New physics searches at the LHC
Where do we go with run II ?

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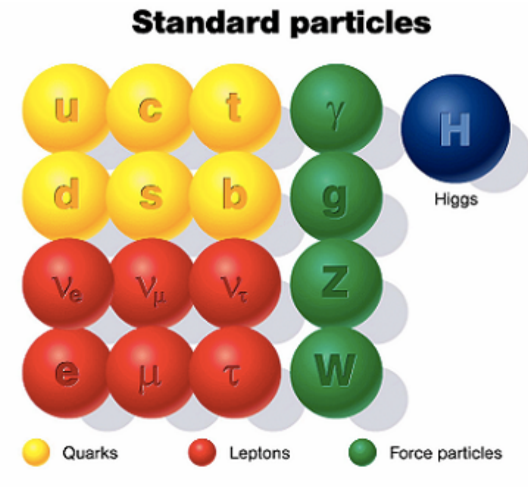
On behalf of the ATLAS and CMS collaborations

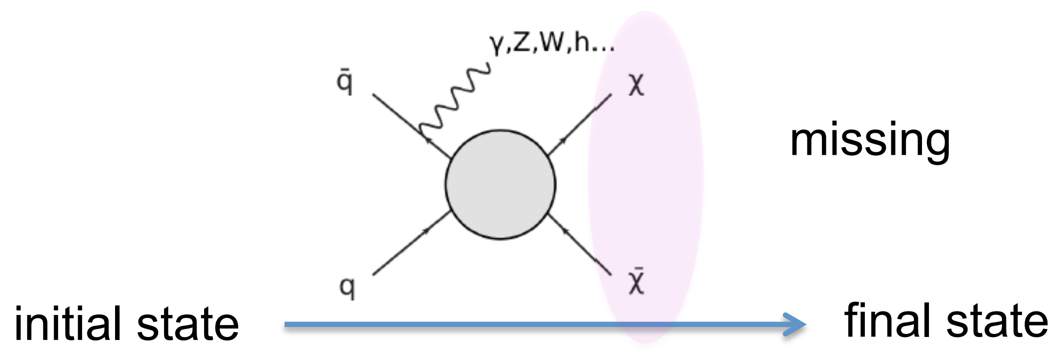
2015. 10. 26
TeVPA Conference 2015

Introduction

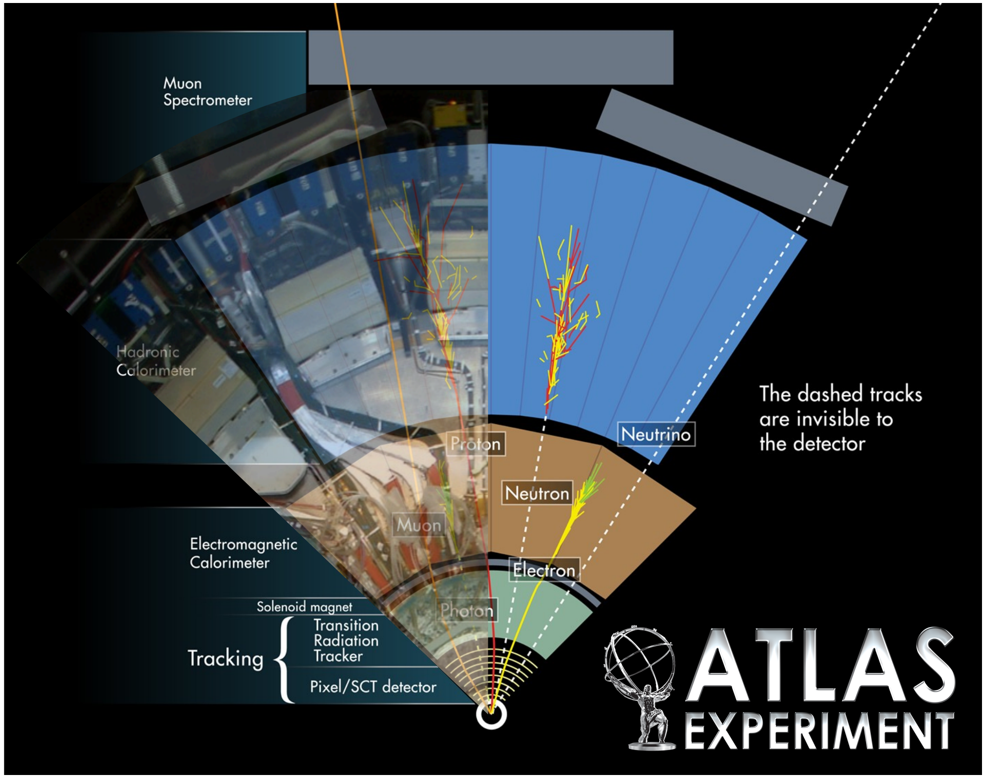


- With the discovery of Higgs boson in 2012, the Standard Model has been completed
- However there are some short comings in the SM
  - hierarchy problem (Higgs mass divergence)
  - matter vs. anti-matter asymmetry
  - unification of the force
  - etc.
- Among all, the origin of the Dark Matter (DM) is one of the biggest mysteries
- In collider experiment, searches for weakly interacting particles (WIMP DM) use large imbalance of p_T (or E_T), assuming they escape detection
- Hence Missing energy measurement is the key

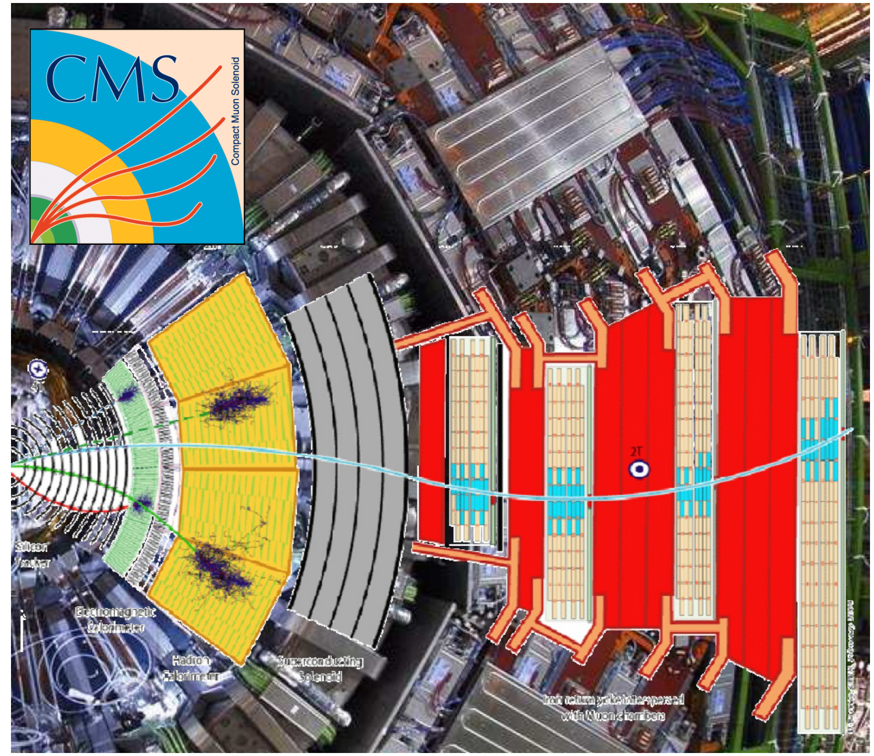
N.B. there are other DM models which predict exotic signatures (e.g. displaced vertices)



Detectors: ATLAS and CMS



ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**)



CMS (**C**ompact **M**uon **S**olenoid)

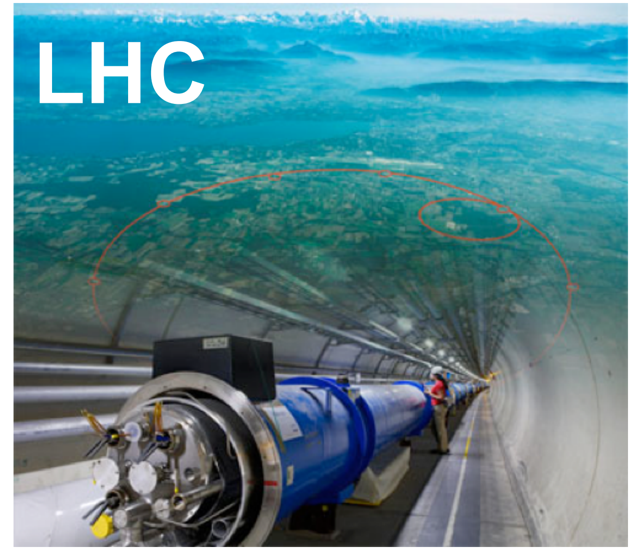
ATLAS and CMS are general-purpose detectors with
- excellent tracking in the central region
- good calorimeter granularity with large coverage ($|\eta| \leqq 5.0$ ~0.8°)

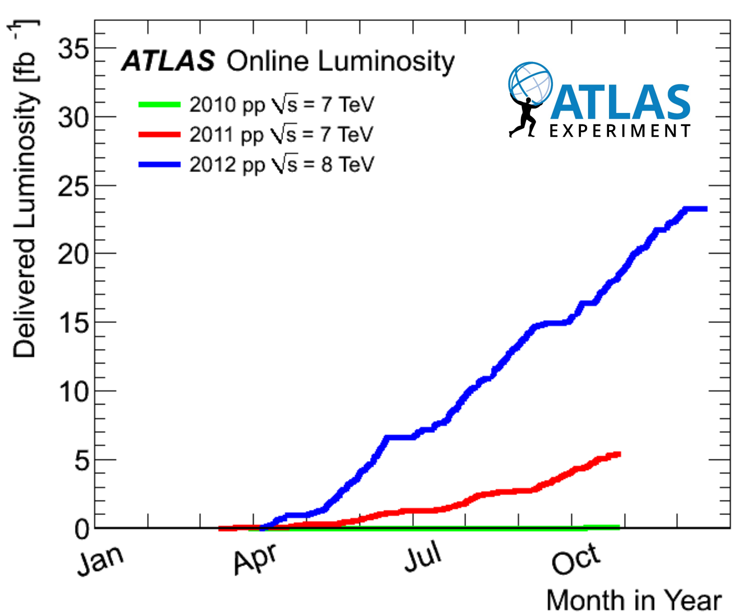
make them good for missing transverse momentum measurements

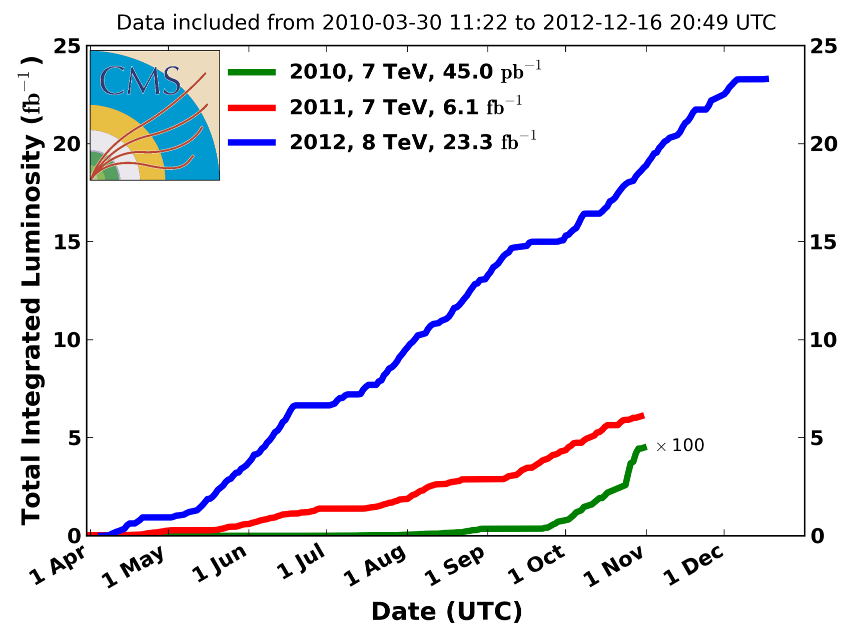
LHC Run-1

Successful operations in both LHC and Experiments

- LHC was in good condition during Run-1 (2010-2012)
- ATLAS and CMS collected good fraction of data (>95%) throughout Run-1
- 8 (7) TeV proton-proton collisions ~20 (5) fb^{-1} good data for physics







General strategy for the new physics

- Define the event selection based on signal and bkg characteristics (e.g. kinematics)
- Compare the data to bkg (MC or by data driven)
  - new physics would produce deviation from bkg prediction
  - If consistent → set the limits, typically on the cross-section x BR
- Then comparisons made for specific models

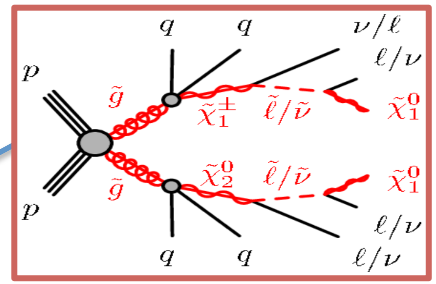
DM search approach with collider exp.

generality

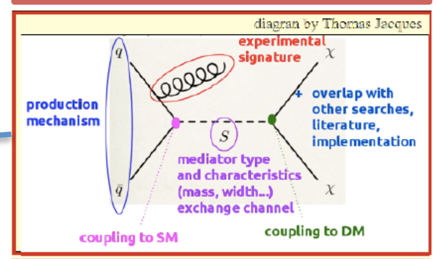
Specific models (e.g. SUSY)

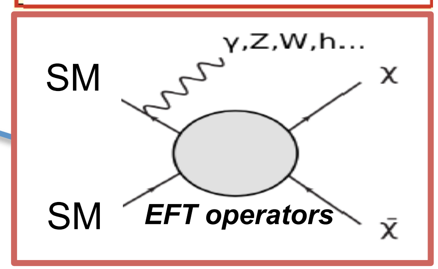
Simplified Models

Effective Field Theory



PART 1 :
Complete models (as targeted by SUSY searches)





