Prospects for BSM Higgs searches at future LHC and other machines

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DESY

Charged16, Uppsala
6 October 2016

Which collider will he work on?

How to search for BSM Higgs bosons?

Experimental signatures

- Is h(125) a BSM Higgs boson?
- Is h(125) fully responsible for EWSB (or further Higgs bosons involved)?

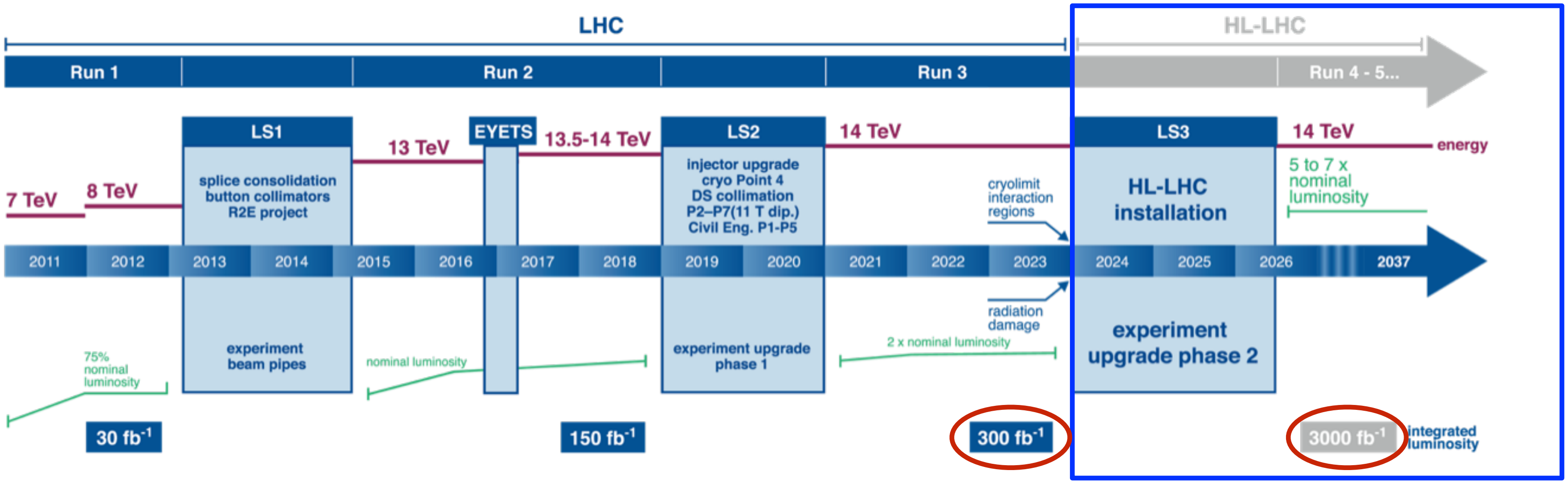
  $\rightarrow$ h(125) property measurements
- Direct searches for additional Higgs bosons (e.g. 2HDM)
- Direct searches for h(125)-BSM particle couplings (e.g. $X \rightarrow hh$, Higgs portal DM) or non-SM decays (e.g. LFV decays)

Possible tools

- LHC / HL-LHC
- Future electron-positron (or muon) colliders
- Future hadron colliders

Towards HL-LHC

Upgrade LHC and detectors to accumulate a data sample of
3 ab^{-1} over a 10 year run period

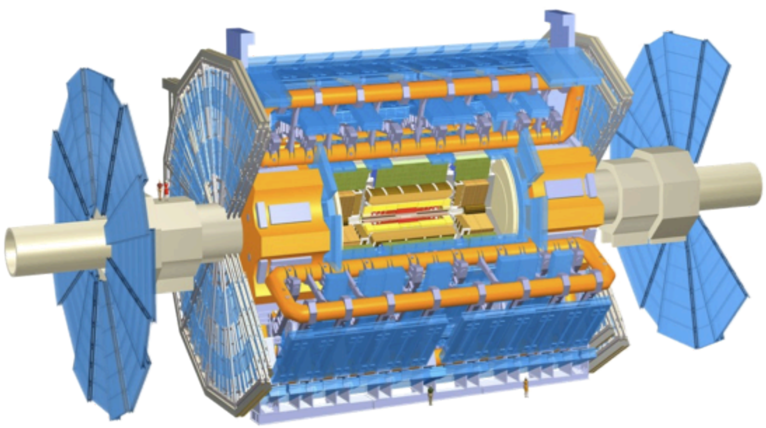


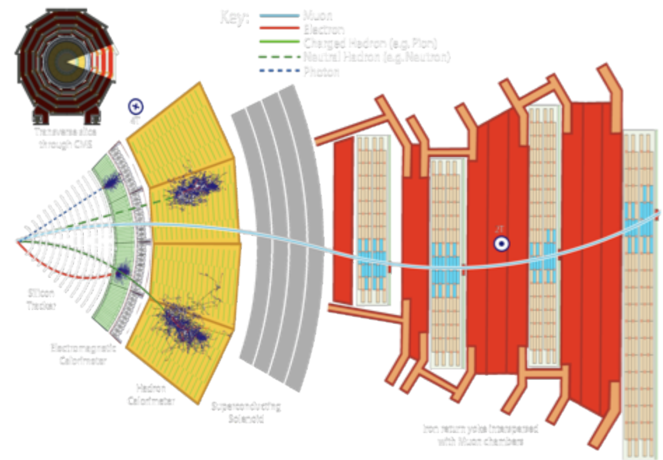
Go to design energy, nominal luminosity
$L = 10^{34}\ cm^{-2}s^{-2}$

Injector and LHC Phase-1 upgrade to design luminosity
$L = 2{*}10^{34}\ cm^{-2}s^{-2}$
$\mu = 55$

HL-LHC Phase-2 upgrade, IR, lumi levelling, ...
$L = 5\ (7.5)\ {*}10^{35}\ cm^{-2}s^{-2}$
$\mu = 140\ (200)$

ATLAS and *CMS* experiments





ATLAS: emphasis on excellent jet and missing E_T resolution, particle identification, and standalone muon measurement

CMS: emphasis on excellent electron/photon and tracking (muon) resolution

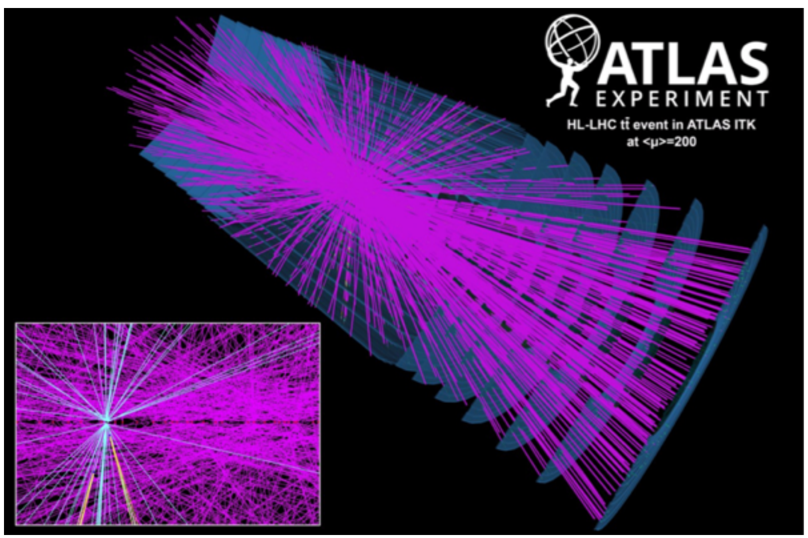
Detectors well understood, stable operation and data taking efficiencies above 90%

The need for new detectors

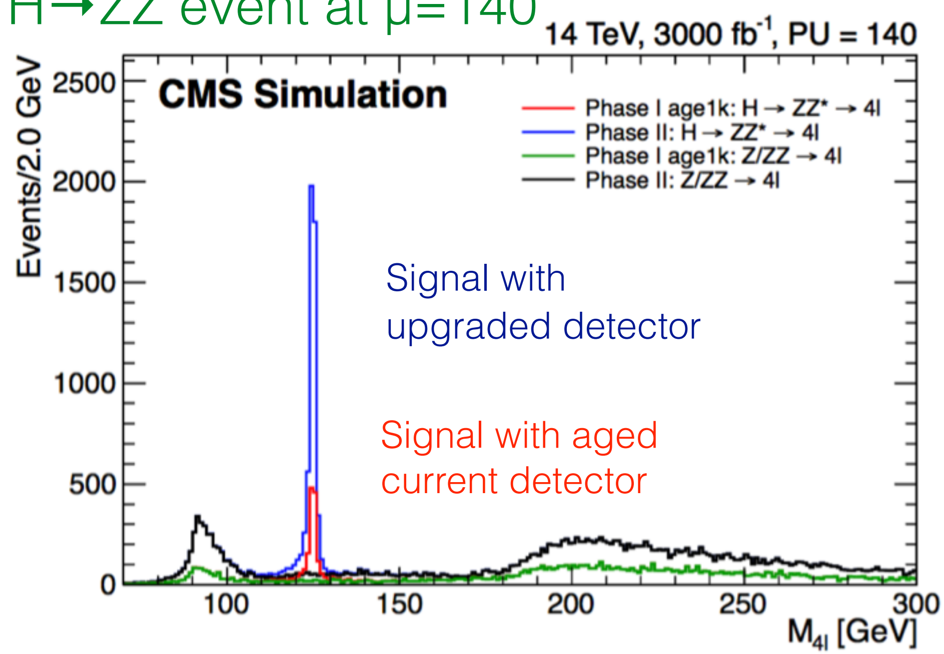
ATLAS and *CMS* designed for μ = 23. Major upgrades mandatory for the HL-LHC

- Cope with the huge pileup and radiation damage
- Maintain similar levels of performance as of today

LH-LHC tt event at μ=200



H→ZZ event at μ=140

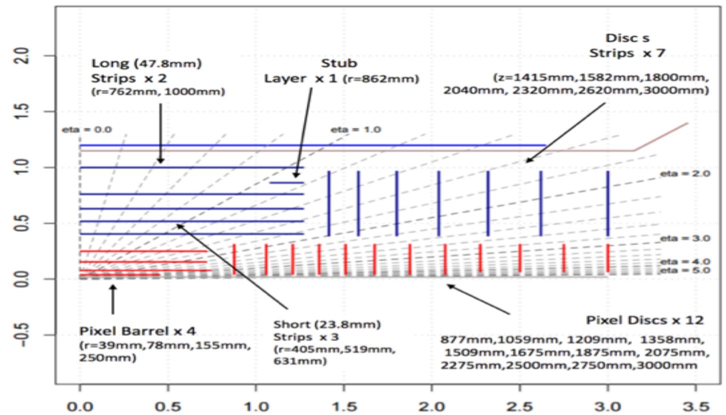


ATLAS and *CMS* upgrades

Similar upgrade plans by two experiments, different layouts under study (decision not yet taken)

Replacement of inner tracker with fully silicon-based tracker

- Higher granularity, better radiation tolerance (loss of transition radiation measurement for *ATLAS*)
- Extended coverage up to |η|=4 under consideration (pileup mitigation in the forward region)



New trigger and data-acquisition system to enable trigger rates up to an order of magnitude larger than the current systems

- Requires replacing almost all of the current readout electronics

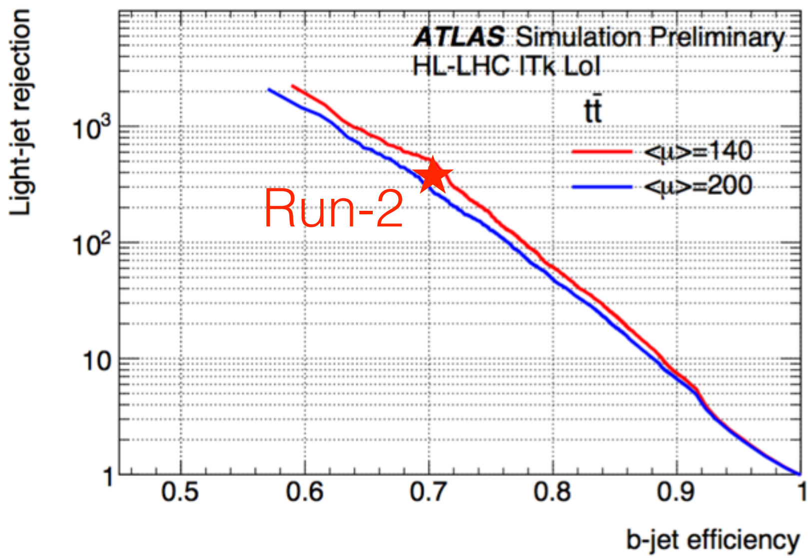
Upgrades to muon system and calorimetry in the forward region

Experimental performance

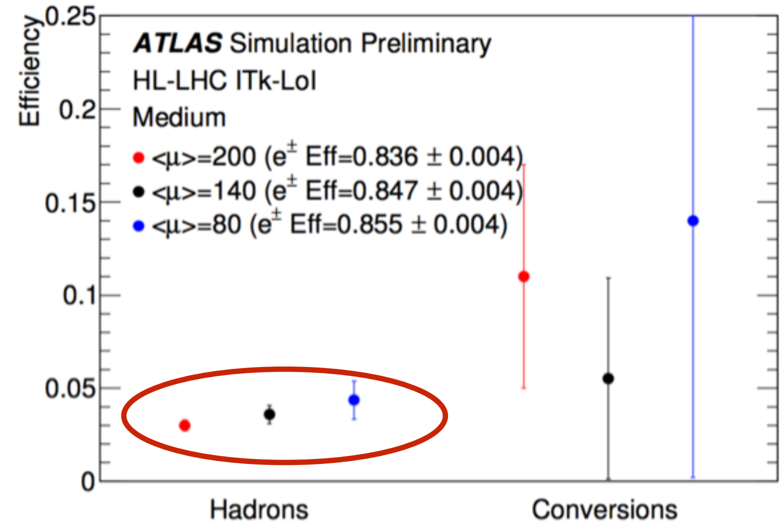
ECFA16!

Performance evaluation based on full simulation

b-tag performance



rejection of electron fakes



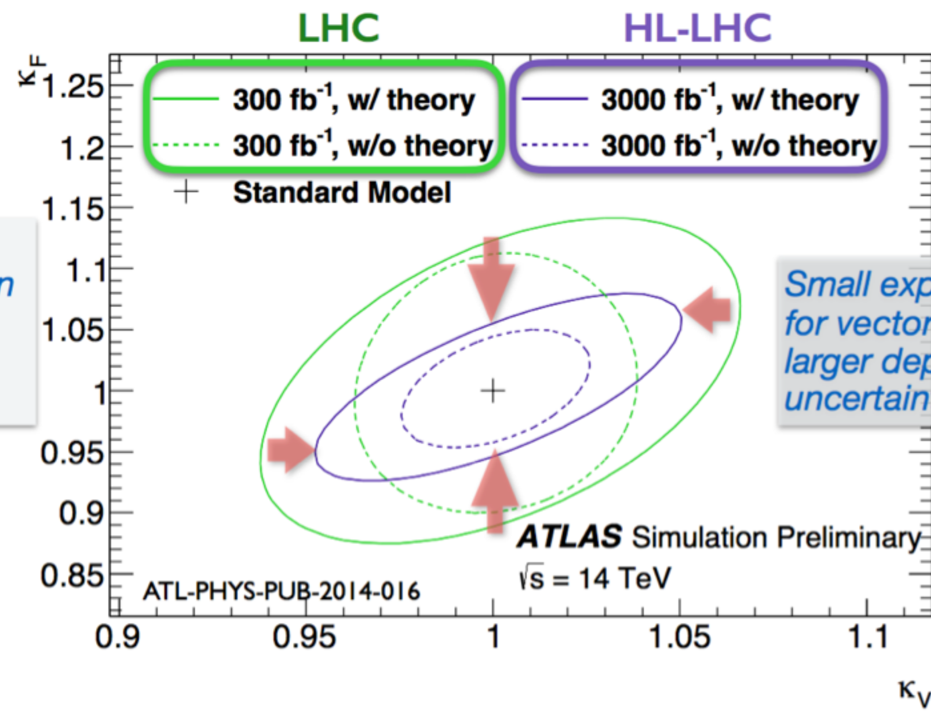
Similar performance compared to Run-2 for μ = 200, 30% better rejection for μ = 140

Pileup robust fake rejection

Higgs physics at the HL-LHC

Measure couplings of h(125) with a few percent accuracy

The larger dataset will improve mostly the fermion coupling measurements which generally benefit from higher statistics



Small experimental uncertainties for vector boson couplings, so larger dependence on theoretical uncertainties

[I. Nomidis]

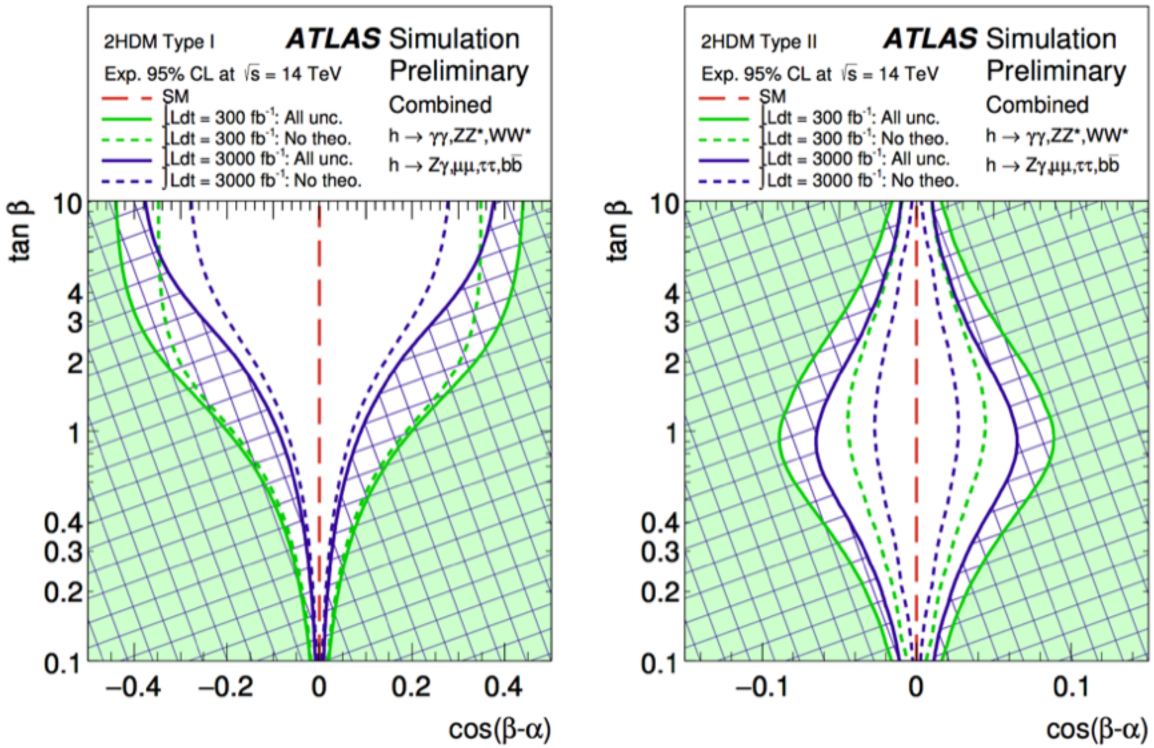
Access to Higgs pair production and rare decays

Direct searches for heavy Higgs partners

2HDMs - constraints from h(125)

Additional Higgs doublet, yielding 5 Higgs bosons

Higgs sector described by Higgs boson masses, $\tan\beta \equiv v_2/v_1$ and mixing angle *α* between the two CP-even states



(a) Type I

(b) Type II

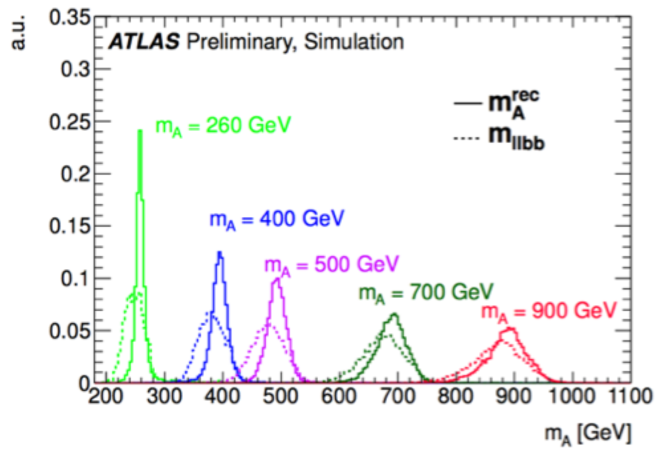
Coupling scale factors constrain *α* and *β*

Coupling scale factor	Type I	Type II
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$

Independent of heavy Higgs masses

2HDMs - direct searches

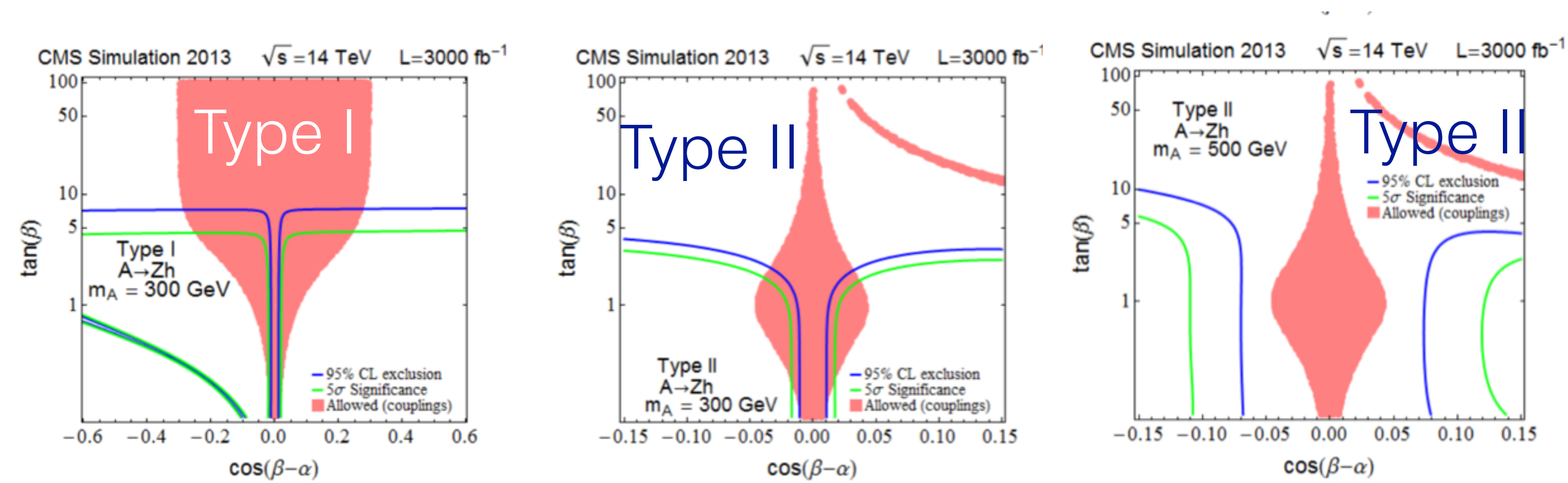
A→ Z(ll)h(bb) / H→ Z(ll)Z(ll) in gluon fusion production, dominant decay modes until tt threshold



Scale bb decay to mh=125 GeV

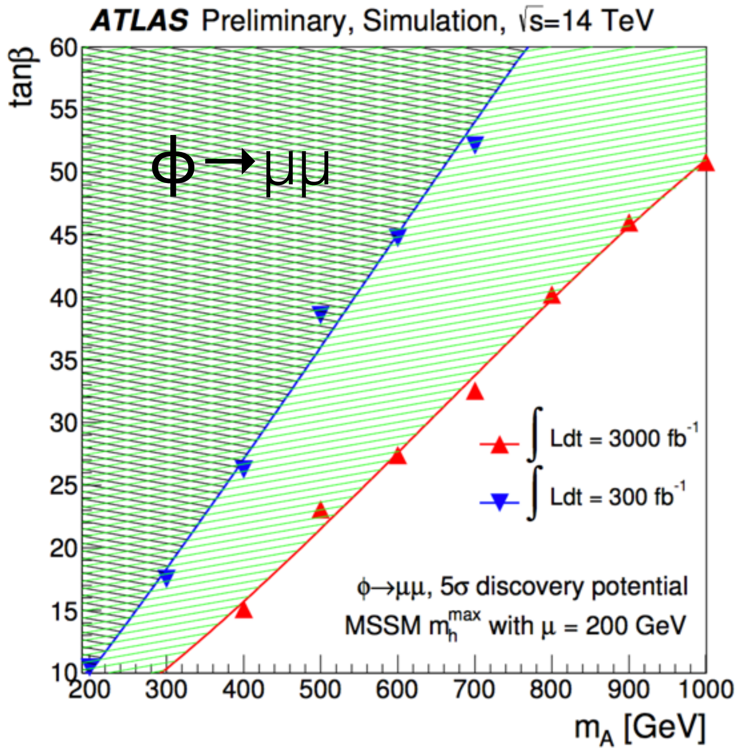
Powerful in the low tan β region, for higher mH tt BR takes over

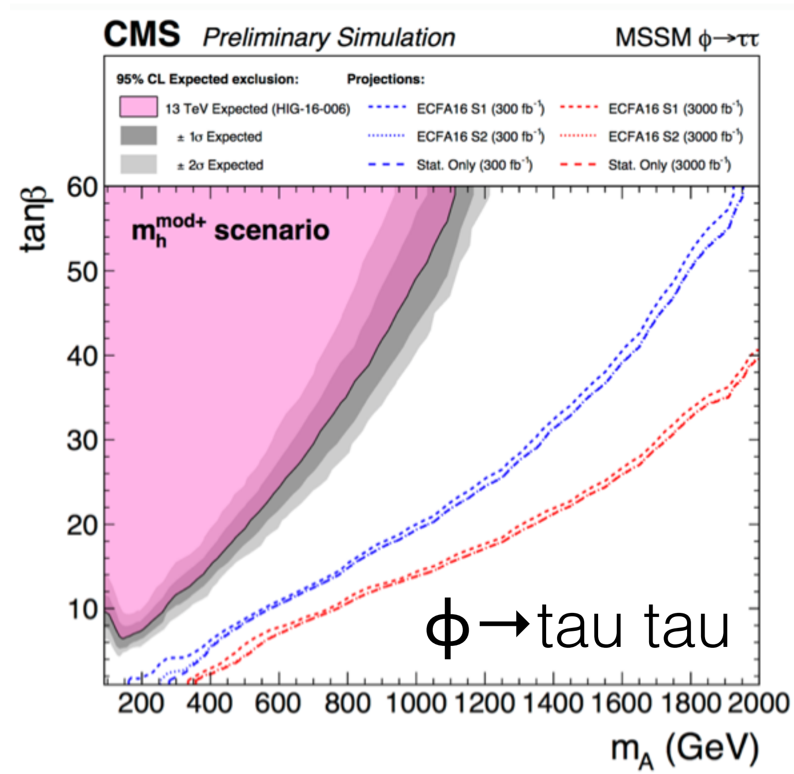
Complementary to constraints from h(125) coupling



Projections for MSSM

ECFA16!





Excellent mass resolution

Low signal yield

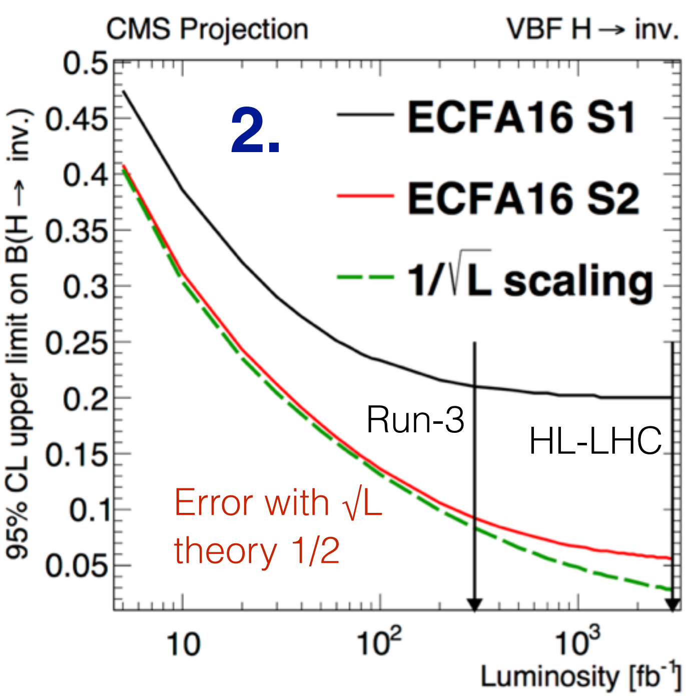
Large BR

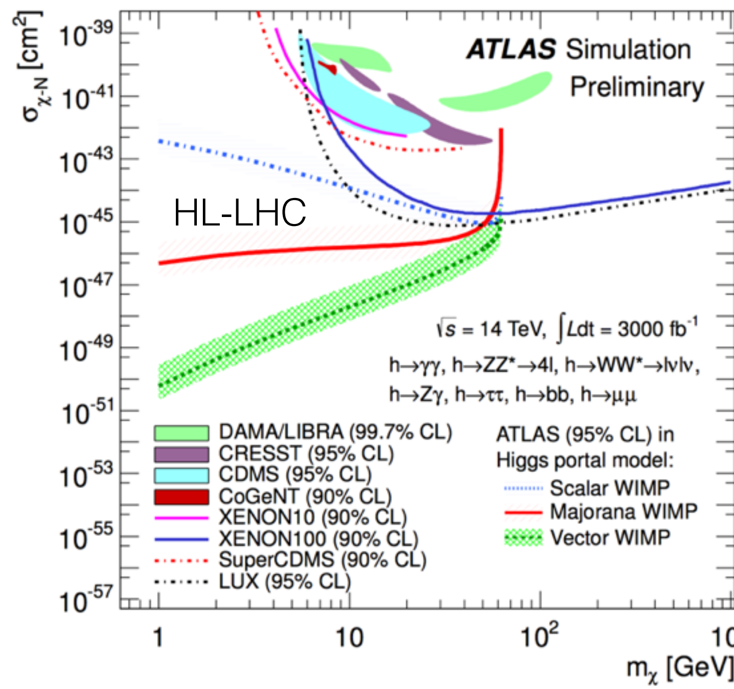
Sensitivity at high mA still dominated by statistics

Higgs portal dark matter

DM particle interacts with SM particles via the Higgs boson

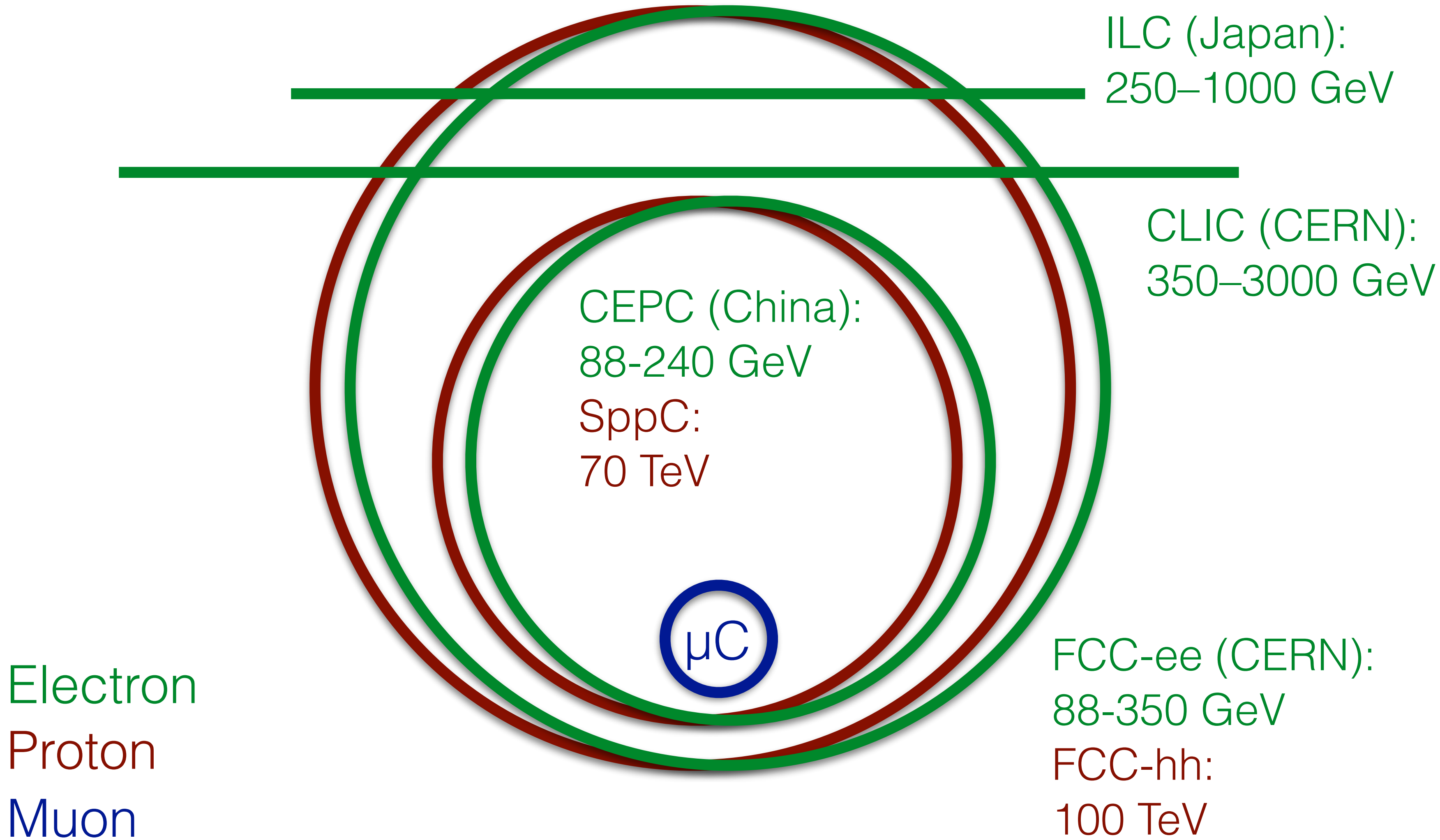
1. Derive upper limit on the H→inv. BR using the combination of rate measurements (assume SM couplings to visible particles)
→ $BR_i < 0.13$ (0.09) at 95% CL (without) theory unc. for 3 ab^{-1}





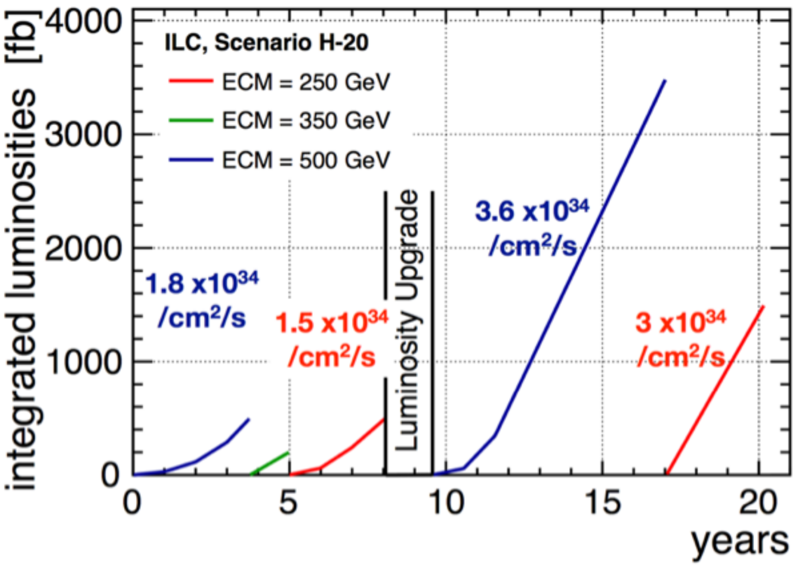
Ultimate sensitivity from e^+e^- colliders

Future colliders



International linear collider

20y running programme

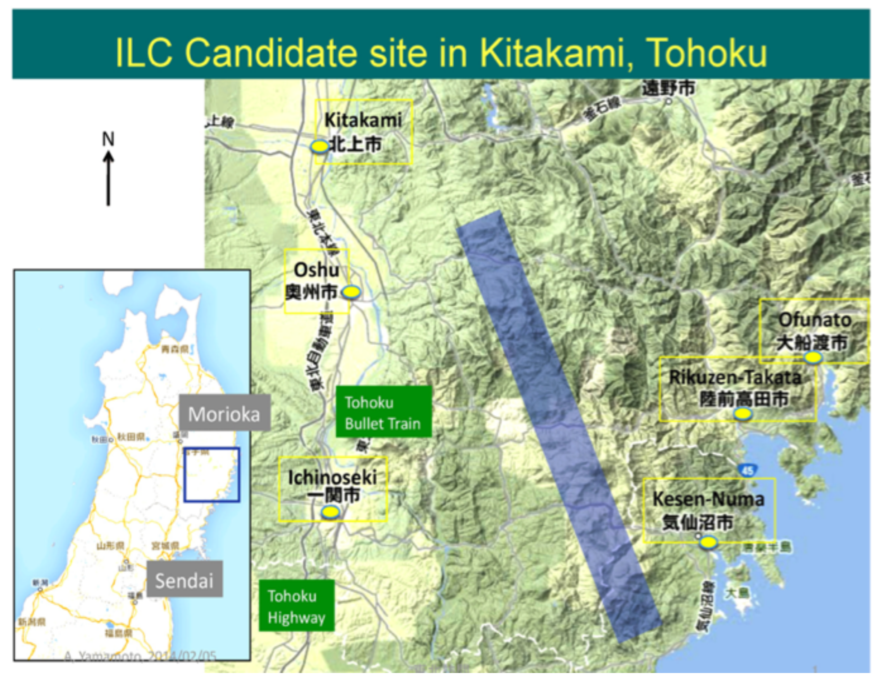


2 ab^{-1} @ 250 GeV   4 ab^{-1} @ 500 GeV

Polarised beams

c.m.s. energy upgrade 1 TeV

Total length (500 GeV): 34 km



20y of R&D and innovation:
TDR published 2013, technically ready to be built, site chosen

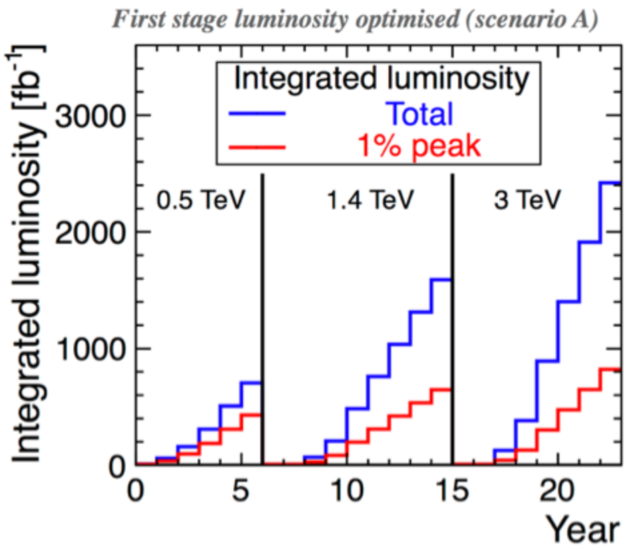
Internal expert review at MEXT (Japanese science ministry)

Compact Linear Collider (CLIC)

50km long at 3 TeV (ultimate energy)

Start with 380 GeV (Higgs and top)

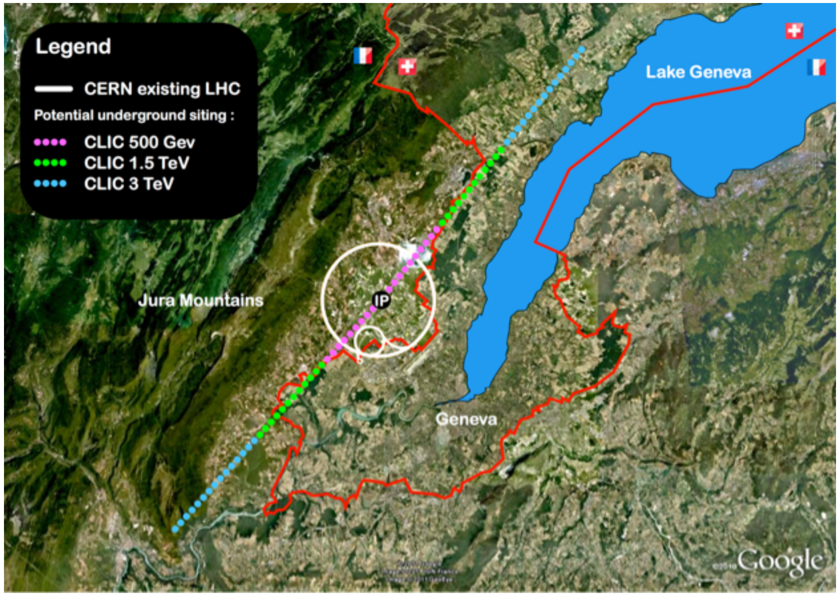
Physics comparable to ILC, energy upgrade increases BSM reach in direct searches



CDR published 2012

R&D ongoing

Challenges: nm-size beams, power consumption at 3 TeV



Future circular collider (FCC)

Main goal: 100 TeV pp machine

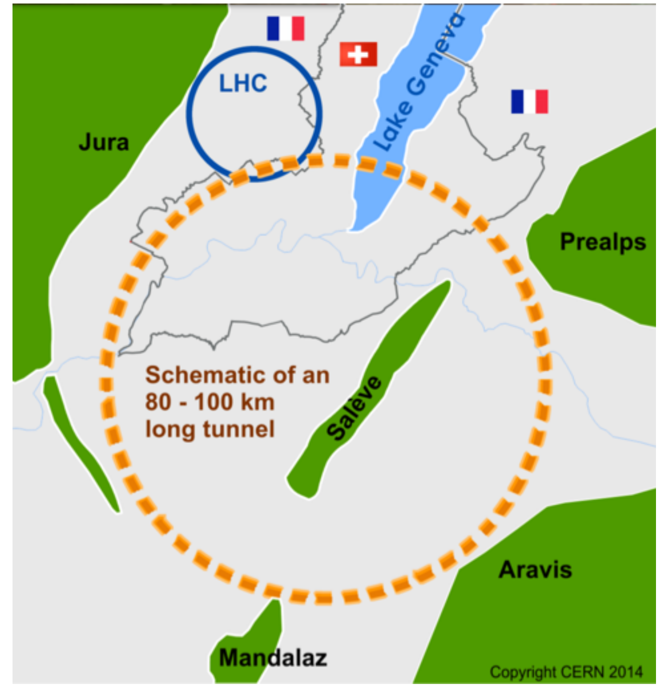
- In 10y ~HL-LHC total luminosity
- Ultimately 20 ab^{-1} in ~25y operation

100 km circumference with ~16T

- Fits geology (driven by pp machine)

e^+e^- collider as intermediate step

- Energy tunable from MZ to *O*(365) GeV
- Top-up injection from separate storage ring (B-factories)
- CDR by end of 2018 (for the next European Strategy Update 2019)



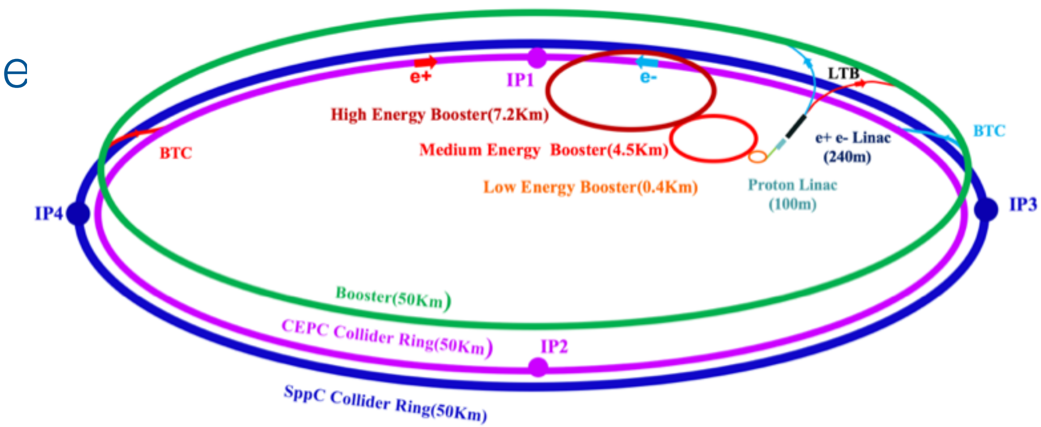
Baseline: conservative optics / 2 IPs

√s	Z	WW	ZH	≥ tt	total
Lumi / year [ab -1]	42	3.8	1	0.25	
#years	3	2	5	5.5	15 yrs
#events	5 10^{12} Z	30 M WW	1 M Higgs	800 k tt	

CEPC / SppC

Circular Electron Positron Collider (CEPC)

- Default: 54 km circumference
- Center of mass energy tunable from MZ up to 250 GeV
- Pre-CDR published 2015



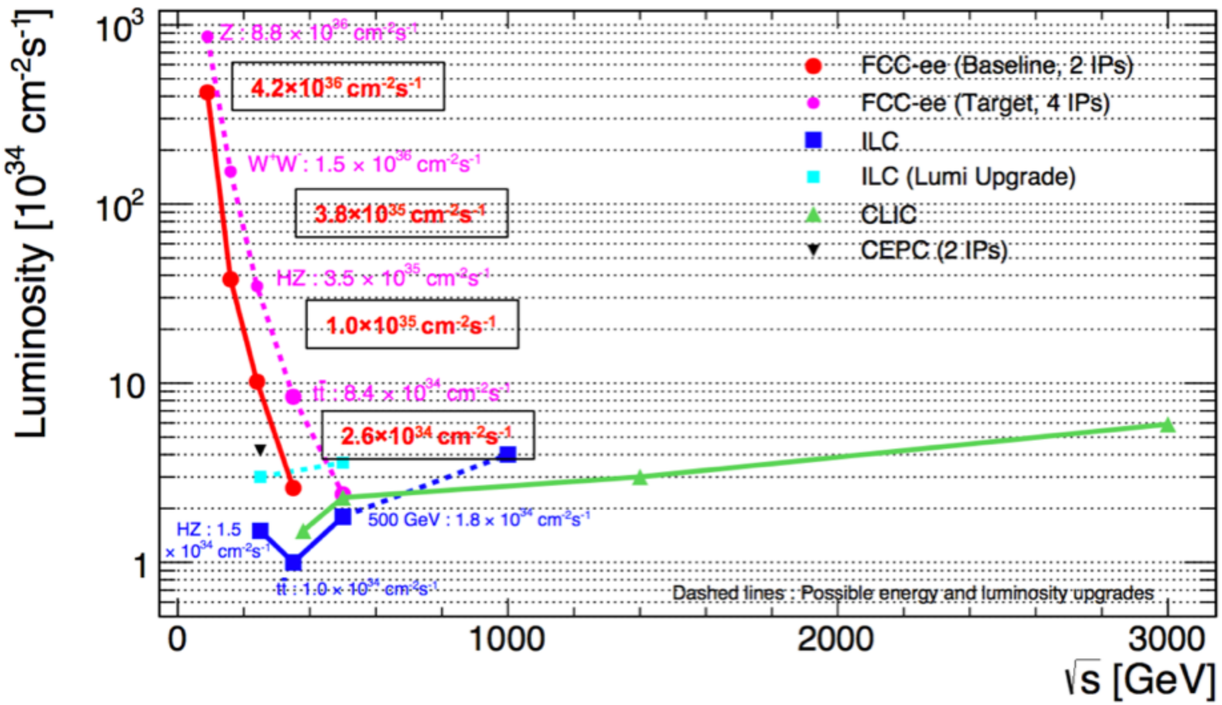
Conceptually challenging

- One ring machine and head-on collisions (in contrast to FCC-ee)
- Work ongoing towards CDR (2016?)

Super Proton-Proton Collider (SppC)

- Follow-up project in same tunnel with 70 TeV pp collisions

e+e- colliders

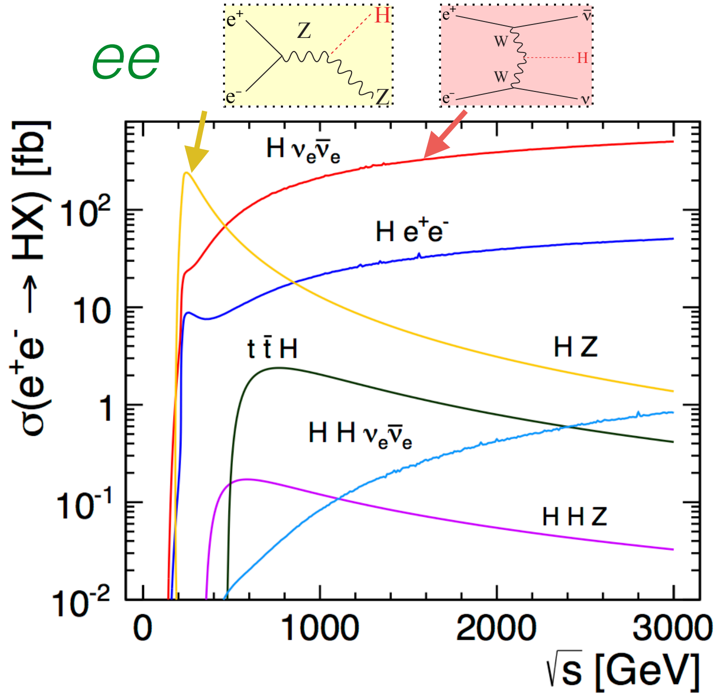


Not only about luminosity and c.m.s. energy:

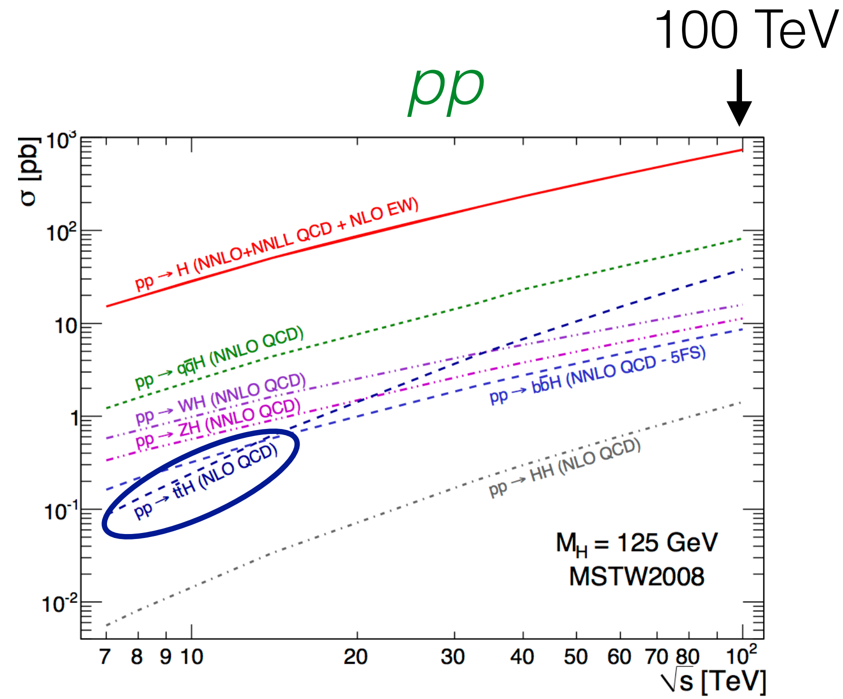
- Beam polarisation
- Beamstrahlung and beam energy spread
- Bunch structure (important for detectors)
- Number of interaction points

SM Higgs production

ee



pp



Low backgrounds → all decay modes accessible

Model-independent coupling measurements

ttH and HH require $\sqrt{s} \geq 500$ GeV

Huge cross-sections and high energy good for clean/rare decays and heavy final states

Due to large backgrounds not every decay accessible

SM Higgs measurements

Coupling	LHC	CepC	FCC-ee	ILC	CLIC	FCC-hh
$\sqrt{s}$ (TeV)→	14	0.24	0.24 +0.35	0.25+0.5	0.38+1.4+3	100
L (fb^{-1}) →	3000(1 expt)	5000	13000	6000	4000	40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	~ 2
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1%	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19%	<0.29	<1%	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~ 1 ?
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

Units are %

Few preliminary estimates available
SppC : similar reach

from K_γ/K_Z, using
K_Z from FCC-ee

rare decays → pp
competitive/better

from ttH/ttZ,
using ttZ and H
BR from FCC-ee

[Gianotti, EPS15]

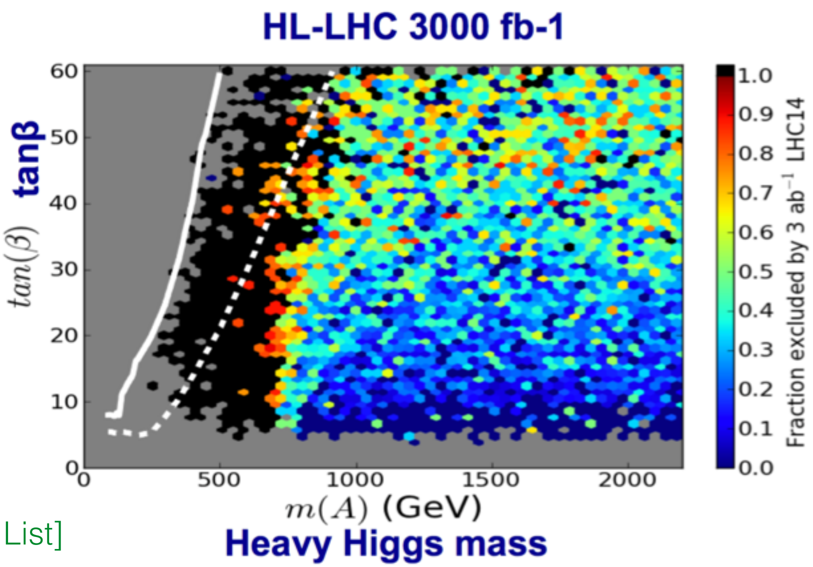
LHC ~20% today → ~5% at HL-LHC

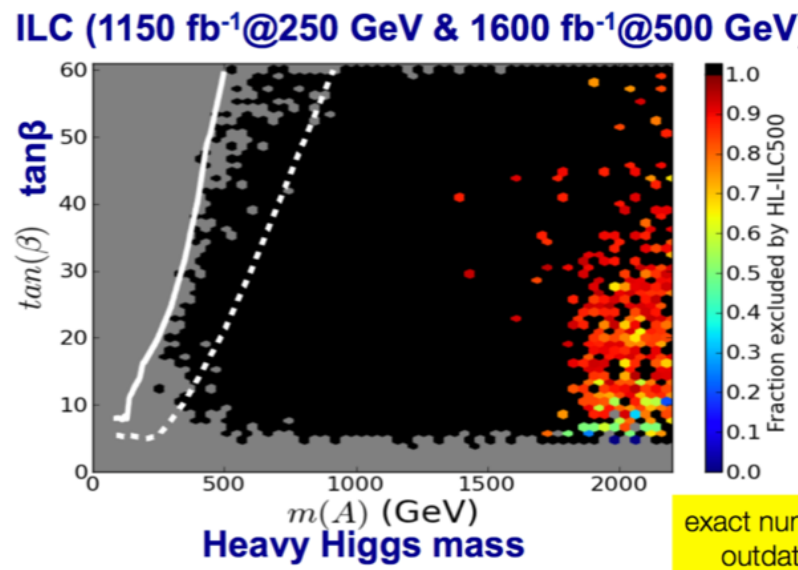
Best precision at FCC-ee due to high lumi. For heavy states (ttH and HH) high energy is needed (ILC/CLIC, FCC-hh/SppC)

Complementarity between ee/pp

BSM Higgs at e+e- colliders

Precisions achievable on h(125) coupling measurements provide powerful probe for heavy Higgs bosons





exact numbers outdated

[J. List]

[Cahill-Rowley, Hewett, Ismail, Rizzo, arXiv:1407.7021 [hep-ph]]

Generate large set of models by randomly scan the pMSSM parameter space

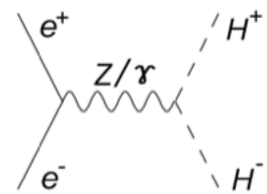
Colour scale: fraction of scan points excluded via coupling measurement

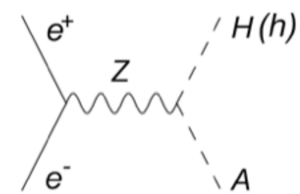
White lines: LHC direct search results for *A^0* at 7/8 TeV

BSM Higgs at e^+e^- colliders

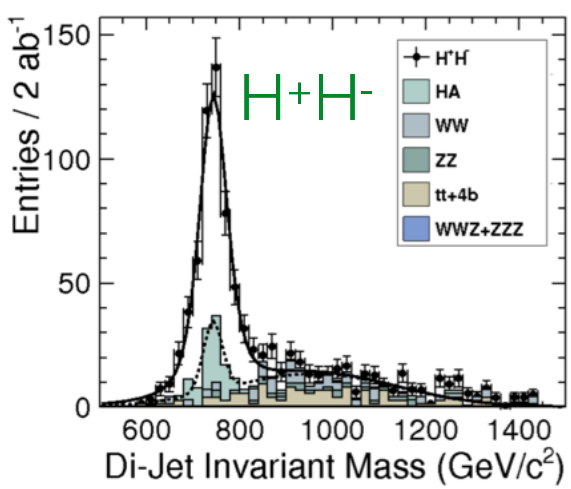
Discovery and precise measurement of BSM Higgs bosons if production within energy threshold

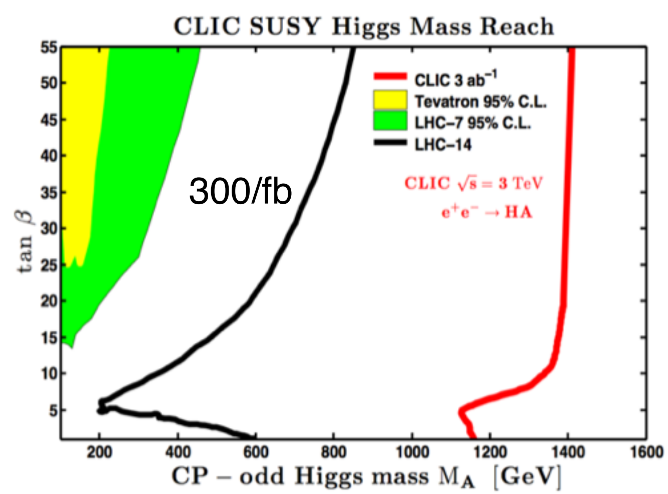
$$M_{H^+} < \sqrt{s}/2, \qquad M_{H^0} + M_{A^0} < \sqrt{s}.$$





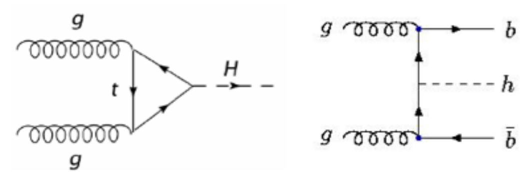
- (For higher masses associated prod. with fermions typically lower XS)
- Main decays
  - H/A → tt, bb, tau tau
  - H^+ → tb (tau ν)
- Percent level mass measurement (improve with kinematic fit)

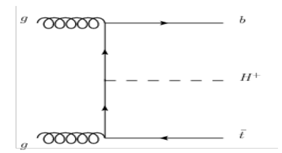




BSM Higgs at future pp colliders

Direct searches for heavy Higgs bosons in the 2HDM





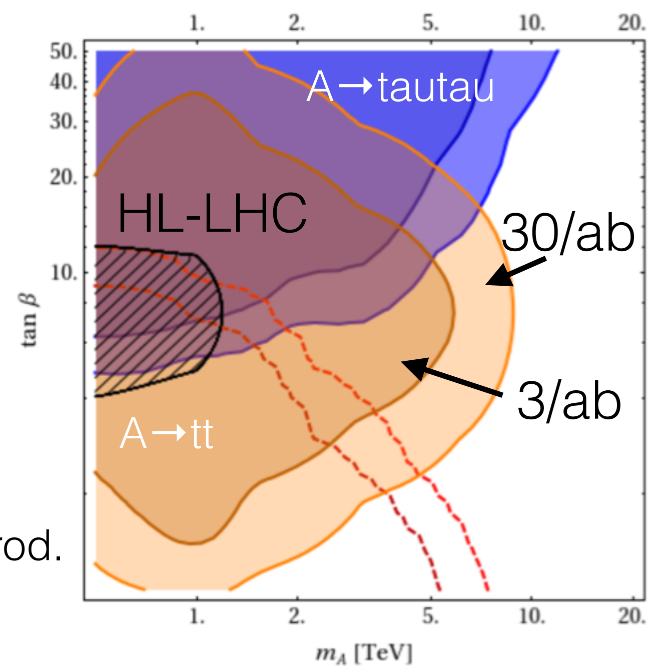
Large XS enhancement
σ(100 TeV)/σ(14 TeV)

30–50

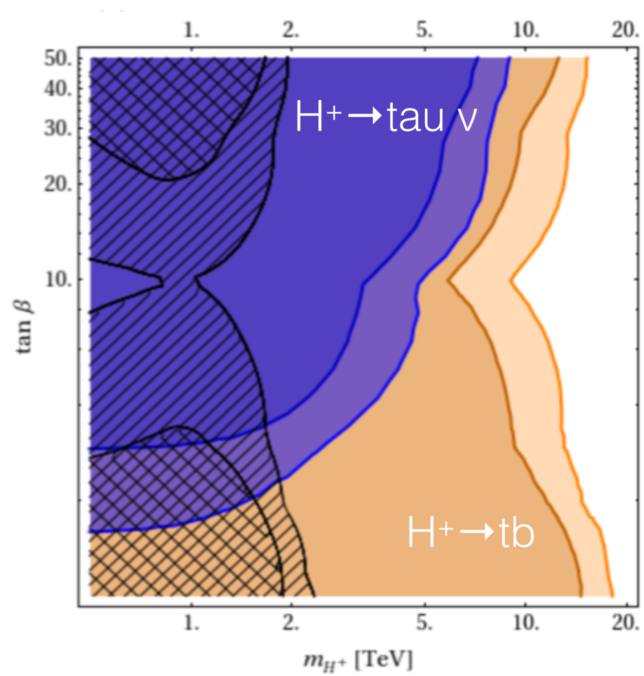
90

for mH = 500 GeV

bbH prod.
only



(c) Exclusion reach for neutral Higgs



(d) Exclusion reach for charged Higgs

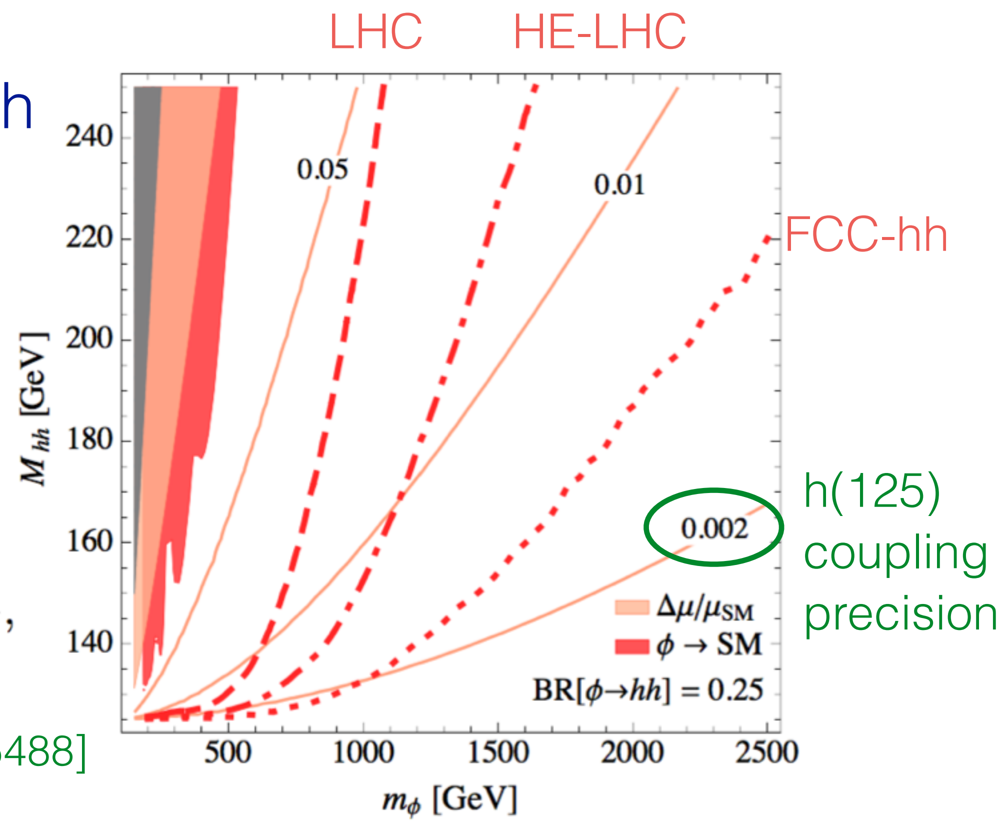
arXiv:1606.09408

Additional electroweak singlet

Mixing between singlet state and h(125): two CP-even bosons

Direct search vs. h(125)

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2},$$



[arXiv:1505.05488]

Complementary sensitivity between direct searches and h(125) measurements at the lower and higher mass region

Conclusions

Understanding the Higgs sector is one of the main goals in particle physics, many more results from the LHC to come

The ultimate precision on h(125) comes from e^+e^- colliders, several excellent options on the market

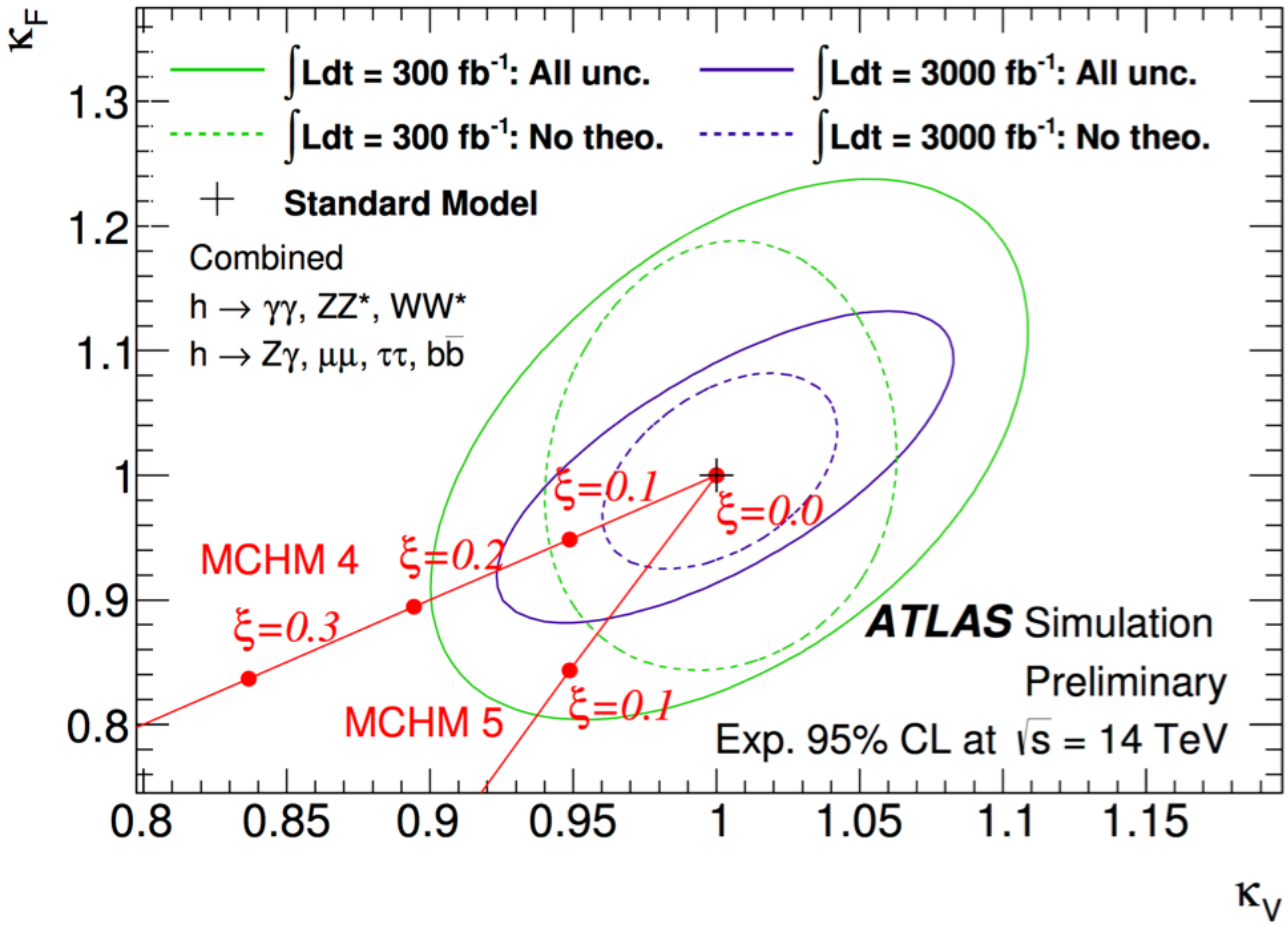
The physics will be in many ways complementary

- Between direct searches and h(125) precision measurements
- Between hadron and lepton colliders

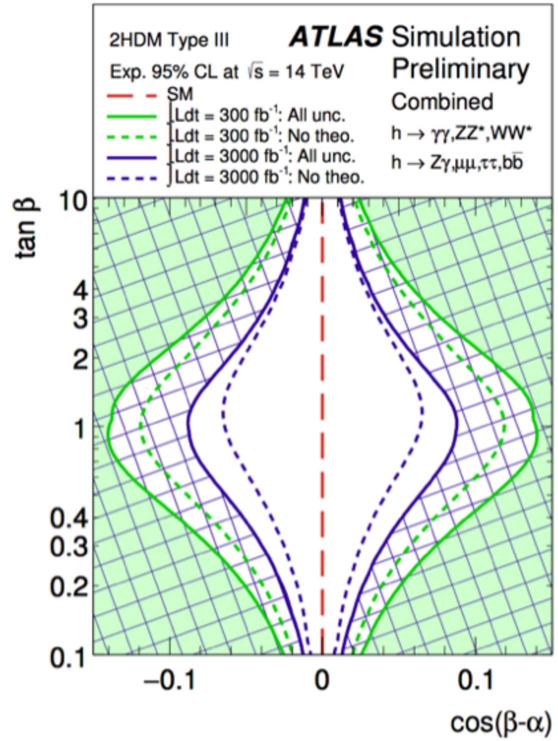
Looking forward to further exciting discoveries!

Additional material

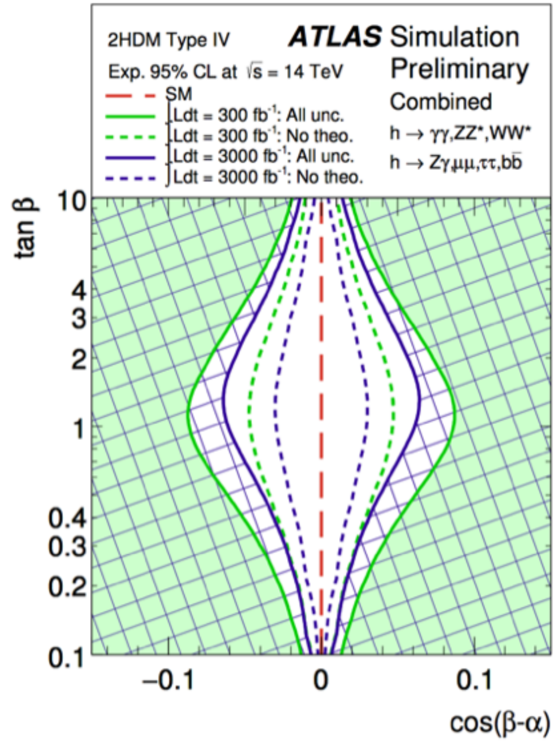
Composite Higgs



2HDMs



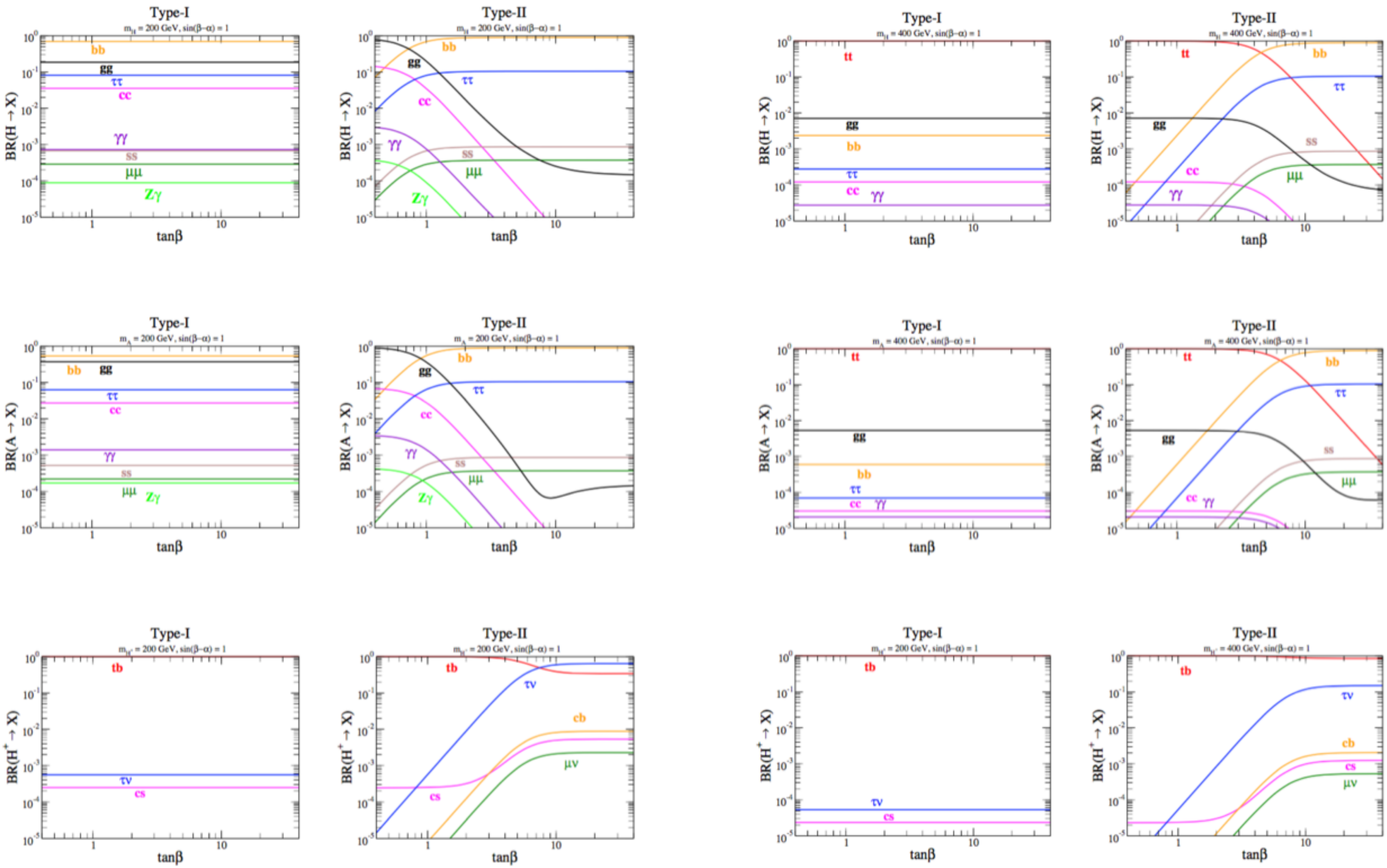
(c) Type III



(d) Type IV

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

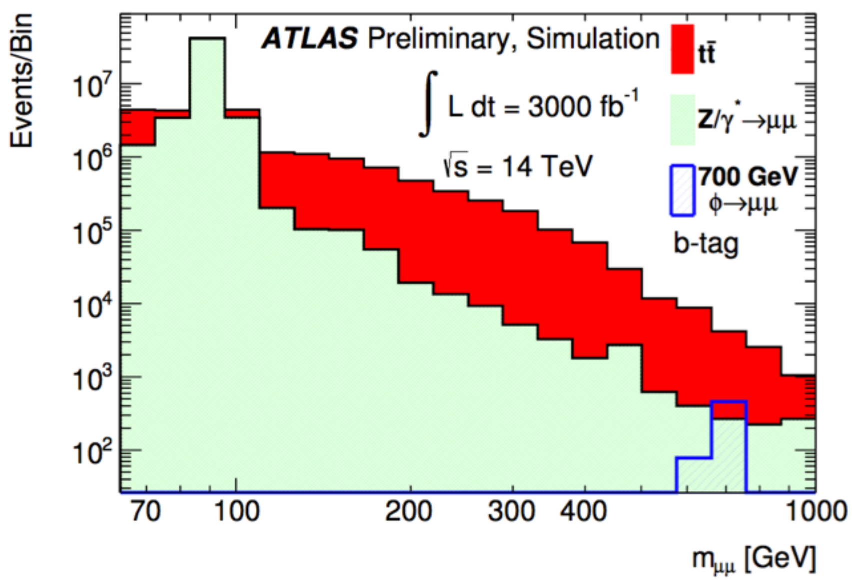
H/A/H+ decay BRs

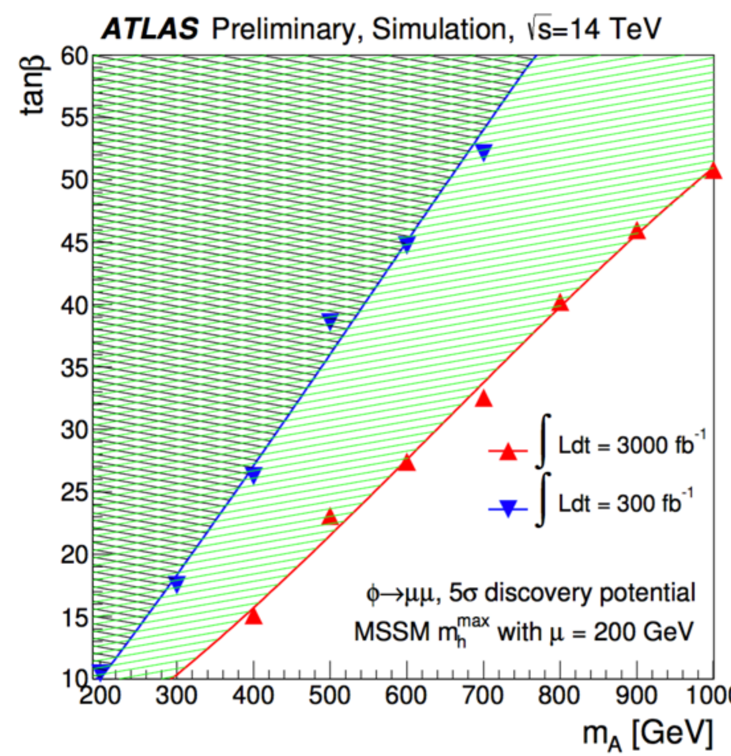


2HDMs - direct searches

A/H→ μμ in gluon-fusion and bbH production. Final state with excellent detector resolution

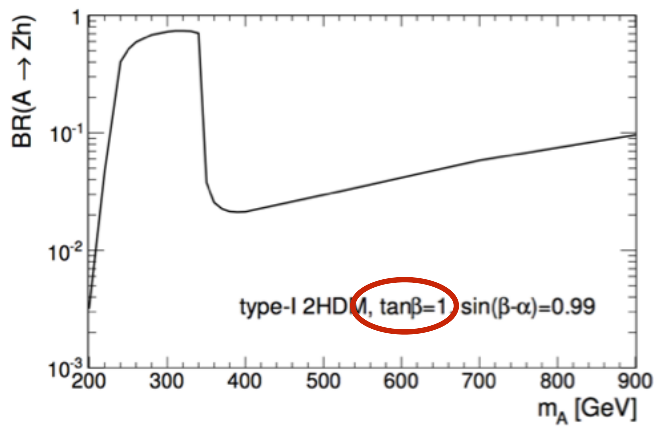
Require two opposite sign high pT muons. Main backgrounds Z and tt production. Categories with and w/o b-tag





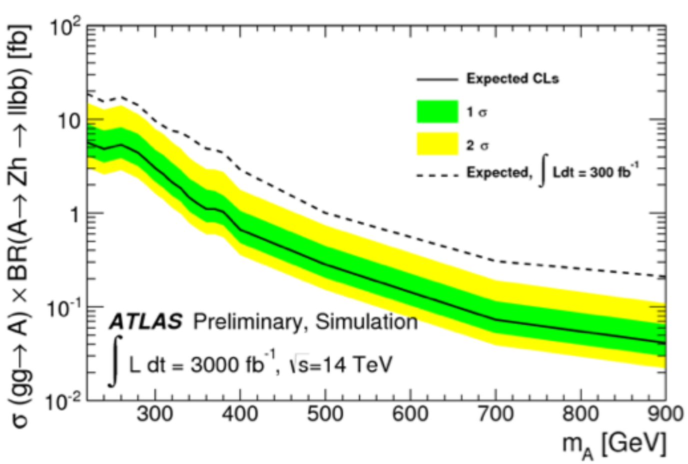
2HDMs - direct searches

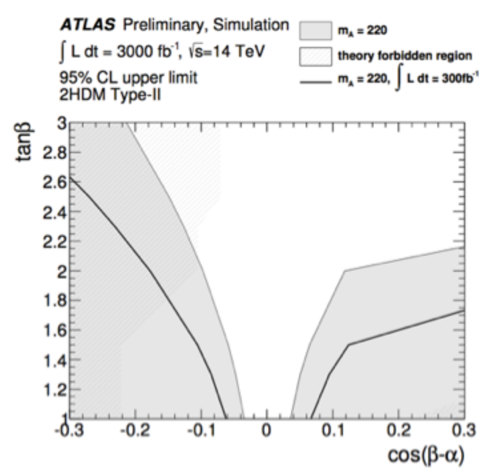
A→ Z(ll)h(bb) in gluon fusion production, clean signature and a fully reconstructible A boson mass

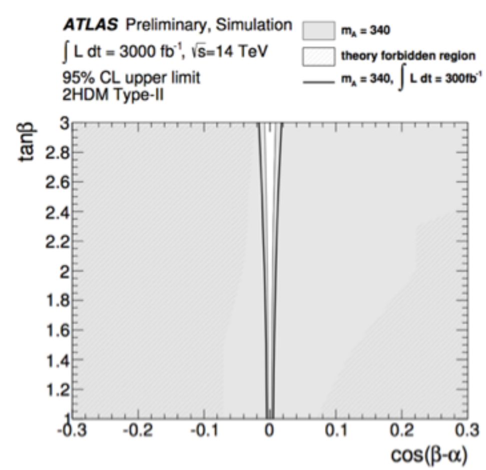


Select 2 high pT same flavour, opposite sing leptons and 2 b-tagged jets

Main backgrounds: Z+jets, tt, ZZ

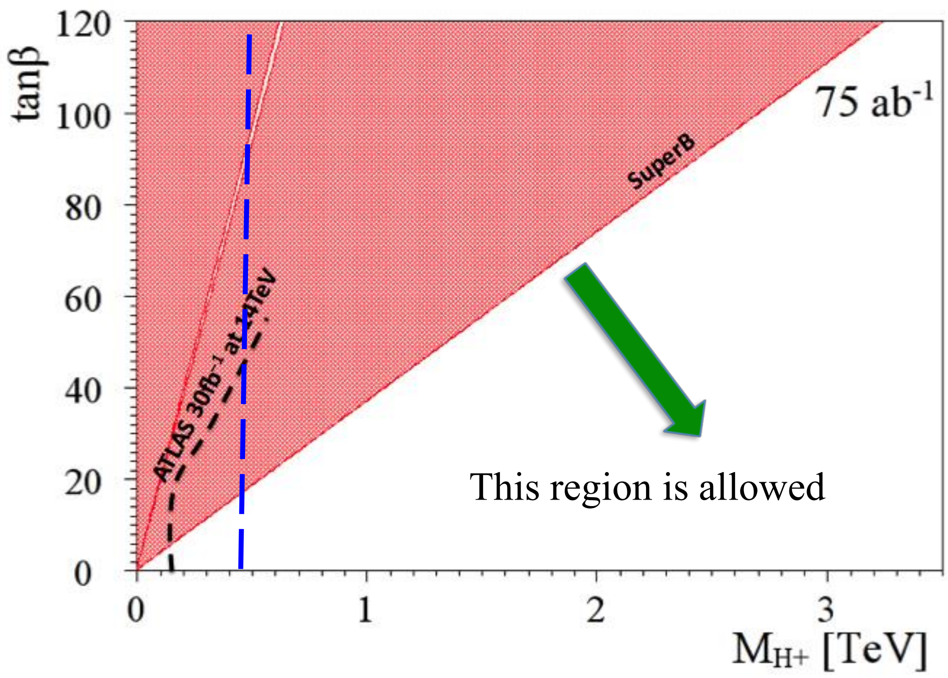




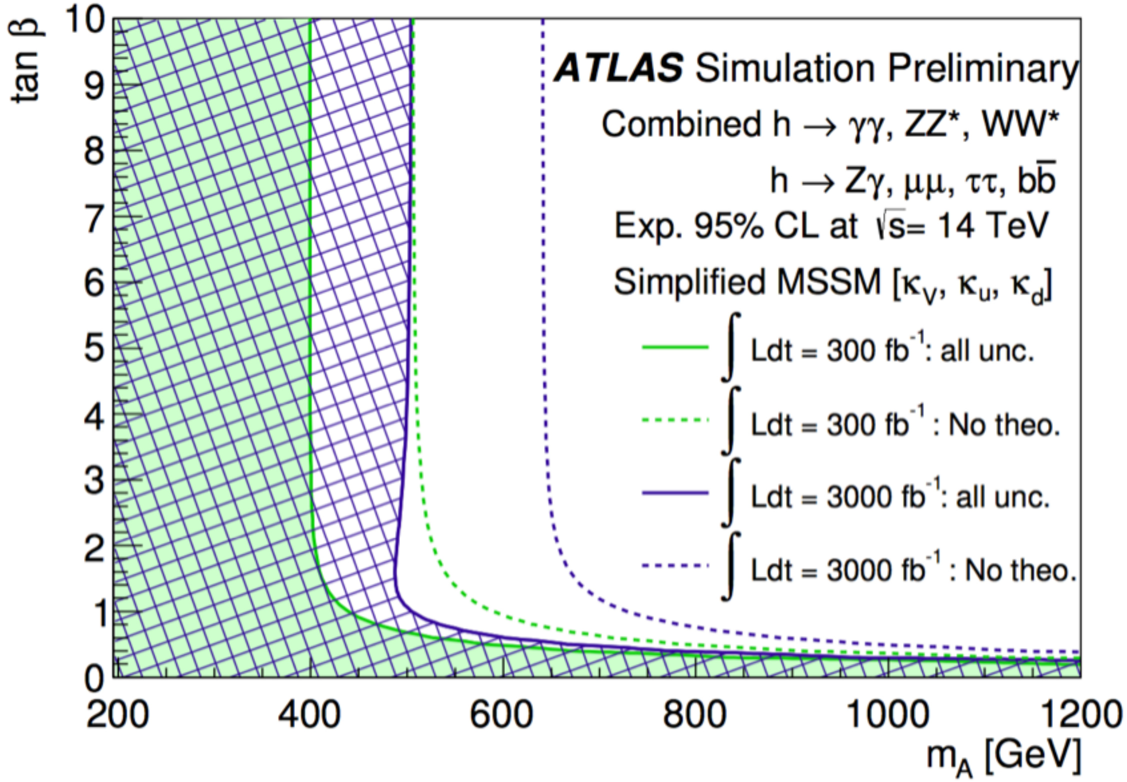


Belle2 projection

Somewhat outdated, expect 50/ab

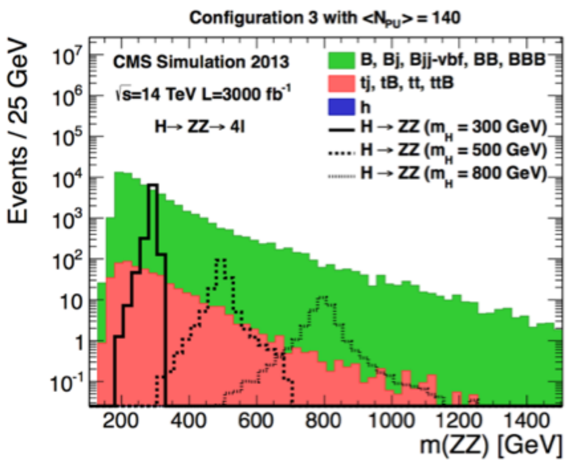


Simplified MSSM

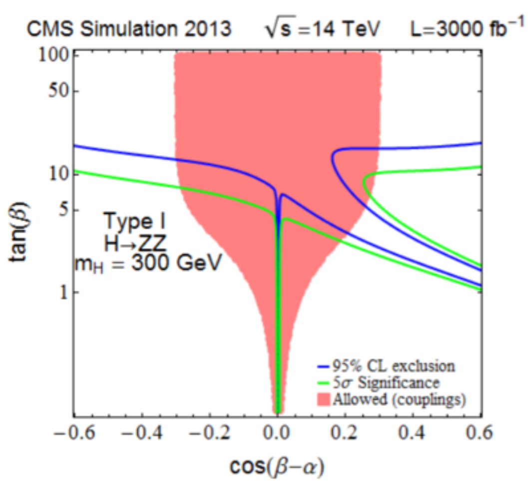


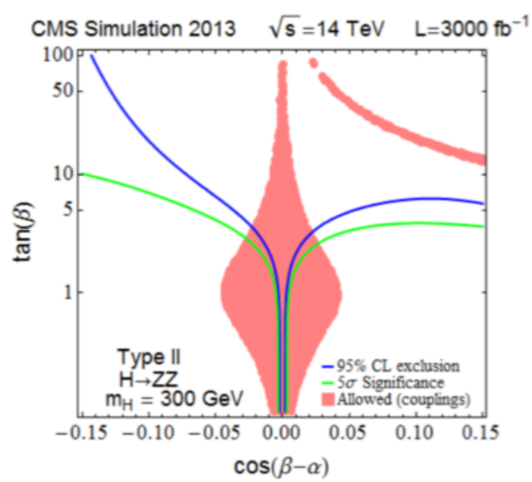
2HDMs - direct searches

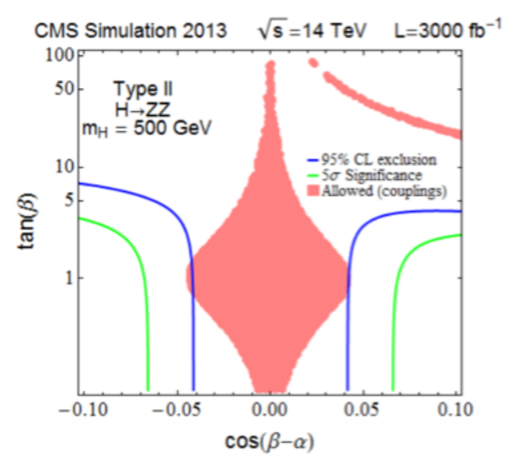
H→ Z(ll)Z(ll) in gluon fusion production, clean final state with excellent H mass resolution (large discovery potential)



Same conclusions as for the A→Zh channel!







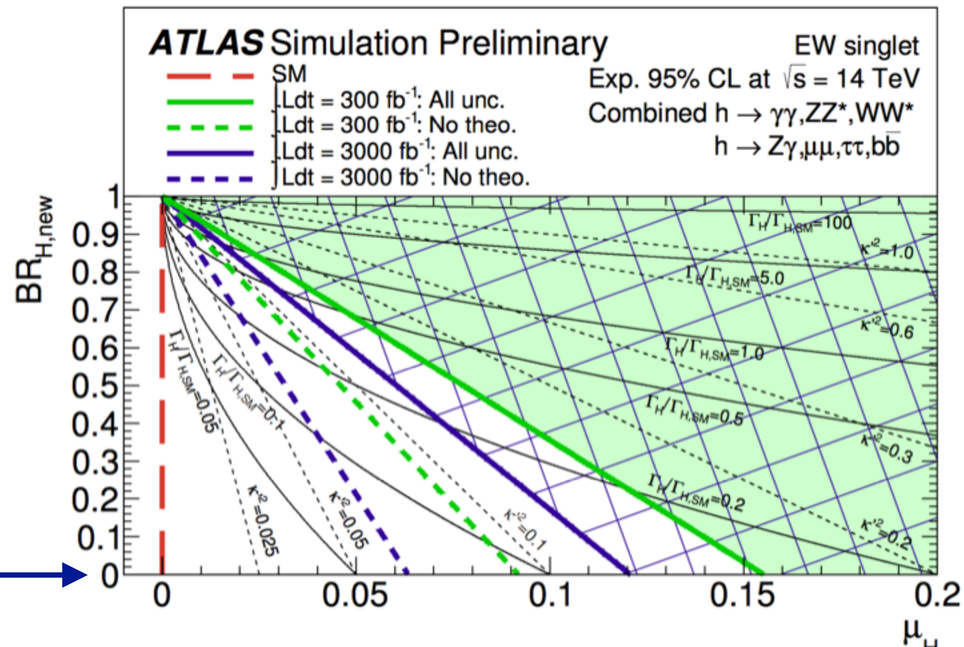
Additional electroweak singlet

Mixing between singlet state and h(125): two CP-even bosons

Coupling to SM particles reduced by common scale factors k' and k, with unitarity constraint: $k'^2 + k^2 = 1$

SM BRs for h, allow BR_{new} for H, such as $H \rightarrow hh$

Reflects directly SM Higgs precision



Heavy H signal strength (wrt. SM) couplings