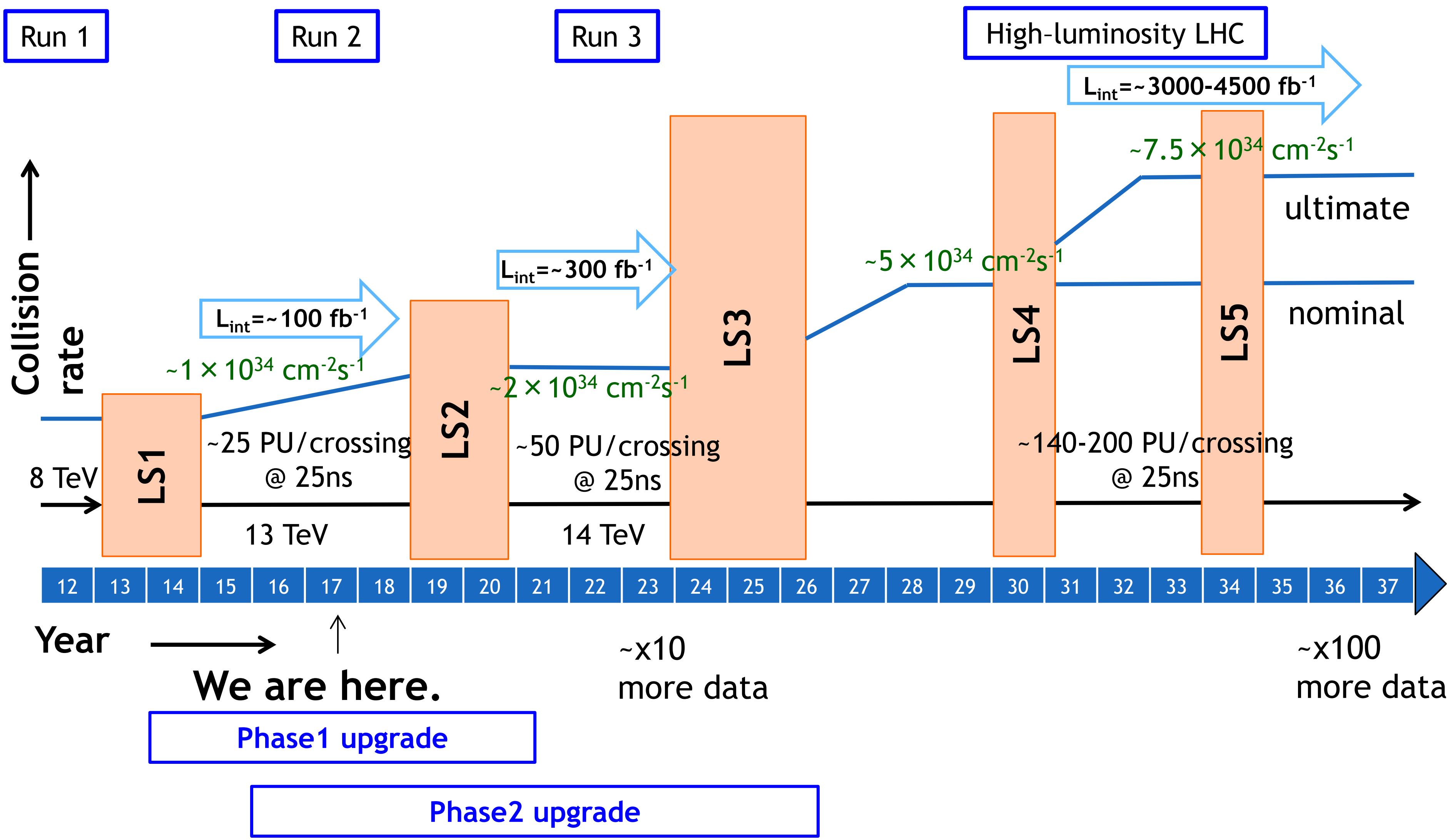
Future Prospects of CMS & ATLAS

Kenichi Hatakeyama
Baylor University
for the CMS and ATLAS Collaborations

Brookhaven Forum 2017: In Search of New Paradigms

October 11-13, 2017

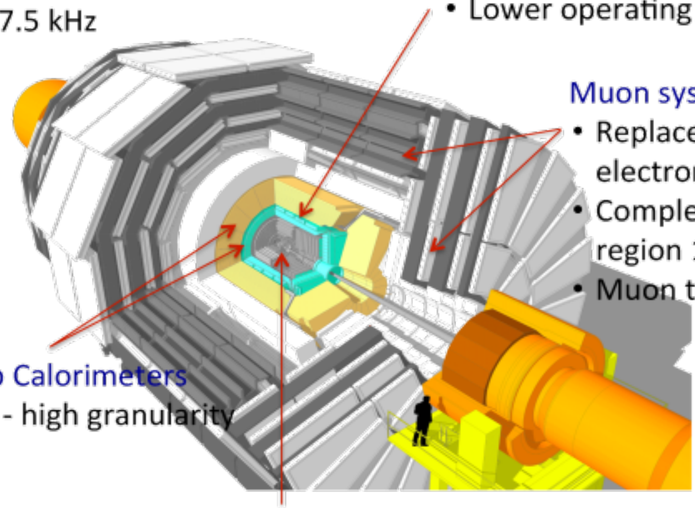
LHC Evolution



CMS Upgrades

- Phase 1 upgrade will complete with the HCAL endcap and barrel front-end electronics upgrade by LS2.
- Phase 2 upgrade includes: replacement of tracker ($|\eta|<3.8$) & endcap calo. Barrel ECAL and muon system electronics. Track trigger@L1. Fast-timing (~30ps) detector etc.

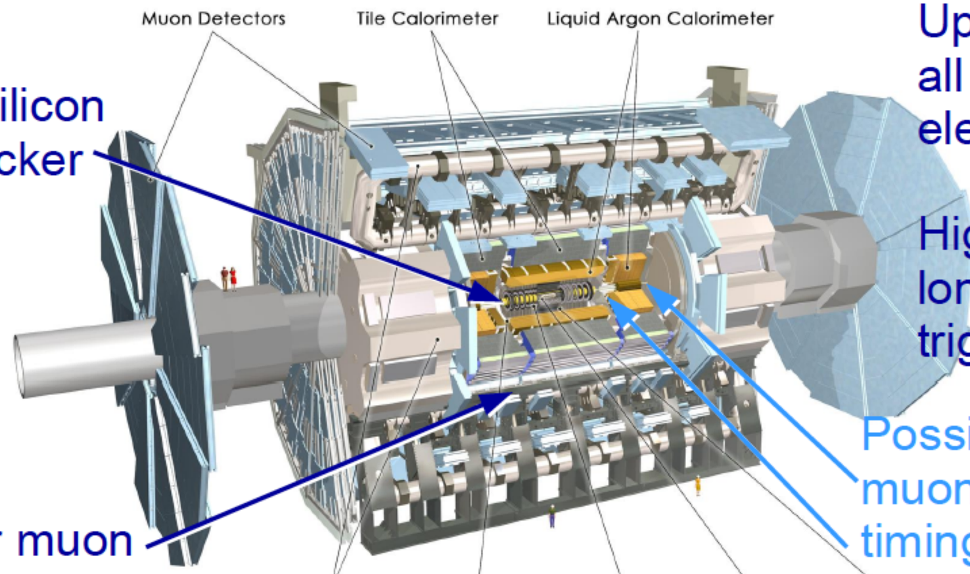
CMS phase 2 upgrade summary:



ATLAS Upgrades

- Phase 1 upgrade will complete with installation of new muon small wheel, topological L1-trigger processors, & improvement of calo trigger granularity
- Phase 2 upgrade include new all-silicon inner tracker (up to $|\eta|$~4), new trigger architecture & hardware at L0/L1, calorimeter electronics upgrade

ATLAS phase 2 upgrade summary:

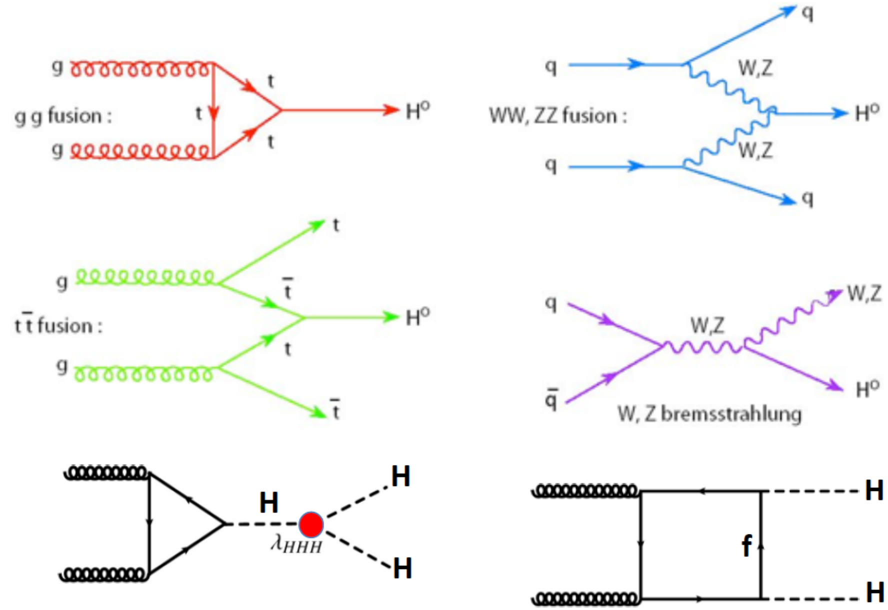


Physics Projections - Strategies

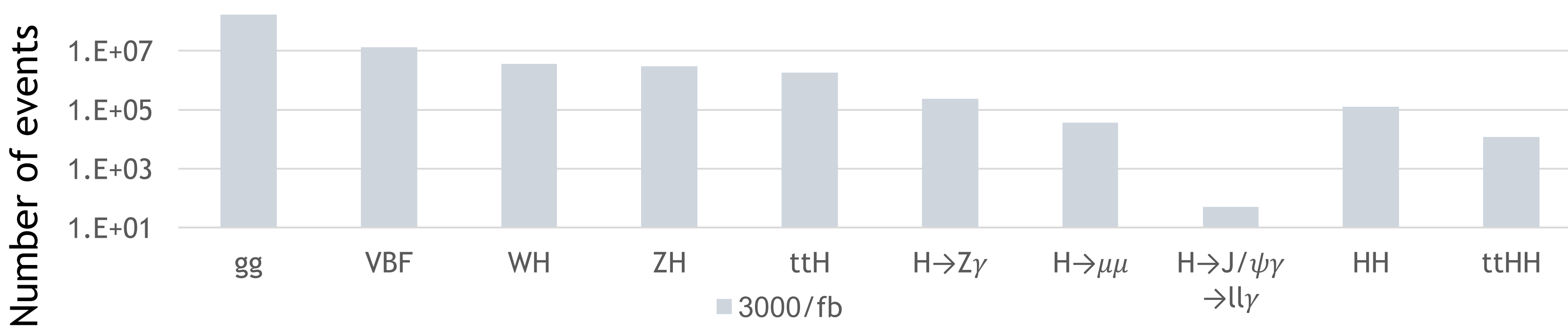
- Some variations for different physics analyses, but baseline is:
- CMS:
  - Extrapolate recent Run2 analyses to (300) 3000/fb. Consider effects of high pileup (PU) conditions and detector performance, based on CMS-TDR-15-002
  - Scenarios for systematics
    - Scenario 1+: theory and experimental uncertainties same as in the corresponding Run2 analyses. High PU and detector upgrades accounted for.
    - Scenario 2+: theory uncertainty halved. Experimental uncertainty $1/\sqrt{L}$ until they reach an estimated lower limit. High PU & upgrades are accounted for.
  - Or full analysis with parametrized detector performance (Delphes)
- ATLAS:
  - Generator-level + smearing function
    - Use the generator-level MC samples. Overlay jets from pileup library to simulate pileup effects
    - Trigger efficiency functions to emulate trigger effects
    - Detector response: smear p_T and energy of reconstructed physics objects. Apply reconstruction efficiencies for electrons, muons, and jets
    - Analysis algorithms derived from Run-2 analyses