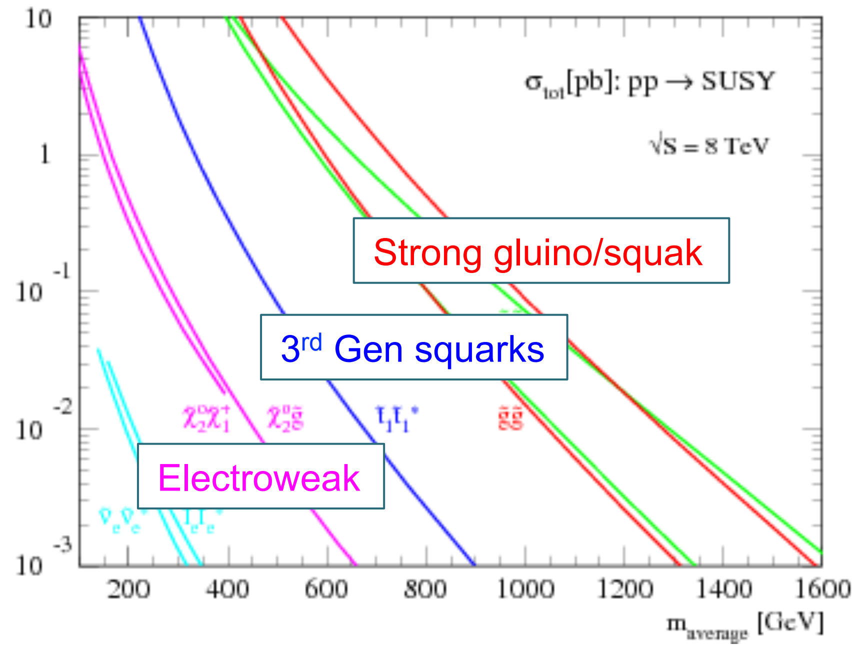
PART 2 :
Run-1 based more often on EFT, sliding to Simplified Models toward Run-2

PART 1
Complete SUSY models

SUSY overview for RUN1

- Searches based on R-parity conservation + neutral lightest SUSY particle
  → look for large Missing E_T final state

  Productions
  - Gluinos/Squarks strong productions
  - Stop/sbottom productions
  - Direct electro-weak productions



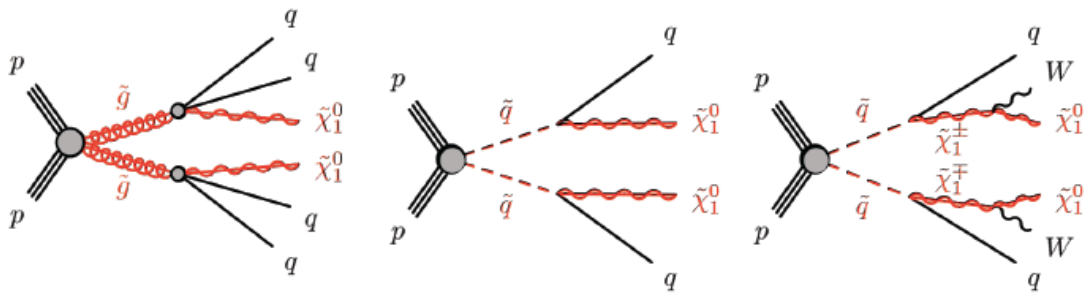
(searches for R-parity violating and long lived signatures are not covered in this talk. But I will briefly show the "disappearing track in the detector volume" search which is relevant for the pMSSM interpretation later on)

- Searches optimized and interpreted with simplified SUSY models (single production & decay mode)
- Results are also interpreted with more sophisticated models (mSUGRA, NUHM, GGM, …)

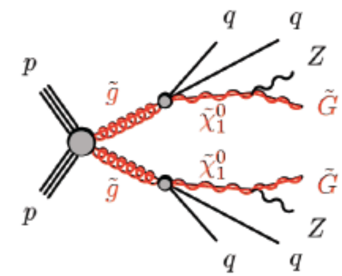
  In this talk → pMSSM (19 parameters)
  consideration with DM relic density

Strong production (0/1/2 leptons + multi jets + E_T^{miss})

- Dominant process at LHC, if squarks/gluinos are not too heavy
- typical signature : high-pT multi-(b) jets, 0-1-2 leptons, EtMiss from LSP



squark/gluino production with neutralino LSP



squark/gluino production with gravitino LSP

ATLAS searches

0-leptons + 2-6 jets + EtMiss	JHEP 09 (2014), 176
0-leptons + 7-10 jets + EtMiss	JHEP 10 (2013), 130
1-leptons + jets + EtMiss	JHEP 04 (2015), 116
2-leptons + 2-6 jets + EtMiss	EPJC 75 (2015), 318
2-leptons SS/3L+jets+EtMiss	JHEP 06 (2014), 035
1-2 taus + jets + EtMiss	JHEP 09 (2014),103
photons + jets + EtMiss	PRD 92 (2015) 072001
Summary paper	arXiv: 1507.05525

CMS searches

3-5,6-7,>=8 jets + EtMiss	JHEP 06 (2014) 055
multi-jets+b-jets+ EtMiss	PLB 725 (2013) 243
1-leptons+jets+bjets+EtMiss	PLB 733 (2014) 328
2-leptos SS+bjets+EtMiss	JHEP 01 (2014),163
multi-jets with MT2 variable	JHEP 05 (2015), 078

numerous analyses for different phase spaces

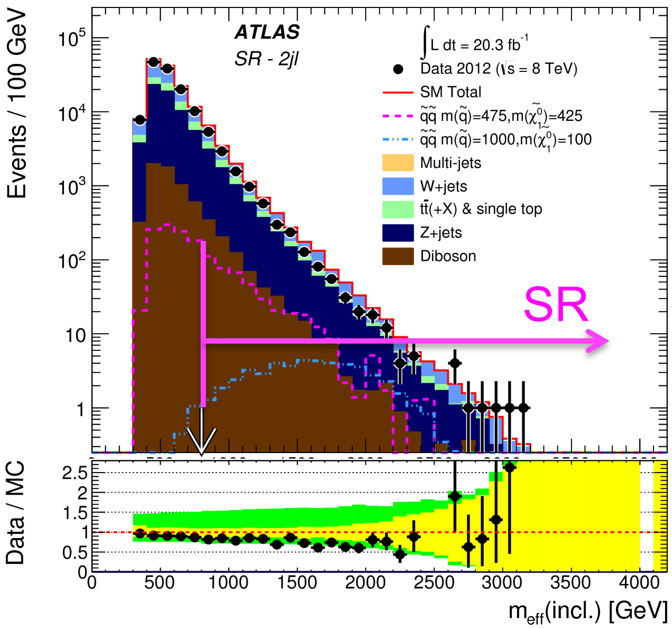
Strong production (0 leptons + ≥2-6jets + E_T^{miss})

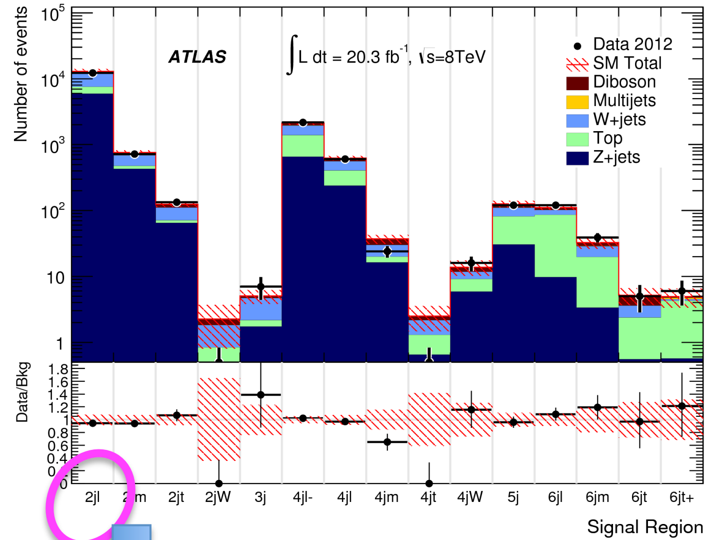
[arXiv:1405.7875] JHEP09(2014)176

- define 15 orthogonal Signal Regions (SR)

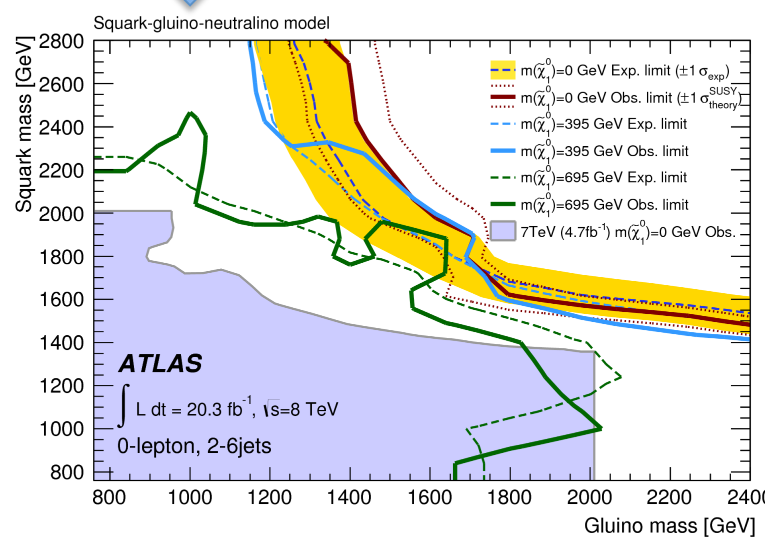
(each with 4 x Control Regions (CR: Bkg dominant))

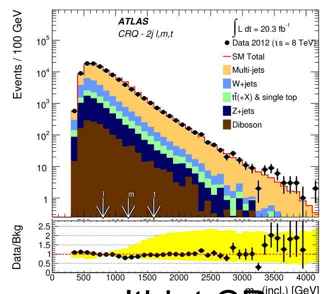
- determine bkg expectations from fit



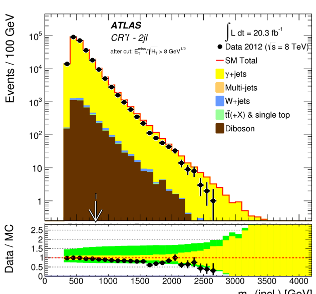


interpret with simplified model

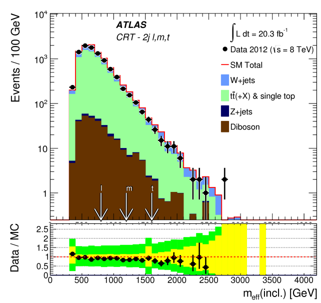




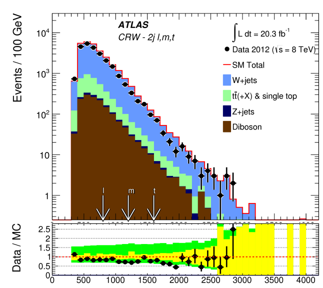
multi-jet CR



gamma-jet CR



ttbar CR

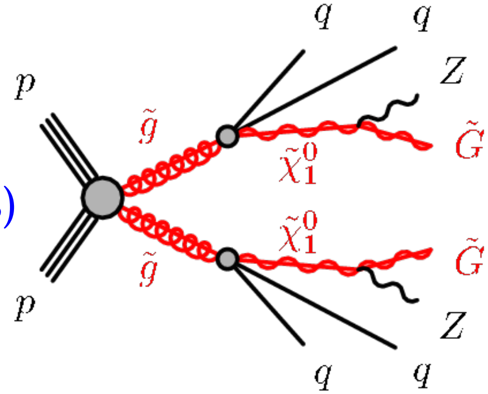


W CR

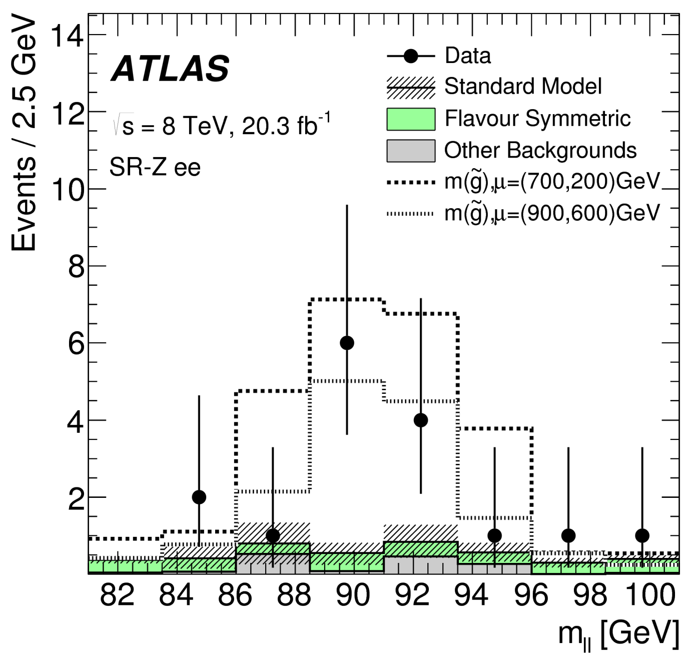
Hint for the Run2 ? (3σ excess)

