# *Beyond the Standard Model Results from the LHC*

## *47th Annual Fermilab Users Meeting*

David W. Miller

Enrico Fermi Institute

THE UNIVERSITY OF CHICAGO

June 11th, 2014

# Outline

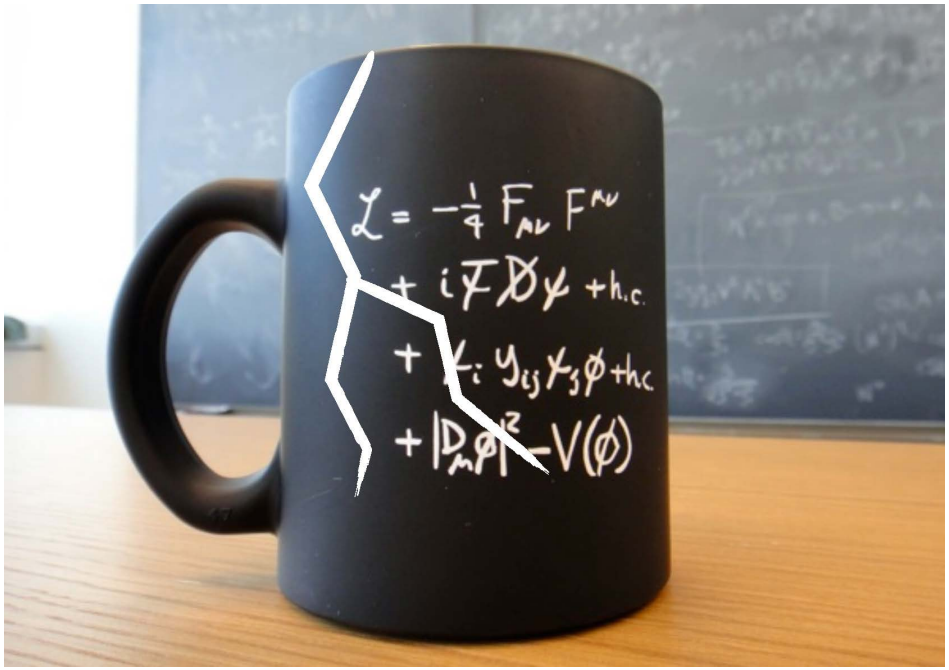

1. *The Search for Cracks in the Standard Model*
2. *Overview of the BSM Searches in ATLAS and CMS*
3. *Key analyses in the search for BSM Physics*
4. *Looking ahead to Run II*

# *Trying to crack the Standard Model*

*New York Times, Thompson, 2006*

# *Trying to crack the Standard Model*

*New York Times, Thompson, 2006*

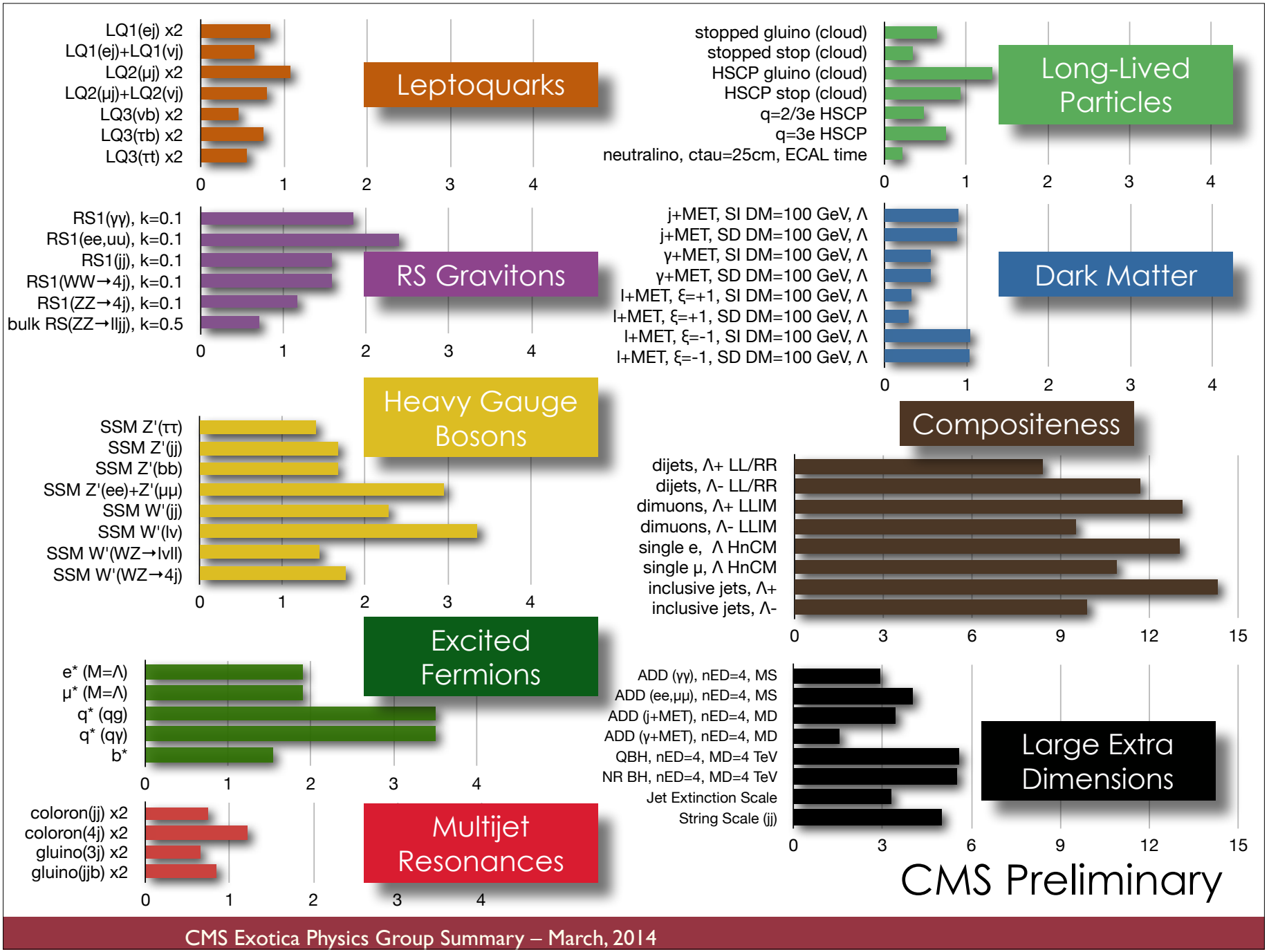


*Fermilab Today, March 2014*

Despite its amazing complexity, ATLAS and CMS are hard at work searching for cracks in the Standard Model using novel methods and precision searches.

# Outline


1. *The Search for Cracks in the Standard Model*
2. *Overview of the BSM Searches in ATLAS and CMS*
3. *Key analyses in the search for BSM Physics*
4. *Looking ahead to Run II*


Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(vj)
LQ2(μj) x2
LQ2(μj)+LQ2(vj)
LQ3(vb) x2
LQ3(τb) x2
LQ3(ττ) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS1(ZZ→4j), k=0.1
bulk RS(ZZ→lljj), k=0.5
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lv)
SSM W'(WZ→lvll)
SSM W'(WZ→4j)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
CMS Preliminary
CMS Exotica Physics Group Summary – March, 2014

# ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

**ATLAS** Preliminary

$\int \mathcal{L}\, dt$ = (4.6 - 22.9) fb$^{-1}$ $\sqrt{s}$ = 7, 8 TeV

| | Model | $e, \mu, \tau, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\, dt$[fb$^{-1}$] | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q}, \tilde{g}$ 1.7 TeV | m($\tilde{q}$)=m($\tilde{g}$) | ATLAS-CONF-2013-047 |
| | MSUGRA/CMSSM | 1 $e, \mu$ | 3-6 jets | Yes | 20.3 | $\tilde{g}$ 1.2 TeV | any m($\tilde{q}$) | ATLAS-CONF-2013-062 |
| | MSUGRA/CMSSM | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.1 TeV | any m($\tilde{q}$) | 1308.1841 |
| | $\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q}$ 740 GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-047 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{g}$ 1.3 TeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-047 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$ | 1 $e, \mu$ | 3-6 jets | Yes | 20.3 | $\tilde{g}$ 1.18 TeV | m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$)) | ATLAS-CONF-2013-062 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ | 2 $e, \mu$ | 0-3 jets | - | 20.3 | $\tilde{g}$ 1.12 TeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-089 |
| | GMSB ($\tilde{\ell}$ NLSP) | 2 $e, \mu$ | 2-4 jets | Yes | 4.7 | $\tilde{g}$ 1.24 TeV | tan$\beta$<15 | 1208.4688 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 $\tau$ | 0-2 jets | Yes | 20.7 | $\tilde{g}$ 1.4 TeV | tan$\beta$ >18 | ATLAS-CONF-2013-026 |
| | GGM (bino NLSP) | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{g}$ 1.28 TeV | m($\tilde{\chi}_1^0$)>50 GeV | ATLAS-CONF-2014-001 |
| | GGM (wino NLSP) | 1 $e, \mu + \gamma$ | - | Yes | 4.8 | $\tilde{g}$ 619 GeV | m($\tilde{\chi}_1^0$)>50 GeV | ATLAS-CONF-2012-144 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 1 $b$ | Yes | 4.8 | $\tilde{g}$ 900 GeV | m($\tilde{\chi}_1^0$)>220 GeV | 1211.1167 |
| | GGM (higgsino NLSP) | 2 $e, \mu$ ($Z$) | 0-3 jets | Yes | 5.8 | $\tilde{g}$ 690 GeV | m($\tilde{H}$)>200 GeV | ATLAS-CONF-2012-152 |
| | Gravitino LSP | 0 | mono-jet | Yes | 10.5 | $F^{1/2}$ scale 645 GeV | m($\tilde{g}$)>$10^{-4}$ eV | ATLAS-CONF-2012-147 |
| 3$^{rd}$ gen. $\tilde{g}$ med. | $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.2 TeV | m($\tilde{\chi}_1^0$)<600 GeV | ATLAS-CONF-2013-061 |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.1 TeV | m($\tilde{\chi}_1^0$) <350 GeV | 1308.1841 |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e, \mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.34 TeV | m($\tilde{\chi}_1^0$)<400 GeV | ATLAS-CONF-2013-061 |
| | $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 $e, \mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.3 TeV | m($\tilde{\chi}_1^0$)<300 GeV | ATLAS-CONF-2013-061 |
| 3$^{rd}$ gen. squarks direct production | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 $b$ | Yes | 20.1 | $\tilde{b}_1$ 100-620 GeV | m($\tilde{\chi}_1^0$)<90 GeV | 1308.2631 |
| | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$ | 2 $e, \mu$ (SS) | 0-3 $b$ | Yes | 20.7 | $\tilde{b}_1$ 275-430 GeV | m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$) | ATLAS-CONF-2013-007 |
| | $\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 1-2 $e, \mu$ | 1-2 $b$ | Yes | 4.7 | $\tilde{t}_1$ 110-167 GeV | m($\tilde{\chi}_1^0$)=55 GeV | 1208.4305, 1209.2102 |
| | $\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ | 2 $e, \mu$ | 0-2 jets | Yes | 20.3 | $\tilde{t}_1$ 130-210 GeV | m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m($W$)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$) | 1403.4853 |
| | $\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 2 $e, \mu$ | 2 jets | Yes | 20.3 | $\tilde{t}_1$ 215-530 GeV | m($\tilde{\chi}_1^0$)=1 GeV | 1403.4853 |
| | $\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 0 | 2 $b$ | Yes | 20.1 | $\tilde{t}_1$ 150-580 GeV | m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV | 1308.2631 |
| | $\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 1 $e, \mu$ | 1 $b$ | Yes | 20.7 | $\tilde{t}_1$ 200-610 GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-037 |
| | $\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 0 | 2 $b$ | Yes | 20.5 | $\tilde{t}_1$ 320-660 GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2013-024 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet/$c$-tag | Yes | 20.3 | $\tilde{t}_1$ 90-200 GeV | m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV | ATLAS-CONF-2013-068 |
| | $\tilde{t}_1\tilde{t}_1$(natural GMSB) | 2 $e, \mu$ ($Z$) | 1 $b$ | Yes | 20.3 | $\tilde{t}_1$ 150-580 GeV | m($\tilde{\chi}_1^0$)>150 GeV | 1403.5222 |
| | $\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$ | 3 $e, \mu$ ($Z$) | 1 $b$ | Yes | 20.3 | $\tilde{t}_2$ 290-600 GeV | m($\tilde{\chi}_1^0$)<200 GeV | 1403.5222 |
| EW direct | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e, \mu$ | 0 | Yes | 20.3 | $\tilde{\ell}$ 90-325 GeV | m($\tilde{\chi}_1^0$)=0 GeV | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 $e, \mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 140-465 GeV | m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ | 2 $\tau$ | - | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 180-330 GeV | m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2013-028 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 $e, \mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 700 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | 1402.7029 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$ | 2-3 $e, \mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 420 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled | 1403.5294, 1402.7029 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$ | 1 $e, \mu$ | 2 $b$ | Yes | 20.3 | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled | ATLAS-CONF-2013-093 |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 270 GeV | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, $\tau$($\tilde{\chi}_1^\pm$)=0.2 ns | ATLAS-CONF-2013-069 |
| | Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 22.9 | $\tilde{g}$ 832 GeV | m($\tilde{\chi}_1^0$)=100 GeV, 10 $\mu$s<$\tau$($\tilde{g}$)<1000 s | ATLAS-CONF-2013-057 |
| | GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$ | 1-2 $\mu$ | - | - | 15.9 | $\tilde{\chi}_1^0$ 475 GeV | 10<tan$\beta$<50 | ATLAS-CONF-2013-058 |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 4.7 | $\tilde{\chi}_1^0$ 230 GeV | 0.4<$\tau$($\tilde{\chi}_1^0$)<2 ns | 1304.6310 |
| | $\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV) | 1 $\mu$, displ. vtx | - | - | 20.3 | $\tilde{q}$ 1.0 TeV | 1.5 <$c\tau$<156 mm, BR($\mu$)=1, m($\tilde{\chi}_1^0$)=108 GeV | ATLAS-CONF-2013-092 |
| RPV | LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$ | 2 $e, \mu$ | - | - | 4.6 | $\tilde{\nu}_\tau$ 1.61 TeV | $\lambda'_{311}$=0.10, $\lambda_{132}$=0.05 | 1212.1272 |
| | LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$ | 1 $e, \mu + \tau$ | - | - | 4.6 | $\tilde{\nu}_\tau$ 1.1 TeV | $\lambda'_{311}$=0.10, $\lambda_{1(2)33}$=0.05 | 1212.1272 |
| | Bilinear RPV CMSSM | 1 $e, \mu$ | 7 jets | Yes | 4.7 | $\tilde{q}, \tilde{g}$ 1.2 TeV | m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm | ATLAS-CONF-2012-140 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 $e, \mu$ | - | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 760 GeV | m($\tilde{\chi}_1^0$)>300 GeV, $\lambda_{121}$>0 | ATLAS-CONF-2013-036 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 $e, \mu + \tau$ | - | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 350 GeV | m($\tilde{\chi}_1^0$)>80 GeV, $\lambda_{133}$>0 | ATLAS-CONF-2013-036 |
| | $\tilde{g}\to qqq$ | 0 | 6-7 jets | - | 20.3 | $\tilde{g}$ 916 GeV | BR($t$)=BR($b$)=BR($c$)=0% | ATLAS-CONF-2013-091 |
| | $\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$ | 2 $e, \mu$ (SS) | 0-3 $b$ | Yes | 20.7 | $\tilde{g}$ 880 GeV | | ATLAS-CONF-2013-007 |
| Other | Scalar gluon pair, sgluon$\to q\bar{q}$ | 0 | 4 jets | - | 4.6 | sgluon 100-287 GeV | incl. limit from 1110.2693 | 1210.4826 |
| | Scalar gluon pair, sgluon$\to t\bar{t}$ | 2 $e, \mu$ (SS) | 2 $b$ | Yes | 14.3 | sgluon 350-800 GeV | | ATLAS-CONF-2013-051 |
| | WIMP interaction (D5, Dirac $\chi$) | 0 | mono-jet | Yes | 10.5 | M* scale 704 GeV | m($\chi$)<80 GeV, limit of<687 GeV for D8 | ATLAS-CONF-2012-147 |

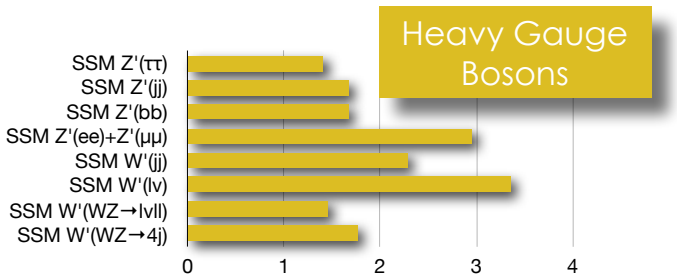
$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

$10^{-1}$ 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1$\sigma$ theoretical signal cross section uncertainty.

