University of Zurich[UZH]
Physik-Institut

Beyond SM Higgs

> why can there be physics beyond the Standard Model?
> how do we look for it?
> what are the analysis challenges?

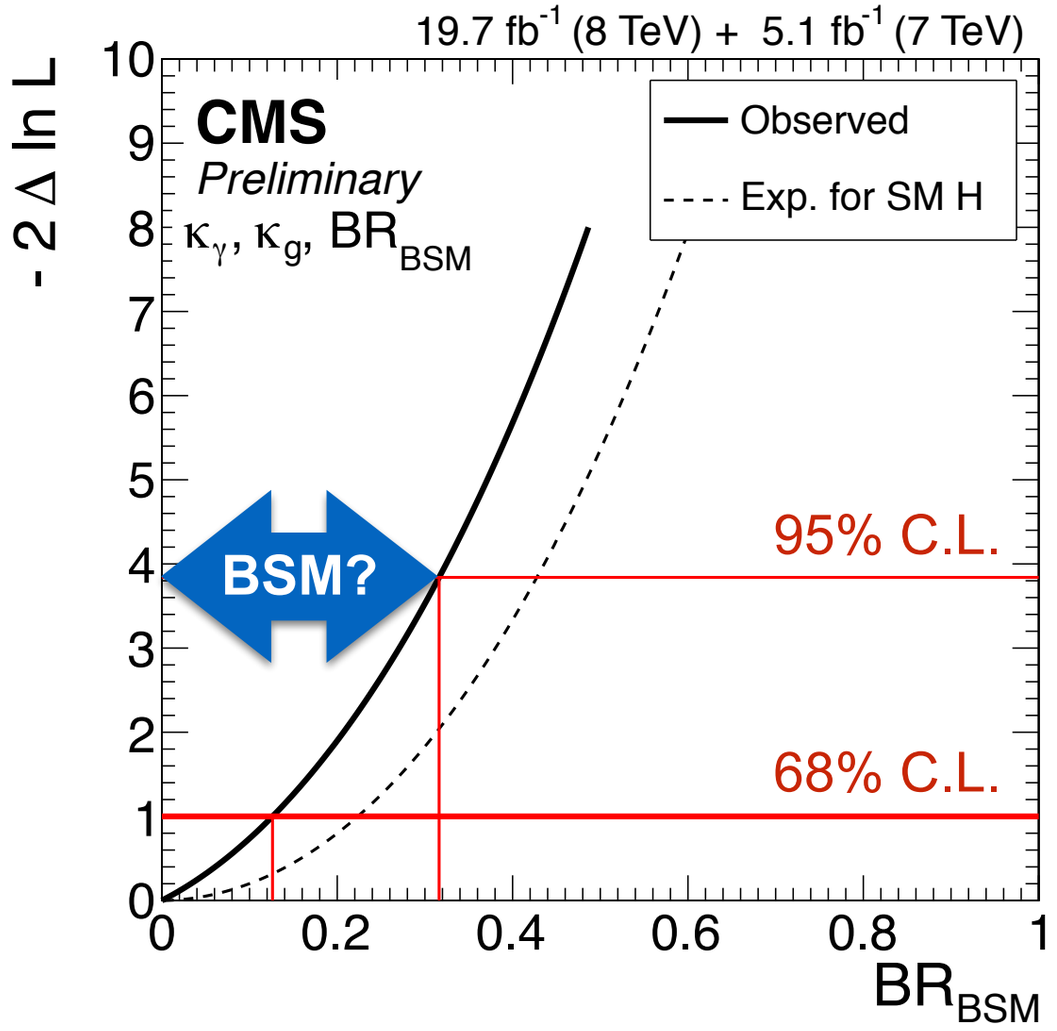
Clemens Lange (UZH)
on behalf of the ATLAS and CMS collaborations
PIC2014 - Bloomington, Indiana, USA
18th September 2014

going beyond

CMS-PAS-HIG-14-009

ATLAS-CONF-2014-010

- after discovery of Higgs boson @ 125 GeV:
  - is this the Standard Model (SM) Higgs?
  - are there additional Higgs bosons?
- currently, observed state is compatible with SM Higgs
  - mind quadratically divergent self-energy corrections at high energies (hierarchy problem)
  - also does not explain dark matter, etc.
- SM most likely incomplete
- plenty of room for beyond SM (BSM) physics
  - e.g. Higgs coupling analysis: $BR_{BSM} < 32\%$ @ 95% C.L. (assuming no modification at tree level)



models with extended Higgs sector

> 2 Higgs Doublet Models (2HDM) → two complex scalar SU(2) doublets

- effective extension of SM
- generally 4 types, distinguished by Yukawa couplings

2HDM Higgs bosons ϕ
CP even: h, H
CP odd: A
charged: H

2HDM parameters
m_h, m_H masses
m_A mass
$m_{H\pm}$ masses
tanβ: ratio of VEVs

> supersymmetry: MSSM (minimal supersymmetric SM - Higgs sector equivalent to 2HDM type II, but constrained) + NMSSM (next-to MSSM)

- bring along super-partners of SM particles
- NMSSM has an additional scalar field → seven physical Higgs states (mixtures)

> (warped) extra dimensions: new heavy particles that can decay to Higgs pairs

> these models are intriguing since they each solve at least one SM problem

brief overview of searches

heavy neutral Higgs decays to leptons and vector bosons

heavy resonances decaying to neutral Higgs pairs

invisible Higgs decays

light and heavy charged Higgs

lepton flavour violating Higgs decays

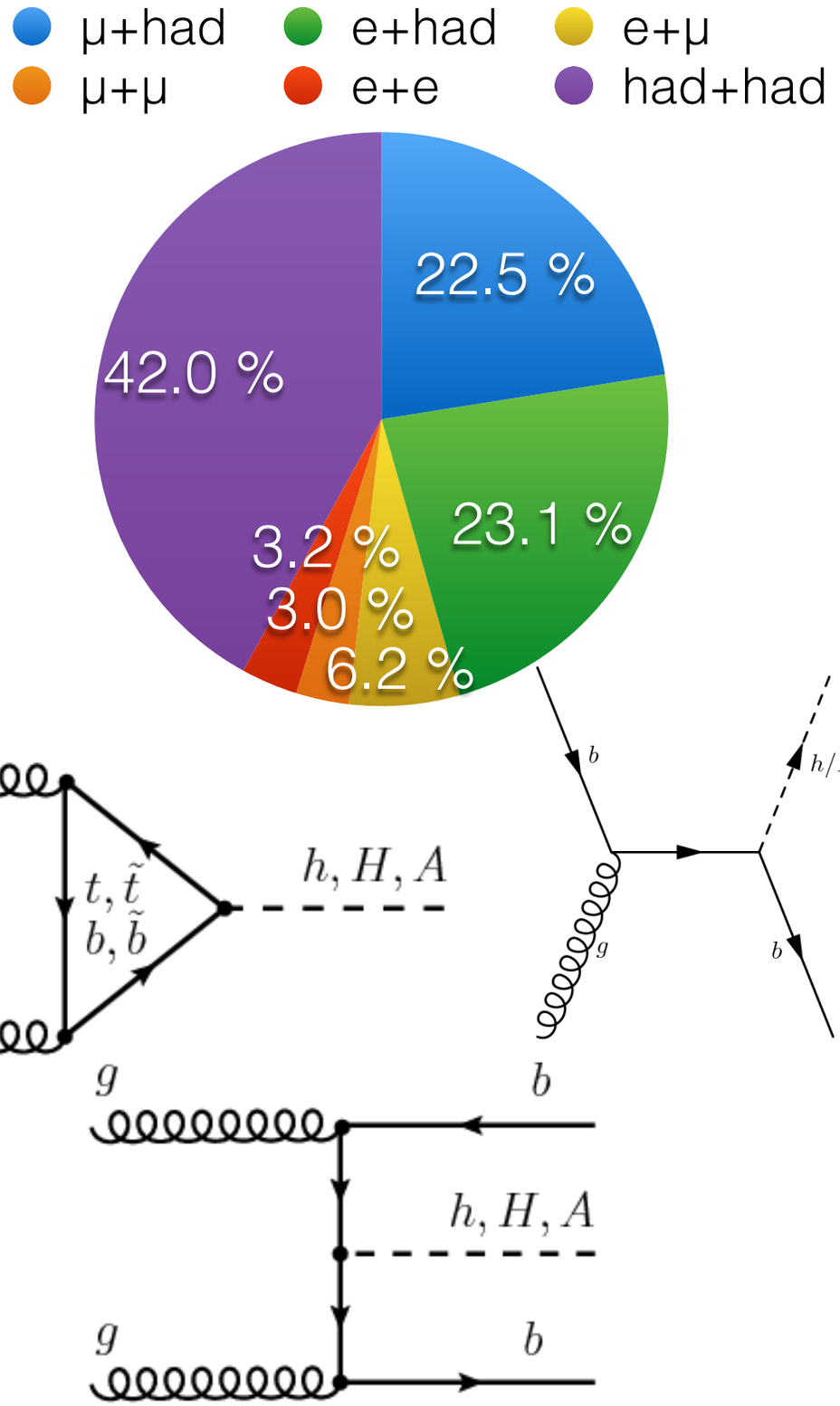
Higgs in long-lived particle searches

- this talk can only point out highlights and does not claim to be complete
- will present about one analysis each for topics mentioned above

heavy neutral Higgs: ϕ→ττ

Submitted to JHEP (arXiv:1408.3316)
ATLAS-CONF-2014-049

- decay to τ-leptons: rather large branching ratio with manageable backgrounds
- analysis exploits 5 (CMS)/3 (ATLAS) decay channels
- two analysis categories:
  - b-tagged (associated production)
  - b-tag veto (gluon-gluon fusion)
- mass of τ-pair reconstruction:
  - CMS+ATLAS: from visible τ decay products (maximum likelihood fit, slightly different methods)
  - ATLAS: ττ transverse mass (had+had final state)



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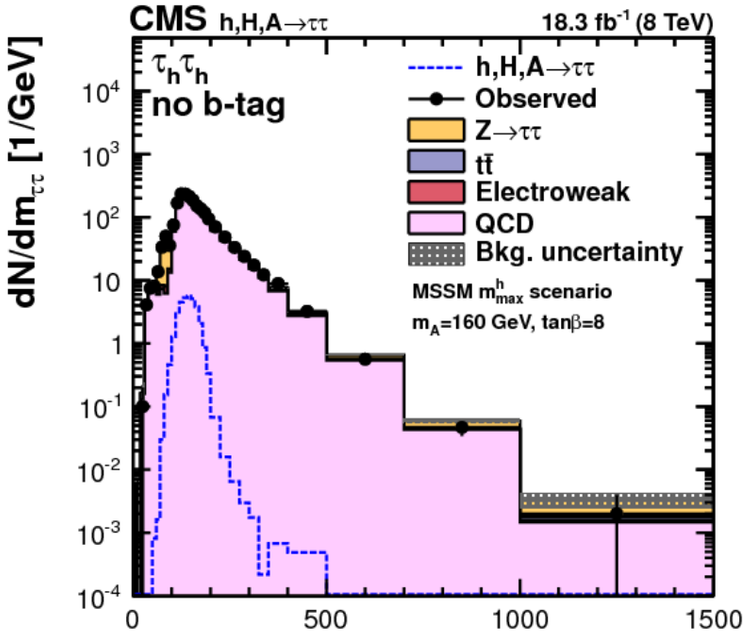

