HL-LHC Physics: ATLAS

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On behalf of the ATLAS collaboration

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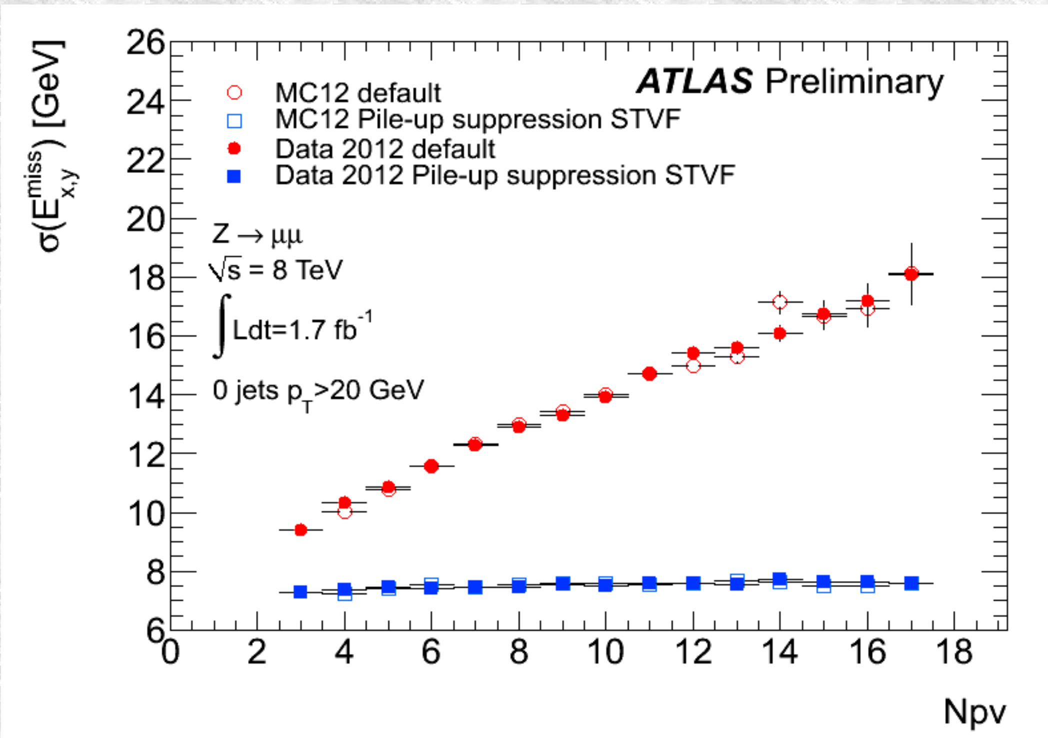
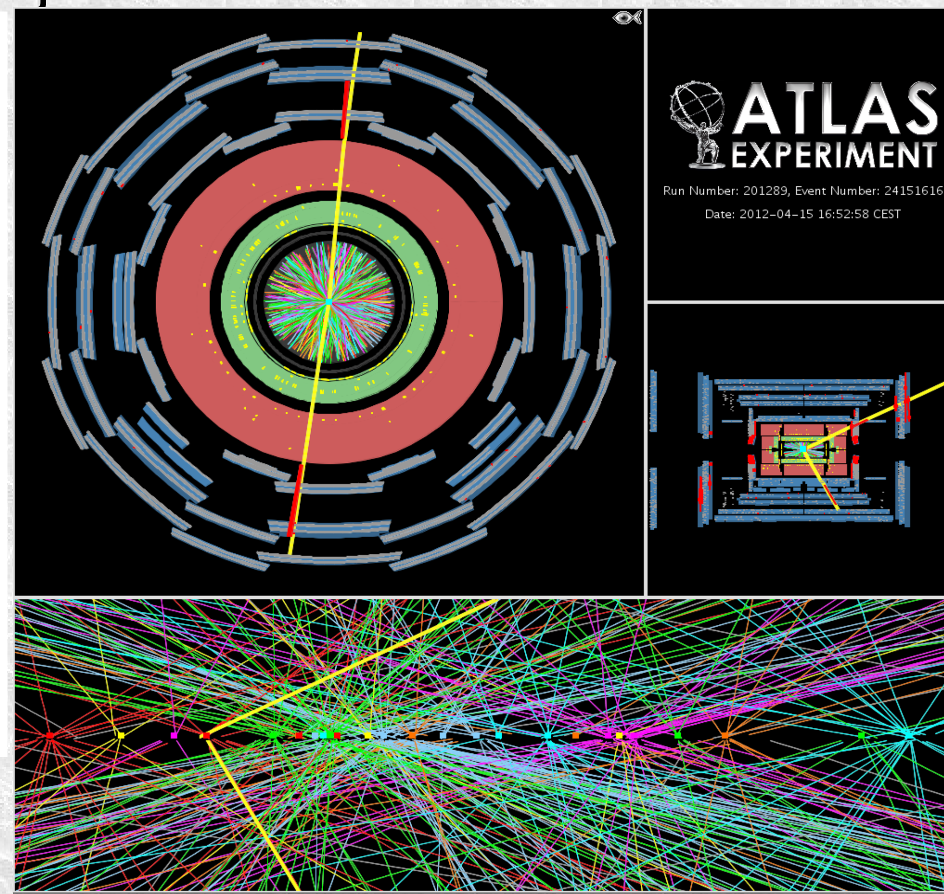
Benchmark Scenario

- Approved running to deliver 300 fb^{-1} by ~2021
  - With 40x Higgs production so far reported on
- Post LS3 operation at $5x10^{34}cm^{-2}s^{-1}$ (with lumi levelling)
  - 25 ns bunch spacing
  - 140 events per bunch crossing
  - 3000 fb^{-1} over 10 years
- Significant detector upgrades required:
  - ITK all-silicon detector replacing current tracker
  - L0/L1 hardware trigger 200KHz output
  - Major readout and DAQ work
  - Achieve similar detector performance in harsher environment
- Trigger is a key component:
  - multi-object triggers essential
  - Thresholds not too dissimilar to today
    - Mandated by need to study Higgs-like boson
- LOI for ATLAS HL-LHC (Phase 2) upgrades in preparation

