The HL-LHC physics program

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for the ATLAS & CMS Collaborations

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- LHC operation schedule
- Challenges at High Luminosity LHC (HL-LHC) and detector upgrade plans
- Physics prospects for HL-LHC
  - Higgs properties and couplings
  - Higgs self-coupling
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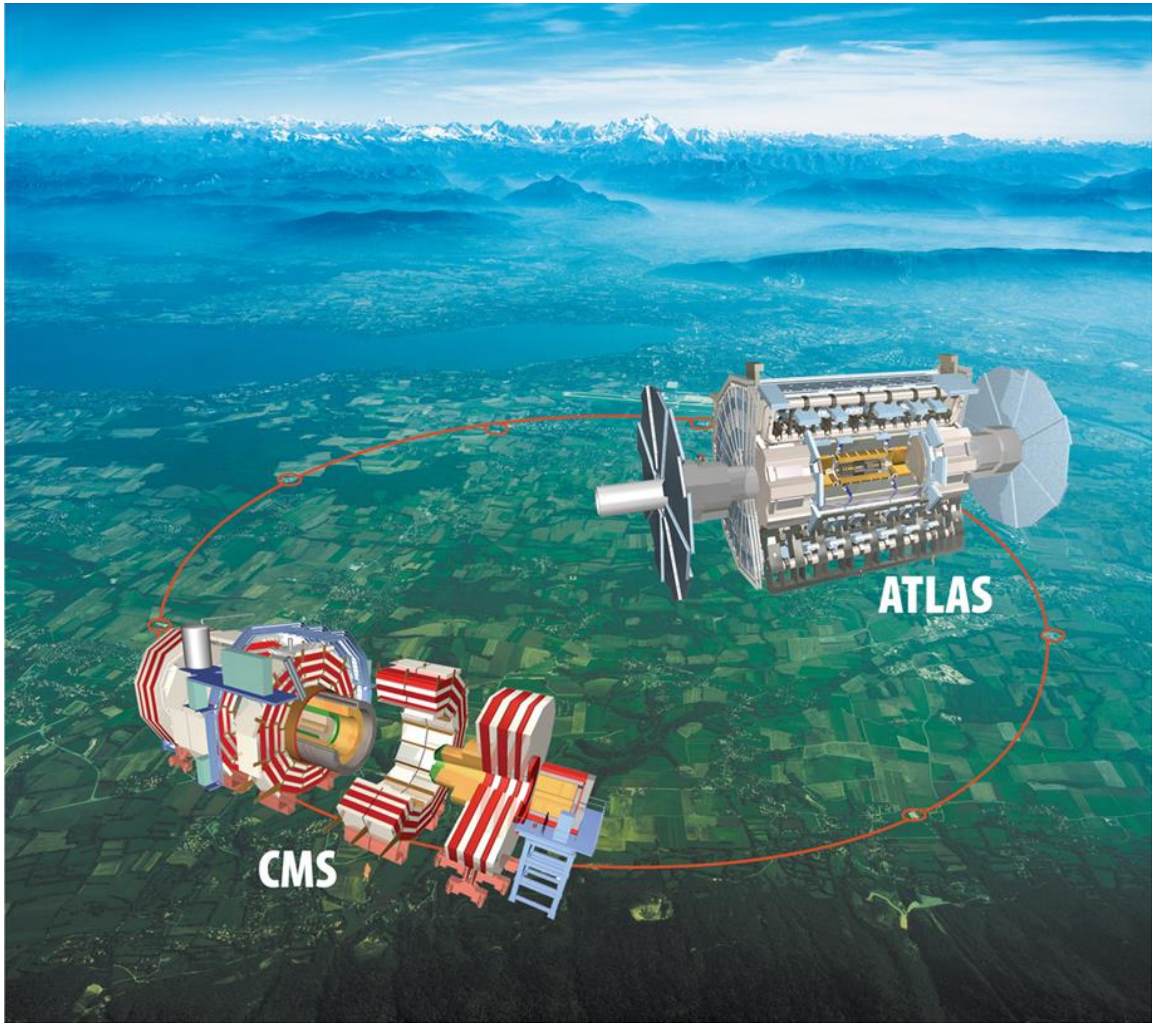
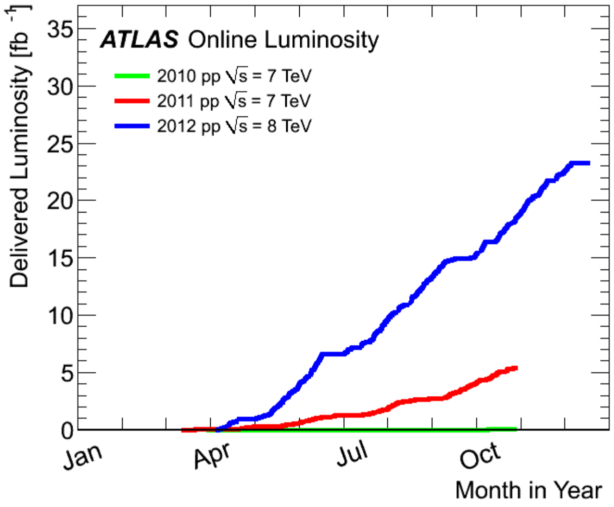
  - Rare processes

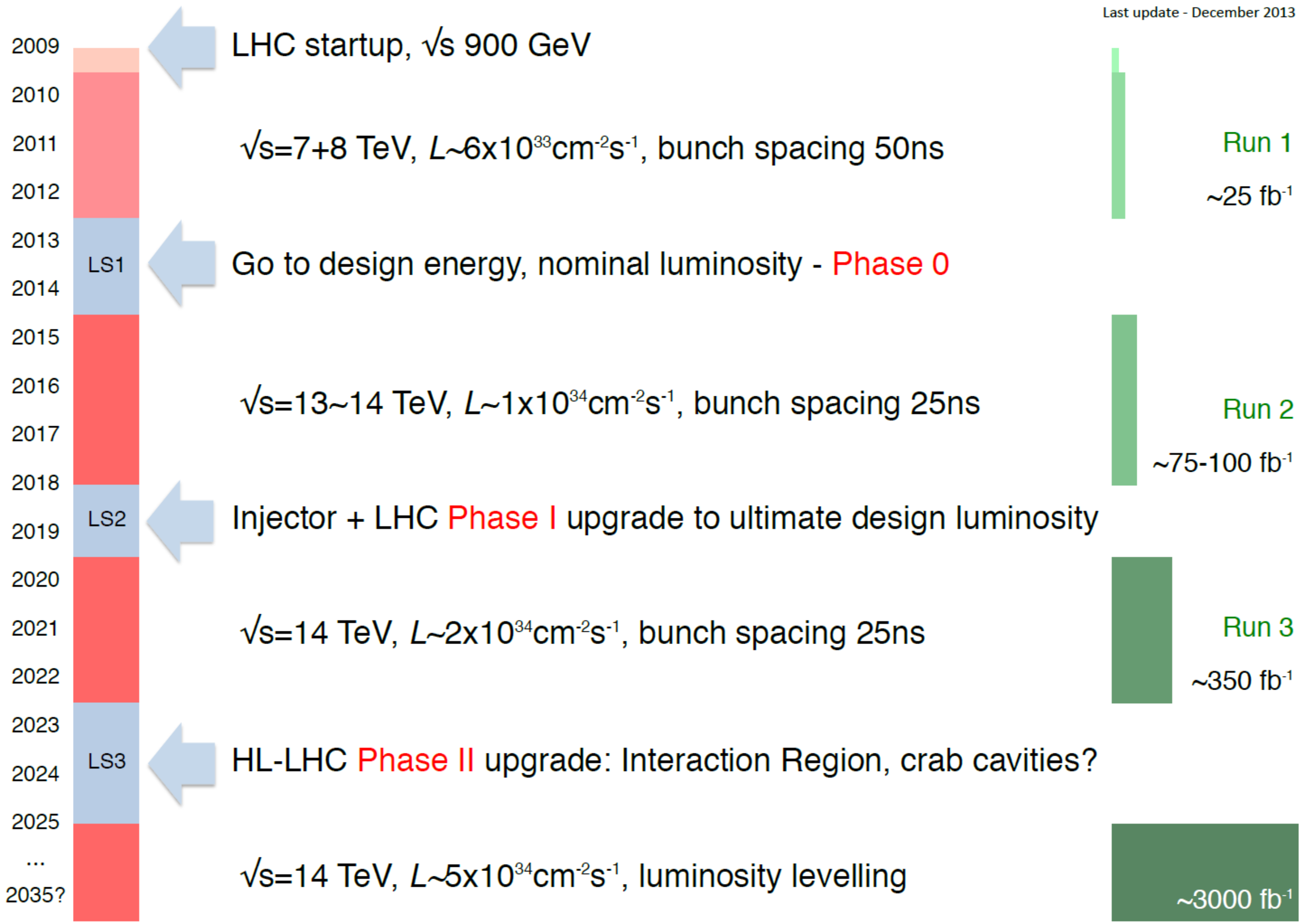
The Large Hadron Collider (LHC)



- Circumference: 27 km
- Design values
  - $\sqrt{s} = 14$ TeV
  - L=$2 \cdot 10^{34}$ $cm^{-2}s^{-1}$



LHC roadmap



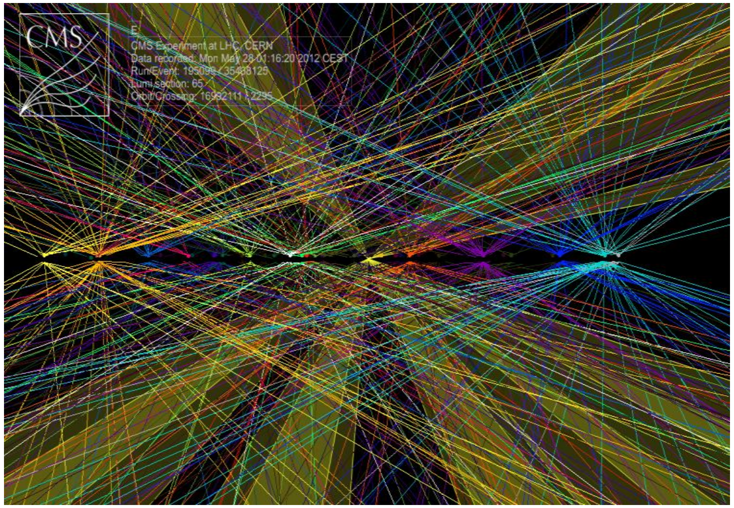
From LHCC Open meeting, 03.12.2013

High Luminosity LHC

<u>HL-LHC conditions</u>

- Increased LHC instantaneous luminosity
- Large number of pileup events (μ) in the same bunch crossing

➔ Luminosity leveling at $L = 5 \times 10^{34}$ ($cm^{-2}s^{-1}$) with $\langle\mu\rangle = 140$



	Peak L ($cm^{-2}s^{-1}$)
Until 2012	7×10^{33}
After Phase-1 upgrade	2.5×10^{34}
After Phase-2 upgrade	2×10^{35} (*)

(*) Maximum peak luminosity achievable by the machine

- ATLAS and CMS detectors must be upgraded to cope with high pileup condition
- Inner trackers must be replaced due to radiation damage
- Need new detectors (both hardware and software) to keep similar performance as now

ATLAS detector upgrade plans

<u>Phase-0</u>

- Insertable B-layer (IBL)
- L1 topological trigger
- Fast Track Trigger (FTK)

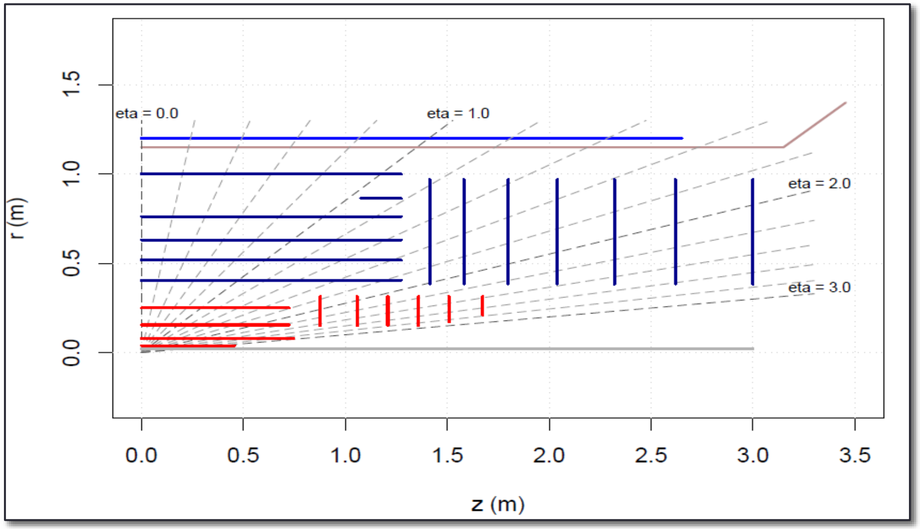
<u>Phase-1</u>

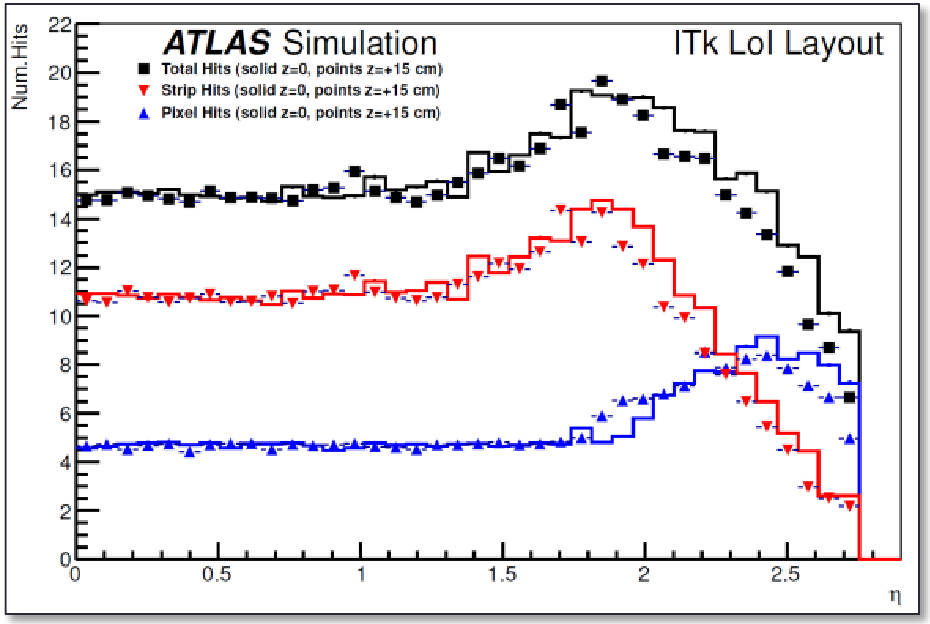
- High granularity at L1 calorimeter trigger
- New small wheel for L1 endcap muon trigger

<u>Phase-2</u>

- New silicon tracker (ITK)
- L0/L1 trigger scheme (500/100 kHz)

Work on detector consolidation is ongoing: cooling, power supply, electronic, etc.