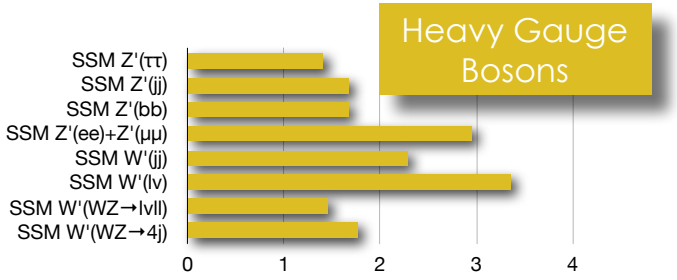
# *Highlighting a few key searches among the many*

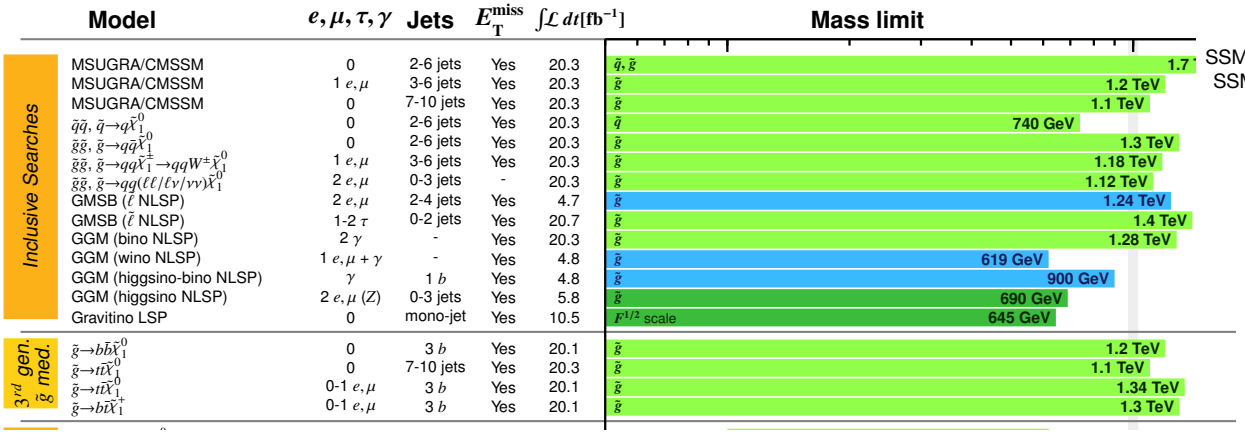
- Heavy resonances decaying to $W/Z/H$ pairs
- Inclusive strongly produced SUSY scenarios
- Vector-like quarks top partners
- $R$-parity violating (RPV) SUSY and long-lived scenarios



# *Highlighting a few key searches among the many*

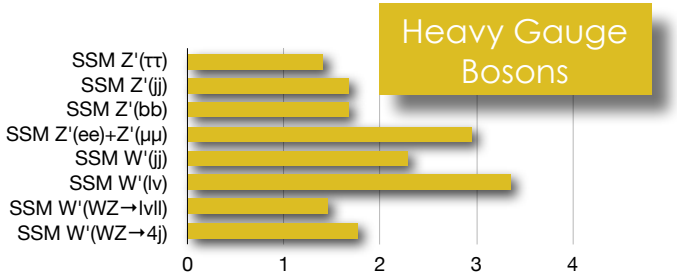
- Heavy resonances decaying to $W/Z/H$ pairs
- Inclusive strongly produced SUSY scenarios
- Vector-like quarks top partners
- $R$-parity violating (RPV) SUSY and long-lived scenarios

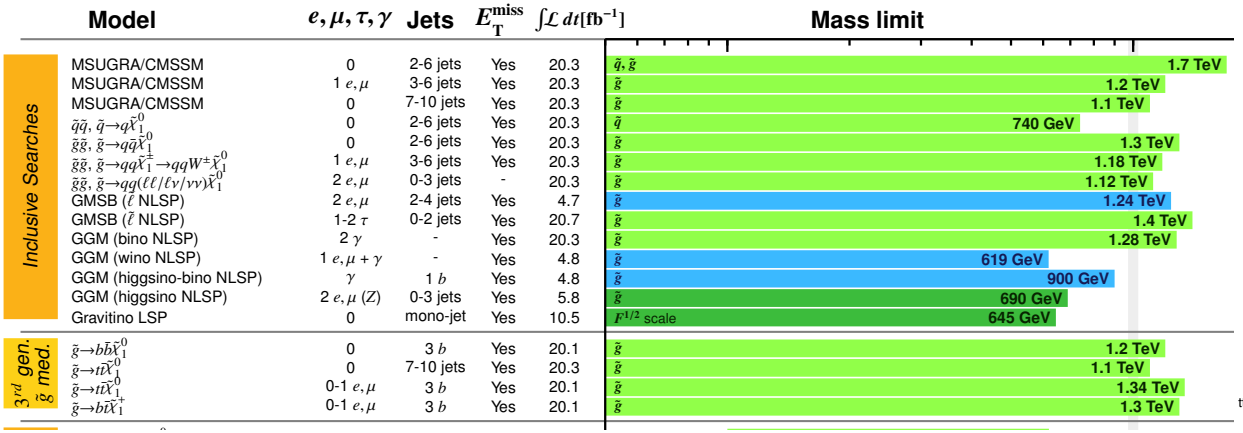


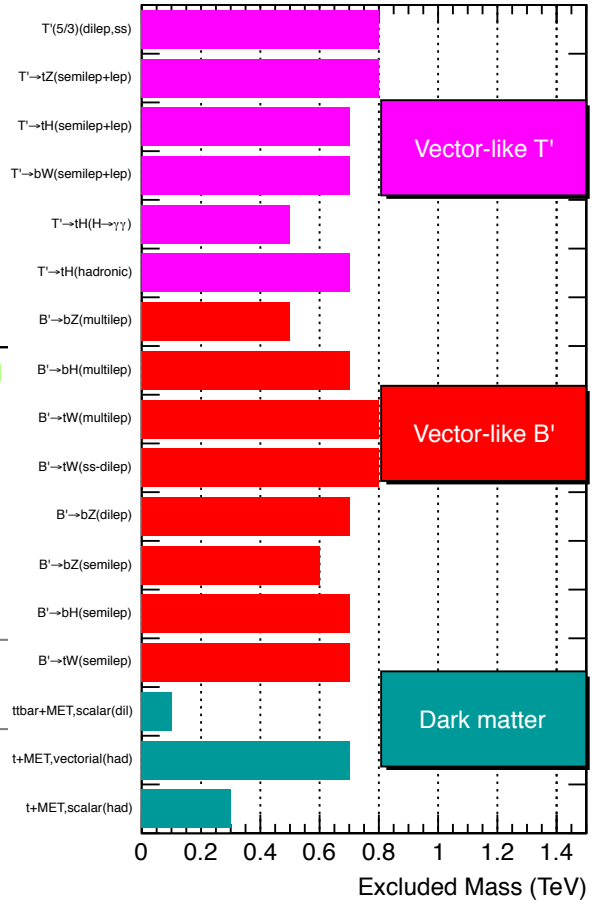



# *Highlighting a few key searches among the many*

- Heavy resonances decaying to $W/Z/H$ pairs
- Inclusive strongly produced SUSY scenarios
- Vector-like quarks top partners
- $R$-parity violating (RPV) SUSY and long-lived scenarios

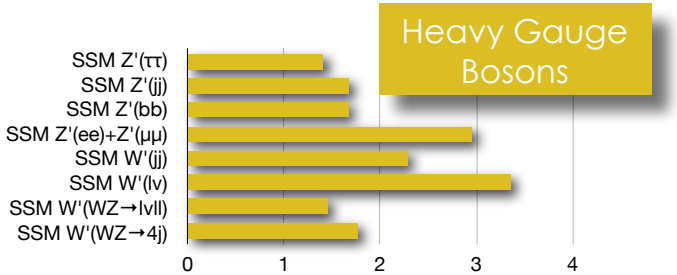


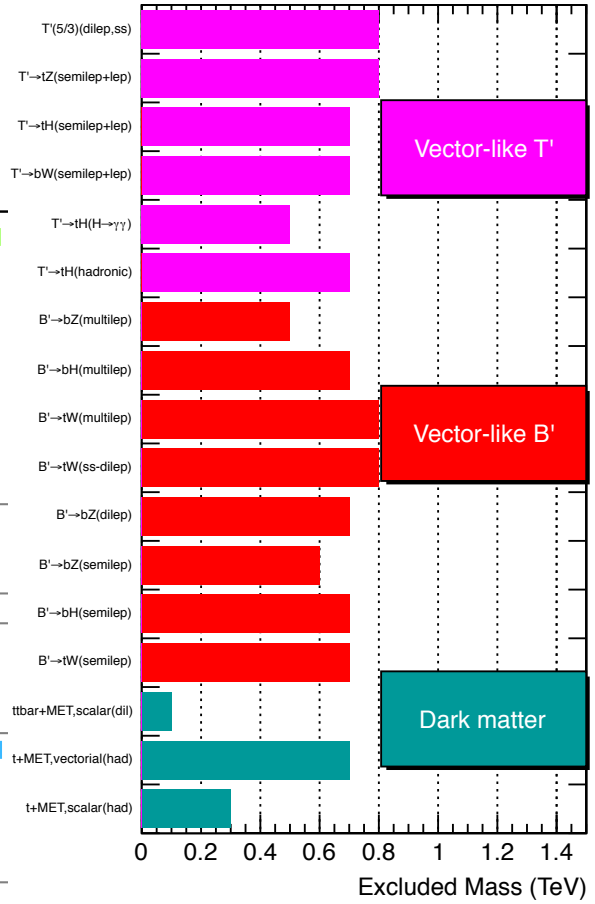



# *Highlighting a few key searches among the many*

- Heavy resonances decaying to $W/Z/H$ pairs
- Inclusive strongly produced SUSY scenarios
- Vector-like quarks top partners
- $R$-parity violating (RPV) SUSY and long-lived scenarios




| | Model | $e,\mu,\tau,\gamma$ | Jets | $E_T^{miss}$ | $\int\mathcal{L}\,dt[fb^{-1}]$ | Mass limit |
|---|---|---|---|---|---|---|
| Inclusive Searches | MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.7 TeV |
| | MSUGRA/CMSSM | 1 $e,\mu$ | 3-6 jets | Yes | 20.3 | $\tilde{g}$ 1.2 TeV |
| | MSUGRA/CMSSM | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.1 TeV |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q}$ 740 GeV |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{g}$ 1.3 TeV |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$ | 1 $e,\mu$ | 3-6 jets | Yes | 20.3 | $\tilde{g}$ 1.18 TeV |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0-3 jets | - | 20.3 | $\tilde{g}$ 1.12 TeV |
| | GMSB ($\tilde{\ell}$ NLSP) | 2 $e,\mu$ | 2-4 jets | Yes | 4.7 | $\tilde{g}$ 1.24 TeV |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 $\tau$ | 0-2 jets | Yes | 20.7 | $\tilde{g}$ 1.4 TeV |
| | GGM (bino NLSP) | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{g}$ 1.28 TeV |
| | GGM (wino NLSP) | 1 $e,\mu+\gamma$ | - | Yes | 4.8 | $\tilde{g}$ 619 GeV |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 1 $b$ | Yes | 4.8 | $\tilde{g}$ 900 GeV |
| | GGM (higgsino NLSP) | 2 $e,\mu$ (Z) | 0-3 jets | Yes | 5.8 | $\tilde{g}$ 690 GeV |
| | Gravitino LSP | 0 | mono-jet | Yes | 10.5 | $F^{1/2}$ scale 645 GeV |
| 3rd gen. $\tilde{g}$ med. | $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.2 TeV |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.1 TeV |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.34 TeV |
| | $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.3 TeV |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 270 GeV |
| | Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 22.9 | $\tilde{g}$ 832 GeV |
| | GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ | 1-2 $\mu$ | - | - | 15.9 | $\tilde{\chi}_1^0$ 475 GeV |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 4.7 | $\tilde{\chi}_1^0$ 230 GeV |
| | $\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV) | 1 $\mu$, displ. vtx | - | - | 20.3 | $\tilde{q}$ 1.0 TeV |
| RPV | LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$ | 2 $e,\mu$ | - | - | 4.6 | $\tilde{\nu}_\tau$ 1.61 TeV |
| | LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$ | 1 $e,\mu+\tau$ | - | - | 4.6 | $\tilde{\nu}_\tau$ 1.1 TeV |
| | Bilinear RPV CMSSM | 1 $e,\mu$ | 7 jets | Yes | 4.7 | $\tilde{q},\tilde{g}$ 1.2 TeV |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 $e,\mu$ | - | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 760 GeV |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 $e,\mu+\tau$ | - | Yes | 20.7 | $\tilde{\chi}_1^\pm$ 350 GeV |
| | $\tilde{g}\to qqq$ | 0 | 6-7 jets | - | 20.3 | $\tilde{g}$ 916 GeV |
| | $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$ | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.7 | $\tilde{g}$ 880 GeV |



# Outline


1. *The Search for Cracks in the Standard Model*
2. *Overview of the BSM Searches in ATLAS and CMS*
3. *Key analyses in the search for BSM Physics*
4. *Looking ahead to Run II*

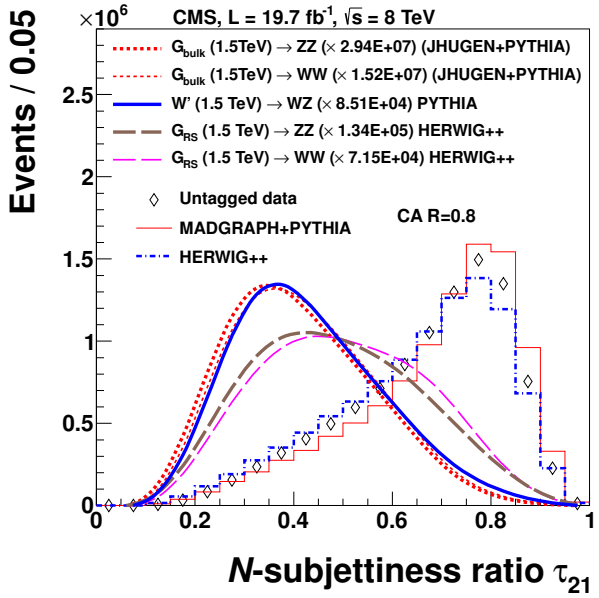
# *Searching for heavy resonances using $W/Z/H$ boson pairs*