Event complexity

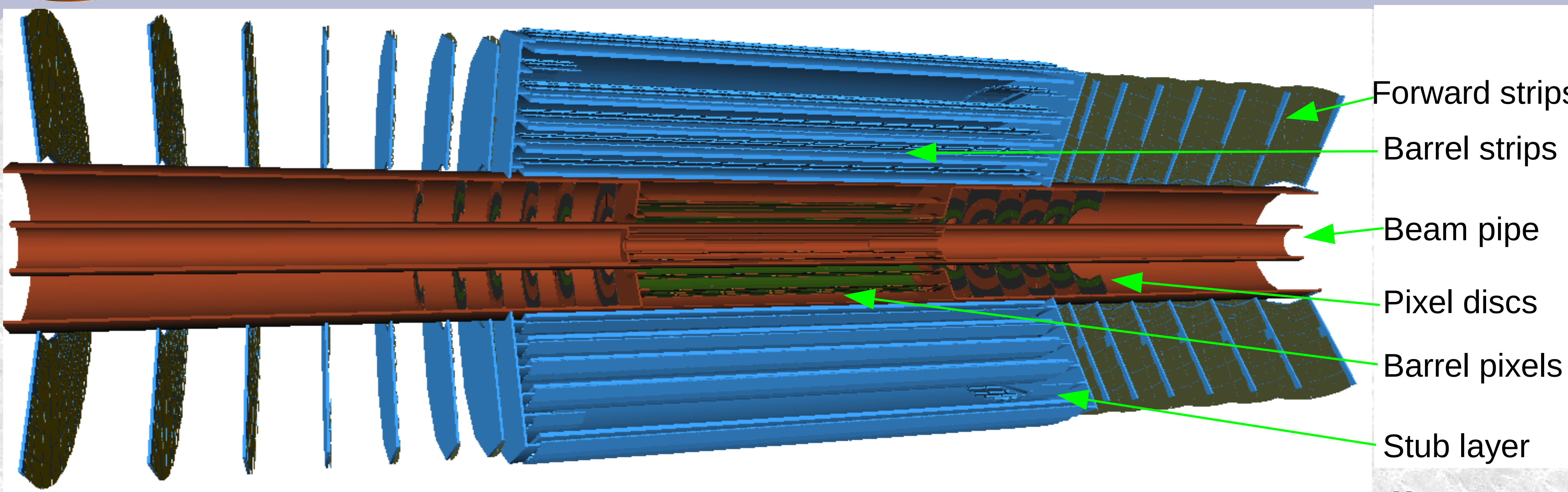
- ATLAS was designed for 23 events per bunch-crossing
  - And continues to do an excellent job with 35





- But it will not handle 140 events of pileup

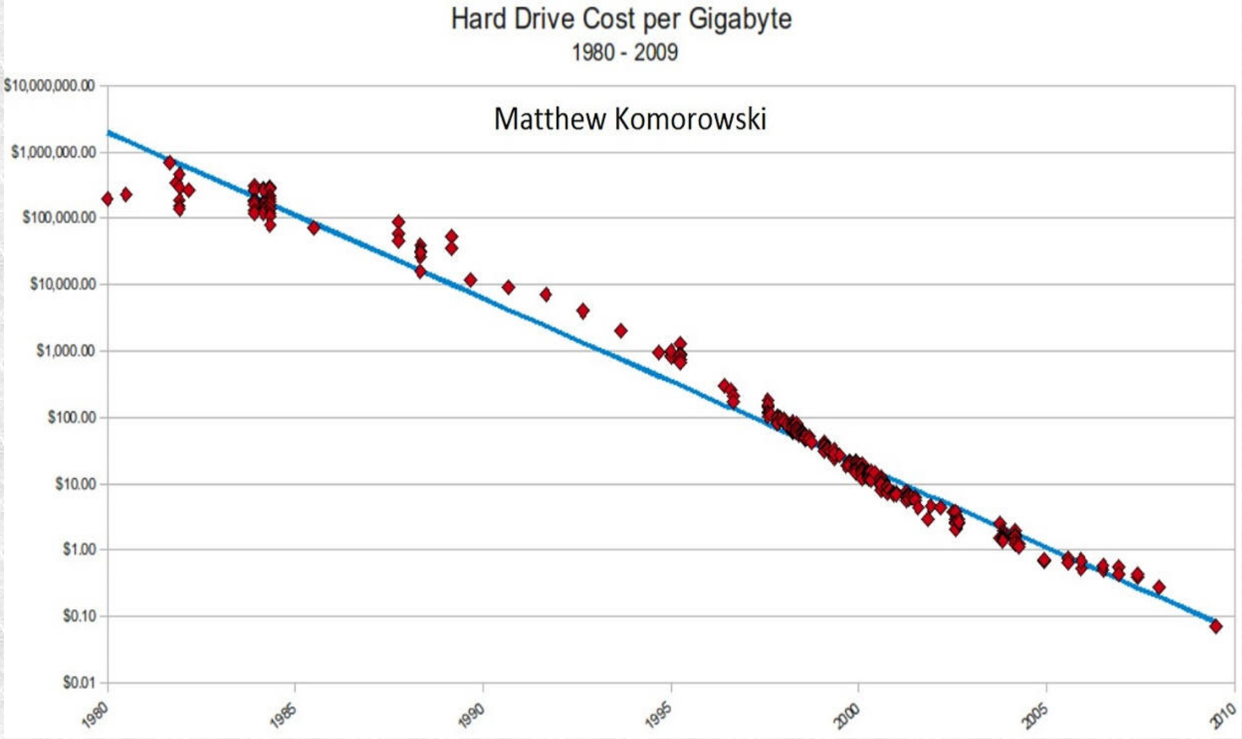
Inner Tracker Replacement



- All-silicon tracker to meet the needs of 150 events pileup
- Tracker designs are well in hand
  - much work to do but it looks achievable
- Physics object performance retained through granularity
  - Also contributes to new L1 track trigger
- Current studies assume that single object performance is comparable to today

Can we handle the data?

- Event complexity will increase (data per bunch crossing)
- The physics goals will require higher trigger rates

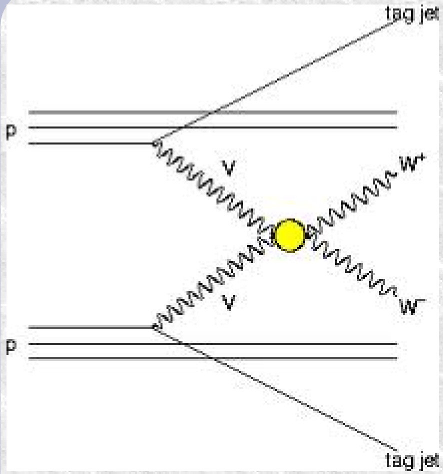


- However Moores Law will help - in ten years disk costs have dropped by a factor 100
- Gives confidence that the computing needs can be met

HL-LHC Physics goals

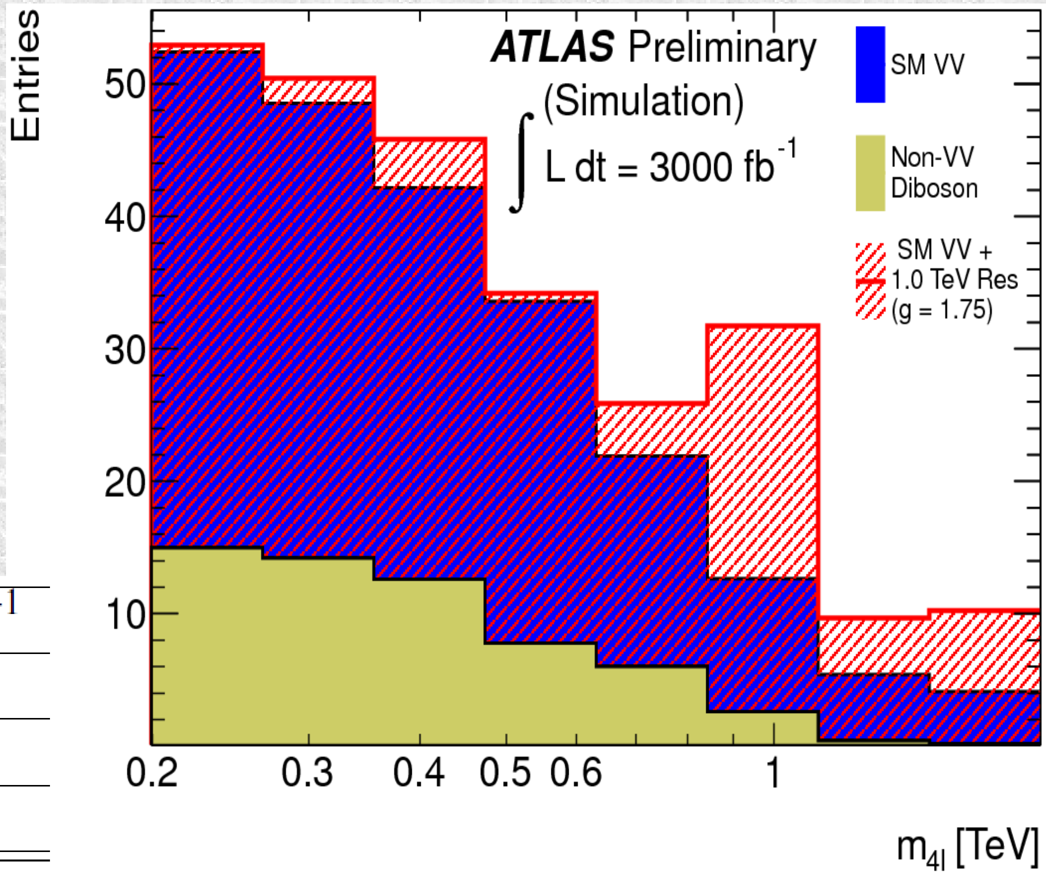
- HL-LHC will be the only machine exploring above 1 TeV
  - There will be a wide physics programme
  - Curent studies focussed on a subset of key items
- Standard Model
  - Vector boson scattering at high mass
- Exotics
  - Z'
- SUSY
  - Squarks/gluinos
  - Third generation squarks
  - Charginos/Neutralinos
- Higgs
  - Couplings
  - Self-coupling
  - CP studies in backup

