ATLAS Physics Prospects at the High Luminosity LHC
ICNFP, Kolymbari, Greece

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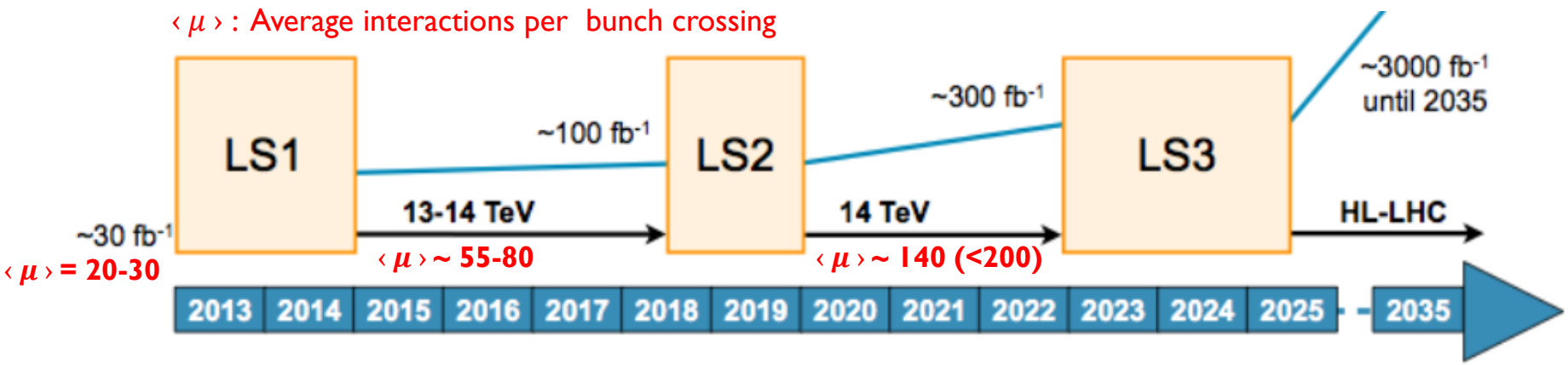
July 28- Aug6, 2014

Outline

- Introduction
  - Upgrades Overview
  - Open Standard Model (SM) Questions
- Higgs Prospects
- SUSY Prospects
- Exotics Prospects
- Conclusion

Introduction: Upgrades Overview



ICHEP

ATLAS Phase-0

Upgrades to Tracking, small detector improvements

ATLAS Phase-1

Trigger improvements to deal with higher rates

ATLAS Phase-1

New higher granularity, more radiation hard Inner Tracker. New Trigger scheme. Muon/calorimeter electronics upgrades

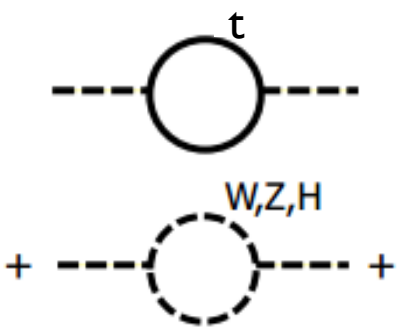
Many more interactions for each bunch crossing in the future! Challenge to reconstruct objects with same accuracy. Nonetheless we assume detector will keep current performance due to hardware/software upgrades. Most treatment of systematics is based on Run1

See Atlas Upgrades by T. Alexopoulos

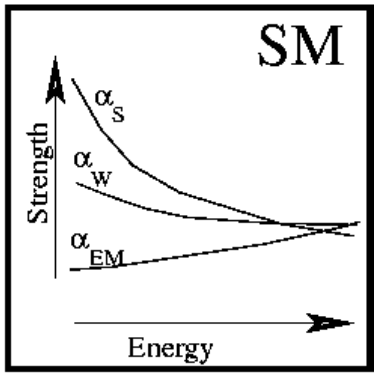
Introduction: Open SM Questions

- Got the Higgs: last piece of the Standard Model (SM)
- Now what? SM does not explain

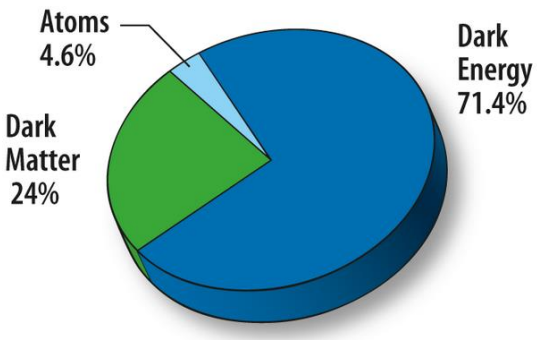
Why do the corrections to Higgs mass blow up at loop level?



Why don't the EM, weak and strong coupling constant unify?



What is Dark Matter/Energy? Why is the universe expanding at an accelerating rate?



Why is there more matter than antimatter?

Why doesn't QCD break CP symmetry?

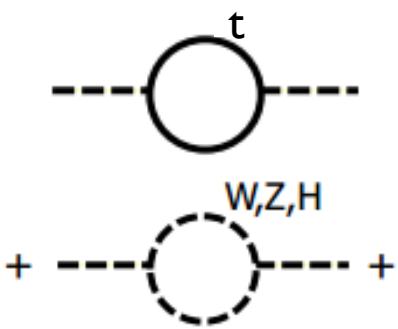
Why is gravity not included, and why is it so weak?

Introduction: Open SM Questions

- Got the Higgs: last piece of the Standard Model (SM)
- Now what? SM does not explain

A few ways to solve this

Why do the corrections to Higgs mass blow up at loop level?



Supersymmetry, Composite-Higgs, vector-like quarks

Why is there more matter than antimatter?

Baryongenesis

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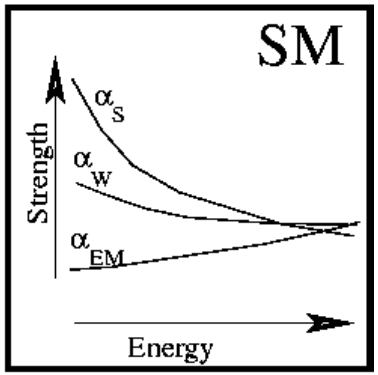

Grand Unified Theories (GUT)

Why doesn't QCD break CP symmetry?

Axions Models

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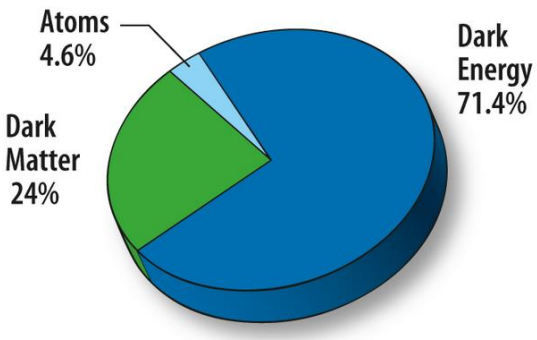


Theories of Everything (ToF) (String Theory)

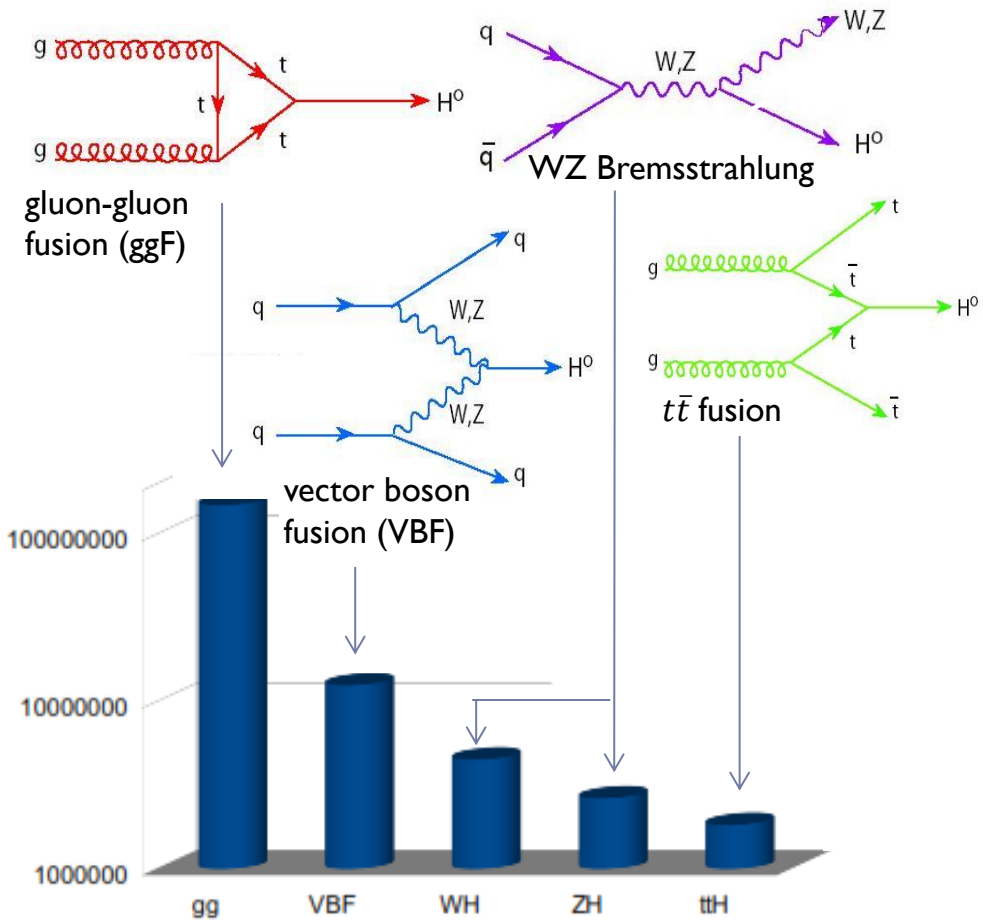
Why is gravity not included, and why is it so weak?

Extra dimensions , quantum loop gravity

Higgs Prospects

Higgs Factory HL-LHC

How do we make Higgs at LHC?



