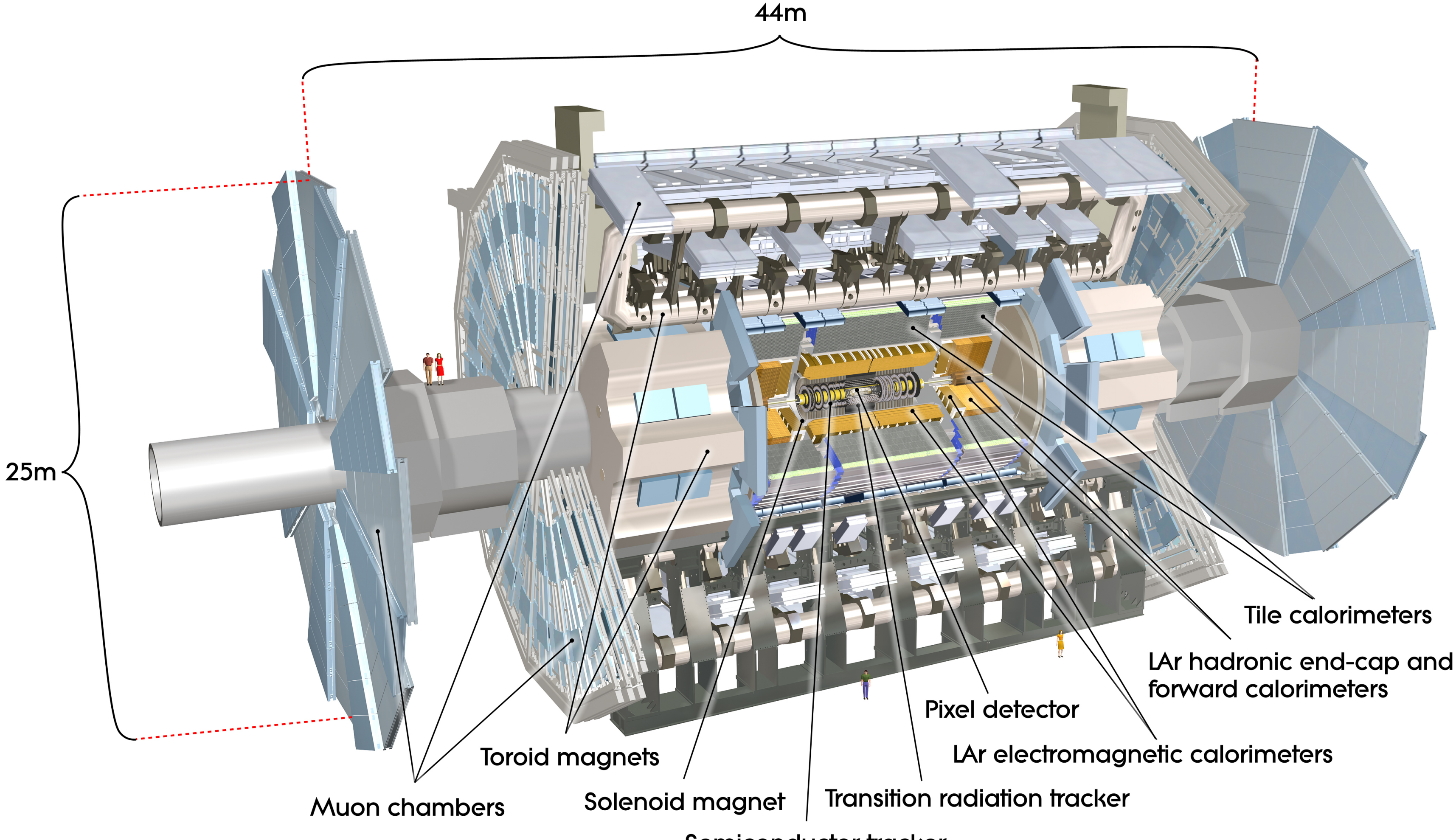
# Dark mattet at LHC
# (Mostly ATLAS)

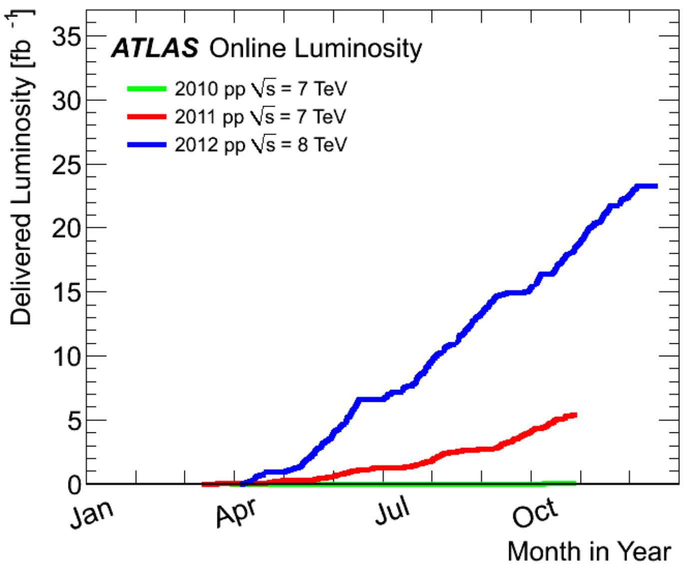
## Ian Hinchliffe

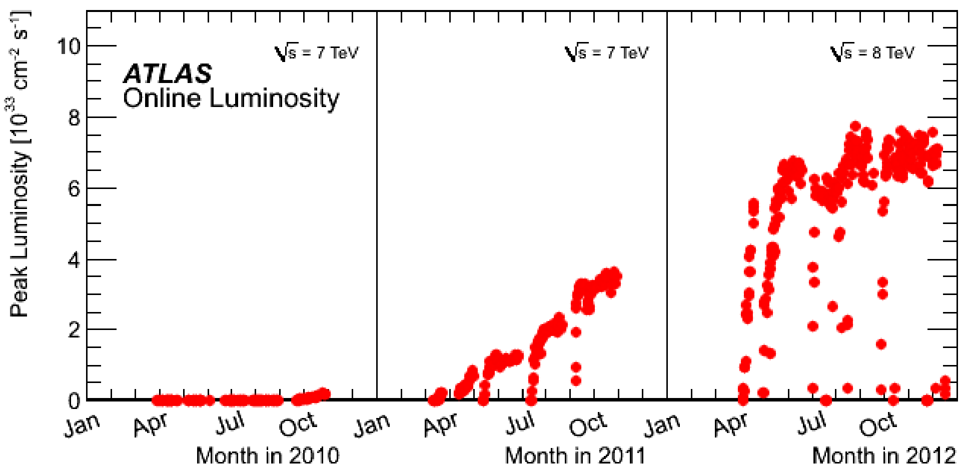
LBNL



# Superb LHC and ATLAS performance

- This talk would not be possible without it.
- No time to pay due credit to those involved
  - You are all in their debt
- I will show results from pp at 7 TeV and 8 TeV
  - Some 8 TeV data analysis is incomplete





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# Dark matter at LHC

- Might produce DM particle
  - Either directly
  - Or in decay of other new particles
  - Stability of particle protected by quantum number
    - Particles produced in pairs
- All limits will be model dependent
- If a candidate is observed
  - Cannot prove it is stable
  - Can constrain couplings and mass
- If a candidate is not observed
  - Can exclude a particular model
  - Can only make some general statements

# Dark matter "detection" at LHC

- DM particle (wimp) produced in proton-proton collision
  - Neutral
  - Has "weak" interactions
  - Deposits no energy in detector
    - Similar to neutrino
- Events will have
  - Missing (transverse) energy ($E_t^{Miss}$)
  - Other objects produced
- Events must be triggered
  - Missing transverse energy
  - Other objects, e.g jets or leptons (muon or electron)

# Higgs and Dark Matter

- A very simple well defined model
  - Higgs decays to pairs of DM particles
  - DM particles only couple to matter via Higgs ("Higgs Portal")
- Measurements of Higgs properties can constrain this
  - DM contributes to "Invisible Higgs decays"
  - Invisible width limited by experiment
    - $M_{DM}<M_H/2$ has bound on coupling to Higgs
    - Bound depends on spin of DM
    - Can compare to direct searches (three spins are shown
- Powerful at low values of $M_{DM}$

"Higgs portal" model

# Higgs to "invisible"

- Uses production of Z+Higgs
- Detect Z to leptons
  - (Can also use Z to bbar)
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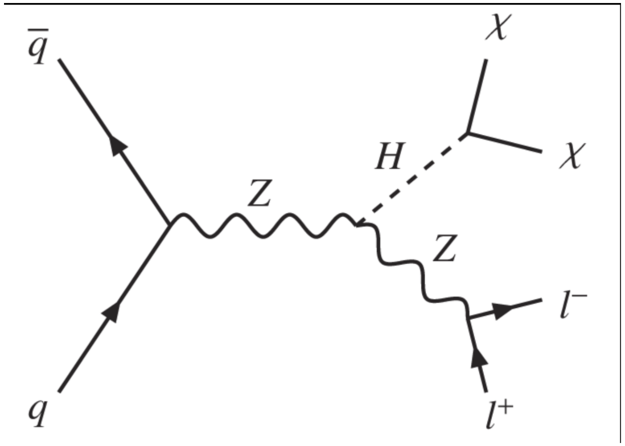


- Event selection
  - Cut A: 2 e or 2 μ, pt>20 GeV, mass consistent with Z
  - Cut B:EtMiss> 90 GeV
  - Cut C: ΔΦ(Z,Etmiss)>2.6 rad
  - Cut D: $|Etmiss – p_{TZ}|/p_{TZ} < 0.3$
  - Cut E:No jet with $p_T$>20 GeV, η<2.4
-

# Higgs to “invisible”: Backgrounds

- ZZ, WZ from MC.:Validated from data
- WW, ttbar, Wt from MC and data:
  - These make eμ final states: signal does not
- Z+jets with jet mismeasured or lost
  - Data driven using $\Delta\Phi$(Z,Etmiss) and |Etmiss – $p_{TZ}$|/$p_{TZ}$
    - Use regions outside of selections
  - Agrees within 10% with pure MC estimate
- Final background dominated by ZZ
  - Note that Higgs discovery itself validates this background.

# Higgs to “invisible”: selection

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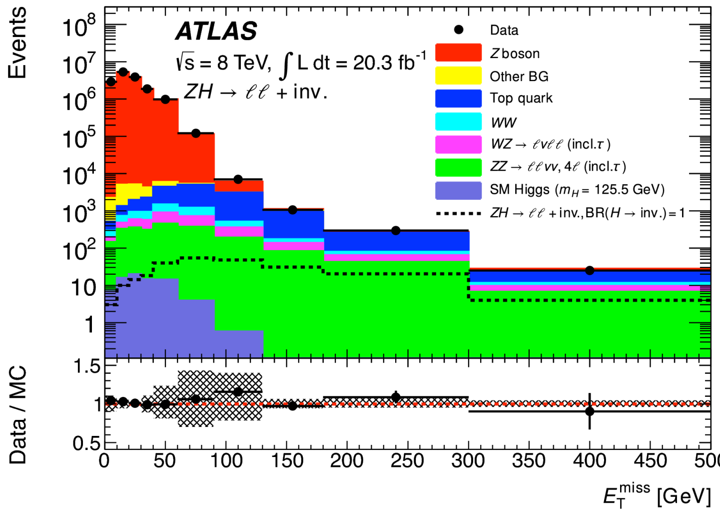
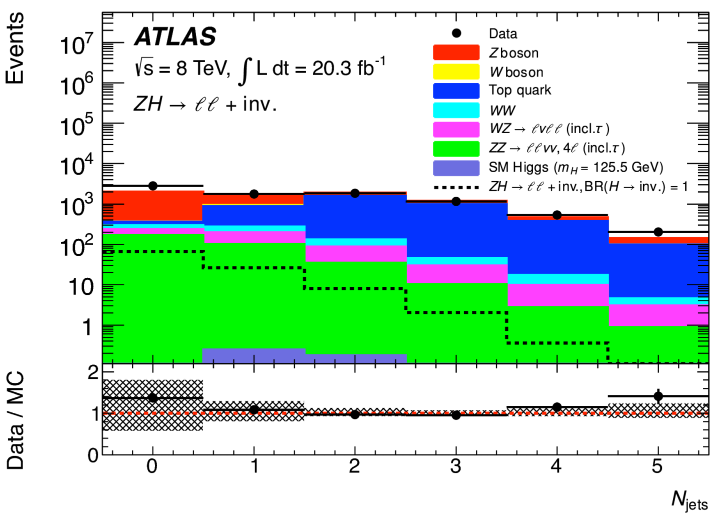
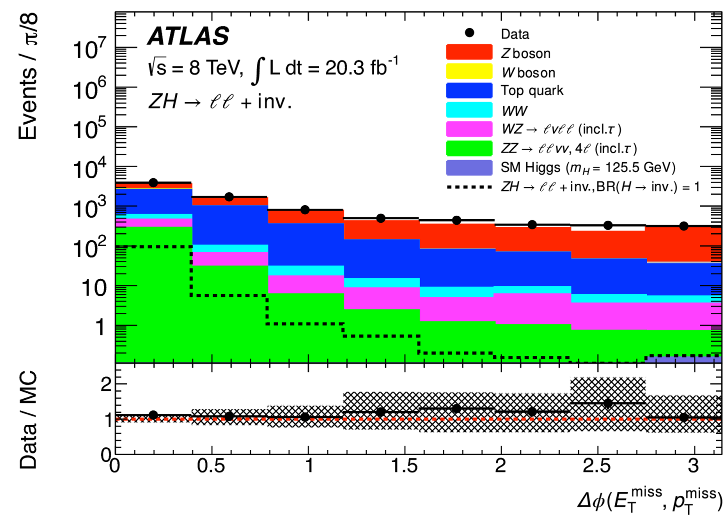