Vector boson scattering: ZZ

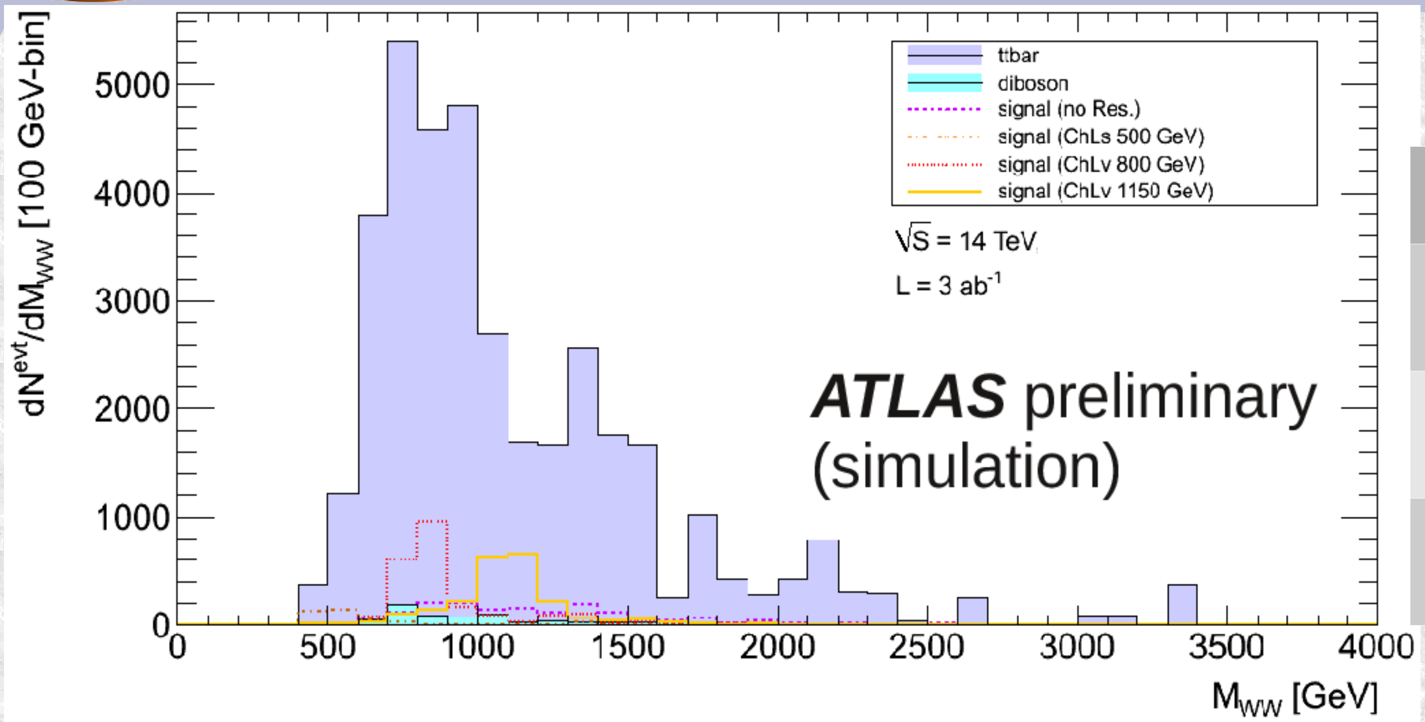


- Vector boson scattering fundamental test
  - Higgs regularises the scattering SM cross-section
  - But there any many other possibilities
- WHIZARD used to model new high-mass resonance
- ZZ decay to four leptons
- Require m_{jj}>1TeV
- Clean peak with 3000fb^{-1}

model	300 fb^{-1}	3000 fb^{-1}
$m_{resonance}$ = 500 GeV, g = 1.0	2.4σ	7.5σ
$m_{resonance}$ = 1 TeV, g = 1.75	1.7σ	5.5σ
$m_{resonance}$ = 1 TeV, g = 2.5	3.0σ	9.4σ



Vector boson scattering: WW



Following:
Phys. Rev. D62 (2000) 055011

	$300fb^{-1}$	$3000fb^{-1}$
500GeV scalar	0.6σ	1.6σ
800GeV vector	3.3σ	10.4σ
1150GeV vector	3.9σ	12.4σ