**Generic signature of new strong dynamics**

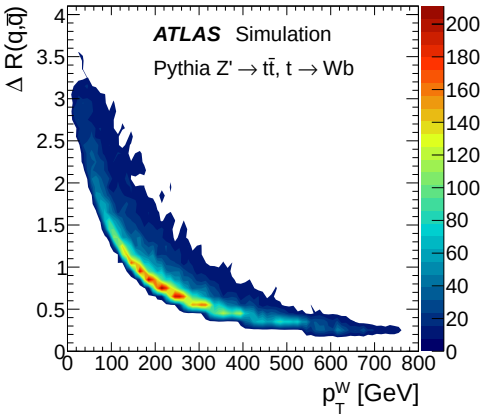
- **Expect couplings between new resonances (e.g. $W'$, graviton) and SM $W/Z/H$ bosons**
- **Signature-based searches benchmarked with reference models**

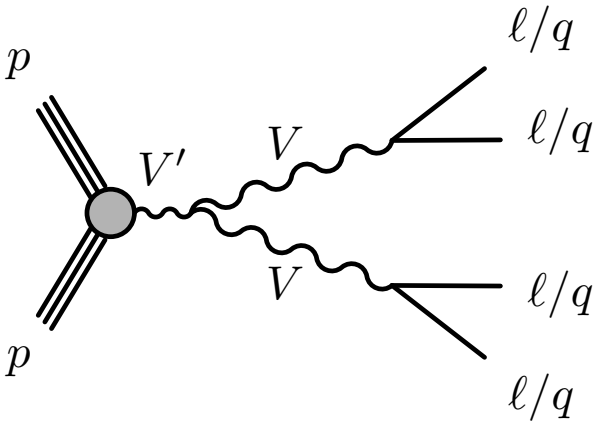
**Tag boosted $W/Z$ bosons using jet substructure ($N$-subjettiness, $\tau_{21}$) for high mass resonances**

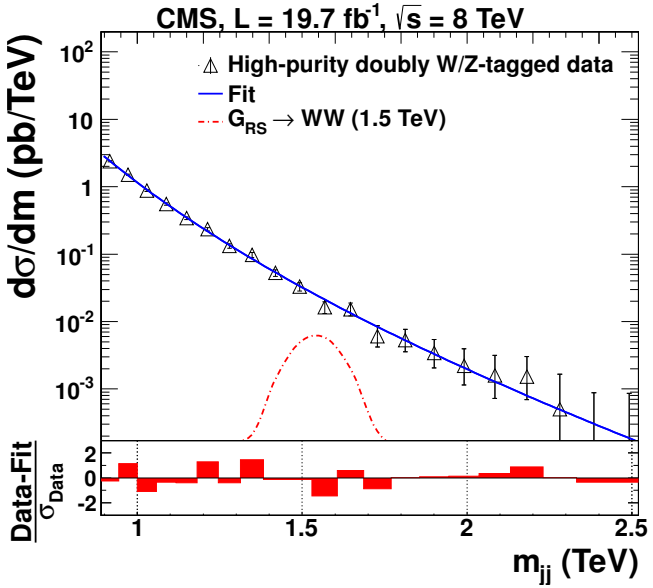
→ ***Extremely novel tagging and background estimation techniques employed***




→ CMS all-hadronic VV (arXiv:1405.1994)



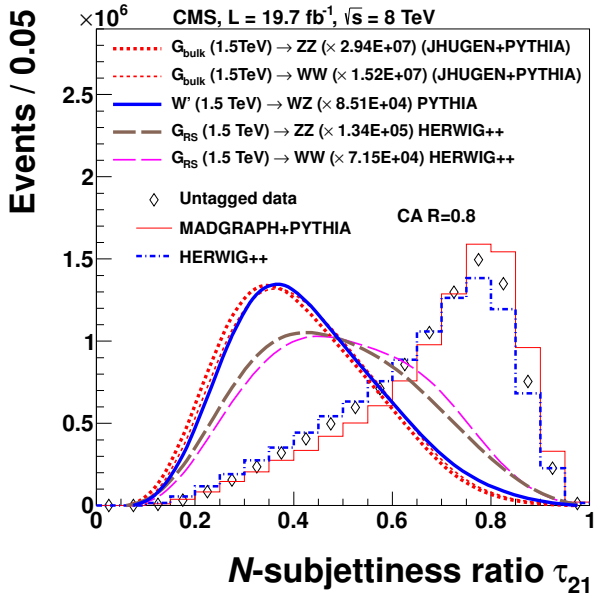
# *Searching for heavy resonances using $W/Z/H$ boson pairs*

**Generic signature of new strong dynamics**

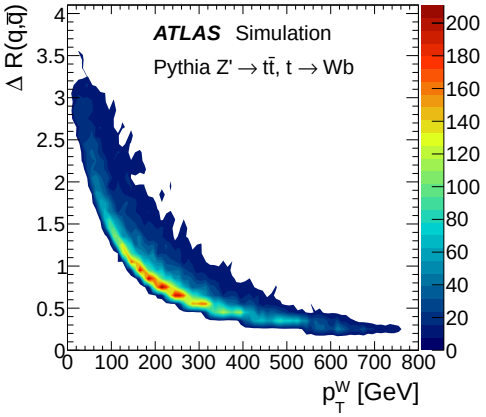
- **Expect couplings between new resonances (e.g. $W'$, graviton) and SM $W/Z/H$ bosons**
- **Signature-based searches benchmarked with reference models**

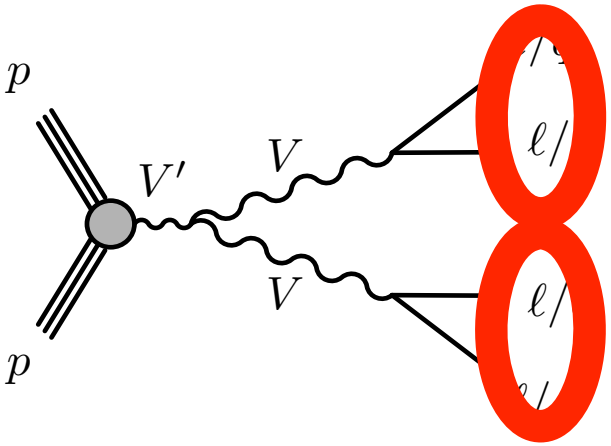
**Tag boosted $W/Z$ bosons using jet substructure ($N$-subjettiness, $\tau_{21}$) for high mass resonances**

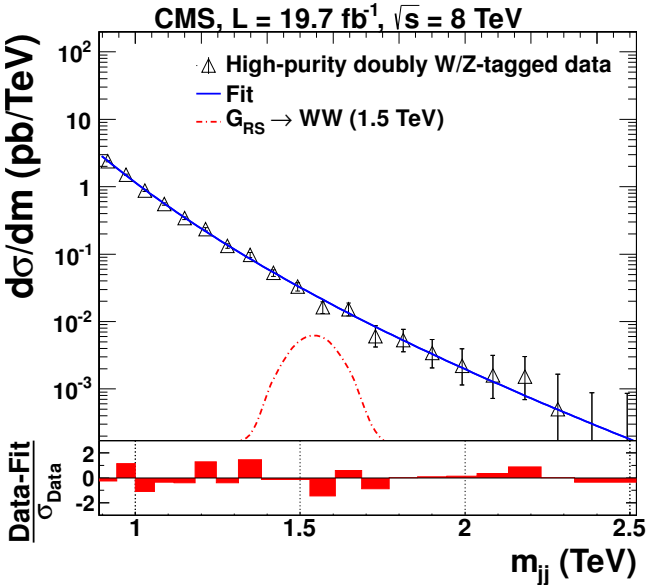
→ ***Extremely novel tagging and background estimation techniques employed***




→ CMS all-hadronic VV (arXiv:1405.1994)



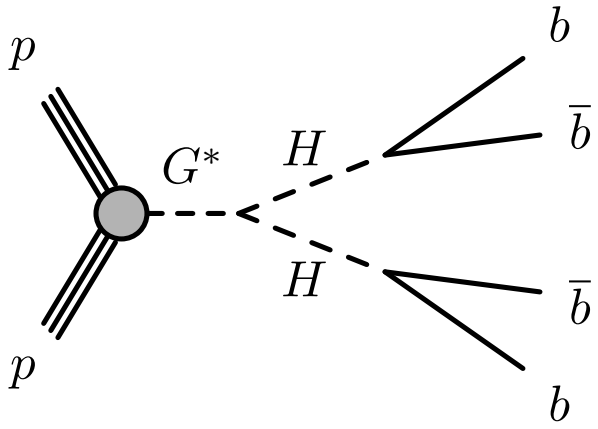
# *Searching for heavy resonances using $W/Z/H$ boson pairs*

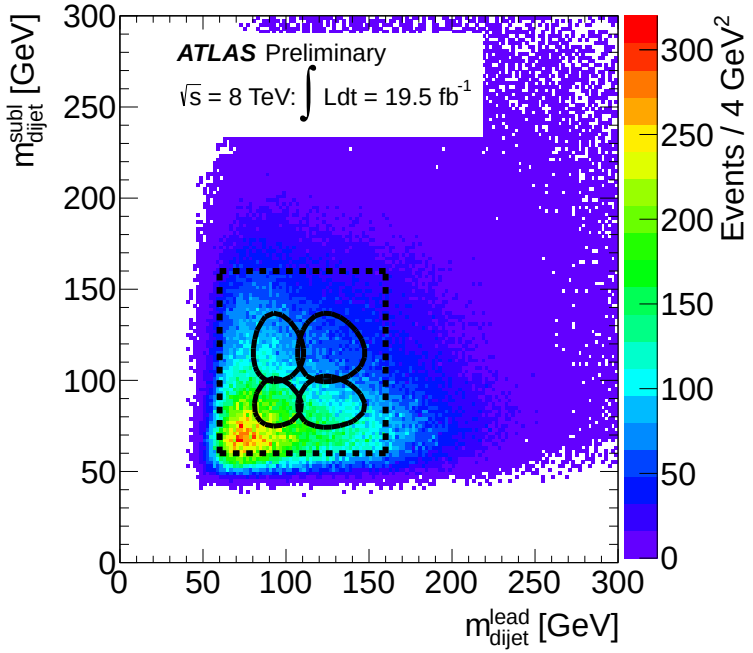
**Generic signature of new strong dynamics**

- **Expect couplings between new resonances (e.g. $W'$, graviton) and SM $W/Z/H$ bosons**
- **Signature-based searches benchmarked with reference models**

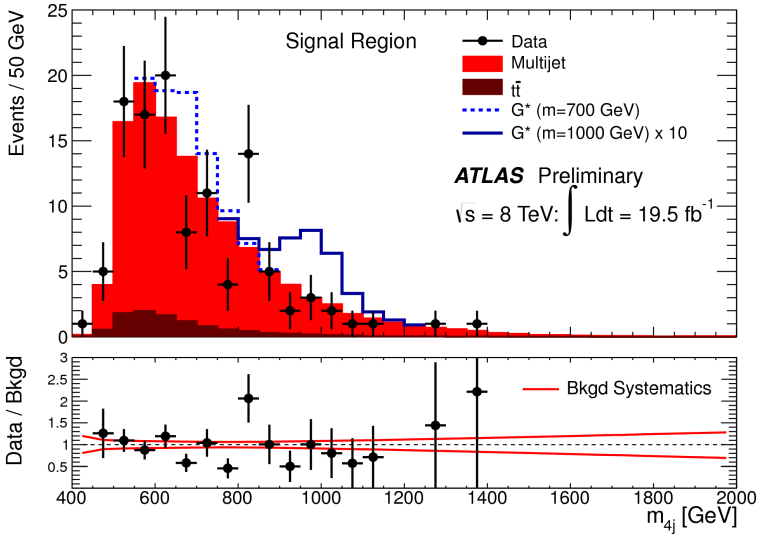
**Data-driven background estimation for unique di-Higgs $\rightarrow$ 4 $b$-jet final state**

$\rightarrow$ ***Using Higgs boson as a search tool for BSM physics***

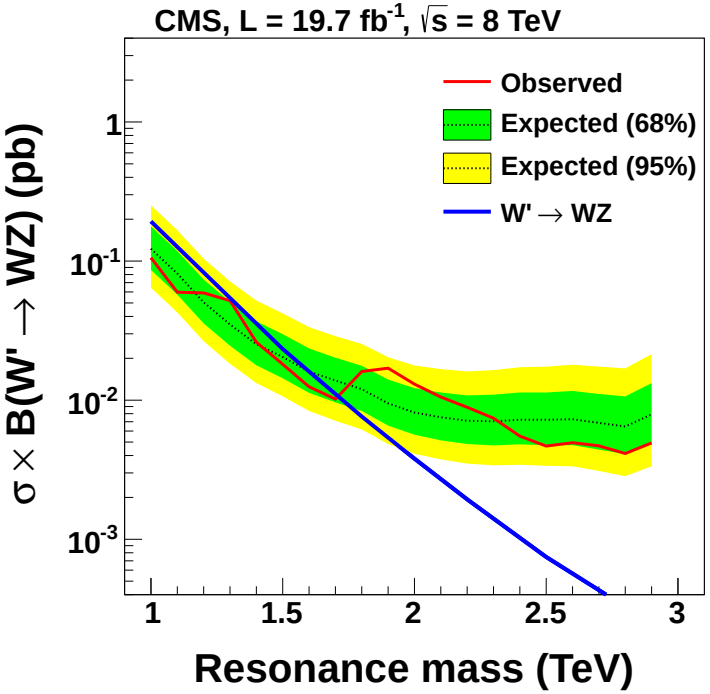


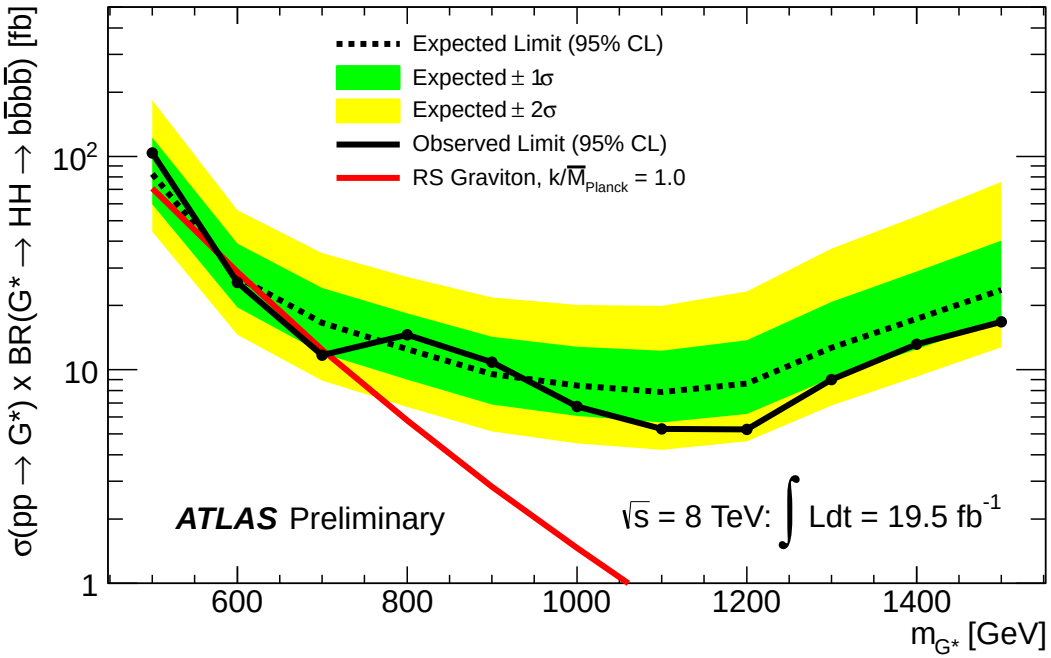

$\rightarrow$ ATLAS all-hadronic HH (ATLAS-CONF-2014-005)



