Higgs* Prospects for the Future at an Upgraded LHC

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On behalf of the ATLAS and CMS Collaborations
LHCP14
Columbia University in the City of New York, June 4, 2014

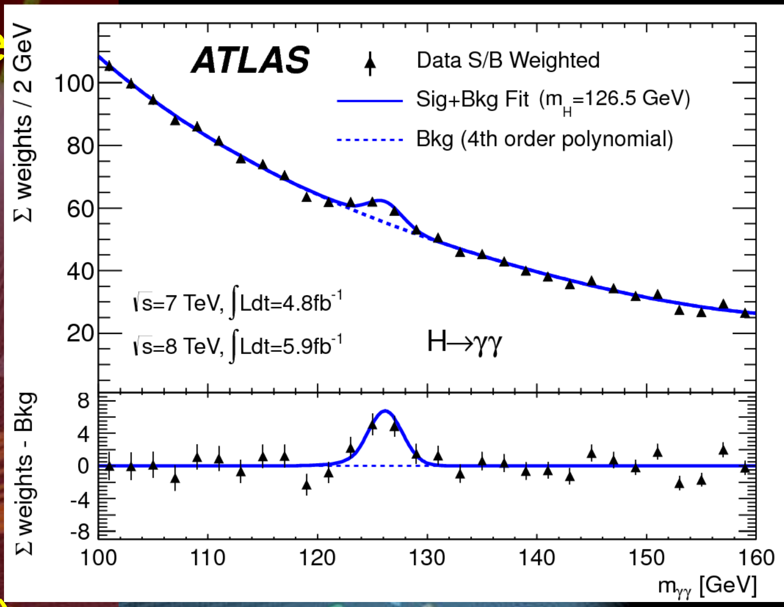
*'Higgs' =BEHGHK (Brout-Englert-Higgs-Guralnik -Hagen-Kibble)

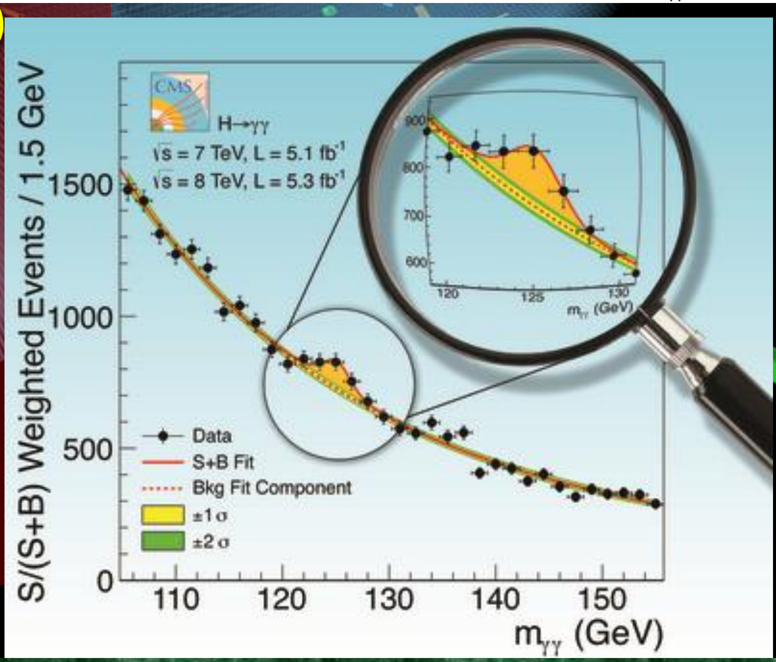
Pileup at 25 ns and $L = 2x10^{34}$ $cm^{-2}s^{-1}$

Outline

- Introduction
- LHC Upgrades calendar and experimental challenge
- Assumptions, methods and scenarios
- Properties of the observed Higgs boson
  - Signal strengths
  - Couplings and coupling ratios
  - Natural Width
  - Invisible Branching Fraction and Higgs-Portal interpretation
  - Field Strength Tensor Structure
  - Rare Decays: $H\to\mu\mu$, $H\to Z\gamma$, $t\to cH$, $H\to\gamma\gamma$ (FCNC)
- Search for additional (BSM) Higgs bosons:
  - Indirect from couplings measurements
  - Direct from
    - $H/A\to\mu\mu$
    - $H\to ZZ\to 4\ell$
    - $A\to Zh\to\ell\ell bb$
- Summary and Conclusion
- Acknowledgements

Phys. Lett. B716 (2012)

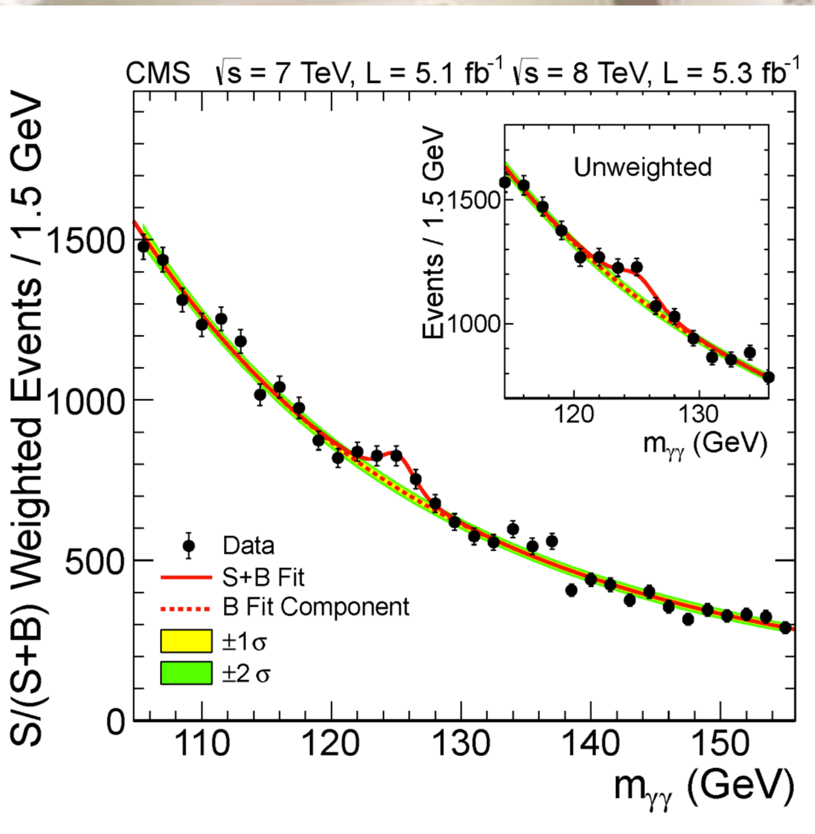




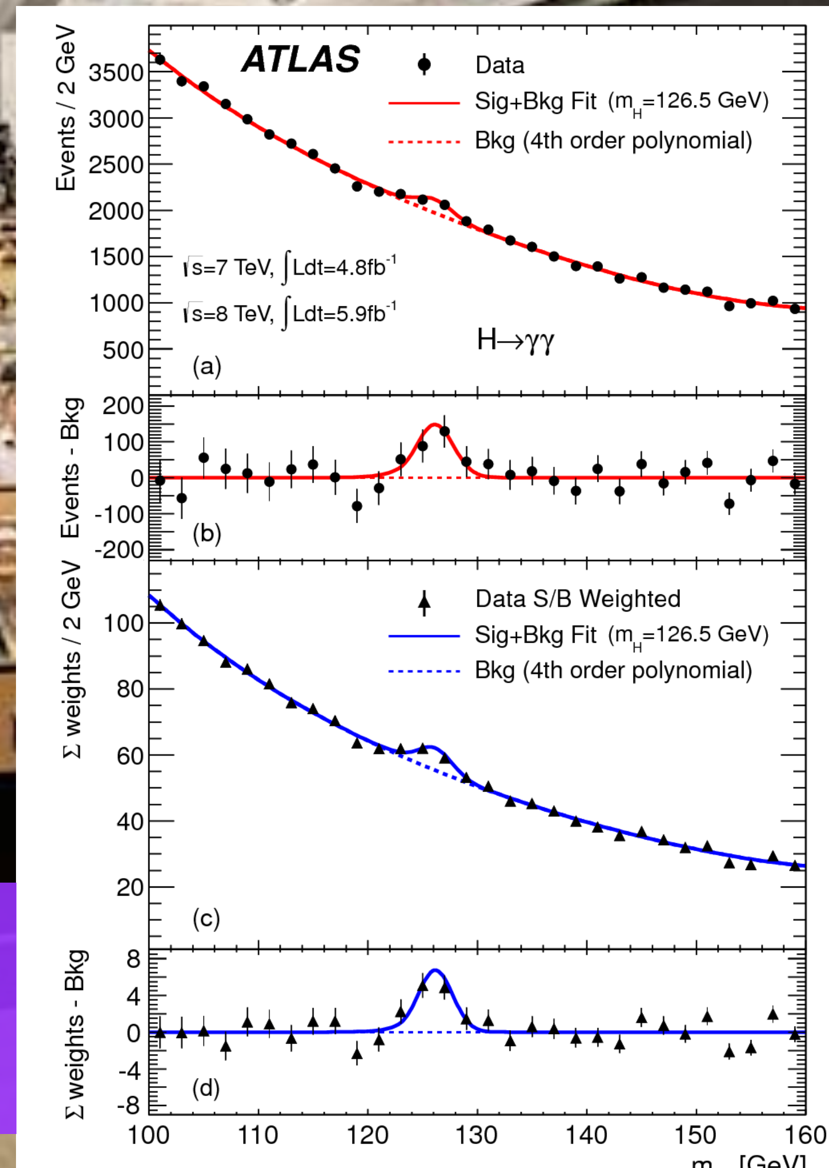
See dedicated parallel talk on future CMS Higgs prospects (M. Marono) in Higgs 3 Thursday afternoon

Introduction: July 4 2012, 9:30 AM…..

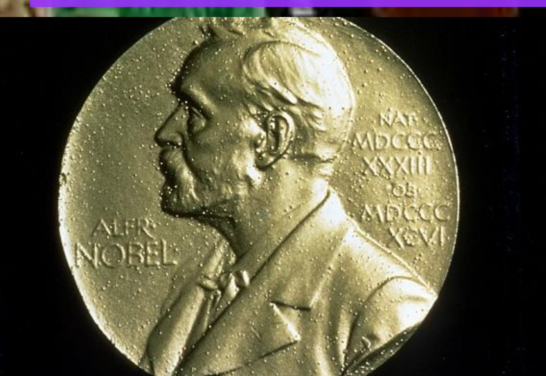
Phys. Lett. B716 (2012)



- "This result constitutes evidence for the existence of a new massive state that decays into two photons."



- "Clear evidence for the production of a neutral boson …is presented."



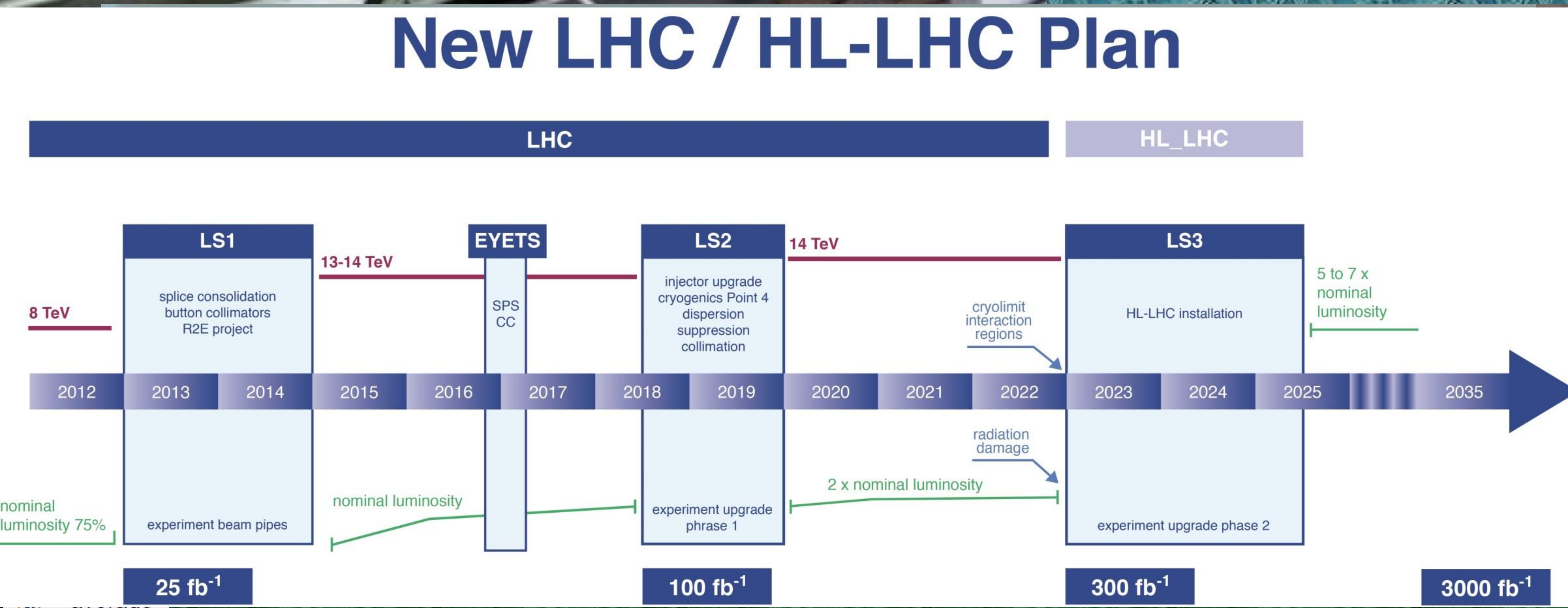
- In Runs 2-3-4-5…
  - Continue to measure its properties
  - Is it alone?

LHC Upgrades Calendar and experimental challenge

Phase 1 Upgrade→Run 3 (2020-2022): twice LHC design luminosity
Event pileup reaches ~50-60 collisions per beam crossing (@ 25 ns)
Factor 5 increase in trigger rates relative to 2012 run
Phase 2 Upgrade→HL-LHC Runs 4,5,..(2025-2035+…): 5-7x LHC design luminosity
Event pileup reaches ~140 collisions per beam crossing (@ 25 ns)
Need solutions to cope with very high rates (10-15 x 2012), radiation and pileup

with design L= 1-2 x10^{34} $cm^{-2}s^{-1}$

CERN,F. Bordry, HL-LHC Project

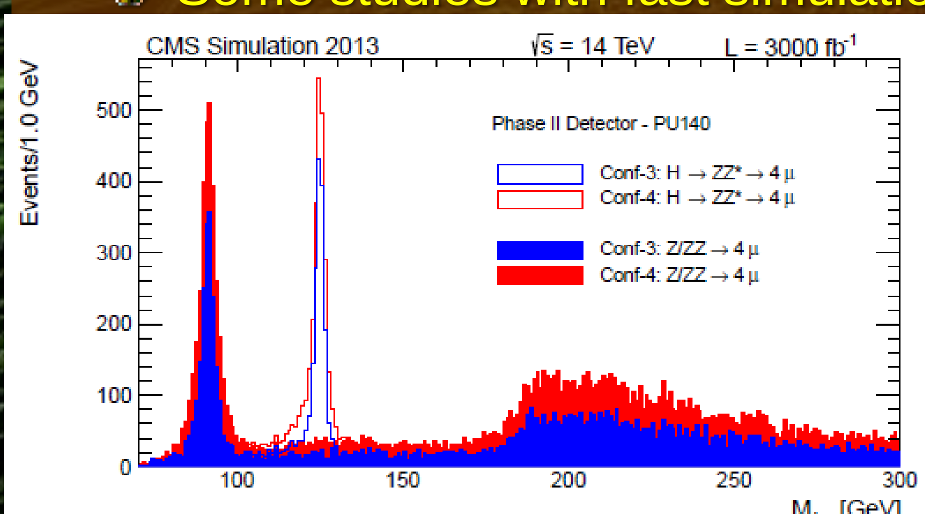


number of
pile-up events

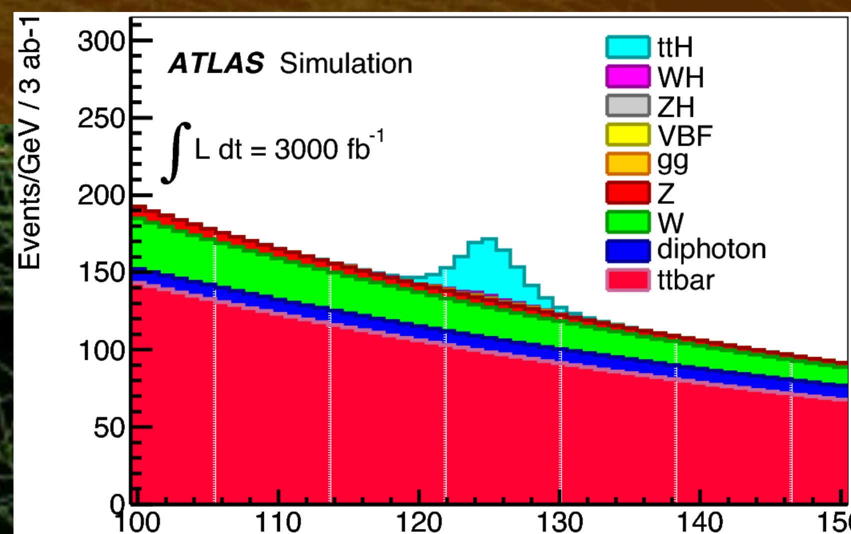
See plenary talks on ATLAS (C. Gemme) and CMS (M. Mannelli) upgrades Friday morning

Assumptions, methods and scenarios

- ATLAS: Use fast simulation to mimic the beam effects on momentum and energy resolution, acceptance, identification and reconstruction efficiencies, fake rates, etc. Some rescaling of Run1 results for some analyses.
- CMS: Assume that upgraded detector will compensate the effects of higher pile-up, use three different scenarios:
  - Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses
  - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by 1/√L
  - Scenario 3: set theoretical uncertainties to zero, leave other syst. uncertainties the same as in 2012
  - Some studies with fast simulation