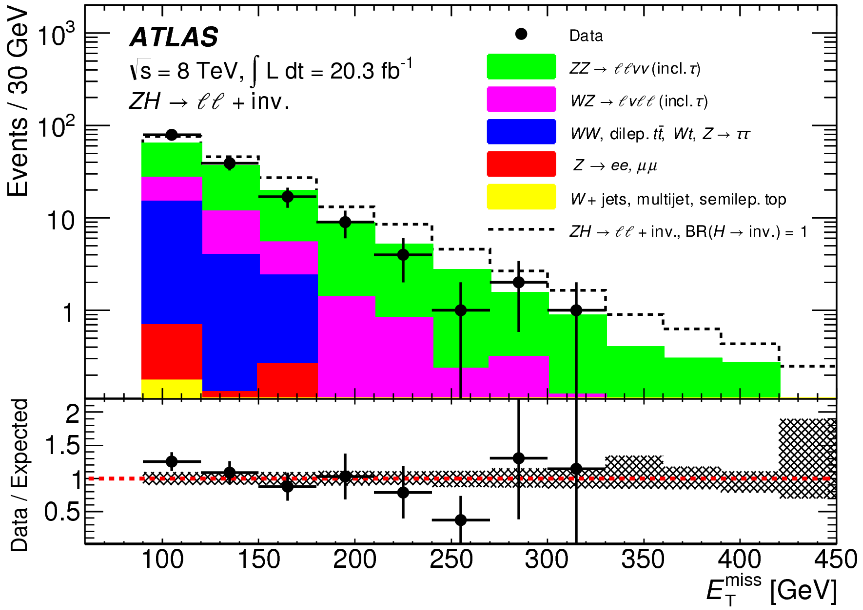

After A




After A+B



# Invisible Higgs decay: Result

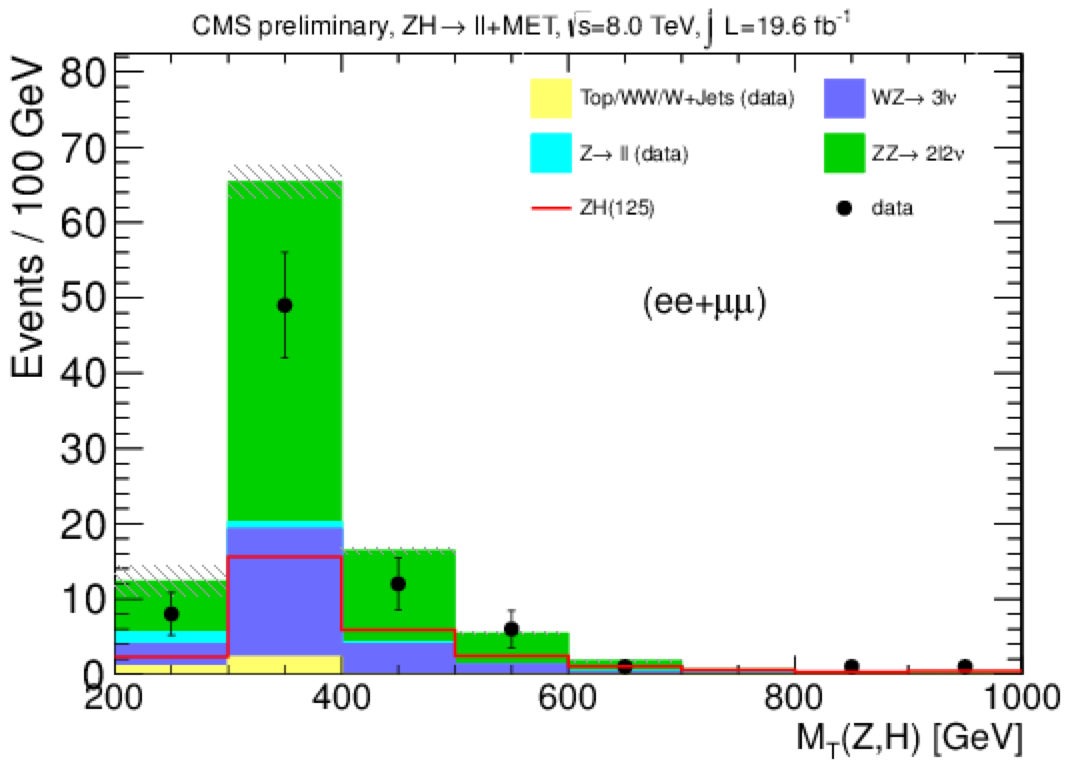



"Signal" assumes H> invisible dominates decays

Sensitive to large BR

Combined with 7 TeV data: BR(H> invisible)<75%

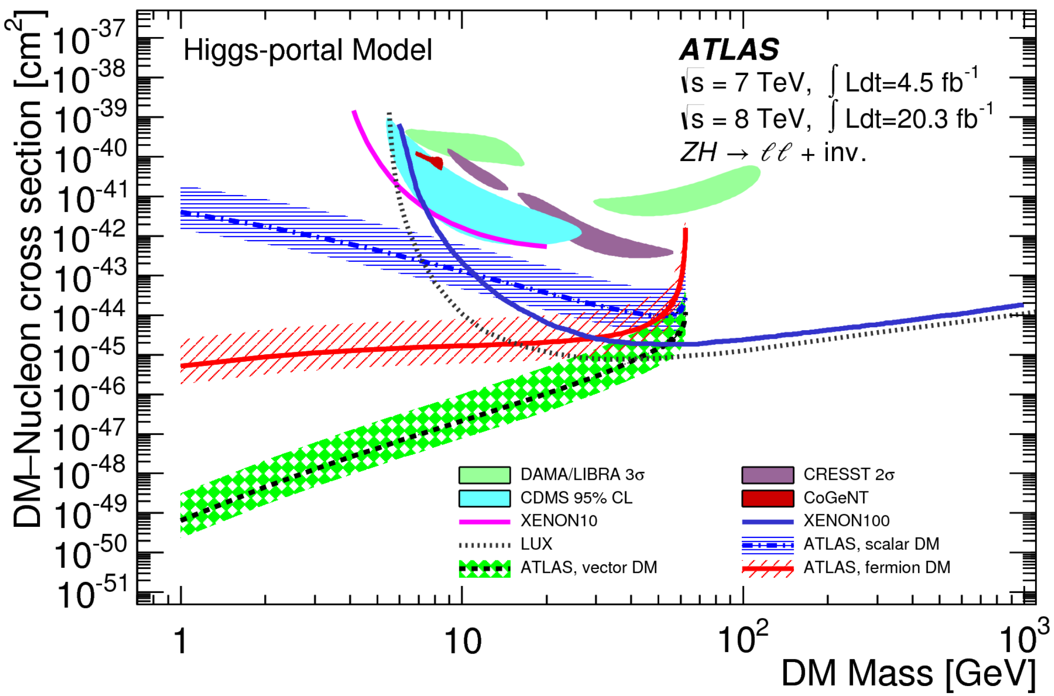
- **Analysis similar: uses transverse mass of Z+etmiss as discriminant**
- **Similar cuts on Etmiss, jet veto etc.**

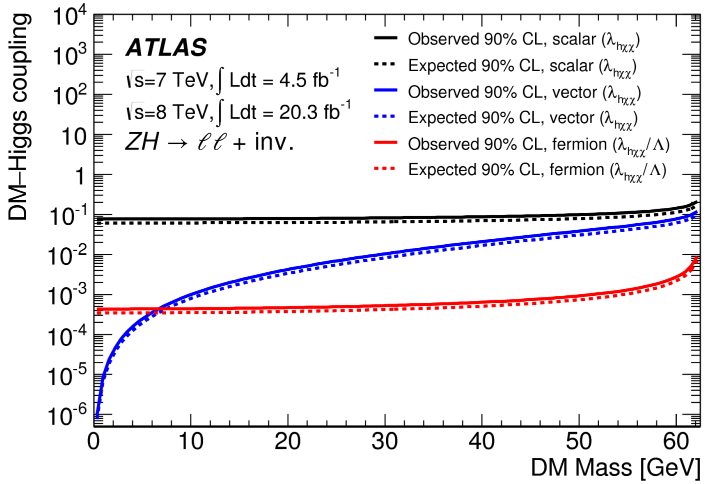



Combined with 7 TeV data: BR(H> invisible)<95%

# Higgs and Dark Matter

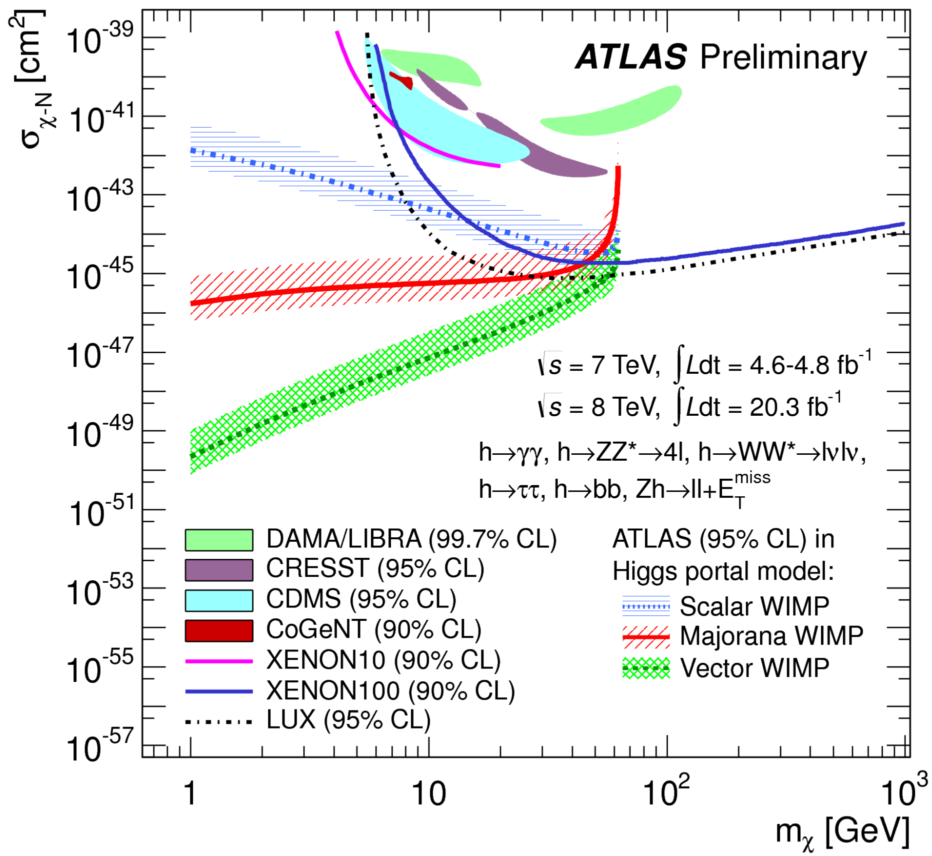
- **Translate limit to coupling of Higgs to DM**
  - **Three options: Scalar, Majorana Fermion, Vector**
  - **Compare to direct detection: Very powerful at low mass**



# Invisible Higgs: Global fit

- **Previous limit improves slightly if all Higgs data is used in a combined fit.**

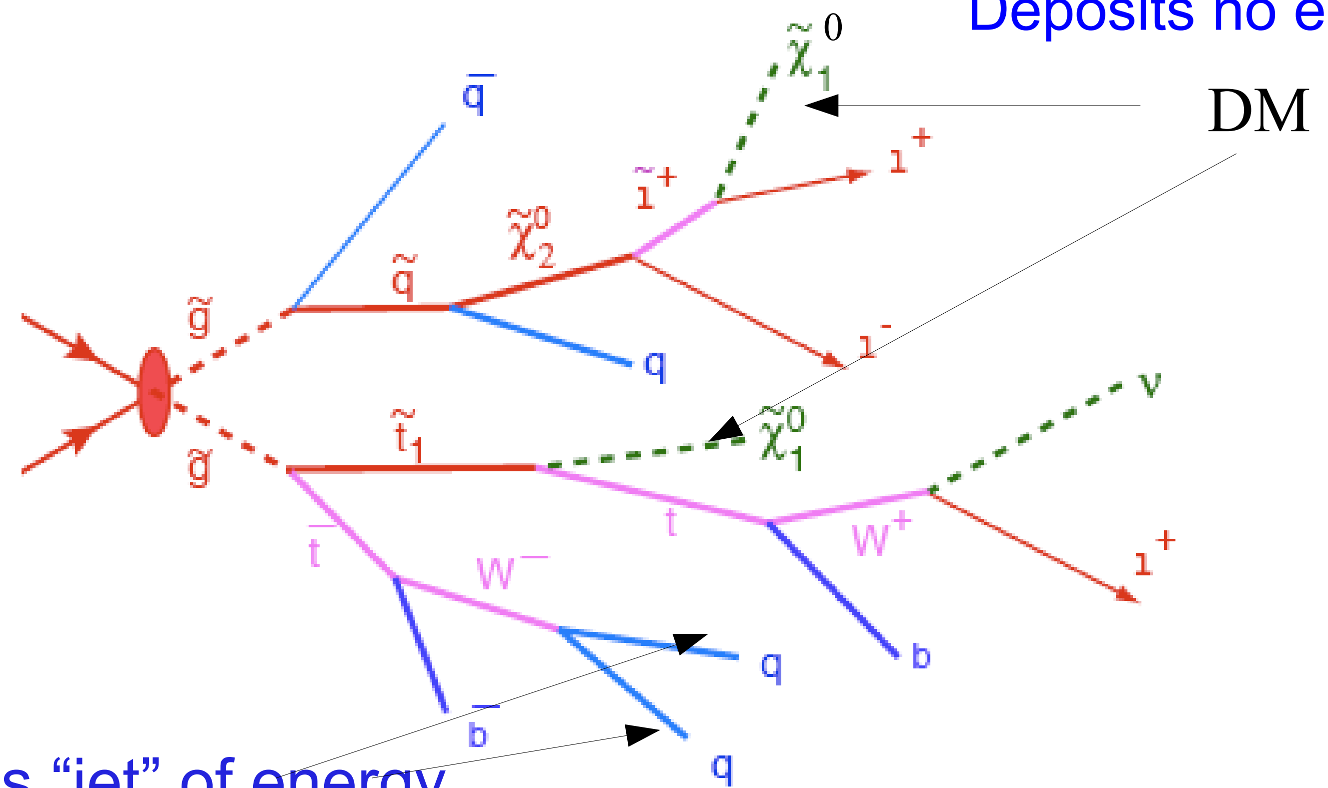


# SUSY and Dark Matter

- Supersymmetry models can provide dark matter candidates
  - R parity conservation --> Lightest SUSY particle (LSP) stable
    - Must be Neutral and probably weakly interacting
- Models have strongly interacting SUSY particles
  - Heavier than LSP
  - But production rates might be larger at LHC
- Generic searches for SUSY particles cannot be easily interpreted as Dark Matter constraints
  - Direct production of LSP small (but not negligible)
- Searches within fully defined model can provide constraints
- General statements impossible

- **Typically complicated decay at LHC**
  - **Electrons, muons, jets....**

Deposits no energy




Observed as "jet" of energy

Many searches in many models: nothing seen

# SUSY at LHC:example

## CMSSM/MSugra

- Very constrained complete model
  - relates DM to other new particles
- Very few parameters: falsifiable
- Severely constrained now (dead?) by LHC searches
  - Example next

