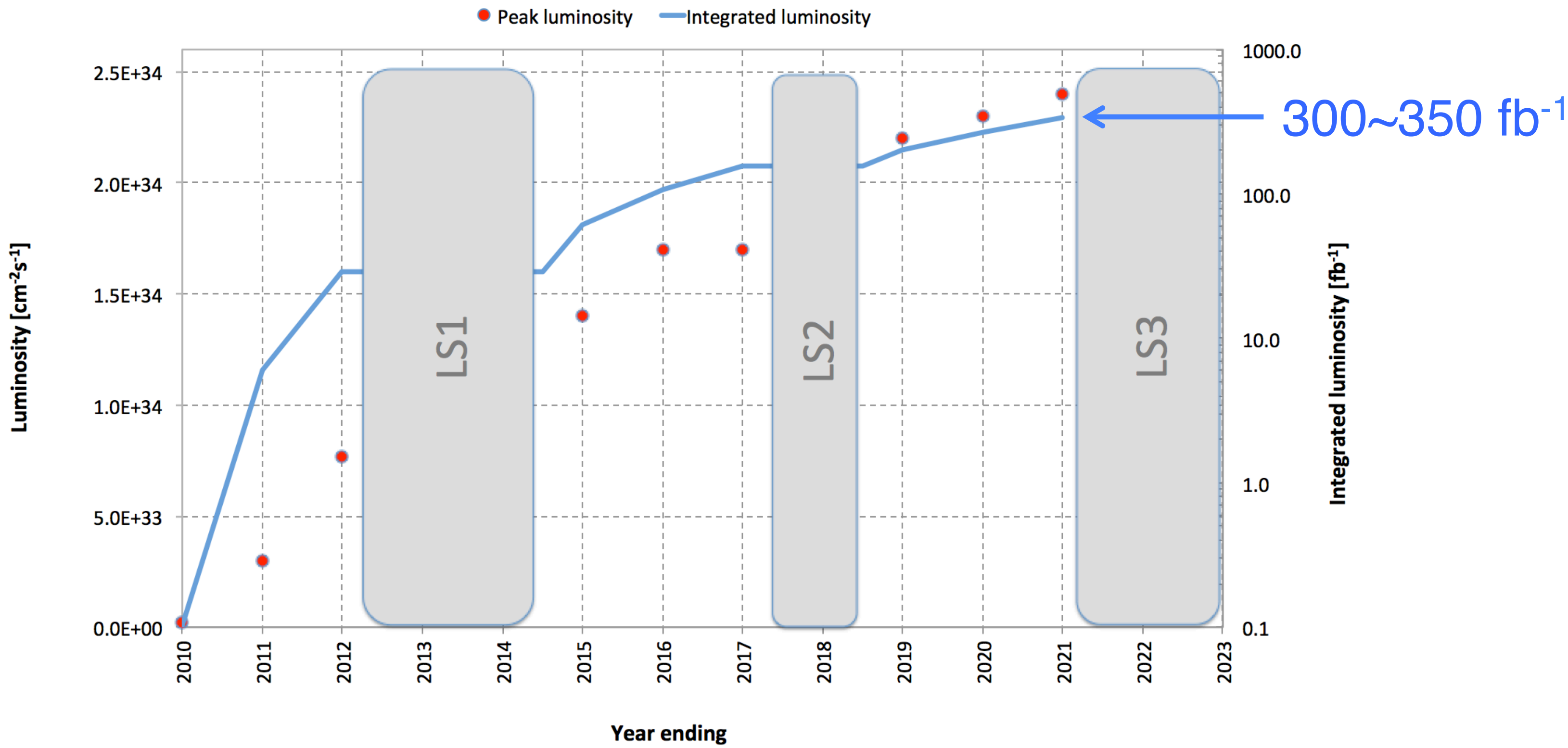
Physics Program of the LHC Upgrades

- LHC timeline
  - From Run 1 to 3000 fb^{-1} with HL-LHC
- ATLAS and CMS detector upgrades
  - Phase 0, Phase I and Phase II
- Physics program
  - Measurements and search reach

2013 Lepton Photon Conference

Pippa Wells, CERN, on behalf of ATLAS and CMS

Approved LHC programme



- LS1: fix interconnects and overcome energy limitation
- LS2: overcome beam intensity limitation (collimation, cryogenics, injector upgrade for high intensity, low emittance bunches)
- By 2022, luminosity is saturated, and final focus Inner Triplet magnets in interaction regions reach the end of their useful life due to radiation damage → Upgrade: High Luminosity LHC.

European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

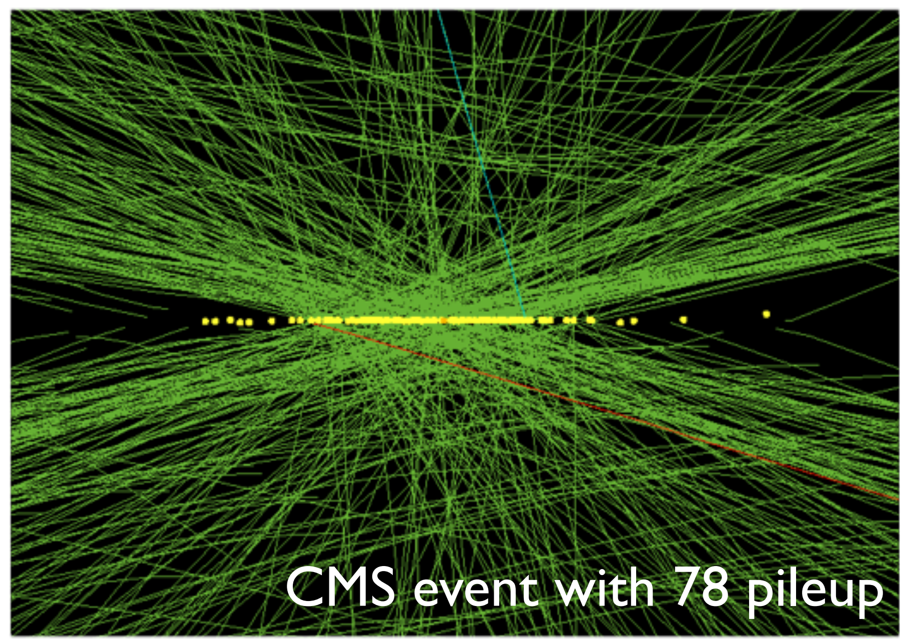
European Strategy Update

LHC roadmap to achieve full potential

2009		LHC startup, √s 900 GeV	
2010–2012		$\sqrt{s}$=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns	Run 1 ~25 fb^{-1}
2013–2014	LS1	Go to design energy, nominal luminosity - Phase 0	
2015–2017		$\sqrt{s}$=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	~75-100 fb^{-1}
2018	LS2	Injector + LHC Phase I upgrade to ultimate design luminosity	
2019–2021		$\sqrt{s}$=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	~350 fb^{-1}
2022	LS3	HL-LHC Phase II upgrade: Interaction Region, crab cavities?	
2023 … 2030?		$\sqrt{s}$=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling	~3000 fb^{-1}

Detector upgrades

- In a nutshell – detector upgrades are planned so as to maintain or improve on the present performance as the instantaneous luminosity increases
- A particular challenge is to refine the hardware (level-1) and software (high level) triggers to maintain sensitivity with many interactions per bunch crossing – "pileup"
- Offline algorithms also need to be developed to maintain performance with pileup
- Focus here on upgrades which change the performance. In addition, there is a continuous huge effort in consolidation, eg. new cooling systems, improved electronics and power supplies, shielding additions...
- Phase 0/I upgrades are better defined than Phase II

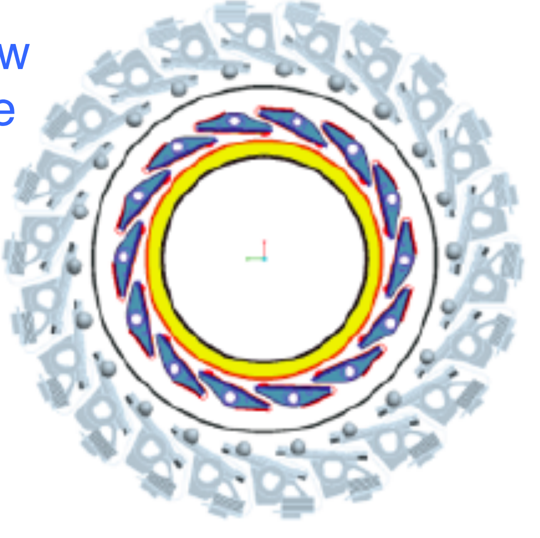


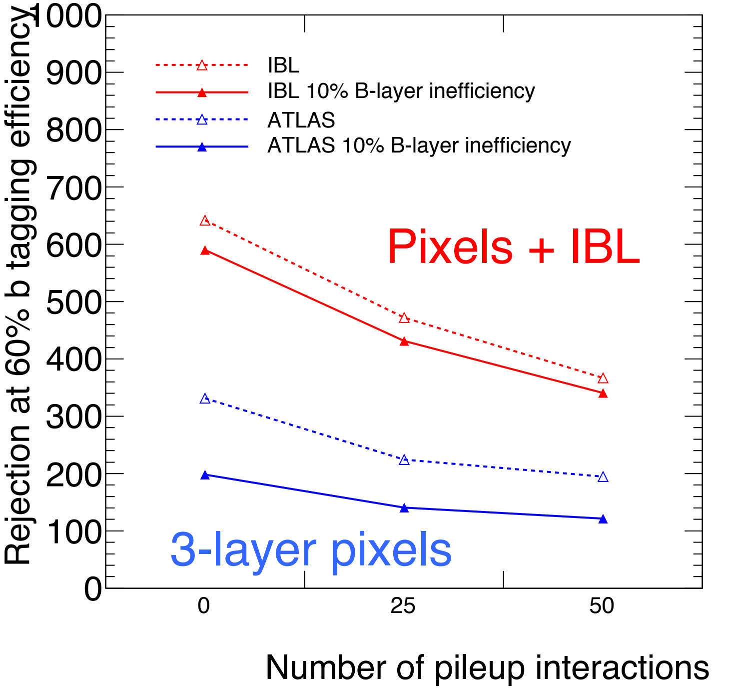
ATLAS Phase 0 - pixels

- New inner pixel layer (insertable b-layer, IBL) with smaller radius Be beam pipe.
  - Smaller pixels (50x400 μm → 50x250 μm)
  - New readout chip
- Also refurbishing the front end readout of existing pixel layers
- → Improved tracking, vertexing, b-tagging and τ-reconstruction at high pileup

