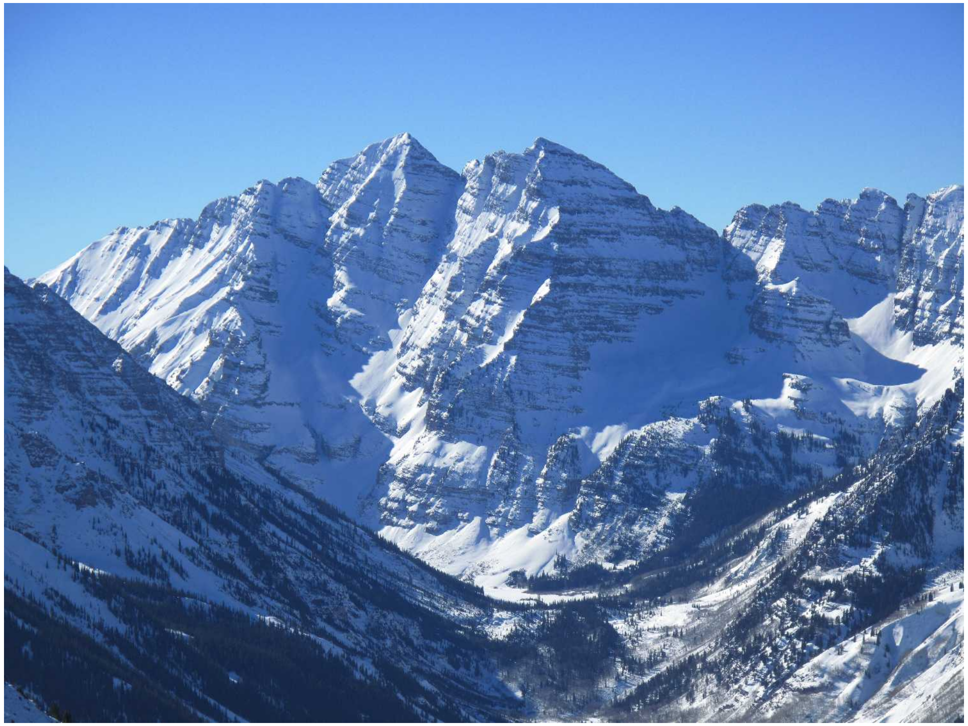
Supersymmetry and Exotic Searches at ATLAS

Henri Bachacou
on behalf of the ATLAS Collaboration

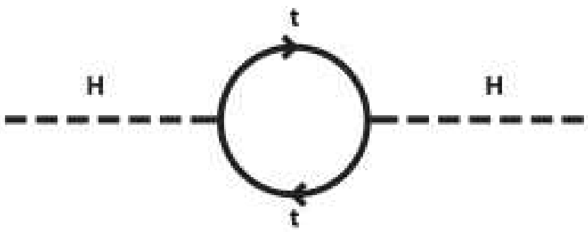


Aspen

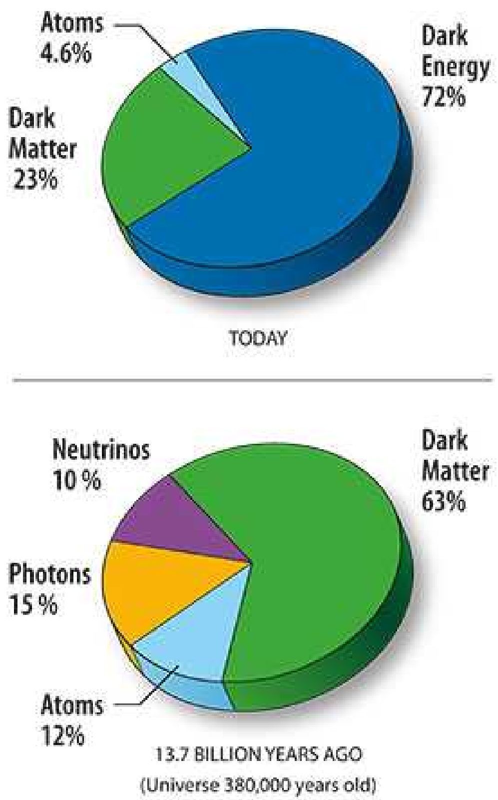
18-24 January 2014

Why look "beyond" the Standard Model?

- Hierarchy problem: quadratic divergence of the Higgs mass, extremely fine-tuned
  - → What is the underlying nature of EWSB?



- Dark Matter cannot be explained by SM
- BSM models attempt to solve the SM limitations:
  - → SUSY
  - → Extra-dimensions
  - → Compositeness and Strong Interactions
  - → Etc...
- BSM models guide searches, but more importantly we must leave no stone unturned:
  - → Try to cover all possible signatures
  - → model-independent searches interpreted in terms of benchmark models
  - → We want to discover something!
    Limit-setting is only the fall-back option

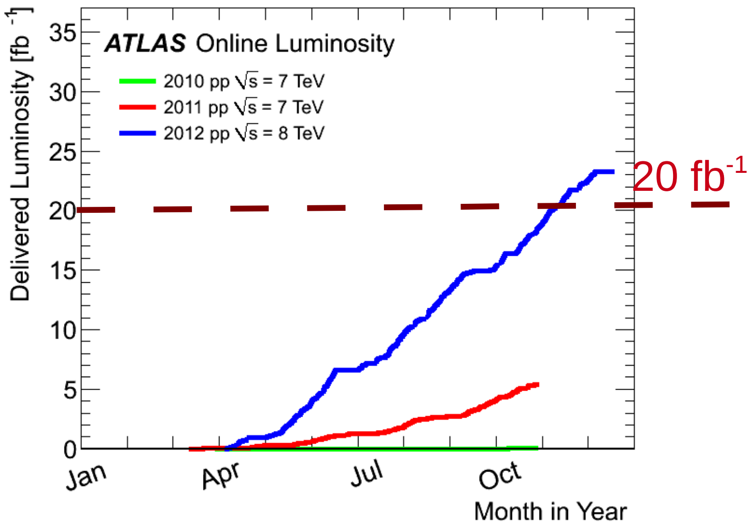


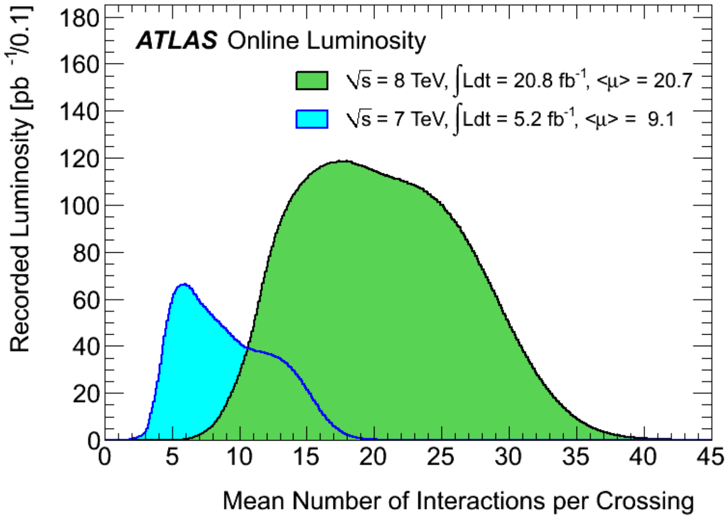
Condensed list of signatures

- With large missing ET:
  - → 2-10 jets
  - → w/ or w/o b-jets, w/ or w/o leptons (e,μ,τ)
  - → w/ or w/o photon or Z
  - → mono-X (X = jet, photon, W, Z)
- Without missing ET:
  - → Multijet (RPV)
  - → Black holes (w/ or w/o MET, w/ or w/o leptons)
- “Resonances”:
  - → dijet, photon-jet, diphoton
  - → dilepton (ee, μμ, ττ, eμ, eτ, μτ, eυ, μυ)
  - → lepton-photon (excited lep)
  - → lepton-jet (e,μ,τ, leptoquark)
  - → WW/WZ/ZZ
- Non-resonance:
  - → dilepton C.I.
  - → dijet angular distribution
- Same-sign dilepton / multilepton
  - → w/ or w/ (b)jets, w/ or w/o MET
  - → $l^{\pm}l^{\pm}$- jet-jet (heavy neutrino, ee, μμ, eμ)
  - → $H^{\pm\pm}$
- With top:
  - → top-antitop resonance
  - → top-jet, top-bottom resonance
  - → VLQ's
- Higgs MSSM/2HDM/invisible
- Long-lived particles:
  - → displaced photons
  - → displaced vertices
  - → stopped particles, out-of-time decay
  - → highly-ionizing particles: slow-heavy, multi-charge, monopole
- Even more exotic:
  - → “lepton-jets” (collimated, high-multiplicity, e, μ, photon, prompt or long lived)

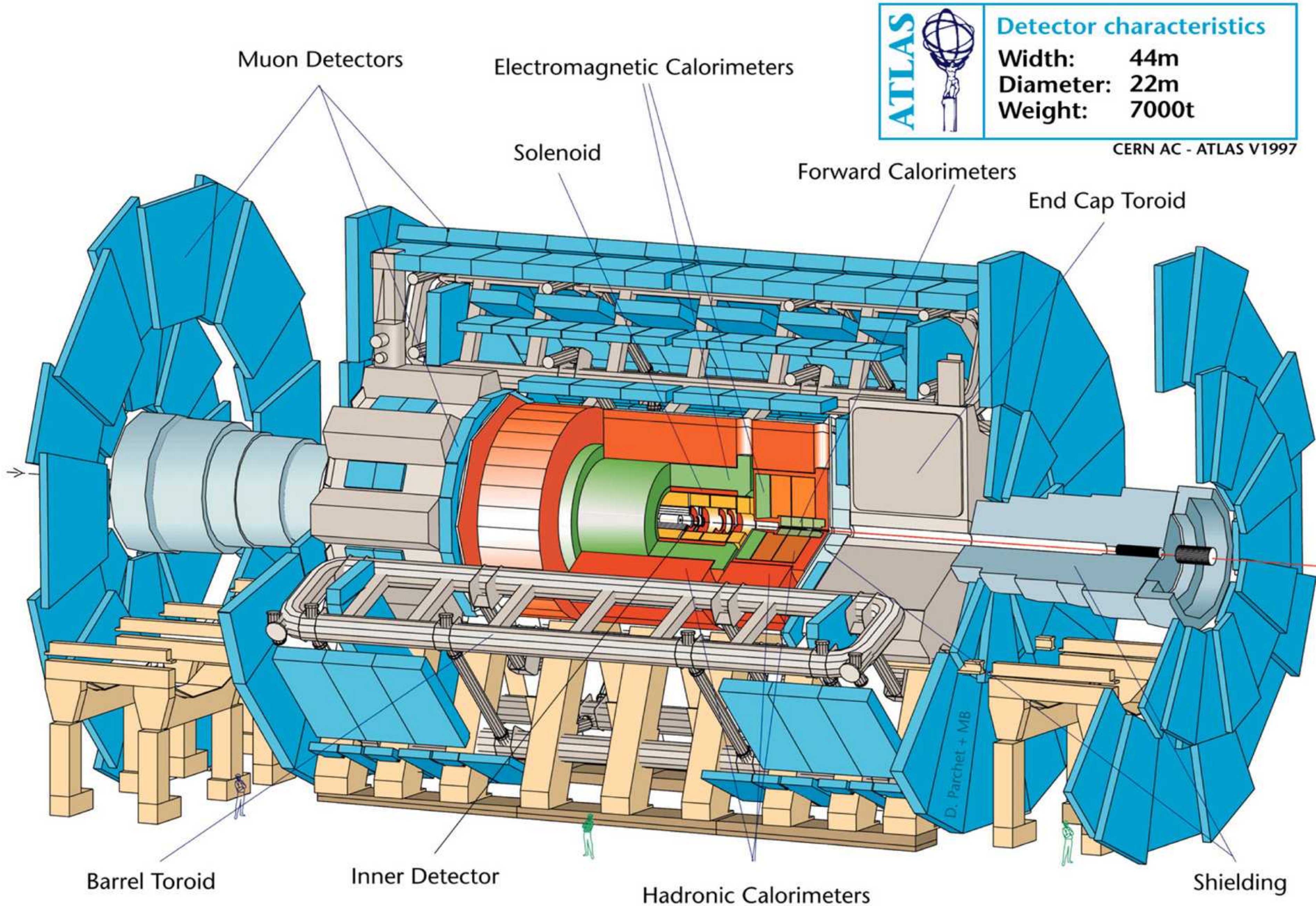
The Large Hadron Collider (LHC)

- pp collisions:
  - → 5 fb^{-1} at $\sqrt{s}$ = 7 TeV in 2011
  - → 20 fb^{-1} at $\sqrt{s}$ = 8 TeV in 2012
- LHC has performed extremely well in 2012:
  - → 7.7 10^{33} $/cm^2/s$ peak luminosity
  - → More than 20 fb^{-1} delivered to both experiments
- 50 ns bunch spacing
- Pile-up: ~ 20 collisions / crossing
- Many ATLAS results still need to be updated with full dataset

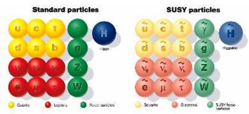




The ATLAS Detector



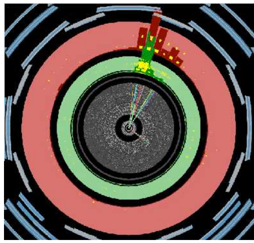
Outline



Supersymmetry

- → Strong production
- → 3rd generation
- → EW production
- → GMSB

Dark Matter

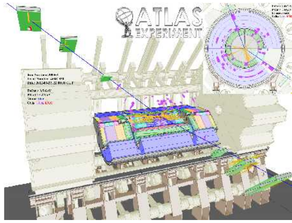


- → Monojet
- → Mono-photon
- → Mono-Z
- → Mono-W

Long-Lived Particles

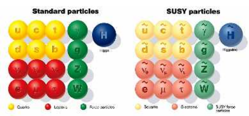
- → Stopped particles
- → Disappearing track
- → Lepton-jet

Heavy Resonances



- → Dilepton
- → Dijet
- → Top-antitop

Outline



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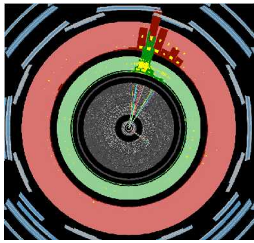

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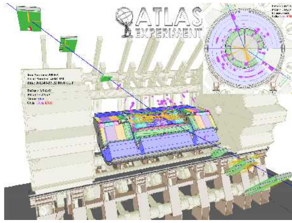

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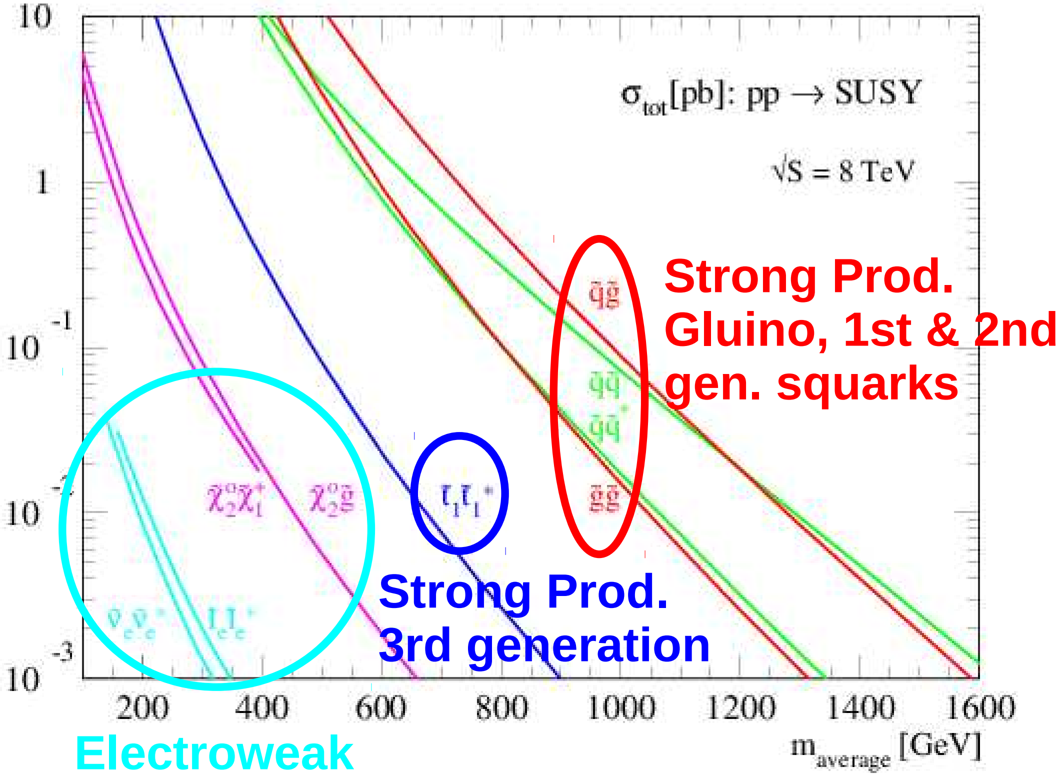
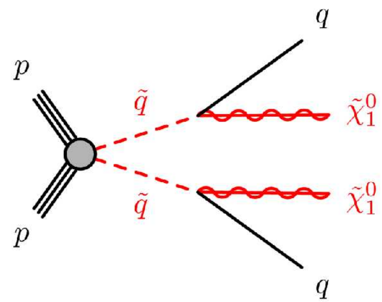