Higgs Physics

- Higgs program at the LHC is broad:
  - Higgs couplings
  - Higgs-self coupling
  - Rare Higgs decays, including BSM
  - Heavy Higgs searches

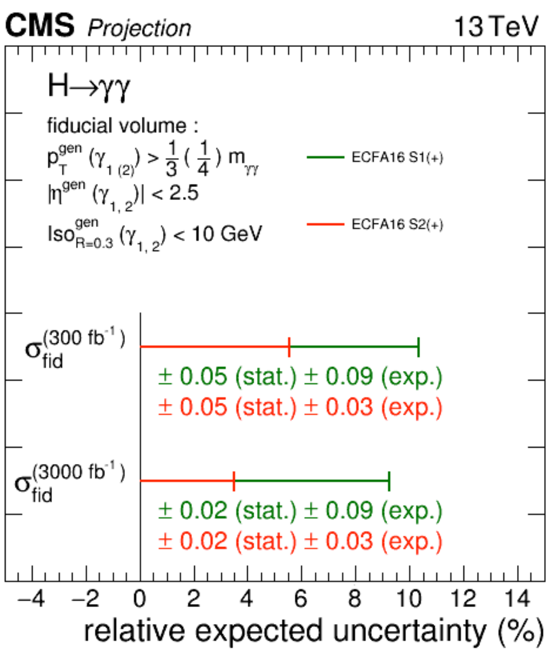


- Large Higgs statistics enable this broad program



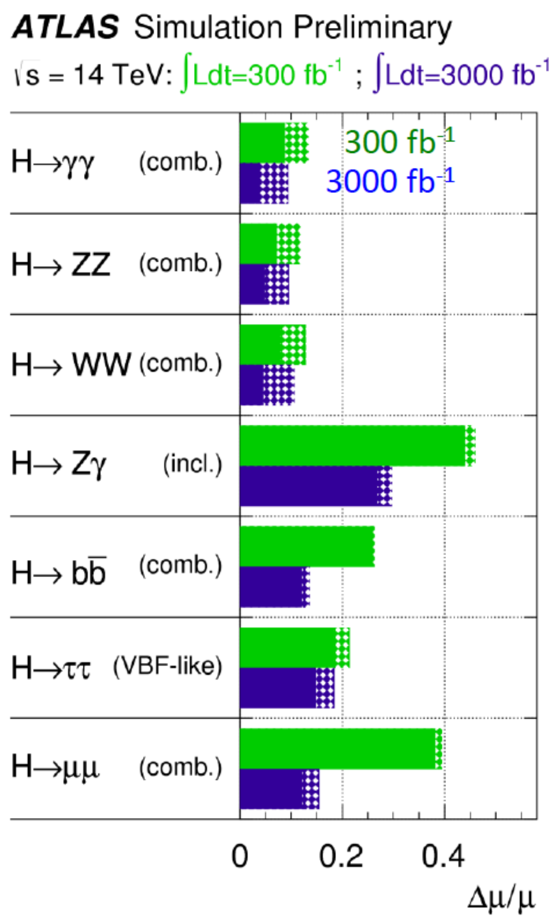
Higgs Production / Coupling

CMS-PAS-FTR-16-002
CMS-PAS-HIG-16-020 (reference)



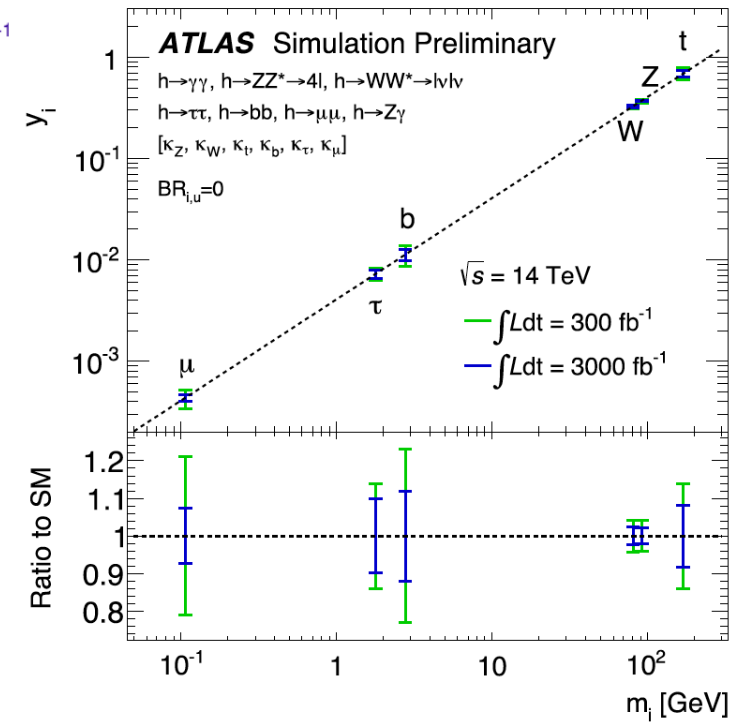
Fiducial cross section in the diphoton channel, likely exp. systematics dominated

ATL-PHYS-PUB-2014-016



Uncertainty on signal strength (hashed region = effect of “current” theoretical uncertainties)

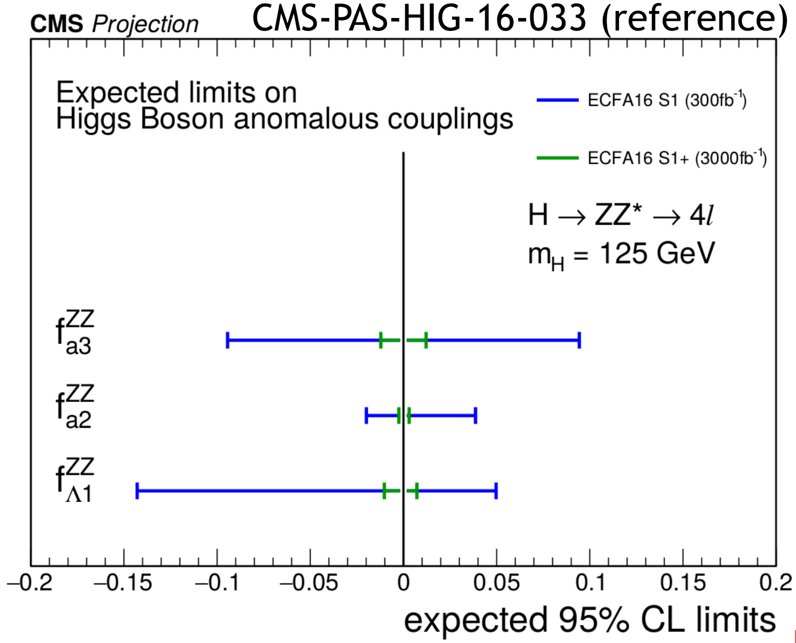
ATL-PHYS-PUB-2014-017

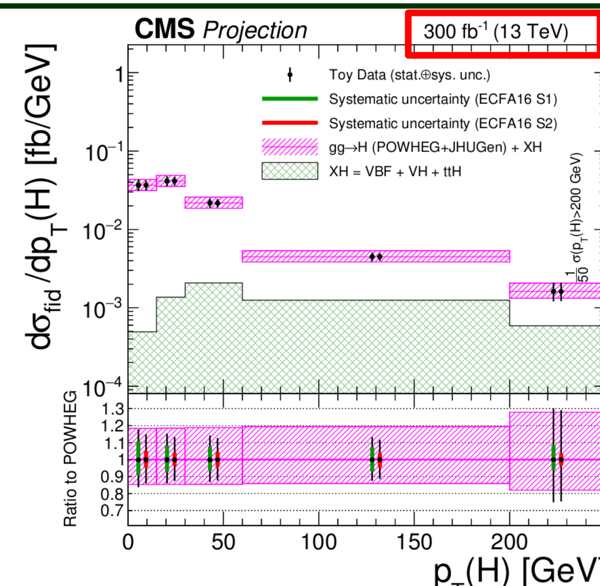


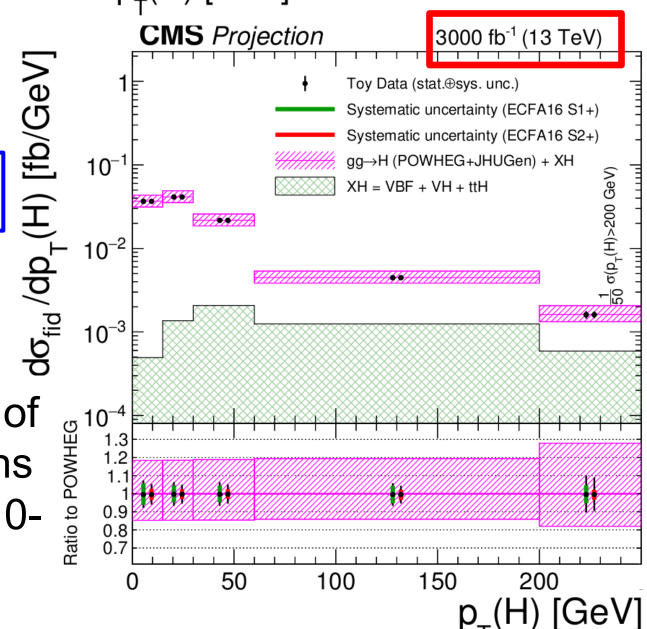
- W, Z couplings to 3%
- μ coupling to 7%
- t,b,τ couplings to 8-12%

Anomalous Coupling, Differential Cross Section

CMS-DP-2016-064
CMS-PAS-HIG-16-033 (reference)







BSM CP even

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{(\Lambda_1^{\mathrm{VV}})^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

BSM CP odd

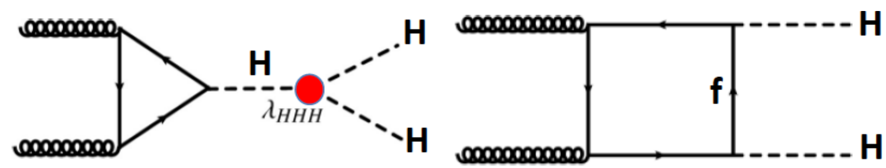
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\,(\Lambda_1)^4 + \ldots},$$

Statistically dominated: huge increase in sensitivity in anomalous coupling sensitivity going from 300 to 3000 fb^{-1}.