# *Searching for heavy resonances using W/Z/H boson pairs*




$V' \to VV \to 4q$: arXiv:1405.1994

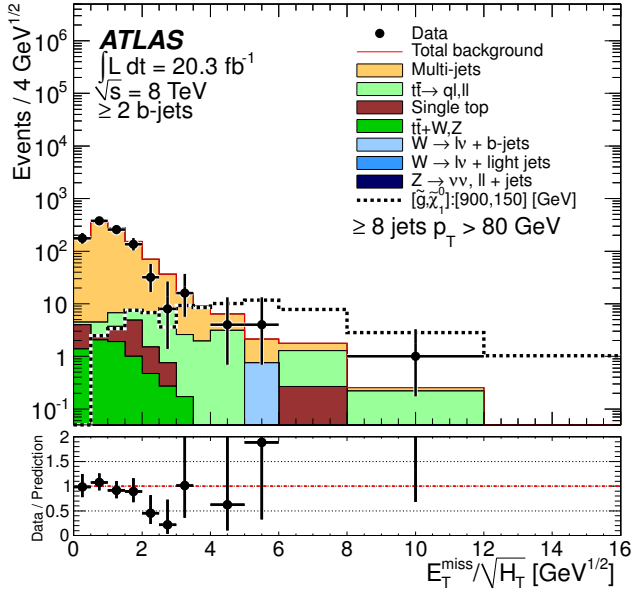


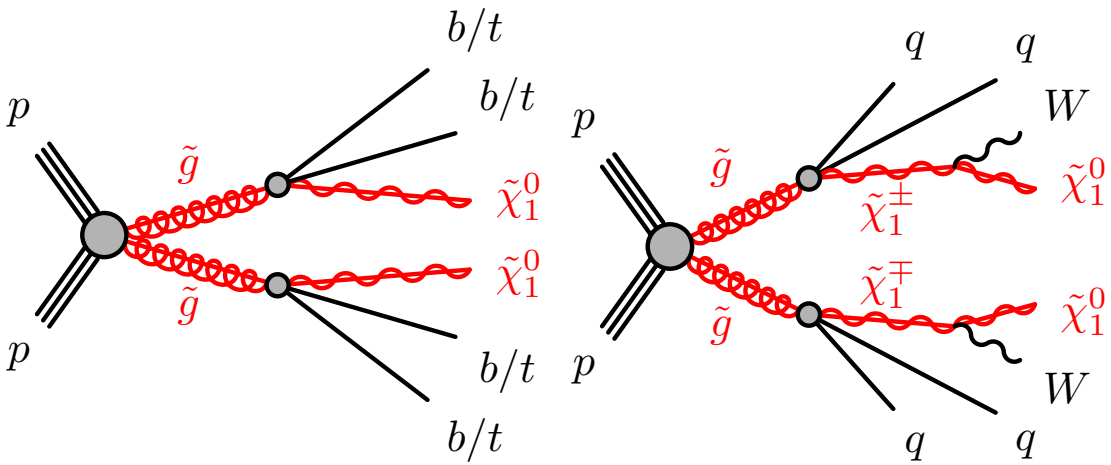

$X \to HH \to 4b$: ATLAS-CONF-2014-005

- Model independent limits vs. mass and width
- Big gains on branching ratios by exploiting hadronic final states, sophisticated background estimation methods, and state-of-the art tools
- Some of the first searches of this kind ($4b$, hadronic $VV$)

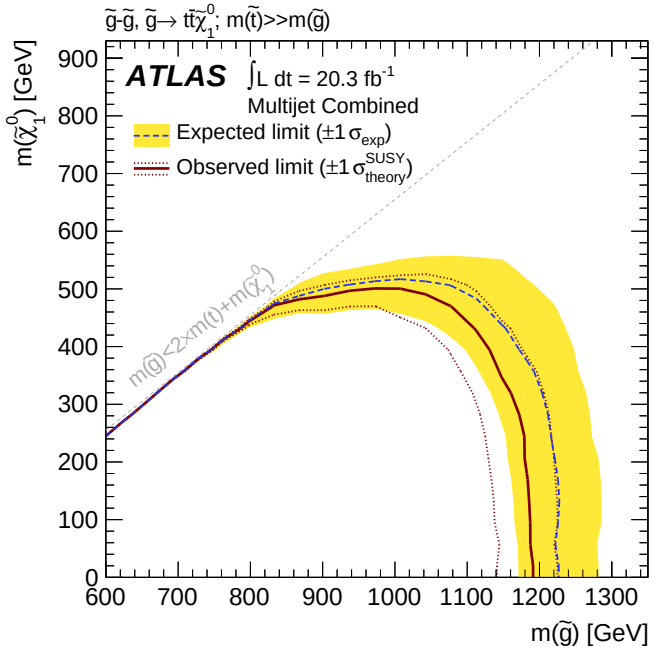
# *Searching for strongly produced SUSY final states*

- Decay chain leads to **many jets and $E_T^{miss}$ (in *most* cases)**
- Very sensitive **searches for colored particles**
- Search strategies so far have relied on **number of jets, heavy flavor composition of final state, and $E_T^{miss}$**

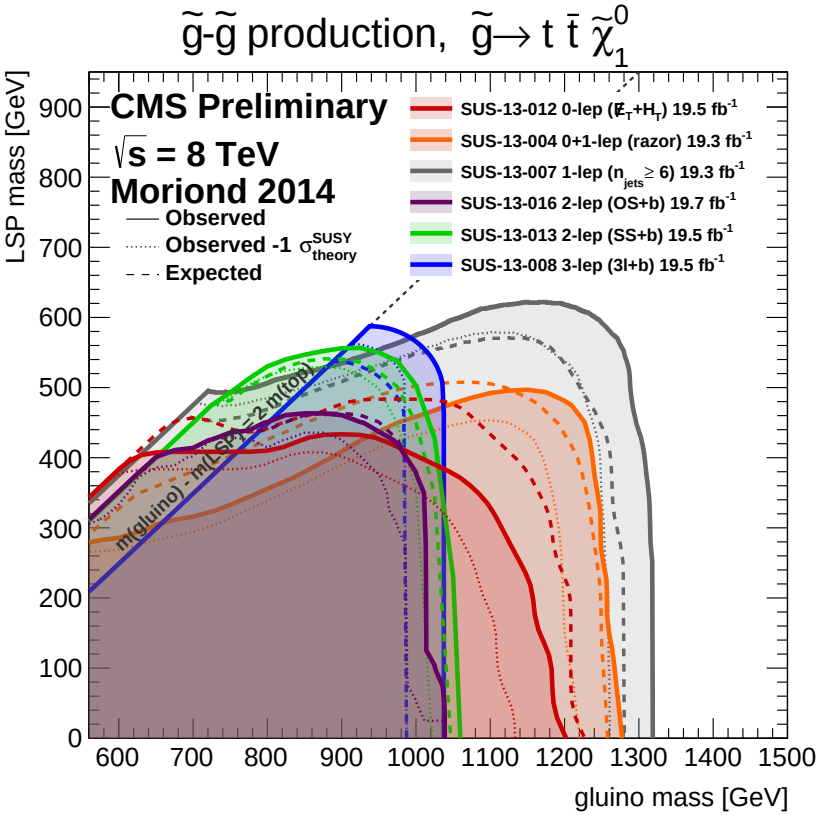


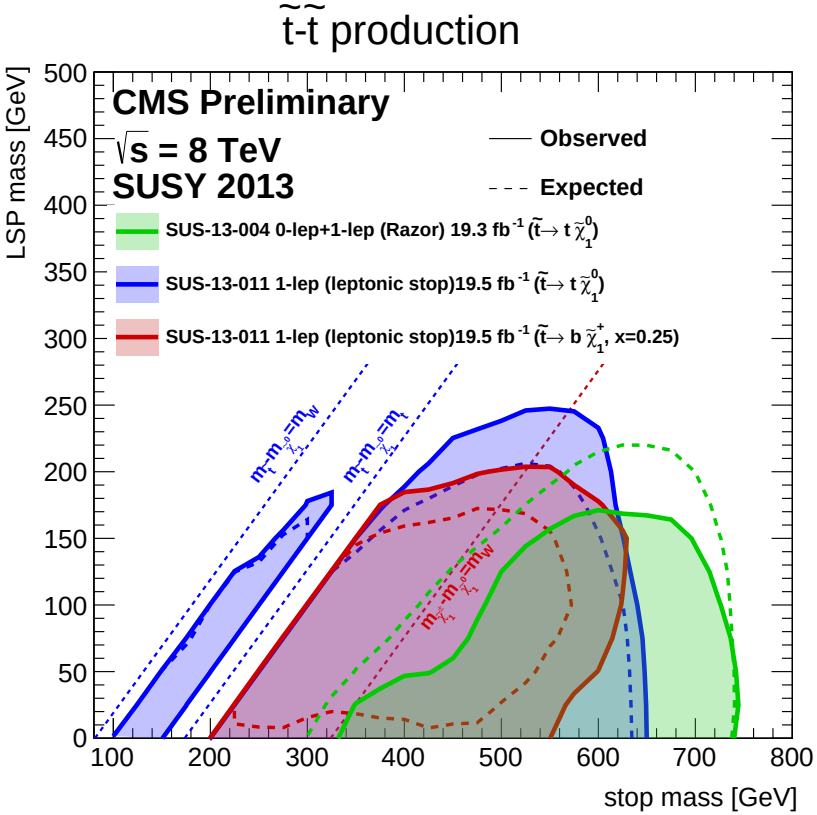




→ ATLAS 7–10 jet+$E_T^{miss}$ (arXiv:1308.1841)



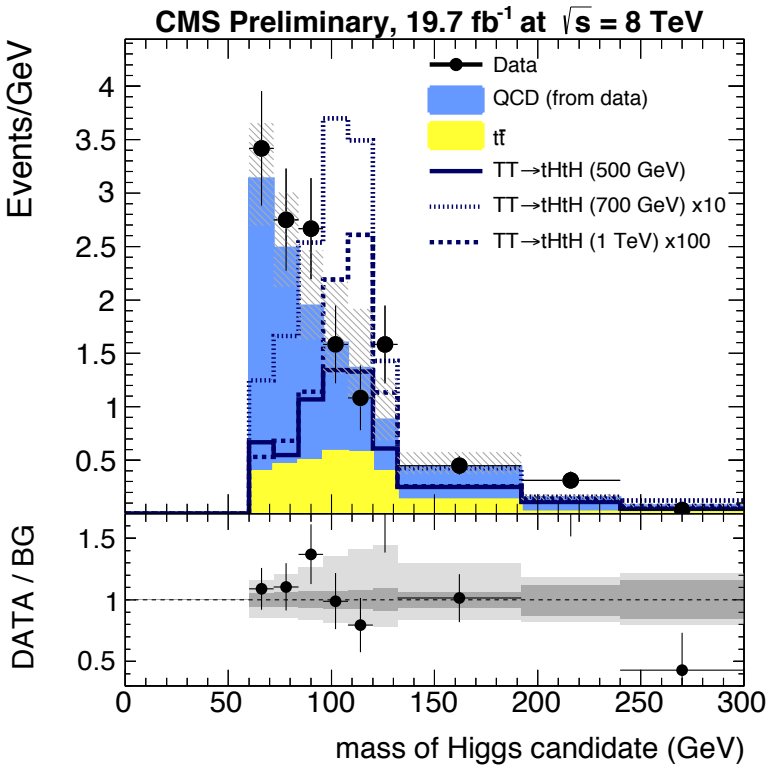
# *Searching for strongly produced SUSY final states*



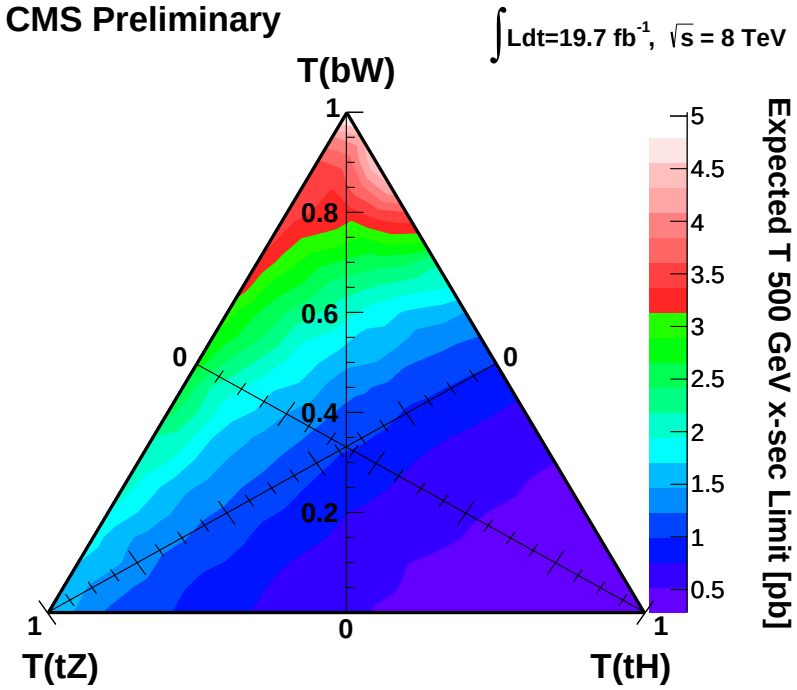




- Novel search techniques (e.g. razor) and large jet multiplicity final states (e.g. 1 lepton + 6 or more jets) are leading the way to higher gluino and stop mass sensitivity
- Vanilla SUSY excluded below about 1 TeV, but **room for specific stop scenarios**

# *Broad searches for top quark partners...using Higgs!*




Boosted Higgs candidate mass CMS-PAS-B2G-14-002



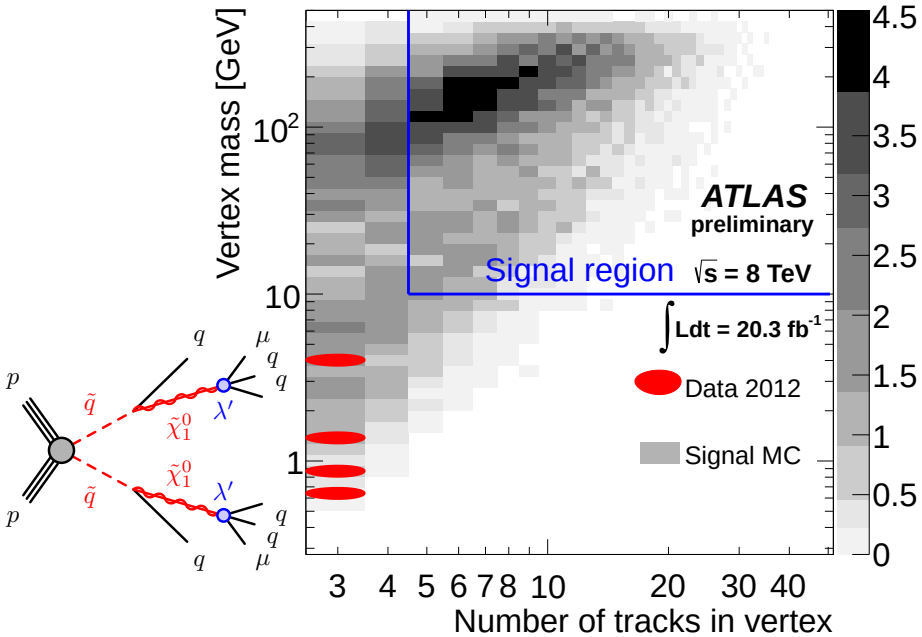

CMS hadronic final states w/ jet substructure

CMS-PAS-B2G-14-002

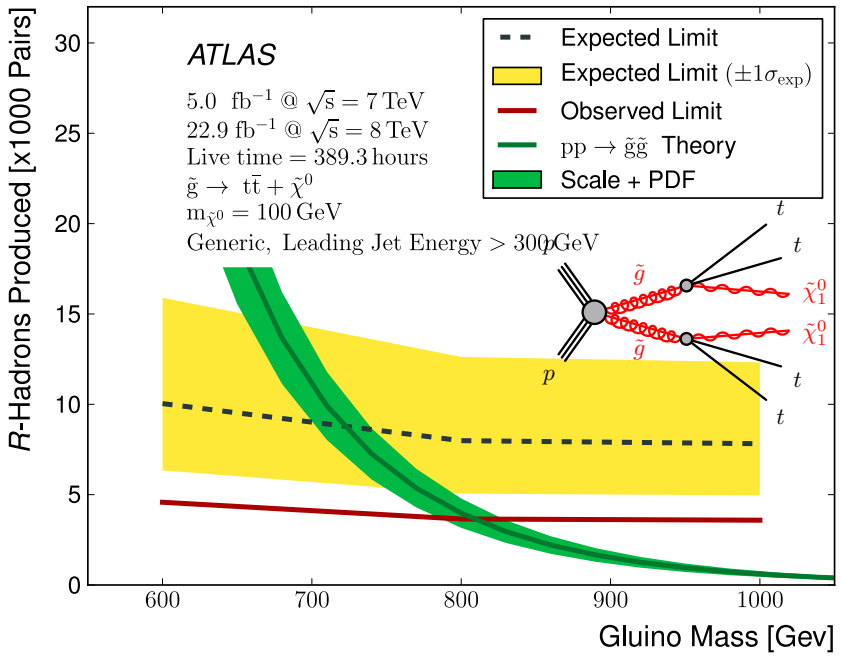
- Very active search programs for **fourth-generation fermions**
- Rich phenomenology, with **many signatures: top, $b$, $W/Z$ ($\ell$, jets), Higgs, etc**, but VLQ generally excluded below about 700 GeV
- Continuing to use **Higgs as a search tool** in conjunction with sophisticated **jet substructure techniques** in the boosted regime

