Prospects of New Physics Searches at the HL-LHC

Jessica Metcalfe, On behalf of the ATLAS Collaboration

4th International Conference on New Frontiers in Physics

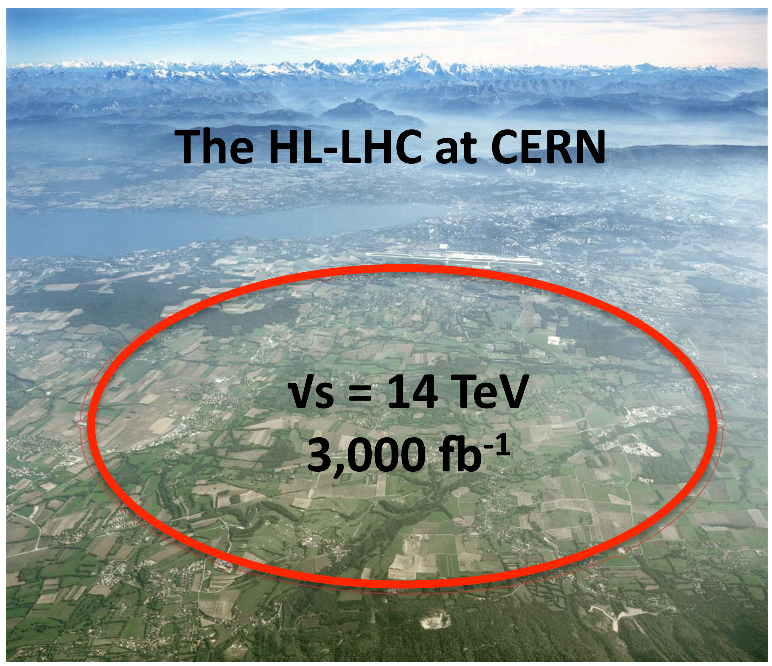
Outline

➔Beyond Standard Model searches at the high luminosity LHC (HL-LHC)

- pp collider at $\sqrt{s}$ = 14 TeV

What new physics will we look for?

➔ Anomalous triple and quartic gauge boson couplings
➔ Higgs couplings, Heavy Higgs
➔ SUSY
➔ Dark Matter
➔ Extra Dimensions

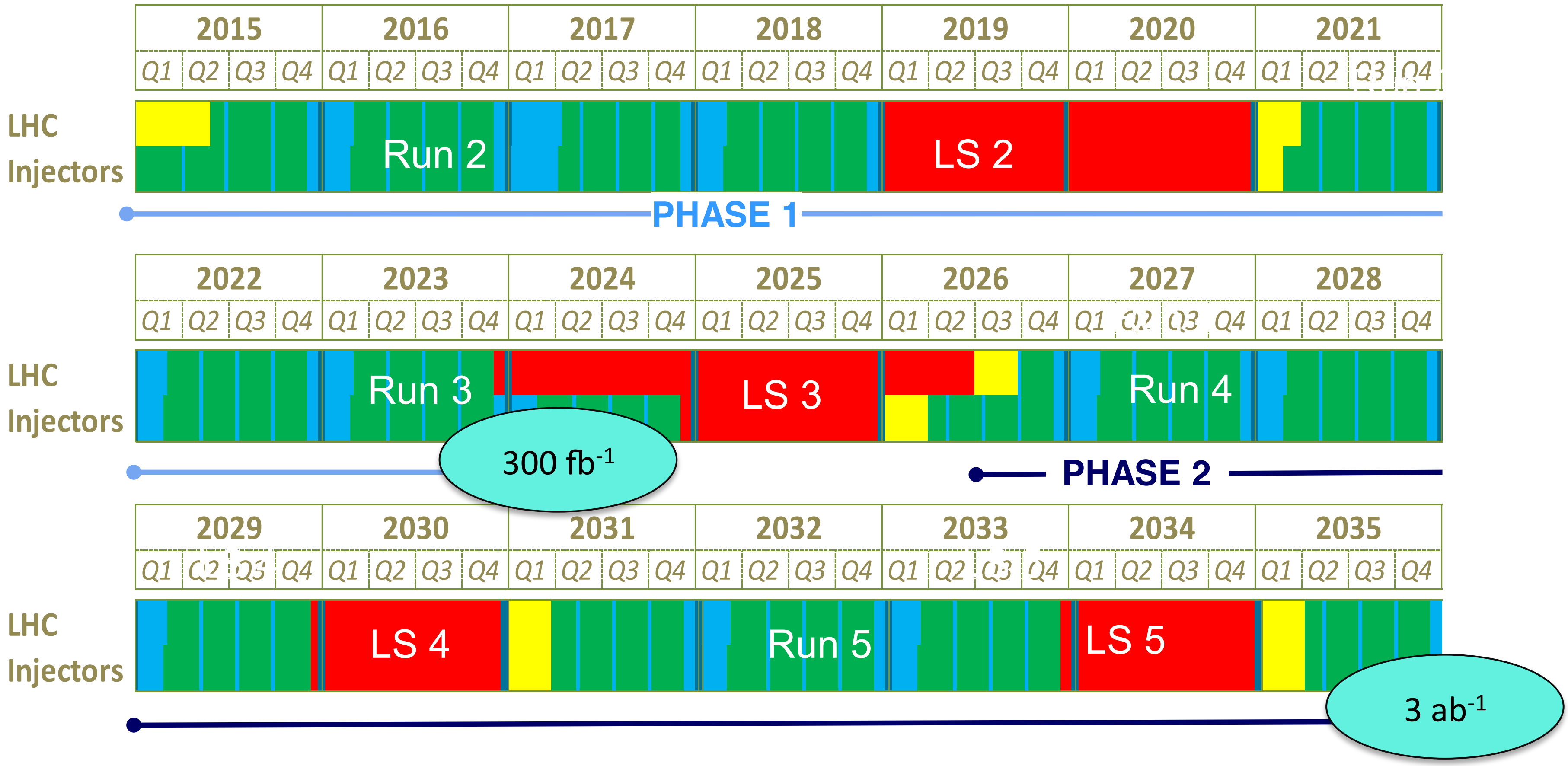


HL-LHC Schedule

LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC

- Physics
- Shutdown
- Beam commissioning
- Technical stop

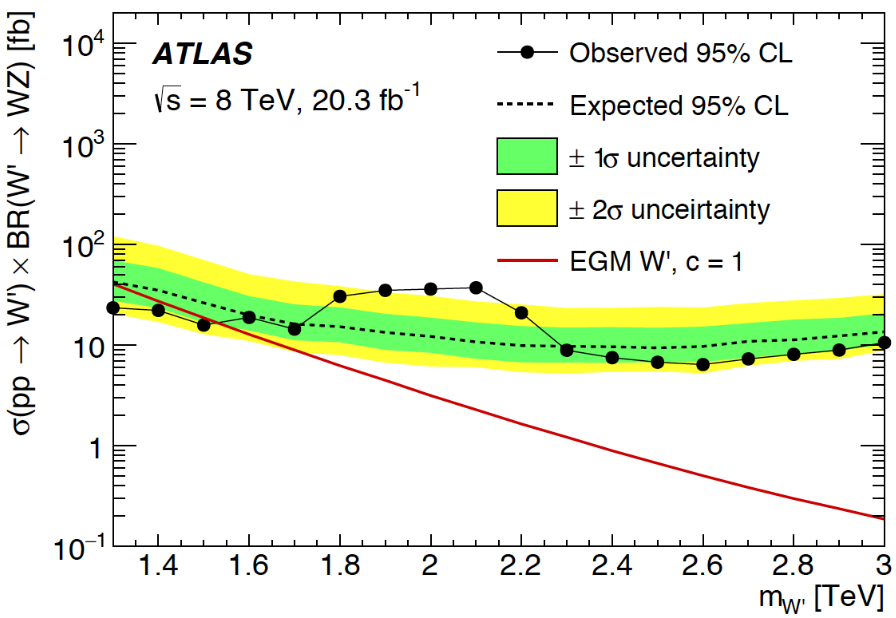


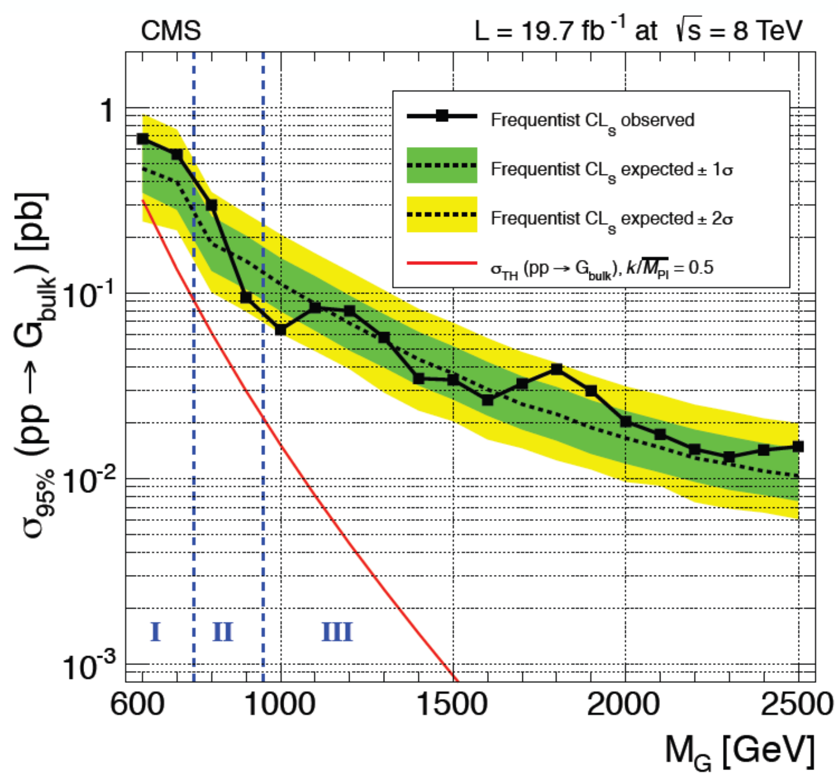
Hints From Run 1

Diboson Bump Hunt at √s = 8 TeV

- tantalizing hints or statistical fluctuations?

arXiv:1506.00962





Search for narrow resonance decaying to boson pairs (WW, WZ, ZZ) via boson tagged jets

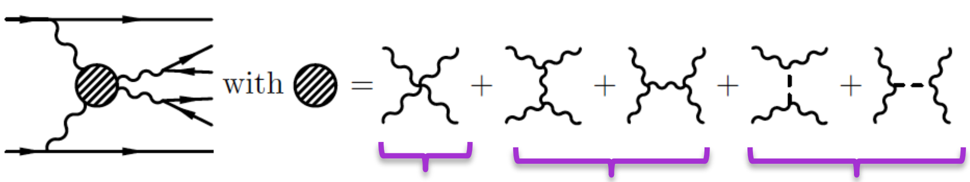
Vector Boson Scattering @ HL-LHC

Where to look?

