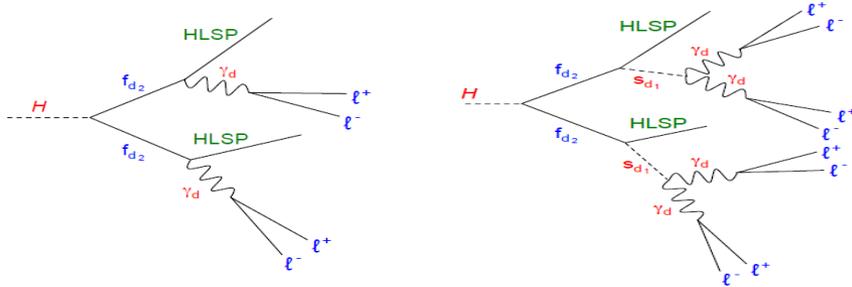
Charge $ q $	2e	3e	4e	5e	6e
Mass exclusion	660GeV	740GeV	780GeV	785GeV	760GeV

LLP search: Hidden sector search (dark γ_d)

Dark γ --lepton jet (Lj) search@ATLAS

JHEP11(2014)088

Falkowski–Ruderman–Volansky–Zupan (FRVZ) models
 γ_d is the long-lived particle



- Displaced isolated Ljs
- No matched inner tracker
- Large $\Delta\phi$ between Ljs

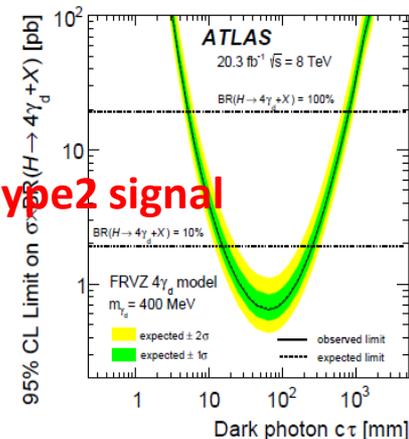
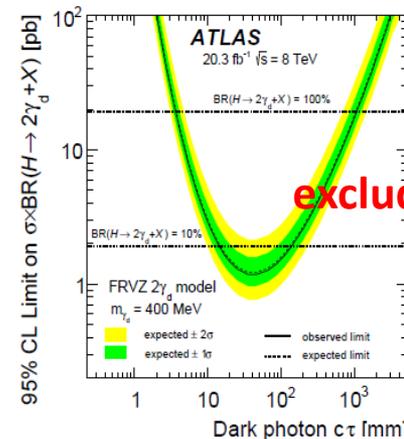
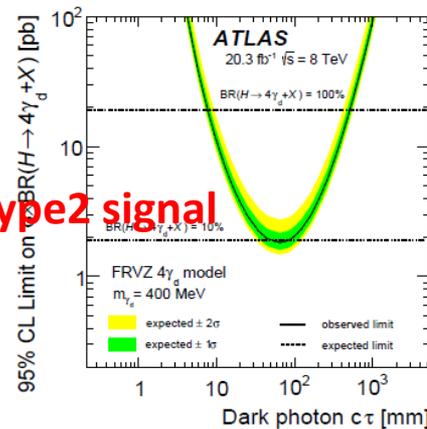
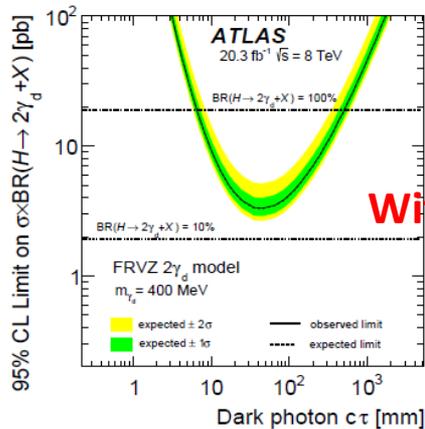
Backgrounds

- ✓ Multijet
- ✓ Cosmic ray

3 types of signals

- ◆ Type0: At least 2 muons, no jet
- ◆ Type1: At least 2 muons, only 1 jet in cone
- ◆ Type2: Jets, with no muon in cone

