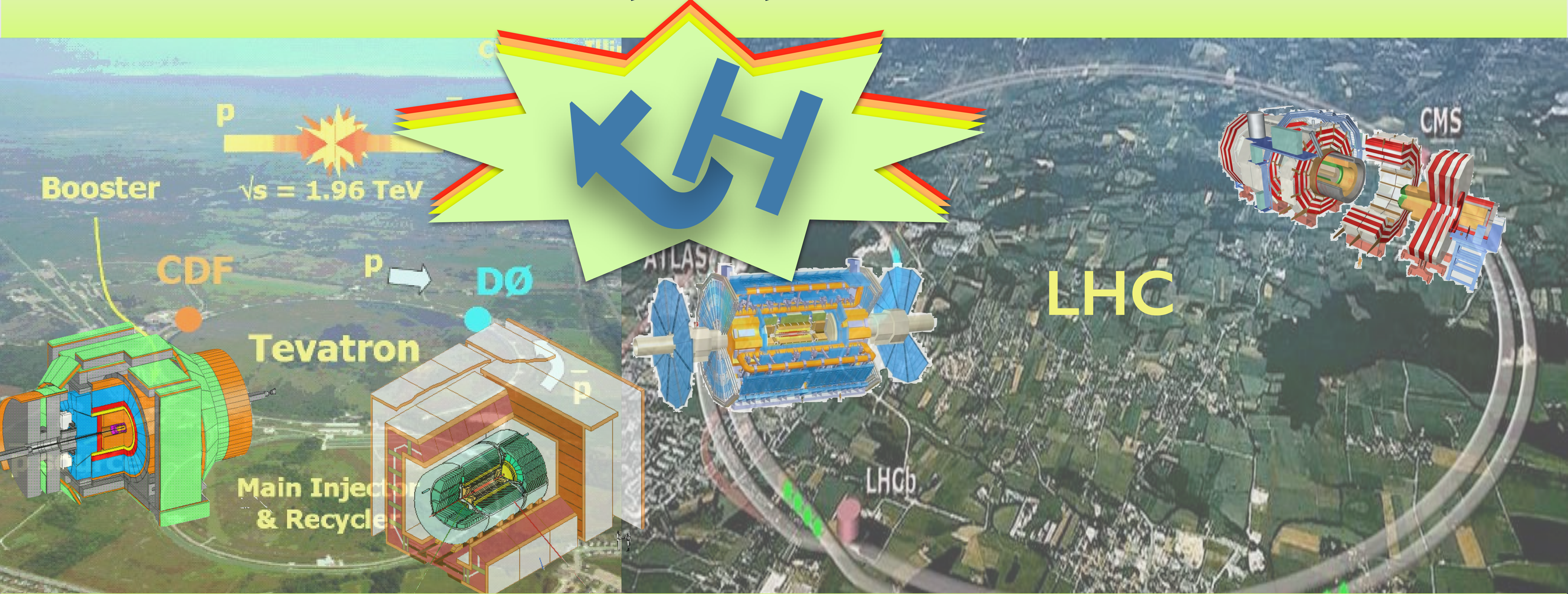
Interplay between the top quark and the Higgs boson - LHC + Tevatron