First production stave

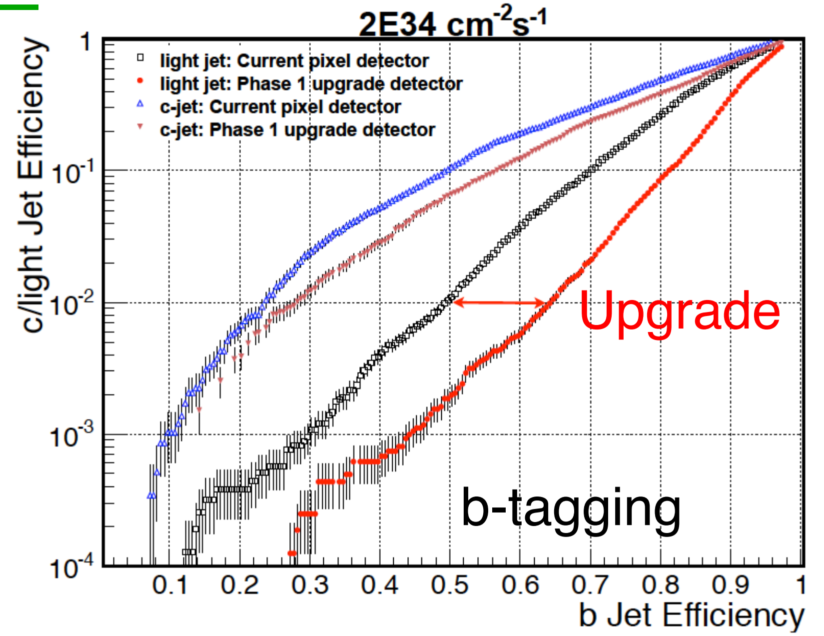
IBL on new beam pipe

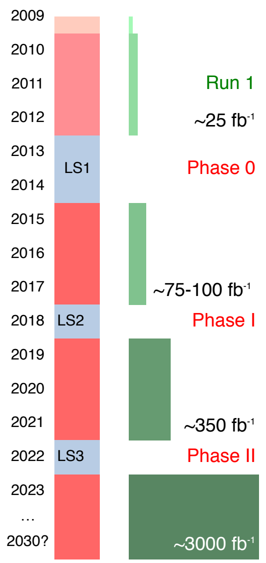


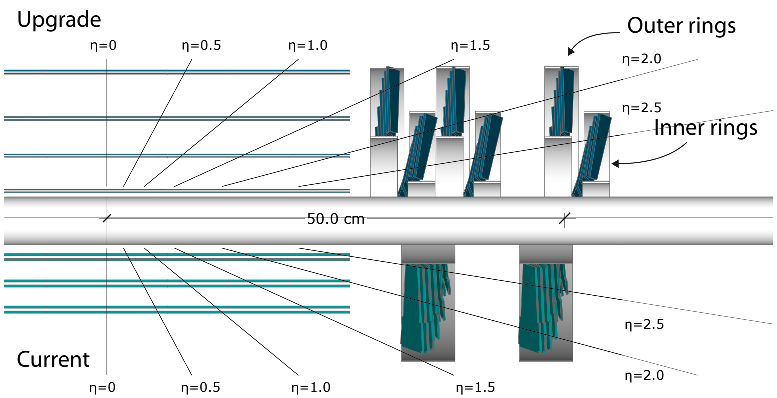


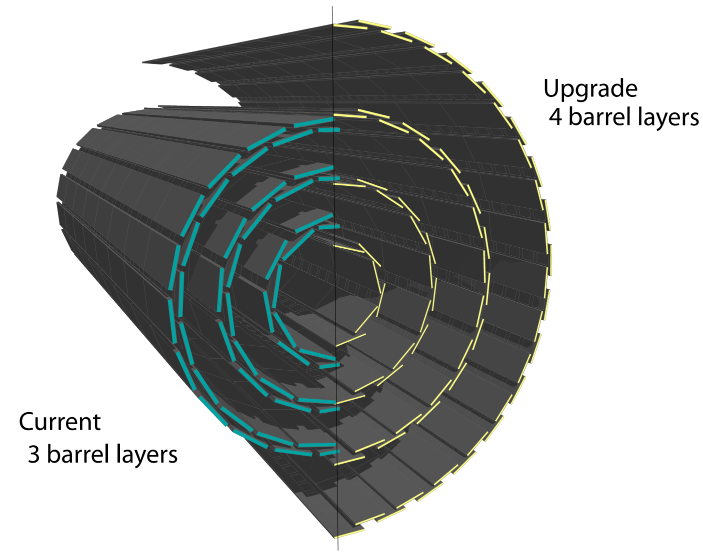
CMS (pre)Phase I pixels

- Additional layer (→ 4 barrels, 3 disks).
- Install smaller radius beam pipe in LS1, and plan to install new pixels in extended 2016-2017 shutdown
- Improved read out chip to prevent data loss
- CO_2 cooling and re-routed services → less total material than present pixel

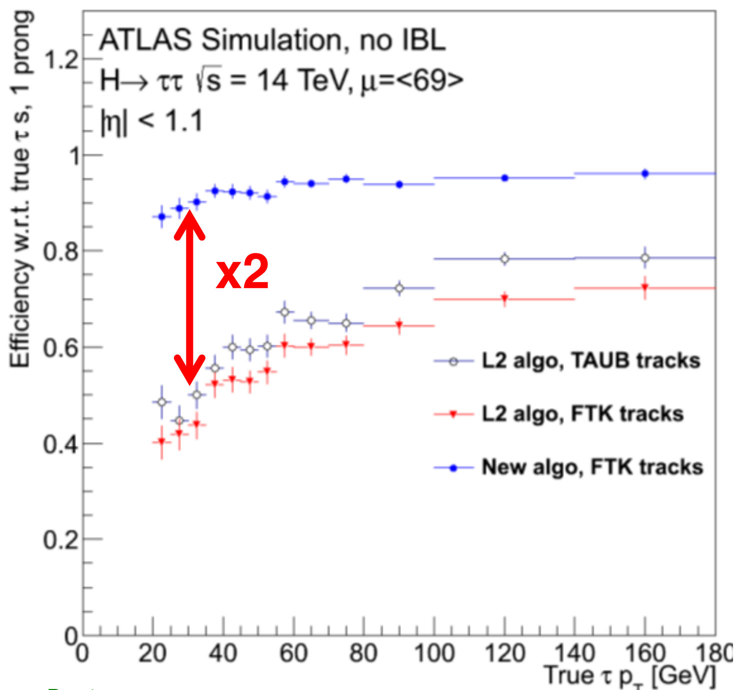




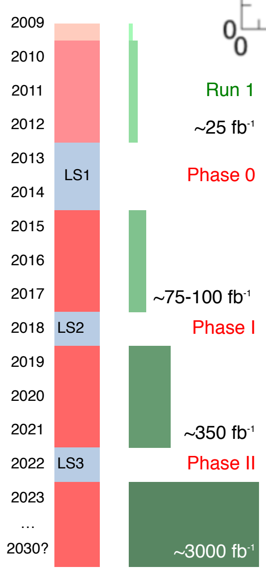




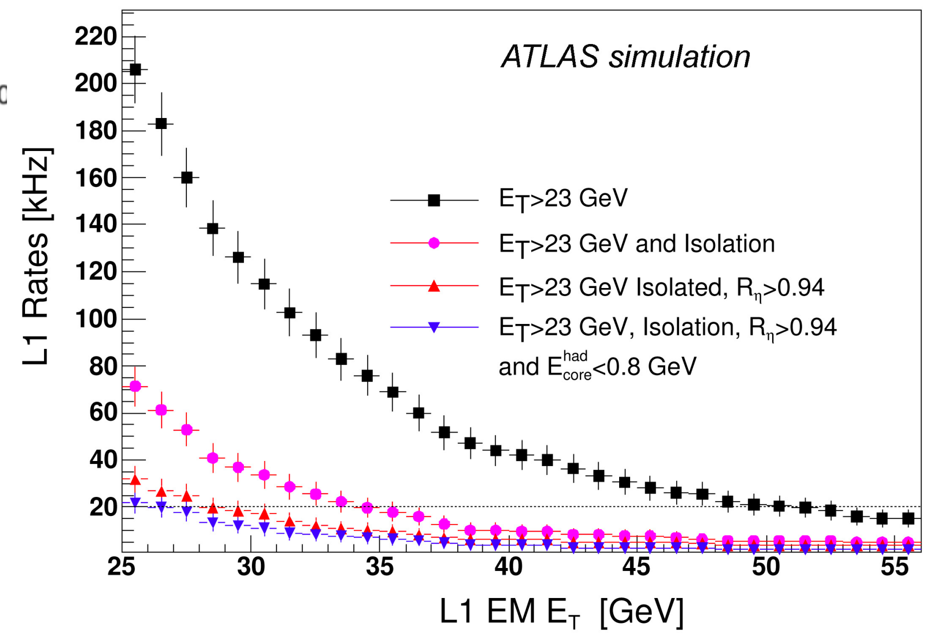
ATLAS (pre)Phase I upgrades



- Track trigger input to level 2 trigger "FTK" (staged installation from 2015)
- Example – improved τ trigger by using track information before tight calorimeter cuts are applied