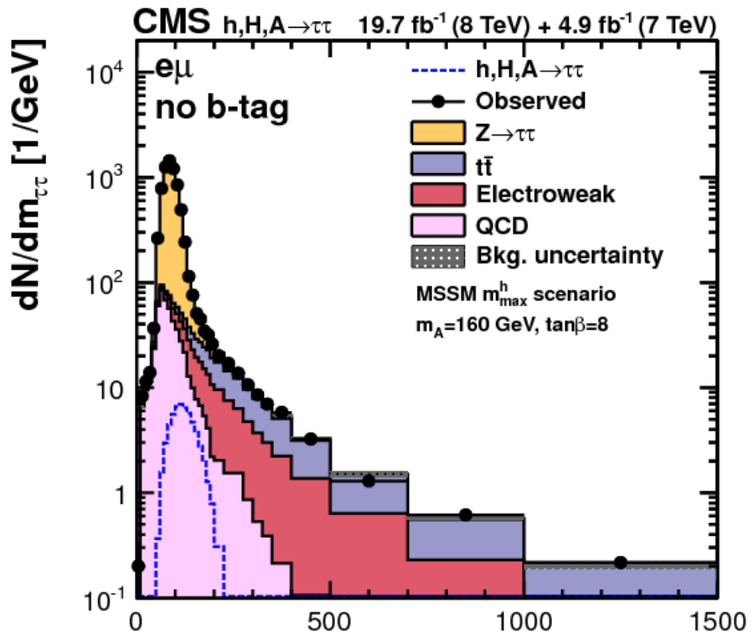

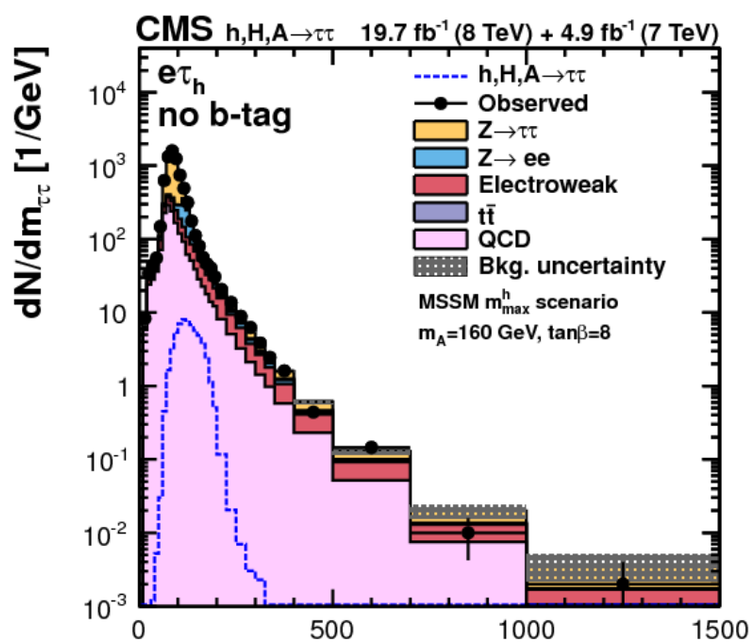

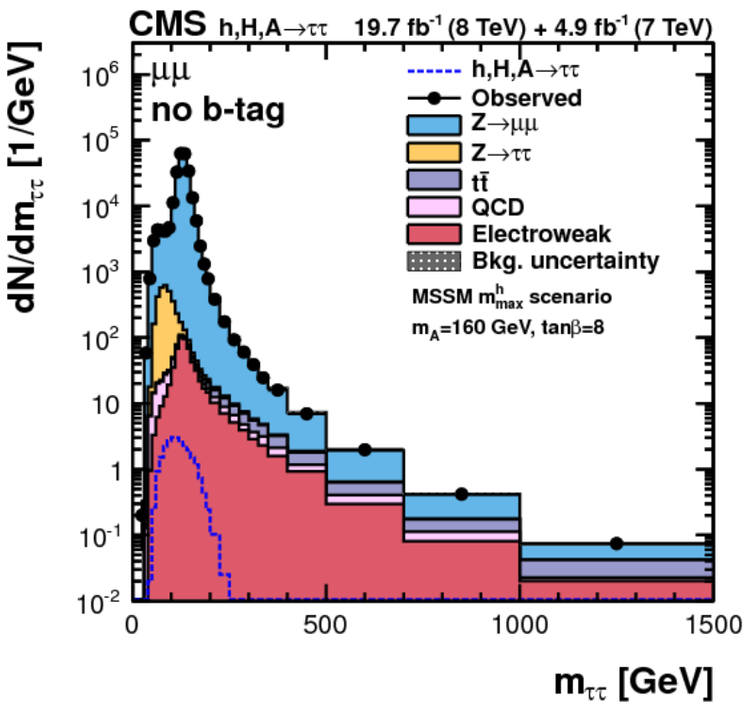

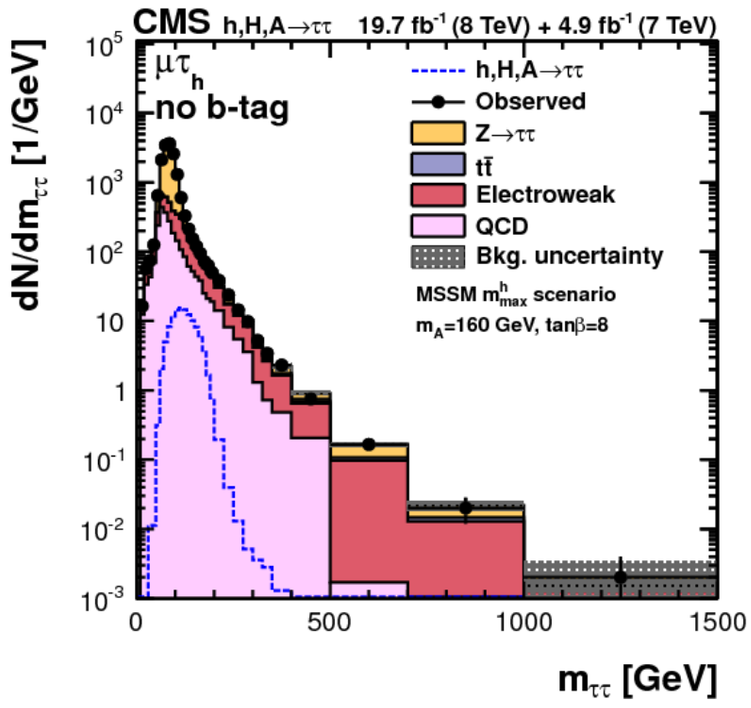

- dominant background Z→ττ estimated using „embedding technique“
  - replace μ by simulated τ decay products in Z→μμ events
- all distributions well described by background-only hypothesis

heavy neutral Higgs: ϕ→ττ

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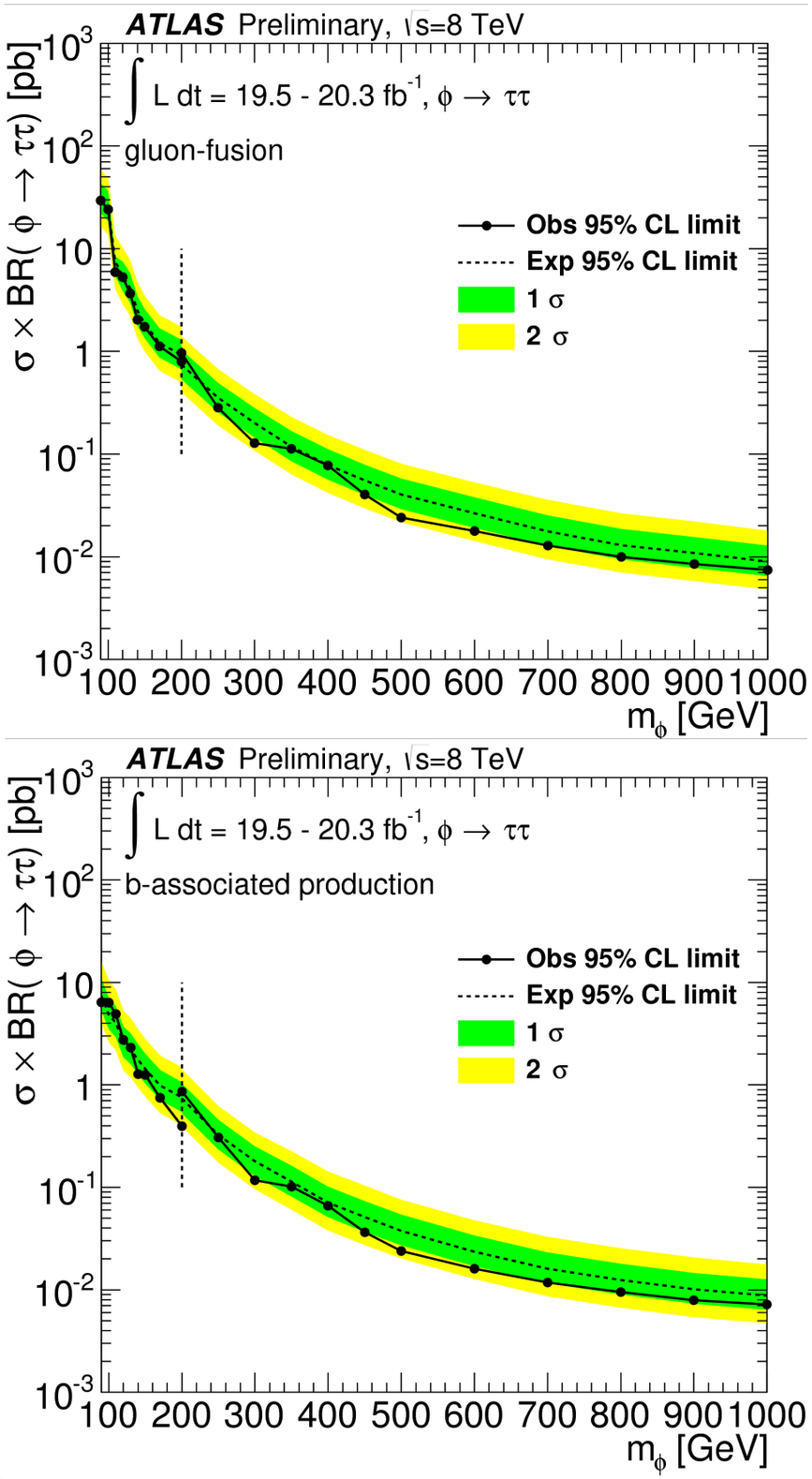
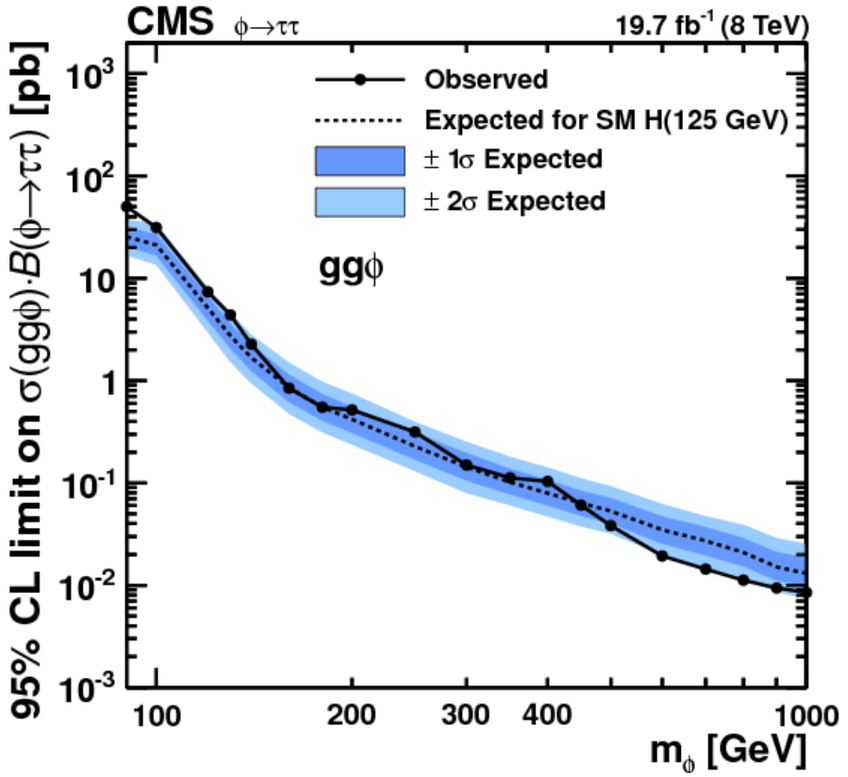
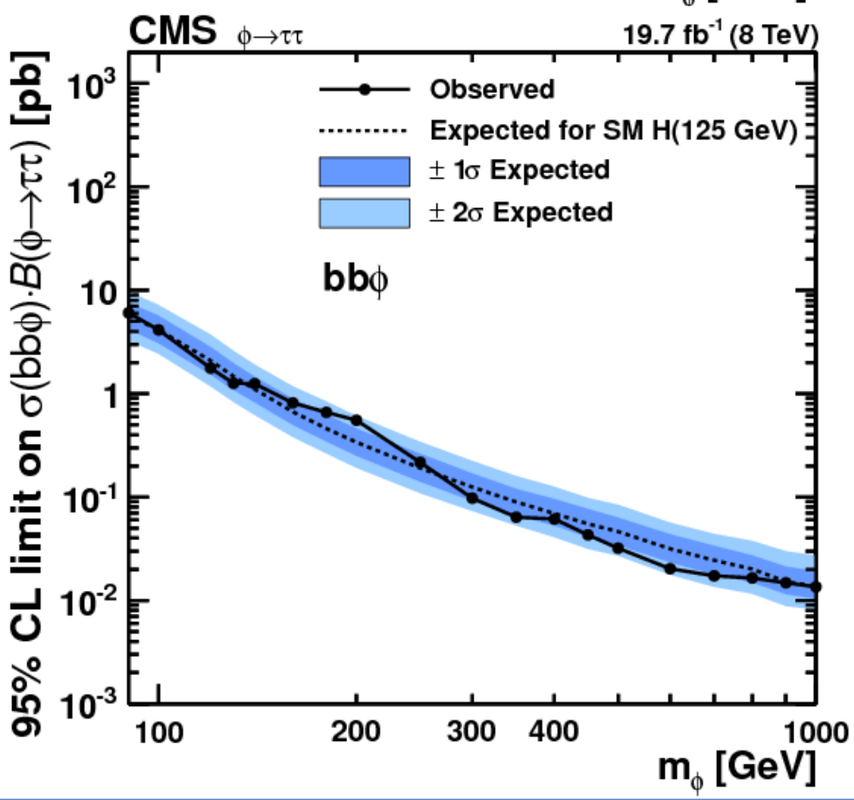
ATLAS-CONF-2014-049