Jelena Jovićević - TRIUMF, Canada

on behalf of **ATLAS, CMS, CDF** and **D0** collaborations



CKM Unitarity Triangle 2016, Mumbai, India

Two big discoveries

Top quark

2nd of March 1995 - CDF & D0

Higgs boson

4th of July 2012 - ATLAS & CMS

Two big discoveries

Top quark

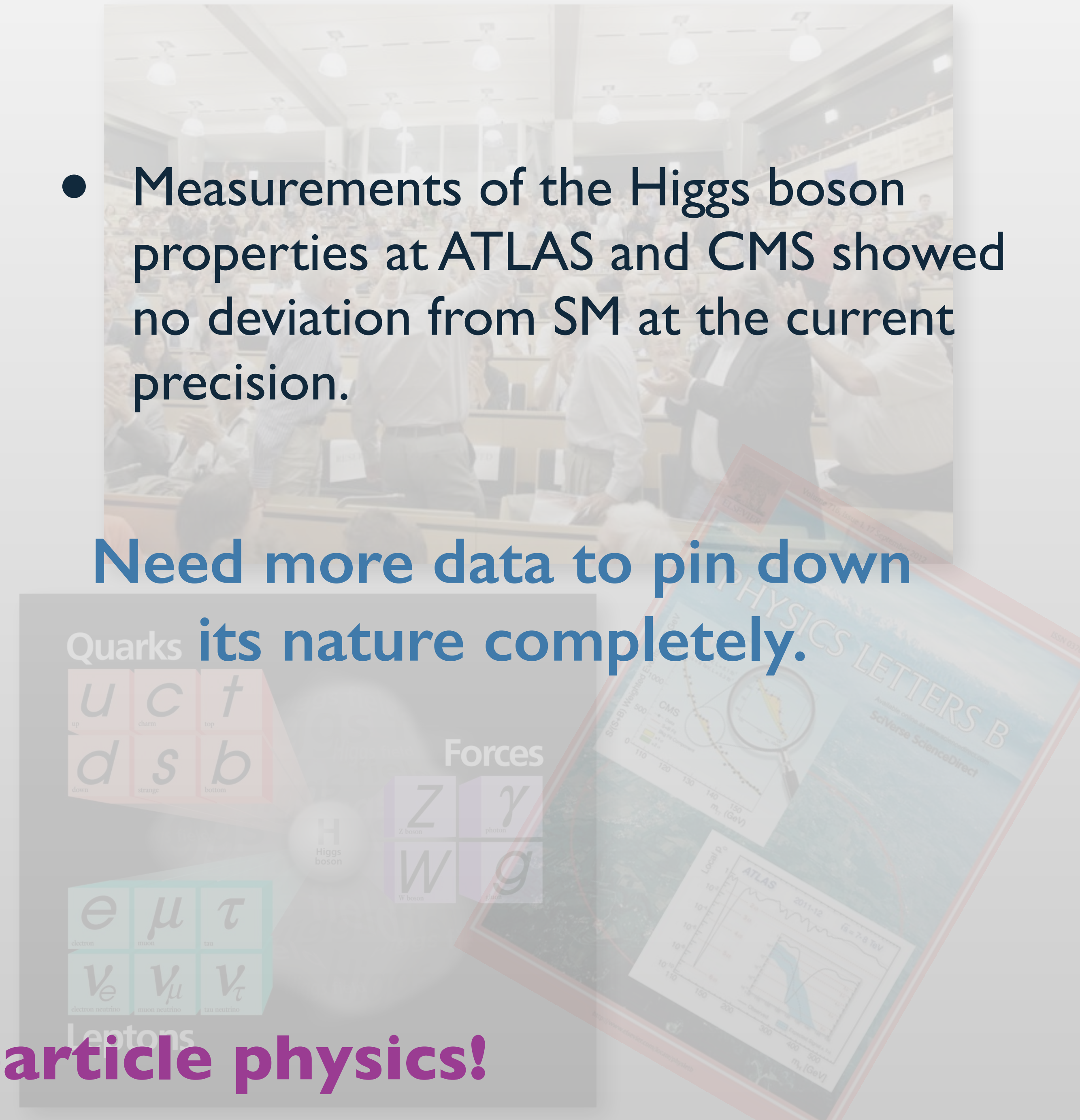
2nd of March 1995 - CDF & D0

- Top quark properties well measured at CDF and D0 at 1.96TeV;
- Complementary measurements by ATLAS and CMS at 7, 8, 13 TeV;

Please see dedicated talks at the conference!

Higgs boson

4th of July 2012 - ATLAS & CMS



- Measurements of the Higgs boson properties at ATLAS and CMS showed no deviation from SM at the current precision.

Need more data to pin down its nature completely.

EXCITING era for particle physics!

Outline

Interplay between the Higgs and top masses

- Most precise Higgs boson mass measurement:
- Top mass measurement covered in dedicated talk by Oleg Brandt (WG 6);
- Constraints from the current mass measurements.

Higgs-top Yukawa coupling measurement

- Most precise coupling measurement - LHC Run 1 ATLAS+CMS combination and importance of individual channels.

$t\bar{t}H$ production measurement

- Most sensitive channel to directly probe Higgs-top-Yukawa coupling;
- $H\rightarrow bb$, $H\rightarrow WW/ZZ/\tau\tau$. $H\rightarrow\gamma\gamma$ considered;

