ATLAS:
Higgs Physics and BSM Searches
MPP Project Review 2015

Claudia Giuliani on behalf of the MPP ATLAS group

Max Planck Institute for Physics
(Werner-Heisenberg-Institut)

December 15th, 2015

Introduction
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Higgs Boson
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Supersymmetry
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Dark Matter
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Summary
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Higgs & Physics Beyond the Standard Model

Standard Model (SM) Higgs boson searches and measurements:

- Measurement of the Higgs properties
    - Precision mass measurement
    - Measurement of couplings to vector bosons and fermions
    - Observation of $H \rightarrow b\bar{b}$ decays and $t\bar{t}H$ production still needed

Search for physics beyond the Standard Model (BSM):

- Searches for supersymmetric (SUSY) particles
    - Both R-parity conserving and R-parity violating scenarios considered

- Direct searches for dark matter (DM) production
    - DM in association with a Higgs boson
    - DM in association with heavy flavour quarks

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Run-1 legacy: the Higgs Boson

Higgs Boson Discovery:

- Contributions both in bosonic and fermionic decay channels
  - Discovered in bosonic and $\tau\tau$ decay channels
  - No discovery yet in $H \to b\bar{b}$

  ♦ Data S/B Weighted
  — Sig+Bkg Fit (m$_H$=126.5 GeV)
  ⋯⋯ Bkg (4th order polynomial)

- Mass measurement:
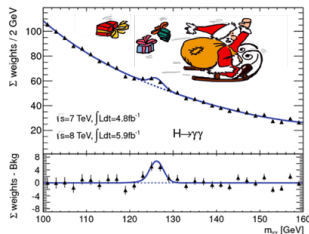 - $H \to ZZ^* \to 4\ell$:
    channel with lowest systematic uncertainty

- Couplings to vector bosons:
  - First studies of couplings and spin^{CP} properties in $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$ channels

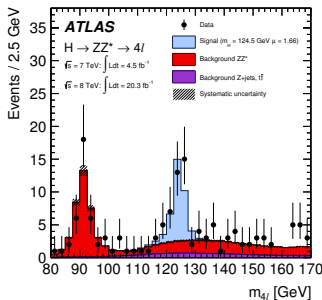- Couplings to fermions:
  - Contributions to measurement of $H \to \tau\tau$ and $W(H \to b\bar{b})$ processes

- Searches for Supersymmetric Higgs bosons

Phys. Lett. B 716 (2012) 1-29

Phys. Rev. D. 90, 052004 (2014)

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Supersymmetry
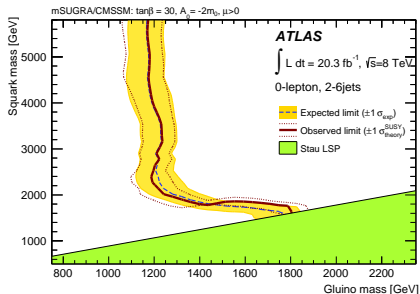○○○○○○

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Run-1 legacy: Searches for Supersymmetry

JHEP09(2014)176

Searches for Supersymmetric particles:

- Inclusive searches for SUSY particles:
  - With first ATLAS data $\sqrt{s} = 7$ TeV
  - Very tight limits on squark and gluino production cross section

mSUGRA/CMSSM: tanβ = 30, A_0 = -2m_0, μ>0

ATLAS

$\int$ L dt = 20.3 fb^{-1}, $\sqrt{s}$=8 TeV

0-lepton, 2-6jets

- - - Expected limit (±1 σ_{exp})
— Observed limit (±1 σ^{SUSY}_{theory})
Stau LSP

- R-parity violating (RPV) and Electroweak (EW) production models
  - Lower production cross section
  - With dataset recorded at $\sqrt{s} = 8$ TeV
  - Searches in final states with multiple leptons
  - SUSY models with long-lived particles:
    first ATLAS search for displaced high-mass dilepton vertices

- Searches for the top squark
  - $m(\tilde{t}) \simeq m(t)$: spin-correlation measurement