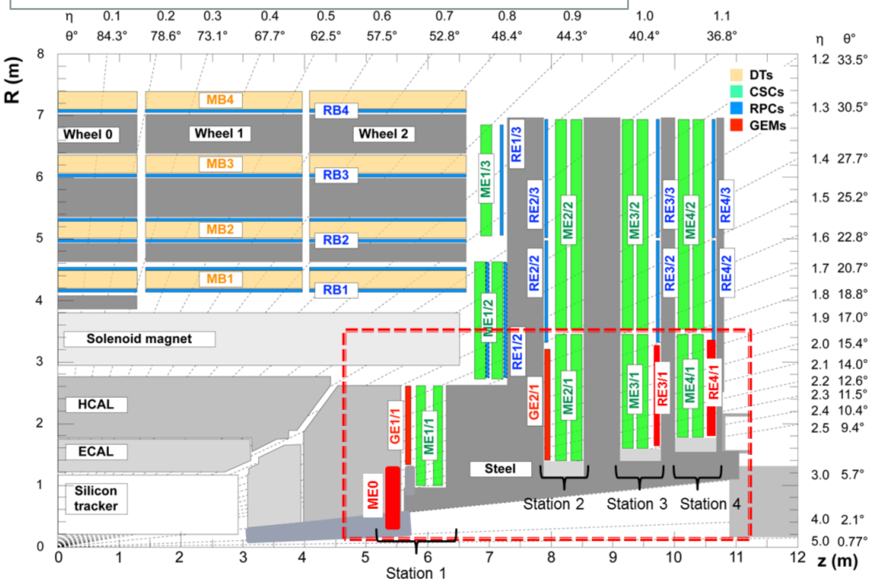
CMS detector upgrade plans

Phase-0
- 4th muon endcap station
- Detector consolidation

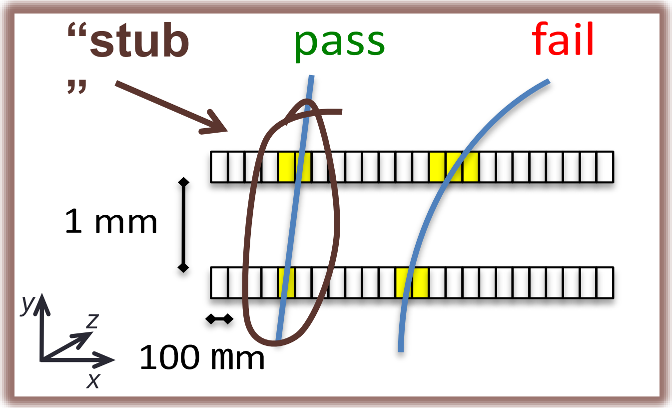
Phase-1
- New L1 trigger system
- New pixel detector
- HCAL upgrade (photo-detector and electronics)

Phase-2
- Details to be defined in Technical Proposal (2014)
- New tracker with L1 track trigger capability (pT>2.5 GeV)
- DAQ/HLT upgrade to have 1 MHz at L1 and 10 kHz recording rate
- Replace endcap & forward calorimeters
- Possible extension of muon coverage
- Possible EM preshower system to have photon pointing

Phase-2 CMS muon layout



Trigger track selection in FE



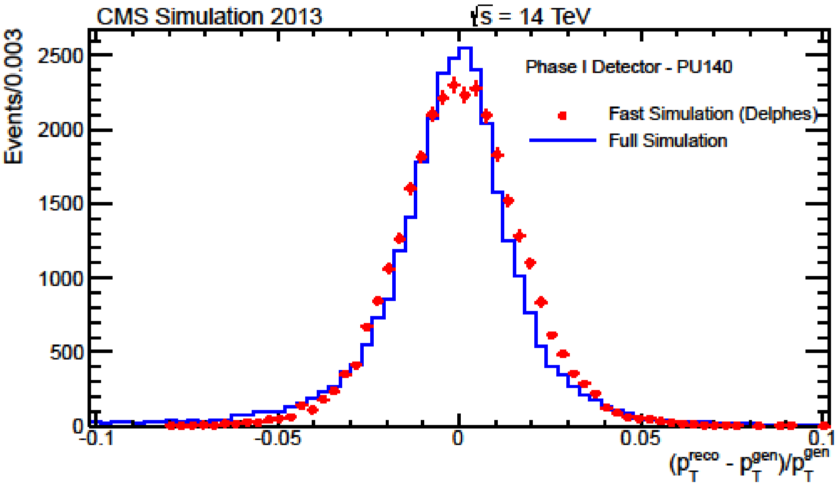
Detector performance for HL-LHC physics studies

- ATLAS
  - Parameterize the detector response based on GEANT4 full simulation
    - The simulation includes the currently proposed layout of the upgraded tracker
  - $\langle\mu\rangle = 140$ ($\langle\mu\rangle = 50$) is assumed for 3,000 fb^{-1} (300 fb^{-1})
- CMS
  - Studies scale current analysis
  - Assumes detector upgrades maintain current performance
  - Fast detector simulation using DELPHES
  - Cross checked with full simulation in some cases

Detector performance (1)

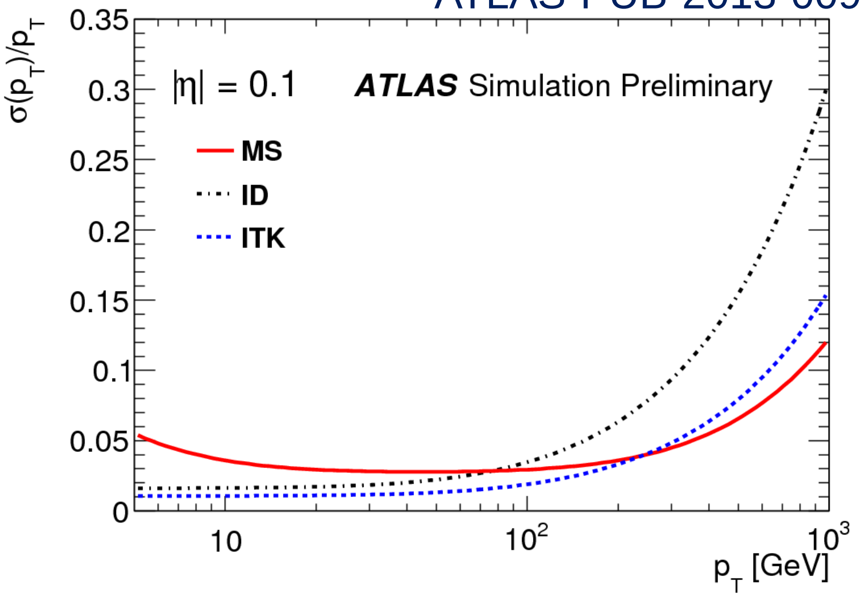
CMS-PAS-FTR-13-003

- CMS muon p_T resolution comparison between full simulation and DELPHES fast simulation
- Good agreement is observed



ATLAS-PUB-2013-009

- Parameterization of ATLAS muon p_T resolution based on full simulation
- Better performance is obtained with ITK than with the current ID



Detector performance (2)

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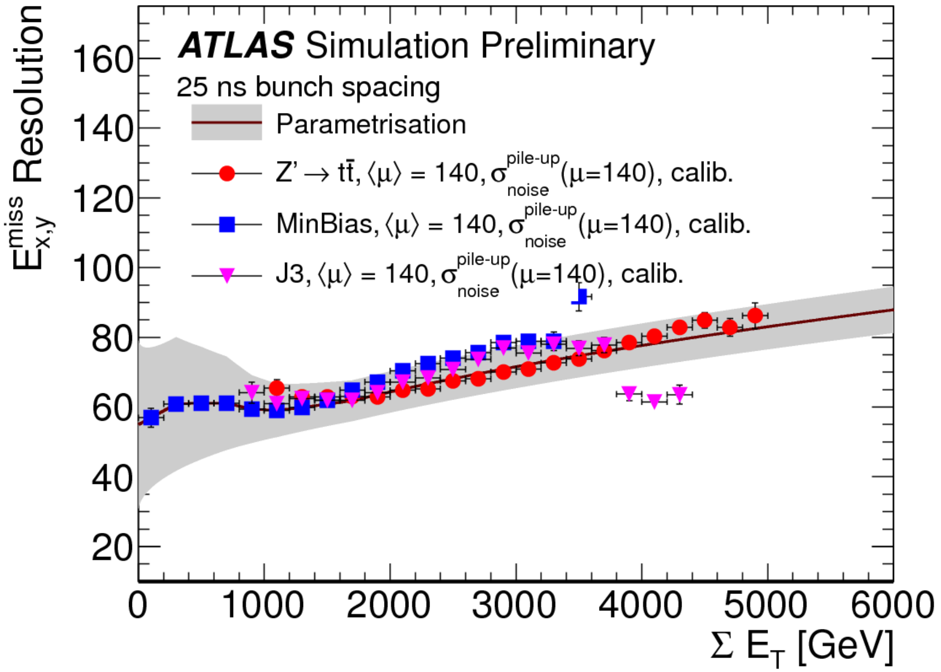
Parameterization of E_T^{miss} resolution

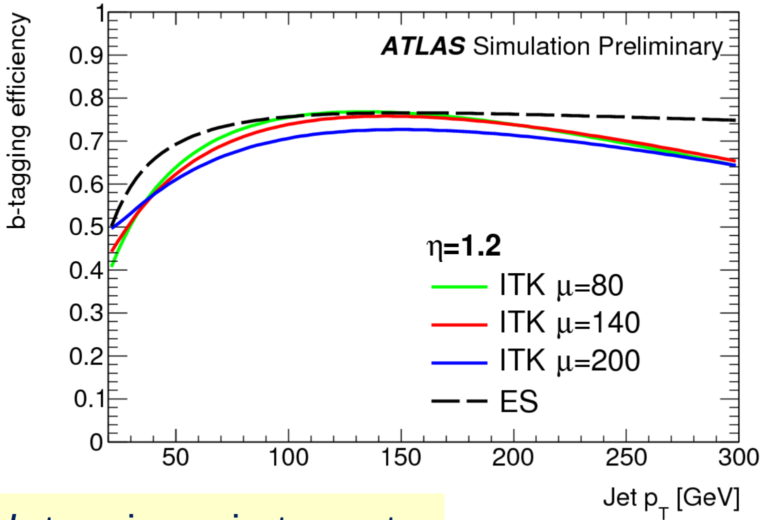
b-tagging

- 70% efficiency as a typical working point
- 0.05% mis-tag rate at $\langle\mu\rangle = 140$

