HL-LHC Higgs Potential
Plus 2 words on ILC

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TLEP workshop
UCL
29th October 2013

Based on a talk given at the ECFA Aix les Bains workshop on HL-LHC, 1st October 2013
On behalf of the ATLAS & CMS collaborations

- The HL-LHC landscape
- SM Higgs boson couplings
- ILC

Future Colliders

- High-luminosity LHC
- ILC
- TLEP
- HE-LHC
- VLHC

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

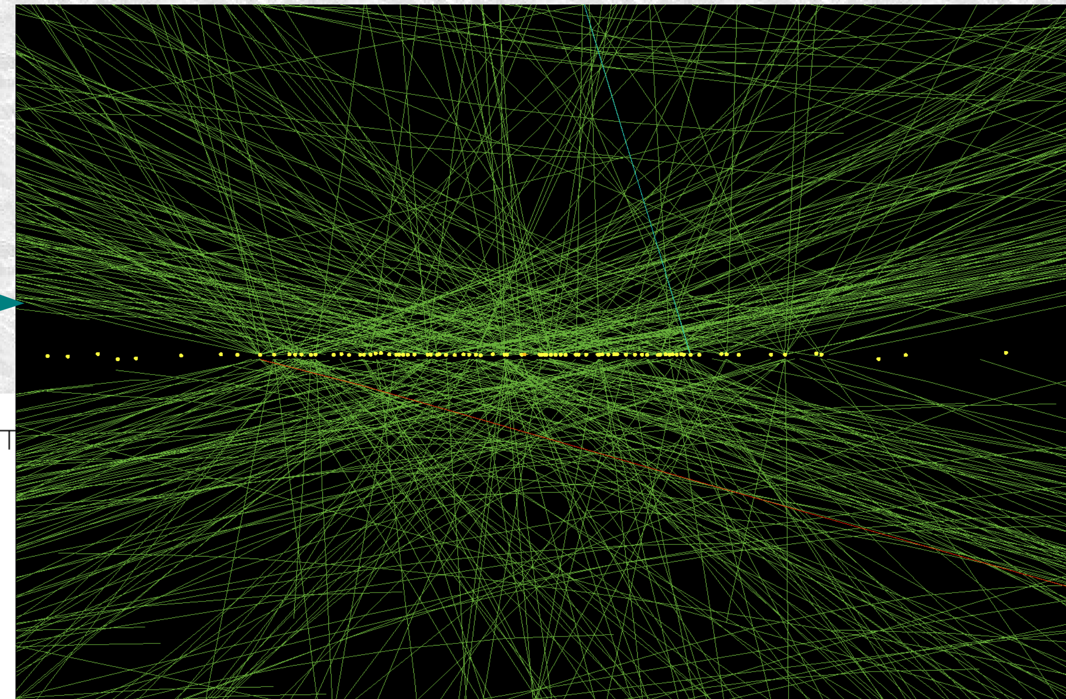
- Electron colliders offer clean environment but reduced rate
  - Complimentary to LHC programme?

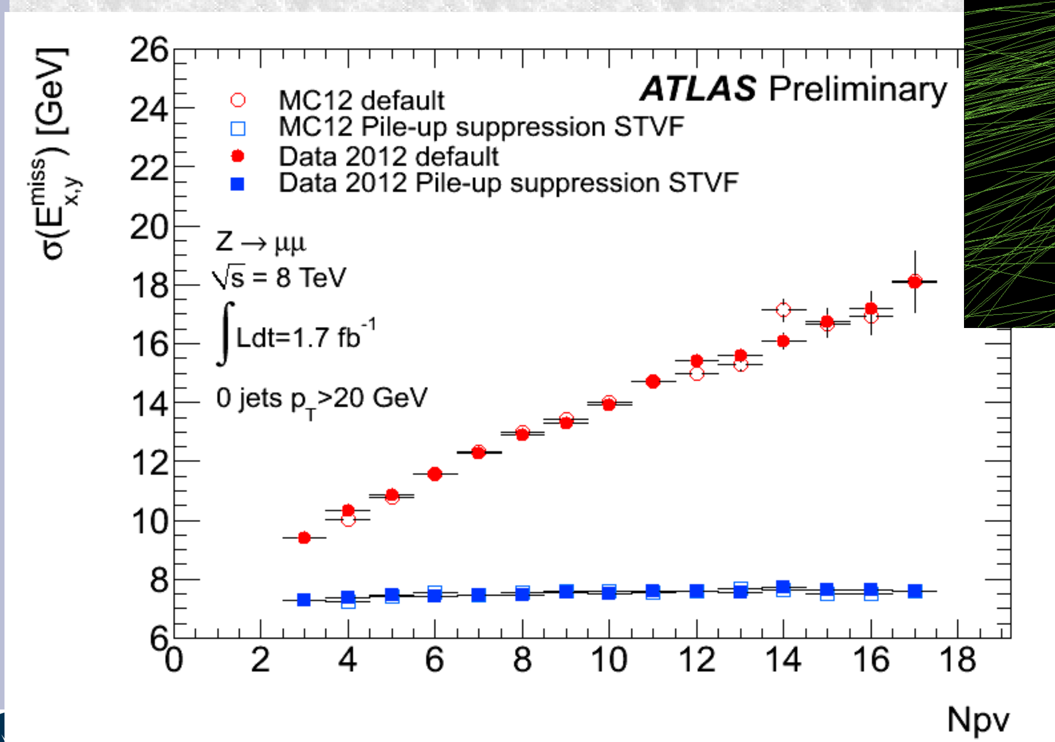
HL-LHC Benchmark Scenario

- Approved running to deliver 300 fb^{-1} by ~2021
  - With 20x Higgs boson production so far
- Post LS3 operation at $5x10^{34}cm^{-2}s^{-1}$ (lumi leveling)
  - 25 ns bunch spacing (deign, c/f 50ns so far)
  - 140 events per bunch crossing (c/f 20 in 2012)
  - 3000 fb^{-1} over 10 years
- Detector upgrades needed
  - Detectors deigned for 10 years only
  - Need to cope with radiation damage and pileup
  - Aim to maintain or enhance physics performance
- Trigger is a key component:
  - Thresholds not too dissimilar to today
    - Mandated by need to study the Higgs boson

Event complexity

- ATLAS & CMS were designed for mean 23 events per bunch-crossing
  - And continue to do an excellent job with 35
  - Or even 78

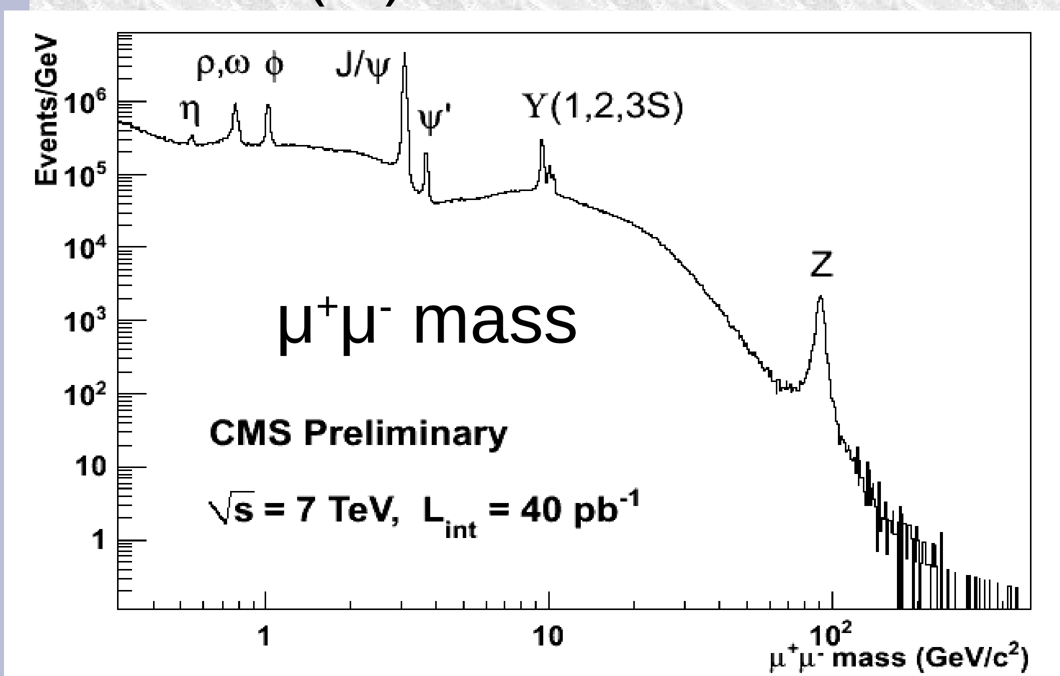


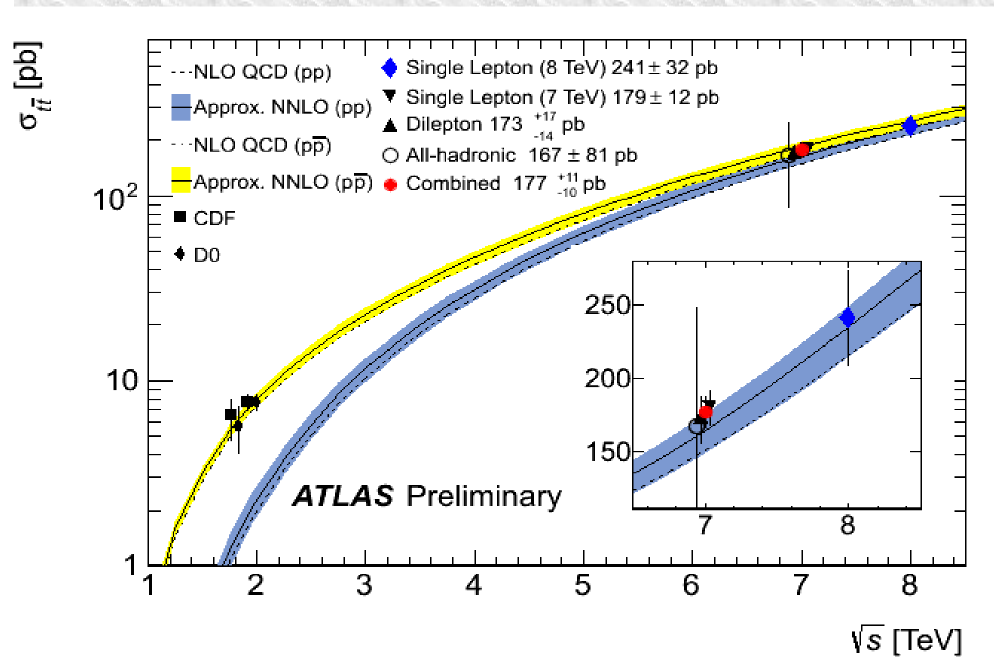


- But they will not handle 140 events of pileup

What have we learned?

- The experiments are working remarkably
  - Operations, detector performance and simulation
- The SM is in great shape
  - N(N)LO calculations match data very well





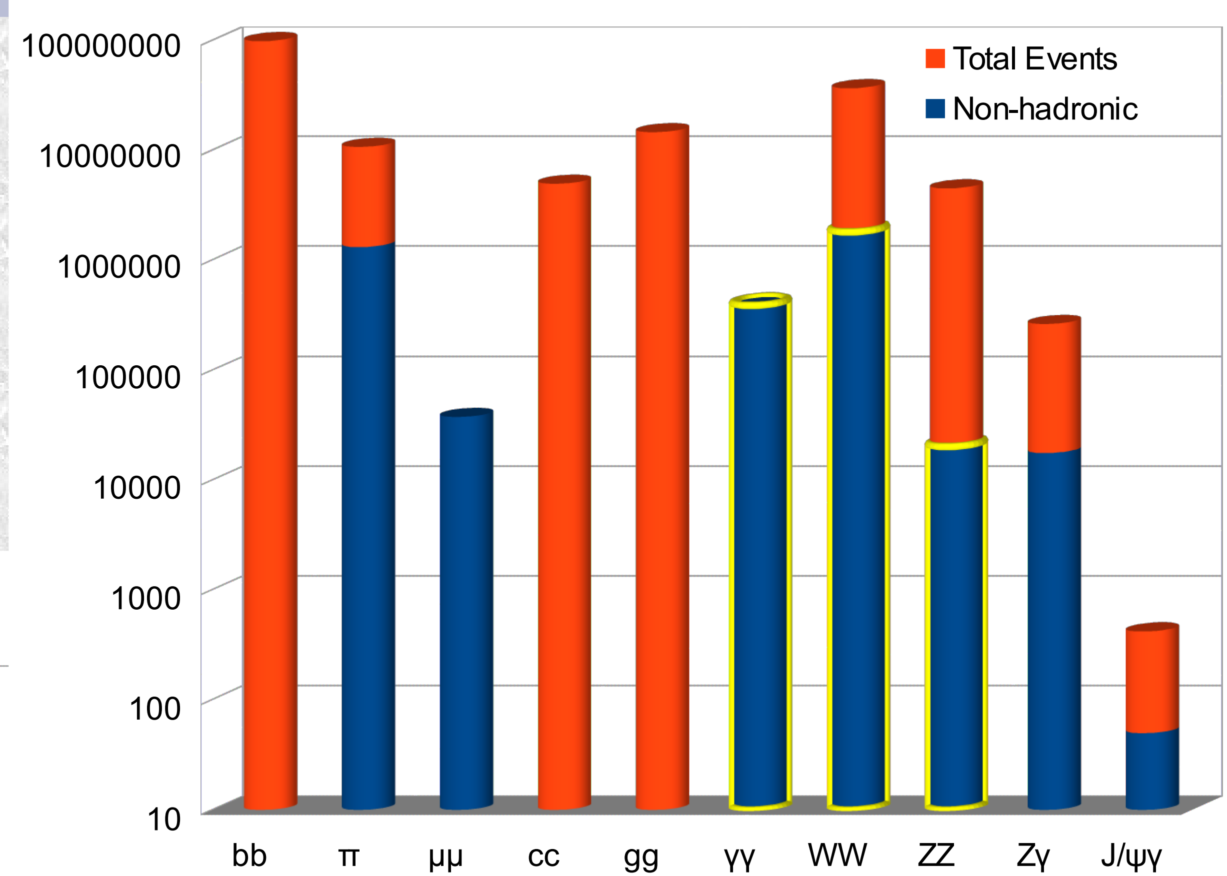
φ, ψ, Ψ, W, Z, top, all well-behaved

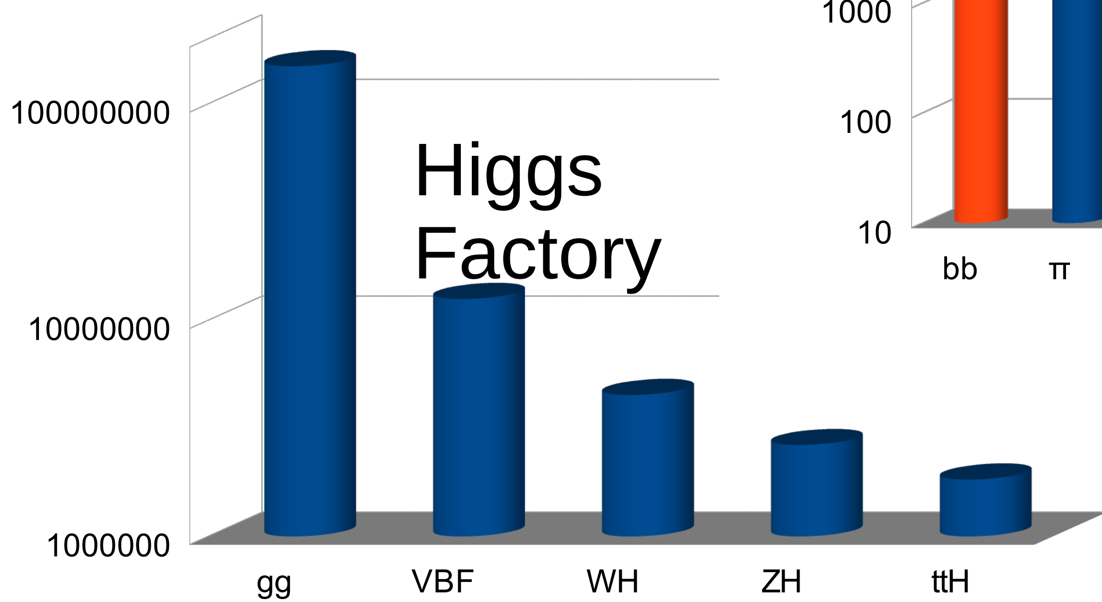
HL-LHC Physics goals

- HL-LHC will be alone exploring multi-TeV
  - There will be a wide physics programme
  - I report on some of the Higgs boson studies
- Higgs Sector
  - Couplings
  - Rare decays
  - CP studies
  - BSM Higgs boson searches
  - Higgs boson pair production

Higgs bosons: 14 TeV, 3ab^{-1}

- 100M Higgs
  - c/f 2M TLEP
- 20K $H \rightarrow ZZ \rightarrow llll$
- 400K $\gamma\gamma$
- 50 $H \rightarrow J/\psi\gamma$

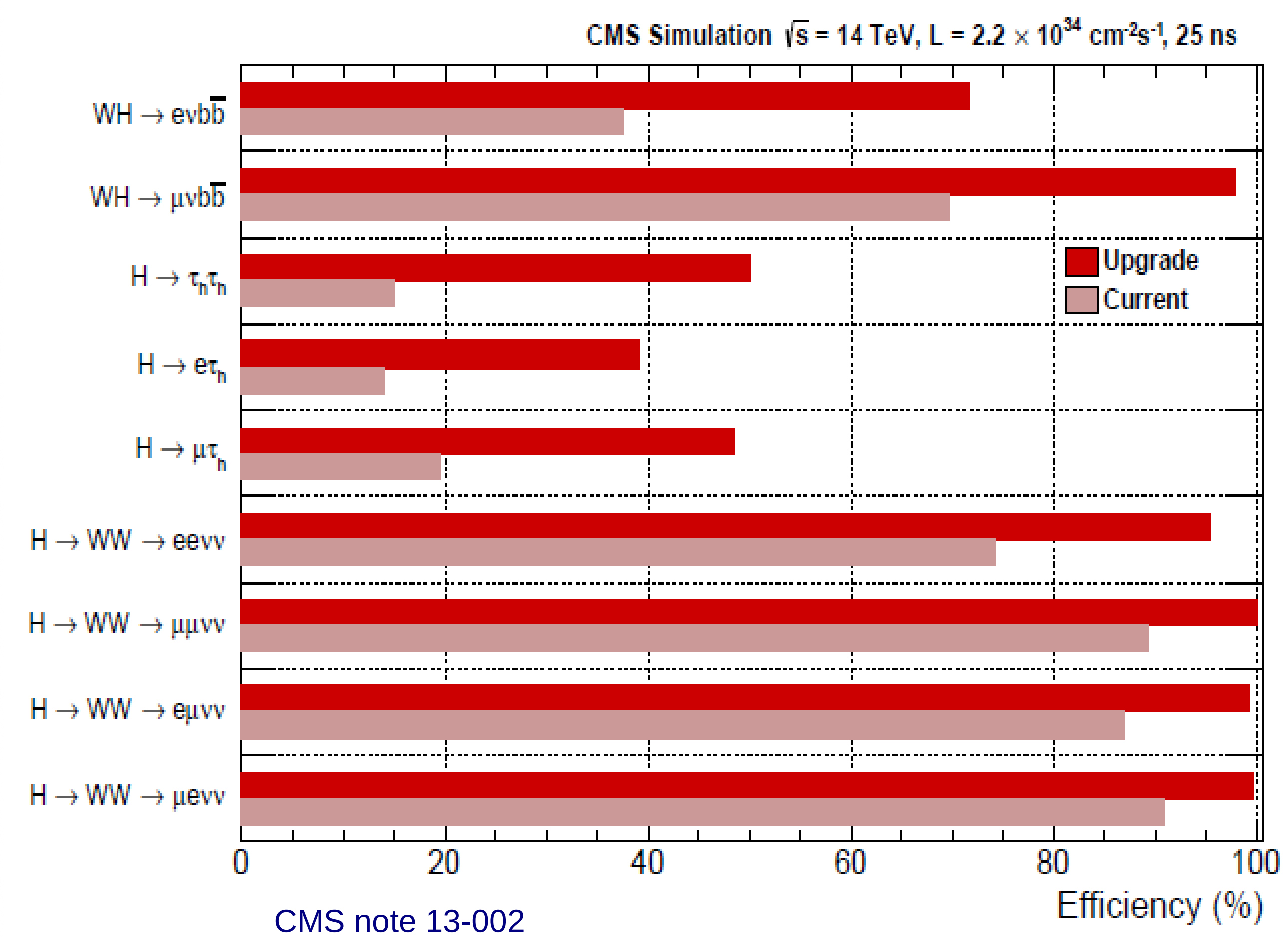




- Over 1M in all major production modes

Trigger upgrades

- No physics can be done if the data are not recorded
- Plot contrasts current and Phase 1 CMS trigger eff.
- Physics with $5x10^{34}cm^{-2}s^{-1}$ will need an effective trigger



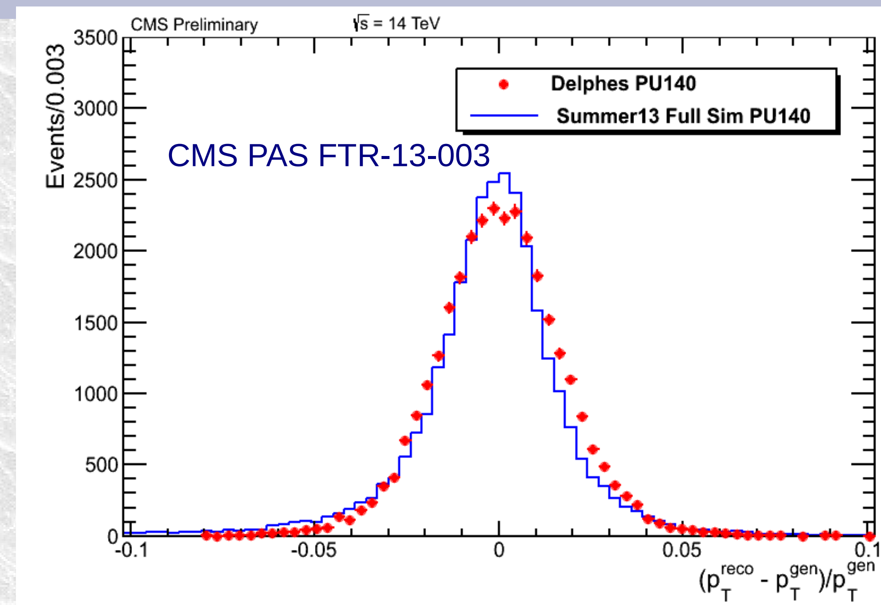
CMS note 13-002
ArXiv:1307.7135v1

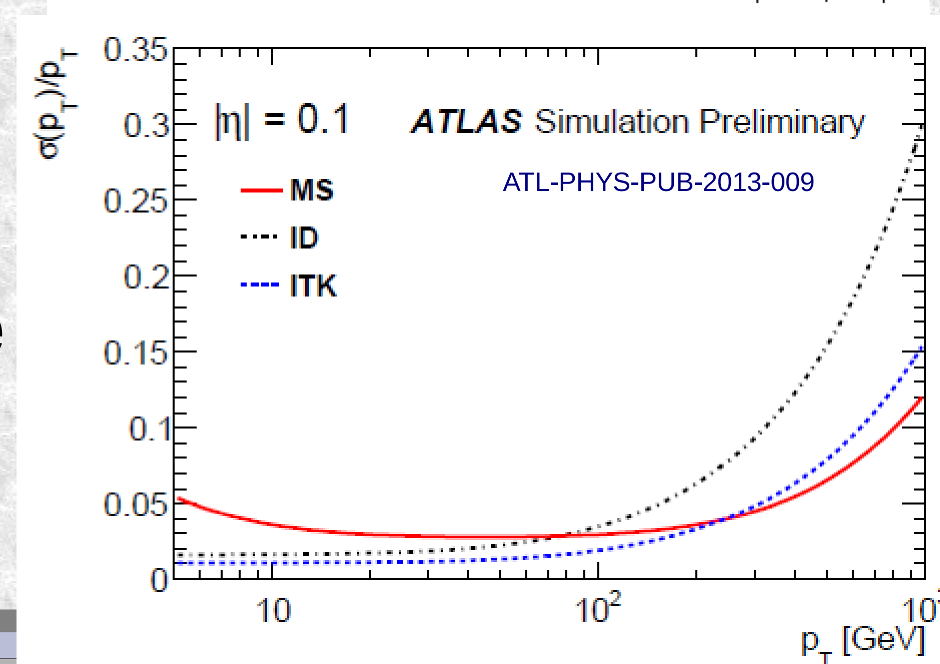
Tools used for study here

- ATLAS derived detector response functions from full Geant4 simulation under two conditions:
  - <μ>~50 assumed for 300fb^{-1}
    - Includes IBL and LAr trigger upgrades
  - <μ>~140 assumed for 3000fb^{-1}
    - Full ITK inside ATLAS
    - Also studies of pileup variation on calorimetry.
  - Largely validate ES extrapolations
    - Photons slightly worse, MET and b-tag improved
- CMS
  - Studies scale current analyses
  - Assume detector upgrades keep current performance
  - Augmented with full-simulation studies

Full G4 studies

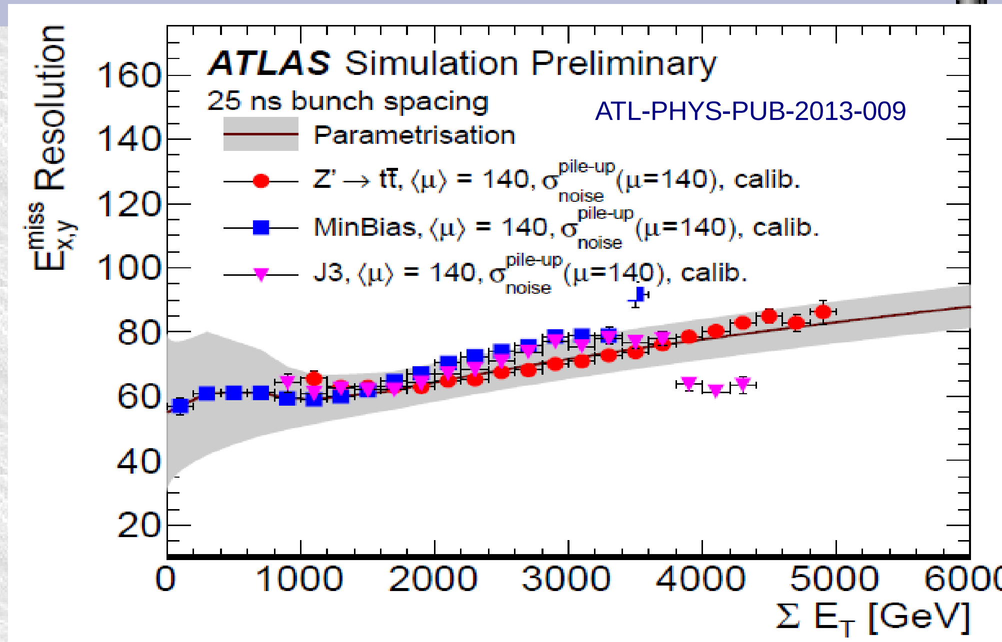
- CMS muon momentum in fullsim compared with Delphes parametrization used here
- ATLAS muon p_T resolution in ITK and current ID compared
  - Important gains at low p_T
- Both detectors use more pessimistic performance for current studies

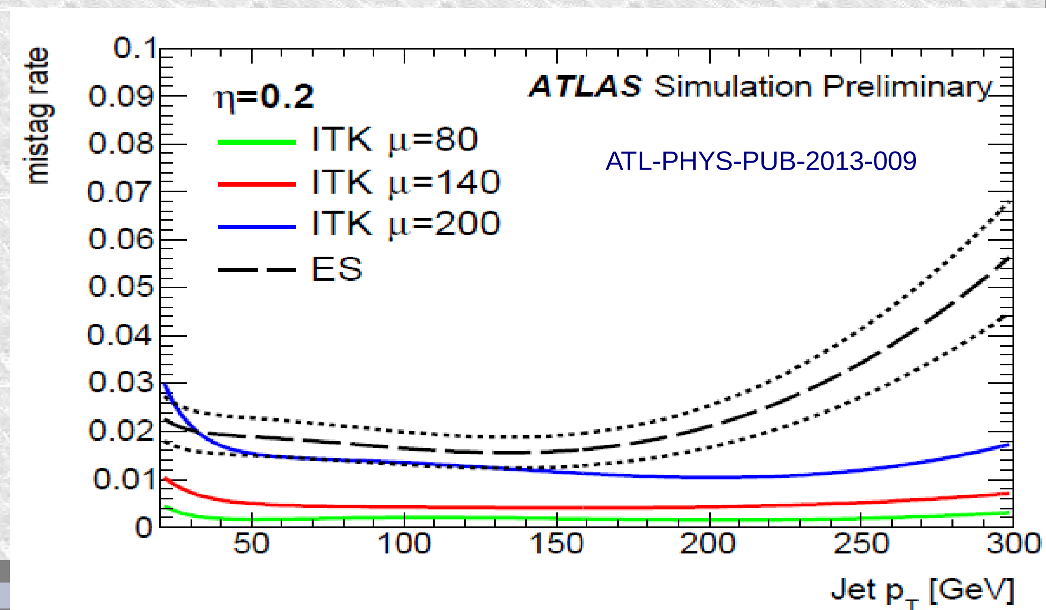




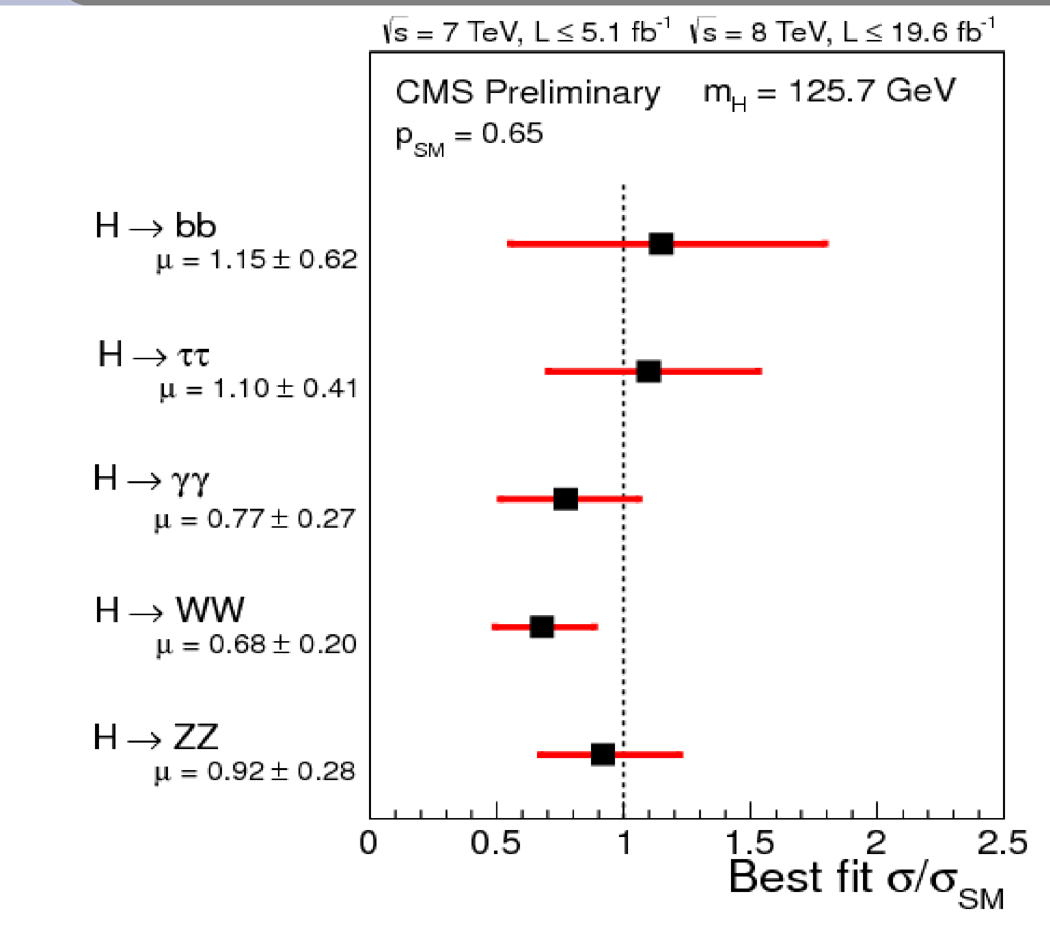
More G4 studies

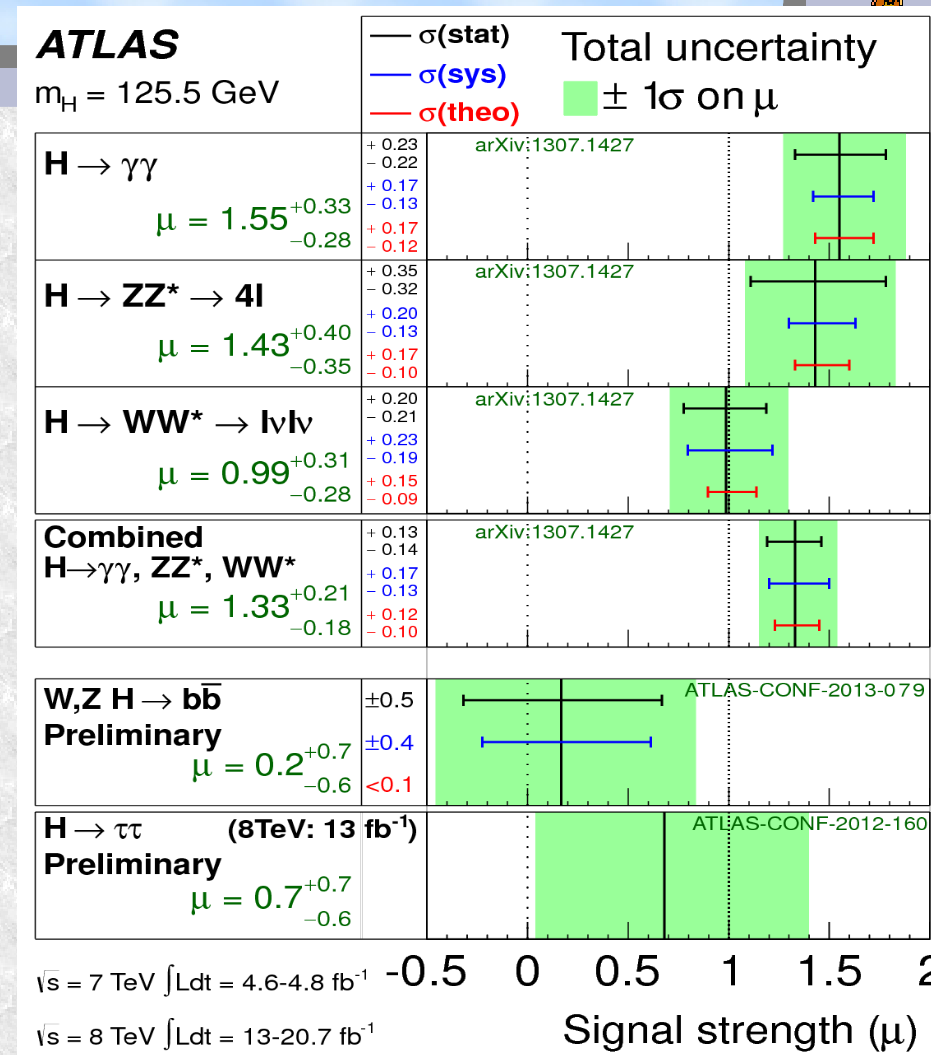
- ATLAS E_T^{miss} resolution with parametrization overlayed
- ATLAS b-tag fake rate for 70% efficiency compared with rate assumed for ES studies
  - ITK brings enhanced tracking
  - Mistag below 0.5% for <μ>=140 p_T=100GeV





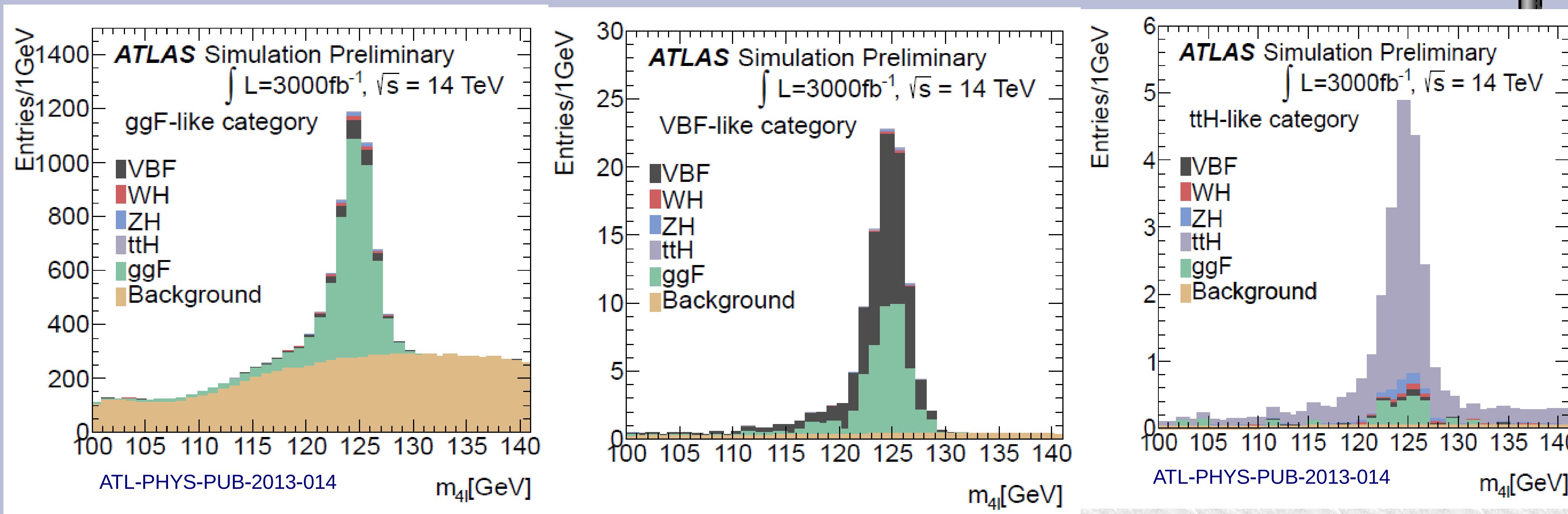
Higgs results so far





- Sensitivity of 'big 5' differs only by about a factor 3
- There is a rich programme

H →ZZ

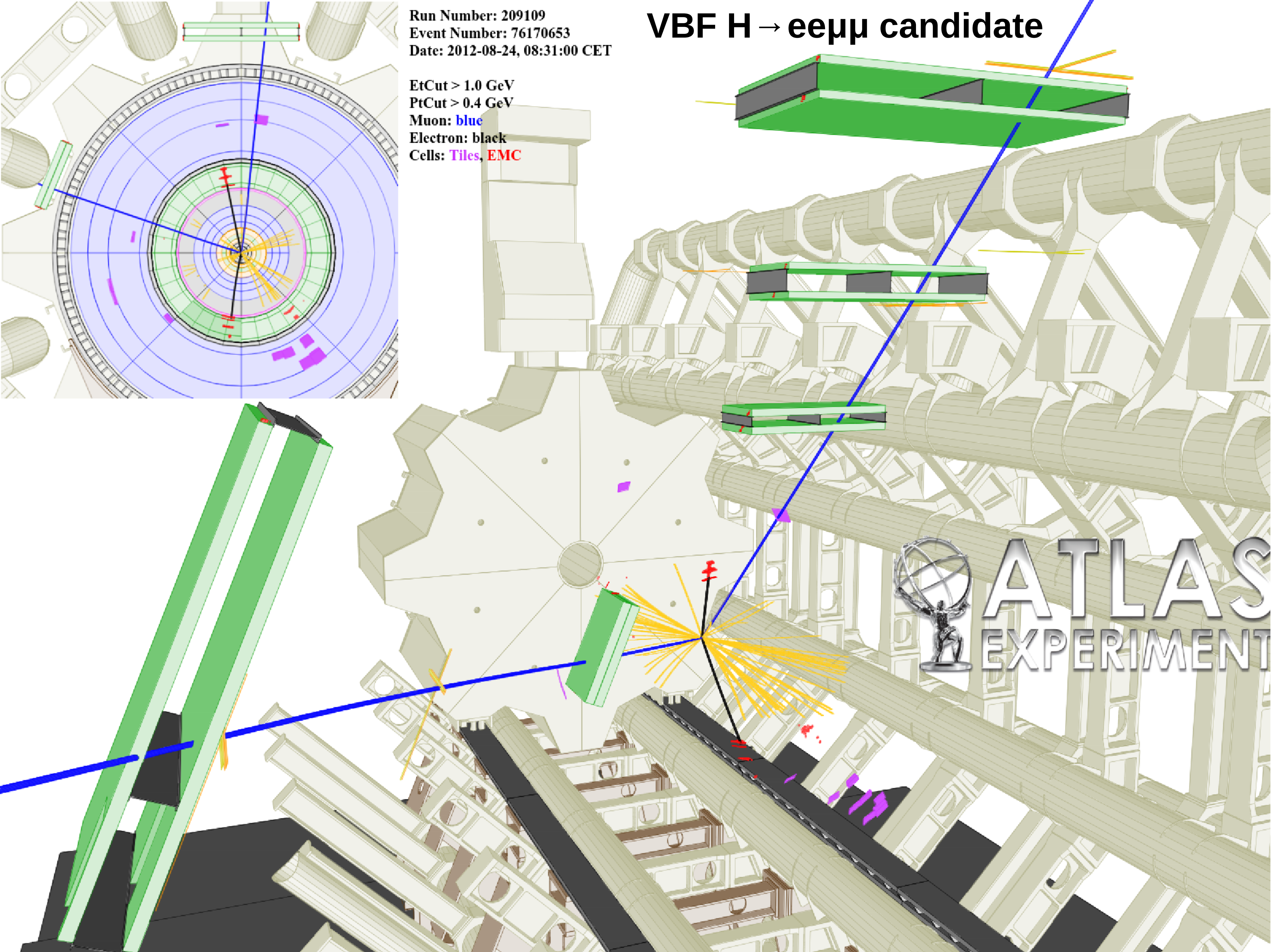


- High purity signal possible
- Separate into all 5 production modes
- WH, ZH use lepton tags

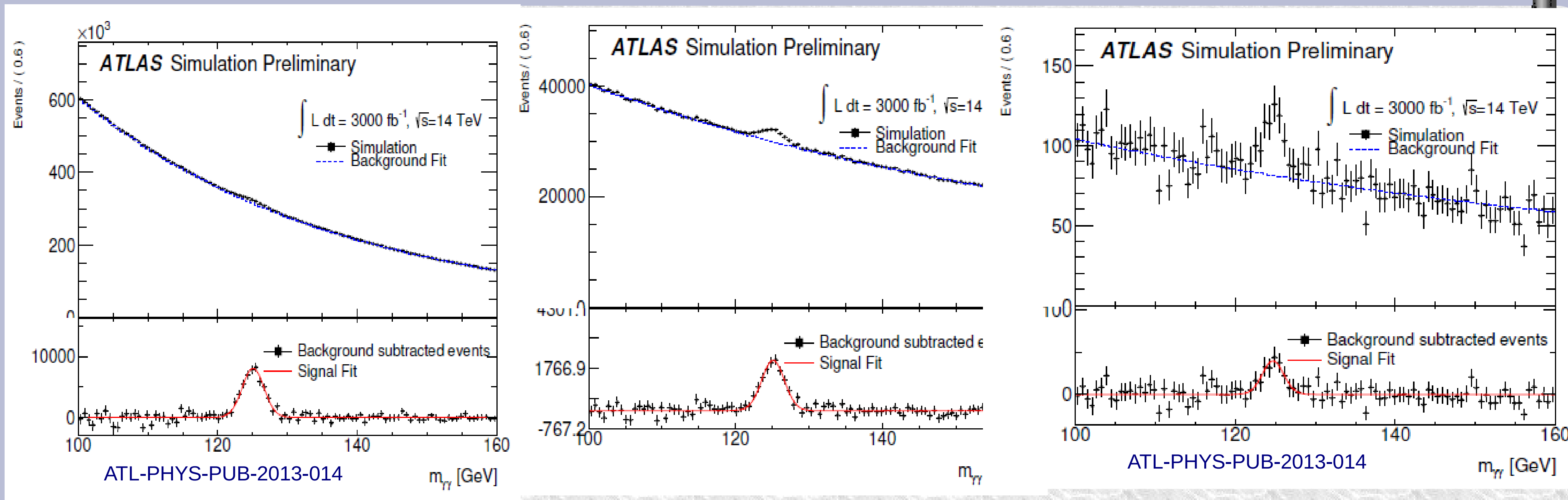
Selected signal event rates

	ttH	ZH	WH	VBF	ggH
3000fb^{-1}	35	5.7	67	97	3800

ttH, H→ZZ
Only possible at HL-LHC


Run Number: 209109
Event Number: 76170653
Date: 2012-08-24, 08:31:00 CET
EtCut > 1.0 GeV
PtCut > 0.4 GeV
Muon: blue
Electron: black
Cells: Tiles, EMC
VBF H→eeμμ candidate
ATLAS
EXPERIMENT

H →γγ



- Yield of 0-jet scales well with σxL
- But VBF signal rate is only 10x current
  - Is tracker optimal?

Selected signal event rates

	0 jet	1 jet	2 jet
3000fb^{-1}	490,000	12000	210

ttH, WH and ZH from ES study

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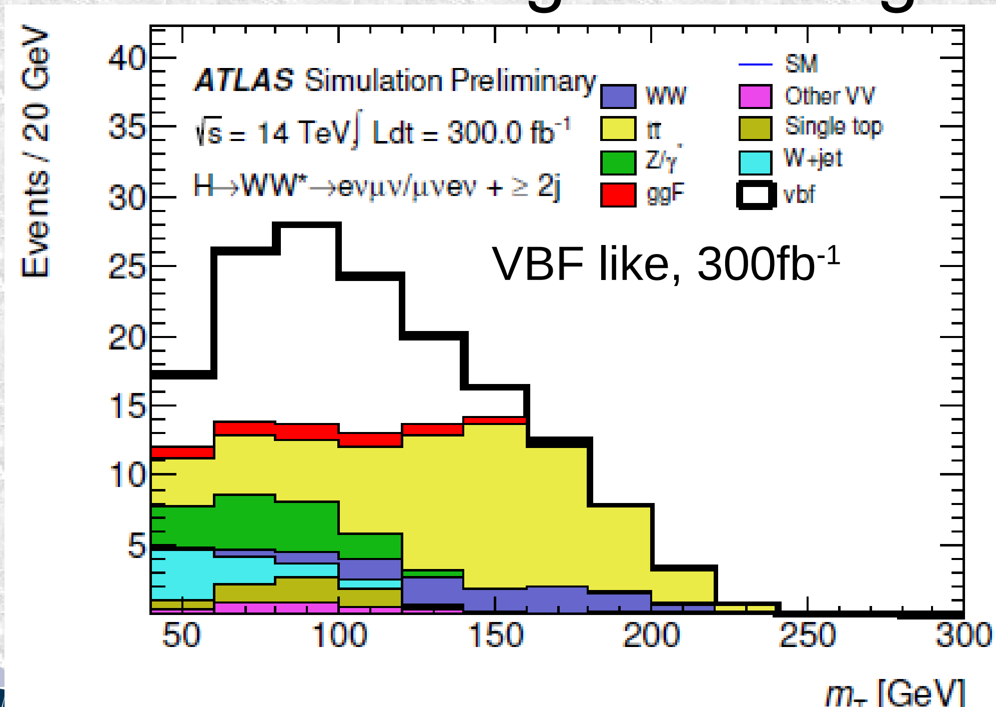
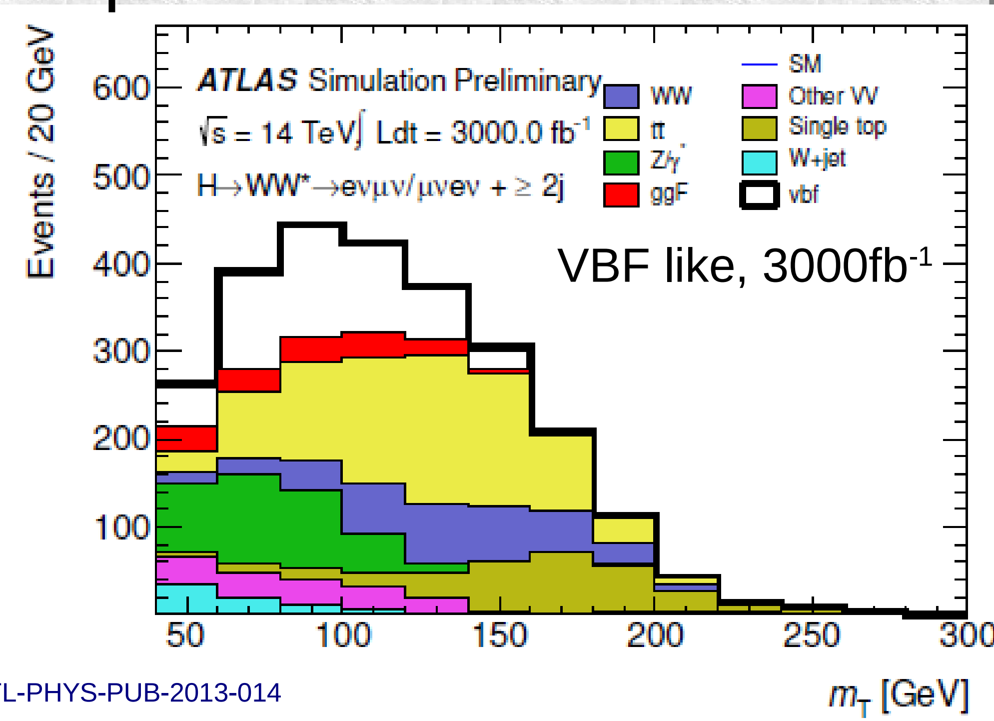
H→WW

- ATLAS has done studies with re-weighting 8TeV
  - Applying the HL-LHC performance smearings
  - Jet p_T 30/35 GeV (300/3000fb)
- Backgrounds from $t\bar{t}$,WW rise with event pileup
  - But s/b is good enough to exploit increased rate





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H→WW

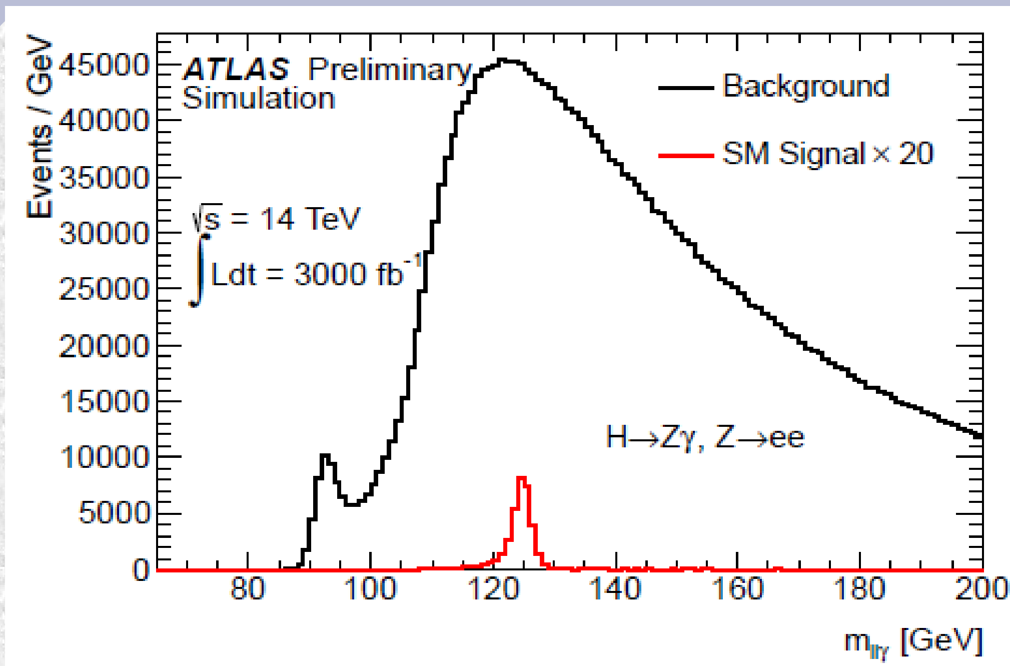
- The event yields in the WW mode are large
- The systematic errors are therefore critical
  - And under study
- The bottom right table shows the estimated error on the background processes in current estimate and the published results

Selected signal event rates

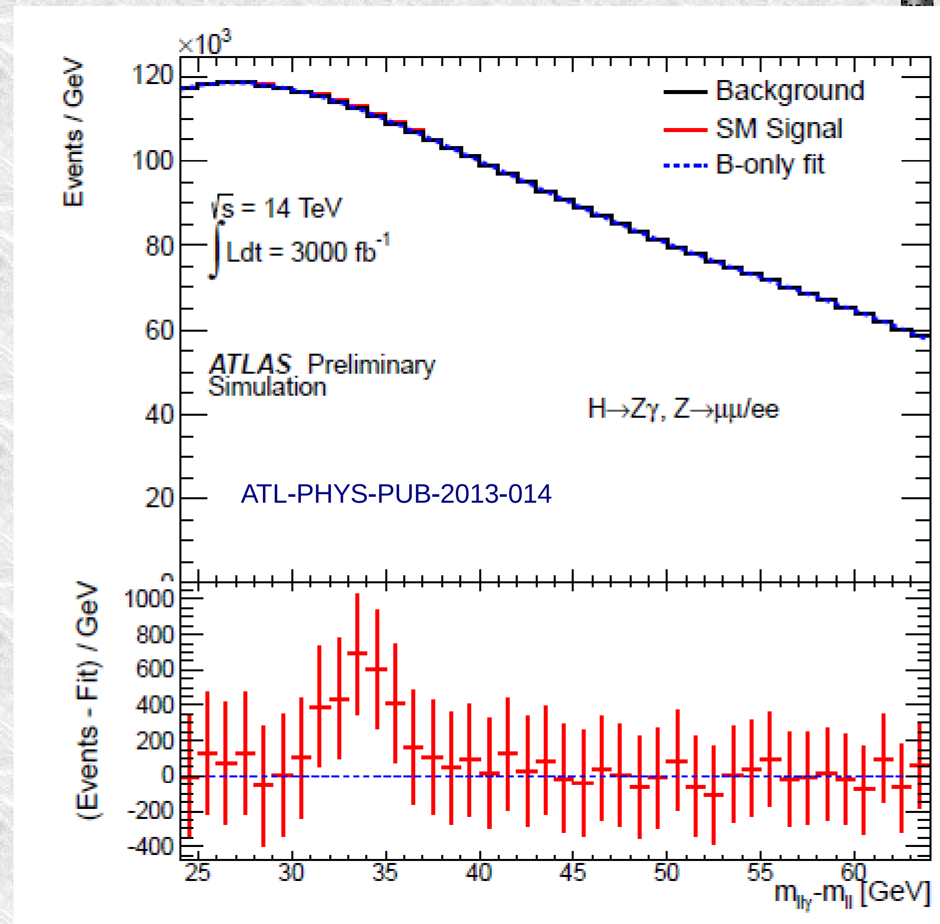
$3000fb^{-1}$	0 jet	1 jet	2 jet
ATLAS	42,000	22000	590

Error, %	14 TeV	8TeV
WW	1.5	5
VV	2	15
top	7	12
Z+jets	10	15
W+jets	20	30

H →Zγ



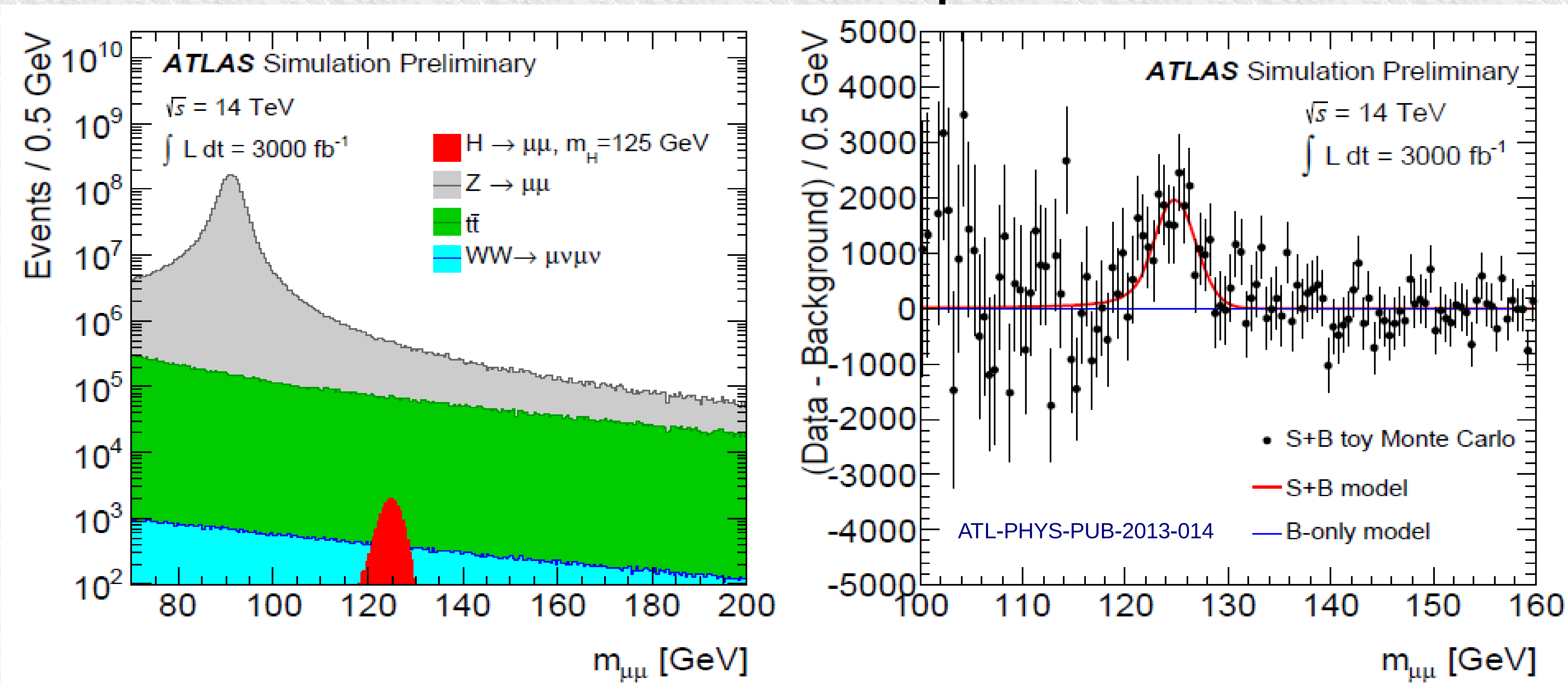
- Tests loop structure
  - Related to H→γγ
- S/b marginal
- But so was H→γγ



	eeγ	μμγ	eeγ VBF	μμγ VBF
$3000fb^{-1}$	1500	1700	21	23

H→μμ

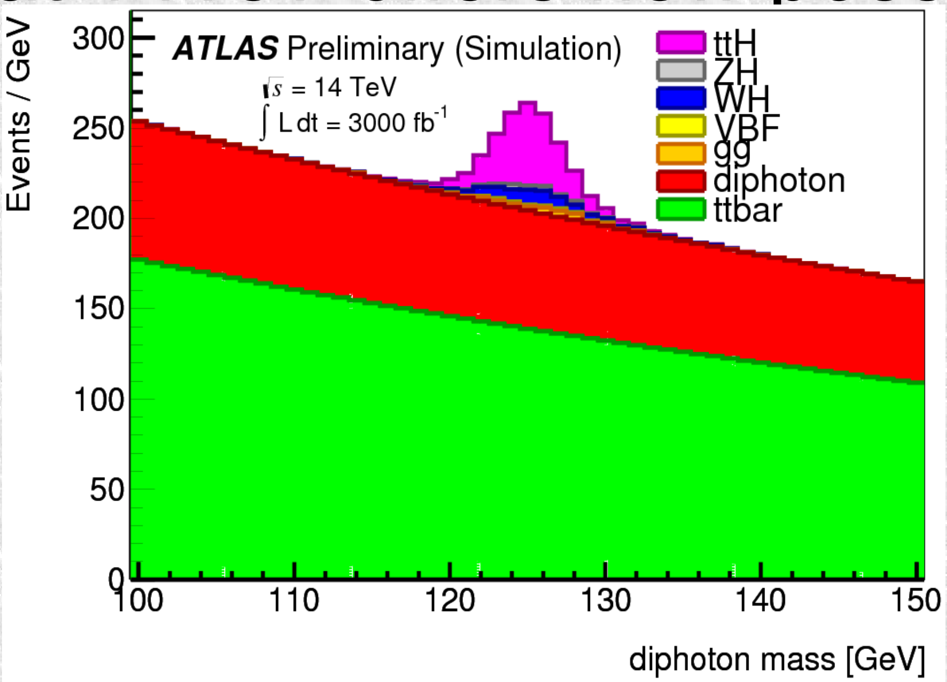
3000fb^{-1} at 14TeV offers new possibilities



- H → μμ
  - Allows direct study of coupling to two different leptons
  - Test lepton flavour-universality carefully

ttH, H→γγ

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



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- ttH,H→γγ
  - Sensitive to top in both production and decay
  - Yields top Yukawa coupling

Higgs strength: μ

		$H\to\gamma\gamma$	$H\to WW$	$H\to ZZ$	$H\to bb$	$H\to\tau\tau$	$H\to Z\gamma$	$H\to\mu\mu$
$300fb^{-1}$	ATLAS	[9,14]	[8,13]	[6,12]	N/a	[16,22]	[145,147]	[38,39]
	CMS	[6,12]	[6,11]	[7,11]	[11,14]	[8,14]	[62,62]	[40,42]
$3000fb^{-1}$	ATLAS	[4,10]	[5,9]	[4,10]	N/a	[12,19]	[54,57]	[12,15]
	CMS	[4,8]	[4,7]	[4,7]	[5,7]	[5,8]	[20,24]	[14,20]

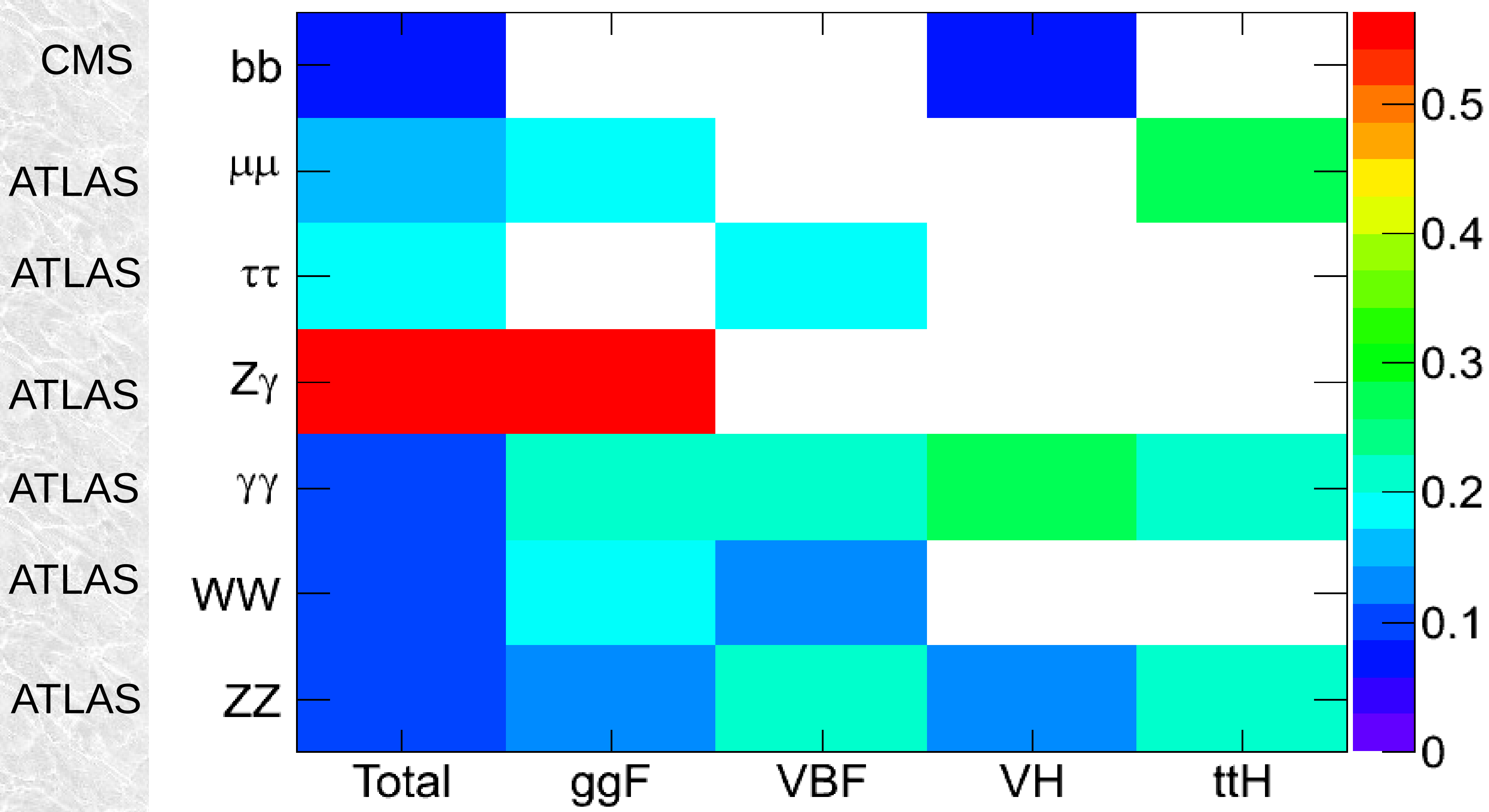
- The ranges [x,y] above are not directly comparable
- ATLAS compares two results
  - Systematic errors as estimated today
    - Experimental control region statistics rise helps a lot
  - With no theory systematic uncertainties
- CMS
  - Systematic errors as today
  - Scale systematic errors: $1/\sqrt{L}$ (exp.) & 1/2 (theo.)

Signal strength: details

- Total μ is only part of story
- Separation of production modes is also vital

$\Delta\mu/\mu$	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

Overview of $3000fb^{-1}$ precision



15 distinct modes expected to be measurable (back in 2009 we expected 7!)

Extraction of couplings

- Extracting Higgs couplings from the σxBR requires assumptions at LHC

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

- As Γ_H is not measurable, assume it is sum of SM channel widths
  - Total width controlled by $H \to b\bar{b}$
  - $c\bar{c}$ is a 5% unmeasured contribution
    - Assumed to scale with bb
    - For ATLAS $b\bar{b}/c\bar{c}$ scale with ττ
  - Assume no new invisible/undetectable modes
- Production/decay to particle a scales as κ_a^2.

Coupling fit results

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
$300 fb^{-1}$	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]
$3000 fb^{-1}$	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]

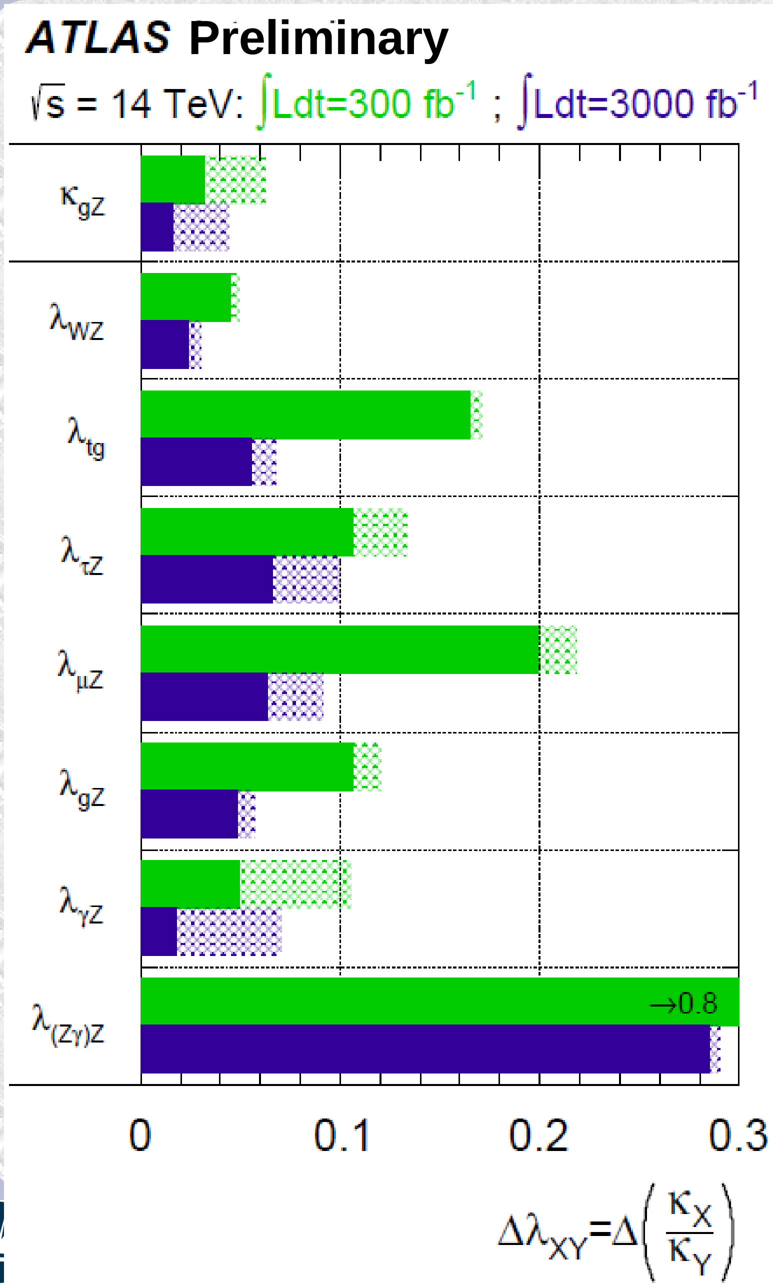
- Fits assumes no new undetectable modes
- The upper ranges are directly comparable
- Sensitivity is a factor 2 apart
  - ATLAS fit lacks bb mode; uses ττ to fix fermions
- Next: look at ratios of couplings for more stability

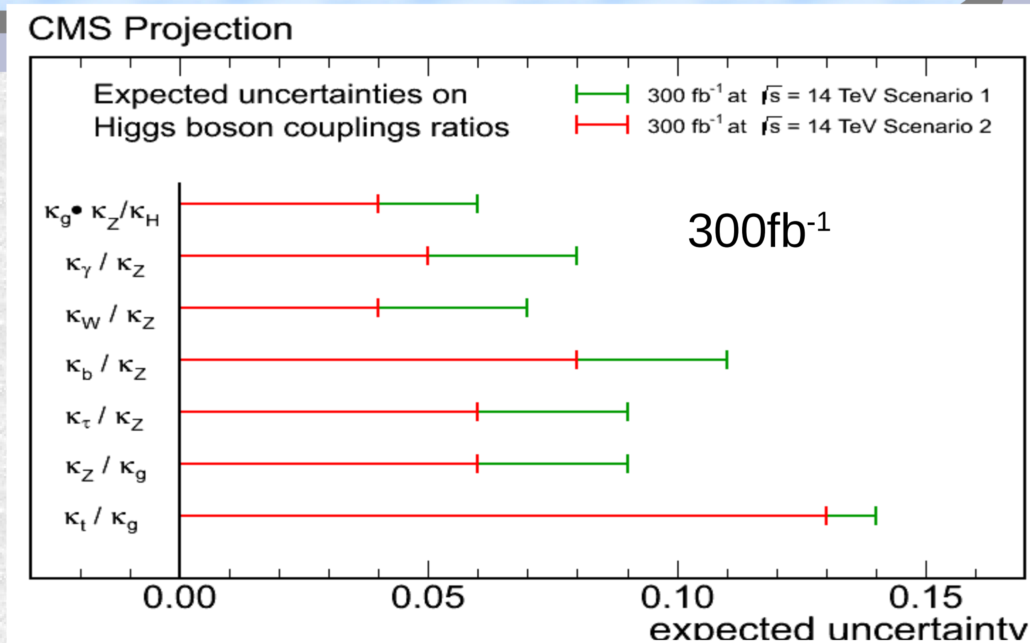
Coupling ratio fits

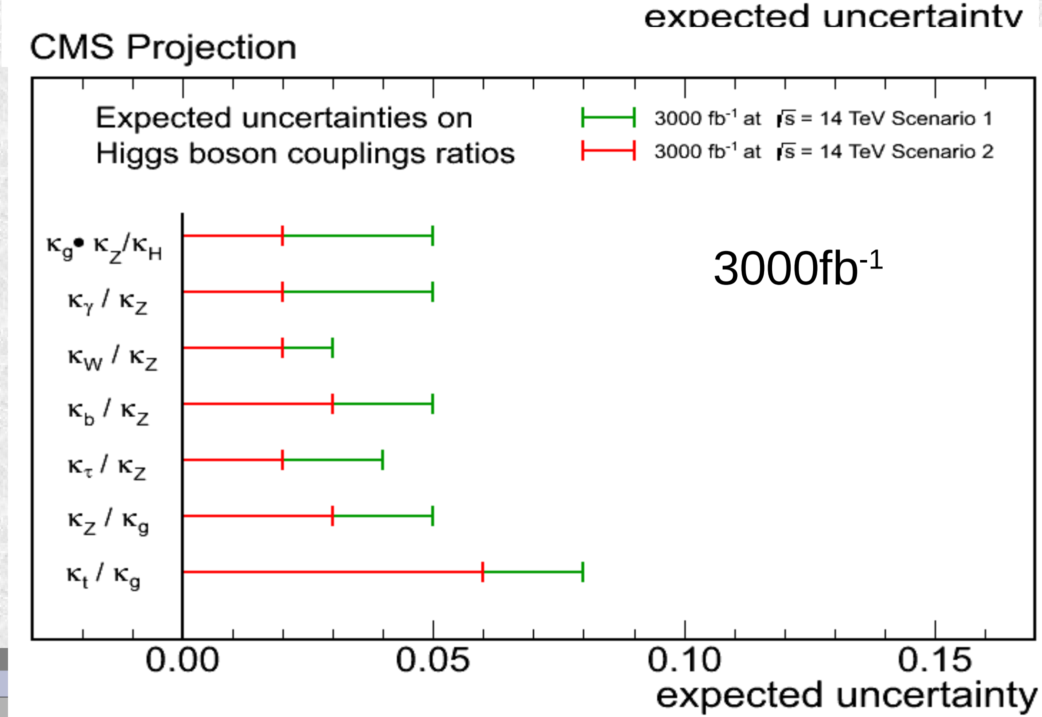
		$\kappa_g\kappa_Z/\kappa_H$	κ_W/κ_Z	κ_γ/κ_Z	κ_g/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_μ/κ_Z	$\kappa_{Z\gamma}\kappa_Z$	κ_t/κ_g
$300fb^{-1}$	ATLAS	[3,6]	[4,5]	[5,11]	[11,12]	N/a	[11,13]	[20,22]	[78,78]	[17,18]
	CMS	[4,6]	[4,7]	[5,8]	[6,9]	[8,11]	[6,9]	[22,23]	[40,42]	[13,14]
$3000fb^{-1}$	ATLAS	[2,5]	[2,3]	[2,7]	[5,6]	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]

- Generally good agreement between the two estimates
- HL-LHC offers roughly a factor 2-3 improvement in coupling ratio determinations.
  - Especially if theory errors can be reduced.

Coupling expectations



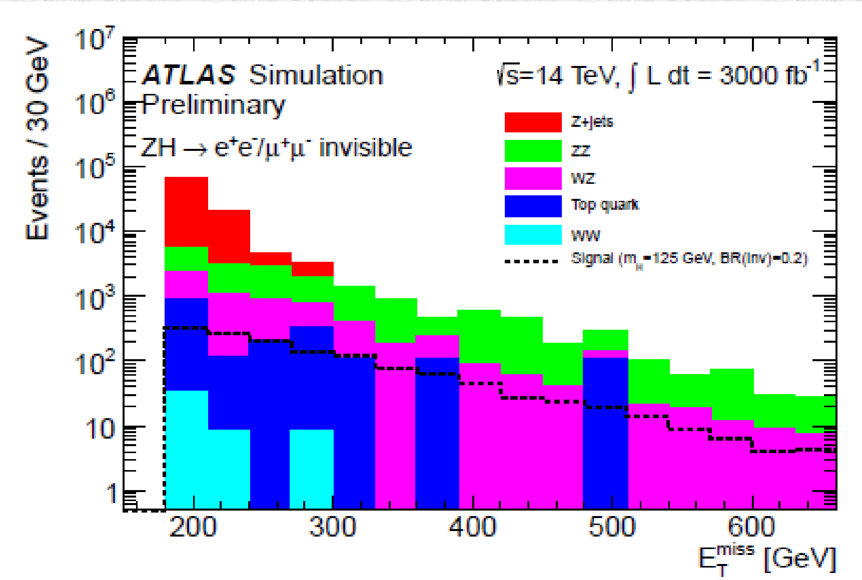


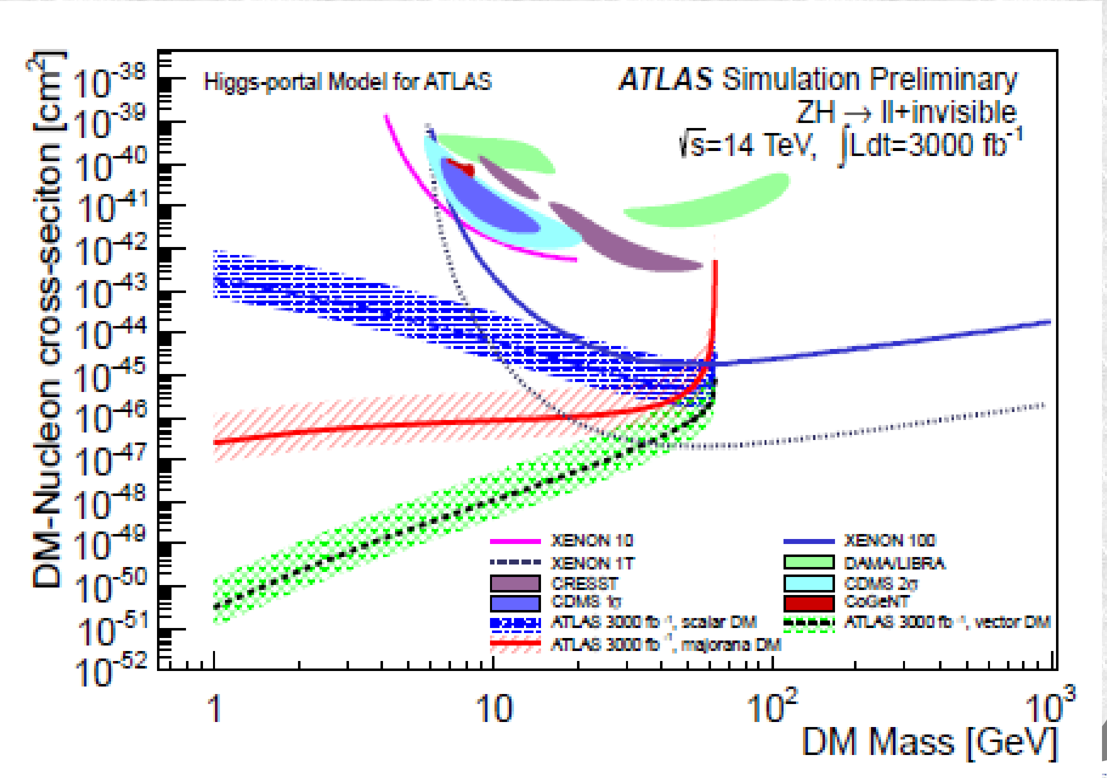


Invisible Higgs search

- ATLAS has studied ZH→ll+XX
- Sensitive to invisible Br about 10% with 3 ab^{-1}
- E_T^{miss} control vital

	300fb-1	3000fb^{-1}
ATLAS	[22,31]	[8,17]

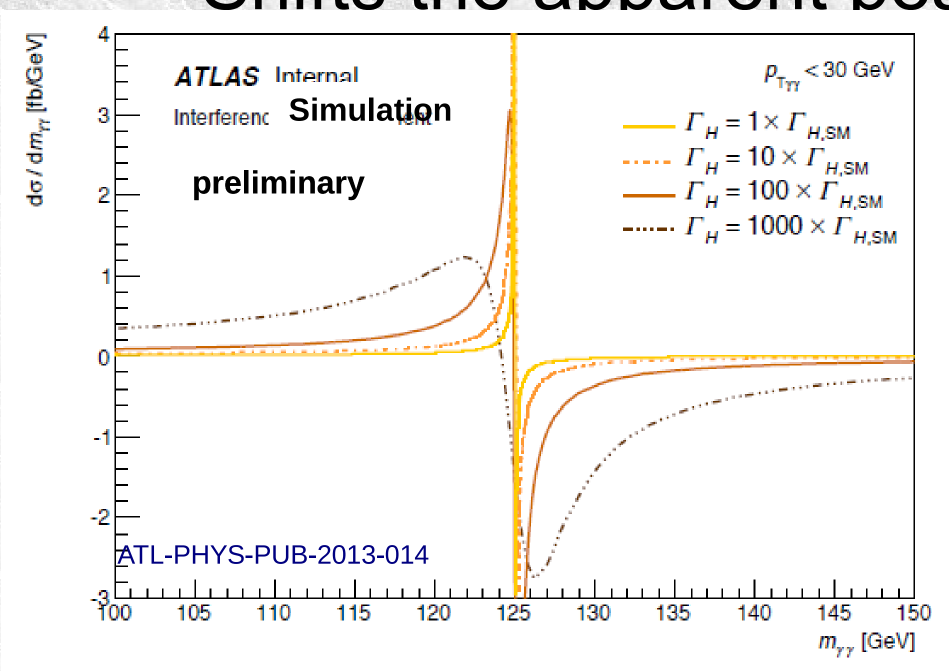


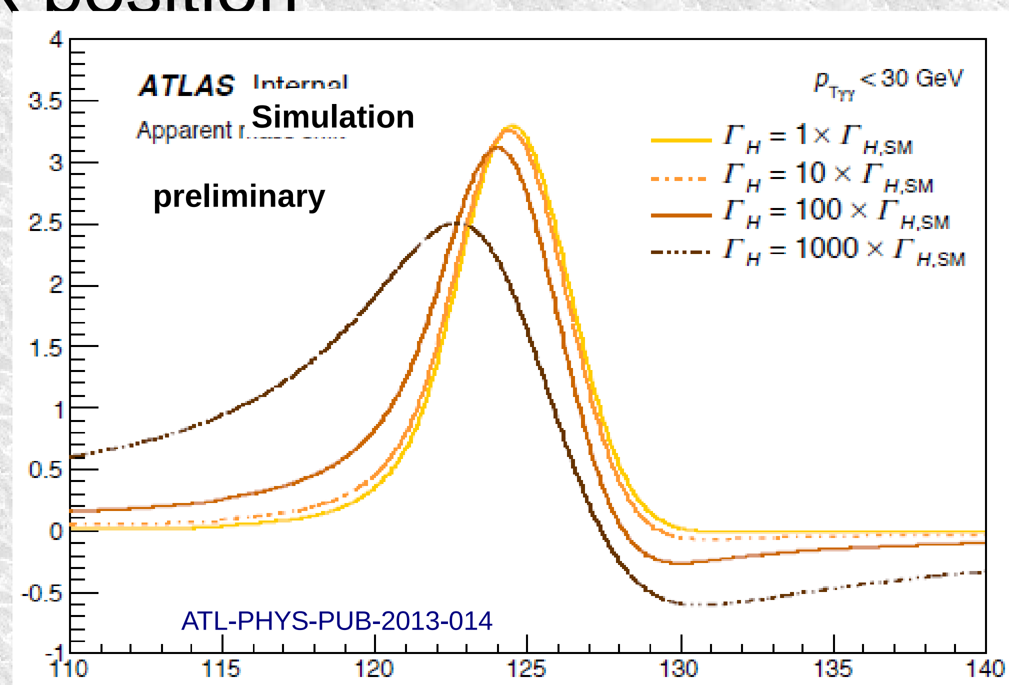


Direcct Higgs width study

Dixon and Li arXiv:1305.3854

- CMS extract Γ_H<6.9GeV from width of γγ
  - But Γ_H^{SM}=4.2MeV
- Interference exists between signal and bkd
  - Shifts the apparent peak position

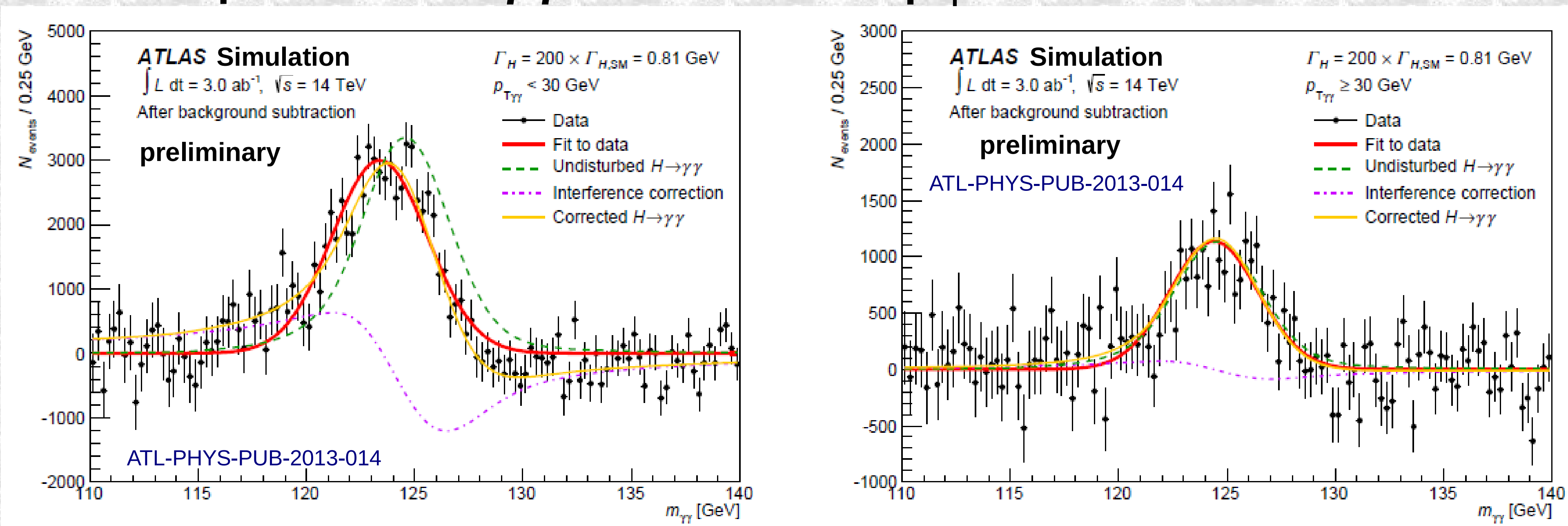




- Could compare γγ and ZZ peak: systematics :(

Higgs width in γγ

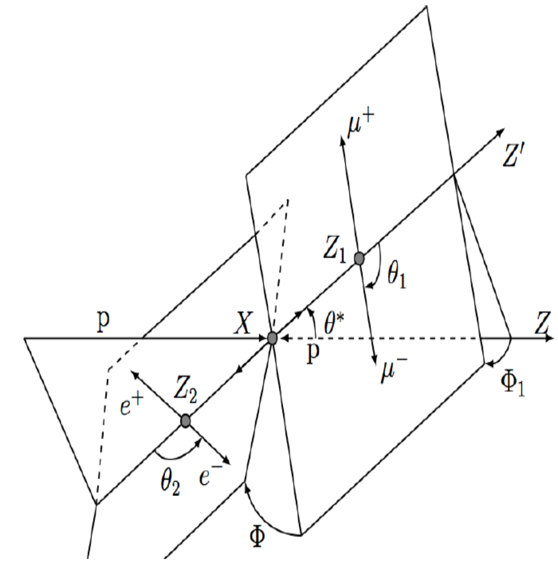
- Interference depends on s/b & hence p_T
- Compare H→γγ divided at p_T=30GeV



- Comparing peak positions gives sensitivity:
  - Γ_H<920MeV from 300fb^{-1}, 200MeV from 3ab^{-1}
- Systematic errors not dominating

HZZ coupling structure

- Analyze decay angles of ZZ system
- Express CP-odd(CP-even) structure as g_4(g_2)
- Big sensitivity gains from HL-LHC



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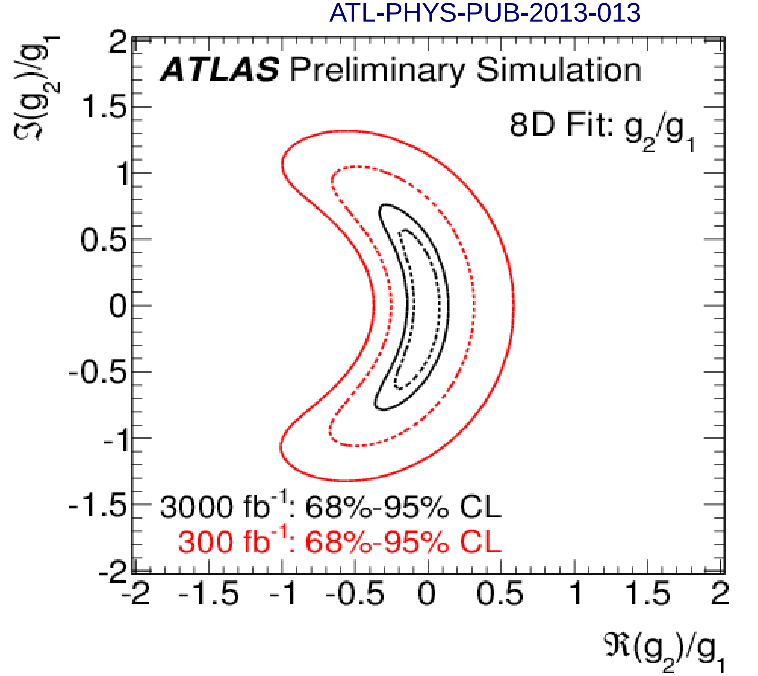
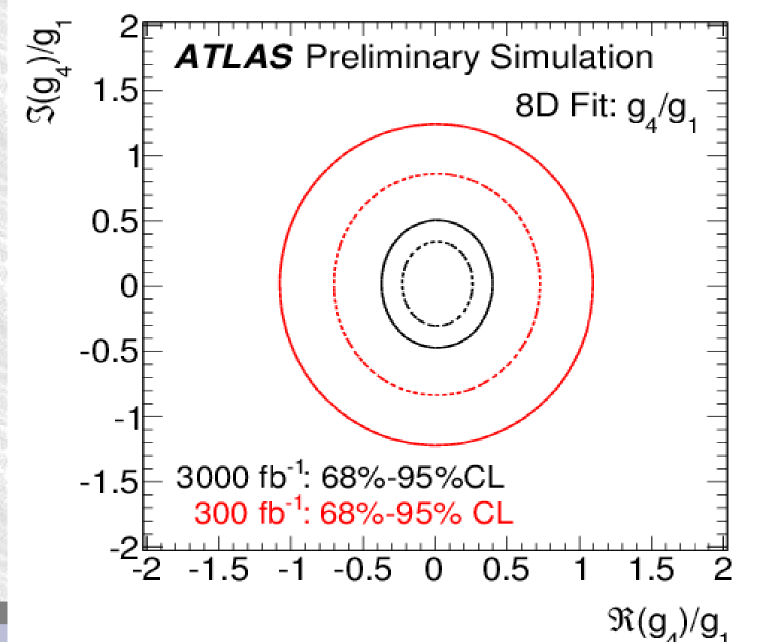
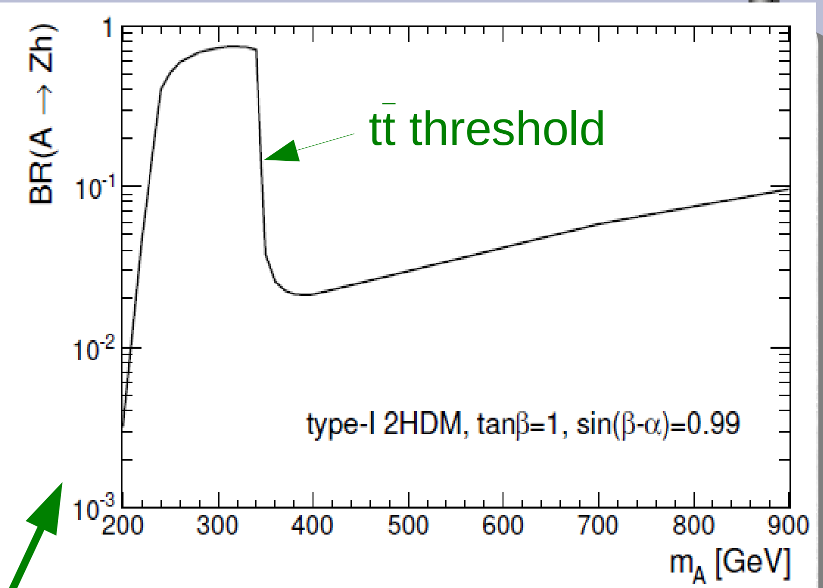
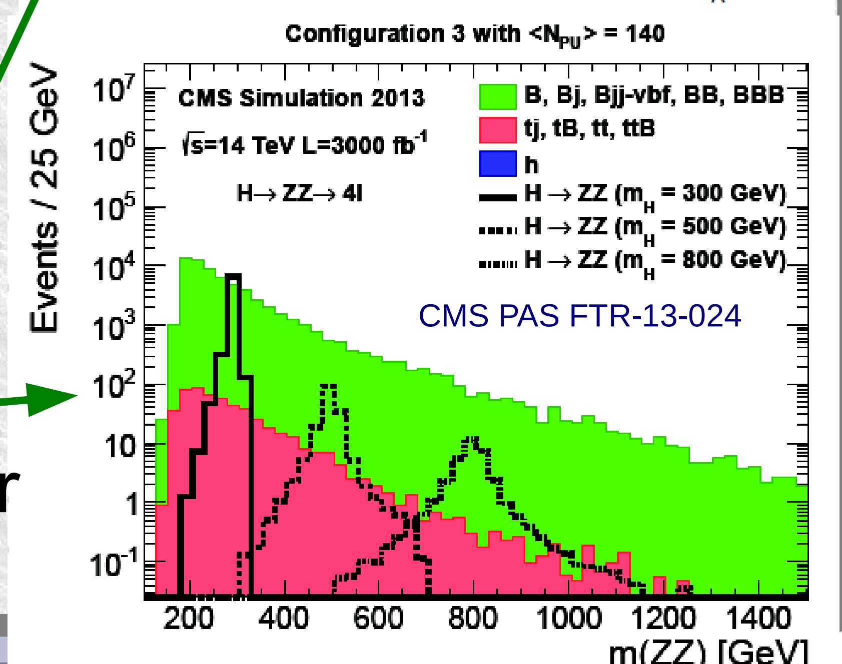




2HDM sensitivity

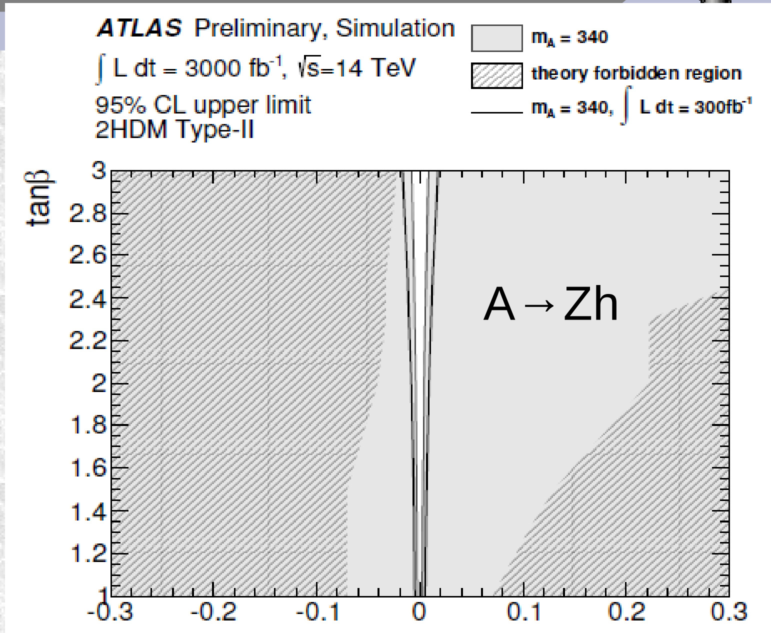
- 2HDM's have extra doublet (H, A, H^+, H^-)
- Coupling patterns Type I to IV are studied
  - Type II includes MSSM
- Studies of neutral sector sensitive to the mixing, tanβ and m_A.
  - H/A decays have $t\bar{t}$ threshold
- Example search for H to ZZ
  - Discovery potential $m_H < 2m_t$ for type II.





2HDM II: direct v couplings

- Both experiments study A→Zh search and coupling analysis of same model
- Two approaches complementary
  - Couplings independent of m_A



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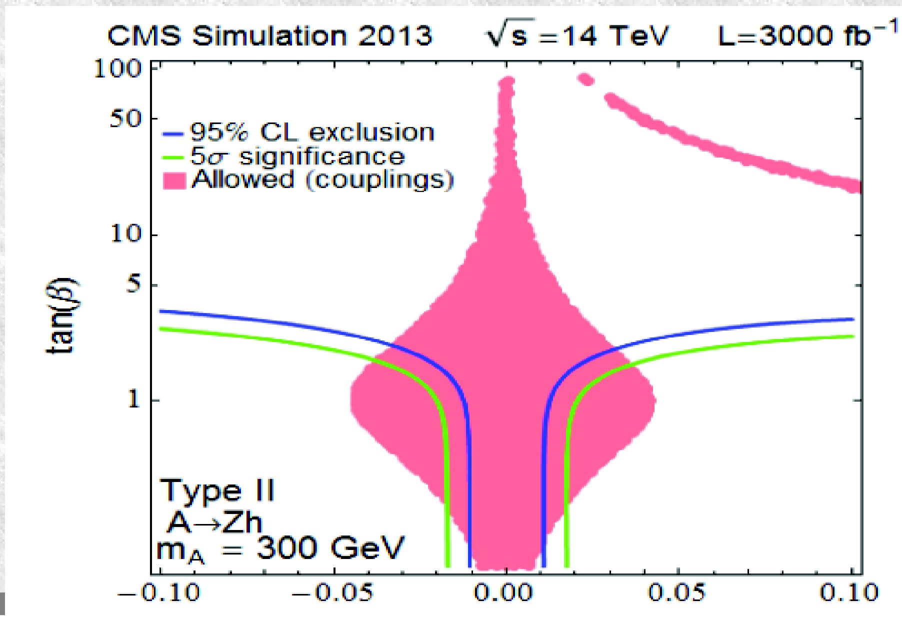
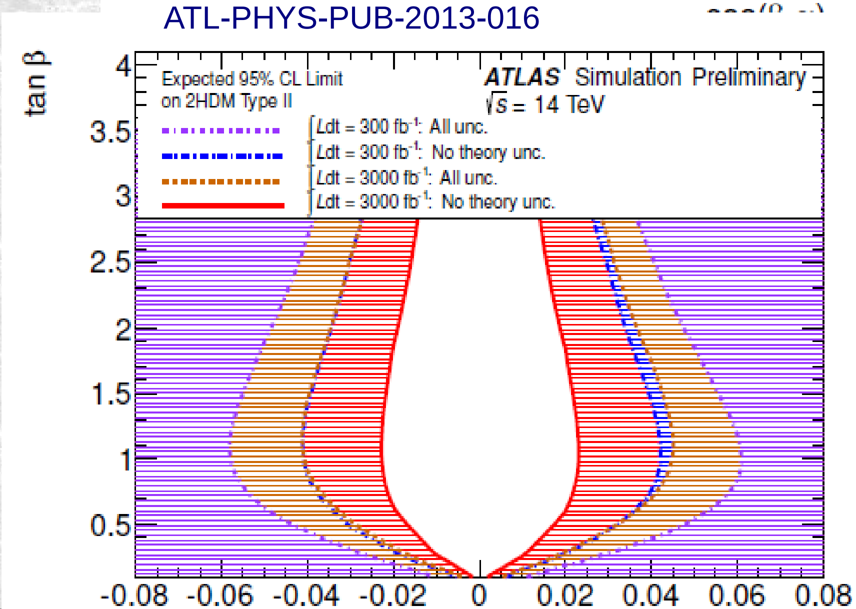


CMS PAS FTR-13-024 cos(β−α)

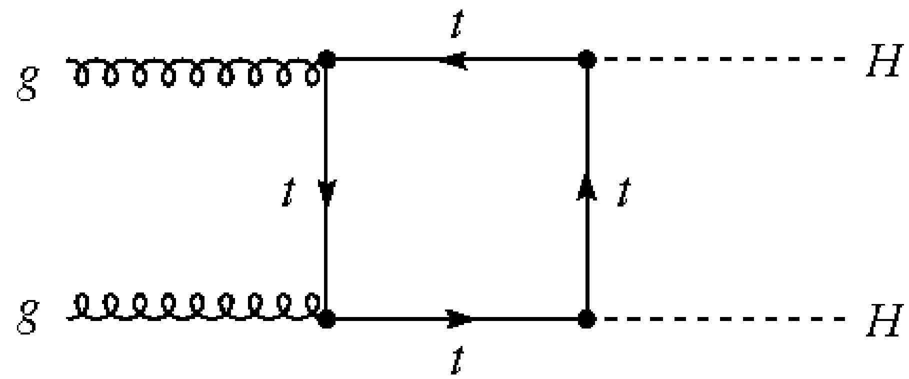


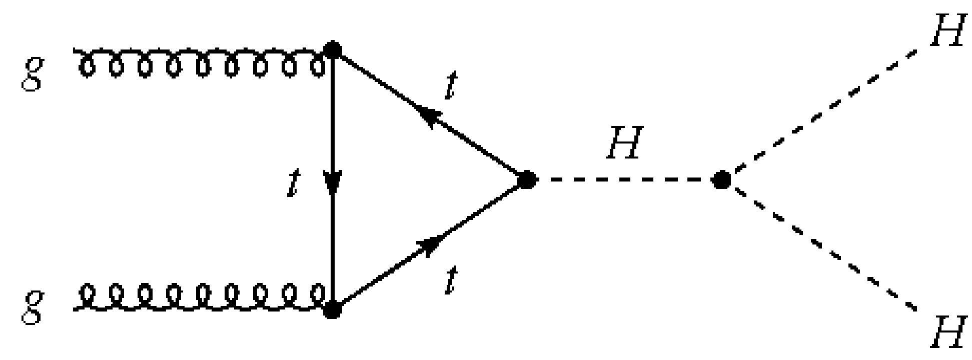
ATL-PHYS-PUB-2013-015 cos(β - α)

Can we see the BEH field?

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

Higgs boson pair-production





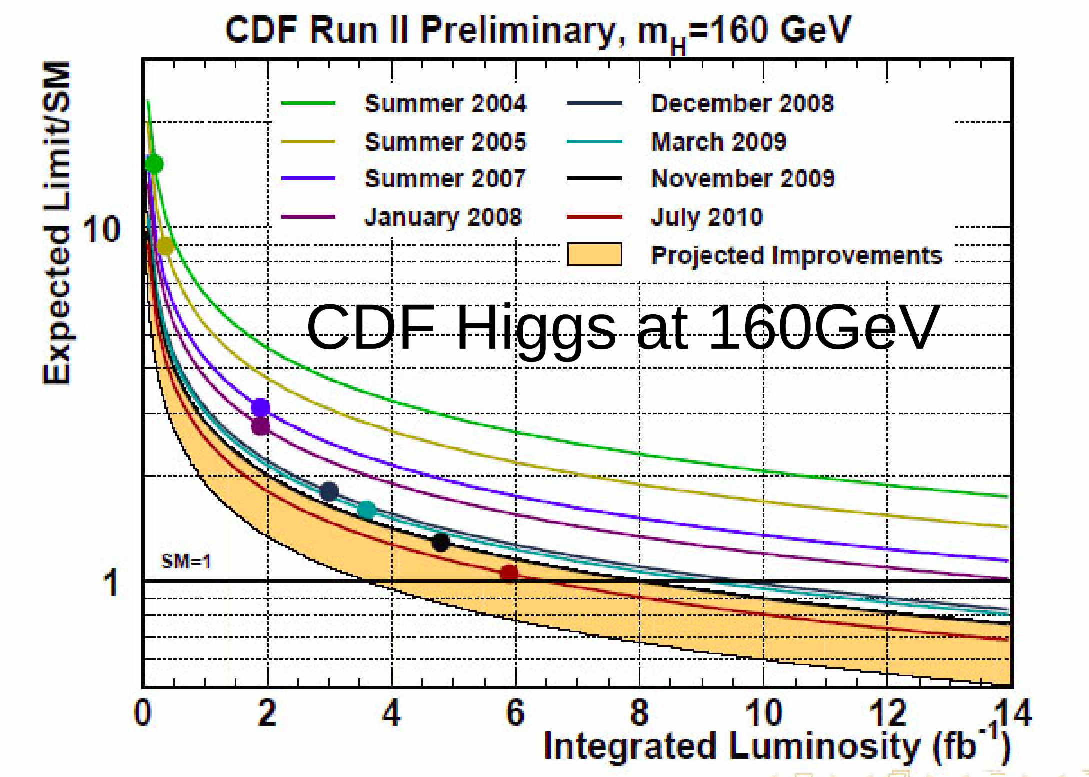
- Needs observation of Higgs pairs
  - Expected σ_{HH}=40±3fb → 120K events
  - Finding one was tough with ~500K events
- But it is not enough
  - Both the above diagrams (and more) contribute
  - Negative interference :(
- Ongoing studies suggest some sensitivity
  - Low rate makes high demands on detectors & lumi
  - Theoretical studies suggest possible: 1309.6318

Expected events

bbWW	30000
bbττ	9000
WWWW	6000
γγbb	320
γγγγ	1

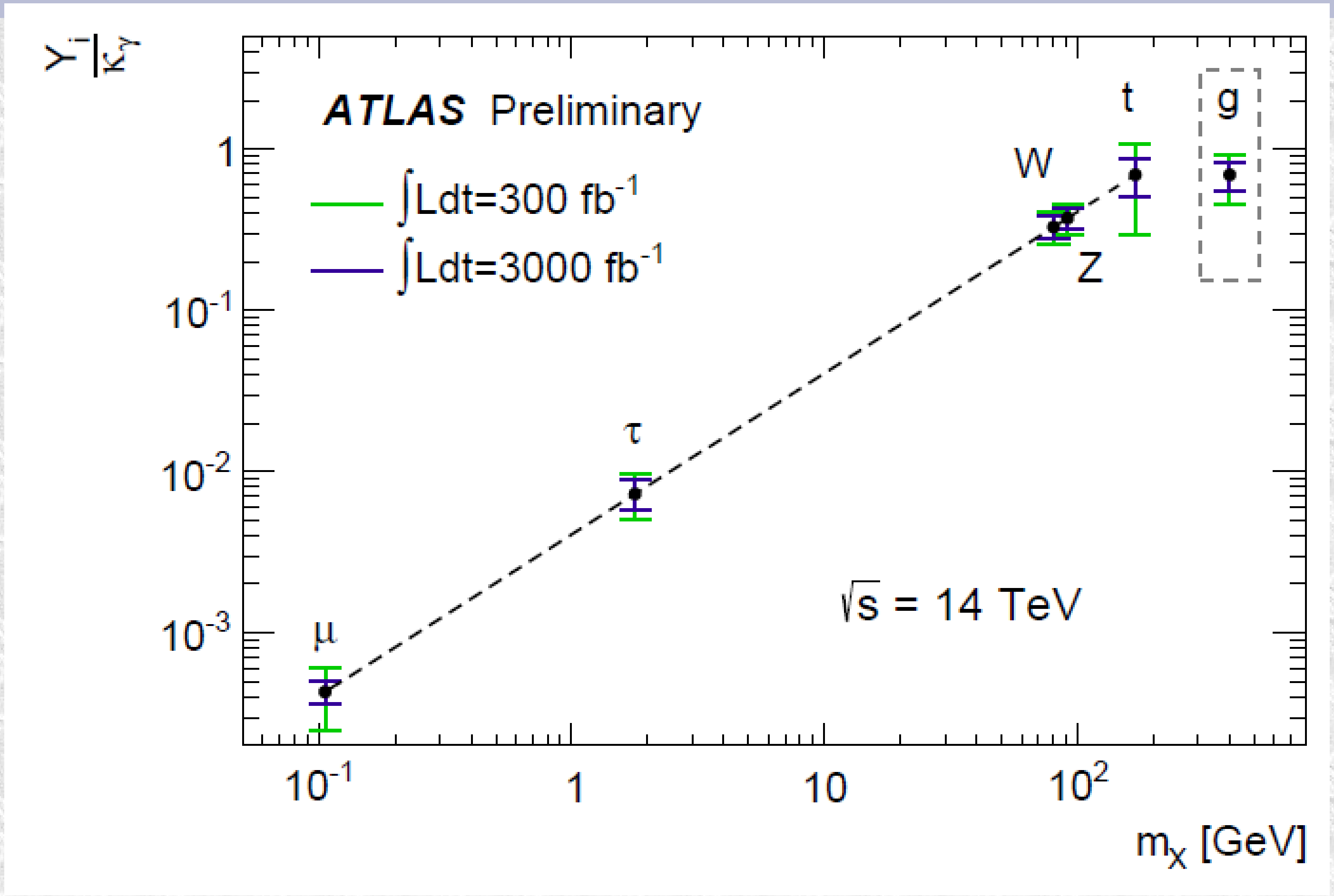
New ideas

- Expect improvements to the programme
- Experimentally many analysis improvements will be made in 15 years
- New theoretical ideas too. e.g.
  - ArXiv:1306.5770v1
    - Possible Hcc vertex
  - ArXiv:1305.3854
    - Width through interference



- The programme will be richer than we see
  - Thanks to huge Higgs sample + **work**

Putting it all together



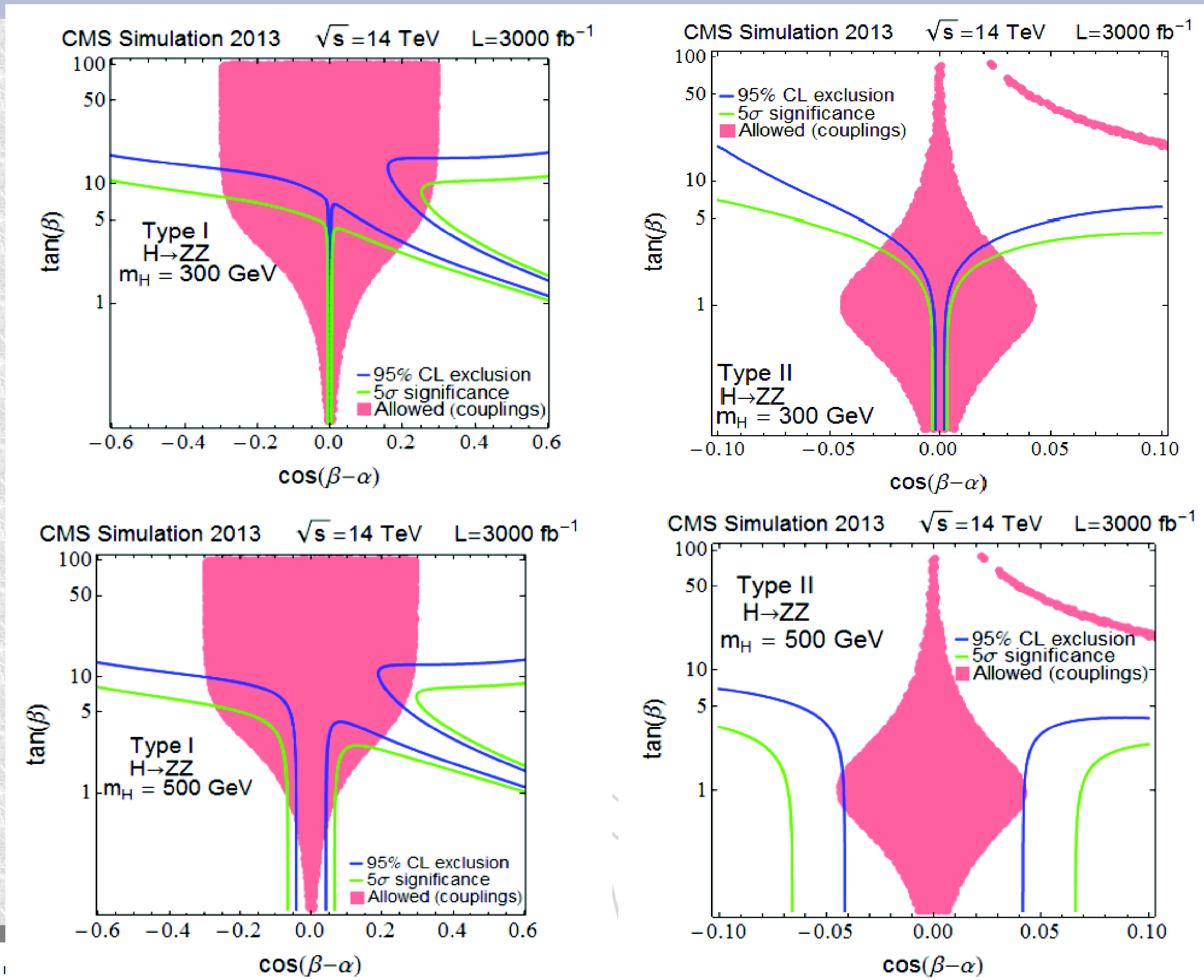
- The Higgs coupling strength plot
  - Is this the 'blueband' plot for the next 15 years?

Summary

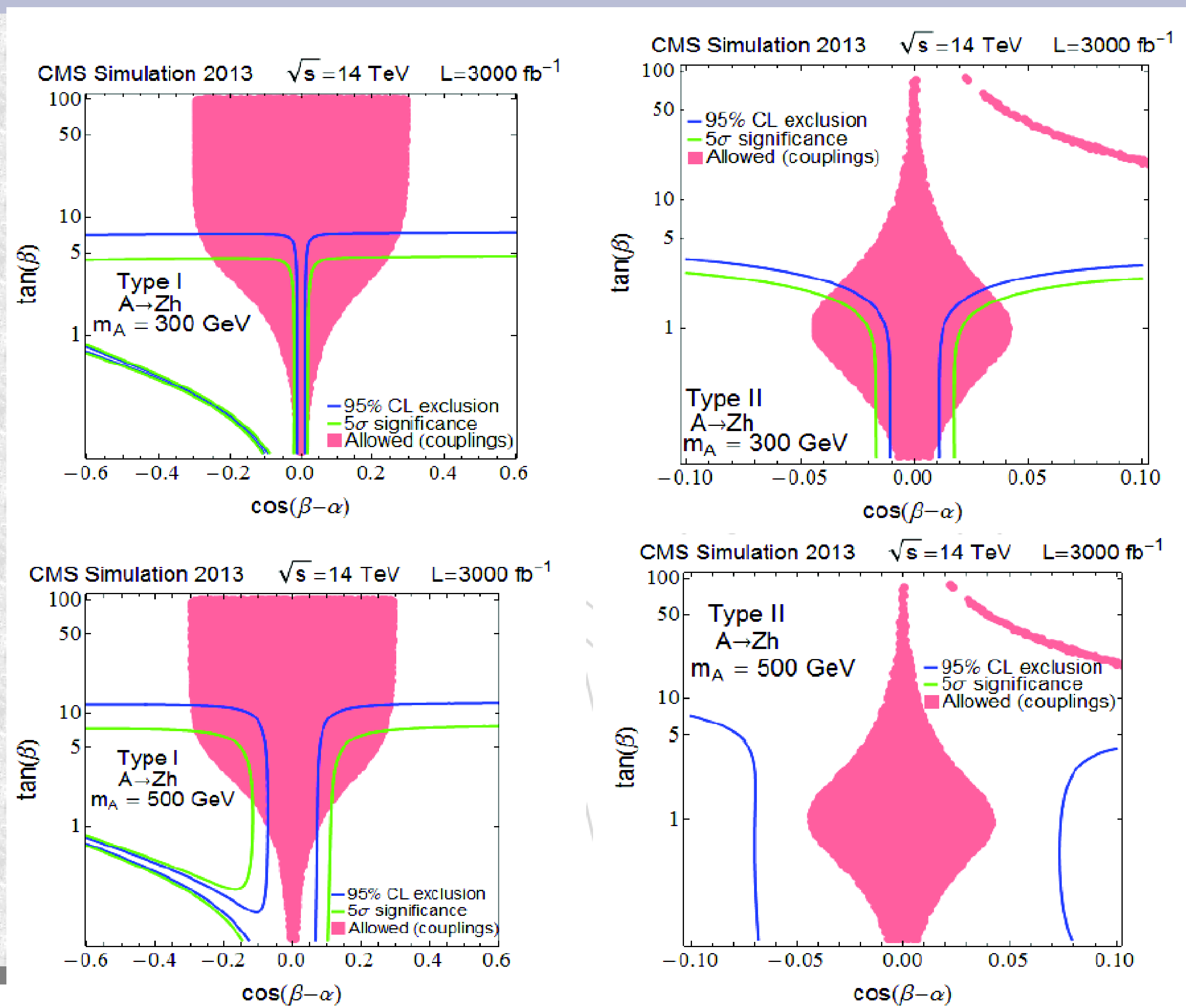
- 30 fb^{-1} of LHC data allowed the Higgs discovery
- 300fb^{-1} at 14 TeV allows many measurements
- 3000fb^{-1} allows much more:
  - Precision Higgs couplings to 8 particles
  - Coupling structure
  - Higgs invisible width
  - Discovery potential for heavier Higgs bosons
  - Some sensitivity to self coupling
- The physics possible at a hadron collider grows with experience
  - We will surely exceed this programme

Backup

2HDM: H→ZZ

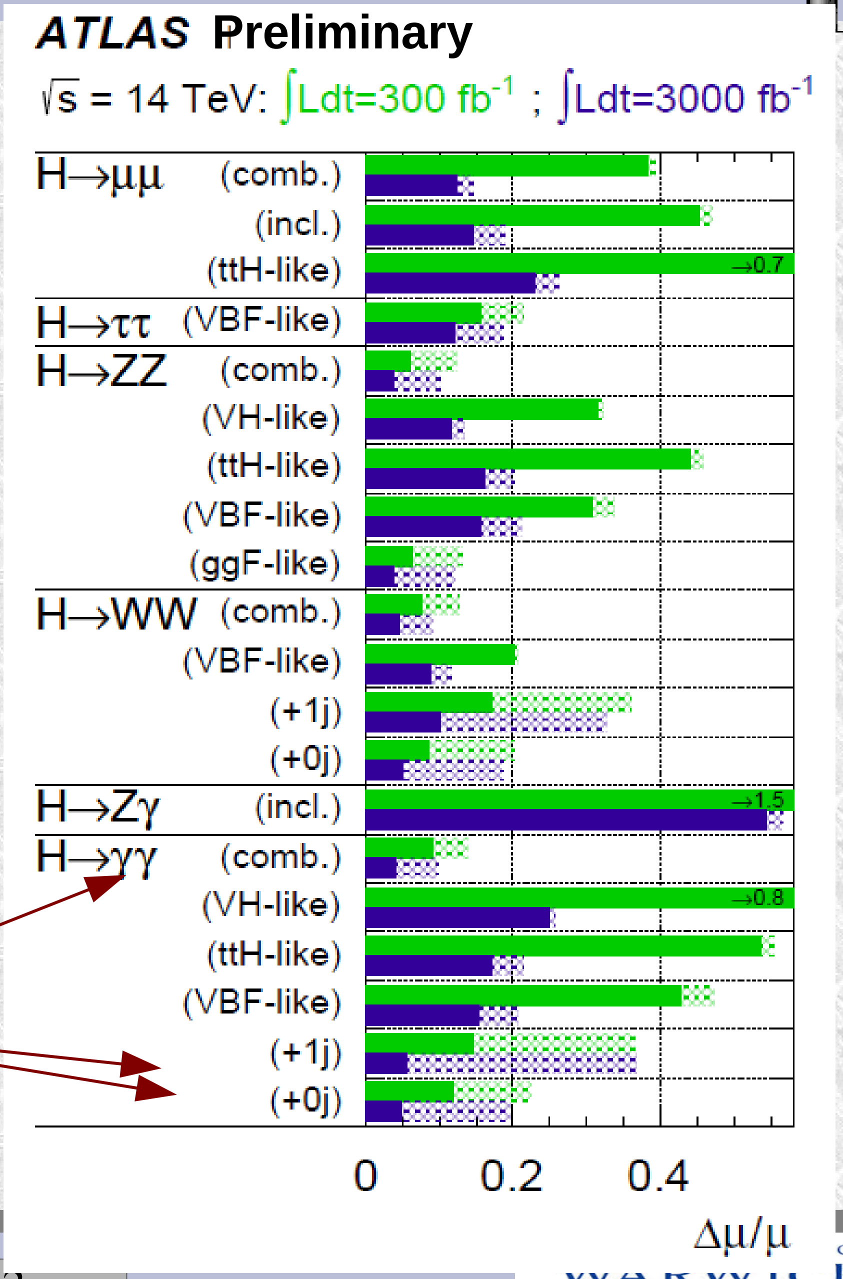

CMS Simulation 2013
√s = 14 TeV
L=3000 fb⁻¹
Type I
H→ZZ
m_H = 300 GeV
95% CL exclusion
5σ significance
Allowed (couplings)
tan(β)
cos(β−α)
Type II
H→ZZ
m_H = 300 GeV
Type I
H→ZZ
m_H = 500 GeV
Type II
H→ZZ
m_H = 500 GeV

2HDM: A→Zh study



Full list: graphically

- This shows the Higgs-signal strength in many analysis channels
  - Nb ggF like shows TOTAL Higgs strength accepted in analysis, not the VBF strength
    - Needs coupling fit
- Strong anti-correlation between 0j/1j strengths is exploited in fit



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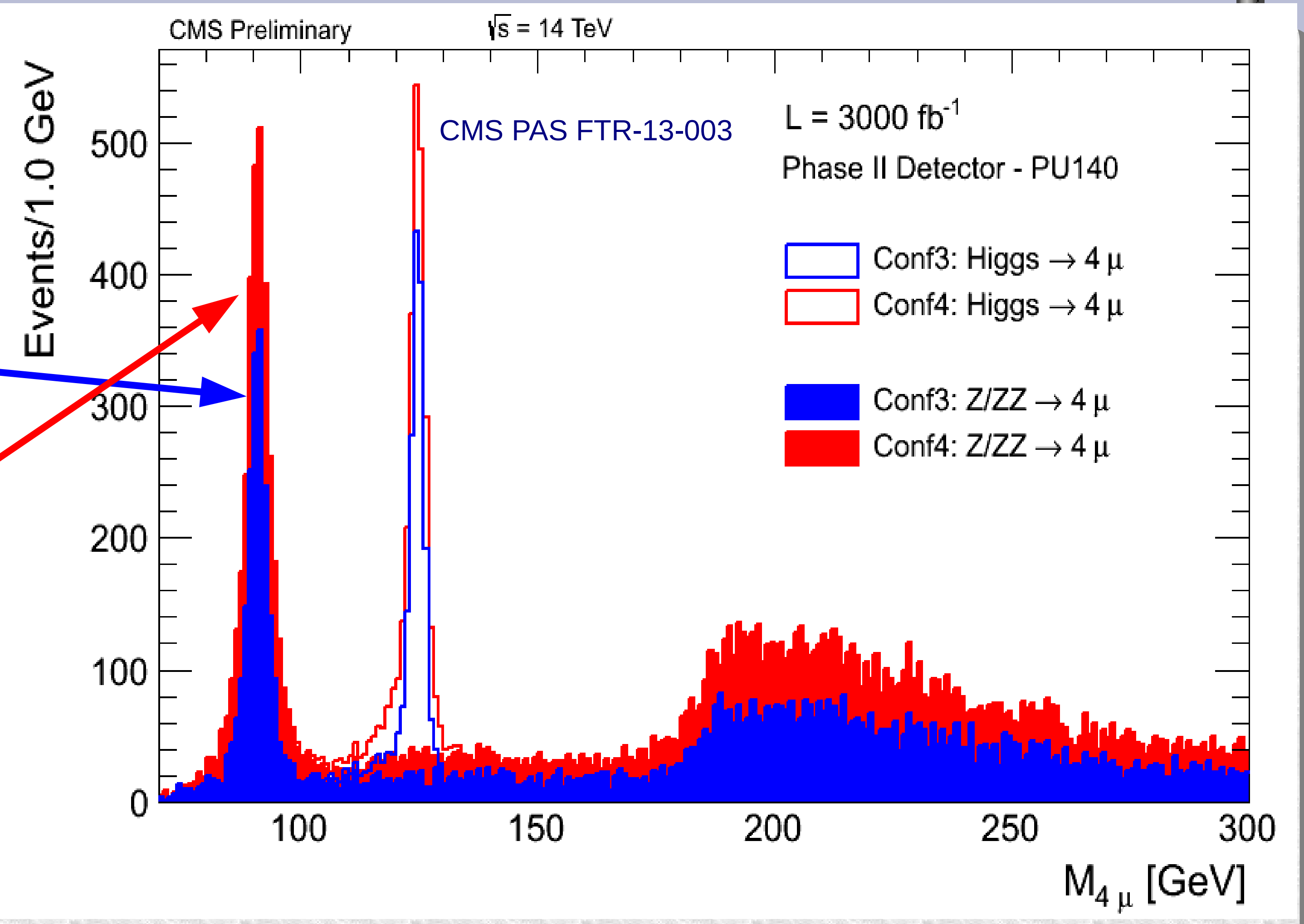
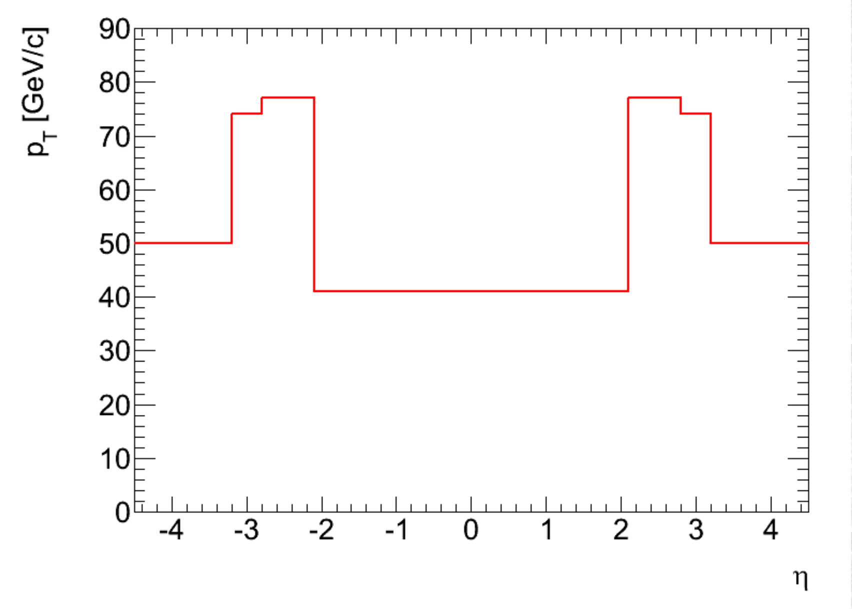
H →ZZ: η acceptance

- Contrast CMS detector with |η|<2.5 with |η|<4 extension
- Acceptance increases 40%
- Worth full study



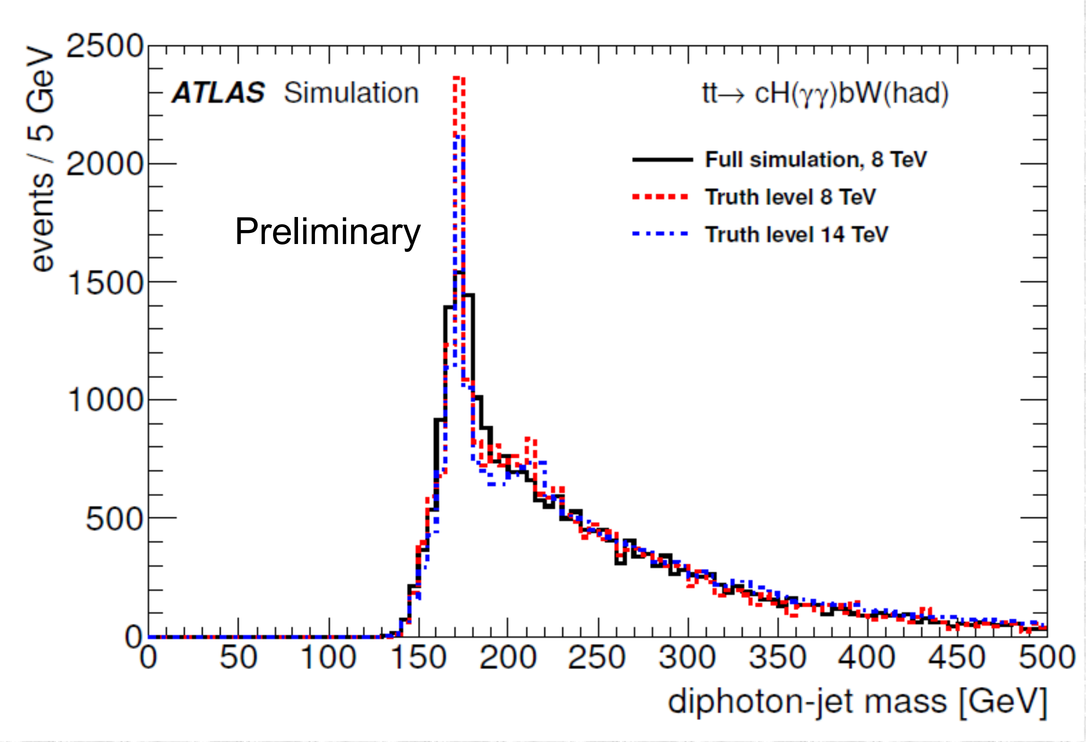
Jet thresholds

- Several ATLAS analyses use set of jet thresholds designed to give 1% pileup fake rate
  - ZZ, γγ, Zγ
  - These are calorimeter jets
  - Validated by tracks from PV
    - When available
- Inside |η|<2.1 tracks are available
- For η~4 a 50 GeV p_T jet has E=1.4TeV: rare
- But for 2.1<|η|<2.8 the threshold is high
  - This impacts their physics



t→cH sensitivity

- t→cH can be O(10^{-3}) in 2HDM-III models, 10x allowed t→cZ rate.
- tt→WbHc is studied with H→γγ
- Look for γγj peak
- Combine W→lν and W→qq



- Sensitivity to Br of 1.5×10^{-4}
- Other decay modes only add.

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