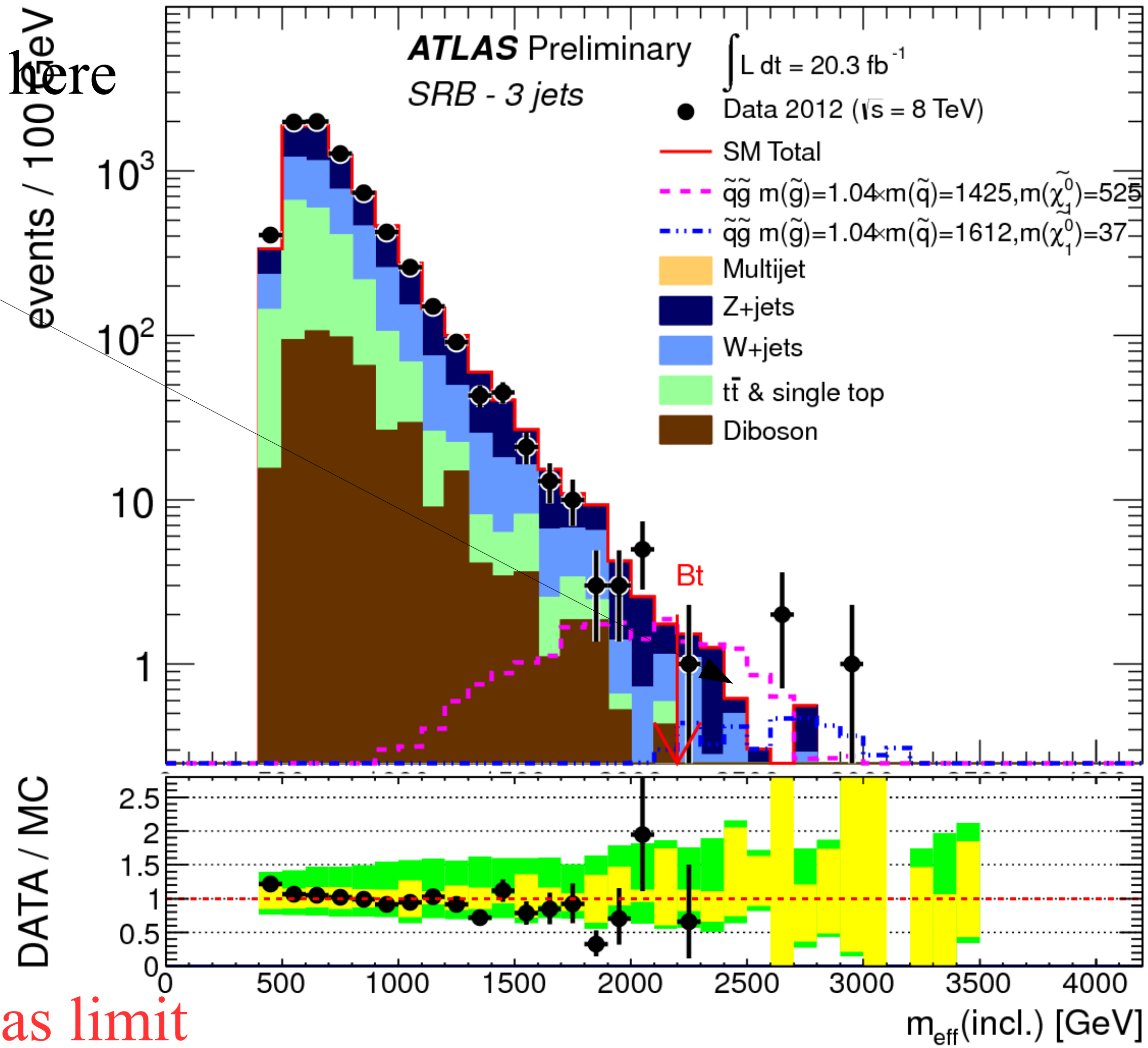
# Jets +$E_t^{miss}$: search example

- Final states can be complex
  - Quarks, gluons (jets): momenta measured
  - Leptons (electrons, muons, tau), momenta measured
  - Neutrinos, LSP: sum or transverse momenta (energy) measured: two component vector.
- Example search
  - Missing transverse energy and at least 2 jets.
  - $E_t^{miss}$ >160 GeV, $pt_{J1}$>130 GeV, $pt_{J\text{-}other}$>60 GeV
- Basic variable: $M_{eff}=\Sigma\, pt_{Jet} + E_t^{miss}$
- Look for excess at large $M_{eff}$
- Separate into final states by numbers of jets
- Backgrounds dominated by top,W/Z+jets
  - Composition varies with jet multiplicity
    - Differently than for a signal

# Jets +$E_t^{miss}$ example: 3 jets

Signal would appear here

Dominated by W/Z

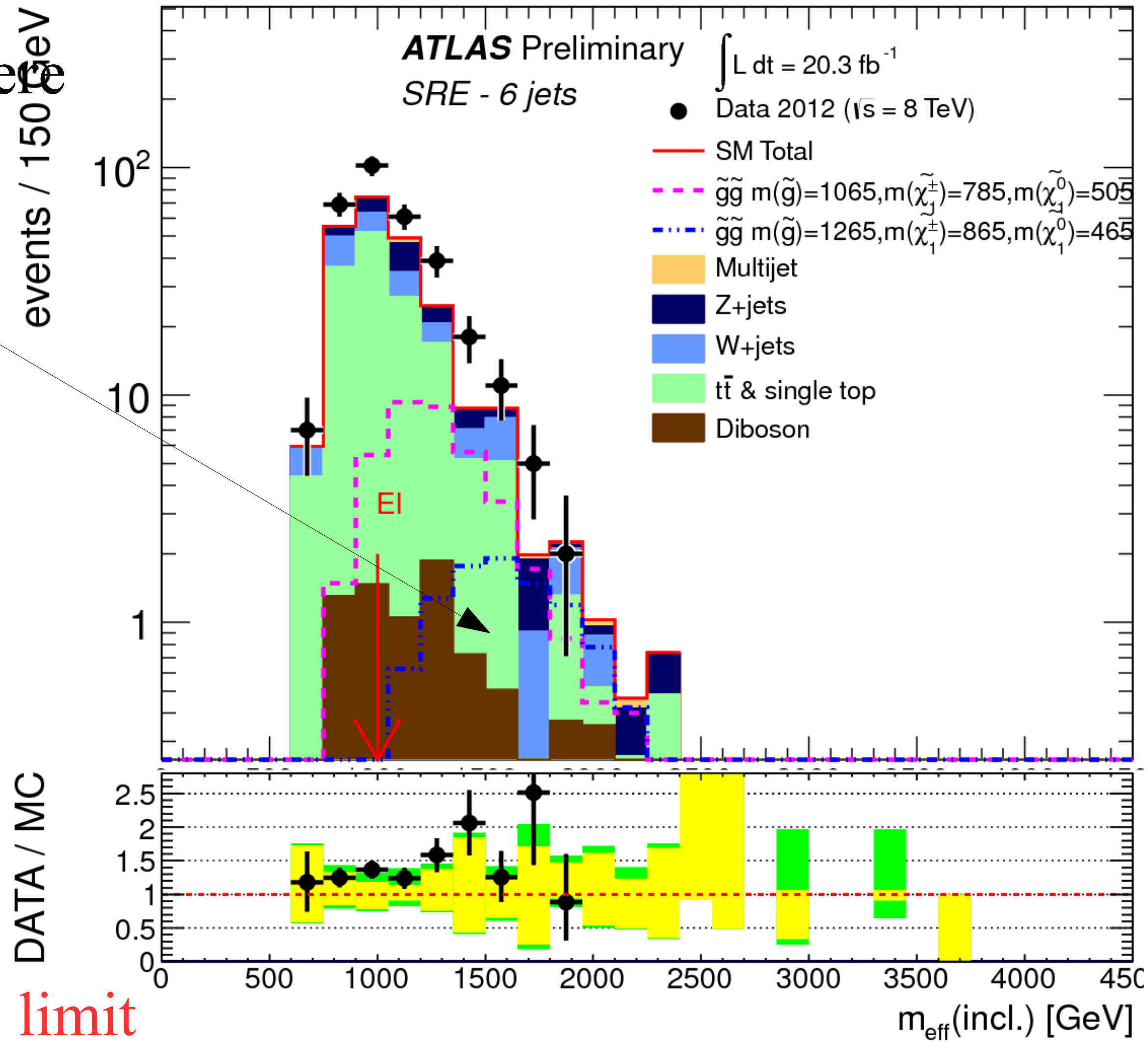



Null result interpreted as limit

# Jets $+E_t^{miss}$ example: 6 jets

Signal would appear here

Dominated by top




Null result interpreted as limit

# SUSY limits (nothing observed)

## ATLAS SUSY Searches* - 95% CL Lower Limits

**ATLAS** Preliminary

Status: Moriond 2014

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

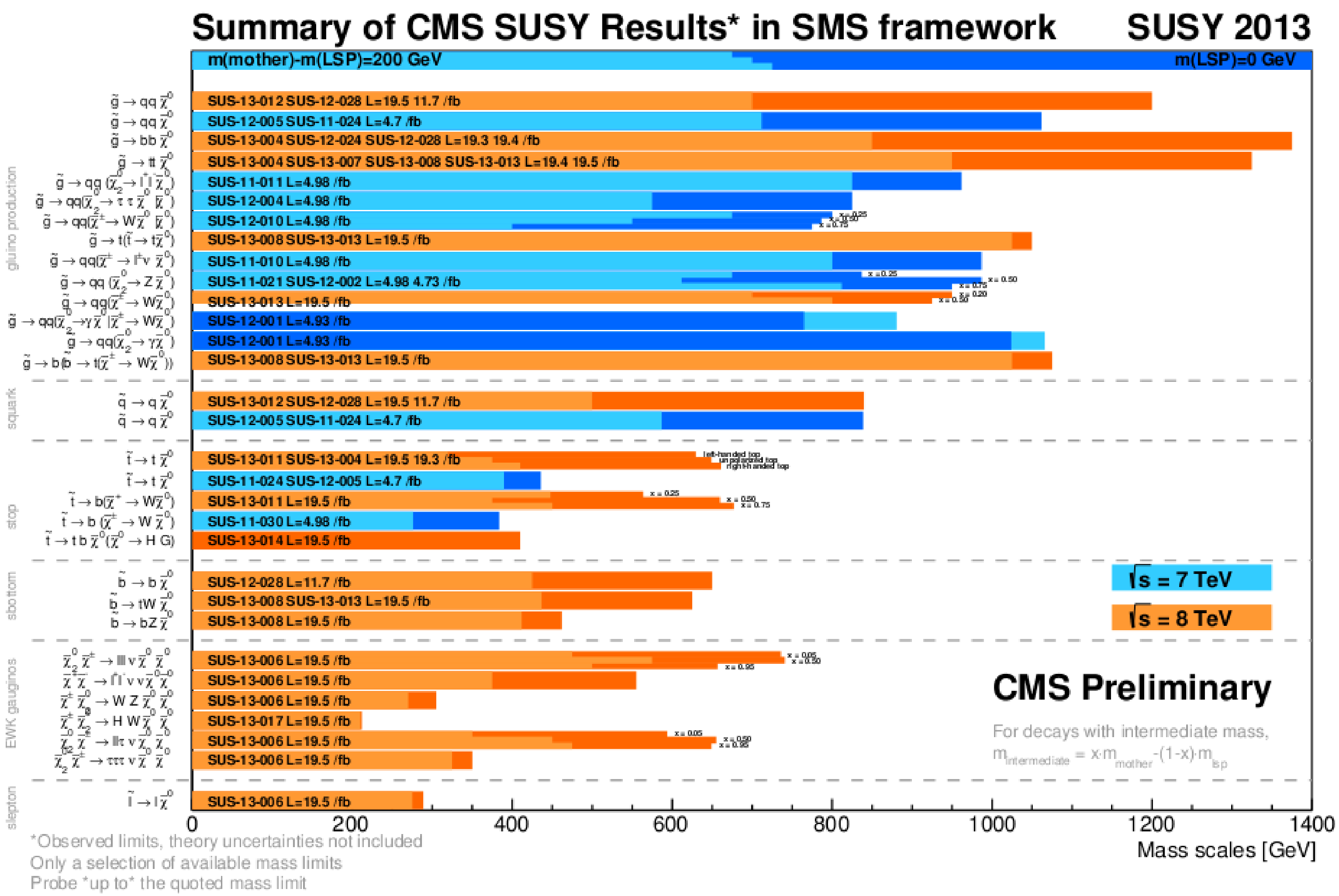
| | Model | $e,\mu,\tau,\gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$ | | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q},\tilde{g}$ | 1.7 TeV | $m(\tilde{q})=m(\tilde{g})$ | 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.

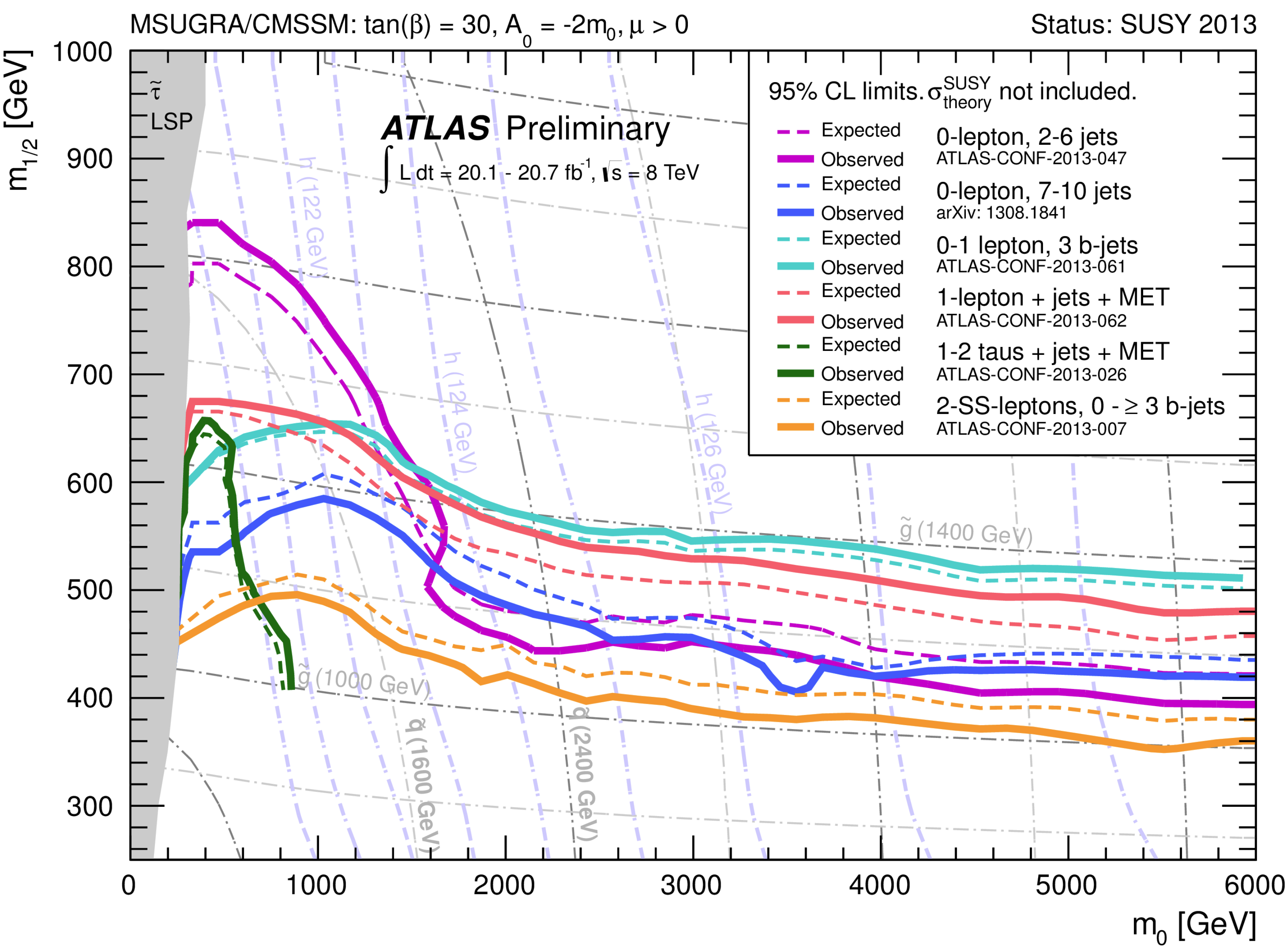
# SUSY limits (nothing observed)