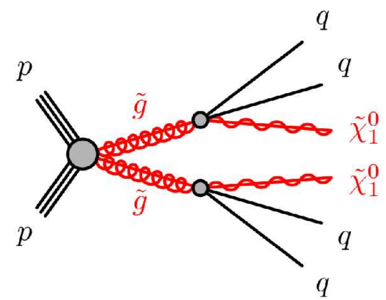
Electroweak Production

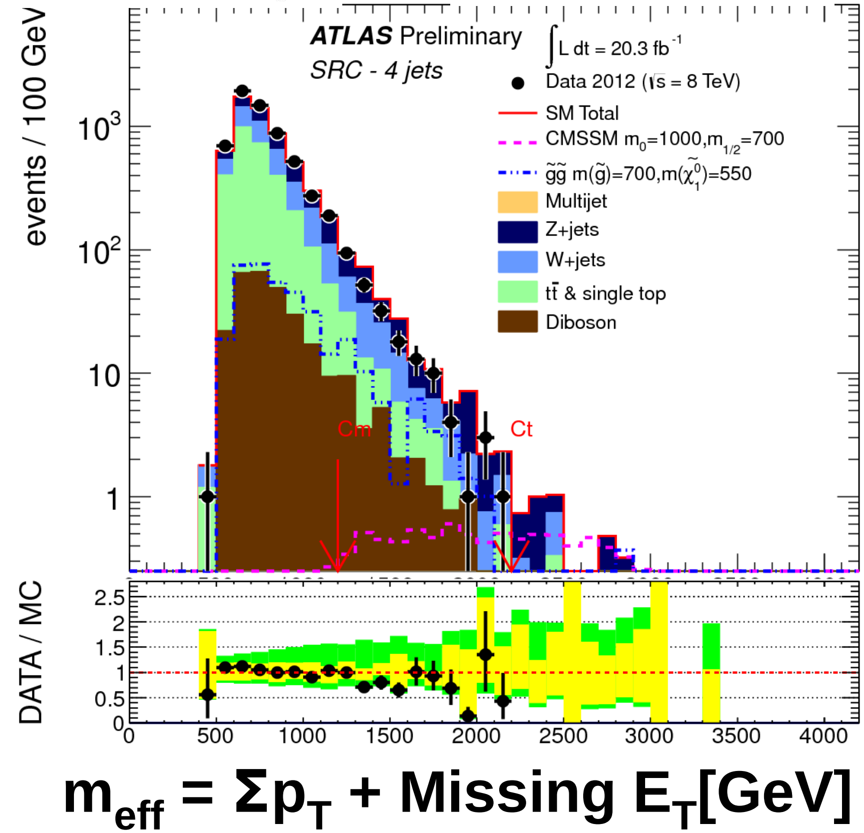
- Very diverse phenomenology...
- Comprehensive program
  - → Cannot cover all here
- Increasing luminosity → sensitive to low cross-section processes
- Also looking for more challenging signatures: long-lived particles, RPV

Supersymmetry: Strong Production

- “Standard” SUSY search
  - → Gluino and Squark production dominates → high-momentum jets
  - → Cascade ending with LSP → large Missing Transverse Energy (MET)
- Combine several channels (# jets; # lep)
- Ex: 4-jets, 0-lepton







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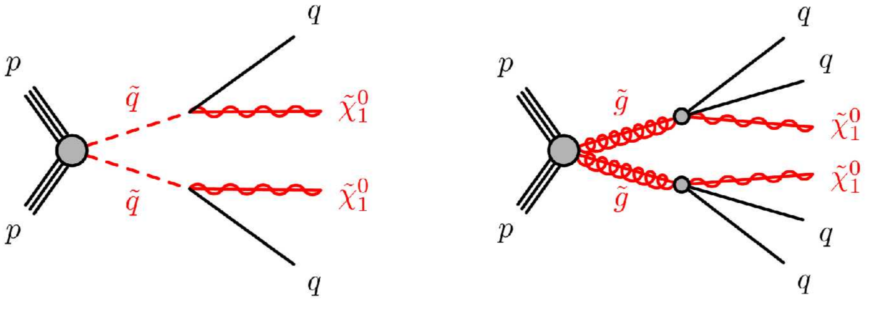
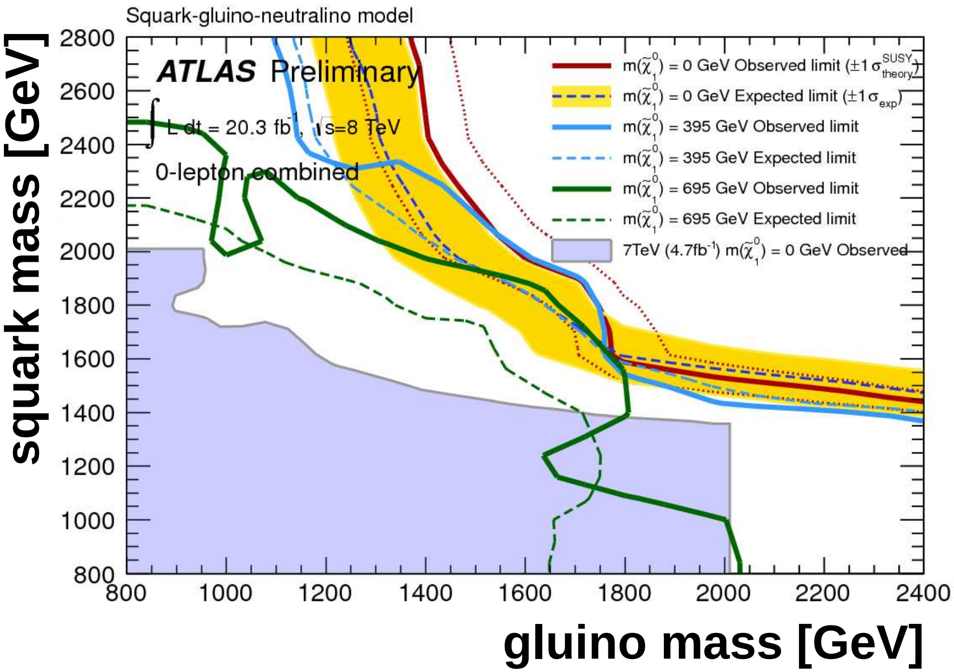
- Combine several channels (# jets; # lep)
- Simplified-model interpretation

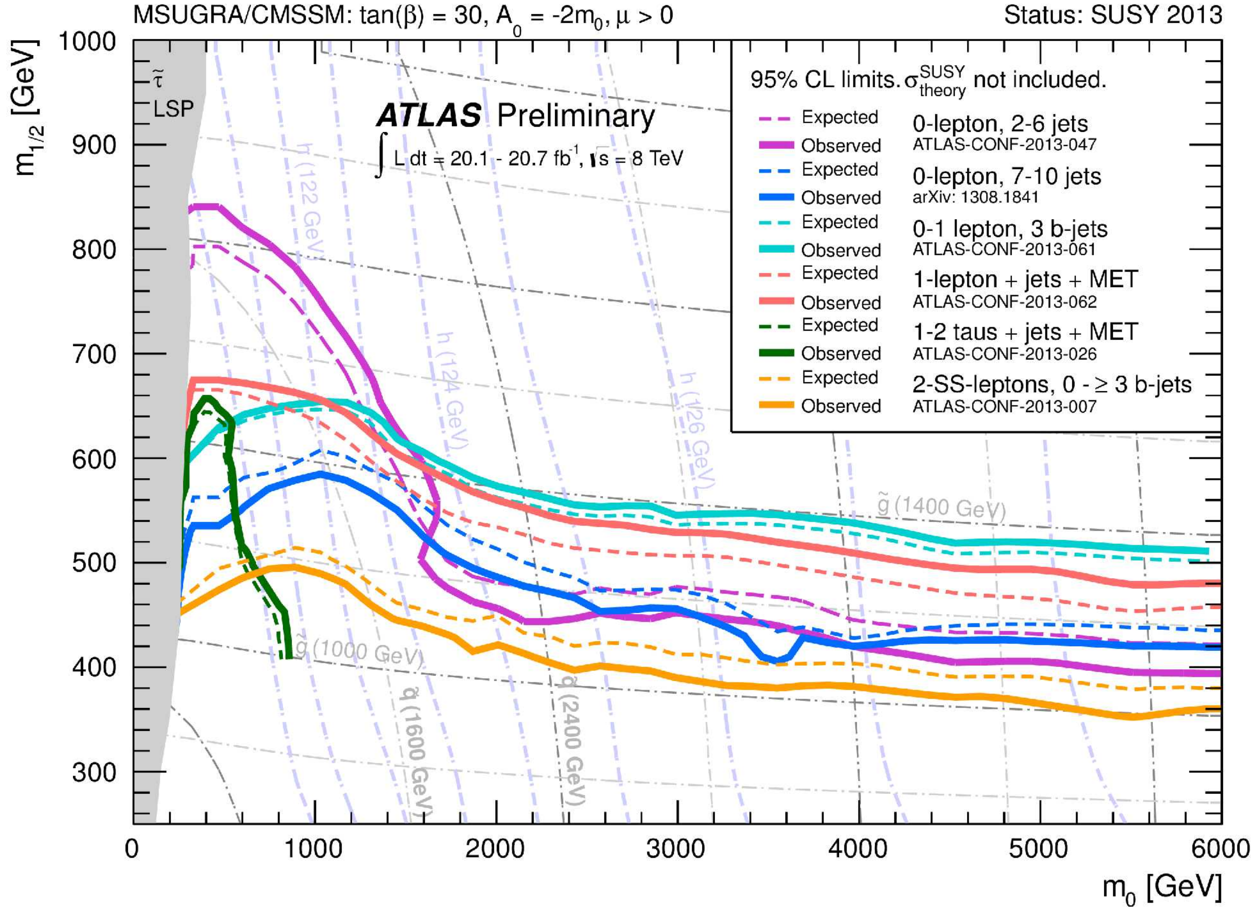


squark-gluino-neutralino model



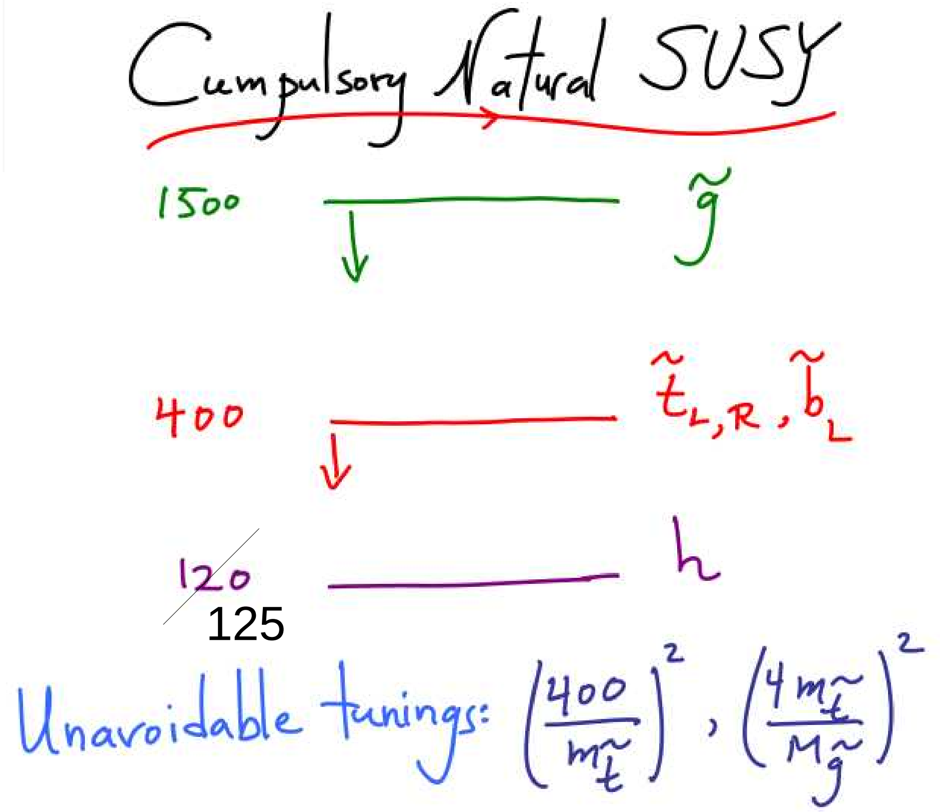
Supersymmetry: Strong Production

- Summary of strong-production searches
- cMSSM interpretation: squark and gluino mass > 1.4 TeV (95% CL)
- Conclusion: cMSSM is fine-tuned



Supersymmetry: 3rd generation

- Natural (i.e. not fine-tuned) SUSY requires:
  - → stop/sbottom are light
  - → gluino somewhat light
  - → 1st and 2nd generation squarks are allowed to be very heavy



N. Arkani-Hamed

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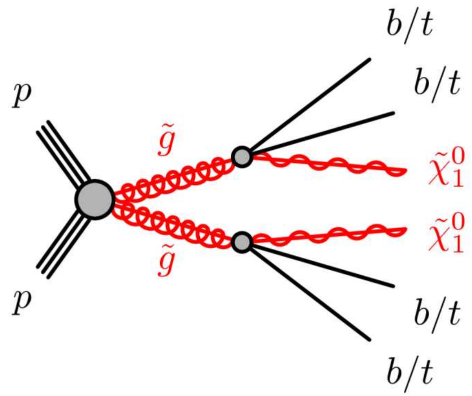
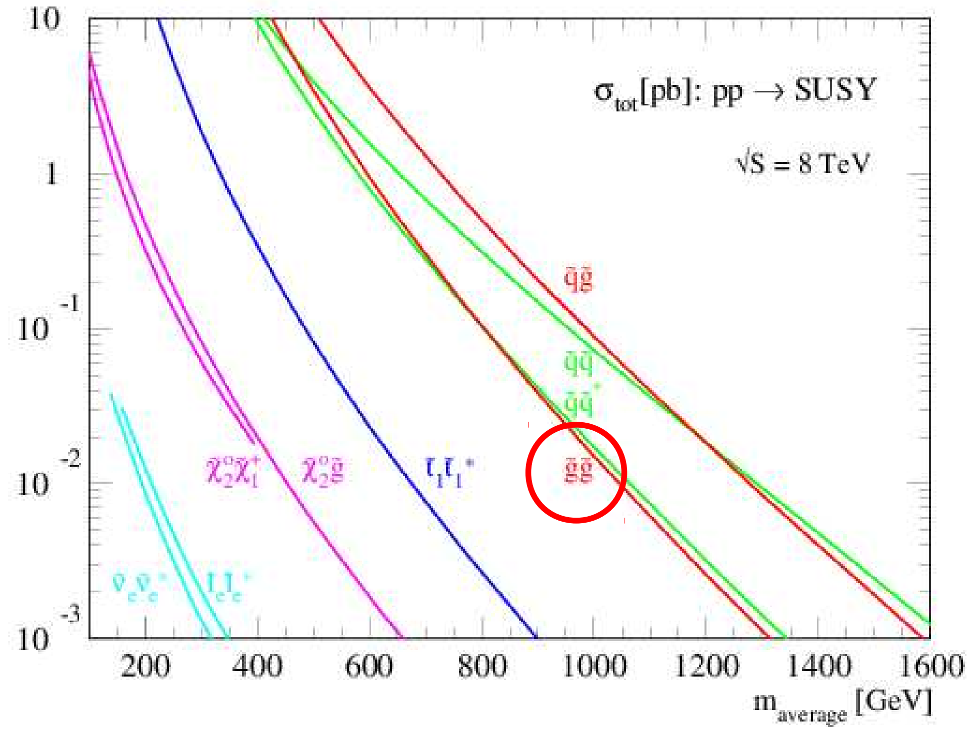
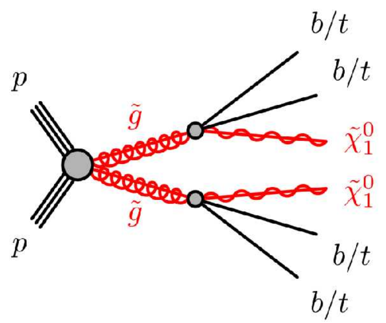
  - → gluino production decaying to stop/sbottom
  - → direct production of stop/sbottom

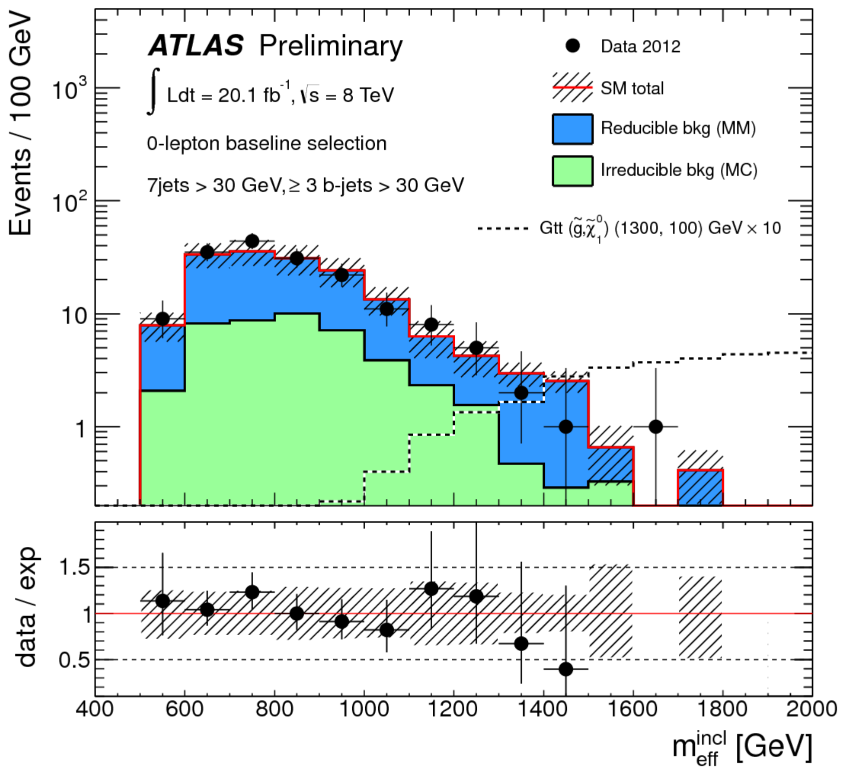


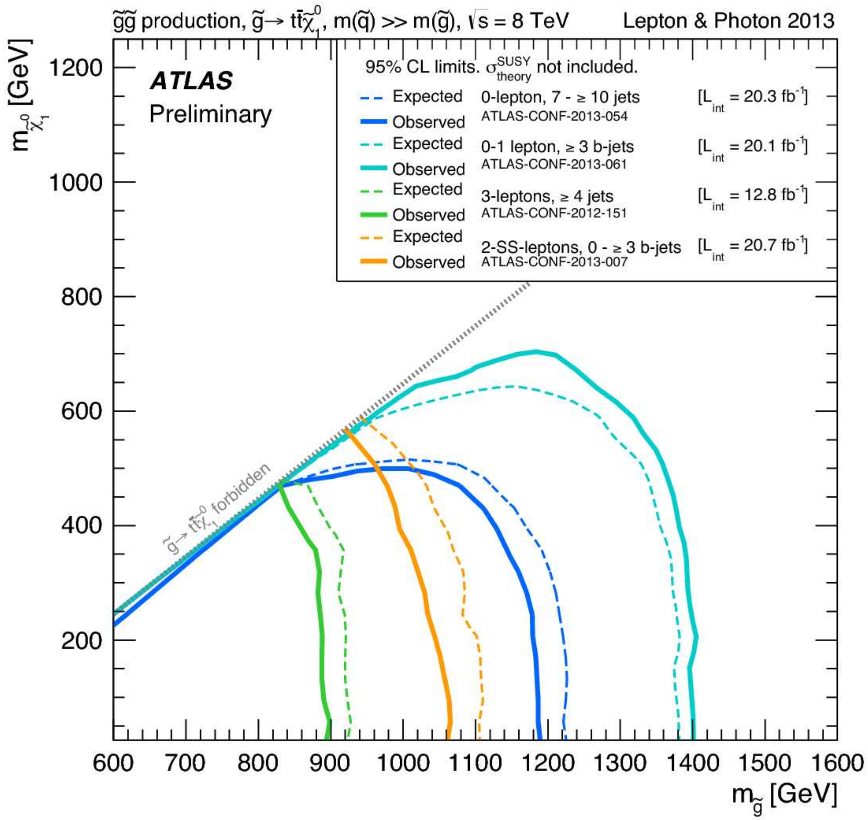


Supersymmetry: 3rd generation

- Gluino-mediated stop/sbottom production:
- Most sensitive channel:
  ≥ 3 b-jets + 0-1 lepton + MET