# *Long-lived Particle Searches with Squarks and Gluinos*

- **Long-lived $\tilde{\chi}_1^0$ with a displaced vertex:** DV+$\mu$ signature using $m_{\text{vertex}}$ and $N_{\text{track}}$
  - ID vertex using dedicated tracking and vertexing algorithm
  - Fully data-driven background estimation: **exp. bckg very small** $\rightarrow N_{\text{bckg}}^{\text{exp}} = 0.02 \pm 0.02$
  - **3 benchmark models excluded for wide range of $c\tau$**
- **Long-lived, stopped $\tilde{g}$:** large calorimeter energy in empty bunch crossings
  - Looking for $\tilde{g}$ $R$-hadrons using jet shape and muon spectrometer information
  - Muon segment veto to remove background from cosmic rays and beam-halo
  - **For $m_{\tilde{\chi}_1^0}$ =100 GeV, exclude $m_{\tilde{g}}$ < 600 GeV for $\tau_{\tilde{g}} < 2$ years!**




**DV+$\mu$:** ATLAS-CONF-2013-092




**stopped $\tilde{g}$:** arXiv:1310.6584

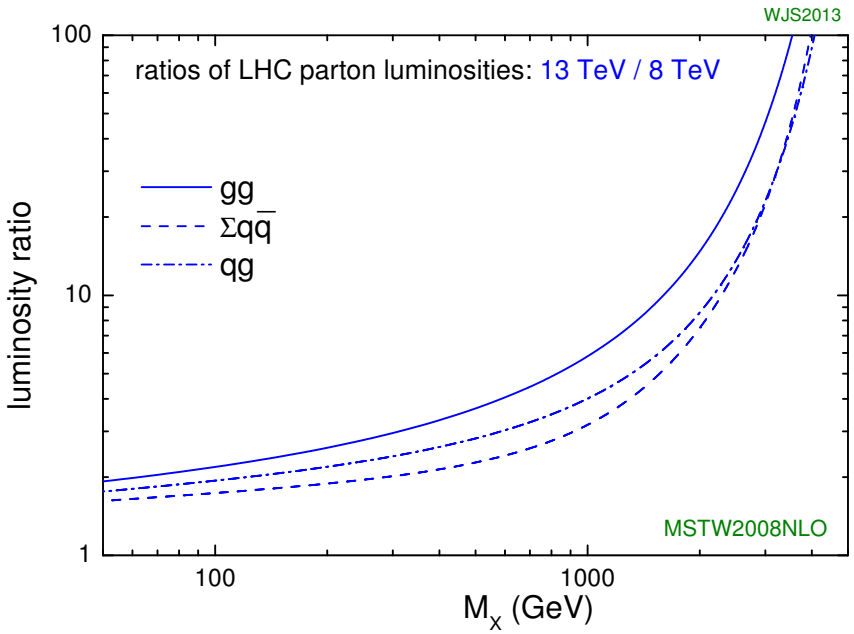
# Outline


1. *The Search for Cracks in the Standard Model*
2. *Overview of the BSM Searches in ATLAS and CMS*
3. *Key analyses in the search for BSM Physics*
4. *Looking ahead to Run II*

# *Early Run II Expectations*

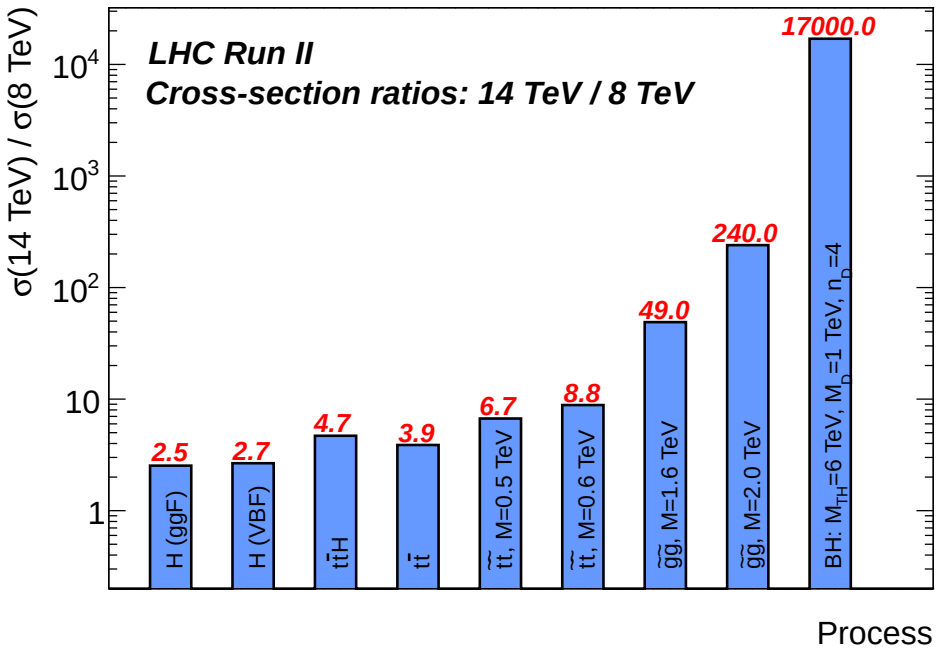
Early 2015 LHC Program:

- **May:** Stable beams operation with 50ns bunch spacing after intensity ramp-up
- **June:** Stable beams operation with 25ns bunch spacing after intensity ramp-up



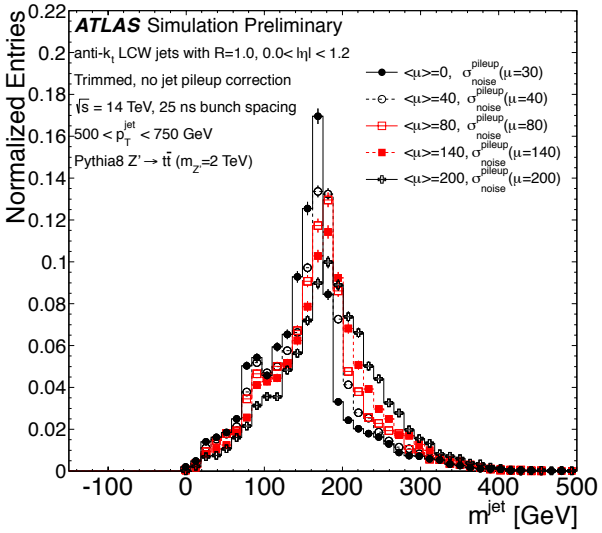

Outlook for 2015:

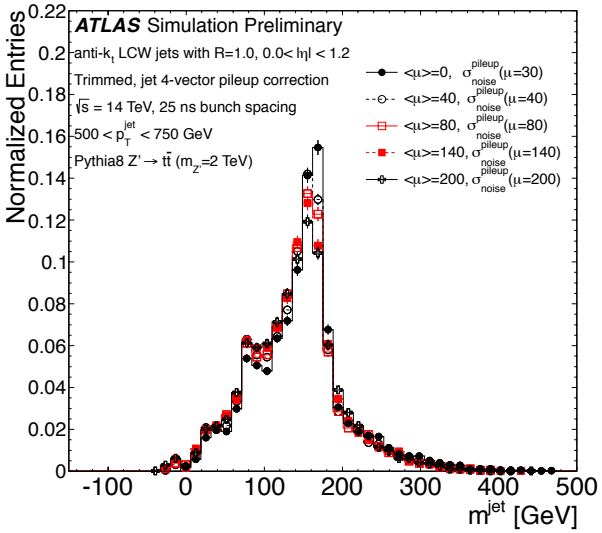
- Huge increase in discovery potential
- Suggests a strong focus on targeted searches very early
- Both short-term and longer-term efforts will depend on detector performance
- With 3 $\text{fb}^{-1}$ many searches reach or surpass current sensitivity



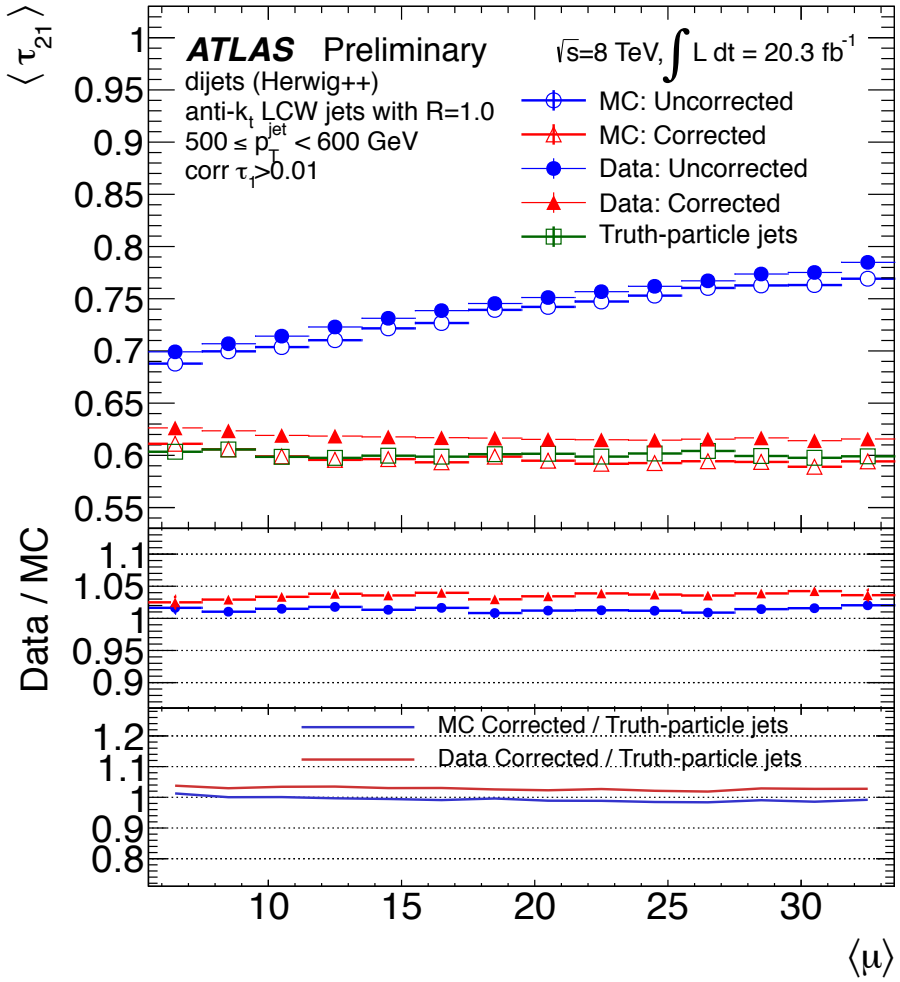
# *Preparing to use complex hadronic final states in Run II*

Already studying substructure-compatible corrections for 14 TeV pile-up scenarios.



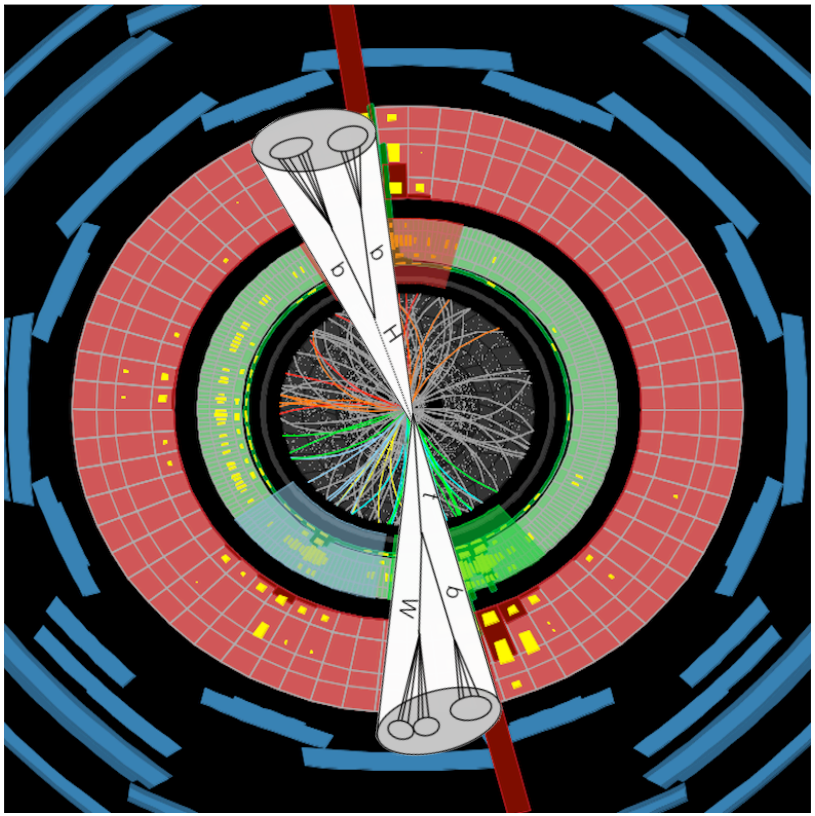

Also studying sophisticated shape corrections (ATLAS-CONF-2013-085) to mitigate the effects of pileup on jet shapes.