cross section × BR limits separately for the two production mechanisms

heavy neutral Higgs: ϕ→ττ

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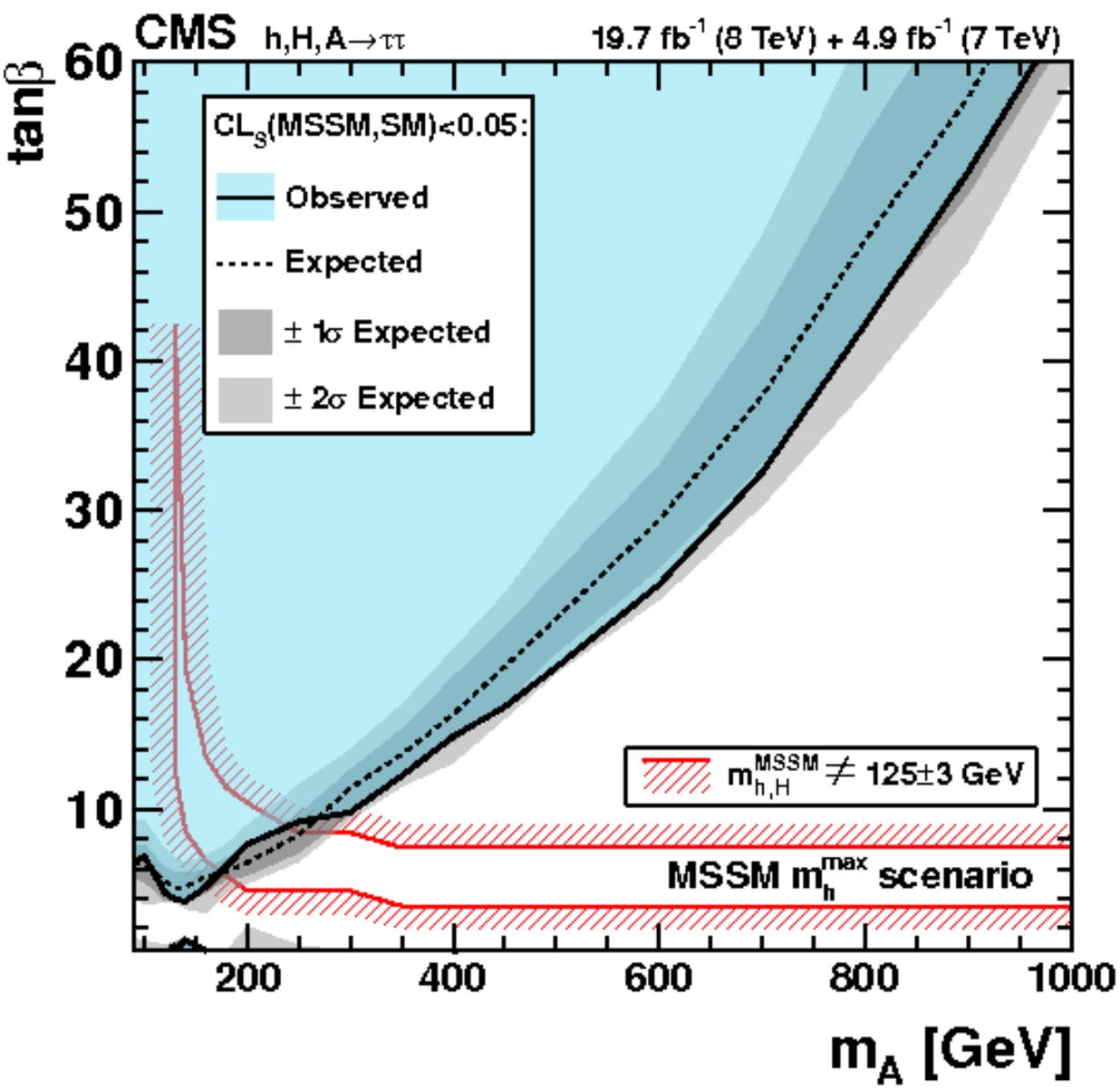
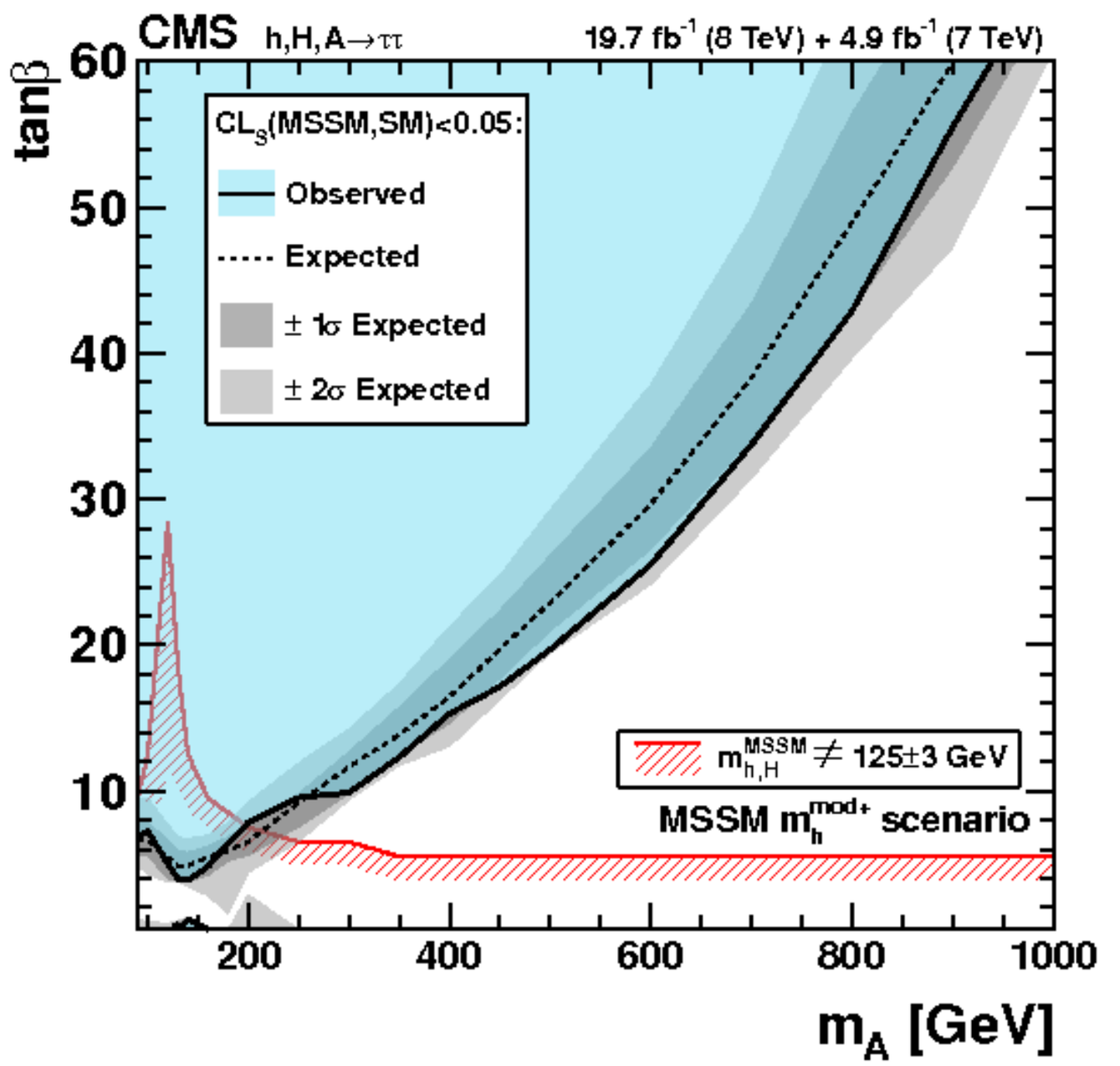




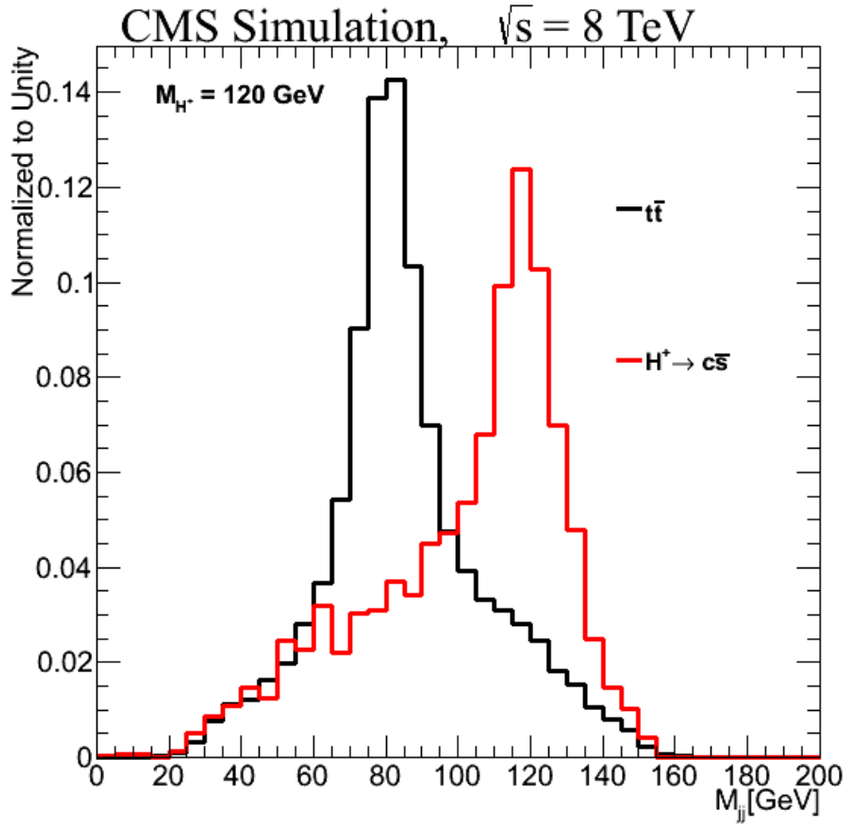
- interpretation in several scenarios taking Higgs @ 125 GeV into account
- m_h^{mod+} scenario better suited than m_h^{max} for known Higgs mass (see Eur.Phys.J. C73 (2013) 2552)
- very low tanβ upper limits for low Higgs masses!