Probing the Standard Model with the Higgs Boson

- Study all possible combinations of Higgs production and decay processes
  - $\rightarrow$ search for deviations from the SM

production / decay		$b\bar{b}$	$\tau\tau$	WW*	ZZ*	$\gamma\gamma$
σ [pb] / BR		0.577	0.063	0.215	0.026	0.002
gluon fusion	19.27	−	0	✓	✓	✓
vector boson fusion	1.58	0	✓	✓	✓	✓
H associated with W and Z	1.12	✓	✓	✓	✓	✓
H associated with $t\bar{t}$	0.13	0	0	0	0	−

SM predictions: m(H) $= 125$ GeV, $\sqrt{s} = 8$ TeV   ✓: observed
pure couplings to vector bosons   0: not observed
pure couplings to fermions   −: not measured

- Combinations of all measurements

  - $\rightarrow$ best sensitivity to Higgs couplings to SM particles

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Higgs Mass Measurement

Phys. Rev. Lett. 114 (2015) 191803

- Higgs boson mass: free parameter of the Standard Model

- Precision measurement: to predict and test all Higgs boson properties

- Mass Measurement - (Combination of ATLAS and CMS results) Master Thesis: K. Ecker, R. Röhrig
  $\rightarrow$ Strong contribution in $H \rightarrow ZZ^* \rightarrow 4\ell$ channel:
    - Developed analytical signal description for low statistics environments
    - Channel with lowest systematic uncertainty:
      thanks to MPP work on muon momentum calibration
    - Limited by statistics in Run-1 $\rightarrow$ most promising channel in Run-2

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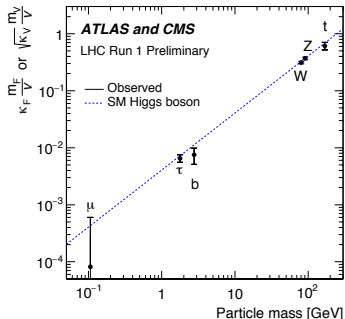Supersymmetry
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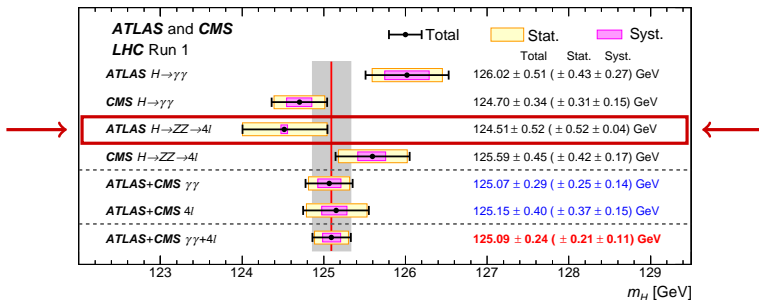
Higgs Couplings Combination

ATLAS-CONF-2015-044

- ATLAS-CMS combination of Higgs search results
  - All decay channels and production modes combined
  - Couplings to vector bosons better understood than couplings to fermions
  - Couplings scale with particle mass as predicted by the SM
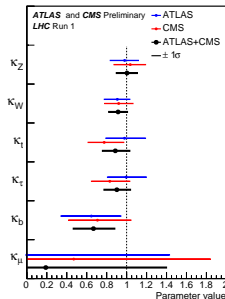
- Strong contributions in almost all key-channels to combined ATLAS-CMS Run-1 results
- Need to better constrain production and decay couplings to be able to see deviations from SM
- Very important to improve precision in fermionic channels

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Higgs Couplings to Heavy Quarks:
WH and $t\bar{t}$H production, $H \to b\bar{b}$

JHEP01(2015)069

- Higgs boson not yet discovered in $H \to b\bar{b}$ channel:
  Combined Run-1 significance 2.6σ (expected 3.7σ)

- Study of $WH \to \ell\nu b\bar{b}$ channel for Run-2:
  - Optimisation of signal-like selection
  - Reconstruction of boosted $H \to b\bar{b}$ decays
    $\to$ study sub-structure of "large" Higgs jets
    ATL-PHYS-PUB-2015-035