- Anomalous Triple and Quartic Gauge Couplings (aTGC's aQGC's)
- Generic Effective Field Theory (EFT) framework
  - add all possible boson couplings

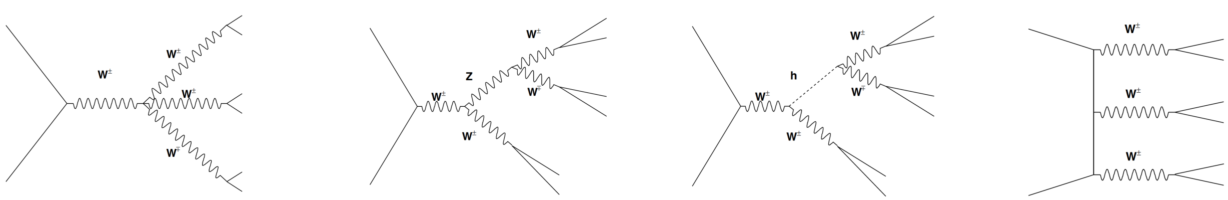
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \underbrace{\sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i}_{\text{Dimension-6}} + \underbrace{\sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}}_{\text{Dimension-8}} + \ldots$$

Vector Boson Scattering:



Quartic Triple Higgs

Tri-boson Processes:



Vector Boson Scattering @ HL-LHC

FS0

$W^{\pm}W^{\pm} \to l\nu l\nu$

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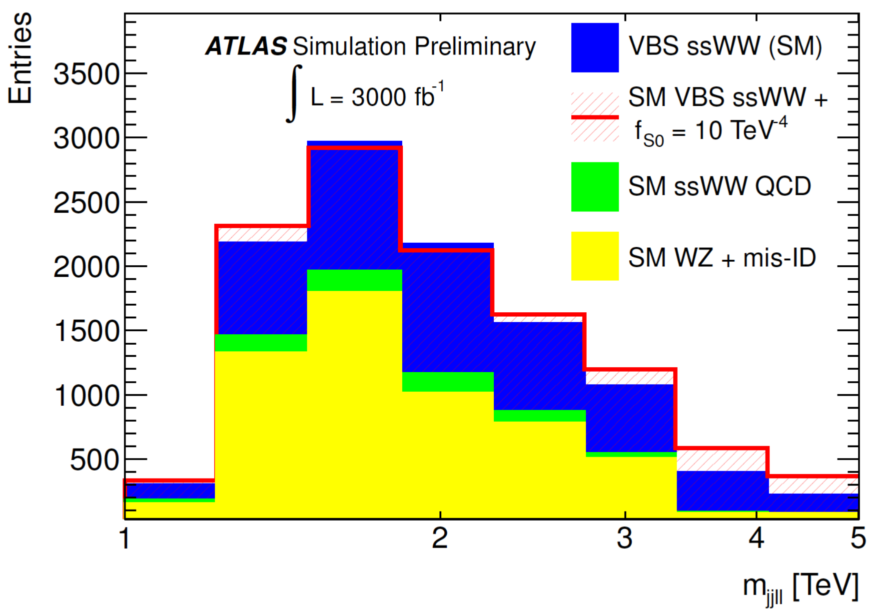
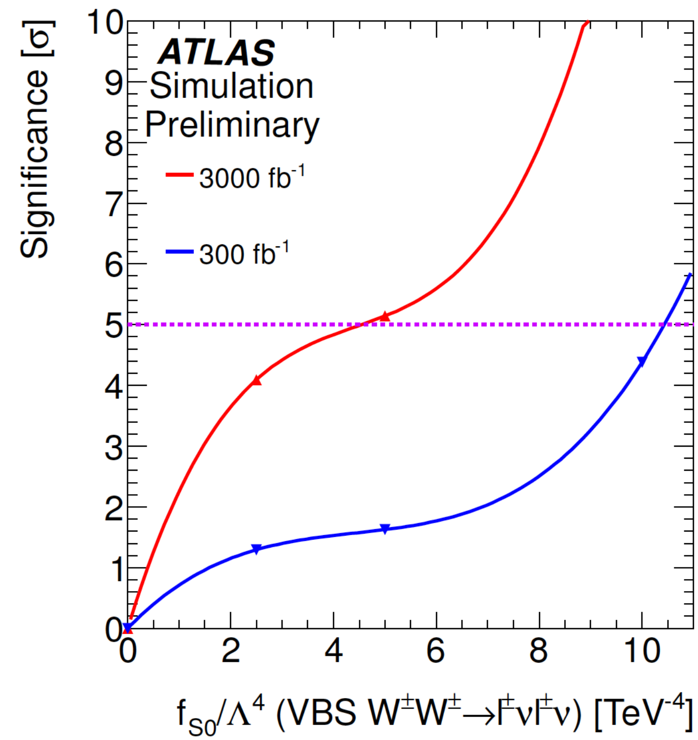




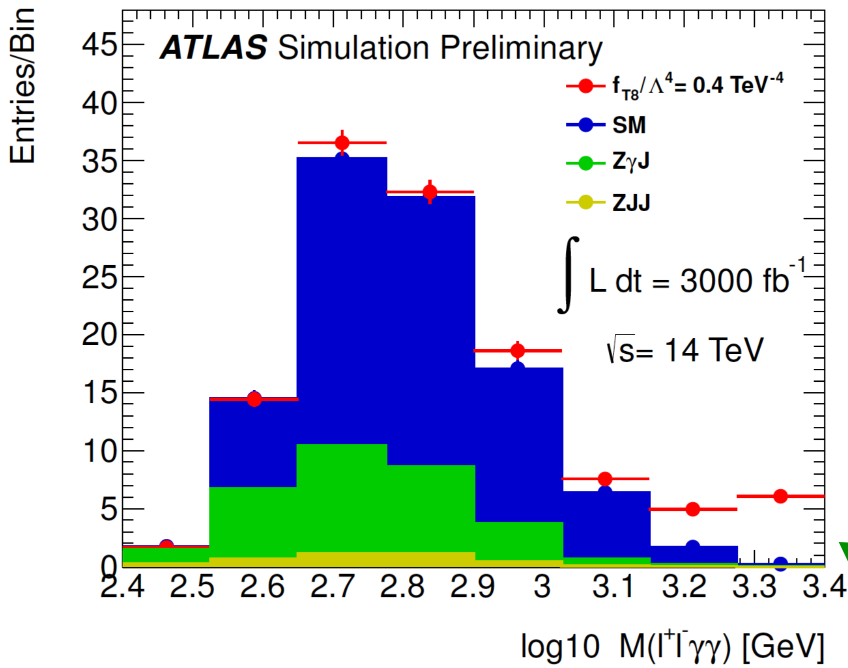
5σ discovery potential:

model	300 fb^{-1}	3 ab^{-1}
f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}

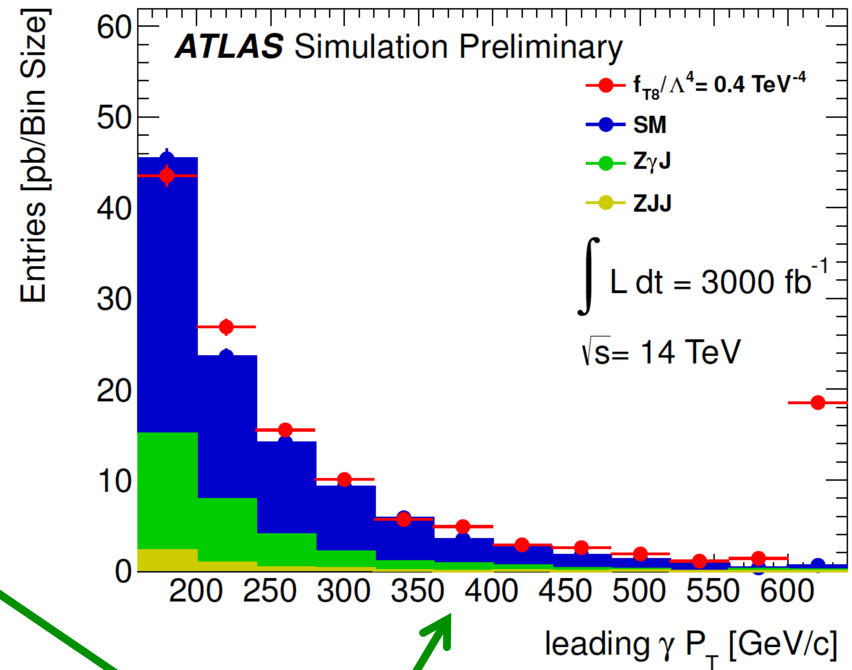
Vector Boson Scattering @ HL-LHC

Zγγ -> llγγ

FT8



FT8



5σ discovery potential:

	$300\ \text{fb}^{-1}$	$3000\ \text{fb}^{-1}$
f_{T8}/Λ^4	$0.9\ \text{TeV}^{-4}$	$0.4\ \text{TeV}^{-4}$
f_{T9}/Λ^4	$2.0\ \text{TeV}^{-4}$	$0.7\ \text{TeV}^{-4}$

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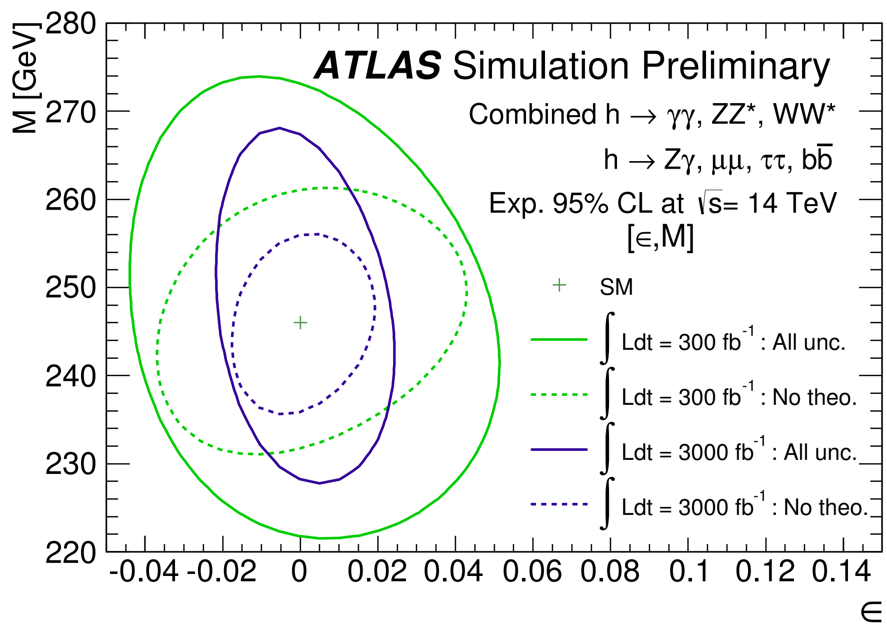
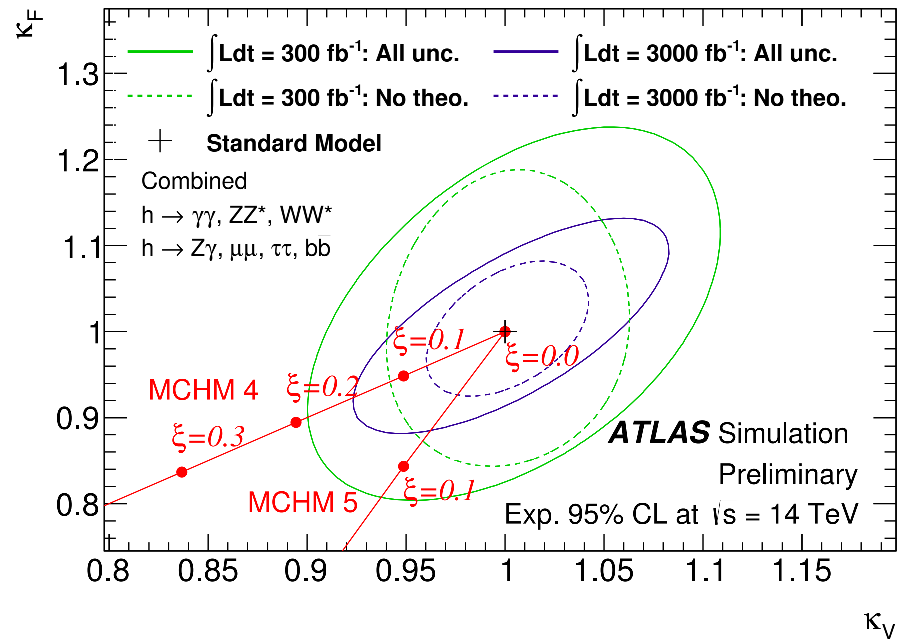
Higgs Couplings @ HL-LHC

Higgs coupling expectations using combined channels:

ATLAS-2014-017





- ∈ = mass coupling parameter between SM Higgs and other particles
- M = vacuum expectation value
- κ_F = scale factor from SM for fermion couplings beyond SM
- κ_V = scale factor from SM for the vector boson couplings beyond SM

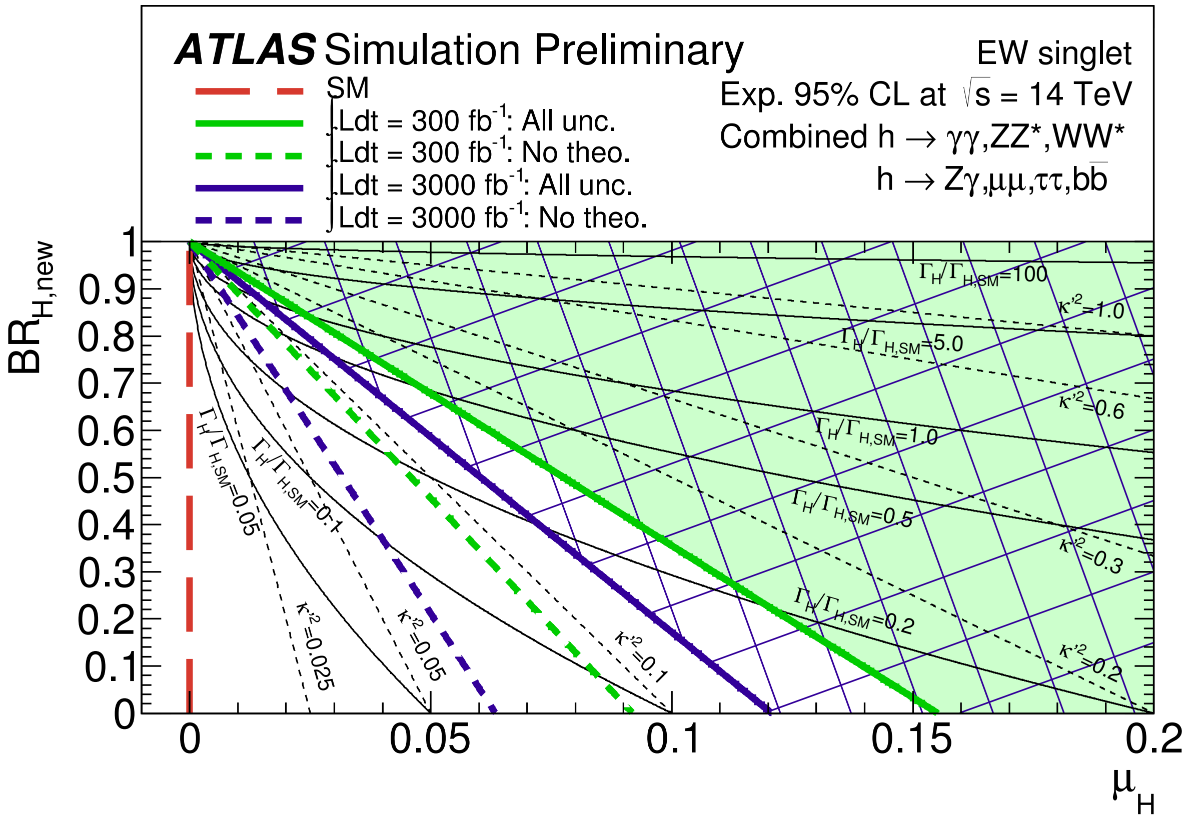
- Minimal Composite Higgs Model (MCHM)
  - Assumes the Higgs boson is a pseudo-Nambu-Goldstone boson instead of an elementary particle
    → Modifies the Higgs couplings to vector bosons and fermions

Heavy Higgs @ HL-LHC

ATLAS-2014-017

Heavy Higgs through an additional electroweak singlet:

- for modified couplings and widths

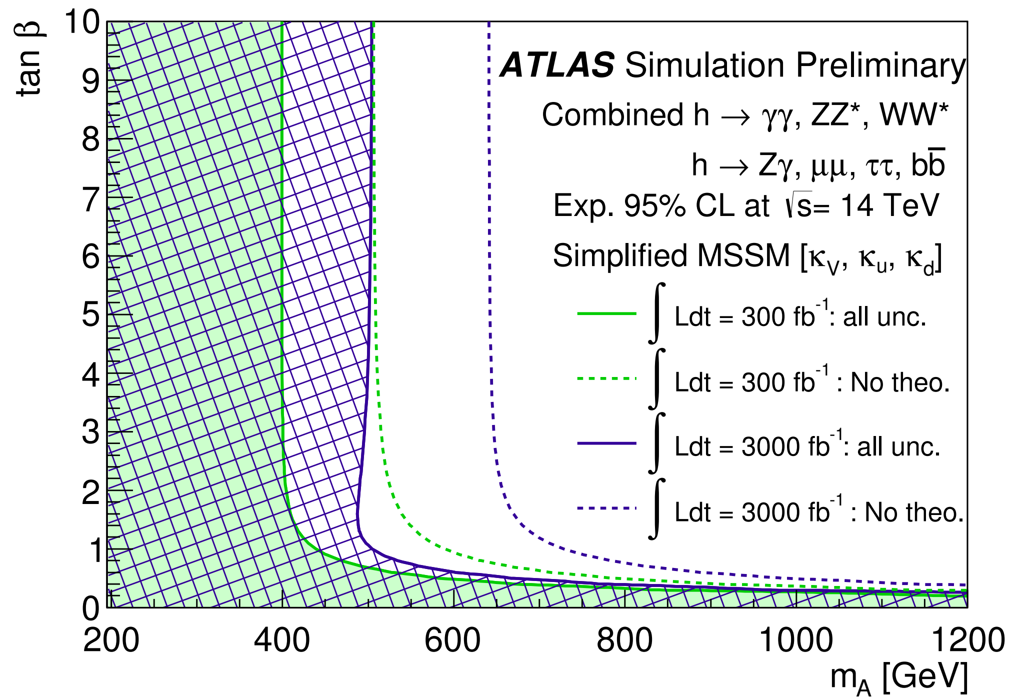


Coupling	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
κ'^2	0.17	0.10	0.13	0.06