LHC/ATLAS/CMS

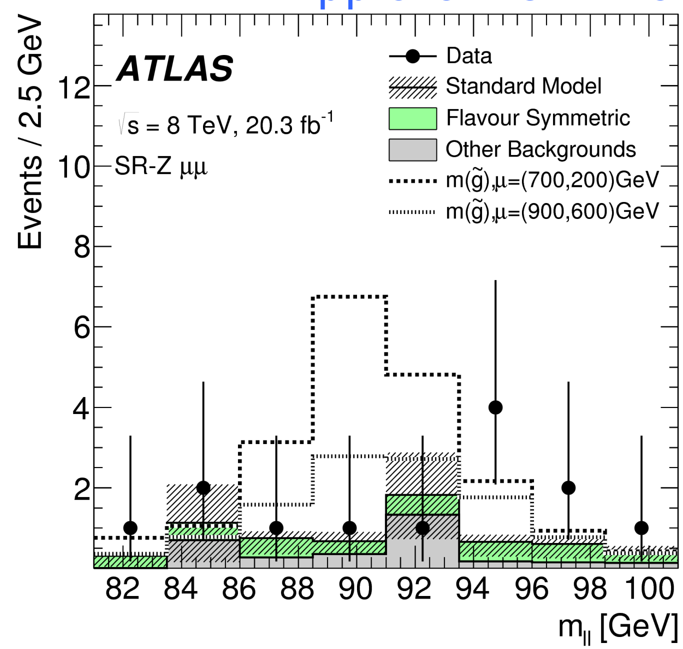
- ATLAS search for the jets + E_T^{miss} + Z signature
  - At least 2 jets (P_T>35GeV)
  - H_T> 600 GeV (high jet activity) $H_T = \sum p_T(jets) + p_T(\mathrm{leptons})$
  - E_T^{miss} >225 GeV then select SFOS lepton pair (ee, μμ)
  - M(ll) = Mz ± 10 GeV
- Main Bkg: ‘flavour symmetric’, estimated from eμ data)



ee channel 3.0 σ



μμ channel 1.7 σ



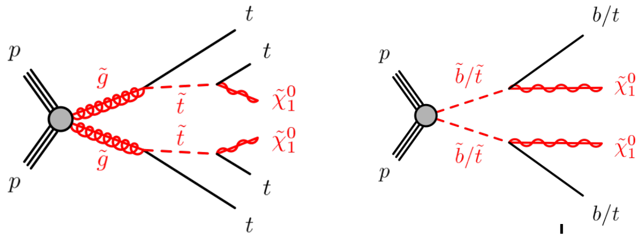
ATLAS EXPERIMENT

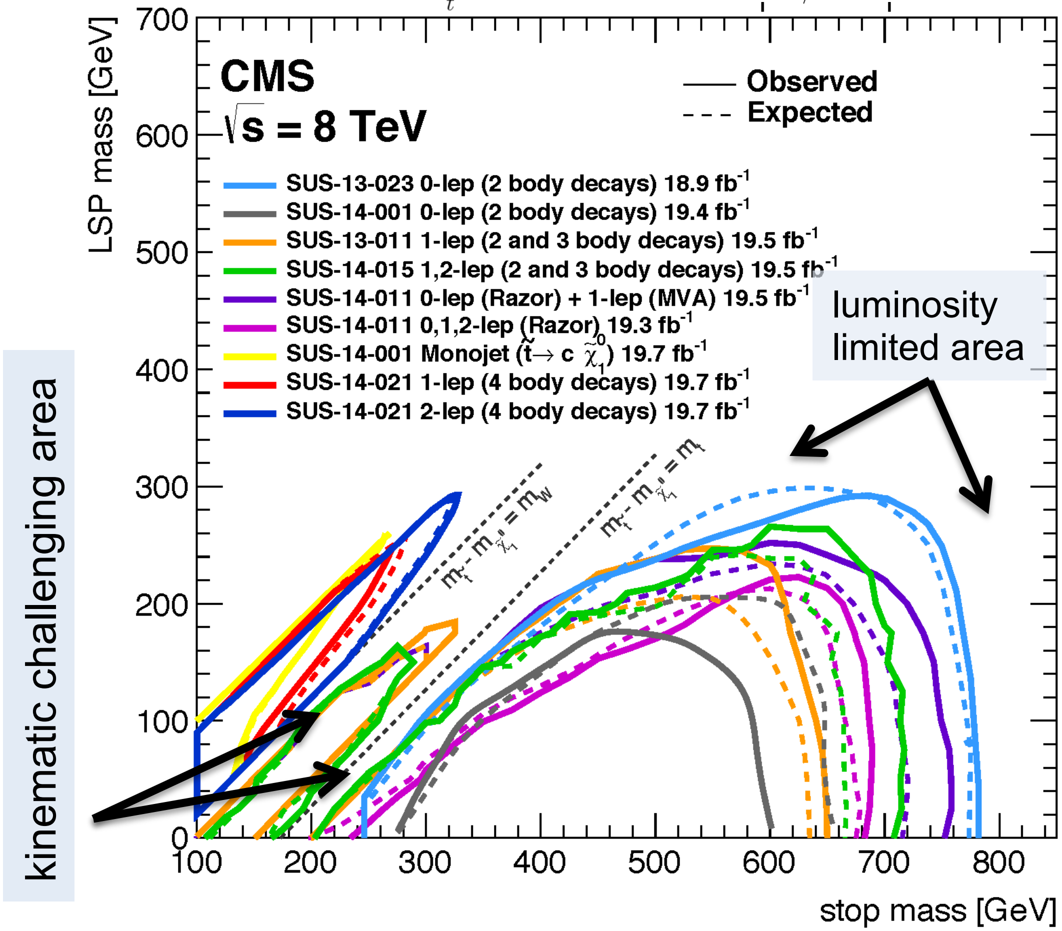
arXiv:1503.03290

N.B. CMS (JHEP 04(2015),124) observes no such excess

3rd gen. squark production

- Searches for gluino mediated or direct stop/sbottom productions
- Natural (non-fine tuning) SUSY requires light stop/sbottom





numerous channels covering different decay chains, mass splitting

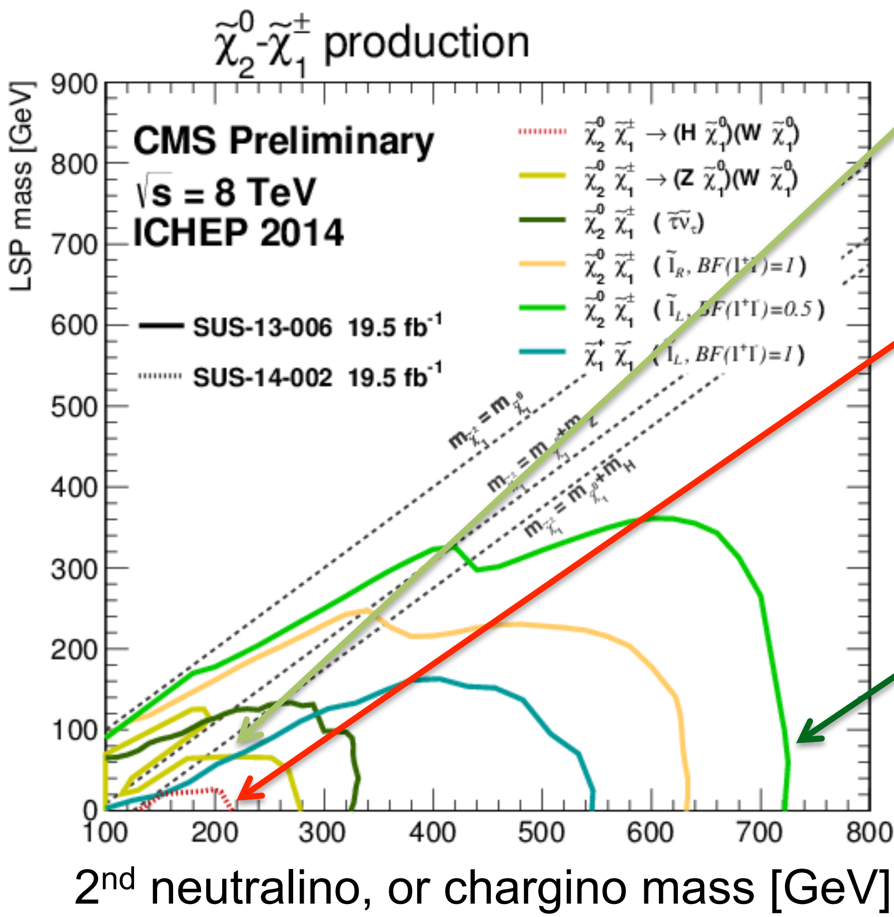
$m_{stop} < 700\ (750)$ **GeV excluded for ATLAS (CMS)**

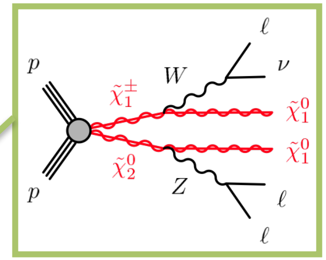
Summary Paper : JHEP 06 (2015), 116

ATLAS 3rd gen summary arXiv:1506.08616 (accepted by EPJC)

Electro-weak production

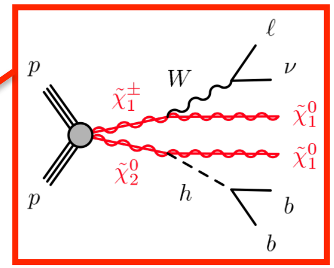
- If squarks/gluinos are all heavy, EW SUSY productions dominate
- Multi-lepton signatures with low hadronic activity
  - 2-leptons + EtMiss, 3-leptons + EtMiss, ≥ 4-leptons + EtMiss, ≥ 2-taus + EtMiss, 1-lepton+2 b-jets+EtMiss, etc





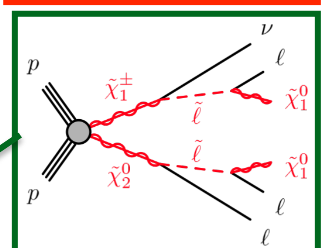
decay via W/Z

PRD 90, 092007 (2014)



if decay via Higgs is allowed

PRD 90, 092007 (2014)



with intermediate slepton decays

EPJC 74 (2014) 3036

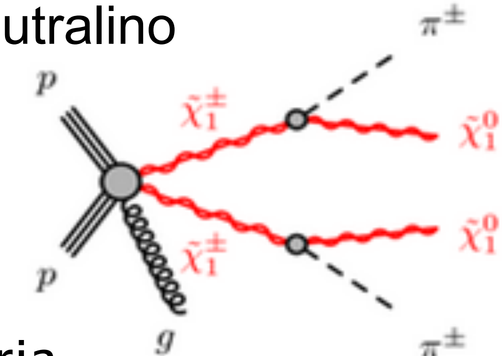
ATLAS EW summary

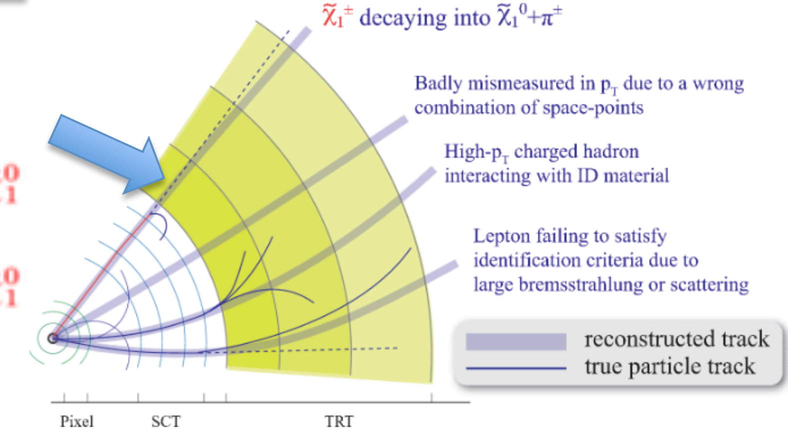
arXiv:1509.07152 (submitted to PRD)

Long-lived $\tilde{\chi}_1^{\pm}$ search

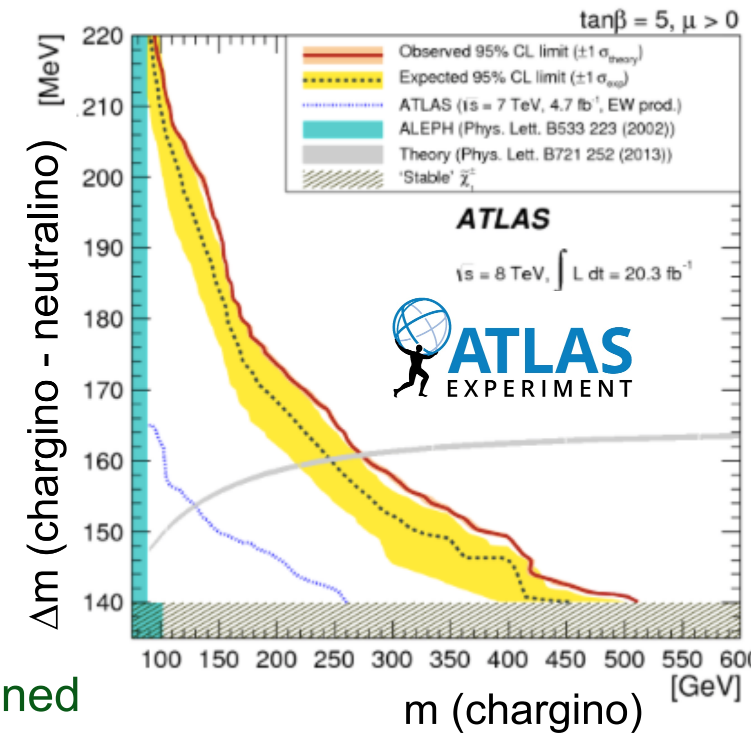
Long lived chargino → π + neutralino

- Backgrounds
  - hadrons interacting with material in ID
  - Leptons fails id criteria
  - p_T mis-measured track
- ATLAS/CMS
  - Similar approach with different inner detector configuration





ATLAS: Phys. Rev. D 88, 112006 (2013) ATLAS
Charginos mass <270 GeV is excluded (95% CL)
CMS: (JHEP01 (2015) 096)) CMS
has excluded up to 260GeV (95% CL)



constraints on chargino lifetime vs. mass is also obtained

pMSSM interpretation (ATLAS)

ATLAS arXiv:1508.06608 (accepted by JHEP)

- Evaluate the general pMSSM (19 parameters) limit from 22 Run1 searches
  - R-parity conserving
  - neutralino LSP
- Random sampling of the parameters 500 million model points (up to 4 TeV)
- Apply constraints from
  - Precision EW and flavor
  - DM abundance
  - LEP, Tevatron
  - Higgs mass

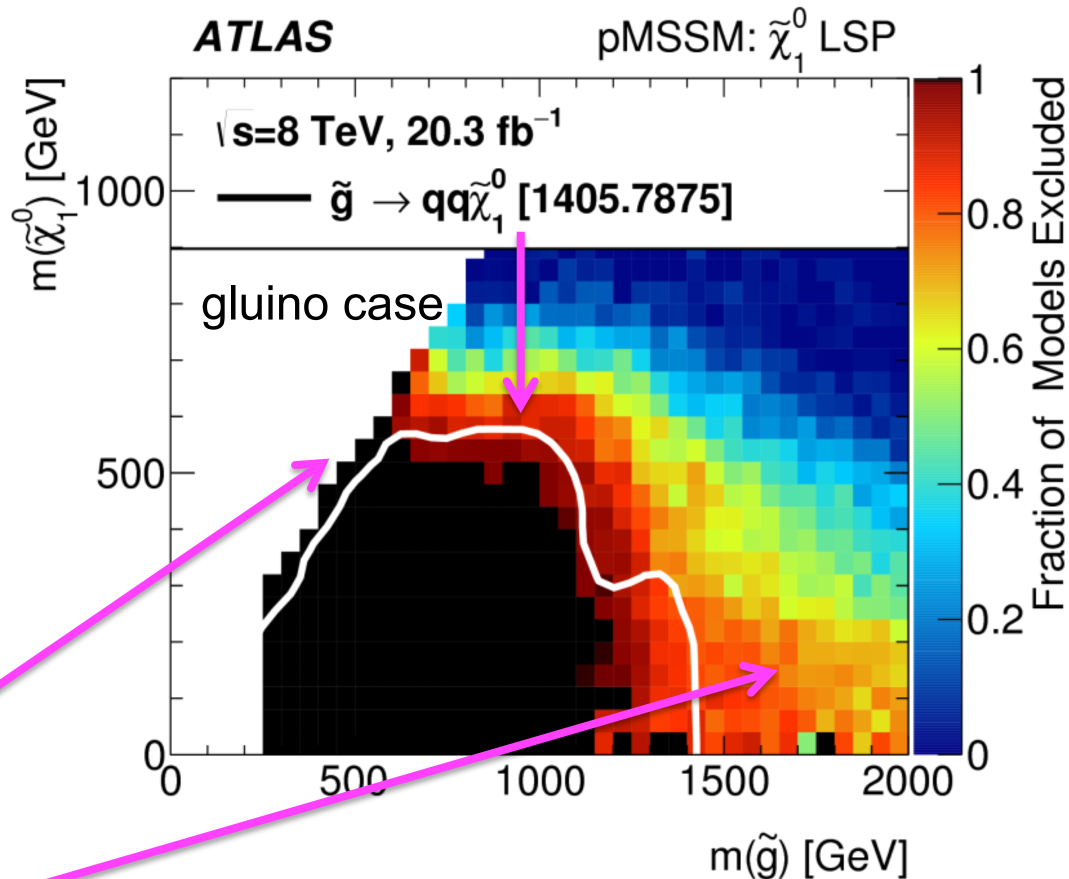
  → 310,327 models (Before Run-1)
- Generate/reconstructed 44,559 models 600 million simulated signal events
- Use 22 search results (200 signal regions), present in 2D the fraction of models excluded