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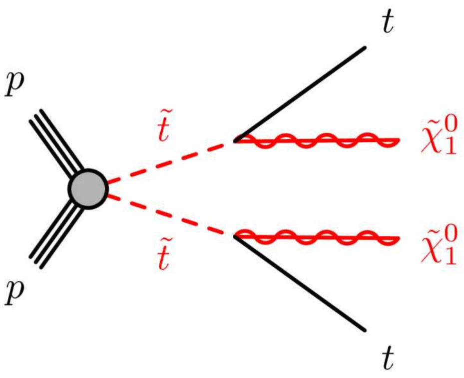
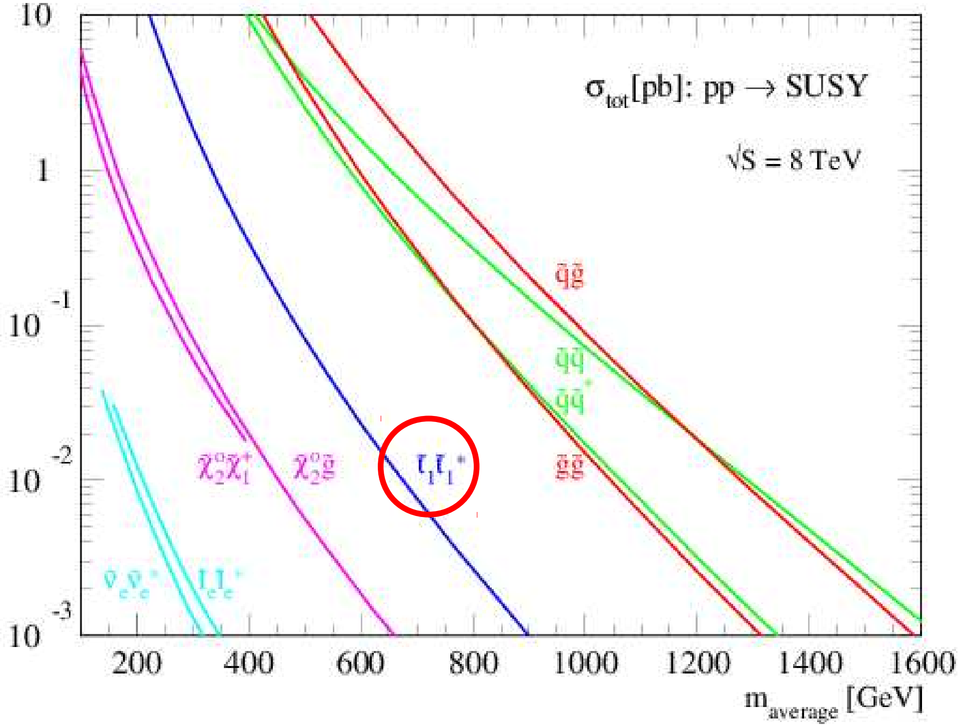
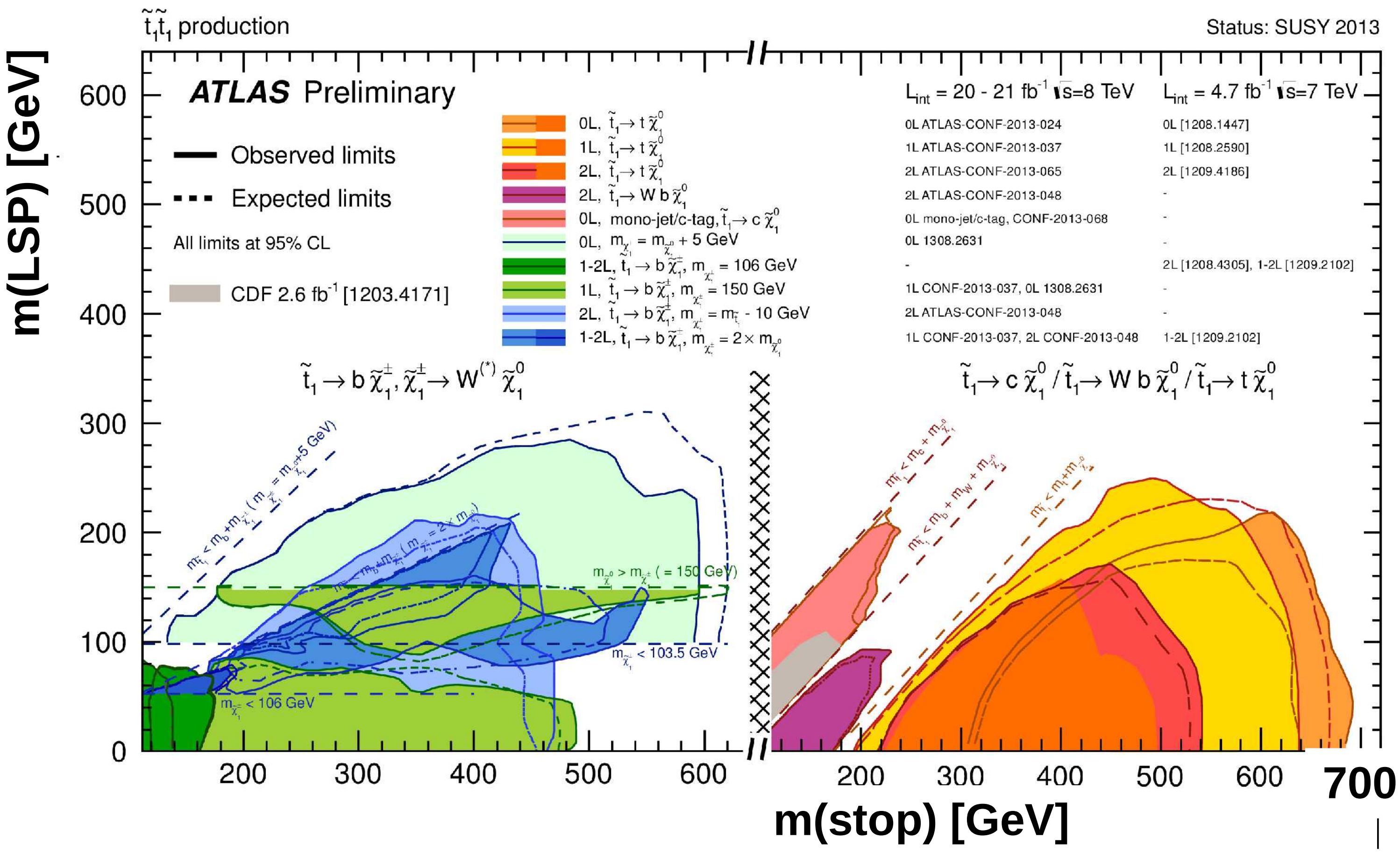




Supersymmetry: 3rd generation

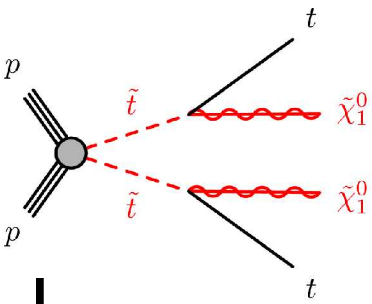
- Direct stop production:

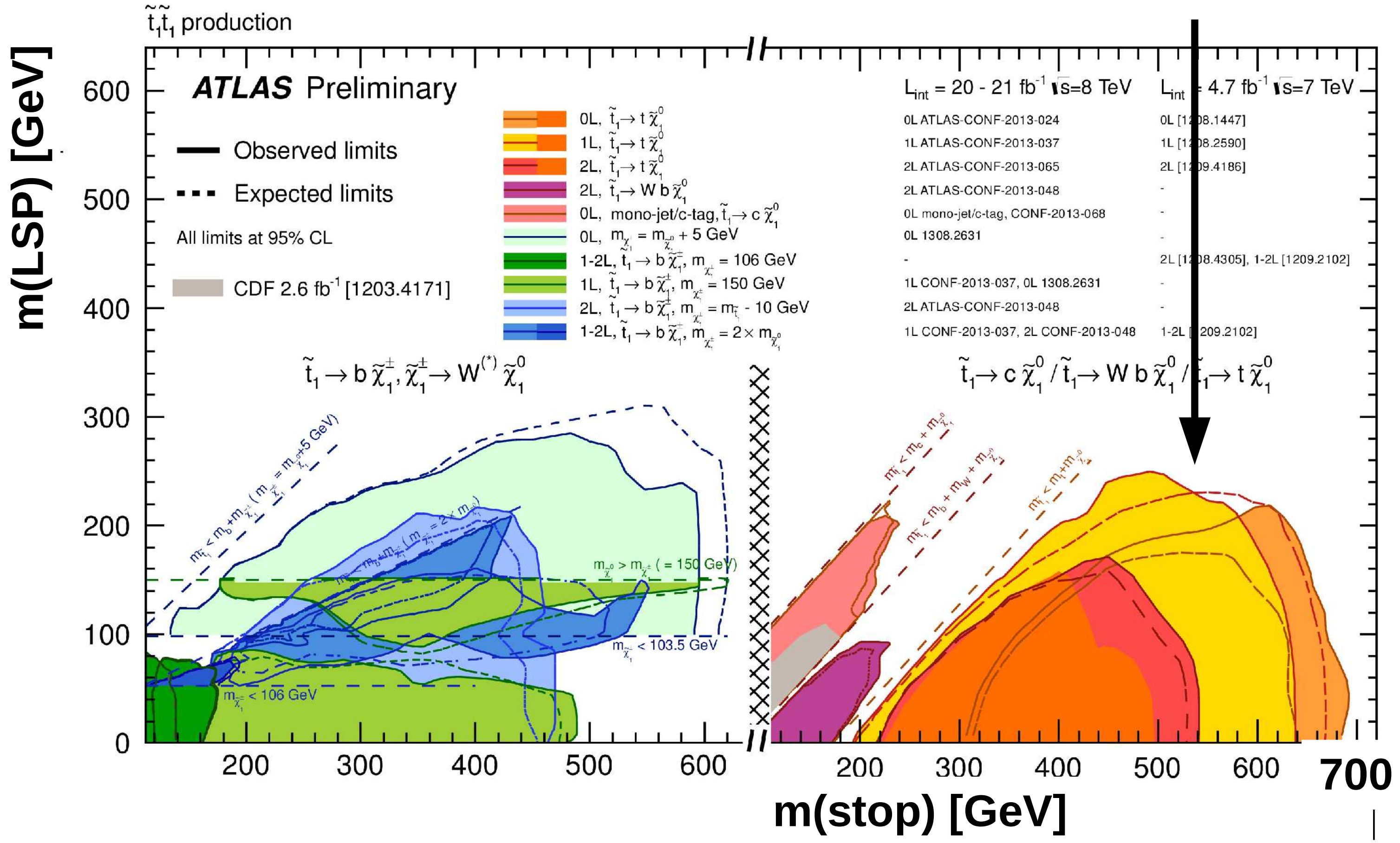


Supersymmetry: 3rd generation

- Direct stop production:

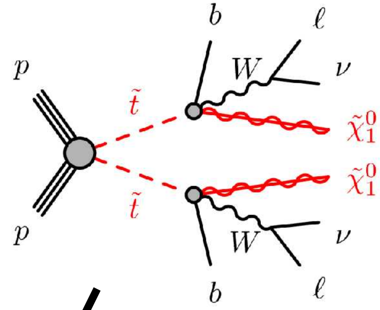
$m_{stop} > m_{top} + m_{LSP}$ →

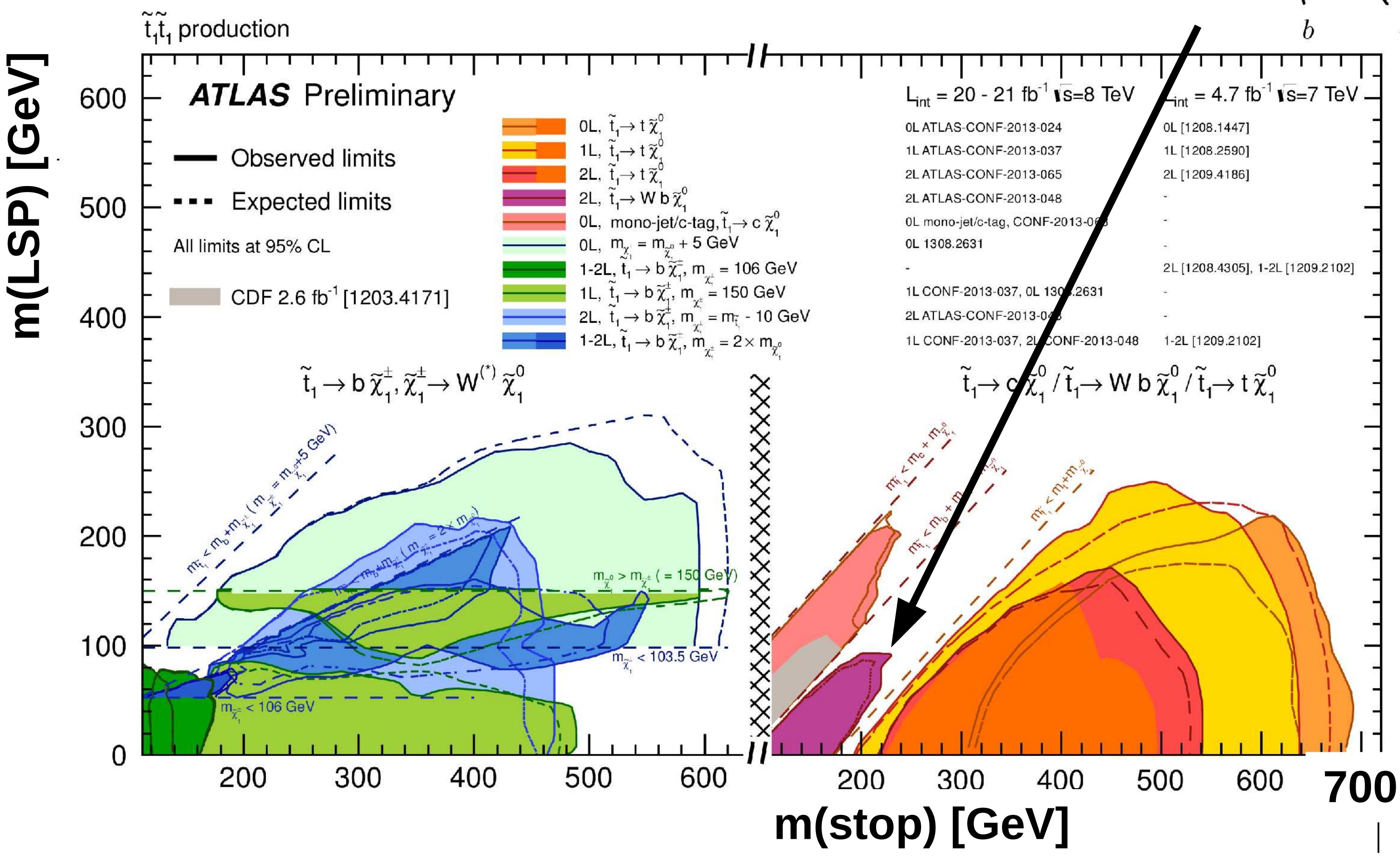




- Direct stop production:

$m_{stop} > m_{bottom} + m_W + m_{LSP}$ →

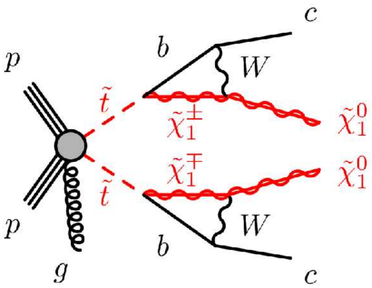




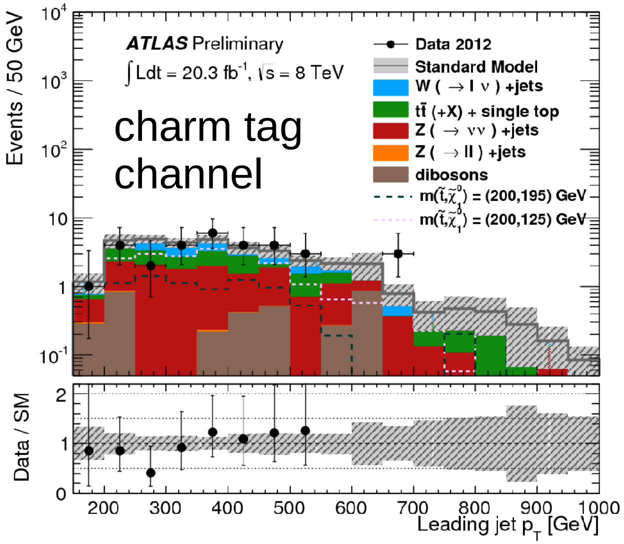
Supersymmetry: 3rd generation

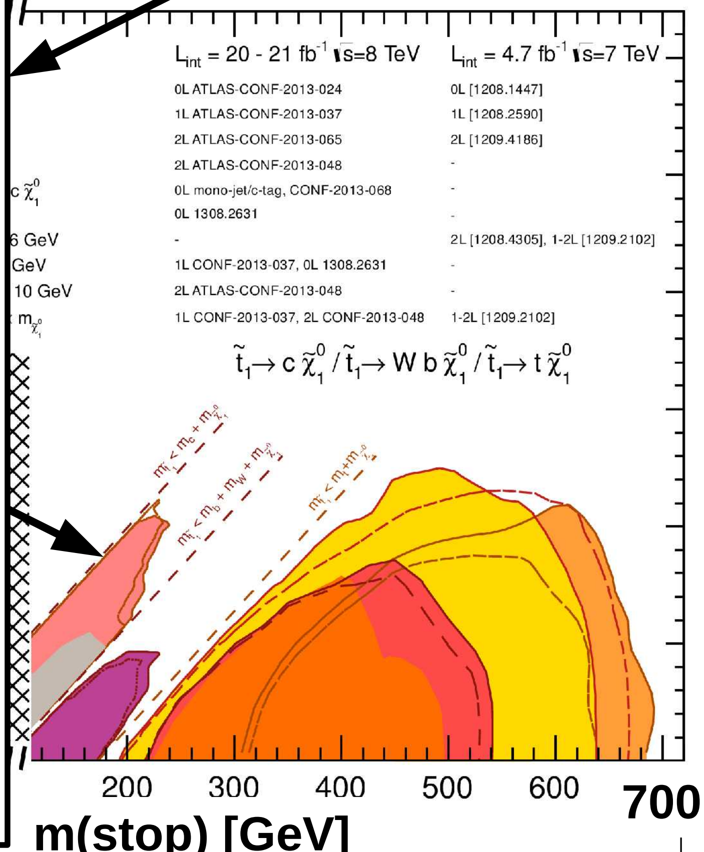
- Direct stop production:

$m_{stop} > m_{charm} + m_{LSP}$ →



- stop → charm + LSP
- Combine monojet and monojet+charm-jets channels
- First LHC SUSY search with charm tagging!

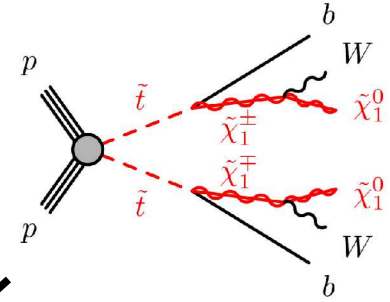


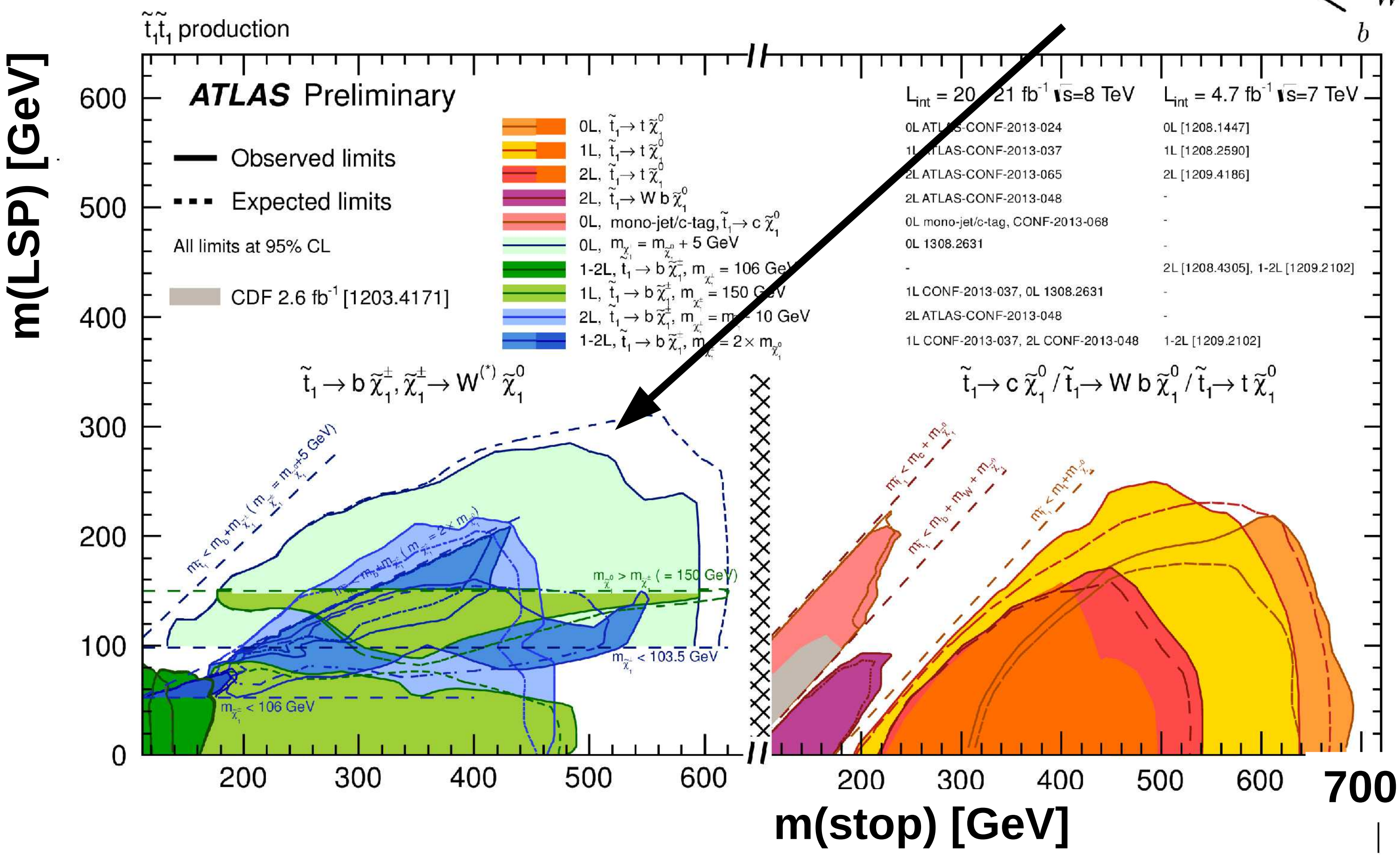


Supersymmetry: 3rd generation

- Direct stop production:

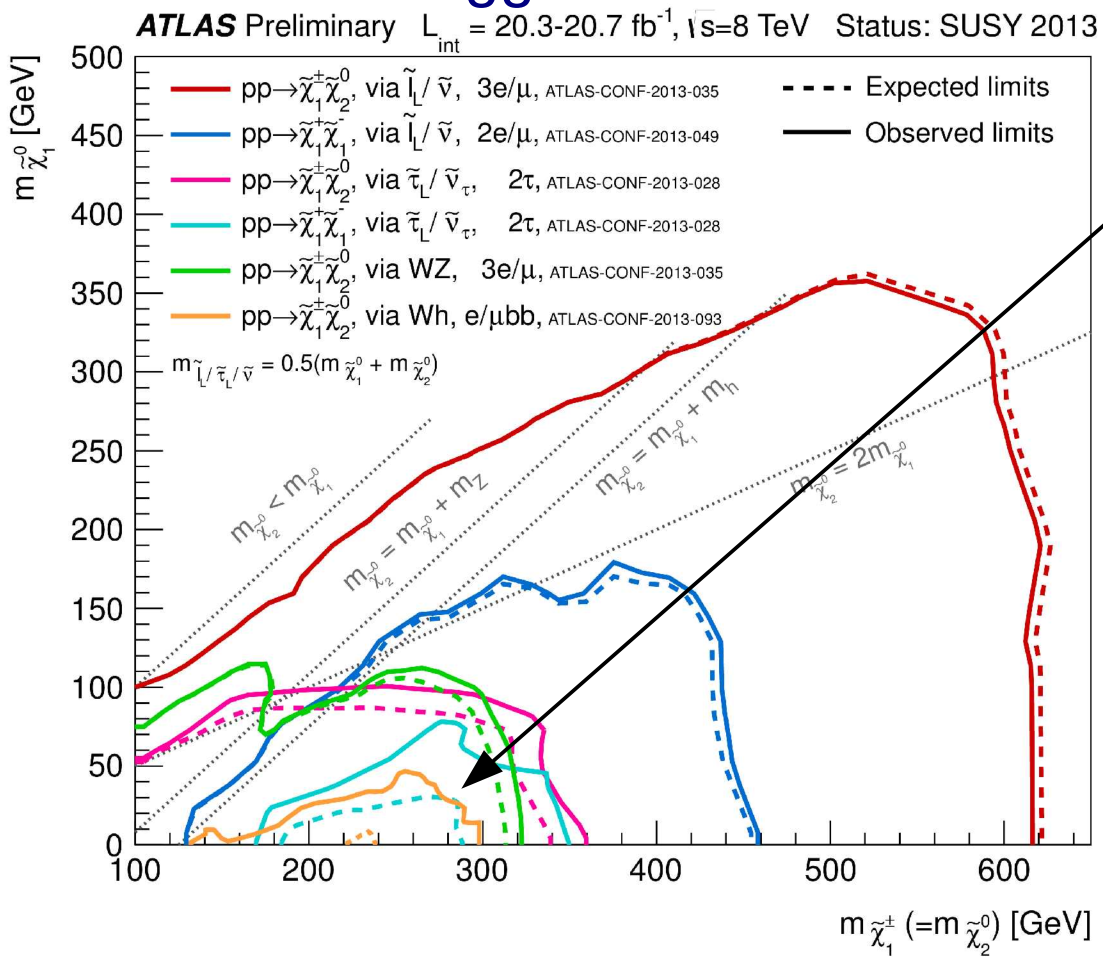
stop decay to chargino →

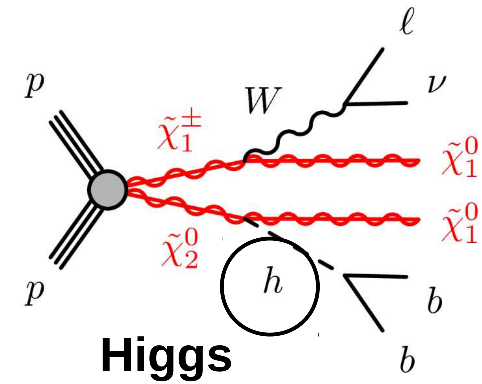


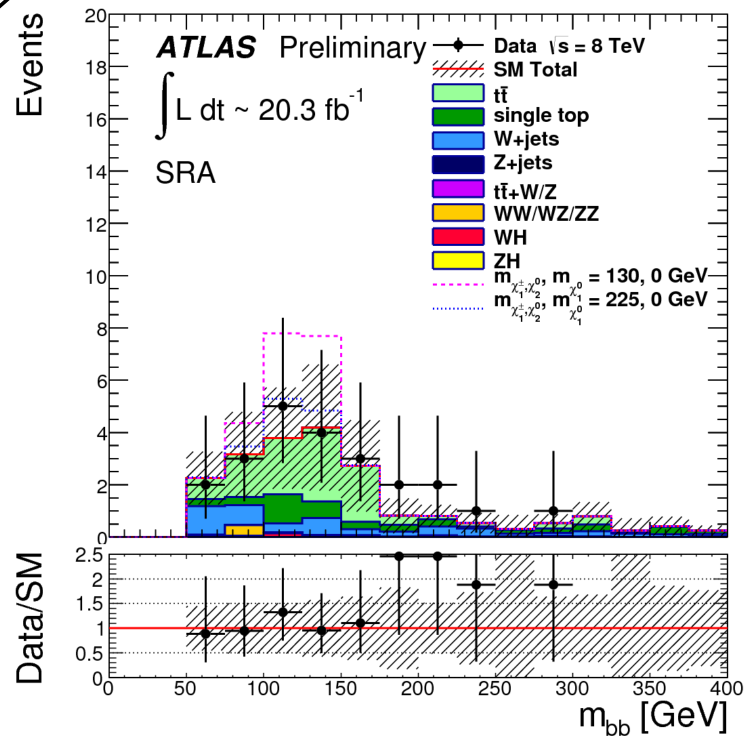


Supersymmetry: Electroweak Production

- Chargino production: also consider cascade to Higgs





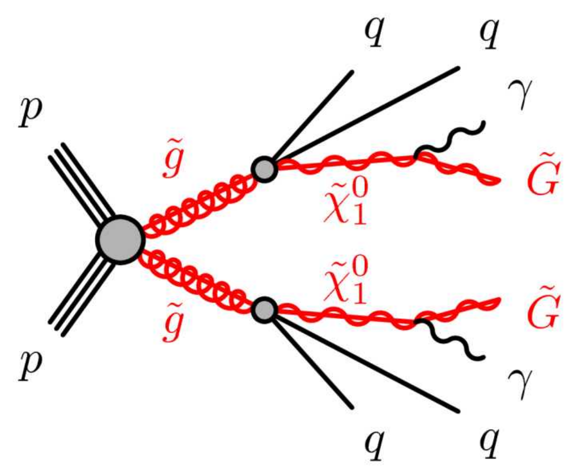


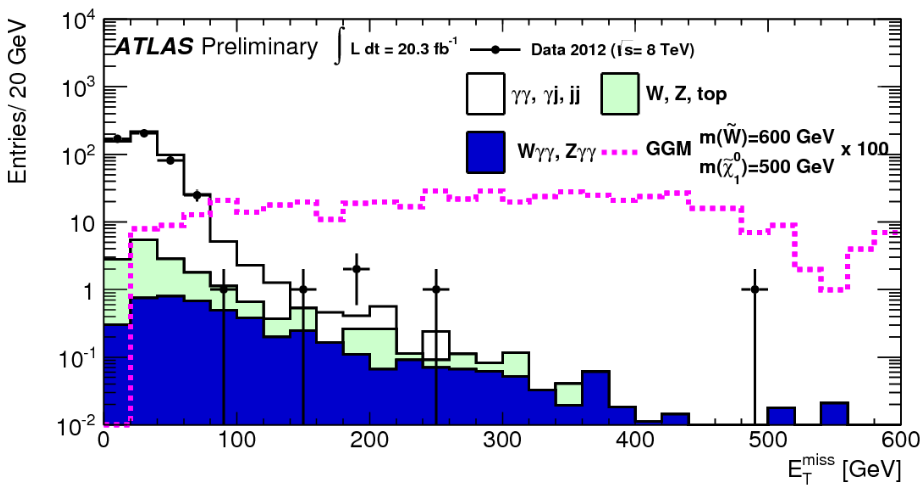
Supersymmetry: GMSB

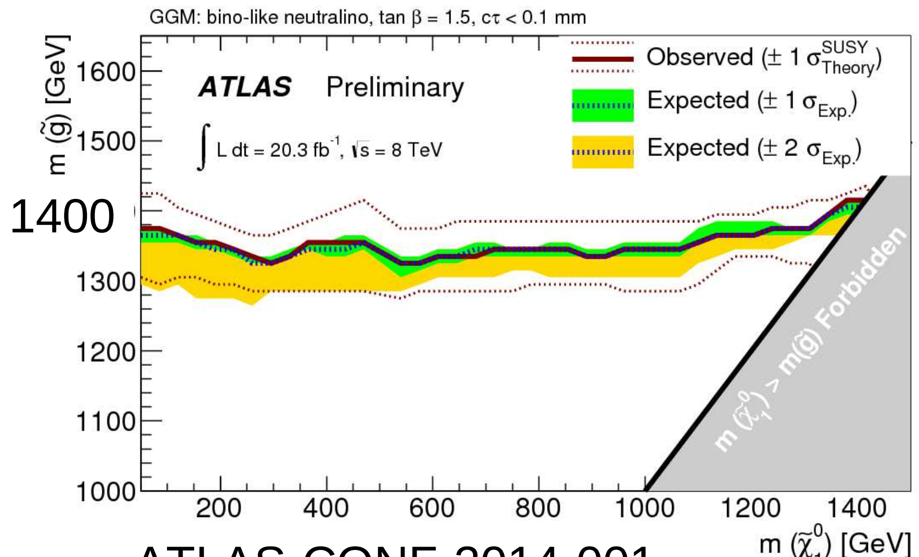
NEW!

- Gauge-Mediated SUSY-Breaking:
  - → LSP = Gravitino
  - → NLSP = Neutralino
  - → NLSP → LSP + Photon or W or Z
- Inclusive selection:

  2 photons with E_T > 75 GeV







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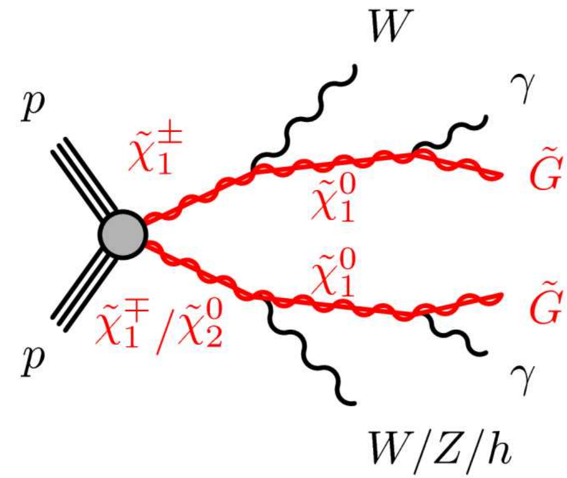
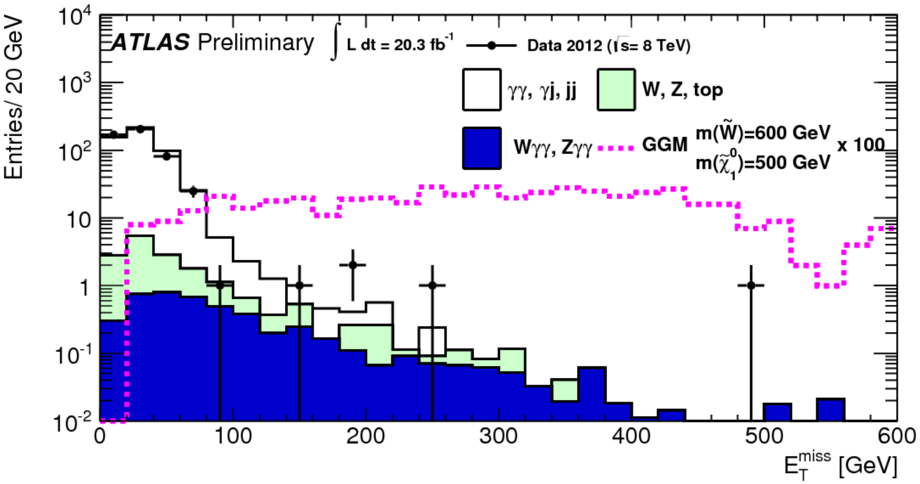
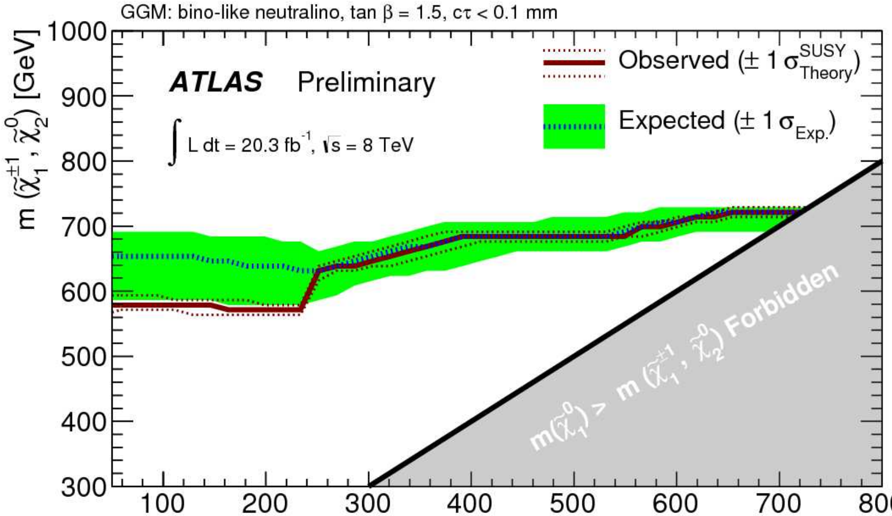
- New: search for GMSB chargino production







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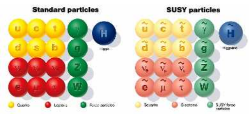
Outline



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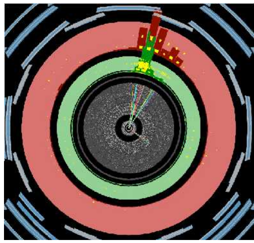
Dark Matter



- → Monojet
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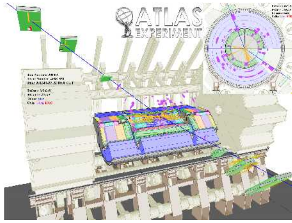
Long-Lived Particles

- → Stopped particles
- → Disappearing track
- → Lepton-jet

Heavy Resonances



- → Dilepton
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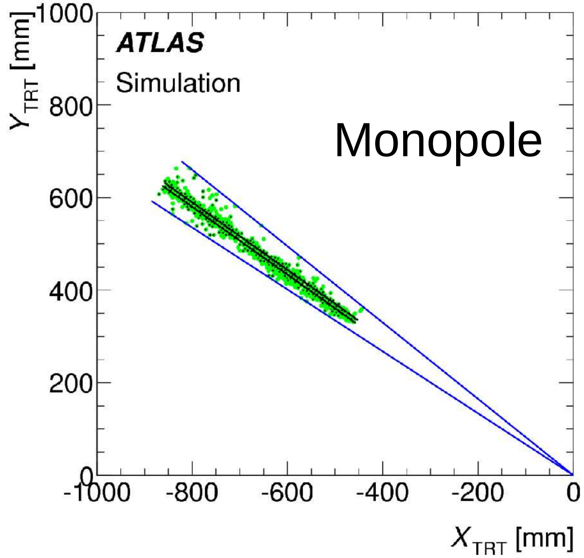
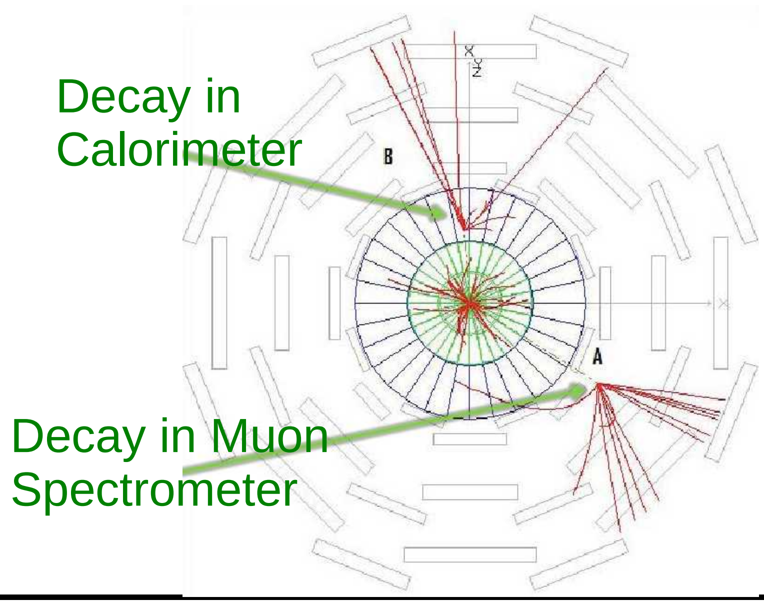
Long-Lived Particles (LLP)

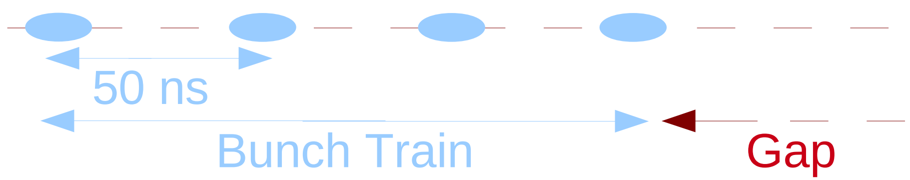
- Predicted by:
  - → SUSY: Weak couplings (RPV), mass-degenerate states (e.g. AMSB SUSY) or very heavy mediator (e.g. split-SUSY)
  - → Hidden Valley
  - → Monopole
- Experimentally very diverse:
  - → Depends on particle's properties: life-time, charge, decay
  - → highly ionizing (dE/dx)
  - → slow (time-of-flight)
  - → out-of-time (wrt collision) decay
  - → disappearing tracks
  - → highly displaced vertices

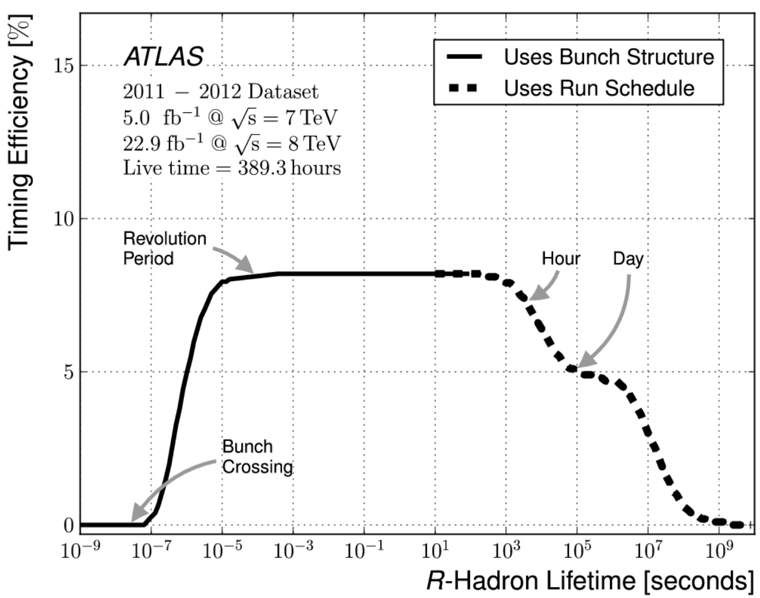




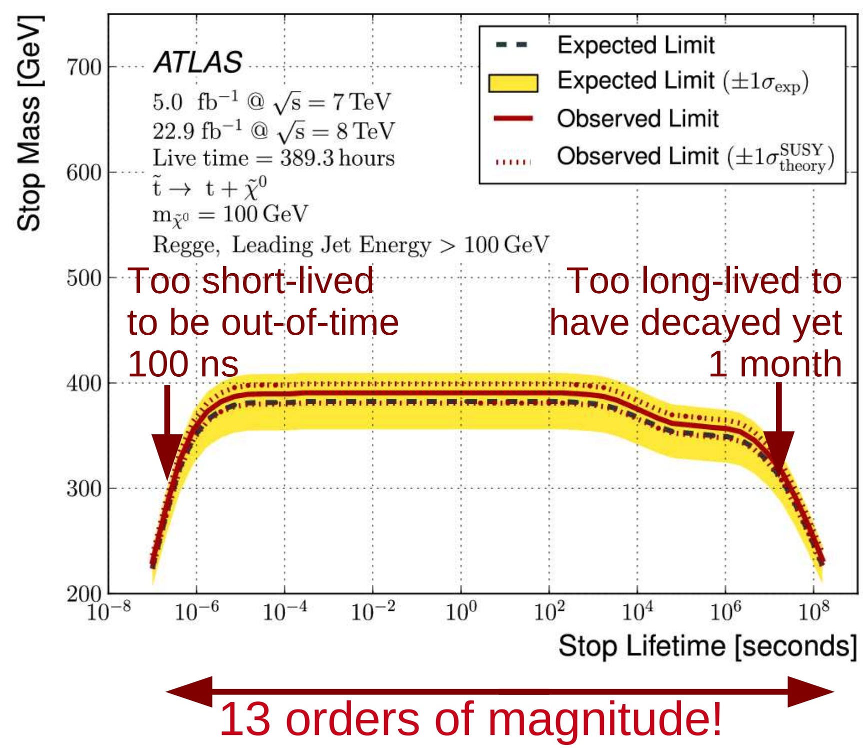
LLP: Stopped particles decaying out-of-time

- Out-of-time decay of heavy particles stopped in the detector
- Look for high energy jet-like signal without collisions:
  - → When no beam in the machine
  - → Between bunch trains
- Veto muon segments to reject cosmic ray and beam halo backgrounds

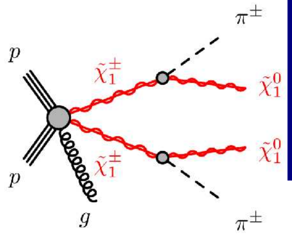




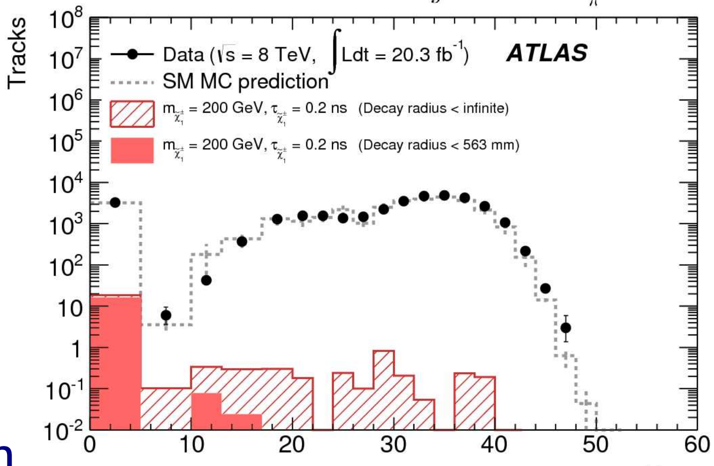
arXiv:1310.6584 Phys. Rev. D 88, 112003 (2013)



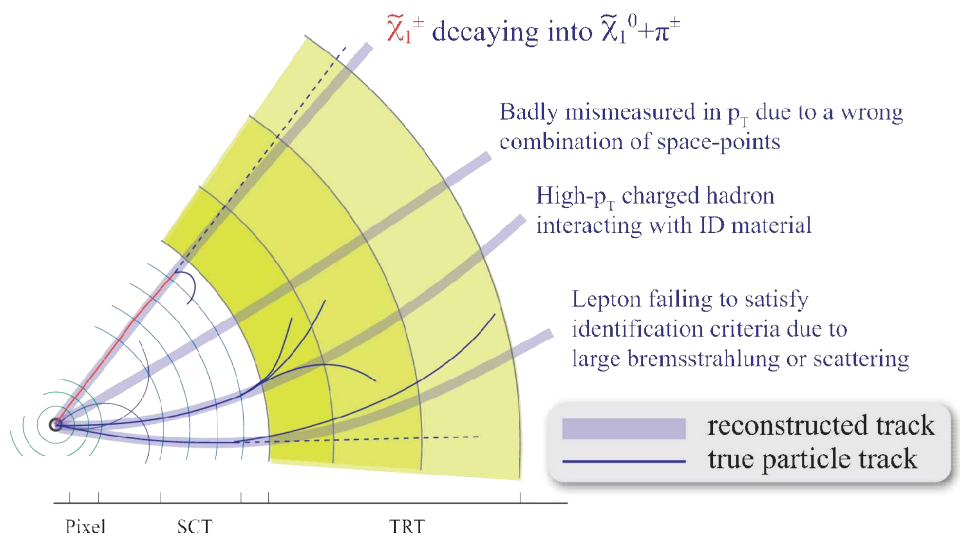
LLP: Disappearing Track

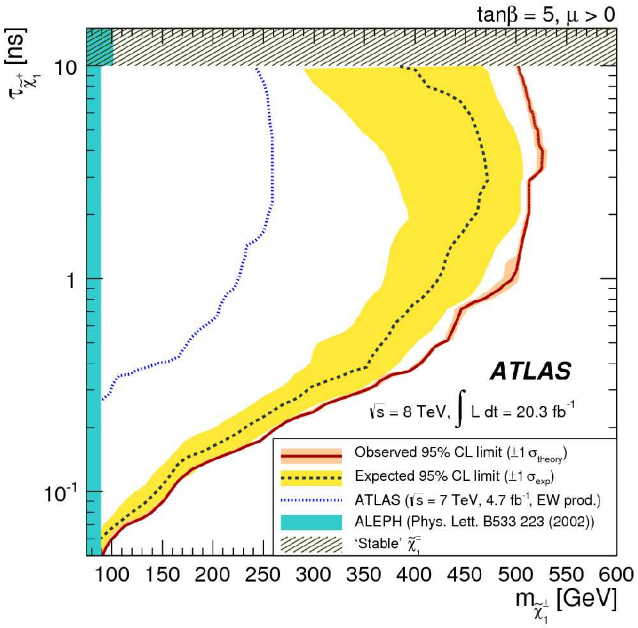


- AMSB compressed spectrum
  m(chargino) ~ m(neutralino) → long life-time
- chargino decays to neutralino + soft pion
- Trigger on ISR jet
- Look for "short" track
- Background estimated from fit to pT spectrum



Phys. Rev. D 88, 112006 (2013)

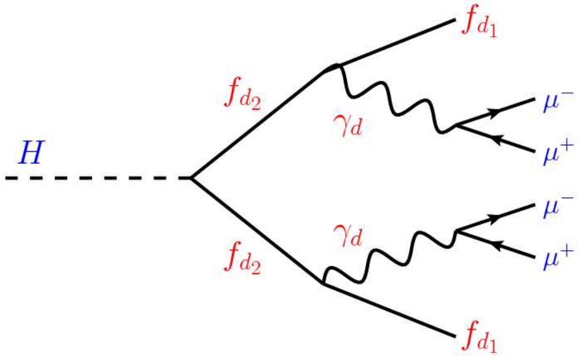


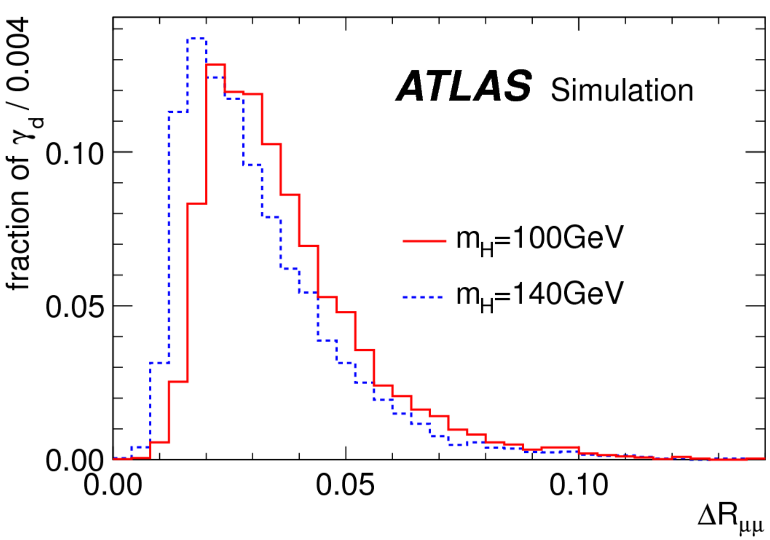


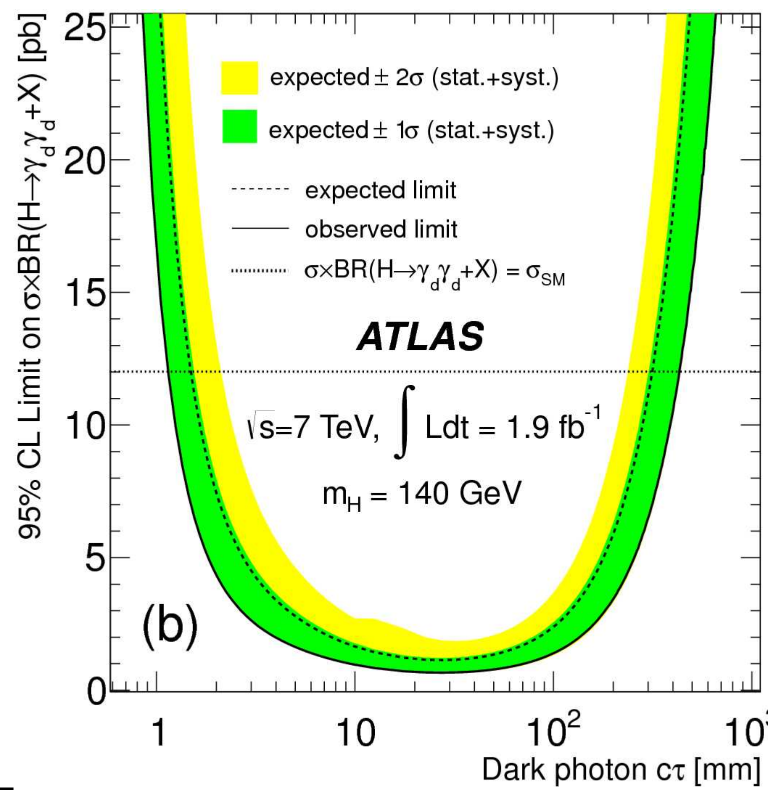
arXiv:1310.3675

Lepton-Jets from Higgs Exotic Decay

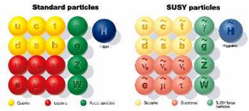
- SM Higgs decay to long-lived hidden-sector particles
- Signature: Pairs of collimated muons observed in Muon Spectrometer (w/o associated Inner Detector track)







Outline

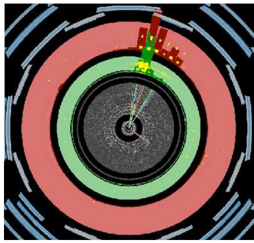


Supersymmetry

→ Strong production
→ 3rd generation
→ EW production
→ GMSB

Dark Matter

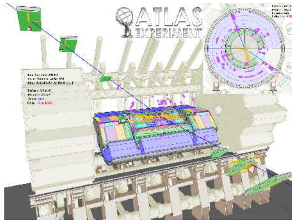
→ Monojet
→ Mono-photon
→ Mono-Z
→ Mono-W



Long-Lived Particles

→ Stopped particles
→ Disappearing track
→ Lepton-jet

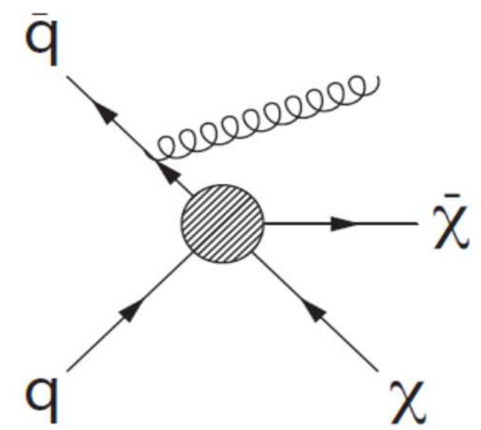
Heavy Resonances

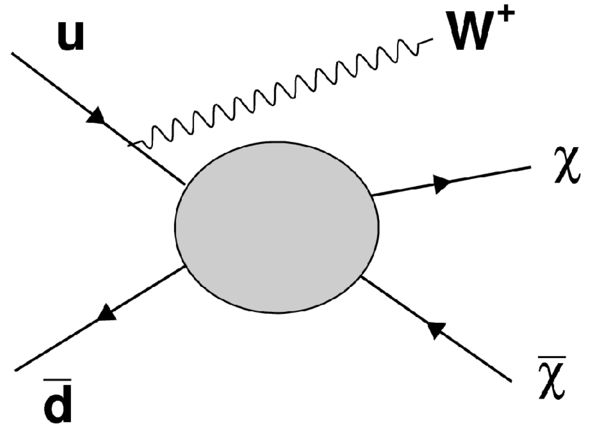


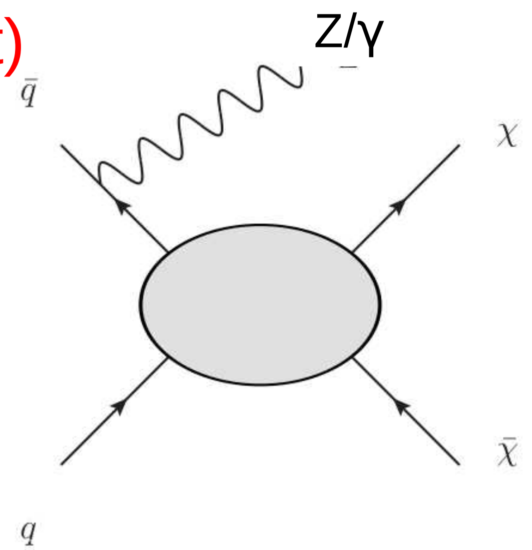
→ Dilepton
→ Dijet
→ Top-antitop

Search for Dark Matter at ATLAS

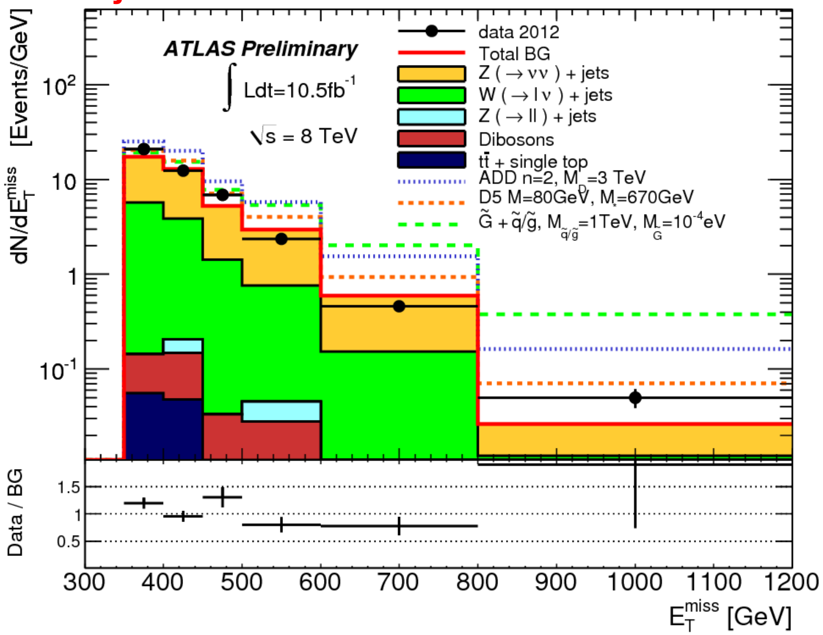
- Dark matter pair-production
  - → Observe only the Initial State Radiation
  - → Consider g/γ/W/Z radiation:
    - mono-jet + missing ET
    - mono-photon + missing ET
    - W or Z → dijet + missing ET
    - Z → dilepton + missing ET (new result)







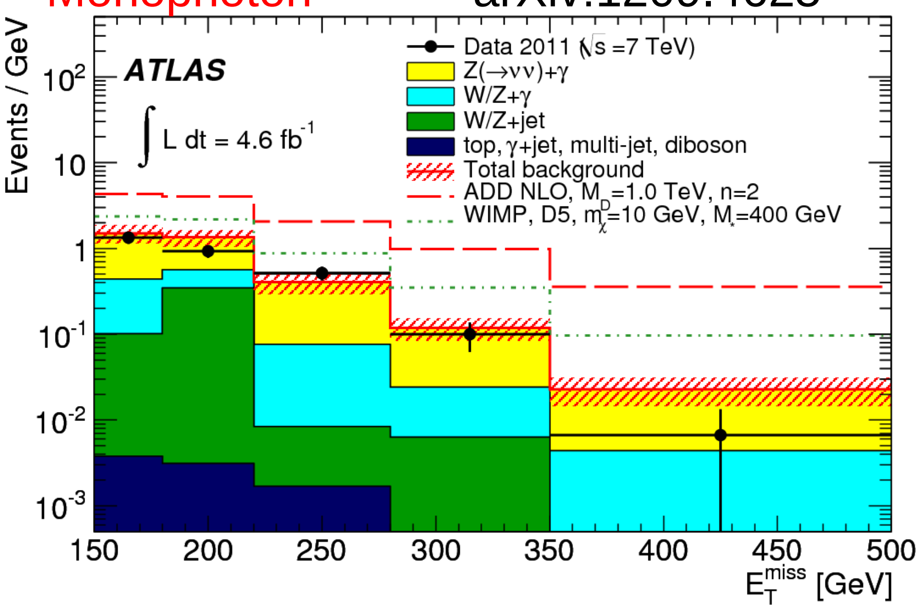
Monojet ATLAS-CONF-2014-001



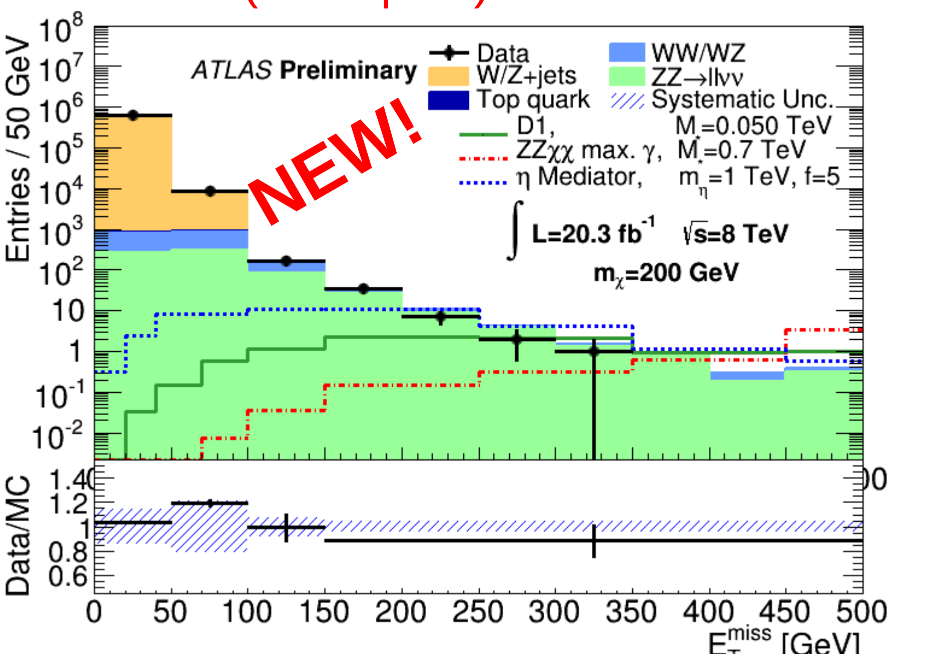
Mono-W/Z (hadronic) arXiv:1309.4017

Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu,\ Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

Monophoton arXiv:1209.4625

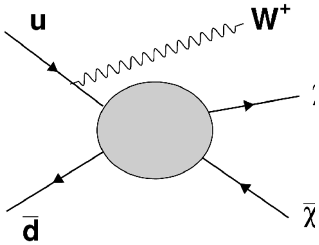


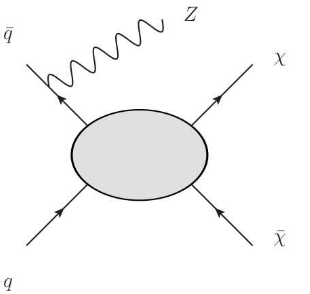
Mono-Z (→dilepton) to be submitted

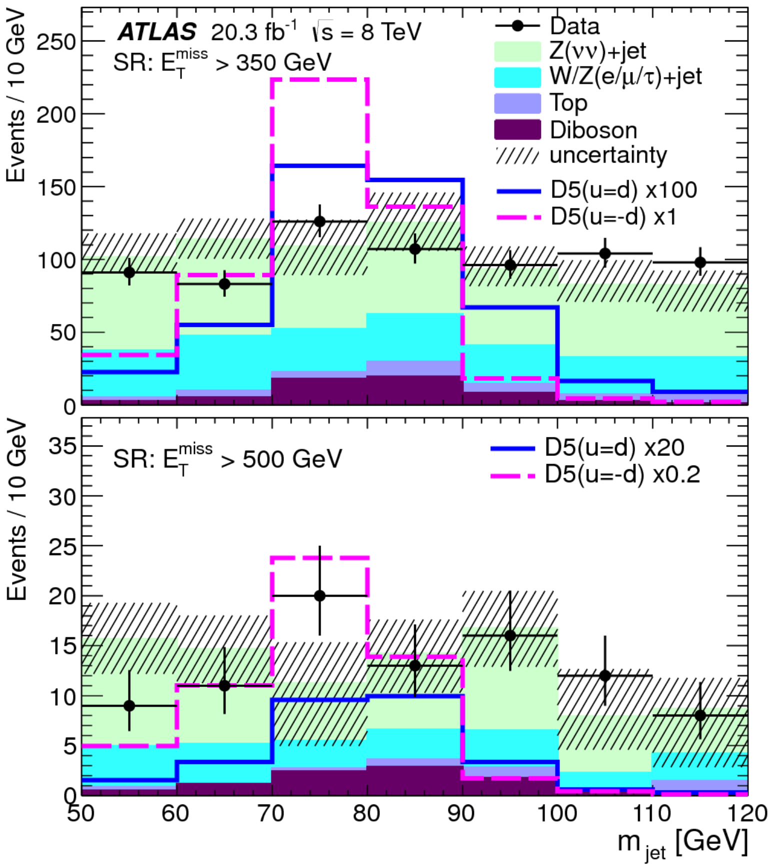


Search for Mono-W & Mono-Z (hadronic decay)

- High-momentum W → qq or Z → qq reconstructed with one large-radius jet
  - → Cambridge–Aachen algorithm with a radius parameter of 1.2
- Select jets with mass consistent with W or Z hadronic decay
- Inclusive trigger MET > 150 GeV
- Final selection:
  - → MET > 350 GeV
  - → MET > 500 GeV



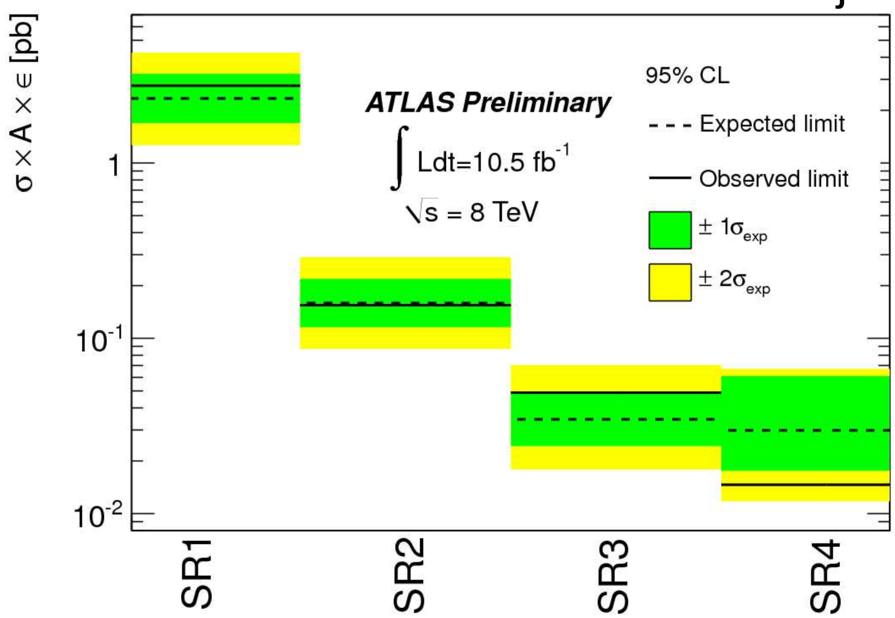




Search for Dark Matter

- Limits presented in several ways:
  - → Folded "model-independent" cross-section limit σ x Acceptance x Efficiency
  - → Provide information on Acceptance and reconstruction Efficiency for some benchmark models → total and fiducial cross-section limits

monojet



Search for Dark Matter

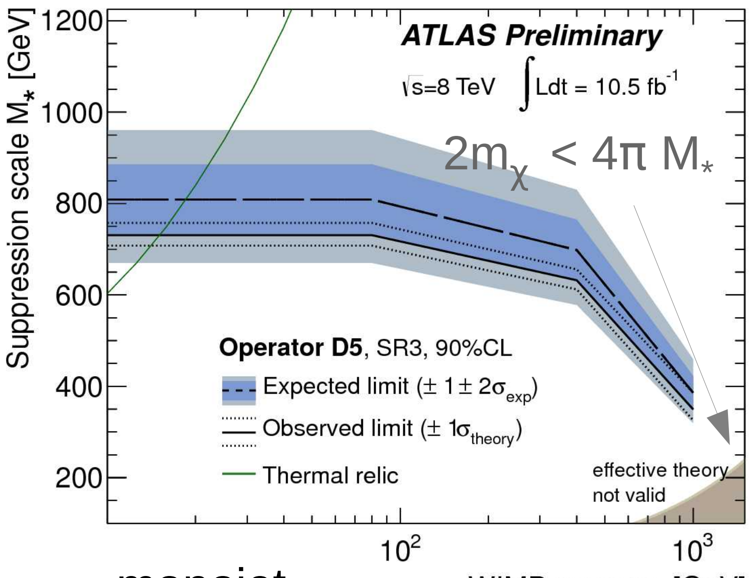
- Limits presented in several ways:
  - → Consider several operators of effective theory described in arXiv:1008.1783
  - → Loose constraint on EFT validity assumes WIMP production is near threshold: $q^2 \sim 2m_\chi < 4\pi M_*$
  - → M = mediator mass = $M_* \sqrt{(g_q g_\chi)}$

    Perturbativity requires $M < 4\pi M_*$

    → Back-of-the-envelope:

    if $M_* < 400$ GeV, mediator is produced on-shell i.e. at much higher q^2

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



monojet

Thanks to T. Volansky and K. Zurek for very useful discussions!

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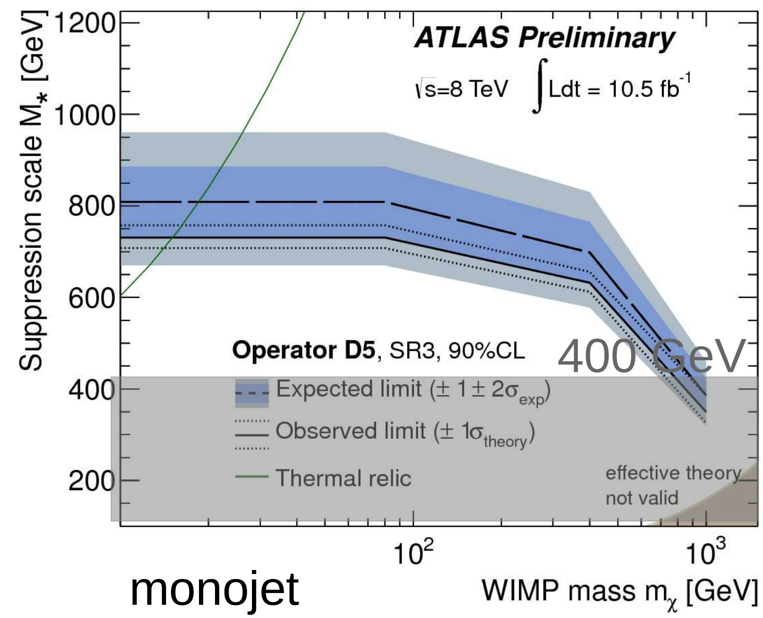

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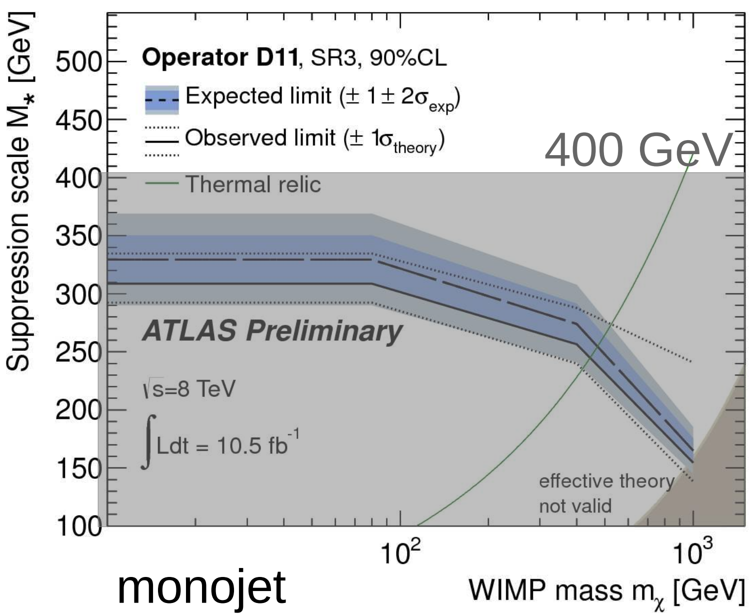

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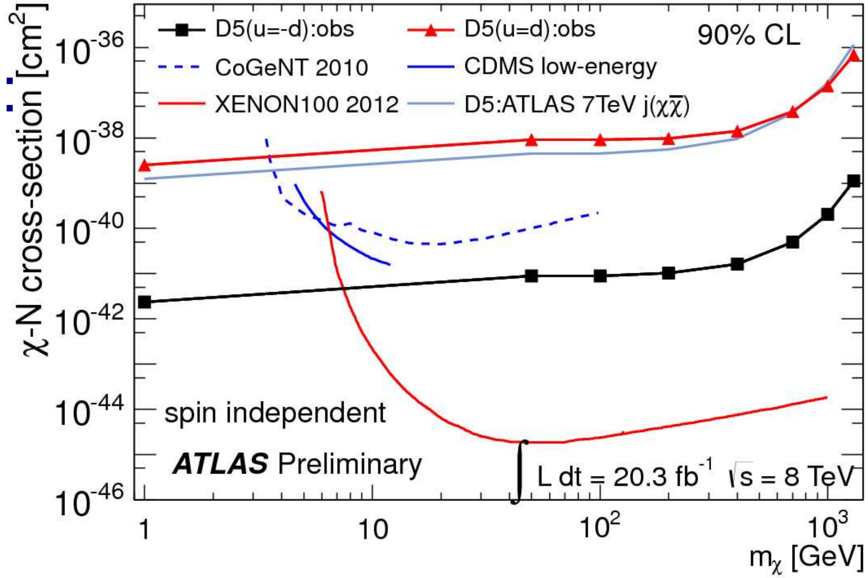
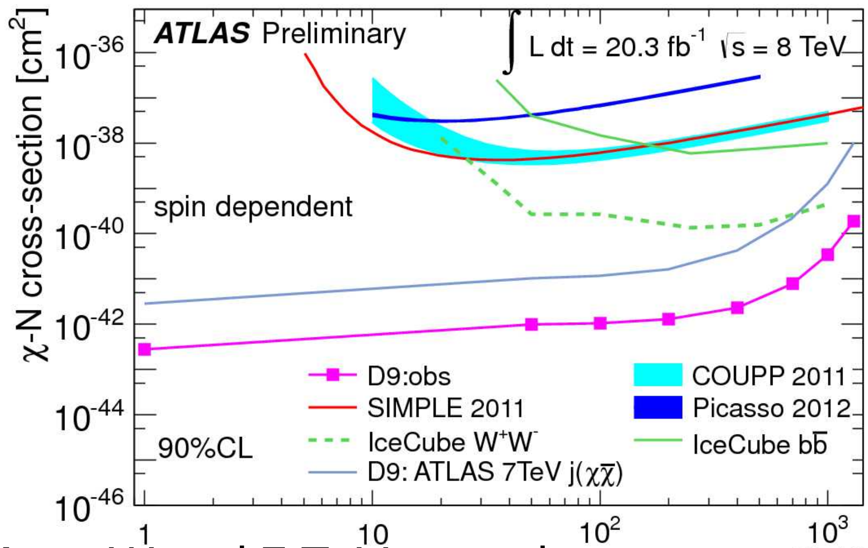




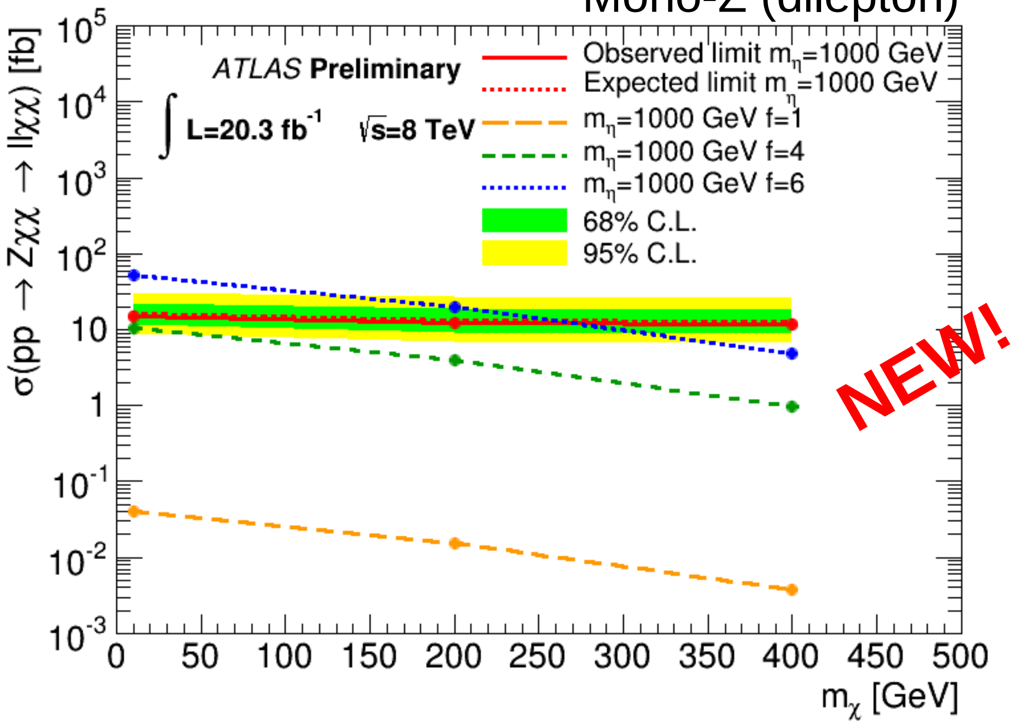
Mono-W and 7 TeV mono-jet

Thanks to T. Volansky and K. Zurek for very useful discussions!

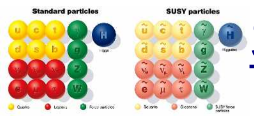
Search for Dark Matter

- Limits presented in several ways:
  - → Now also considering UV-complete models with a specific mediator
  - → Scalar mediator η
  - → Parametrized in terms of m_χ, m_η, and coupling to WIMP f

Mono-Z (dilepton)



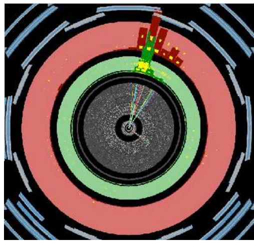
Outline



Supersymmetry

- → Strong production
- → 3rd generation
- → EW production
- → GMSB

Dark Matter

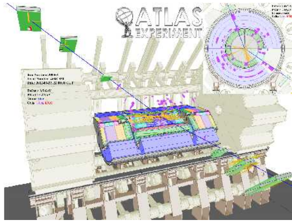


- → Monojet
- → Mono-photon
- → Mono-Z
- → Mono-W

Long-Lived Particles

- → Stopped particles
- → Disappearing track
- → Lepton-jet

Heavy Resonances



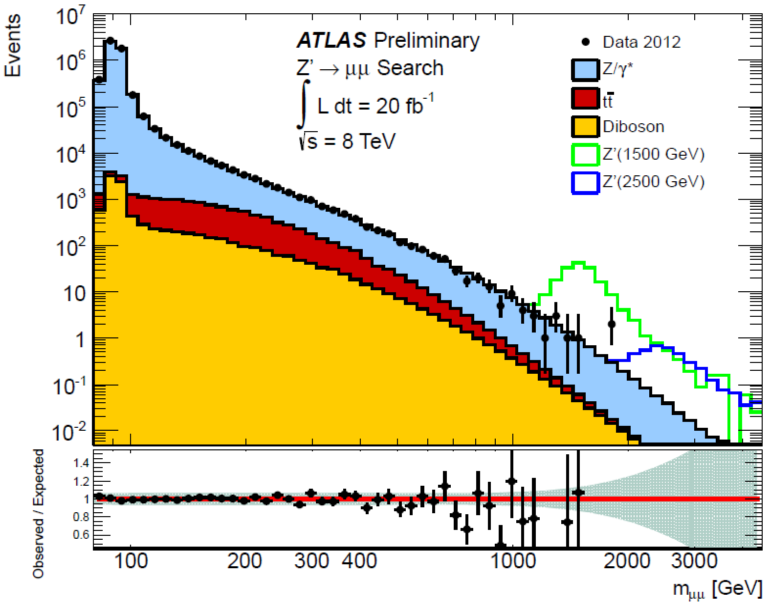
- → Dilepton
- → Dijet
- → Top-antitop

Search for Heavy Resonance

- Predicted by numerous extensions of the Standard Model:
  - → Heavy gauge boson(s) Z' (W'): GUT-inspired theories, Little Higgs
  - → Kaluza-Klein excitations: Randall-Sundrum extra-dimensions
- Systematic search for two-body decays:
  - → dijet, photon-jet, diphoton
  - → dilepton (ee, μμ, ττ, eμ, eτ, μτ, eυ, μυ)
  - → top-antitop
  - → lepton-photon (excited lepton)
  - → lepton-jet (e,μ,τ, leptoquark)
  - → WW/WZ/ZZ

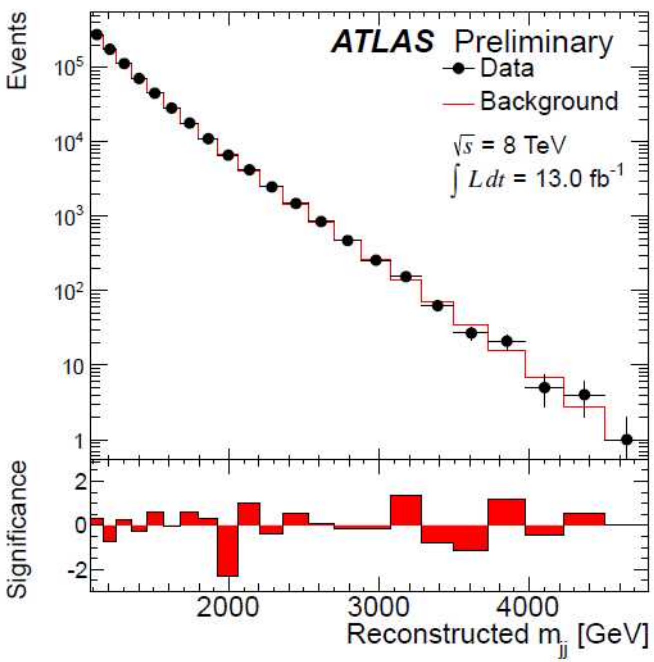
Search for Heavy Resonance

- Predicted by numerous extensions of the Standard Model:
  - → Heavy gauge boson(s) Z' (W'): GUT-inspired theories, Little Higgs
  - → Kaluza-Klein excitations: Randall-Sundrum extra-dimensions
- Usual suspects: dilepton and dijet resonances



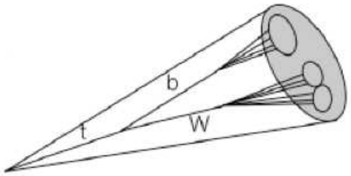
Sequential-SM Z': m > 2.9 TeV

RS graviton (k/M_{pl} = 0.1): m > 2.5 TeV

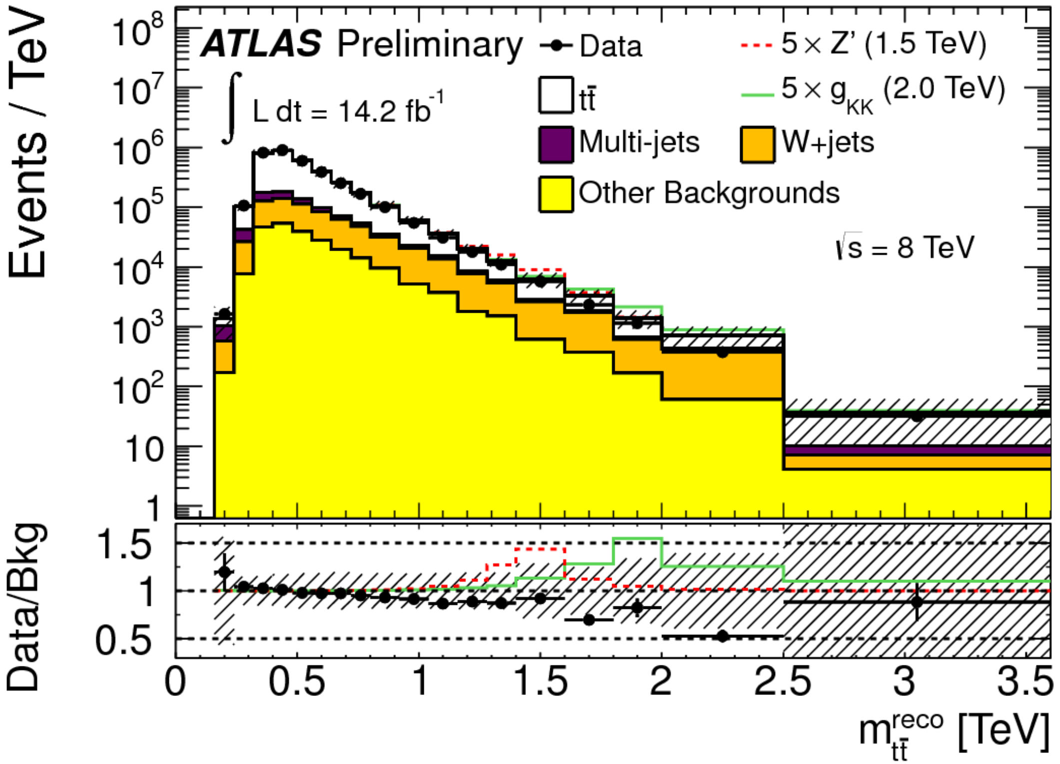


Excited quark excluded up to 3.8 TeV

Top-antitop Resonance L+Jets Channel

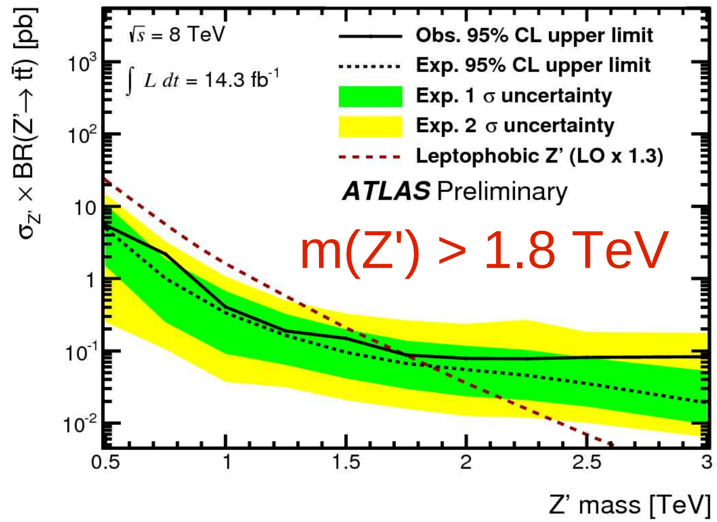


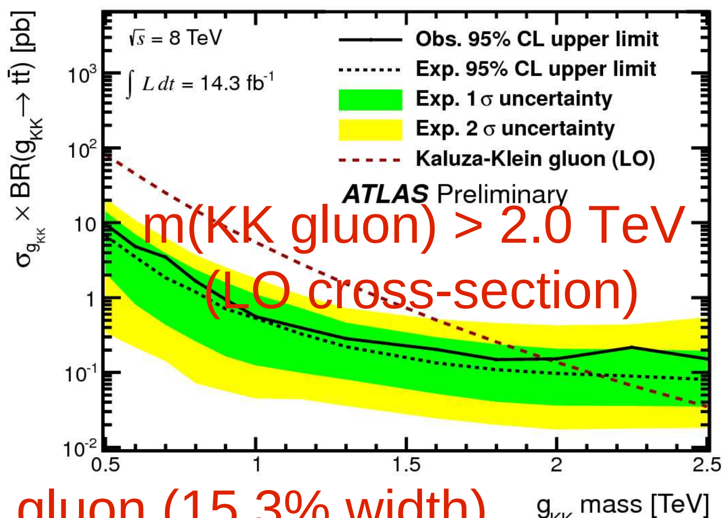
- Top-antitop mass spectrum:



[ATLAS-CONF-2013-052]

Leptophobic Z' (1.2% width)





RS KK gluon (15.3% width)

A short (over-simplified) summary

- The 8 TeV LHC data have been investigated extensively

  but still a lot of work in progress
- Unfortunately, still no hint of BSM physics in the LHC data...

	Approx. Lower Limit (95% C.L.)
VLQ T and stop ($tt \rightarrow tt\chi\chi$)	700 GeV
gluino	1.4 TeV
KK gluon → tt (15%, LO xs)	2 TeV
Z' → dilepton (SSM)	3 TeV
Excited quark → dijet	4 TeV

Outlook: What are we missing?

