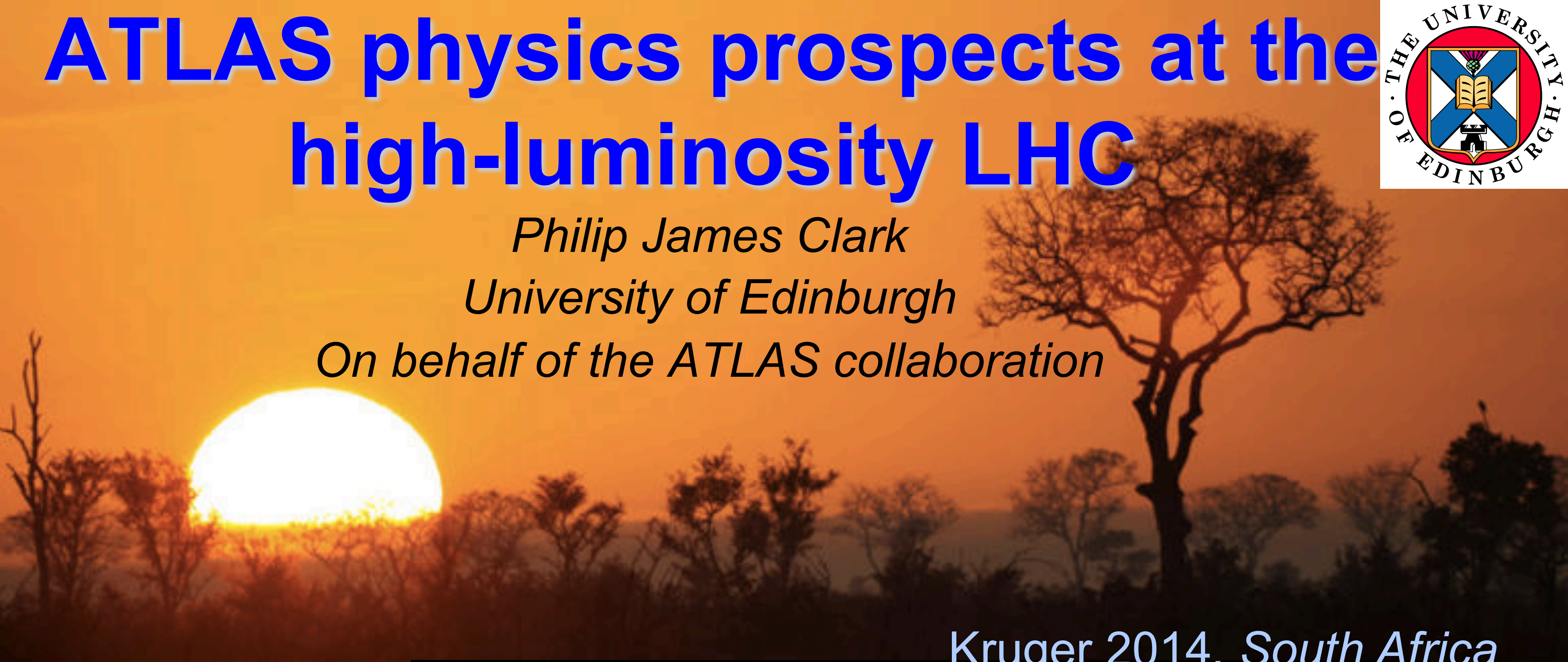
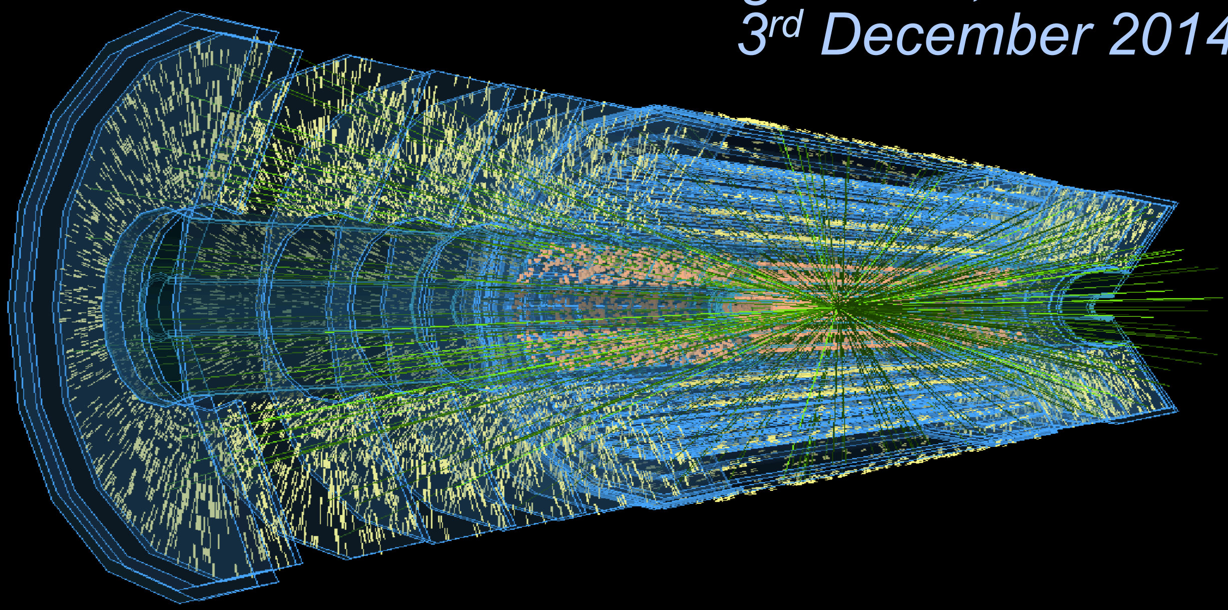


ATLAS physics prospects at the high-luminosity LHC

Philip James Clark
University of Edinburgh
On behalf of the ATLAS collaboration



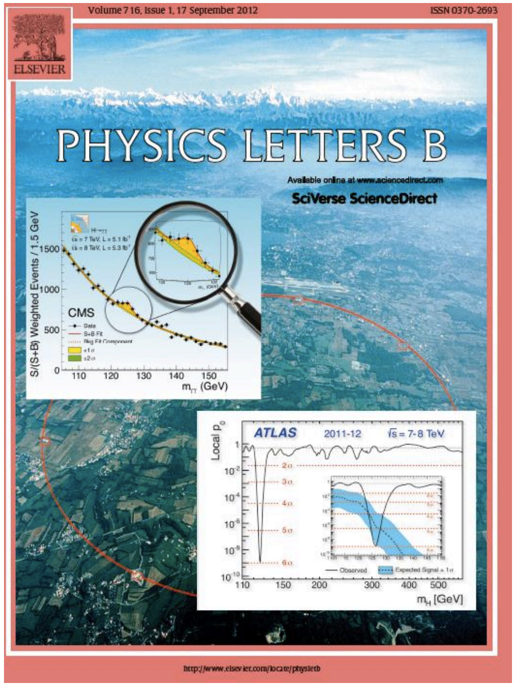
Kruger 2014, *South Africa*
3rd December 2014

Overview

- Introduction
- Prospects for Higgs Physics
- Searches for super-symmetric particles
- Dark matter search potential
- Conclusions

Discovered a Higgs boson

- Both ATLAS and CMS have close to 10σ significance



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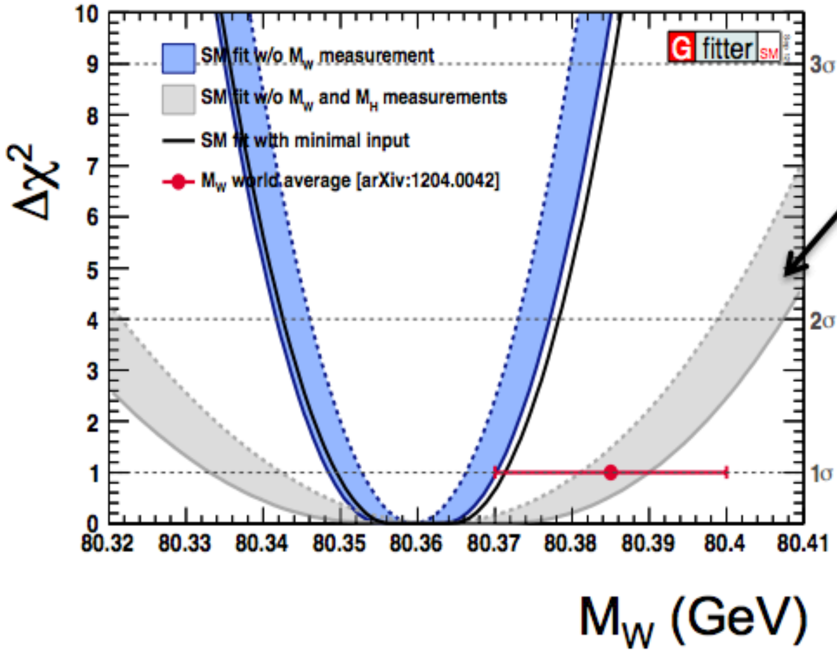
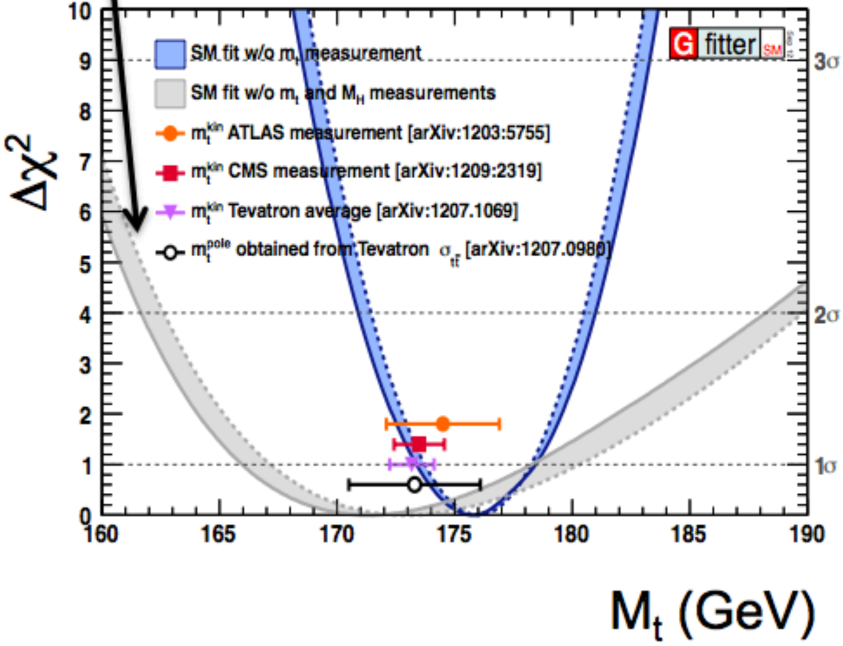
- Minimal Higgs model is very predictive - only free parameter is m_h
- Now we will begin the full exploration for the properties of EWSB

Era of precision physics



Fit without Higgs

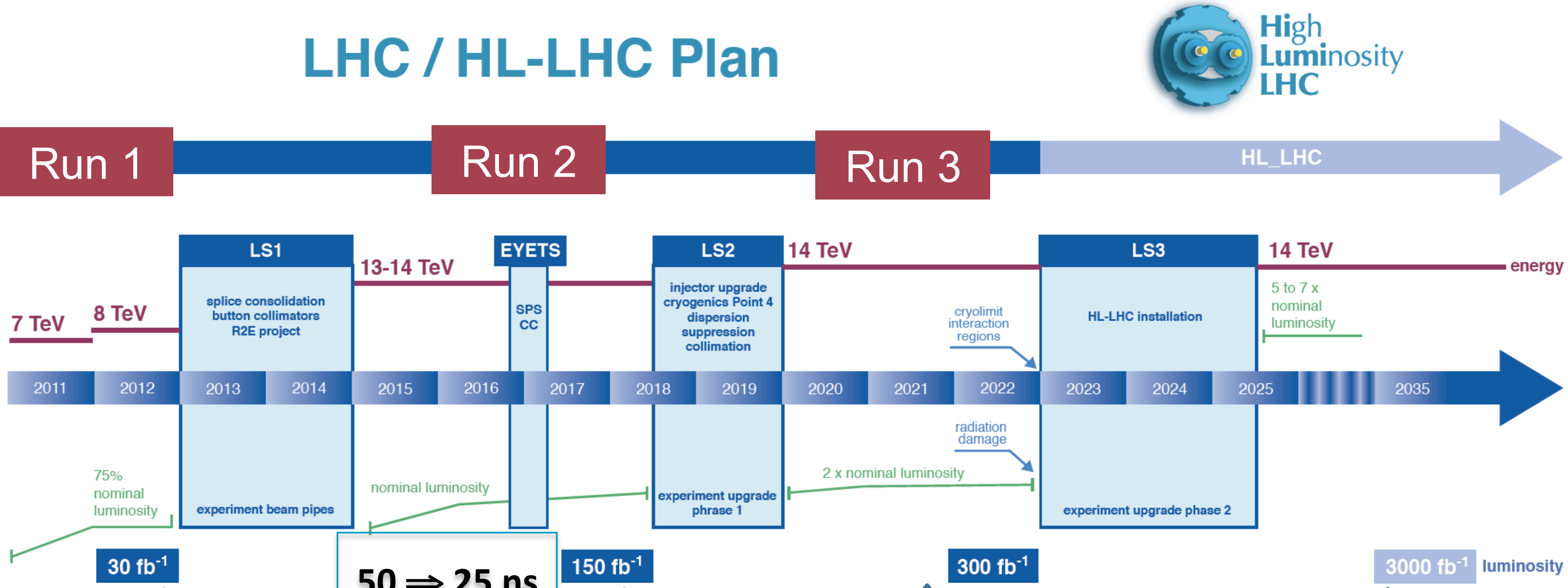


- SM works extremely well as an effective low energy theory
- We can still discover new Higgs particles, signals in new channels, and precision measurements of properties
- Big questions remaining: flavour, dark matter, hierarchy …

High luminosity LHC

ATLAS:

- $300\ \text{fb}^{-1}$ by 2022: new silicon layer (IBL) and trigger upgrades
- $3000\ \text{fb}^{-1}$ by ~2035: new radiation hard tracker (ITk) required



LHC / HL-LHC Plan

50 ⇒ 25 ns

$0.75\ 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
50 ns bunch
high pile up ~40

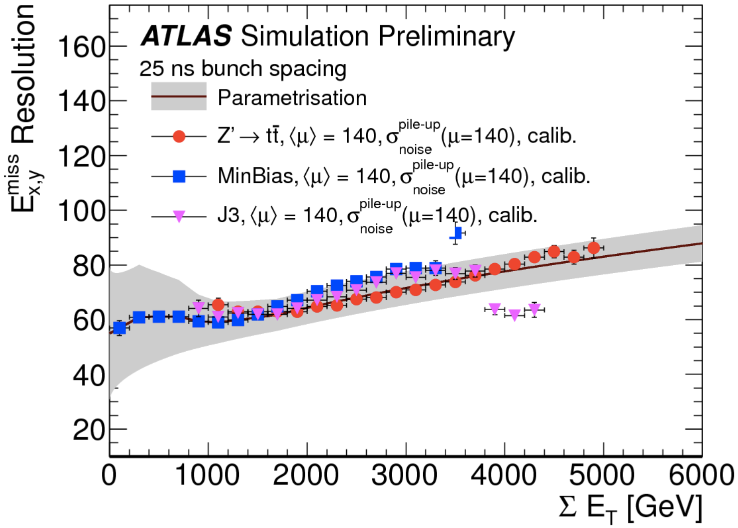
$1.5\ 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
25 ns bunch
pile up ~40

$1.7\text{-}2.2\ 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
25 ns bunch
pile up ~60

$5.0\ 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
25 ns bunch
pile up ~140

ATLAS performance

- Parametrisations for the upgraded ATLAS detector response
  - ➢ Resolution and reconstruction efficiency for e, μ, τ, γ, jets & E_T^{miss}
  - ➢ Rates for light and c jets to pass b-tag requirements
  - ➢ Parametrisations are checked against full simulations
- Systematic uncertainties
  - ➢ Based on completed Run-1 analyses, or if statistical limitation from control regions, then improvements are estimated
- Run-1 style analysis techniques (⇒sensitivity can be improved)