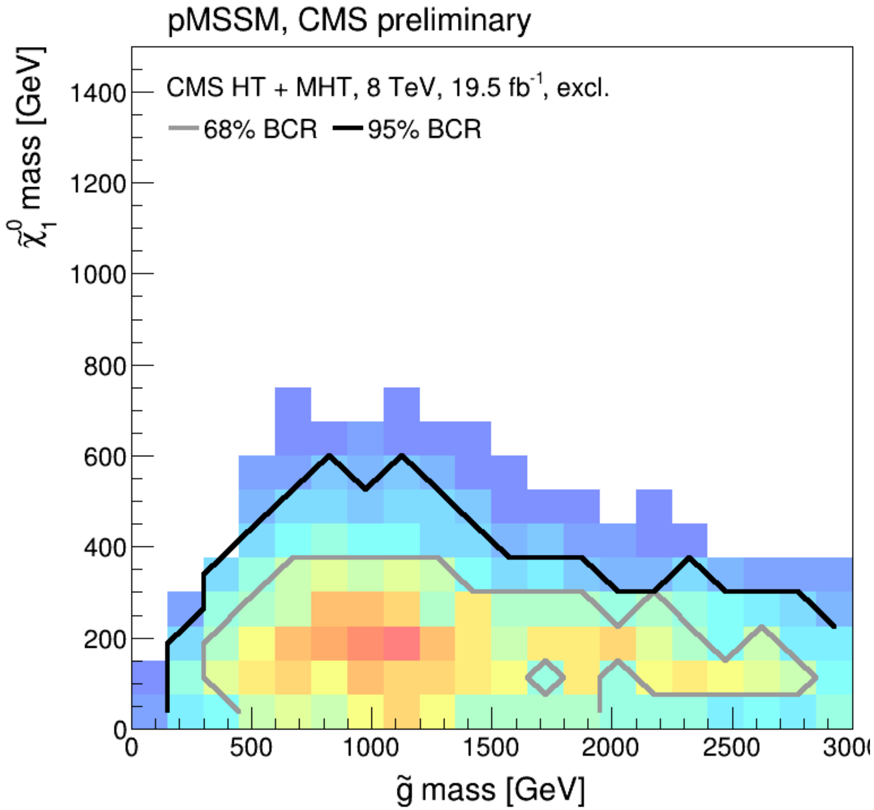
# SUSY Limits

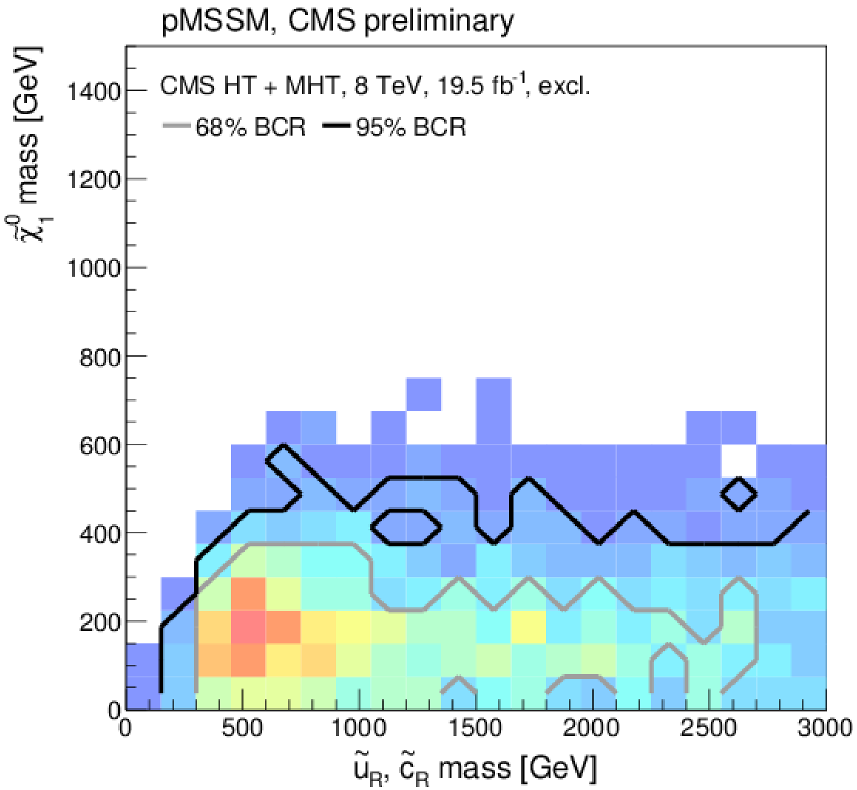
- Translating this limit to compare with Direct DM search needs a model
- Simplest CMSSM model with 5 parameters is almost dead
  - Once this is relaxed, huge number of parameters
- PMSSM is next simplest version: 19 parameters
  - Not easy to show on 2d plot
- The Baysian who knows SUSY is right can examine parameter space
  - Favoured space tends to have large DM mass.

# CMSSM: Limits



# pMSSM: Limits

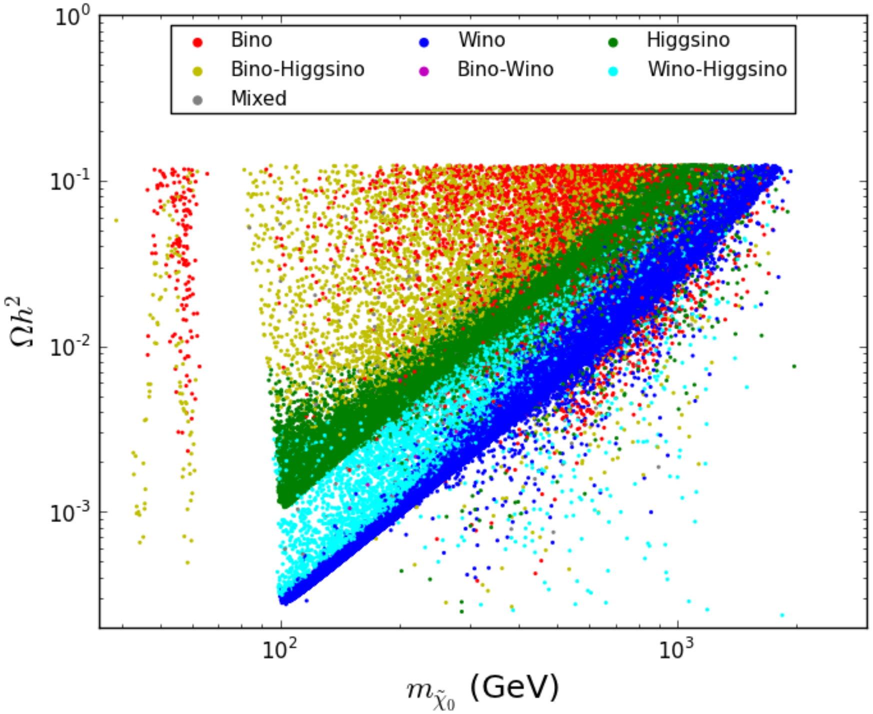


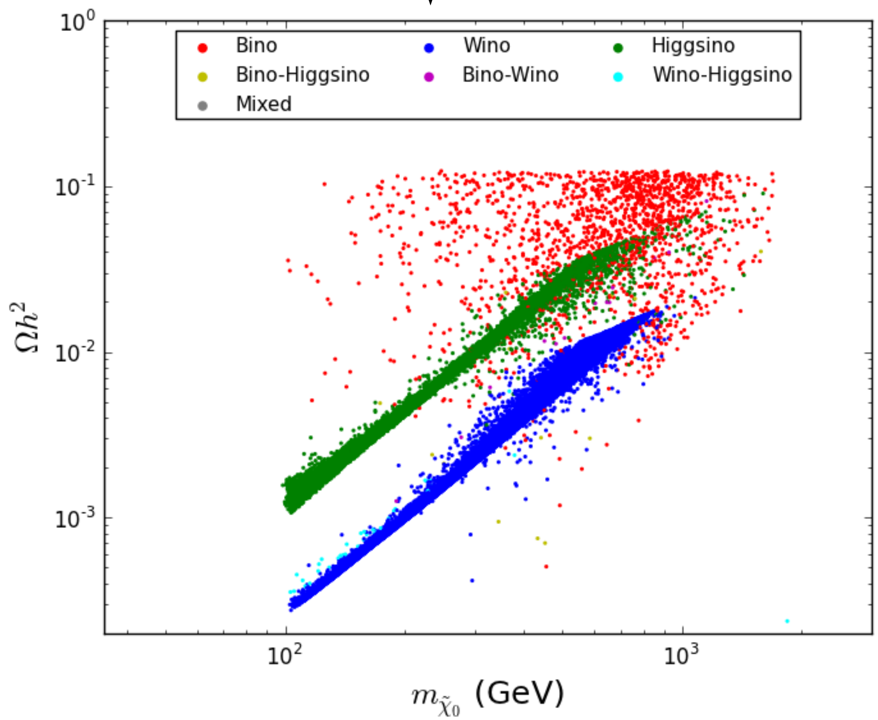
# SUSY: General statements

- Work in pMSSM
- Example here (list of refs at end)
- Some comments
  - LSP>100 GeV?
  - Hard to explain all DM with SUSY
    - Allow for something else

# PMSSM allowed?




LHC+ID+DD

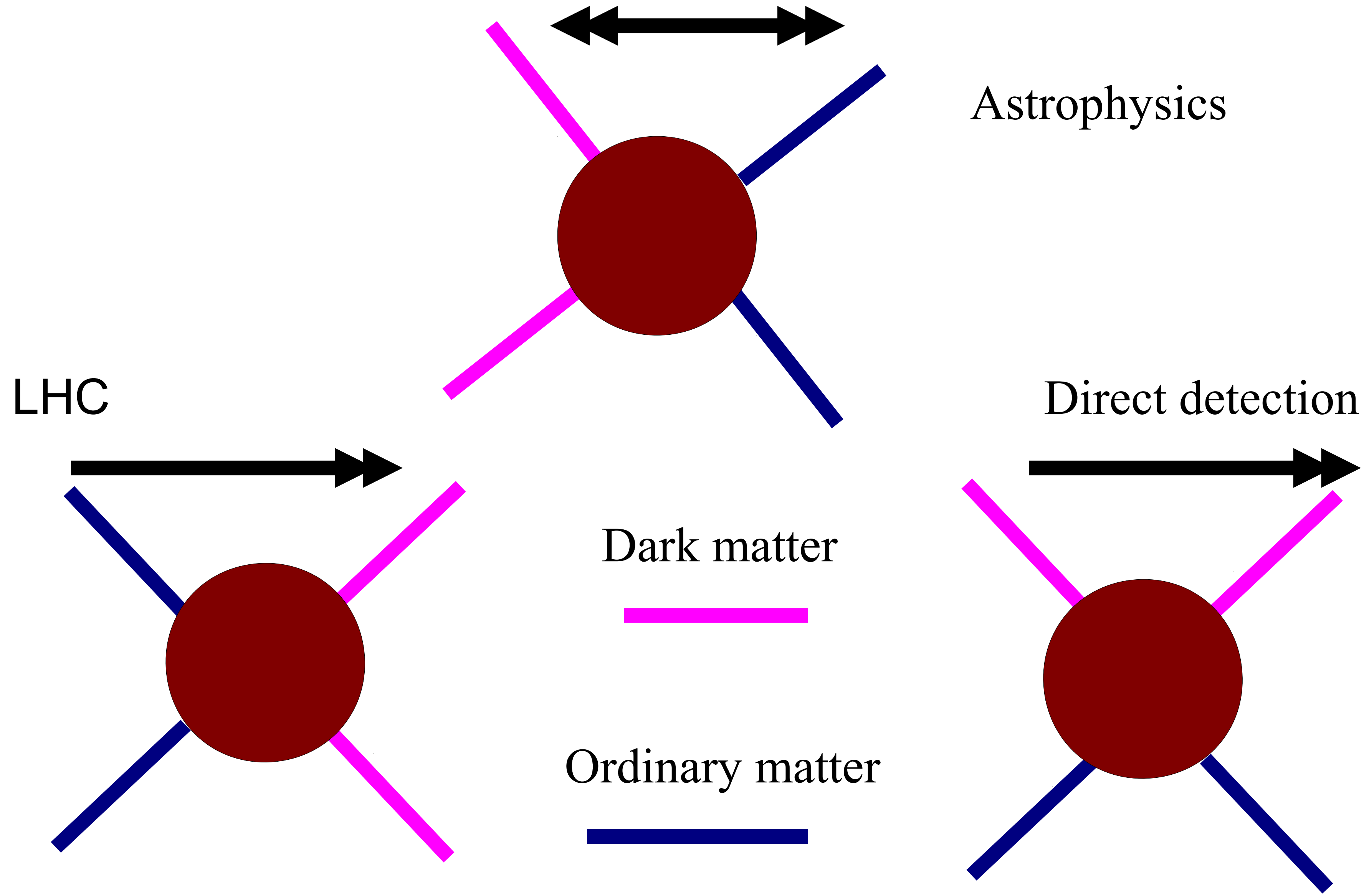



Cahill-Rowley et al

# SUSY: General statements

- **Cannot be killed**
- **Low LSP (<50 GeV) masses disfavoured.**

# Generic approach



# Generic production

- **Parameterize interactions of DM and quarks/gluons by effective operators**

| Name | Initial state | Type | Operator |
|---|---|---|---|
| D1 | $qq$ | scalar | $\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$ |
| D5 | $qq$ | vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ |
| D8 | $qq$ | axial-vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ |
| D9 | $qq$ | tensor | $\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ |
| D11 | $gg$ | scalar | $\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$ |

# Generic production

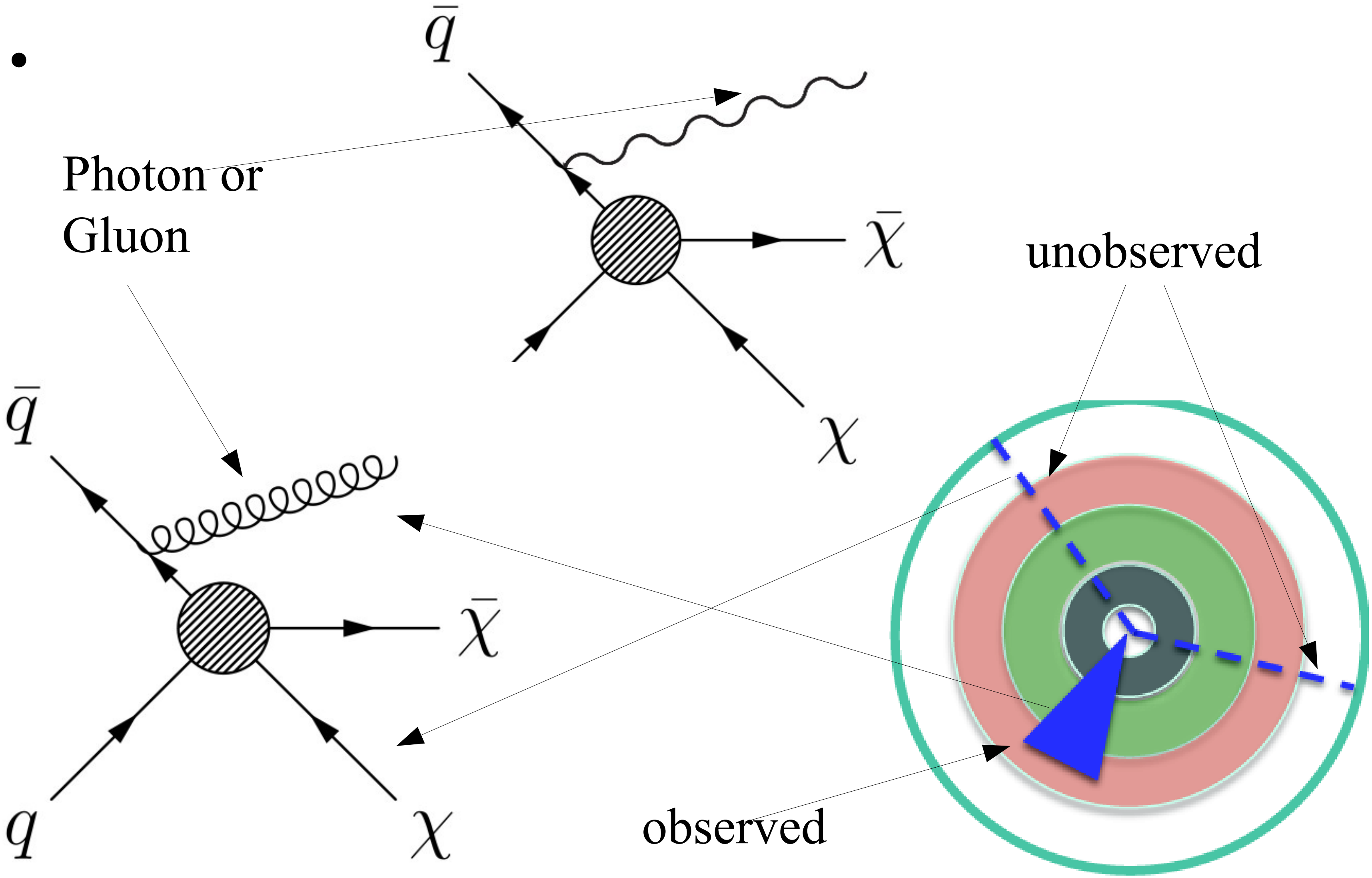
- **Parameterized by**
  - **DM mass**
  - **Interaction strength (M*)**
- **Assumptions**
  - **Only SM and DM produced**
    - **No other new particles**
  - **Interaction is treated as point**
    - **M*> kinematics of production**
- **Need something else in the event to observe**
  - **Get this by QCD or QED radiation.**
  - **Only small fraction of total production observable**