ATLAS-2014-017

Minimal Supersymmetric Standard Model (MSSM):

- mixing angle vs. mixing strength
- SM decoupling limit is $m_A \rightarrow \infty$



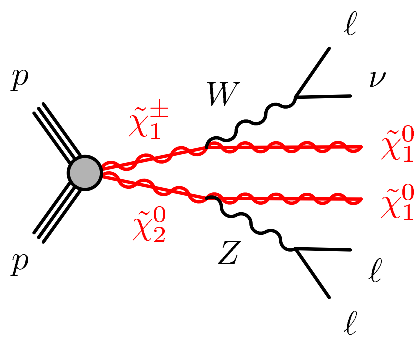
Limits with (without) theory uncertainties:

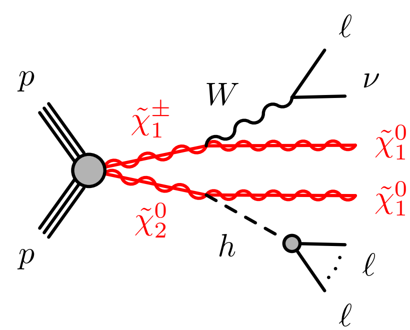
	300 fb^{-1}	3000 fb^{-1}
m_A	> 390 GeV (490 GeV)	> 480 GeV (640 GeV)