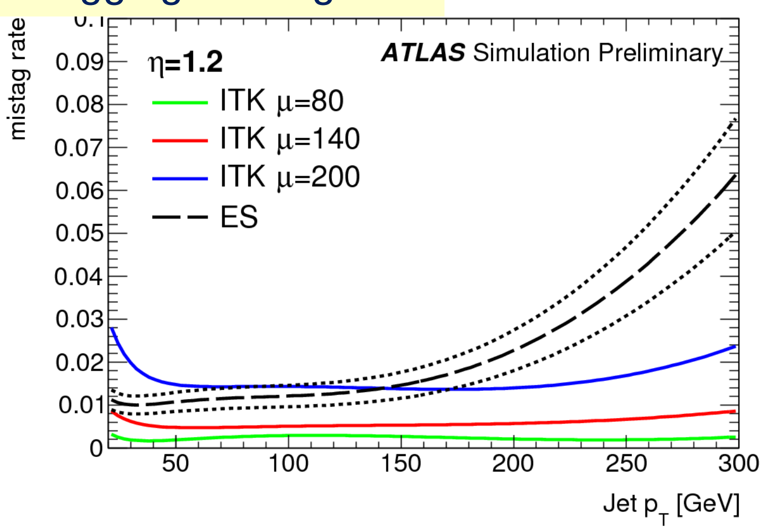
E_T^{miss} resolution



b-tagging efficiency



b-tagging mis-tag rate

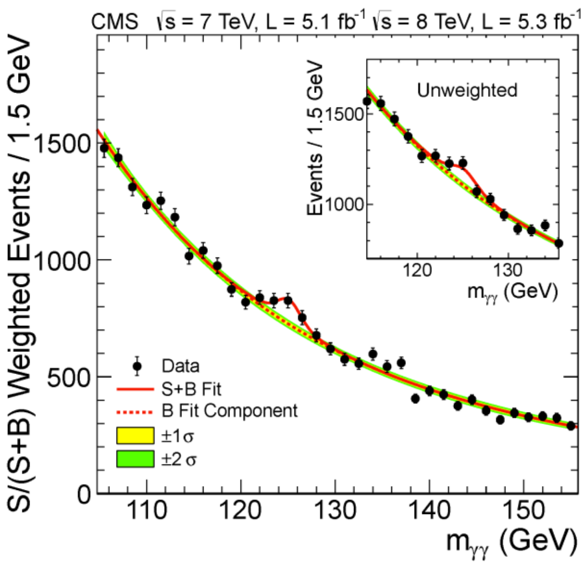


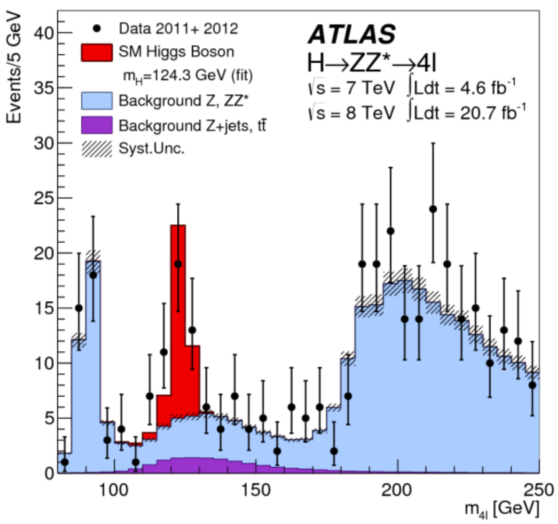
Physics after the Higgs discovery

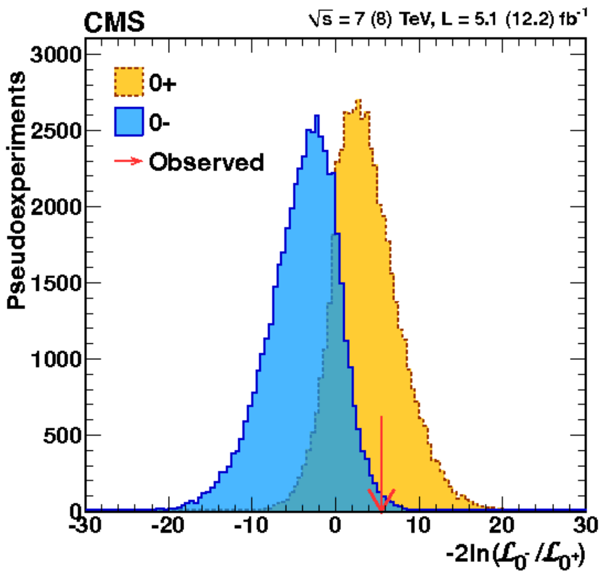
- Measurements of properties and couplings of the Higgs boson
  - Couplings to various particles including rare decay modes
  - Natural width (very difficult, $\Gamma_H = 4.2$ MeV)
  - BSM Higgs search
- Investigation of Electroweak symmetry breaking (EWSB)
  - Higgs self-coupling measurement
  - Vector boson scattering
- Searches for physics beyond the SM
  - Strong motivation due to the evidence of dark matter from cosmology
  - Supersymmetry (SUSY)
  - Rare decays

Higgs results in LHC Run-1

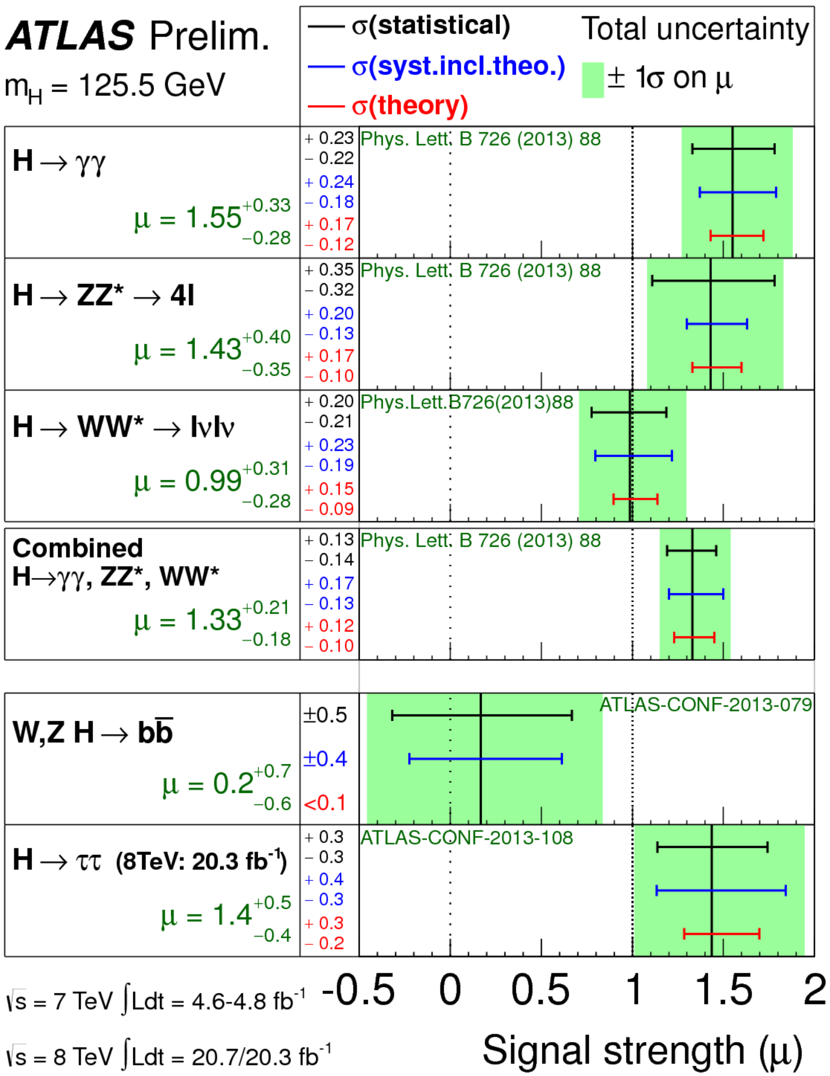
- A resonance is observed in $H \to \gamma\gamma$ and $H \to ZZ$ decay modes
- Mass : $126.0 \pm 0.4(stat) \pm 0.4(sys)$ GeV (ATLAS), $125.3 \pm 0.4(stat) \pm 0.5(sys)$ (CMS)
- Spin/parity of 0^+ is strongly favored
- Constraints on the signal strength in various final states
  - → Constraints on the couplings

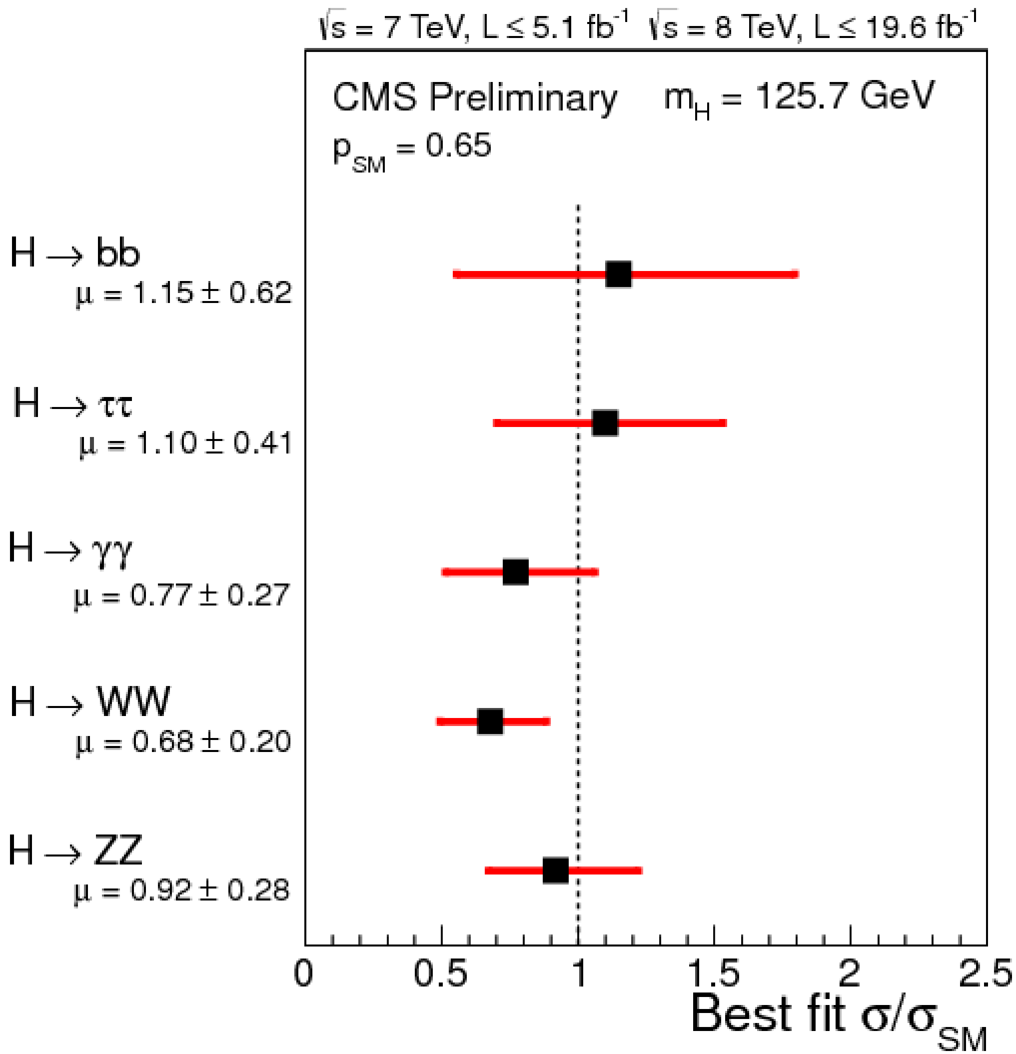




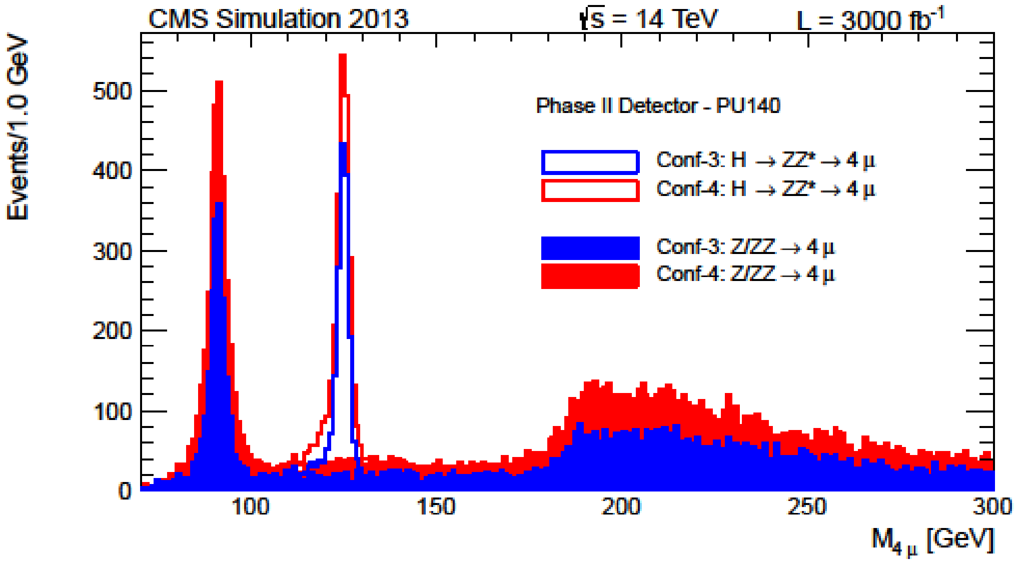


Latest results on Higgs signal strength





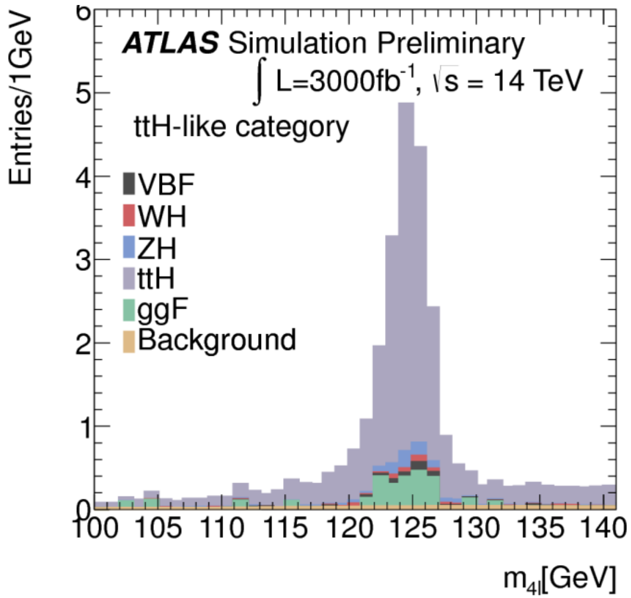
$H \to ZZ^{(*)}$ channel with 3,000 fb^{-1}



CMS-PAS-FTR-13-003

- Red histogram shows the distribution with wider η acceptance ($|\eta| < 4$)

ATLAS-PUB-2013-014



- $H \to ZZ^{(*)}$ can be observed in the $t\bar{t}H$ production mode with 3,000 fb^{-1}

$H \rightarrow WW^{(*)}$ channel with 300 and 3,000 fb^{-1}

- Feasibility was studied by extrapolating the study for 8 TeV to 14 TeV, using smearing functions
- The background ($t\bar{t}$ and WW) increases in 3,000 fb^{-1} due to the higher pileup
- Measurement of $H \rightarrow WW^{(*)}$ is still possible