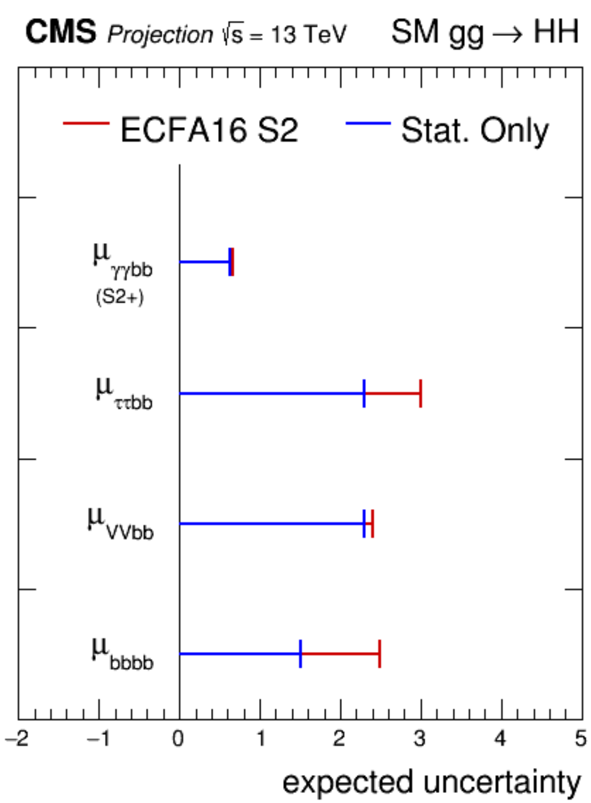
Precise measurements of differential cross sections (ZZ channel shown) ~ 10-29% (4-9%) (stat.) for 300 (3000) fb^{-1}.

Di-Higgs, Self-Coupling

- Next milestone in Higgs physics: access to the Higgs self-coupling $\boldsymbol{\lambda}$
  - Cross section ~ 40 fb @14 TeV
  - Destructive interference

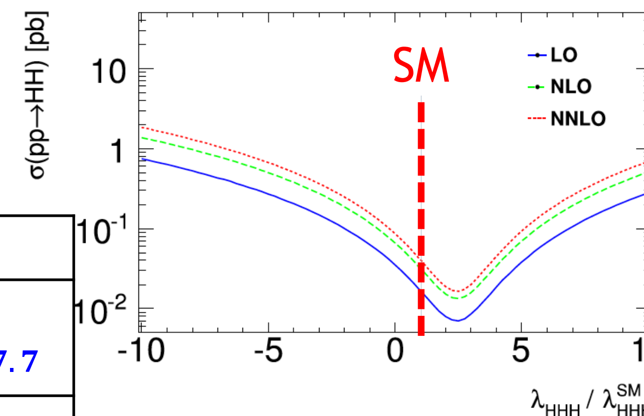


CMS-DP-2016-064



ATL-PHYS-PUB-2017-001
ATL-PHYS-PUB-2015-046
ATL-PHYS-PUB-2016-024
ATL-PHYS-PUB-2016-023

HH Channel	Results
$HH \to bb\gamma\gamma$	$1.05\ \sigma$, $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$
$HH \to bb\tau\tau$	$0.6\ \sigma$, $-4 < \lambda_{HHH}/\lambda_{SM} < 12$
$HH \to bbbb$	$-1.3 < /\lambda_{SM} < 8.7$
$ttHH$, $HH \to bbbb$	$0.35\ \sigma$

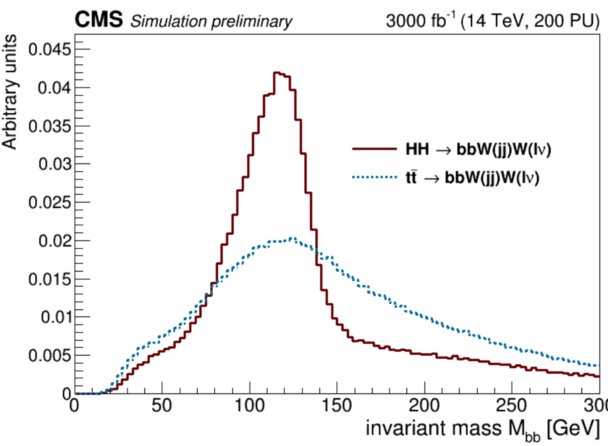


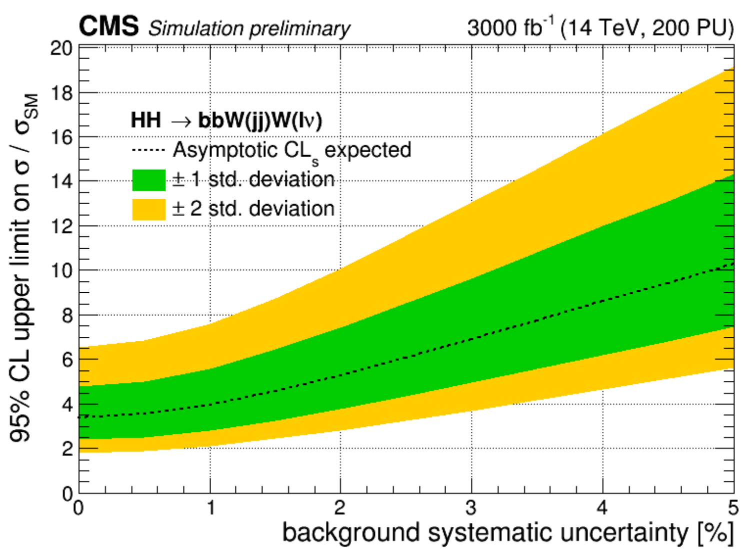
Challenging…
Likely that we need to use as many production mechanisms and final states as possible

HH->bbWW->bbqqlv, ttHH

CMS-DP-2016-064

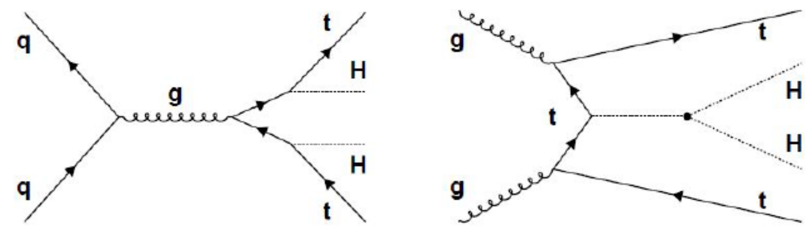
- BDT analysis to separate HH from tt
- Key variables: m(bb), ΔR(bb)

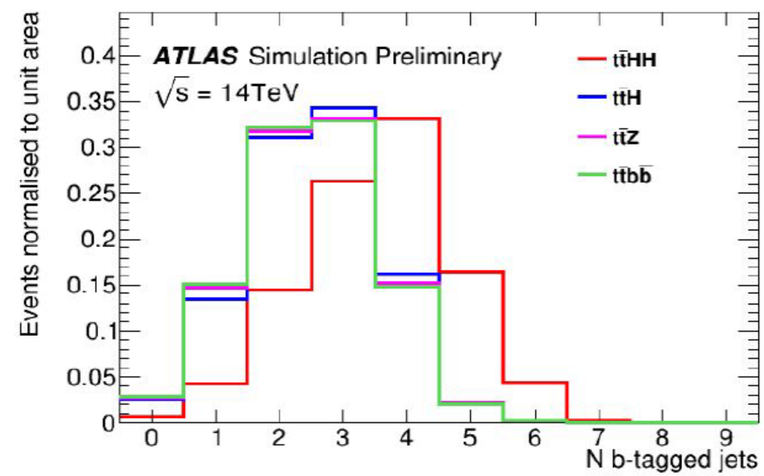




ATL-PHYS-PUB-2016-023

- σ(ttHH)~1fb
  - Use HH->bbbb, 1-lepton ttbar
  - 6 b-jets, 2 light-jets, e/mu, MET





Cut & count analysis for now

Estimated significance: 0.36**σ** @3000 fb^{-1}

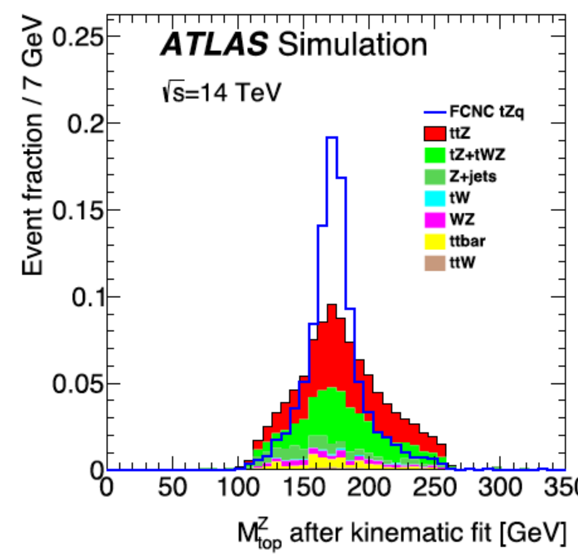
FCNC Top Decays

- Search for flavor-changing neutral-current (FCNC) t->Zq and t->Hq in tt events (ATL-PHYS-PUB-2016-019)
  - t->Zq->ℓℓq, t->Wb->ℓνb → 3ℓ+b jet
  - t->Hq->bbq, t->Wb->ℓνb → 1ℓ+3bjets