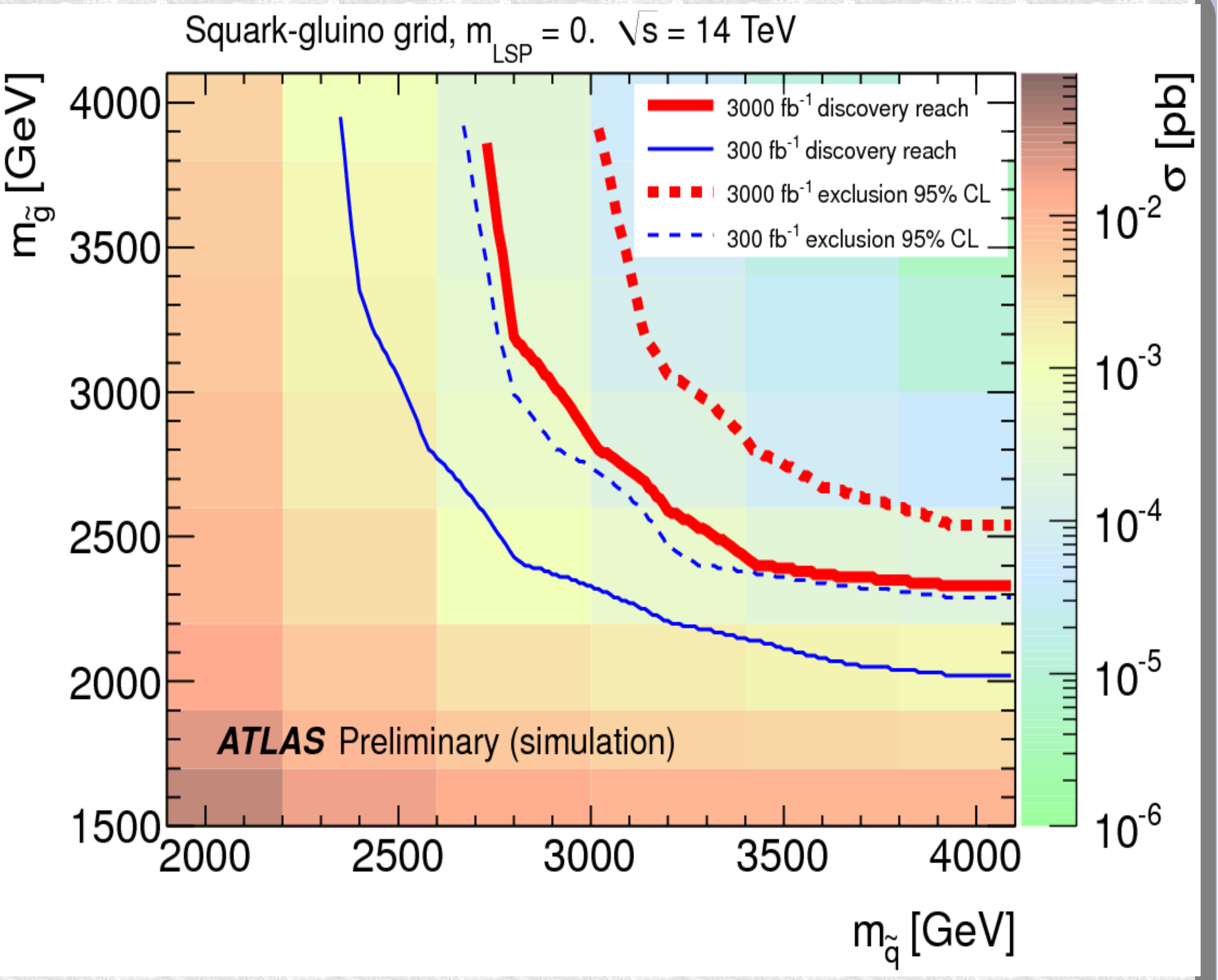
- Semileptonic WW→lνjj mass
  - 1 missing neutrino can be reconstructed →mass measurement
- Request 2 tag jets, lepton plus fat jet
  - Need for forward jet tagging
- Allows O(10σ) measurement of a ~TeV vector resonance
- Dileptonic mode allows sensitive limits

SUSY searches

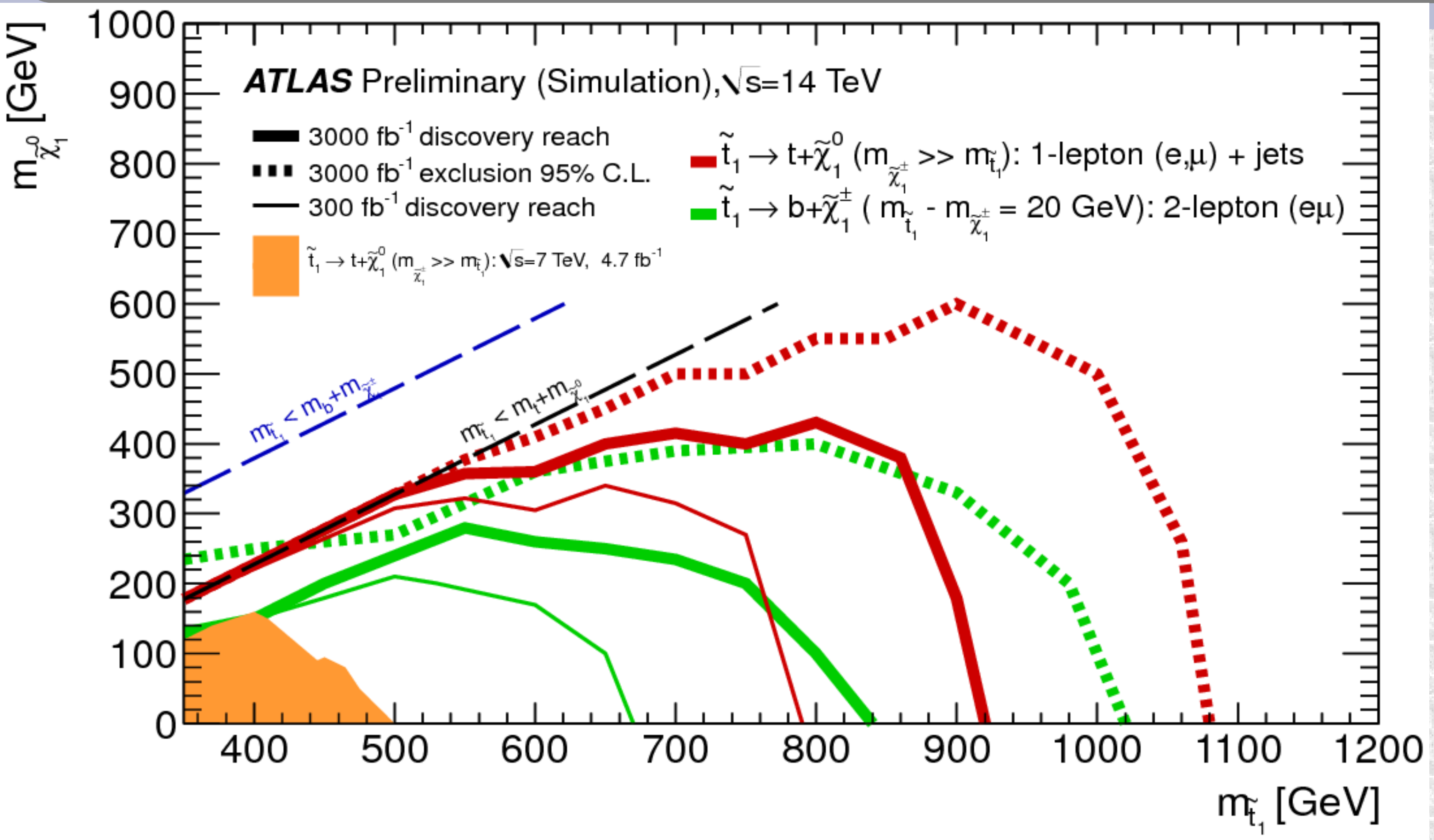
- So far there has been no sign of supersymmetry at LHC
  - There are a lot of constraints on weak-scale SUSY
  - But only a tiny fraction of the total LHC data has been studied
    - 3rd generation squarks have low cross-sections
    - Colourless SUSY particles lower still
- If we find it:
  - We have a large set of particles to study in detail
  - Thus a SUSY discovery will mandate more luminosity
- If we do not find it by 2020
  - HL-LHC offers a ~25% increase in mass reach
    - e.g. Hundreds of GeV more
  - Exploring a space no other machine will explore for decades

Squarks and Gluinos

- HL-LHC gives tight limits:
  - 3TeV squarks
  - 2.5TeV gluinos
- 400 GeV rise in sensitivity c/f $300fb^{-1}$
  - For discovery or exclusion
- This plot assumes common masses and a massless neutralino