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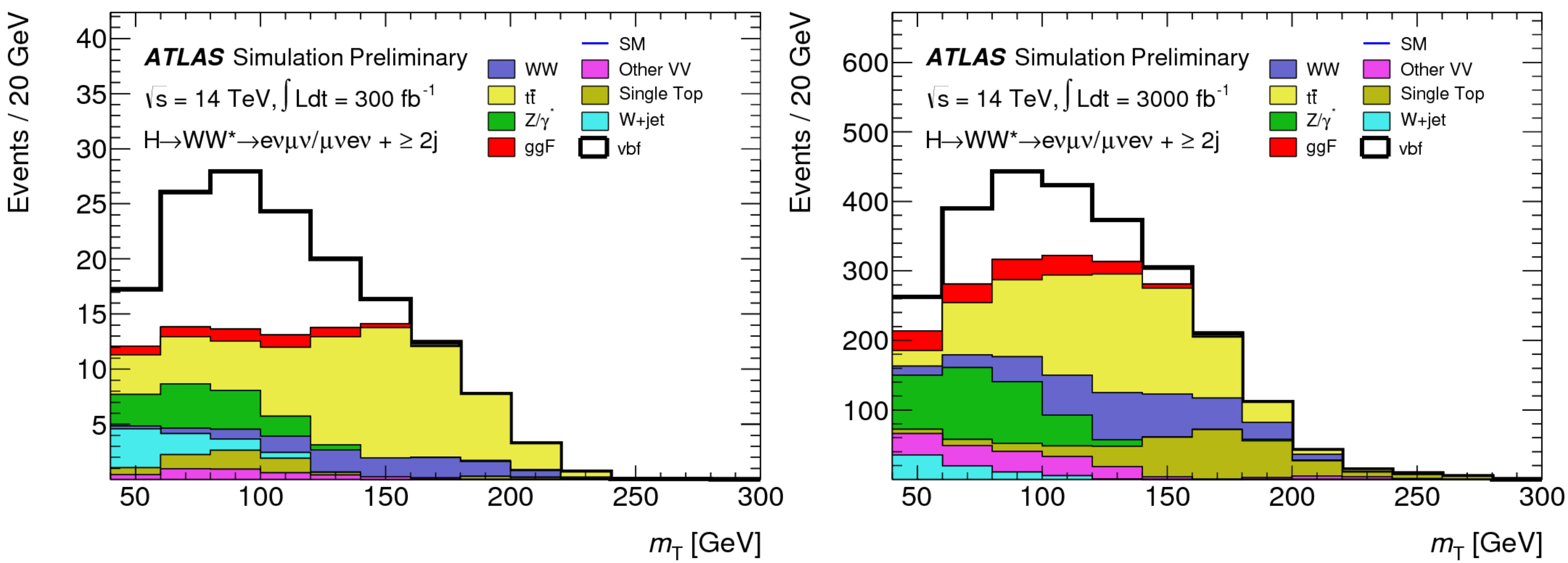

$H \to \mu\mu$ channel

- Direct verification of the Higgs coupling to 2nd generation leptons
- ATLAS (CMS) expects >6σ (>5σ) significance
- Coupling measurement with 10-20% precision

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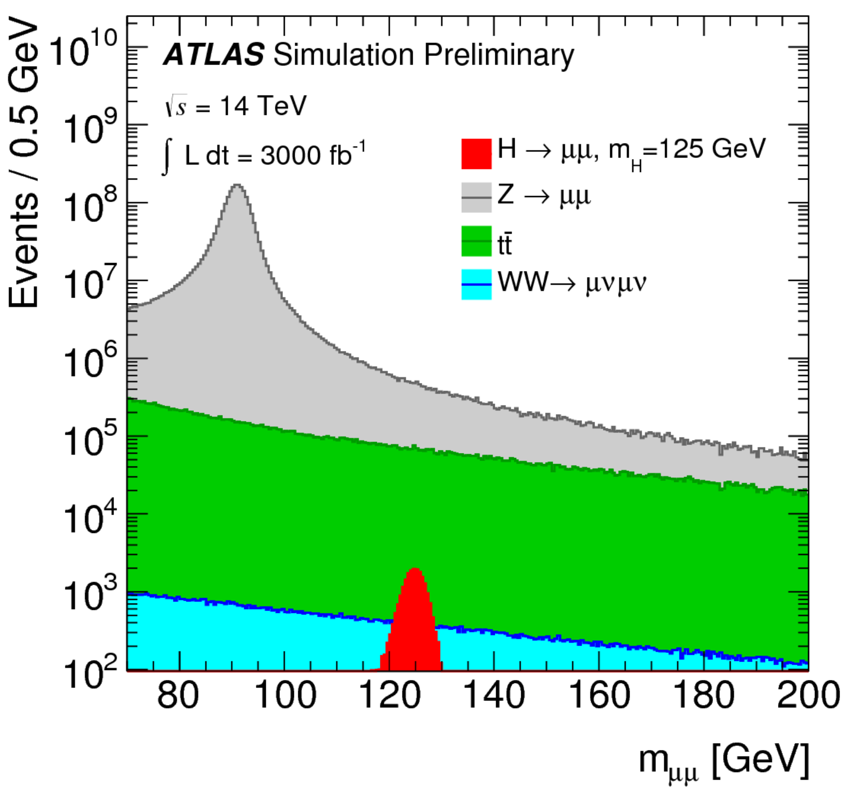

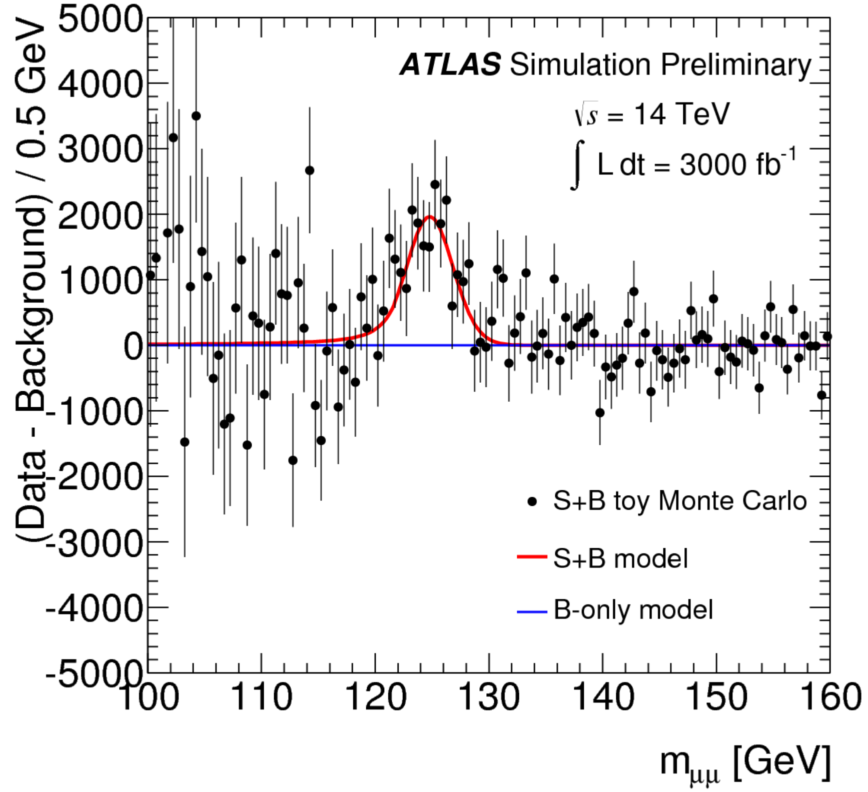

$H \rightarrow Z\gamma$ channel

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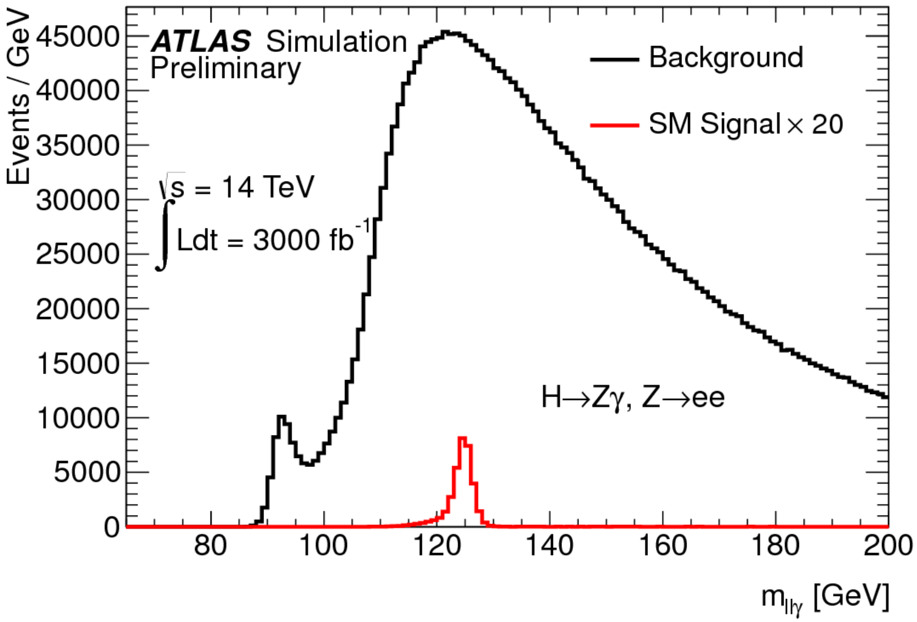

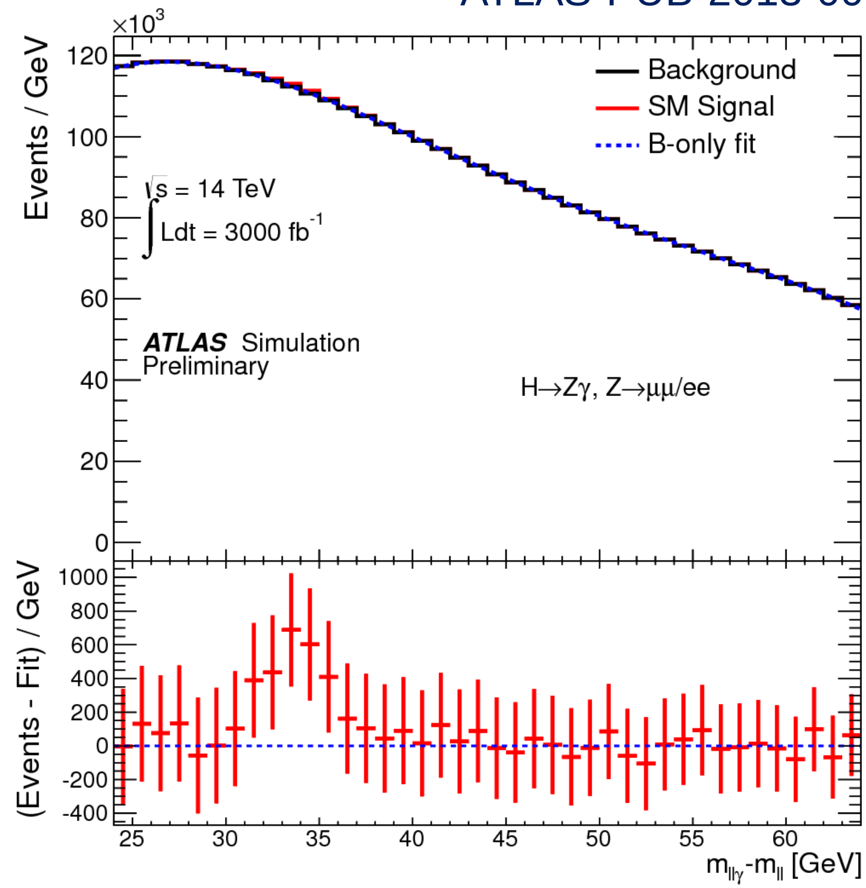

- Sensitive to new charged particles in the loop
- Large background due to radiative Z decay but the measurement is possible

Channel	$ee\gamma$ inclusive	$\mu\mu\gamma$ inclusive	$ee\gamma$ VBF	$\mu\mu\gamma$ VBF
S	1465	1667	21.5	23.2
B	$4.05 \cdot 10^5$	$4.84 \cdot 10^5$	609	726
S/B (%)	0.36	0.35	3.5	3.3
VBF/(VBF+ggF)	0.09	0.09	0.55	0.55

Coupling measurement

- Fit the scale factors (κ_i) for the couplings with respect to their SM value
  - Width (Γ_i) scales with κ_i^2

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

- Measure ratios of coupling scale factors which are independent of the total width

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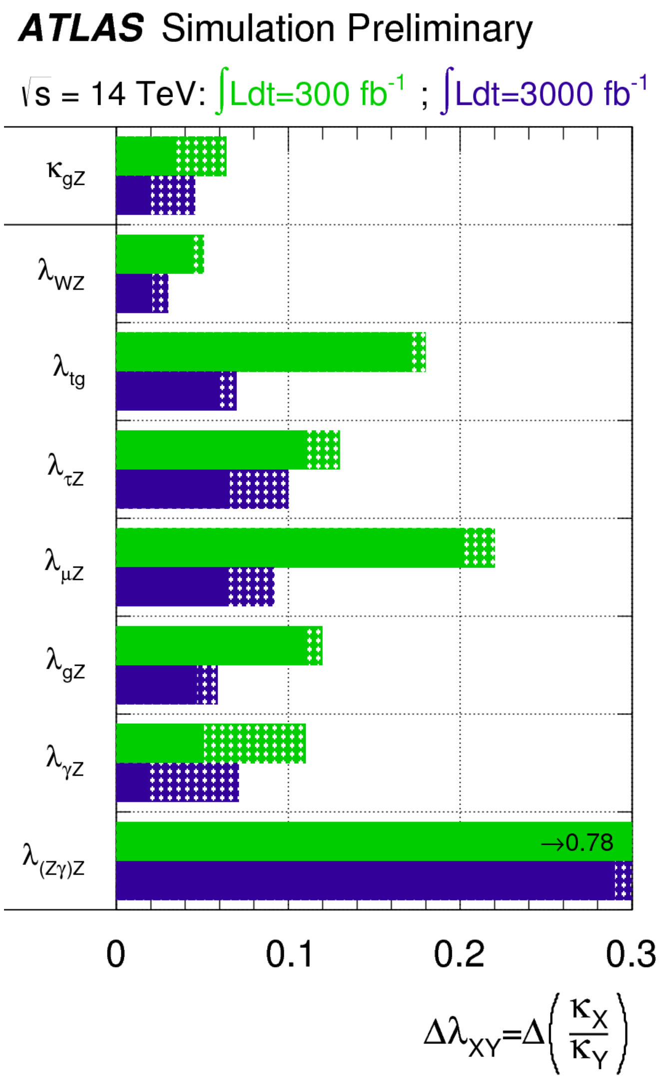
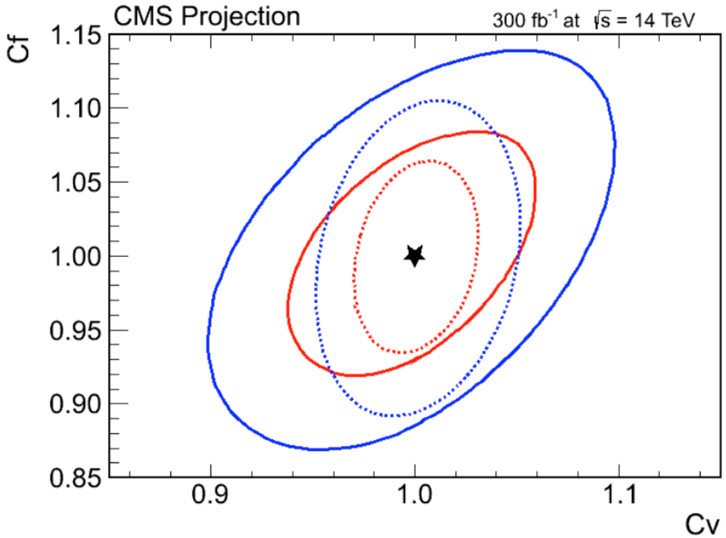