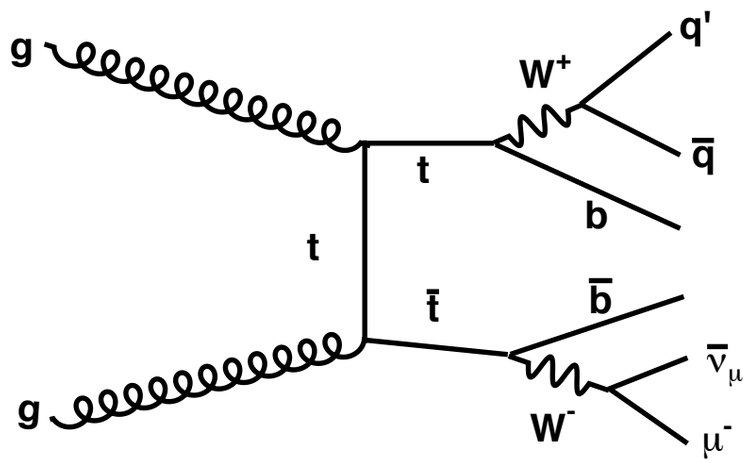
charged Higgs $H^+ \rightarrow cs$

CMS-PAS-HIG-13-035

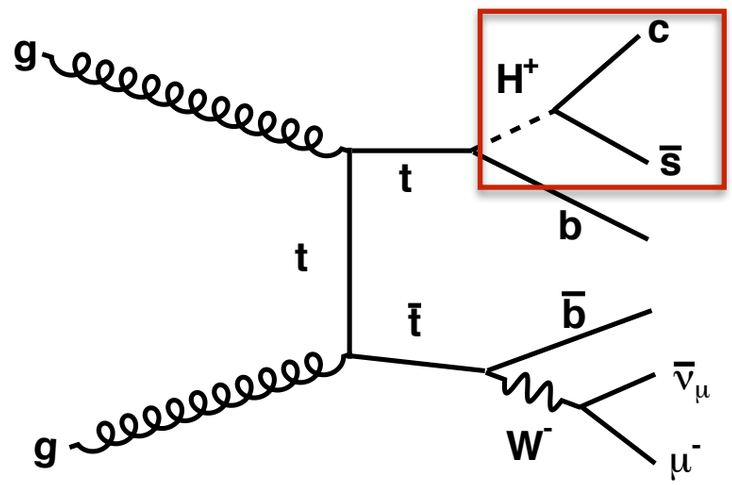
Eur. Phys. J. C, 73 6 (2013) 2465

- m_{H+}-m_t relation dictates both production mode and decay channels
  - here: $m_{H+} < m_t$
- $H^+ \rightarrow cs$ dominant decay for tanβ < 1
- same topology as top quark pair events
- search for second peak in dijet mass spectrum (non b-tagged jets)
- kinematic fit constraining both top quark candidates to m = 172.5 GeV





SM top quark pair decay



H+ production in top decays

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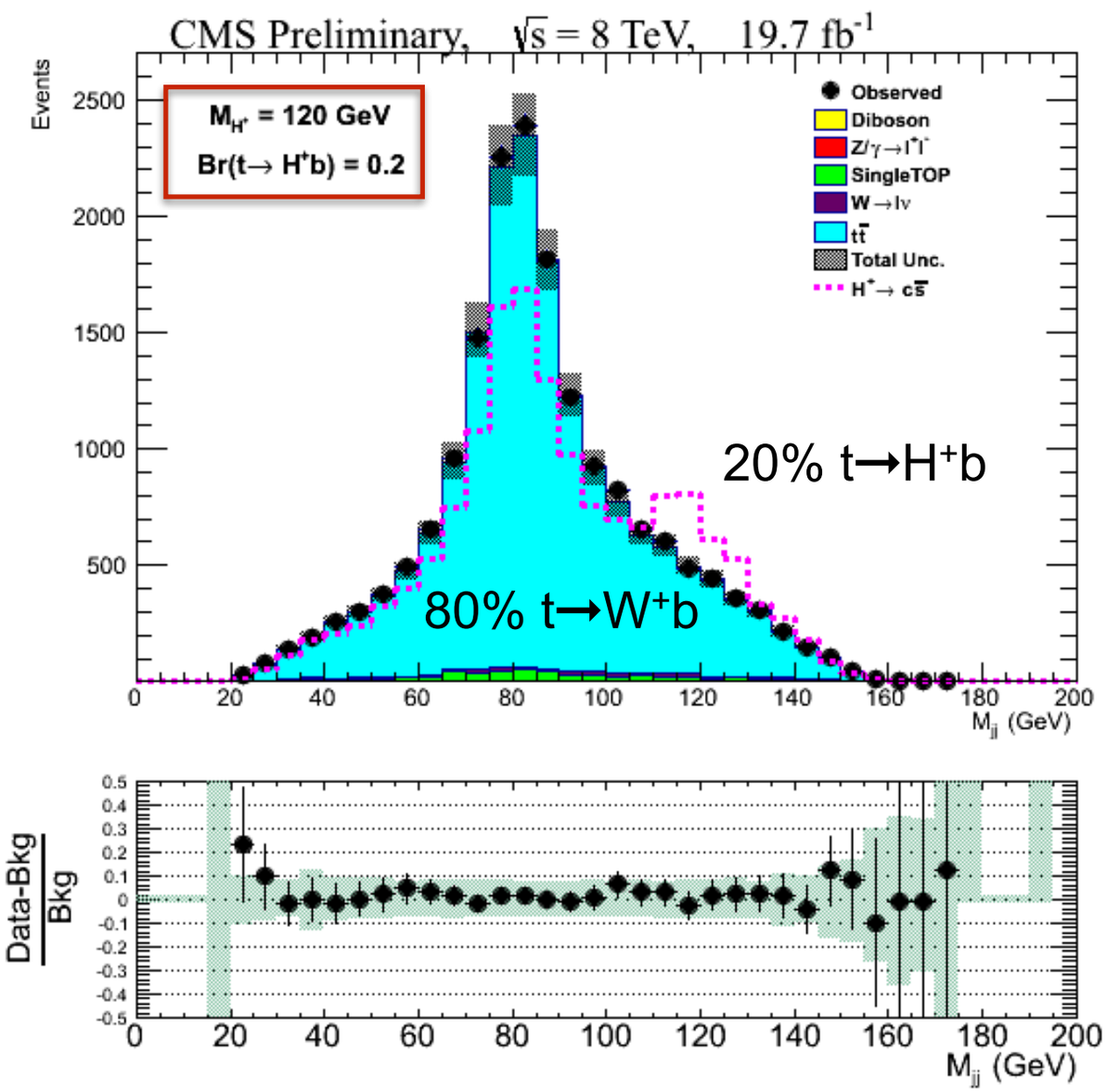
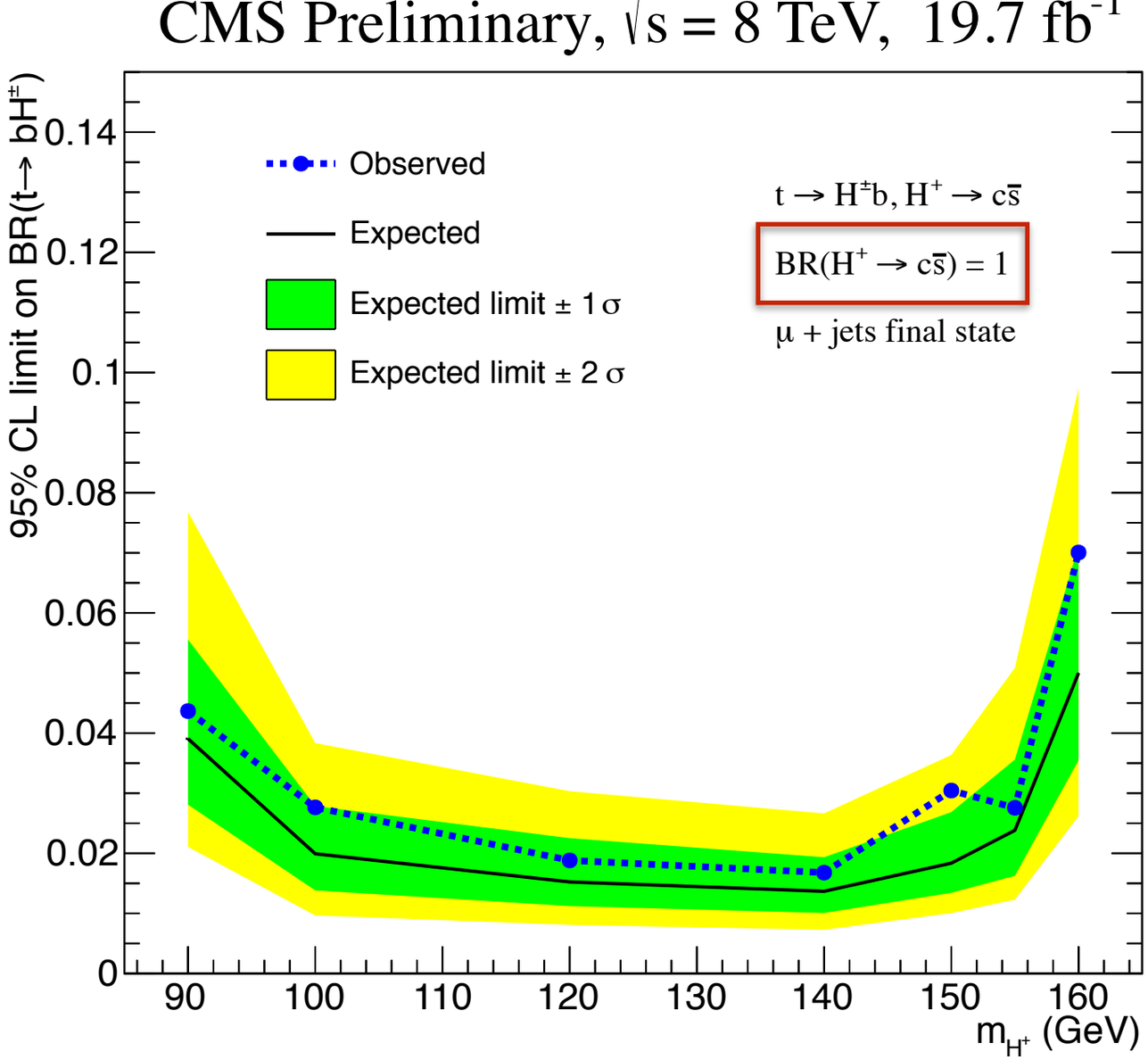
charged Higgs $H^+ \rightarrow cs$