	SM	2HDM	MSSM
BF($t\to cg$)	$5\cdot 10^{-12}$	$10^{-8}-10^{-4}$	$10^{-7}-10^{-6}$
BF($t\to cZ$)	$1\cdot 10^{-14}$	$10^{-10}-10^{-6}$	$10^{-7}-10^{-6}$
BF($t\to c\gamma$)	$5\cdot 10^{-14}$	$10^{-9}-10^{-7}$	$10^{-9}-10^{-8}$
BF($t\to cH$)	$3\cdot 10^{-15}$	$10^{-5}-10^{-3}$	$10^{-9}-10^{-5}$

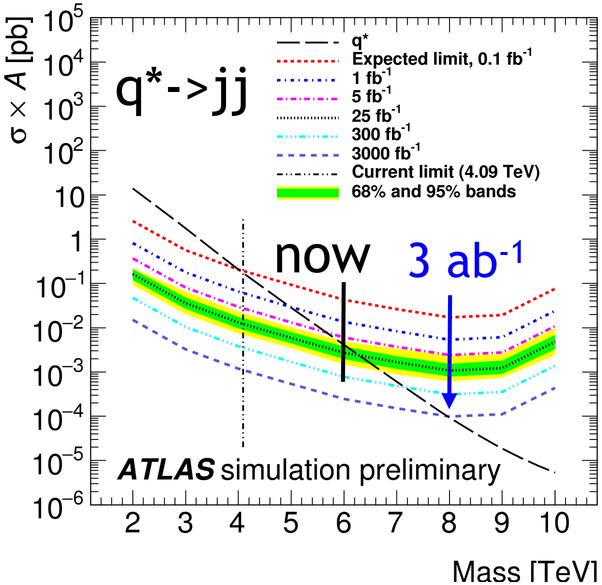
B(t → Zq) < 2.4 – 5.8 x 10^{-5}	(FCNC modelling)	5x10^{-4}	Run-1 results
B(t → Hq) < 0.55 – 1.2 x 10^{-4}	(flavour of q)	45x10^{-4}	

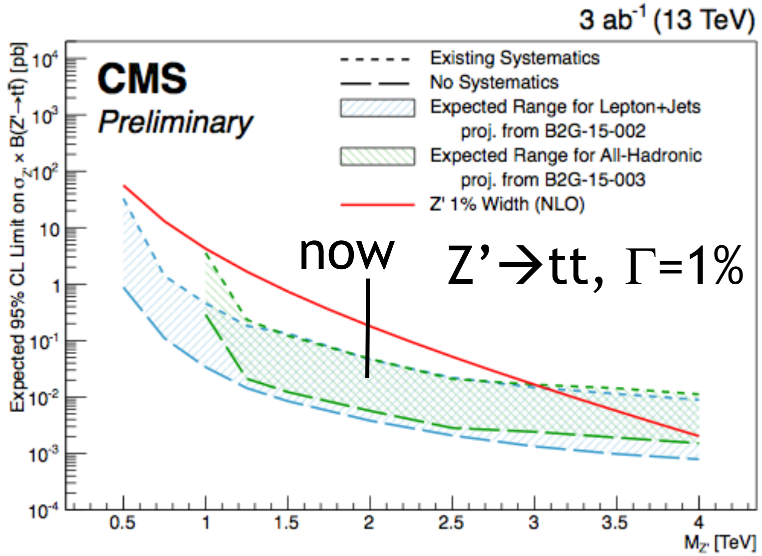
@3ab^{-1}



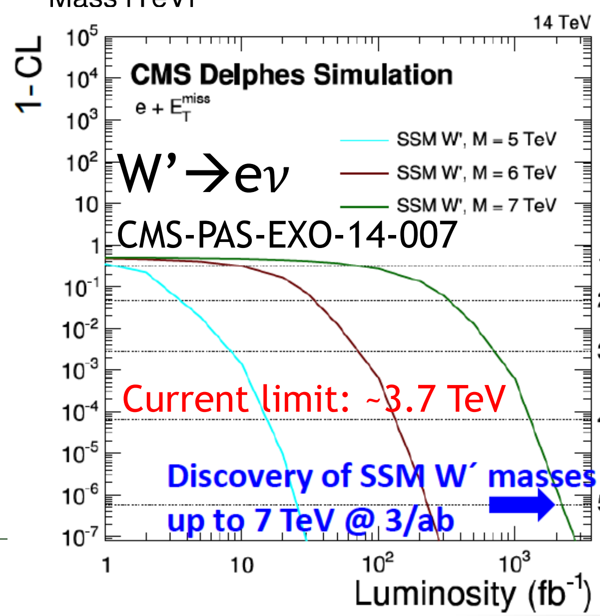
Heavy Resonances

ATL-PHYS-PUB-2015-004

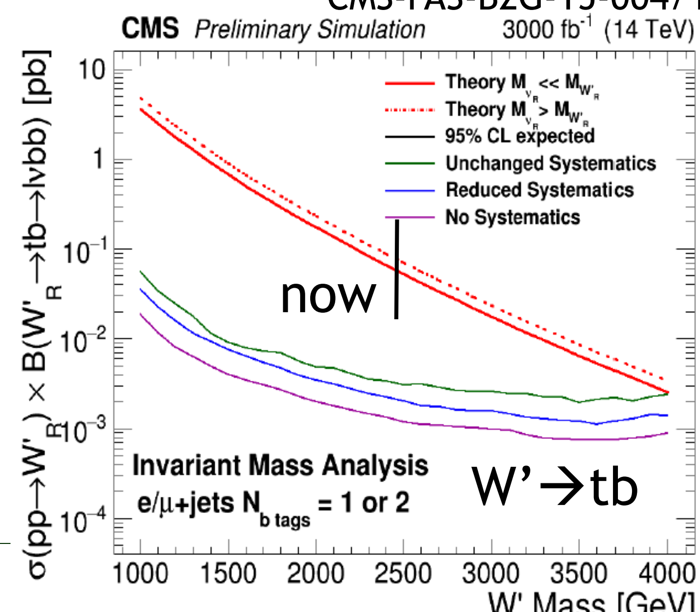




CMS-DP-2016-064
CMS-PAS-B2G-15-002/3
(Similar results in ATL-PHYS-PUB-2017-002)



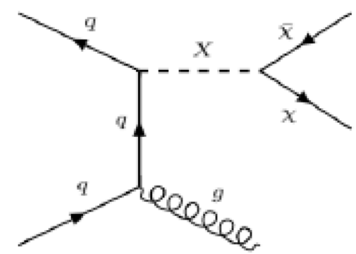
CMS-DP-2016-064
CMS-PAS-B2G-15-004/16-017

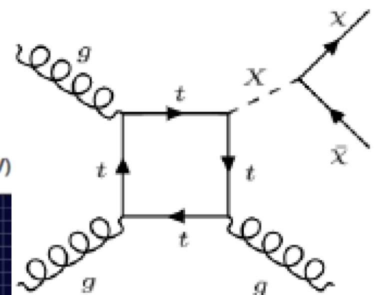


Dark Matter (DM)

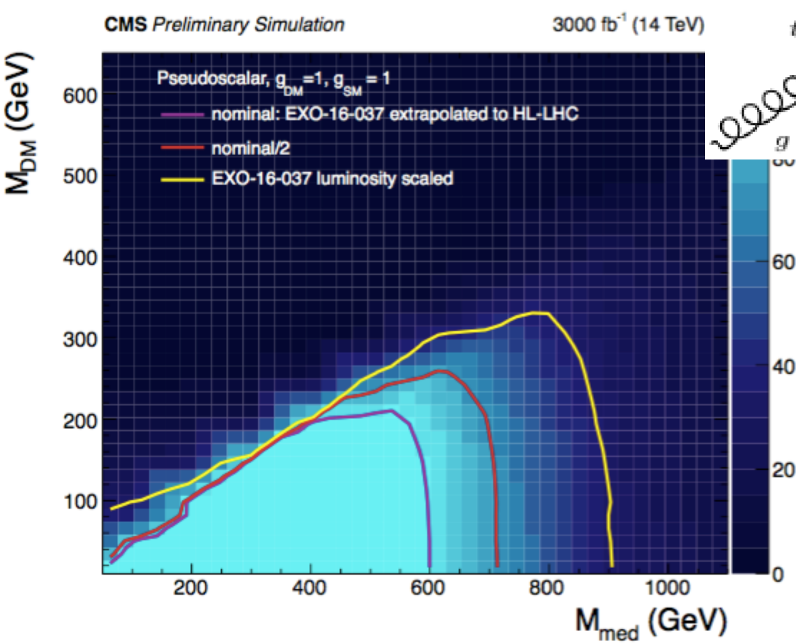
- Many indications for its existence but what is its nature?
- LHC searches complement direct detection experiments
- Interpretation in simplified models following LHC DM forum (arXiv:1507.00967) with 4 parameters (M_{med}, M_{DM}, g_{SM}, g_{DM})

CMS-DP-2016-064
EXO-16-037 (reference)