Constraints on the universal fermion (boson) coupling scale factor C_F (C_V)



Summary of the coupling measurement

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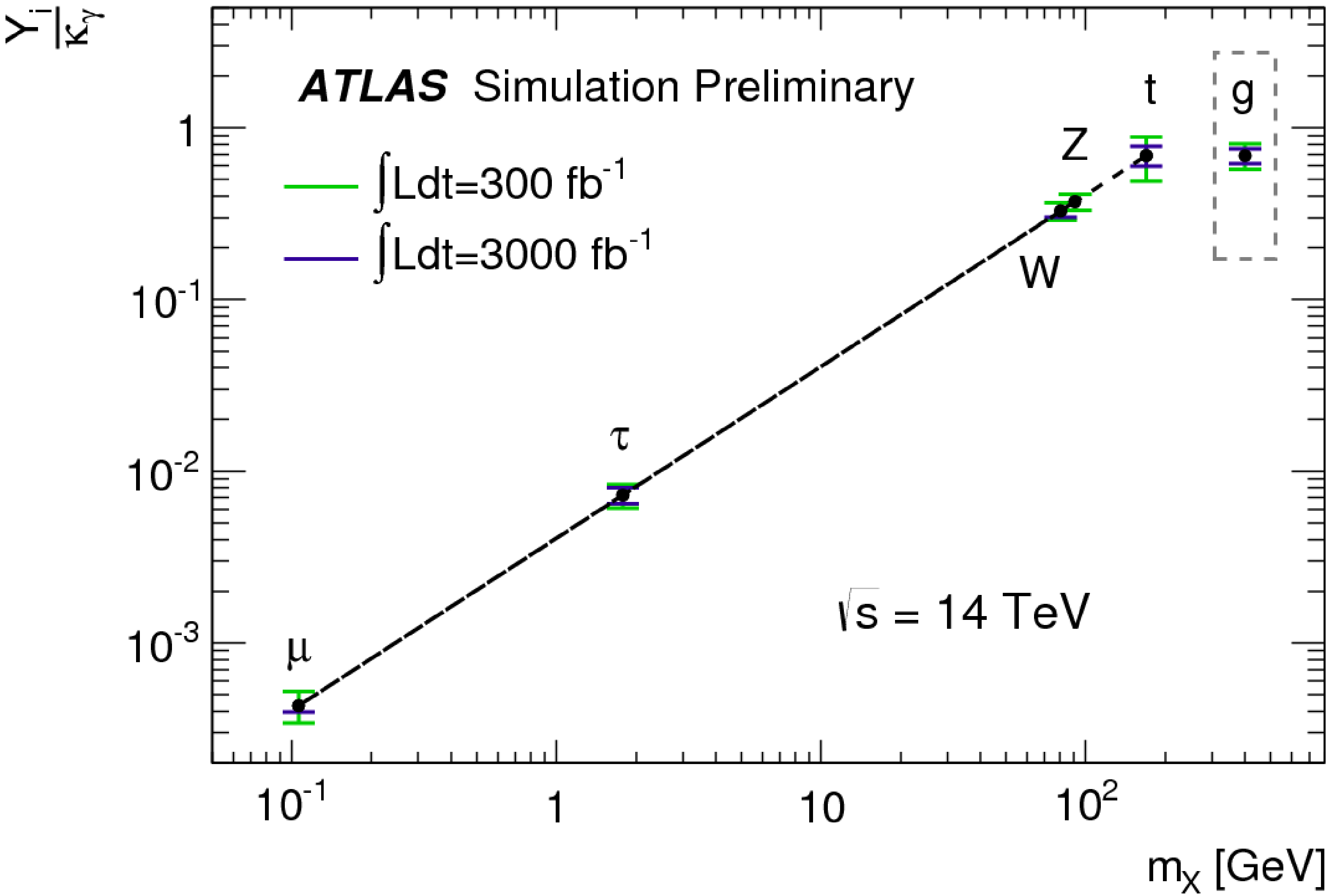
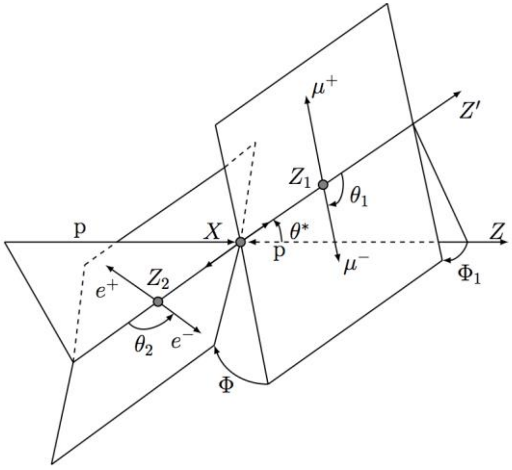


HZZ vertex structure

- In a general expression, the HZZ vertex may contain CP-even (CP-odd) terms with coefficients g_2 (g_4)
- Set constraints using the angular distribution of the decay products of Z bosons
- Large improvement with 3,000 fb^{-1}



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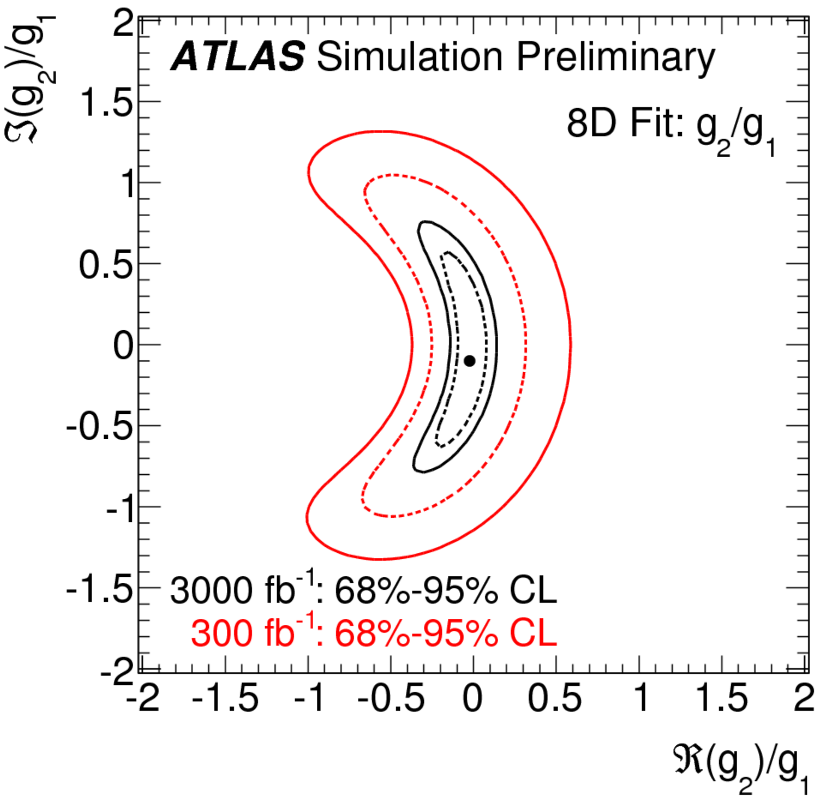
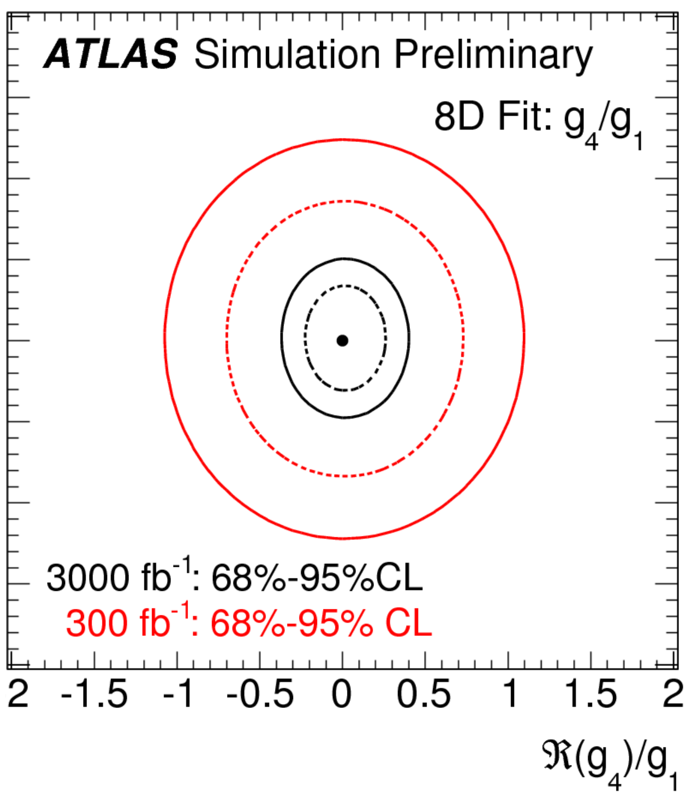


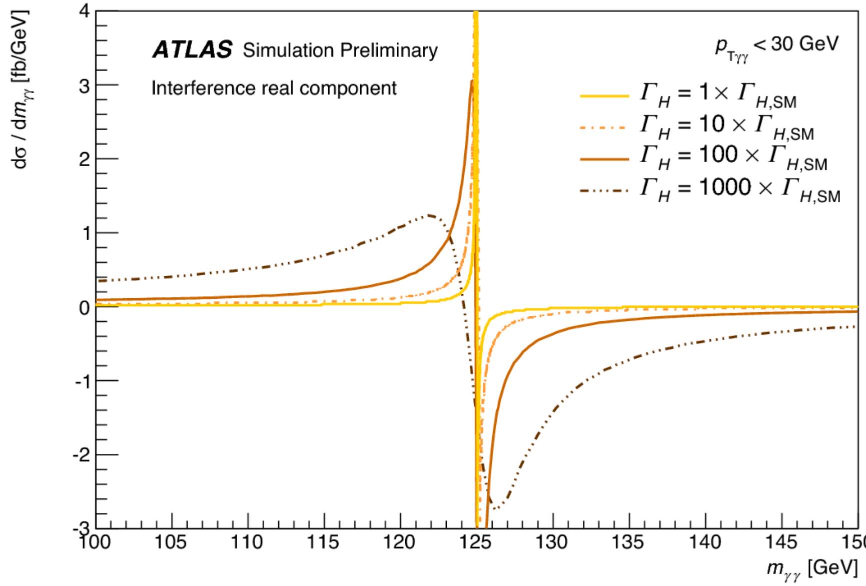


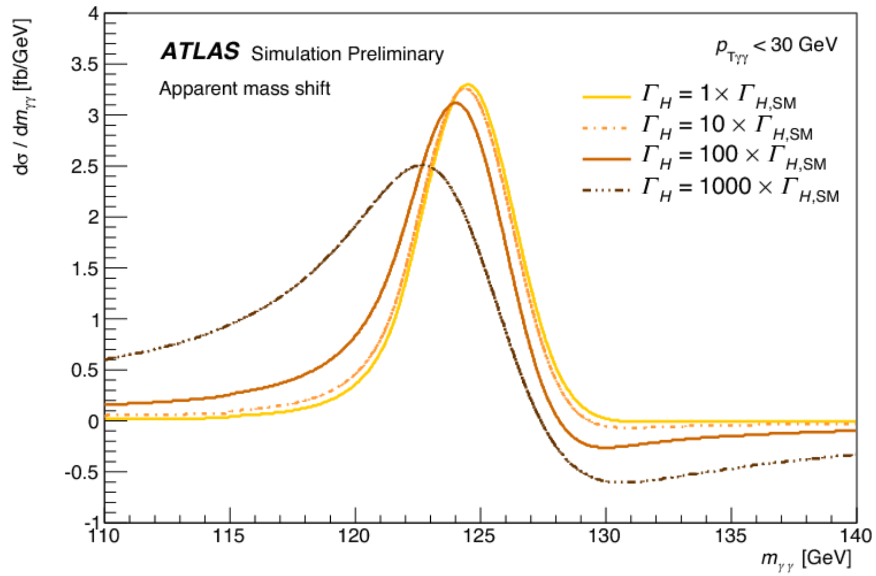
Measurement of the total width

ATLAS-PUB-2013-009

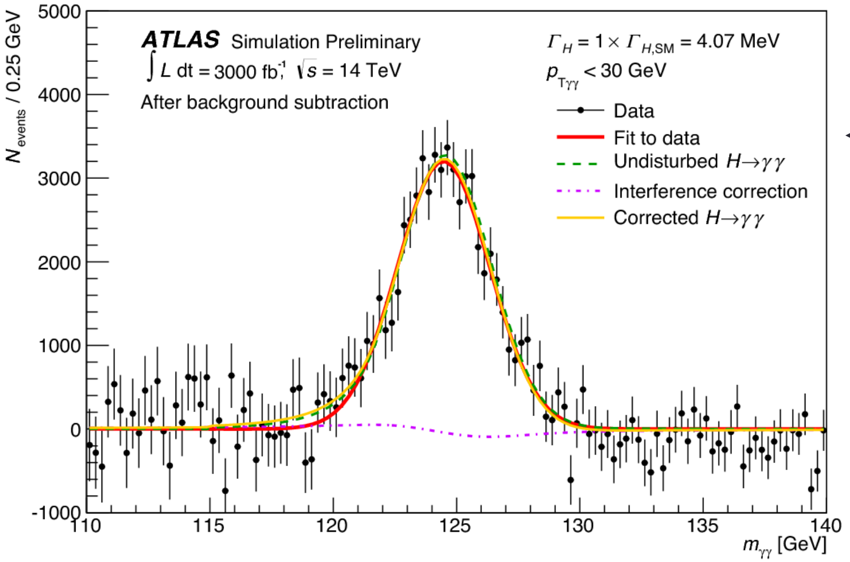
- The natural width of Higgs particle is $\Gamma_H = 4.2\ \text{MeV}$
  - Much smaller than detector resolution
- There is an interference of signal and background amplitudes in $H \to \gamma\gamma$ and $H \to ZZ$
  - Shifts the mass peak to lower value