Inclusive	0-lepton + 2–6 jets + E_T^{miss}
	0-lepton + 7–10 jets + E_T^{miss}
	1-lepton + jets + E_T^{miss}
	$\tau(\tau/\ell)$ + jets + E_T^{miss}
	SS/3-leptons + jets + E_T^{miss}
	0/1-lepton + $3b$-jets + E_T^{miss}
	Monojet
3rd Gen	0-lepton stop
	1-lepton stop
	2-leptons stop
	Monojet stop
	Stop with Z boson
	$2b$-jets + E_T^{miss}
	tb+E_T^{miss}, stop
EW	ℓh
	2-leptons
	2-τ
	3-leptons
	4-leptons
	Disappearing Track
	Long-lived particles
	$H/A \to \tau^+\tau^-$

Similar extensive analyses by CMS (SUS15010)

pMSSM interpretation (ATLAS)

- The plot shows the fraction of the models excluded by Run-1
  - Black : 100% excluded
  - White : no model points excluded at pre-selection
  - White line : 95% CL limit from a simplified model for comparison (not much different!)

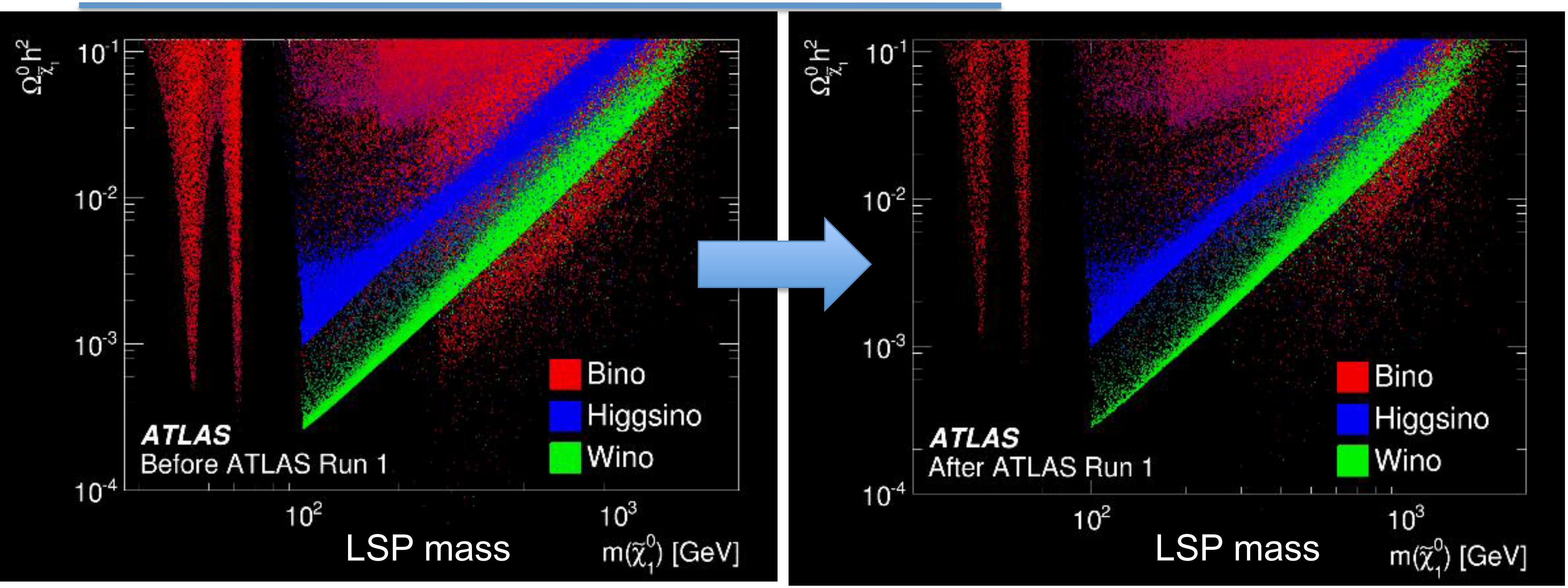


- Compressed gluino-neutralino models are excluded up to 600GeV by mono-jet search
- Sensitivity for wino-like LSP model from disappearing track search ($\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 + \pi$)

arXiv:1508.06608

Other scenarios are in the back up slides

Impact of ATLAS Run1 searches on SUSY DM



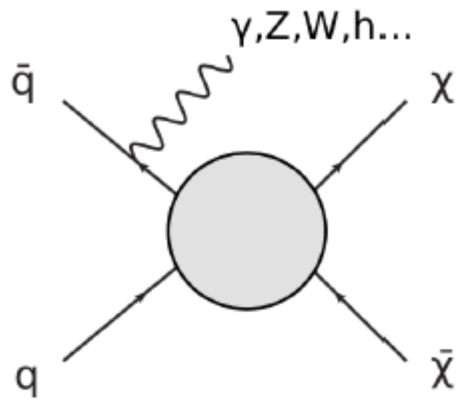
arXiv:1508.06608

- Bino LSP models:
  - 2/3 are excluded, sensitivity up to $m(\tilde{\chi}^0_1)$~800GeV
- Wino LSP models:
  - Sensitivity up to 800GeV, especially below 200GeV (80% excluded)
  - Constraints from disappearing track analysis
- Higgsino LSP models:
  - Charged higgsino lifetime too short, not much constrained

PART 2
Effective Field Theories and Simplified Models

Mono-X searches

- Effective Field Theory (EFT) approach



Cross section depends on:
$M_* = m_V/\sqrt{g_f g_\chi}$ Suppression mass
m_V: mediator mass
$g_f g_\chi$: coupling strength

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Phys.Rev.D82:116010,2010

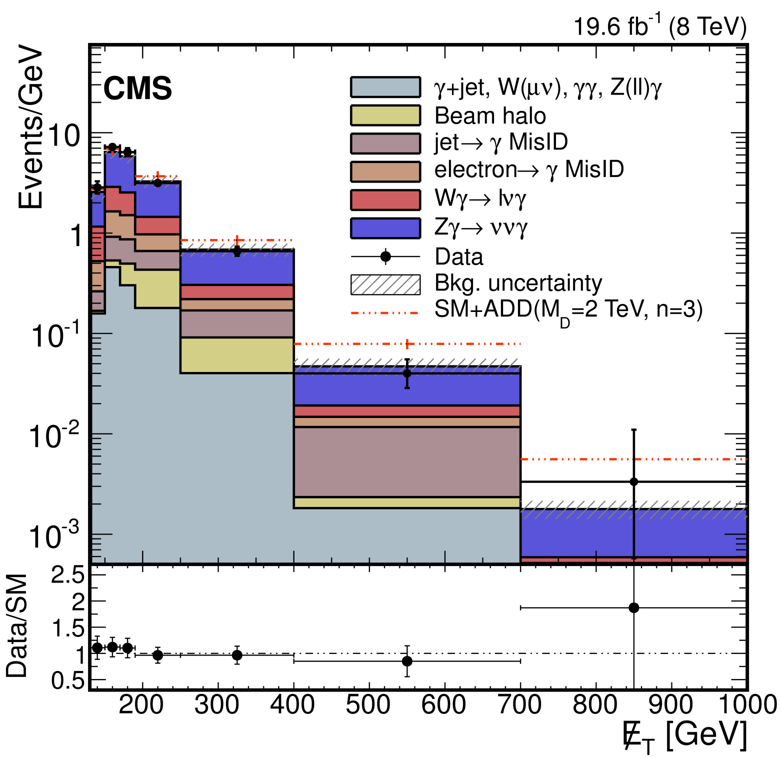
- Search for particle X (=γ, jet, Z/W, etc) recoiling against DM (=Missing E_T)
- Result interpretation:
  - Cross section
  - Effective operators

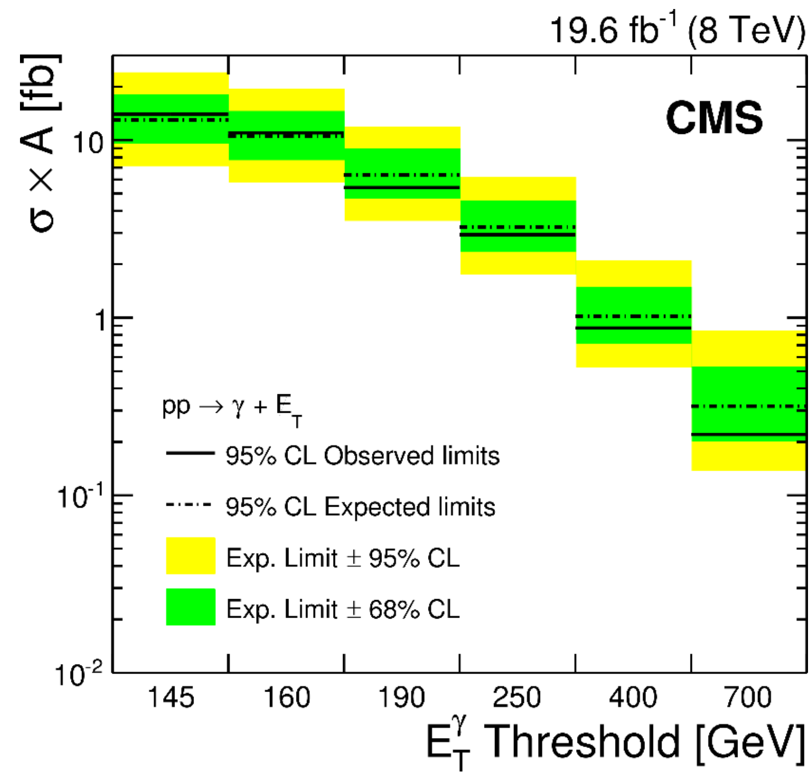
Mono-photon search

- E_T^{miss} > 140 GeV
- p_T > 145 GeV (central) accept up to 1jet
- Bkg estimation with simulation corrected for data/MC differences
- Similar analysis from ATLAS (Phys. Rev. D 91, 012008 (2015))

630 events for 614 ± 63 expected

CMS, arXiv:1410.8812

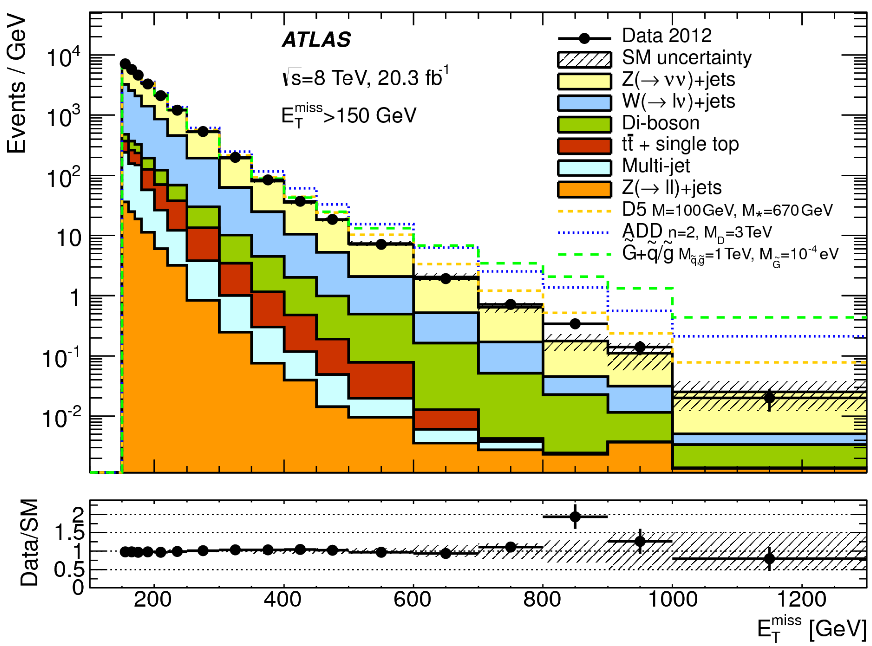


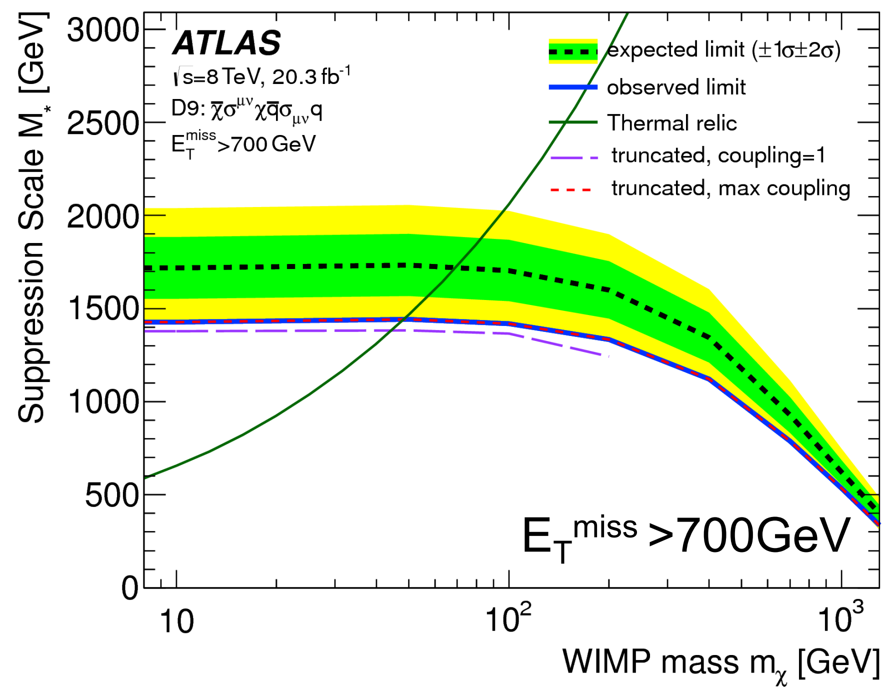


Mono-Jet search

- p_T^{jet}>125 GeV (central)
- p_T^{jet}/E_T^{miss}>0.5
- at least 1jet, lepton and isolated track vetoes
- Bkg estimation in CRs, Cross check in VRs
- E_T^{miss} : SR1 (>150GeV)– SR9 (>700GeV)
- Similar analysis from CMS (Eur. Phys. J. C75 (2015) 235)