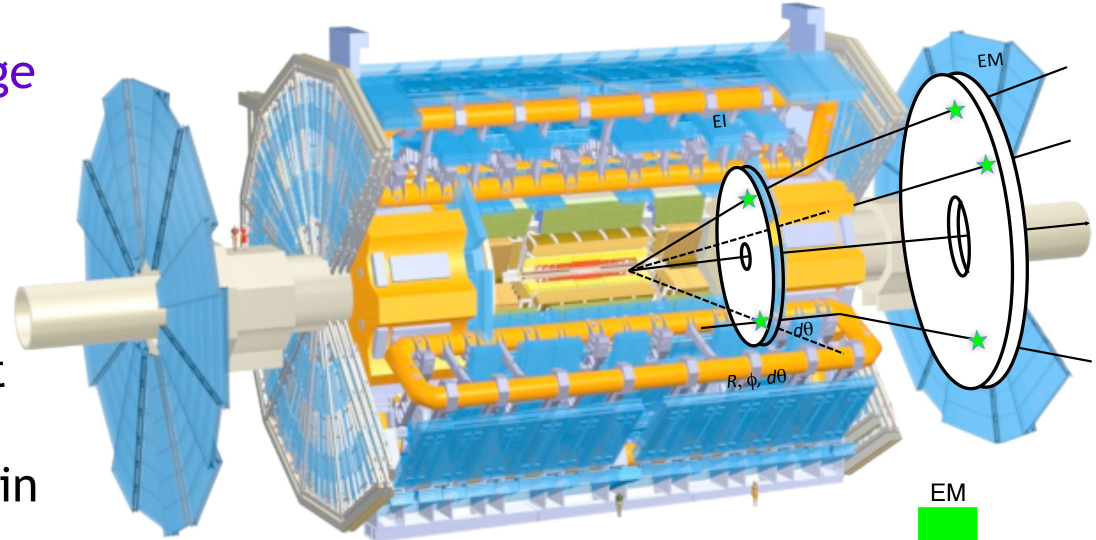
- Improved granularity available to L1 calorimeter trigger → more precise isolation variables at level 1
- Example – L1 electron trigger rate with improved selections

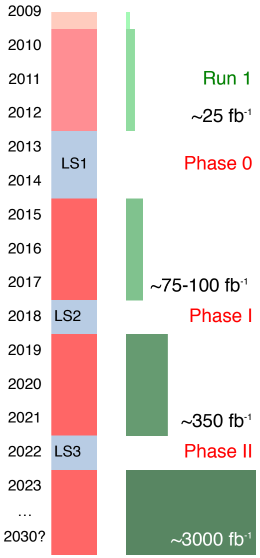


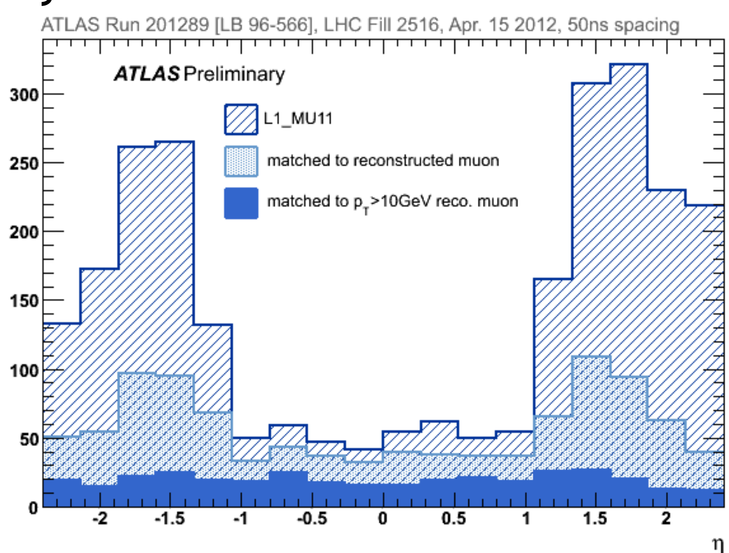
ATLAS (pre)Phase I muon system

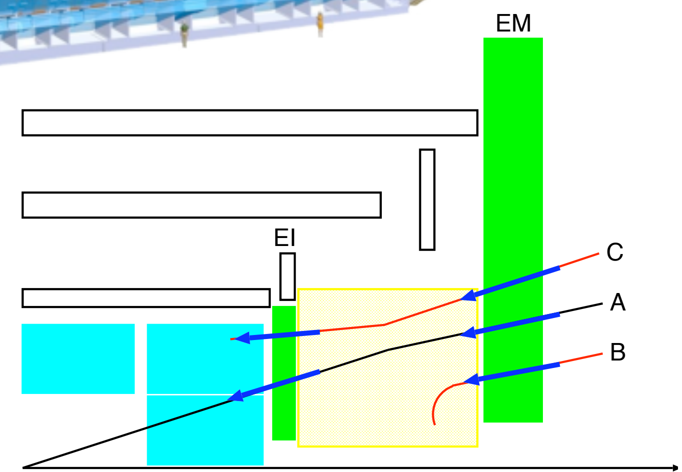
small & big wheels

- Phase 0: Improved coverage with staged chambers in barrel/endcap transition
- Phase I: New Small Wheel with fast track segment finding for L1 trigger input to reduce endcap fakes & precise tracking to maintain p_T resolution with high occupancy.





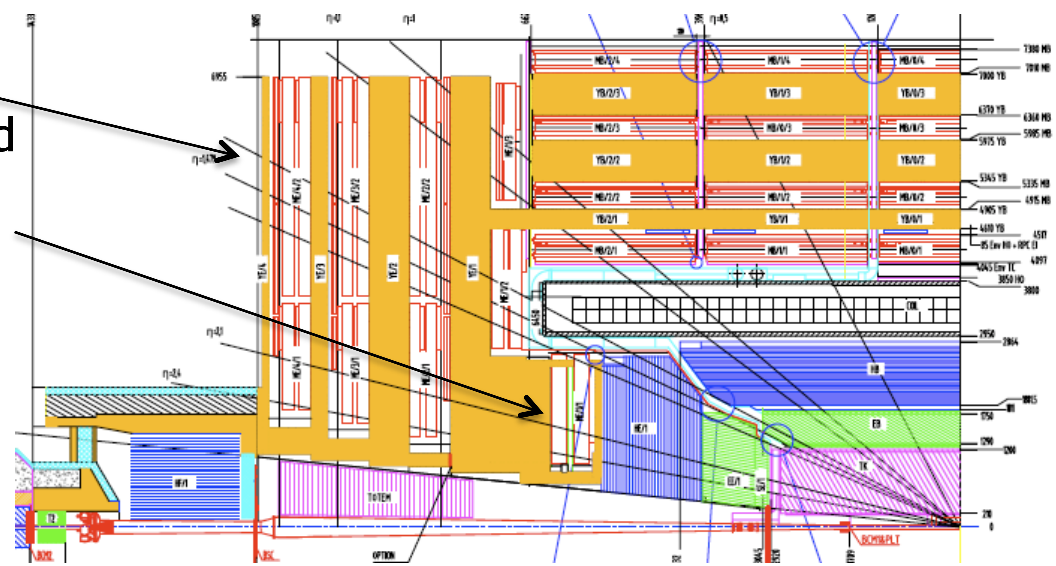




A: good, B+C: fakes.
NSW with micromegas & small-strip thin gap chambers

CMS (pre)Phase I HCAL and muons

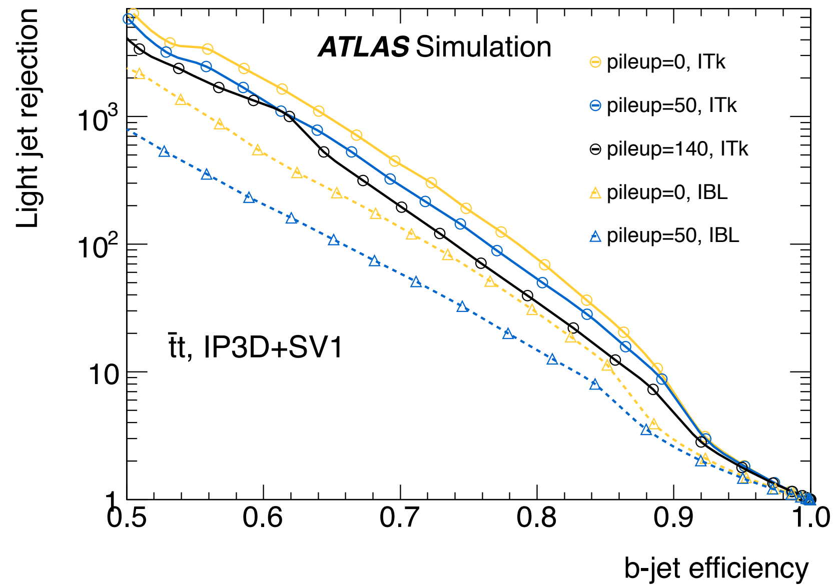
- Hybrid Photodiodes (HPD) of HCAL will be replaced with Silicon Photomultipliers (SiPM) in the barrel and endcap.
  - Outer HCAL replacement in LS1
  - In barrel+endcap will allow more readout segmentation in depth
  - The single-channel PMTs of the Forward Hadron Calorimeter will be replaced by multi-anode phototubes
- Complete muon coverage in LS1:
  - Layer 4, install CSC and RPC
  - Layer 1 CSC improved read-out granularity