Master Thesis: I. Weimer , Bachelor: D. Nebe, D.Joseph

- New study started in $t\bar{t}$H production, $H \to b\bar{b}$:
  - Higgs couples to quarks both in production
    and decay
  - Direct probe of top Yukawa couplings
  - Not yet sensitive to SM cross section:
    exclusion limits $3.4\times$ SM 95% C.L.

signal $\times$ 10

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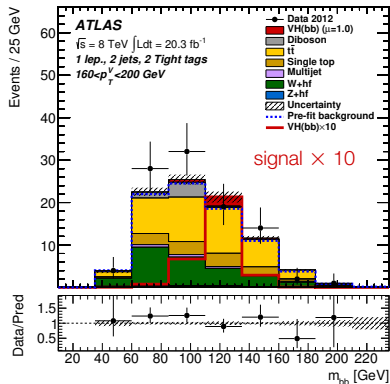
Higgs spin^{CP} and Couplings to Vector Bosons

Eur. Phys. J. C75 (2015) 476

- First spin^{CP} results favour SM Higgs: CP-even spin 0 particle
- Still room for deviations
  - Probe for Higgs tensor structure and CP odd admixtures through couplings to bosons
- $H \rightarrow ZZ \rightarrow 4\ell$ one of the most sensitive channels: full decay reconstruction
  - Study differential properties of Higgs decay: angles and masses of lepton pairs
  - Matrix element approach
  - Boosted Decision Tree from decay observables

z - proton beam axis
z' - Higgs (X) rest frame
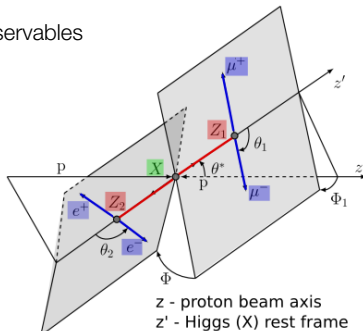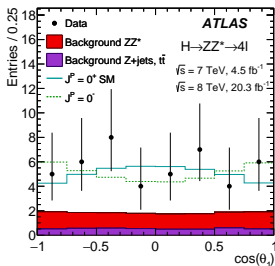
Higgs spin$^{\text{CP}}$ and Couplings to Vector Bosons

Eur. Phys. J. C75 (2015) 476
PhD Thesis: K. Ecker

- Run-1 result:
  - Strong contribution in $H \rightarrow ZZ^* \rightarrow 4\ell$ channel
  - Allowed BSM Higgs couplings (95% C.L. limits):
    - CP-even coupling w.r.t. SM [-0.7,0.6]
    - CP-odd coupling w.r.t. SM [-2.2,0.8]
  - Expected BSM deviations of order 1%

- Run-2 work in progress:
  - Higgs boson re-discovery and inclusive and differential cross-section measurement Master Thesis: V. Walbrecht
    - $\rightarrow$ first Run-2 results will be shown today 3 p.m.
  - Improved measurement of the tensor structure of the couplings to vector bosons
    - New signal modelling framework for combination of all channels (ATL-PHYS-PUB-2015-047):
    - $\rightarrow$ Measurement in multidimensional space of coupling parameters
    - $\rightarrow$ Exploiting both Higgs production rate and decay properties $\rightarrow$ sensitivity improvement
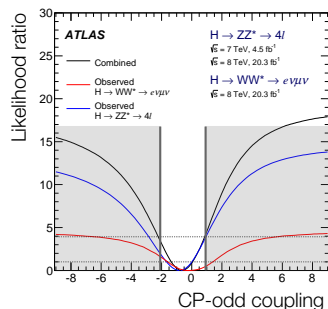
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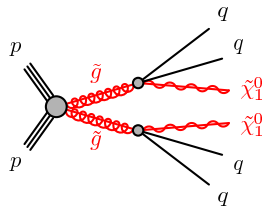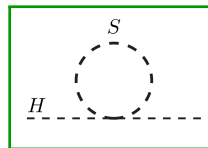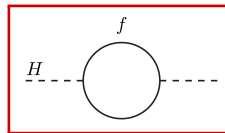Higgs Boson
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Supersymmetry
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Dark Matter
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Summary
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Searches for Supersymmetry

Supersymmetry

- Symmetry bosons↔fermions

- Solves the Higgs boson mass hierarchy problem:

$$\Delta m_H^2 \propto \boxed{-\frac{y_f^2}{8\pi^2}\Lambda_c^2} \boxed{+\frac{\lambda_s}{16\pi^2}\Lambda_c^2} +...$$

- SUSY is a broken symmetry

- Minimal Supersymmetric Standard Model (MSSM):
  - each SM particle has a SUSY partner

- New quantum number R-parity = $(-1)^{3(B-L)+2s}$
  - R-parity conserving (RPC) models:
    - At colliders SUSY particles produced in pair
    - Lightest SUSY particle (LSP) stable
      → Dark Matter candidate
  - R-parity violating (RPV) models:
    - Consider lepton number violating RPV couplings
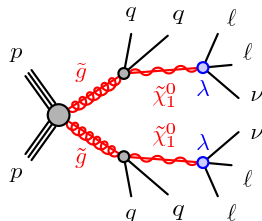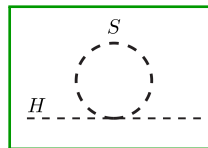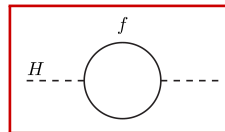
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4-leptons final state search: RPV and EW

- Search in 4 or more leptons final states
  - Very general signature quite model independent
  - Rare signature in the SM
  - Powerful for EW SUSY production and for RPV decays
- Run-1 results:
  - Efforts led by MPP group
    PhD Thesis: M. Goblirsch
  - Contribution to electroweak summary paper:
    arXiv:1509.07152
  - RPV signature: LSP decays into leptons
    $\rightarrow$ lepton flavour violating (LFV) couplings
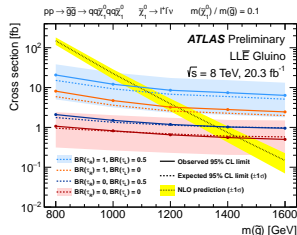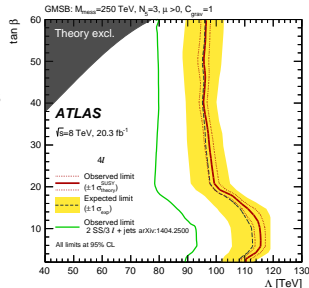 - Additional RPV models and interpretations
    in ATLAS-CONF-2015-018 - Master Thesis: D. Krauss
- Analysis of $\sqrt{s} = 13$ TeV data:
  - Focus on Electroweak production and on RPV decays
  - Design of new signal models and analysis optimisation

Phys. Rev. D. 90, 052001 (2014)

Master: J. Junggeburth, S. Maschek; Bachelor: D. Kresse, M. Rendel

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RPV Displaced Vertices

Phys. Rev. D 92, 072004 (2015)

- Search for metastable SUSY particles
  - Decays at radii R $= 4 - 300$ mm from interaction vertex
  - Displaced decay verteces from charged leptons
  - Vertices e.g. from RPV decay models with LFV: $\tilde{\chi}_1^0 \rightarrow \ell_1^+ \ell_2^- \nu$

- Run-1 results:
  - First collider constraints on $\tilde{\chi}_1^0 \rightarrow e^\pm \mu^\mp \nu$
  - Limits set also for $e^+ e^-$ and $\mu^+ \mu^-$ vertices
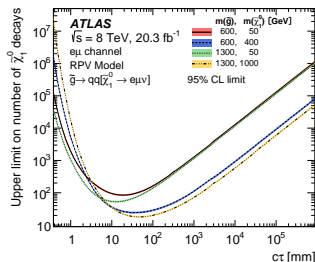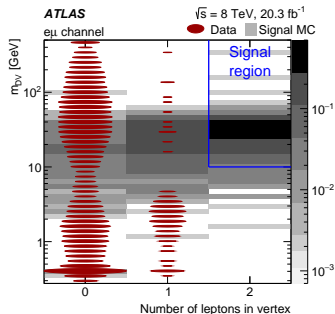 - Novel background estimate method
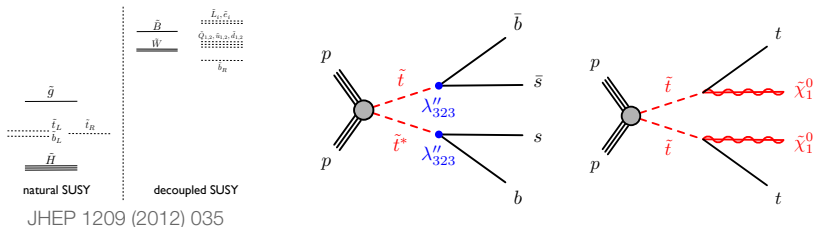   PhD Thesis: M. Goblirsch

- Run-2 work in progress:
  - Filters to select events for large-d_0, tracking in place and running at Tier 0
  - Analysis work now starting
    PhD Thesis: D. Krauss

Top Squark Searches and Naturalness


JHEP 1209 (2012) 035

- Top squark, or stop: SUSY partner of the top quark

- Top and stop: main loop contributions to Higgs boson squared mass parameter

- Stop mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$
    - from the mixing of $\tilde{t}_L$ and $\tilde{t}_R$: can be large due to top Yukawa coupling

- Good cancellation of loop corrections to Higgs mass parameter
    - light higgsinos
    - gluinos below ~ 2 TeV
    - light stop, $\tilde{t}_1$, below ~ 1 TeV

- Searches in R-parity conserving and R-parity violating models

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Direct Top Squark Search - RPC
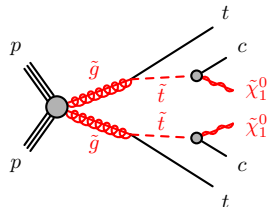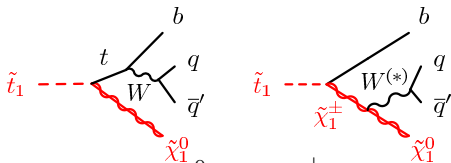
- Decay modes: $\tilde{t} \to t\tilde{\chi}_1^0$, $\tilde{t} \to b\tilde{\chi}_1^\pm$, asymmetric decay
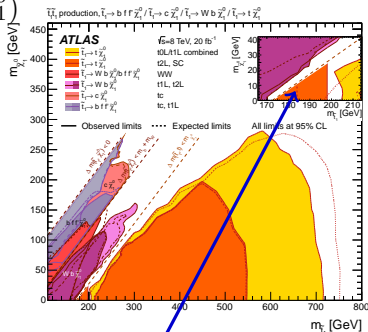
- Gluino mediated stop production, small $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$

- Run-1 results:

  - Explored region $m(\tilde{t}) \simeq m(t)$: spin correlations
    Master Thesis: N. Köhler

  - Contributed to summary paper results
   Eur. Phys. J. C75 (2015) 510

- Run-2 focus:

  - Fully hadronic final states
    PhD Thesis: N. Köhler; Bachelor: L. Schlechter

  - Heavy stops and top decay reconstruction

  - Expect to improve sensitivity with $\sim 10\,\text{fb}^{-1}$ of data

spin correlation measurment

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Direct Top Squark Search - RPV

- Interesting scenario with RPV top squark decay
- Minimal flavour violation $\tilde{t} \rightarrow \bar{b}\bar{s}$
- Sensitive to low stop mass range
- ATLAS result with $\sqrt{s} = 8$ TeV:
  ATLAS-CONF-2015-026
- Run-2 preparation:
  - Decays in 2x2 jets
  - Boosted reconstruction to explore higher mass range
  - Exploit mass of reclustered jets to select signal-like events