CMS-FTR-13-003



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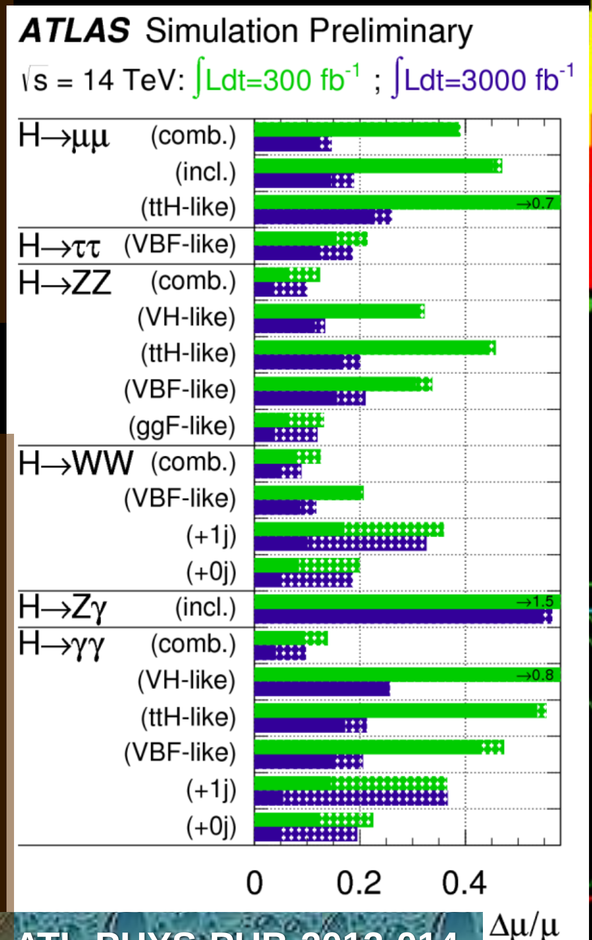
Higgs Boson Properties: Signal Strengths $\mu = \sigma/\sigma_{SM}$

- Precision $\Delta\mu/\mu$:
ATLAS: without (solid) and with (hatched) theory errors
CMS: Scenario 2 / 1

- For H→γγ, WW, ZZ, bb, ττ:
300fb-1: Ranges from 6-22% (ATLAS), 6-14% (CMS)

3000fb-1: Ranges from 4-19%(ATLAS) , 4-8% (CMS)



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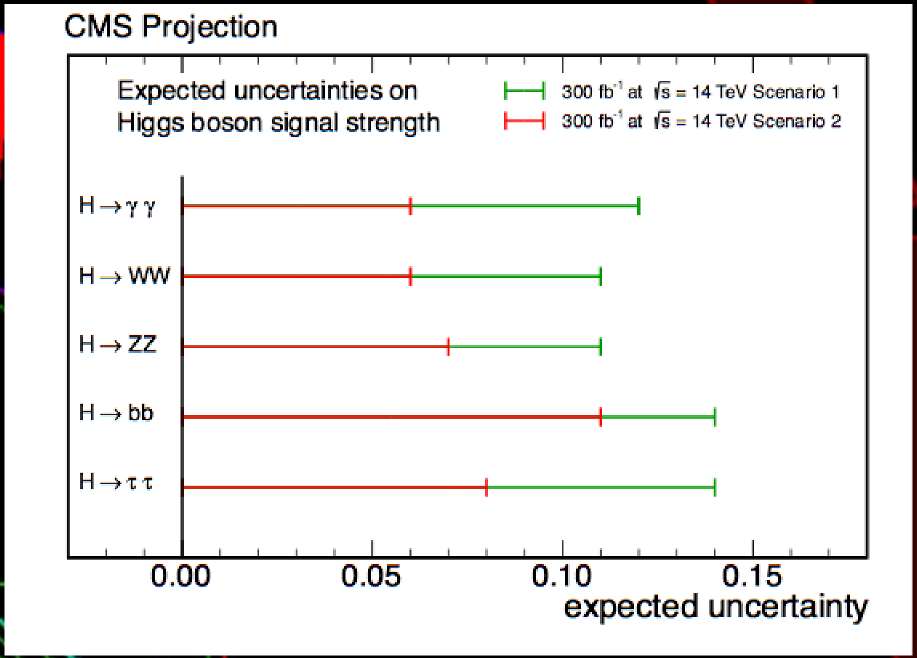
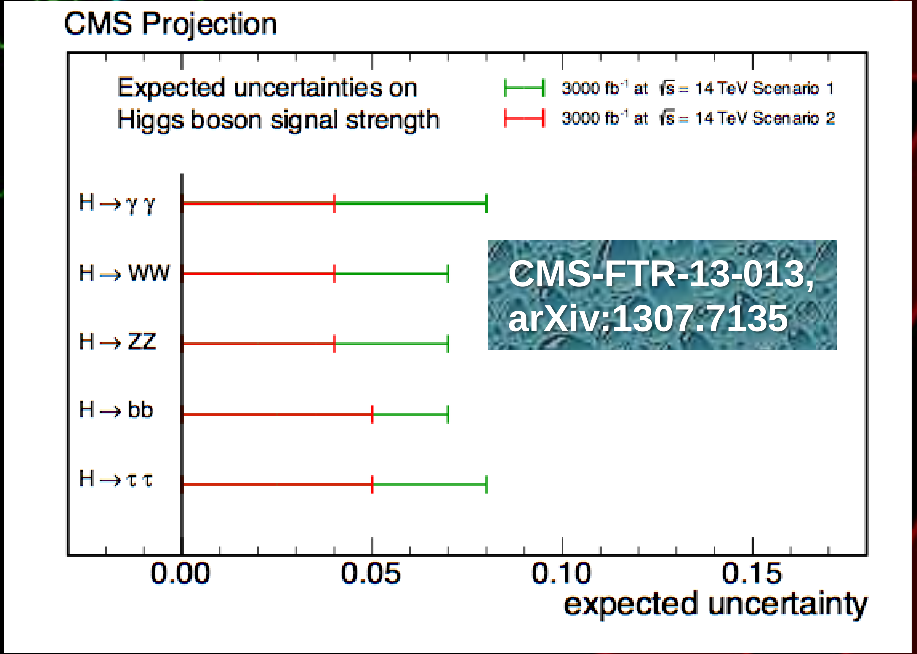


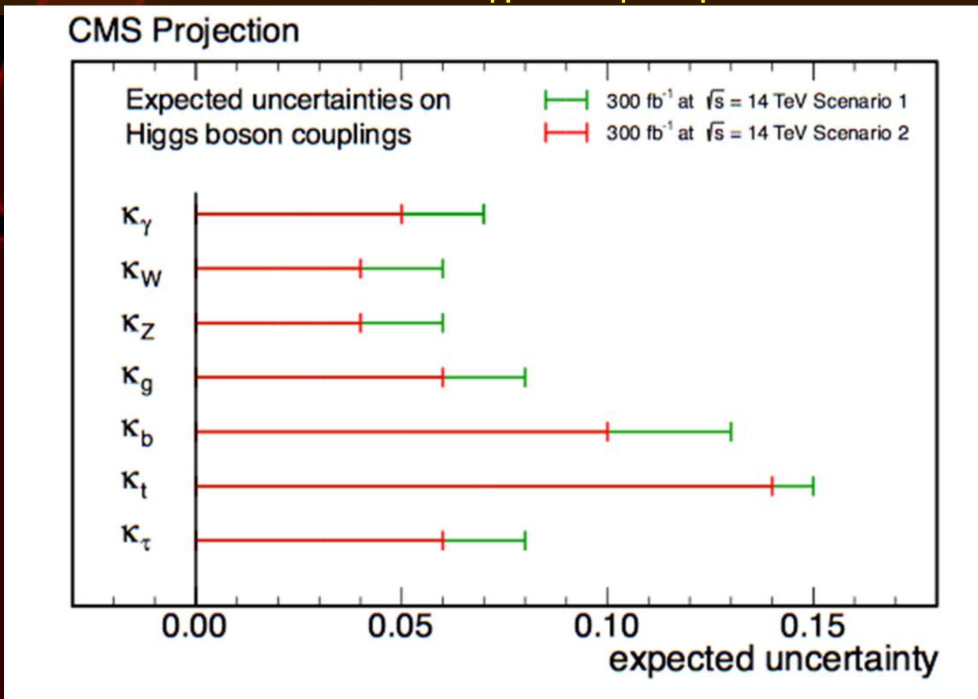


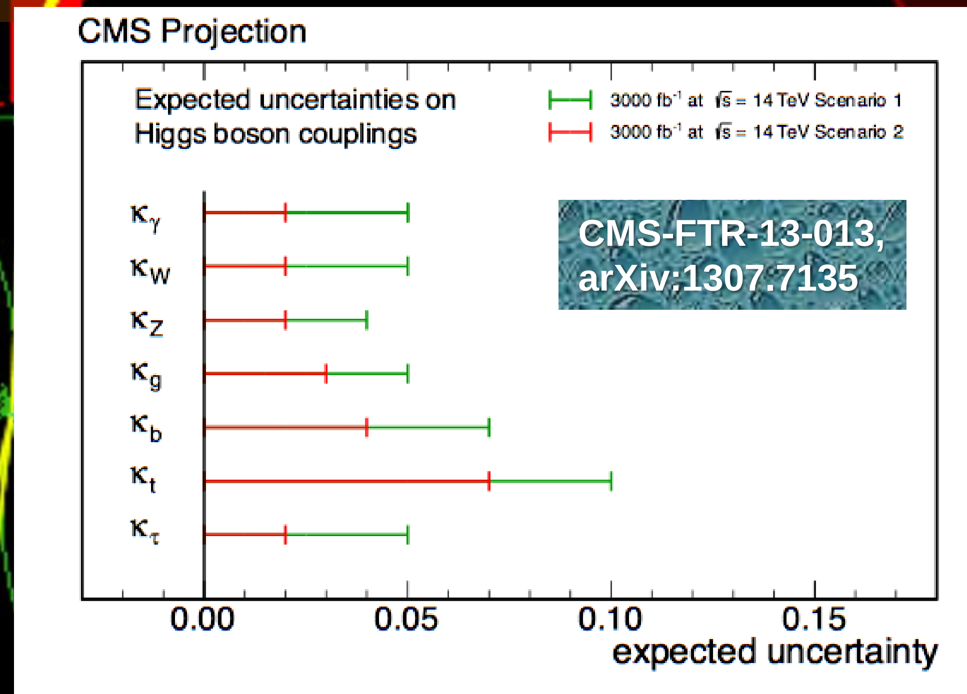
CMS-FTR-13-013, arXiv:1307.7135

Higgs Boson Properties: Couplings and Coupling ratios (1)

- Global fit procedure of LHC-Higgs XS WG (arXiv:1307.1347), modifier for each κ, effective κ for loops, $\kappa_H = \Sigma \kappa_i BR_i$ for i in SM

$$\sigma \cdot BR(ii \to H \to ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa}{\kappa_H^2}$$





-2ΔLnL=1, (%)		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[8,13]	[6,8]	[7,8]	[8,11]	N/a	[20,22]	[13,18]	[78,79]	[21,23]
	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[5,9]	[4,6]	[4,6]	[5,7]	N/a	[8,10]	[10,15]	[29,30]	[8,11]
	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

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Higgs Boson Properties: Couplings and Coupling ratios (2)

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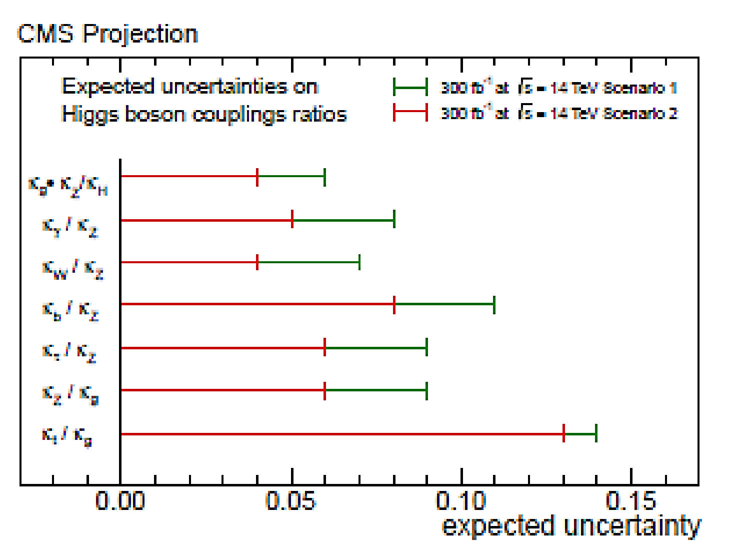
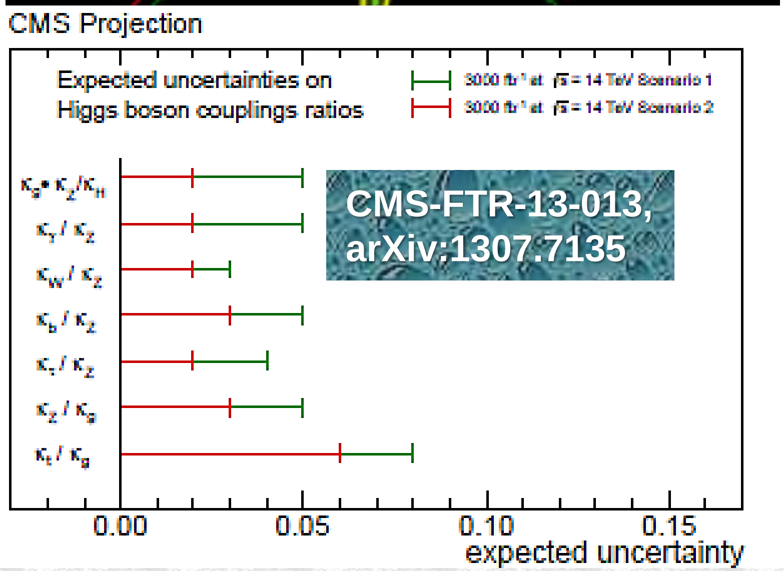
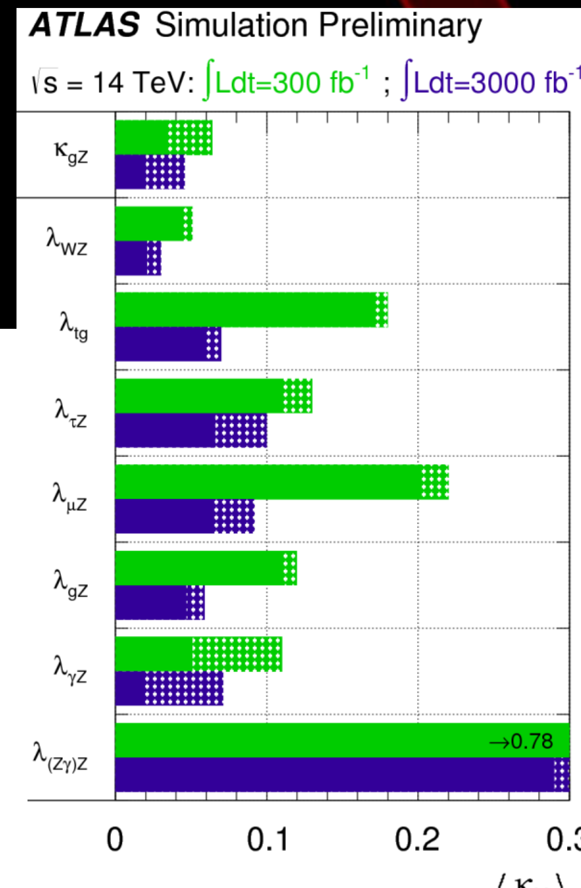
- Fit coupling ratios to avoid assumption on total width

300fb-1: Ranges from 3-22% (ATLAS), 4-23% (CMS)

3000fb-1: Ranges from 2-10%(ATLAS) , 2-8% (CMS)





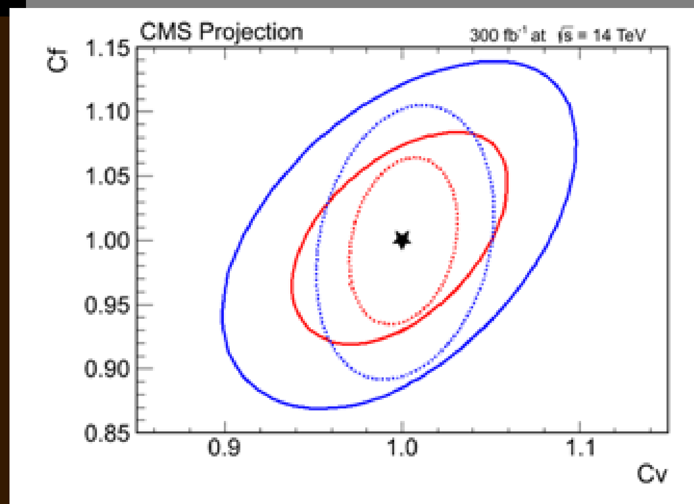


$\Delta\lambda_{XY}=\Delta\left(\frac{\kappa_X}{\kappa_Y}\right)$

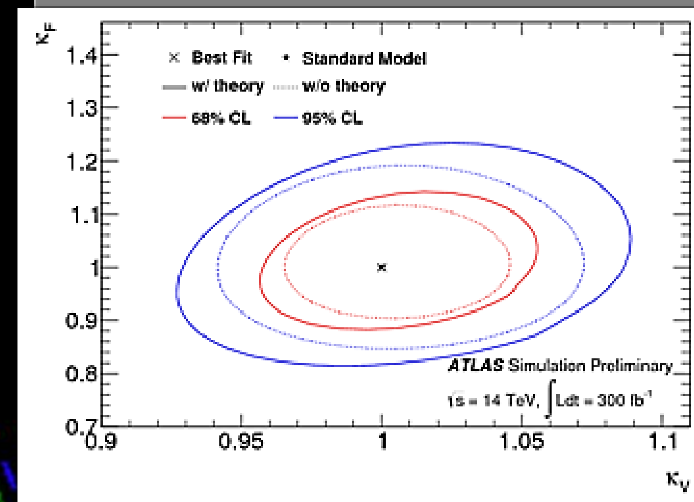
		K_gK_{Z}/K_H	K_W/K_Z	K_γ/K_Z	K_g/K_Z	K_b/K_Z	K_τ/K_Z	K_μ/K_Z	$\kappa_{Z\gamma}/K_Z$	K_t/K_g
300fb-1	ATLAS	[3,6]	[4,5]	[5,11]	[11,12]	N/a	[11,13]	[20,22]	[78,78]	[17,18]
	CMS	[4,6]	[4,7]	[5,8]	[6,9]	[8,11]	[6,9]	[22,23]	[40,42]	[13,14]
3000fb-1	ATLAS	[2,5]	[2,3]	[2,7]	[5,6]	N/a	[7,10]	[6,9]	[29,30]	[6,7]
	CMS	[2,5]	[2,3]	[2,5]	[3,5]	[3,5]	[2,4]	[7,8]	[12,12]	[6,8]