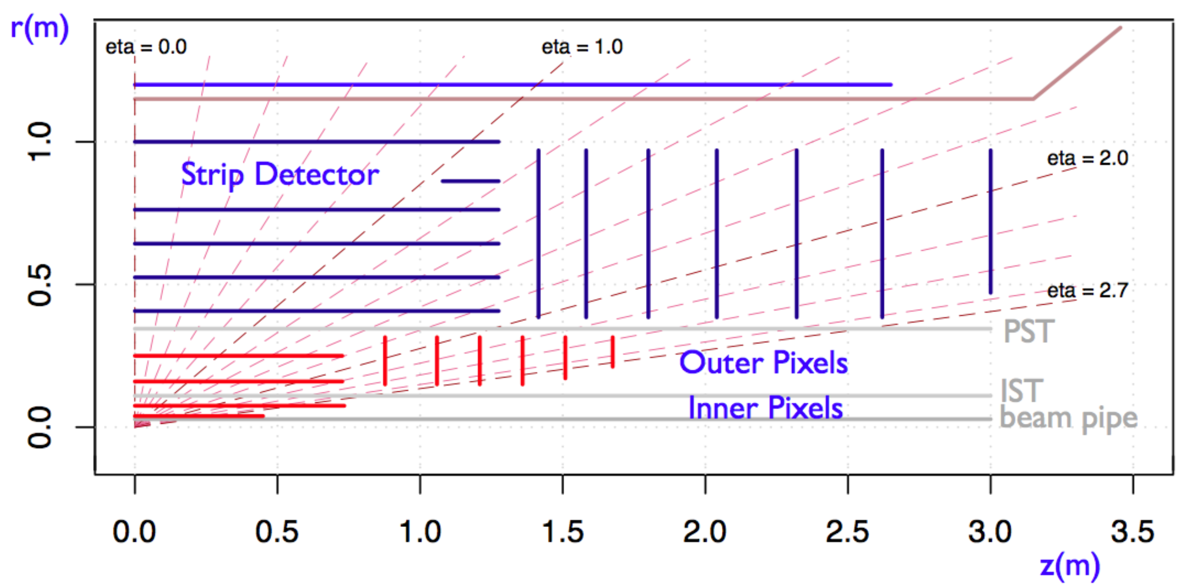
ATLAS Phase II

- Radiation damage & occupancy of present tracker → full replacement
- New L0(500kHz)/L1 trigger scheme, with RoI based L1 track trigger
- Phase I calo/muon upgrades are Phase II compatible. Additional readout electronics upgrade.
- Forward calorimeter options
- Computing & software upgrades

b-tagging: ITk with 140 pileup better than ATLAS+IBL with no pileup

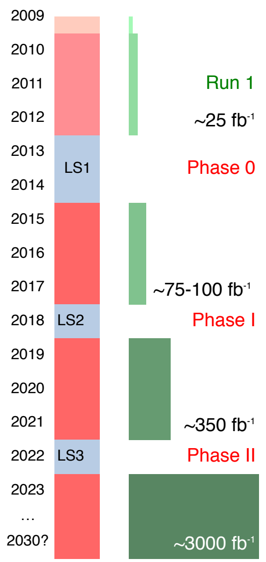


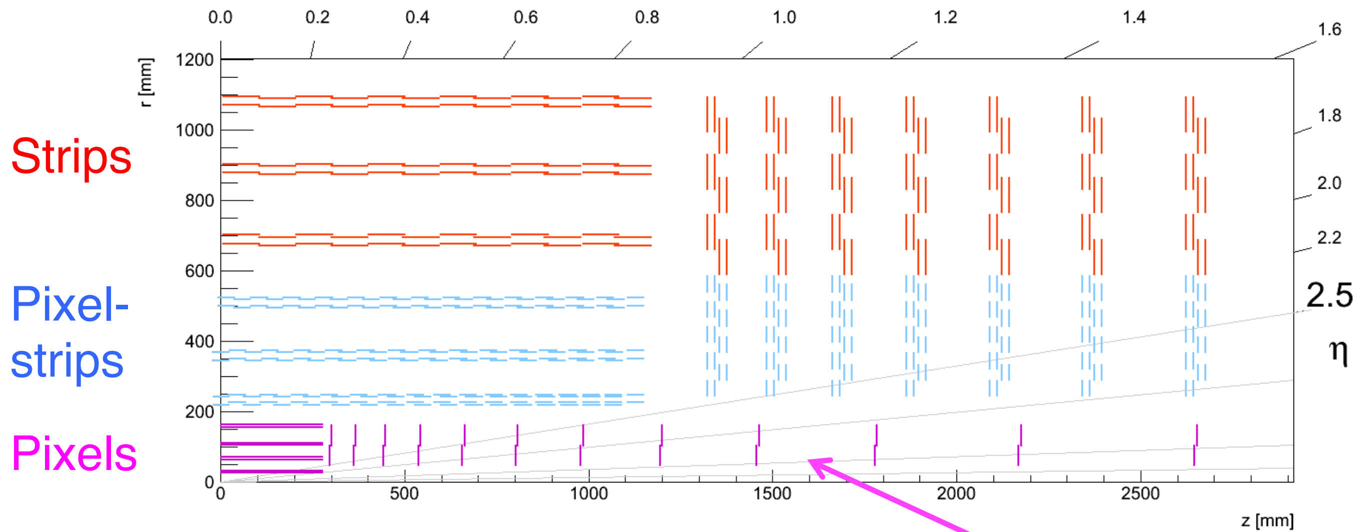
Baseline LoI ITk tracker design: all silicon with reduced granularity



CMS Phase II

- Scope to be defined in Technical Proposal (2014)
  - New tracker with possible increased coverage to $|\eta|<4$, with an L1 track trigger (p_T>2.5 GeV)
  - DAQ and HLT upgrade → 1 MHz L1, 10 kHz event storage
  - Replace endcap and forward calorimeters
  - Possible electromagnetic preshower system to provide photon pointing and pileup discrimination from time-of-flight





Possible tracker layout with forward pixel disks

Physics Prospects - introduction

- Emphasis on prospects with “LHC” 300 fb^{-1} and “HL-LHC” 3000 fb^{-1}
- ATLAS has implemented functions to transform from generator level “truth” to reconstructed physics objects for HL-LHC
  - Based on present detector with realistic/pessimistic assumptions on the effect of pileup of up to ~140 (for $L = 5 \times 10^{34}\ cm^{-2}s^{-1}$)
  - eg. b-tagging performance from fully simulated ITk now shown to be better than that assumed for physics studies.
- CMS extrapolate from the present analyses with different scenarios
  1. Experimental systematic and theoretical uncertainties unchanged. (Statistical uncertainties scale with $1/\sqrt{L}$)
  2. Statistical and experimental systematic uncertainties scale with $1/\sqrt{L}$, theoretical uncertainties are reduced by a factor 2.
  3. Experimental errors unchanged, theoretical uncertainties zero

- i.e. systematic uncertainties are always included, with different assumptions on possible detector/algorithm/theoretical improvements

Theoretical uncertainties

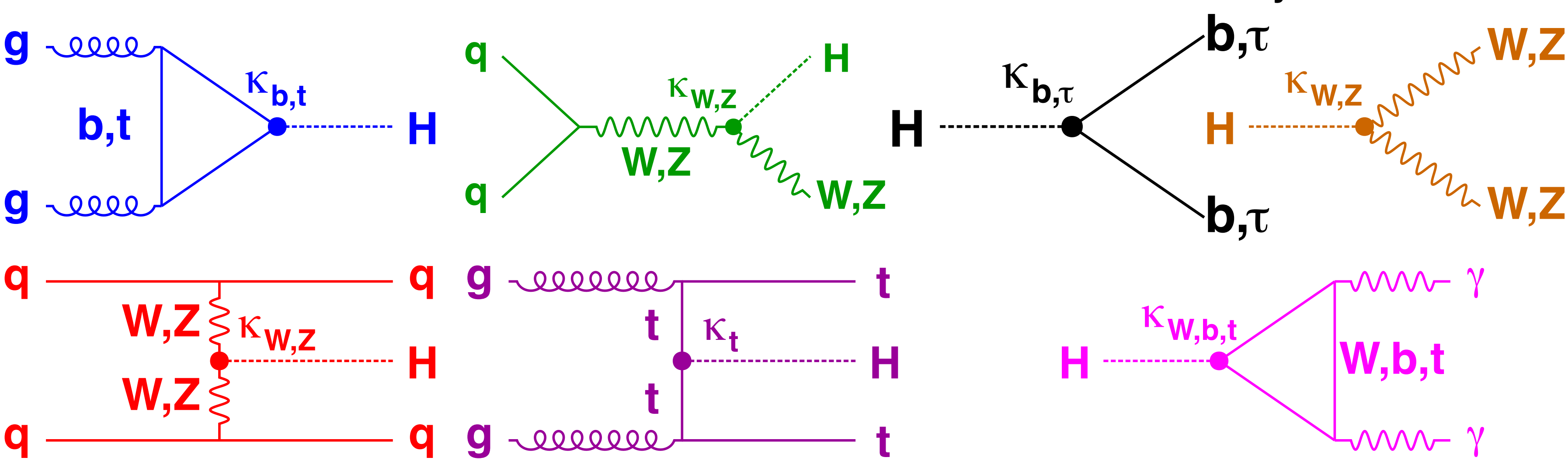
- Theoretical predictions for known and new processes are critical
  - Missing higher order (QCD) radiative corrections are estimated by varying factorisation and renormalisation scales (0.5 ~ 2.0)
  - Electroweak corrections
  - Treatment of heavy quarks
  - PDF uncertainties (which also depend on the order of calculation available)
  - m_H=125 GeV @ 14 TeV: $\sigma(pp(gg) \rightarrow H+X)$ scale $^{+9}_{-12}$%, PDF ±8.5%
- PDF uncertainties can be reduced by future precise experimental measurements at LHC, including
  - W, Z σ and differential distributions for lower x quarks
  - High mass Drell-Yan measurements for higher x quarks
  - Inclusive jets, dijets for high x quarks and gluons
  - Top pair differential distributions for medium/large x gluons
  - Single top for gluon and b-quark
  - Direct photons for small/medium x gluons

Measurements of the 125 GeV boson

- Mass & width are hard to improve beyond Run 2
  - Direct measurement of width limited by resolution
- Dominant spin/parity will probably be established as 0^+
  - Investigate a CP-violating contribution
- At LHC, we can only measure σ×BR. Express a ratio μ to SM value.
  - Ratios of partial widths can be made without further assumptions
  - Interpretation as coupling measurements is model dependent