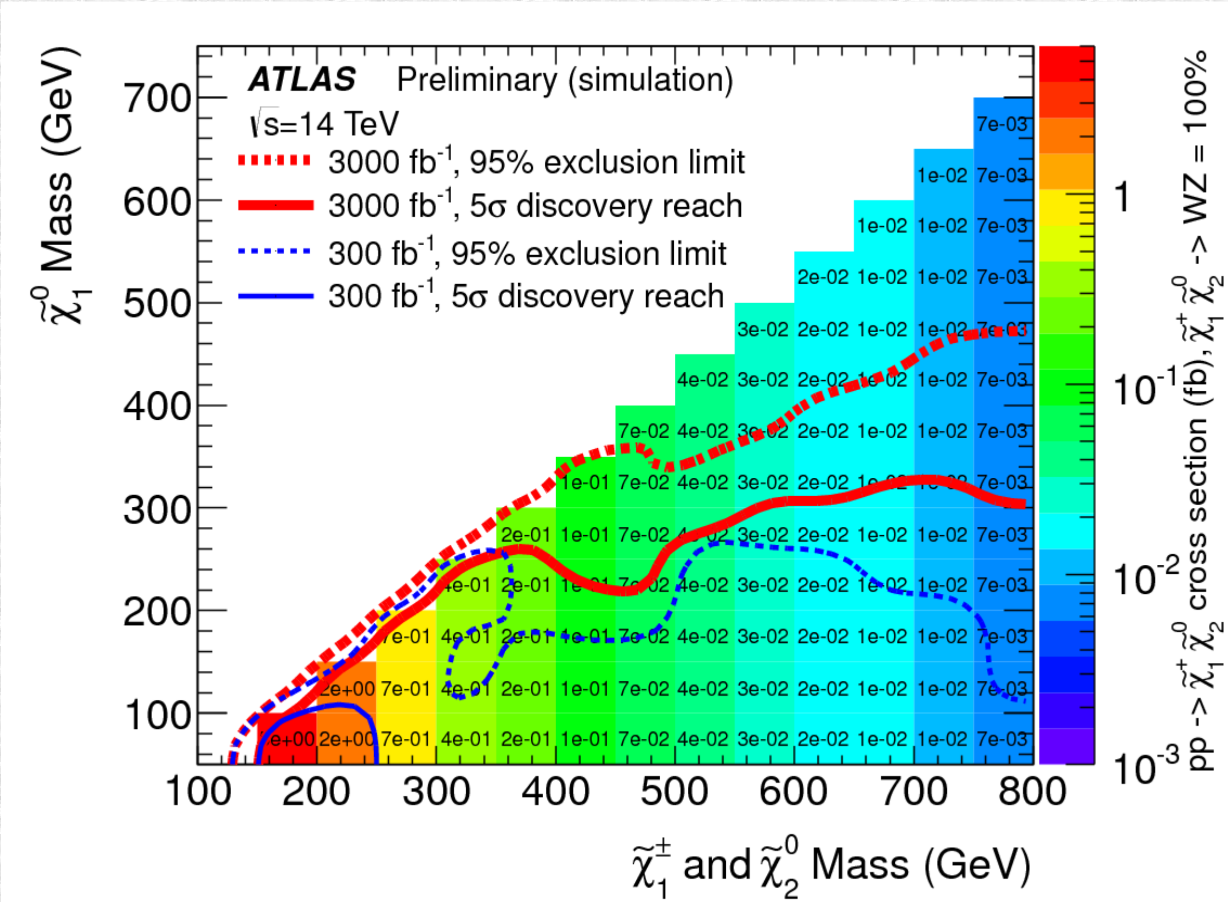
Searches for stop



- Search for $\tilde{t}\rightarrow t+\chi_1^0$ and $\tilde{t}\rightarrow b+\chi_1^\pm$
  - One lepton (top) and two lepton (chargino) modes
- Naturalness requires sub-TeV $\tilde{t}_1$ - explored by HL-LHC

Gaugino sector

- Search for $\chi_1^{\pm}\chi_2^0$ in decay to $W\chi_1^0 Z\chi_1^0$
- Three leptons and excess E_t^{miss} c/f SM WZ production
- Background also from top
- 3000 fb^{-1} hugely extends discovery reach
  - This is rate limited



- Similar increase 450→950GeV in sensitivity in $W\chi_1^0 h\chi_1^0$ decay mode

Exotics Searches

- Searches for $t\bar{t}$ resonances or Z' to leptons can exploit the high luminosity effectively:

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\text{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

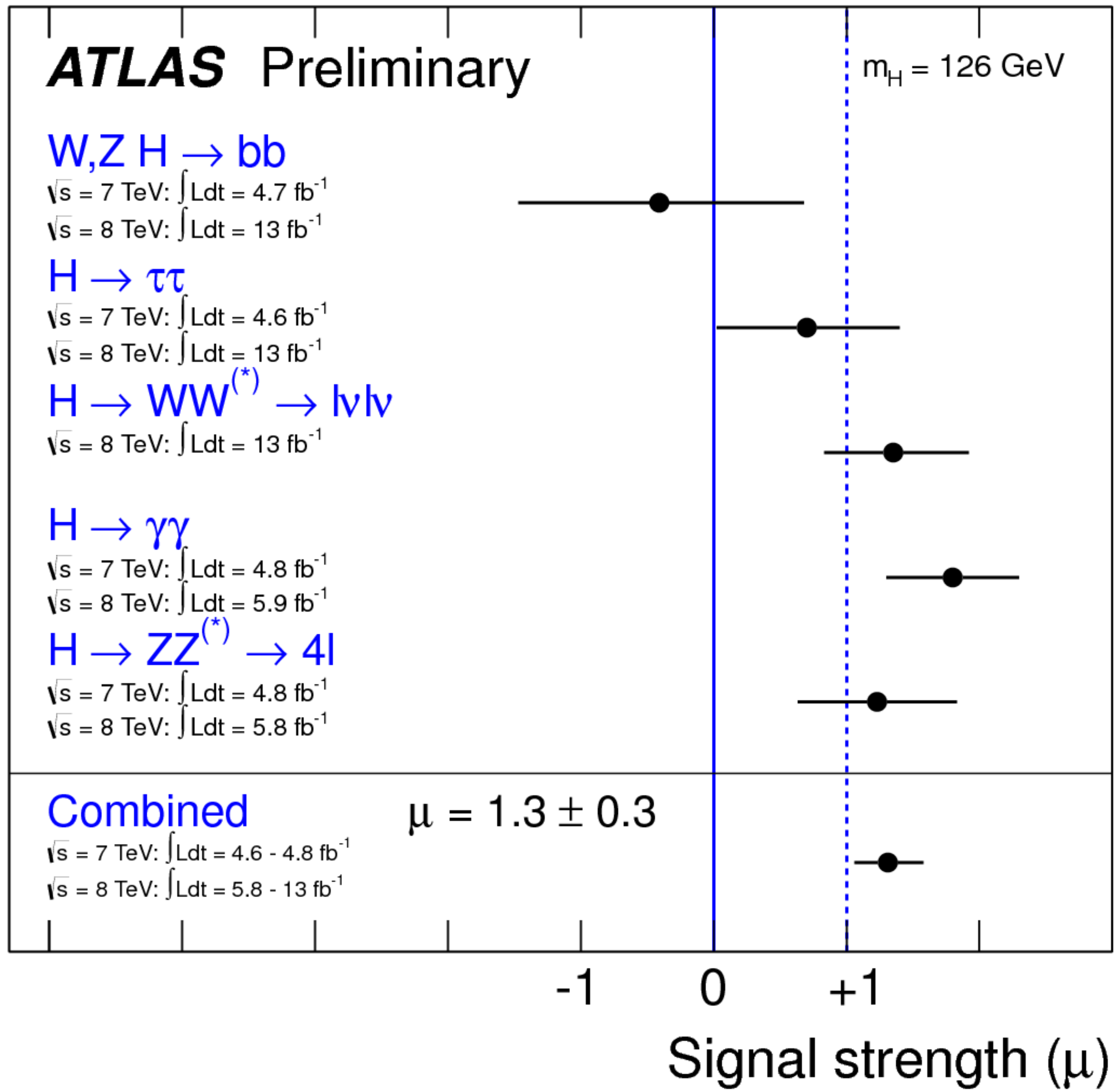
- Main challenges are
  - Reconstructing highly boosted top
    - Very dense jet cores expected
  - Ensuring lepton measurement at high p_T
    - Leakage from calorimeter could be an issue
    - Muon alignment critical