Higgs Boson Properties: Couplings and Coupling Ratios (3)

- Precision on universal couplings to fermions (kF) and bosons (kV) at 1/ 2 sigma
- ~5% (10%) precision in Higgs couplings to vector bosons (fermions) with 3000fb-1



http://cds.cern.ch/record/1494600?ln=en



- Mass-scaled coupling ratios

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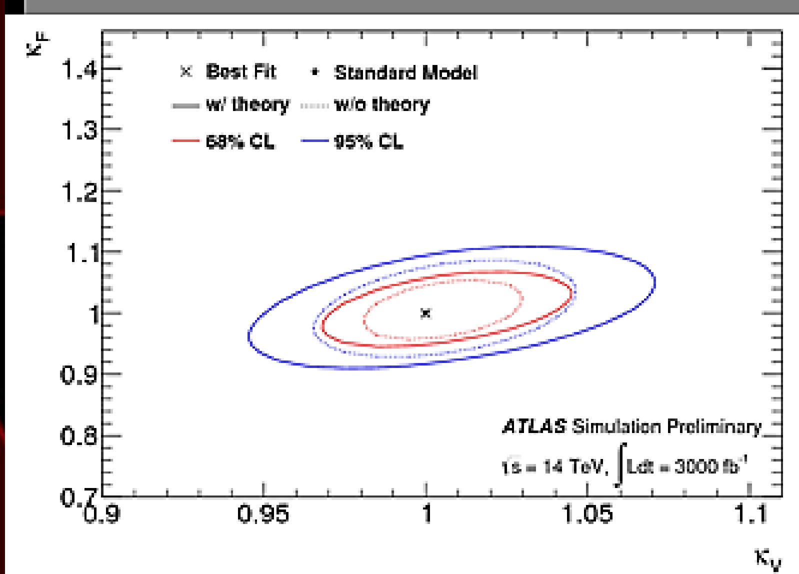
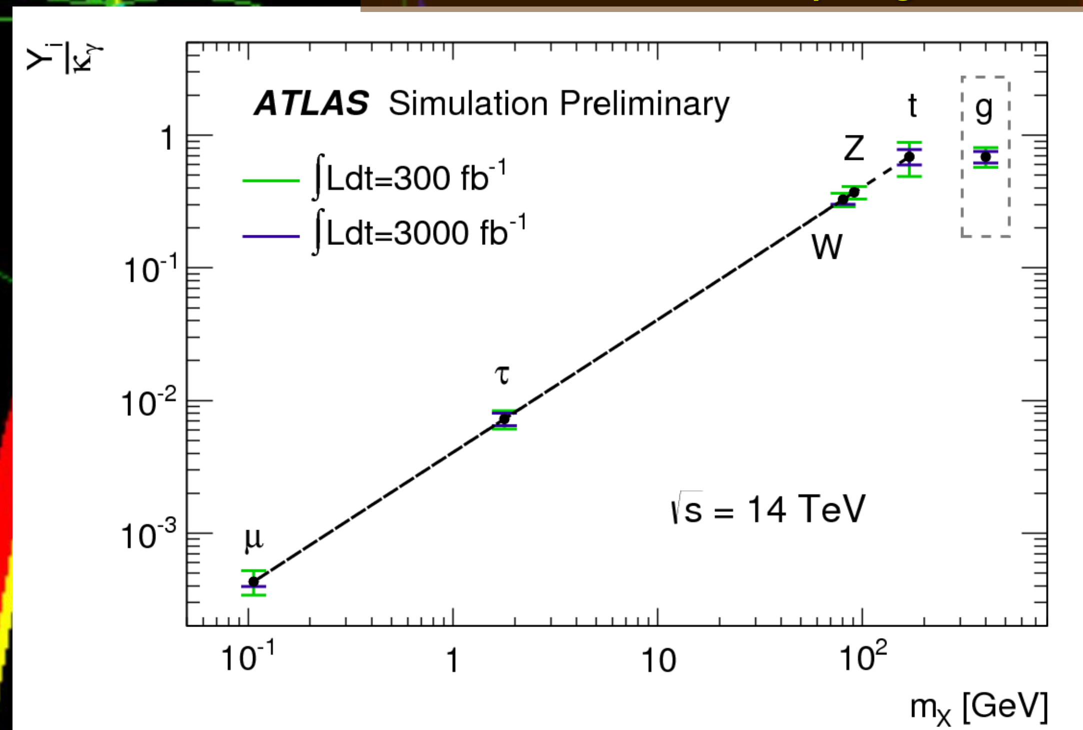
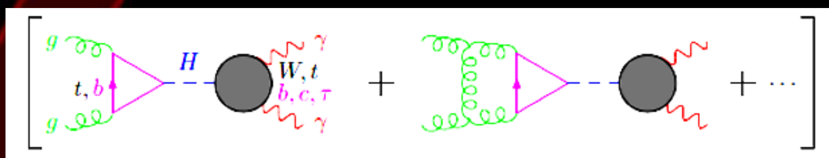




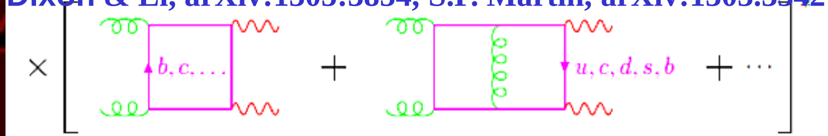
Higgs Boson Properties: Natural Width via H→γγ

Recall from S. Dittmaier's plenary talk yesterday

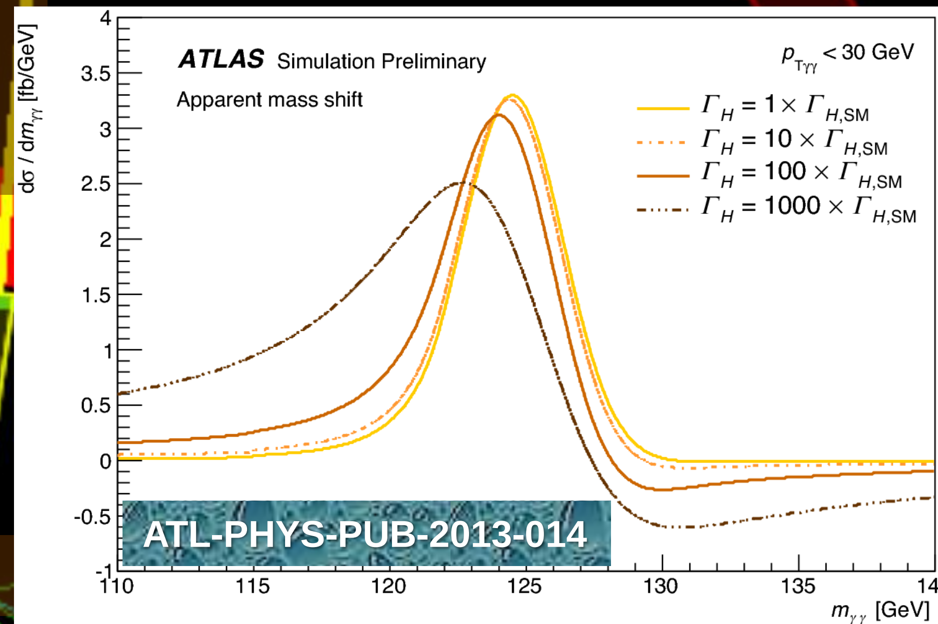
- gg→γγ/gg→H→gg interference convoluted with detector resolution shifts mass peak, function of natural width (Γ_{SM}=4.1 MeV), probable via $pt_{\gamma\gamma}$

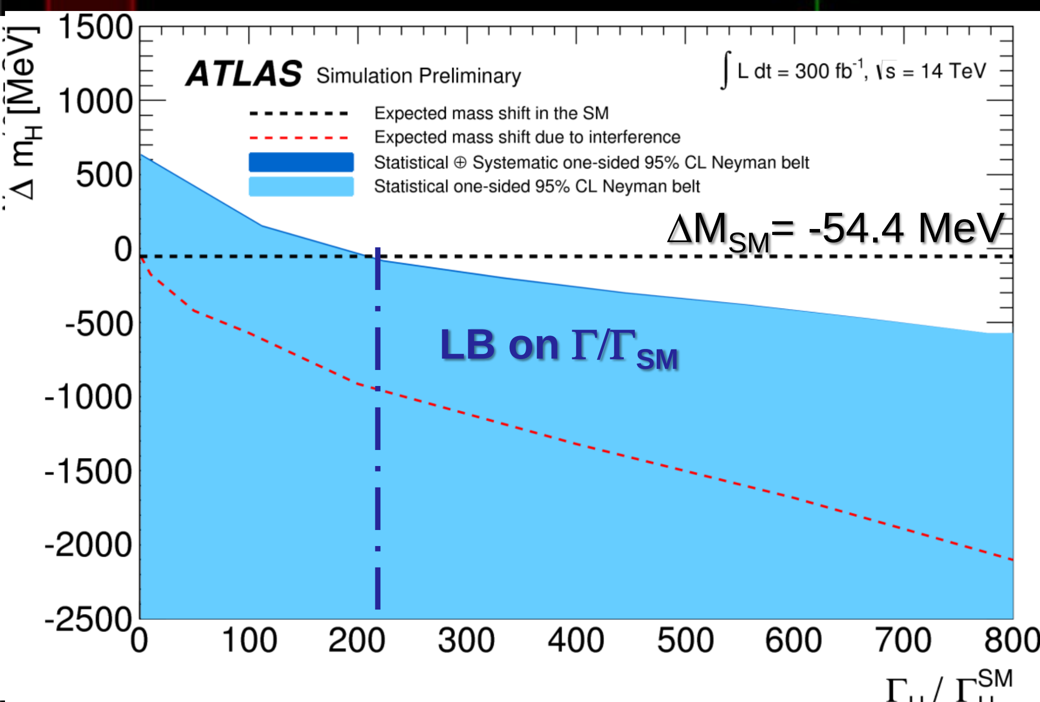


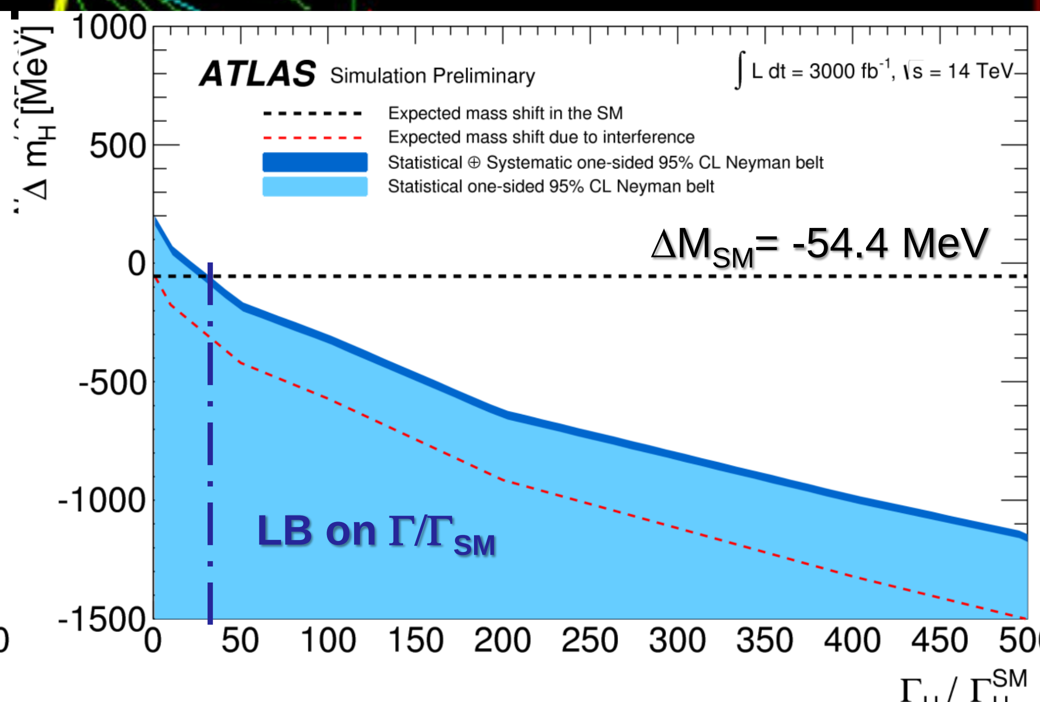
Dixon & Li, arXiv:1305:3854, S.P. Martin, arXiv:1303.3342



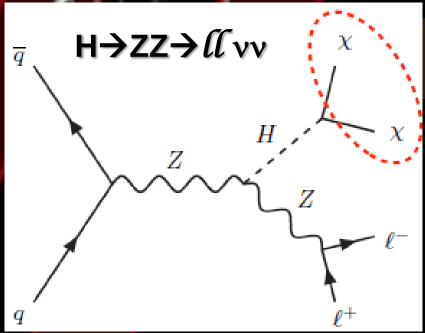
- 95% CL Γ_H< 920 (200) MeV for 300(3000)fb-1







Higgs Boson Properties: Invisible Branching Fraction and Higgs-Portal Interpretation



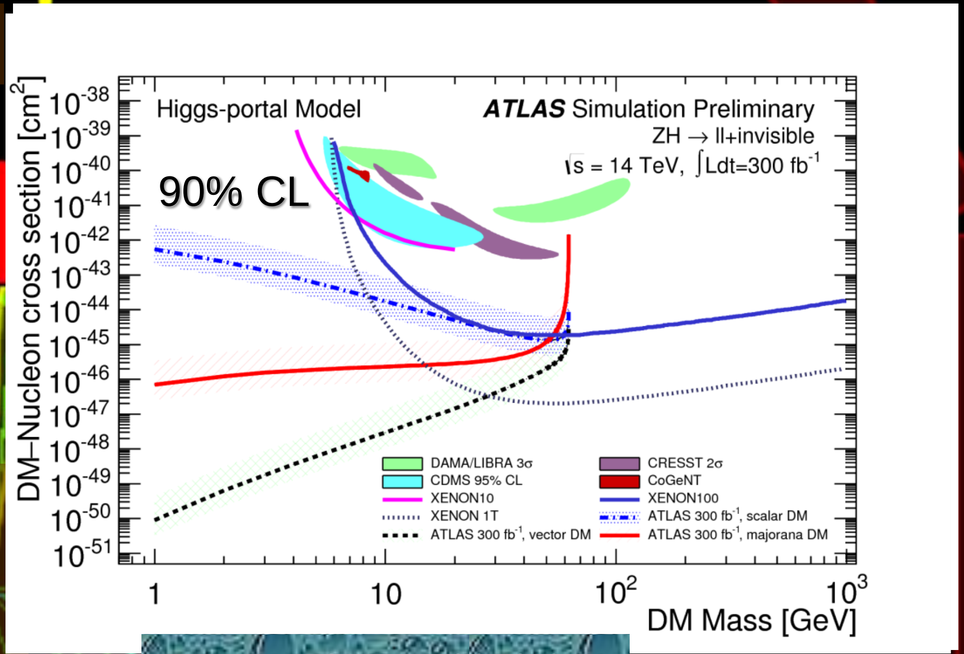
- Maximum LH fit to E_{Tmiss}

H→ZZ→ℓℓνν	ATLAS	CMS
300 fb^{-1}	[23,32]%	[17,28]%
3000 fb^{-1}	[8,16]%	[6,17]%

Ind. couplings	ATLAS	CMS
300 fb^{-1}	[25,28]%	[14,18]%
3000 fb^{-1}	[12,15]%	[7,11]%

- 95% UL on Br_{inv} [real., cons.]:

- Exclusion in σ (DM-nucleon) –m_{DM} plane: sensitivity up to $m_H/2$, complementary to direct detection DM experiments



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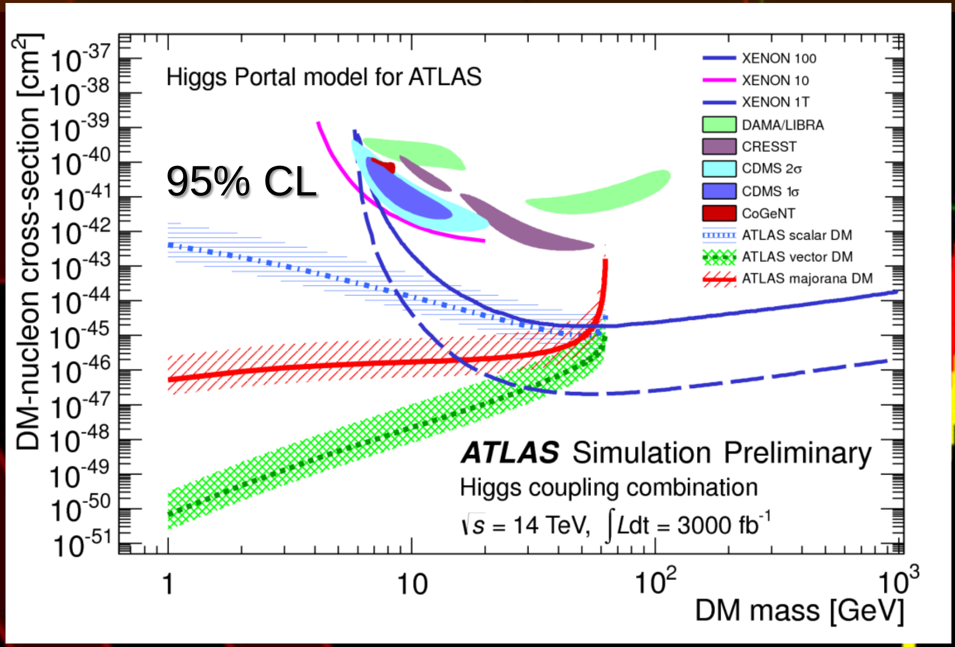