tH production measurement

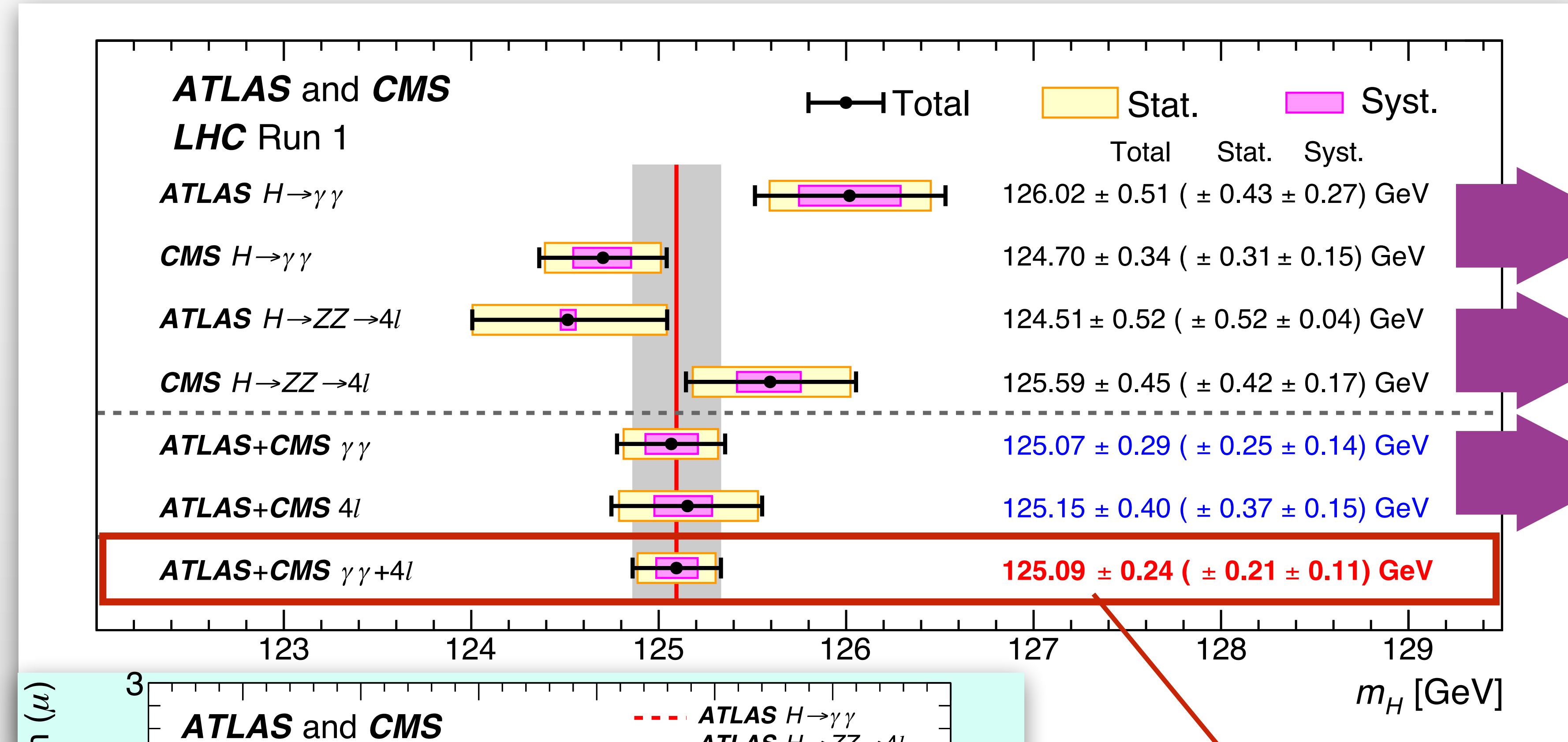
- Direct test of sign and magnitude of Higgs-top-Yukawa coupling.