SUSY @ HL-LHC

Search for R-parity conserving SUSY: charginos and neutralinos

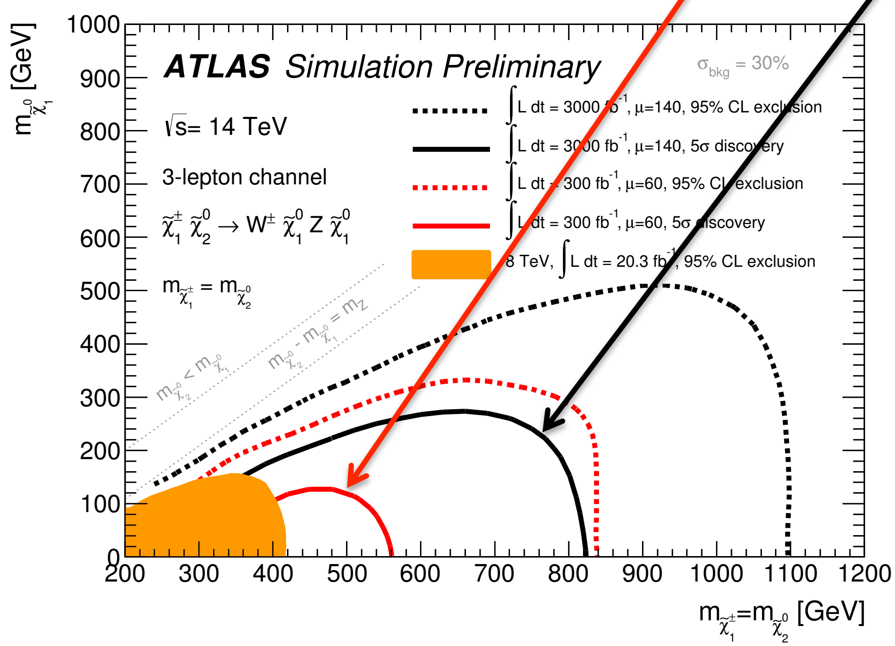
ATLAS-2014-010

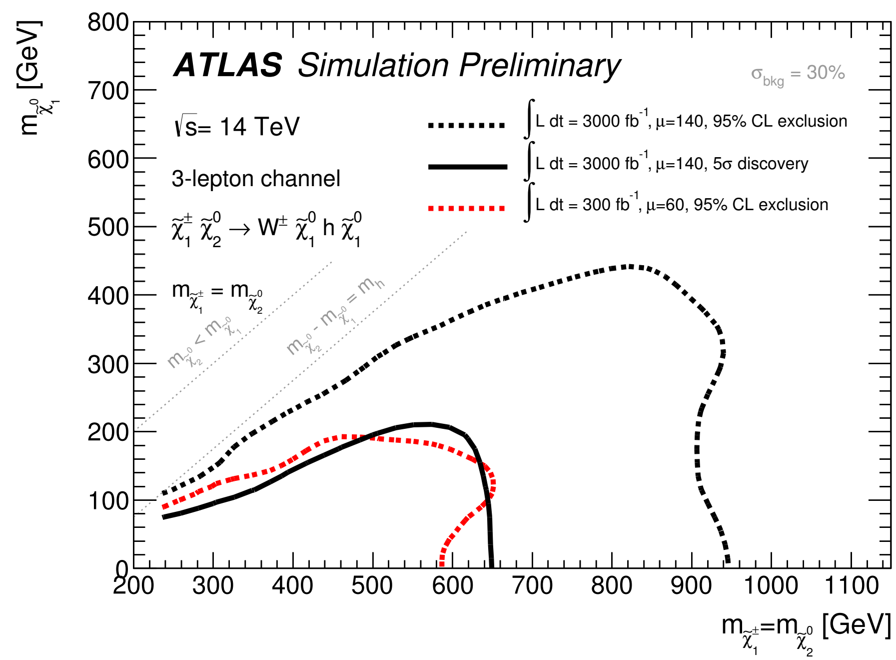




300 fb^{-1}

3,000 fb^{-1}

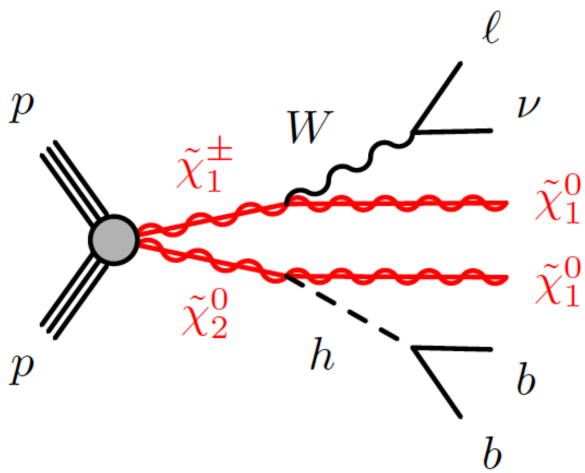


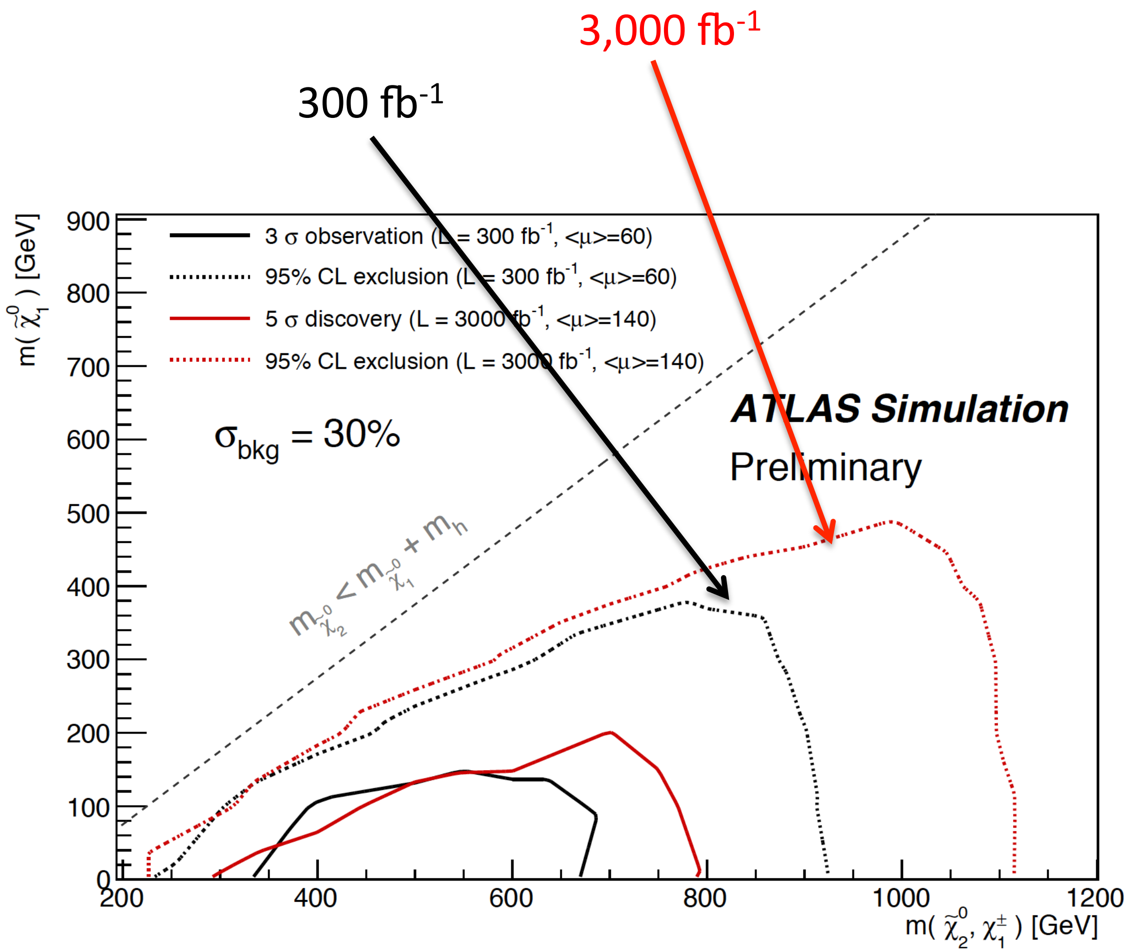


SUSY @ HL-LHC

ATLAS-2015-032

SUSY: chargino and neutralino via W boson and SM Higgs and bb final state

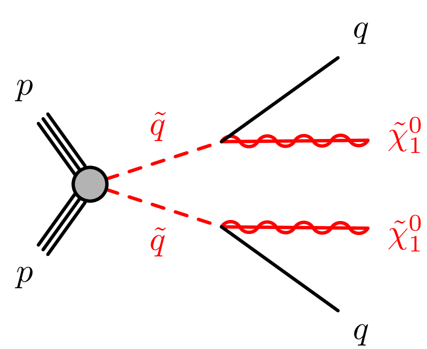


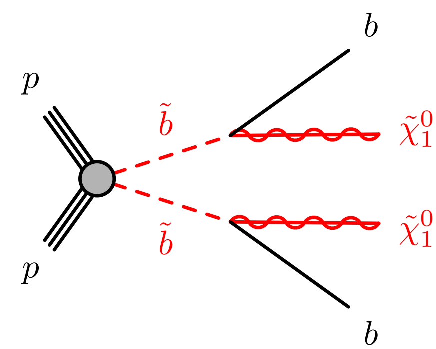


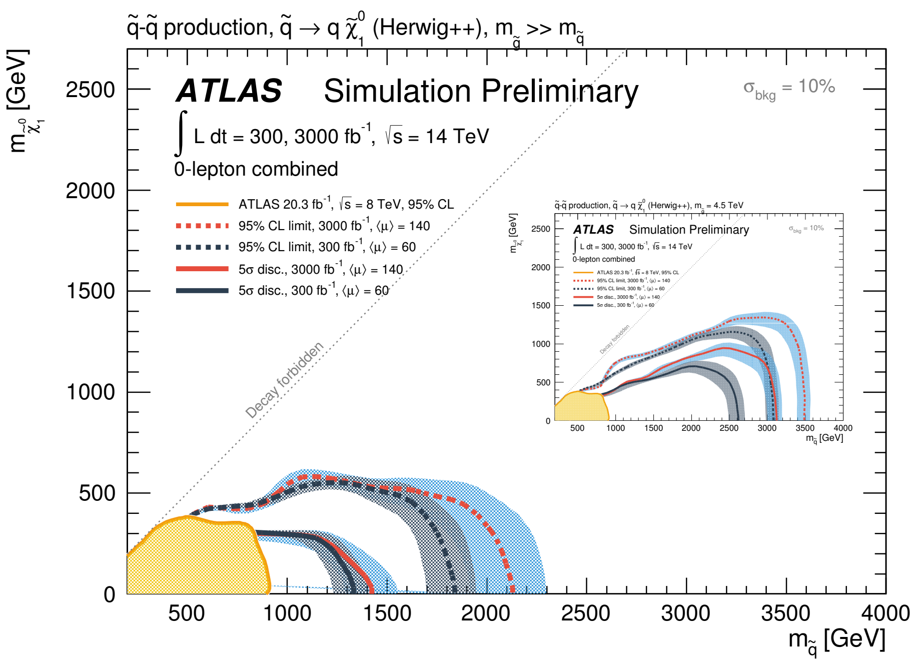
SUSY @ HL-LHC

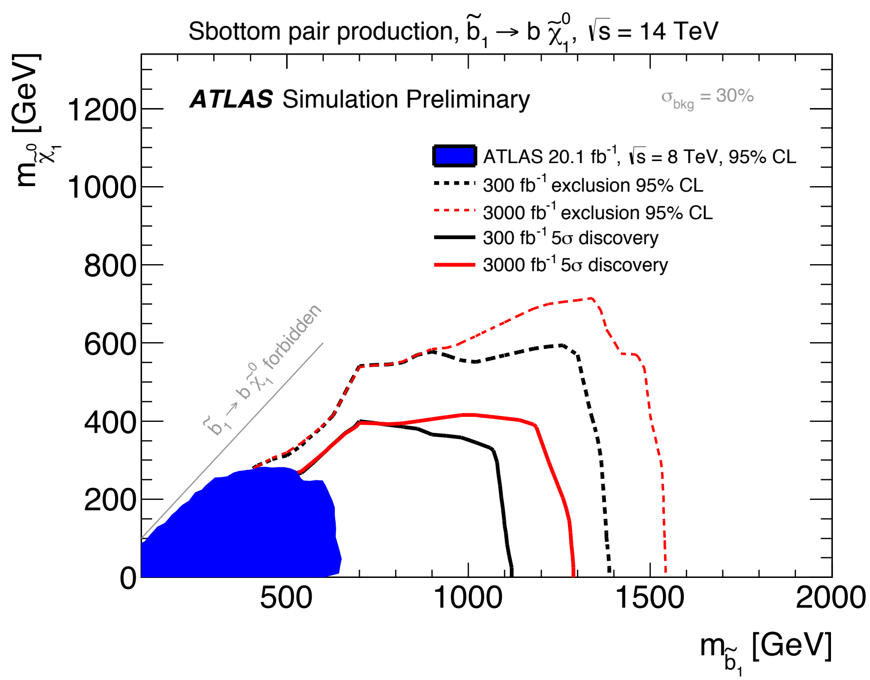
ATLAS-2014-010

SUSY: squark and sbottom production:





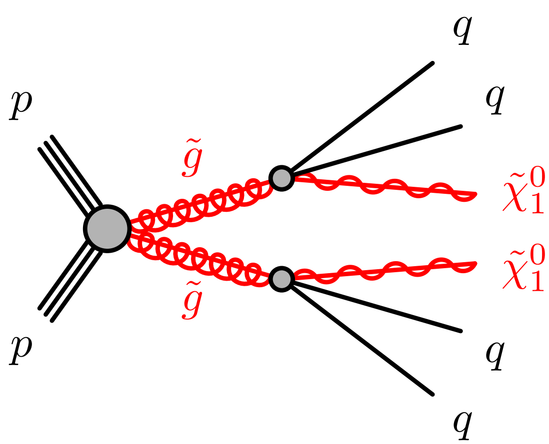


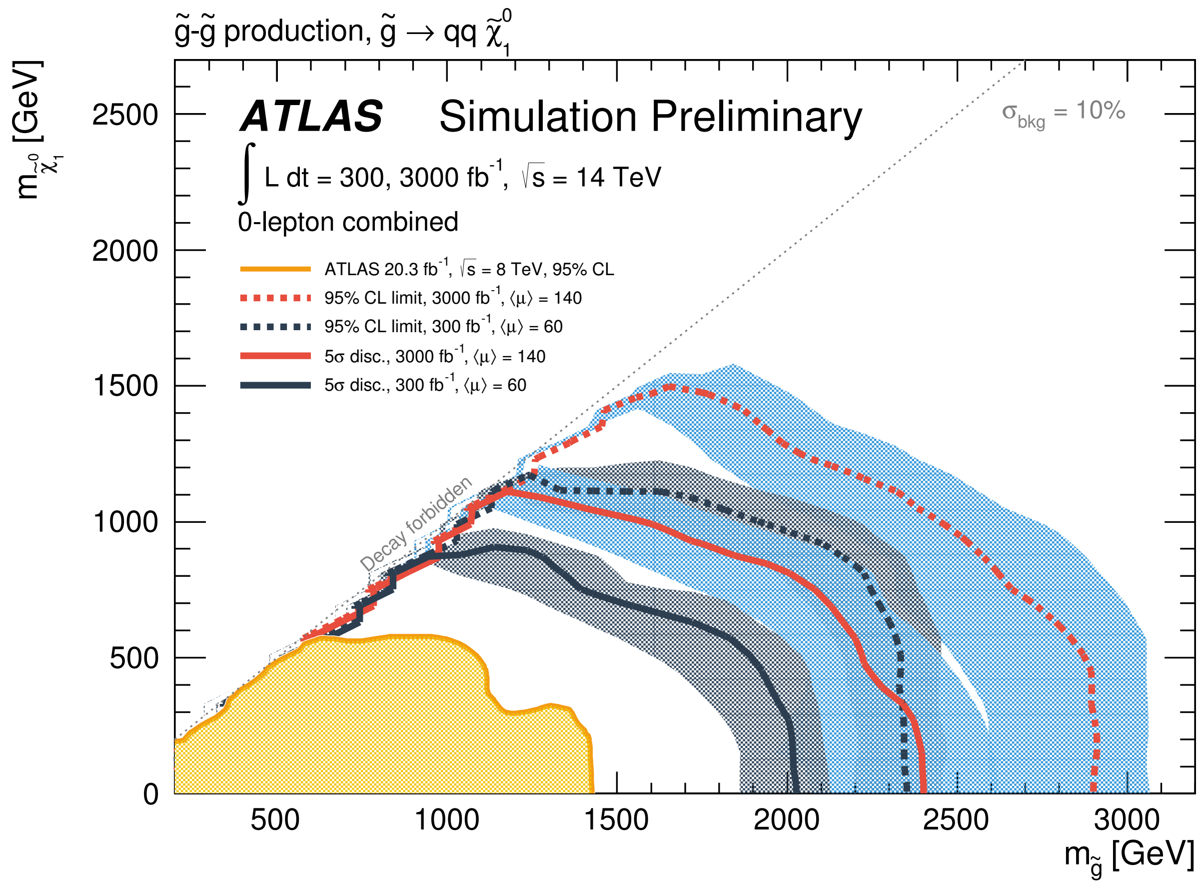


SUSY @ HL-LHC

ATLAS-2014-010

SUSY: gluino production:

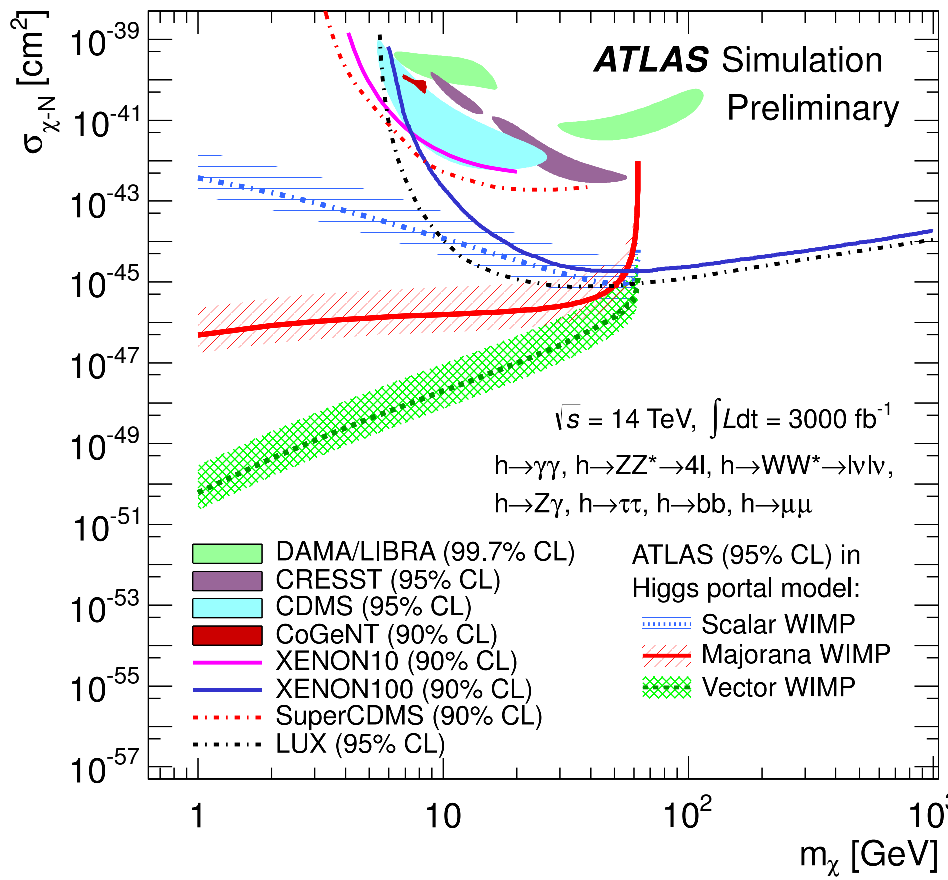




Dark Matter @ HL-LHC

Argonne NATIONAL LABORATORY

Higgs Portal: WIMP interacts very weakly with the SM particles except the Higgs
WIMP-nucleon scattering cross-section vs. mass of dark matter particle:



ATLAS-2014-017

Limits with (without) theory uncertainties

	$300\ fb^{-1}$	$3000\ fb^{-1}$
BR_i	< 0.22 (0.19)	< 0.13 (0.09)

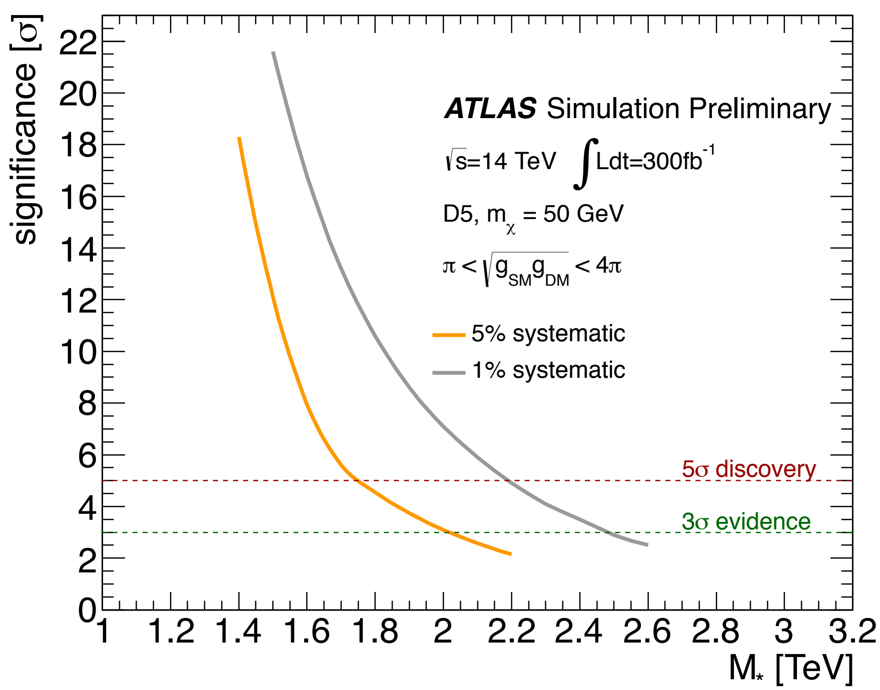
Dark Matter @ HL-LHC

ATLAS-2014-007

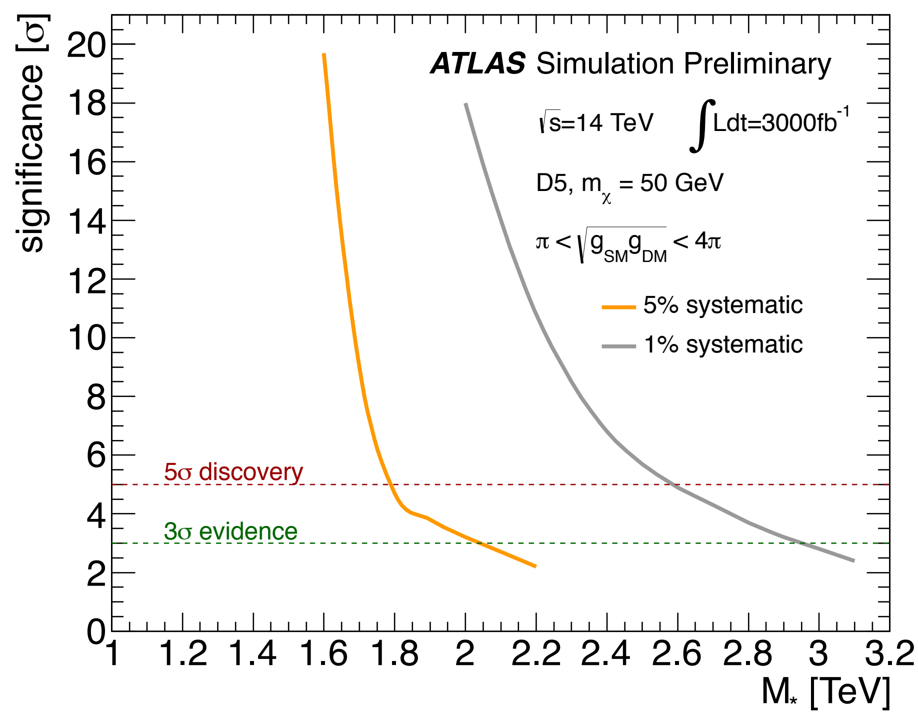
Dark Matter WIMP:

- WIMP pair production described by EFT
- M_* = suppression scale = $M_{mediator}/\sqrt{(g_{SM}g_{DM})}$

300 fb^{-1}



3,000 fb^{-1}



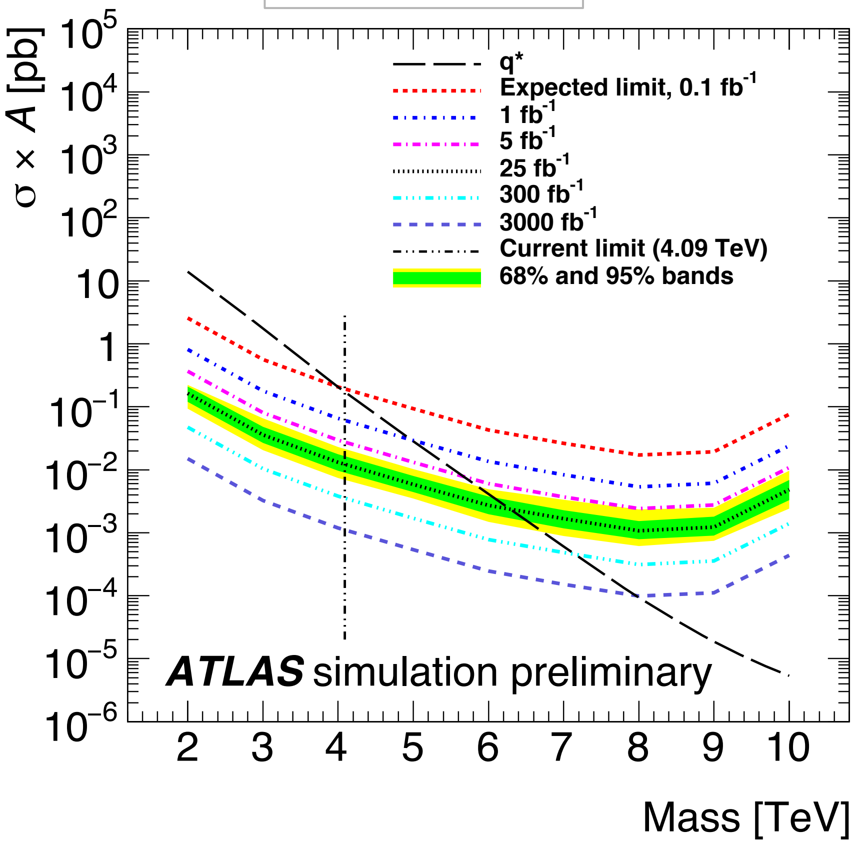
5σ discovery potential will benefit from a reduction in systematic uncertainty