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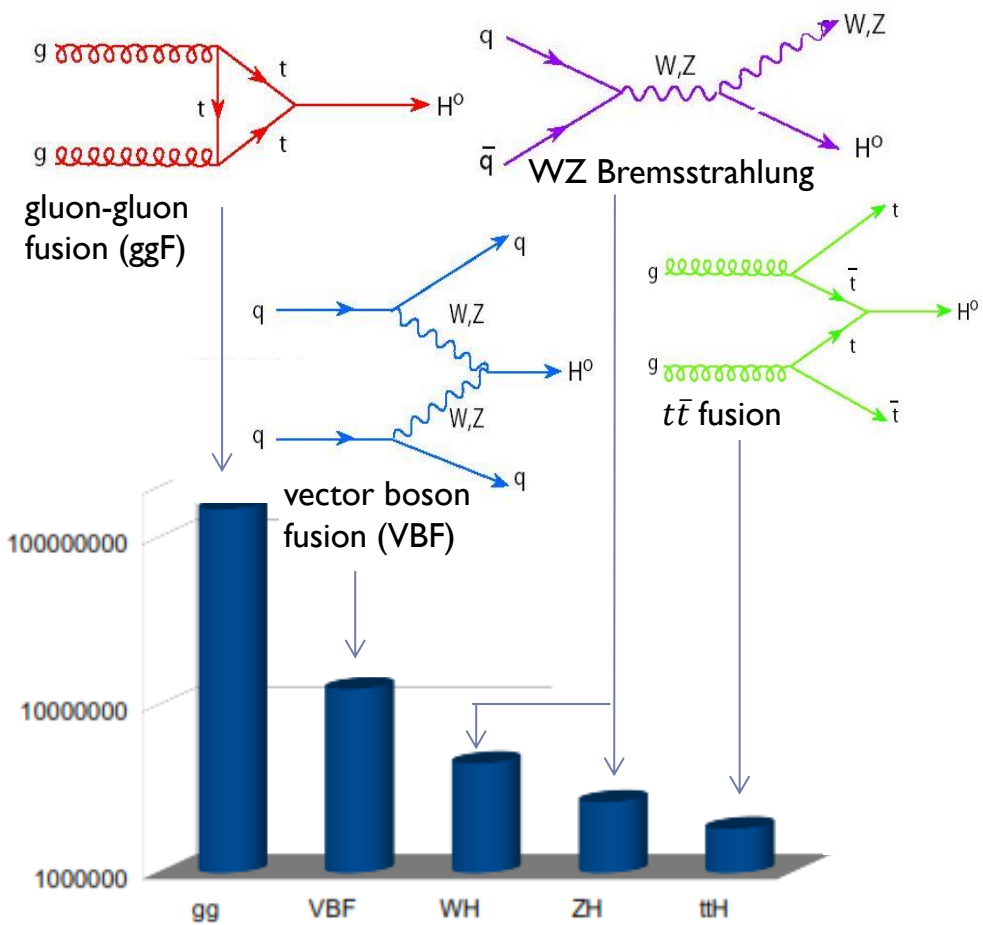
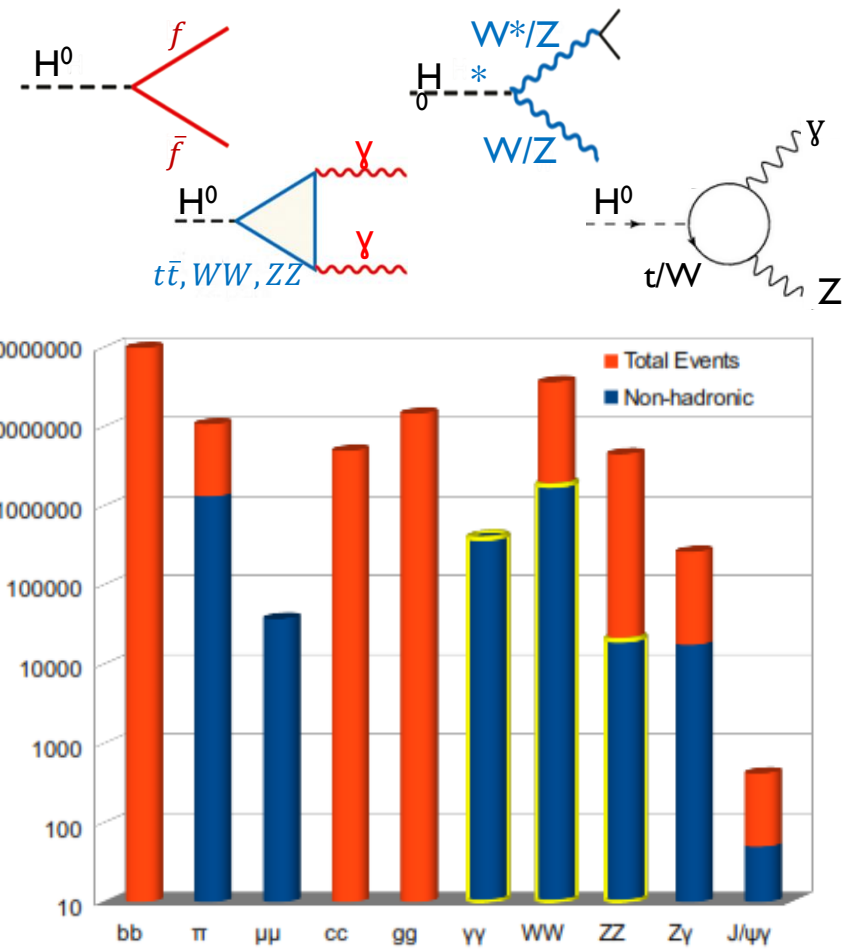


What does H decay to?



Projections for Current Analyses

- Most channels include all production modes (H →WW missing ttH, and H→$b\bar{b}$ is VH only). Mostly leptonic decays considered.

Signal Strength, $\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$

Significance : Z , excess of events wrt background-only hypothesis

Process	Value	Now	300fb^{-1}	3000fb^{-1}
H→γγ	$\Delta\mu/\mu$	20%	--	<10%
H→ZZ→ 4ℓ	$\Delta\mu/\mu$	27%	15%	13%
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H→ττ→ 2ℓ 4ν / $\ell\tau_{had}$+ 3ν	Z	4.1σ	6.9σ	--
	$\Delta\mu/\mu$	31%	15%	--
H→$b\bar{b}$	Z	0	3.9σ	8.8σ
	$\Delta\mu/\mu$	100%	25%	14%

ATL-PHYS-PUB-2013-014, ATL-PHYS-PUB-2014-011 ,ATLAS-CONF-2013-079, CERN-PH-EP-2013-103,ATL-PHYS-PUB-2014-012

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Factor of ~ 2 improvement at HL-LHC in $\Delta\mu/\mu$

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Sensitive to see H→ bb already at 300 fb $^{-1}$

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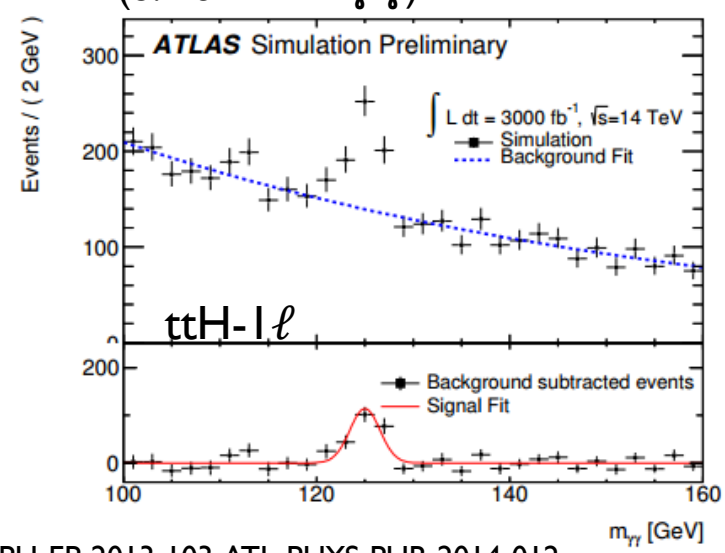
In ttH , can measure the large Yukawa coupling of Higgs to top (8.2 σ in H→γ γ)



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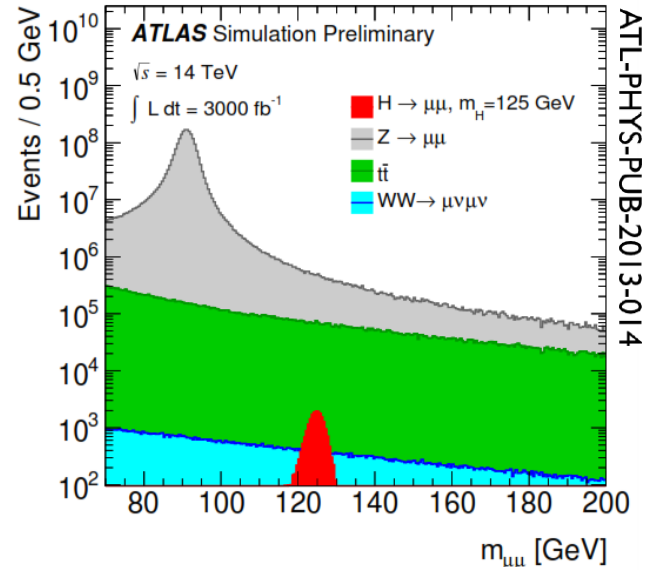
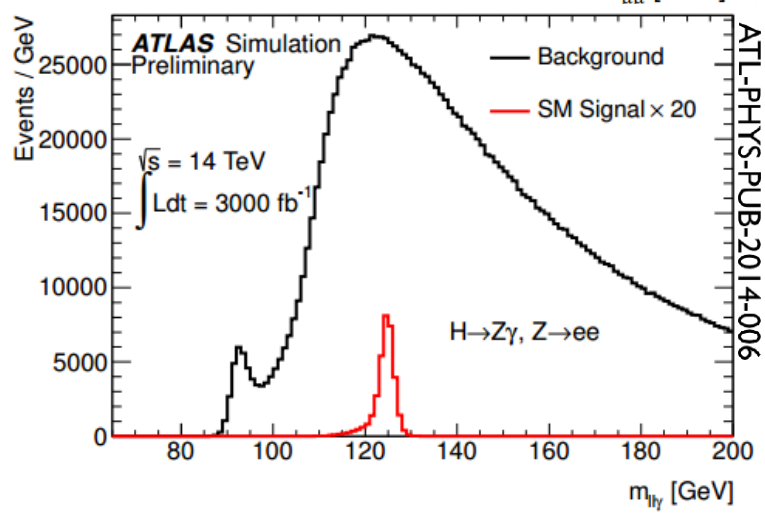
New Higgs Searches within Reach

- H→μμ, (ggF,VBF,VH, ttH)
  - Can probe couplings to 2nd generation fermions!
  - Significance of 7σ, and $\Delta\mu/\mu$ of 21% at 3000 fb^{-1}



- H →Zγ (ggF,VBF)
  - Sensitive to new particles in loop
  - Significance of 3.9 σ, and $\Delta\mu/\mu$ of 30% at 3000 fb^{-1}

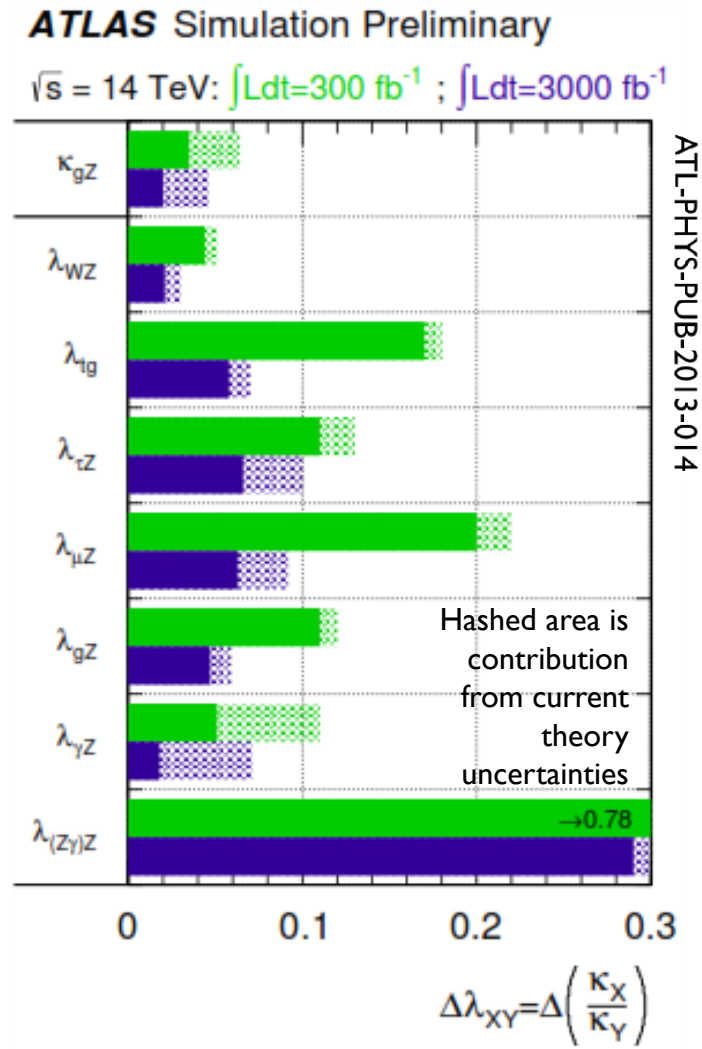


Couplings

- Production rate is proportional to coupling squared (g^2). Parameterize deviations with, $\kappa = g/g_{SM}$

$$\frac{\sigma \cdot B\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot B_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- Total width, κ_H, is sum of all components
- If no assumption on total width, measure ratio of couplings, λ
- Can determine λ to within 3-10% for bosons/gluons/fermions, 30% for Zɣ for 3000fb^{-1} (2-3 factor improvement compared to 300fb^{-1})

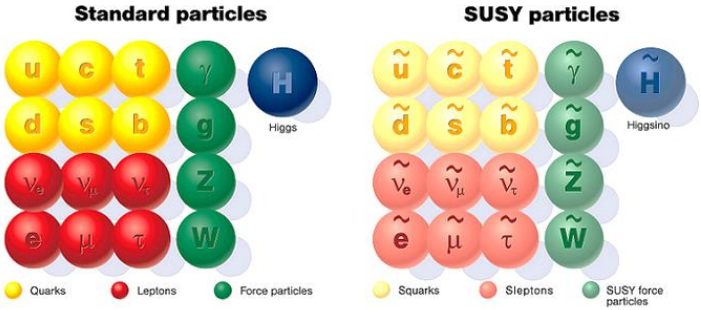


* Note updated VHbb, VH/ttH → ɣɣ, VHbb, inputs have not been used in couplings (fix κ_b fixed from κ_τ)

Supersymmetry (SUSY) Prospects

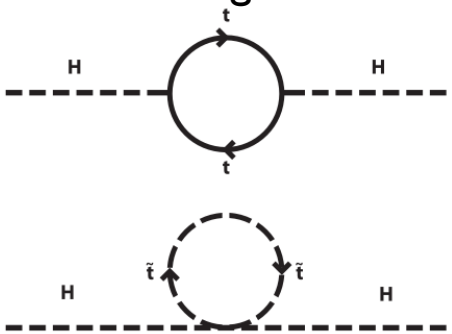
SUSY Introduction

- SUSY predicts SM parter particles (sparticles) whose spin differes by ½



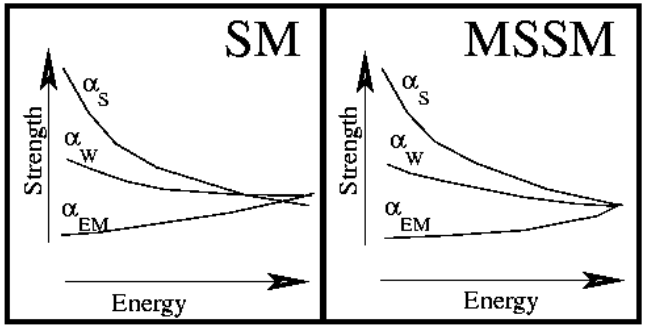
- Why SUSY?