Search for BSM charged Higgs bosons within top sector

Higgs boson mass and top quark mass interplay

Higgs mass - ATLAS+CMS Run I

- Measured using H→γγ and H→ZZ→*4l* channels Phys. Rev. Lett. 114, 191803

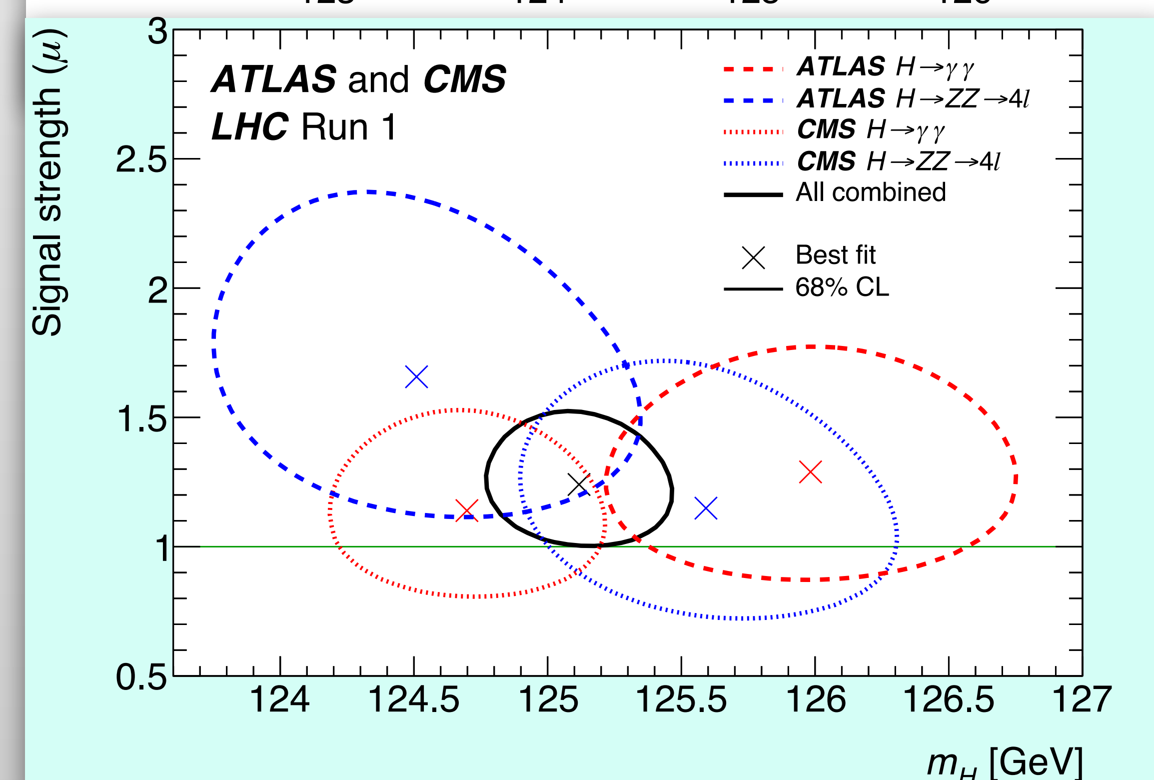


ATLAS/CMS compatibility

H→γγ: 2.1σ

H→ZZ→4l: 1.3σ

Combined: <1σ



Most precise measurement:

m_H=125.09 ± 0.24 GeV

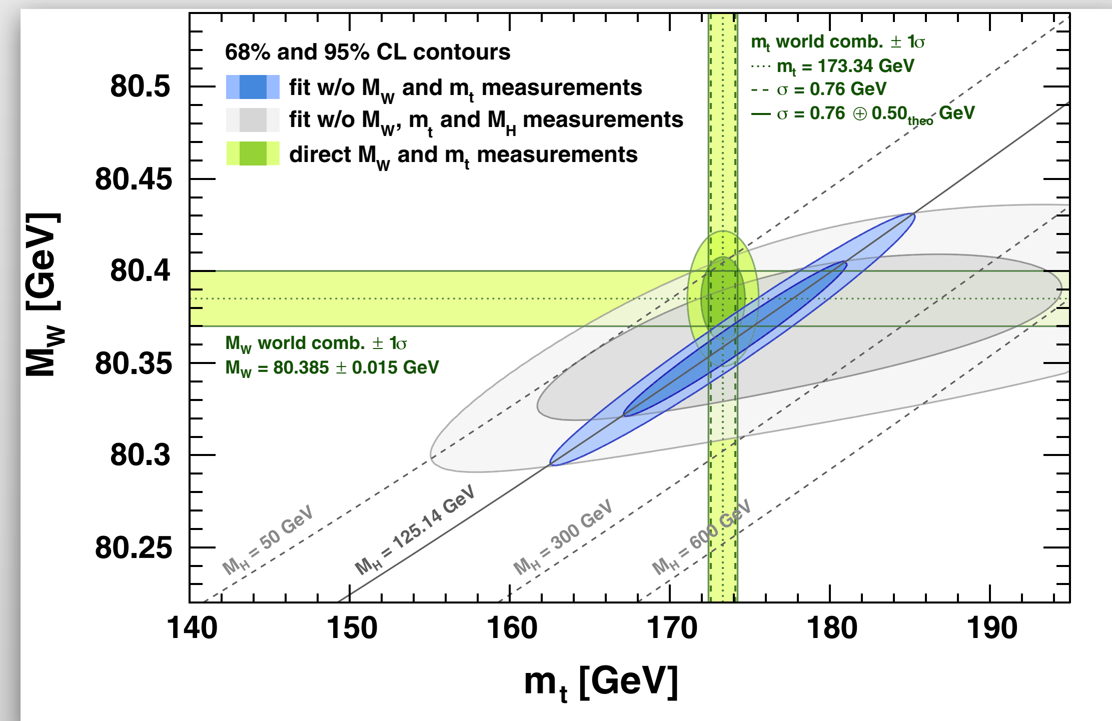
2D likelihood contours as a function of signal strength for γγ, *4l* and combined channels.

Constraints from Higgs and top masses

- The top mass, the W mass, and the Higgs mass are related through radiative corrections;
  - Before the Higgs boson discovery, the indirect constraint on its mass was based on direct top quark and W boson mass measurements at Tevatron and LEP, and requirement for the consistency of the electroweak theory as a quantum field theory.
- Where do we stand now?