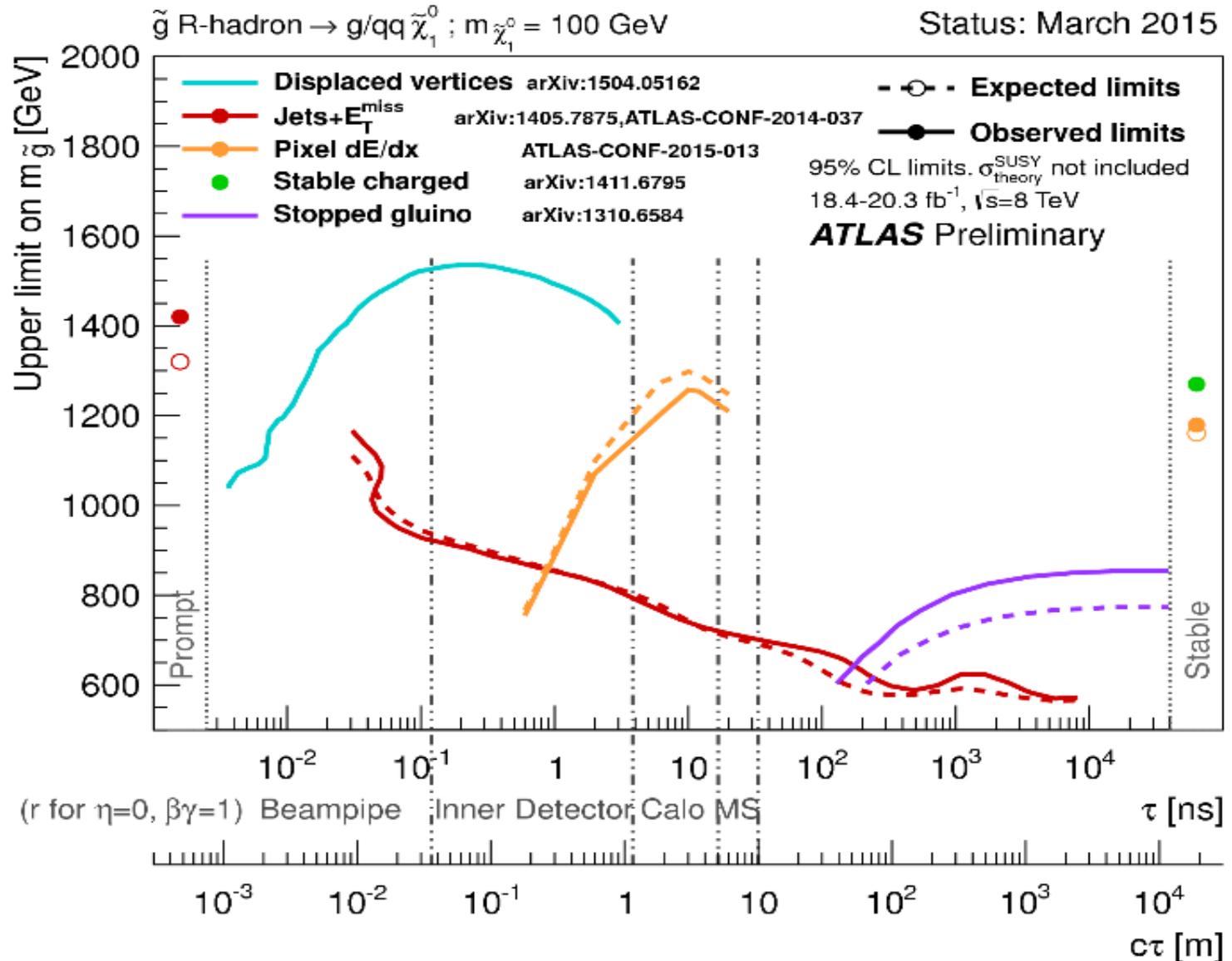
	All LJ pair types	TYPE2-TYPE2 LJs excluded
Data	119	29
Cosmic rays	40 ± 11 ± 9	29 ± 9 ± 29
Multi-jets (ABCD)	70 ± 58 ± 11	12 ± 9 ± 2
Total background	110 ± 59 ± 14	41 ± 12 ± 29



FRVZ model	Excluded $c\tau$ [mm] BR(10%)
$H \rightarrow 2\gamma_d + X$	no limit
$H \rightarrow 4\gamma_d + X$	$52 \leq c\tau \leq 85$

FRVZ model	Excluded $c\tau$ [mm] BR(10%)
$H \rightarrow 2\gamma_d + X$	$14 \leq c\tau \leq 140$
$H \rightarrow 4\gamma_d + X$	$15 \leq c\tau \leq 260$