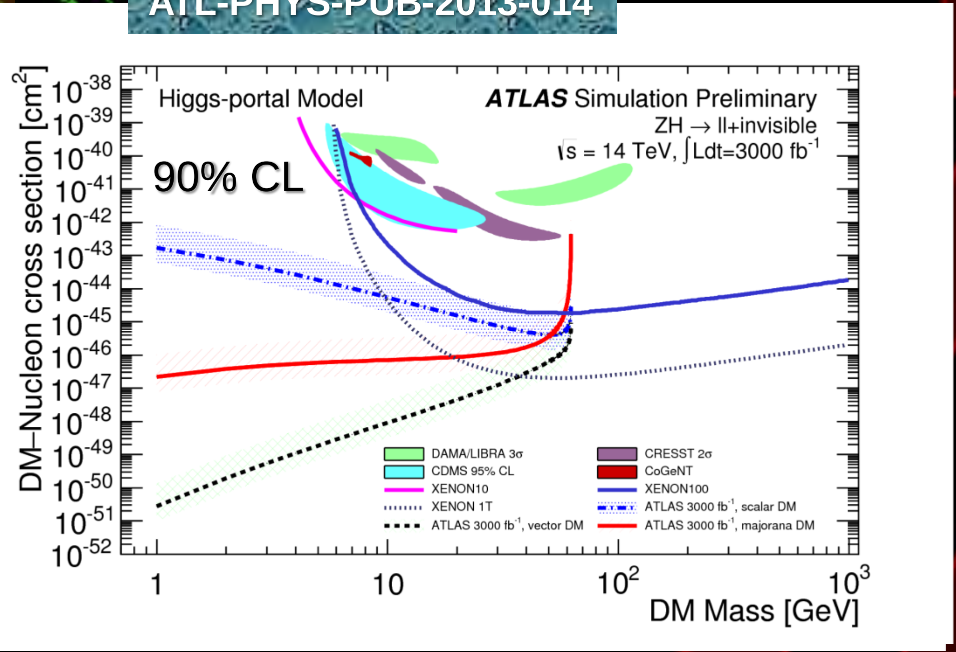

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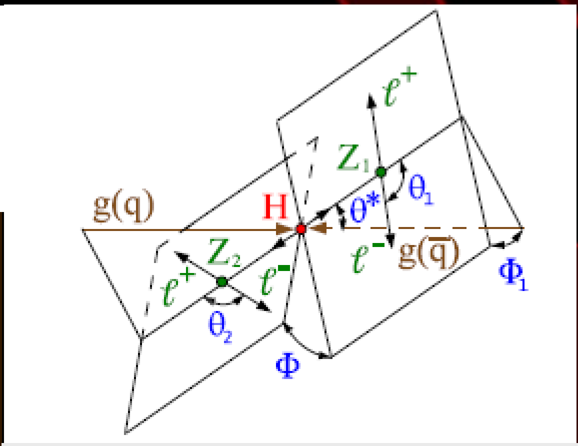
Higgs Boson Properties: Field Strength Tensor Structure via $H\rightarrow ZZ^*\rightarrow 4\ell$

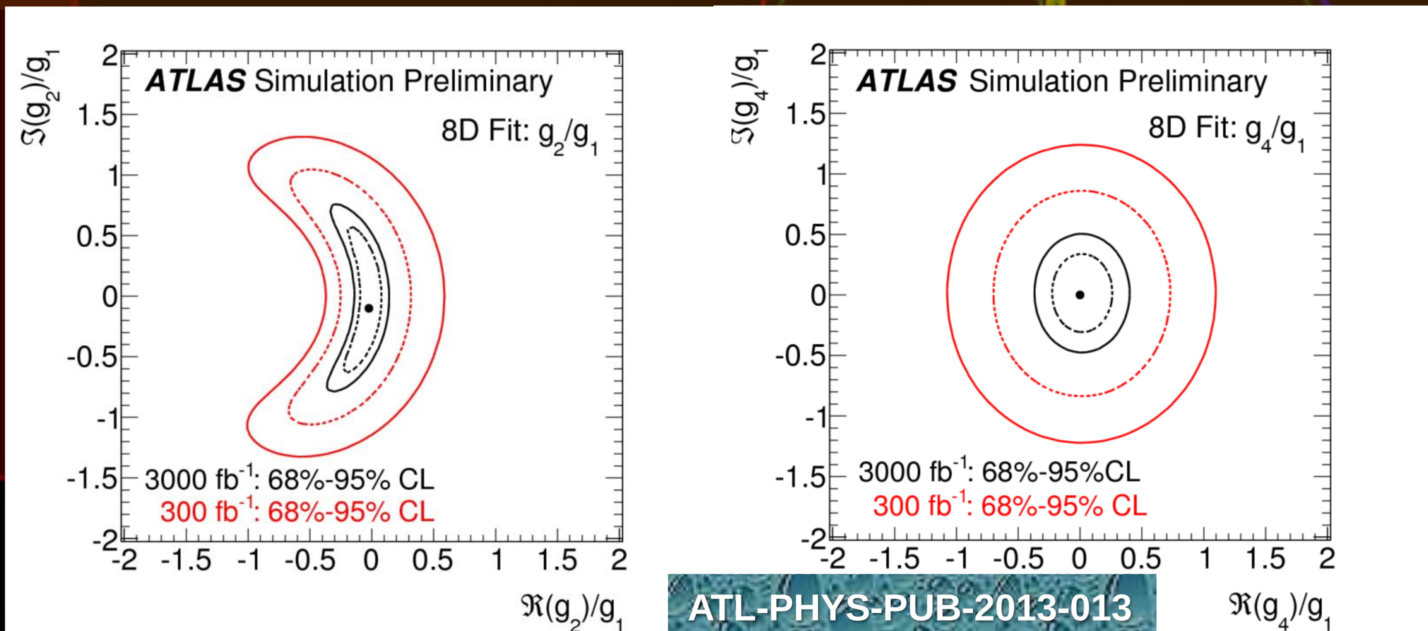
$$A(H \rightarrow ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}\right)$$

SM tree process — loop CP-even contributions — CP-odd contributions (BSM)



$(m_{4l}, m_{Z_{1,2}}, \theta_{1,2}, \varphi, \varphi_1, \theta^*)$

- Test for presence of extra anomalous CP-even (coupling $a_2 \leftarrow\rightarrow g_2$) and CP-odd (coupling $a_3 \leftarrow\rightarrow g_4$) components
- 8D fit involving kinematical variables sensitive to a_2 and a_3 with free parameters $Re(a_i)/a_1$ and $Im(a_i)/a_1$, $i=\{2,3\}$



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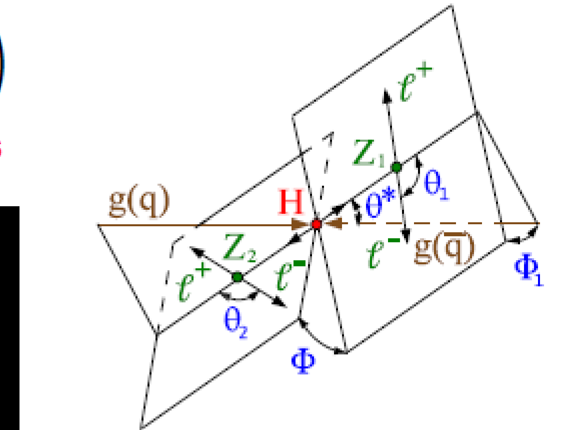
- 95% CL limits: (0,0) corresponds to pure CP-even '0+' SM state
- Factor ~2-3 improvement in precision between 300 and 3000fb-1

Luminosity	$\|g_4\|/g_1$	$\Re(g_4)/g_1$	$\Im(g_4)/g_1$	$\|g_2\|/g_1$	$\Re(g_2)/g_1$	$\Im(g_2)/g_1$
300 fb-1	1.20	(-0.88, 0.91)	(-1.02, 1.05)	1.02	(-0.84,0.44)	(-1.19, 1.18)
3000 fb-1	0.60	(-0.30, 0.33)	(-0.39, 0.42)	0.60	(-0.30,0.11)	(-0.71, 0.68)

Higgs Boson Properties: Field Strength Tensor Structure via H→ZZ*→4ℓ

$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

SM tree process | loop CP-even contributions | CP-odd contributions (BSM)



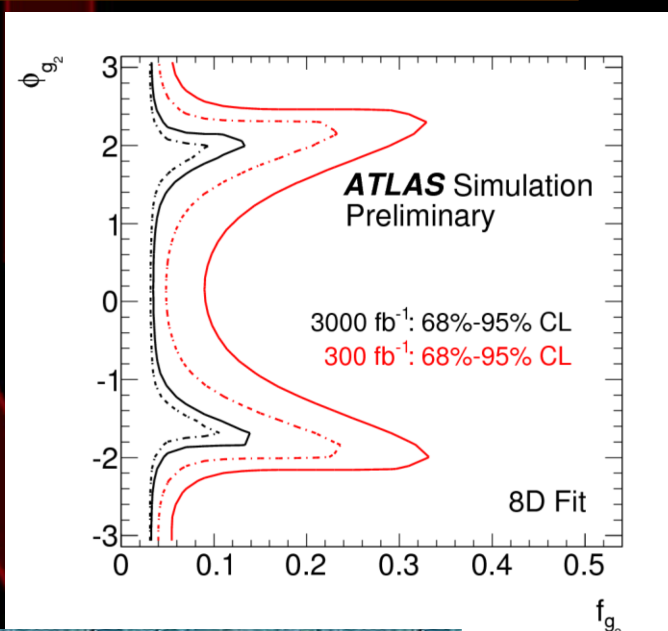
$(m_{4l}, m_{Z_{1,2}}, \theta_{1,2}, \varphi, \varphi_1, \theta^*)$

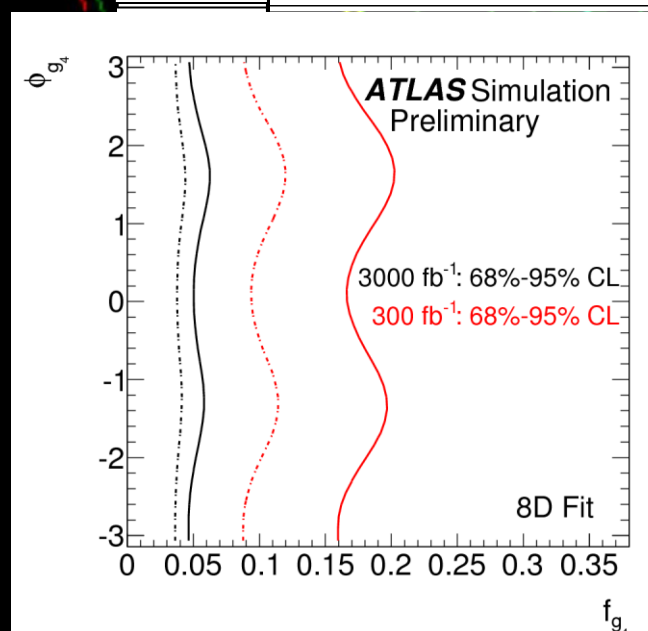
- Alternative method: Fit fraction of events f_{ai} and phases ϕ_i in 0-contribution to kinematic discriminant distribution

$$f_{a_i} = \frac{|a_i|^2\sigma_i}{|a_1|^2\sigma_1 + |a_i|^2\sigma_i} \qquad \phi_{a_i} = \arg\left(\frac{a_i}{a_1}\right)$$

- 95% CL limits:

CMS f_{g4}	95% CL Luminosity	ATLAS f_{g4}	ATLAS f_{g2}
0.13	300 fb^{-1}	0.20	0.29
0.04	3000 fb^{-1}	0.06	0.12





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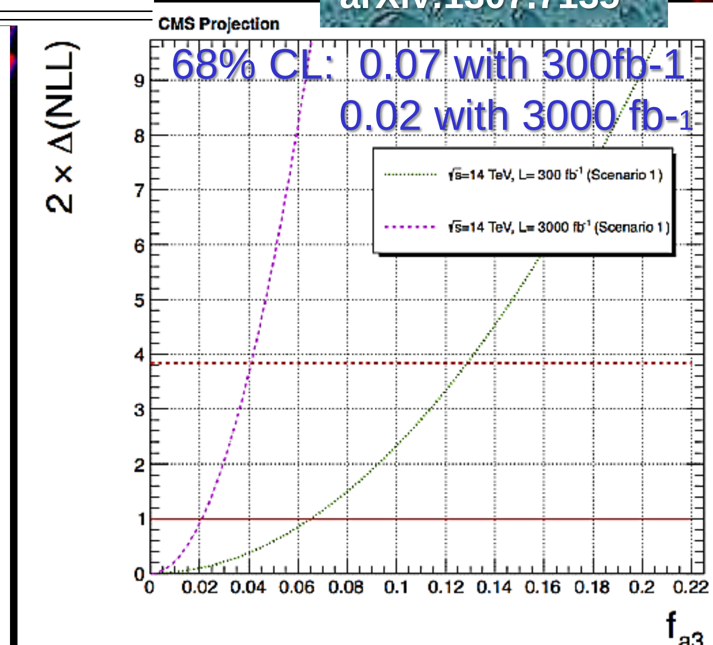
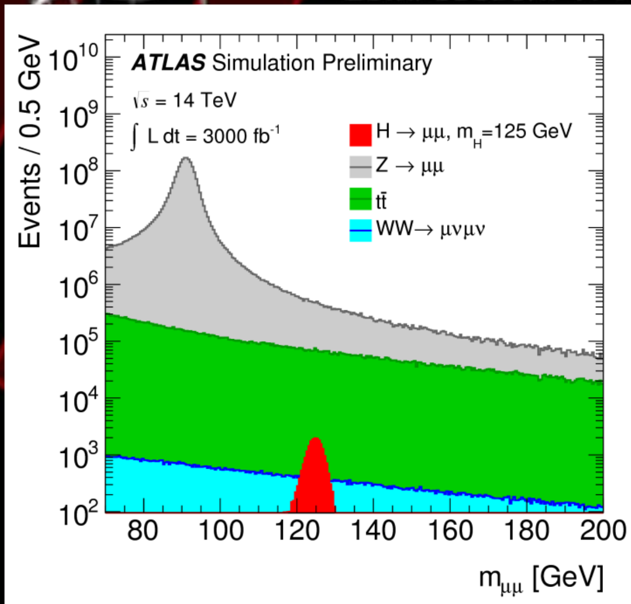
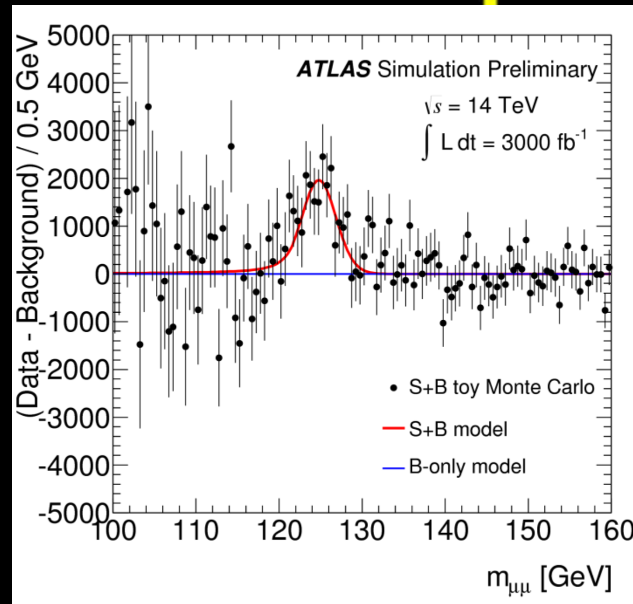
CMS-FTR-13-013, arXiv:1307.7135



Rare Decays: H→μμ (probe 2nd generation)





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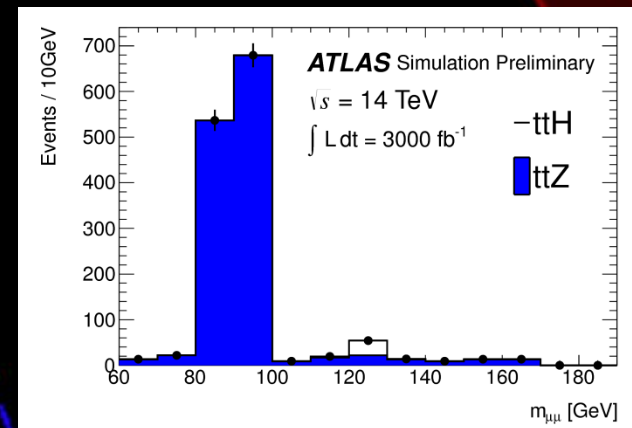
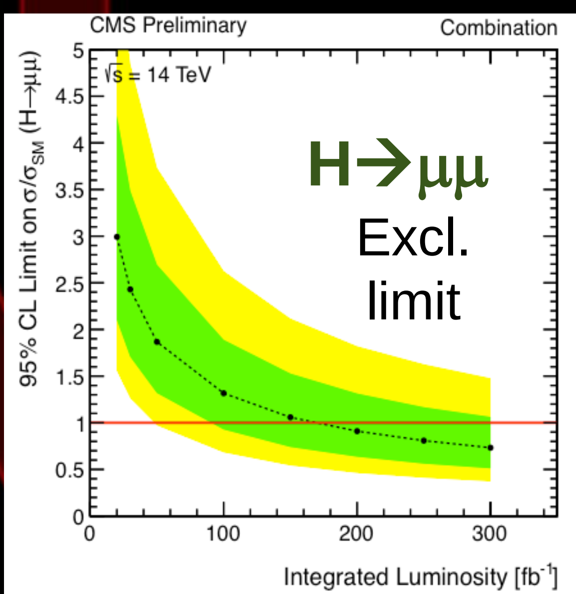


- ttbarH, H→μμ observability

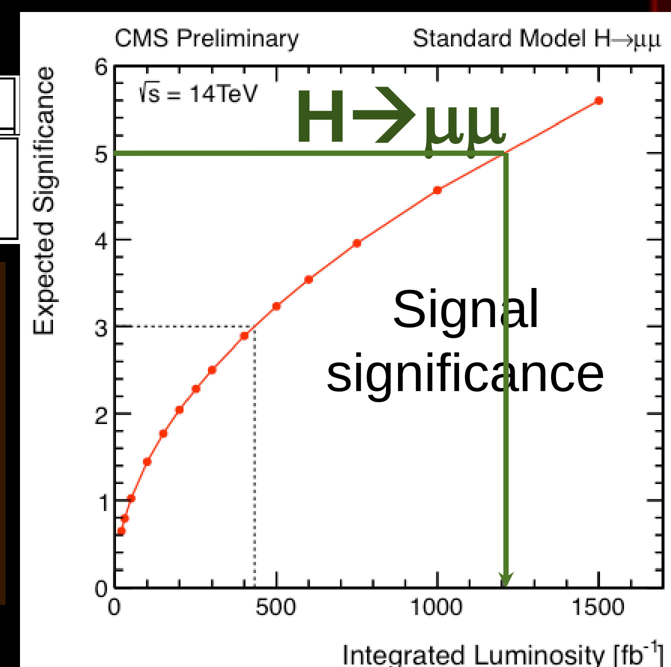
- Background from binned LH fit to the $\mu^+ \mu^-$ mass distribution