CMS-PAS-HIG-13-035
Eur. Phys. J. C, 73 6 (2013) 2465



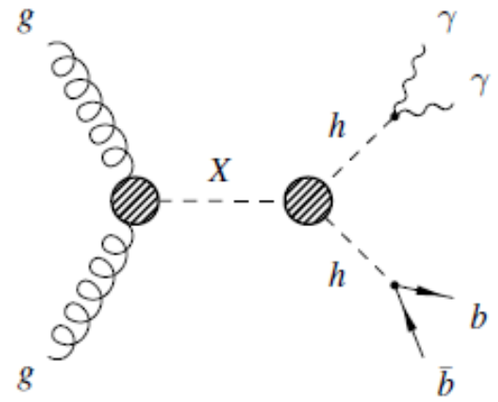


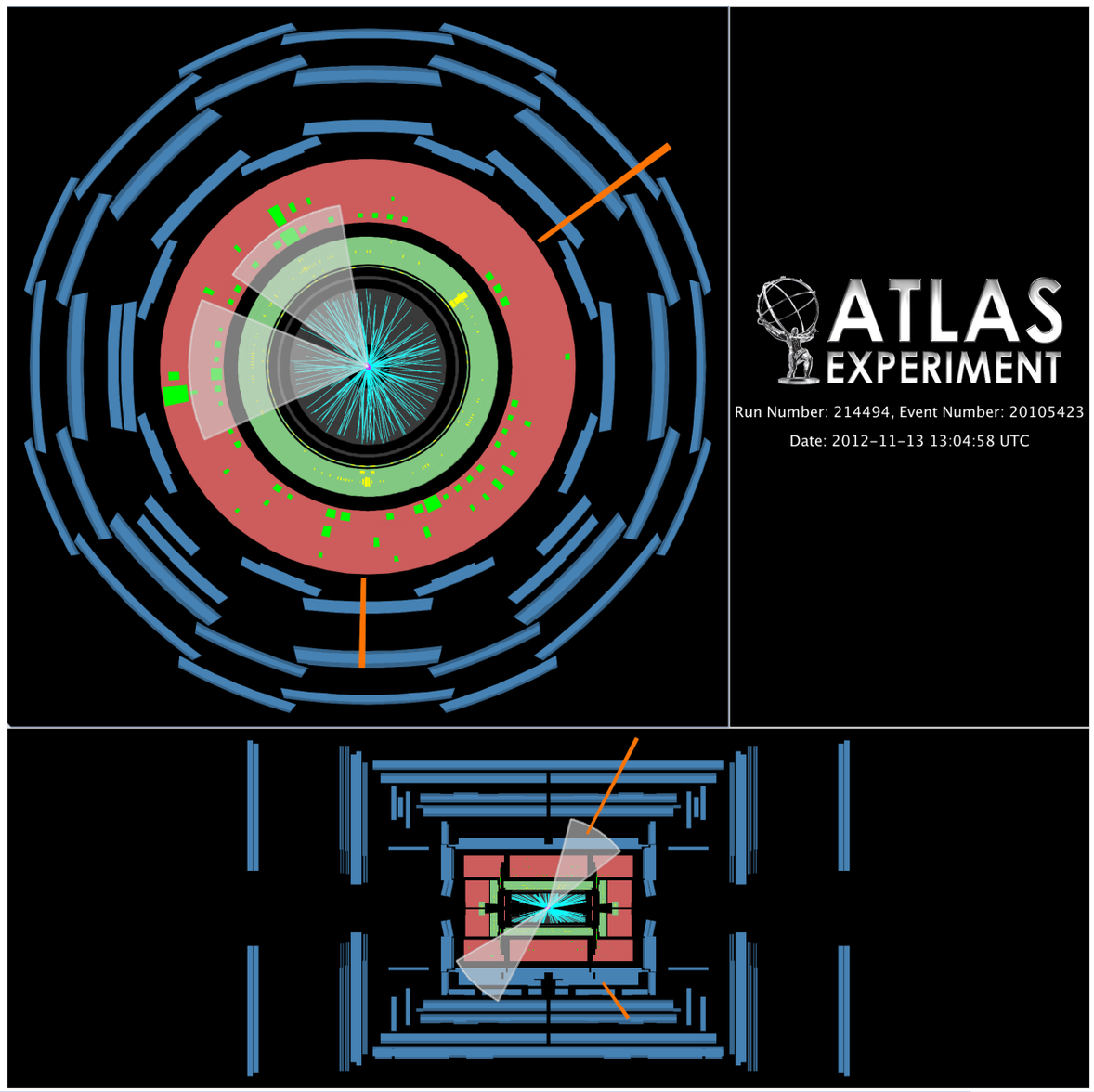
- BR(t→H$^+$b) determined assuming BR(H$^+$→cs) = 1
- upper limit 2-4% for m_{H+} from 90-155 GeV
- applicable to any BSM resonance with corresponding production & decay topology

heavy H → hh → 4b/bbɣɣ

CMS-PAS-HIG-14-013
ATLAS-CONF-2014-005
CMS-PAS-HIG-13-032
arXiv:1406.5053 (submitted to PRL)

- SM rate of Higgs pair production very small
- but: resonant pair production motivated by several beyond SM models
  - decays of heavy (N)MSSM Higgs bosons
  - Radion/Kaluza-Klein excitations of graviton (warped extra dimensions)
- enhanced cross sections - already sensitive with current dataset
- exploit bbɣɣ final state
  - high BR of H→bb
  - high mass resolution of H→ɣɣ (see also e.g. CERN-PH-EP-2014-142)
- also exploit bbbb final state for higher BR

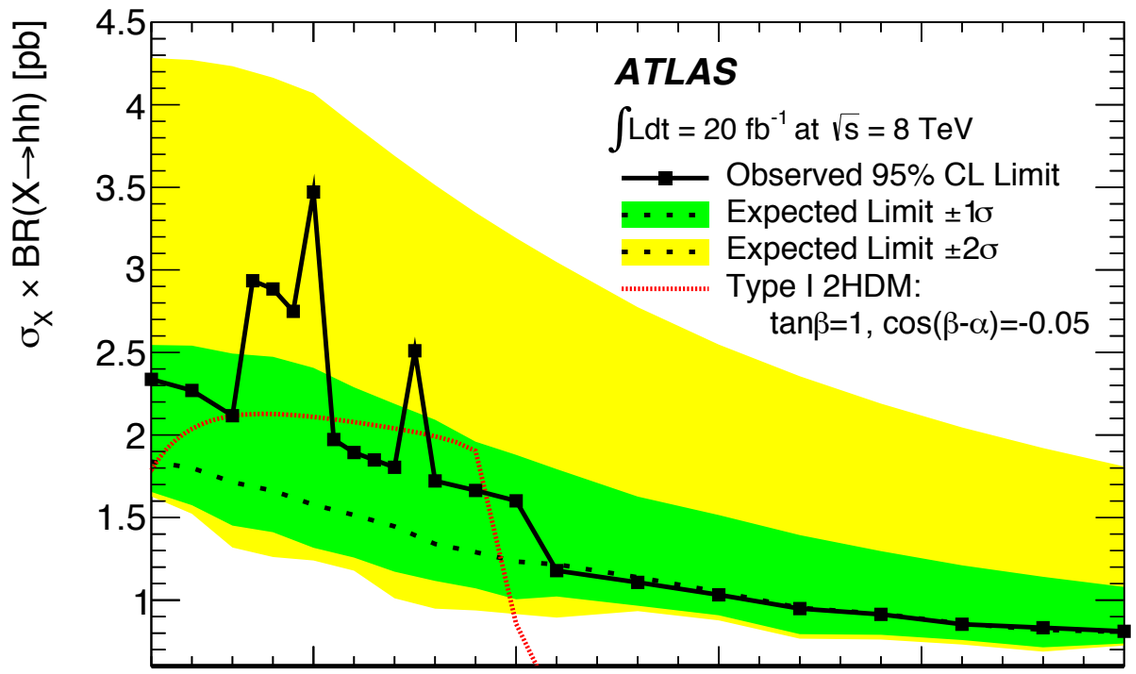


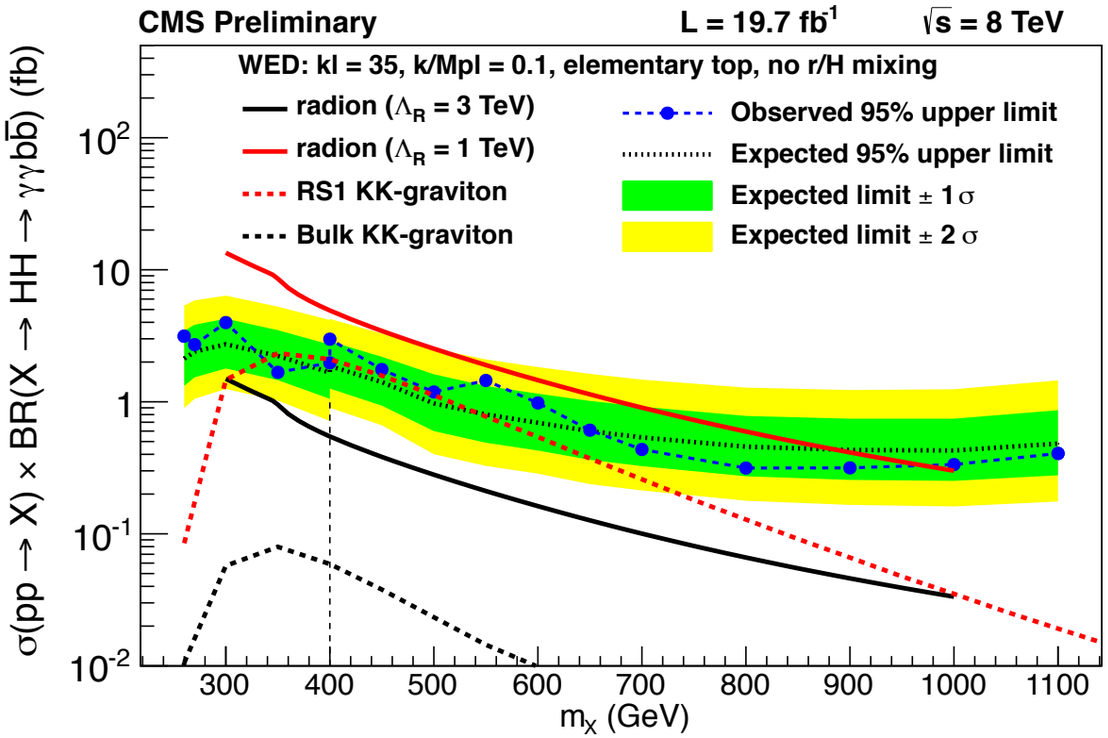


heavy H → hh → bbγγ

CMS-PAS-HIG-13-032
arXiv:1406.5053 (submitted to PRL)

- hh → bbγγ: selection similar to SM Higgs analyses
- mass constraint (CMS)/mass window (ATLAS) on bb candidate using known H(125) mass
  - suppress SM continuum
- ATLAS: search also for non-resonant hh production
  - observe 2.4σ excess compatible e.g. with a type I 2HDM
- resonant searches do not show deviation from SM expectations
  - ATLAS range up to 500 GeV
  - CMS 260-400 and 400-1100 GeV
  - exclude radions with m < 970 GeV
  - exclude RS1 KK-graviton from 340-400 GeV

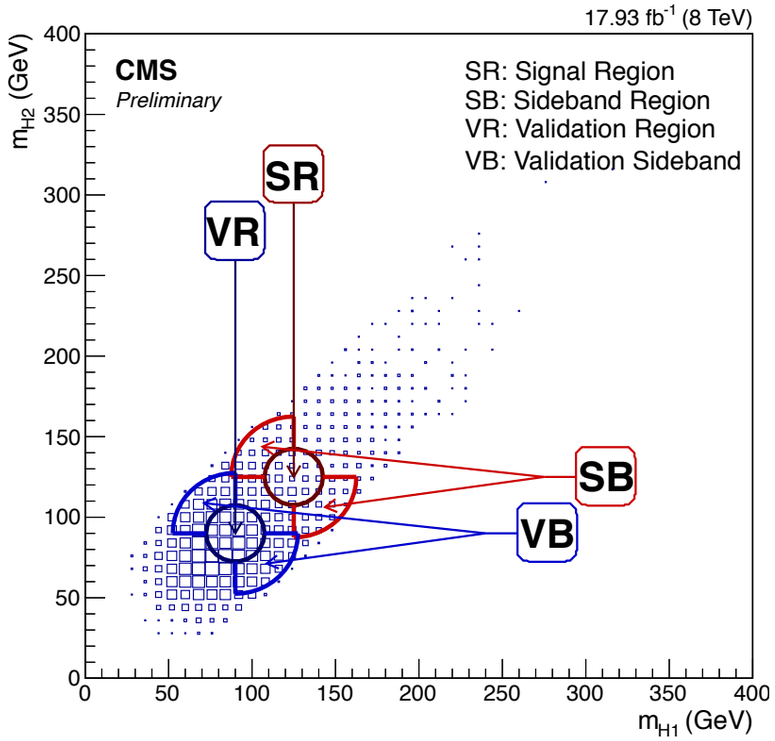


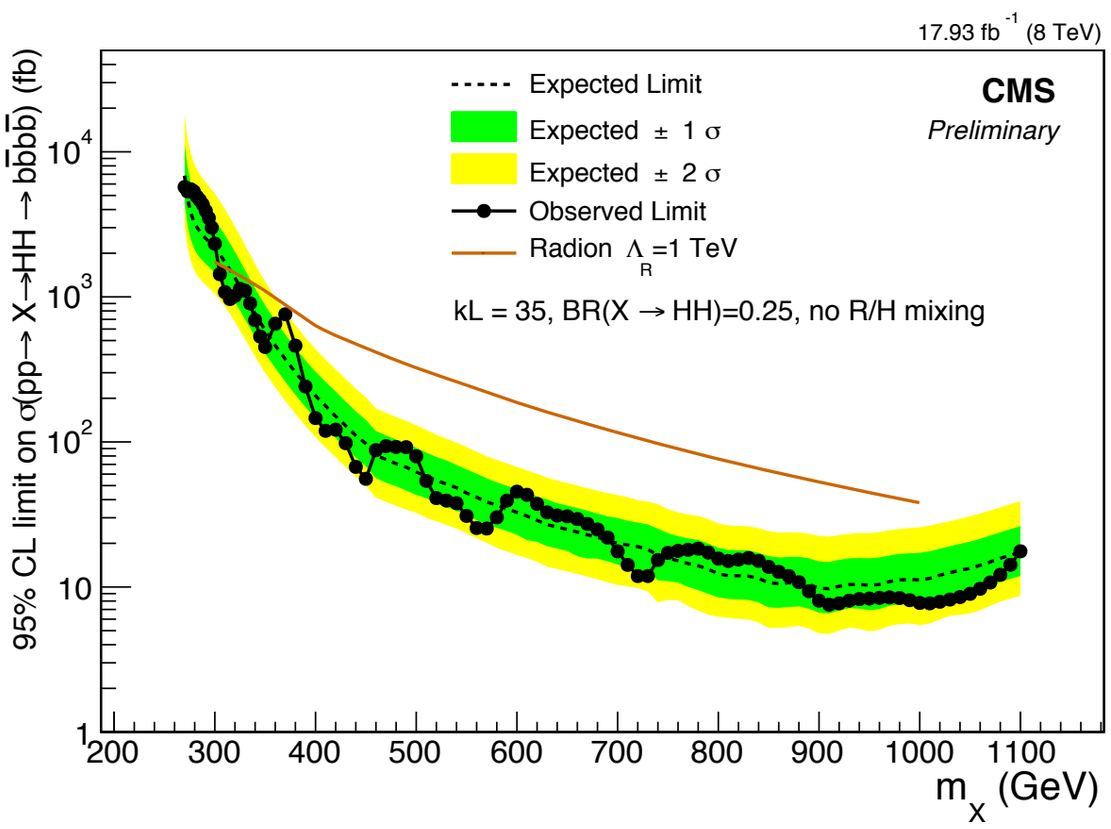


heavy H → hh → 4b

CMS-PAS-HIG-14-013
ATLAS-CONF-2014-005

- hh → 4b search for narrow resonance
- ±35-GeV wide mass window around Higgs mass
- uses combination of CMS b-tagging algorithms
- dominant backgrounds:
  - QCD multi-jets (fit using analytic function)
  - top quark pair events
  - validation in sideband regions
- no statistically significant signal observed
  - limits set for mass range of 270-1100 GeV (CMS) / 500-1400 GeV (ATLAS)