The Higgs search

- 1964 Brout & Englert, Higgs, Guralnik, Hagen & Kibble,
- 1973 Experimental acceptance of the 'Standard Model'
- 1983 Discovery of W and Z bosons
- 1989-95 LEP studies Z's and rules out m_H<53 GeV
  - And indicates that m_H<300GeV
- 2000 LEP limits reach 114.4 GeV
- 2012 LHC finds new particle at 126 GeV
  - Consistent with the Higgs
- 2020 Six σxB rates known to 40% or better
- 2030 Seven σxB rates known to 20% or better
  - HHH measured to 3σ combining ATLAS+CMS

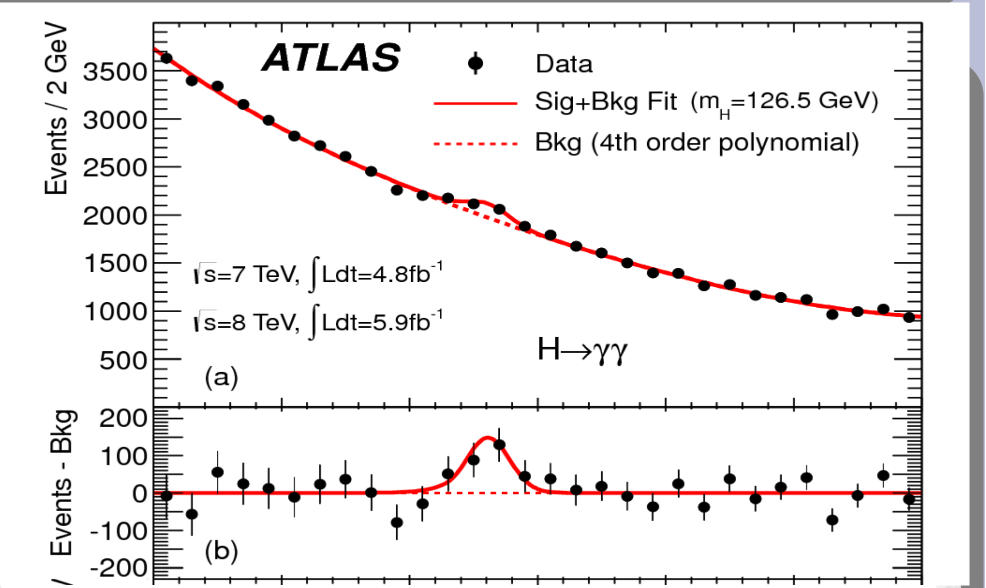
Higgs decay modes

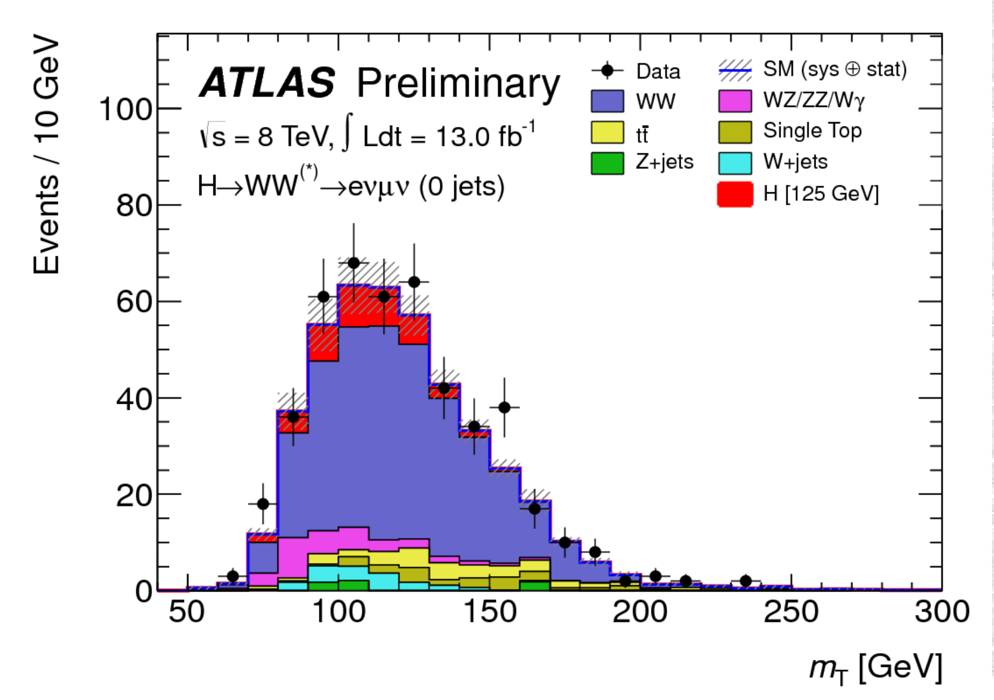
- Significant results in 3 channels already
- Sensitivity of 'big 5' differs only by about a factor 3
  - These will all improve
  - Plus we will distinguish gluon fusion, VBF, VH and ttH production
- There is a rich programme

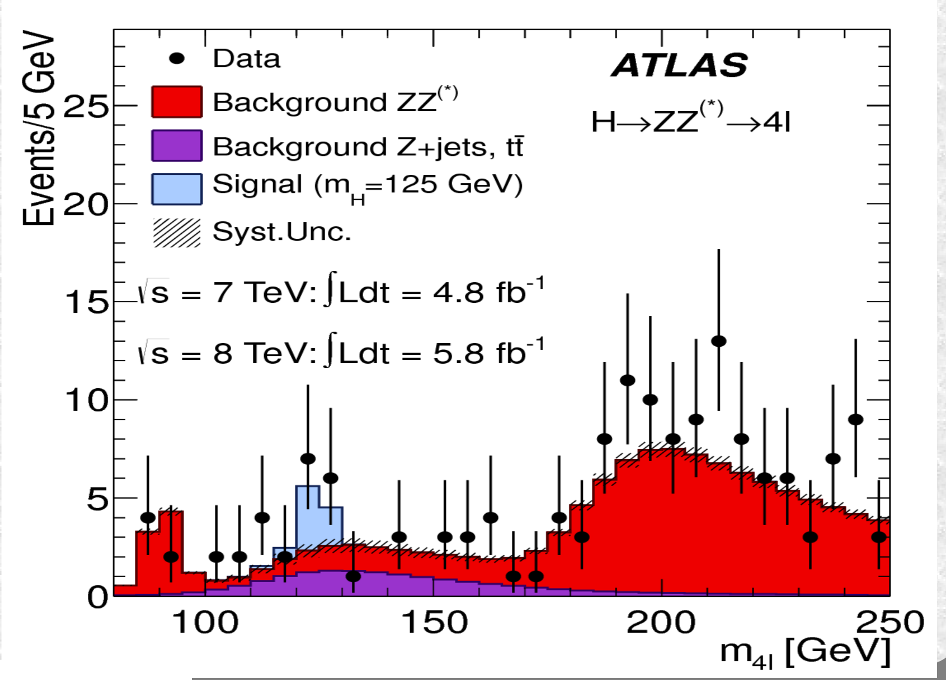


Production rates so far

- H to γγ and llll have narrow peaks
  - Without E_T^{Miss} requirement
  - Will survive high pileup
- WW, bb and ττ are harder to predict with certainty