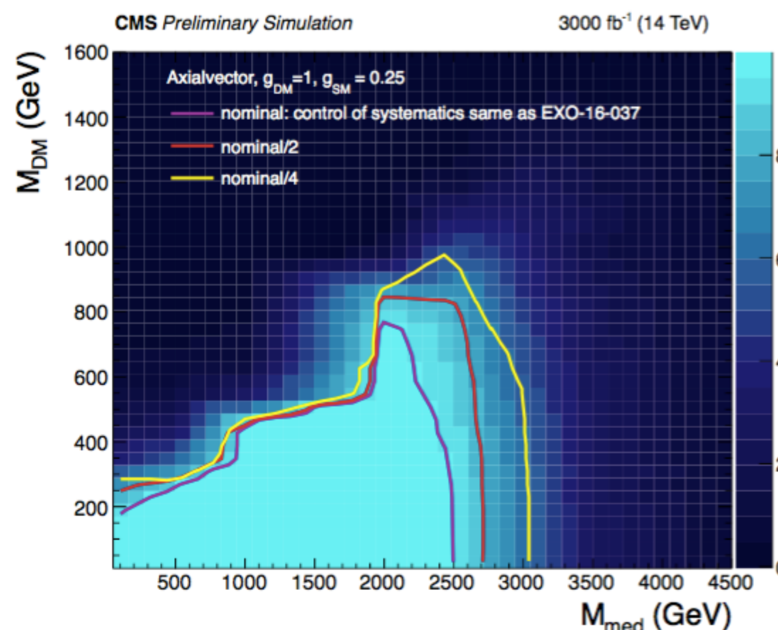


Pseudo-scalar



Current reach for M_{med} ~ 0.4 TeV

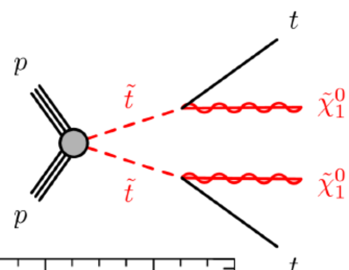
Axial-vector

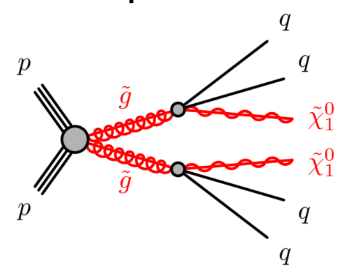


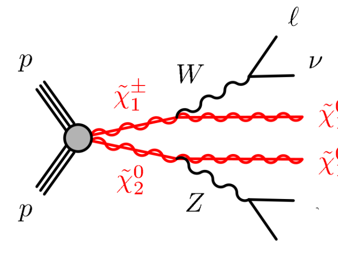
Current reach for M_{med}~ 2 TeV

Supersymmetry

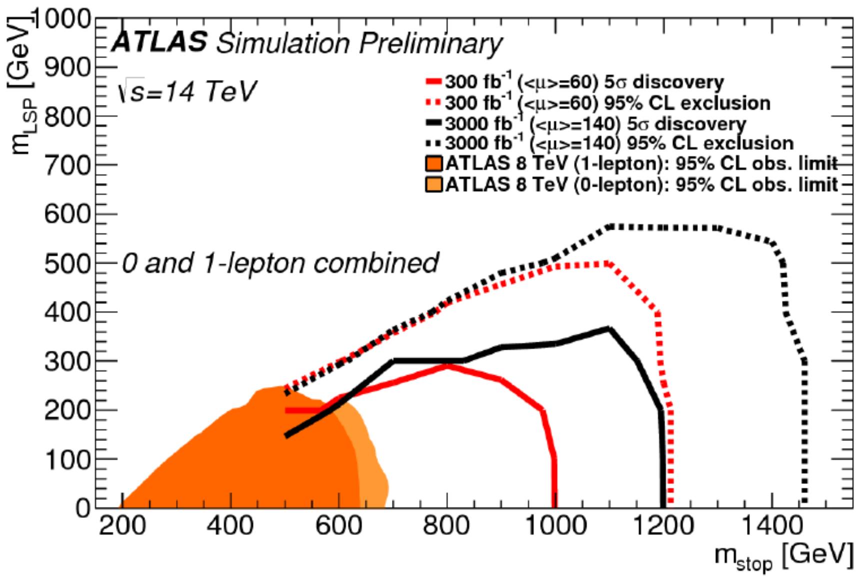
- Search for SUSY is one of the main LHC goals
- Larger luminosity allows
  - Explore higher mass, low cross section & compressed mass spectra.
  - Upon discovery, measure its properties, SUSY spectrum

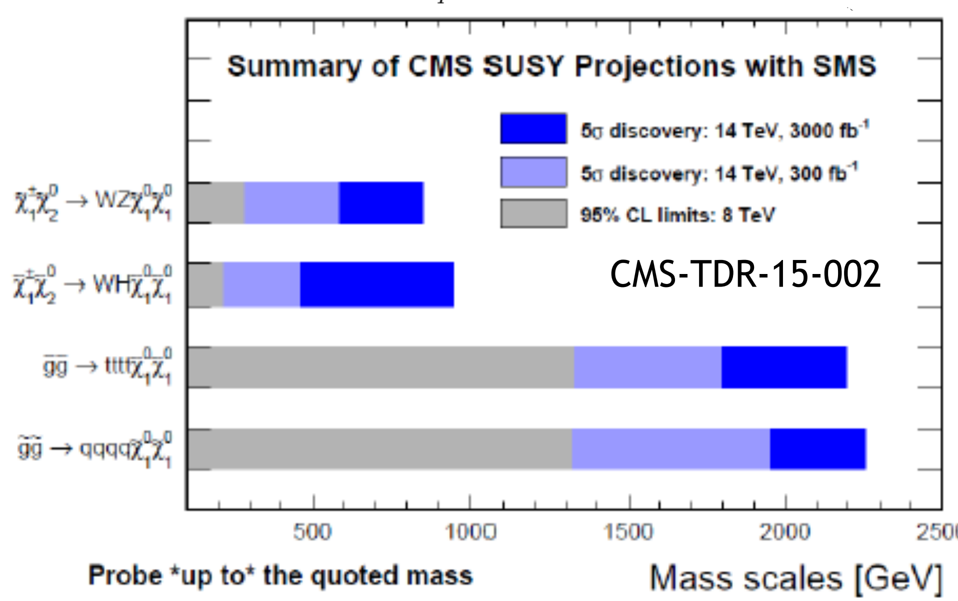






ATL-PHYS-PUB-2013-011



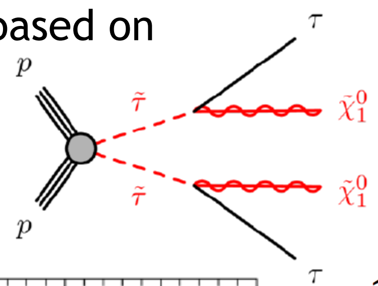


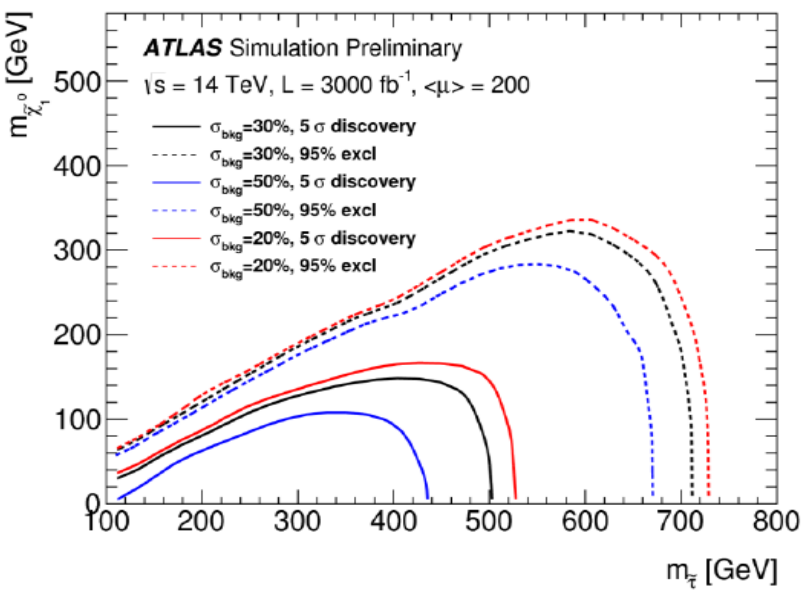
Largest relative gains in weak production processes

Stau & EWKino

ATL-PHYS-PUB-2016-021

- Search for stau pair production
  - 2 tau jets + MET
  - Signal region based on $m_T(\tau_1)+m_T(\tau_2)$

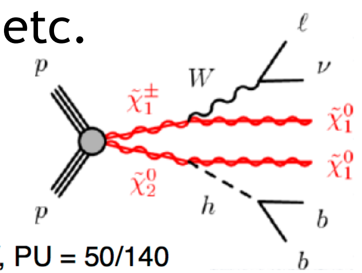


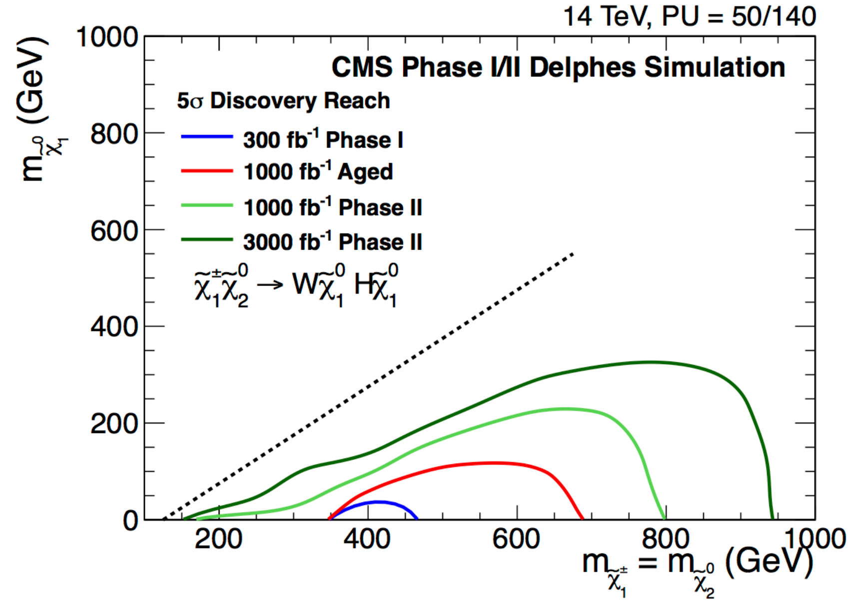


Discovery reach 430-520 GeV @ 3/ab

CMS-PAS-SUS-14-012

- Search for $\chi_1^{\pm}\chi_2^0$ production
  - Signal region defined by M(bb), MT, MET etc.