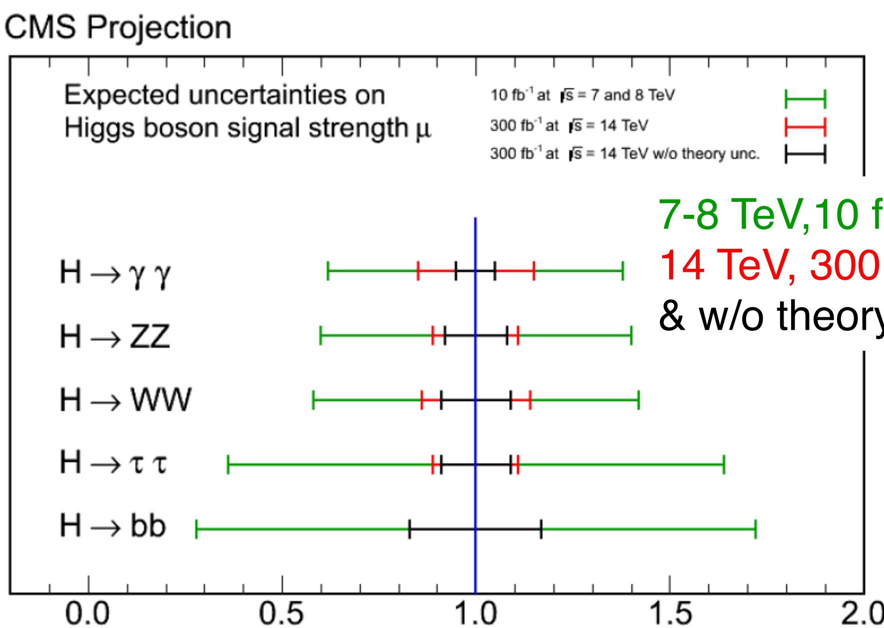
Production

Decay



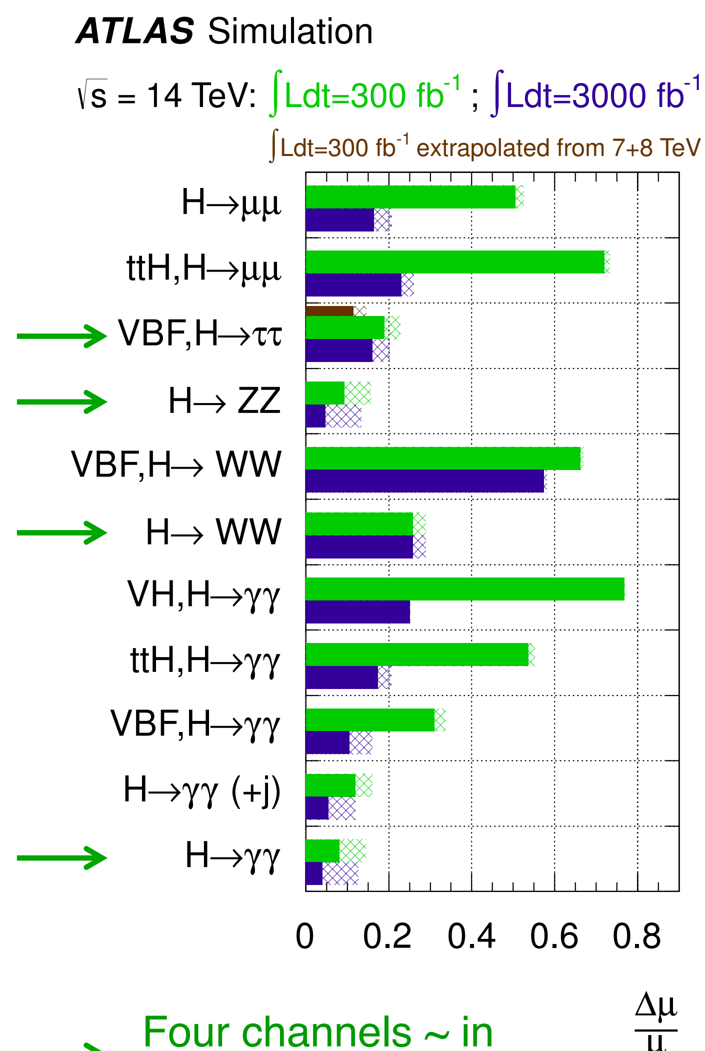
Higgs boson μ values

- CMS results from 7-8 TeV 10 fb^{-1} and extrapolated to 300 fb^{-1} with fixed systematic uncertainties with or w/o theory uncertainties



7-8 TeV,10 fb^{-1}
14 TeV, 300 fb^{-1}
& w/o theory unc.

Note sensitivity to μμ, and ttH with 3000 fb^{-1}



Four channels ~ in common with CMS study

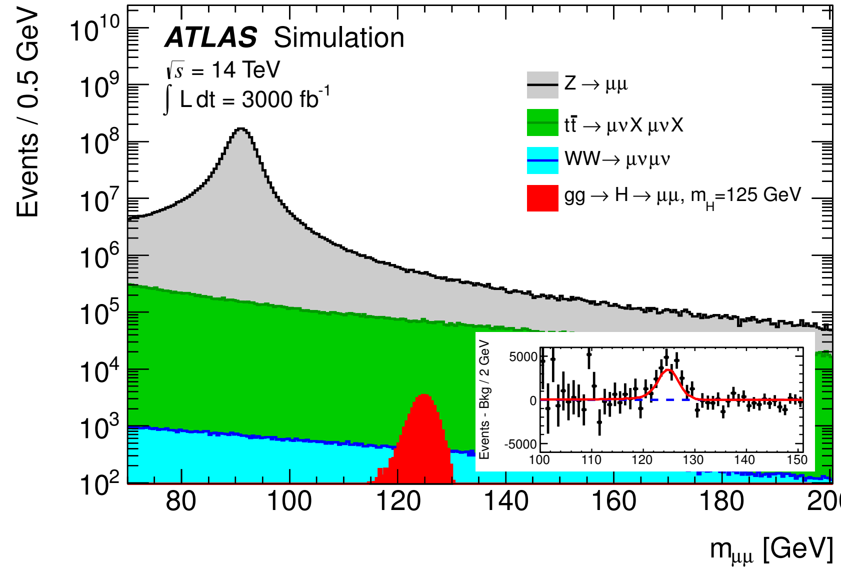
- Achieve 10-15% precision with 300 fb^{-1} for these main channels

Rare H processes

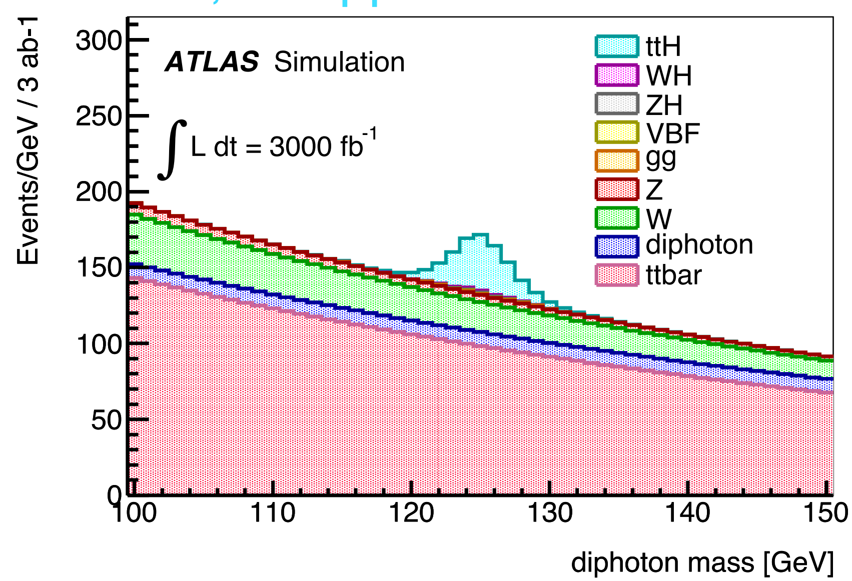
- $H \rightarrow \mu\mu$
  - ATLAS expect >6σ significance with 3000 fb^{-1}
  - CMS also expect >5σ significance
  - → coupling measured to 10~20%

- ttH, $H \rightarrow \gamma\gamma$ (ATLAS)
  - >100 signal events
  - Signal/background 20%
- ttH, $H \rightarrow \mu\mu$ (ATLAS)
  - Only ~30 signal events with 3000 fb^{-1} but S/B~1.

$H \rightarrow \mu\mu$

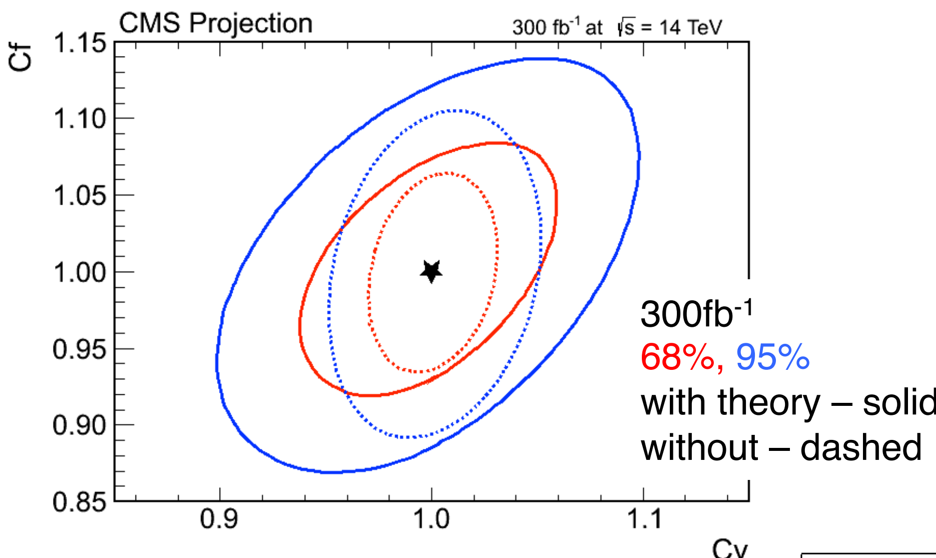


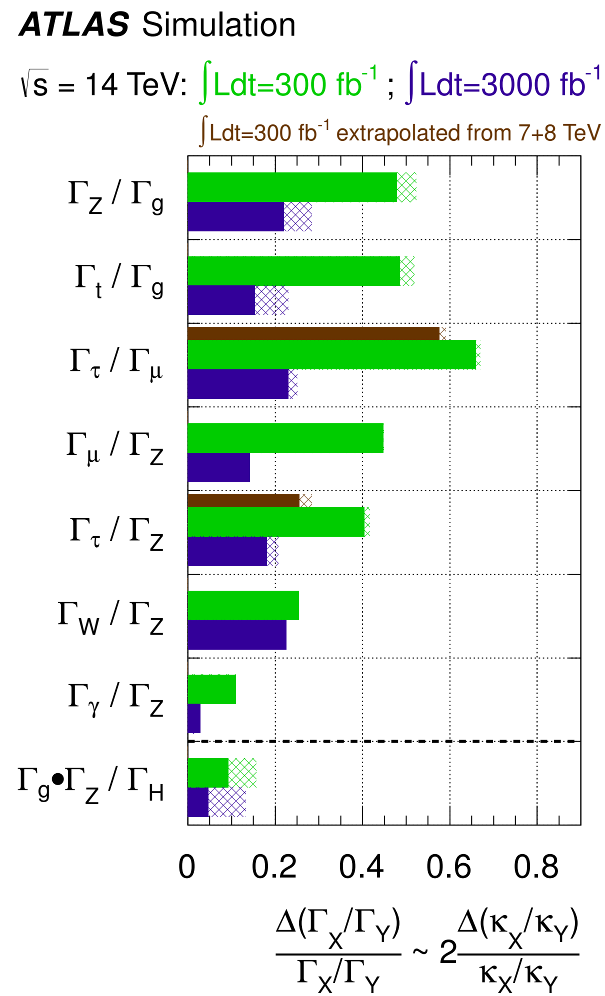
ttH, $H \rightarrow \gamma\gamma$



Higgs boson couplings

- ATLAS provides model independent ratios of partial widths (proportional to squares of couplings).
- ATLAS and CMS investigate two parameter fit with universal vector boson and fermion couplings (V and F)





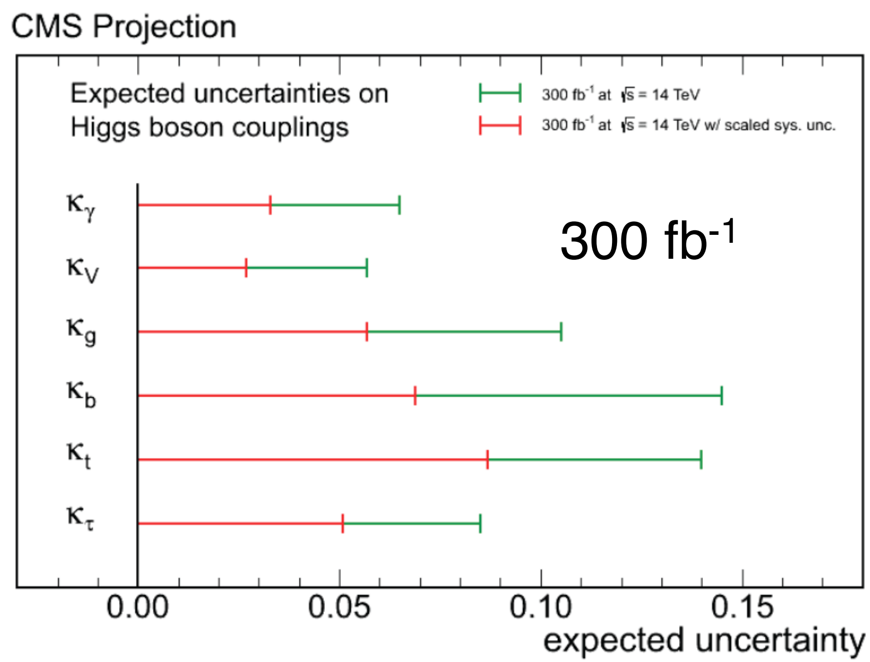
ATLAS two parameter fit without (with) theory error:

ATLAS	300 fb^{-1}	3000 fb^{-1}
K_V	3.0 % (5.6 %)	1.9 % (4.5 %)
K_F	8.9 % (10 %)	3.6 % (5.9 %)

Higgs couplings

- Extending to a 6 parameter fit assuming no invisible decays
- Allows for eg. new particles in the gluon fusion production or two-photon decay loops

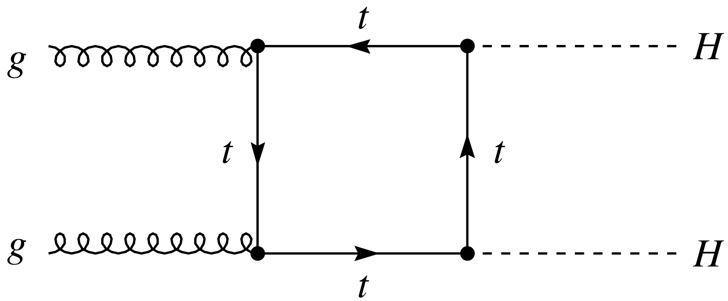
1. No change in syst. errors
2. Theory÷2, syst. ~$1/\sqrt{L}$

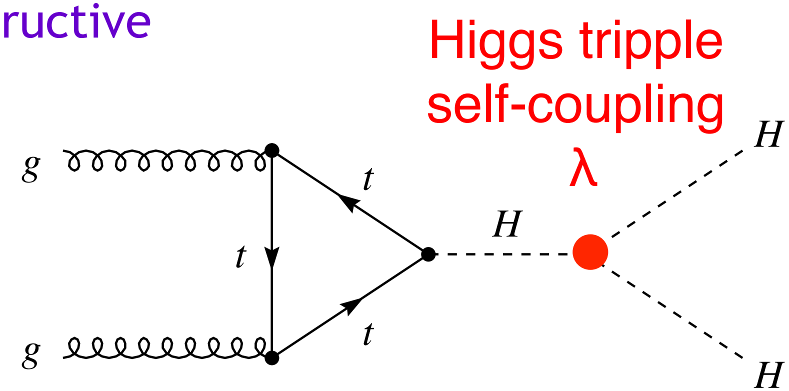


CMS	Uncertainty (%)			
Coupling	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Higgs Self coupling

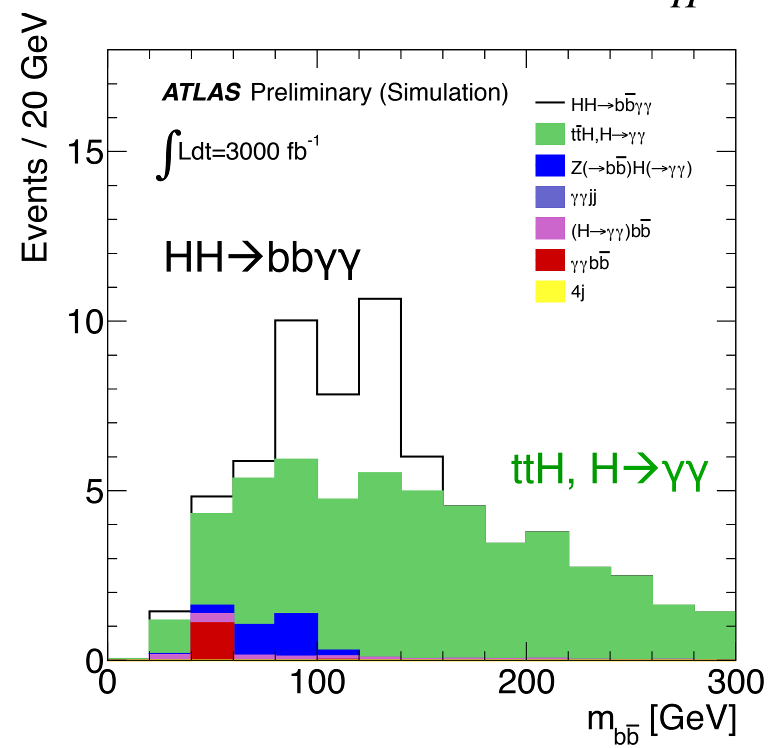
- Higgs pair production includes destructive interference between processes:





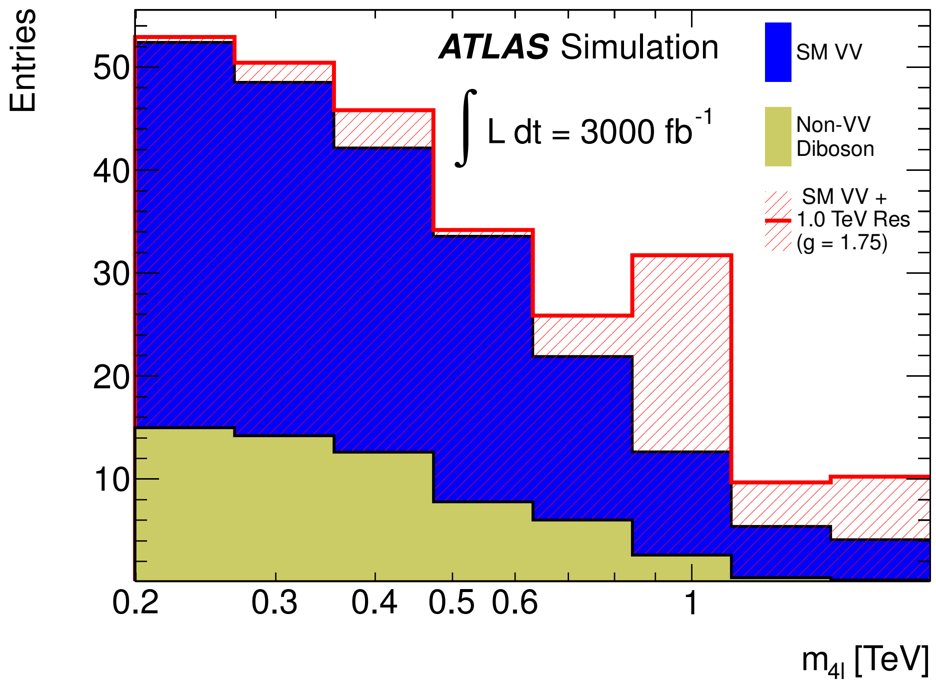
- λ=SM, σ=34 fb
  λ=0, σ=71 fb
  λ=2xSM, σ=16 fb