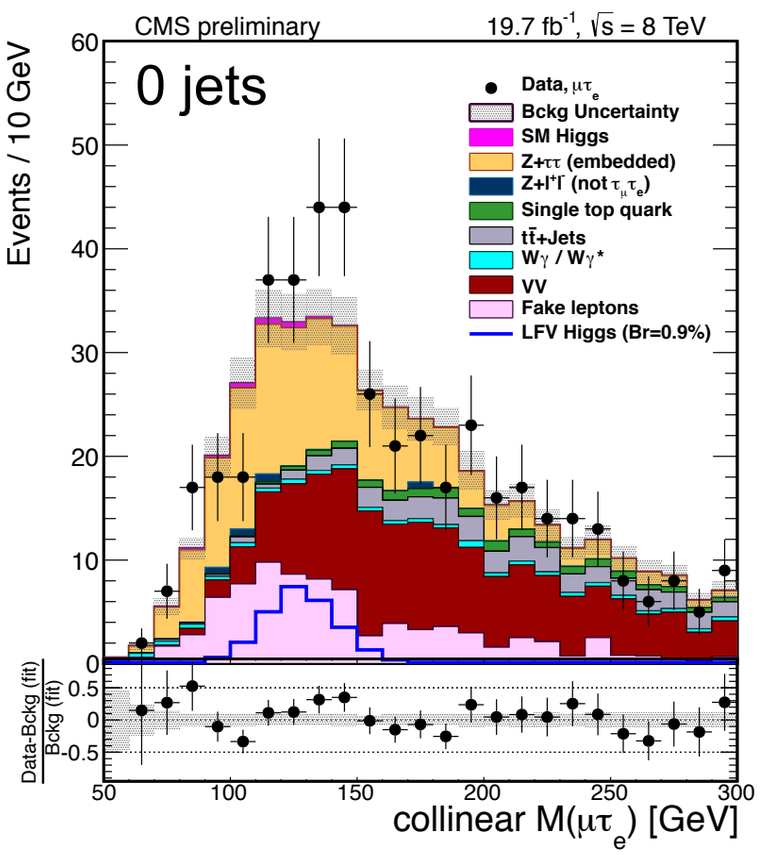


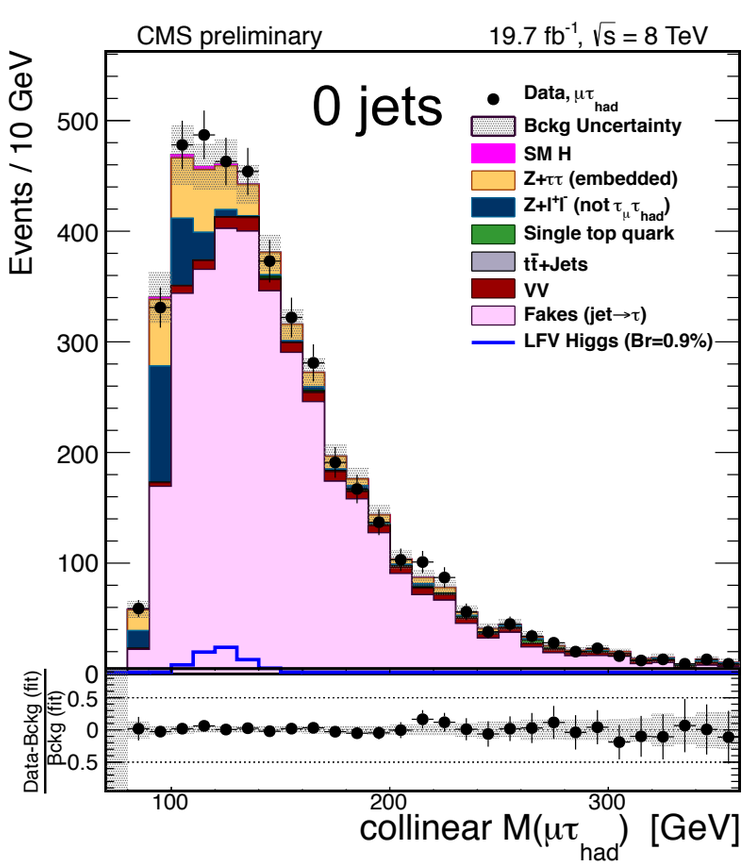


lepton flavour violating Higgs

CMS-PAS-HIG-14-005

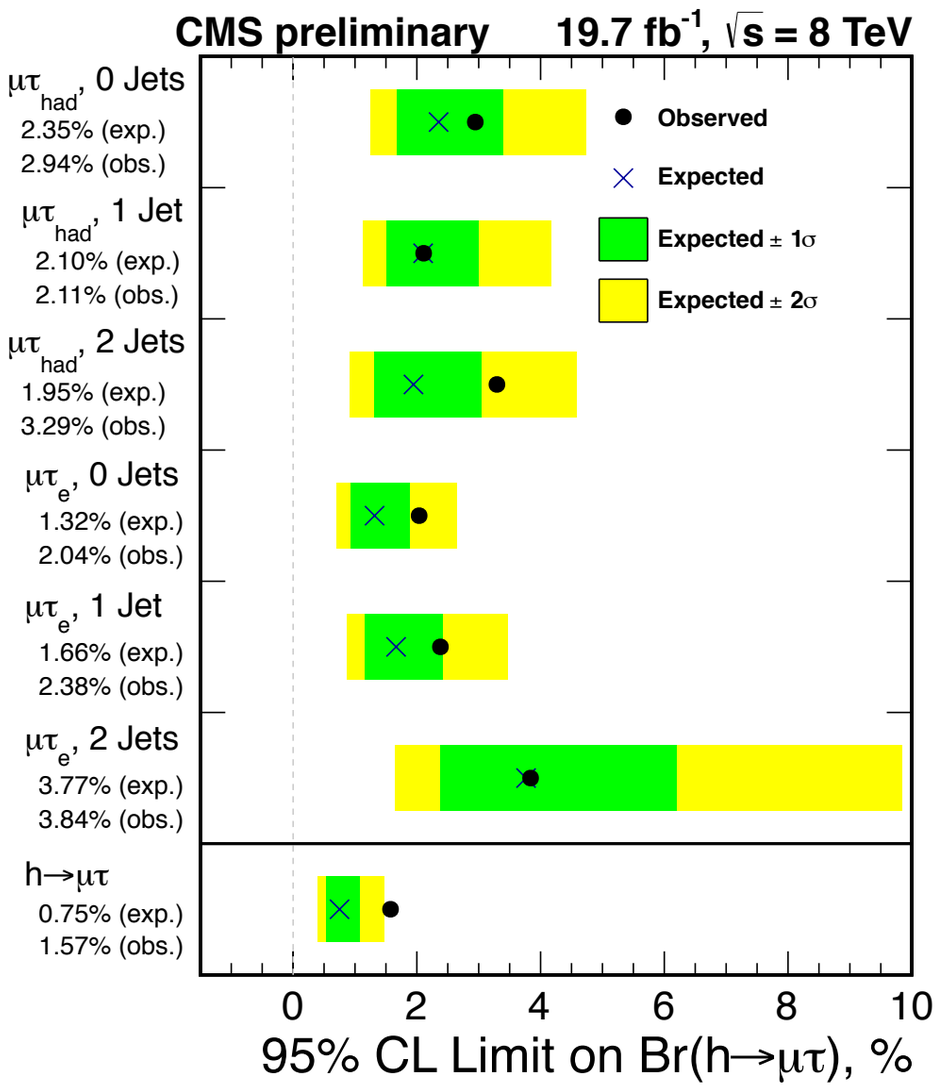
- possible in 2HDM and Randall-Sundrum models
- search for $H \rightarrow \mu\tau$ in $\mu\tau_e$ and $\mu\tau_h$ channels (opposite charge) mass resonance
- similar signature as $\phi \rightarrow \tau\tau$ analysis, but different kinematics
- use collinear (τ decay products) mass approximation
- categorise in jet multiplicity bins (0, 1, 2 (VBF) jets)