Consistency check of the SM (top-W-Higgs)

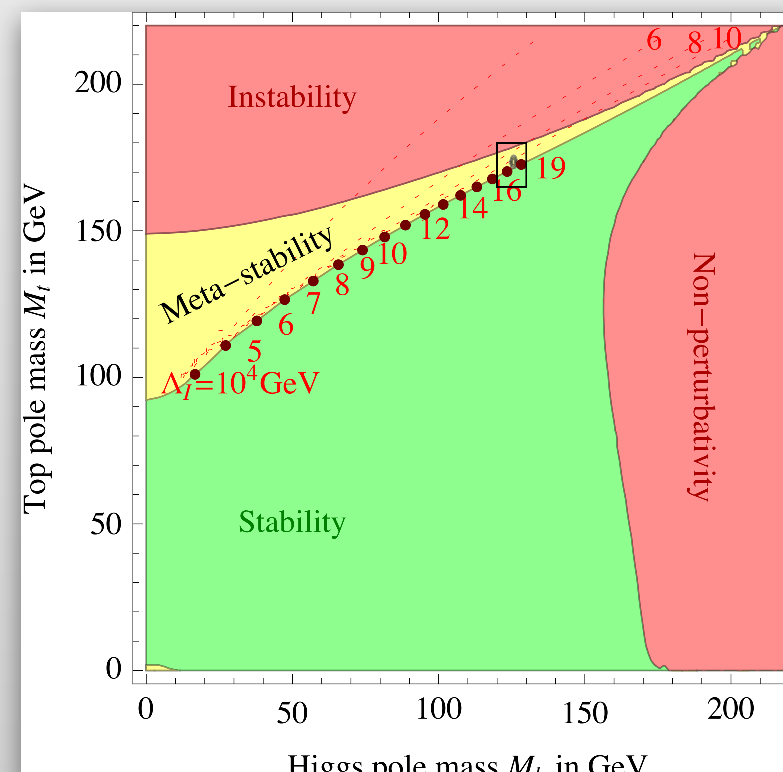
Eur. Phys. J. C (2014) 74: 3046.



Future precise measurements of the m(H), m(W), m(t) could unveil a discrepancy that might lead to the discovery of new physics

Stability of the EW vacuum

JHEP 1312 (2013) 089



Do we live in the stable vacuum?

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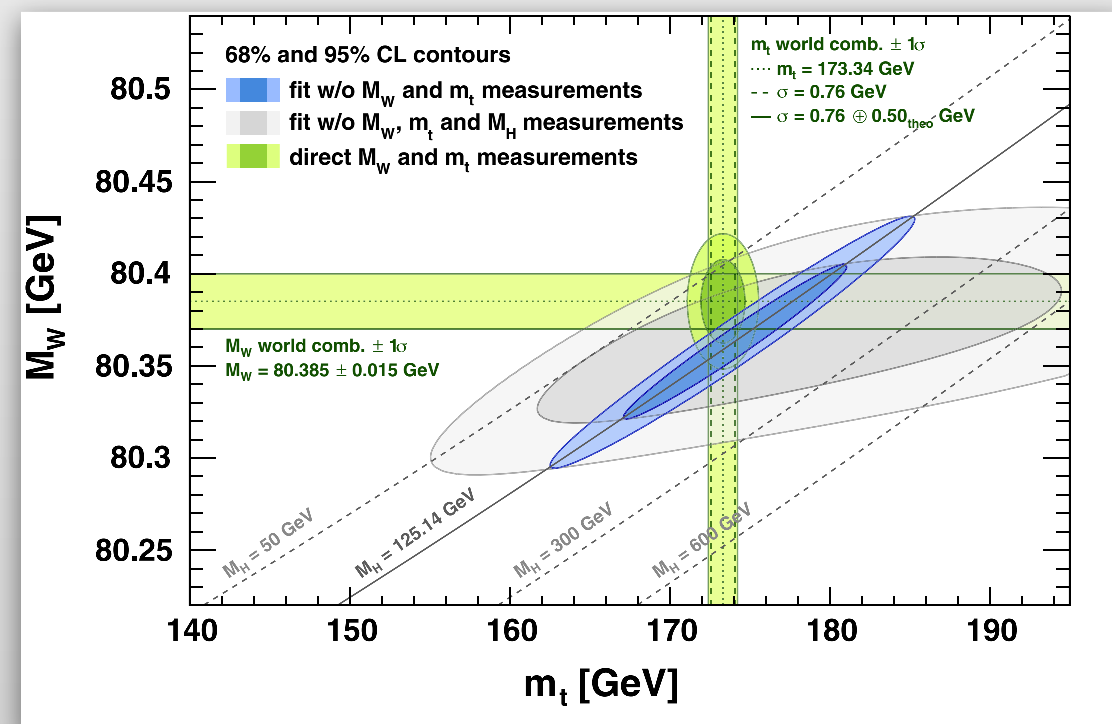