- ATLAS HH→bbγγ yields 3σ significance with 3000fb[-1]
- Combining with HH→bbττ, & with two experiments, hope to reach 30% precision on λ



Weak boson scattering

- Weak boson scattering important to test dynamics of EW symmetry breaking and nature of Higgs boson
- Example – sensitivity to new ~TeV scale resonance in pp→ZZjj→4l jj
- Clean signal, with significant gain in sensitivity at HL-LHC



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

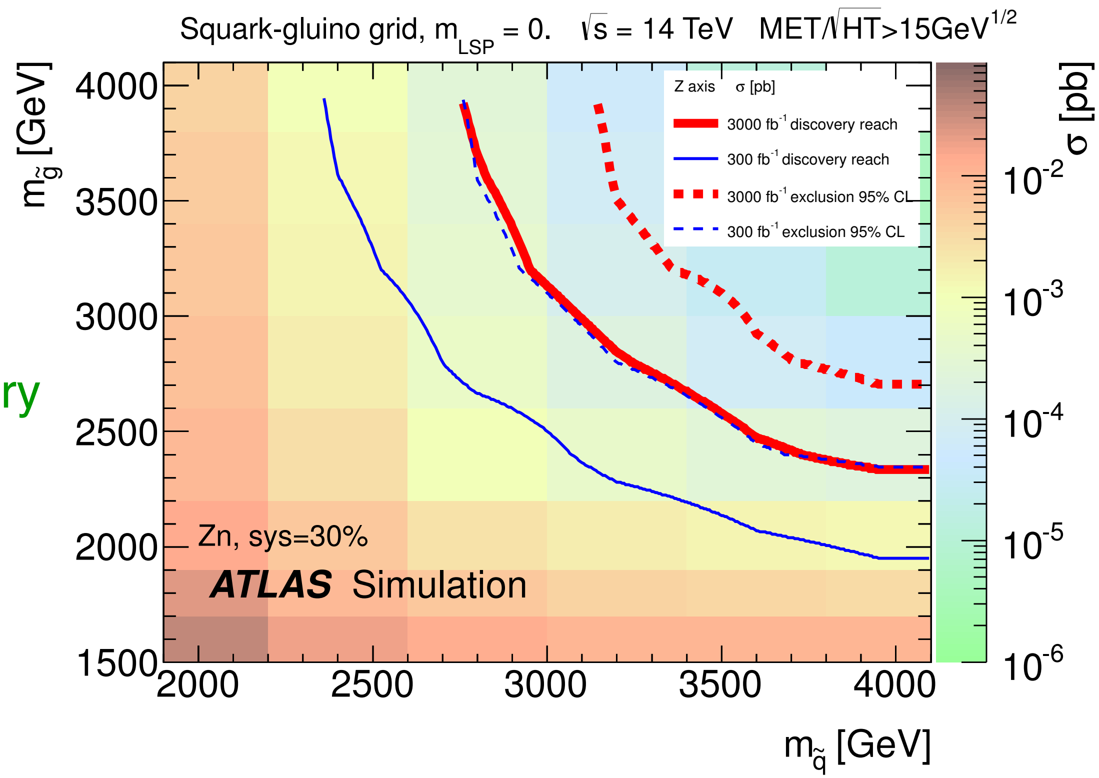
SUSY generic squark/gluino

- Increase in reach for a generic squark/gluino search
- CMS: improvement from 0.8 (300 fb^{-1}) to 1.1 TeV (3000 fb^{-1}) in the discovery reach for generic squarks/gluinos

Solid – 5σ discovery
Dashed – 95% exclusion

ATLAS simplified model with zero mass LSP

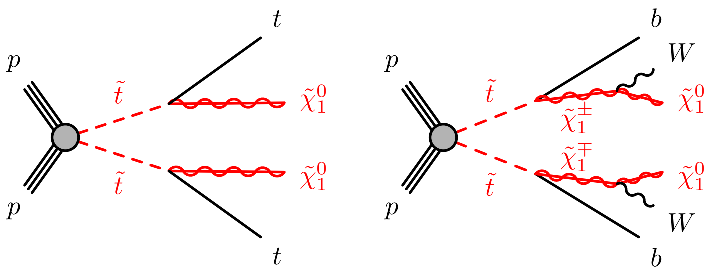
HL-LHC improves the discovery reach by 400~500 GeV



SUSY – 3rd family

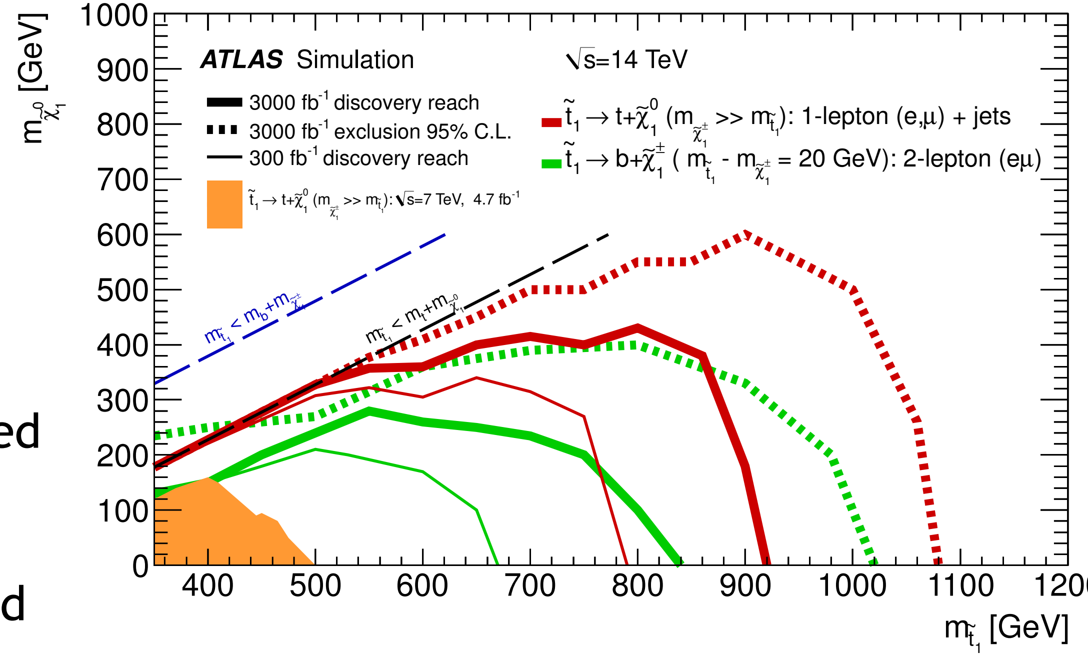
- Light stop/sbottom favoured by naturalness arguments

- ATLAS stop search with 1 lepton and 2 lepton signatures



- Discovery reach increased by >100 GeV. This relative gain should be maintained for optimised analysis.

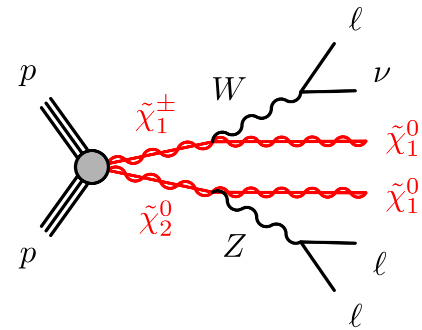
Solid – 5σ discovery
Dashed – 95% exclusion



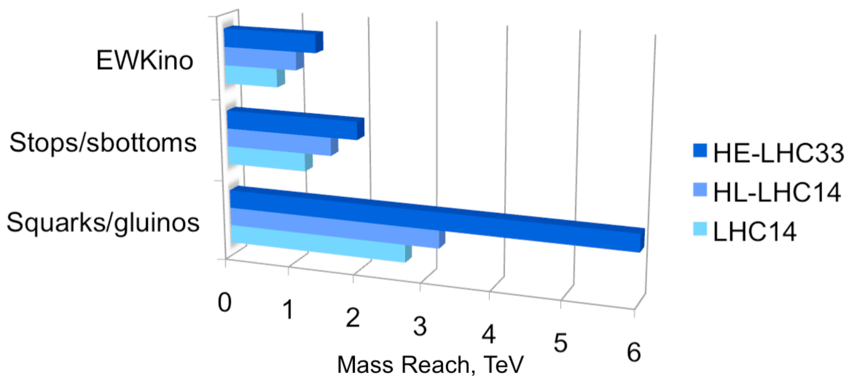
- CMS discovery reach increases from 1.2 to 1.6 TeV in the search reach for stop/sbottom squarks, assuming that only the lightest stop/sbottom is directly produced

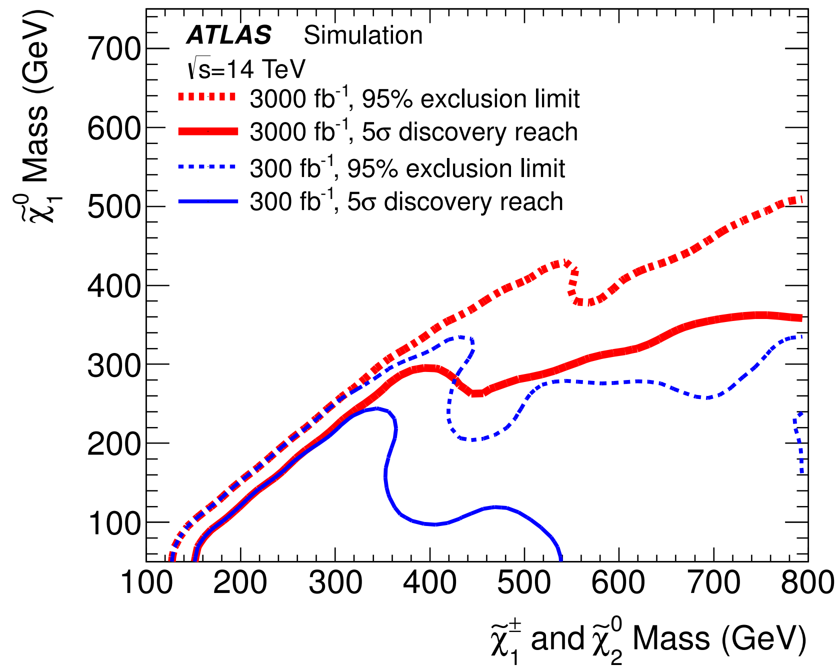
SUSY - electroweak production

- LHC can also probe electroweak production of charginos, neutralinos and sleptons.
- eg. ATLAS $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ discovery potential increased from 500 GeV to TeV scale.