ATLAS: Eur. Phys. J. C75 (2015) 299



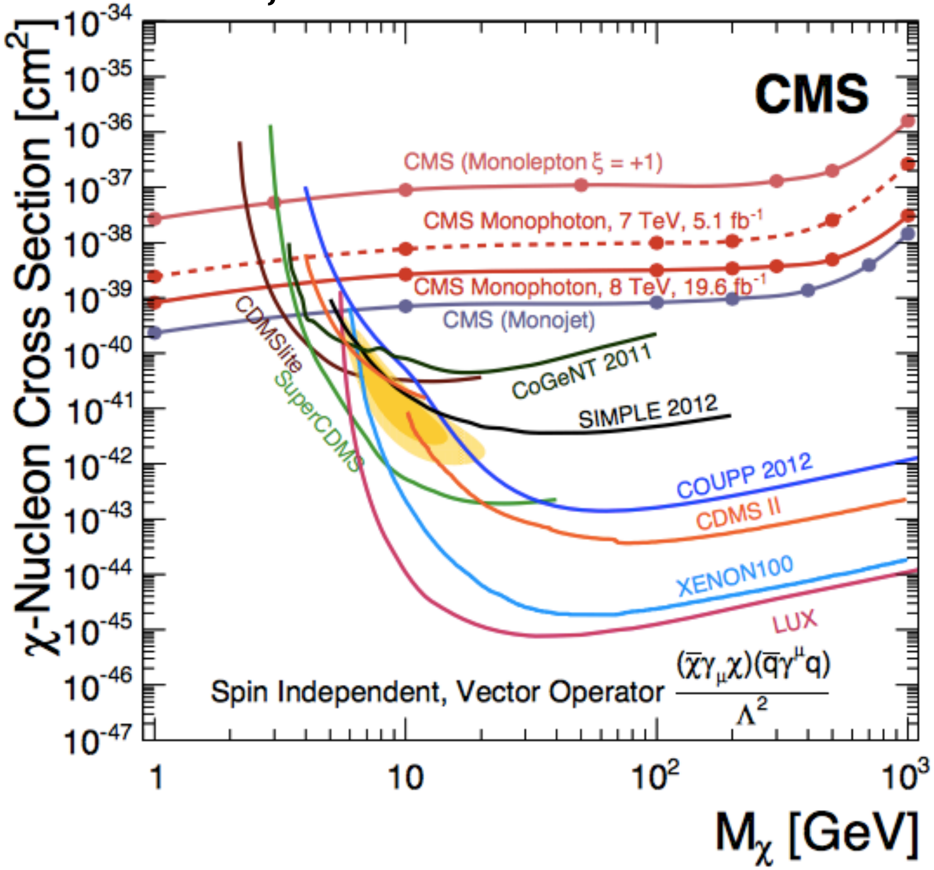


Comparison plots

- Comparison with other experiments
- Complementary with direct searches, esp. LHC has sensitivities for low DM mass
- LHC mono-X searches also have similar sensitivity for spin-dependent operators, where direct searches are weaker (backup slide)

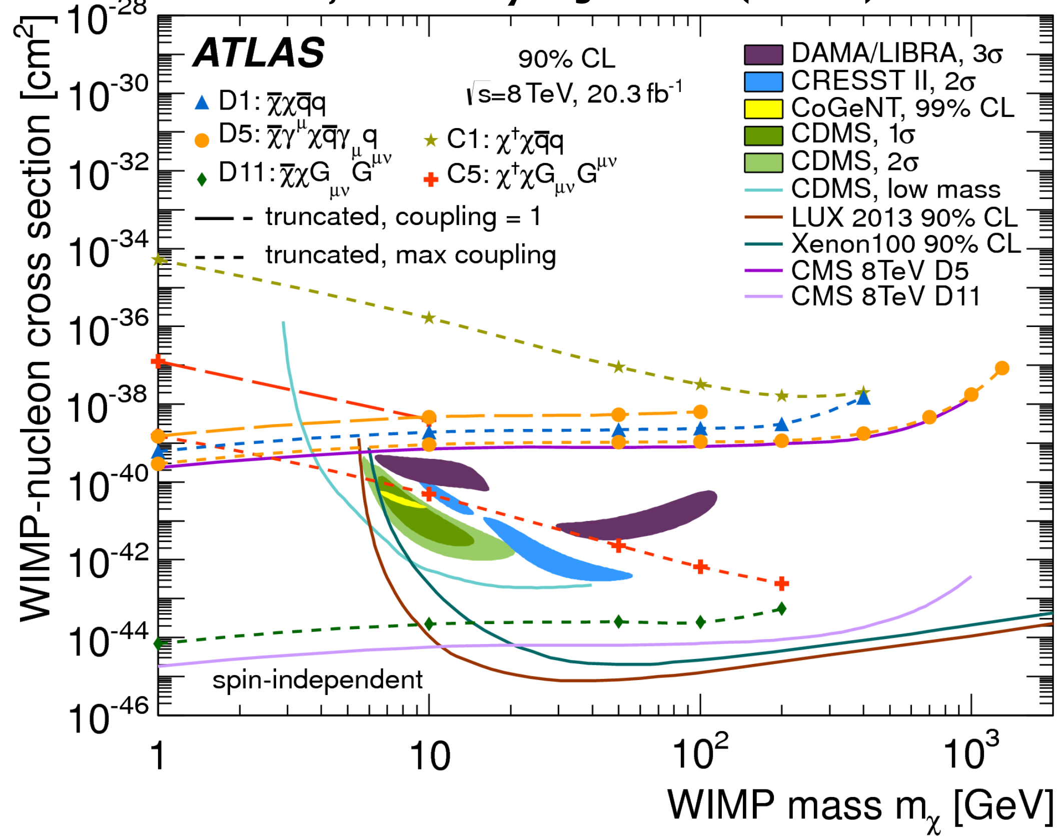
mono-photon

CMS, arXiv:1410.8812



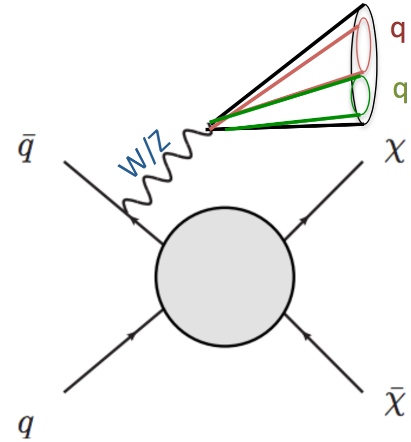
mono-jet

ATLAS, Eur. Phys. J. C 75 (2015) 235

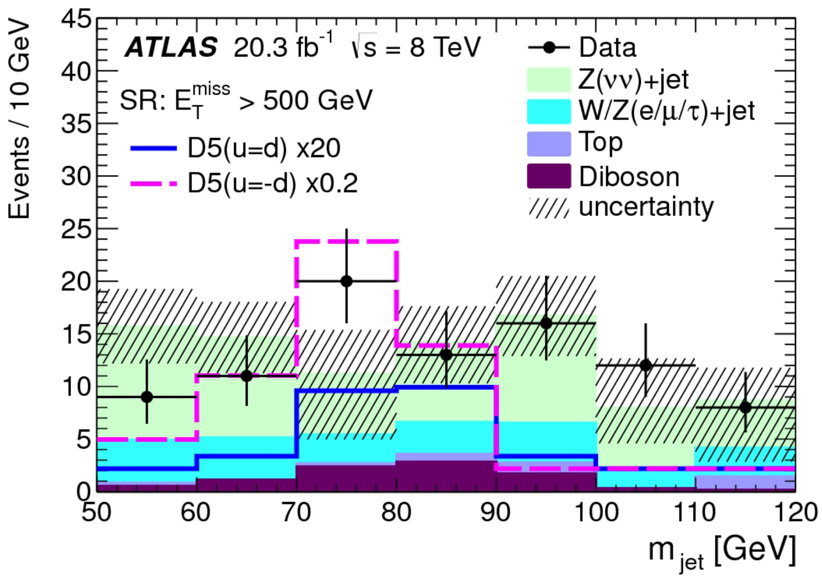


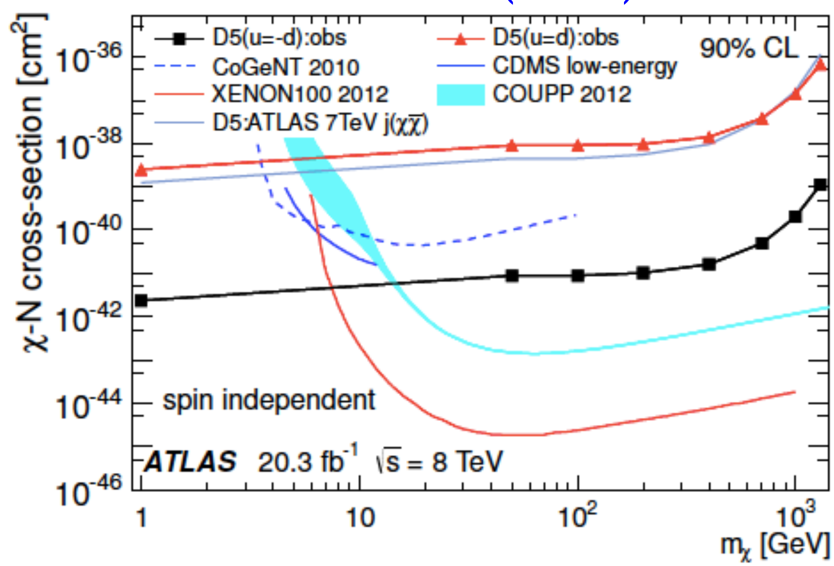
Mono–W or Z searches

- Search for DM signature with gauge boson
- Lower background, complementary to mono–jet search
- Both hadronic, leptonic decays covered (hadronic channel has stronger sensitivity)



PRL 112 (2014) 041802



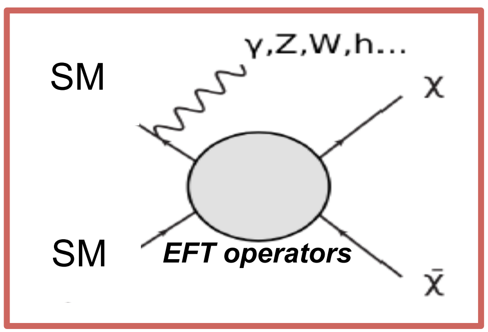


- a large radius jet (pT>250GeV)
- mjet = [50, 120] GeV
- lepton, photon vetoes
- Data driven background estimation

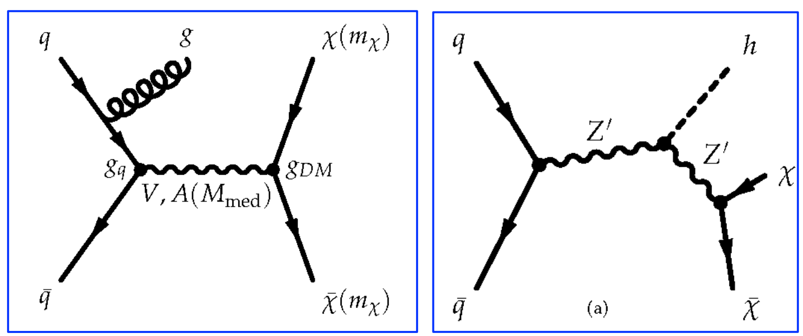
CMS DM+Z search
EXO12054

Searches with Simplified Models

- Less simple and versatile as it is more model-dependent
  However it overcomes the problems of EFT
  (validity, comparisons with the direct detection experiments)
- Additional parameters are needed (e.g. mediator mass, couplings…)
- ATLAS+CMS(+theorists) Dark Matter Forum created Run-2 benchmark implementations based on Run-1 experience
  (Dark Matter Forum report: *Phys.Dark Univ.9-10(2015)8-23*)
- already in use by ATLAS and CMS during Run-1



EFT



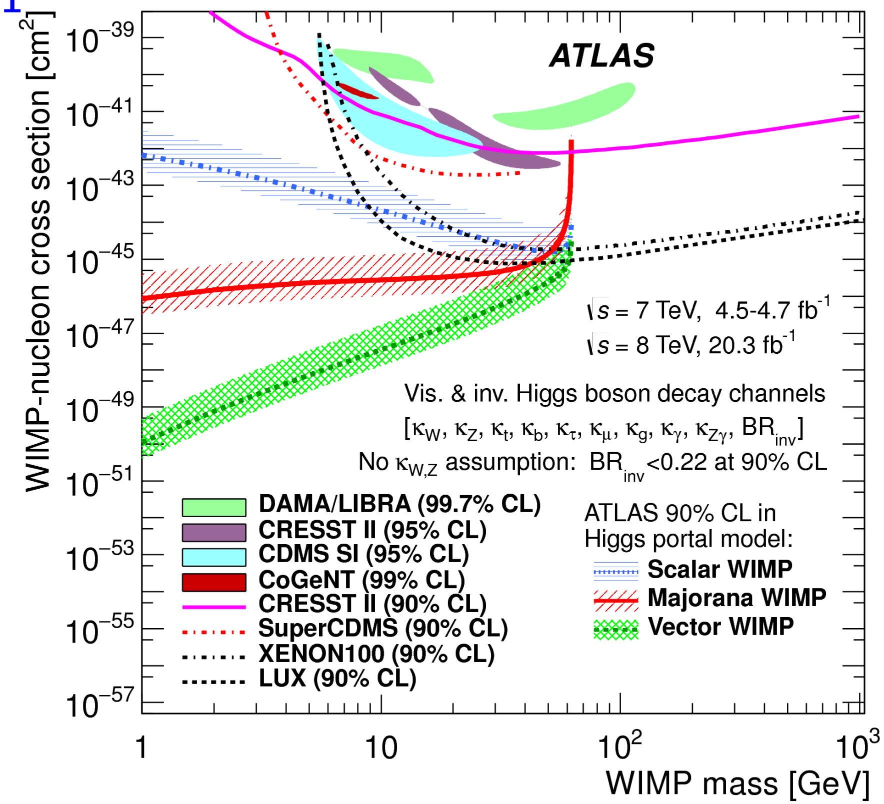
Simplified Models

- Signatures:
  - Jet + E_T^{miss}
  - Boson + E_T^{miss}
  - Higgs + E_T^{miss}
  - HeavyFlavor q + E_t^{miss}
- Free parameters
  - g (=g_{SM}=g_{DM})
  - m_{DM}, m_{med}