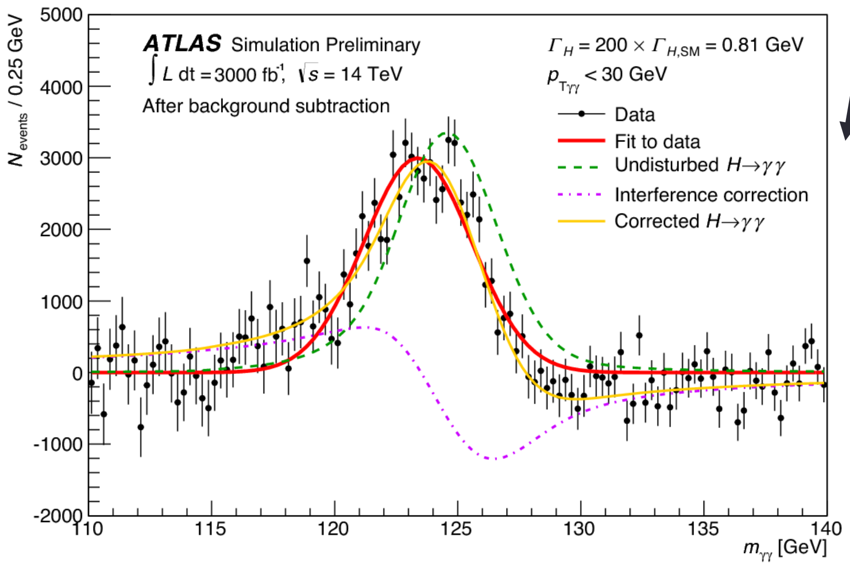
L. J. Dixon, Y. Li, PRL 111 (2013) 111802





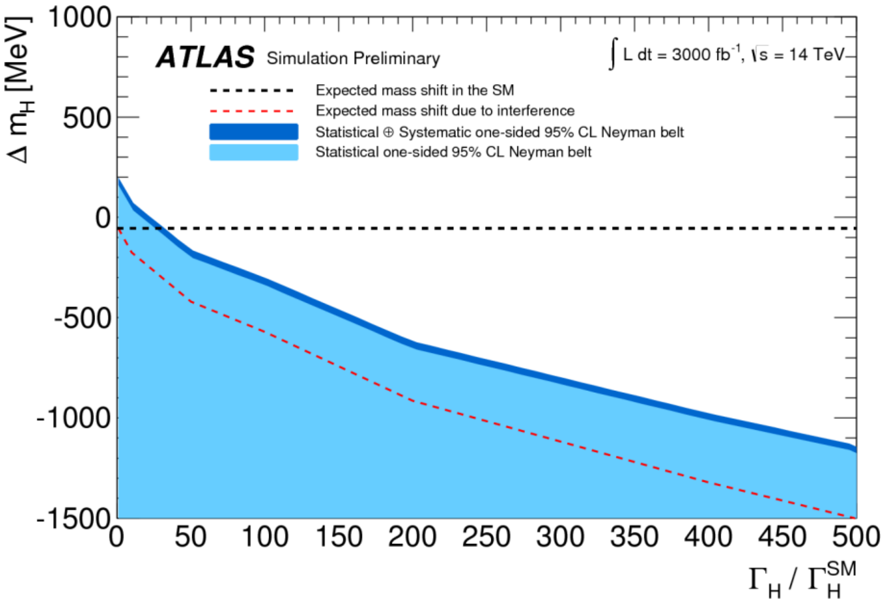
Higgs width from $H \to \gamma\gamma$





ATLAS-PUB-2013-009

- Mass shifts for $\Gamma_H = 1 \times \Gamma_H^{SM}$ and $\Gamma_H = 200 \times \Gamma_H^{SM}$
- A 95% C.L. upper limit can be set
  - $220 \times \Gamma_H^{SM}$ with 300 fb^{-1}
  - $40 \times \Gamma_H^{SM} \sim 160$ MeV with 3,000 fb^{-1}
- Current limit by CMS: 6.9 GeV (without using the interference technique)

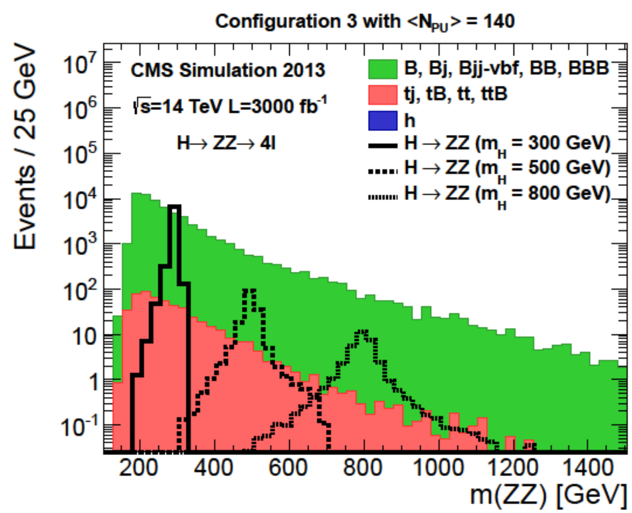


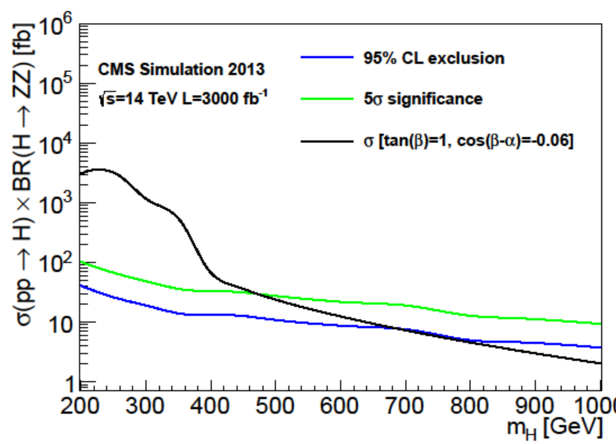
Two Higgs Double Model (2HDM)

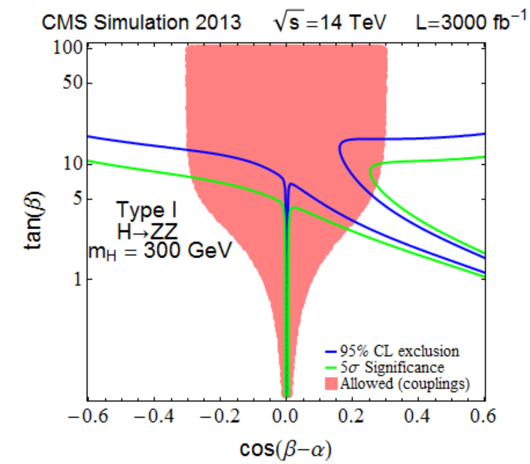
- 2HDM introduces 5 physical Higgs particles ($h, H, H^{\pm}, A$)
- Search for heavy Higgs bosons in decay modes: H→ZZ or A→Zh
  - Performed by ATLAS & CMS for Type I-IV models

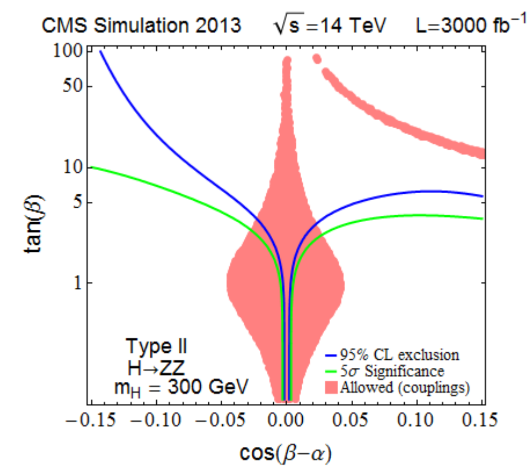
$H \rightarrow ZZ \rightarrow 4l$

- Derive the limit on $\sigma \cdot Br$ for each m_H
- Exclude the parameter region if $\sigma \cdot Br$ is excluded
- Exclusion limit set for 200 GeV<m_H<1 TeV



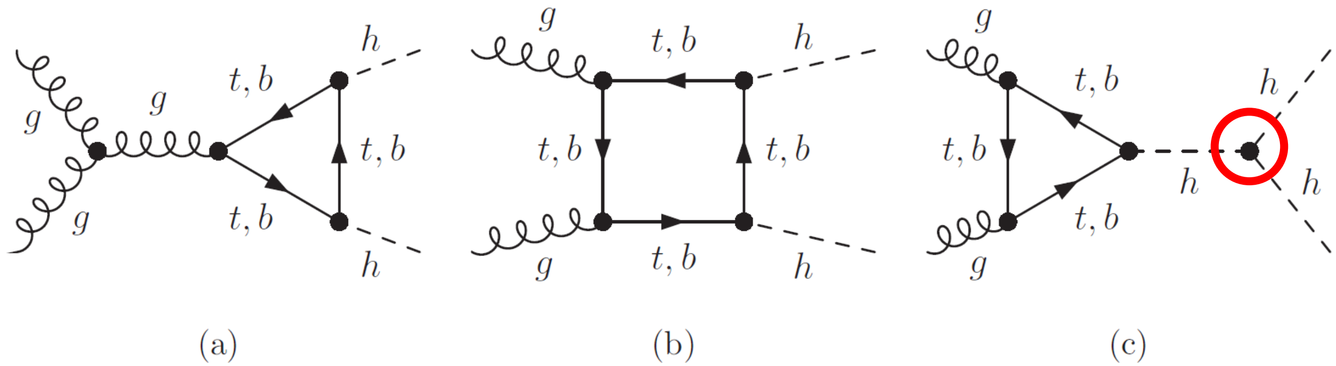






ATLAS-PUB-2013-016
CMS-PAS-FTR-13-024

Higgs self-coupling measurement



- In order to determine the parameters of the SM completely, a measurement of the Higgs self-coupling is essential
  - Higgs potential and the EWSB mechanism
- Measurement of double Higgs production
- Destructive interference between diagrams with triple Higgs coupling and other diagrams

	σ_{HH} **(fb)**
$\lambda = 0$	71
$\lambda = \lambda_{SM}$	34
$\lambda = 2 \cdot \lambda_{SM}$	16

Double Higgs production yields

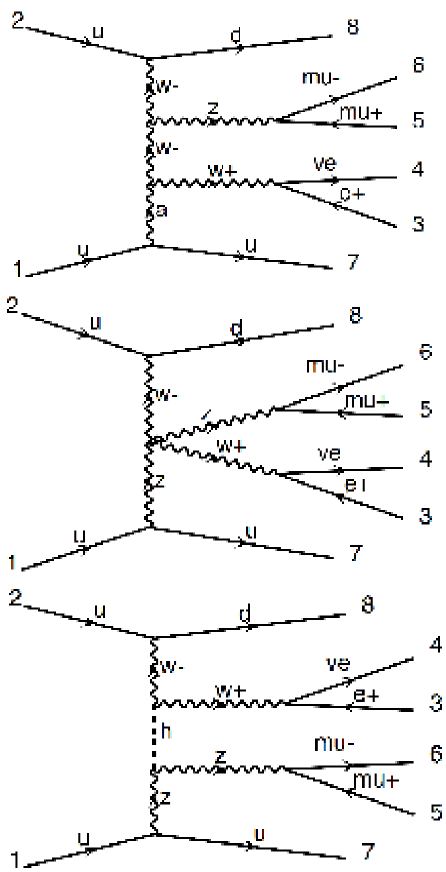
Event yields of various channels

Decay channel	Branching ratio (%)	Yield with 3 ab^{-1}
$b\bar{b}b\bar{b}$	33.4	34,000
$b\bar{b}W^+W^-$	25.0	25,500
$b\bar{b}\tau\tau$	7.36	7,500
$W^+W^-W^+W^-$	4.66	4,750
$b\bar{b}ZZ$	3.09	3,150
ZZW^+W^-	1.15	1,170
$b\bar{b}\gamma\gamma$	0.26	265

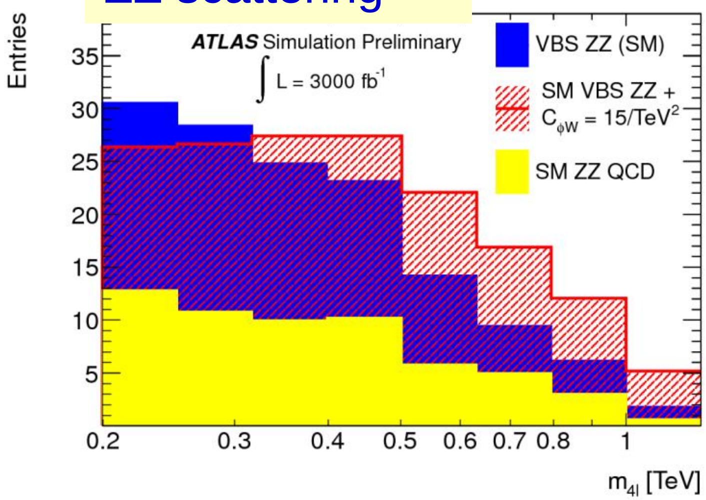
- Very challenging due to low yield and contributions from irreducible backgrounds ($t\bar{t}H, ZH,$ etc.)
- Ongoing studies suggest some sensitivity to constrain the triple Higgs coupling
- Also, several phenomenological papers suggest this possibility