# *Summary and conclusions*

**Rich programs in BSM physics searches in ATLAS and CMS exploiting complex final states, multi-object topologies, and the newly discovered Higgs boson.**

- **Strong constraints on new physics from the LHC**
  - No $W/Z$ di-boson resonance with SM-like couplings below 1 TeV
  - Vanilla SUSY excluded below about 1 TeV
  - VLQ excluded below about 700 GeV
- **Extending and improving existing searches**
  - Higgs as a standard search tool for BSM physics
  - Complex hadronic final states being fully exploited
  - Increased focus on boosted topologies
- **Many holes left and Run II will provide an opportunity to extend reach and close those gaps**
  - Long-lived particles and degenerate mass splittings still extremely hard to isolate
  - Complex mixed branching ratio final states still not fully explored, but we're getting there




## *Conclusions*

- **CMS and ATLAS are leveraging advances in detector technology, search strategies, and theoretical foundations to investigate the limits of the energy frontier**

# *Outline*

5 *Backup slides and additional information*

# Additional Material

# ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

**ATLAS** Preliminary

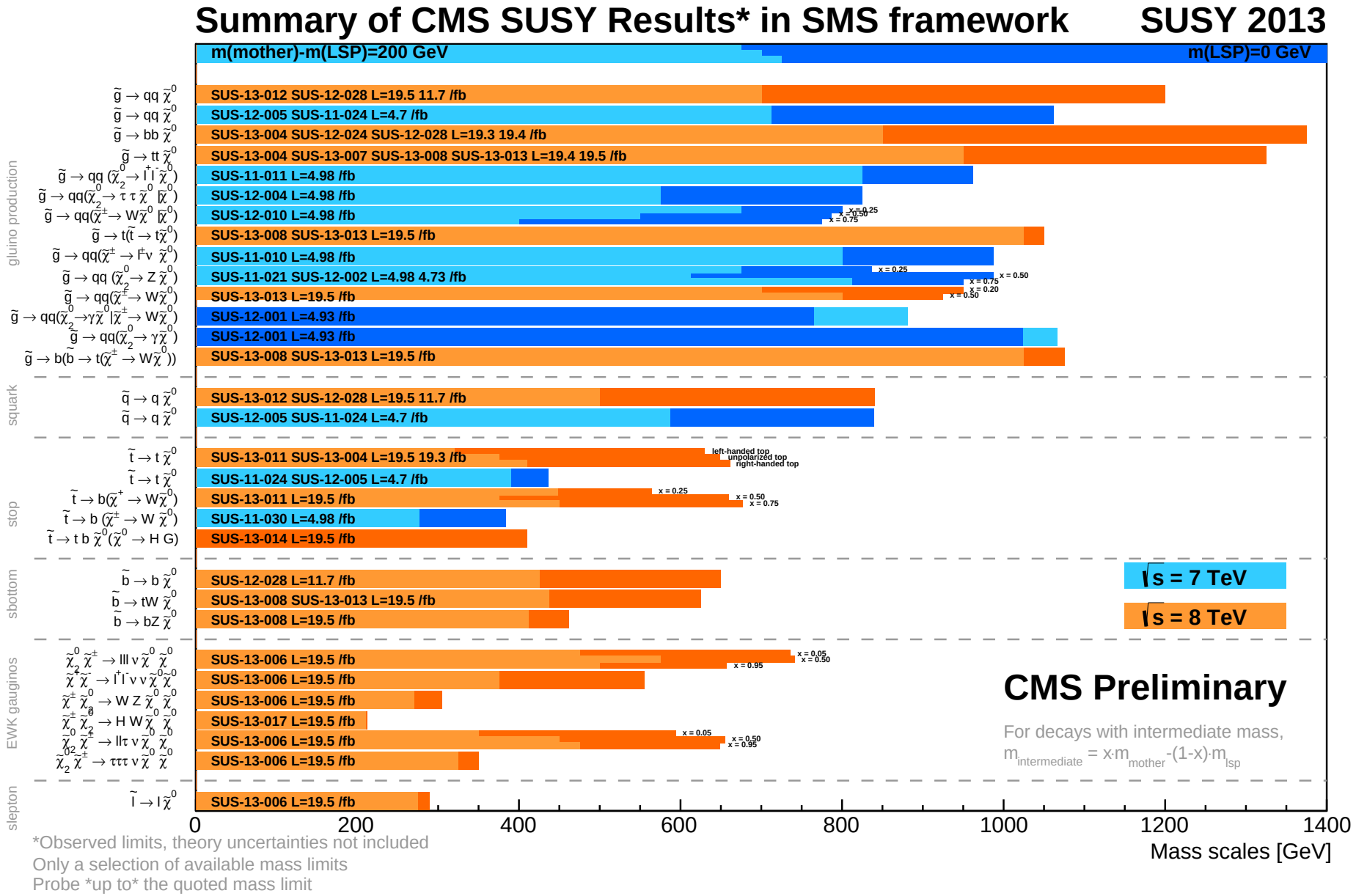
$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

| | Model | $\ell, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$ | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | – | 1-2 j | Yes | 4.7 | $M_D$ 4.37 TeV | $n = 2$ | 1210.4491 |
| | ADD non-resonant $\ell\ell/\gamma\gamma$ | $2\gamma$ or $2e, \mu$ | – | – | 4.7 | $M_S$ 4.18 TeV | $n = 3$ HLZ NLO | 1211.1150 |
| | ADD QBH $\to \ell q$ | $1\ e, \mu$ | 1 j | – | 20.3 | $M_{th}$ 5.2 TeV | $n = 6$ | 1311.2006 |
| | ADD BH high $N_{trk}$ | $2\ \mu$ (SS) | – | – | 20.3 | $M_{th}$ 5.7 TeV | $n = 6$, $M_D = 1.5$ TeV, non-rot BH | 1308.4075 |
| | ADD BH high $\sum p_T$ | $\geq 1\ e, \mu$ | $\geq 2$ j | – | 20.3 | $M_{th}$ 6.2 TeV | $n = 6$, $M_D = 1.5$ TeV, non-rot BH | ATLAS-CONF-2014-016 |
| | RS1 $G_{KK} \to \ell\ell$ | $2\ e, \mu$ | – | – | 20.3 | $G_{KK}$ mass 2.47 TeV | $k/\overline{M}_{Pl} = 0.1$ | ATLAS-CONF-2013-017 |
| | RS1 $G_{KK} \to ZZ \to \ell\ell qq/\ell\ell\ell\ell$ | 2 or 4 $e, \mu$ | 2 j or – | – | 1.0 | $G_{KK}$ mass 845 GeV | $k/\overline{M}_{Pl} = 0.1$ | 1203.0718 |
| | RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$ | $2\ e, \mu$ | – | Yes | 4.7 | $G_{KK}$ mass 1.23 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1208.2880 |
| | Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$ | – | 4 b | – | 19.5 | $G_{KK}$ mass 590-710 GeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2014-005 |
| | Bulk RS $g_{KK} \to t\bar{t}$ | $1\ e, \mu$ | $\geq 1$ b, $\geq 1$J/2j | Yes | 14.3 | $g_{KK}$ mass 0.5-2.0 TeV | BR = 0.925 | ATLAS-CONF-2013-052 |
| | $S^1/Z_2$ ED | $2\ e, \mu$ | – | – | 5.0 | $M_{KK} \approx R^{-1}$ 4.71 TeV | | 1209.2535 |
| | UED | $2\ \gamma$ | – | Yes | 4.8 | Compact. scale $R^{-1}$ 1.41 TeV | | ATLAS-CONF-2012-072 |
| Gauge bosons | SSM $Z' \to \ell\ell$ | $2\ e, \mu$ | – | – | 20.3 | $Z'$ mass 2.86 TeV | | ATLAS-CONF-2013-017 |
| | SSM $Z' \to \tau\tau$ | $2\ \tau$ | – | – | 19.5 | $Z'$ mass 1.9 TeV | | ATLAS-CONF-2013-066 |
| | SSM $W' \to \ell\nu$ | $1\ e, \mu$ | – | Yes | 20.3 | $W'$ mass 3.28 TeV | | ATLAS-CONF-2014-017 |
| | EGM $W' \to WZ \to \ell\nu\ell'\ell'$ | $3\ e, \mu$ | – | Yes | 20.3 | $W'$ mass 1.52 TeV | | ATLAS-CONF-2014-015 |
| | LRSM $W'_R \to t\bar{b}$ | $1\ e, \mu$ | 2 b, 0-1 j | Yes | 14.3 | $W'$ mass 1.84 TeV | | ATLAS-CONF-2013-050 |
| CI | CI $qqqq$ | – | 2 j | – | 4.8 | $\Lambda$ 7.6 TeV | $\eta = +1$ | 1210.1718 |
| | CI $qq\ell\ell$ | $2\ e, \mu$ | – | – | 5.0 | $\Lambda$ 13.9 TeV | $\eta_{LL} = -1$ | 1211.1150 |
| | CI $uutt$ | $2\ e, \mu$ (SS) | $\geq 1$ b, $\geq 1$ j | Yes | 14.3 | $\Lambda$ 3.3 TeV | $\lvert C \rvert = 1$ | ATLAS-CONF-2013-051 |
| DM | EFT D5 operator | – | 1-2 j | Yes | 10.5 | $M_*$ 731 GeV | at 90% CL for $m(\chi) < 80$ GeV | ATLAS-CONF-2012-147 |
| | EFT D9 operator | – | 1 J, $\leq 1$ j | Yes | 20.3 | $M_*$ 2.4 TeV | at 90% CL for $m(\chi) < 100$ GeV | 1309.4017 |
| LQ | Scalar LQ 1st gen | $2\ e$ | $\geq 2$ j | – | 1.0 | LQ mass 660 GeV | $\beta = 1$ | 1112.4828 |
| | Scalar LQ 2nd gen | $2\ \mu$ | $\geq 2$ j | – | 1.0 | LQ mass 685 GeV | $\beta = 1$ | 1203.3172 |
| | Scalar LQ 3rd gen | $1\ e, \mu, 1\ \tau$ | 1 b, 1 j | – | 4.7 | LQ mass 534 GeV | $\beta = 1$ | 1303.0526 |
| Heavy quarks | Vector-like quark $TT \to Ht + X$ | $1\ e, \mu$ | $\geq 2$ b, $\geq 4$ j | Yes | 14.3 | T mass 790 GeV | T in (T,B) doublet | ATLAS-CONF-2013-018 |
| | Vector-like quark $TT \to Wb + X$ | $1\ e, \mu$ | $\geq 1$ b, $\geq 3$ j | Yes | 14.3 | T mass 670 GeV | isospin singlet | ATLAS-CONF-2013-060 |
| | Vector-like quark $BB \to Zb + X$ | $2\ e, \mu$ | $\geq 2$ b | – | 14.3 | B mass 725 GeV | B in (B,Y) doublet | ATLAS-CONF-2013-056 |
| | Vector-like quark $BB \to Wt + X$ | $2\ e, \mu$ (SS) | $\geq 1$ b, $\geq 1$ j | Yes | 14.3 | B mass 720 GeV | B in (T,B) doublet | ATLAS-CONF-2013-051 |
| Excited fermions | Excited quark $q^* \to q\gamma$ | $1\ \gamma$ | 1 j | – | 20.3 | $q^*$ mass 3.5 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1309.3230 |
| | Excited quark $q^* \to qg$ | – | 2 j | – | 13.0 | $q^*$ mass 3.84 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | ATLAS-CONF-2012-148 |
| | Excited quark $b^* \to Wt$ | 1 or 2 $e, \mu$ | 1 b, 2 j or 1 j | Yes | 4.7 | $b^*$ mass 870 GeV | left-handed coupling | 1301.1583 |
| | Excited lepton $\ell^* \to \ell\gamma$ | $2\ e, \mu, 1\ \gamma$ | – | – | 13.0 | $\ell^*$ mass 2.2 TeV | $\Lambda = 2.2$ TeV | 1308.1364 |
| Other | LRSM Majorana $\nu$ | $2\ e, \mu$ | 2 j | – | 2.1 | $N^0$ mass 1.5 TeV | $m(W_R) = 2$ TeV, no mixing | 1203.5420 |
| | Type III Seesaw | $2\ e, \mu$ | – | – | 5.8 | $N^\pm$ mass 245 GeV | $\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0 | ATLAS-CONF-2013-019 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | $2\ e, \mu$ (SS) | – | – | 4.7 | $H^{\pm\pm}$ mass 409 GeV | DY production, BR($H^{\pm\pm} \to \ell\ell$)=1 | 1210.5070 |
| | Multi-charged particles | – | – | – | 4.4 | multi-charged particle mass 490 GeV | DY production, $\lvert q \rvert = 4e$ | 1301.5272 |
| | Magnetic monopoles | – | – | – | 2.0 | monopole mass 862 GeV | DY production, $\lvert g \rvert = 1 g_D$ | 1207.6411 |

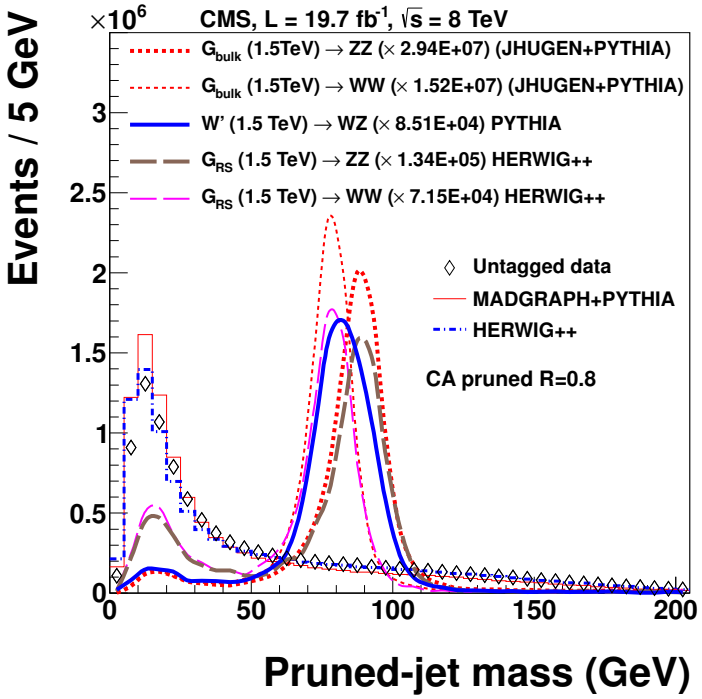
$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

$10^{-1}$ 1 10 **Mass scale [TeV]**

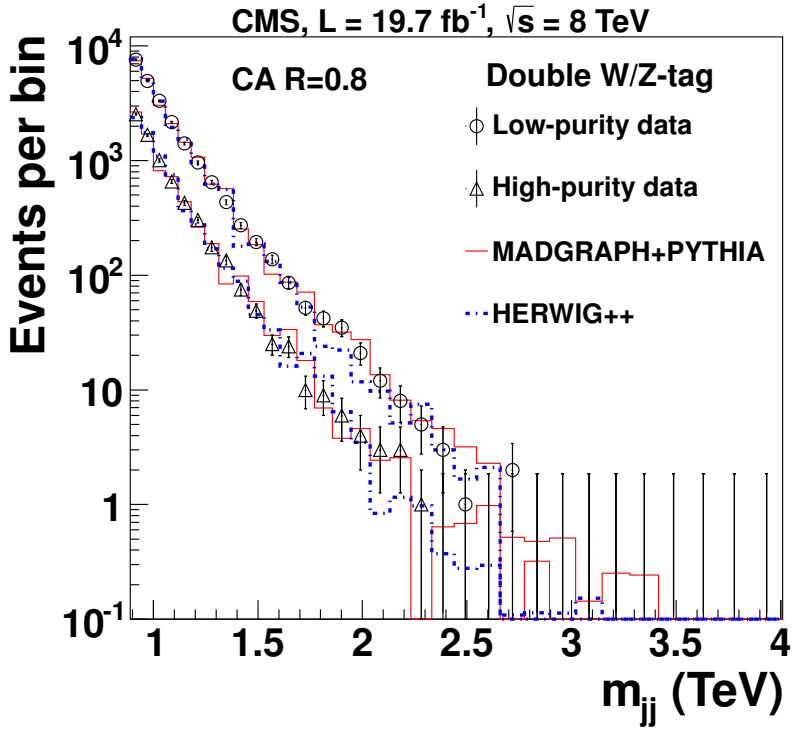
*Only a selection of the available mass limits on new states or phenomena is shown.


Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother -(1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

# *Details for the CMS all-hadronic VV Resonances Search*




Single jet mass arXiv:1405.1994

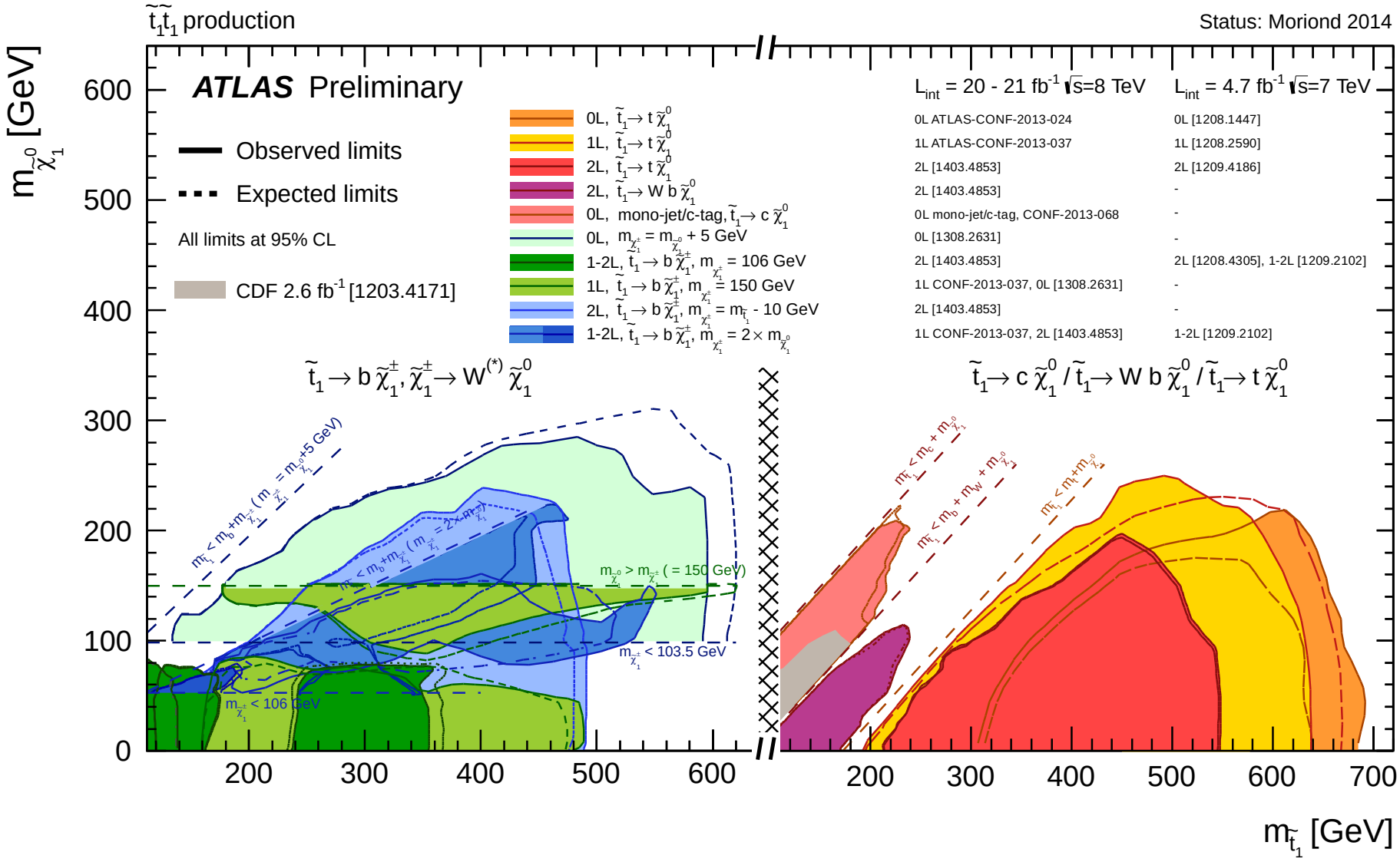



Di$-V$ invariant mass distribution arXiv:1405.1994

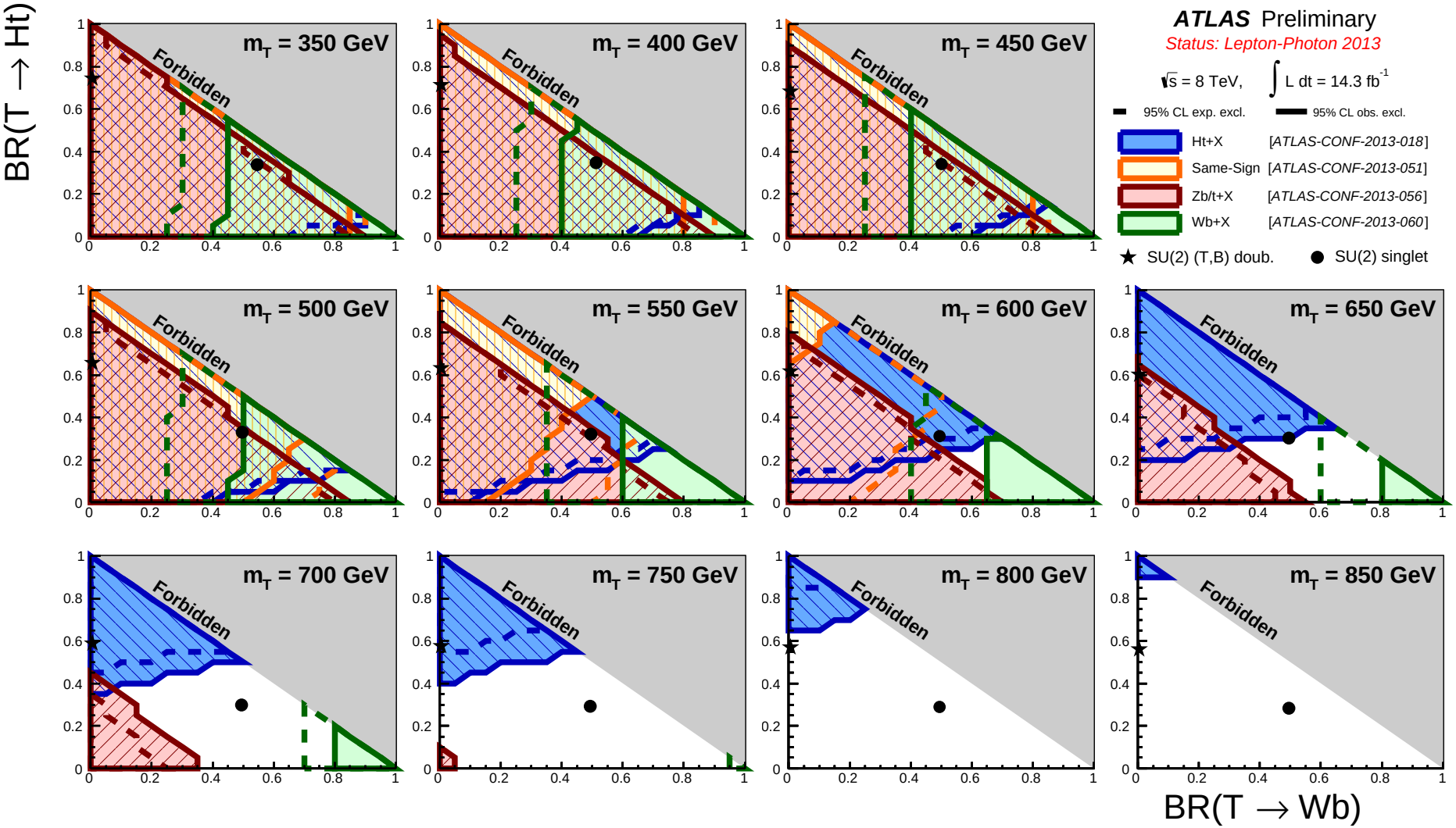
*Left:* Distribution for pruned-jet mass mj in data, and in simulations of signal and background events. All simulated distributions are scaled to match the number of events in data. MADGRAPH/PYTHIA and HERWIG++ refer to QCD multijet event simulations.

*Right:* The mjj distributions for doubly tagged events in data, and for QCD multijet (MADGRAPH/PYTHIA and HERWIG++) simulations, normalized to data.

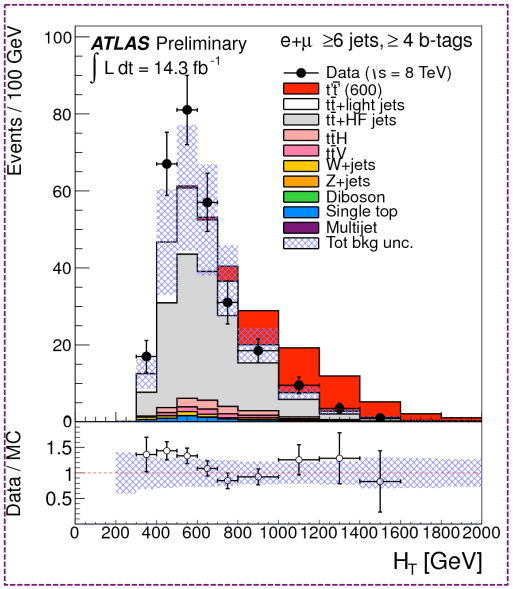
# 3rd Generation SUSY Search Summary in ATLAS



# *Summary of Constraints on T′ from ATLAS*



# *Summary of Analysis for T′ in ATLAS*




## Ht+X

[ATLAS-CONF-2013-018]

- Single lepton + missing $E_T$
- At least 4 jets, one or (many) more b-jets

≥ 6 jets

≥ 4 b-tags

Test $H_T$(all)

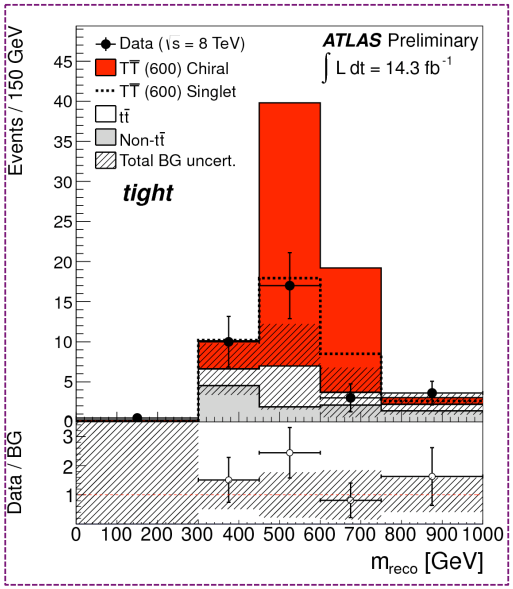
## Wb+X

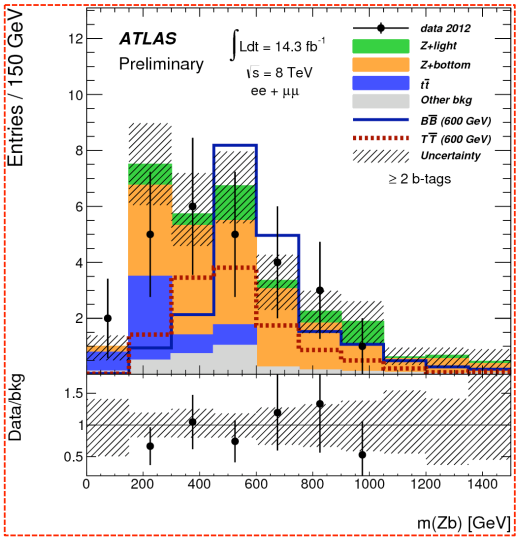
[ATLAS-CONF-2013-060]

Reco high-$p_T$ $W_{had}$

Reco WbWb system

Test $M(W_{had}b)$




## Zb/t+X

[ATLAS-CONF-2013-056]

- OS/SF leptons
- Z candidate
- High $p_T$(Z)
- ≥ 2 b-jets
- Large $H_T$(jets)

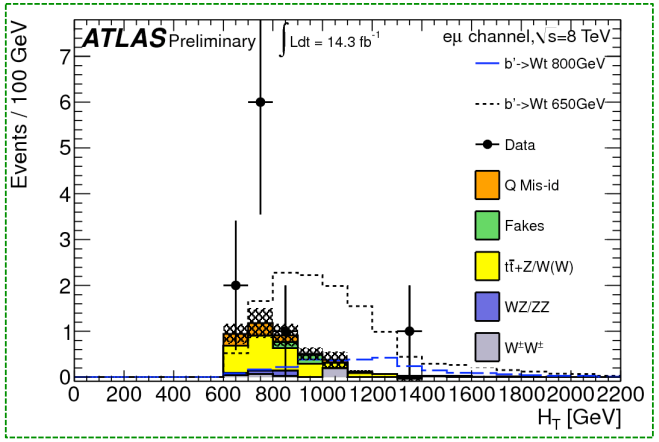
Test m(Zb)

## Same-Sign

[ATLAS-CONF-2013-056]

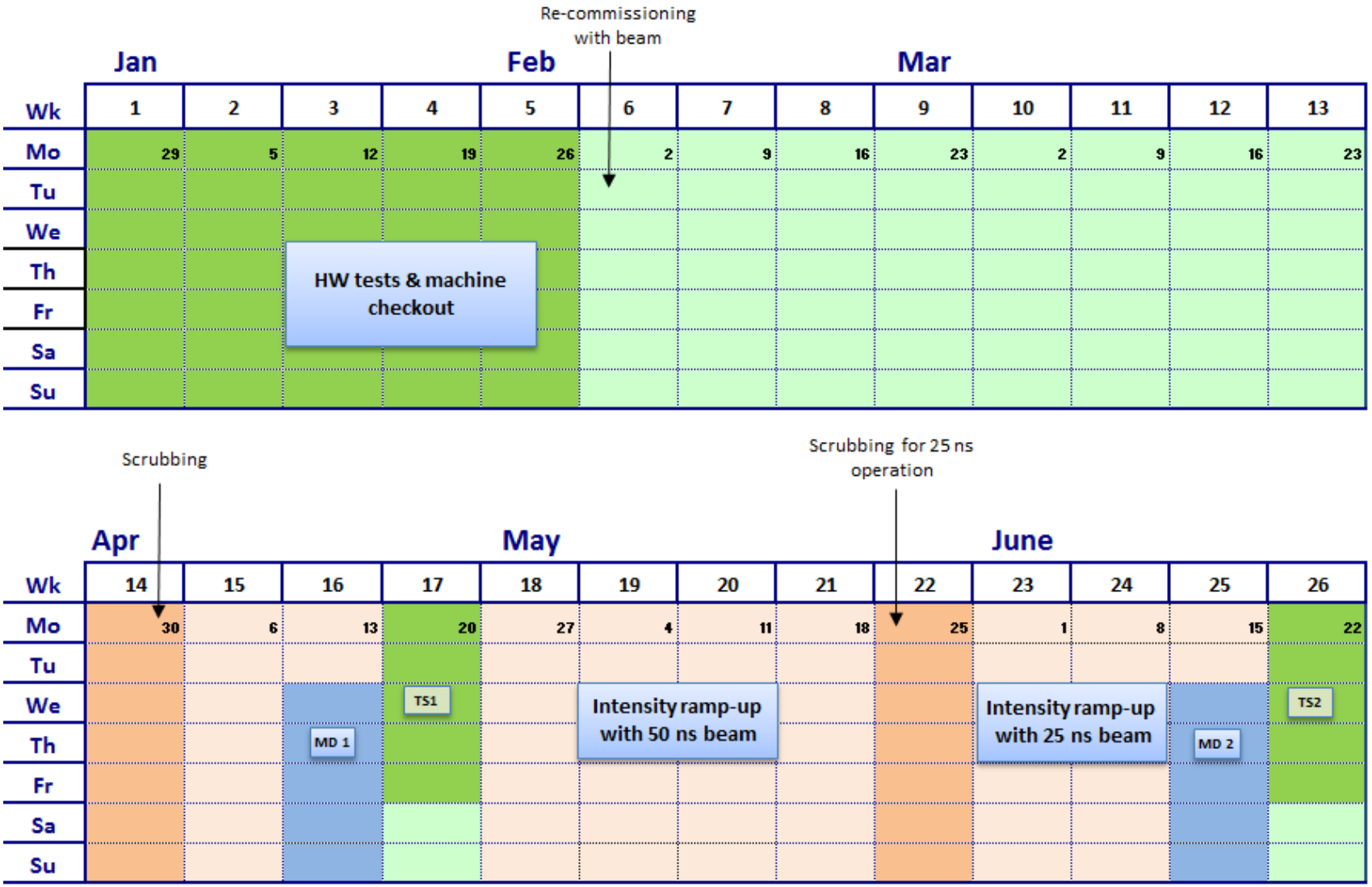
- SS leptons
- Missing $E_T$
- ≥ 2 jets
- ≥ 1 b-jets
- Large $H_T$(all)