Dijet Resonances @ HL-LHC

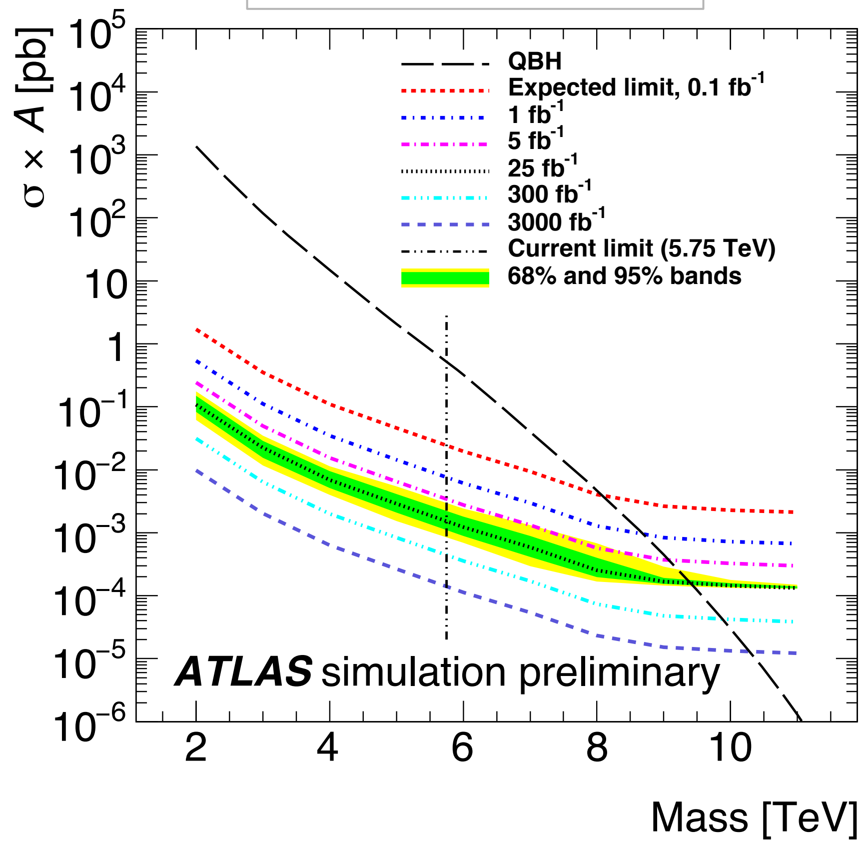
ATLAS-2015-004

Dijet Resonances:
Sensitive to technicolor, warped extra dimensions, Grand Unified Theories, …

Excited quarks



Quantum Black Holes



BSM @ HL-LHC

Summary:

- The discovery of the Higgs has launched a new era of unknown exploration
- HL-LHC will push the boundaries of known territory
- Many methods and channels to look for new physics
    - generic EFT
    - Heavy Higgs
    - Higgs doublets
    - SUSY
    - Dark Matter
    - Extra dimensions
    - Many more

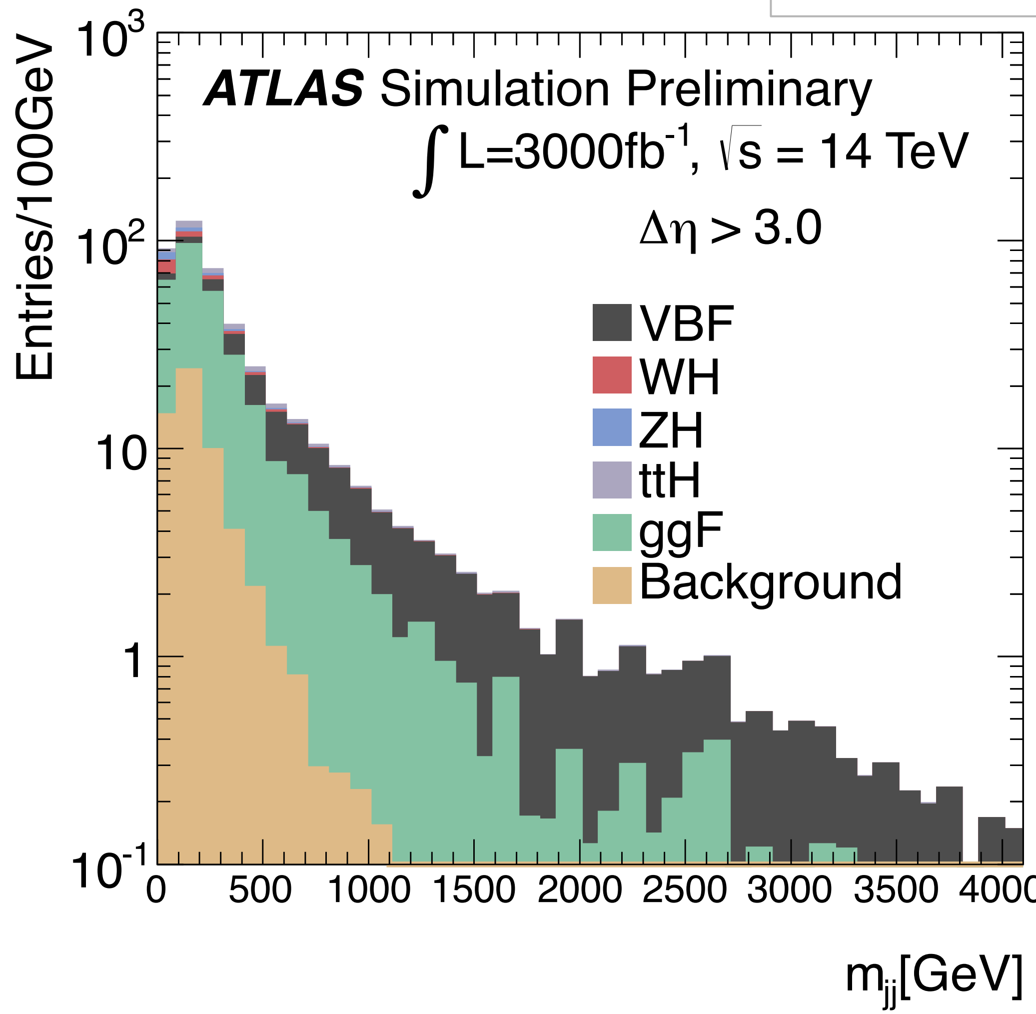
➔ Exciting road ahead!!

Backup

BSM @ HL-LHC

ATLAS-2013-014

VBF and VBS signatures



EFT Dim-8

Effective Field Theory Dimension-8 Operators: $\sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j}$

Higgs Field

$$\mathcal{O}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right]$$

Gauge Boson Fields

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \times \mathrm{Tr}\left[W_{\alpha\beta} W^{\alpha\beta} \right]$$

$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \times \mathrm{Tr}\left[W_{\mu\beta} W^{\alpha\nu} \right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \times \mathrm{Tr}\left[W_{\beta\nu} W^{\nu\alpha} \right]$$

$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta} ,$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu} ,$$

$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha} ,$$

$$\mathcal{O}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha} .$$

Higgs and Gauge Boson Fields

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu} W^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

$$\mathcal{O}_{M,2} = \left[B_{\mu\nu} B^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] ,$$

$$\mathcal{O}_{M,3} = \left[B_{\mu\nu} B^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] ,$$

$$\mathcal{O}_{M,4} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\mu \Phi \right] \times B^{\beta\nu} ,$$

$$\mathcal{O}_{M,5} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\nu \Phi \right] \times B^{\beta\mu} ,$$

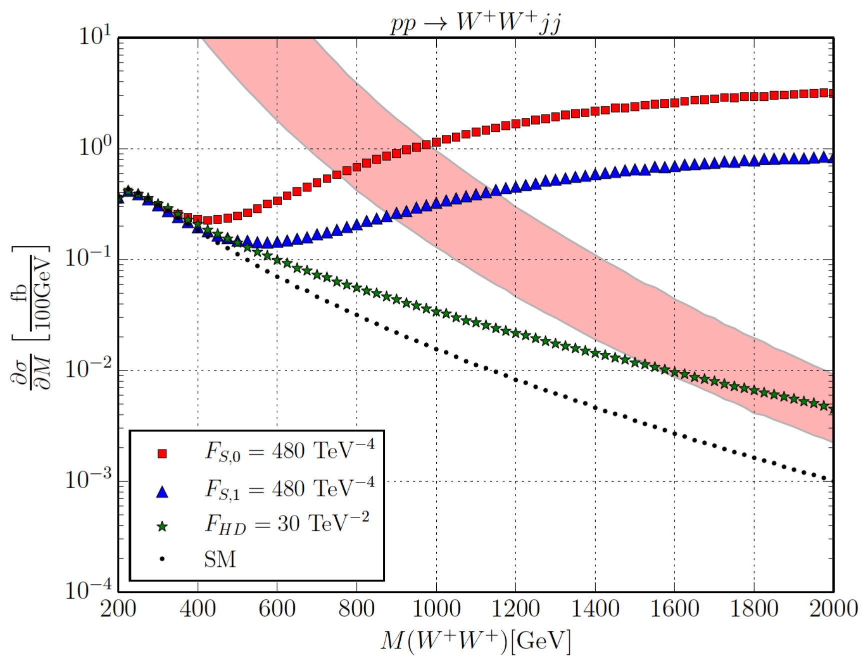
$$\mathcal{O}_{M,6} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\nu} D^\mu \Phi \right] ,$$

$$\mathcal{O}_{M,7} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu \Phi \right] ,$$