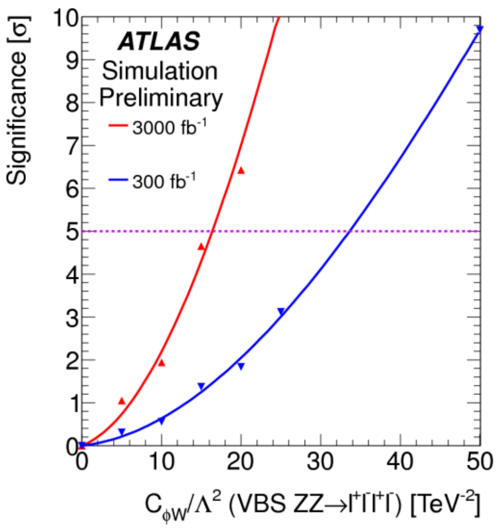
Vector boson scattering

- Vector boson ($V = W^{\pm}, Z, \gamma$) scattering involves:
  - Triple gauge couplings
  - Quadratic gauge coupling
  - Higgs boson propagator in s- and/or t-channel
- The interference of all contributions → unitarity
- Deviation of VVH coupling from the SM value
  - → violates unitarity
- Higher dimensional operators
  - → new physics



ZZ scattering



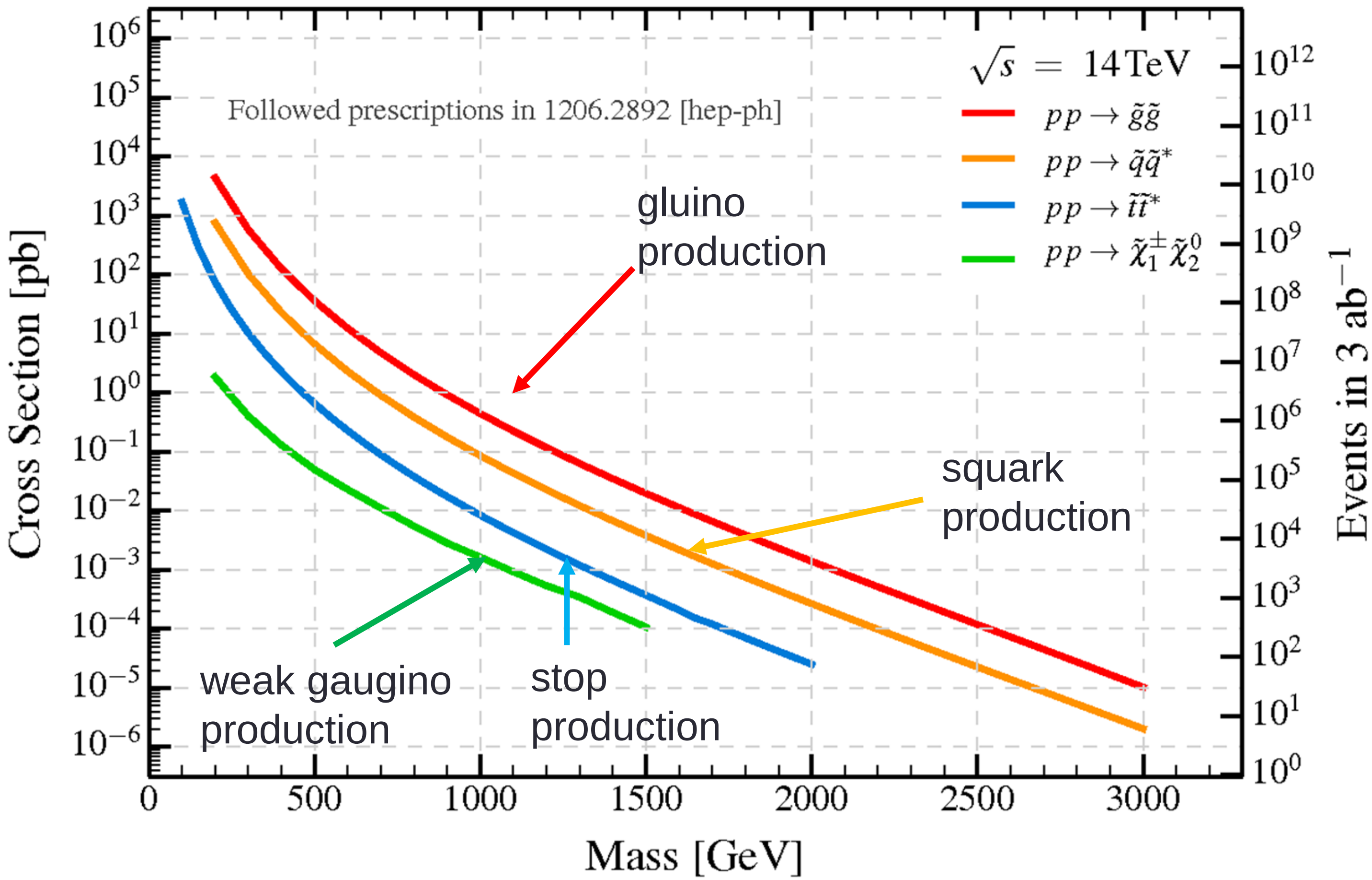


ATLAS-PUB-2013-006
CMS-PAS-FTR-13-006

SUSY Search

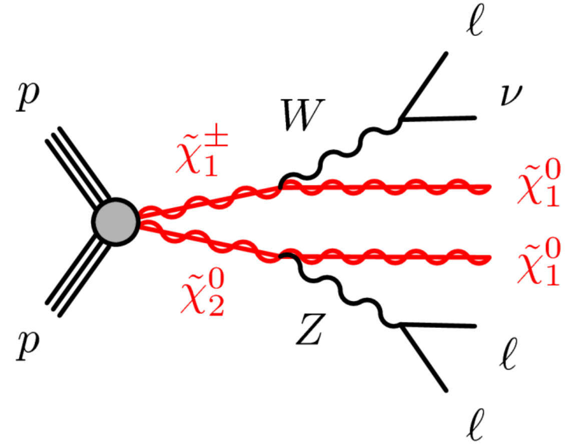
SUSY search at HL-LHC

- Limits set by Run-1 LHC: $m_{\tilde{q}} < 0.7$ TeV, $m_{\tilde{g}} < 1.3$ TeV
- Less stringent limits on sleptons, 3rd generation squark, weak gauginos
    - → Accessible at HL-LHC



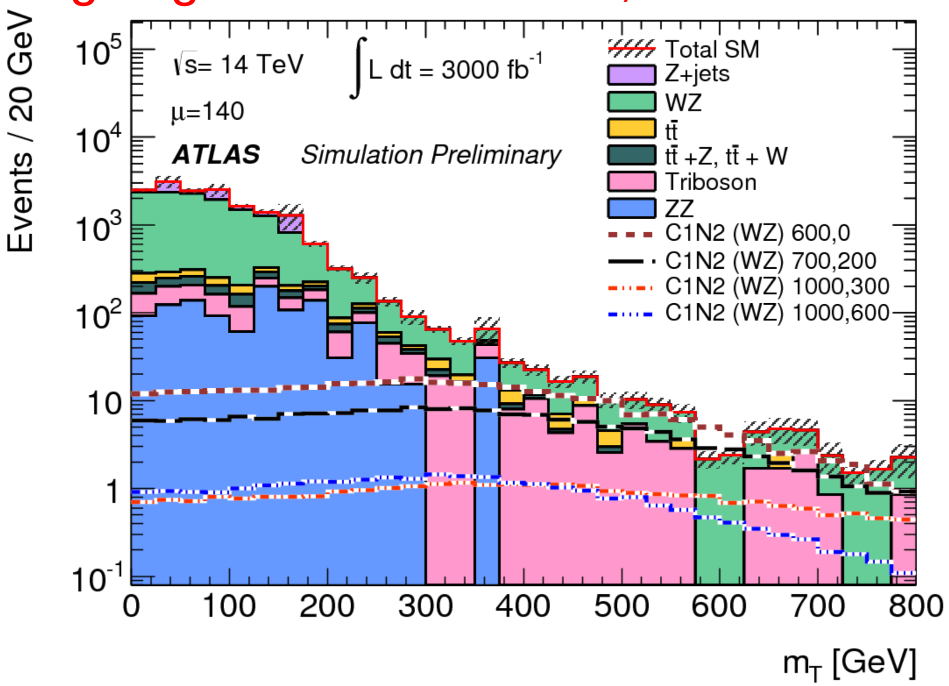
Weak gaugino production (1)

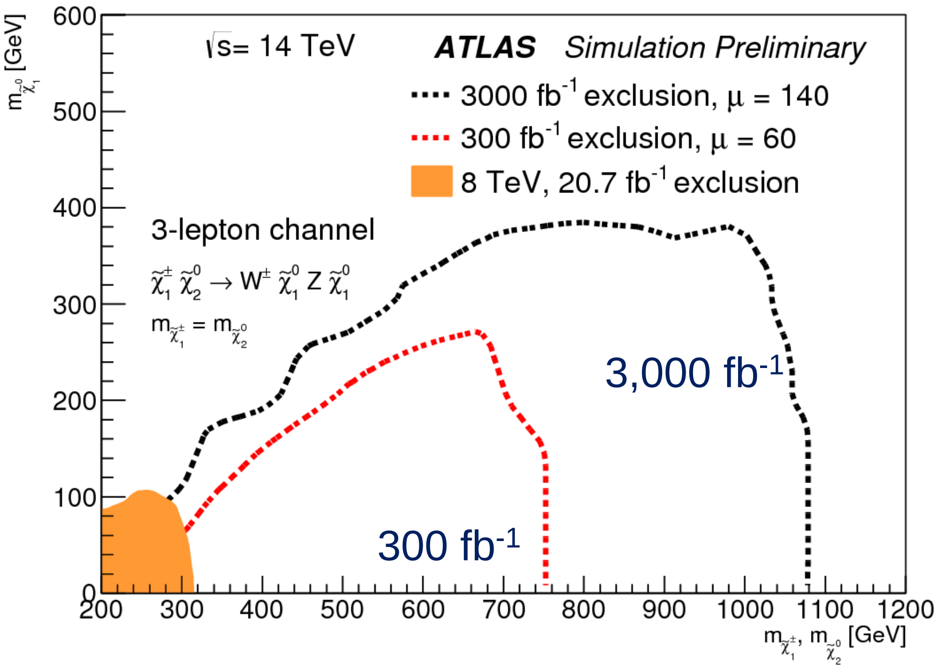
ATLAS-PUB-2013-011



- Direct production of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$
- Signature:
  - 3 leptons (>10 GeV)
  - $E_T^{miss} > 50$ GeV
  - b-jet veto

Excluded chargino mass (for massless LSP) is increased by 300 GeV by going from 300 fb^{-1} to 3,000 fb^{-1}

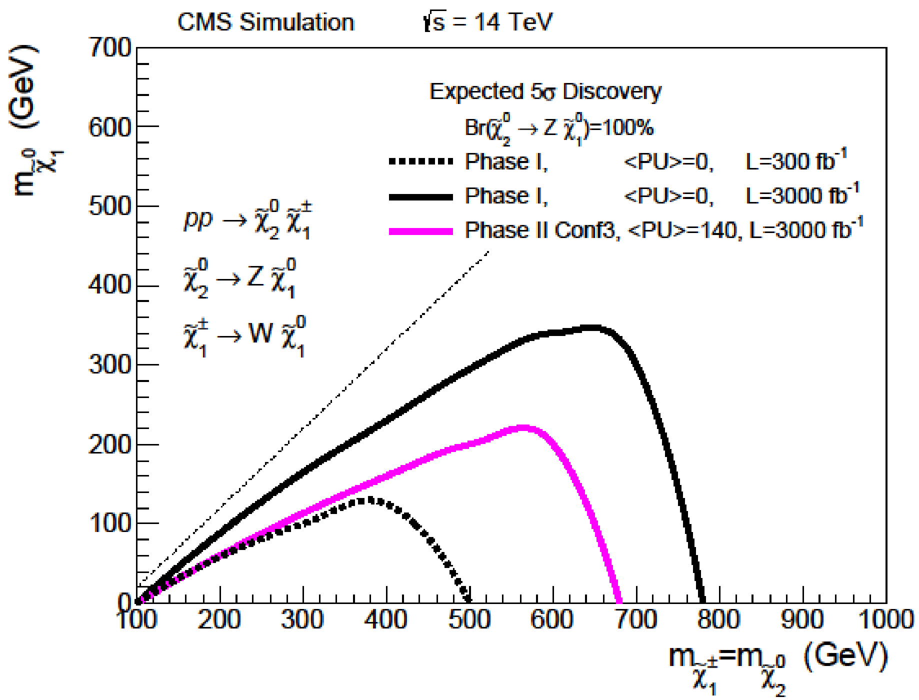


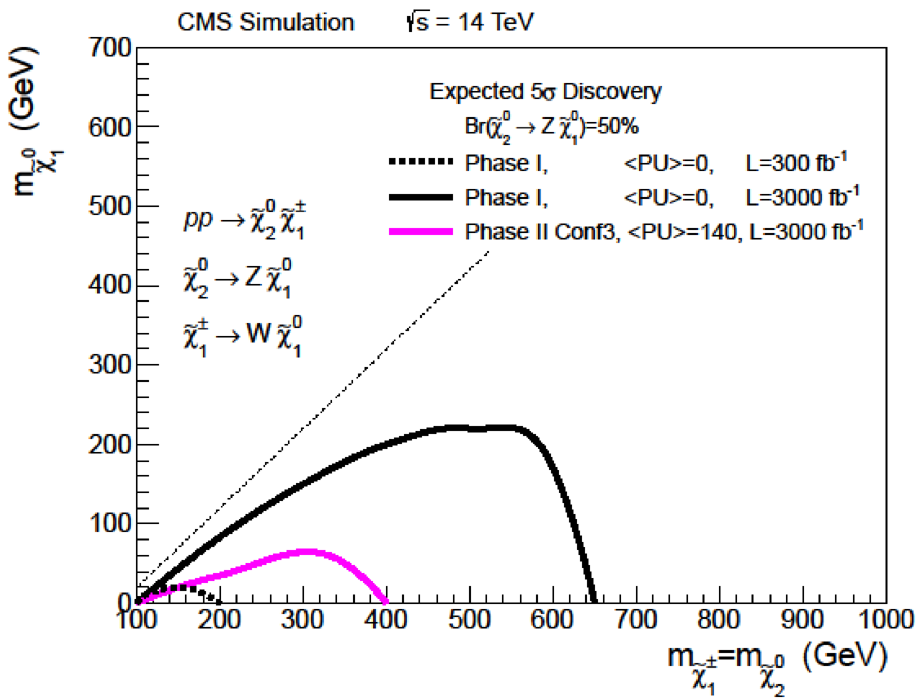


Weak gaugino production (2)