M*

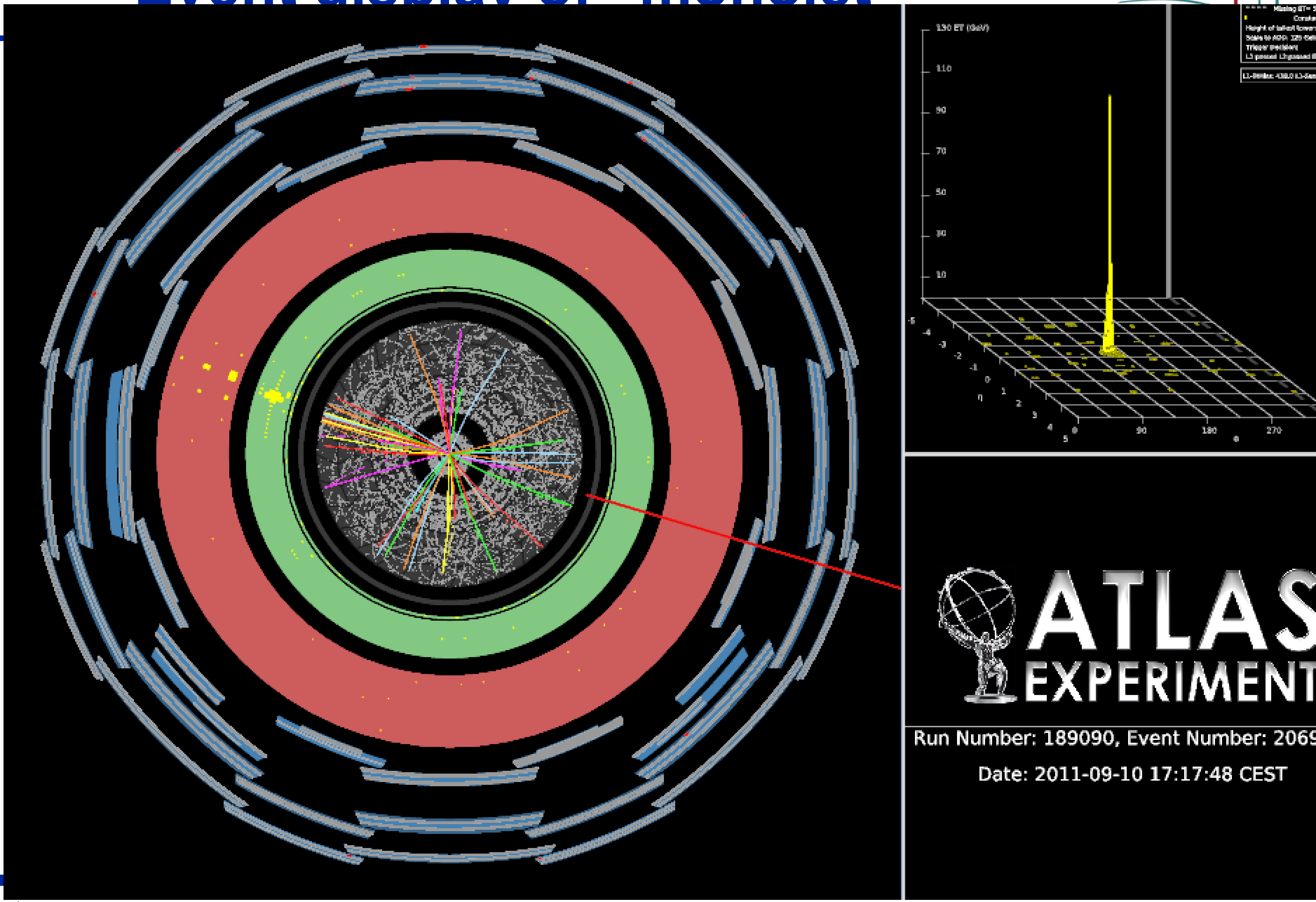
Energy of collision

m(wimp)

•


$\bar{q}$
Photon or
Gluon
$\bar{\chi}$
$\chi$
unobserved
$\bar{q}$
$\bar{\chi}$
$q$
$\chi$
observed

# Event display of "monojet"



# Search 1: Event selection: jet+$E_t^{miss}$

Uses 2011 ATLAS pp data (4.7 fb-1)

- $E_t^{miss}$ trigger (plateau above 150 GeV, 98% efficient at 120 GeV)
- Primary vertex with at least 2 associated tracks
- Biggest jet $p_T$ > 120 GeV, $|\eta|$ < 2 (central part of detector)
- $|\Delta\varphi(\text{jet2}, E^t_{miss})|$ > 0.5 in order to suppress back-to-back dijet events
- No more than two jets with pT > 30 GeV, $|\eta|$ < 4.5 (full detector range)
- no electrons with $p_T$ > 20 GeV, $|\eta|$ < 2.47
- no muons with $p_T$ > 7 GeV, $|\eta|$ < 2.5
- Four signal regions with symmetric cuts on the leading jet $p_T$ and Etmiss $p_T$, $E_t^{miss}$ > 120, 220, 350, 500 GeV
  - Look for event excess above known physics expectation
  - Each of these has different sensitivity to wimp

# Sources of background

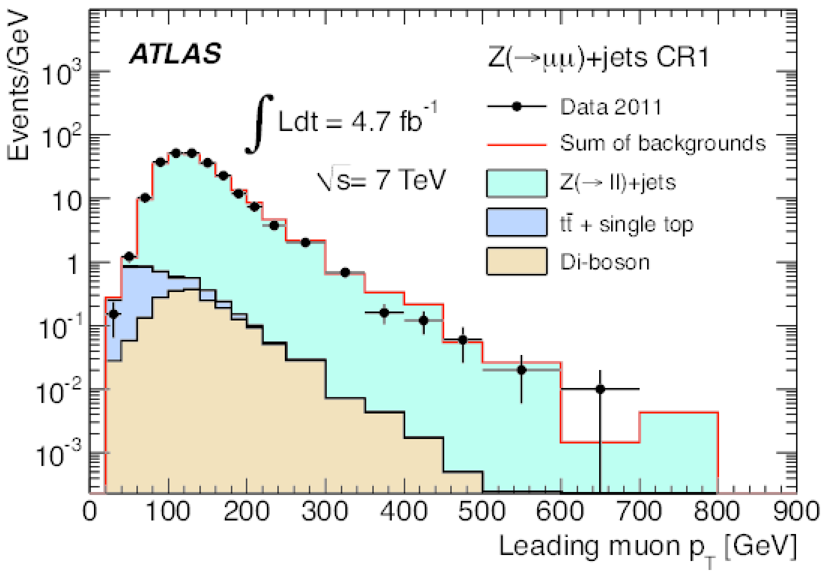
- Must mimic final state
  - Instrumental backgrounds
    - Non collision background, cosmics etc
    - Jet events with badly mis-measured or lost jet
      - Use data
  - Real physics backgrounds giving rise to same final state
    - $Z(\nu\nu)$+jets
    - $W(\mu\nu)$+jets ($\mu$ outside acceptance)
    - Top (small from MC)
    - Gauge boson pairs (WZ etc) (small from MC)
  - W/Z +jets dominates:
    - Estimate rest first then
    - Normalize from these data

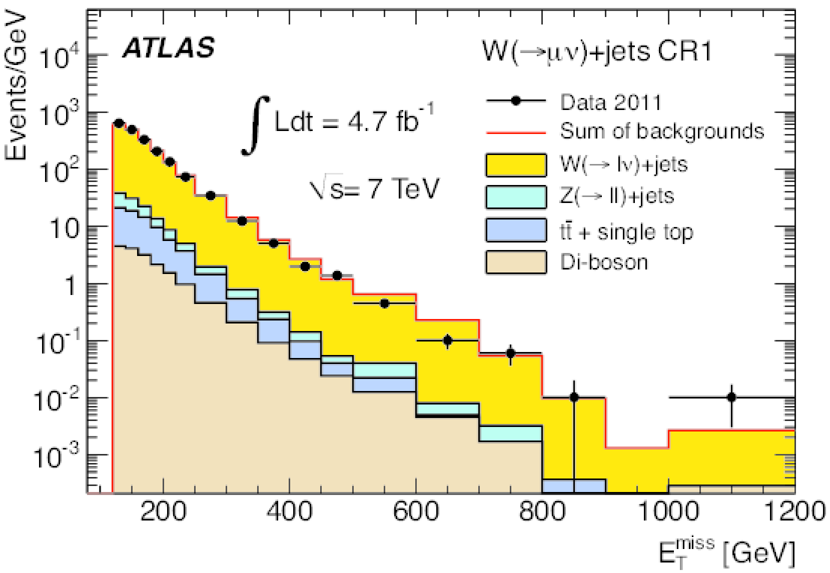
# W/Z backgrounds

- Basic idea
  - Use related process to measure
    - Eg Z-> ee
    - Limited by statistics
  - Muon leaves little energy in calorimeter
    - Use W($\mu\nu$)
    - W and Z production dynamics similar
- Define control regions
  - "replace $E_t^{miss}$ by leptons"
  - Selection contains leptons
  - Same jet selections as signal candidates
- Details in backup

# Control regions

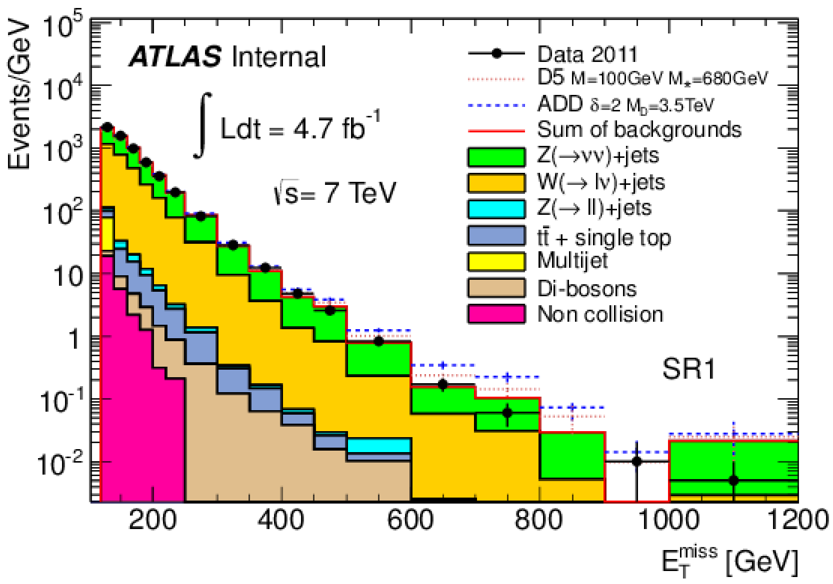
Quite well modeled
Therefore corrections applied to MC are small

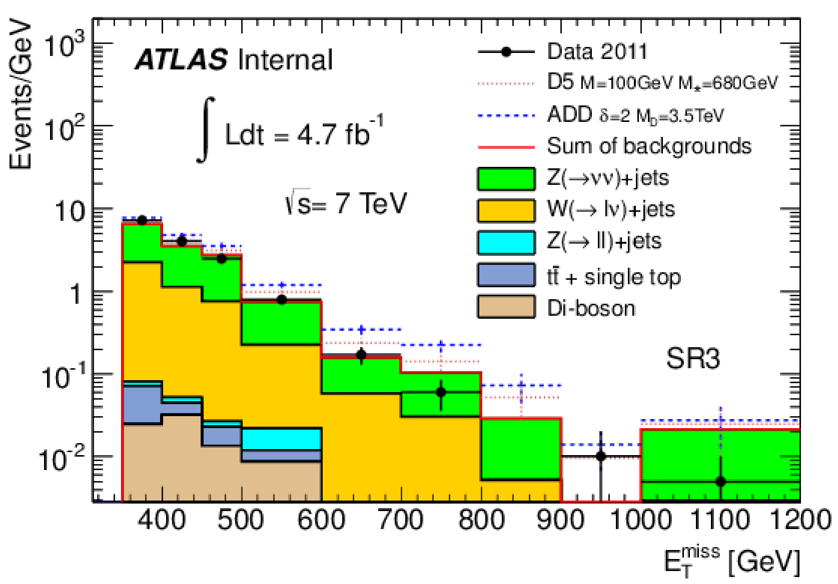


# Signal regions

New physics examples show excess at large values



# Jet Results: events observed

| Etmiss, Pt (jet | 120 GeV | 220 GeV | 350 GeV | 500 GeV |
|---|---|---|---|---|
| | SR1 | SR2 | SR3 | SR4 |
| $Z \to \nu\bar{\nu}$+jets | 63000 ± 2100 | 5300 ± 280 | 500 ± 40 | 58 ± 9 |
| $W \to \tau\nu$+jets | 31400 ± 1000 | 1853 ± 81 | 133 ± 13 | 13 ± 3 |
| $W \to e\nu$+jets | 14600 ± 500 | 679 ± 43 | 40 ± 8 | 5 ± 2 |
| $W \to \mu\nu$+jets | 11100 ± 600 | 704 ± 60 | 55 ± 6 | 6 ± 1 |
| $t\bar{t}$ + single $t$ | 1240 ± 250 | 57 ± 12 | 4 ± 1 | - |
| Multijets | 1100 ± 900 | 64 ± 64 | 8 ± 9 | - |
| Non-coll. Background | 575 ± 83 | 25 ± 13 | - | - |
| $Z/\gamma^* \to \tau\tau$+jets | 421 ± 25 | 15 ± 2 | 2 ± 1 | - |
| Di-bosons | 302 ± 61 | 29 ± 5 | 5 ± 1 | 1 ± 1 |
| $Z/\gamma^* \to \mu\mu$+jets | 204 ± 19 | 8 ± 4 | - | - |
| Total Background | 124000 ± 4000 | 8800 ± 400 | 748 ± 60 | 83 ± 14 |
| Events in Data (4.7fb$^{-1}$) | 124703 | 8631 | 785 | 77 |

No excess

# Background uncertainties

| Source | SR1 | SR2 | SR3 | SR4 |
|---|---|---|---|---|
| JES/JER/$E_{\mathrm{T}}^{\mathrm{miss}}$ | 1.0 | 2.6 | 4.9 | 5.8 |
| MC $Z/W$ modelling | 2.9 | 2.9 | 2.9 | 3.0 |
| MC statistical uncertainty | 0.5 | 1.4 | 3.4 | 8.9 |
| $1 - f_{\mathrm{EW}}$ | 1.0 | 1.0 | 0.7 | 0.7 |
| Muon scale and resolution | 0.03 | 0.02 | 0.08 | 0.61 |
| Lepton scale factors | 0.4 | 0.5 | 0.6 | 0.7 |
| Multijet BG in electron CR | 0.1 | 0.1 | 0.3 | 0.6 |
| Di-boson, top, multijet, non-collisions | 0.8 | 0.7 | 1.1 | 0.3 |
| Total systematic uncertainty | 3.4 | 4.4 | 6.8 | 11.1 |
| Total data statistical uncertainty | 0.5 | 1.7 | 4.3 | 11.8 |