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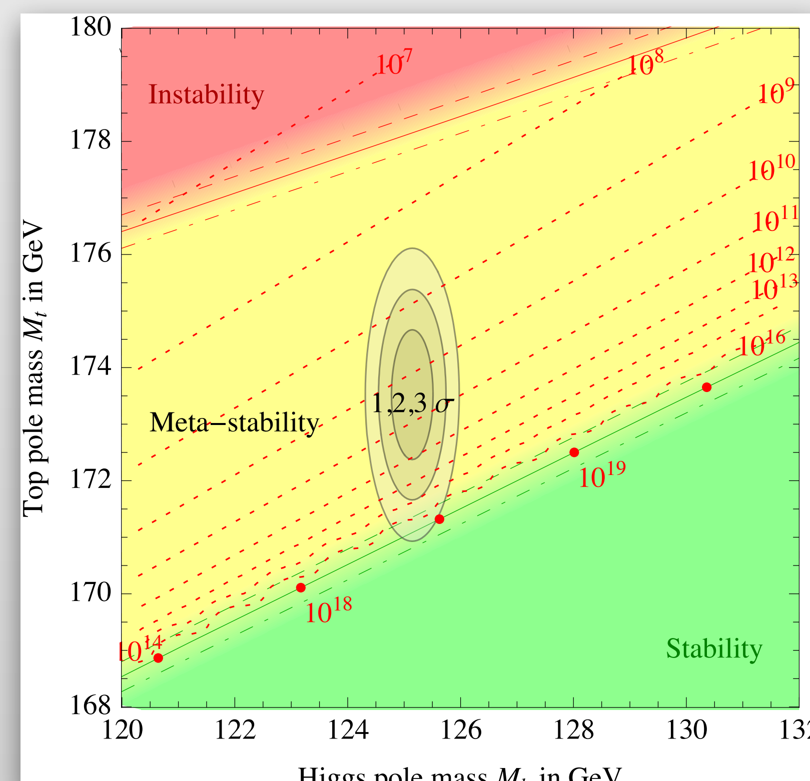


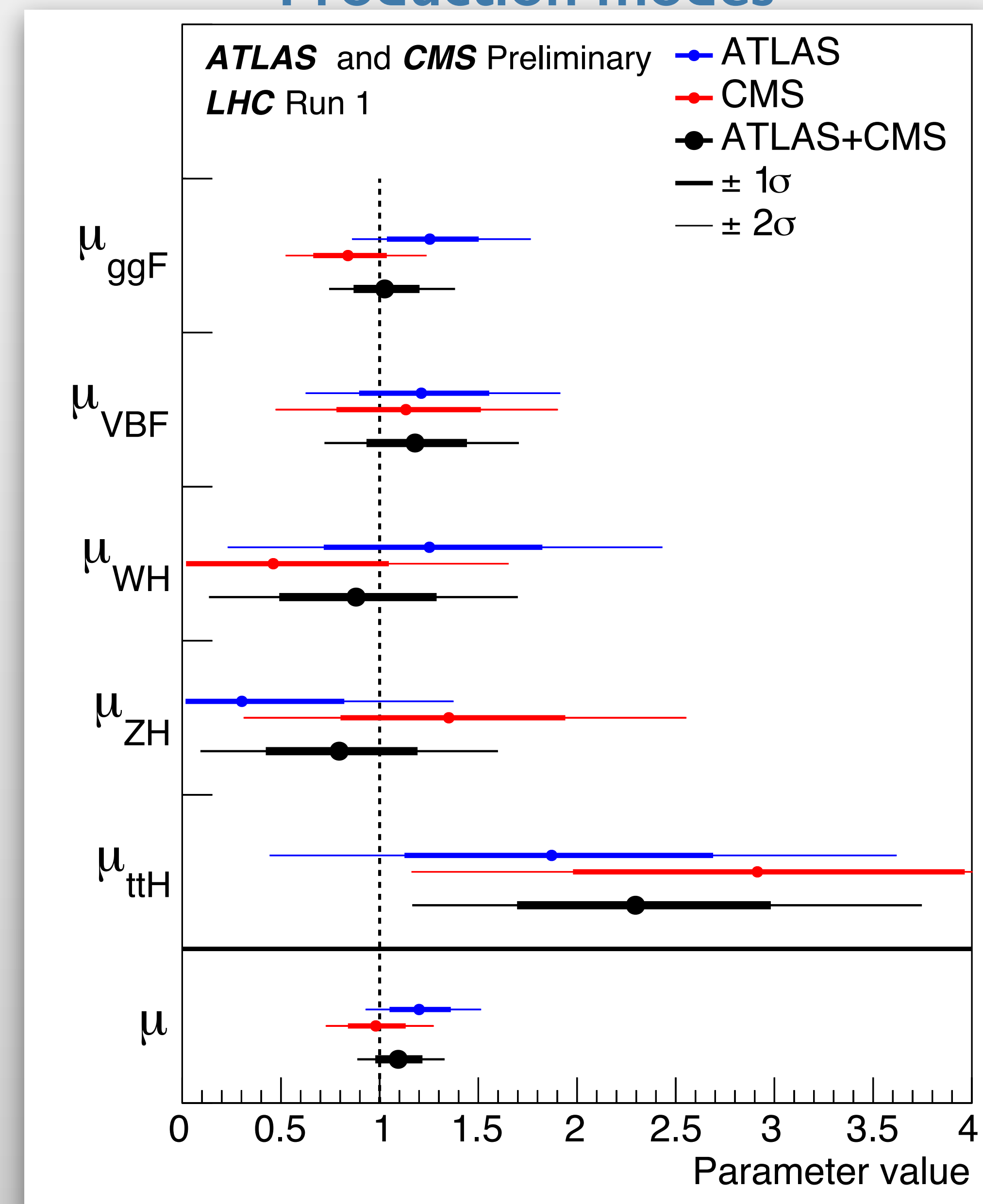
Do we live in the stable vacuum?