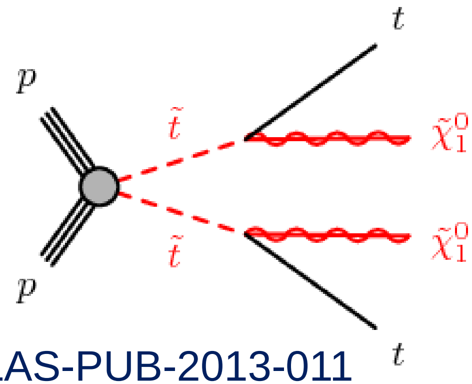
- 5σ exclusion region from CMS
  - Extend the mass range up to 700 GeV with 3,000 fb^{-1}
- Assuming 100% or 50% branching ratios of $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to Z \tilde{\chi}_1^0$

CMS-PAS-FTR-13-014





Stop pair production

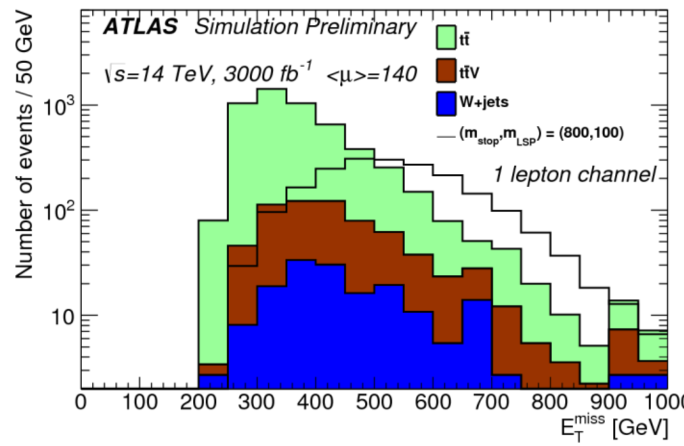


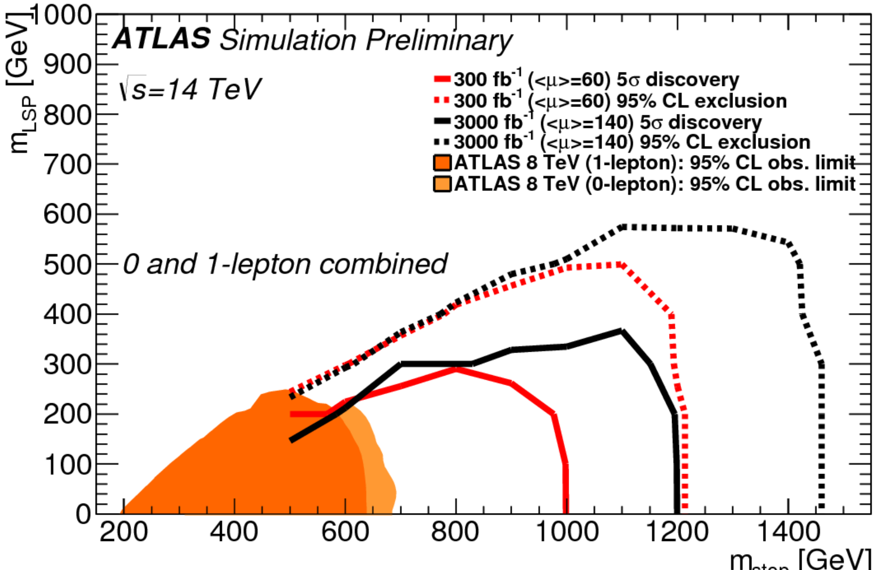
Signature:

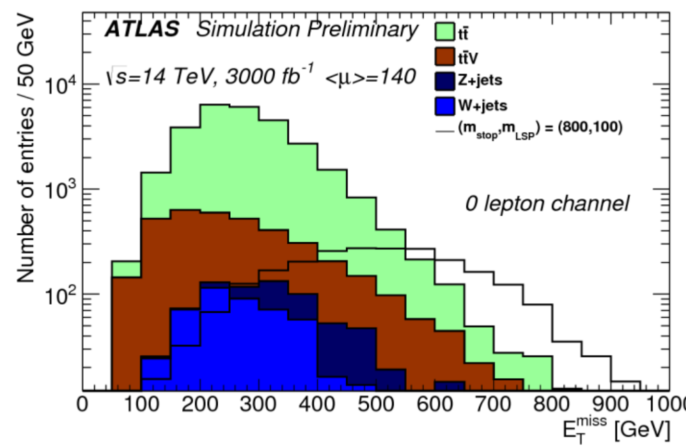
- Fully hadronic top decay:
  - 0-lepton, >6 jets with 2 *b*-tagged, E_T^{miss}
- Semi-leptonic top decay:
  - 1-lepton, >4 jets with 1 *b*-tagged, E_T^{miss}

5σ discovery up to 1.2 TeV at 3,000 fb^{-1}
(200 GeV gain from 300 fb^{-1})

ATLAS-PUB-2013-011

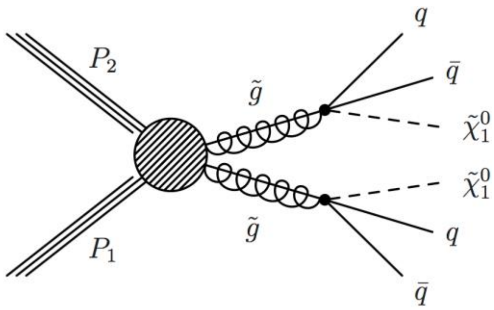






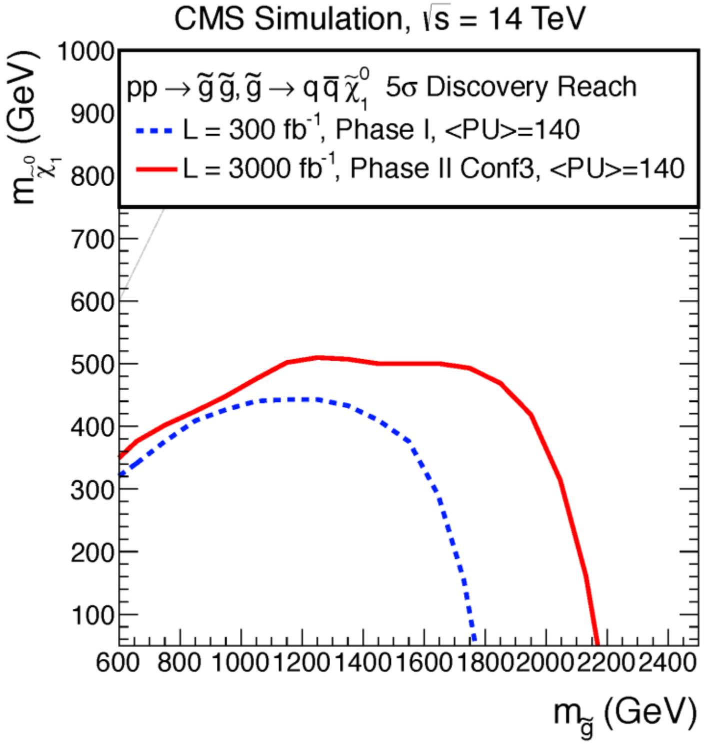
Gluino production

CMS-PAS-FTR-13-014

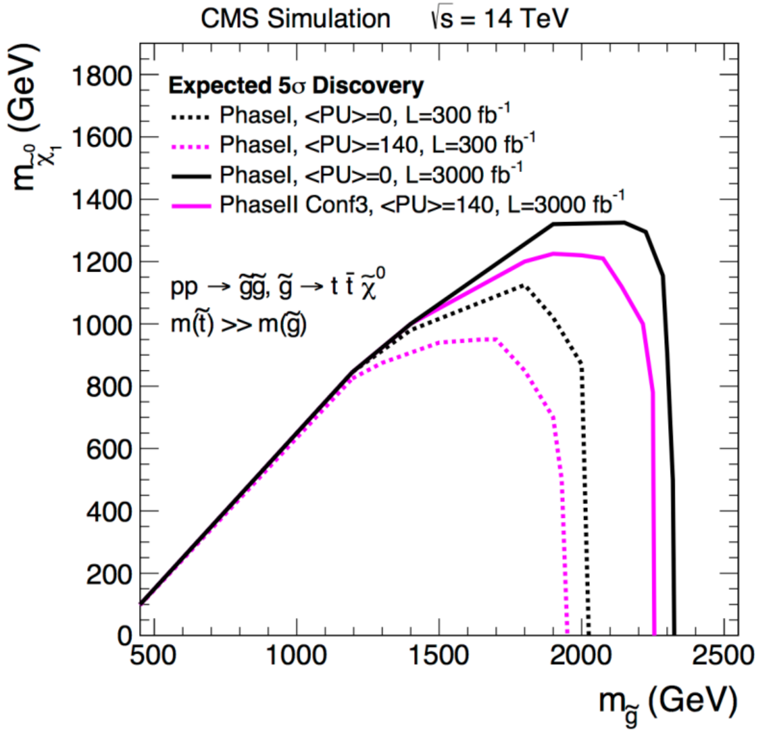


- Large production cross section
- Gluino masses up to 2.2 (1.8) TeV and LSP mass up to 500 (400) GeV can be discovered with 3,000 (300) fb^{-1}

$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$: Multijet, E_T^{miss}

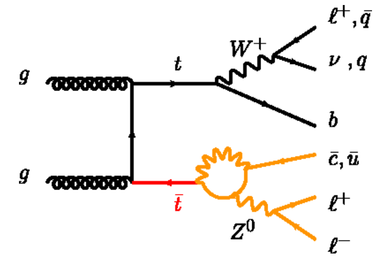


- In case gluino decays preferentially to top
  - $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$: Multijet, E_T^{miss}, 1-lepton

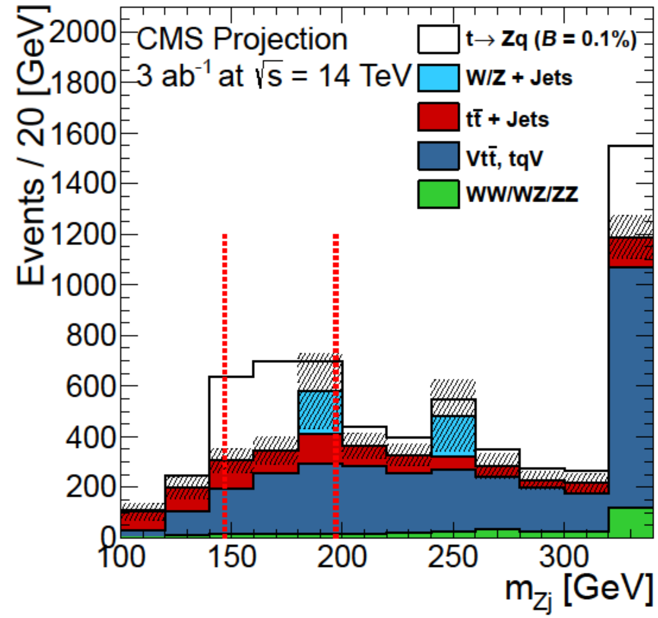


FCNC with top decay

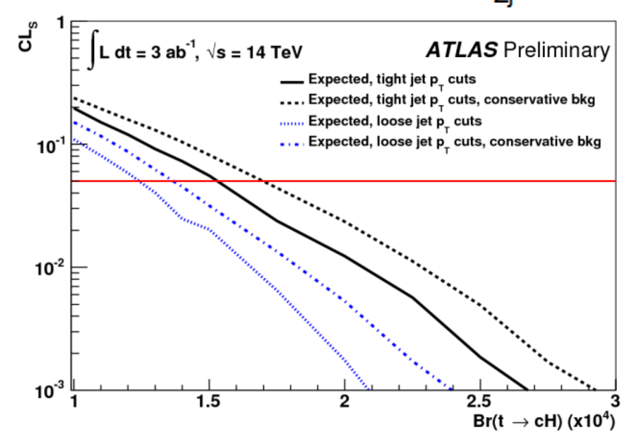
ATLAS-PUB-2013-012
CMS-PAS-FTR-13-016



- Br($t \rightarrow Wb$)~100% in SM
- Flavor changing neutral current (FCNC) decay is highly suppressed
  - Br($t \rightarrow Zq$)~10^{-14} (SM)
  - Br($t \rightarrow cH$)~3×10^{-17}(SM)
- Search for or llq or $c\gamma\gamma$ final states
- ATLAS & CMS studies show sensitivity of 10^{-4} can be achieved in these channels with 3,000 fb^{-1}
  - Predicted by several extensions of SM (2HDM, RPV SUSY etc.)



Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \rightarrow u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \rightarrow uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \rightarrow uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \rightarrow c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \rightarrow cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \rightarrow cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}



Conclusion

- There is a well-defined LHC roadmap including the High Luminosity LHC
- Detector upgrade R&D is in progress
  - Expect to have similar performance as the current detector even with higher pileup
- Many measurements are possible at HL-LHC
  - Higgs coupling to various particles
  - Natural width
  - Sensitivity to Higgs self-coupling
  - Vector boson scattering
  - Extension of search region for SUSY particles
  - Measurements of rare processes

Backup slides