Percentage uncertainties from various sources

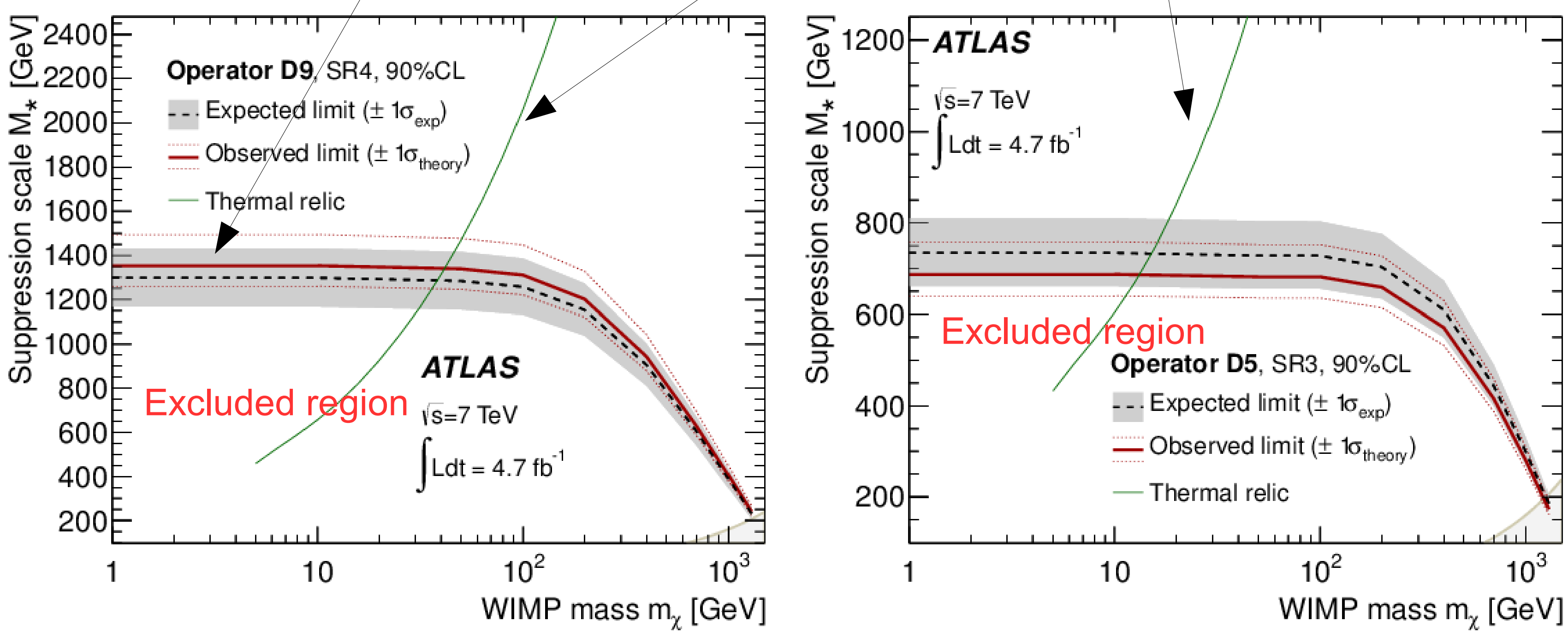
Systematics dominate: usually Jet energy scale (JES)

# Observed limits

Convert to limit on wimp mass and M*

Value required for DM

Note mass independence here

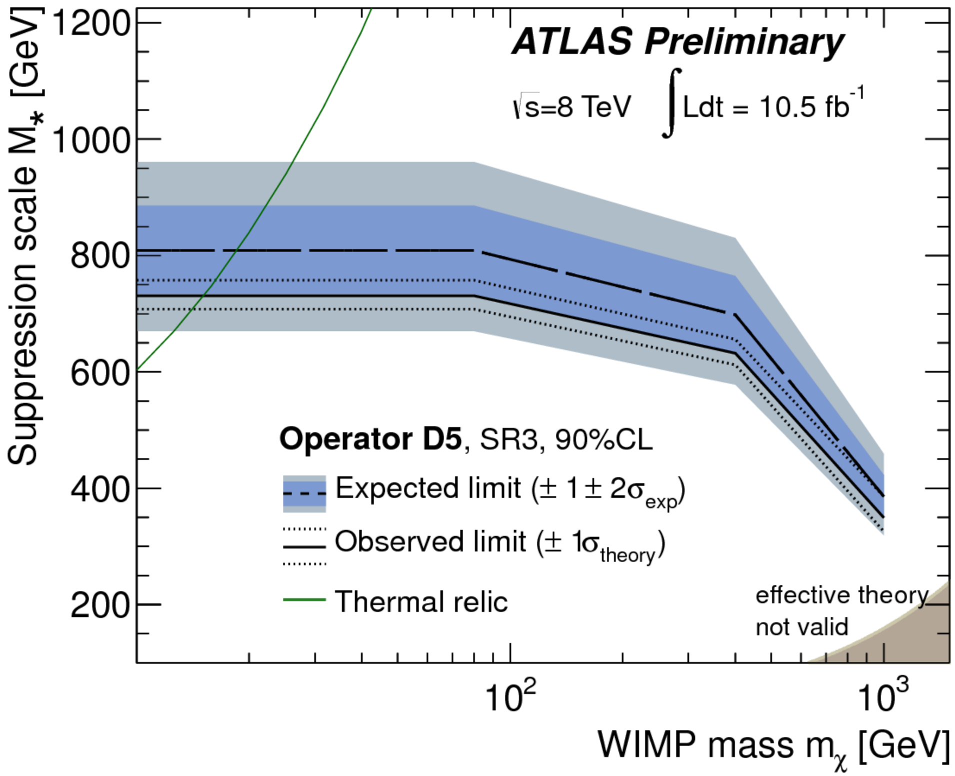


# Comments

- **Limits insensitive to mass at small values**
  - Production rates controlled by event selection, ($p_t$Jet,$E_t^{miss}$) not mass
- **Rates fall off at large masses**
- **Now compare to other searches**
  - Recall caveat about other states and mass spectrum in full model
    - Comparison may not be valid