- With large missing ET:
  - → 2-10 jets
  - → w/ or w/o b-jets, w/ or w/o leptons (e,μ,τ)
  - → w/ or w/o photon or Z
  - → mono-X (X = jet, photon, W, Z)
- Without missing ET:
  - → Multijet (RPV)
  - → Black holes (w/ or w/o MET, w/ or w/o leptons)
- "Resonances":
  - → dijet, photon-jet, diphoton
  - → dilepton (ee, μμ, ττ, eμ, eτ, μτ, eυ, μυ)
  - → lepton-photon (excited lep)
  - → lepton-jet (e,μ,τ, leptoquark)
  - → WW/WZ/ZZ
- Non-resonance:
  - → dilepton C.I.
  - → dijet angular
- Same-sign dilepton / multilepton
  - → w/ or w/ (b)jets, w/ or w/o MET
  - → $l^{\pm}l^{\pm}$- jet-jet (heavy neutrino, ee, μμ, eμ)
  - → $H^{\pm\pm}$
- With top:
  - → top-antitop resonance
  - → top-jet, top-bottom resonance
  - → VLQ's
- Higgs MSSM/2HDM/invisible
- Long-lived particles:
  - → displaced photons
  - → displaced vertices
  - → stopped particles, out-of-time decay
  - → highly-ionizing particles: slow-heavy, multi-charge, monopole
- Even more exotic:
  - → "lepton-jets" (collimated, high-multiplicity, e, μ, photon, prompt or long lived)

Outlook: What are we missing?

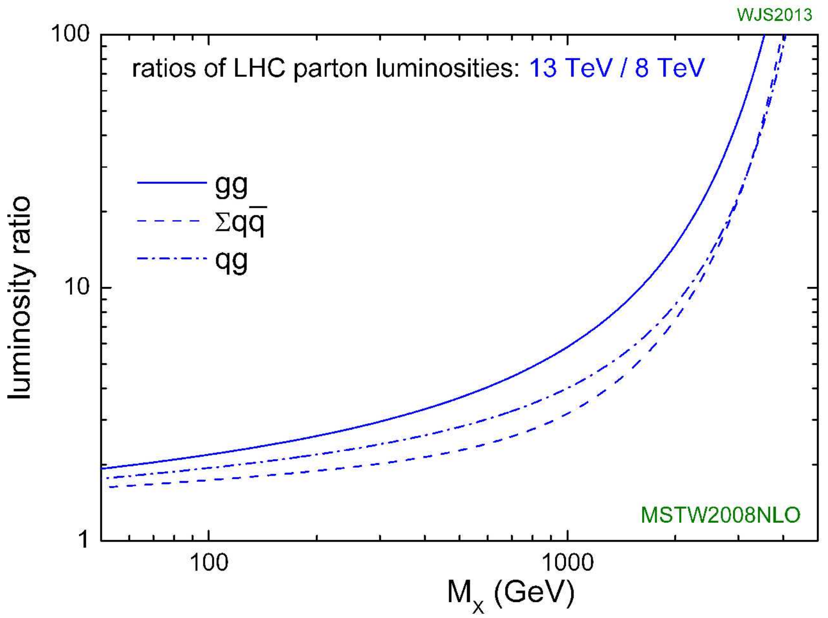
- We have cast a wide net over pretty much all thinkable signatures.
- But going into detail, still a lot of places where new physics can hide.
- Examples given this week:

  KK g → TT → tt+X

  exotic Higgs decays
- So far focus has been on high-momentum (where LHC had clear advantage over previous experiments)
  - → with high luminosity, reach weakly-coupled, low-mass signals
  - → close the gap between high-momentum searches and SM precision measurements

Outlook: What are we missing?

- Run 2 is starting in one year at 13 TeV
  - → New significant window of opportunity for discovery
- Let's hang on and keep exploring ungroomed territories...

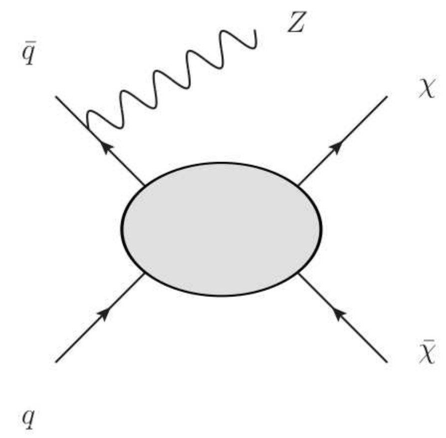


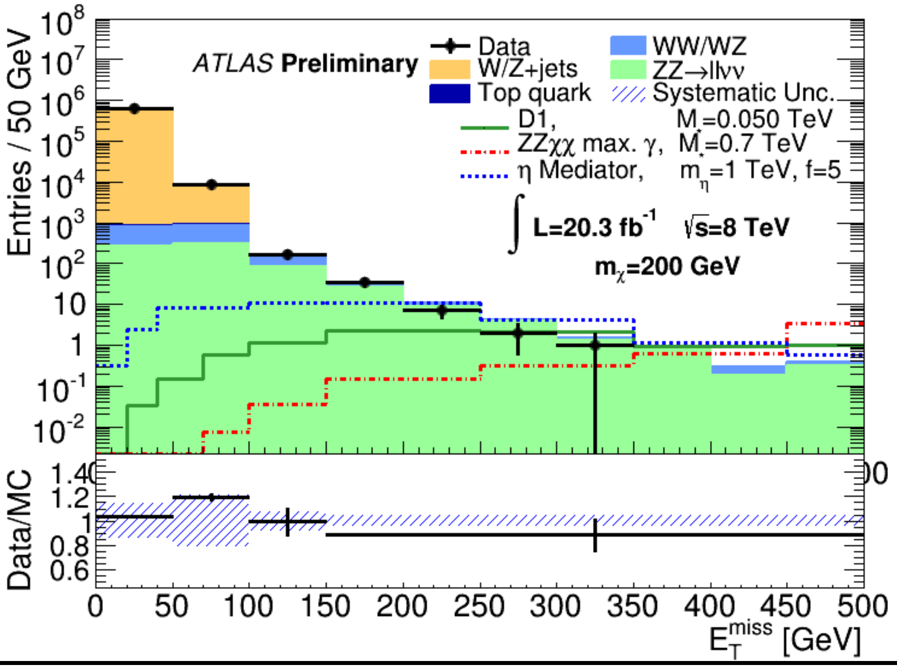
Backup

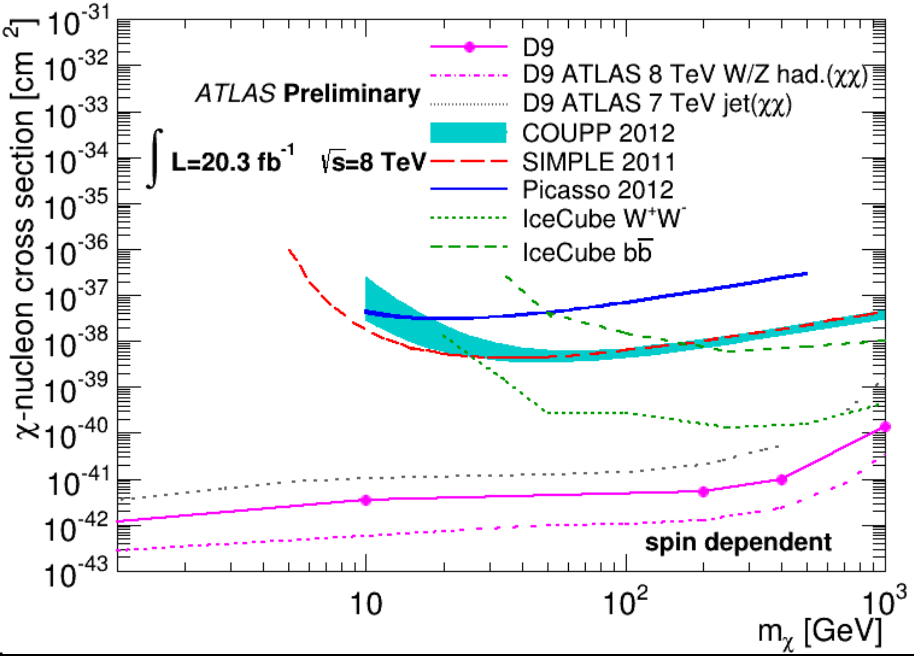
Search for Mono-Z (leptonic decay)

NEW!

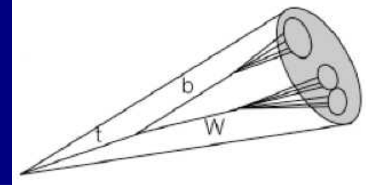
- Z → dielectron or dimuon
- Reject Z + jets background:
  - → Veto jet
  - → | pT(dilepton) − MET | / pT(dilepton) < 0.5
- Large MET





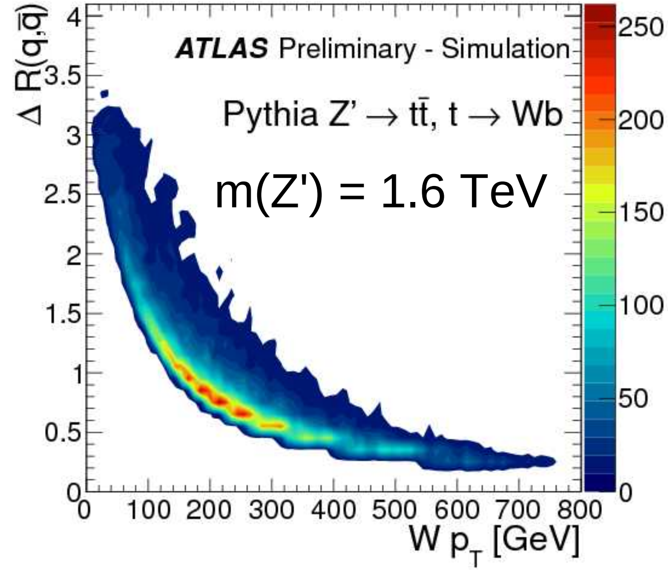


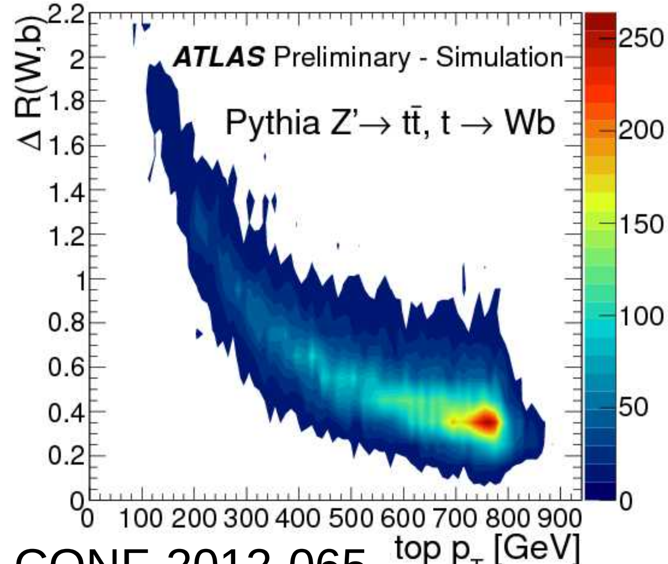
Top-antitop Resonance



- Leptophobic Z' (topcolor)
- KK gluon (bulk RS models)
- Large Branching Ratio to top-antitop.
  - → BR(Z' → tt) ~ 33%
  - → BR(KK g → tt) > 90%

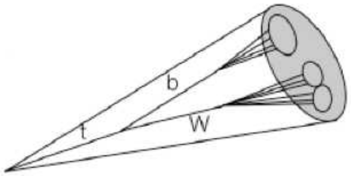
- For m(tt) > 1 TeV, specific boosted top reconstruction needed
  - → Experimentally: a whole new field!



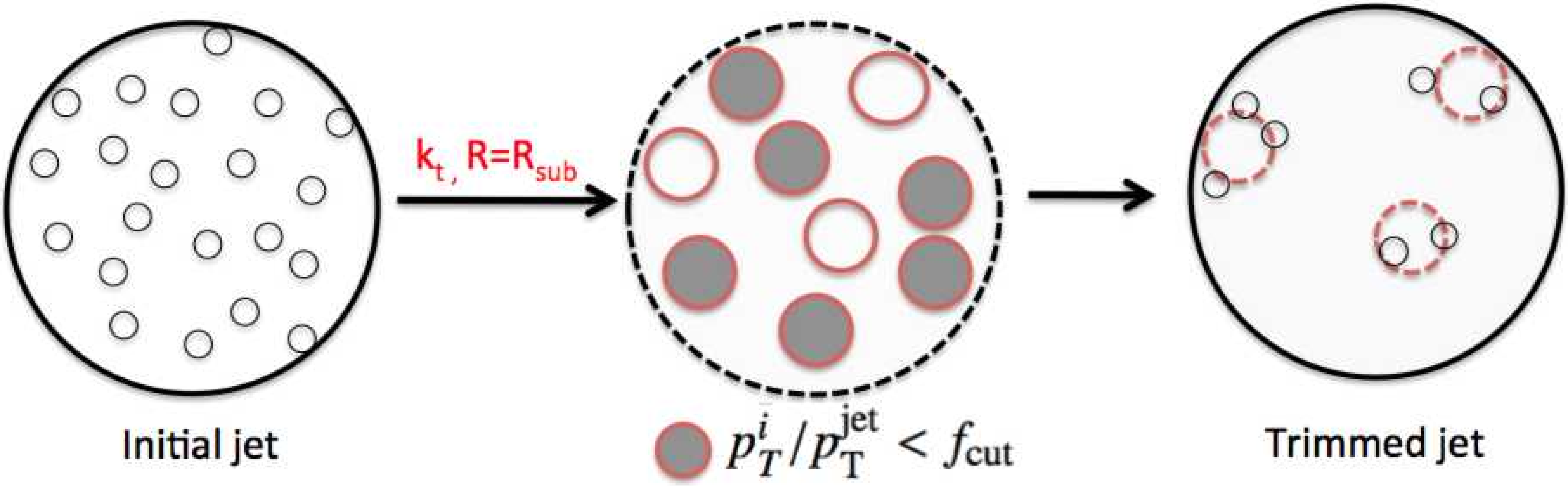


ATLAS-CONF-2012-065

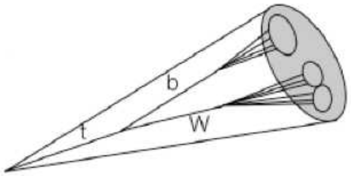
"Fat" Jets and Jet "Trimming"



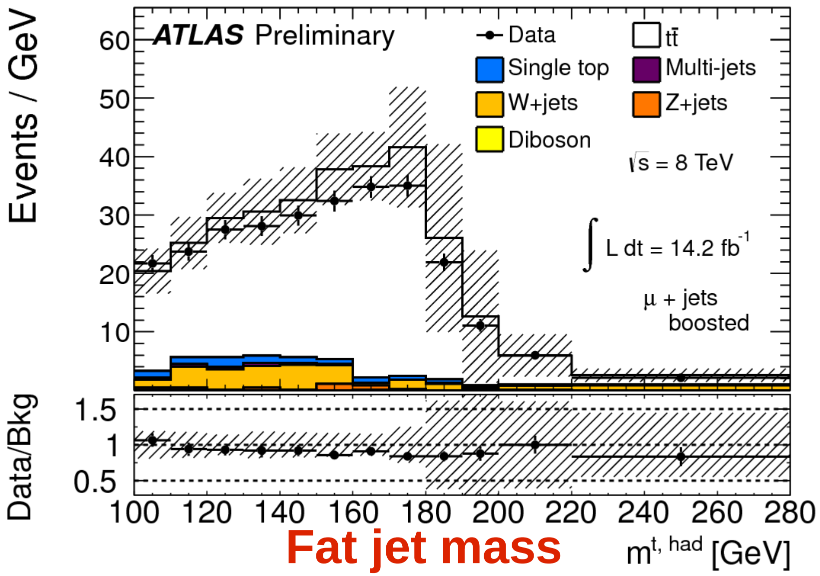
- Reconstruct jets with a large cone (R ~ 1 or more), a.k.a. "fat" jets, to encompass all decay products
- Soft radiation (incl. pile-up) important → must be removed
- "Trimming":
  - → Run k_t algorithm on clusters within the fat jet
  - → Keep only clusters with pT > pT(fat jet) . f_{cut}

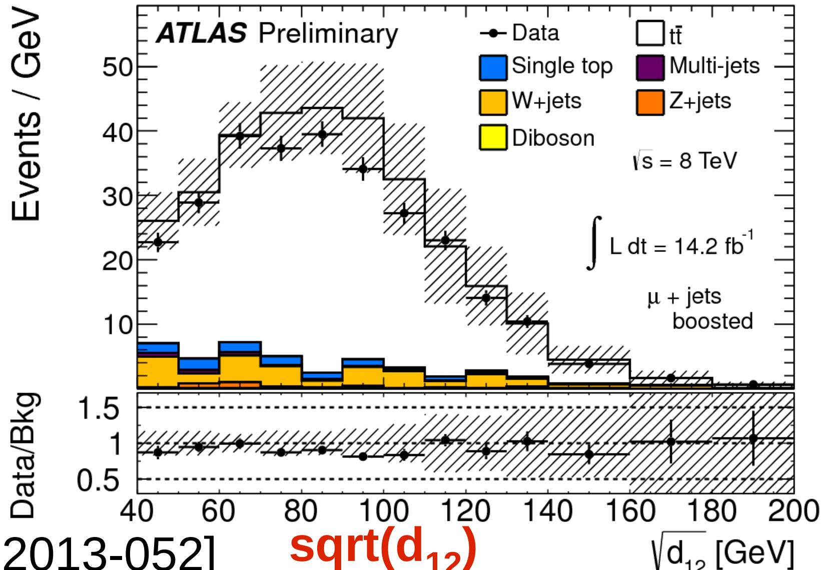


Top-antitop Resonance Lepton+Jets Channel (ATLAS)



- Combine two event selections:
  - → "resolved" : standard top reconstruction with narrow jets
  - → "boosted" : anti-kT R=1.0, p_T>350 GeV, m>100GeV, $\sqrt{d_{12}}$>40GeV
- Improve efficiency at high t-tbar mass with:
  - → Lepton "mini-isolation": smaller isolation cone at high momentum
  - → Trigger: Fat Jet trigger (anti-kt jet R=1.0, p_T>240 GeV)
- Thousands of boosted t-tbar events reconstructed





[ATLAS-CONF-2013-052]