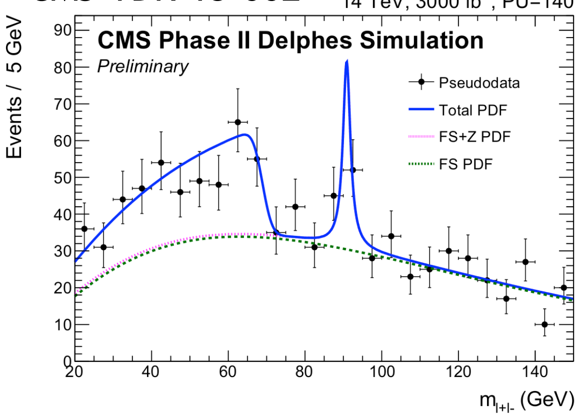


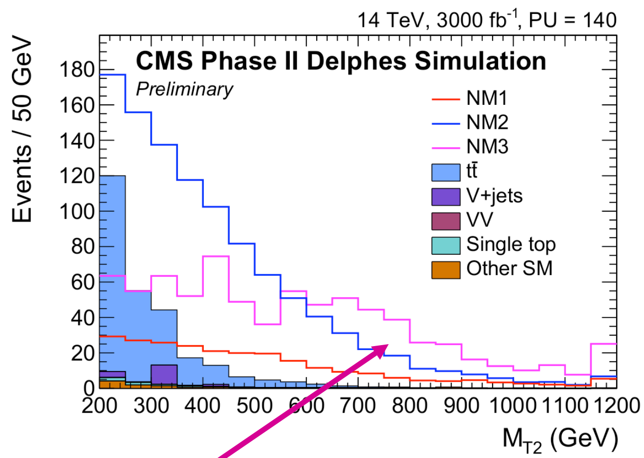


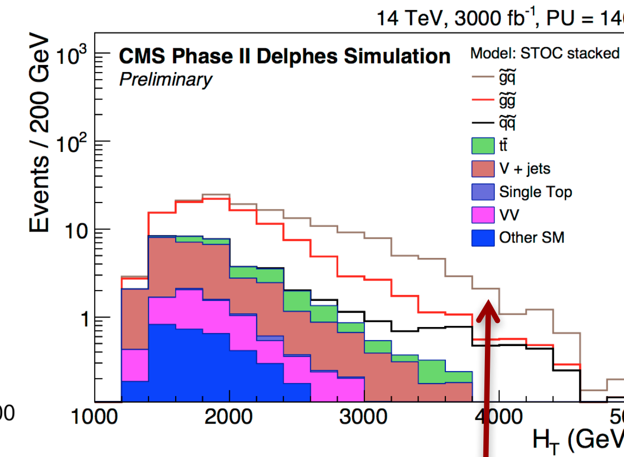
- Large gain in discovery potential
- Detector upgrade is crucial (b-tag, MET)

Example Discovery Scenarios

CMS-TDR-15-002







Dilepton Edge from:

$$\tilde{\chi}_2^0 \to l\tilde{l} \to \tilde{\chi}_1^0 l^+ l^-$$

$$m_{\rm edge} = \sqrt{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1})}/m_{\tilde{l}}$$

Distinctive kinematic distributions indicating:

-> Large mass gaps -> massive m_{T2} tails

-> Gluino-squark production of 3 TeV u/d/s squarks

- Discovery of gluino (m_{gluino}~1.6 TeV) signatures in jets + MET + b-tags in Run 3
- HL-LHC adds detailed measurements of:
  - Weakly interacting sector in gluino cascade decays
  - Distinctive kinematic features of the new physics.
  - Observations in additional final states (particles) not visible yet in Run 3.

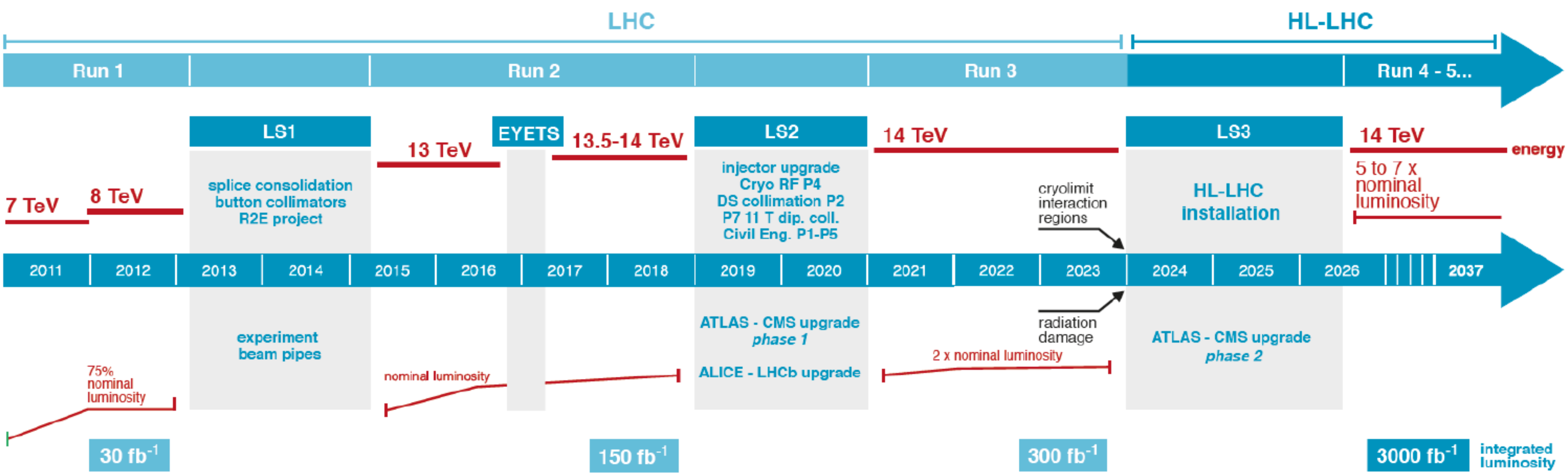
Outlook

- We have gotten a variety of interesting physics results from LHC already, and we expect a lot more during the future LHC running
- Run 2, Run 3, and HL-LHC will provide a comprehensive physics program: Precision Higgs physics, Higgs rare decays, self-coupling, precision top physics, rare decays, new multi-TeV resonances/particles, SUSY up to 2-3 TeV…
- Detector upgrades (phase1 & phase2) are underway to enable this interesting physics program

Stay tuned!

Backup

Luminosity Profile



Nominal Scenario: luminosity leveled at 5 x 10^{34} Hz/cm^2, pile-up $\langle\mu\rangle$ = 140
Ultimate Scenario: 7.5 x 10^{34} Hz/cm^2, pile-up $\langle\mu\rangle$ = 200

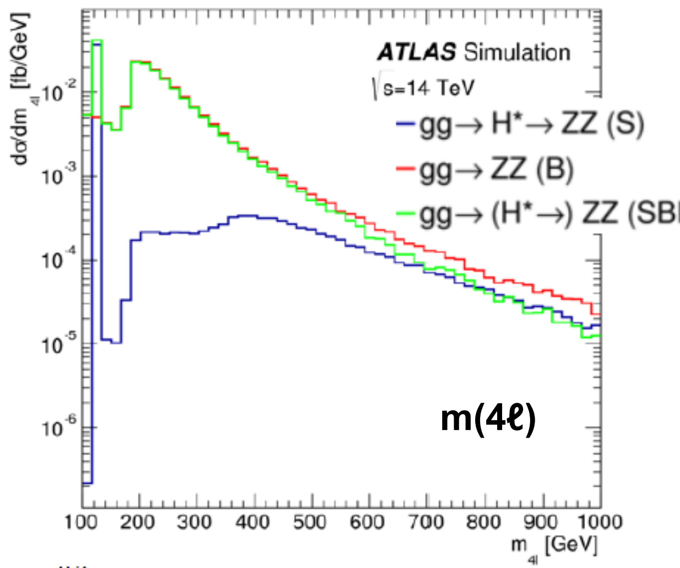
Higgs Width

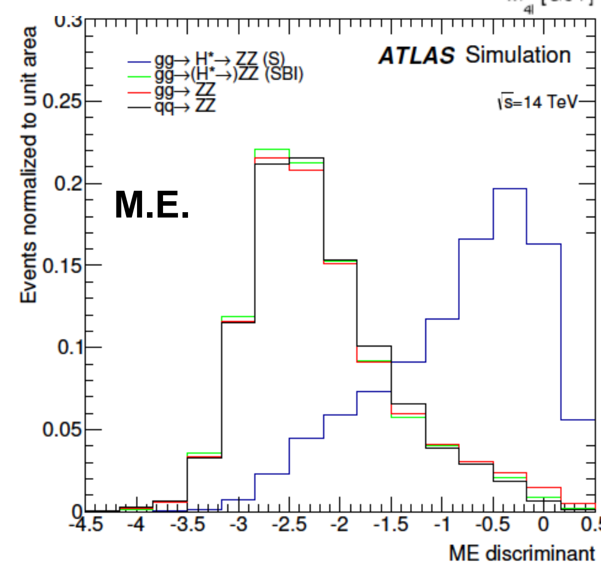
ATL-PHYS-PUB-2015-024

- Measure off-shell production of $H \rightarrow ZZ^* \rightarrow 4\ell$ with $m(4\ell) > 220$ GeV
- Use $m(4\ell)$ shape and matrix element to discriminate between signal and background
  - stat. uncertainties only: $\mu_{\text{off-shell}} = 1.00^{+0.23}_{-0.27}$
  - stat.+syst. uncertainties: $\mu_{\text{off-shell}} = 1.00^{+0.43}_{-0.50}$
- Off-shell production used to constrain the Higgs boson width
- For $\Gamma = \Gamma_{SM}$ combining with on-shell measurement, (assuming off-shell measurement dominates):

$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys)

- Run 1: $\Gamma_H <$ 22.7 MeV @ 95% CL (WW, ZZ)

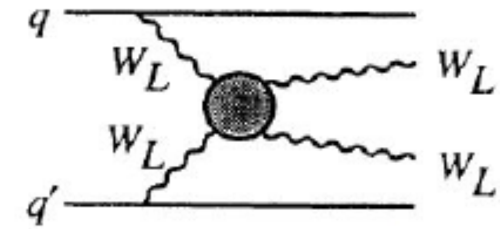


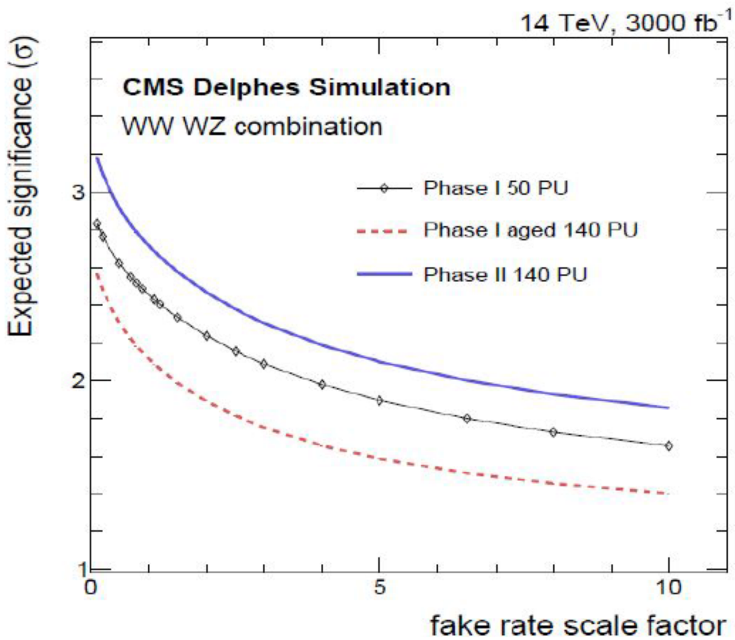


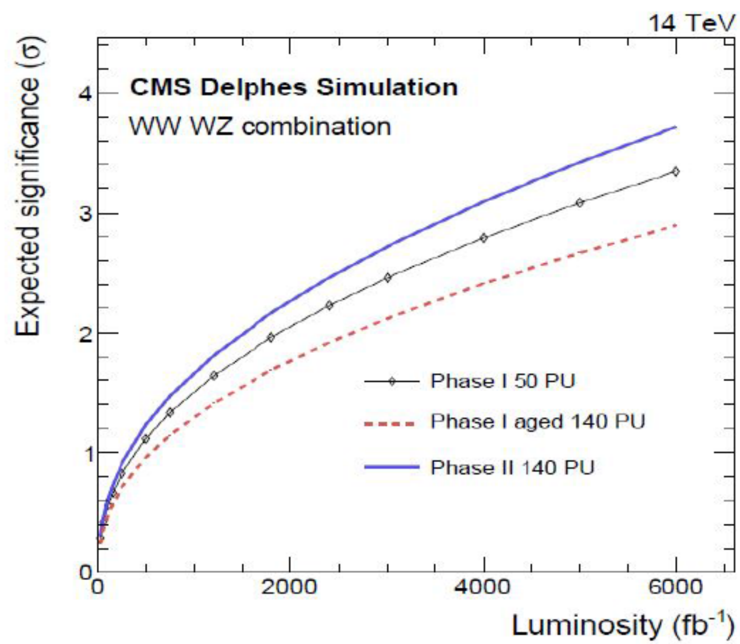
Diboson Production

CMS-PAS-SMP-14-008

- Stringent test of standard model predictions, restoring unitarity at high energies