- ATLAS

$\mathcal{L}$ [fb^{-1}]	300	3000
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%



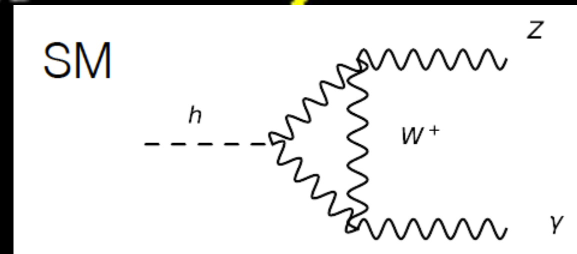
- CMS: SM sensitivity after ~150fb-1, 5σ significance after ~1200fb-1, ~10% precision possible on Yukawa coupling measurement

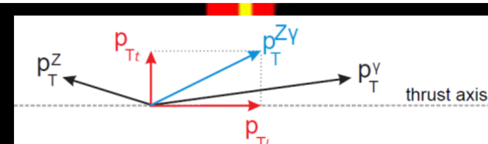


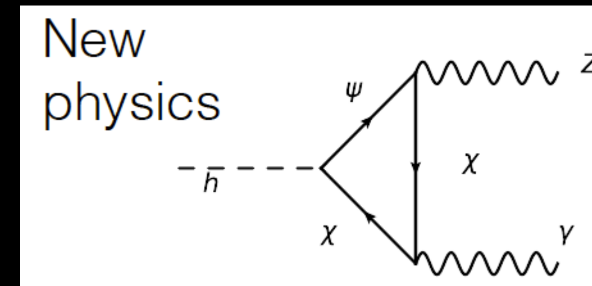
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13007TWiki

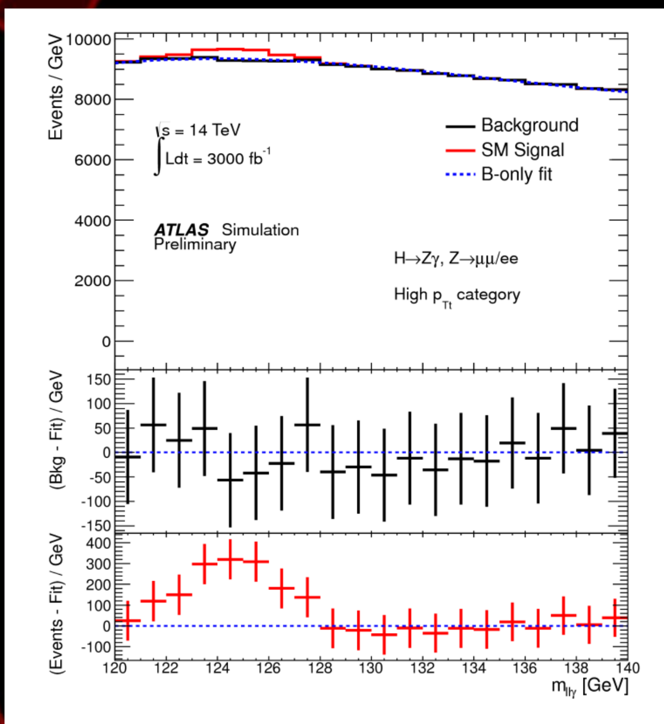
Rare Decays: H→Zγ

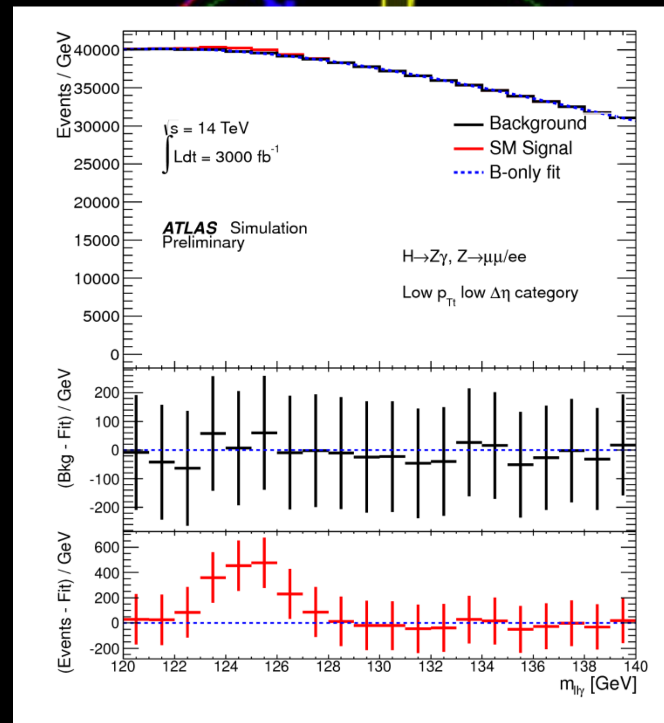
- Probe for new physics in charged particle loops
- Fit to $m_{ll\gamma}$ distribution in 3 categories in pTt and $|\Delta\eta(Z,\gamma)|$

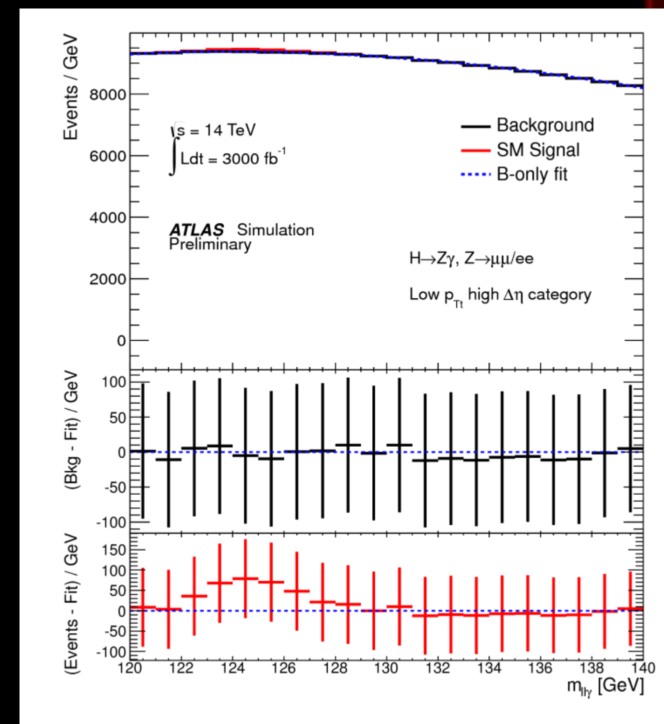












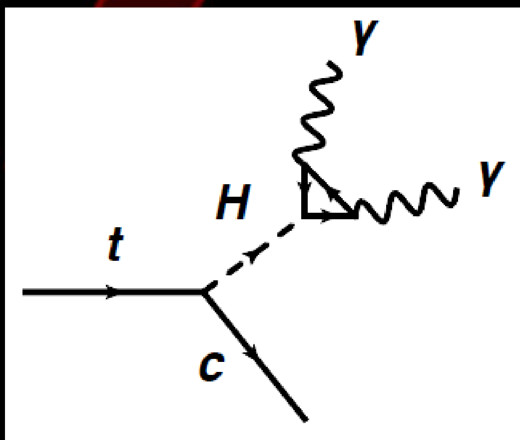
- After 3000fb-1, sensitivity wrt SM expectation: 0.52, p-value for mH=125 GeV: 3.9σ
- Expected measured signal strength: $1.00^{+0.25}_{-0.26}(stat.)^{+0.17}_{-0.15}(sys.)$

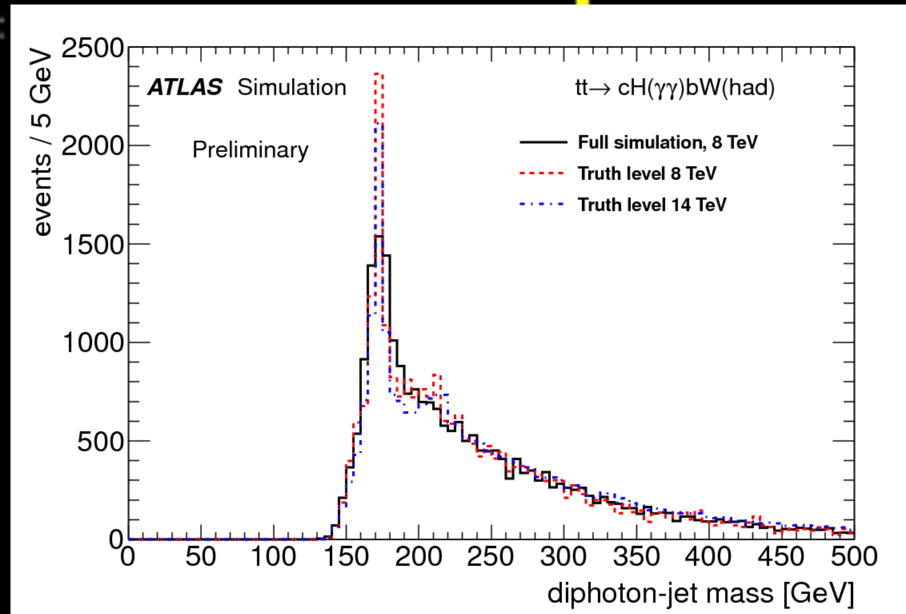
ATL-PHYS-PUB-2014-006

Rare Decays:t→cH, H→γγ (FCNC)

ATL-PHYS-PUB-2013-012

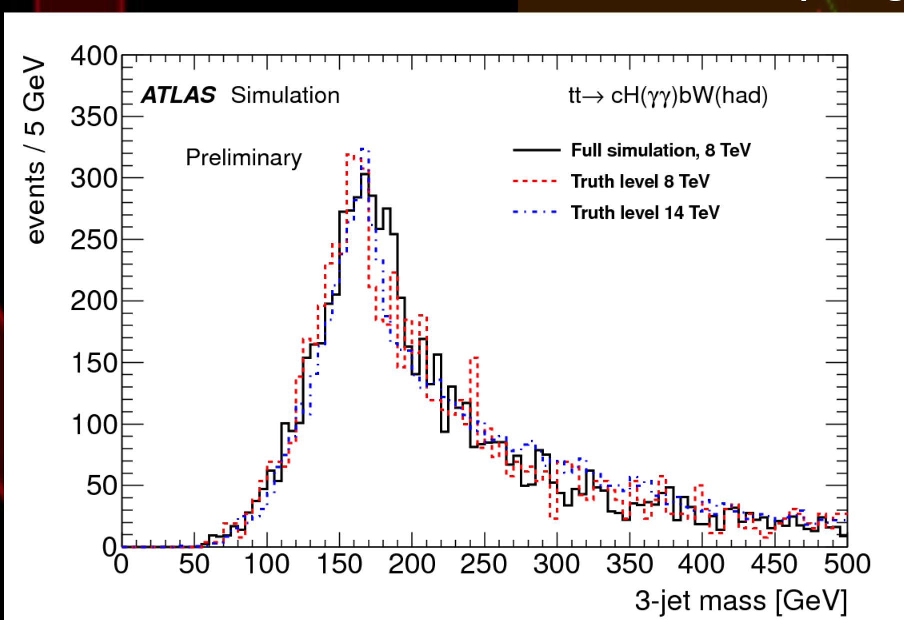
- ttbar→cH + Wb

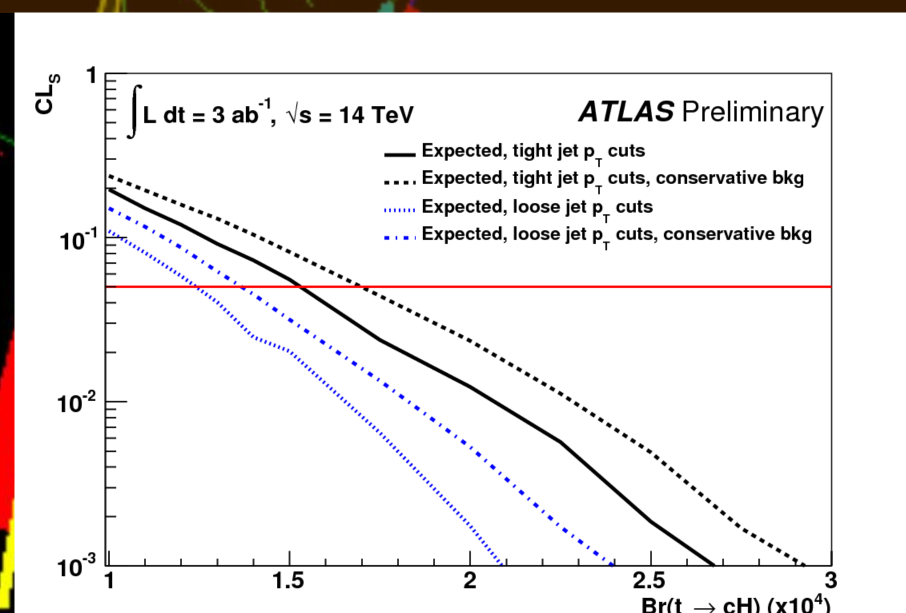




- Include hadronic + leptonic W decays, extrapolated acceptances 8-14 TeV
- SM: BR(t→cH) = 3×10-15
- BSM: BR(t→cH) possibly as large as ~10-5−10-3

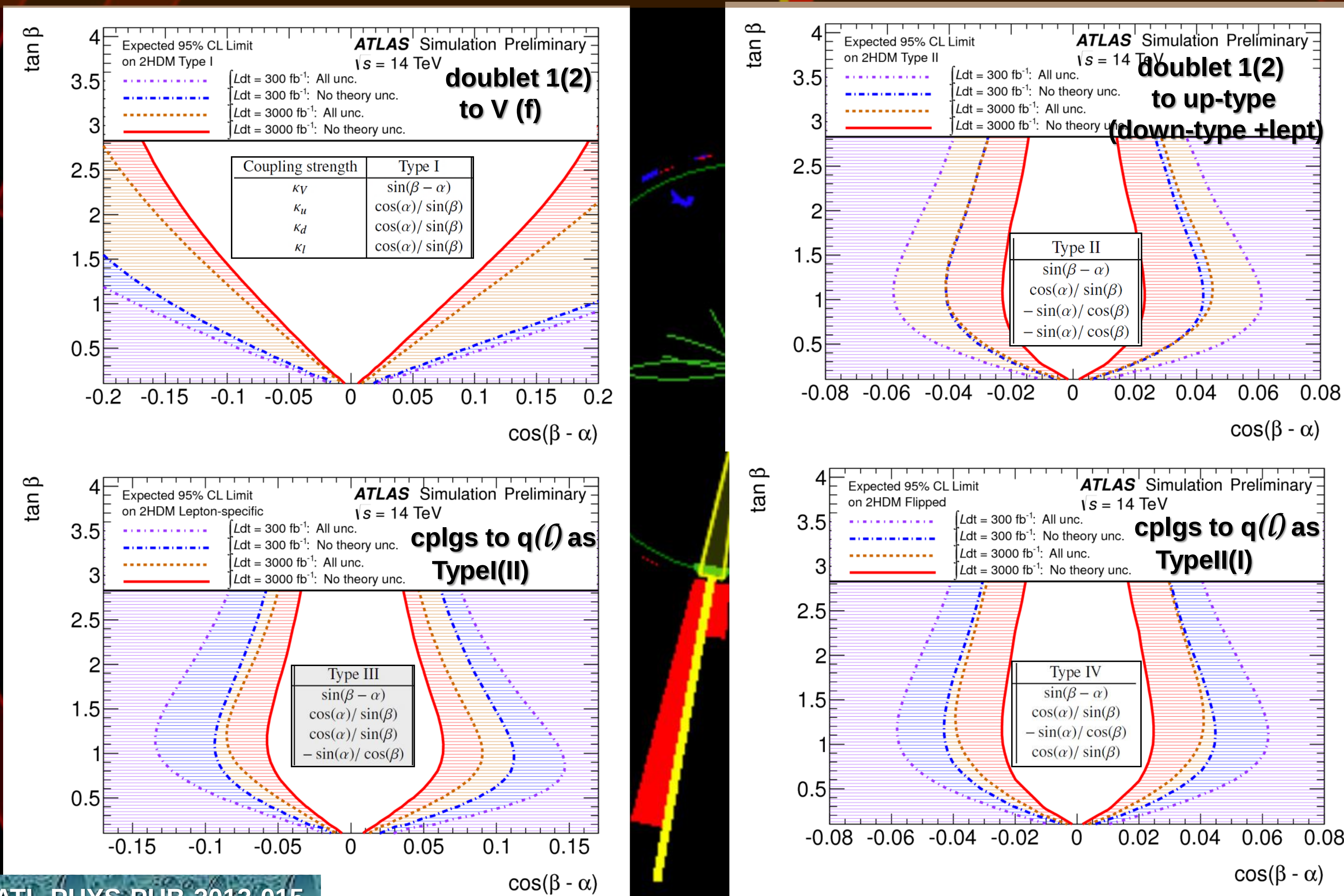
- 95% CL limit on BR(t→cH) for tight jet pt cuts :1.5-1.7 $X10^{-4}$, →tcH coupling<0.024 for 3000fb-1





Search for additional (BSM) Higgs bosons: from coupling measurement reinterpretation

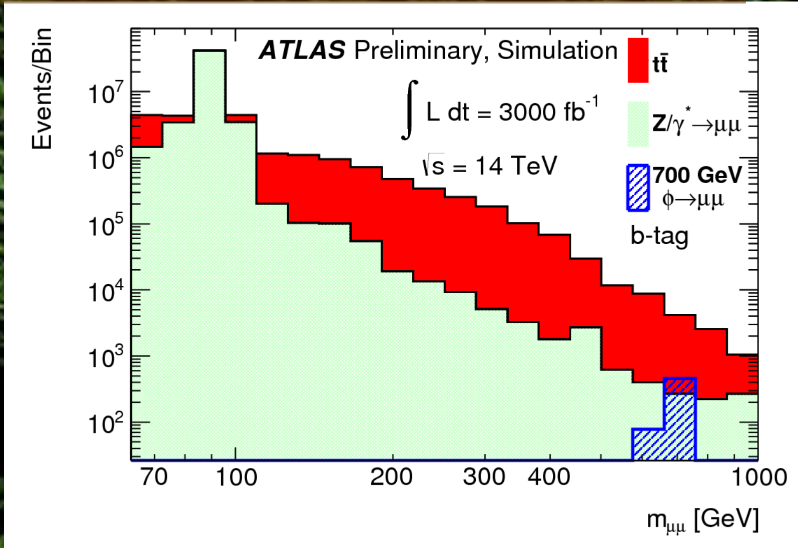
- Rescale production and decay rates as functions of the couplings κV, κu, κd, and κℓ