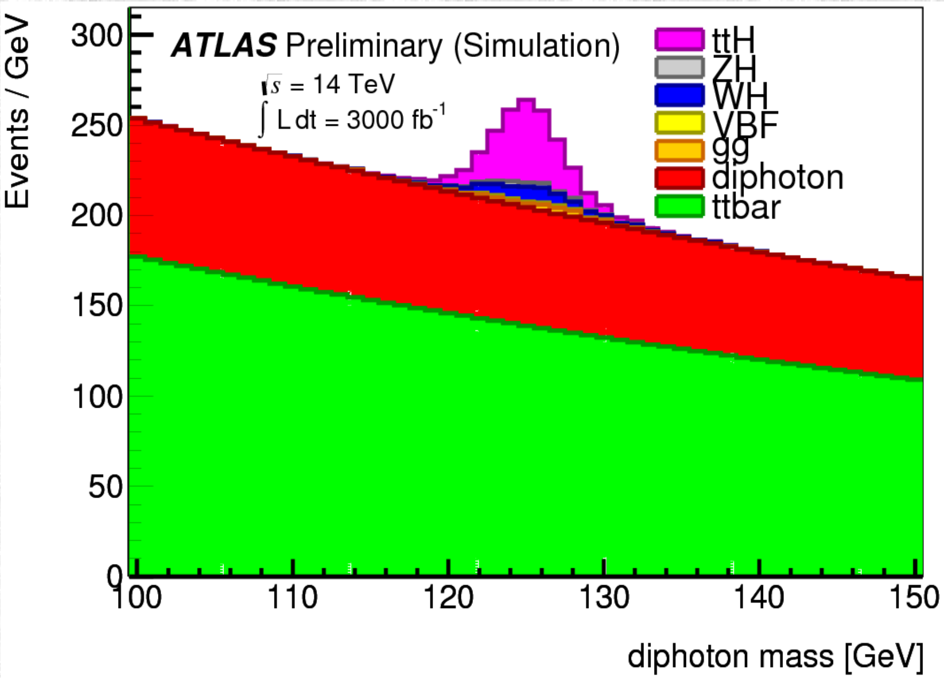


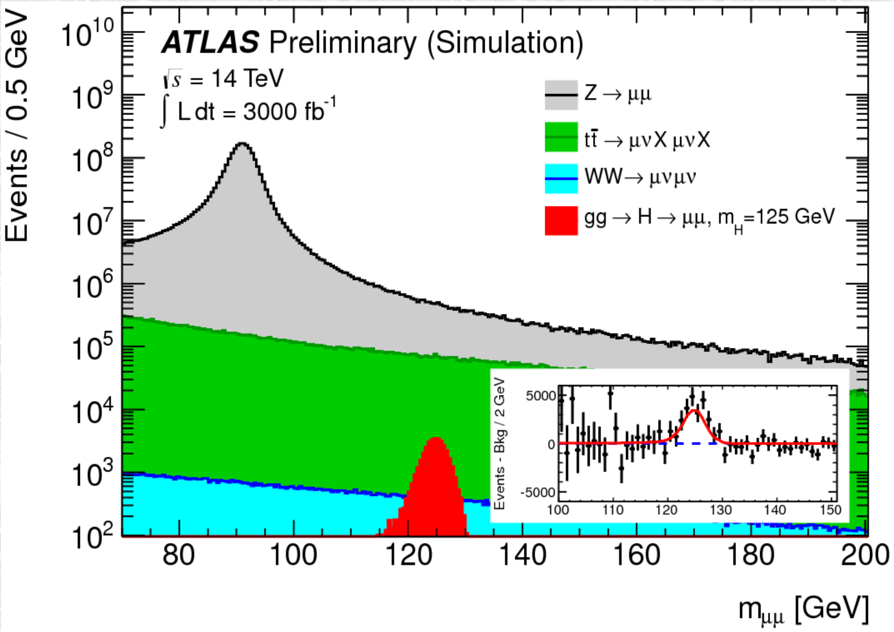




New modes at HL-LHC

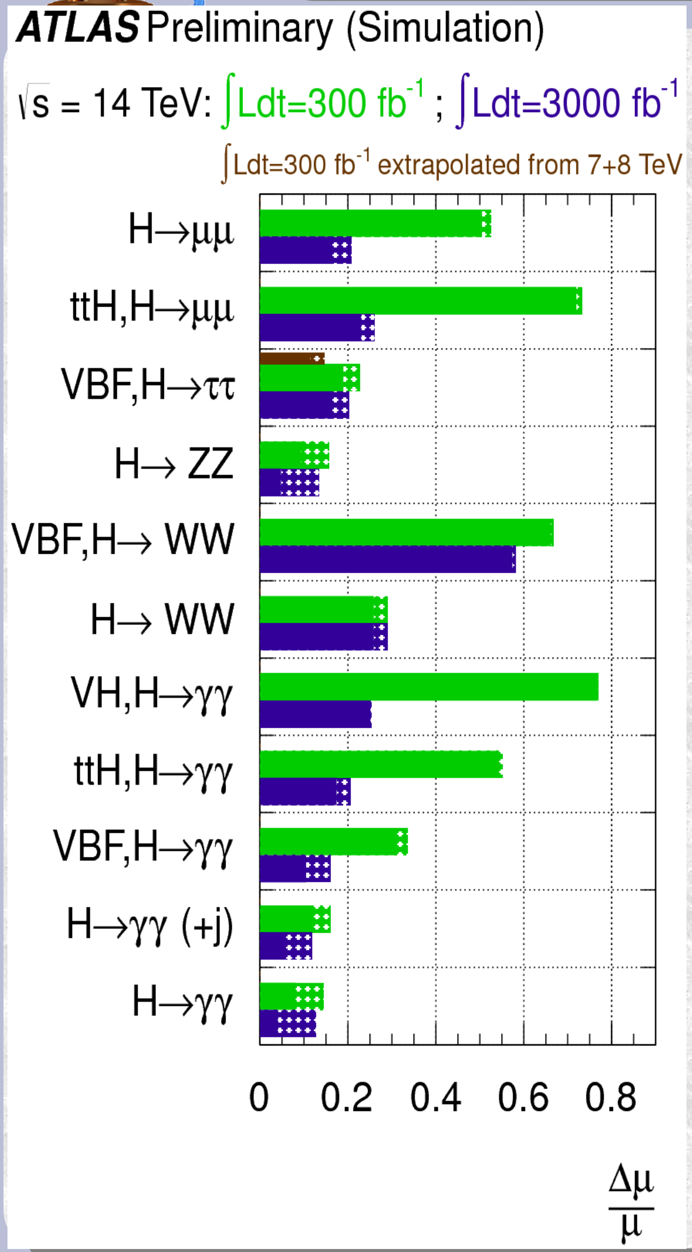
3000fb^{-1} at 14TeV offers new possibilities