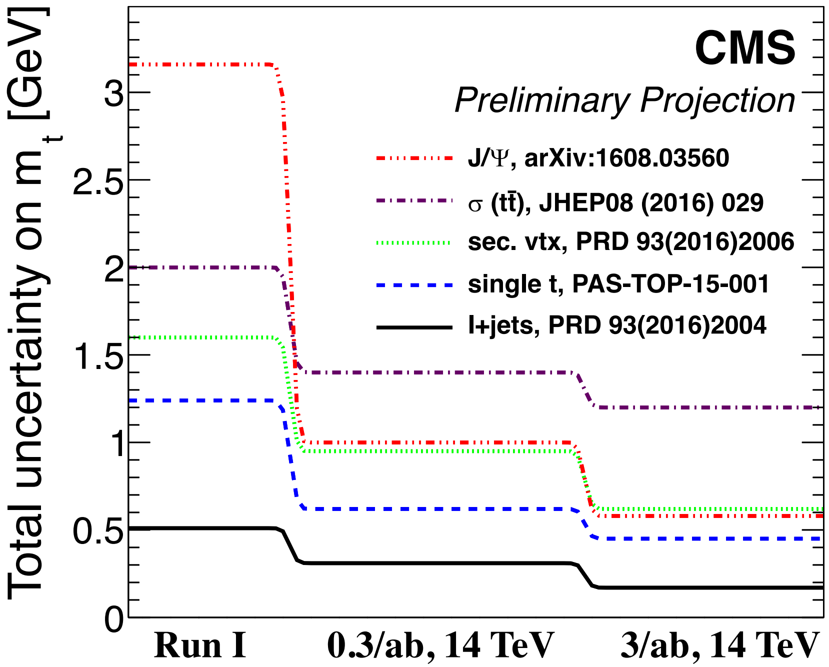


	Phase I	Phase II	Phase I aged
noH 95% CL exclusion	0.14	0.14	0.20
LL scattering discovery significance	2.50	2.75	2.14

Top Quark Mass

- Fundamental parameter of the SM.
- Precise knowledge of M_{top} crucial for testing the consistency of the SM: it participates in quantum loop radiative corrections to M_W constraining M_H.

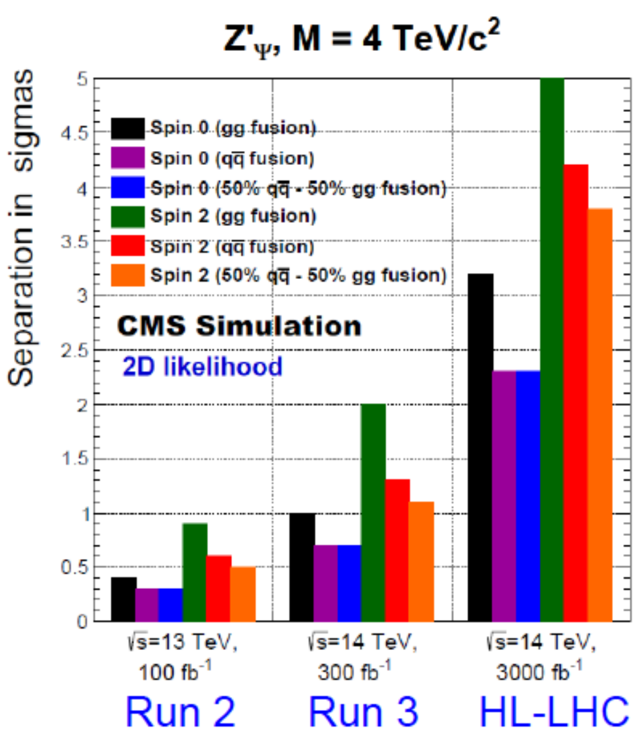
CMS-PAS-FTR-16-006

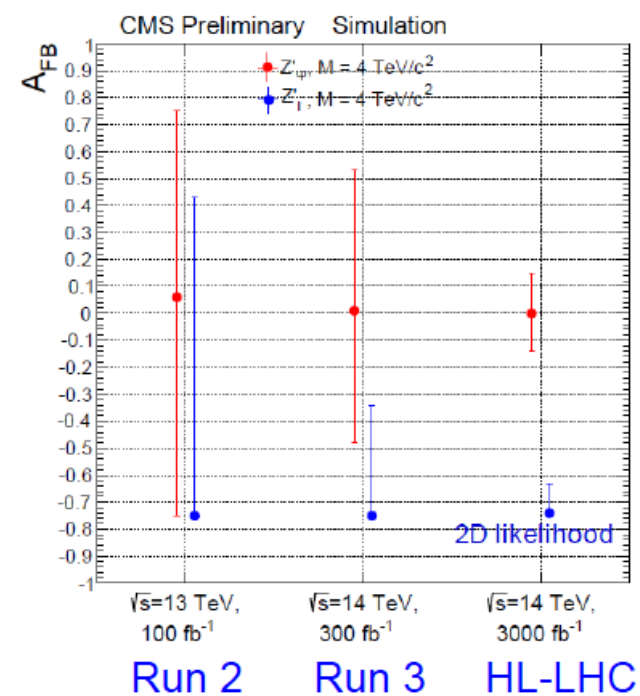


- Ultimate expected uncertainty < 0.1%!
- J/Psi method currently dominated by stat uncertainty would become more important
- Some improvements in theory uncertainties will be crucial (underlying-event, fragmentations, scale and ME-PS matching, etc)

Model discrimination after discovery

- Ability to discriminate improves dramatically with HL-LHC
  - Separate between spin-1 (Z') or spin-2 (GKK) interpretation and other interpretation ranges from ~2 to 5sigma
  - 2D likelihood with dilepton angular and rapidity distributions or forward-backward asymmetry

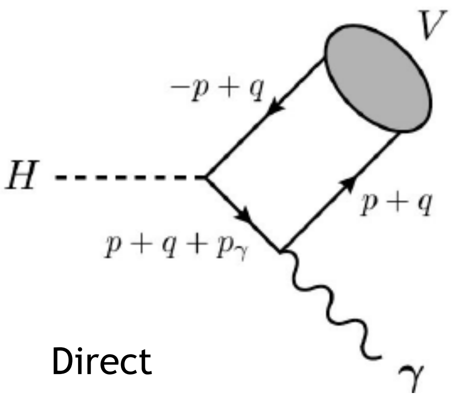




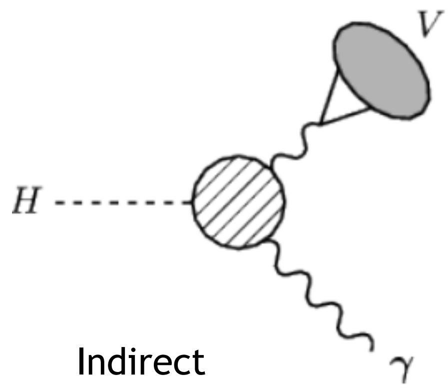
Rare Decay: H->J/Psi gamma

ATL-PHYS-PUB-2015-043

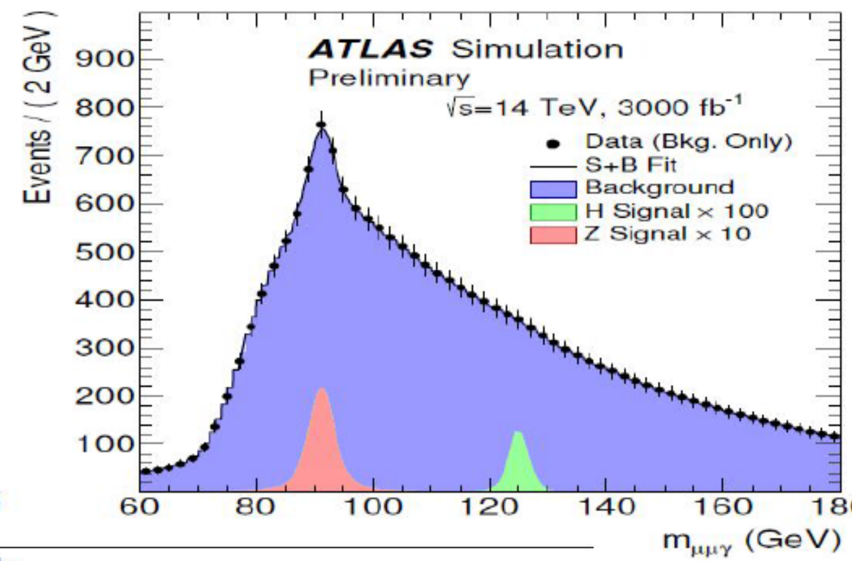
- Higgs coupling to charm is challenging
- ATLAS study of the $H \to J/\psi\gamma \to \mu\mu\gamma$ channel at high LHC luminosities, sensitive to the Higgs-charm coupling via loops



Direct



Indirect



➡ SM expectation: $\mathbf{BR}(H \to J/\psi\,\gamma) = (2.9 \pm 0.2) \times 10^{-6}$