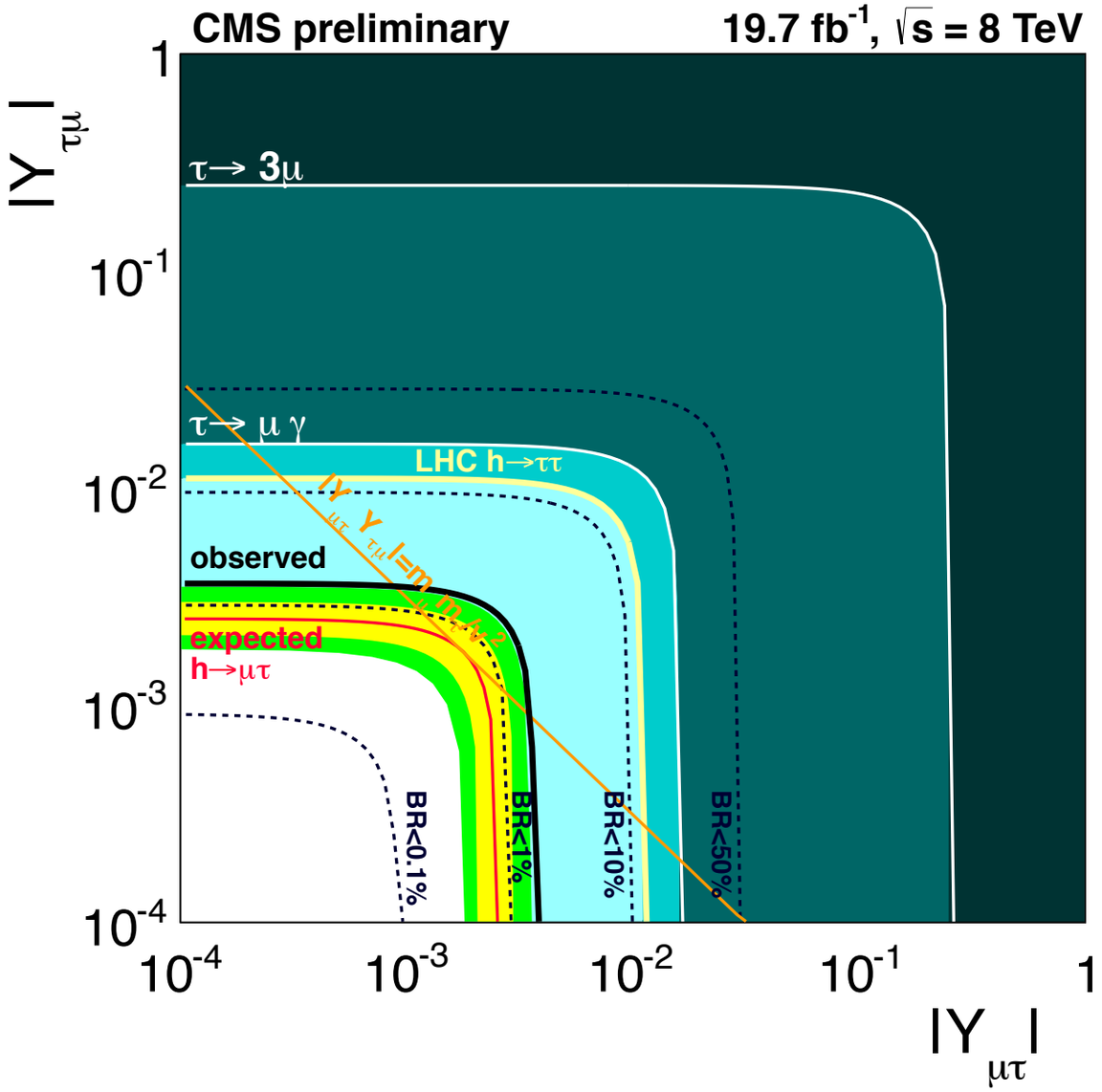




lepton flavour violating Higgs

CMS-PAS-HIG-14-005



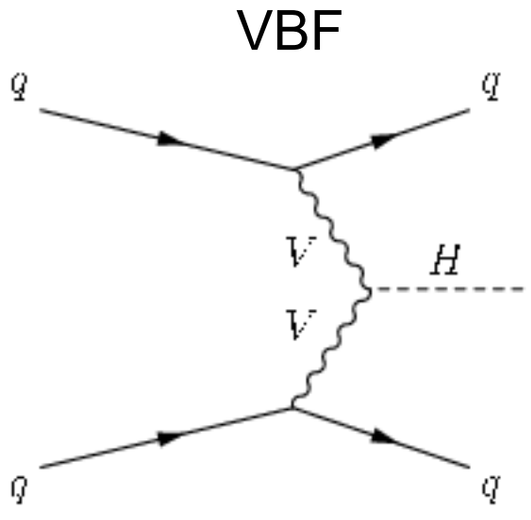


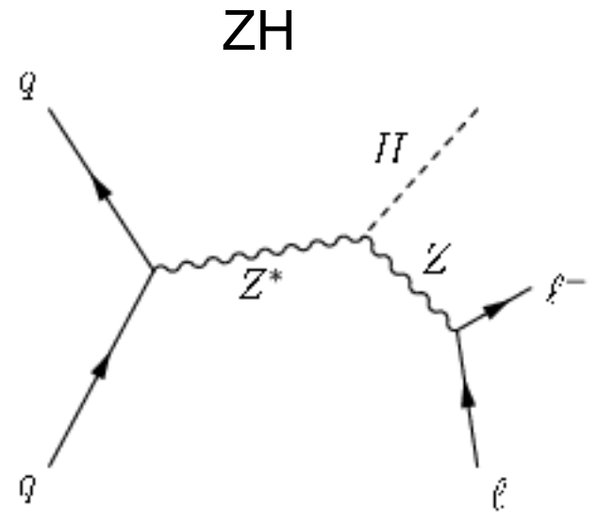
- observed upper limit of BR(H→μτ) of ~1.5%
- best fit yields BR(H→μτ) = (0.89 ± 0.39)% - small excess of 2.5σ, still compatible with 0
- 4.4× improvement of limits w.r.t. indirect measurements
- best limits on flavour-violating τμ Yukawa couplings to date

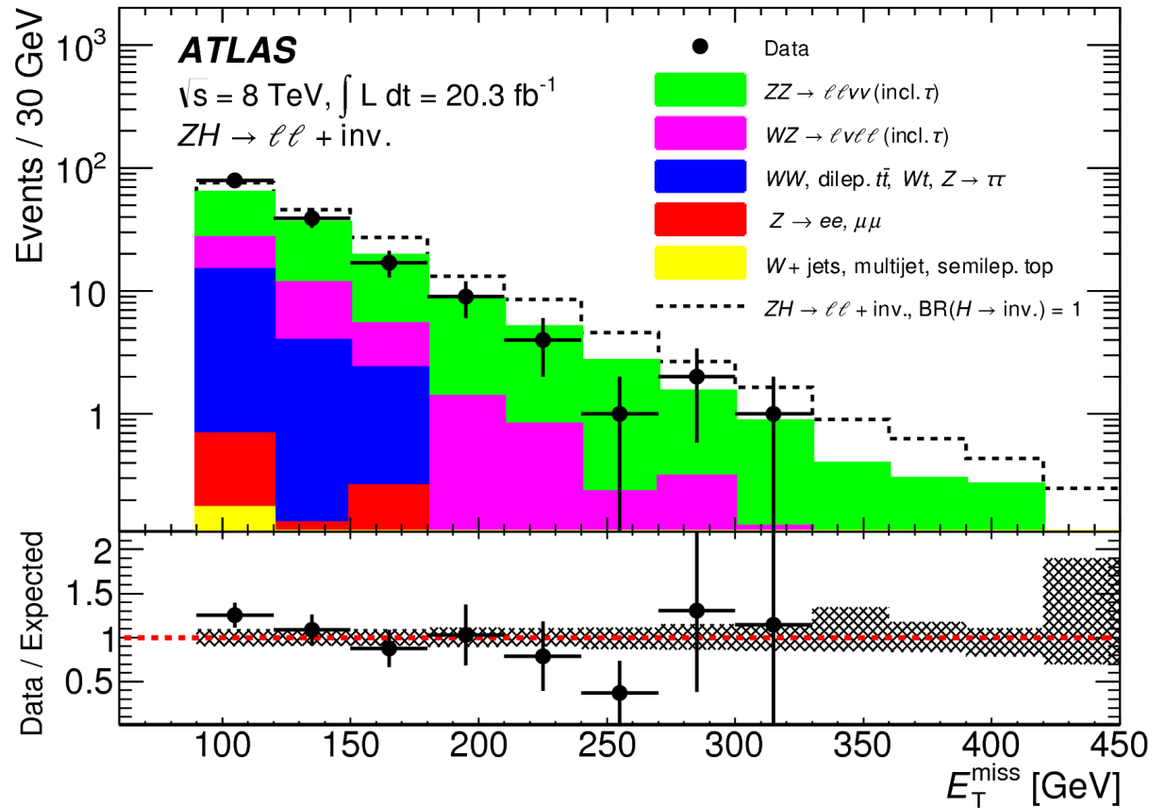
invisible Higgs decays

Eur. Phys. J. C 74 (2014) 2980
Phys. Rev. Lett. 112, 201802 (2014)

- predicted in several new physics models
  - decays to neutralinos (SUSY)
  - decay to graviscalars (extra dimensions)
- accessible if Higgs produced in association with something visible
  - associated ZH production or VBF (VBF features higher cross section)
- signature: two forward jets (VBF)/pair of leptons (ZH) + large missing transverse energy
- main backgrounds: V+jets with unseen V decay (VBF)/VV (ZH)
  - V+jets estimated using visible V decay modes removing their decay products
- data show good agreement with SM backgrounds



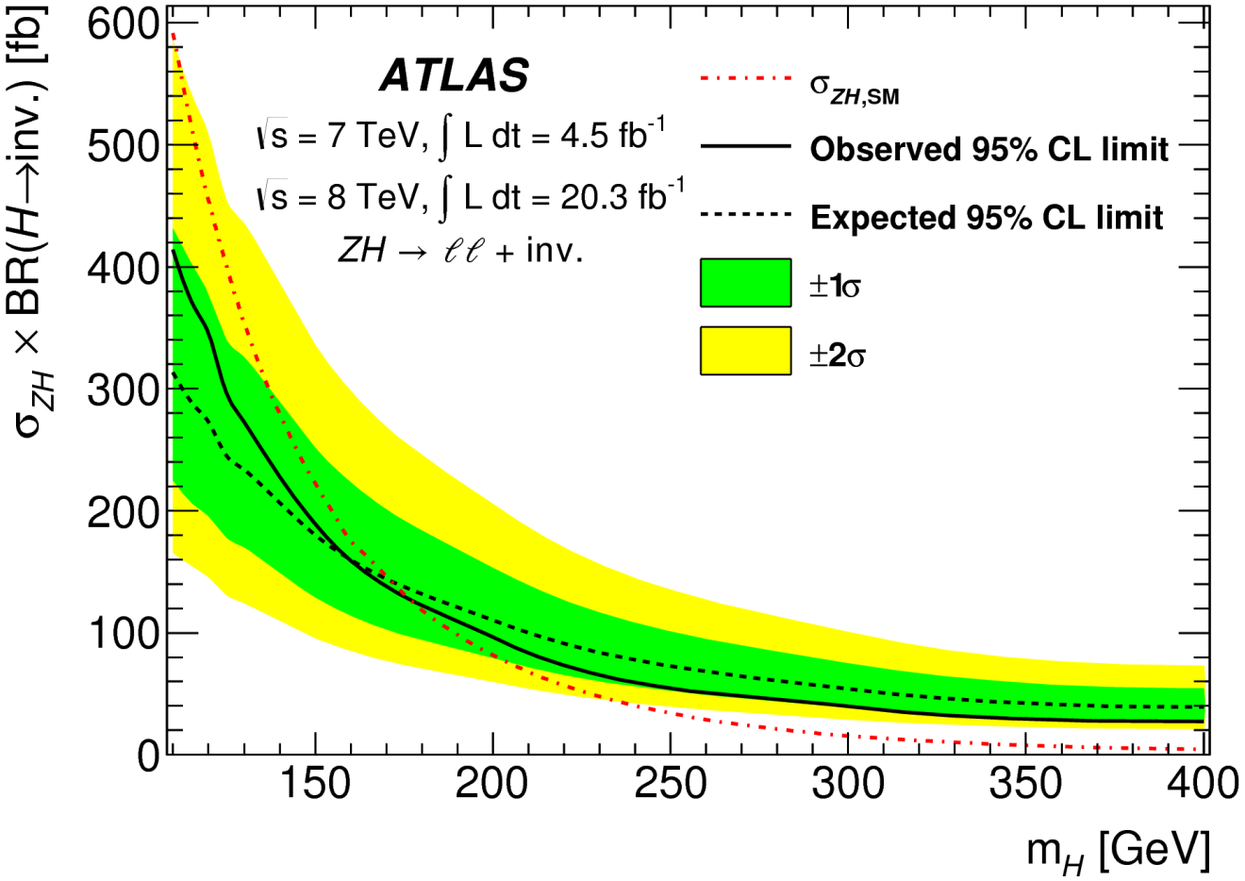


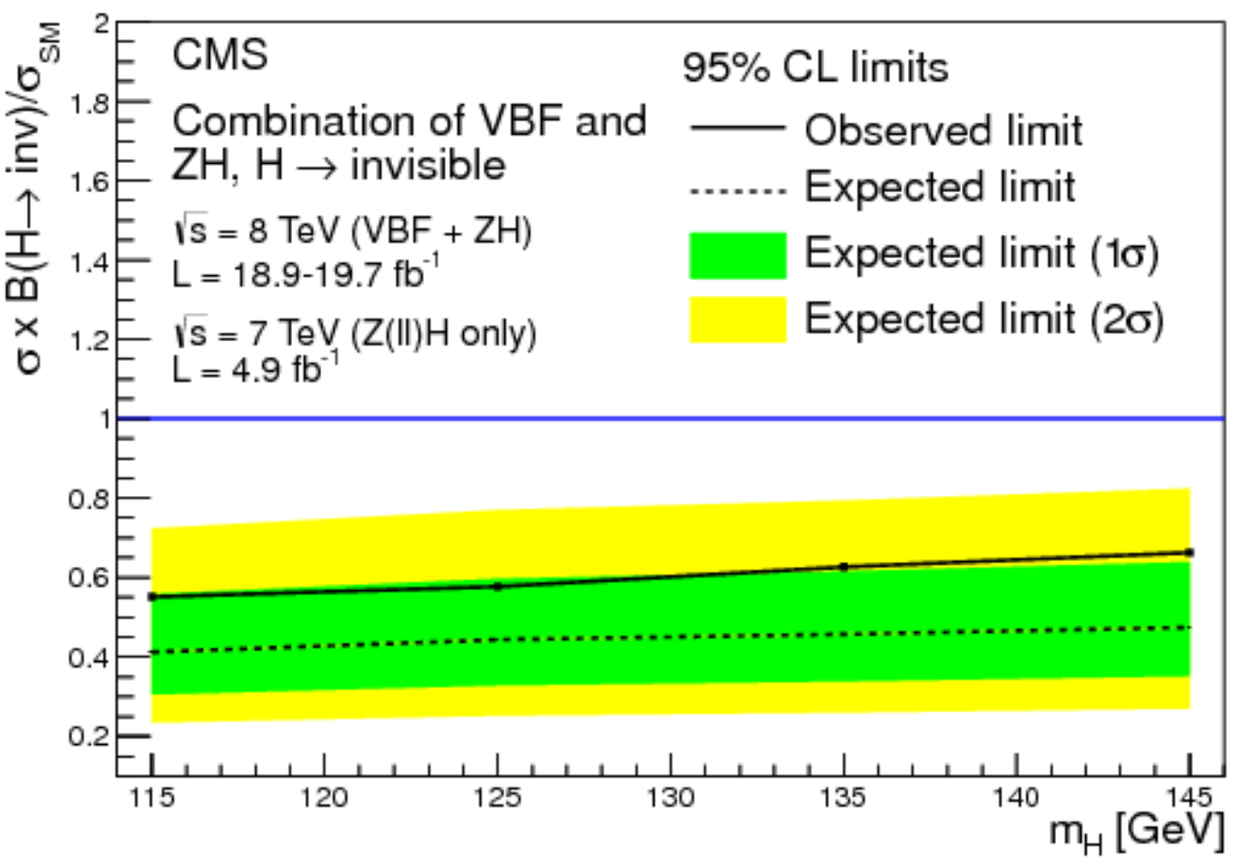


invisible Higgs decays

Eur. Phys. J. C 74 (2014) 2980
Phys. Rev. Lett. 112, 201802 (2014)