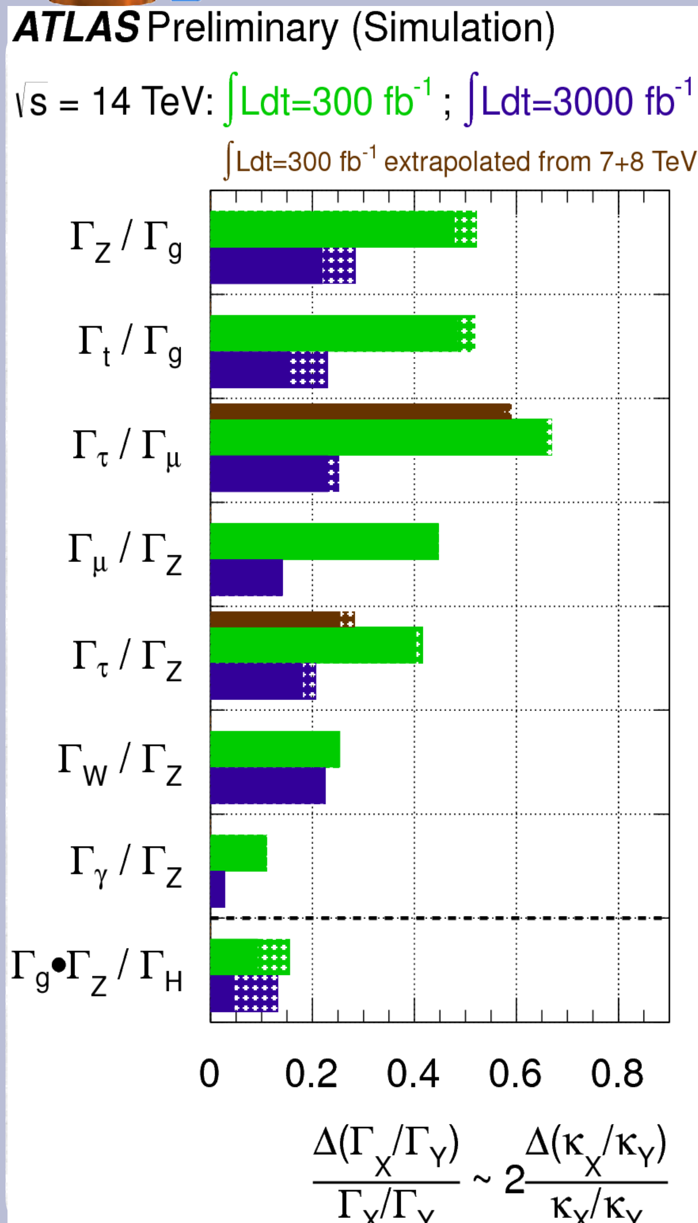
- ttH,H→γγ
  - Sensitive to top in both production and decay
  - Reduces ambiguity in couplings
- H→μμ
  - c/f τ allows direct study of coupling to two different generations

HL-LHC Higgs projections



- Only subset of channels studied
  - But 10 channels will be constrained below 30%
  - 7 of them below about 20%
- Solid region is the error without the current theoretical systematics.
  - These will likely be reduced in 10 years
- The ττ is estimated two ways:
  - using smeared assumptions, like other channels
    - But only VBF, no $\tau_{had}\tau_{had}$ or same-flavour leptons
  - Extrapolating 2011 performance
- No bb results
  - Systematic dominated, estimation hard

HL-LHC Higgs couplings



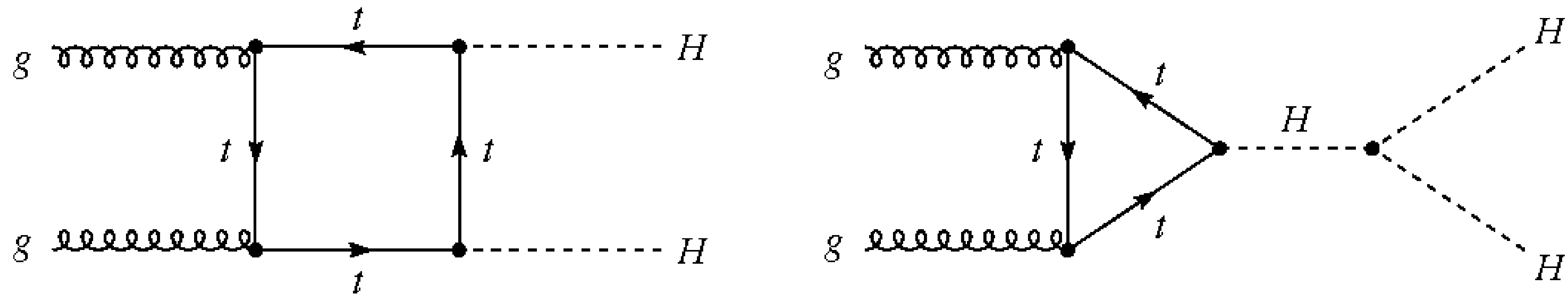
	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

- LHC cannot measure Higgs width
  - But ratios of couplings at <O(20%) level
- Systematic errors are approximate
- Extracted couplings improved by factor 2 or more
  - Except Γ_W/Γ_Z – where WW is *assumed* not to be benefit from HL-LHC.
- Remember – LHC found the Higgs with less luminosity and worse pileup than planned.
  - These may be conservative

Can we see the BEH field?

- The observation of a field filling space with weak charge and energy density poses questions about its gravitational impact
- We have seen the decay to ZZ, where the weak charge of the Higgs is absorbed by the vacuum
- But we need to demonstrate the potential
- i.e. measure the self-coupling

Higgs Self coupling



- Needs observation of Higgs pairs
  - That's a tall order!
- But it is not enough
  - Need to prove triple Higgs involved
  - negative interference :(
- bbγγ allows 3σ HH observation
  - 2 experiments, more channels, may give 3σ *coupling* measurement

- Studied using parametrised performance
- Background ~24 events
  - 18 of them $t\bar{t}H$
- Signal of 15 events expected, λ=1
  - 26/8 for λ=0,2

Summary

- $300fb^{-1}$ at 14TeV allows for remarkable physics
- The increase to $3000fb^{-1}$ extends it substantially.
- HL-LHC will explore:
  - Multi-TeV region for Z'
  - 3TeV for simple SUSY
  - Over 800GeV for charginos and neutralinos
- Will study electroweak symmetry breaking
  - Vector boson scattering at TeV scale
  - Higgs couplings directly
  - First measurement of the self-coupling
- This is a rich and compelling programme

CP violation

- Interaction between spin 0 particle and 2 vector bosons:

$$A(X \to VV) \sim \left(a_1 M_X^2 g_{\mu\nu} + a_2 (q_1 + q_2)_\mu (q_1 + q_2)_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

- Assume a_1=1 and a_2=0 (as SM) and vary a_3
  - the CP violating component
- The expected power to reject various possible a_3:

Integrated Luminosity	Signal (S) and Background (B)	$6+6i$	$6i$	$4+4i$
100 fb^{-1}	$S = 158; B = 110$	3.0	2.4	2.2
200 fb^{-1}	$S = 316; B = 220$	4.2	3.3	3.1
300 fb^{-1}	$S = 474; B = 330$	5.2	4.1	3.8