Higgs-top Yukawa coupling

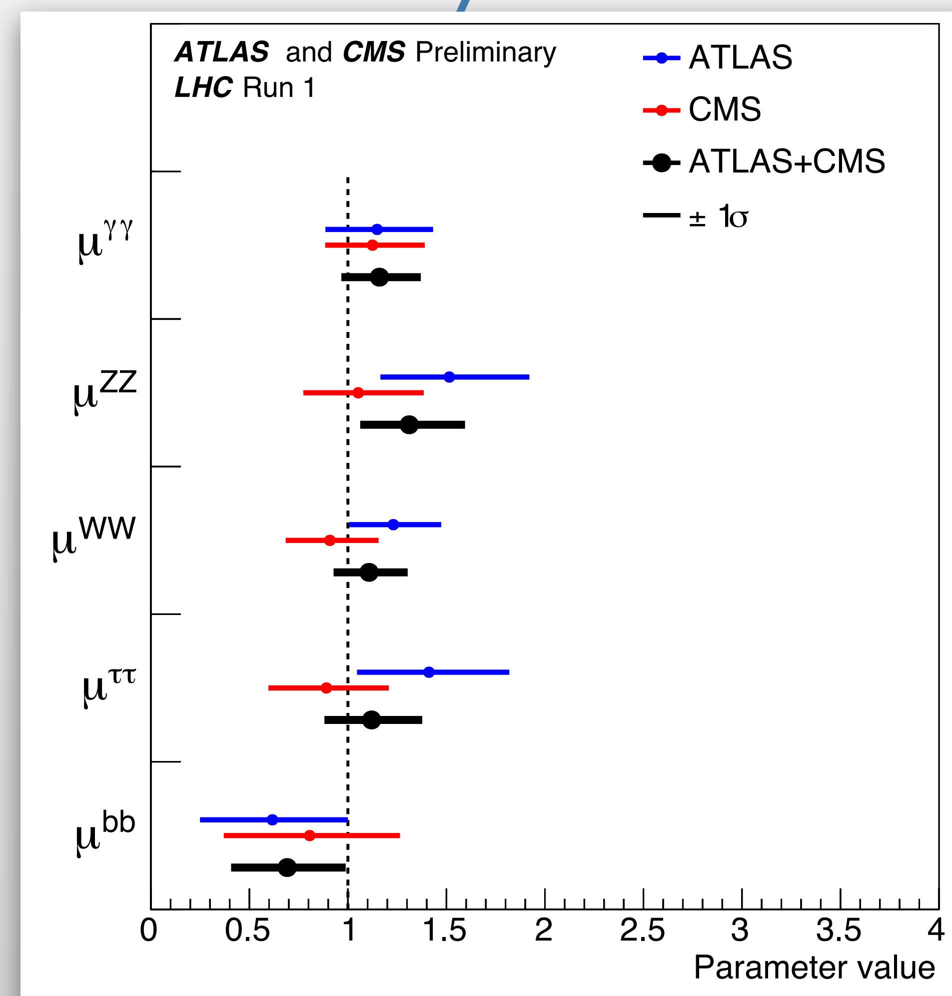
Higgs couplings measurement

- Most precise constraints on Higgs couplings performed through parametrisation of all accessible production and decay modes, ATLAS+CMS Run 1 - JHEP 08 (2016) 045
- Measured signal strength μ, $\mu=\sigma/\sigma_{SM}$ in individual production and decay modes;