Prevents Higgs mass from blowing up: sparticle loops cancel divergences



lightest stable particle ($\tilde{\chi}^0$) is candidate for dark matter (under R-parity)

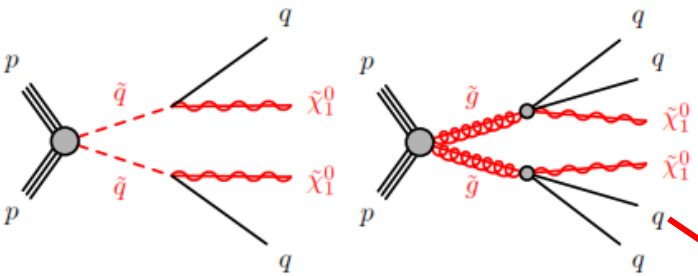
unifies week, strong and EM couplings at high energy



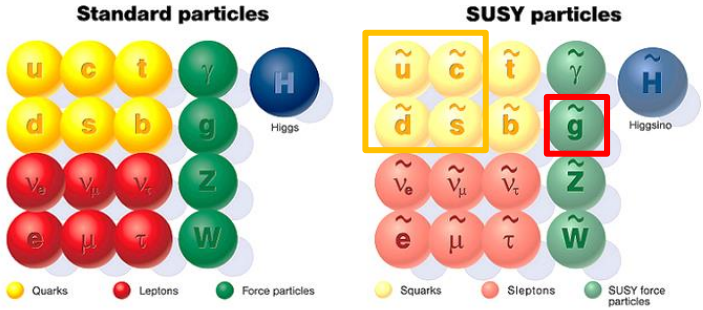
- When SUSY imposed on local symmetry, general relativity pops out : Supergravity
- SUSY is needed for many versions of Theory of Everything

SUSY

Search for



squarks gluinos($\tilde{g}$)



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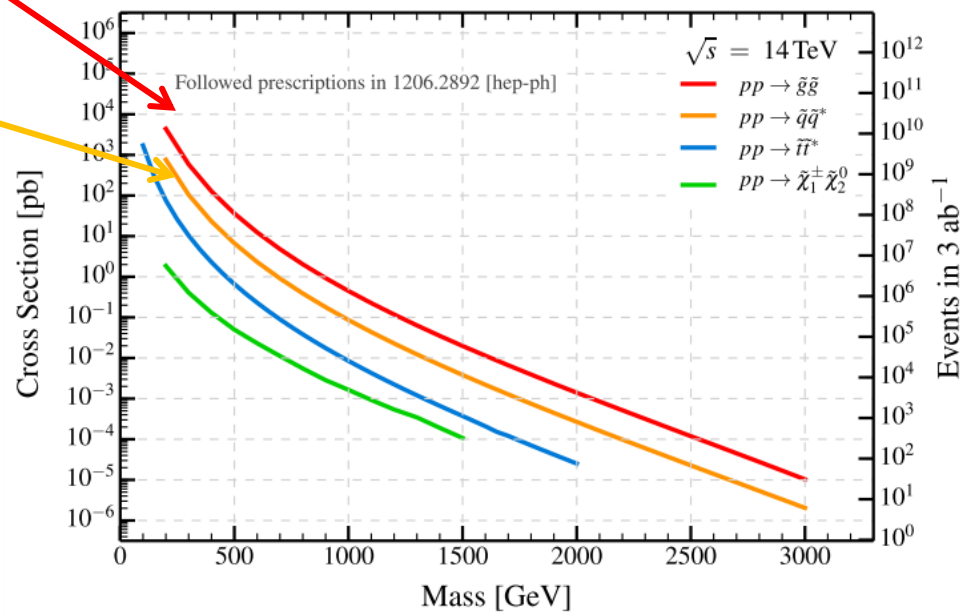
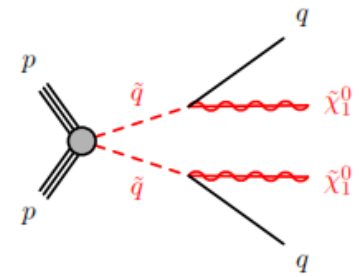


SUSY

Search for



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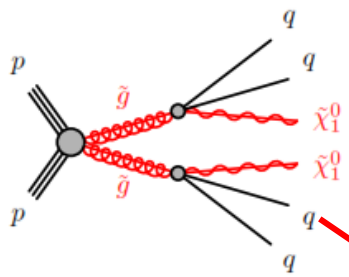
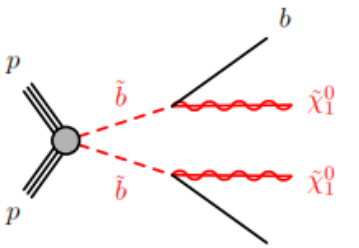
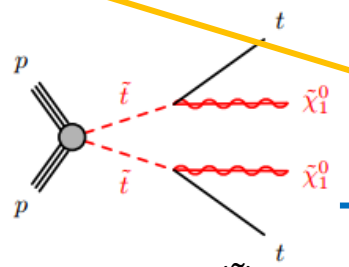


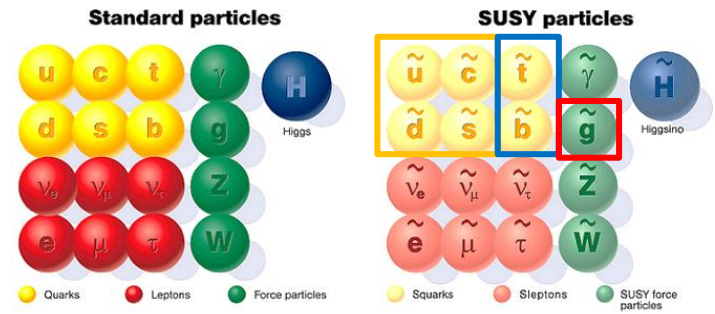
gluinos($\tilde{g}$)



sbottom ($\tilde{b}$)



stop ($\tilde{t}$)



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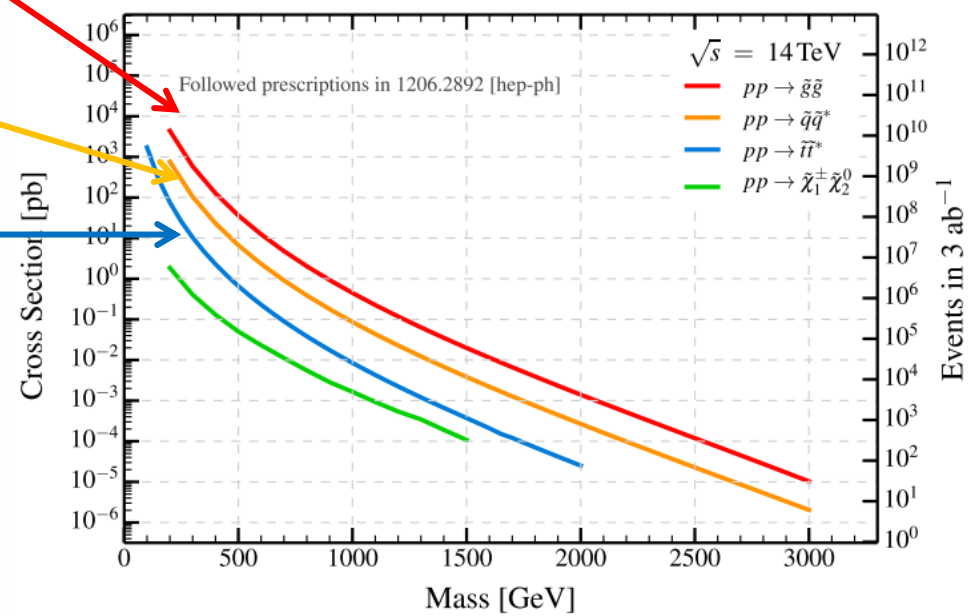

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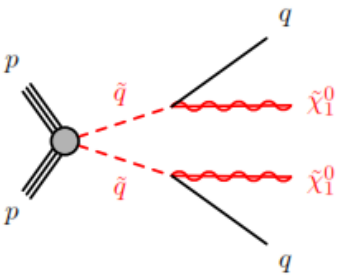

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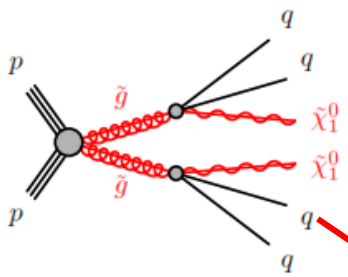

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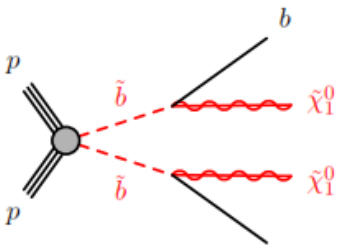

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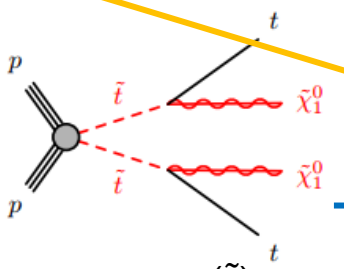

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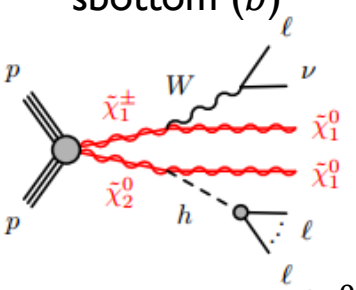
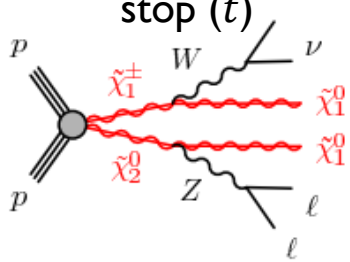
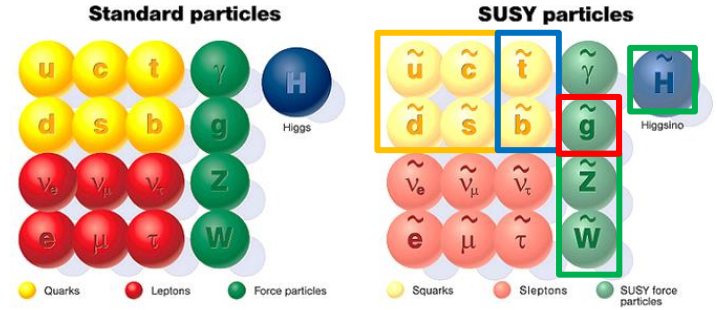




neutrolinos ($\tilde{\chi}^0$)/charginos ($\tilde{\chi}^{\pm}$):
superposition of Higgsino and Wino, Zino