Other DM searches + mini-summary

- There are other searches based on rich phenomenology (interpreted by simplified models)
  - DM + heavy flavours : enhanced coupling
    [with top] ATLAS: EPJC 75(2015) 92, JHEP06(2015)121, CMS: CMS-B2G-13-004
    [with bottom] ATLAS: EPJC 75(2015) 92
  - DM + Higgs
    [Higgs → $\gamma\gamma$] ATLAS: PRL 115(2015) 131801
    NEW→ [Higgs → bb] ATLAS: arXiv:1510.06218 (submitted to PRD)
  - Higgs portal model :
    [invisible decays] ATLAS: arXiv:1508.07869, arXiv:1509.00672
    CMS: CMS-HIG-14-038

arXiv:1509.00672



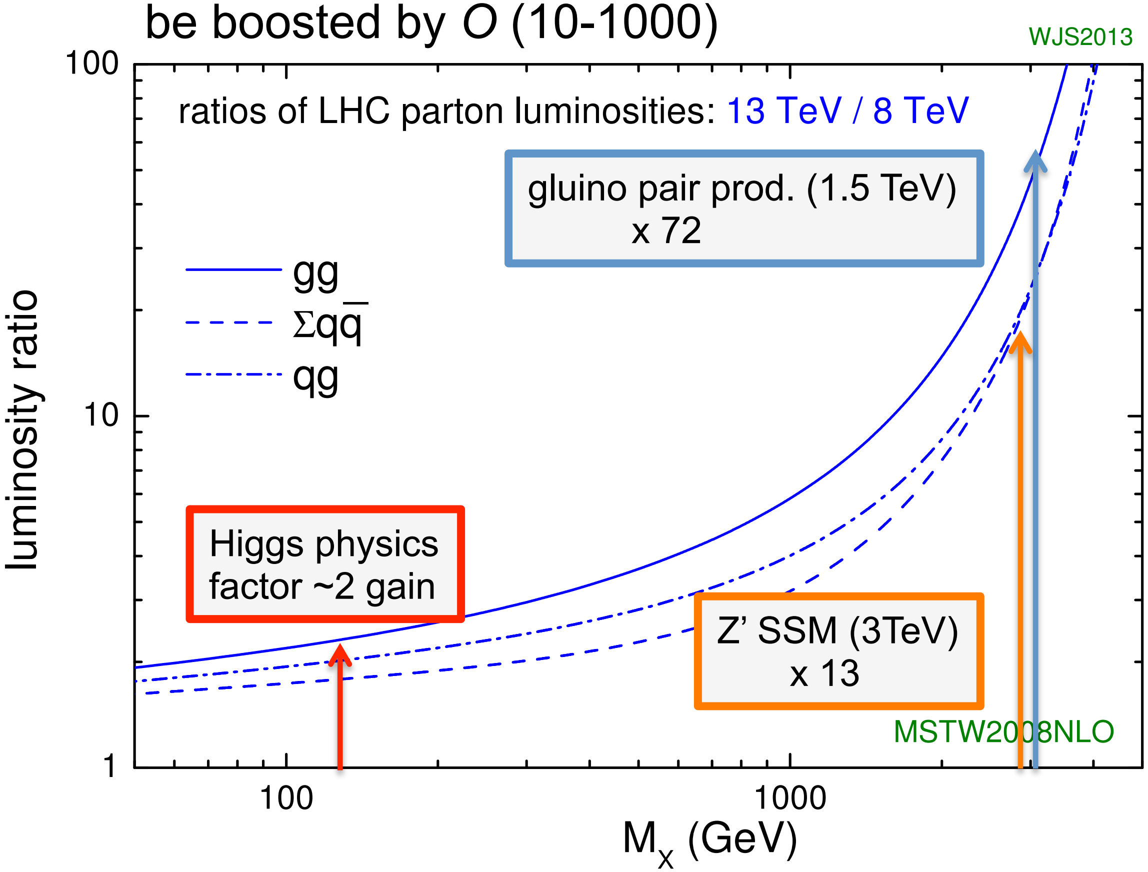
- Broad variety of mono-X searches carried out, so far consistent with SM
- Large range of parameter space was scanned, complementary to direct and indirect DM search experiments

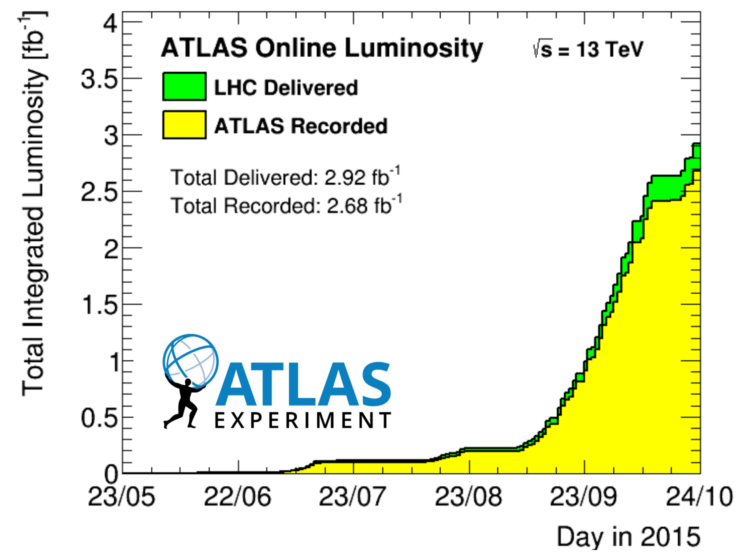
PART 3
Beginning of new era: LHC RUN-2

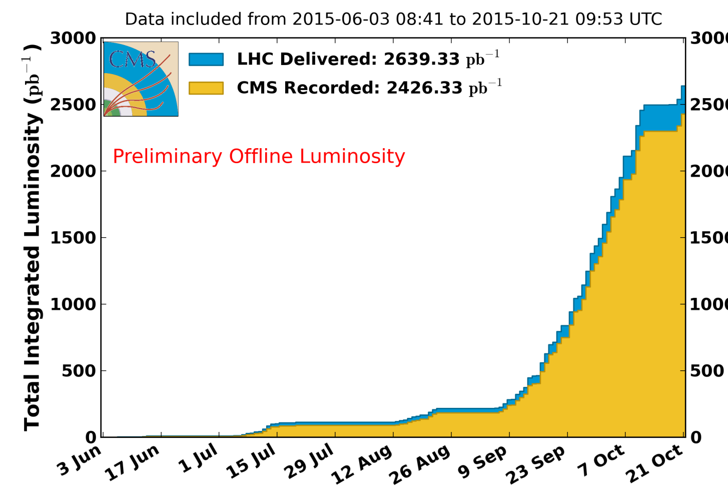
LHC Run2 (2015~2018) started

- Center of mass energy becomes 13TeV (about twice)
- Data taking since June 2015, already used for physics
- Run2 this year ~ a few fb^{-1}
  by the end of Run2 ~ $100fb^{-1}$

Sensitivity for High scale BSM will be boosted by *O* (10-1000)