CMS SUSY summary



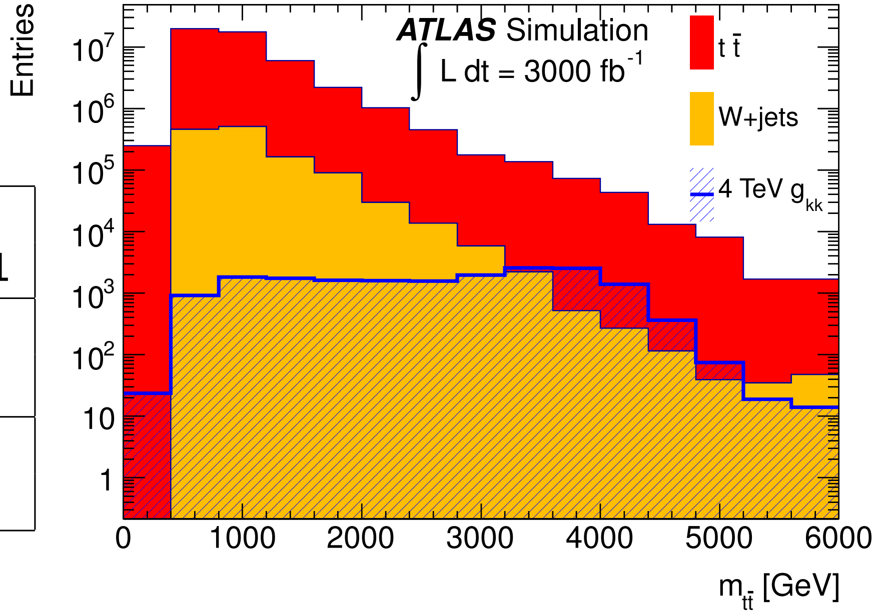


- CMS: improvement from 0.8 to 1.1 TeV in the discovery reach for charginos/neutralinos

High mass resonances

- HL-LHC increases the reach for top-pair and lepton-pair resonances such as Kaluza-Klein graviton or a Z'.
- Larger gains from more luminosity for more complex signals

ATLAS	model	95% CL (TeV)	
		300 fb^{-1}	3000 fb−1
$t\bar{t} \to l\nu jjbb$ ($l\nu l\nu bb$)	g_{KK} $Z'_{\text{Topcolour}}$	4.3 (4.0) 3.3 (1.8)	6.7 (5.6) 5.5 (3.2)
dilepton	$Z'_{SSM} \to ee$ $Z'_{SSM} \to \mu\mu$	6.5 6.4	7.8 7.6



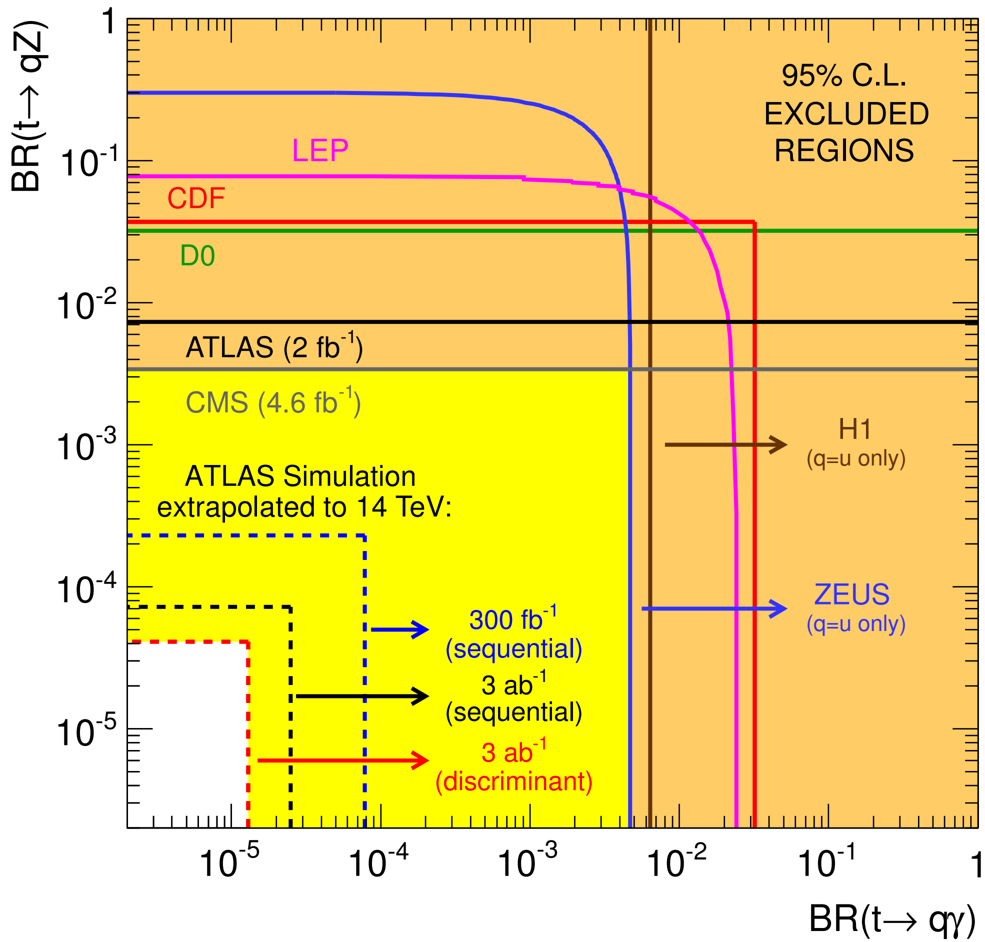
- CMS also show the reach of a scalar leptoquark search in eejj
- BR(LQ→ej)=100%

CMS LQ working point	95% CL (TeV)	
	300 fb^{-1}	3000 fb−1
Low S/B	1.6	1.8
High S/B	1.7	2.3

FCNC in top decays

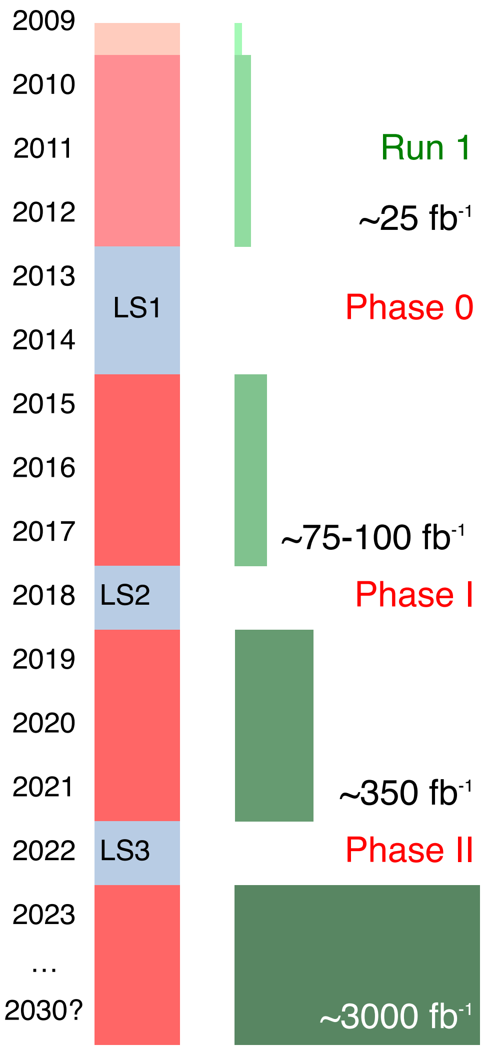
- Opportunity to search for rare processes
  - BR($t \rightarrow bW$)~1, BR($t \rightarrow sW$)<0.18%, BR($t \rightarrow dW$)<0.02%

BR FCNC	$t \to q\gamma$	$t \to qZ$
SM	10^{-14}	10^{-14}
QS	10^{-9}	10^{-4}
2HDM	10^{-6}	10^{-7}
MSSM	10^{-6}	10^{-6}
RPV SUSY	10^{-6}	10^{-5}
TC2	10^{-6}	10^{-4}
RS	10^{-9}	10^{-5}



- Approaching few 10^{-5} precision

Conclusions and outlook



- Europe's top priority should be exploitation of the full potential of the LHC, including the high-luminosity upgrade
- The accelerator and the experiments have a well defined upgrade programme
- Further detector R&D is in progress, in particular for the Phase II upgrades
- The HL-LHC physics case is being refined with more complete studies for meetings in 2013 (Snowmass and ECFA HL-LHC).
- Exact predictions also depend on the assumptions made on developing more sophisticated algorithms, for example to deal with pile-up
- The LHC has a long and productive future ahead

BACKUP

Comparison of μ values with 300 fb^{-1}

Channel	Uncertainty on mu value with 300 fb^{-1} [%]			
	Experimental only		Experimental + theory	
	ATLAS	CMS	ATLAS	CMS
$\gamma\gamma$	8	5	15	15
ZZ	9	8	16	11
WW (1)	26	9	29	14
$\tau\tau$ (2)	11	9	15	11
$\tau\tau$	19	9	23	11

(1) ATLAS uncertainty based on old result

(2) ATLAS uncertainty extrapolated with CMS approach