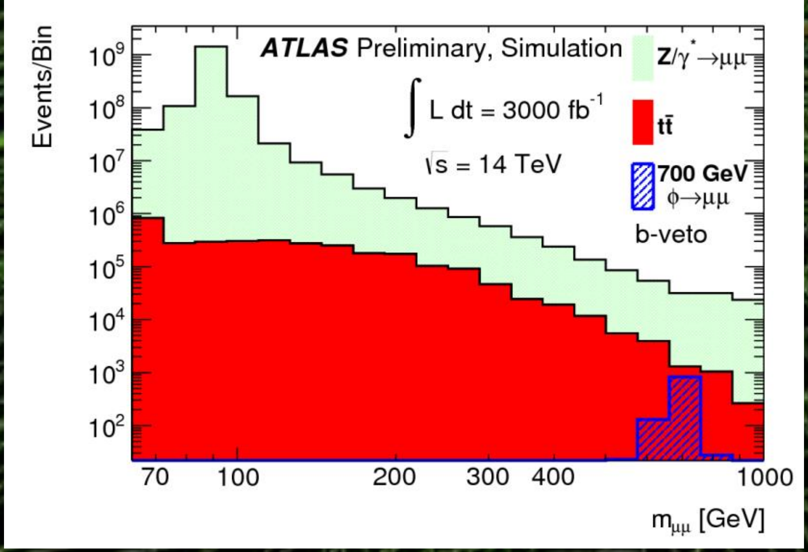


ATL-PHYS-PUB-2013-015

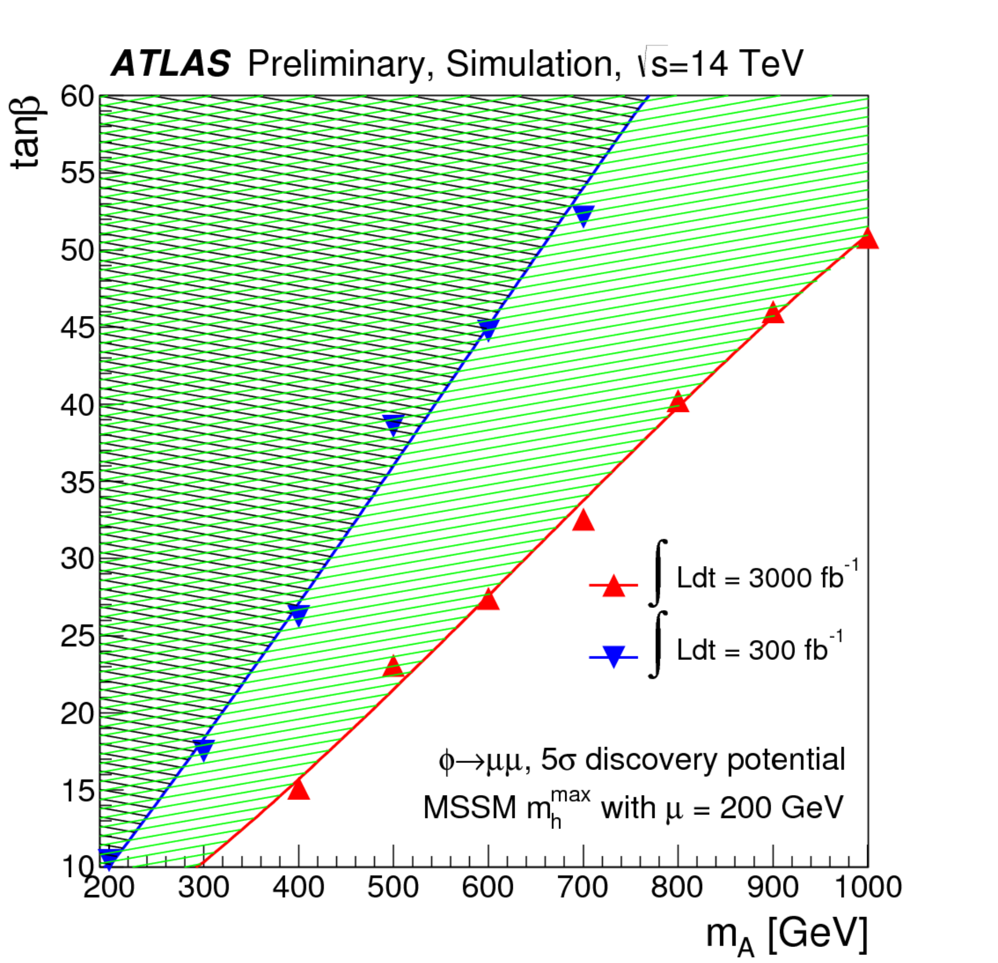
Search for additional (BSM) Higgs bosons: via H/A→μμ

- Binned LH fit to the $\mu^+ \mu^-$ mass distribution, 2 categories (with and without b-tag)





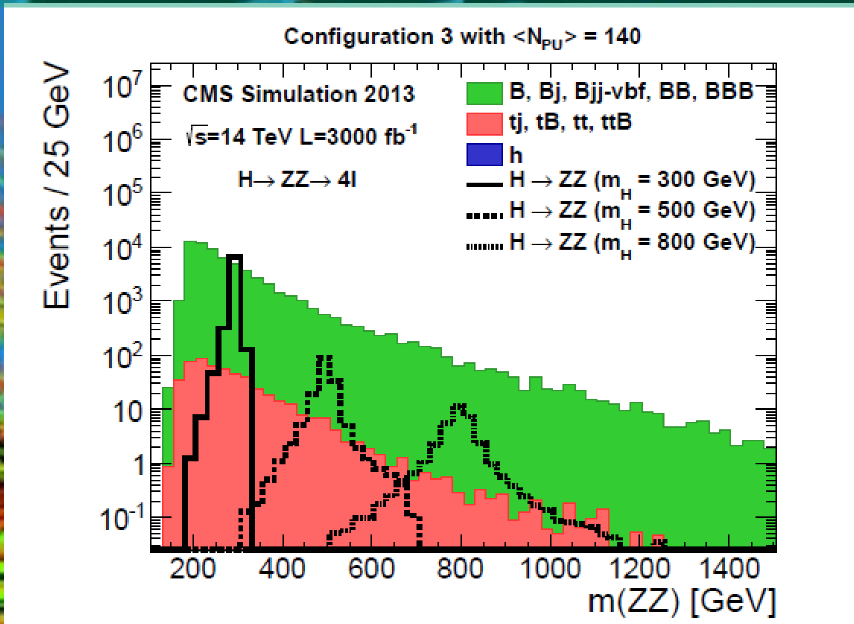
- 5σ contours in the tanβ-mA plane in MSSM, mhMax scenario:

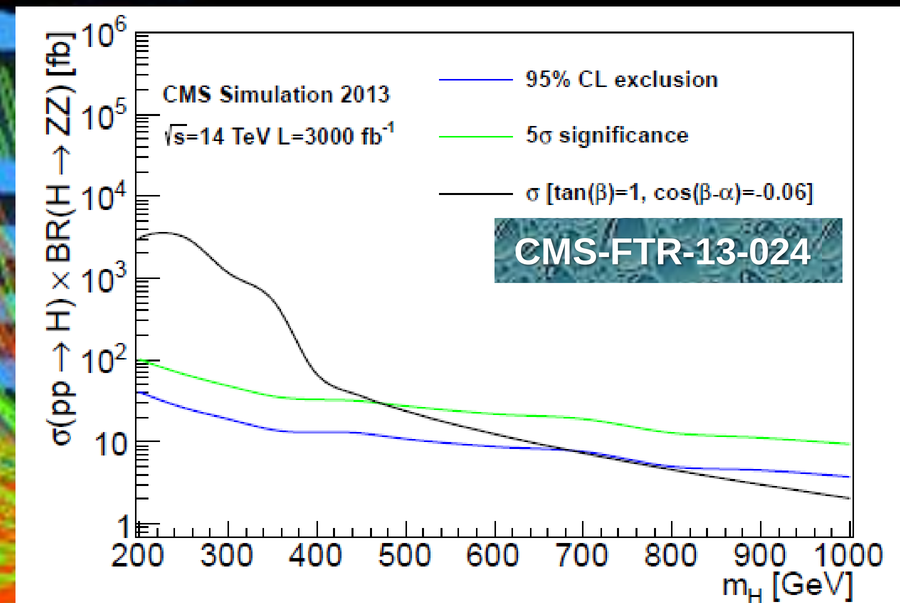


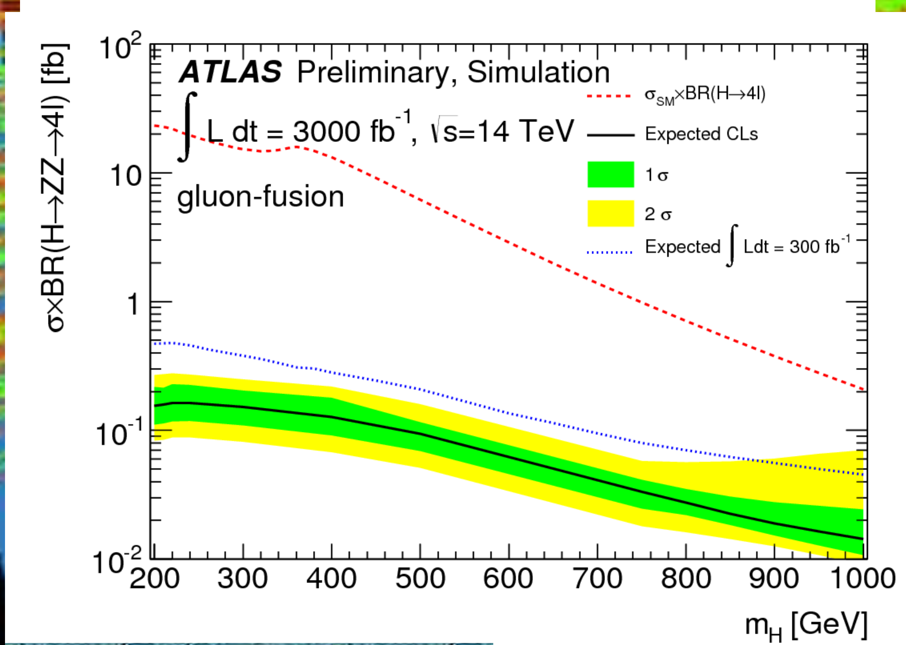
ATL-PHYS-PUB-2013-016

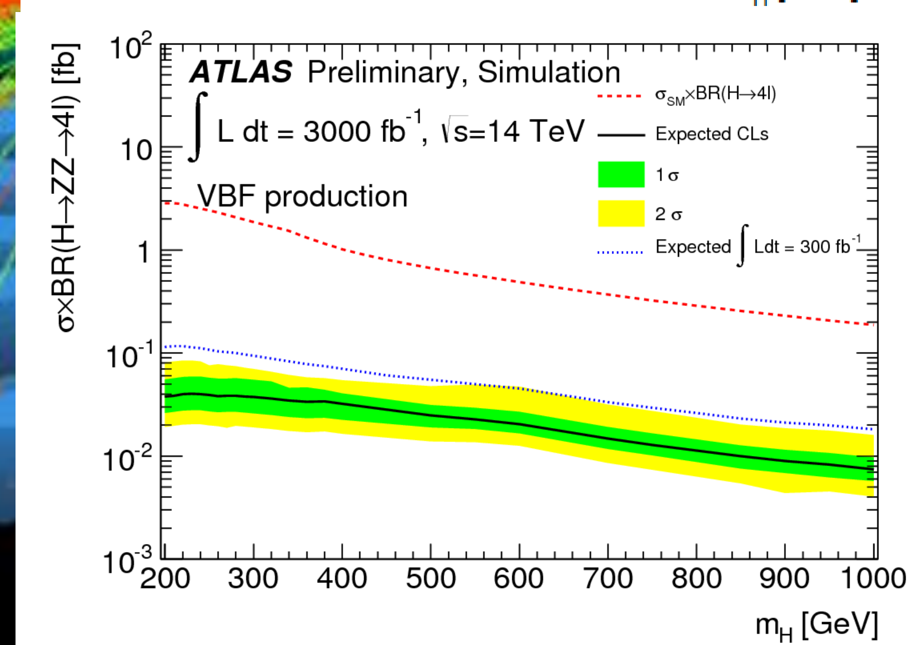
Search for additional (BSM) Higgs bosons via H→ZZ→4ℓ

- σ X BR limits as function of m_H 3000fb-1 (ATLAS includes BR to 4ℓ), probe up to factor 40 below SM





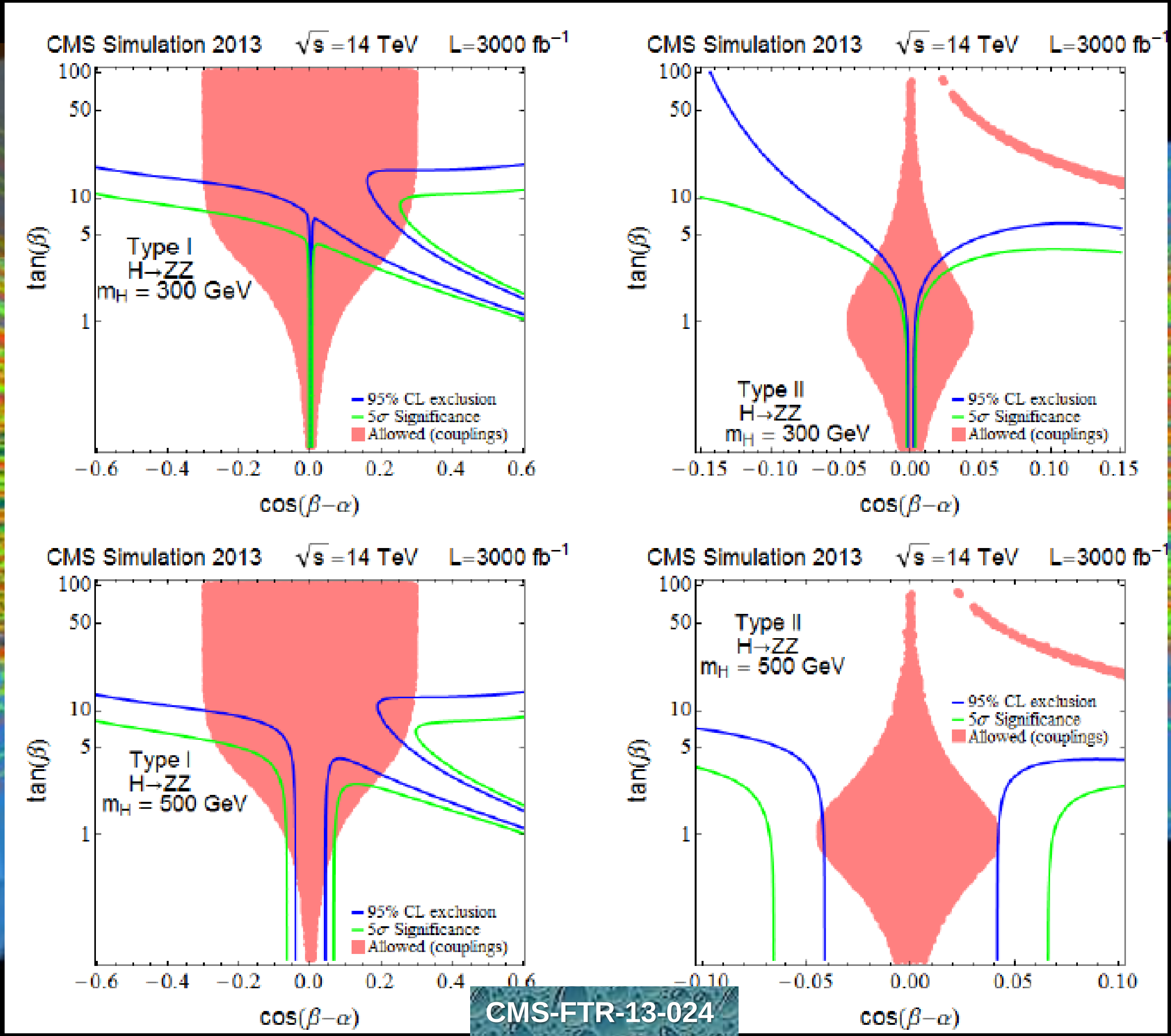




ATL-PHYS-PUB-2013-016

Search for additional (BSM) Higgs bosons via H→ZZ→4ℓ

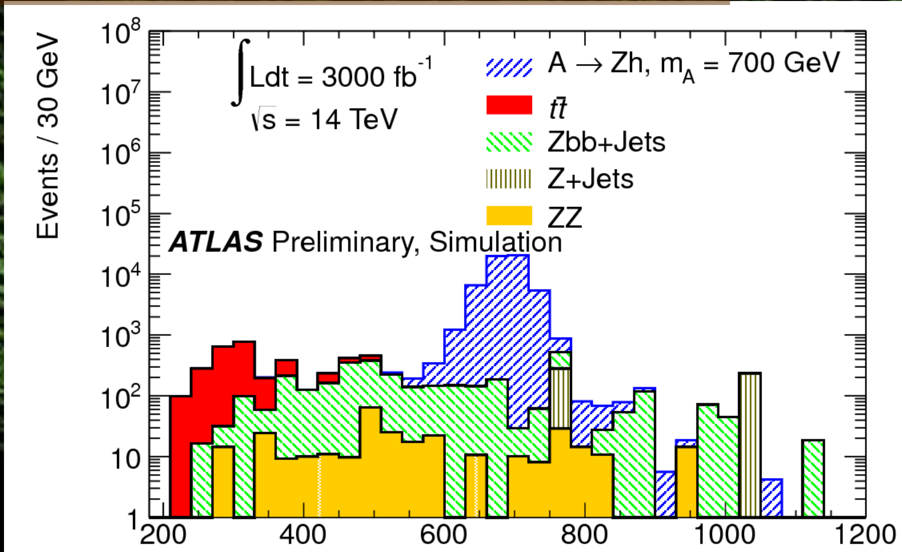
- CMS: 5σ contours in the tanβ-cos(β–α) plane, 2HDM Types I, II for 3000fb-1