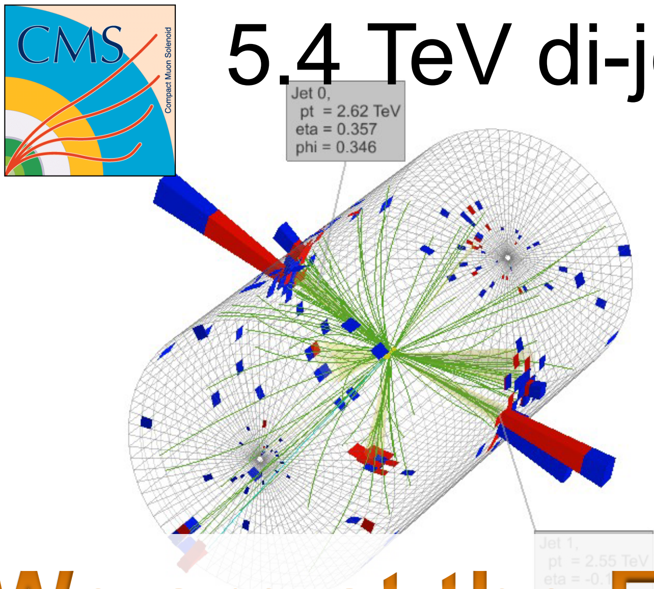


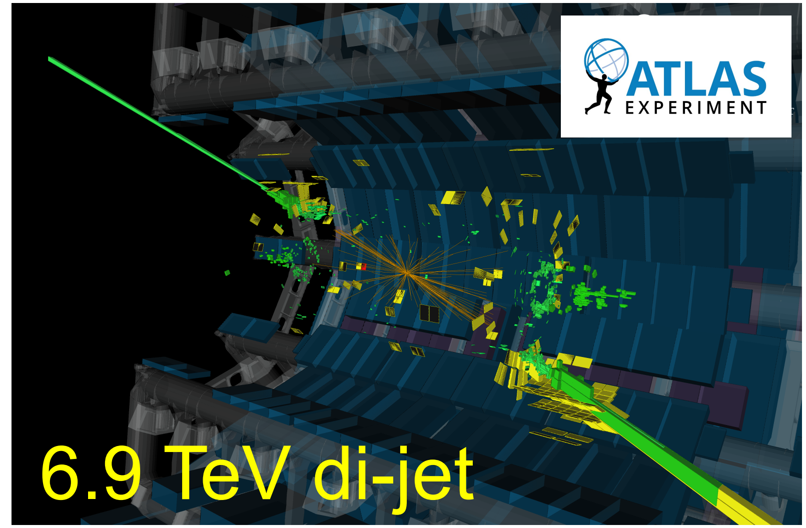




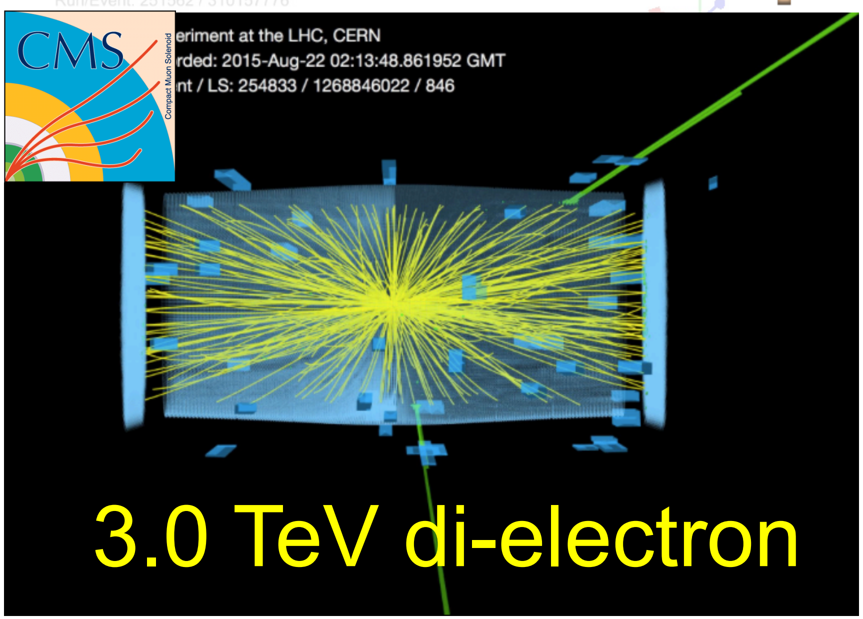
High-mass events

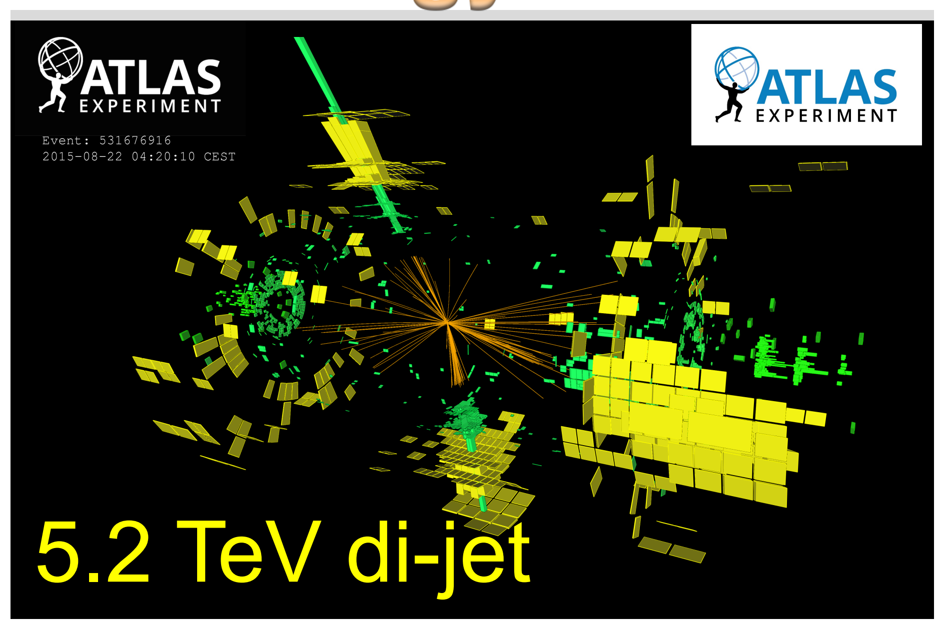
5.4 TeV di-jet





We are at the Experimental Energy Frontier

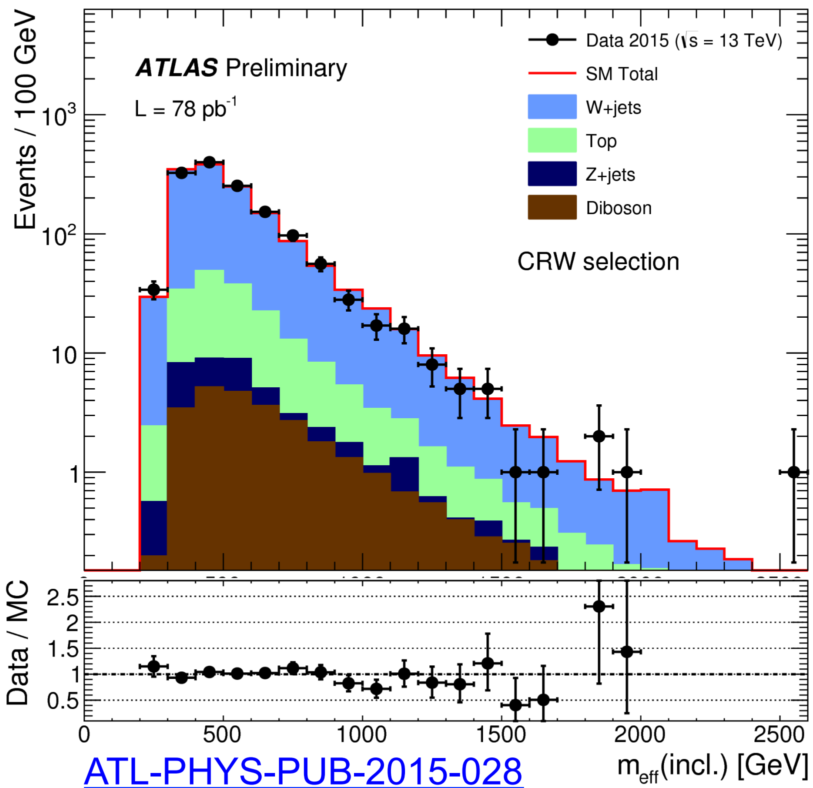




13 TeV analysis in ATLAS

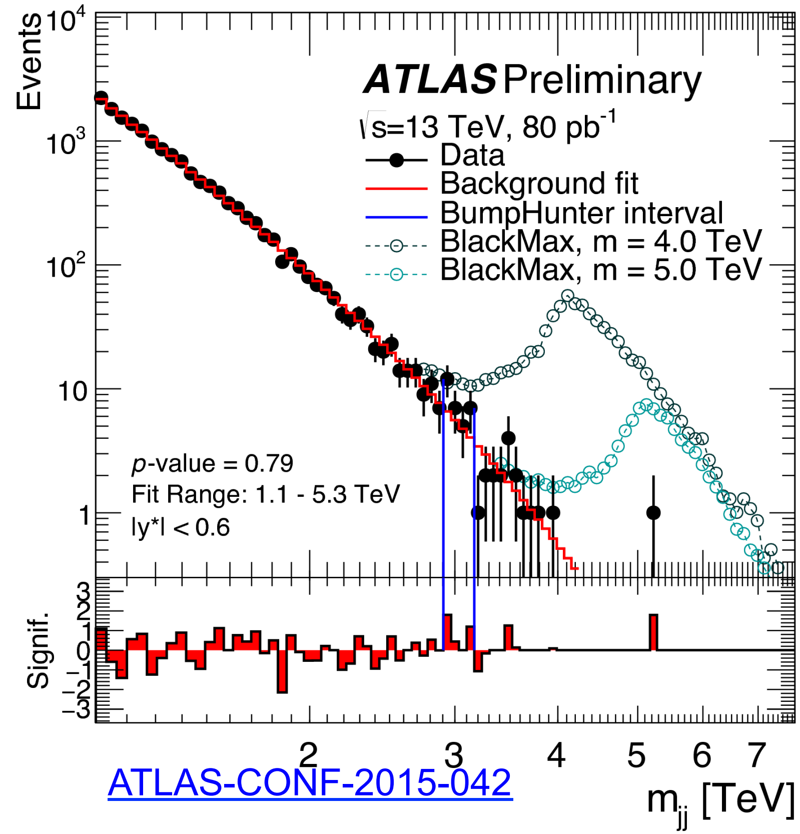
- First control region plots for measurements and searches already available
- Run-1 limits on black hole production has already been surpassed by Run-2 data set (80pb^{-1} ATLAS-CONF-2015-043, ATLAS-CONF-2015-045)
- whole list of analyses (SUSY, Exotics) found here
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

0-lepton 2-6 jets + MET
W+jets control region



ATL-PHYS-PUB-2015-028

Di-jet mass search



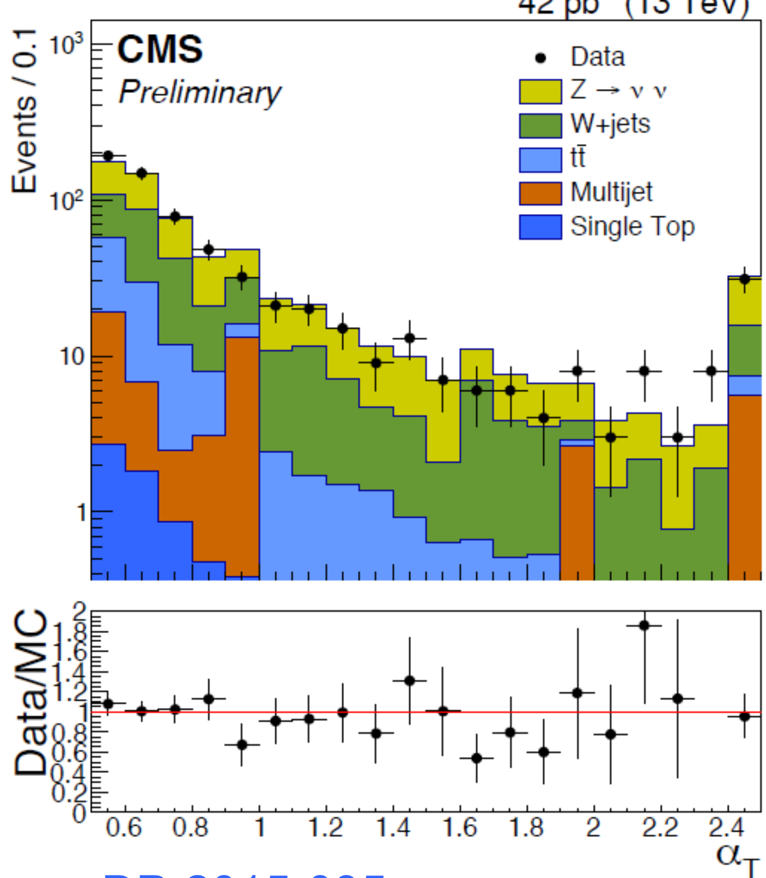
ATLAS-CONF-2015-042

13 TeV analysis in CMS

- Preliminary control region plots based on 42pb^{-1} data
- whole list of analyses (SUSY, Exotics) found here

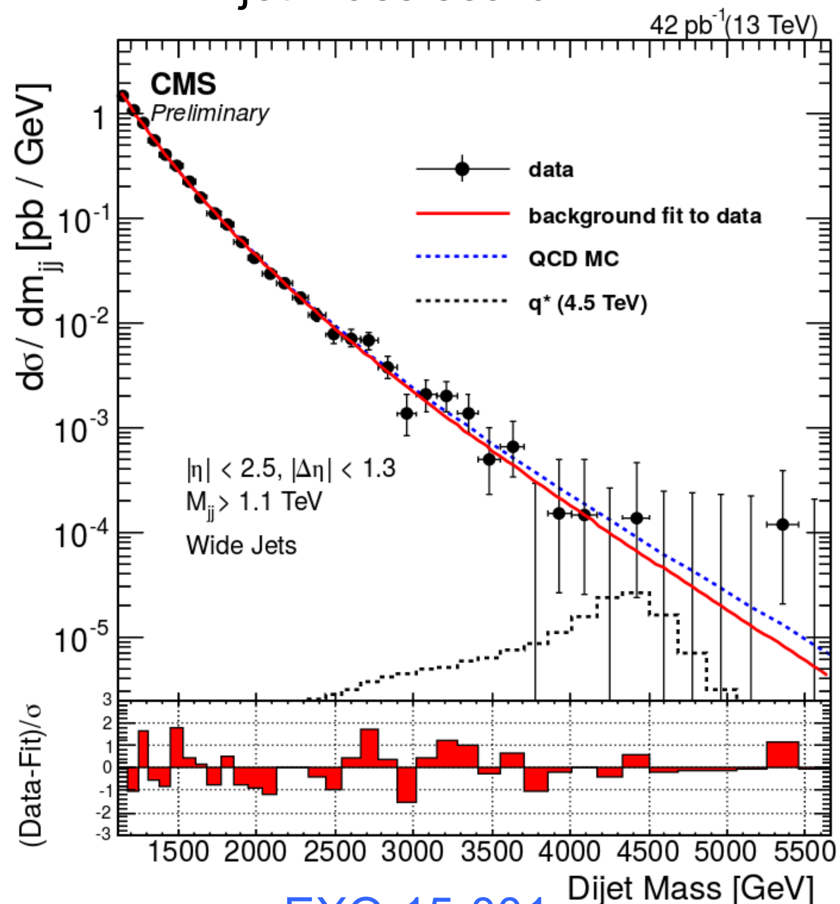
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

α_T distribution for H_T>225GeV



DP-2015-035

Di-jet mass search

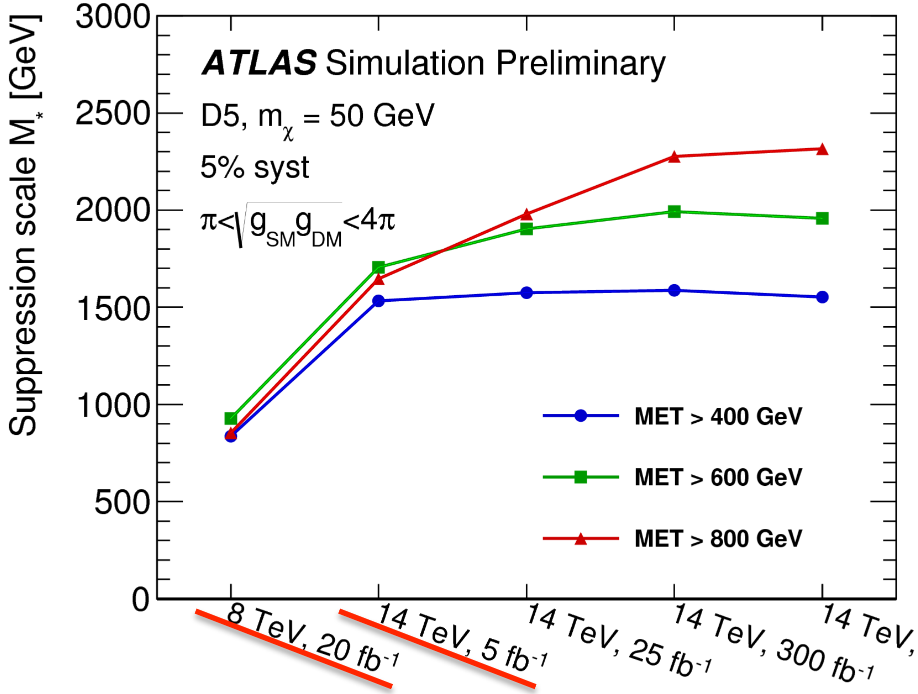


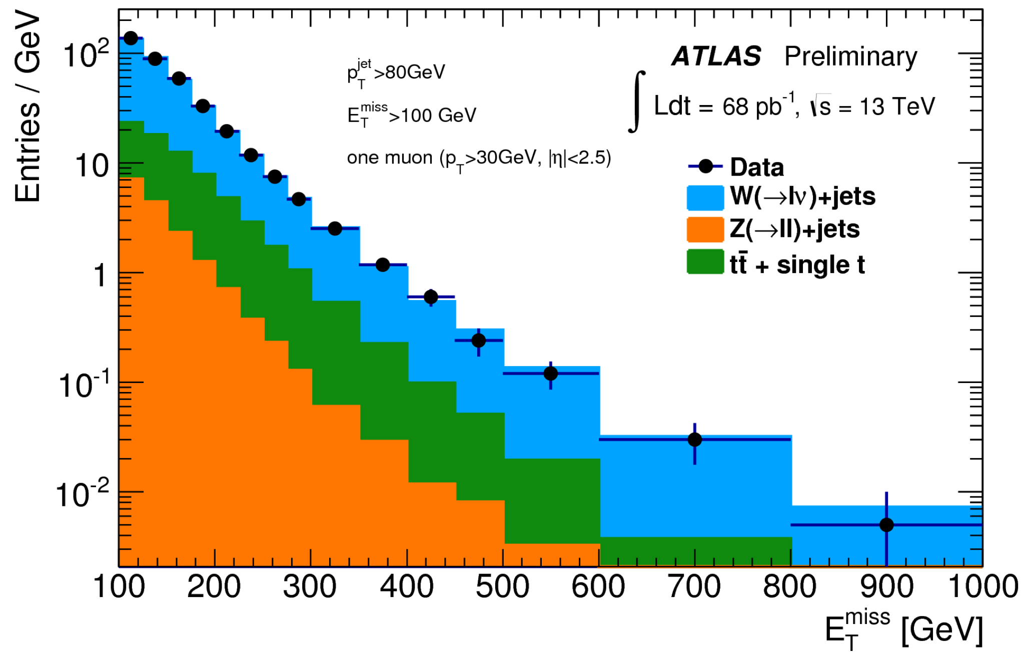
EXO-15-001

Run-2 expectations for DM searches

- Run-1 sensitivity will be surpassed by the first 5 fb^{-1} of Run-2 data

ATL-PHYS-PUB-2014-007





mono-Jet analysis Control Region in early 13TeV Run-2 data

Conclusion and outlook

- From Run1
  - DM Searches from both directions i.e.
    - Complete models (SUSY)
    - Effective Field Theory and Simplified Models
  - no evidences were found (except for some hints)
  - strong limits made in the parameter space
- For Run2 and beyond
  - Higher energy regime ($\sqrt{s}=13$TeV): expected much higher sensitivities for large scale physics
  - Many new schemes, new implementations, even new detector (!) installed : smooth start of the Run-2 owing to the accumulations of knowledge, experiences during Run-1