# 8 TeV data

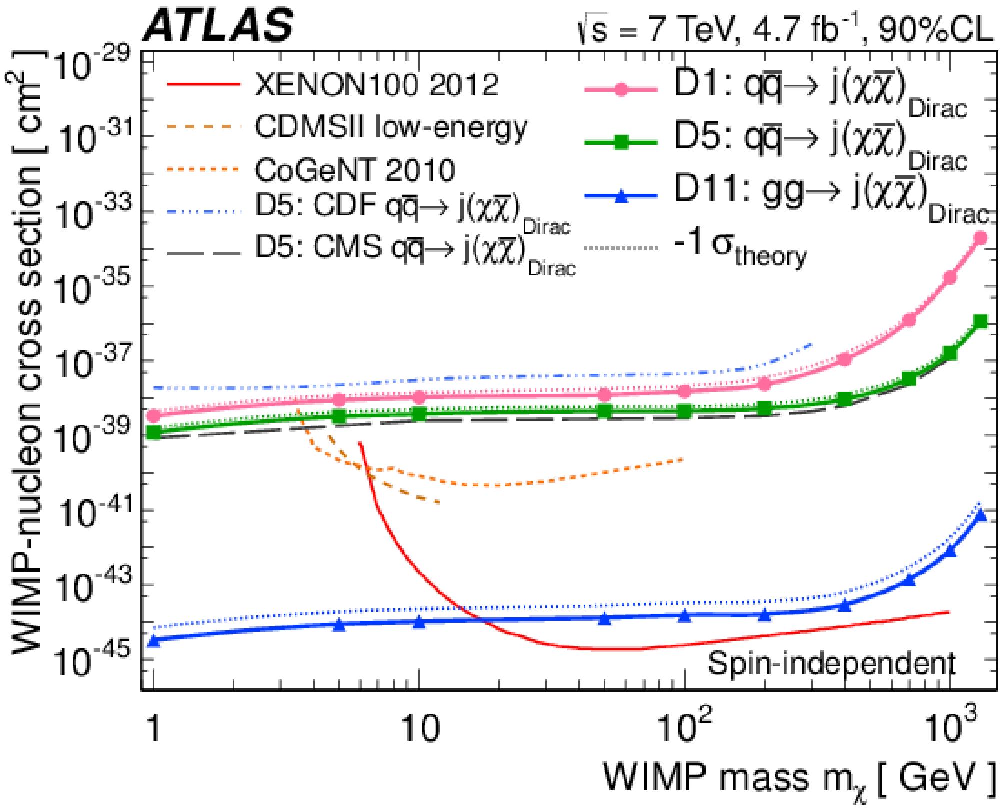
- **Similar analysis**



# Comparisons

Excluded regions above lines

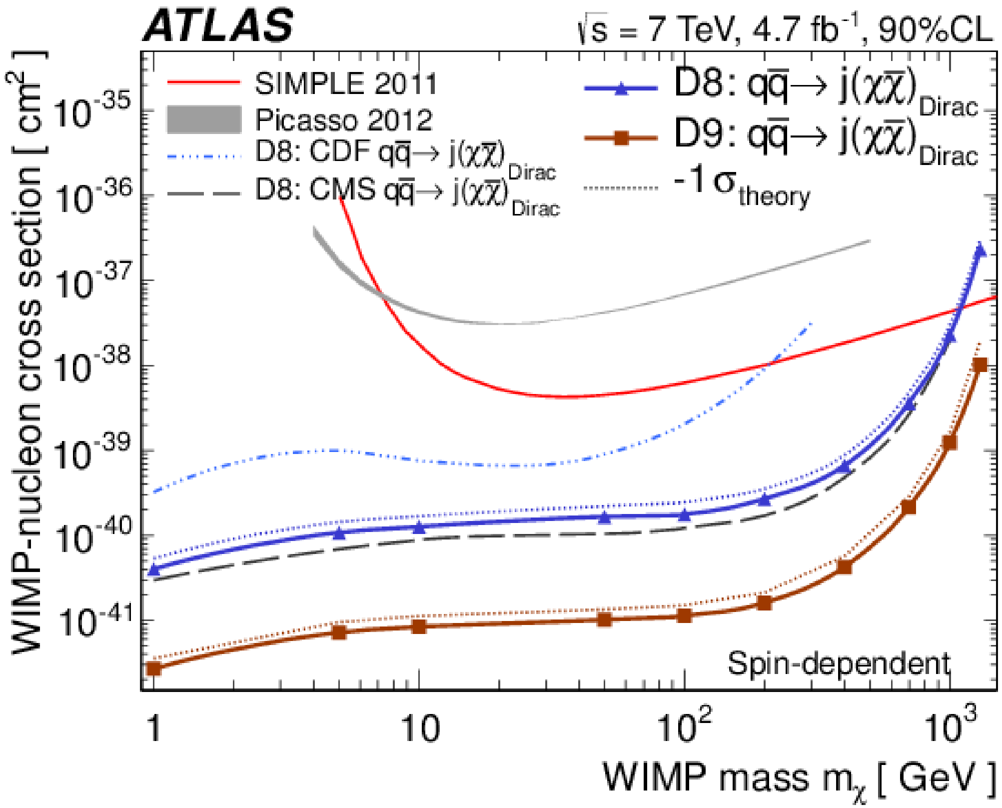
## Spin independent operators



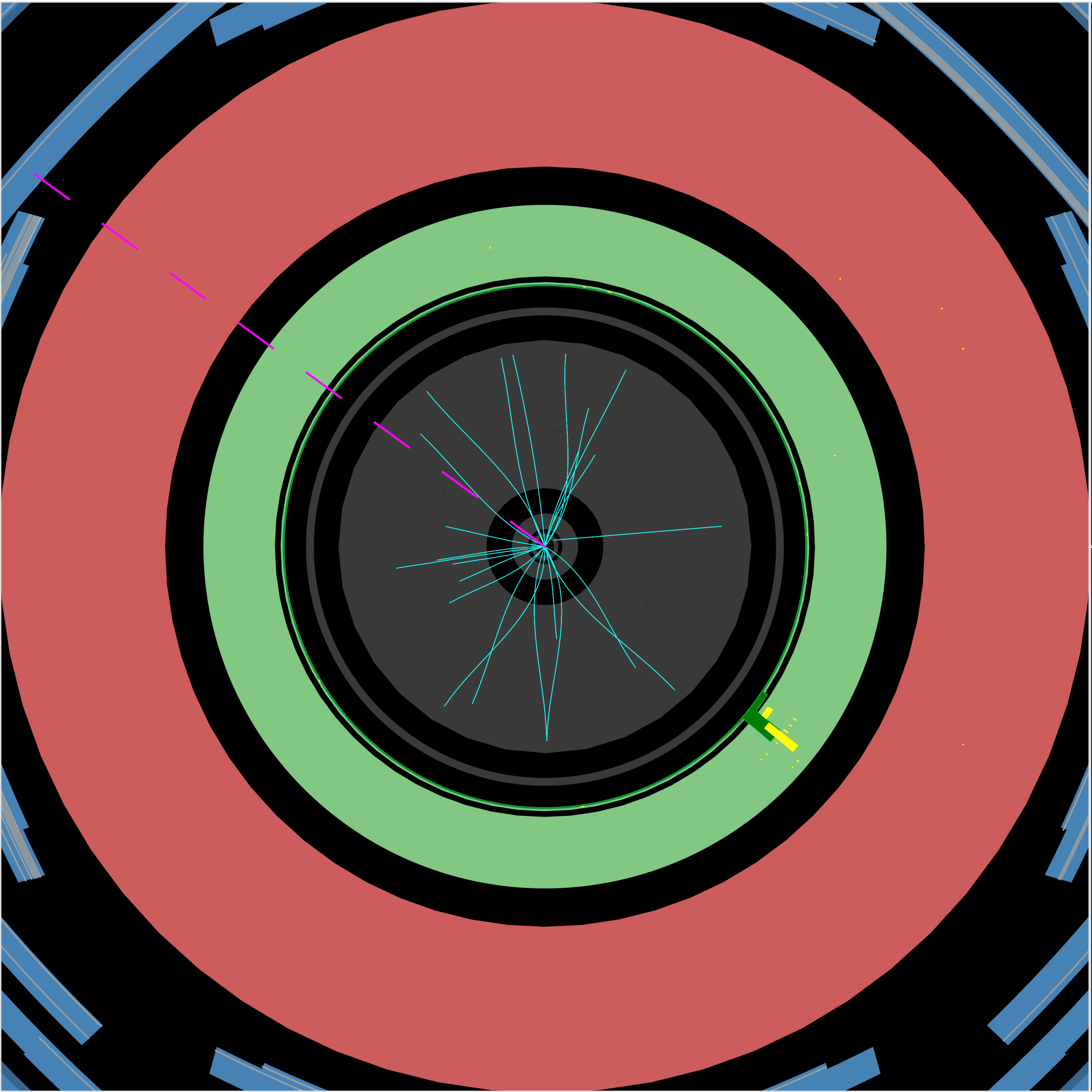
# Comparisons

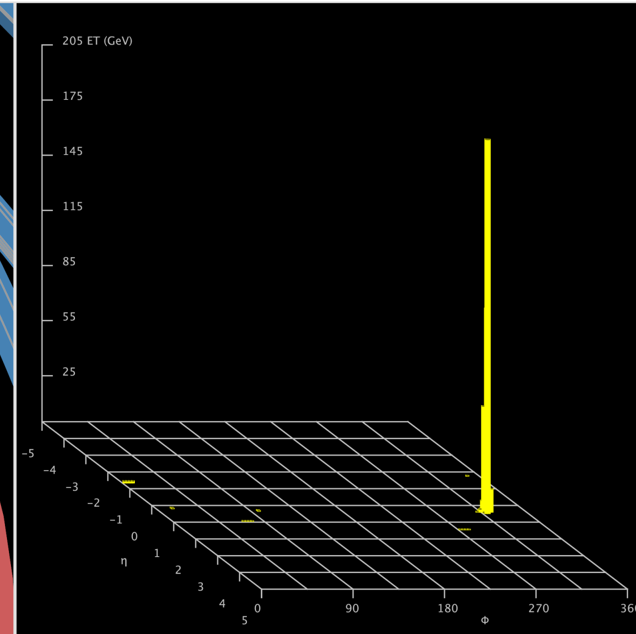
Excluded regions above lines

Spin dependent operators



# Search with photons instead of jets






ATLAS EXPERIMENT

Run Number: 179710, Event Number: 19174449

Date: 2011-04-15 03:48:32 CEST

# Search 2: photon+$E_t^{miss}$

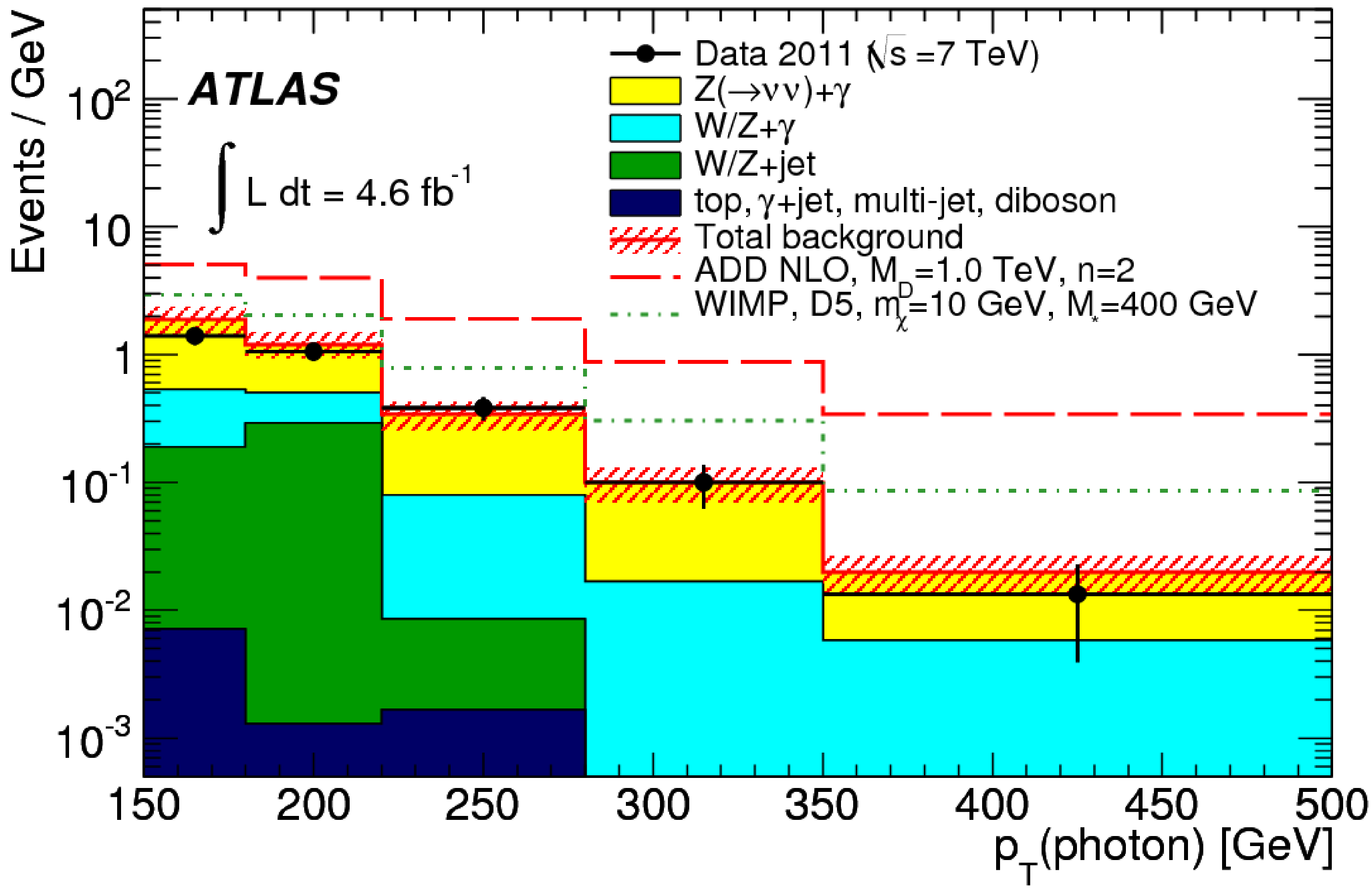
all 2011 ATLAS pp data (4.6 fb-1).

- $E_t^{miss}$ trigger (98% efficient at 150 GeV)
- Leading photon pT > 150 GeV, |η| < 2.37, excluding calorimeter barrel/endcap transition region 1.37 < |η| < 1.52
- Overlap removal |Δφ(γ, $E_t^{miss}$)| > 0.4, |ΔR(jet, γ)| > 0.4,|Δφ(jet,$E_t^{miss}$)| > 0.4
- Not more than one jet with $p_T$ > 30 GeV, |η| < 4.5
- No electrons with $p_T$ > 20 GeV, |η| < 2.47

No muons with $p_T$ > 10 GeV, |η| < 2.5

# Background estimates

- Similar to jet case
- Dominated by W/Z+photon
  - Use W/Z( to leptons) +photon as control
- Smaller background
  - And smaller potential signal



ATLAS
$\int L\,dt = 4.6\ fb^{-1}$
Data 2011 ($\sqrt{s}$ =7 TeV)
Z(→νν)+γ
W/Z+γ
W/Z+jet
top, γ+jet, multi-jet, diboson
Total background
ADD NLO, $M_D$=1.0 TeV, n=2
WIMP, D5, $m_\chi$=10 GeV, $M_*$=400 GeV
Events / GeV
$p_T$(photon) [GeV]

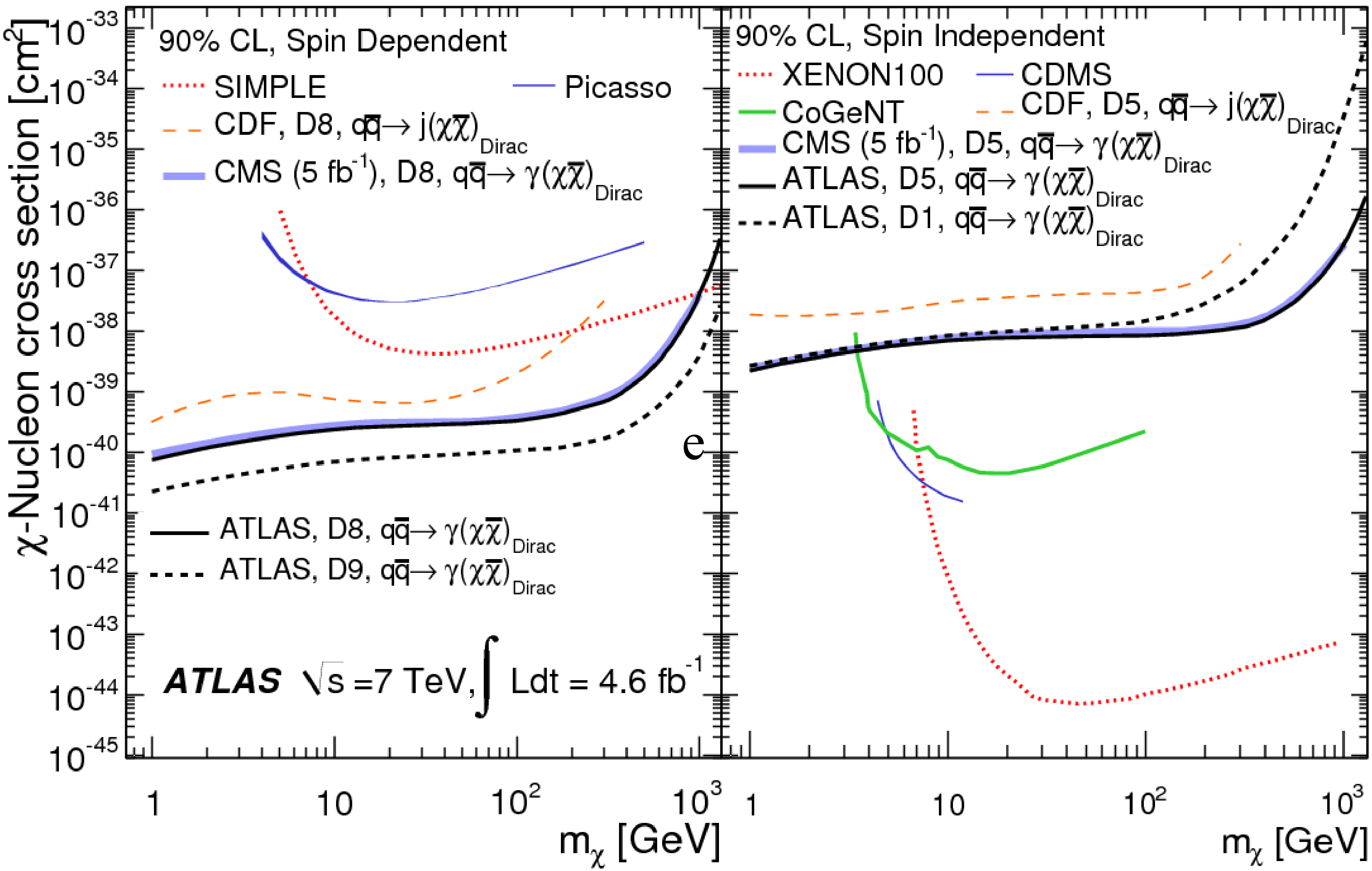
# Photon results

| Background source | Prediction | ± (stat.) | ± (syst.) |
|---|---|---|---|
| $Z(\to \nu\nu) + \gamma$ | 93 | ± 16 | ± 8 |
| $Z/\gamma^{*}(\to \ell^{+}\ell^{-}) + \gamma$ | 0.4 | ± 0.2 | ± 0.1 |
| $W(\to \ell\nu) + \gamma$ | 24 | ± 5 | ± 2 |
| $W/Z$ + jets | 18 | – | ± 6 |
| top | 0.07 | ± 0.07 | ± 0.01 |
| $WW, WZ, ZZ, \gamma\gamma$ | 0.3 | ± 0.1 | ± 0.1 |
| $\gamma$+jets and multi-jet | 1.0 | – | ± 0.5 |
| Non-collision background | – | – | – |
| Total background | 137 | ± 18 | ± 9 |
| Events in data (4.6 $fb^{-1}$) | 116 | | |

No event excess: set limits

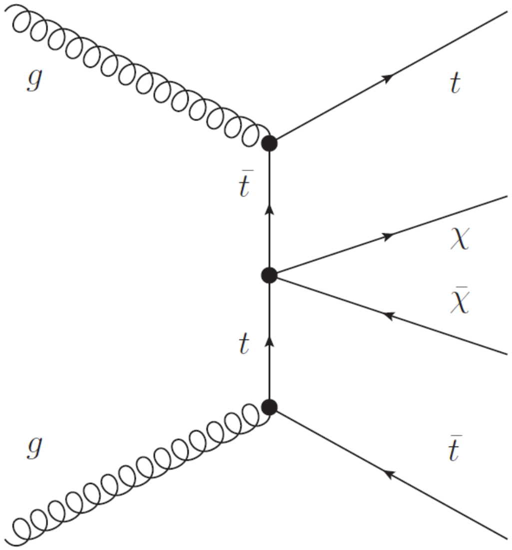
# Photon results

Excluded regions above lines



# CMS: ttbar

- Probing D1 needs heavy quarks
- Look at ttbar production
  - No low jet activity
  - Large Etmiss recoiling against ttbar system
  - Use two leptonic top decays
    -

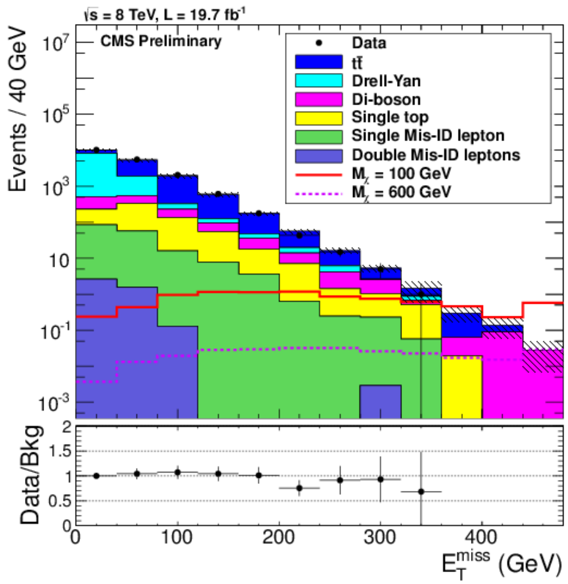


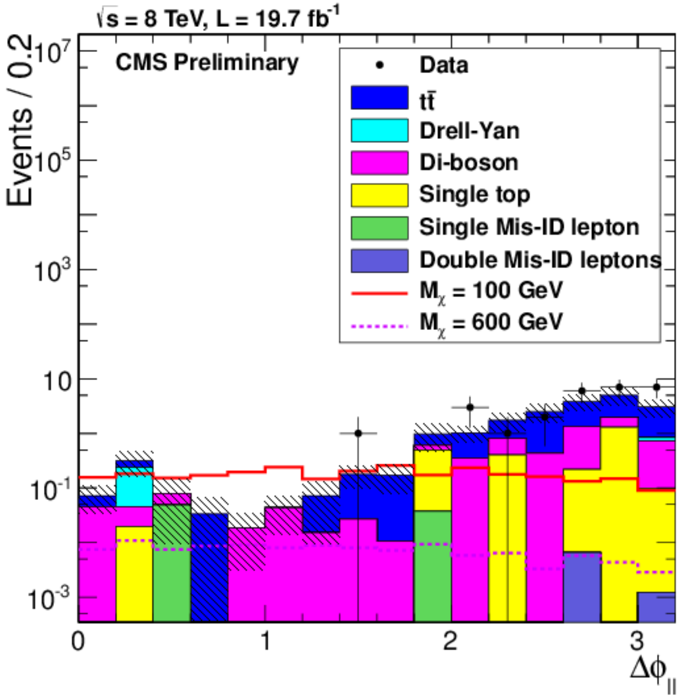
# CMS: ttbar

- **Basic selections**
  - Two e or mu
    - Exclude if consistent with Z decay
  - At least two jets
    - There are 2 b's from top decays
- **Signal selections**
  - p_t(dilepton)>120 GeV
  - Etmiss> 180 GeV
  - Leptons correlated: $\Delta\Phi(l1,l2)<2$ rad

# CMS: ttbar

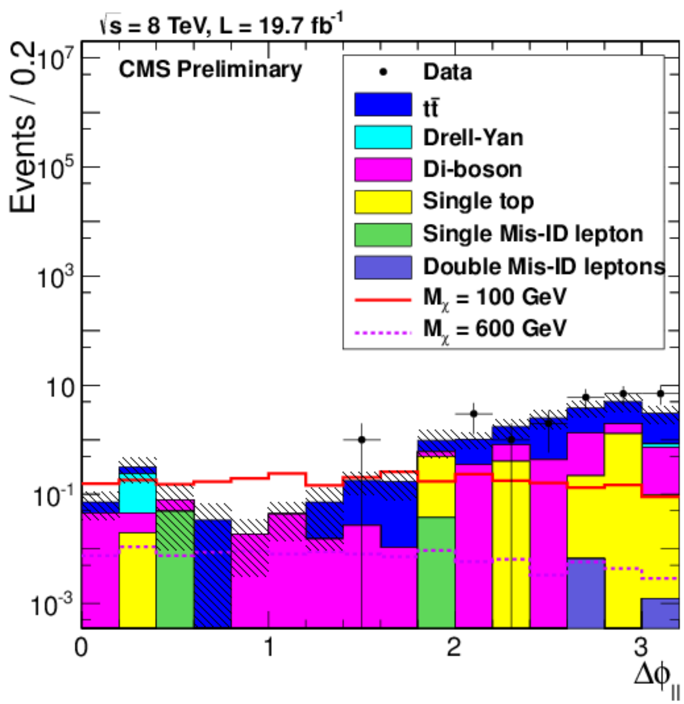
- **Note than in ttbar events, t and tbar are "back to back"**