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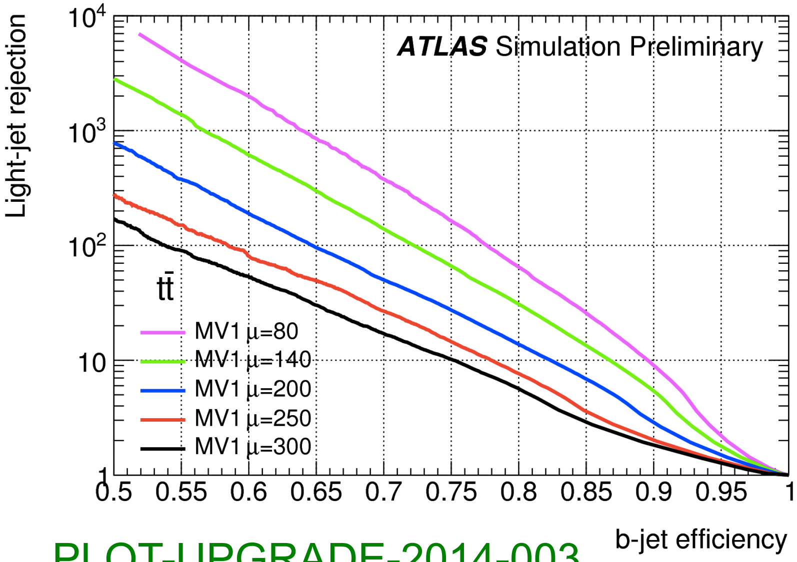
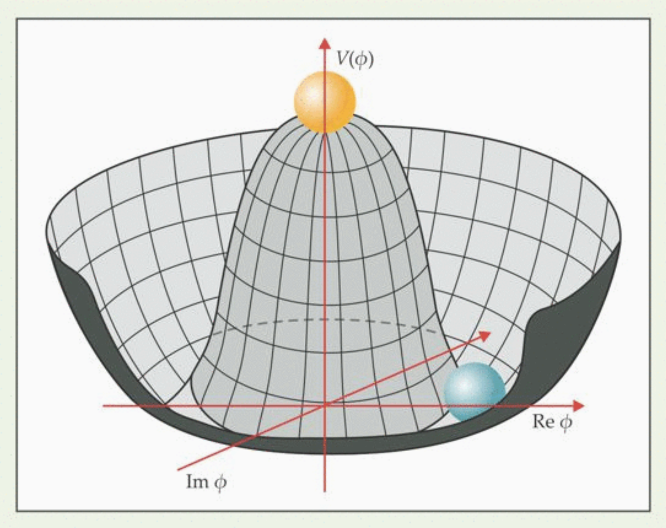


PLOT-UPGRADE-2014-003

Higgs

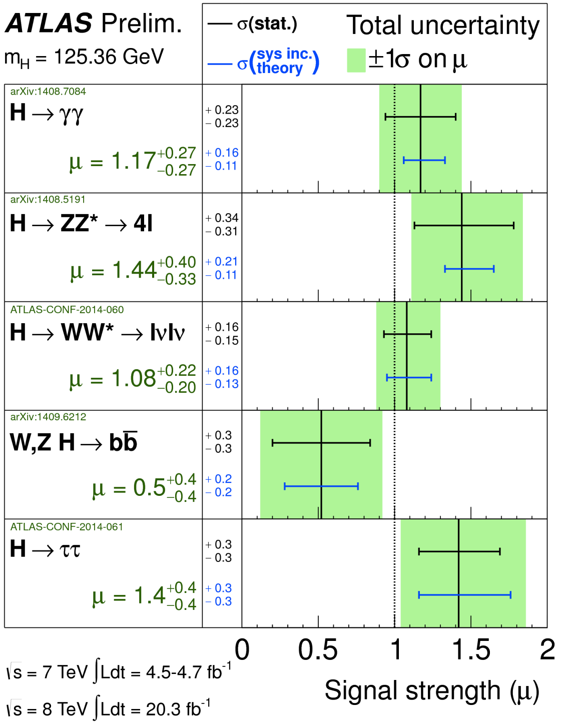
Open Higgs questions

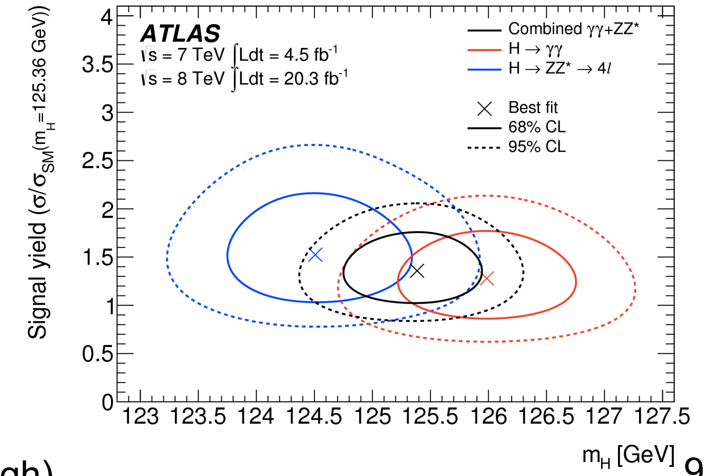


- Is it the SM Higgs?
    - Interactions?
    - Does it give mass to all particles?
    - Spin/parity?
- Are there more Higgs-like particles?
    - Is it part of a MSSM spectrum?
    - Does it couple to dark matter?
- Is it elementary or composite?
- Are there new production/decay channels?

Higgs: where we currently stand

- Need precision measurements of Higgs properties to search for new physics
- Properties measured so far:
  - m_h = 125 ± 0.37 (stat) ± 0.18 (sys) GeV
  - Signal strength: μ = 1.30 ± 0.18
  - Spin-0 nature favoured
  - No significant deviation in couplings
- What next:
  - Observe all production & decay processes
  - Precision measurements to constrain SM
  - Search for BSM processes
  - CP violation in Higgs sector
  - Are there other Higgs bosons?

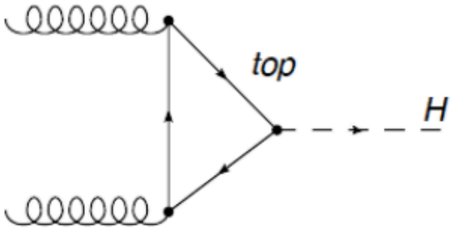


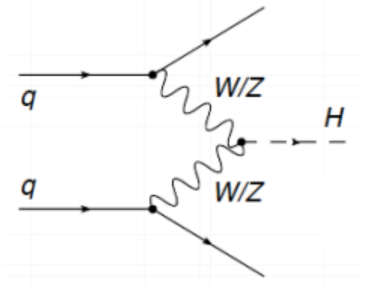


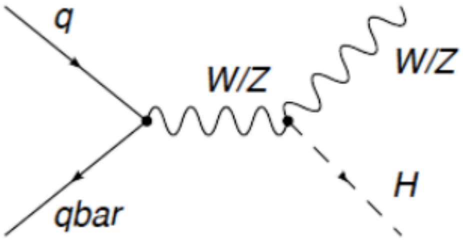
Phys. Rev. D. 90, 052004 (2014)

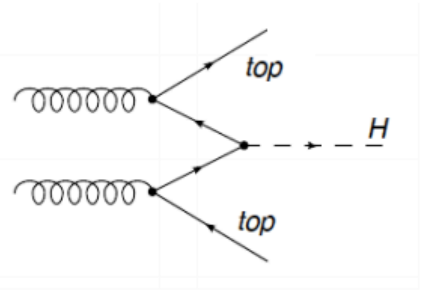
HL-LHC as a Higgs factory

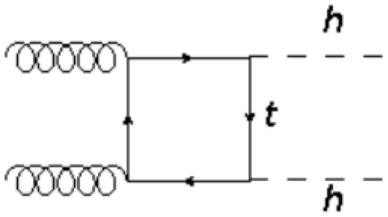
Process at 14 Tev	Higgs bosons at ATLAS with 3000 fb^{-1}
All prod. and decay modes	170 M
VBF (all decays)	13M
tth (all decays)	1.8M
h → Zγ	230k
h → μμ	37k
hh	121k

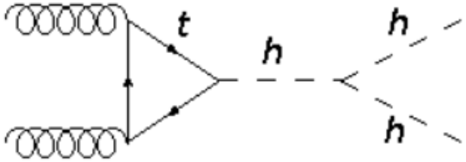






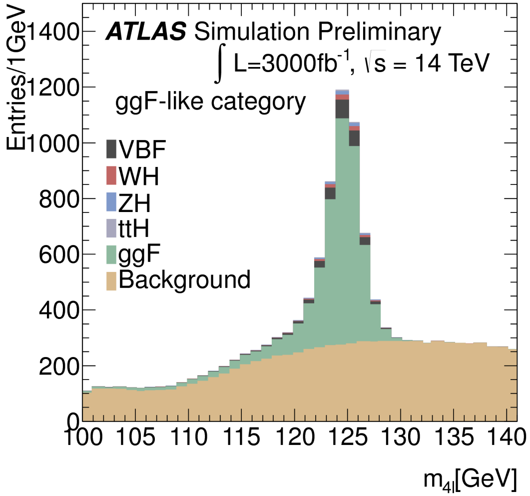


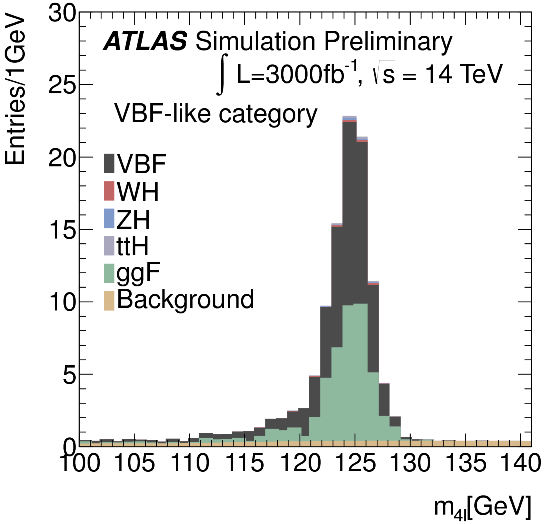


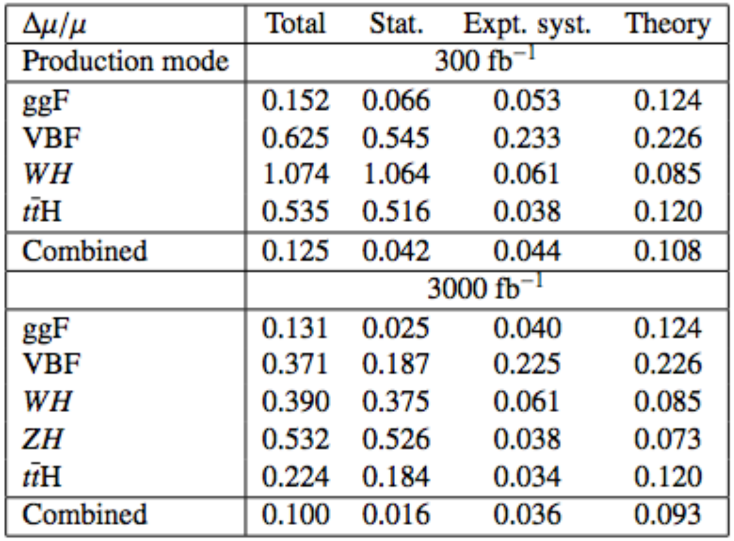


Higgs production (H→ZZ*→4l)

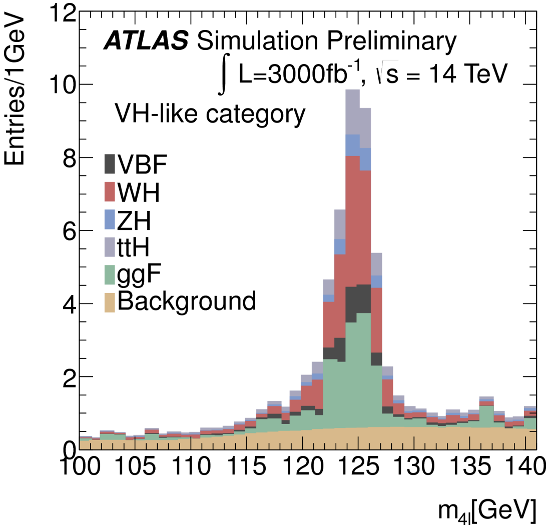
Using 3000 fb^{-1} we can measure all the production modes

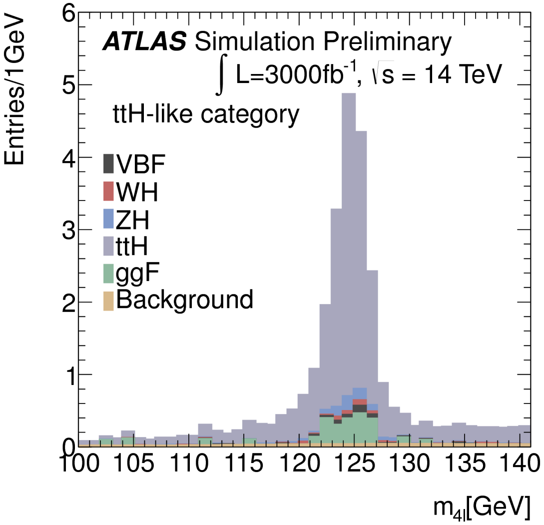






$\Delta\mu/\mu$	Total	Stat.	Expt. syst.	Theory
Production mode	300 fb^{-1}			
ggF	0.152	0.066	0.053	0.124
VBF	0.625	0.545	0.233	0.226
WH	1.074	1.064	0.061	0.085
$t\bar{t}H$	0.535	0.516	0.038	0.120
Combined	0.125	0.042	0.044	0.108
	3000 fb^{-1}			
ggF	0.131	0.025	0.040	0.124
VBF	0.371	0.187	0.225	0.226
WH	0.390	0.375	0.061	0.085
ZH	0.532	0.526	0.038	0.073
$t\bar{t}H$	0.224	0.184	0.034	0.120
Combined	0.100	0.016	0.036	0.093





Expected uncertainties for 300 & 3000fb^{-1}

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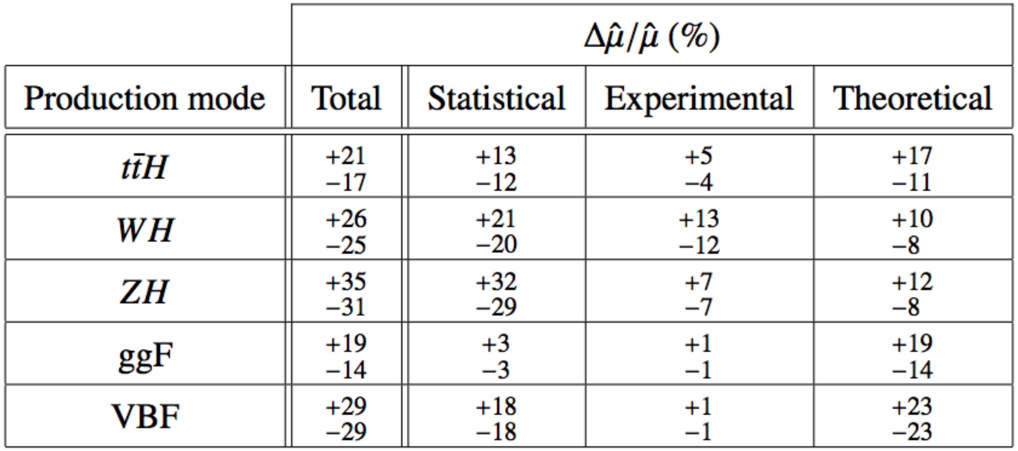
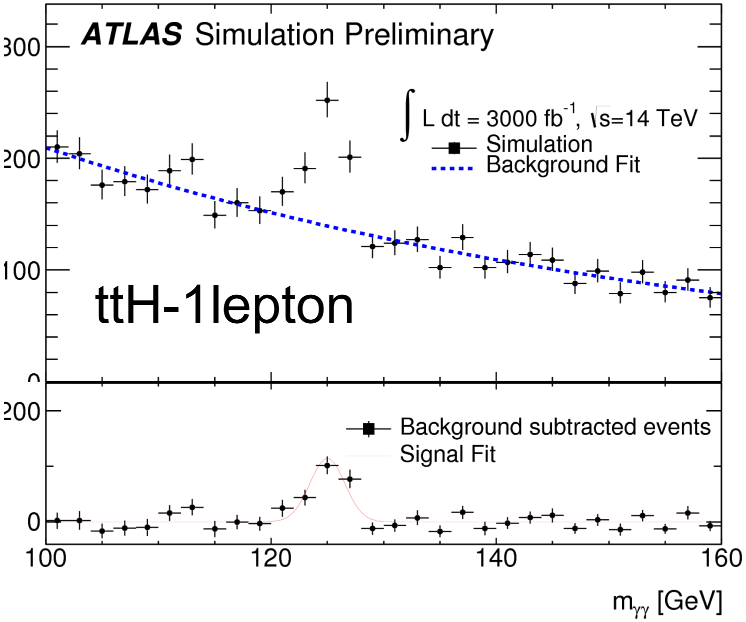
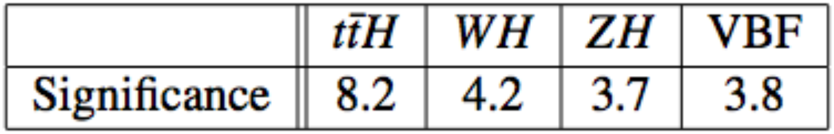
Higgs production (H→γγ)

With 3000 fb^{-1} we can measure all the production modes



	$\Delta\hat{\mu}/\hat{\mu}$ (%)			
Production mode	Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$
WH	$^{+26}_{-25}$	$^{+21}_{-20}$	$^{+13}_{-12}$	$^{+10}_{-8}$
ZH	$^{+35}_{-31}$	$^{+32}_{-29}$	$^{+7}_{-7}$	$^{+12}_{-8}$
ggF	$^{+19}_{-14}$	$^{+3}_{-3}$	$^{+1}_{-1}$	$^{+19}_{-14}$
VBF	$^{+29}_{-29}$	$^{+18}_{-18}$	$^{+1}_{-1}$	$^{+23}_{-23}$



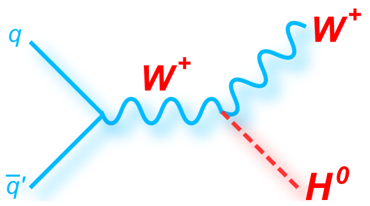


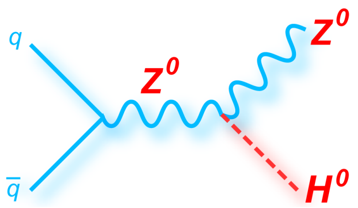
	$t\bar{t}H$	WH	ZH	VBF
Significance	8.2	4.2	3.7	3.8

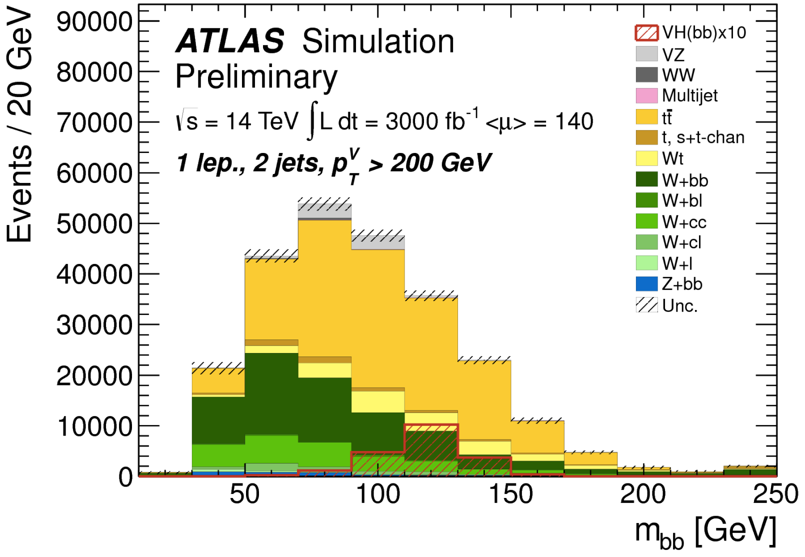
Significance of 8.2σ for ttH, probing the top-quark Higgs Yukawa coupling

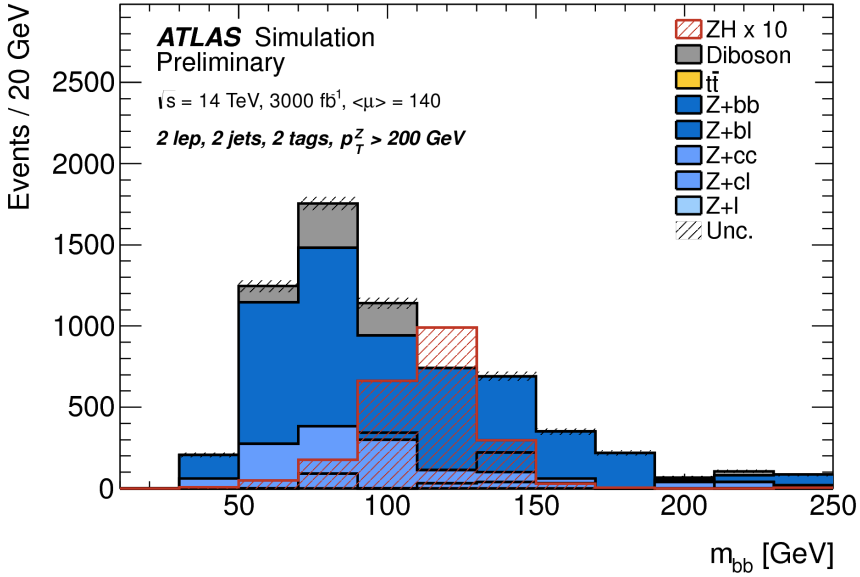
ATL-PHYS-PUB-2014-012

H→bb decay rate (VH → Vbb)







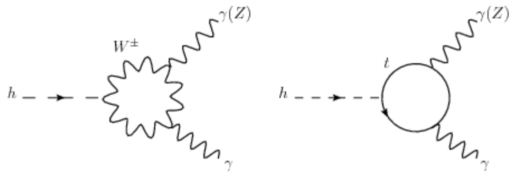


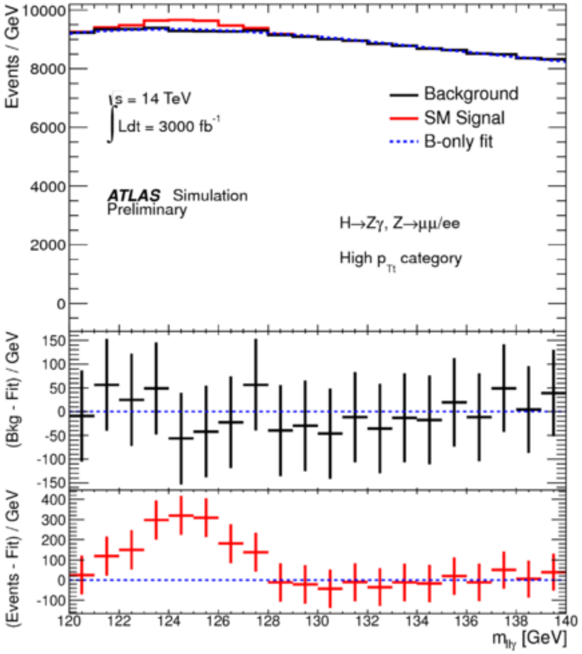
- Decay channel H→bb is crucial for coupling measurements
- For both channels combined significance of 8.8(3.9) and error on signal strength of 15(25)% for 3000(300) fb^{-1}

ATL-PHYS-PUB-2014-011

Rare decay modes

- H→ Zγ, sensitive to new particles in loops

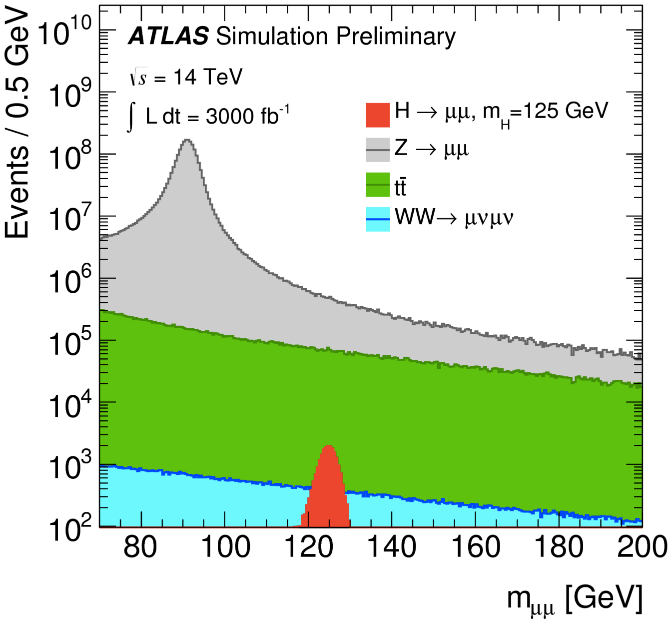


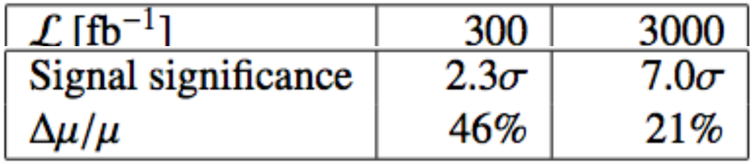


Signficance 3.9(2.3) σ with 3000(300) fb^{-1}

ATL-PHYS-PUB-2014-006

- H→ μμ, sensitive to couplings with 2nd generation





$\mathcal{L}$ [fb^{-1}]	300	3000
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

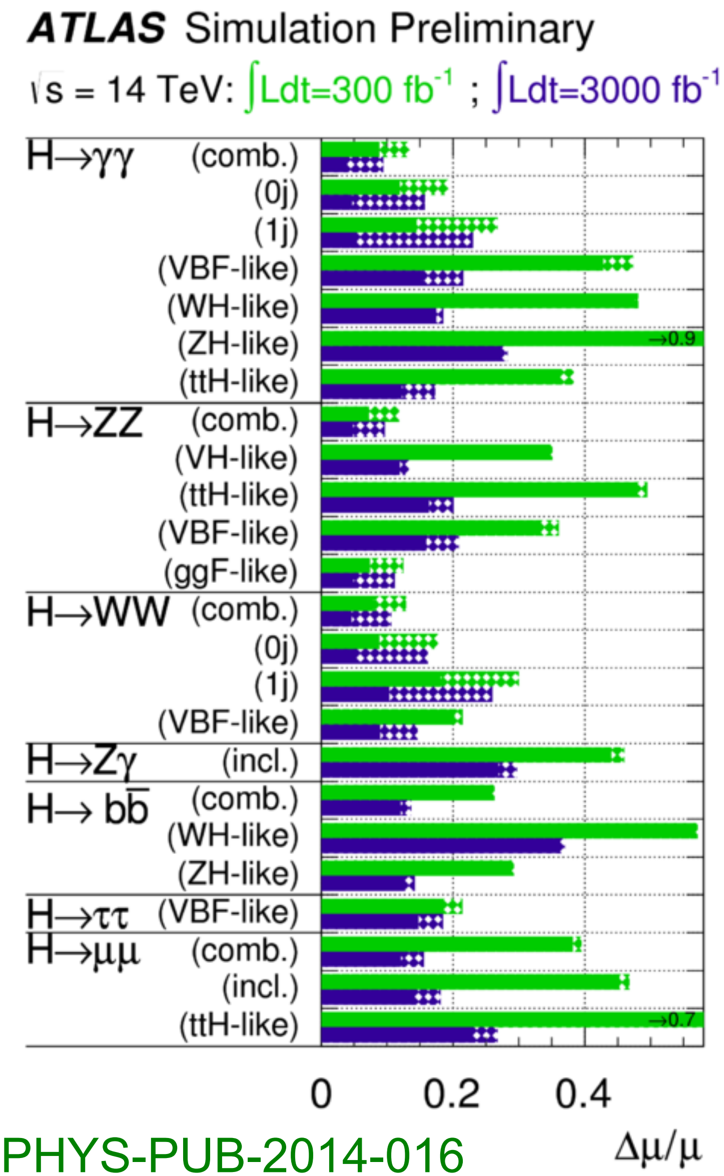
ATL-PHYS-PUB-2013-014

Precision Higgs signal strengths

- Signal strength

  $\mu = \sigma \times BR/(\sigma \times BR)_{SM}$

- Accuracy
  - Channels (γγ, ZZ, WW) accurate to 10(5)% for 3000 fb^{-1} with(out) theory uncertainties
  - Large impact from theory uncertainties (dashed), i.e., QCD scale, jet binning etc
- Separation by production model
  - Vital for coupling measurements



ATL-PHYS-PUB-2014-016

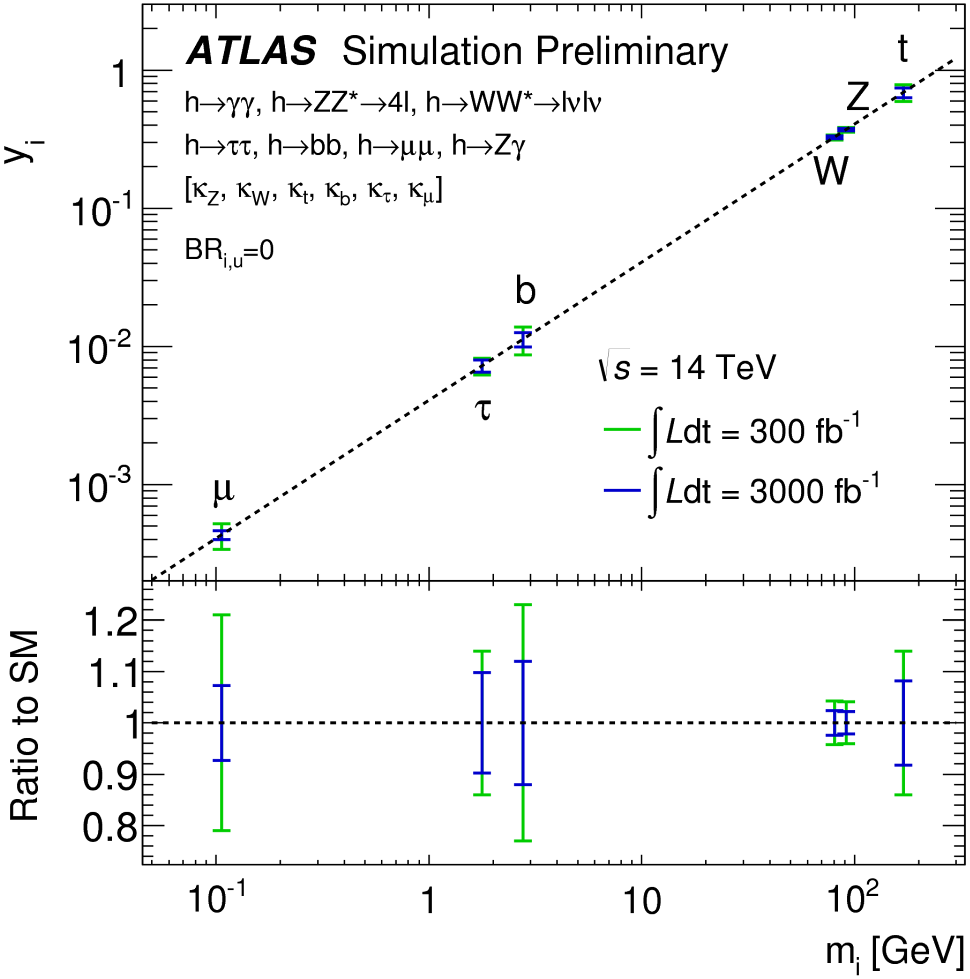
The Higgs couplings

- Precisely predicted in the Standard Model
    - ➢ Couplings to fermions proportional to mass
    - ➢ Coupling to gauge bosons proportional to mass squared

$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v}$$

- ➢ Higgs self-couplings proportional to m_h^2

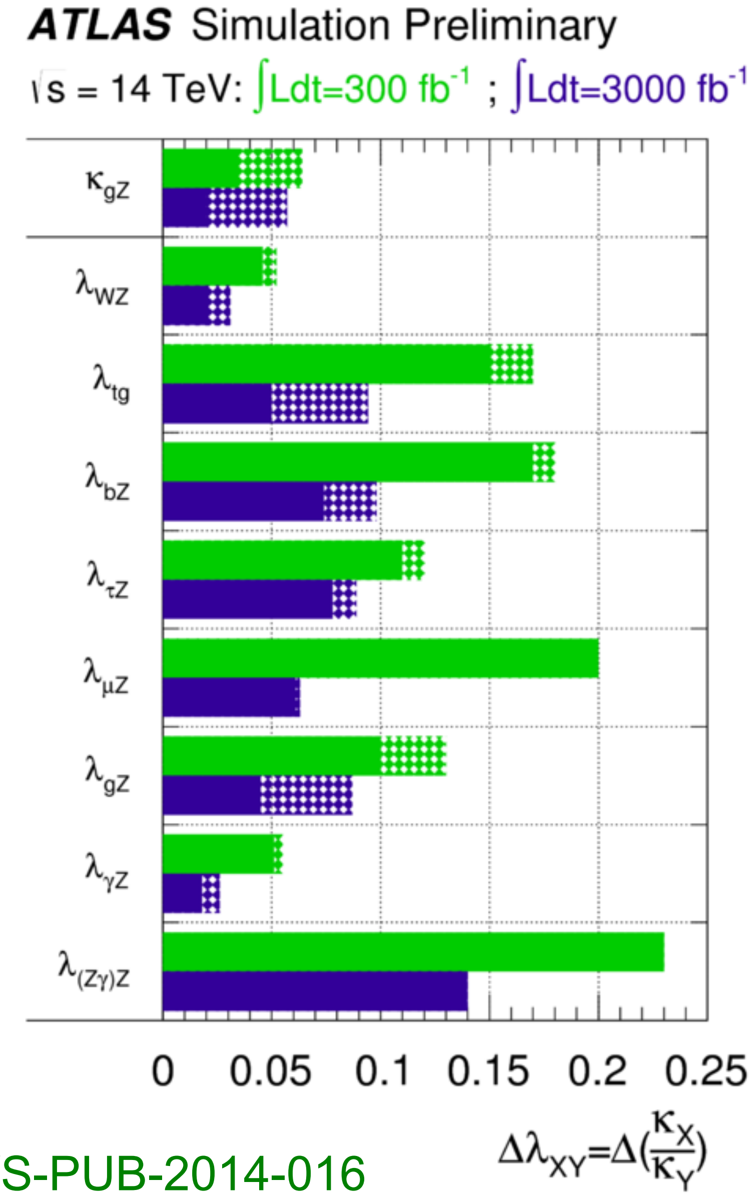


ATL-PHYS-PUB-2014-016

- If couplings don’t agree with predictions
    - ➢ would indicate that not all mass comes from a single Higgs boson

Coupling measurements

- Introduce coupling modifiers, κ_i
  - SM only , i.e., single narrow state, 0^+
- Measure ratios to factor out width
  - $\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ij} = \kappa_i\kappa_j / \kappa_h$, ($\kappa_h$ = width scale factor)
- A generic fit is used
  - Free couplings to SM particles
  - Allow for BSM in loops and un-detected final states
  - HL-LHC will improve experimental precision by a factor of 2-3
  - Coupling ratios can be measured at several %-level with 3000 fb^{-1}



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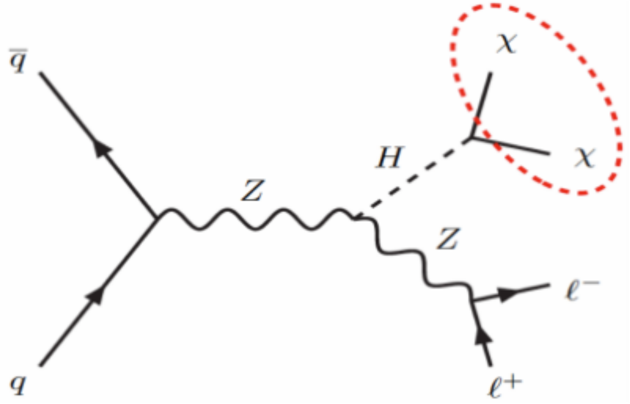
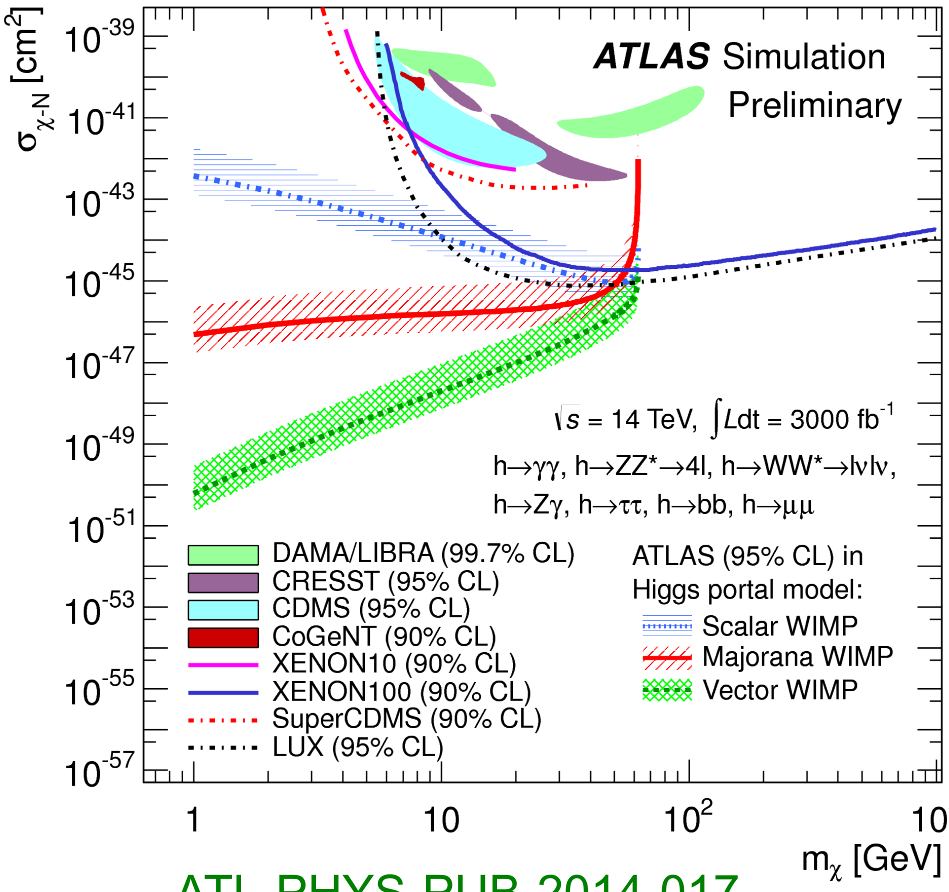
Invisible Higgs decays & dark matter



ATLAS	300 fb^{-1}	3000 fb^{-1}
$ZH \to \ell\ell$+invisible	23-32%	8-16%
Coupling fits	22%	13%

- Two approaches:
  1. Direct search: ZH → l^+l^- + inv
  2. Constraints from couplings
     - WIMP coupling assumed to be free parameter
     - Upper limit derived BR_{inv} from combination of the SM rates

➢ Upper BR_{inv} limits translated to WIMP-nucleon scattering cross-sections



ATL-PHYS-PUB-2014-017

Minimal composite Higgs model

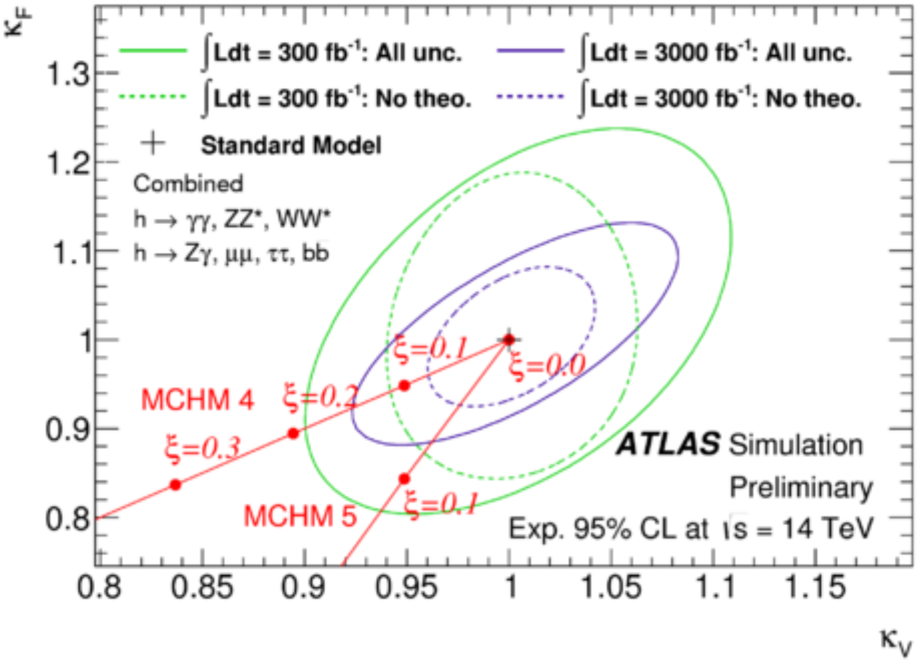
- Pseudo-Nambu-Goldstone boson instead of elementary particle
  - ➢ Modified couplings as a function of scaling parameter $\xi = v^2/f^2$
- MCHM 4 (S04)

$$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$$

MCHM 5 (S05)

$$\kappa_V = \sqrt{1-\xi}$$

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}.$$



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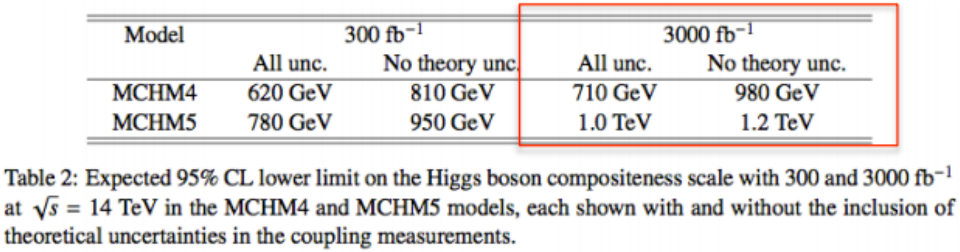


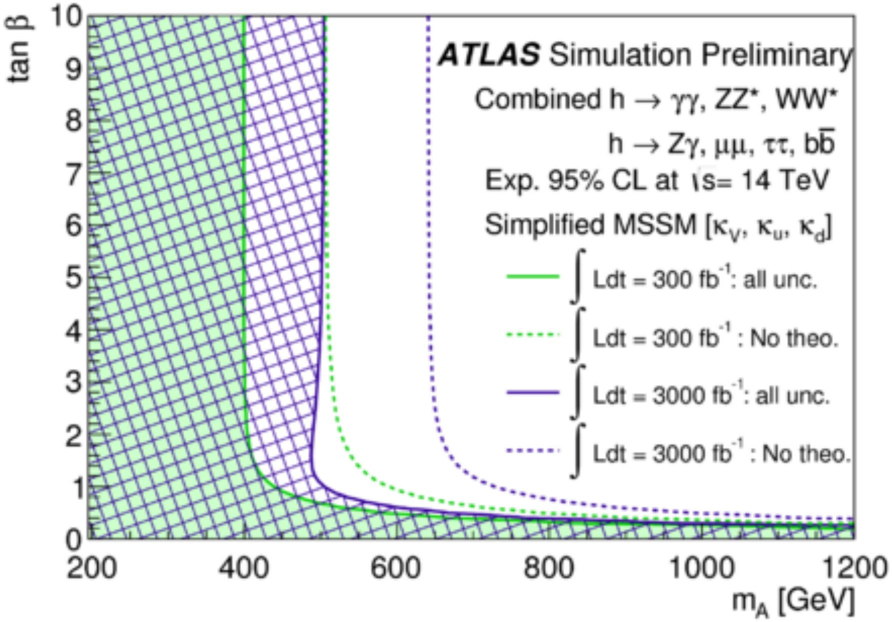
Model	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
MCHM4	620 GeV	810 GeV	710 GeV	980 GeV
MCHM5	780 GeV	950 GeV	1.0 TeV	1.2 TeV

Table 2: Expected 95% CL lower limit on the Higgs boson compositeness scale with 300 and 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV in the MCHM4 and MCHM5 models, each shown with and without the inclusion of theoretical uncertainties in the coupling measurements.

ATL-PHYS-PUB-2014-016

2HDM models

- Second Higgs doublet present in many BSM models
- Existence of 5 observable Higgs bosons
  - Two neutral scalar bosons: h and H (both CP-even)
  - One pseudo scalar boson, A (CP-odd)
  - Two charged bosons $H^{\pm}$
- For tan β > 2, expected limit of m_A > 500 GeV, with 3000 fb^{-1}



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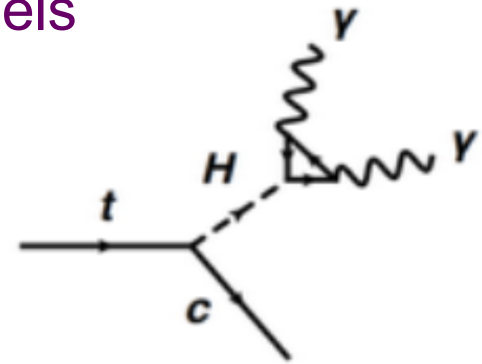
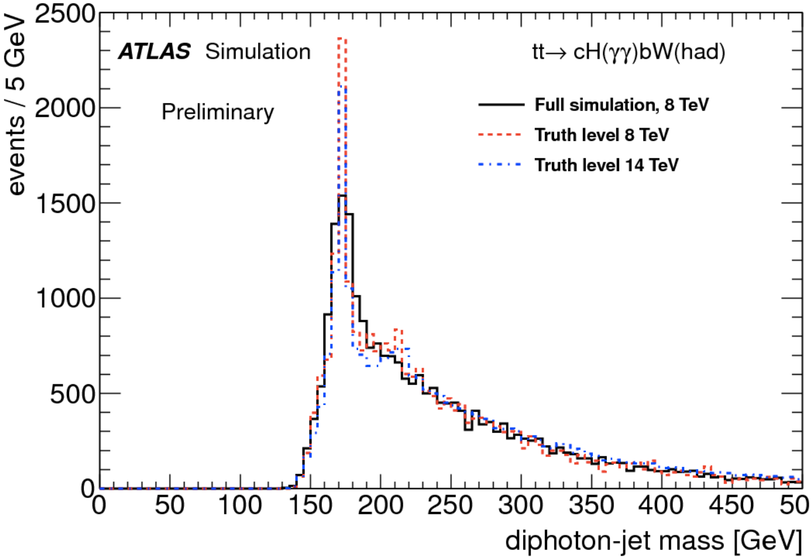
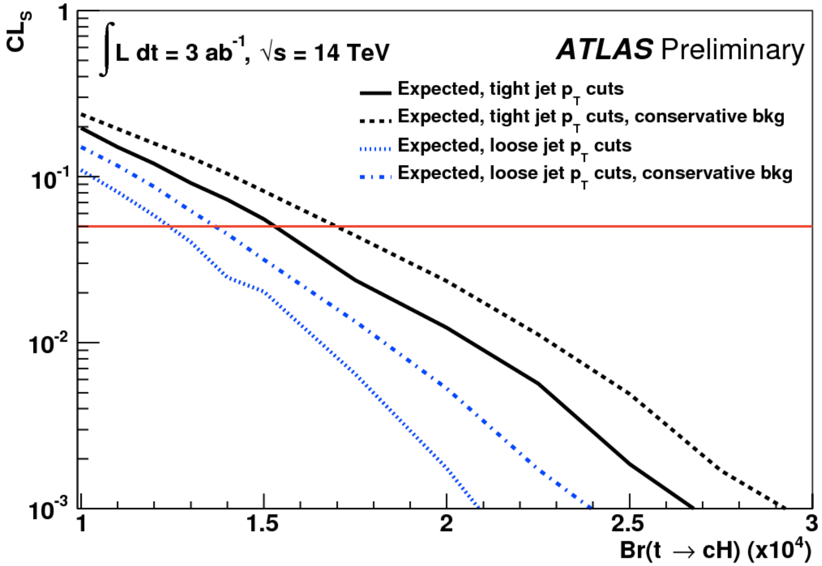
Flavour changing neutral currents

- t→cH can be O(10^{-3}) in some 2HDM-III models
- tt→(Wb)(Hc) is studied with H→γγ
  - Look for γγj (Hc) peak
  - Combine with Wb (W→lν / qq)



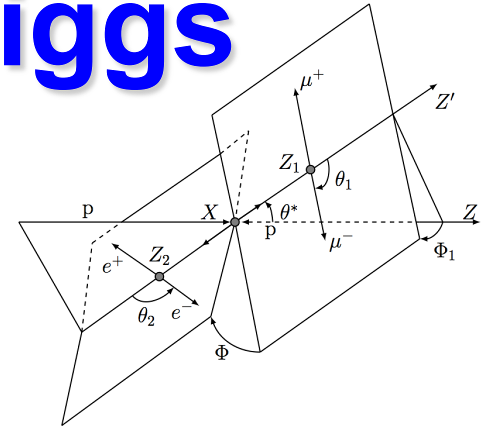
- Expected UL (95% cL) on BR ~ 1.5×10^{-4} ($3000 fb^{-1}$)

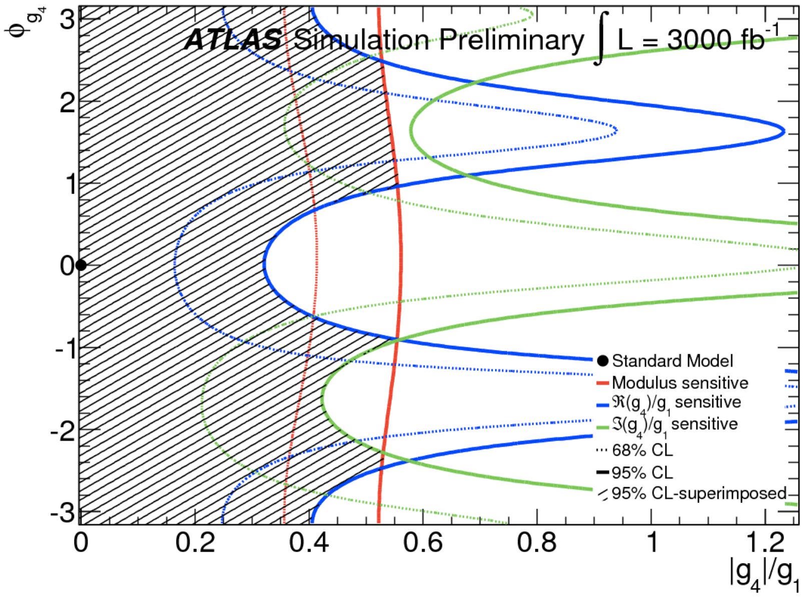


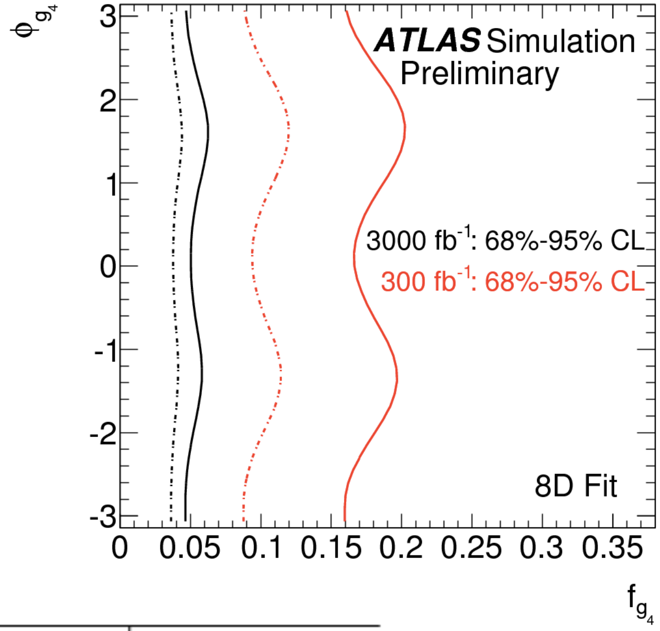


CP structure of the Higgs

- Analyse decay angles of H→ZZ decay angles using a matrix element observable fit
- CP-odd (CP-even) couplings: g_4 ($g_{1,}g_2$)
- Various injected single studies for 3000fb^{-1}







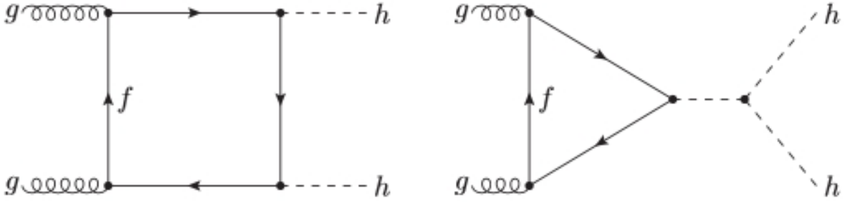
- Expected exclusions (95% CL)
  - Large gain with HL-LHC

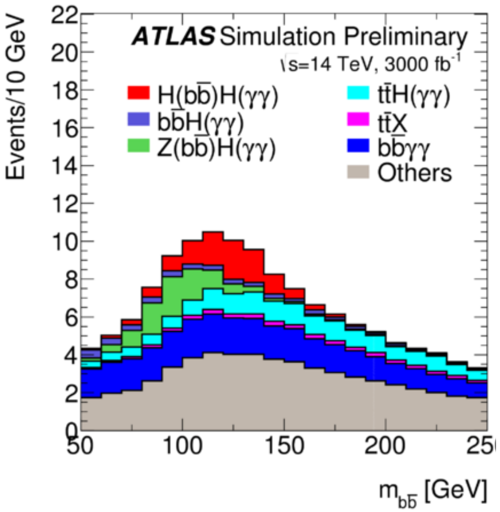
Luminosity	f_{g_4}	f_{g_2}
300 fb^{-1}	0.15	0.43
3000 fb^{-1}	0.037	0.20

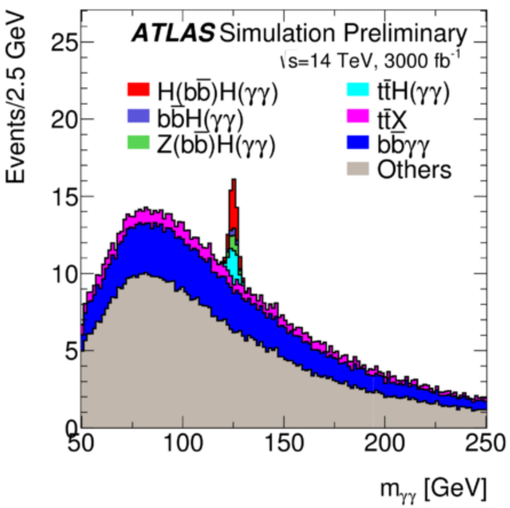
ATL-PHYS-PUB-2013-013

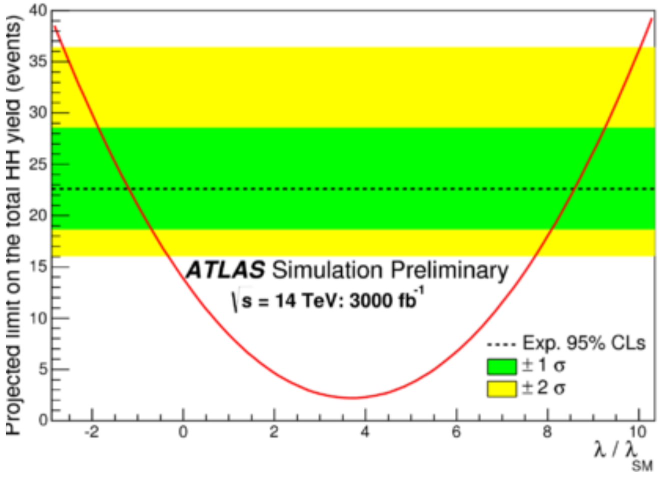
Di-Higgs production

- Direct measurement of Higgs trilinear self-coupling, $\lambda_{hhh,}$ requires the study of Higgs boson pair production
- Cross-section at $\sqrt{s}$ = 14 TeV is 40.8 fb^{-1} [NNLO]







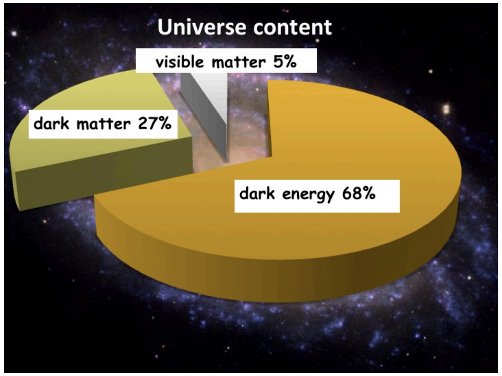


HH→ bbγγ: for $3000 fb^{-1}$ 8.4 signal & ~47 bkg. events ($S/\sqrt{B}$ ~ 1.3)

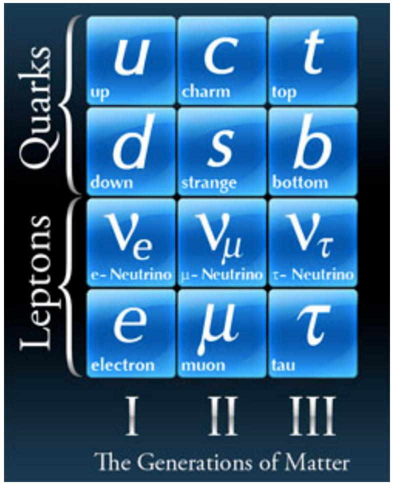
- Values: $\lambda/\lambda_{SM} < -1.3$ & $\lambda/\lambda_{SM} > 8.7$ can be rejected with 3000 fb^{-1}
- Need to combine with other channels (bbWW, bbττ, bbbb)

Unanswered questions beyond Higgs

- Hierarchy between Electroweak and Planck scale
- Why is the recently discovered Higgs boson so light?
- Are there SUSY or vector-like (top) quarks?
- What is the missing dark matter?



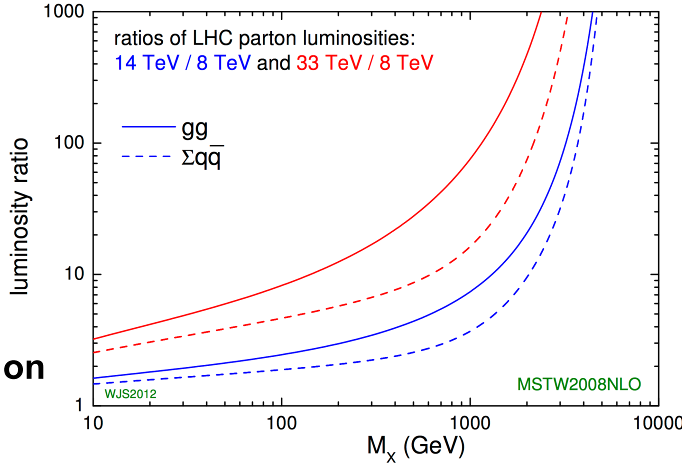
- Unification of forces, and are there other forces, do GUTs exist?
- Flavour: why are there three generations of fundamental particles
  - Lepto(n)-quark symmetry?
  - Composite leptons and quarks?
  - Fermion masses and mixing
- Matter-antimatter asymmetry



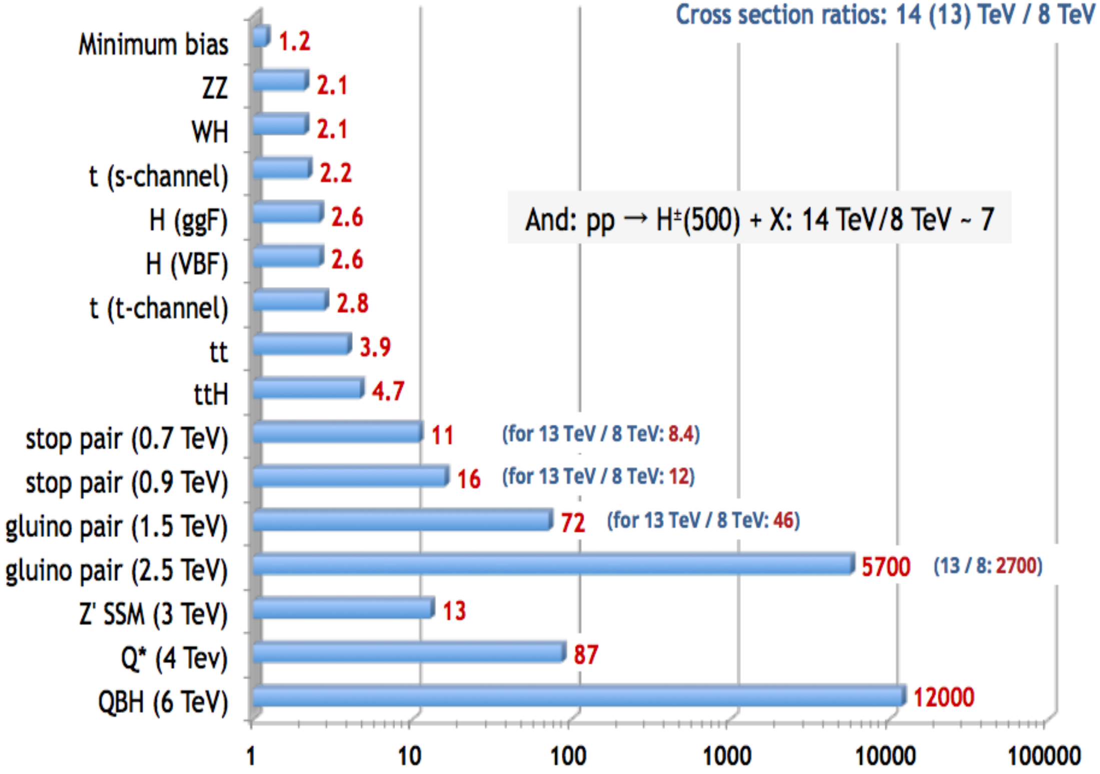
Running at 14 TeV

- Huge increase in discovery reach in multi-TeV region

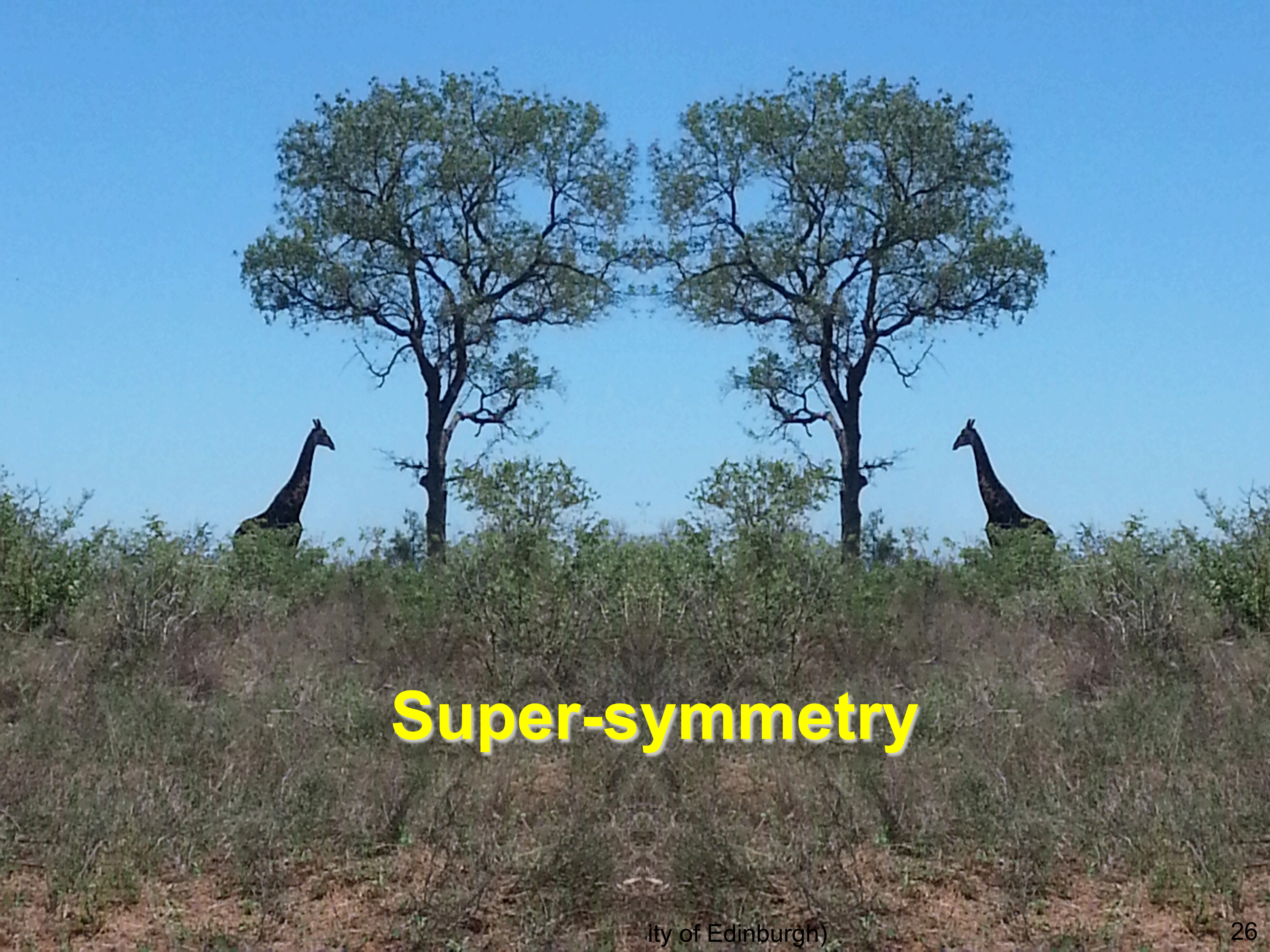
on



Cross section 14 TeV / 8 TeV	gg	Σqq̄
M_X = 2 TeV	~20	~10
M_X = 3 TeV	~70	~30
M_X = 4 TeV	~400	~160



- HL-LHC with 3000fb^{-1} at 14 Tev
  - Luminosity increase (x10) to benefit searches for new physics with lower production cross-sections
- What discoveries are possible only at the HL-LHC?

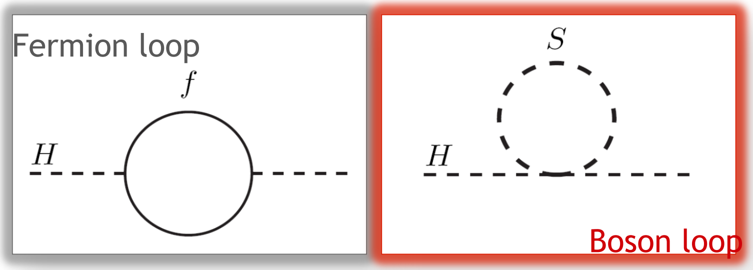


Super-symmetry

Supersymmetry (SUSY) in a nutshell

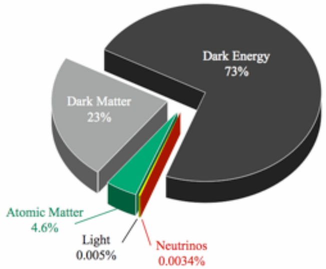
New spin-based symmetry relating fermions and bosons

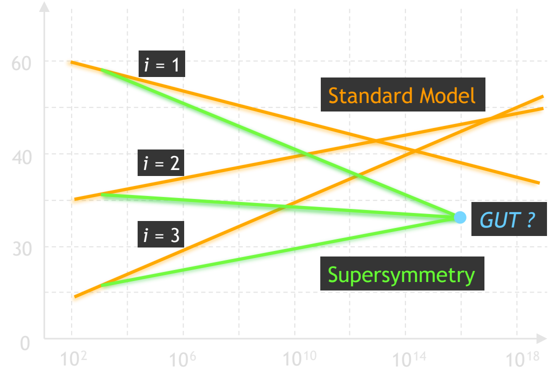
→ more than doubles the particle spectrum w.r.t. the Standard Model.



- **Naturally solves the gauge hierarchy problem**
  - Fermion and boson loops contribute with different signs to the Higgs radiative corrections.
- **SUSY with R-parity conservation predicts a suitable Dark Matter candidate**
  - R-parity = $(-1)^{3(B-L)+2S}$
  - Lightest SUSY particle (LSP) is stab
- **Grand unification of forces**
- **Predicts an elementary Higgs scalar …**
  - 'intriguing' SM-like limit

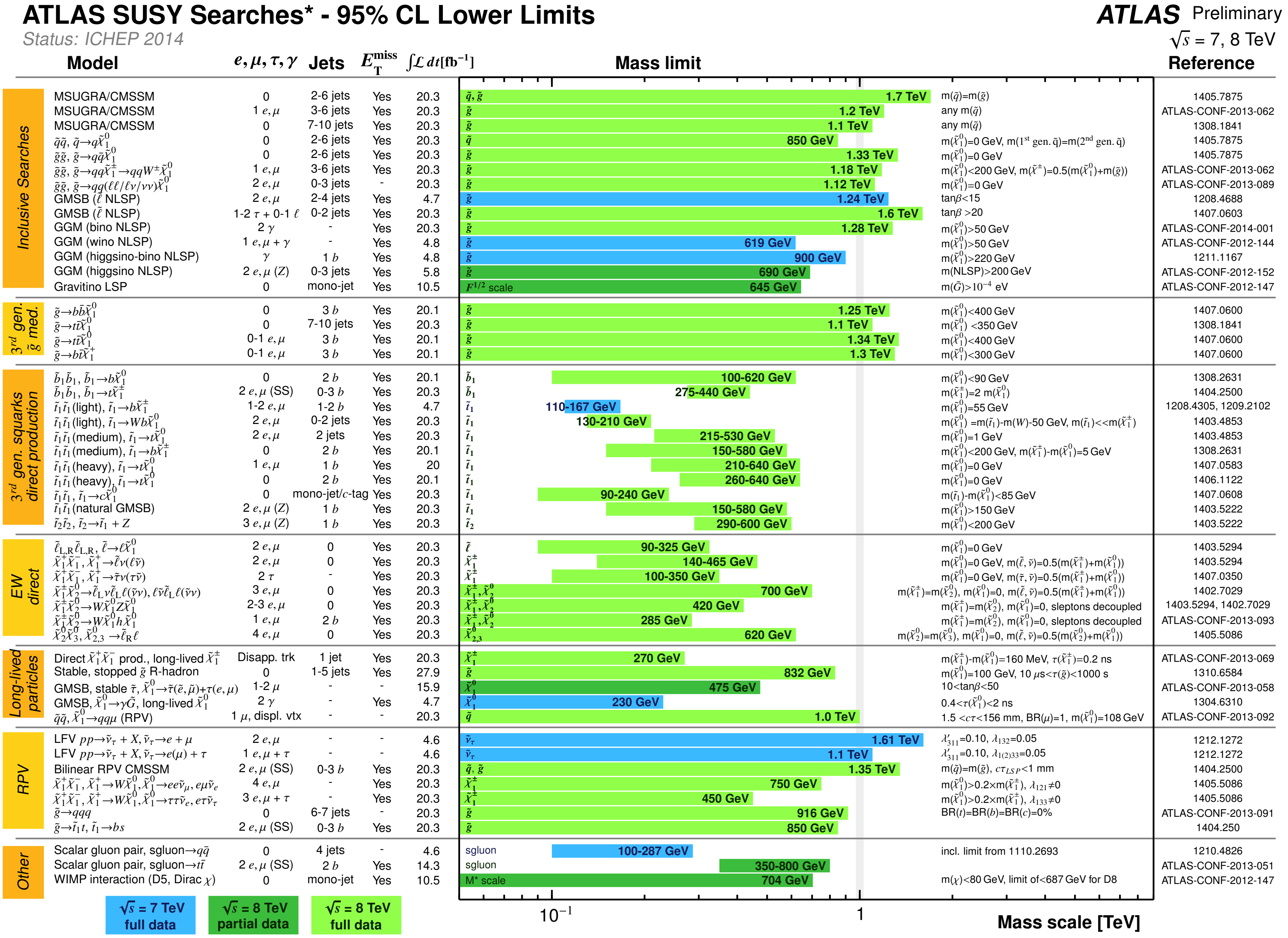
→ mass below 135 GeV (in the MSSM)





SUSY widely considered to remain very important amongst BSM proposals - although the most simplistic versions tightly constrained by experimental results!

Current SUSY exclusions



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

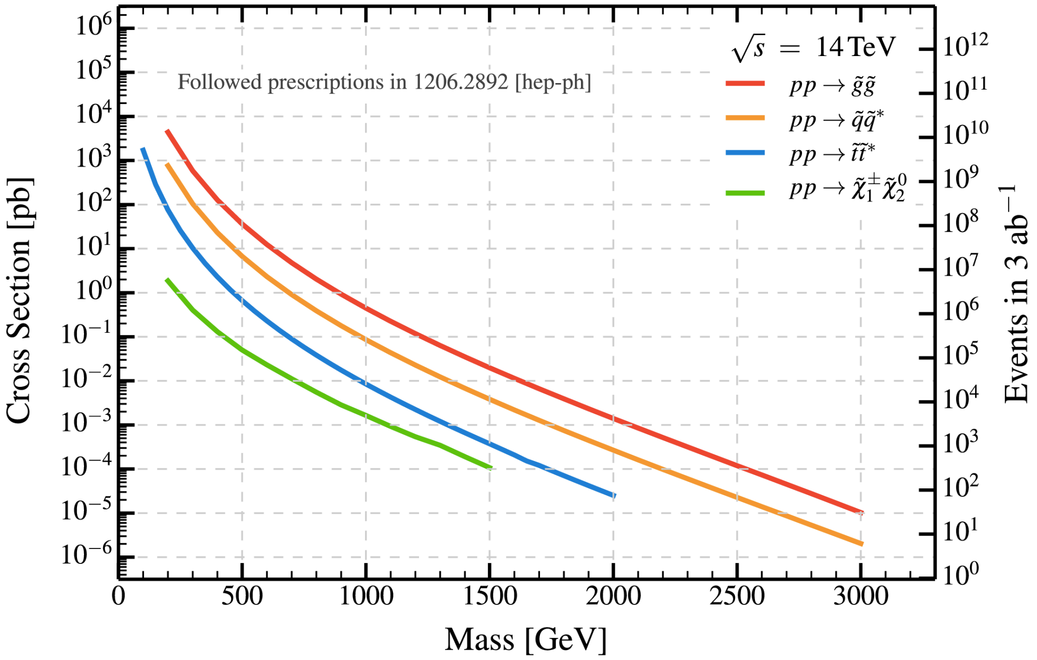
$\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$		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($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e,μ	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
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1^{st} gen. q̃)=m(2^{nd} gen. q̃)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	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
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	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,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	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)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m(NLSP)>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.	$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	1-2 e,μ	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), $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$	2 e,μ	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), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	2 e,μ	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), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	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), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$	210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$	260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{\text{L,R}}\tilde{\ell}_{\text{L,R}}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_{\text{L}}\nu\tilde{\ell}_{\text{L}}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_{\text{L}}\ell(\tilde{\nu}\nu)$	3 e,μ	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	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
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\rightarrow\tilde{\ell}_{\text{R}}\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
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, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\rightarrow qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\rightarrow\tilde{t}_1t$, $\tilde{t}_1\rightarrow bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\rightarrow q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\rightarrow t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

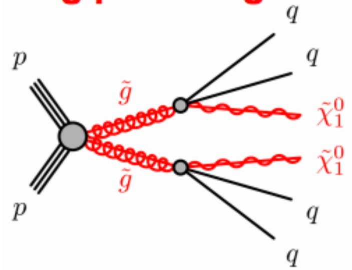
SUSY @ the end of Run 1

- Most simplistic version of SUSY under stress
    - Partially true for ‘Natural’ SUSY, although depends *e.g.* on level of fine-tuning
- Still, lot of open suitable scenarios. A few examples:
    - Generic SUSY models explaining higgs mass indicate top squarks up the TeV range → not yet fully covered
        - If there are such ‘light’ stops, gluinos might be in the 2-3 TeV range → not yet reached
    - Decays of sparticle in most of SUSY models are complex:
        - Limitations on our limits: often valid only if a sparticle decays 100% in one mode
    - High scalar masses (O(10 TeV)) foreseen in several models (e.g. Split SUSY)
        - Focus on EWK sector, where boundaries are less stringent
    - More on the EWK sector: Low higgsino mass scenarios lead to “compressed” SUSY spectra (low ΔM Next-LSP – LSP) → difficult to corner because of low cross sections + low acceptances
    - R-parity violation scenarios not fully covered:
        - Lack of handles such as missing transverse momentum, complex phenomenology, possibly long-lived particles

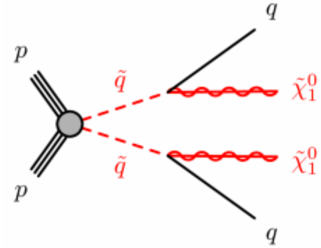
Production and search strategy



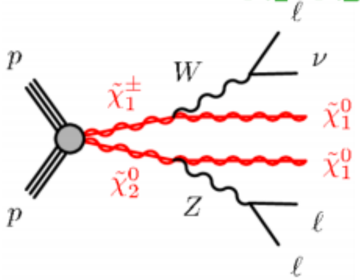
Strong prod. of gluinos



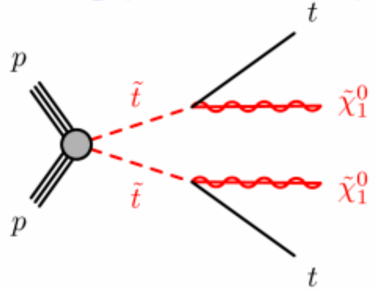
Strong prod. of squarks



EW prod. of $\chi_1^+\chi_2^0$



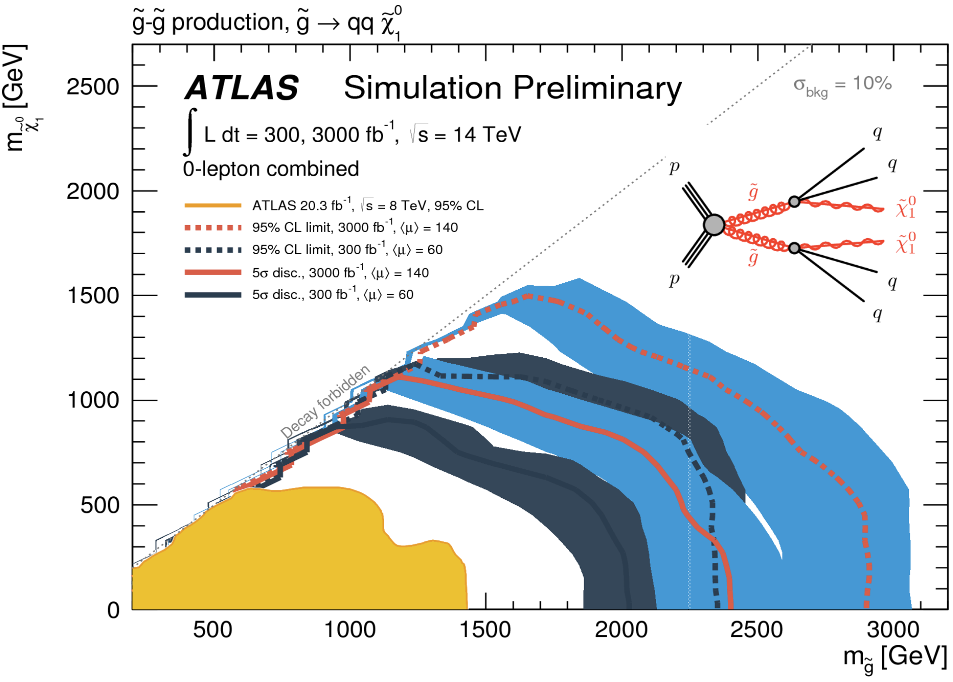
Strong prod. of stops

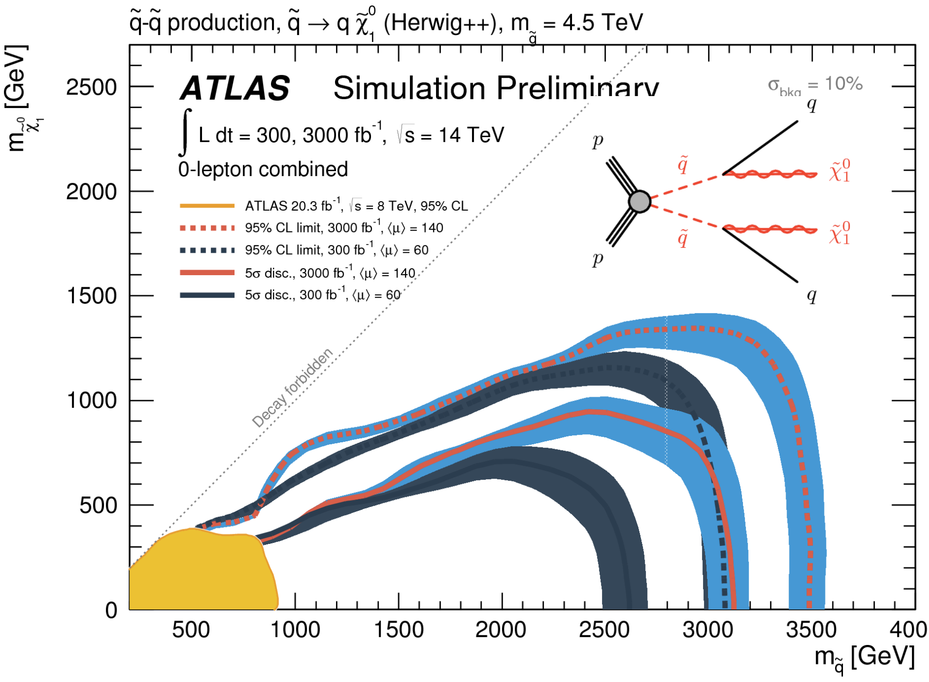


Mass constraints strongly depend on the assumed SUSY mass spectrum

Strong production of gluinos/squarks

- Largest cross-sections: ~ 1fb^{-1} for masses around 2 TeV
  - 0 lepton + 2 - 6jets + E_t^{miss}



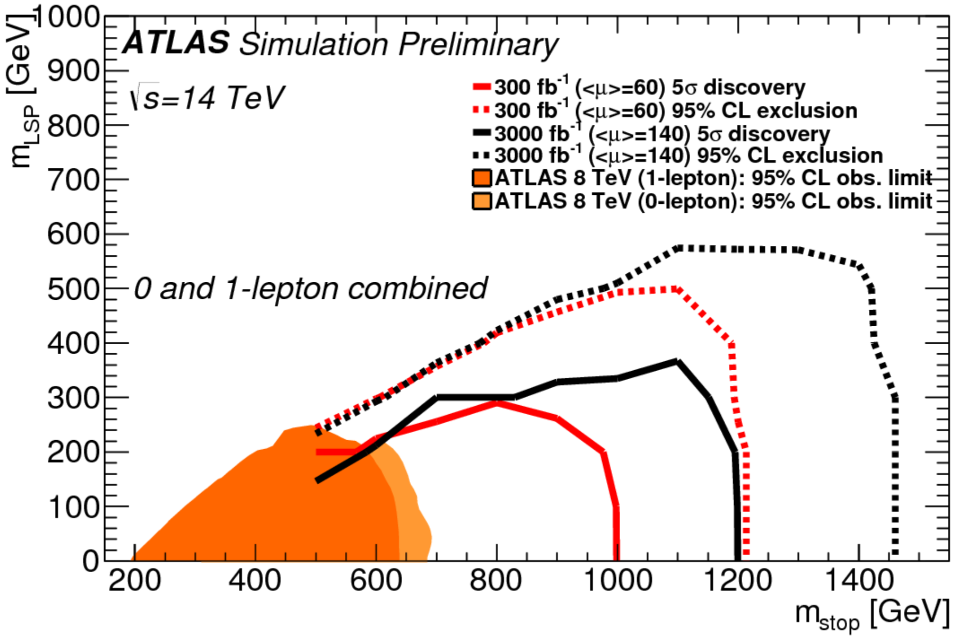


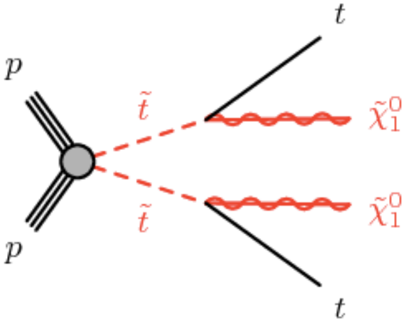
5σ discovery simplified model	300 fb^{-1}	3000 fb^{-1}
Gluino mass	up to 2.0 TeV	up to 2.4 TeV
Squark mass for M(gl) = 4.5 TeV	up to 2.6 TeV	up to 3.1 TeV

ATL-PHYS-PUB-2014-010

Strong production of top squarks

- Naturalness: requires stop mass < ~ 1 TeV
  - ➢ Direct production, feasibility studies only for standard cases (t+LSP)
  - ➢ 0/1 lepton + ≥ 6/4 jets + ≥ 2/1 b-tags + E_T^{miss}





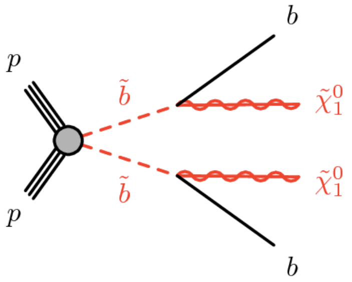
- 5σ discovery potential up to 1.2 (1.0) TeV with 3000 (300) fb^{-1}

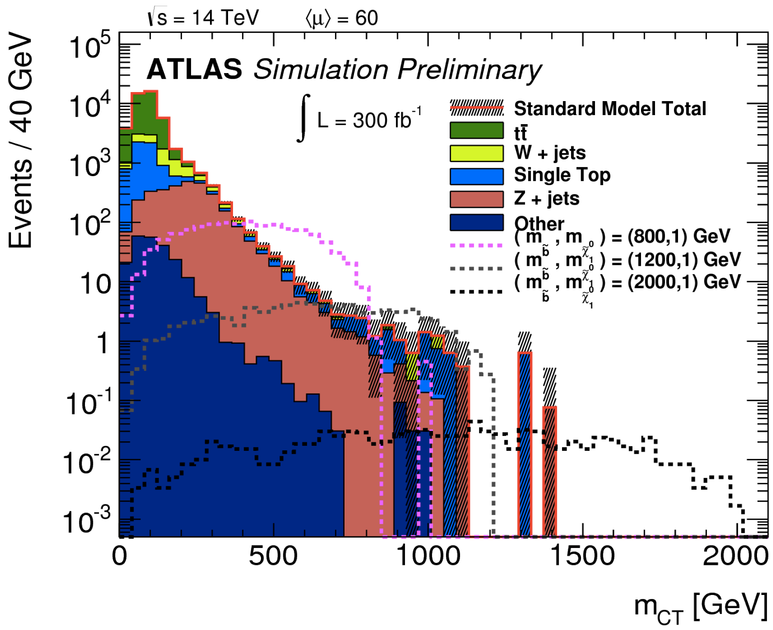
ATL-PHYS-PUB-2013-011

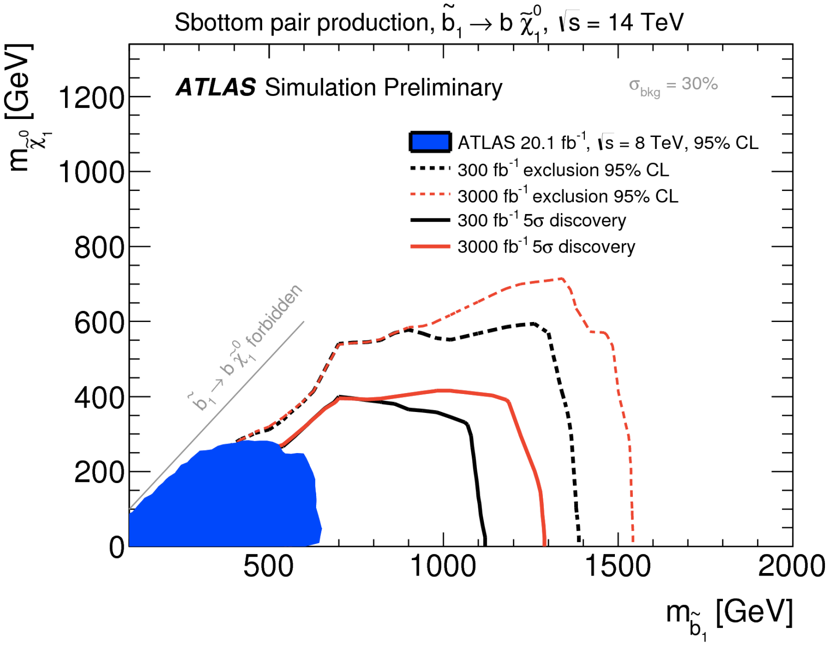
Strong production of bottom squarks

- Third generation quarks need to be light to solve hierachy problem
  - Direct production, feasibility studies only for standard case (b+LSP)
  - 0 lepton + 2 b-tags + E_T^{miss}
  - Uses boost-corrected contransverse mass, m_{CT}, to reduce tt background

$$m_{CT}^{max} = \frac{m^2(\tilde{b}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{b})}$$







- 5σ discovery potential up to 1.3 (1.1) TeV with 3000 (300) fb^{-1}

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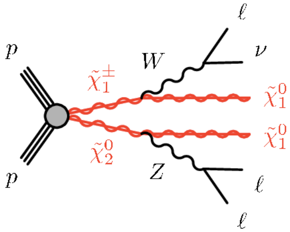
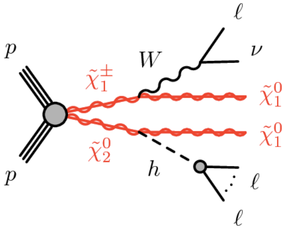
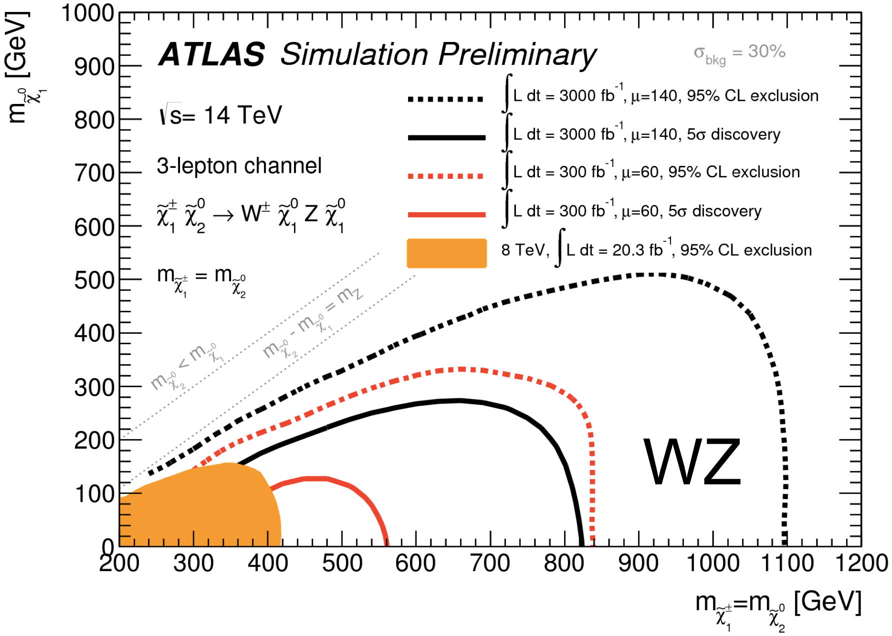
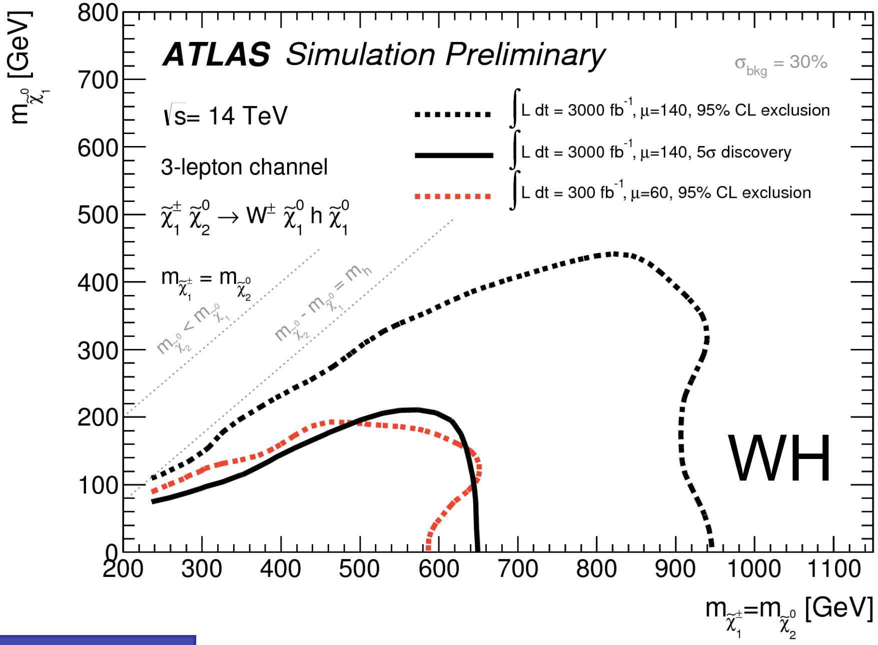
Electroweak production of $\chi_1^+\chi_2^0$

- EW production is 2 orders of magnitude lower, but can dominate if squarks and gluinos are heavy
  - ➢ WZ/H: 3 leptons + E_t^{miss}
  - ➢ Assume $m(\chi_1^+) = m(\chi_2^0)$









Chargino/neutralino mass 5σ discovery simplified model	**300 fb^{-1}**	**3000fb^{-1}**
WZ	Up to 560 GeV	Up to 820 GeV
WH		Up to 650 GeV

H→ lepton final states only, can be improved with H→bb

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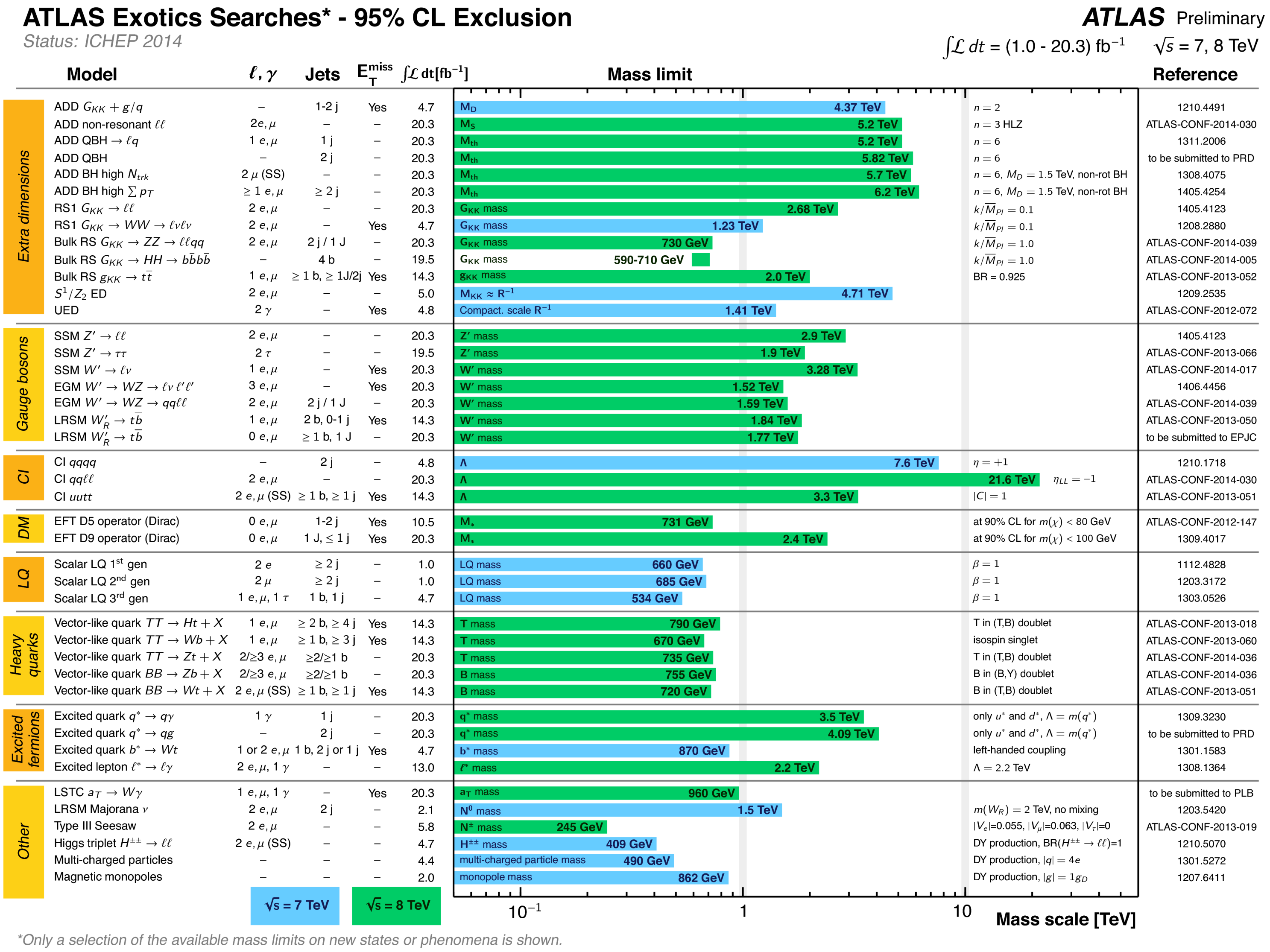
Exotics

Current limits on exotics



ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

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

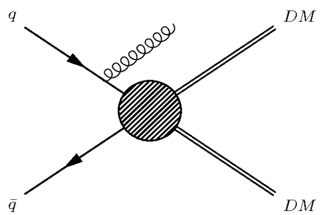
	Model	ℓ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit			Reference
Extra dimensions	ADD $G_{KK}+g/q$	–	1-2 j	Yes	4.7	🟦 M_D	4.37 TeV	$n=2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e,\mu$	–	–	20.3	🟩 M_S	5.2 TeV	$n=3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\rightarrow\ell q$	1 e,μ	1 j	–	20.3	🟩 M_{th}	5.2 TeV	$n=6$	1311.2006
	ADD QBH	–	2 j	–	20.3	🟩 M_{th}	5.82 TeV	$n=6$	to be submitted to PRD
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	🟩 M_{th}	5.7 TeV	$n=6$, $M_D=1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	20.3	🟩 M_{th}	6.2 TeV	$n=6$, $M_D=1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK}\rightarrow\ell\ell$	2 e,μ	–	–	20.3	🟩 G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl}=0.1$	1405.4123
	RS1 $G_{KK}\rightarrow WW\rightarrow\ell\nu\ell\nu$	2 e,μ	–	Yes	4.7	🟦 G_{KK} mass	1.23 TeV	$k/\overline{M}_{Pl}=0.1$	1208.2880
	Bulk RS $G_{KK}\rightarrow ZZ\rightarrow\ell\ell qq$	2 e,μ	2 j / 1 J	–	20.3	🟩 G_{KK} mass	730 GeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK}\rightarrow HH\rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	🟩 G_{KK} mass	590-710 GeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK}\rightarrow t\bar{t}$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	14.3	🟩 g_{KK} mass	2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	2 e,μ	–	–	5.0	🟦 $M_{KK}\approx R^{-1}$	4.71 TeV		1209.2535
	UED	2 γ	–	Yes	4.8	🟦 Compact. scale R^{-1}	1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z'\rightarrow\ell\ell$	2 e,μ	–	–	20.3	🟩 Z' mass	2.9 TeV		1405.4123
	SSM $Z'\rightarrow\tau\tau$	2 τ	–	–	19.5	🟩 Z' mass	1.9 TeV		ATLAS-CONF-2013-066
	SSM $W'\rightarrow\ell\nu$	1 e,μ	–	Yes	20.3	🟩 W' mass	3.28 TeV		ATLAS-CONF-2014-017
	EGM $W'\rightarrow WZ\rightarrow\ell\nu\,\ell'\ell'$	3 e,μ	–	Yes	20.3	🟩 W' mass	1.52 TeV		1406.4456
	EGM $W'\rightarrow WZ\rightarrow qq\ell\ell$	2 e,μ	2 j / 1 J	–	20.3	🟩 W' mass	1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R\rightarrow t\bar{b}$	1 e,μ	2 b, 0-1 j	Yes	14.3	🟩 W' mass	1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R\rightarrow t\bar{b}$	0 e,μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass	1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	🟦 Λ	7.6 TeV	$\eta=+1$	1210.1718
	CI $qq\ell\ell$	2 e,μ	–	–	20.3	🟩 Λ	21.6 TeV	$\eta_{LL}=-1$	ATLAS-CONF-2014-030
	CI $uutt$	2 e,μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 Λ	3.3 TeV	$\lvert C\rvert=1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	0 e,μ	1-2 j	Yes	10.5	🟩 M_*	731 GeV	at 90% CL for $m(\chi)<80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	0 e,μ	1 J, ≤ 1 j	Yes	20.3	🟩 M_*	2.4 TeV	at 90% CL for $m(\chi)<100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	🟦 LQ mass	660 GeV	$\beta=1$	1112.4828
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	🟦 LQ mass	685 GeV	$\beta=1$	1203.3172
	Scalar LQ 3rd gen	1 e,μ, 1 τ	1 b, 1 j	–	4.7	🟦 LQ mass	534 GeV	$\beta=1$	1303.0526
Heavy quarks	Vector-like quark $TT\rightarrow Ht+X$	1 e,μ	≥ 2 b, ≥ 4 j	Yes	14.3	🟩 T mass	790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT\rightarrow Wb+X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	14.3	🟩 T mass	670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT\rightarrow Zt+X$	2/$\geq$3 e,μ	$\geq$2/$\geq$1 b	–	20.3	🟩 T mass	735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB\rightarrow Zb+X$	2/$\geq$3 e,μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass	755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB\rightarrow Wt+X$	2 e,μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 B mass	720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^*\rightarrow q\gamma$	1 γ	1 j	–	20.3	🟩 q^* mass	3.5 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1309.3230
	Excited quark $q^*\rightarrow qg$	–	2 j	–	20.3	🟩 q^* mass	4.09 TeV	only u^* and d^*, $\Lambda=m(q^*)$	to be submitted to PRD
	Excited quark $b^*\rightarrow Wt$	1 or 2 e,μ	1 b, 2 j or 1 j	Yes	4.7	🟦 b^* mass	870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^*\rightarrow\ell\gamma$	2 e,μ, 1 γ	–	–	13.0	🟩 ℓ^* mass	2.2 TeV	$\Lambda=2.2$ TeV	1308.1364
Other	LSTC $a_T\rightarrow W\gamma$	1 e,μ, 1 γ	–	Yes	20.3	🟩 a_T mass	960 GeV		to be submitted to PLB
	LRSM Majorana ν	2 e,μ	2 j	–	2.1	🟦 N^0 mass	1.5 TeV	$m(W_R)=2$ TeV, no mixing	1203.5420
	Type III Seesaw	2 e,μ	–	–	5.8	🟩 $N^\pm$ mass	245 GeV	$\lvert V_e\rvert$=0.055, $\lvert V_\mu\rvert$=0.063, $\lvert V_\tau\rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm}\rightarrow\ell\ell$	2 e,μ (SS)	–	–	4.7	🟦 $H^{\pm\pm}$ mass	409 GeV	DY production, BR($H^{\pm\pm}\rightarrow\ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	🟦 multi-charged particle mass	490 GeV	DY production, $\lvert q\rvert=4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	🟦 monopole mass	862 GeV	DY production, $\lvert g\rvert=1g_D$	1207.6411

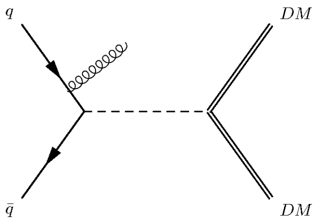
🟦 $\sqrt{s}$ = 7 TeV

🟩 $\sqrt{s}$ = 8 TeV

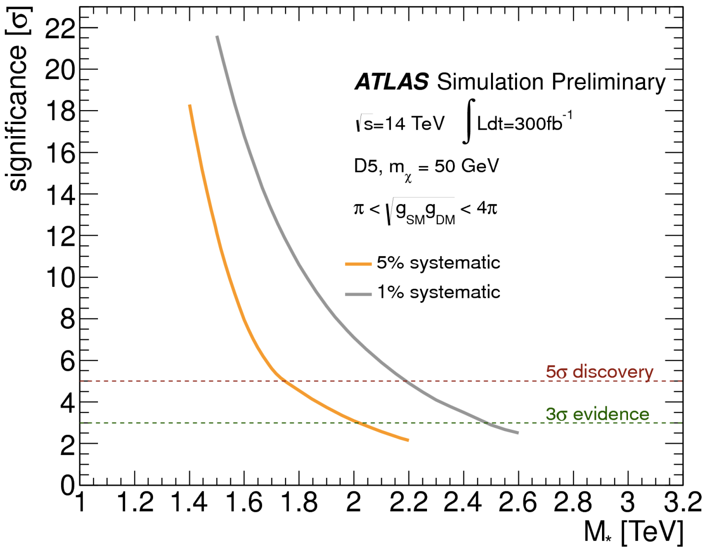
**Only a selection of the available mass limits on new states or phenomena is shown.*

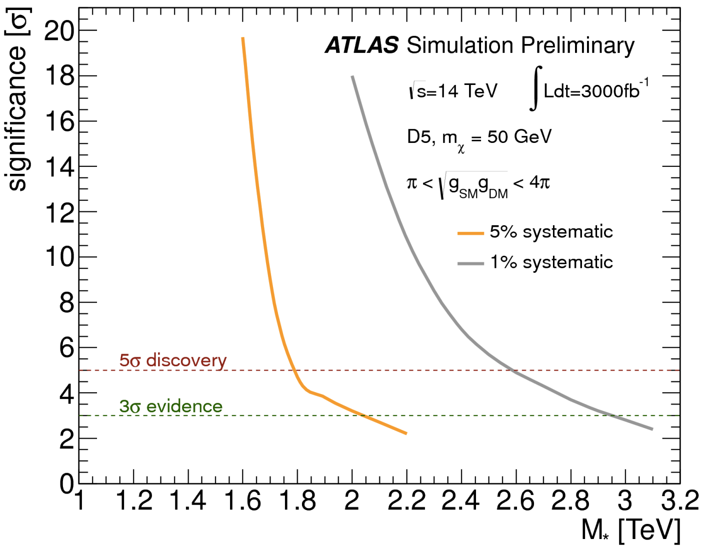
Dark matter





- Models
  - ➢ Effective field theory
    (contact interaction between SM and DM particles)
  - ➢ Simplified models with explicit mediator
- Signatures ("mono-X")
  - ➢ Initial state radiation
  - ➢ High-p_T leading jet (≤ 2 jets), large E_t^{miss}, e/μ veto





- Prospects
  - ➢ 5σ discovery up to $M^* = 2.6(2.2)$ TeV for 3000(300) fb^{-1}

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Dilepton resonances

- Many theories beyond the SM predict new resonances
  - Heavy gauge bosons W' and Z'
  - Kaluza-Klein excitations of vector bosons

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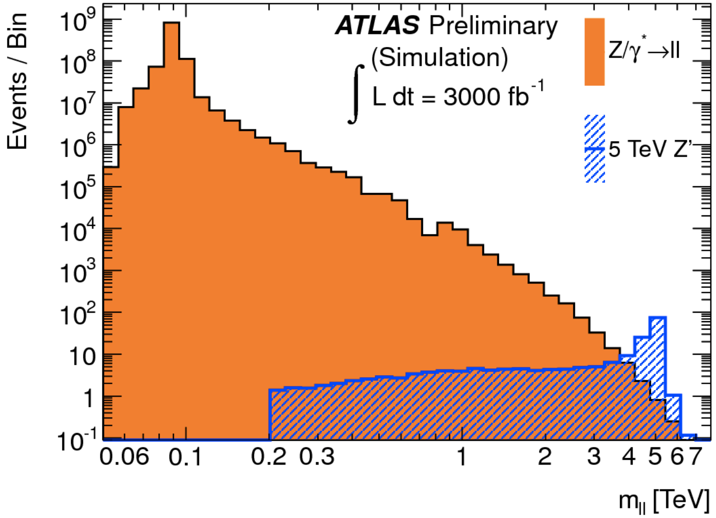
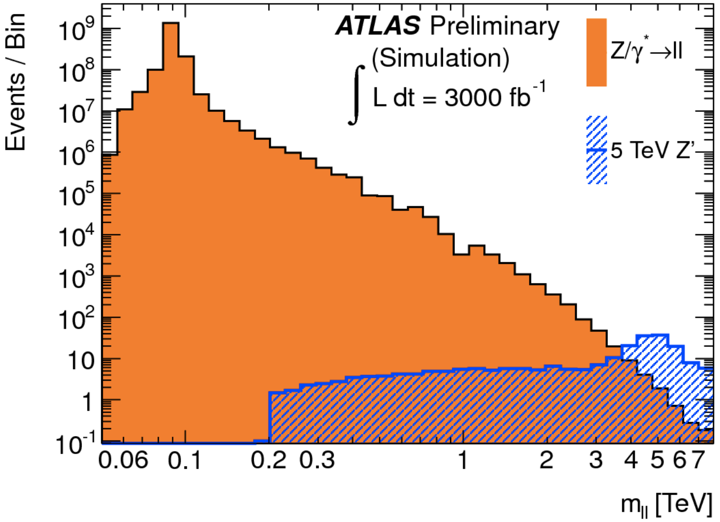
- Signatures are very clean
  - $Z' \rightarrow e^+e^-$

$Z' \rightarrow \mu^+\mu^-$



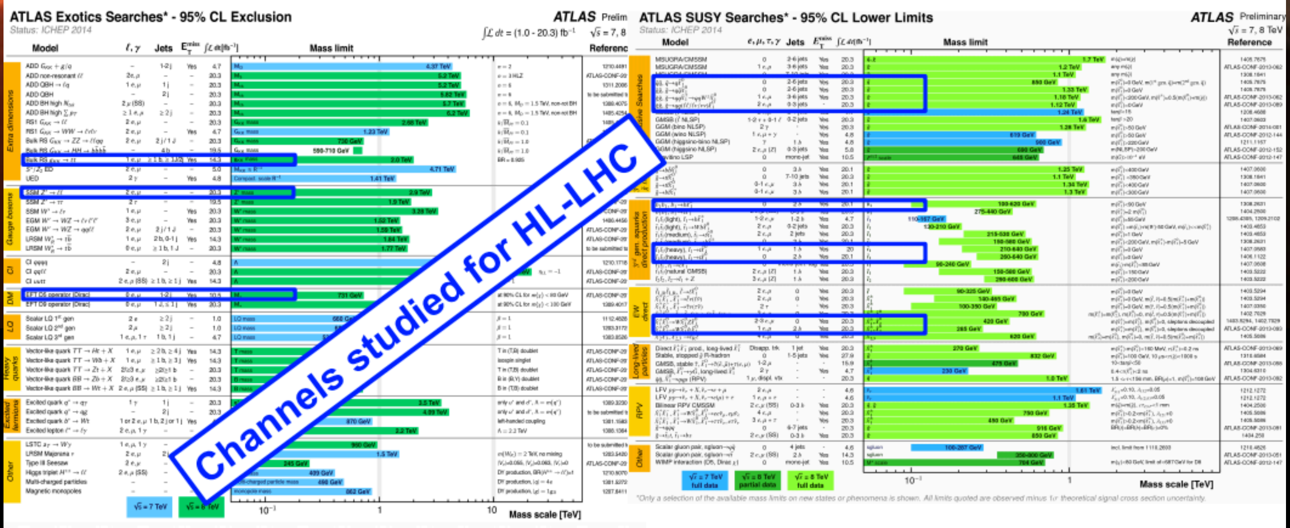


Z' mass lower limit @ 95% CL in SSM [ATLAS]	**Run 1 @ 8 TeV (20 fb^{-1})**	**Run 3 @ 14 TeV (300 fb^{-1})**	**HL-LHC @ 14 TeV (3000 fb^{-1})**
Z' mass (ee)	Up to 2.79 TeV	Up to 6.5 TeV	Up to 7.8 TeV
Z' mass (μμ)	Up to 2.53 TeV	Up to 6.4 TeV	Up to 7.6 TeV

No systematic uncertainties included

Conclusions

- The HL-LHC is necessary to perform precision measurements on the recently discovered Higgs boson
- HL-LHC extends the discovery reach in theoretically motivated areas
- Wide range of signatures and models explored
  - ➢ But this only a small fraction of the full ATLAS physics program!!!



ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

Channels studied for HL-LHC

- The HL-LHC could answer fundamental questions regarding EWSB and dark matter