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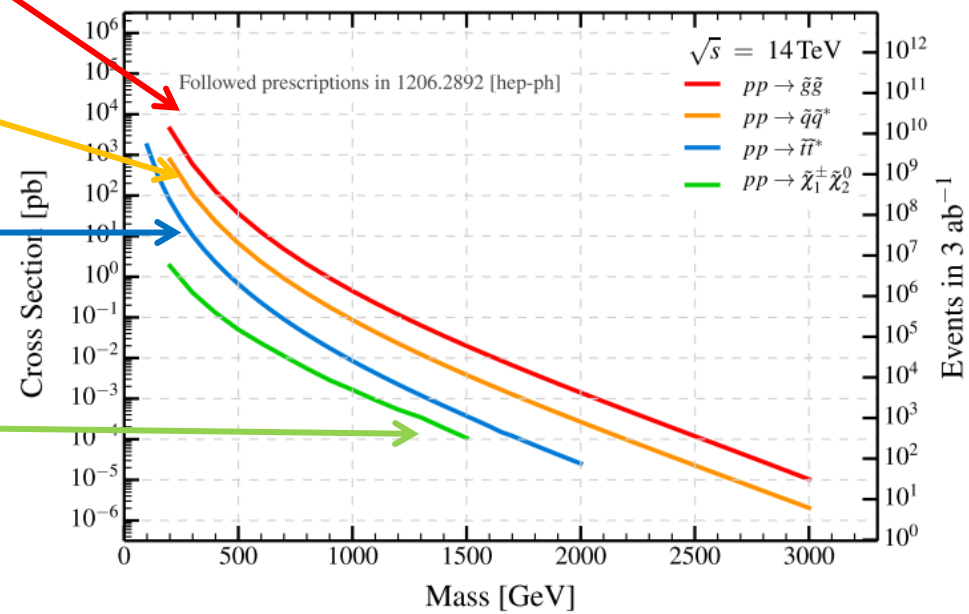
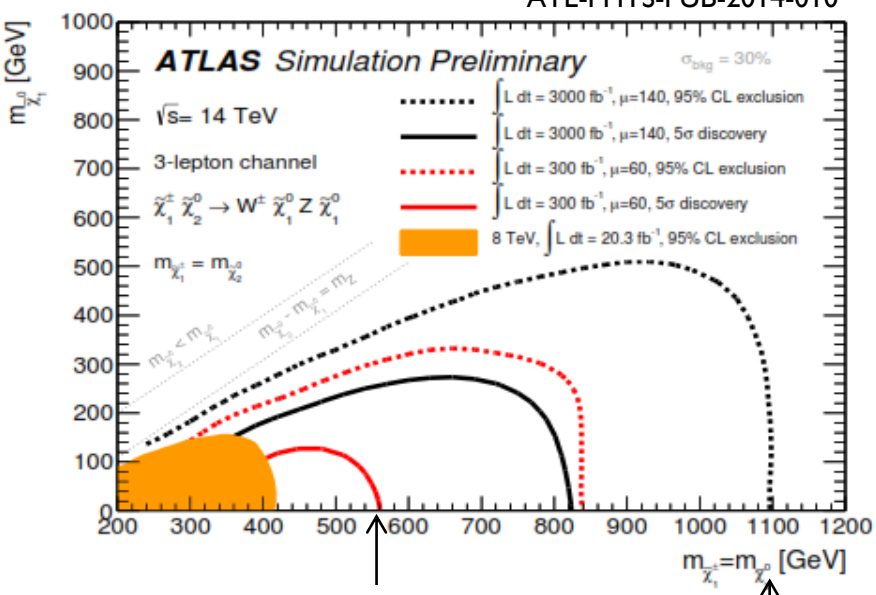


SUSY

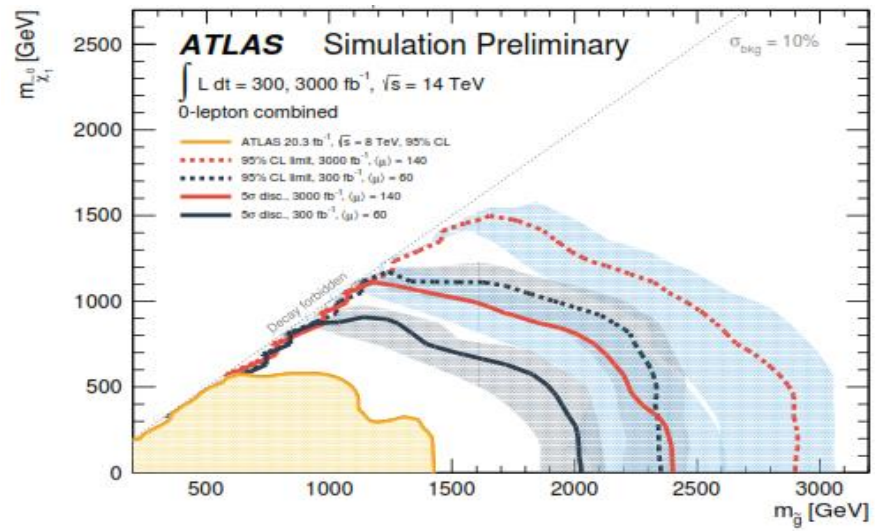
$\tilde{\chi}^{\pm}\tilde{\chi}^{0}$

ATL-PHYS-PUB-2014-010



$\tilde{g}$

ATL-PHYS-PUB-2014-010



Discovery - discover $\tilde{\chi}^{\pm}$ / $\tilde{\chi}^{0}$ at 5σ, if their mass is below 560 (820) at 300(3000) fb $^{-1}$

Exclusion - exclude $\tilde{\chi}^{\pm}$ / $\tilde{\chi}^{0}$ at 95% confidence level if their mass is below 840(1100) GeV 300(3000) fb $^{-1}$

	Exclusion			Discovery	
	Now	300fb^{-1}	3000fb^{-1}	300fb^{-1}	3000fb^{-1}
$\tilde{g}$	1400	2350	2950	2000	2350

more limit plots in BACKUP !

SUSY

	Exclusion Limits			Discovery Limits	
Sparticle	Now	300fb^{-1}	3000fb^{-1}	300fb^{-1}	3000fb^{-1}
squark (heavy $\tilde{g}$)*	900	1850	2000	1300	1400
Squark ($\tilde{g}$= 4.5 TeV) **	900	3100	3500	2400	3100
$\tilde{g}$	1400	2350	2950	2000	2350
$\tilde{b}$	600	1400	1500	1100	1300
$\tilde{t}$	650	1200	1450	1000	1200
$\tilde{\chi}^{\pm}\tilde{\chi}^{0}$ via WZ	420	840	1100	560	820
$\tilde{\chi}^{\pm}\tilde{\chi}^{0}$ via Wh, h $\rightarrow \ell\ell$***	--	650	940	---	650

ATL-PHYS-PUB-2014-010/ ATL-PHYS-PUB-2013-011

The most interesting sparticle mass ranges (~1000 GeV) can be covered!

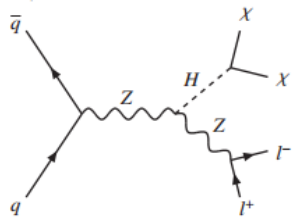
*squark and $\tilde{g}$ decoupled
**squark production enhanced
*** h $\rightarrow$ $\tau\tau$ also explored: 550 GeV exclusion for 3000 fb-1

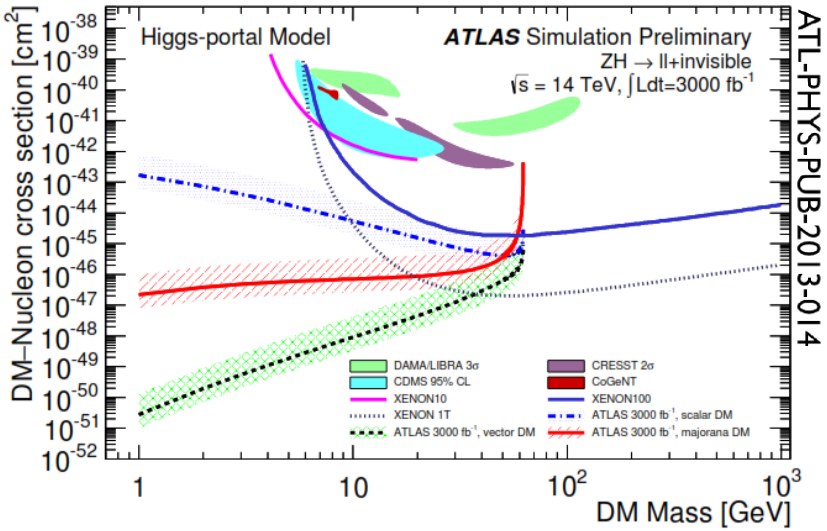
more limit plots in BACKUP !

Exotics Prospects

Dark Matter (DM) Searches

Through
ZH Higgs
Production

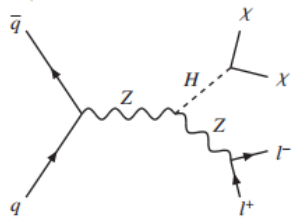


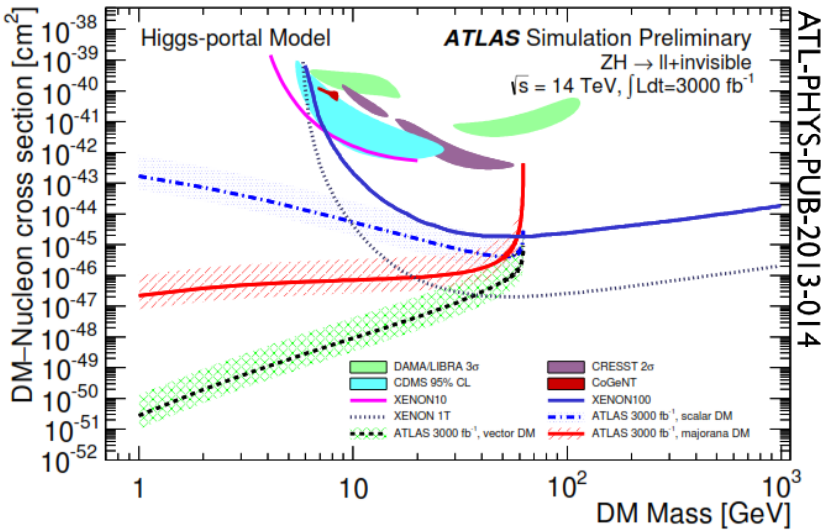


The branching ratio of >23-32% (8-16%) is expected to be excluded at 95% confidence level with 300 fb^{-1} (3000 fb^{-1}). Current exclusion is >65%.

Dark Matter (DM) Searches

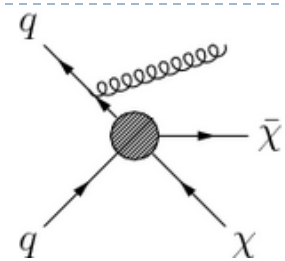
Through ZH Higgs Production

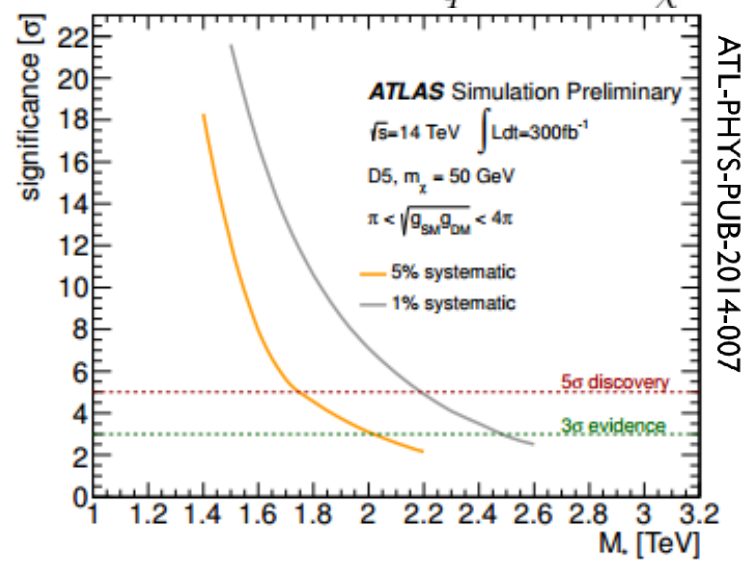




The branching ratio of >23-32% (8-16%) is expected to be excluded at 95% confidence level with 300 fb^{-1} (3000 fb^{-1}). Current exclusion is >65%.