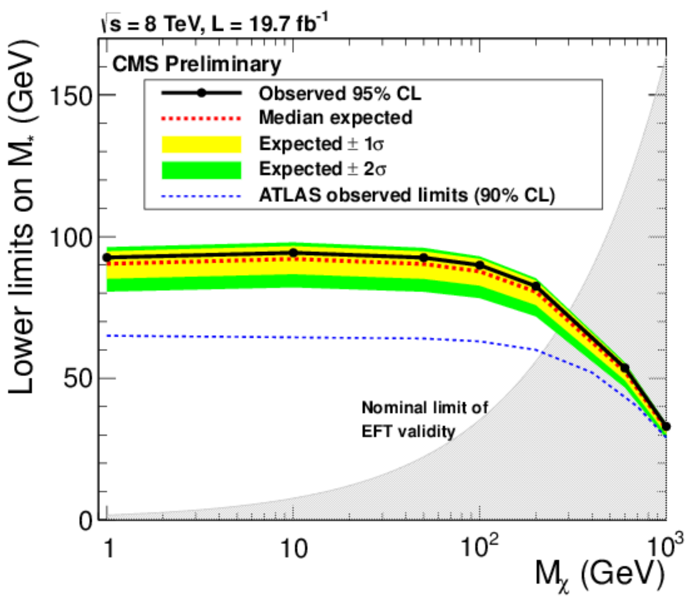


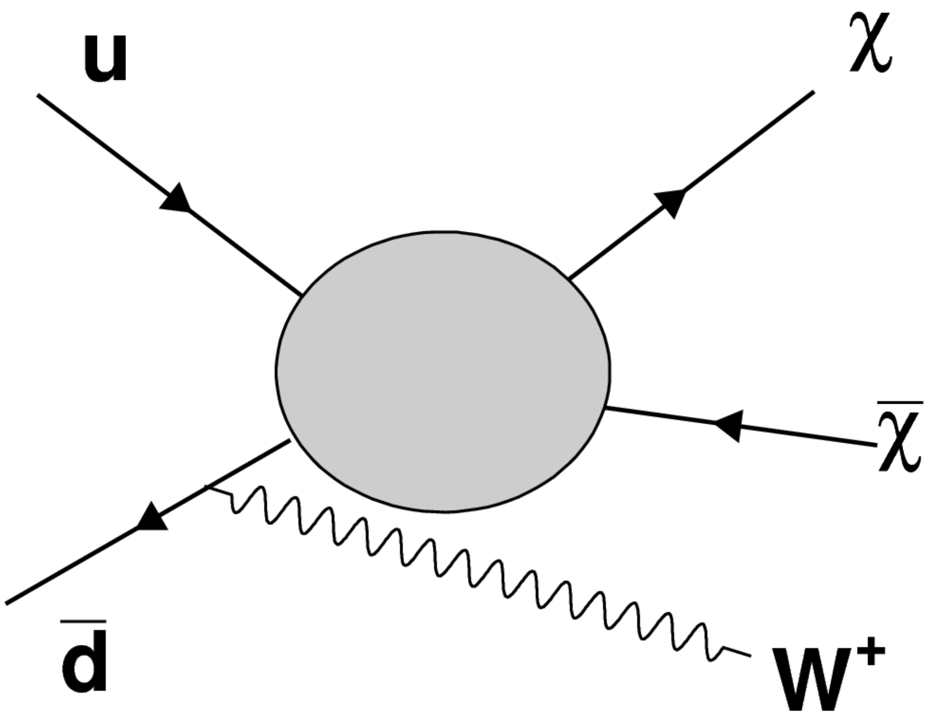
# CMS: ttbar

- **D1: better limit than jet+etmiss**



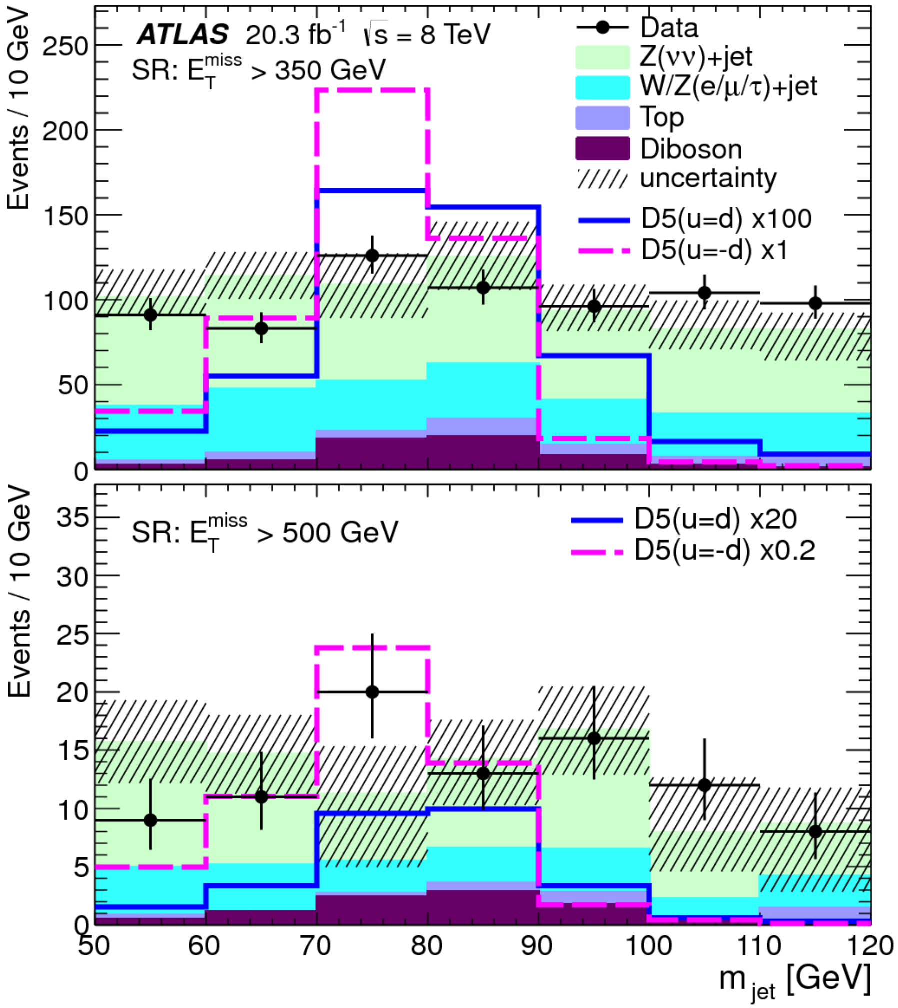
- Hadronic decays of W and Z
  - W and Z cannot be separated
  -



# ATLAS:W/Z+etmiss

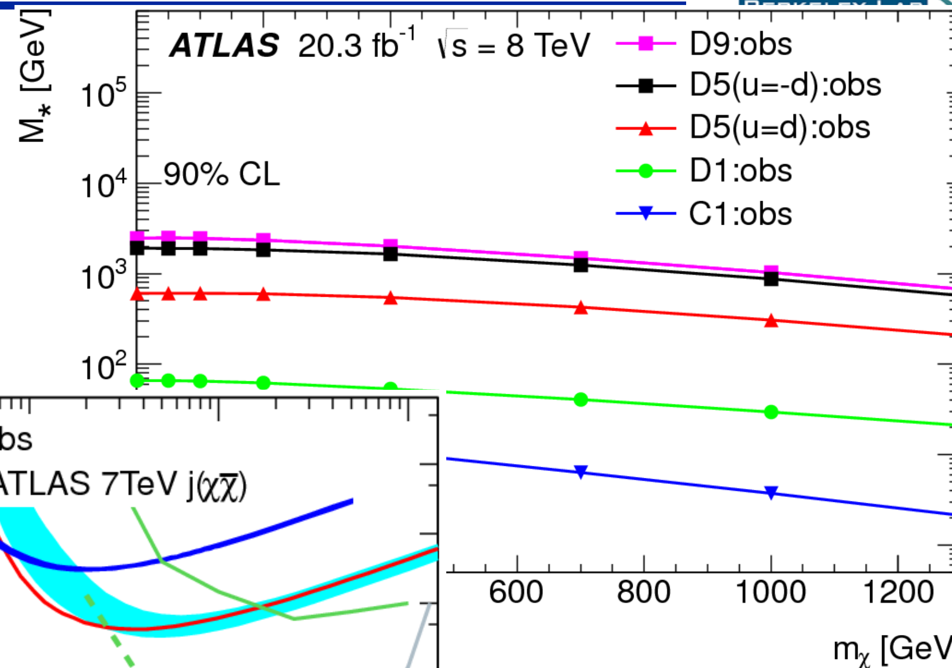
- Etmiss >150 GeV (trigger)
- 1 Fat jet ($\Delta$r=1.4), 50<m(jet)<120
  - Candidate for W or Z
- No leptons
- <2 other jets: reject top decays

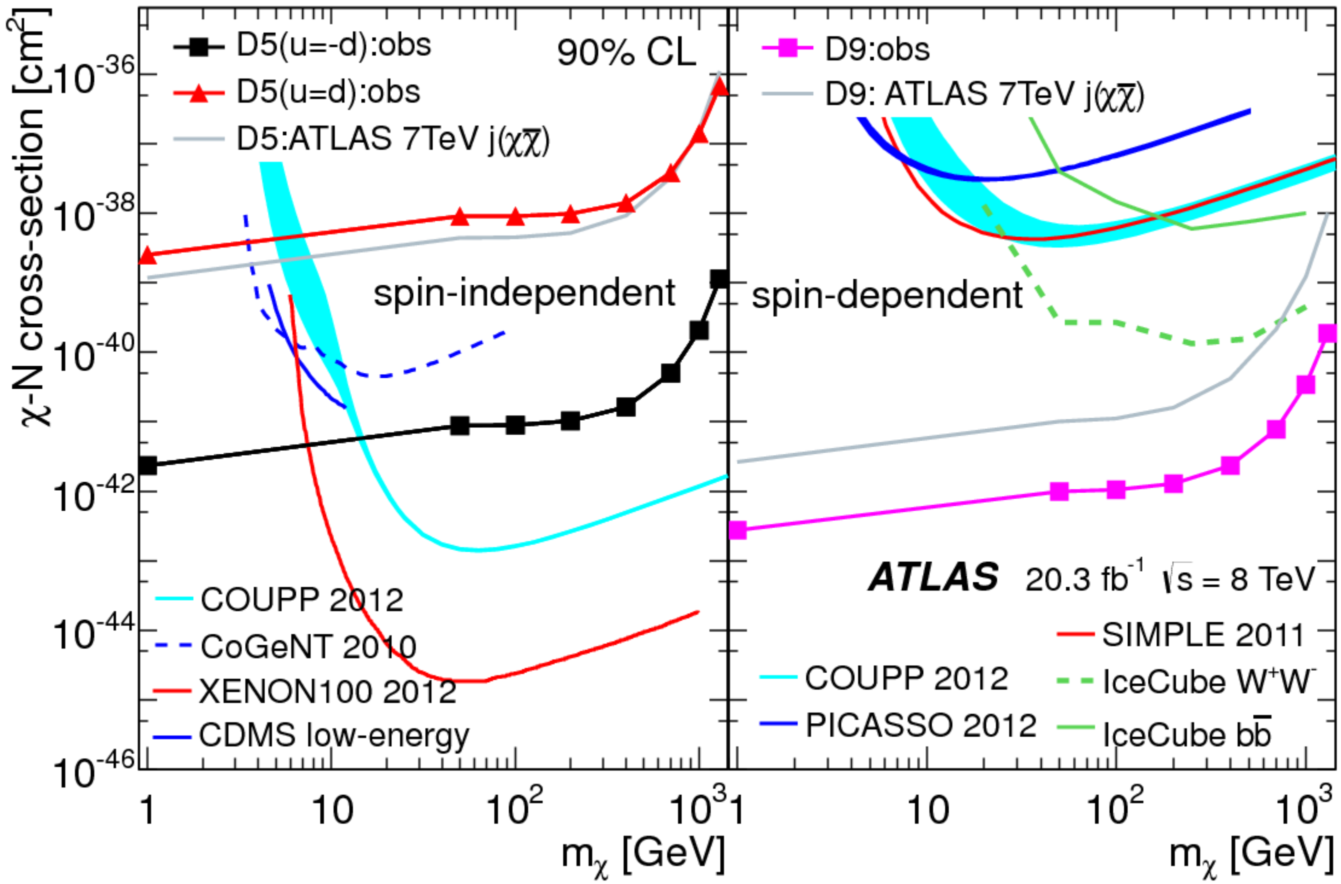
- **Biggest background**
  - **Z(to neutrinos)**




S/B largest at high Etmiss

# ATLAS:W/Z+etmiss



# 14 TeV coming

- Data taking starts spring 2015
- Higgs to invisible
  - Limit will get better slowly
  - Might be able to get to 20% (not soon)
- SUSY
  - Mass reach will double
    - Expect major results for Moriond/summer 2016
    - Better sensitivity for production of electro weak susy particles
- Generic search for DM production
  - Rates in existing signal regions increase by factor of several
  - Expect limits on cross sections drop by 10.

# Summary

- Higgs portal model constrained by Higgs measurements
  - Small mass region challenged
- No SUSY observed
  - Can only be converted into DM limit in a model
  - Specific models have been ruled out
  - CMSSM on life support (vegetative state?)
- Generic search for DM production
  - No signal
  - Limits very competitive
    - Particularly at small wimp mass
  - Beware caveat about mass gaps

# References: Atlas

- (Z(to leptons) +ETmiss)http://arxiv.org/abs/1404.0051
- (Z/W(to hadrons)+Etmiss)
  http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.112.041802
  http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-073/
- (Jets + Etmiss) http://link.springer.com/article/10.1007/JHEP04%282013%29075

  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-147/
- (Photon+Etmiss)http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.110.011802
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-085/
- (Higgs to dark matter)
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-010/
  (Higgs to invisible) http://arxiv.org/abs/1402.3244

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

# References: CMS

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https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

# References: other (incomplete)

- Operator formalism: Goodman et al  Phys.Rev. D82 (2010) 116010 and papers that cite this.
- Higgs portal:  Brian Patt, Frank Wilczek (MIT, LNS). May 2006. 3 pp. MIT-CTP-374, e-Print: hep-ph/0605188.
- SUSY parameter space:  Cahill-Rowley et al,  arXiv:1308.0297, arXiv:1305.6921 etc: Jellis et al  arXiv:1305.6921 etc; Arby et al Eur.Phys.J. C72 (2012) 1906
- 

# References: CMS

- (Photon+Etmiss) http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.108.261803
- (jet+etmiss) http://link.springer.com/article/10.1007%2FJHEP09%282012%29094
- (ttbar+ LSP) http://cds.cern.ch/record/1697173?ln=en
- (higgs to invisible) http://cds.cern.ch/record/1561758?ln=en
- (W+Etmiss) https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO13004
- Atlas results pages

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults