Higgs Beyond the SM at the LHC

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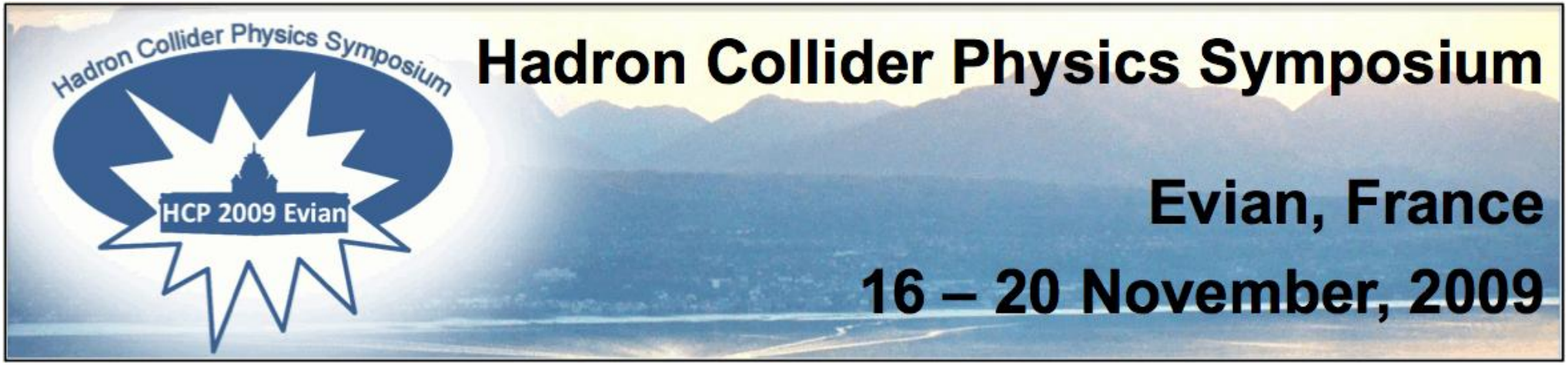
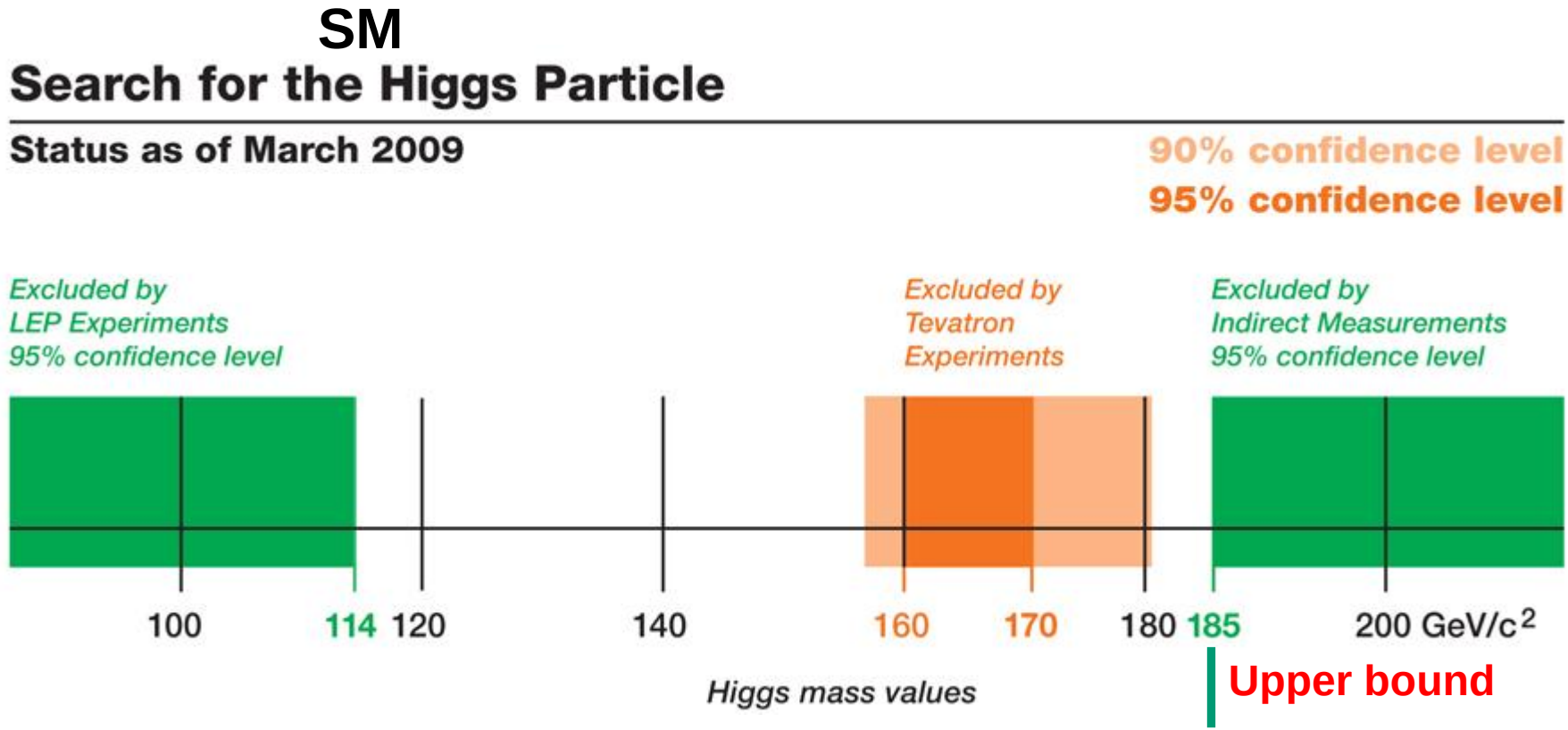
on behalf of the
ATLAS and CMS Collaborations

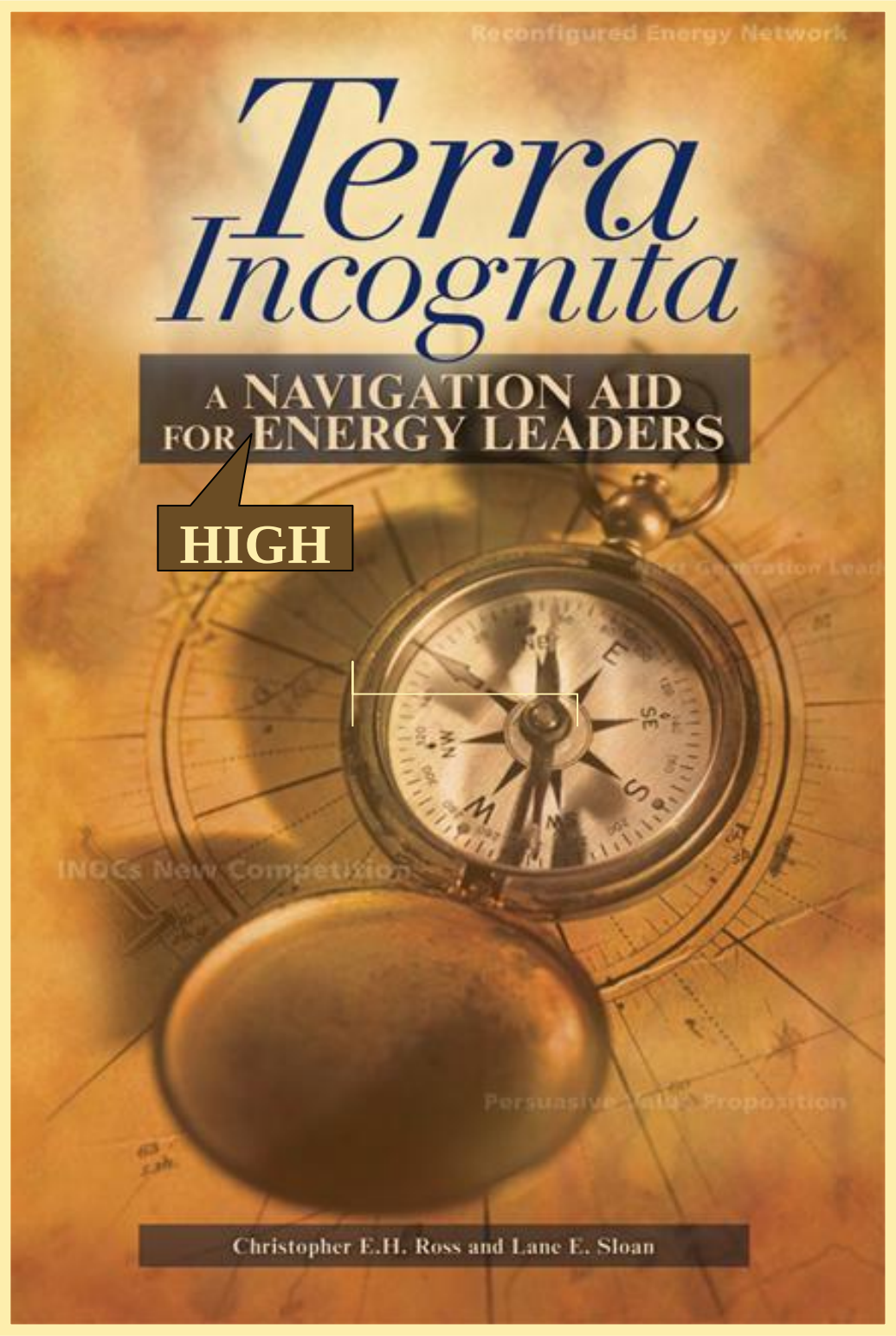


SM Higgs Bounds



http://www.fnal.gov/pub/presspass/images/20090313higgs/HiggsGraph_031309_MedRes.jpg

A part for its mass (only bound by experiments), the other properties of the SM Higgs boson are precisely predicted by theory and the experimental discovery strategy and reach can be reliably evaluated (see F. Cerutti's talk)



BSM Higgs (sector) UnBounded

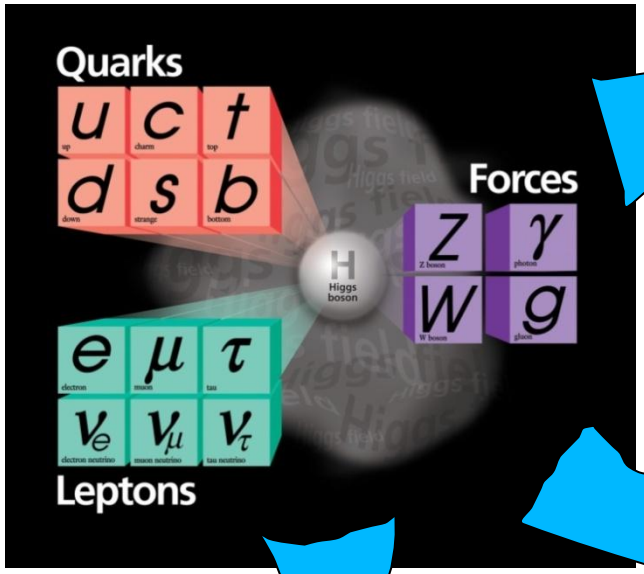
No experimental evidence for BSM…

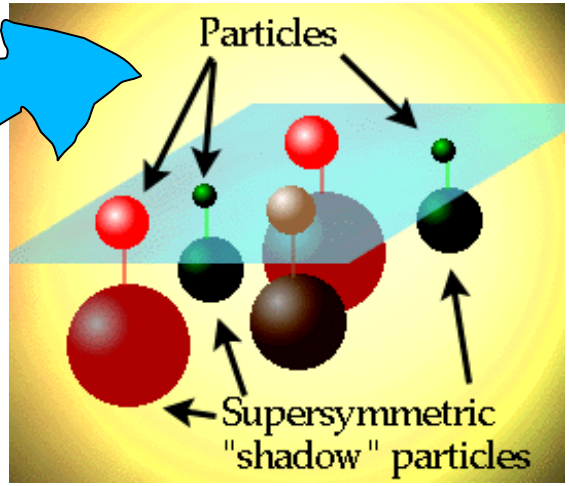
***Terra Incognita*:**

Need a navigation aid

-> BSM directions

What BSM?

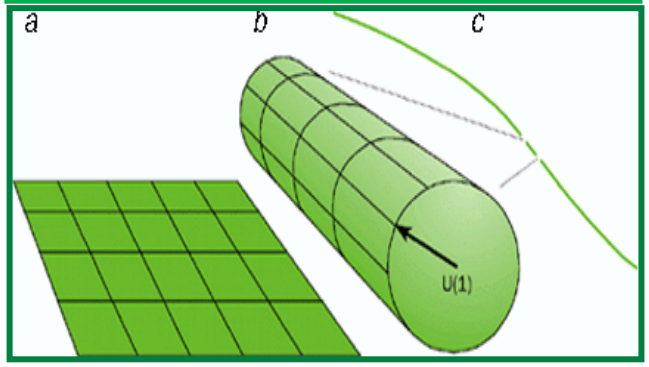




Little Higgs,
Extended Gauge Symmetries,
Fourth generation,...

Z',W',b',t',ν',l',...

Extra-Dimensions



Many possible BSM directions…

Need navigation aid
=>specific BSM models: important as a reference (benchmarks)

to prepare the experimental search strategies
=> particularly trigger (on-line) selections
"an event not passing the trigger is lost forever"

… but always keep an open mind for surprises…

Above: Poor (wo)man pictorial view of BSM scenarios…
for a complete account of the theory and the experimental BSM searches, see talks in yesterday's New Phenomena session…

What BSM Higgs?

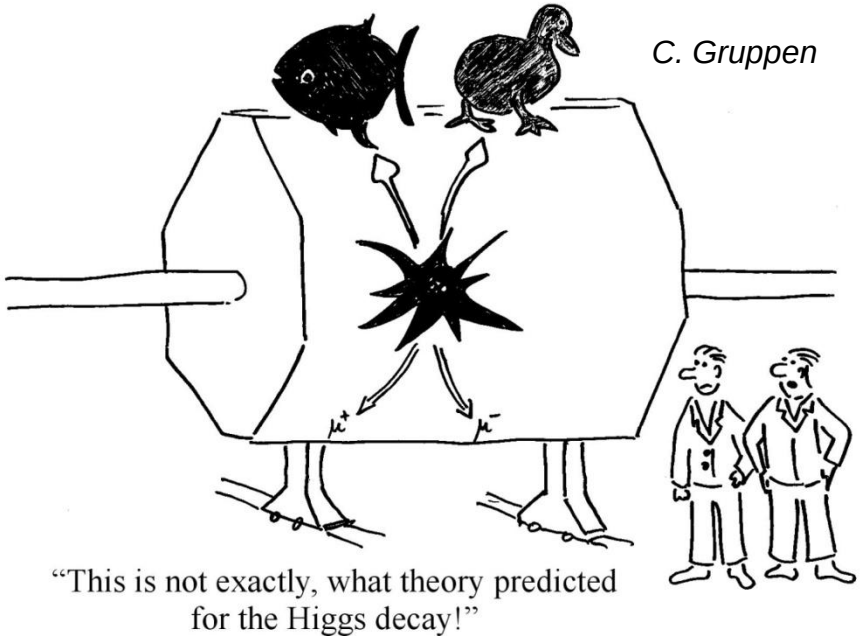
Higgs boson(s) play an essential role in many BSM models. A Higgs particle is expected to be a relatively light (< 1TeV) Other Higgs properties are depending on the specific model.

see talks by C. Anastasiou and R. Contino

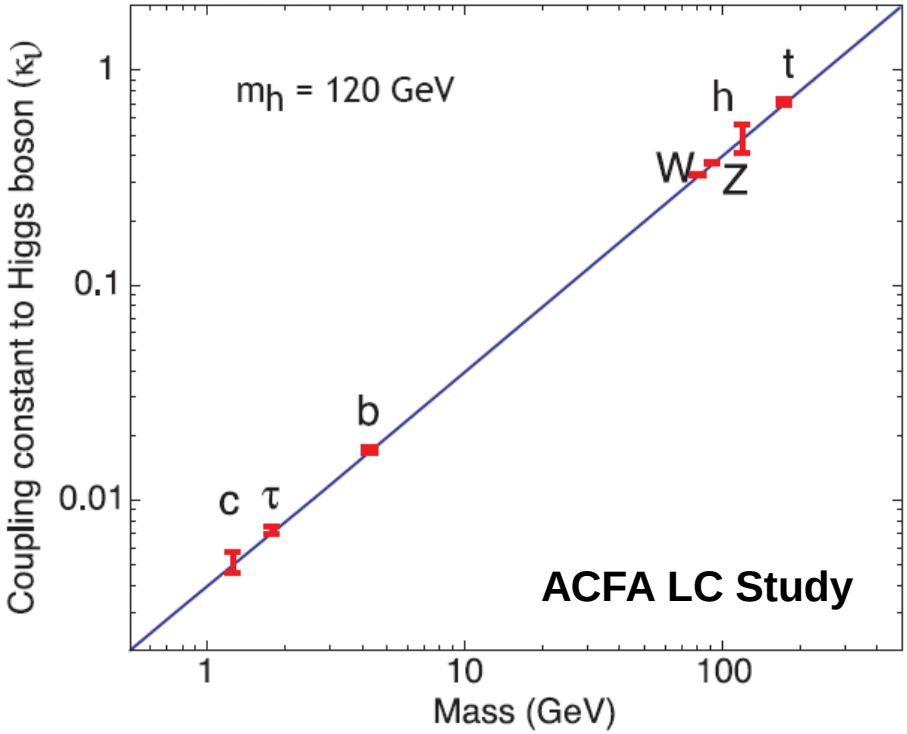
Higgs fingerprints:

- ❑ Mass <~ 1TeV
- ❑ (Pseudo)Scalar: S=0
- ❑ Charge: C=0, 1, 2…
- ❑ Couplings proportional to masses, in the SM, model dependent in BSM models
- ❑ CP-even or CP-odd , with CP-conserving, or CP violating, interactions
- ❑ One Higgs or more…

Beyond early discovery, measuring the Higgs properties is an essential tool for a deeper understanding of the underlying new physics



SM-like Higgs Couplings



BSM Higgs Studies for LHC

The main goal of the Monte Carlo based BSM Higgs experimental studies is to
set-up the search - trigger, background estimation methods, analysis tools -
into final states and topologies different from those studied for the SM Higgs ,
but potentially relevant and even dominant in BSM scenarios.

In BSM scenarios like
- **SUSY: MSSM, NMSSM, THD,…**
- **Extra Dimensions**
- **Little Higgs**
- **Models with extra bosons and fermions**
- **Others…**

Final states with:
- **multiple b's and/or taus**
- **lepton resonances**
- **cascade decays**
- **invisible decays**

…can be dominant Higgs signatures

ATLAS & CMS MC studies result into predictions of the experimental discovery reach
First observation (mass, charge,…) and detailed measurements (couplings, spin, CP,…)
to determine the role of the newly detected Higgs-like particles, in view of possible outcomes

Early discovery and measurement	Observation	Open question
Neutral Higgs low mass<185 GeV	Consistent w/ SM or MSSM	SM, MSSM , other BSM?
Neutral Higgs high mass>185 GeV	Inconsistent with SM	MSSM, other BSM ?
More than one neutral Higgs	inconsistent with SM	MSSM, other BSM ?
Charged Higgs	inconsistent with SM	MSSM, other BSM ?
Other BSM particles /interactions	inconsistent with SM	BSM Model? Higgs sector?

Setting-up the Search for Discovery

Determine trigger conditions to be highly efficient on "BSM look-alike" SM physics (loosely defined signal region, model ind.)

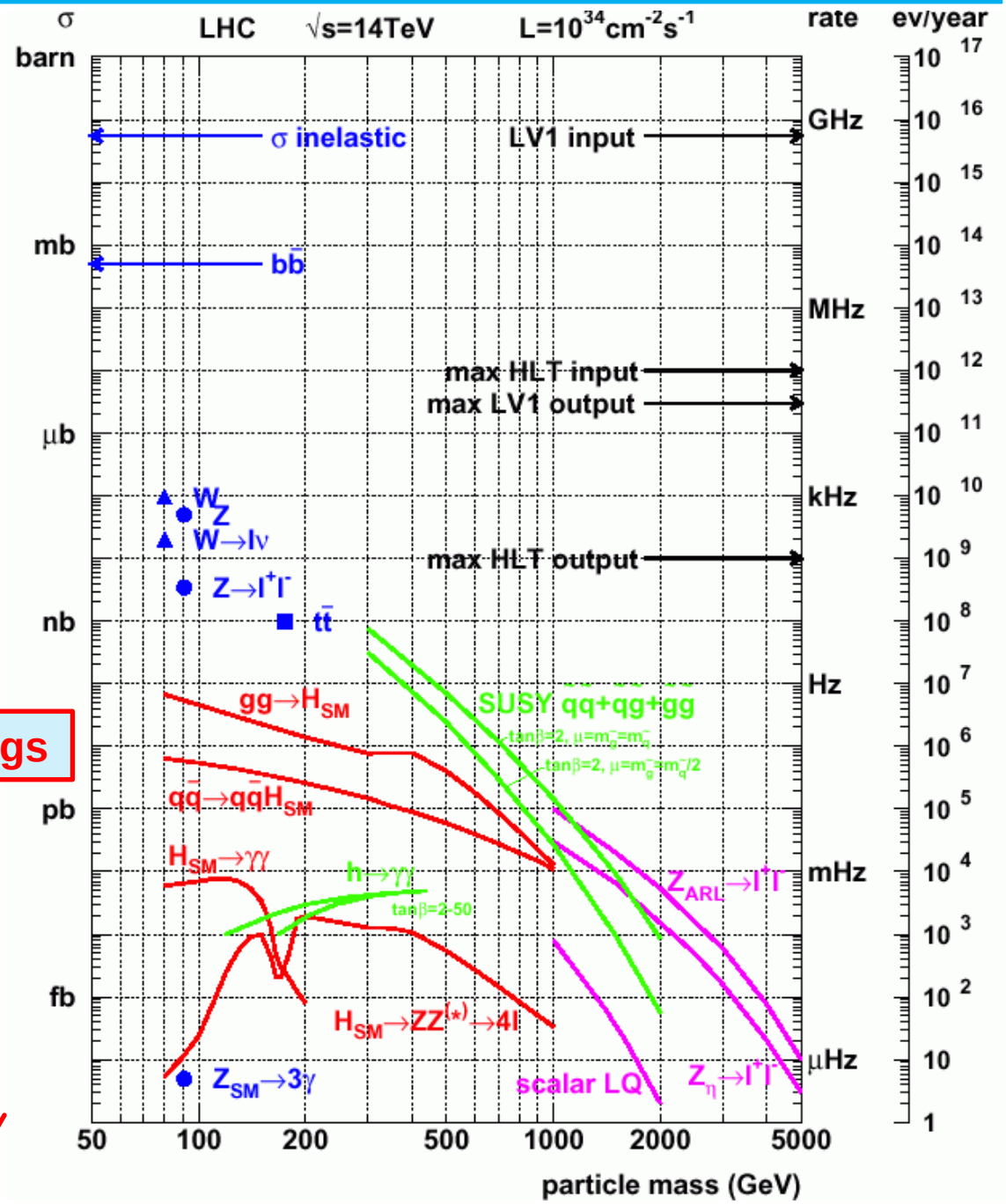
Determine SM background contributions define reliable methods to measure the SM background from data itself (measure SM tails, rare SM processes, W/Z+njets, tt+njets, WW, WZ, ZZ,etc)

Define signal region (model dependent), determine discriminating quantities to maximize signal-to-background ratio and minimize (stat. and syst.) uncertainties

Maximize discovery reach for early observation (event yield, mass, charge,…), as a function of model parameters, depending on integrated luminosity

Define methods for detailed Higgs measurements (couplings, spin, CP,…) to determine the role of the newly detected Higgs-like particles,

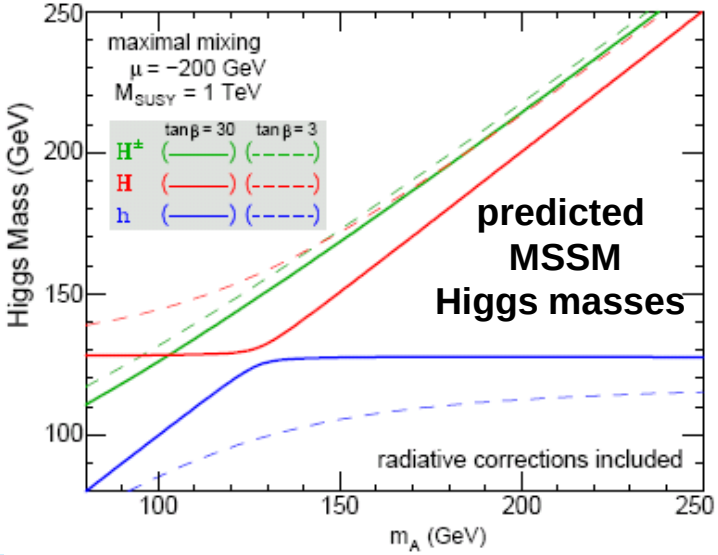
Higgs



Higgs in MSSM and extensions

Model predictions:

- ❑ light (<~130 Gev), neutral CP-even Higgs, h
- ❑ heavier neutral CP-even Higgs, H
- ❑ neutral CP-odd Higgs A
- ❑ charged Higgs bosons (C= +/-1)
- ❑ decays to known gauge bosons and fermions
- ❑ may decays to SUSY particles, if light enough
  -> visible cascade and invisible decays



Present experimental status 2009 : MSSM parameter space bounded by LEP and Tevatron negative searches for neutral and charged Higgs bosons

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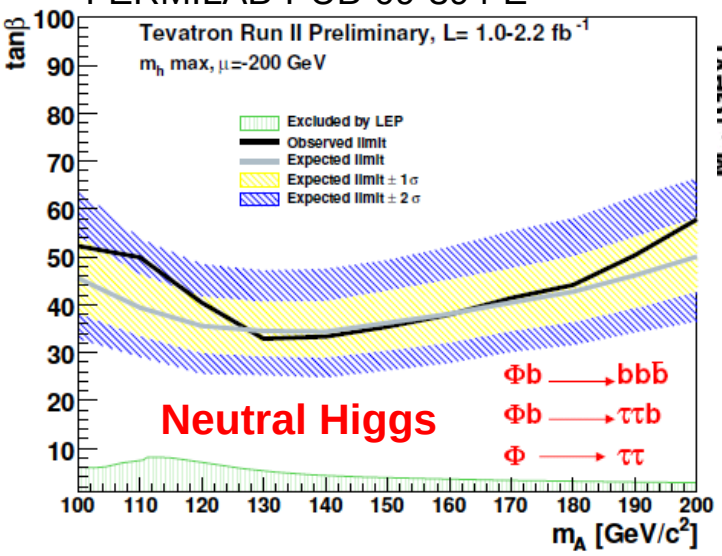
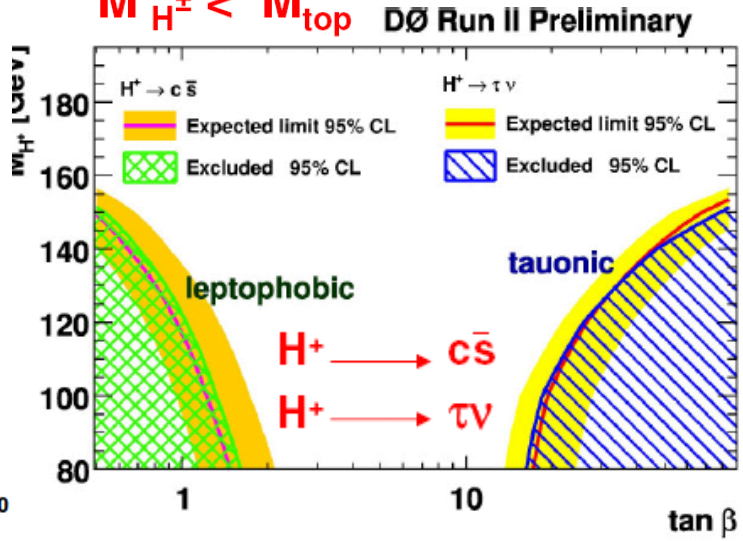
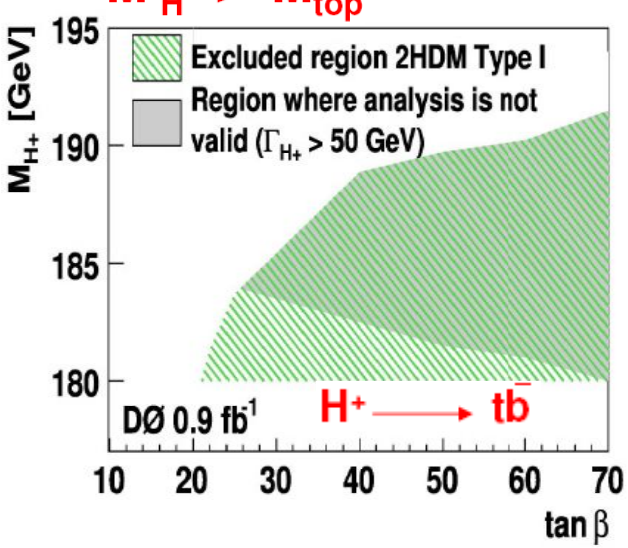


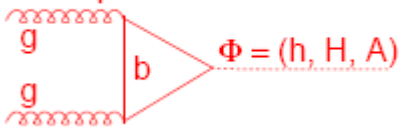
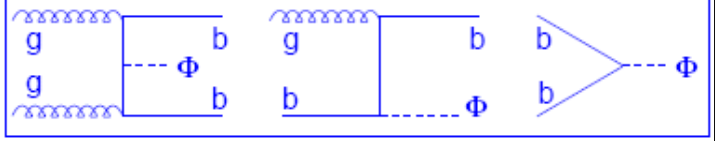
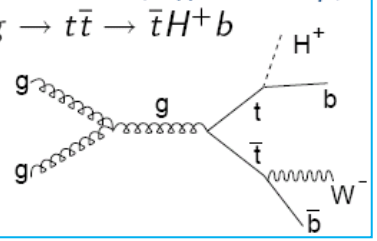
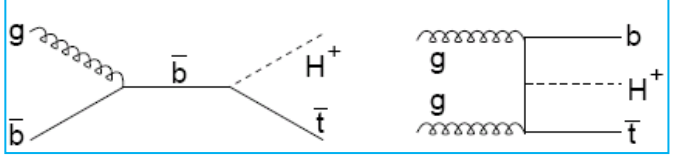
$M_{H^\pm} < M_{top}$



$M_{H^\pm} > M_{top}$



MSSM Higgs LHC Searches at a glance

Particle	Dominant production processes	Decay	Final states investigated
Neutral Higgs Bosons h, H, A	Direct production  Associated production with b−quarks dominating production at large tan β 	$h/H/A \to b\bar{b}$ at large tan β , dominant decay, large background $h/H/A \to \tau^+\tau^-$ L arge BR, clean final state $h/H/A \to \mu^+\mu^-$ Very low BR but very good mass resolution	SM Higgs-like final states, from VBF $qqh/H - \tau\tau$ and direct production with $h \to \gamma\gamma$ $h/H/A \to \tau^+\tau^- \to \ell\ell + 4\nu$ $\to \ell\tau_{jet} + 3\nu$ $\to \tau_{jet}\tau_{jet} + 2\nu$ $h/H/A \to \mu^+\mu^-$
Charged Higgs Bosons H+, H-	Light $H^\pm$ ($m_{H^\pm} < m_{top}$): $gg \to t\bar{t} \to \bar{t}H^+b$  Heavy $H^\pm$ ($m_{H^\pm} > m_{top}$): $g\bar{b} \to \bar{t}H^+$ and $gg \to \bar{t}bH^+$ 	For $m_{H^\pm} < m_{top}$: $H^\pm \to \tau^\pm\nu$ For $m_{H^\pm} > m_{top}$: $H^\pm \to tb$ and $H^\pm \to \tau^\pm\nu$	$tt \to (H^\pm b)(W^\mp b) \to$ $\to (\tau_{jet}\nu\nu b)(\ell^\mp\nu b)$ $\to (\tau_{jet}\nu\nu b)(qqb)$ $\to (\ell\nu\nu\nu b)(qqb)$ $gg, gb \to t[b]H^\pm \to$ $\to (Wb)[b](\tau\nu) \to (bqq)[b](\tau_{jet}\nu\nu)$ $\to (Wb)[b](tb) \to (b\ell\nu)[b](bqqb)$

MSSM Higgs Reach

$b\bar{b}\,(h/H/A \to \tau^+\tau^-)$

$\to \tau_{jet}\tau_{jet} + 2\nu$

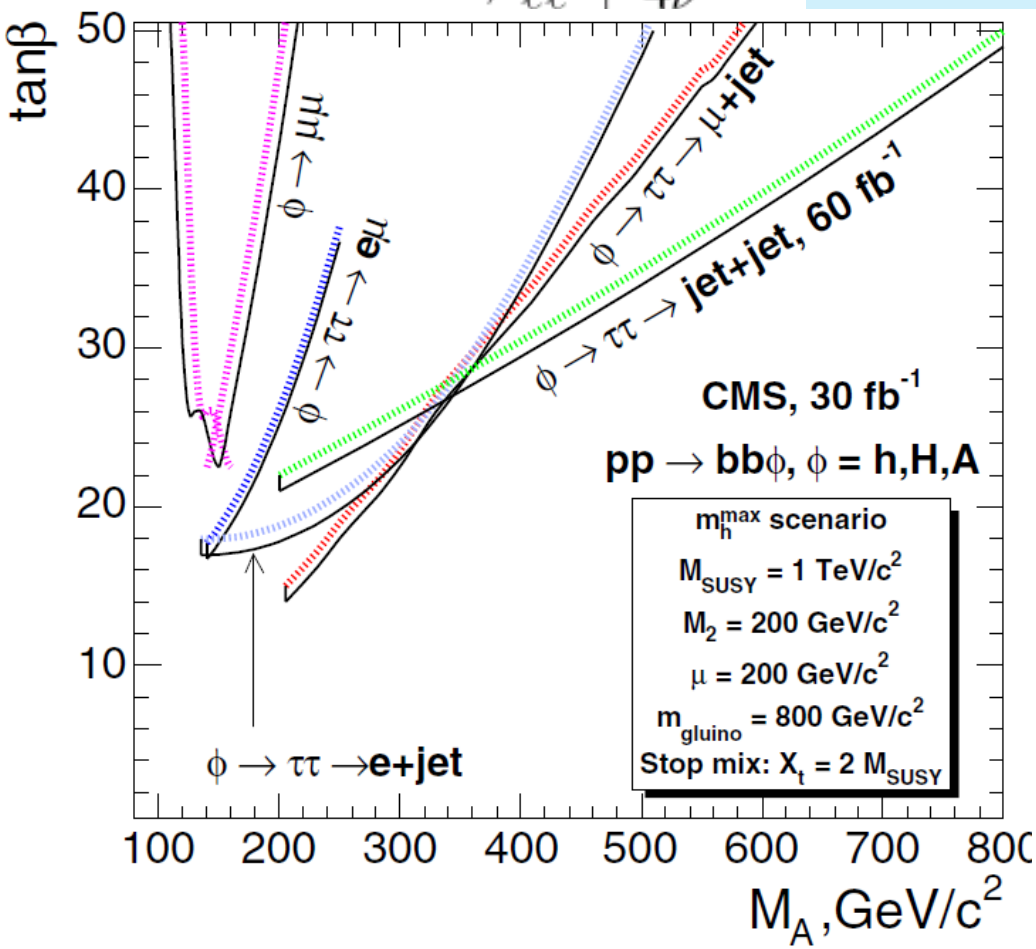
$\to \ell\tau_{jet} + 3\nu$

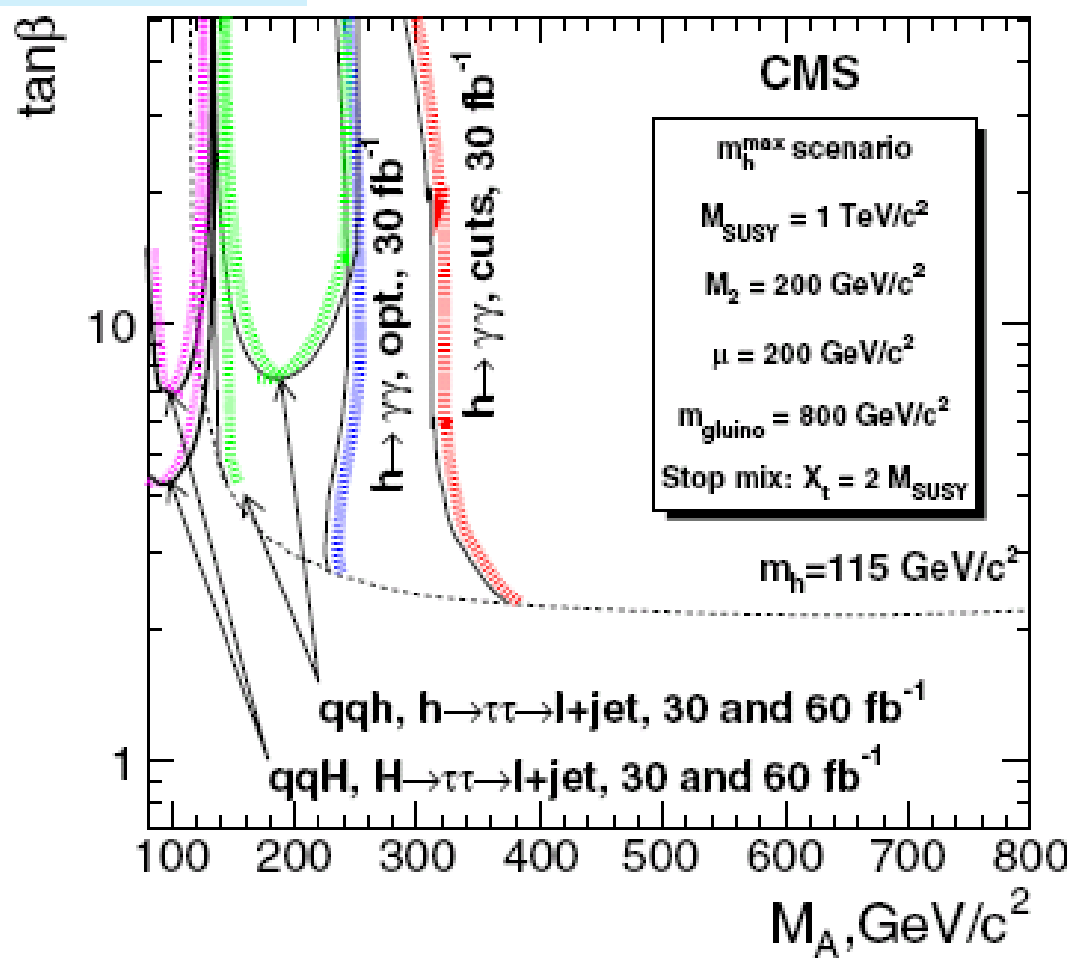
$\to \ell\ell + 4\nu$

VBF $qqh/H \to \tau\tau$ and $h \to \gamma\gamma$

SM Higgs searches interpreted in MSSM

5 σ discovery contours





(*)m_h^{max} **scenario** designed to provide the most conservative MSSM exclusion limits from LEP

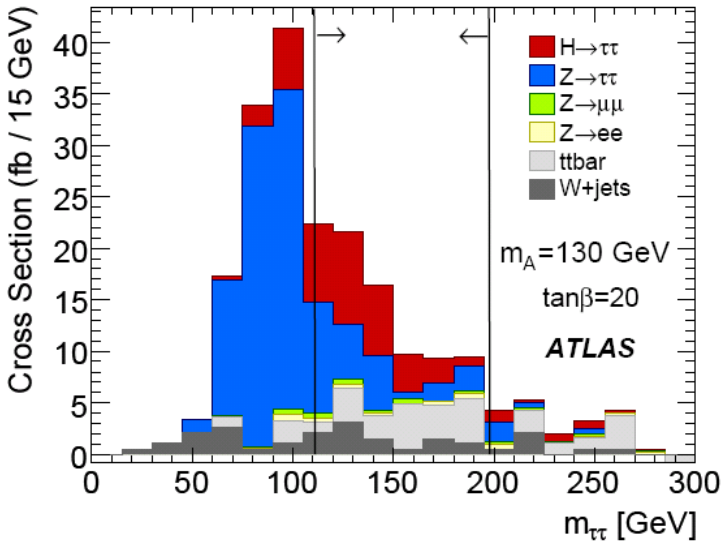
MSSM Higgs Reach with Dilepton Final States

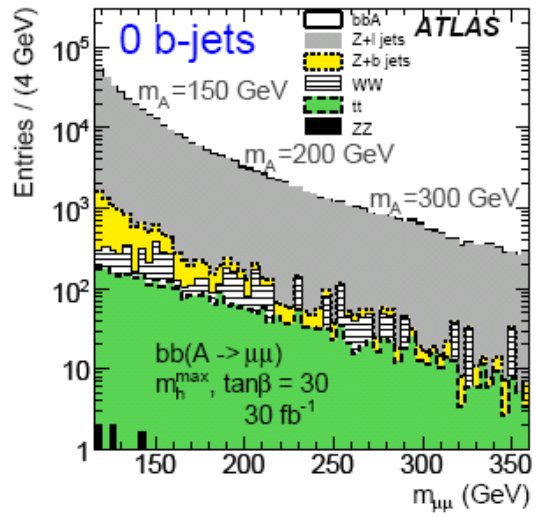
$b\bar{b}\,(h/H/A \to \tau^+\tau^-)$

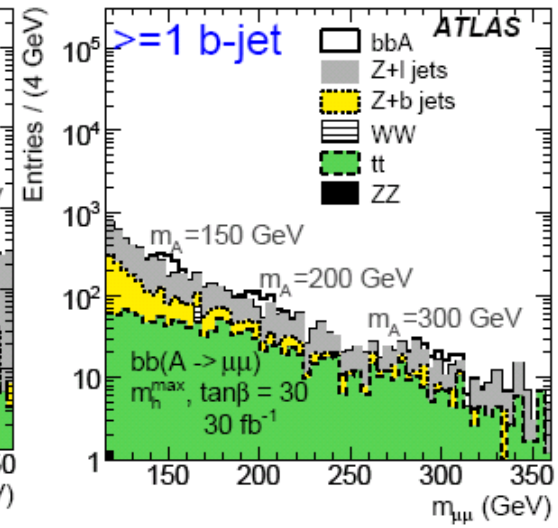
ττ→2l +4ν

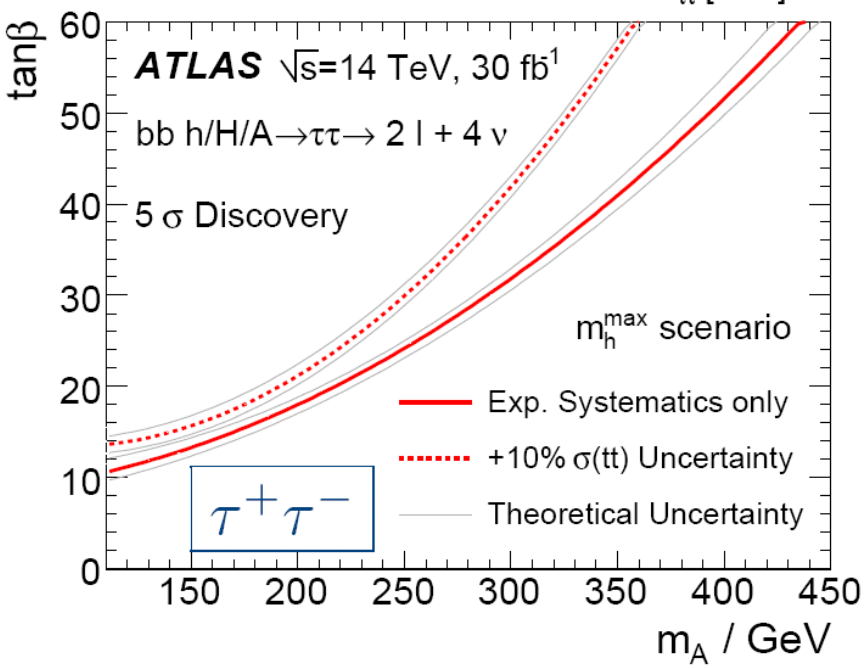
$b\bar{b}\,(h/H/A \to \mu^+\mu^-)$

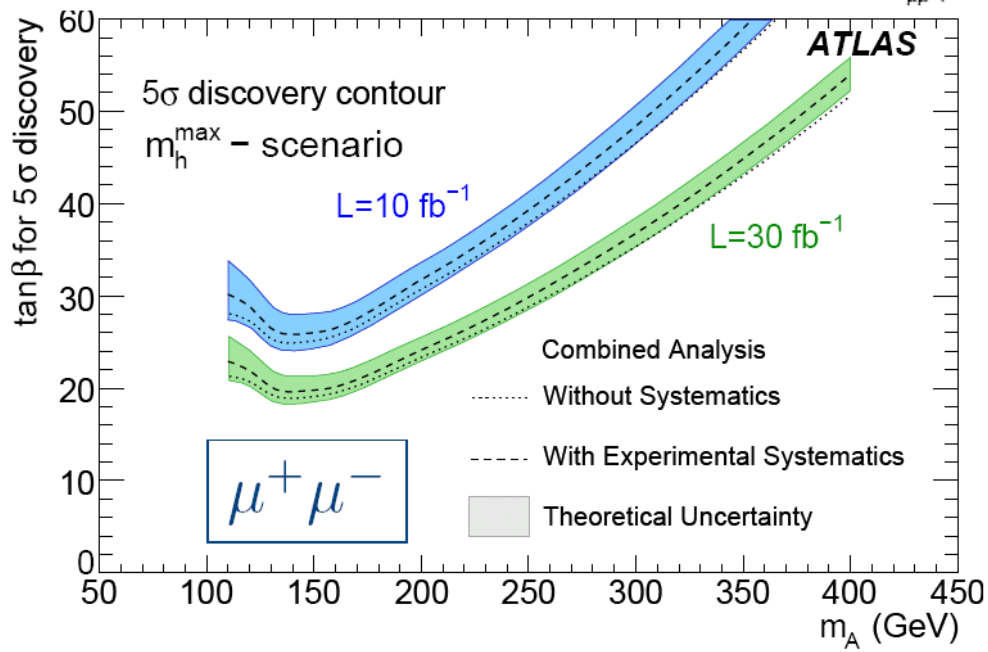
low BR, but good mass resolution





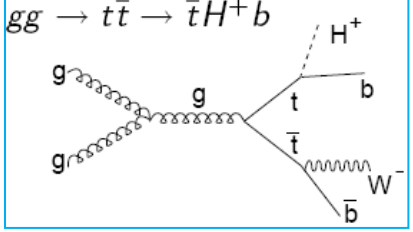






Charged Higgs Discovery Reach

Light $H^{\pm}$ ($m_{H^{\pm}} < m_{top}$):
$gg \to t\bar{t} \to \bar{t}H^{+}b$

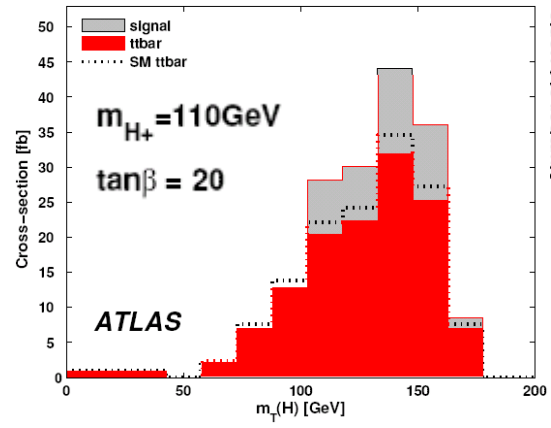


$\to b\tau(had)\nu bqq$

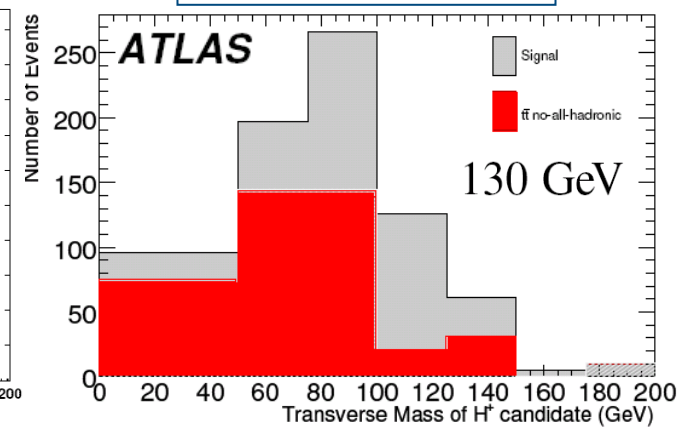
$\to b\tau(lep)\nu bqq$

$\to b\tau(had)\nu b\ell\nu$

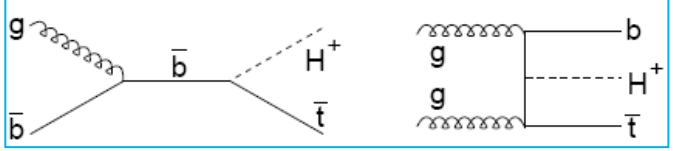
$b\tau(lep)\nu bqq$



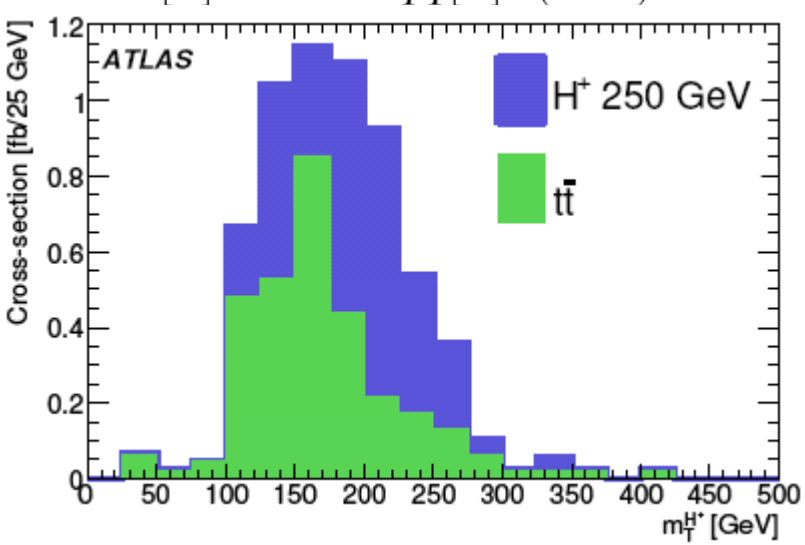
$b\tau(had)\nu bqq$

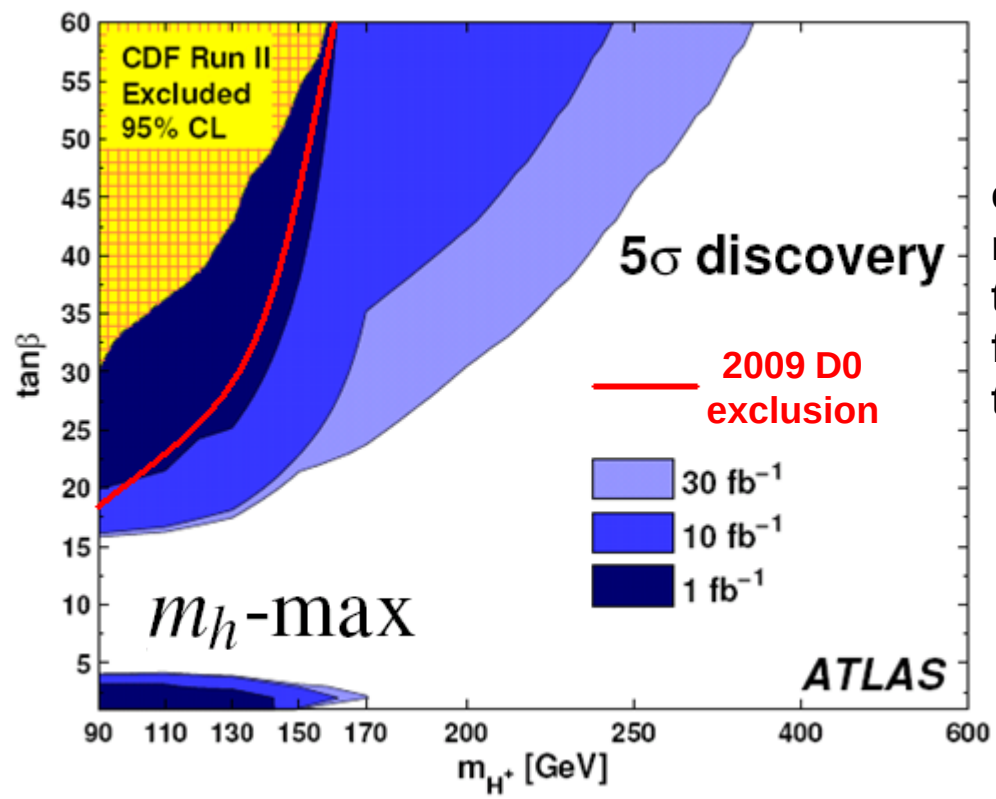


Heavy $H^{\pm}$ ($m_{H^{\pm}} > m_{top}$):
$g\bar{b} \to \bar{t}H^{+}$ and $gg \to \bar{t}bH^{+}$



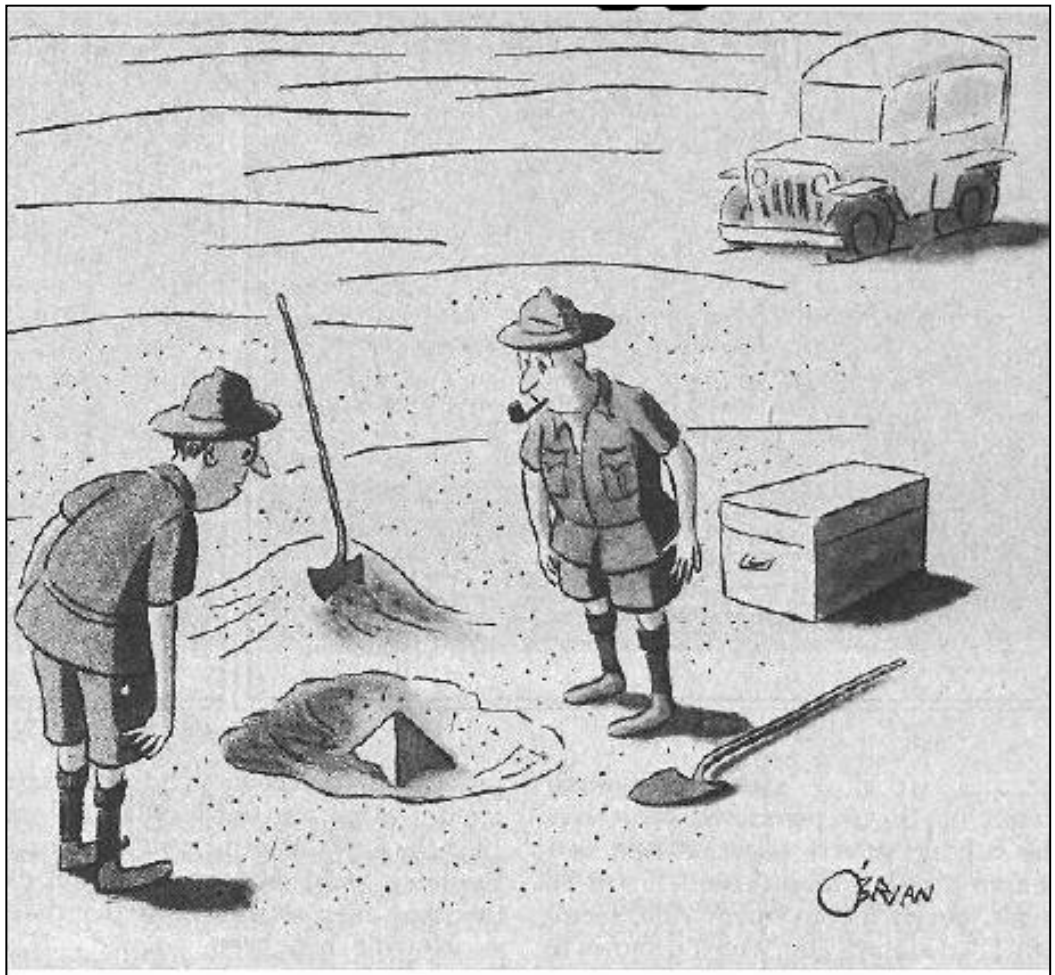
$t[b]H^{+} \to bqq[b]\tau(had)\nu$





exclusion region up to ~600 GeV for large tan β

Beyond MSSM

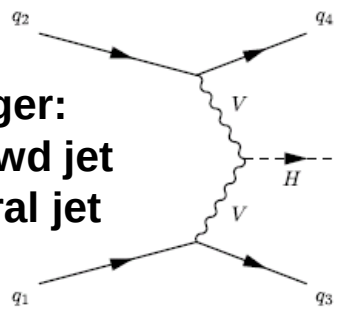


"This could be the discovery of the century. Depending, of course, on how far down it goes."

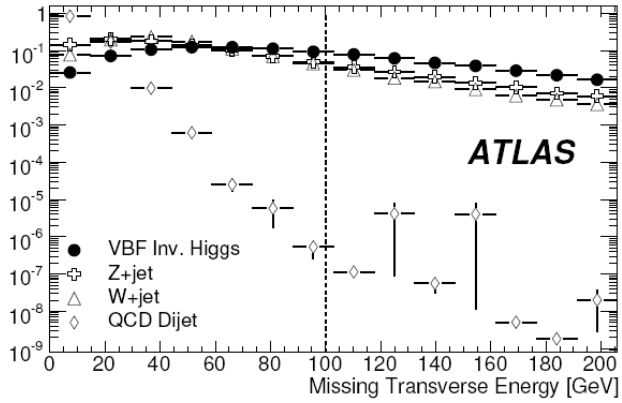
Invisible Higgs

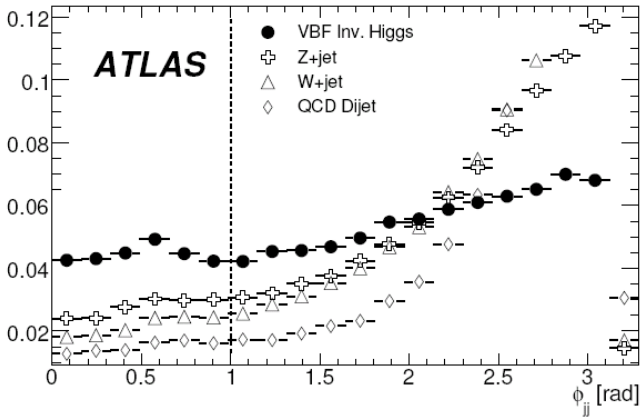
H production via VBF

Trigger: MET+fwd jet +central jet



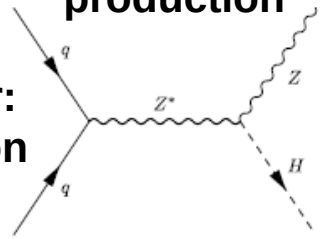
Cut-based and tagging jet azimuthal angle shape analysis



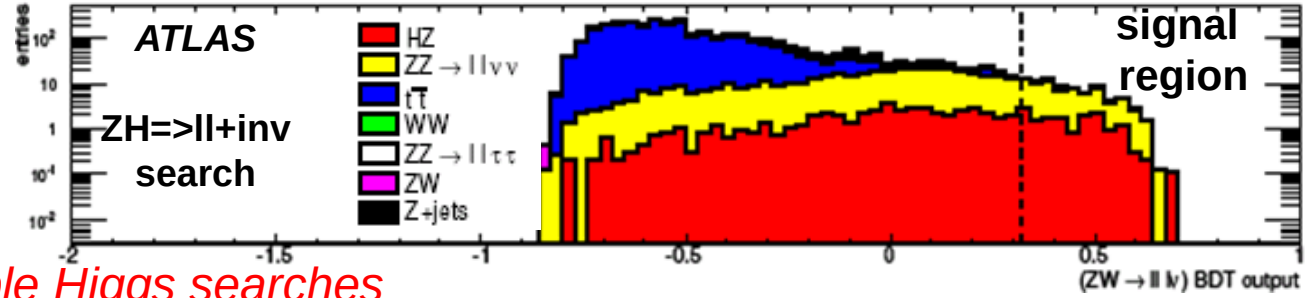


HZ associated production

Trigger: (di)lepton



Boosted Decision Tree (BDT) analysis



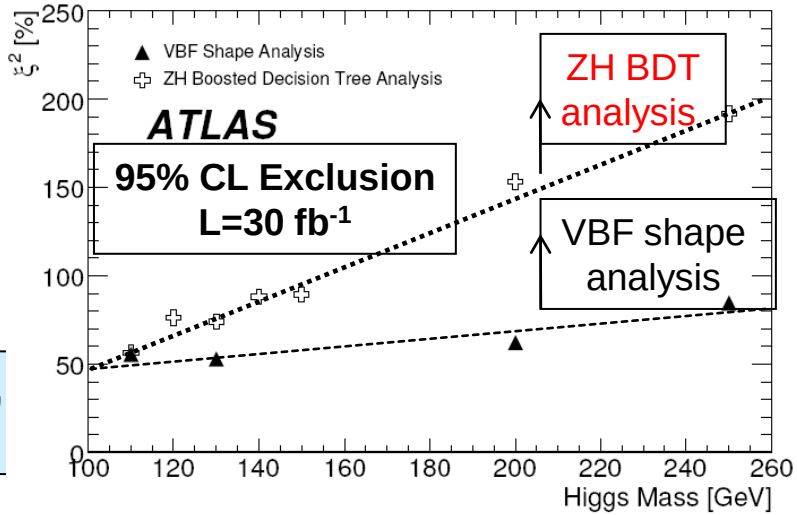
see also CMS poster on invisible Higgs searches

Reach of VBF shape analysis and ZH BDT analysis

$$\xi^2 = BR(H \rightarrow inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$$

VBF shape analysis more performant at high H mass
combine both channels (VBF and ZH) to establish signal.

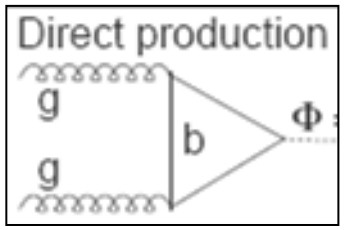
Signal excluded (observable) with 30 (~100) fb-1 for ξ^2> 0.5, as e.g. for σ_{BSM} => 0.5 σ_{SM} and 100% BR_{inv}



Extra Dimensions

5D Randall–Sundrum model:

Scalar sector: Radion ϕ and Higgs h

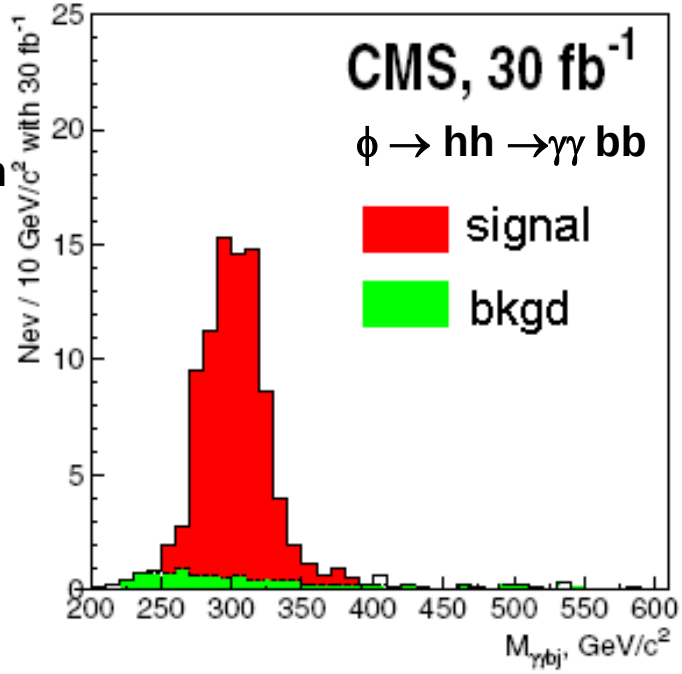


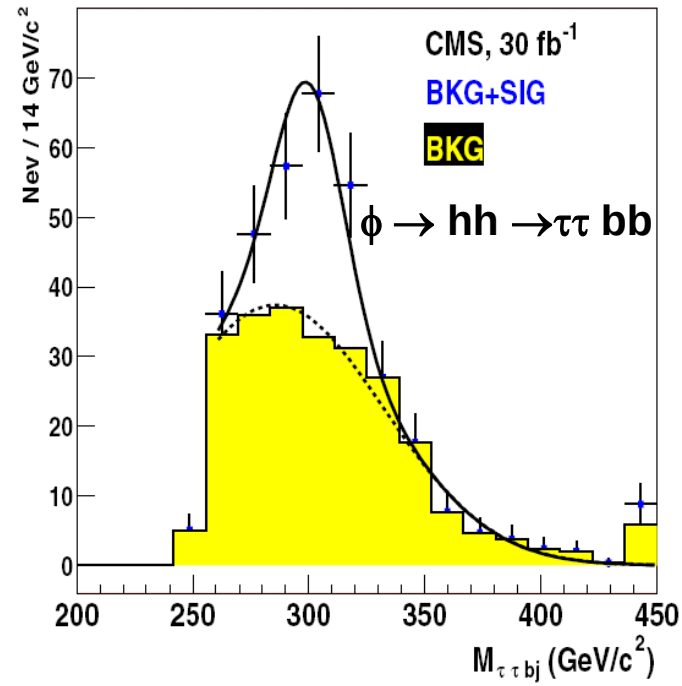
$\phi \rightarrow hh \rightarrow \gamma\gamma\ bb$

$\phi \rightarrow hh \rightarrow \tau\tau\ bb$

$m_\phi = 300$ GeV

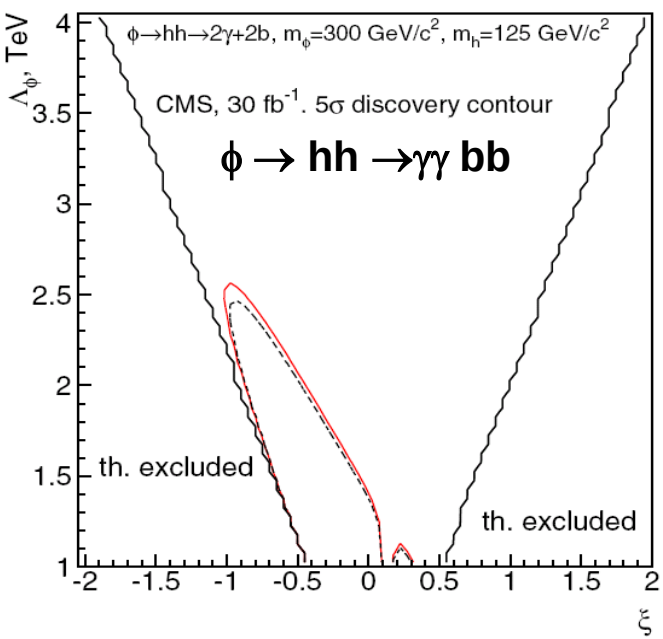
$m_h = 125$ GeV

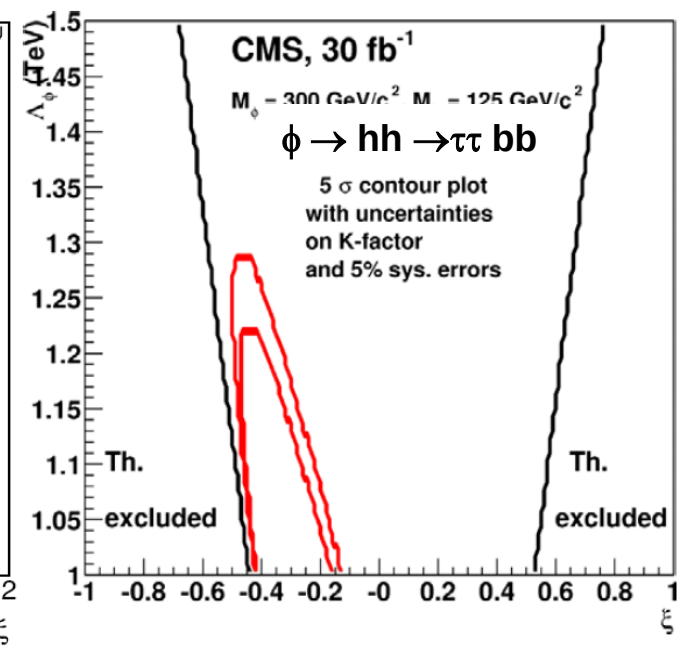




RS scalar sector parameters:

- **Higgs - radion mix. parameter ξ**
- **radion mass m_ϕ**
- **Higgs mass m_h**
- **v.e.v of the radion field Λ_ϕ.**





Littlest Higgs Model - Doubly Charged Higgs

Littlest Higgs or ***Minimal "Little Higgs" model***
N. Arkani-Hamed et al, JHEP07(2002)034

Predicts **a light SM-like Higgs-like particle**
a new set of **heavy gauge bosons *W', Z'***
a vector-like **heavy quark T pair** and
a pair of doubly charged Higgs bosons

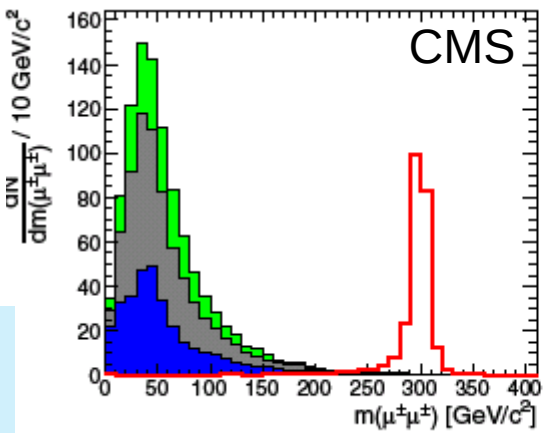
Search in four lepton final states

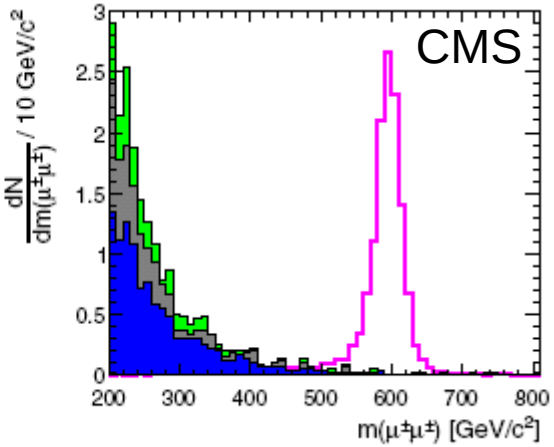
Consider pair production and leptonic decay

Pair production (Drell-Yan): $pp \rightarrow \Delta^{++}\Delta^{--}$

Decay (LV): $\Delta^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$

Reconstruct invariant mass of same charge leptons -> very small SM background



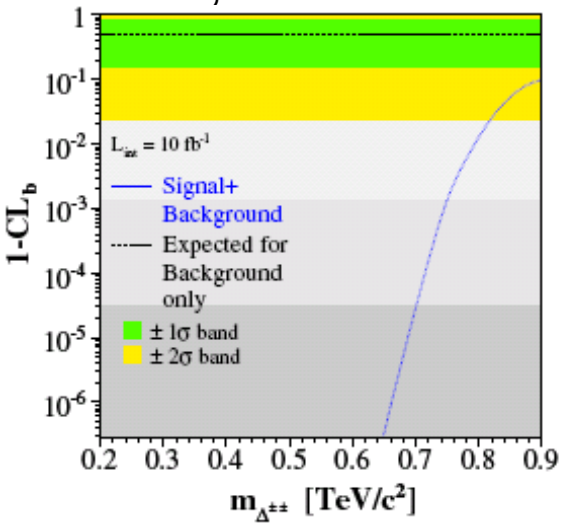


Four muon channel, L=10 fb^{-1}

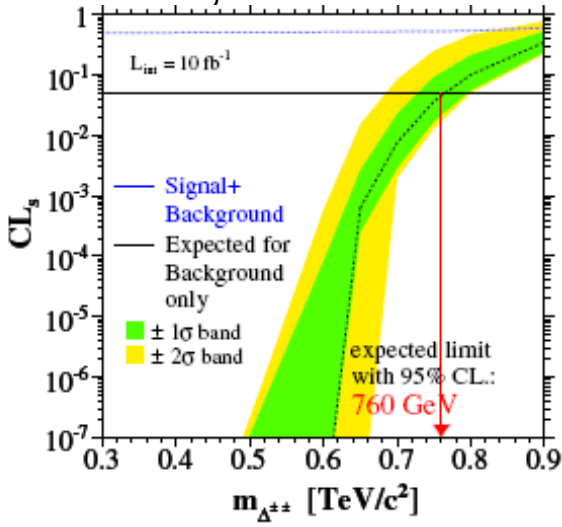
Exclude (95%CL) signal masses up to **760 GeV**

Detect => 5 σ signal for masses up to **650 GeV**

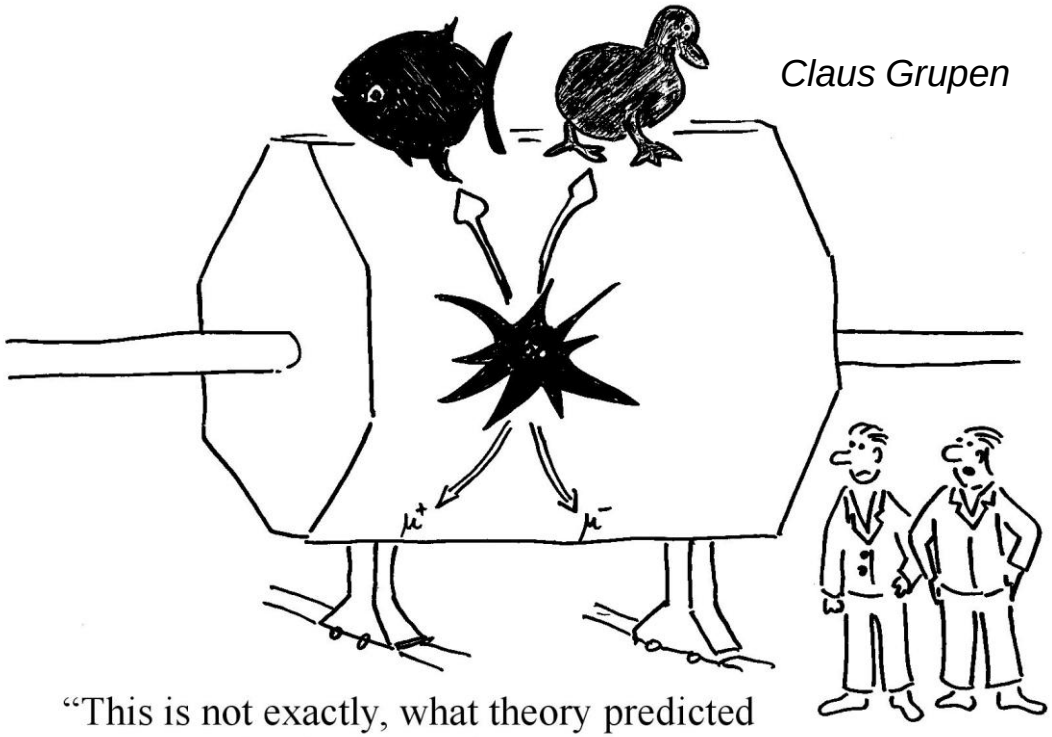
CMS, L=10 fb^{-1}



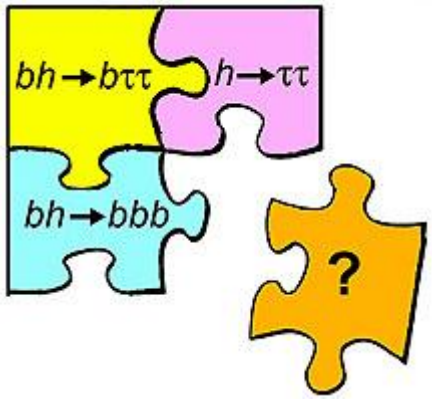
CMS, L=10 fb^{-1}



Higgs Measurements



"This is not exactly, what theory predicted for the Higgs decay!"

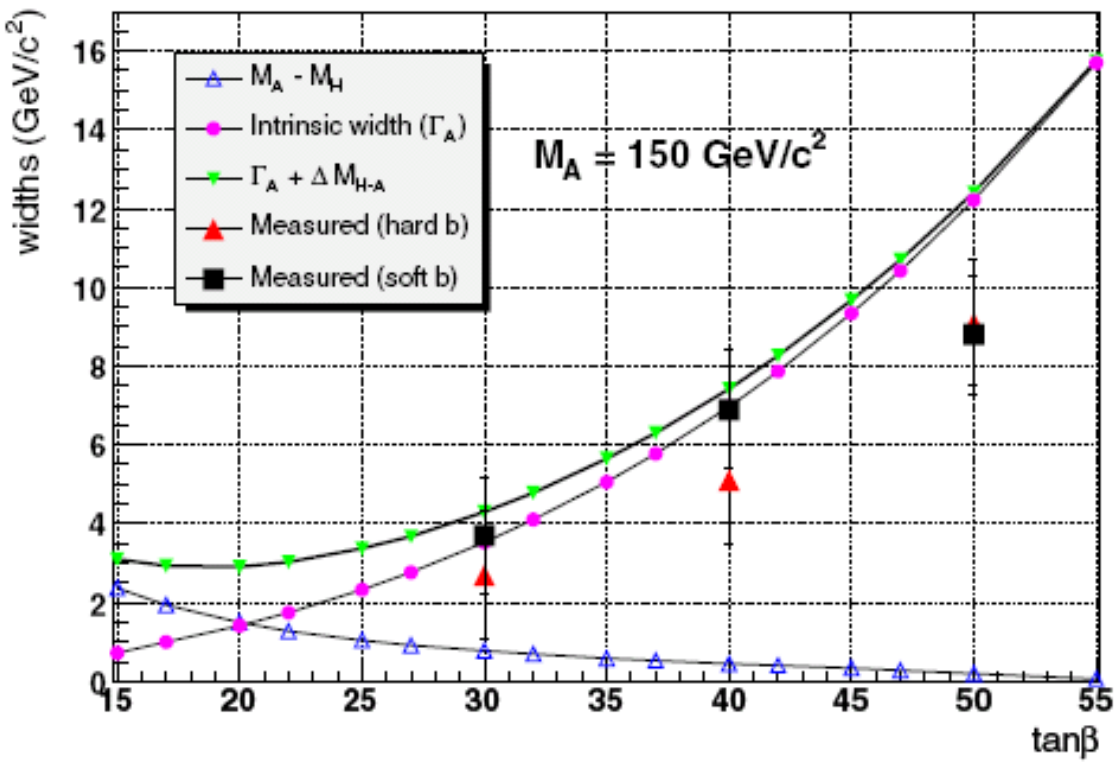


Ex: Measurement of tan β

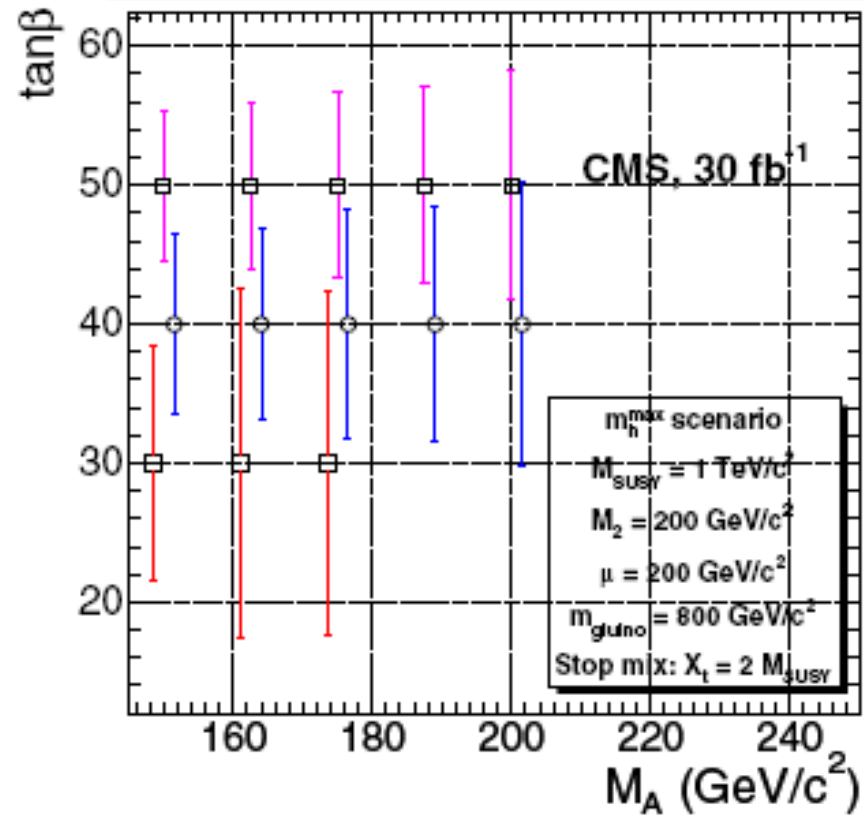
Associated $b\bar{b}H$ production with $H \to \mu^+\mu^-$

Direct measurement of the Higgs boson width, Γ(H/A), sensitive to tan β value

MSSM relation between the Higgs boson width and tan β is exploited in the m_h-max scenario



Uncertainty on tan β measurement from the Higgs width measurement



For **large tan β** values, the A and H mass tends to overlap: $\Delta_{A\text{-}H} = M_A - M_H \Rightarrow 0$ (blue points)
Measured values (black and red) to be compared to $\Gamma_A + \Delta_{A\text{-}H}$ values (green points)

Three set of points for three tan β values as a function of the A mass

Ex: Measurement of Higgs Spin and CP

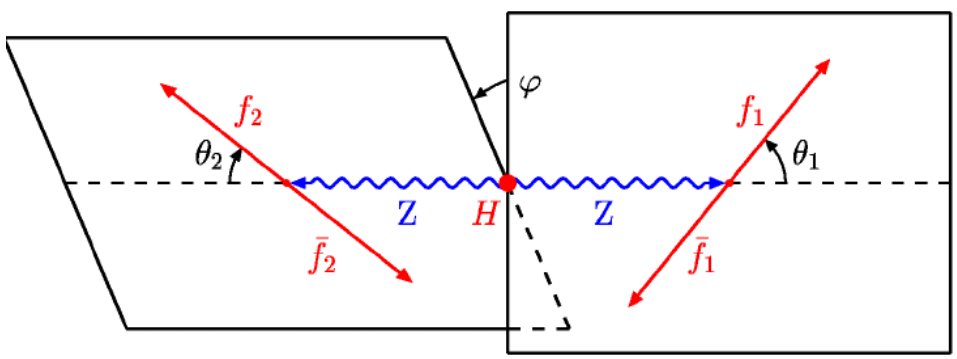
Spin:

- ❑ Spin 1 rouled out if H→γγ or gg→H is observed
- ❑ **Angular correlation of decay products in H→ZZ**
- ❑ Testing for spin 0 in WBF H→WW→lνlν

CP :

- ❑ Angular correlations of decay products in gg→H→ZZ→4l
- ❑ Angular correlations of tagging jets in WBF H→WW and H→ττ
- ❑ Possible : angular correlations in ttH
- ❑ Possible : angular/momentum correlations of τ decay products in H→ττ

Ex.: Determine Spin/CP from angular correlation of decay products in H→ZZ

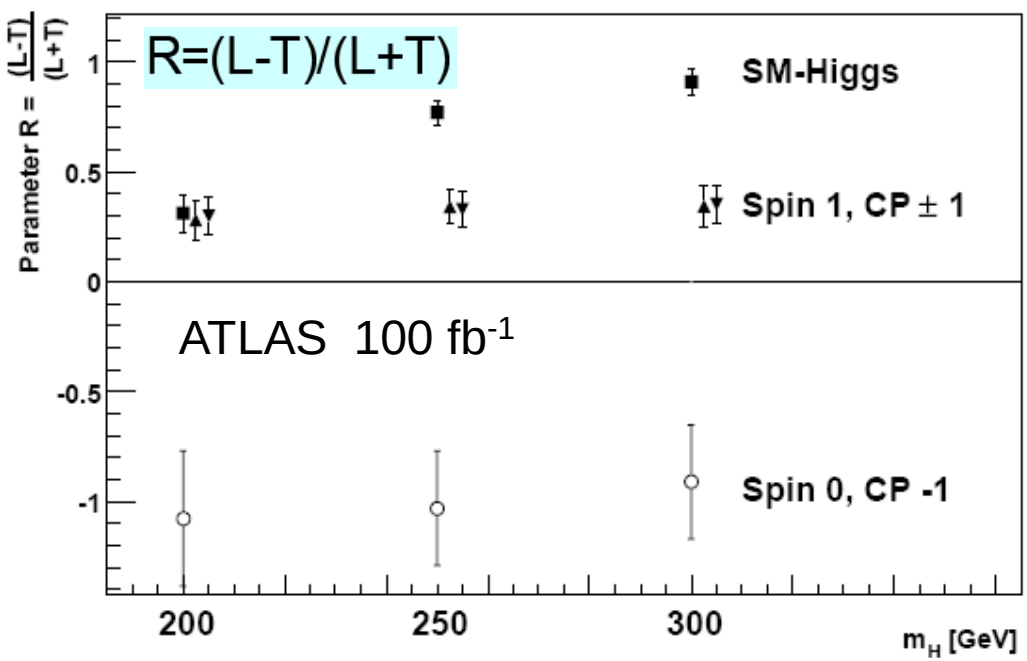


polar angle θ of leptons in Z rest frame

Polar angle distribution:

$$G(\theta)=T*(1+\cos^2\theta)+L*\sin^2\theta$$

$$R=(L-T)/(L+T)$$



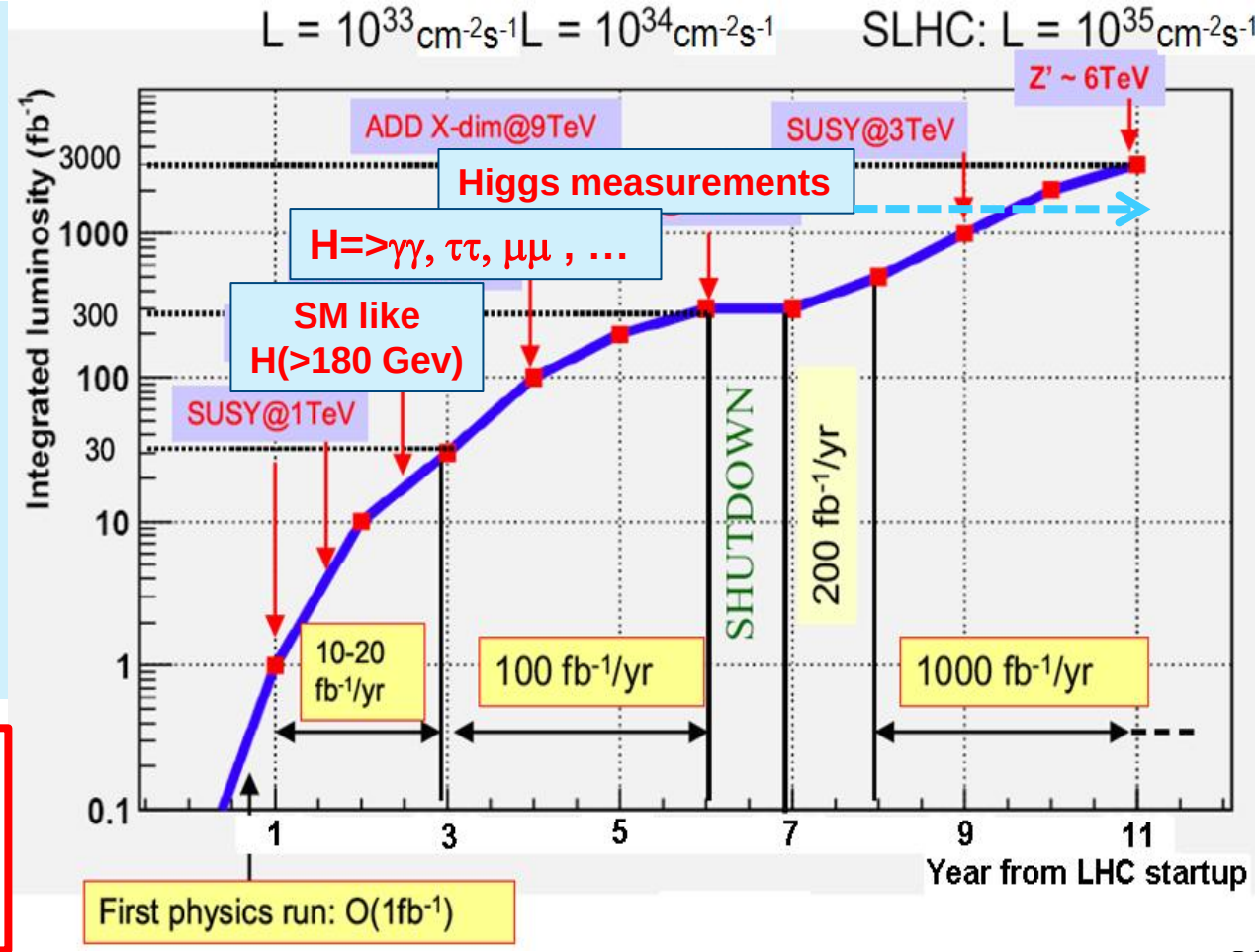
Conclusions

Many BSM models and Higgs signatures have been studied by the LHC collaborations
=> models particularly helpful in setting up search strategies (trigger, data driven background estimation methods, analysis tools,…)

Determined experimental discovery reach, in SUSY (MSSM and extensions) and non SUSY models
=> BSM Higgs-like signals observed and early measured with less then 1 fb^{-1} to few ten fb^{-1}

Detailed properties will be scrutinized to fully establish the nature of the newly discovered particles
⇒Measurement strategies developed
⇒good precision may need high stat.s (ultimate LHC and SLHC) …

More information (e.g. from other discoveries and measurements) may be available - we will combine all (Higgs and non Higgs) measurements to sharpen our understanding…



We are ready for… discoveries…

References

ATLAS and CMS "Expected Performance" Books

ATLAS:
Expected Performance **of the** ATLAS **Experiment - Detector, Trigger and Physics.**
By The ATLAS Collaboration (G. Aad *et al.*). Jan 2009. 1852pp.
e-Print: **arXiv:0901.0512** [hep-ex]; CERN-OPEN-2008-020
http://cdsweb.cern.ch/record/1125884?ln=en
and References therein

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CMS technical design report, volume II: Physics performance.
By The CMS Collaboration (G.L. Bayatian *et al.*). CERN-LHCC-2006-021, CMS-TDR-008-2, 2007.
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and References therein

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