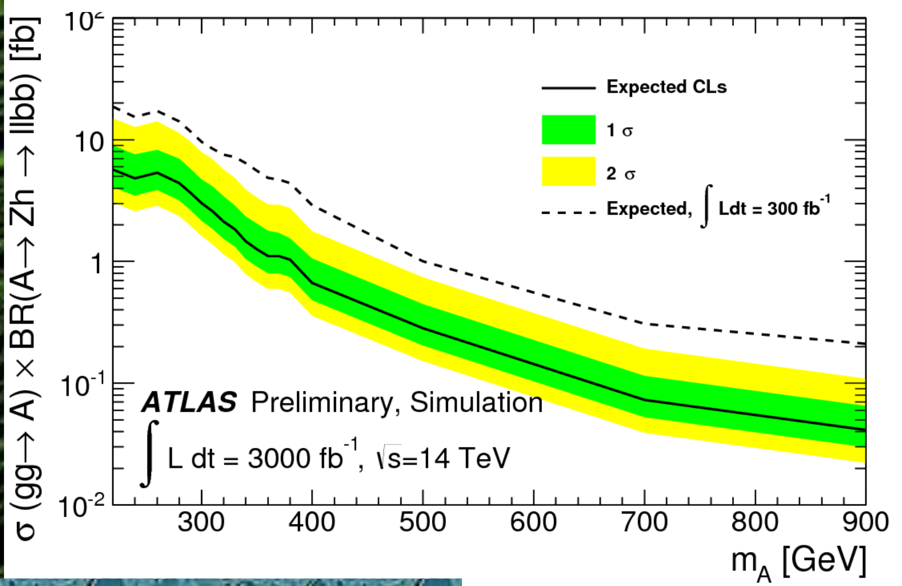
Search for additional (BSM) Higgs bosons via A→Zh→ℓℓbb

- σ X BR limits as function of m_A 3000fb-1 (ATLAS includes BR to ℓℓbb)

Binned LH fit to m_A

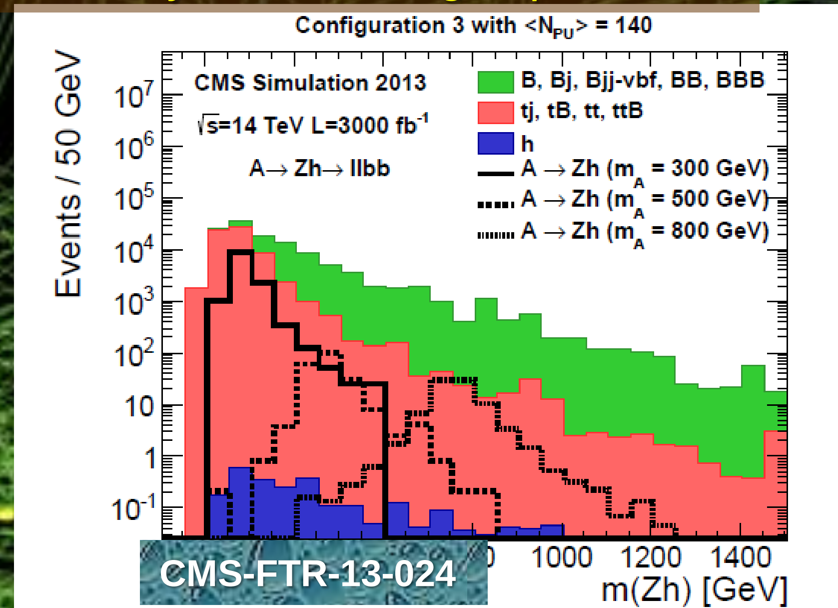


$$m_A^{rec} \equiv m_{llbb} - m_{ll} - m_{bb} + m_Z^0 + m_h^0$$

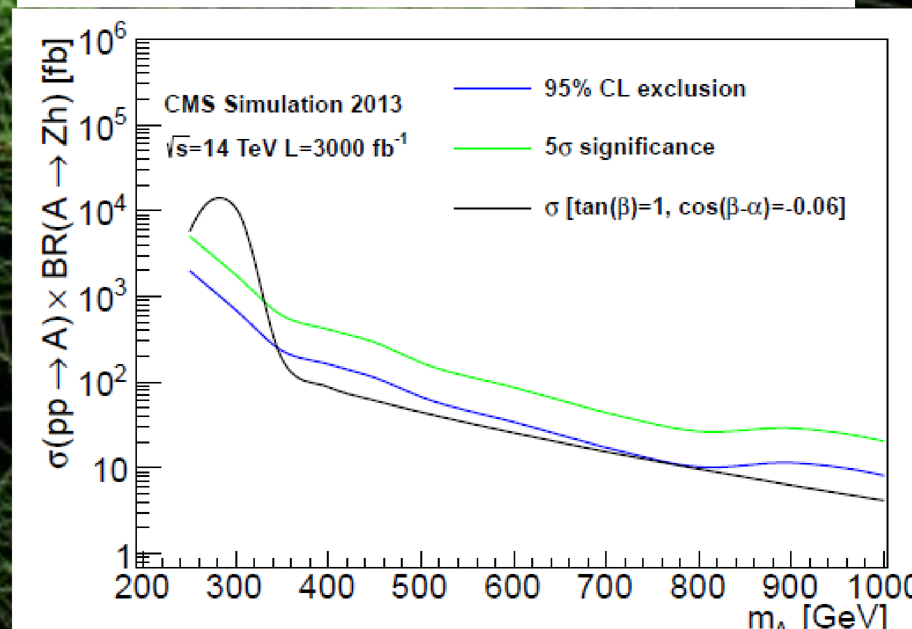


ATL-PHYS-PUB-2013-016

Bin-by-bin counting experiment

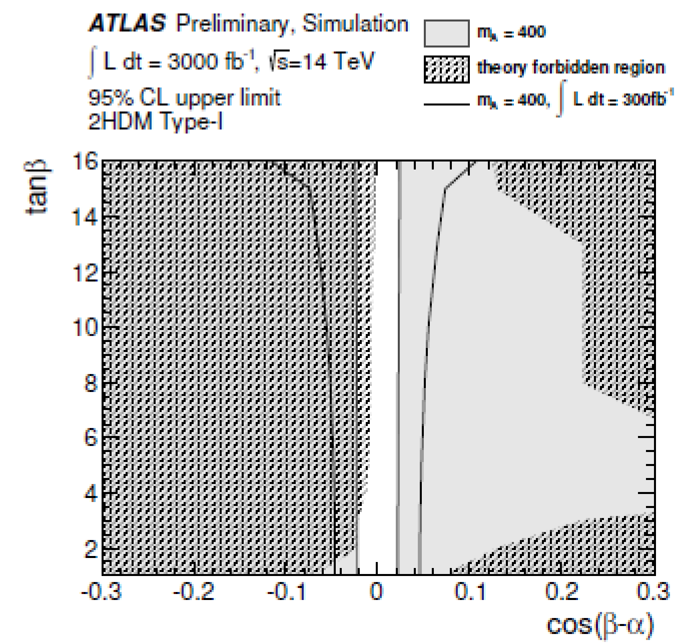


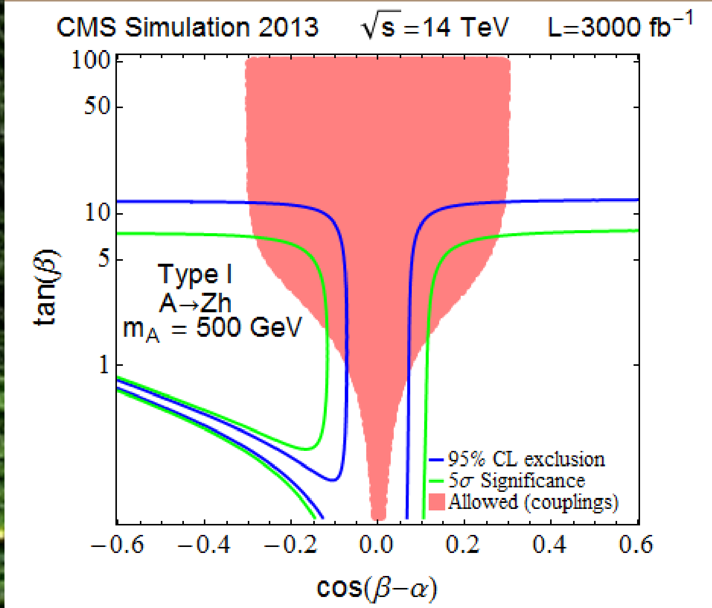
CMS-FTR-13-024

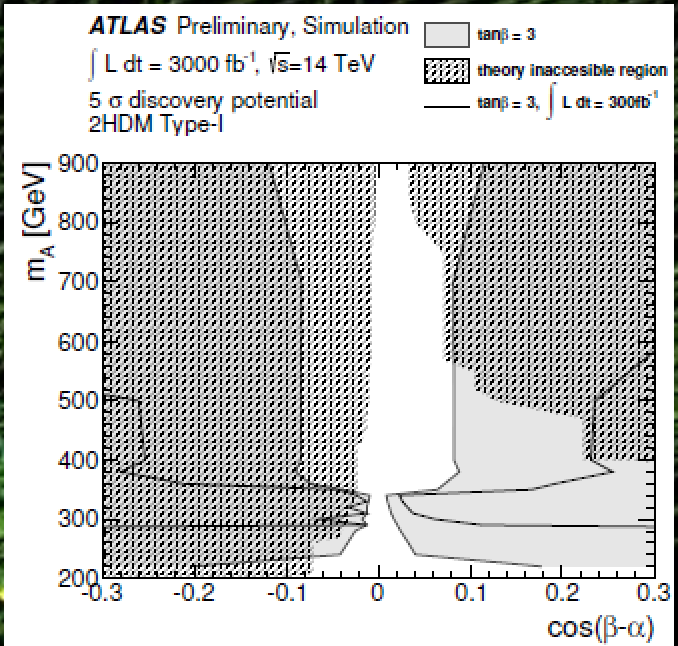


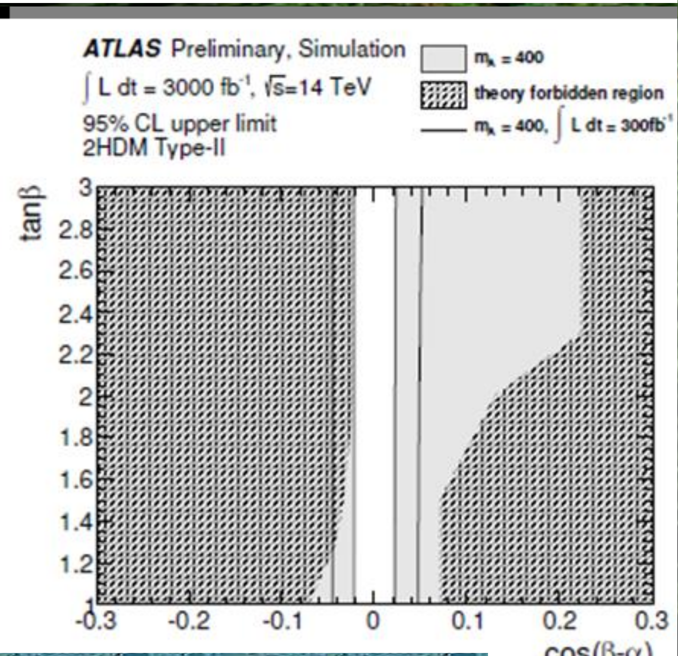
Search for additional (BSM) Higgs bosons via A→Zh→ℓℓbb

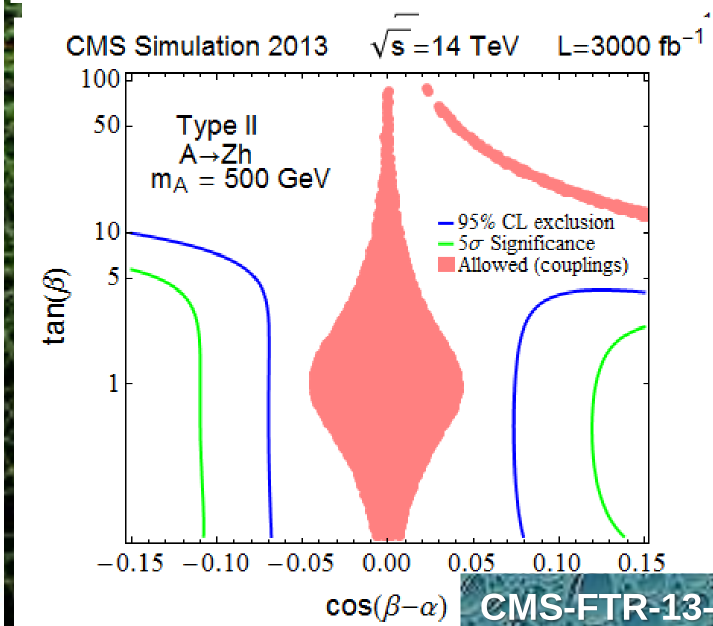
Interpretation in 2HDM I, II

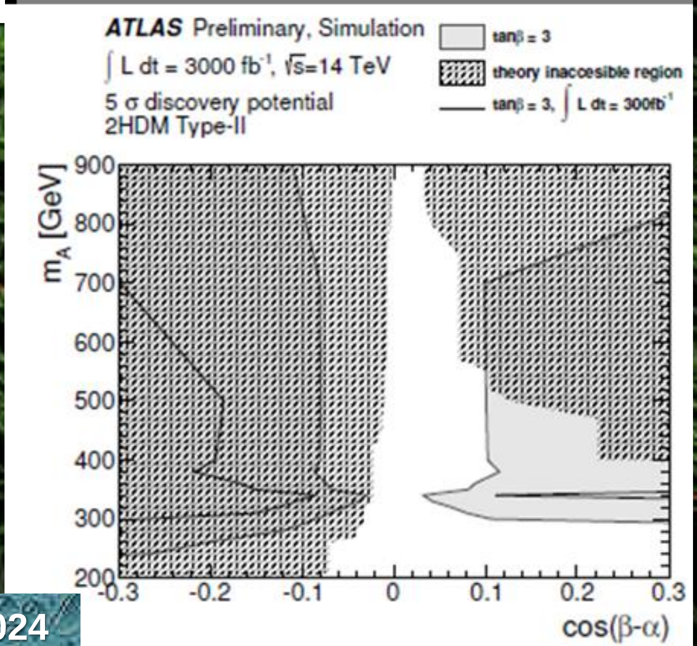










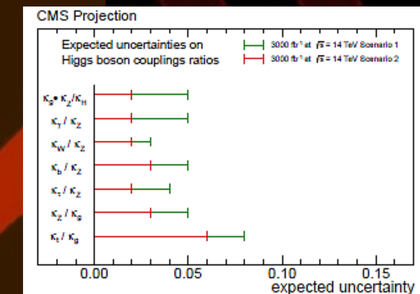


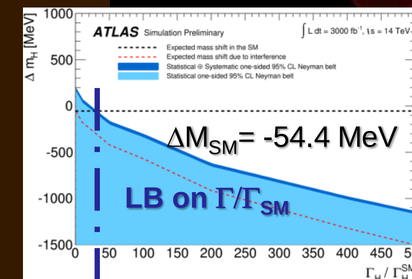
CMS-FTR-13-024

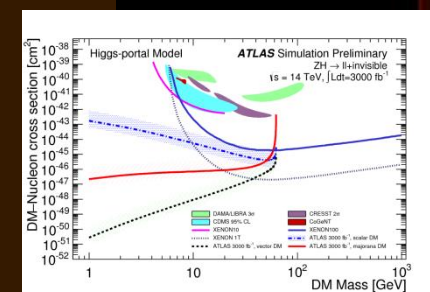
ATL-PHYS-PUB-2013-016

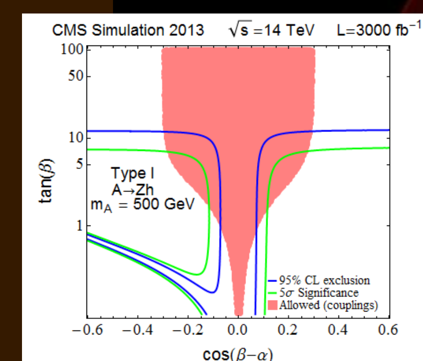
Summary and Conclusion

- Prospects for measurements of properties of the observed Higgs boson:
  - Signal strengths: could be known to ~20% after 300fb-1
    better than 15% after 3000fb-1
  - Couplings and coupling ratios: couplings roughly the same as for signal strengths, coupling ratios known to ~20% after 300fb-1
    better than 10% after 3000fb-1
  - Natural Width: Γ_H< 920 (200) MeV for 300(3000)fb-1 from H→γγ, indep. technique from H→4ℓ, less precise but theoretically more conservative
  - Invisible branching fraction: similar for indirect and direct techniques, constrained to ~30% after 300fb-1
    ~15% after 3000fb-1
  - Field strength tensor structure: fraction of CP-odd contribution constrained to ~20% after 300fb-1, <10% after 3000fb-1
  - Observation of rare decays: H→μμ possible in Run3, the rest Run 4-5
  - HH pair production and self-coupling: detection from tth-hhh interference, studies in progress, $bb\tau^+\tau^-$, bbγγ most promising, also bbZZ with one Z→ℓℓ with ℓ={e, μ} and the other Z→νν worth further exploring
- Prospects for searches for additional (BSM) Higgs bosons:
  - Indirect from couplings measurements and direct: In both cases could probe large portions of 2HDM phase space starting even in Run 3









- If challenges from pileup and trigger rates can be met, the upgraded LHC will provide the opportunity for precise measurements, and hopefully some surprises as well

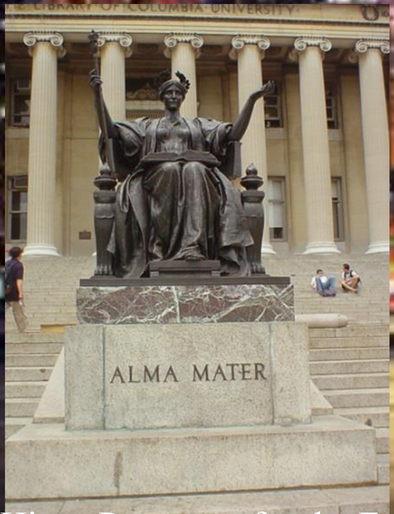
Acknowledgements

- Thanks to :