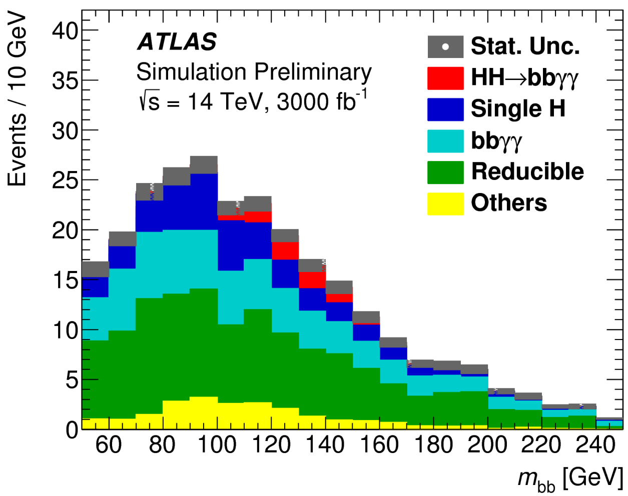
$J/\psi\,\gamma$ Final state

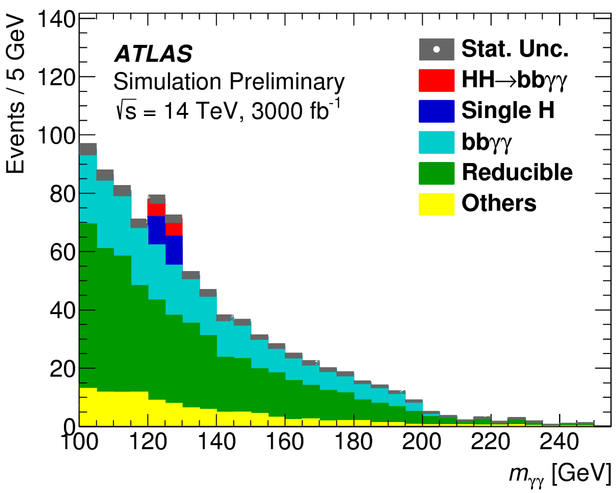
	Expected Background				Signal	
	Inclusive QCD Mass Range [GeV]		Other Backgrounds $Z \to \mu^+\mu^-\gamma$	$H_{\gamma^*\gamma} \to \mu^+\mu^-\gamma$		
	80-100	115-135			Z	H
Cut Based Analysis	7800±500	3500±400	780 ±100	15.1 ±1.4	50±3	3.2±0.1
Multivariate Analysis		1700±200		13.7 ±1.3		2.9±0.1

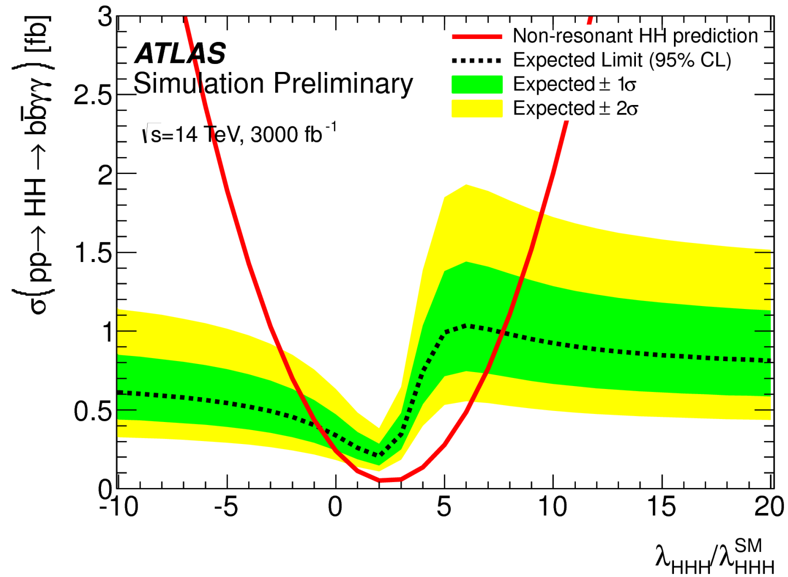
- Current expected limit with 3000 fb^{-1}: 15 times the expected SM Br

HH->bbγγ

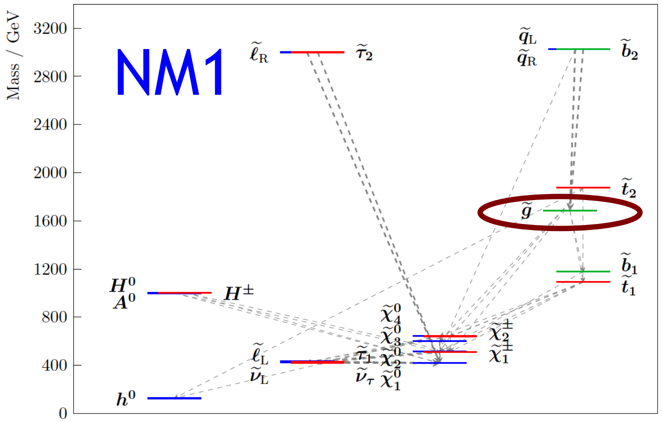
ATL-PHYS-PUB-2017-001

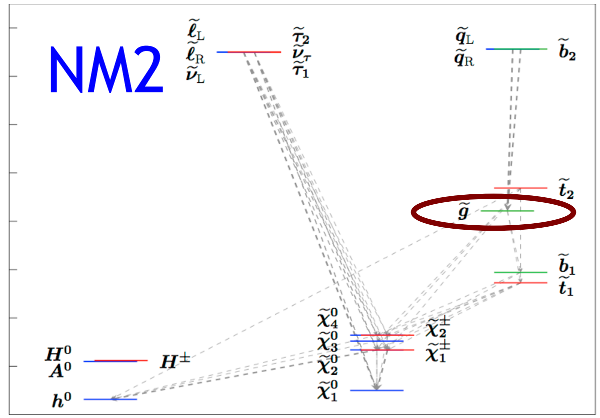


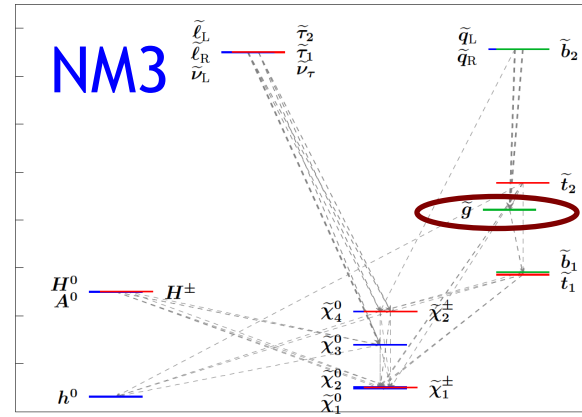


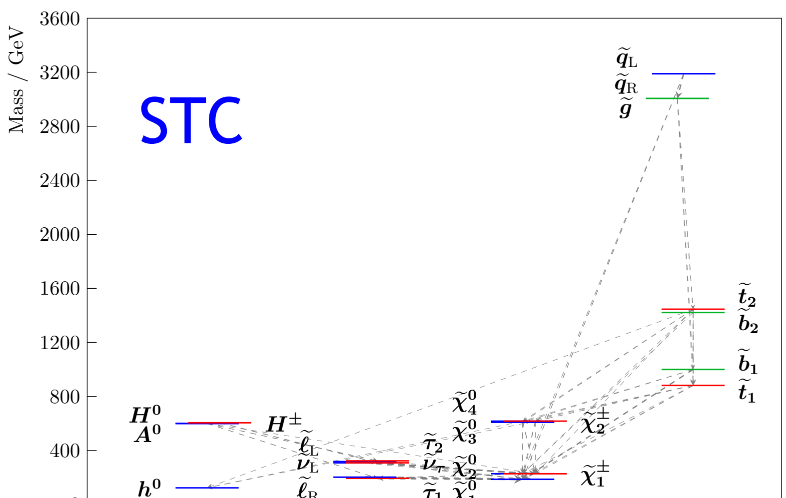


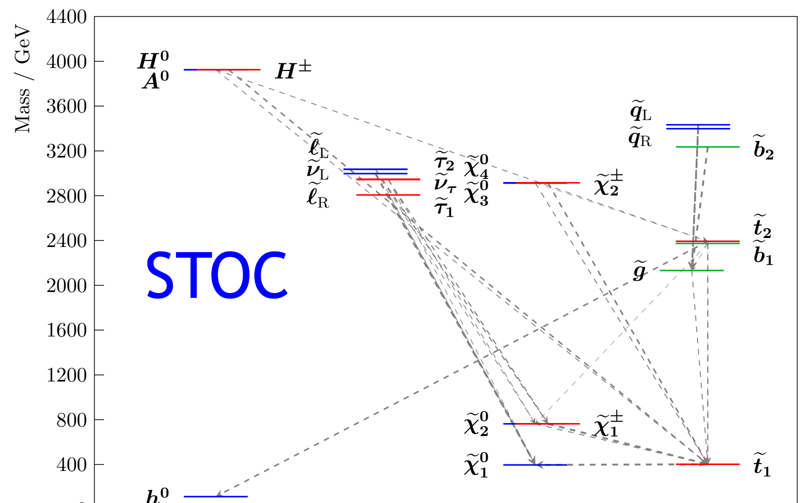
Discovery Scenarios: SUSY Models











HL-LHC measurements to understand a potential Run3 discovery

- Explored:
  - Five different models
    - 3 models motivated by naturalness
    - 2 coannihilation (stop & stau coannihilation) models
  - Nine different experimental signatures.

Exploring SUSY model space →

Exploring experimental signature space ↓

Analysis	Luminosity (fb^{-1})	Model: NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				$< 3\sigma$	$3-5\sigma$
	3000				$3-5\sigma$	$> 5\sigma$
all-hadronic (M_{T2}) search	300	$3-5\sigma$	$> 5\sigma$	$> 5\sigma$		
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$		
all-hadronic $\tilde{b}_1$ search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$3-5\sigma$	$< 3\sigma$
	3000	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$> 5\sigma$	$< 3\sigma$
1-lepton $\tilde{t}_1$ search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	$< 3\sigma$
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$
monojet $\tilde{t}_1$ search	300					$3-5\sigma$
	3000					$3-5\sigma$
$m_{\ell^+\ell^-}$ kinematic edge	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$		
	3000	$> 5\sigma$	$< 3\sigma$	$< 3\sigma$		
multilepton + b-tag search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	
multilepton search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	
	3000	$3-5\sigma$	$3-5\sigma$	$< 3\sigma$	$3-5\sigma$	
ewkino WH search	300		$< 3\sigma$			
	3000		$3-5\sigma$			

$< 3\sigma$ | $3-5\sigma$ | $> 5\sigma$

- Different types of SUSY models lead to different patterns of discoveries in different final states after different amounts of data.
- HL-LHC measurements can be crucial to illuminate a Run 3 discovery, and thus answer fundamental questions about gauge hierarchy or dark matter.