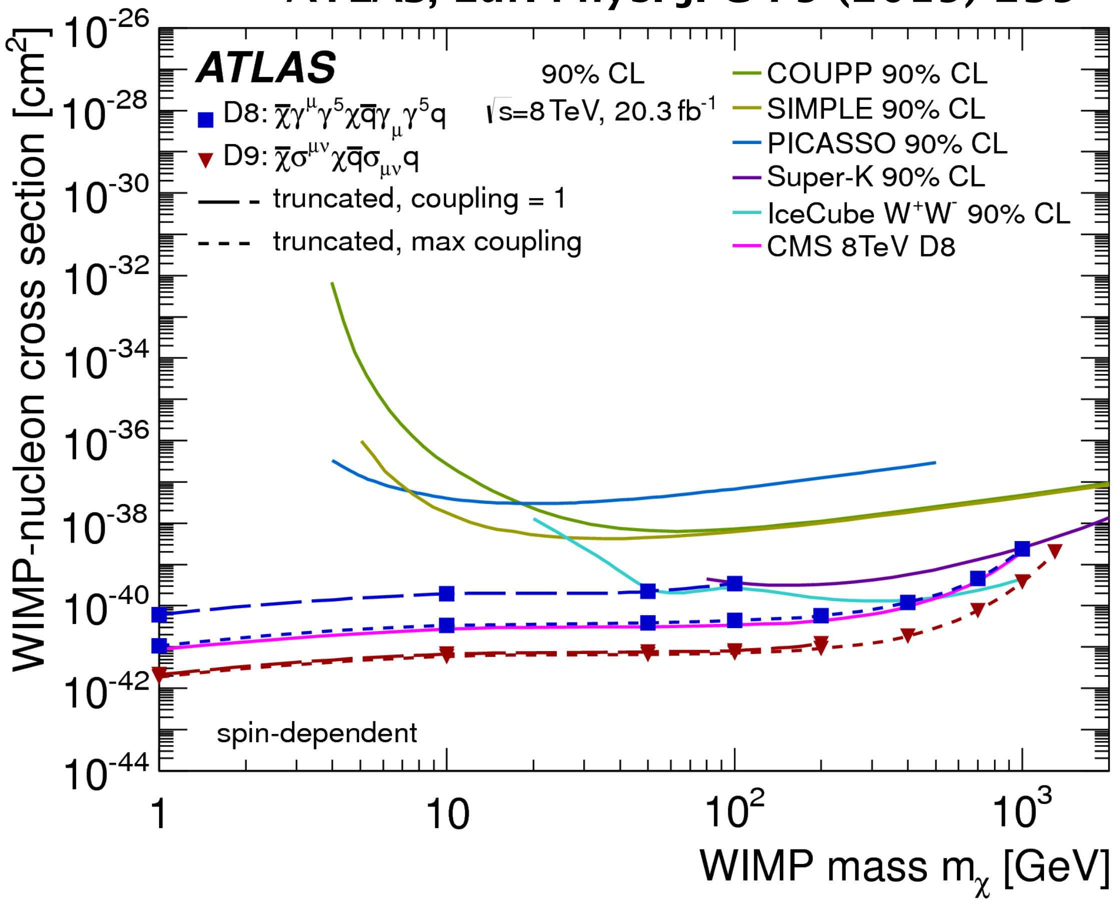
New surprise can happen anytime – stay tuned

EXTRA SLIDES

spin-dependent interaction limit

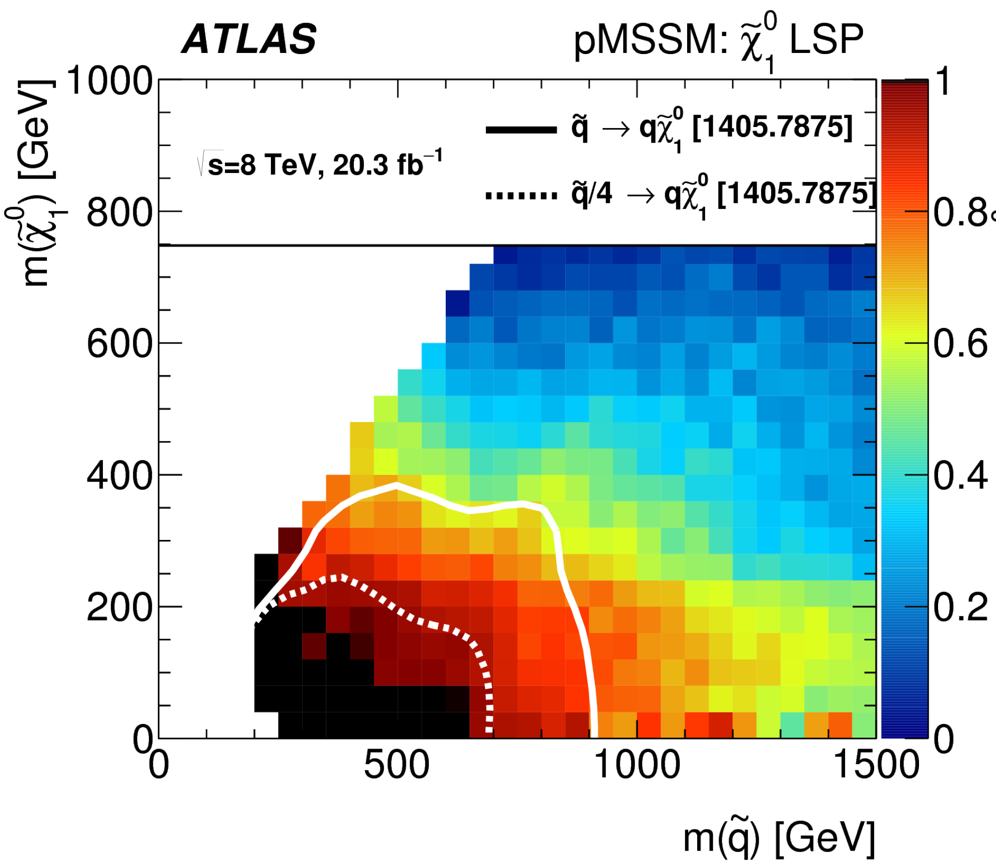
- ATLAS mono-jet search

ATLAS, Eur. Phys. J. C 75 (2015) 235

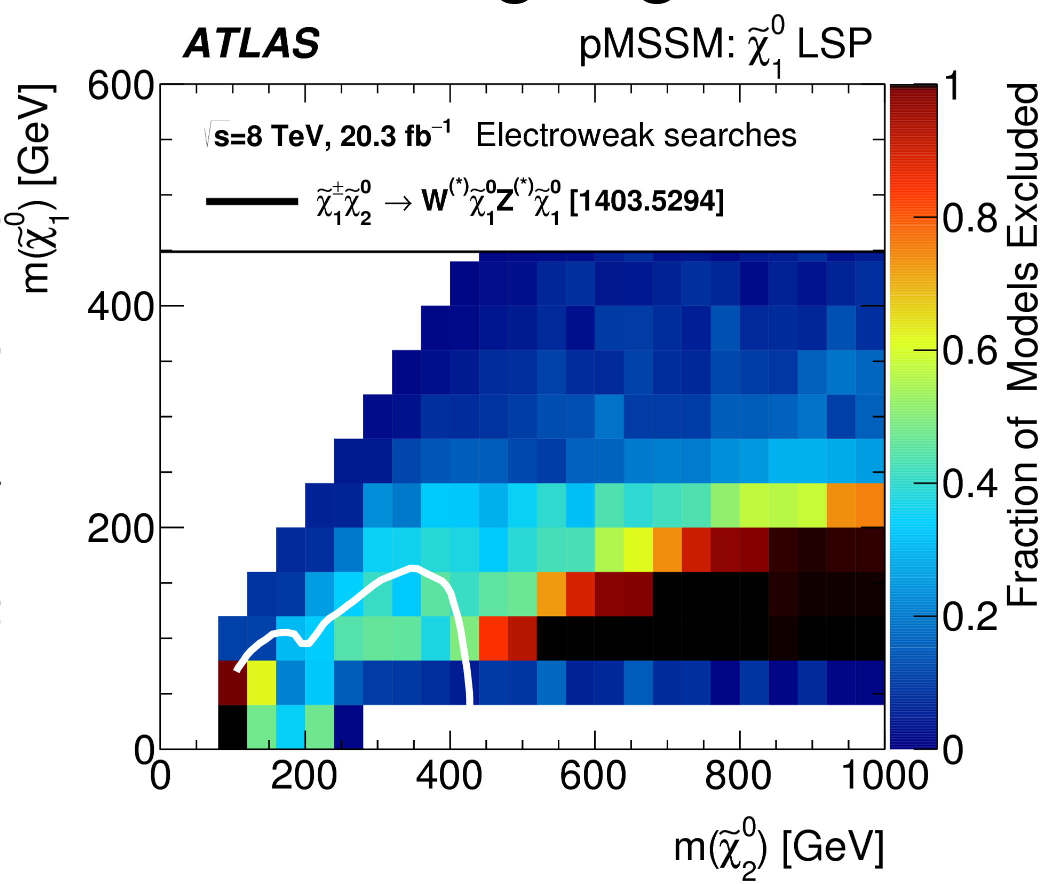


pMSSM mass limits

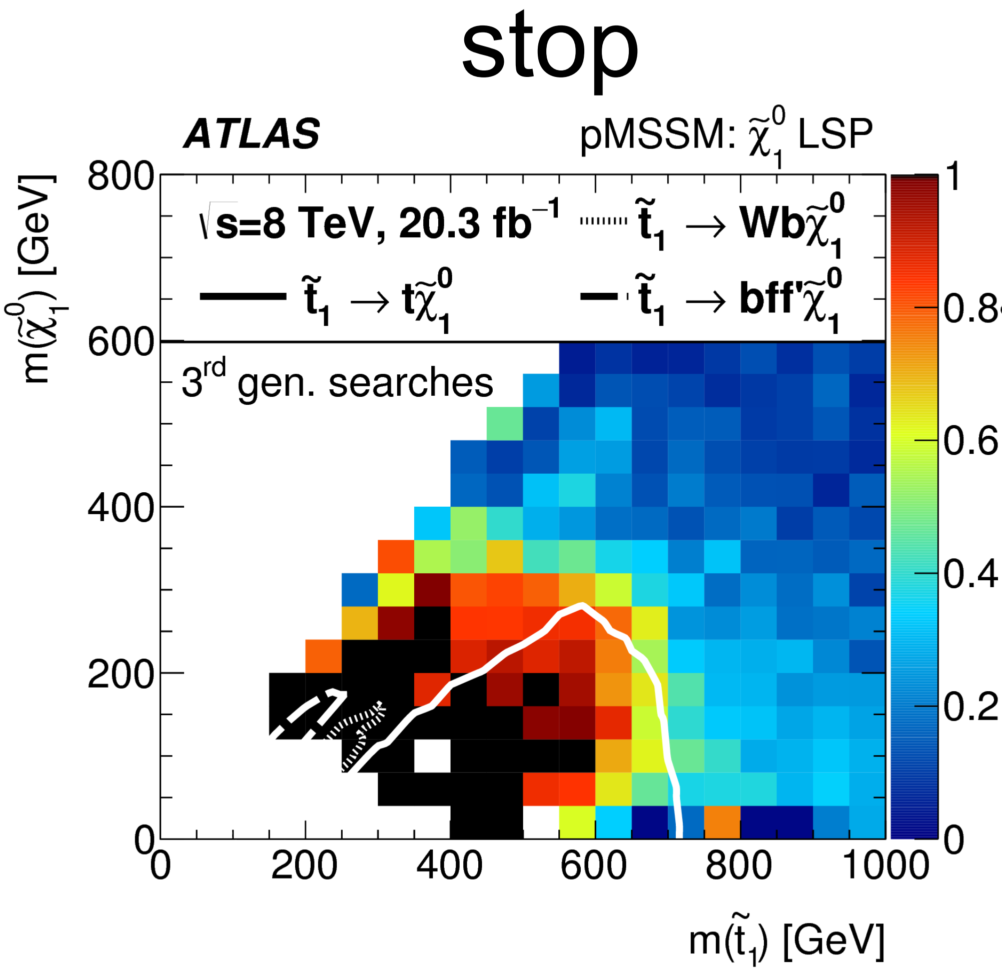
light squarks



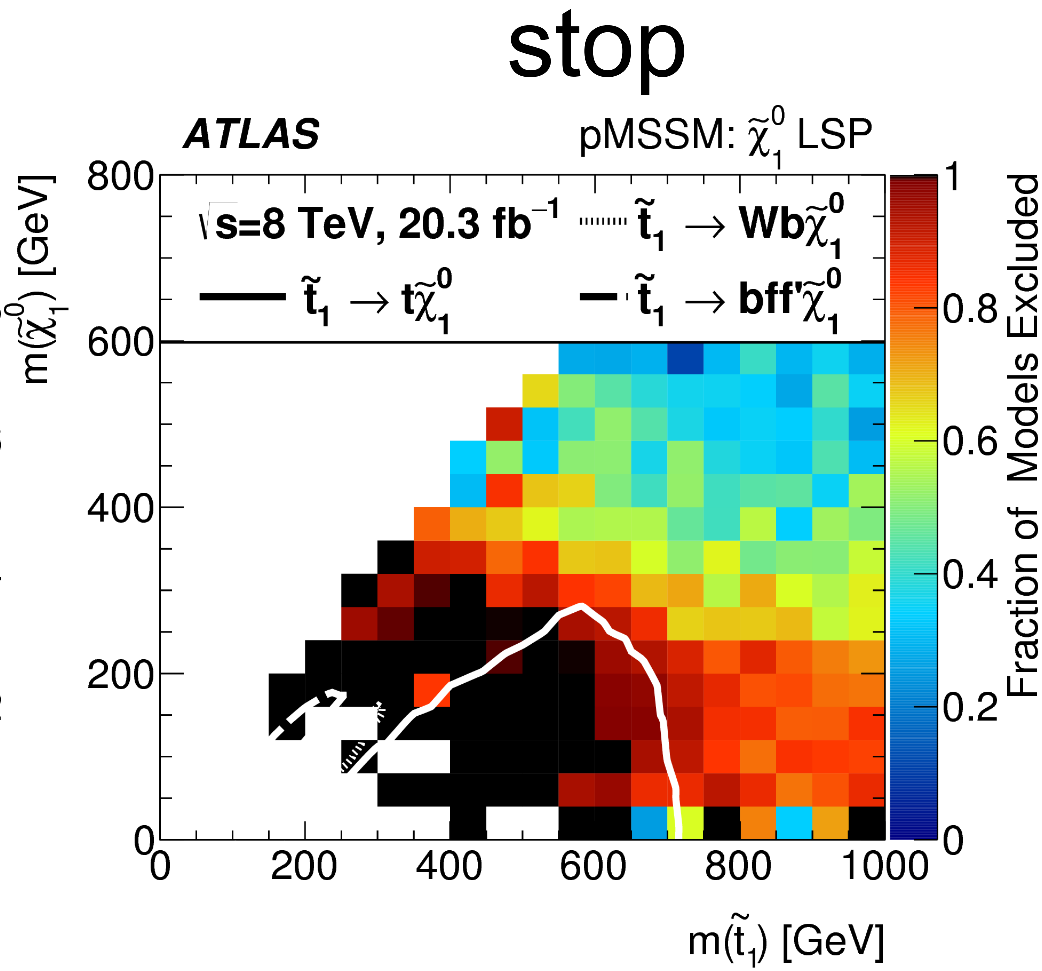
EW gauginos



pMSSM mass limit



use 3rd gen searches



use all searches

pMSSM mass limit