Count



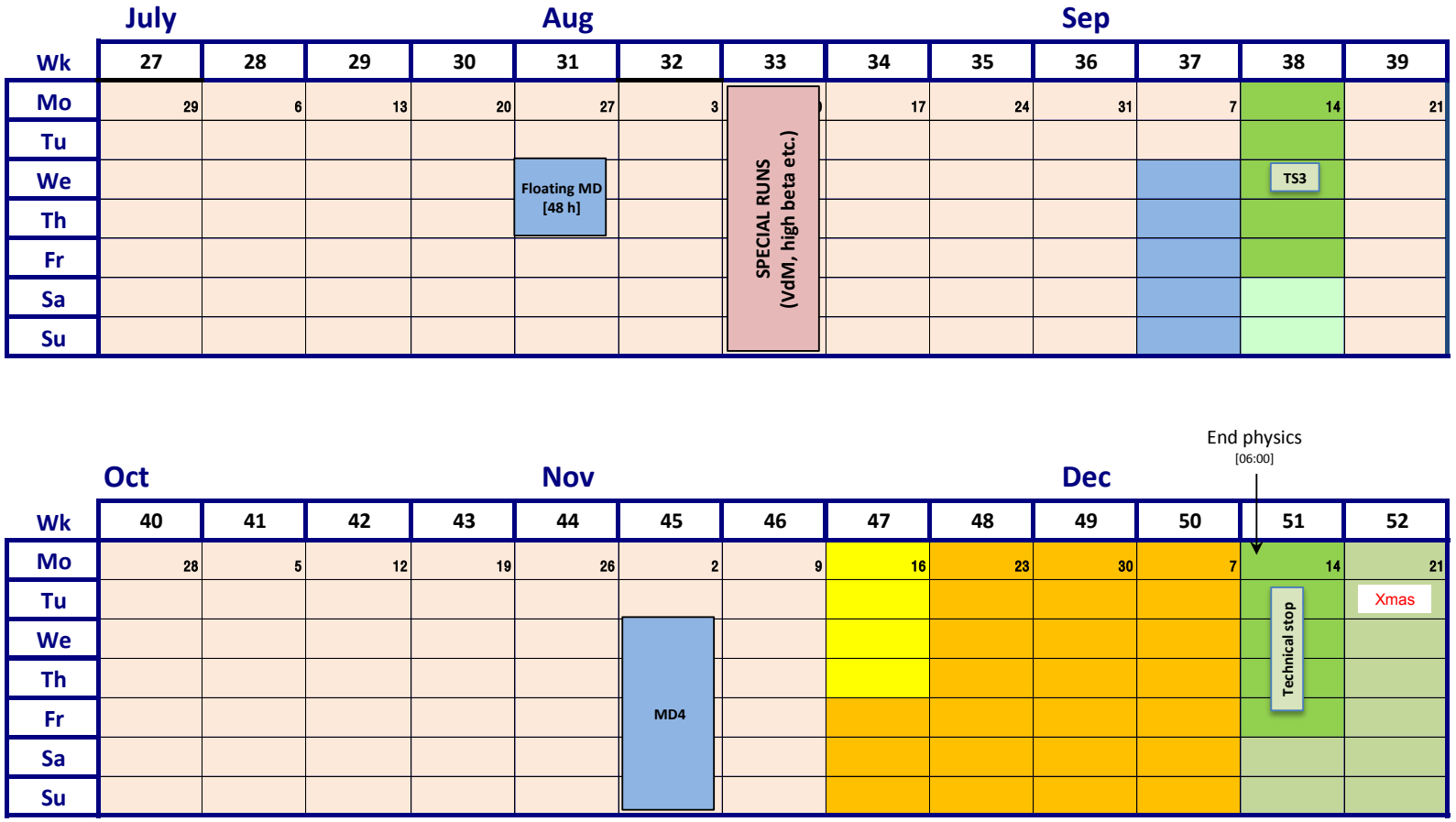
# *The LHC Plan for Early Run II*

http://lhc-commissioning.web.cern.ch/lhc-commissioning/2015/2015-commissioning-outline.htm



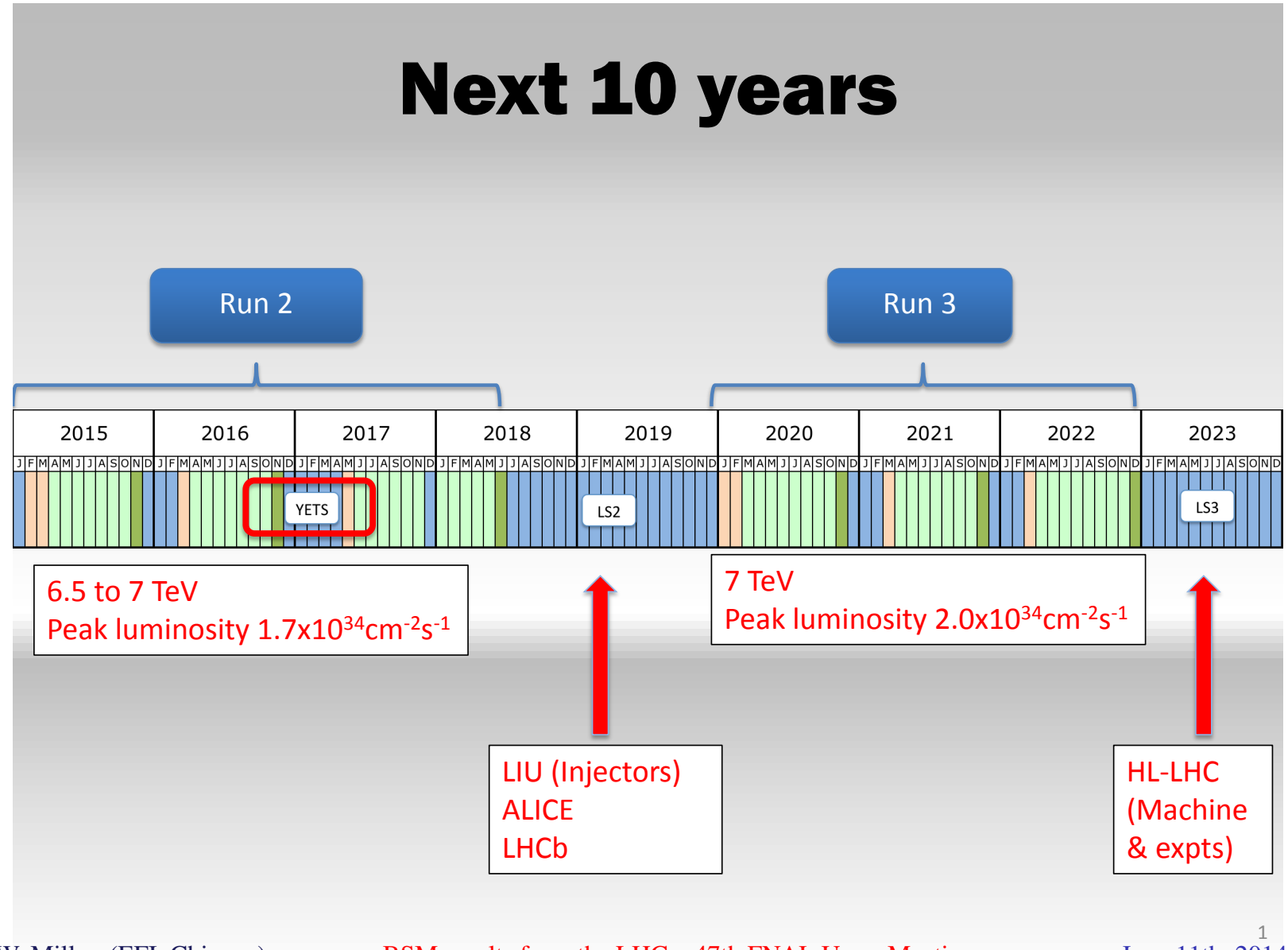
# *The LHC Plan for Early Run II*

http://lhc-commissioning.web.cern.ch/lhc-commissioning/2015/2015-commissioning-outline.htm



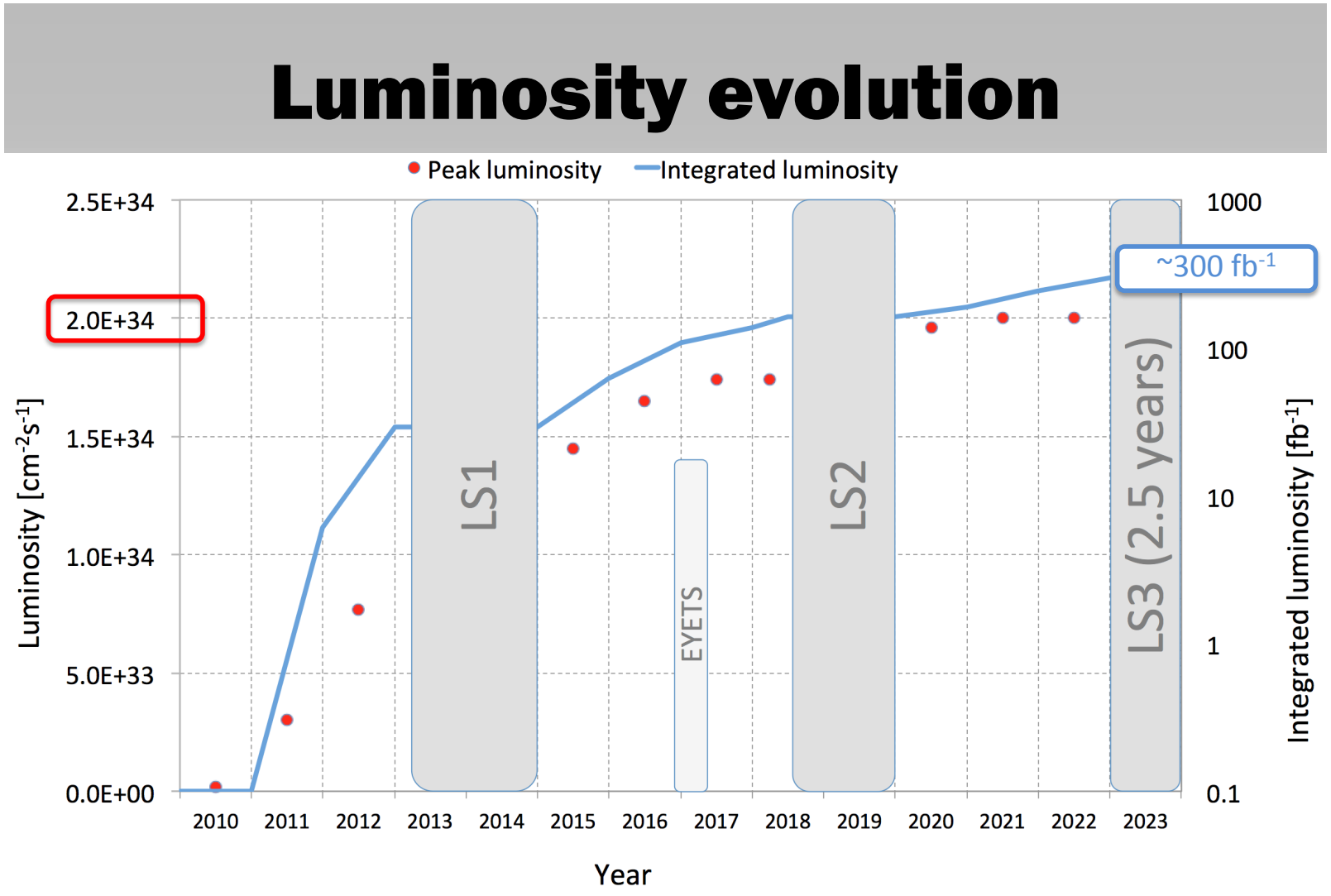
# *Long-Term LHC Plan*

http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm

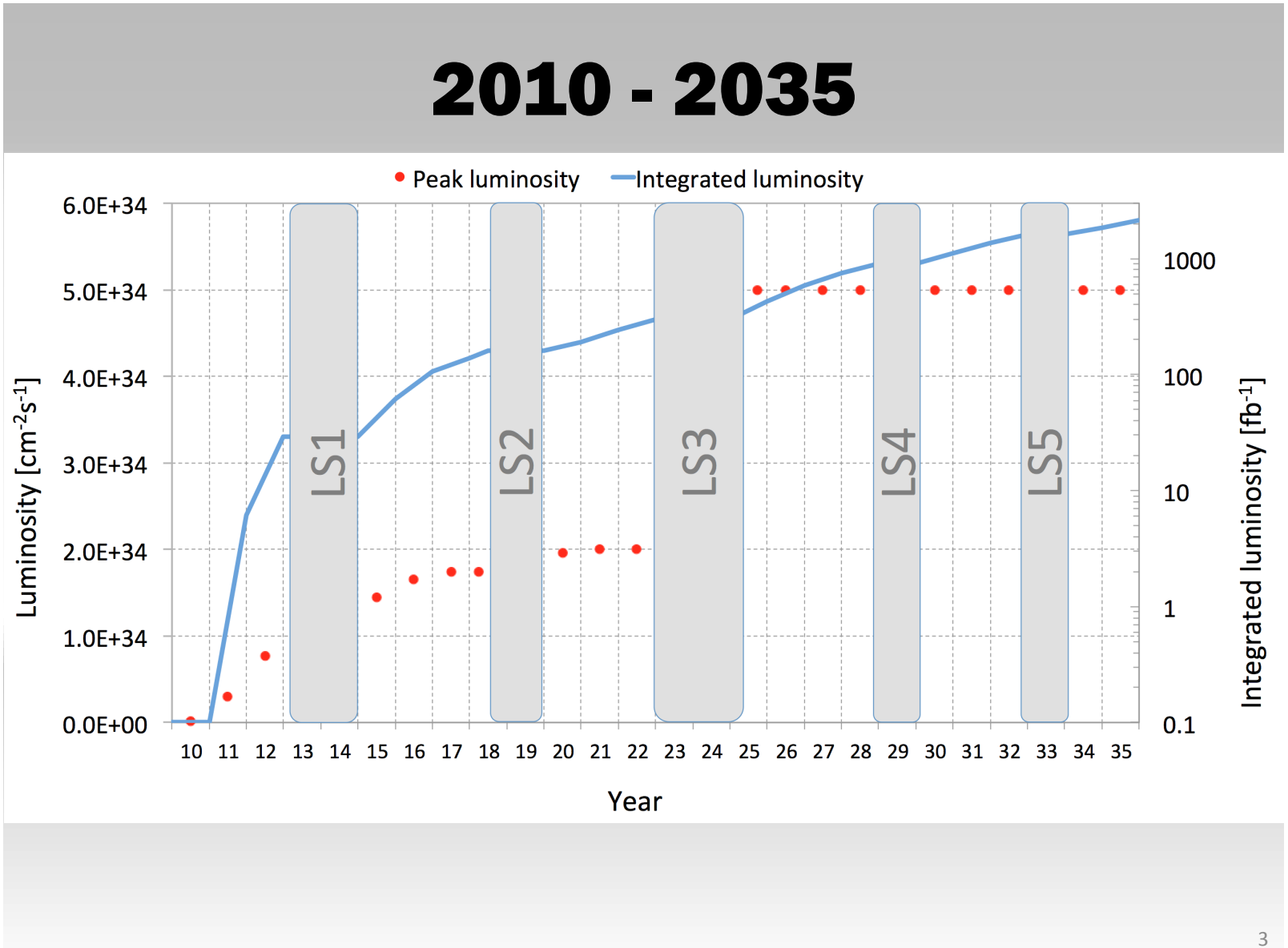


# *Long-Term LHC Plan*

*http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm*




Usual caveats apply

# *Long-Term LHC Plan*

http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-long-term.htm