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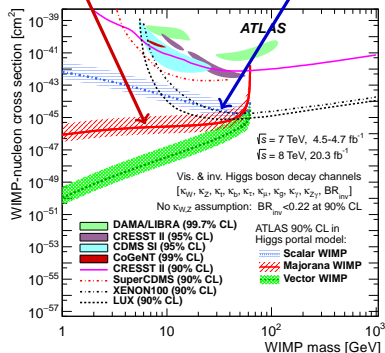○
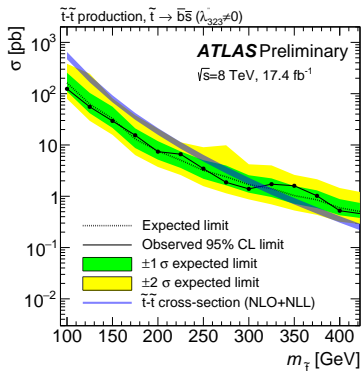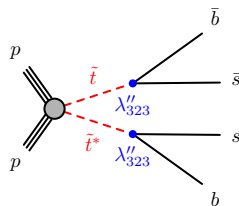
Dark Matter Searches

arXiv:1509.00672

- Dark Matter searches at hadron colliders:
  - Good complementarity with sensitivity of direct DM detection experiments
  - Highest sensitivity to low mass DM particles
  - Study couplings with Higgs boson
  - Strong effort to coordinate with theorists and direct detection experiments:
    - arXiv:1507.00966
    - Strategy for presentation of results and signal models
  - With Run-1 data:
    Effective Field Theory approach
  - Now focus on simplified models

- Current focus of the MPP group:
  - Mono Higgs + DM, H→ b b̄ (arXiv:1312.2592)
  - DM+heavy flavour, b/bb+Met final states (arXiv:1303.6638)
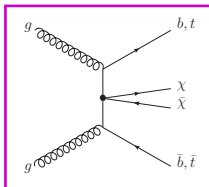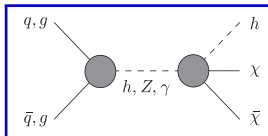
ATLAS 95% C.L. exclusion curve

Direct detection experiments

Vis. & inv. Higgs boson decay channels
[κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_g, κ_γ, κ_{Zγ}, BR_inv]
No κ_{W,Z} assumption: BR_inv <0.22 at 90% CL

√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹

ATLAS 90% CL in Higgs portal model:
Scalar WIMP
Majorana WIMP
Vector WIMP

DAMA/LIBRA (99.7% CL)
CRESST II (95% CL)
CDMS SI (95% CL)
CoGeNT (99% CL)
CRESST II (90% CL)
SuperCDMS (90% CL)
XENON100 (90% CL)
LUX (90% CL)

H → invisible

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Dark Matter + X searches

arXiv:1510.06218, EPJC 75 (2015) 92

- Mono Higgs + DM, H→ b$\bar{\text{b}}$:
  - Complementary to H → invisible:
    covers m(χ) > m(H)/2
  - Higgs boosted regime:
    exploit large-R jets and substructure information
  - Optimise Higgs tagger PhD Thesis: R. Röhrig
    → b-tagging within large-R jets

- DM+heavy flavour, b/b$\bar{\text{b}}$ + E$_T^{miss}$ final states:
  - Soft b-jets and low E$_T^{miss}$
  - Improve trigger strategy
  - Exploit significance and angular variables

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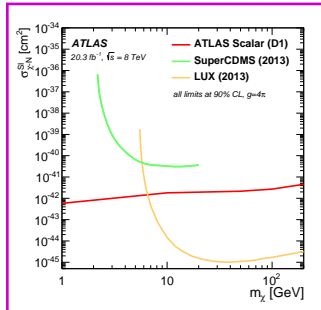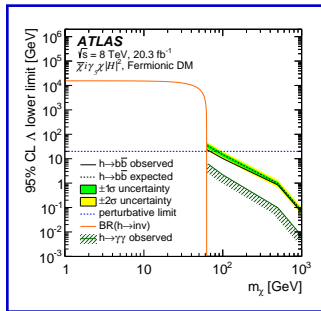
Very exciting times ahead!

- Contributed to 21 ATLAS Higgs and SUSY publications in 2015, 13 in journals

- ATLAS has already recorded 4 fb^{-1} of data at $\sqrt{s} = 13$ TeV

- First results with full $\sqrt{s} = 13$ TeV dataset:
  This afternoon at 3 p.m. in CERN End of the Year Event! - Link to Agenda

- Expecting new results for many searches in summer 2016

Thanks for your attention!

ATLAS Online Luminosity $\sqrt{s}$ = 13 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 4.34 fb^{-1}
Total Recorded: 4.00 fb^{-1}