With high p_T jet





~No improvement for 3000fb^{-1}

Assume SM-DM couples via contact interaction (mass of mediator >> invariant mass of DM)

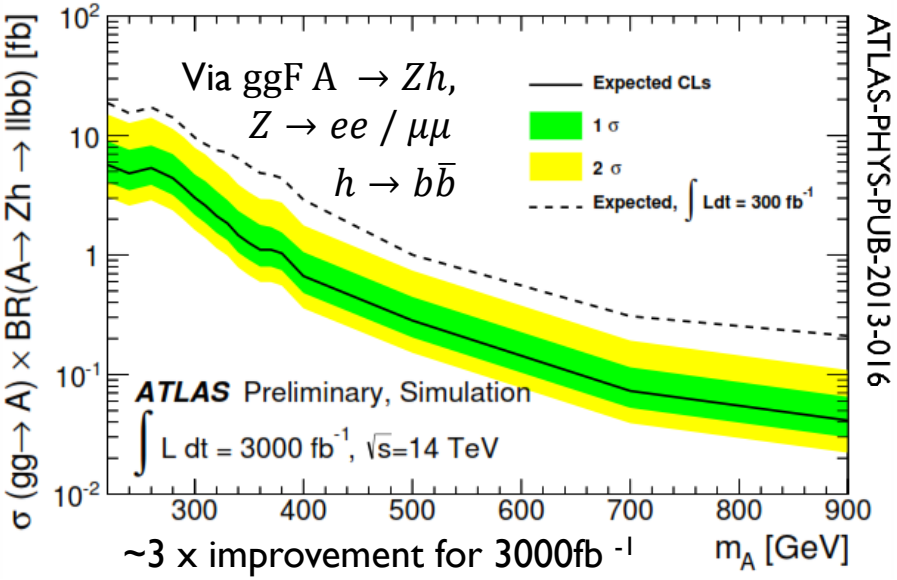
$$M^* = \frac{M_{mediator}}{\sqrt{g_{SM} g_{DM}}}$$

$M_{mediator}$ → mediator mass

$g_{SM} g_{DM}$ → couplings of mediator to SM (DM)

2Higgs Doublet Models (2HDM)

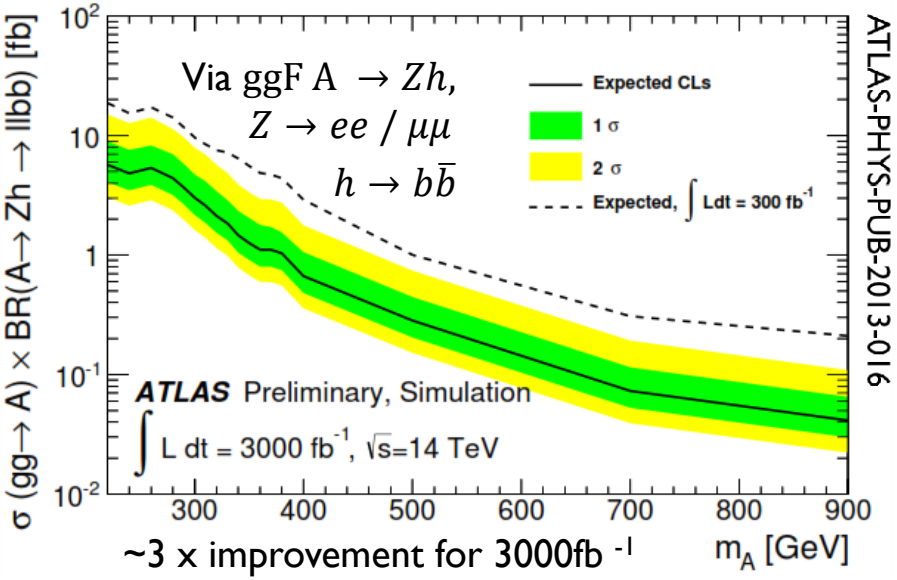
- 2HDM
  - Higgs has additional complex Higgs doublet, predict 5 Higgs particles: $h,\ H^{\pm},\ H^{0},\ A$
  - Models that often include 2HDM are Minimal SUSY, Baryogenesis, Axion Models



~3 x improvement for 3000fb $^{-1}$

2Higgs Doublet Models (2HDM)
Flavour Changing Neutral Currents (FCNC)

- 2HDM
  - Higgs has additional complex Higgs doublet, predict 5 Higgs particles: $h,\ H^{\pm},\ H^{0},\ A$
  - Models that often include 2HDM are Minimal SUSY, Baryogenesis, Axion Models



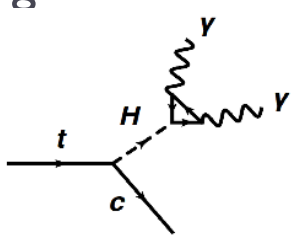
~3 x improvement for 3000fb $^{-1}$

- FCNC
  - In SM highly suppressed. Enhanced in some 2HDMs/SUSY/extra dim.
  - Exclusion in branching ratios in

$t \to qZ$,

$t \to q\gamma$,

$t \to cH \ (H \to \gamma\gamma)$,



Exclusion on branching ratio

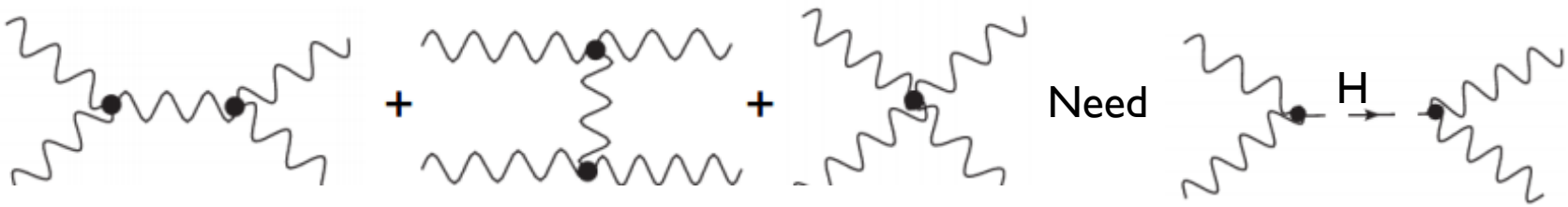
channel	Now	3000fb^{-1}
$t \to qZ$	0.21%	4.1×10^{-5}
$t \to q\gamma$	3.2%	1.3×10^{-5}
$t \to cH$	0.83%	$1.2\text{-}1.4\times10^{-5}$

ATL-PHYS-PUB-2013-007, ATLAS-PHYS-PUB-2013-012

more limit plots in BACKUP!

Vector Boson Scattering,

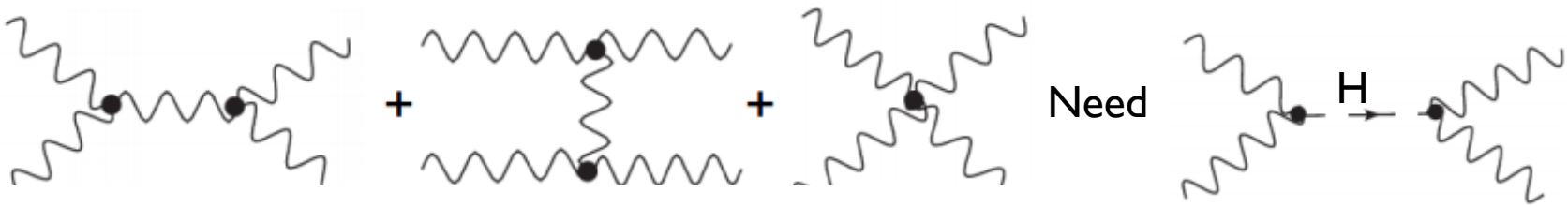
- Vector Boson Scattering (VBS)
  - Confirm that Higgs boson prevents VBS cross section from diverging



  - Parameterize new physics in terms of higher dimensional operators in Lagrangian. Discovery range for operators enhanced by >2 at HL-LHC (ATLAS-PHYS-PUB-2013-003)

Vector Boson Scattering, Di-lepton /Di-top Resonances

- Vector Boson Scattering (VBS)
  - Confirm that Higgs boson prevents VBS cross section from diverging



  - Parameterize new physics in terms of higher dimensional operators in Lagrangian. Discovery range for operators enhanced by >2 at HL-LHC (ATLAS-PHYS-PUB-2013-003)

- Di-Lepton: Most Grand Unified Theories predict existence of Z' boson. Search for $Z' \to ee/\mu\mu$

- Di-top: In extra dimension & composite Higgs models, Klein-Kaluza particles are strongly produced wide resonances that can decay to $t\bar{t}$.

Exclusion limits on mass in TeV

model	Now	300fb^{-1}	3000fb^{-1}
$Z'_{SSM} \to ee$	2.79	6.5	7.8
$Z'_{SSM} \to \mu\mu$	2.53	6.4	7.6
g_{KK}	2.0	4.3	6.7
$Z'_{topcolor}$	1.8	3.3	5.5

ATL-PHYS-PUB-2013-003, CERN-PH-EP-2014-053, ATLAS-CONF-2013-052, ATLAS-CONF-2013-052

Conclusions

- Measuring Higgs properties in different channels is essential in confirming the SM and will point to possible deviations from SM physics

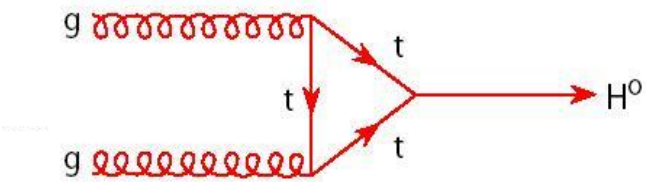
- The most interesting mass ranges for SUSY particles are within reach at 3000 fb^{-1}

- Many general searches for theories beyond the SM will have much farther reach with 300fb^{-1} and 3000 fb^{-1} at 14 TeV

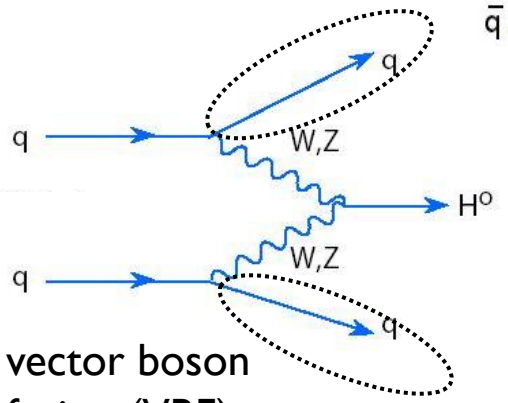
Backup

Higgs Factory HL-LHC

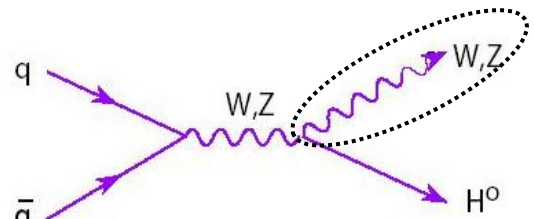
How do we differentiate between production processes?