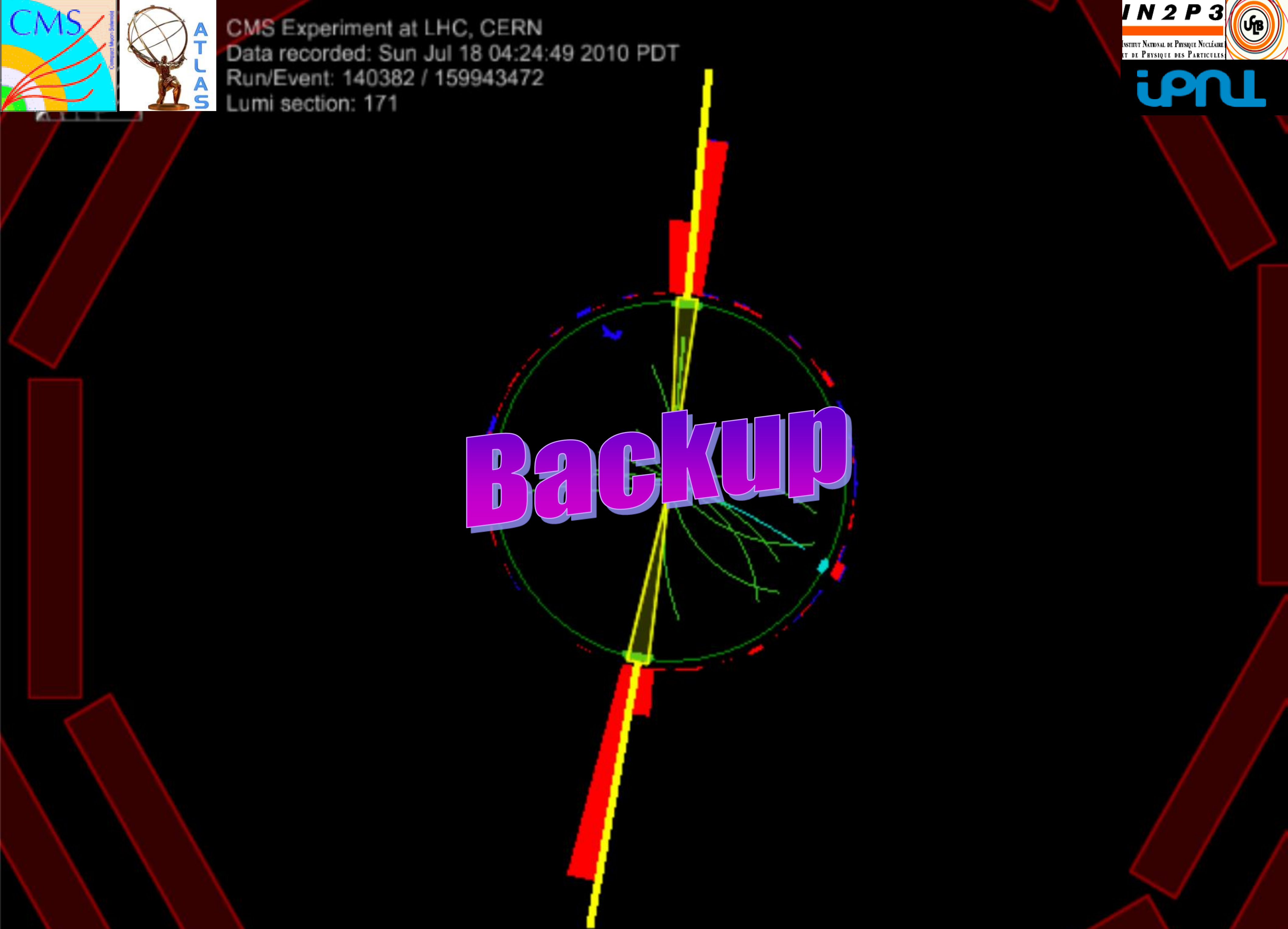
F. Bordry, M. Kado, P. Savard, O. Arnaez, F. Monticelli, J. Baglio, A. Nisati, J. Olsen, M. Pieri, P. Giacomelli, H. Kroha, H. Okawa, M. Zanetti, P. Vankov

And of course the workshop organisers and sponsors and….to Columbia:

Thank you for a great start !



Backup


CMS Experiment at LHC, CERN
Data recorded: Sun Jul 18 04:24:49 2010 PDT
Run/Event: 140382 / 159943472
Lumi section: 171

Signal Strength Precision Details

ATLAS

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \mu\mu$ (comb.)	0.39	0.38	0.15	0.12
(incl.)	0.47	0.45	0.19	0.15
(ttH-like)	0.73	0.72	0.26	0.23
$H \to \tau\tau$ (VBF-like)	0.22	0.16	0.19	0.12
$H \to ZZ$ (comb.)	0.12	0.06	0.10	0.04
(VH-like)	0.32	0.31	0.13	0.12
(ttH-like)	0.46	0.44	0.20	0.16
(VBF-like)	0.34	0.31	0.21	0.16
(ggF-like)	0.13	0.06	0.12	0.04
$H \to WW$ (comb.)	0.13	0.08	0.09	0.05
(VBF-like)	0.21	0.20	0.12	0.09
(+1j)	0.36	0.17	0.33	0.10
(+0j)	0.20	0.08	0.19	0.05
$H \to Z\gamma$ (incl.)	1.47	1.45	0.57	0.54
$H \to \gamma\gamma$ (comb.)	0.14	0.09	0.10	0.04
(VH-like)	0.77	0.77	0.26	0.25
(ttH-like)	0.55	0.54	0.21	0.17
(VBF-like)	0.47	0.43	0.21	0.15
(+1j)	0.37	0.14	0.37	0.05
(+0j)	0.22	0.12	0.20	0.05

CMS: [Scenario2, Scenario1]

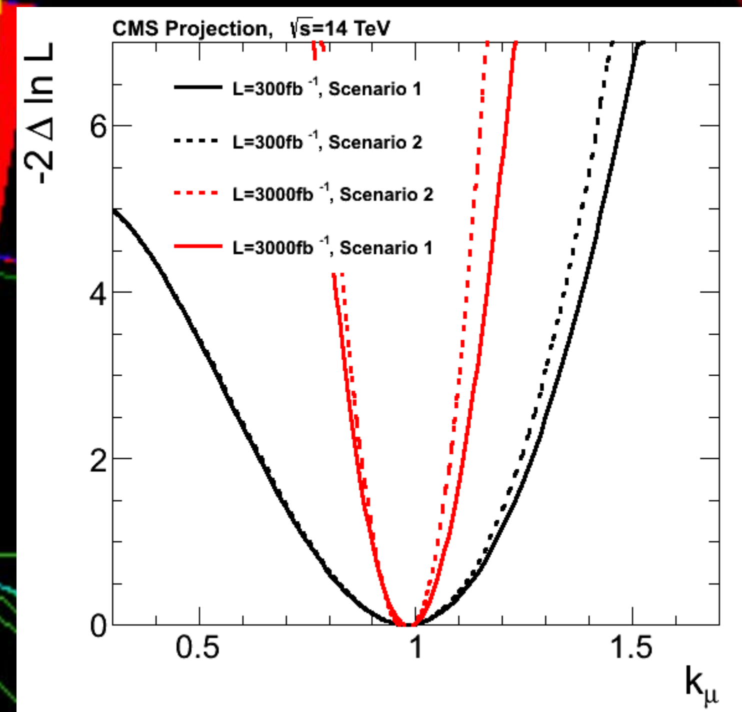
L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]

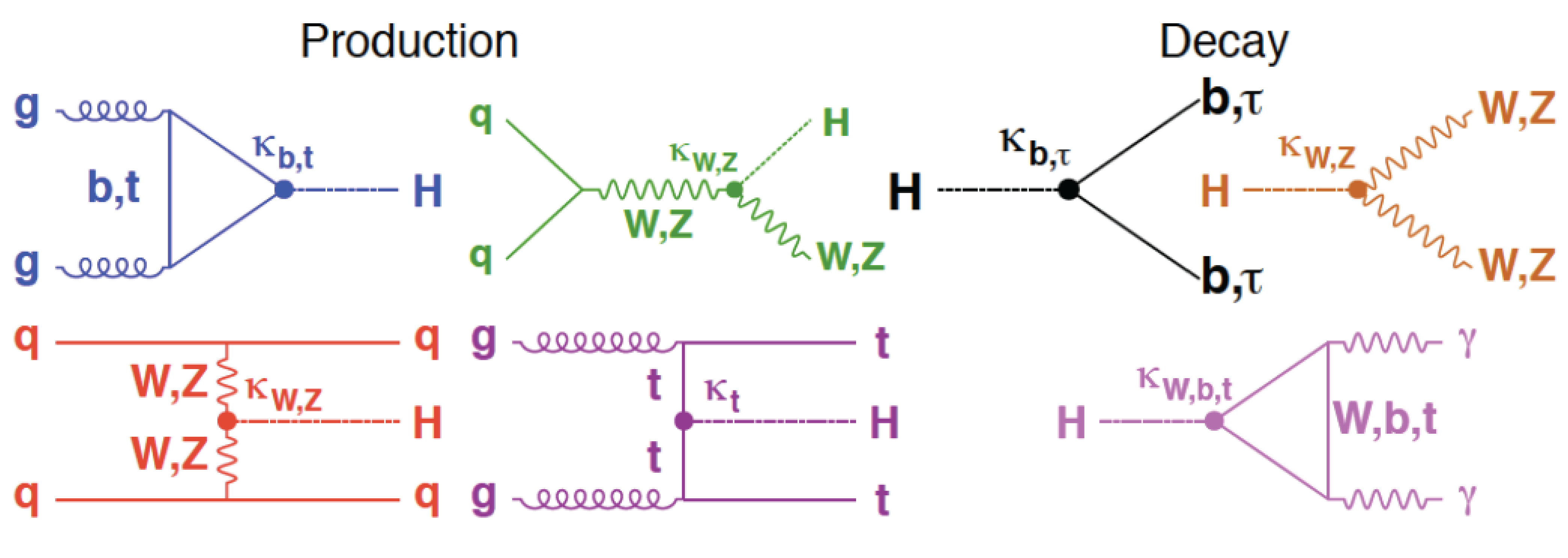
LHC XS WG Coupling Fit Details

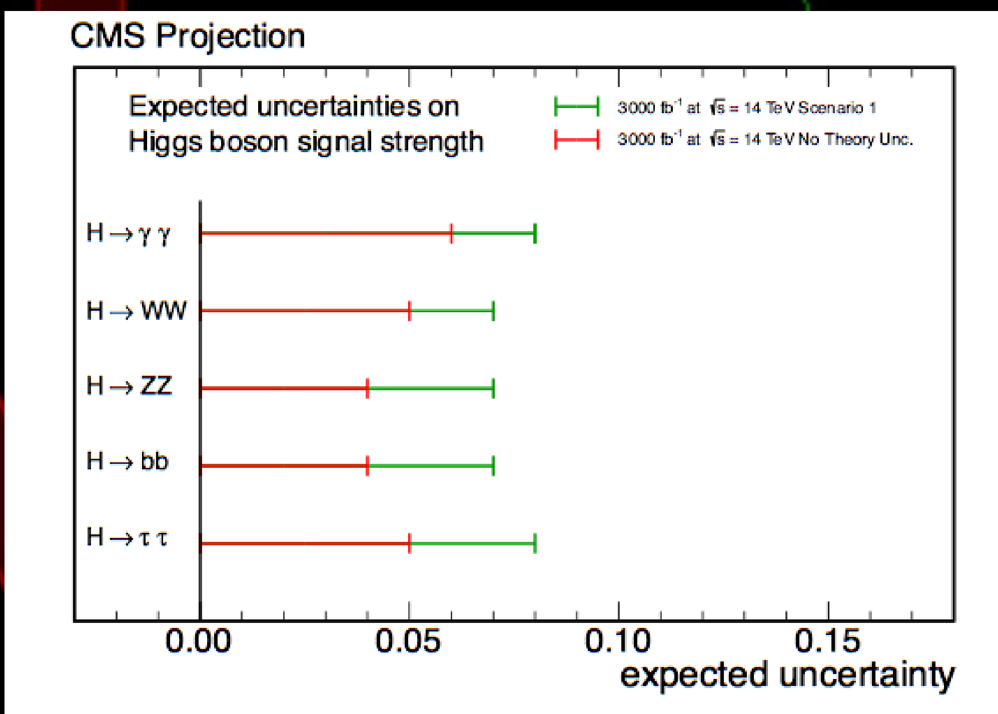
Global fits targeting the *k* factors

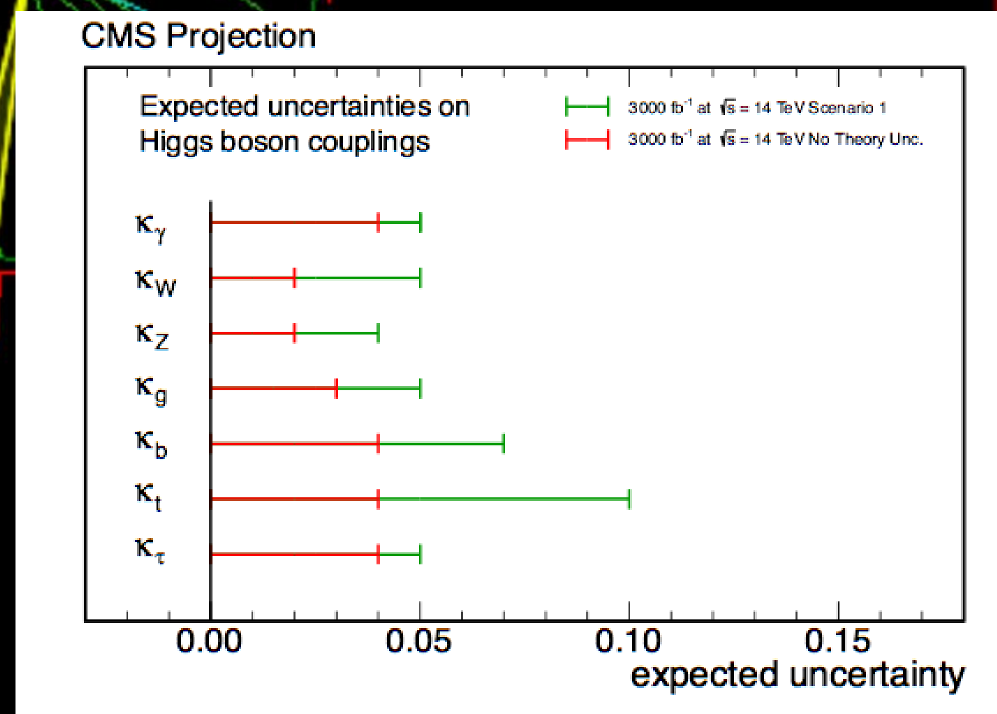
- Assign a modifier to each coupling constant
  - Do not resolve loops, effective coupling instead (k_g, k_g and k_{Zg})
- Results reported in terms of 68% uncertainties (-2DLnL=1) on k

$$\sigma \cdot BR(ii \to H \to ff) = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

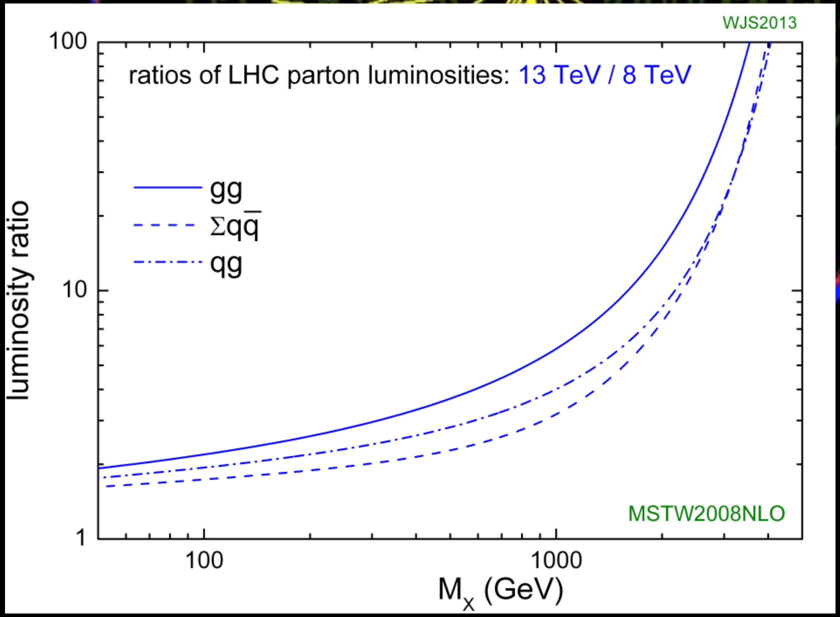



Production
Decay
g
g
b,t
$\kappa_{b,t}$
H
q
q
$\kappa_{W,Z}$
W,Z
H
W,Z
H
$\kappa_{b,\tau}$
b,τ
b,τ
$\kappa_{W,Z}$
H
W,Z
W,Z
q
q
W,Z
W,Z
$\kappa_{W,Z}$
H
q
q
g
g
t
t
κ_t
t
H
t
H
$\kappa_{W,b,t}$
W,b,t
γ
γ


CMS Projection
Expected uncertainties on
Higgs boson signal strength
3000 fb^{-1} at $\sqrt{s}$ = 14 TeV Scenario 1
3000 fb^{-1} at $\sqrt{s}$ = 14 TeV No Theory Unc.
H → γ γ
H → WW
H → ZZ
H → bb
H → τ τ
0.00
0.05
0.10
0.15
expected uncertainty


CMS Projection
Expected uncertainties on
Higgs boson couplings
3000 fb^{-1} at $\sqrt{s}$ = 14 TeV Scenario 1
3000 fb^{-1} at $\sqrt{s}$ = 14 TeV No Theory Unc.
κ_γ
κ_W
κ_Z
κ_g
κ_b
κ_t
κ_τ
0.00
0.05
0.10
0.15
expected uncertainty

- The increase in center-of-mass energy from 8 to 13 or 14 TeV is usually accompanied by a sizeable increase in production cross sections (in general X2 for SM Higgs)
- However the LHC experiments will be dealing with greatly increased pileup (number of interactions per beam crossing will go from ~15 to 40)
- This will affect the efficiency to identify ‘physics objects’ (electrons, photons, muons, jets…) . The experiments are currently reevaluating and reworking the relevant algorithms.
- In particular, for analyses searching for relatively low-mass resonances, triggering will be a major challenge.



CMS Experiment at
Data recorded: Sun
Run/Event: 194108
Lumi section: 575