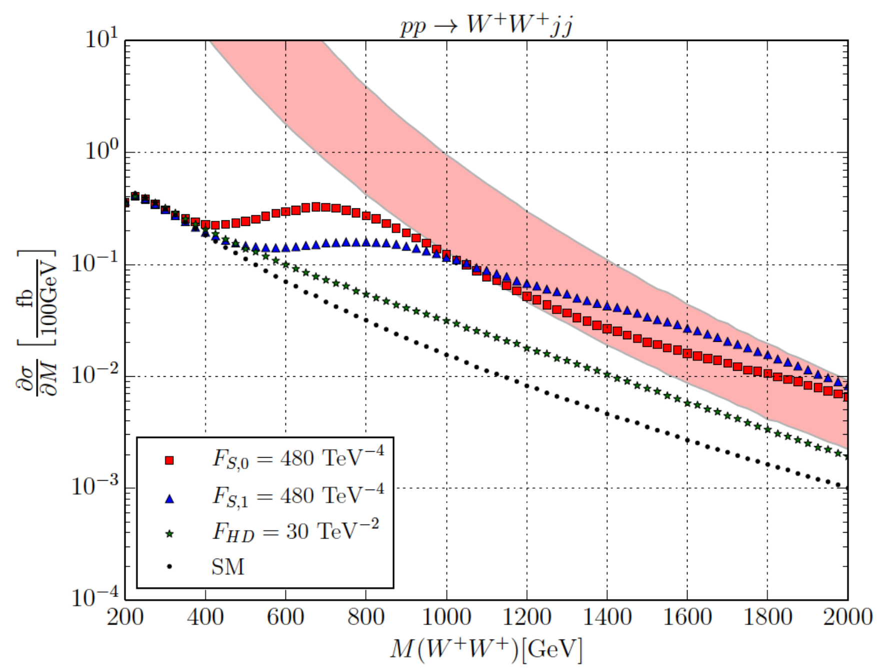
[1] Snowmass EWK arXiv:1310.6708

ssWW

No unitarization



K-matrix unitarization



W. Kilian Multi Boson Interactions Workshop 2014

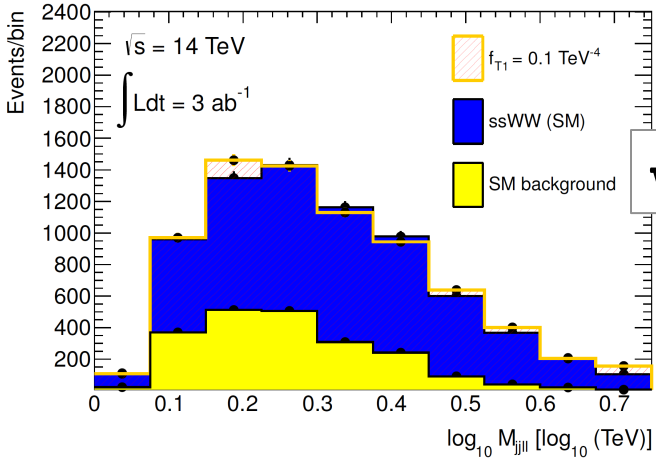
- Unitarity schemes play an important role in the higher dimension operators
- Different methods were employed in different studies to cope with the UV boundary including UV cut-off, UV form-factor, and K-matrix
- All methods introduce some model dependence
- Most studies presented here are without UV treatment for consistent comparison and model independence

FT1

$W^{\pm}W^{\pm} \rightarrow l\nu l\nu$

$FT1/\Lambda^4 = 0.1\ [TeV^{-4}]$

140 PU

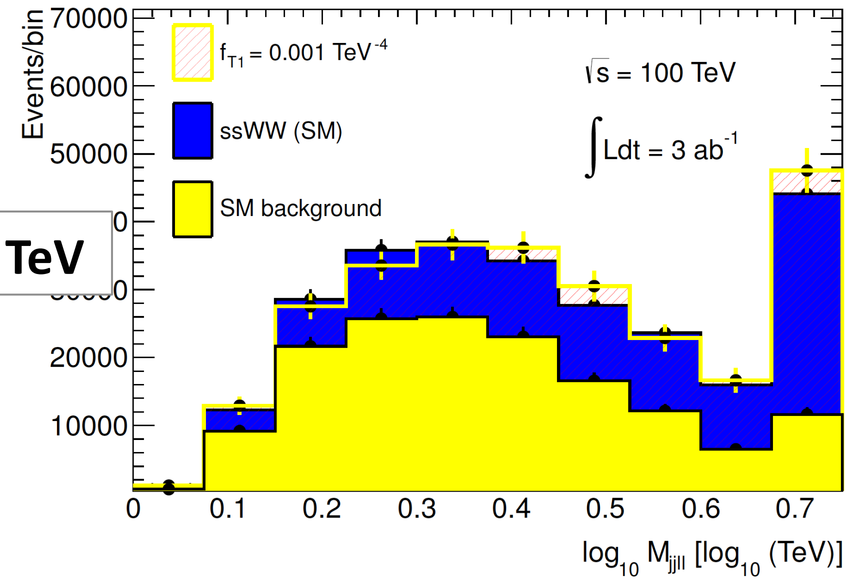


Significance = 4.2σ

√s: 14 -> 100 TeV

$FT1/\Lambda^4 = 0.001\ [TeV^{-4}]$

263 PU



Significance = 4.0σ

- Higher pp center-of-mass energy enhances high m_{jjll} spectrum in SM and new physics
- Significance remains about the same ~4σ (no UV cutoff applied)
  - Different pileup scenarios
  - No selection optimization

[2] Snowmass VBS arXiv:1309.7452v1

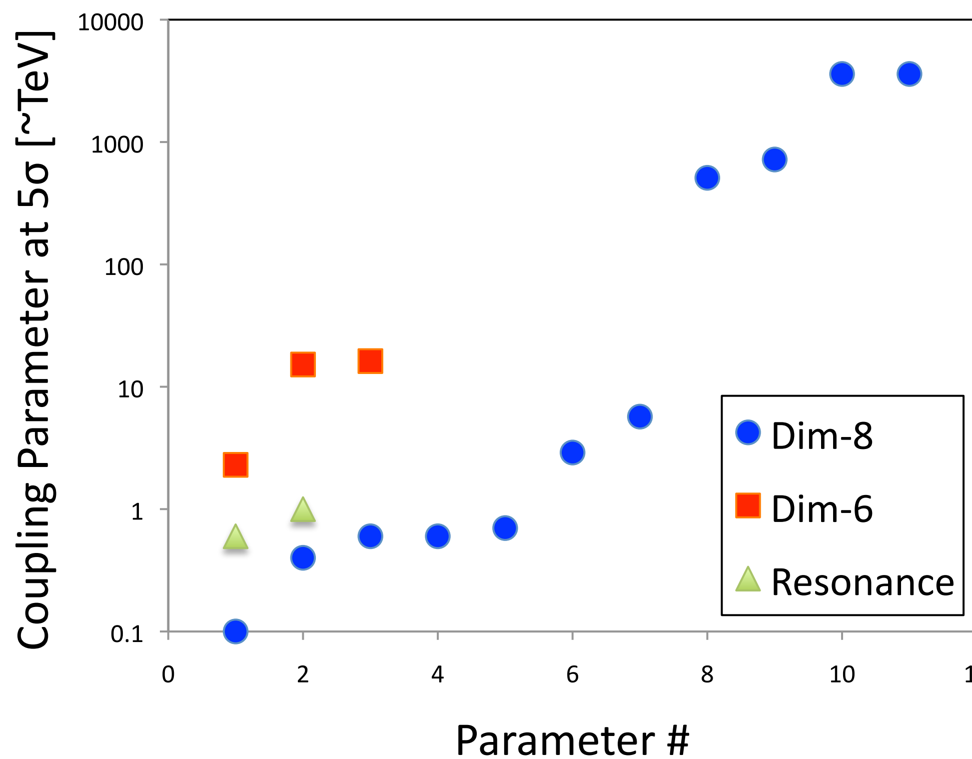
VBS @ HL-LHC

Comparison of ssWW sensitivity to other VBS and Triboson Channels:

Channel	Parameter (#)	Coupling Parameter for 5σ
ssWW	FT1 (1)	0.1
Zγγ	FT8 (2)	0.4
WZ	FT1 (3)	0.6
WWW	FT0 (4)	0.6
Zγγ	FT9 (5)	0.7
WWW	CWWW (1)	2.3
ZZ	FT8 (6)	2.9
ZZ	FT9 (7)	5.7
WZ	CΦd (2)	15.2
ZZ	CΦW (3)	16.2
Zγγ	FM2 (8)	510
Zγγ	FM3 (9)	720
Zγγ	FM0 (10)	3600
Zγγ	FM1 (11)	3600
WW	m_Resonance (1)	0.6
ZZ	m_Resonance (2)	1

@ 14 TeV & 3,000 fb^{-1}

5σ Discovery Potential:



[2] arXiv:1309.7452v1
[3] ATLAS-PHYS-PUB-2013-006
[4] ATL-UPGRADE-PUB-2012-006
[5] arXiv:1407.4922v1

SUSY @ HL-LHC

ATLAS-2014-010

Search for R-parity conserving SUSY: charginos and neutralinos