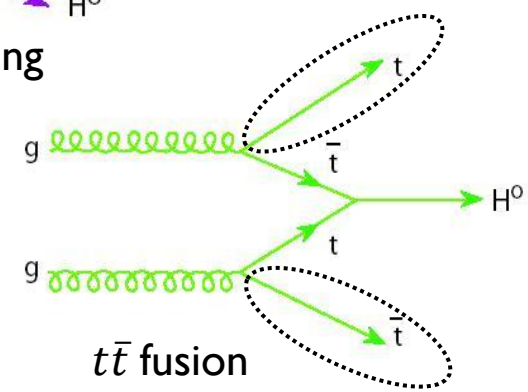
gluon-gluon fusion (ggF)



vector boson fusion (VBF)



WZ Bremsstrahlung



$t\bar{t}$ fusion

Usually have 0 or 1 jet central jet from radiation

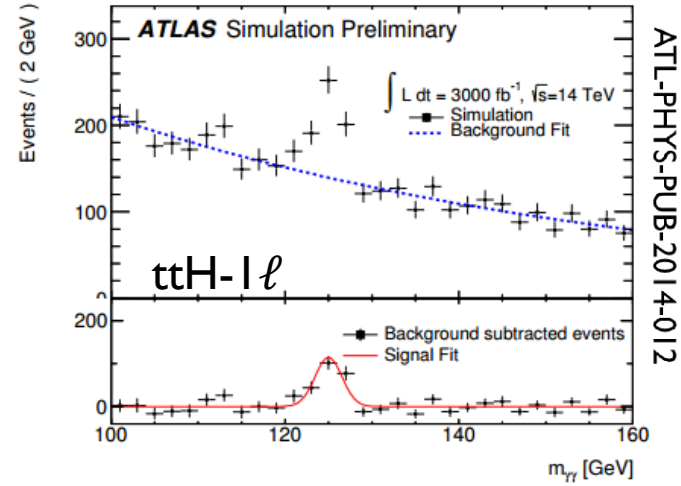
Identify jets in forward direction with high momenta/invariant mass

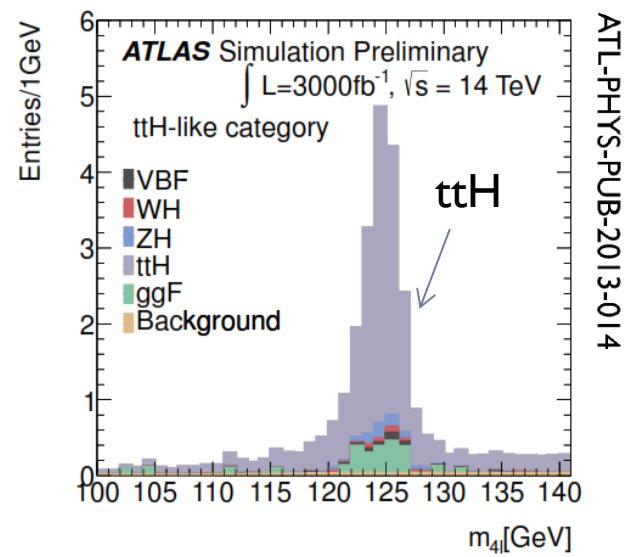
Have additional leptons from leptonic W/Z decays

Identify bottom quark jets from information on displaced vertex

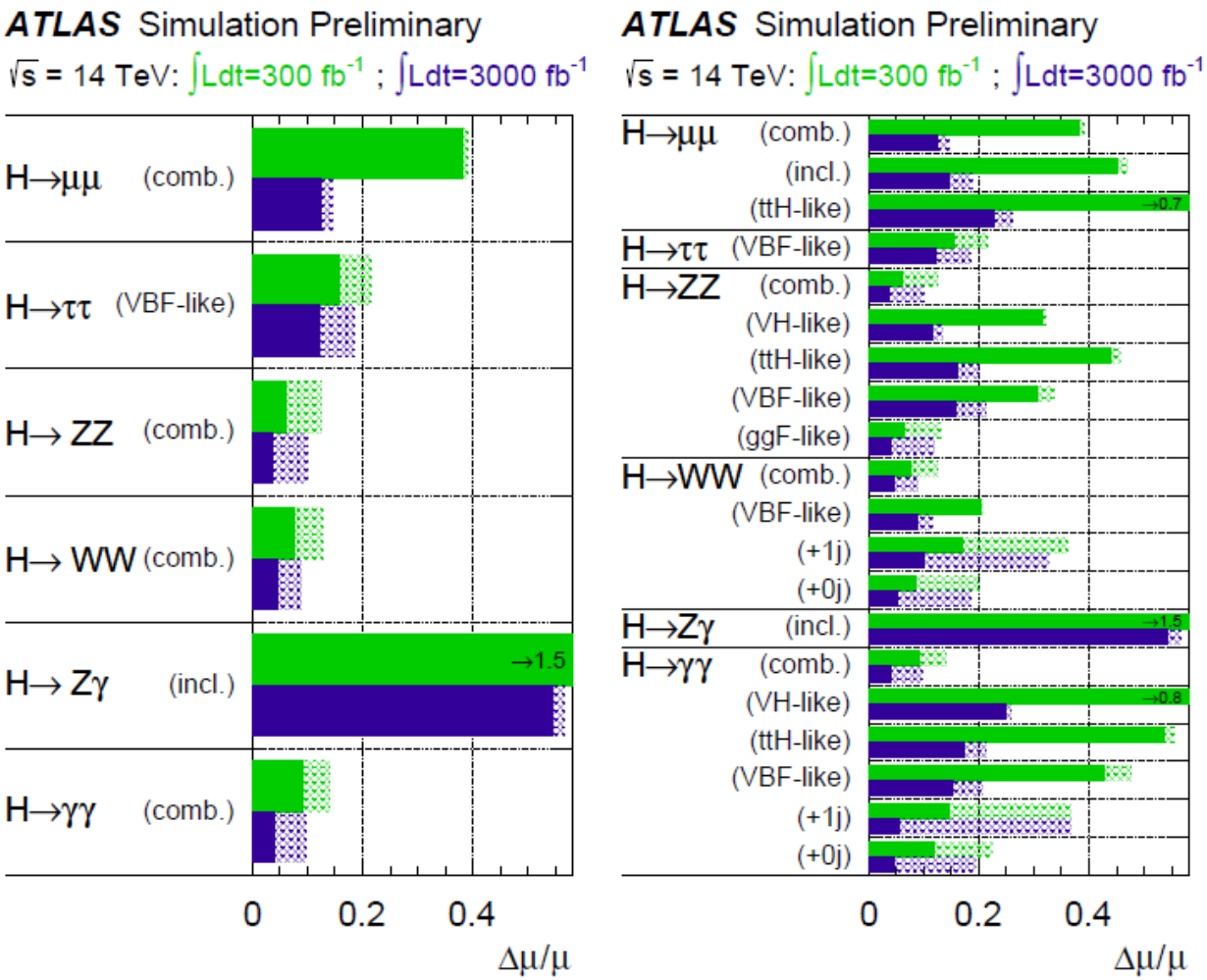
H→γγ / ZZ

- Production via ggF, VBF, VH, and ttH
- In ttH , can measure the large Yukawa coupling of Higgs to top
  - 8.2 σ in H→γ γ
- H→γ γ sensitive to beyond SM due to loop
- Uncertainty on signal strength, $\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$
  - Reduce $\Delta\mu/\mu$ on H→γ γ from current ~20% to 15% (ggF only) for 3000 fb^{-1}
  - Reduce $\Delta\mu/\mu$ on H→ZZ → 4$\ell\ell$ from current 27% to 15(13)% for 300(3000) fb^{-1}



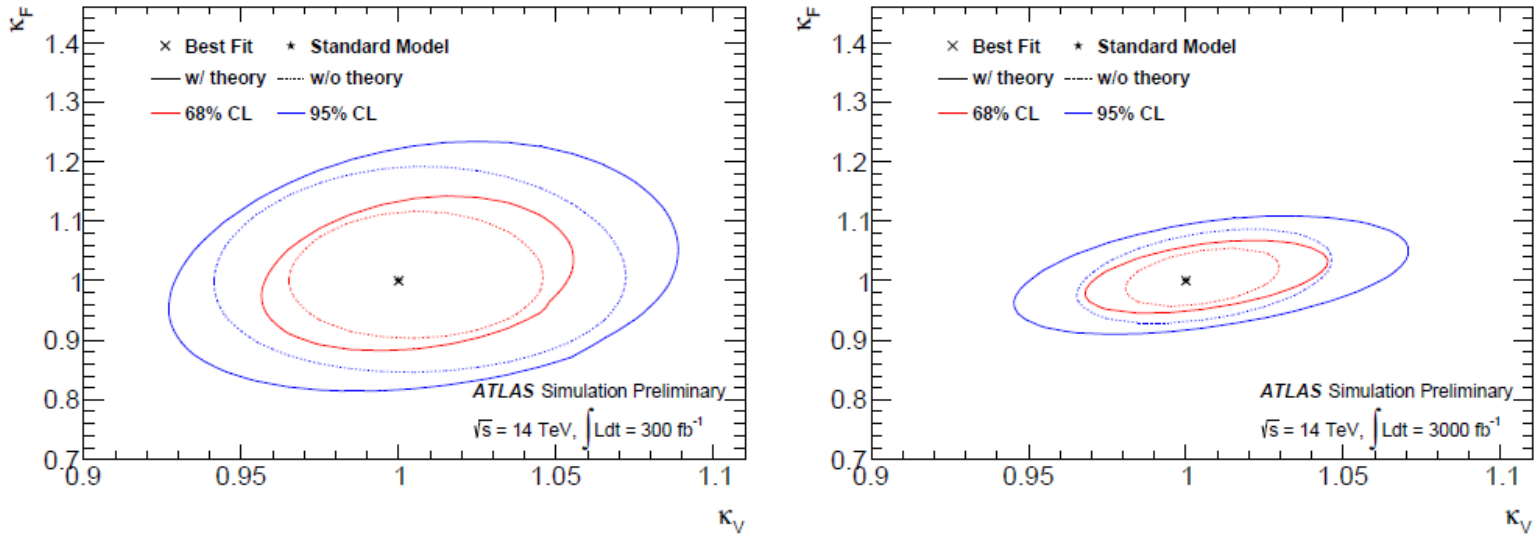


Higgs: Signal Strength Uncertainty/Couplings



Note updated VHbb, VH/ttH → γγ, VHbb, inputs have not been used in couplings (fix κ_b fixed from κ_τ)

Higgs: Signal Strength Uncertainty/Couplings



Assumptions for couplings

- signal in different search channels originates from single resonance at 125 GeV

-width of higgs is narrow, use zero-width approximation

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

-only modifications of coupling strenths considered, tensor structure of Lagrnagian is same as in SM

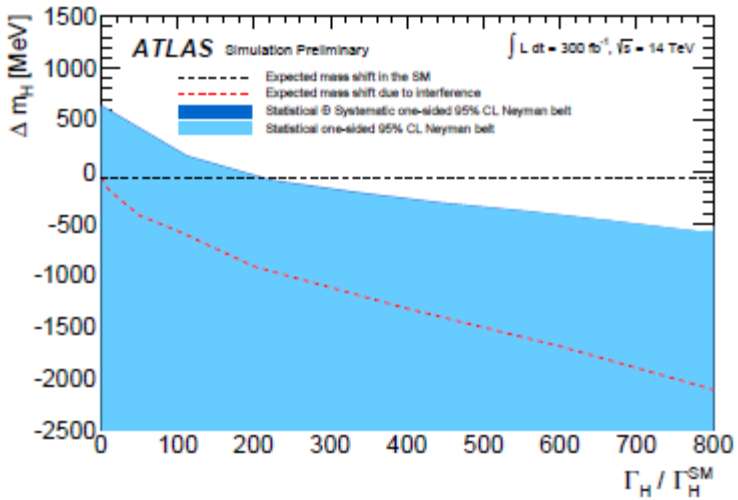
-all fermion and all boson couplings are equal

Note updated VHbb, VH/ttH → γγ, VHbb, inputs have not been used in couplings (fix κ_b fixed from κ_τ)

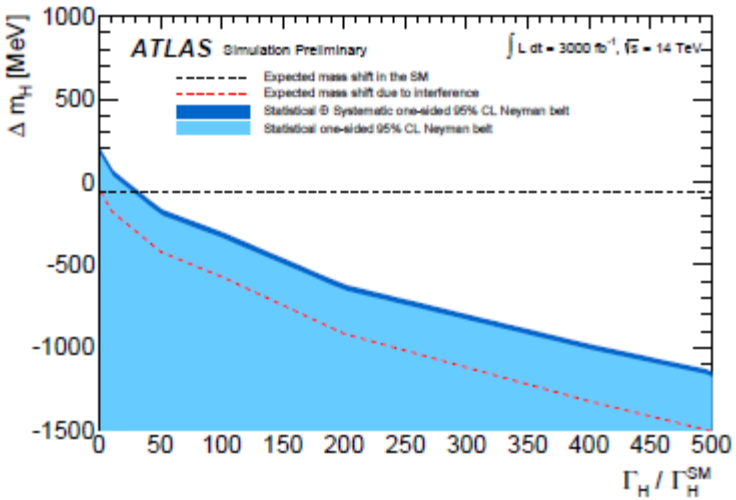
Higgs Couplings

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ	3.2%	2.7%	2.5%	2.5%	1.9%	1.6%
2	$\kappa_V = \kappa_Z = \kappa_W$	3.3%	2.8%	2.7%	2.6%	1.9%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.6%	7.5%	7.1%	4.1%	3.5%	3.2%
3	κ_Z	8.4%	7.3%	6.8%	6.3%	5.0%	4.6%
	κ_W	8.0%	6.7%	6.2%	6.1%	4.8%	4.3%
	κ_t	11%	9.0%	8.3%	7.0%	5.6%	5.1%
	$\kappa_{d3} = \kappa_\tau = \kappa_b$	18%	14%	13%	14%	11%	10%
	κ_μ	22%	20%	20%	10%	8.1%	7.5%
4	κ_Z	8.0%	7.0%	6.6%	5.2%	4.3%	4.0%
	κ_W	7.7%	6.8%	6.5%	4.9%	4.2%	3.9%
	κ_t	19%	18%	18%	7.7%	6.7%	6.3%
	$\kappa_d = \kappa_\tau = \kappa_\mu = \kappa_b$	16%	13%	12%	11%	8.2%	7.2%
	κ_g	8.9%	7.9%	7.5%	4.3%	3.8%	3.6%
	κ_γ	13%	9.3%	7.8%	9.3%	5.9%	4.2%
	$\kappa_{Z\gamma}$	79%	78%	78%	30%	30%	29%
5	κ_Z	8.1%	7.1%	6.7%	6.2%	4.9%	4.4%
	κ_W	7.9%	6.9%	6.5%	5.9%	4.8%	4.4%
	κ_t	22%	20%	20%	10%	8.4%	7.8%
	$\kappa_{d3} = \kappa_\tau = \kappa_b$	18%	15%	13%	15%	11%	9.7%
	κ_μ	23%	21%	21%	11%	8.5%	7.6%
	κ_g	11%	9.1%	8.5%	6.9%	5.5%	4.9%
	κ_γ	13%	9.3%	7.8%	9.4%	6.1%	4.6%
	$\kappa_{Z\gamma}$	79%	78%	78%	30%	30%	29%