LLP search: summary plots



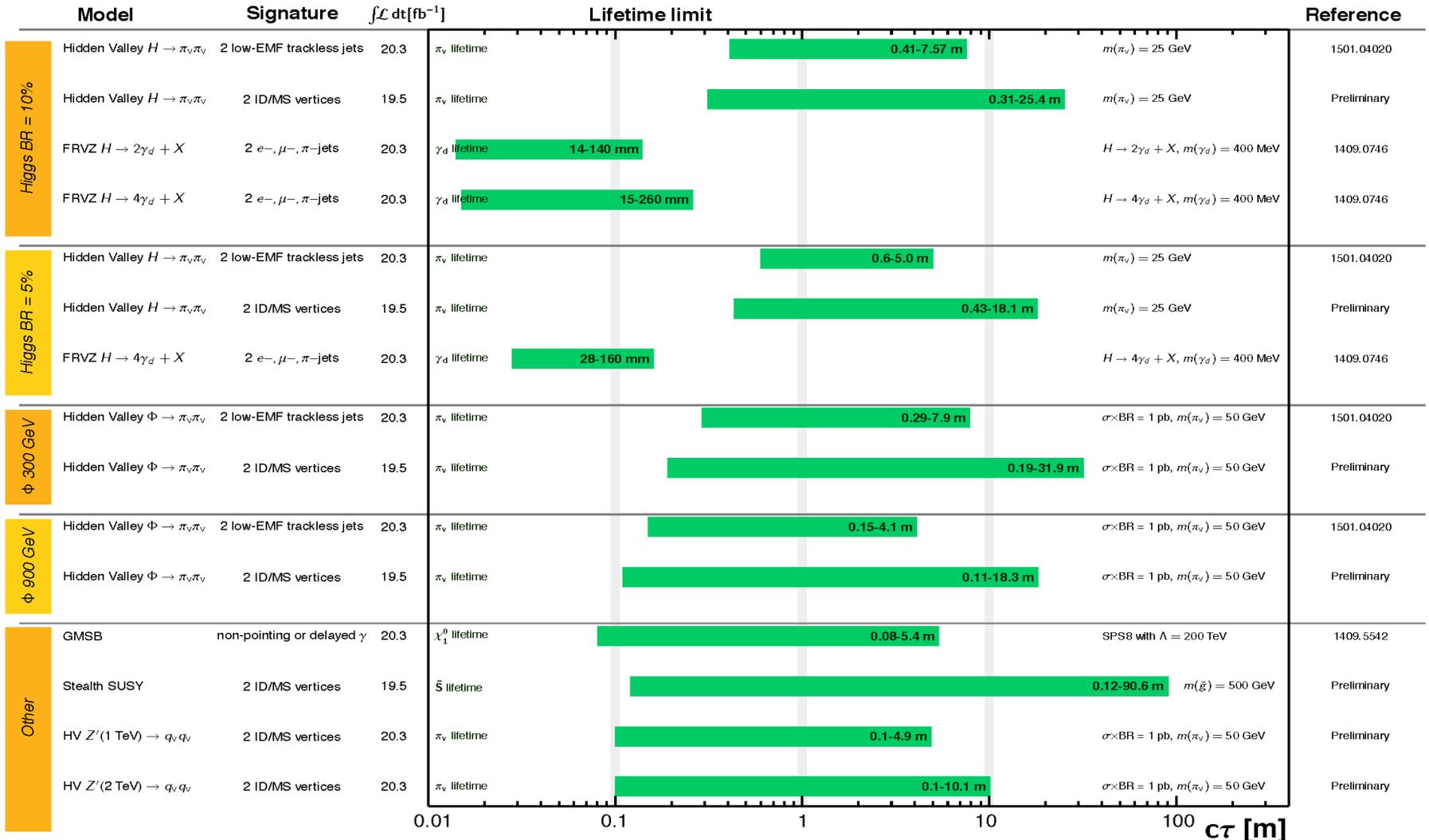
LLP search: summary plots

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

Status: March 2015

ATLAS Preliminary

$\int \mathcal{L} dt = (19.5 - 20.3) \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ TeV}$



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

*Only a selection of the available lifetime limits on new states is shown.

Summary

- **Both ATLAS and CMS have made great effort to search for RPV SUSY and LLP .**
- **Tens of models are used to perform studies, and all the observations seem to be in good agreement with background expectation.**
- **Best limits up to date are put on these new models .**