- ATLAS set limits on $\sigma_{ZH} \times BR(H \rightarrow invis.)$ (extracted from MET distribution)
- CMS analyse both ZH and VBF channels (based on MET and dijet mass distributions), combination:
  - BR_{inv}<58% observed (44% expected) for a SM Higgs @ 125 GeV (95% C.L.)
  - significant improvement w.r.t. earlier direct searches





invisible Higgs decays

Eur. Phys. J. C 74 (2014) 2980
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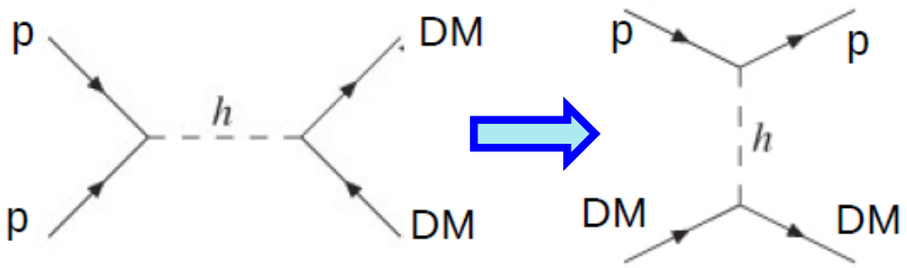
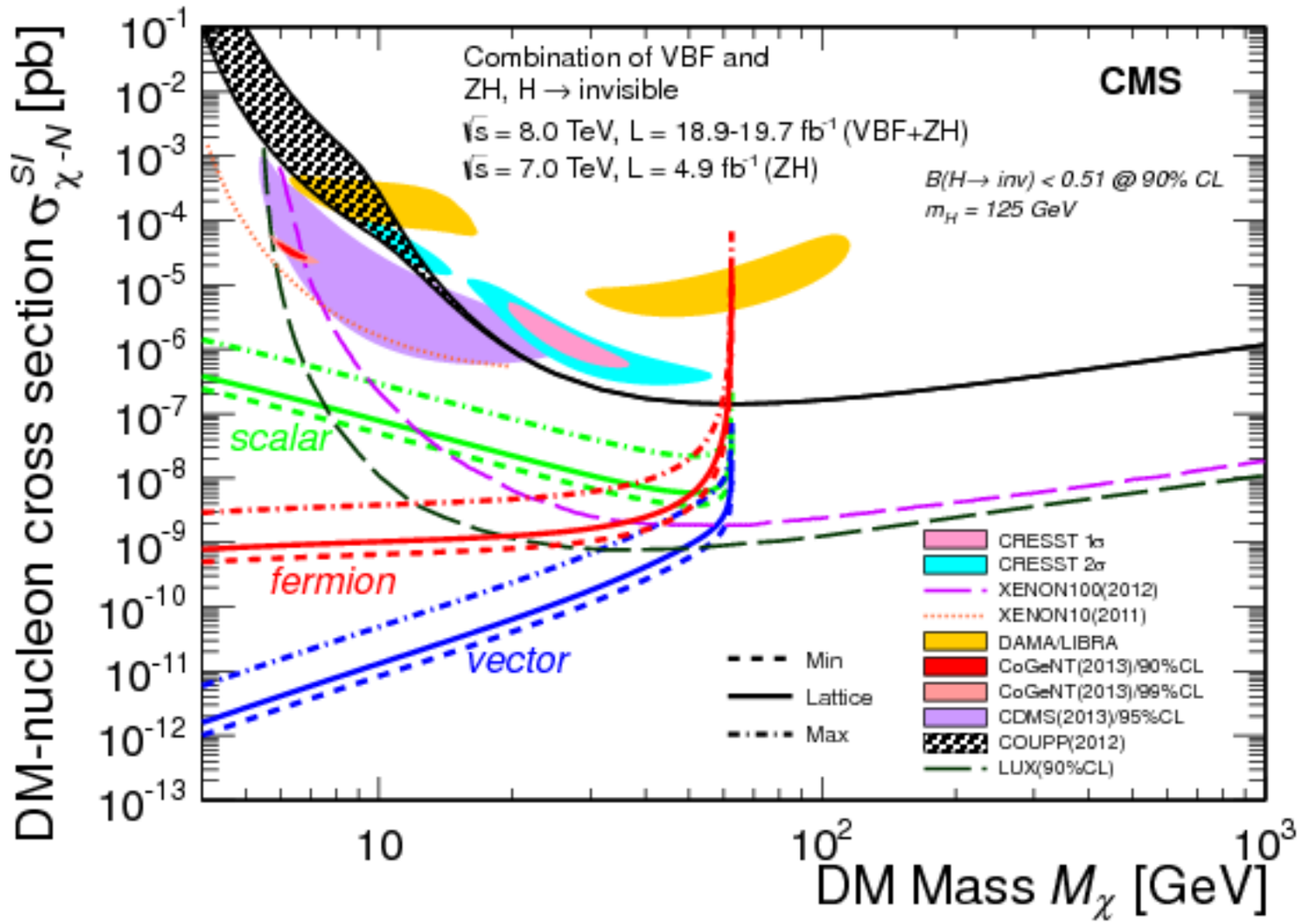
- both experiments perform Dark Matter interpretation (Higgs-portal model)
  - hidden sector with stable DM particles
  - if mass below $m_H/2$: might contribute to Γ_{inv} of Higgs boson
- complementary to direct DM-detection, sensitive to DM-nucleon cross section



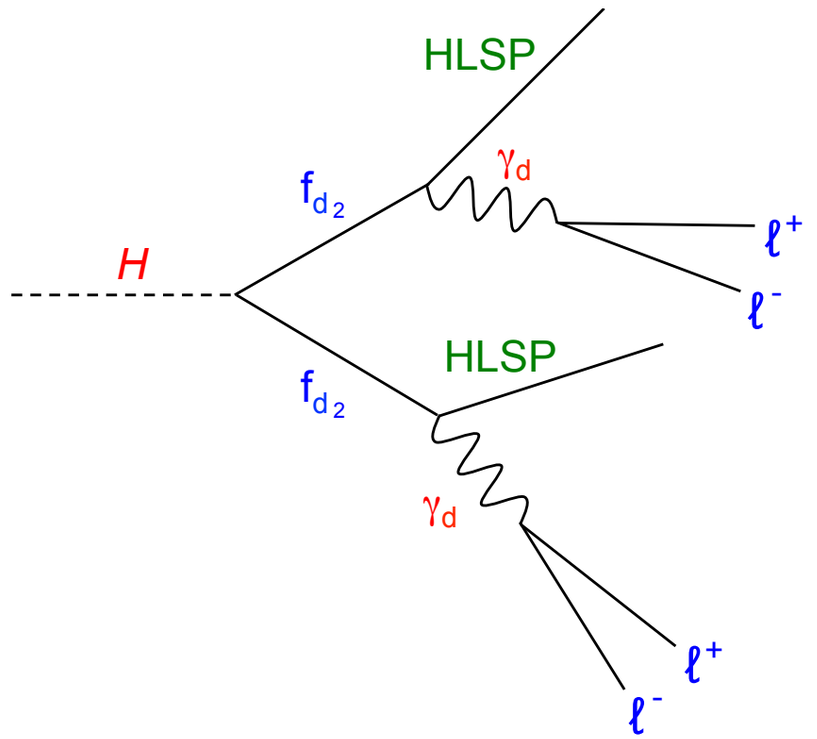
- Convert BR_{inv} to DM-nucleon cross section, assuming Γ_{SM} for total Higgs boson decay width
- limits up to $m_H/2$

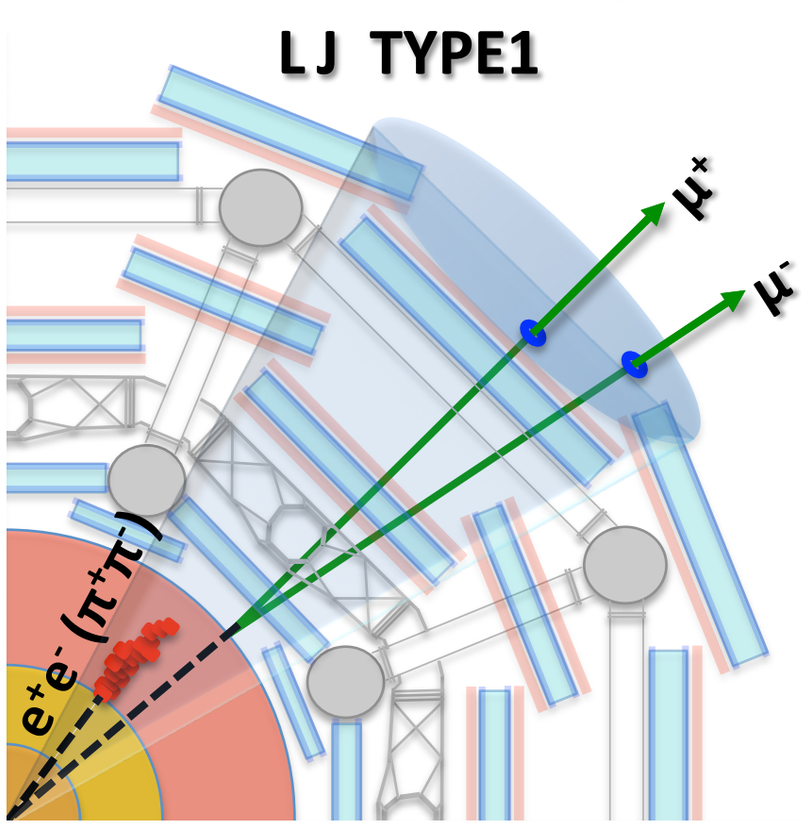


Higgs in long-lived particle searches

CMS-PAS-EXO-12-037
CERN-PH-EP-2014-209
ATLAS-CONF-2014-041

- models such as „split SUSY“ or „hidden valley“ propose existence of long lived particles
  - could be a neutral Higgs boson travelling through detector
- leads to delayed decays in the detector, e.g. search for
  - leptons with transverse large decay lengths
  - jets only created in the hadronic calorimeter
  - lepton jets: collimated jets of leptons and hadrons
- standard reconstruction algorithms not usable any more
  - use of dedicated triggers → e.g. due to different timing
  - needs very good understanding of detector
- no signal found, limits on $c\tau \times BR/\sigma$





summary

- ATLAS and CMS are conducting numerous studies reaching beyond the Standard Model Higgs:
  - is the Higgs boson @ 125 GeV the SM boson (with its properties)?
  - or is it part of an extended Higgs sector (and are there more Higgs bosons)?
- any finding in conflict with SM Higgs would be a hint of New Physics
- several new results based on LHC Run I data
  - each analysis faces different challenges
- LHC Run II will extend the reach of these analyses