Higgs Width Measurements



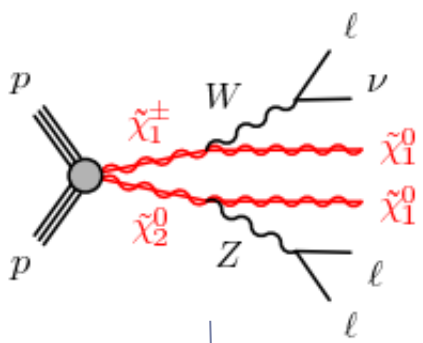
(a) 300 fb^{-1}

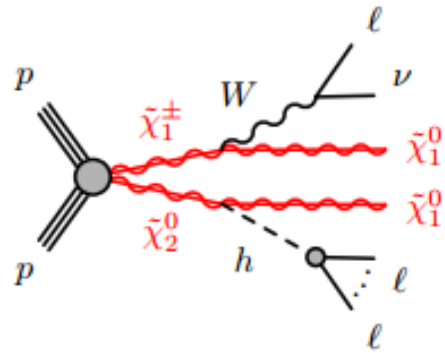


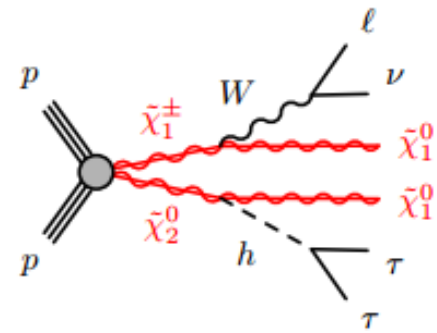
(b) 3000 fb^{-1}

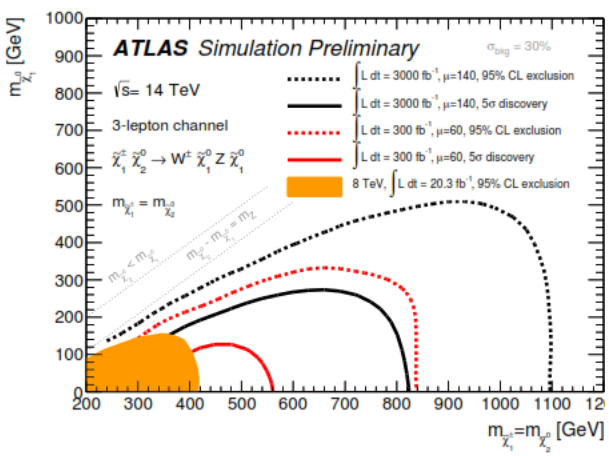
SUSY

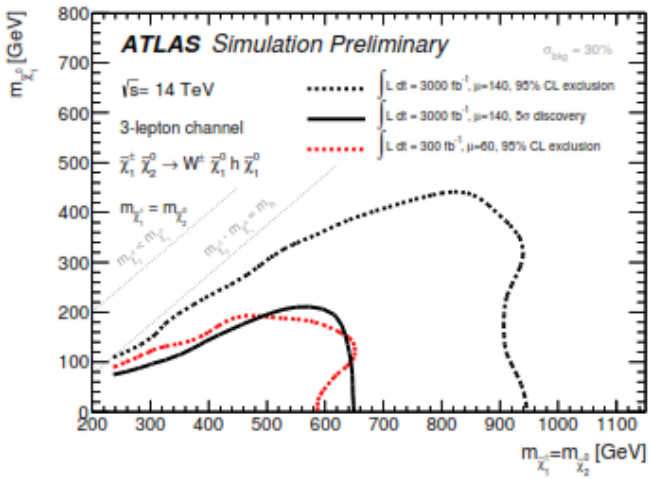
$\tilde{\chi}^{\pm}\tilde{\chi}^{0}$

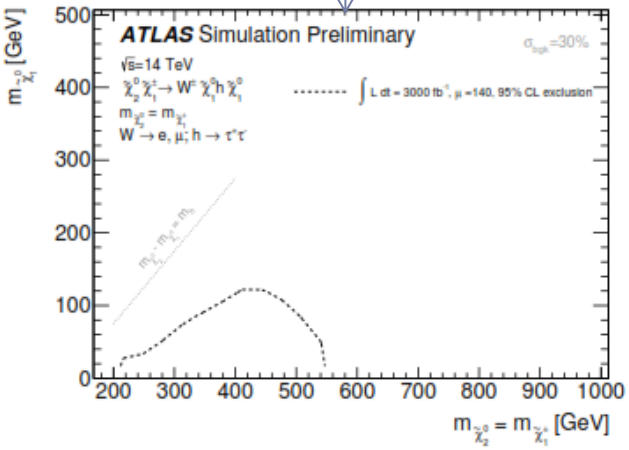




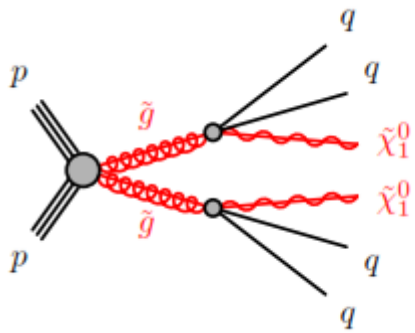


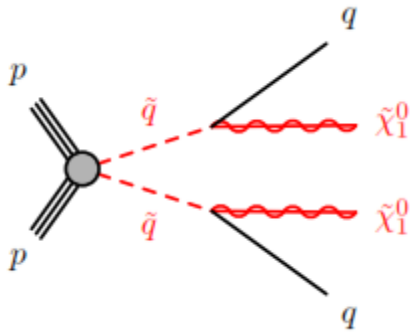


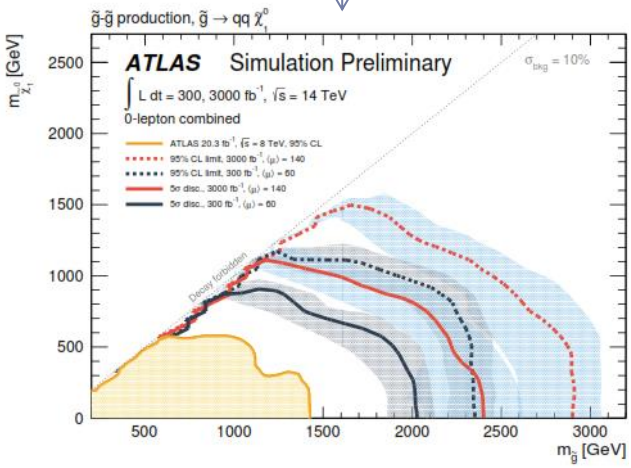


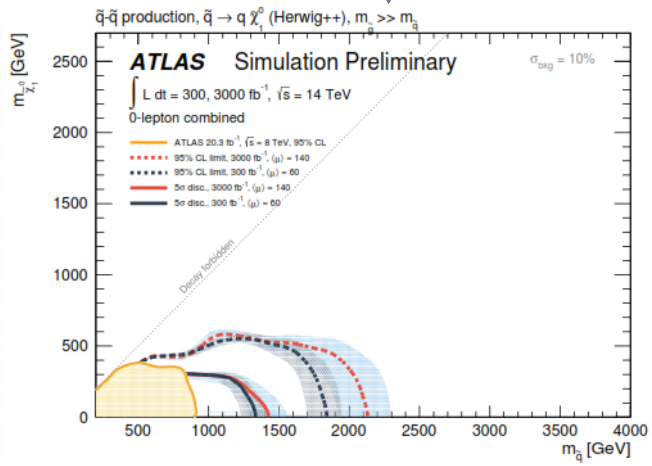


SUSY

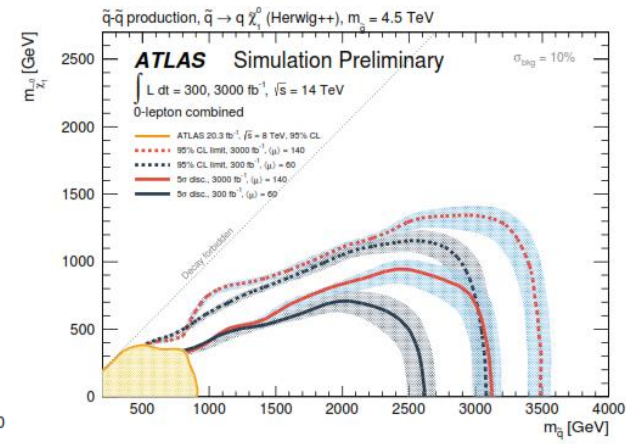






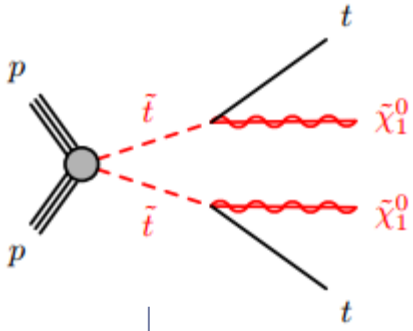


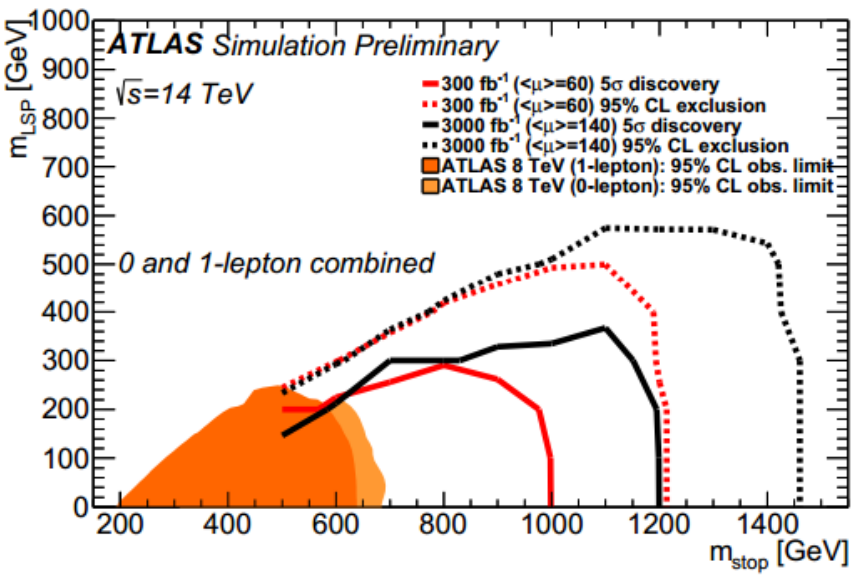
(b) $\tilde{q}\tilde{q}$, decoupled $\tilde{g}$

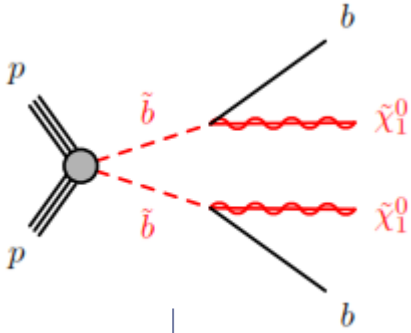


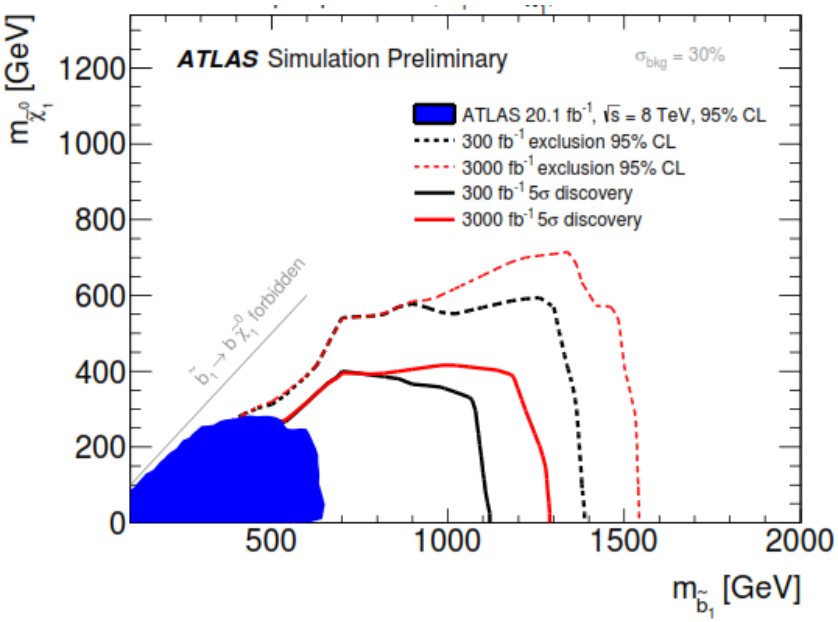
(c) $\tilde{q}\tilde{q}$, $m_{\tilde{g}}$ = 4.5 TeV

SUSY

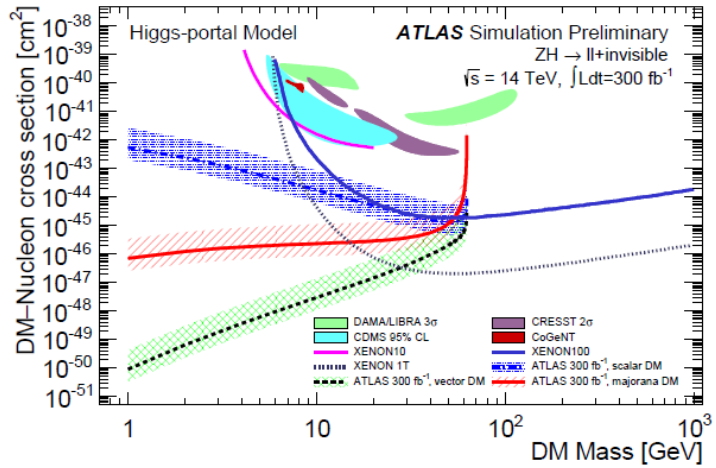

p
p
$\tilde{t}$
$\tilde{t}$
t
t
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$

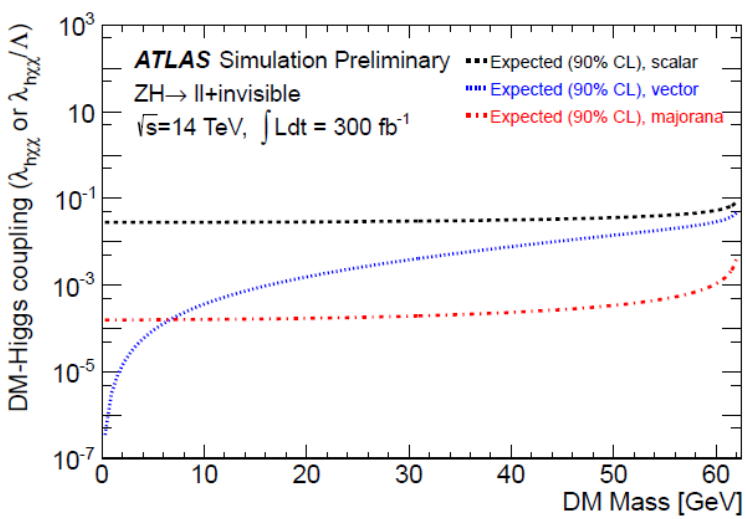

ATLAS Simulation Preliminary
√s=14 TeV
300 fb⁻¹ (<μ>=60) 5σ discovery
300 fb⁻¹ (<μ>=60) 95% CL exclusion
3000 fb⁻¹ (<μ>=140) 5σ discovery
3000 fb⁻¹ (<μ>=140) 95% CL exclusion
ATLAS 8 TeV (1-lepton): 95% CL obs. limit
ATLAS 8 TeV (0-lepton): 95% CL obs. limit
0 and 1-lepton combined
m_LSP [GeV]
m_stop [GeV]

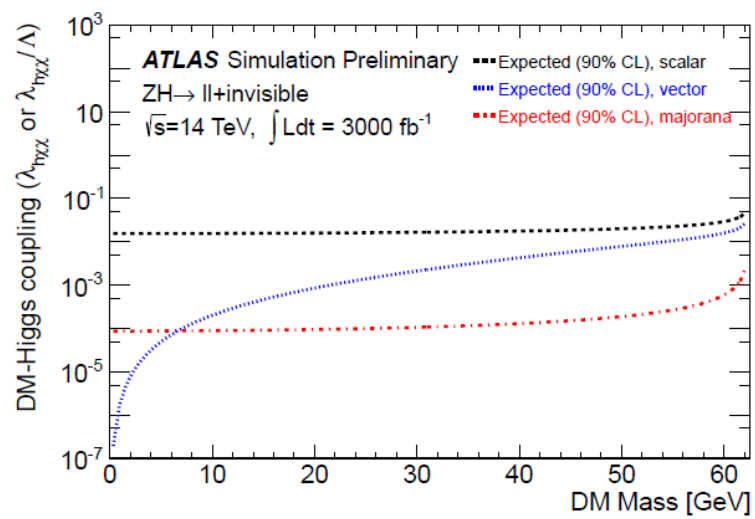

p
p
$\tilde{b}$
$\tilde{b}$
b
b
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$


ATLAS Simulation Preliminary
σ_bkg = 30%
ATLAS 20.1 fb⁻¹, √s = 8 TeV, 95% CL
300 fb⁻¹ exclusion 95% CL
3000 fb⁻¹ exclusion 95% CL
300 fb⁻¹ 5σ discovery
3000 fb⁻¹ 5σ discovery
b̃₁ → b χ̃₁⁰ forbidden
m_χ̃₁⁰ [GeV]
m_b̃₁ [GeV]

Exotics: Dark Matter Coupling to Higgs



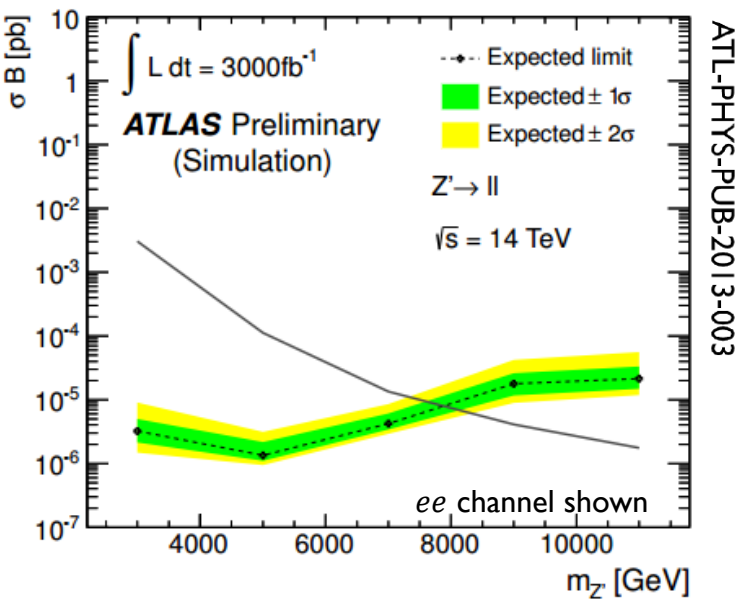




Exotic Prospects: Di-lepton/Di-top Resonances

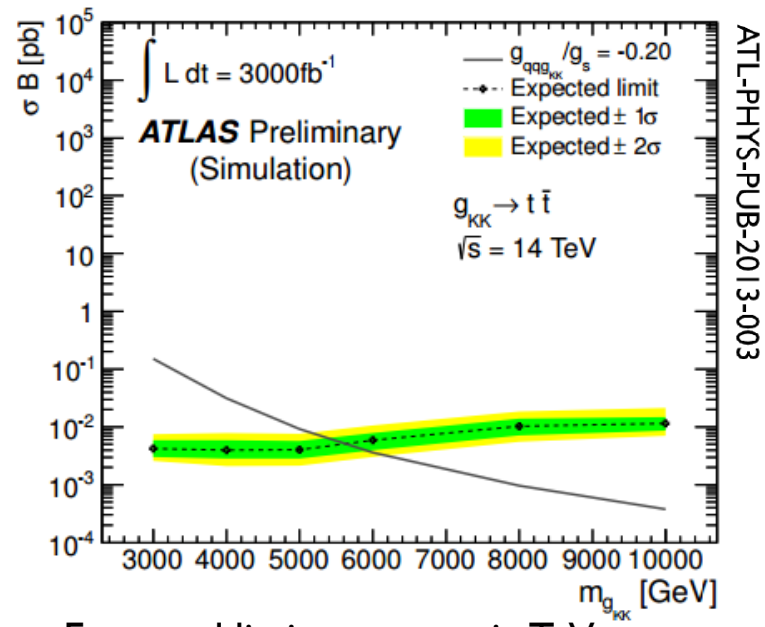
Di-Lepton: Most Grand Unified Theories predict existence of Z' boson. Search for $Z' \rightarrow ee/\ \mu\mu$

Di-top: In extra dimension & composite Higgs models, Klein-Kaluza particles are strongly produced wide resonances that can decay to $t\bar{t}$. In some models (Topcolor), Z' decays to $t\bar{t}$



Expected limits on mass in TeV

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
$Z'_{SSM} \rightarrow ee$	6.5	7.2	7.8
$Z'_{SSM} \rightarrow \mu\mu$	6.4	7.1	7.6

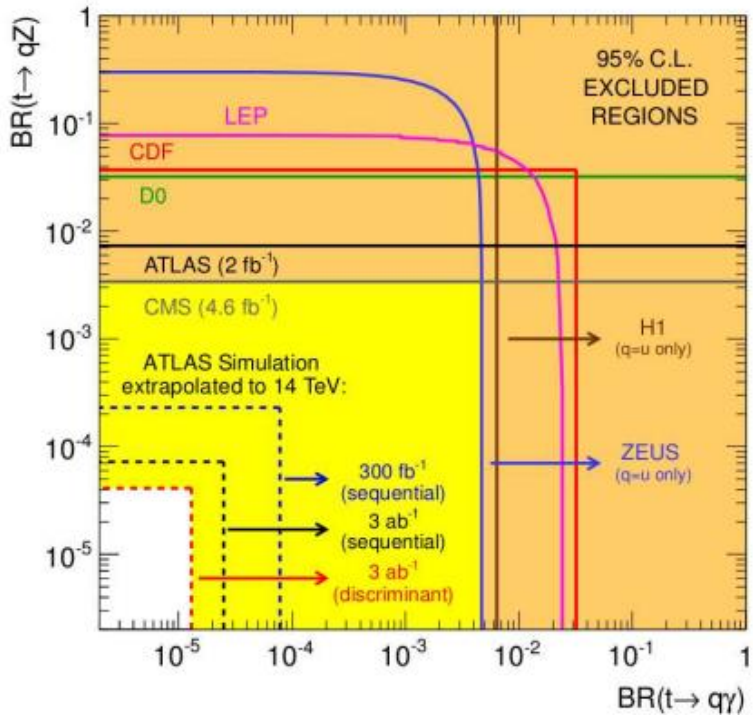


Expected limits on mass in TeV

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{topcolor}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

Exotic Prospects: FCNC

$t \to Zq/H \to q\gamma$



$t \to cH,\ H \to \gamma\gamma$