Production modes



Decay modes



All measurements compatible with SM predictions

Hunting the Higgs-top Yukawa coupling

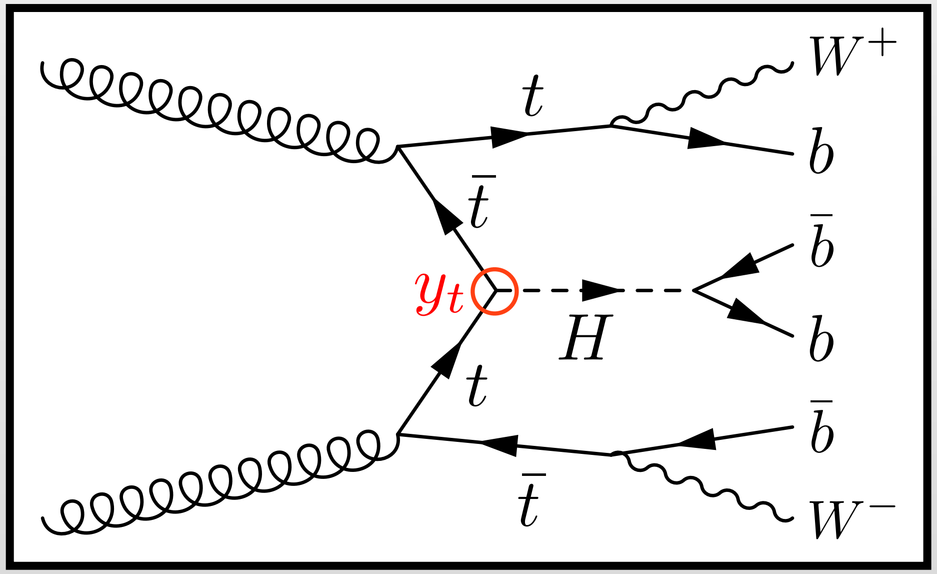
Direct measurement

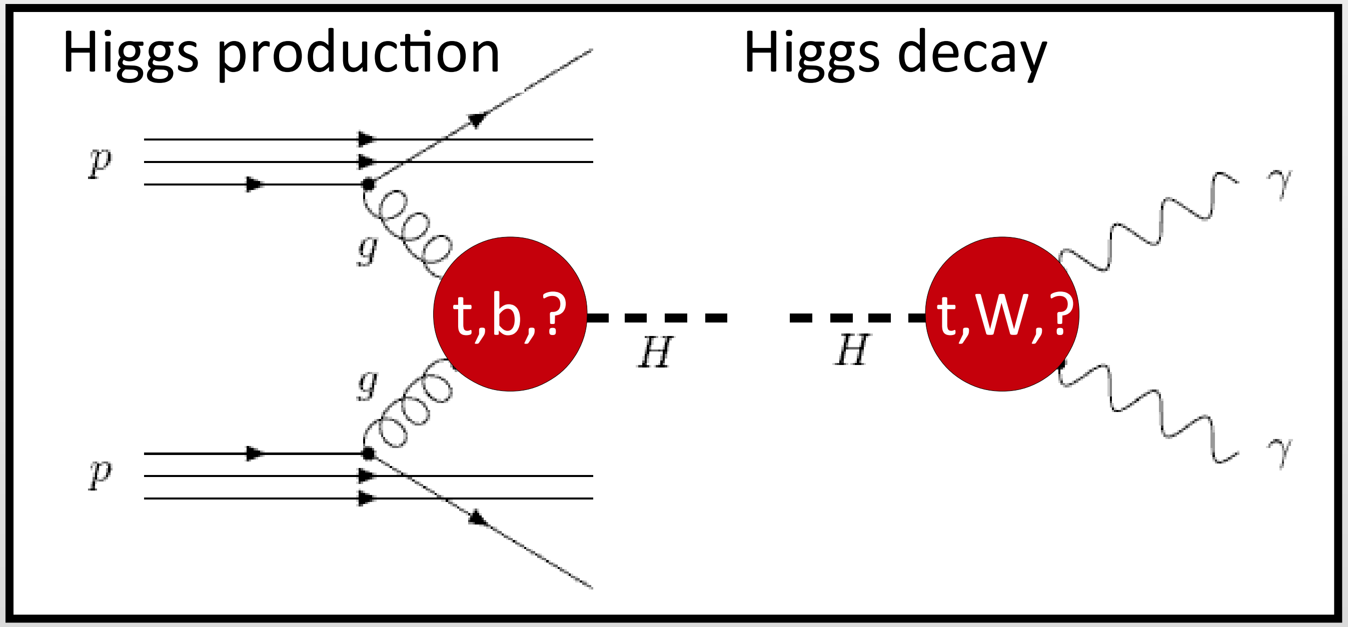
- **Direct** measurement **in $t\bar{t}H$** production

Sensitive to y_t^2

Indirect constraints:

- loops in **ggF** and **H → γγ** vertices;
  - assuming only SM particles contributing to the loops.





- **tH production**: interference between top-mediated and W-mediated diagrams;

Sensitive to y_t

- **H → γγ**: interference between top quark and W boson in the loop;
- **ZH production and H->Zγ**: interference between top quark and W-boson contribution in the loop.

Coupling measurement methodology

TRIUMF

arXiv:1307.1347

Assumptions:

- Observed signal originates from the **single resonance**;
- **Narrow width** approximation: $(\sigma \cdot BR)(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$
- Parametrise deviations with only **coupling strength modifiers {κ_x}.**

Procedure:

- Scale SM cross-section and partial widths as a function of parameters {κ_x}:

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma)\ \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

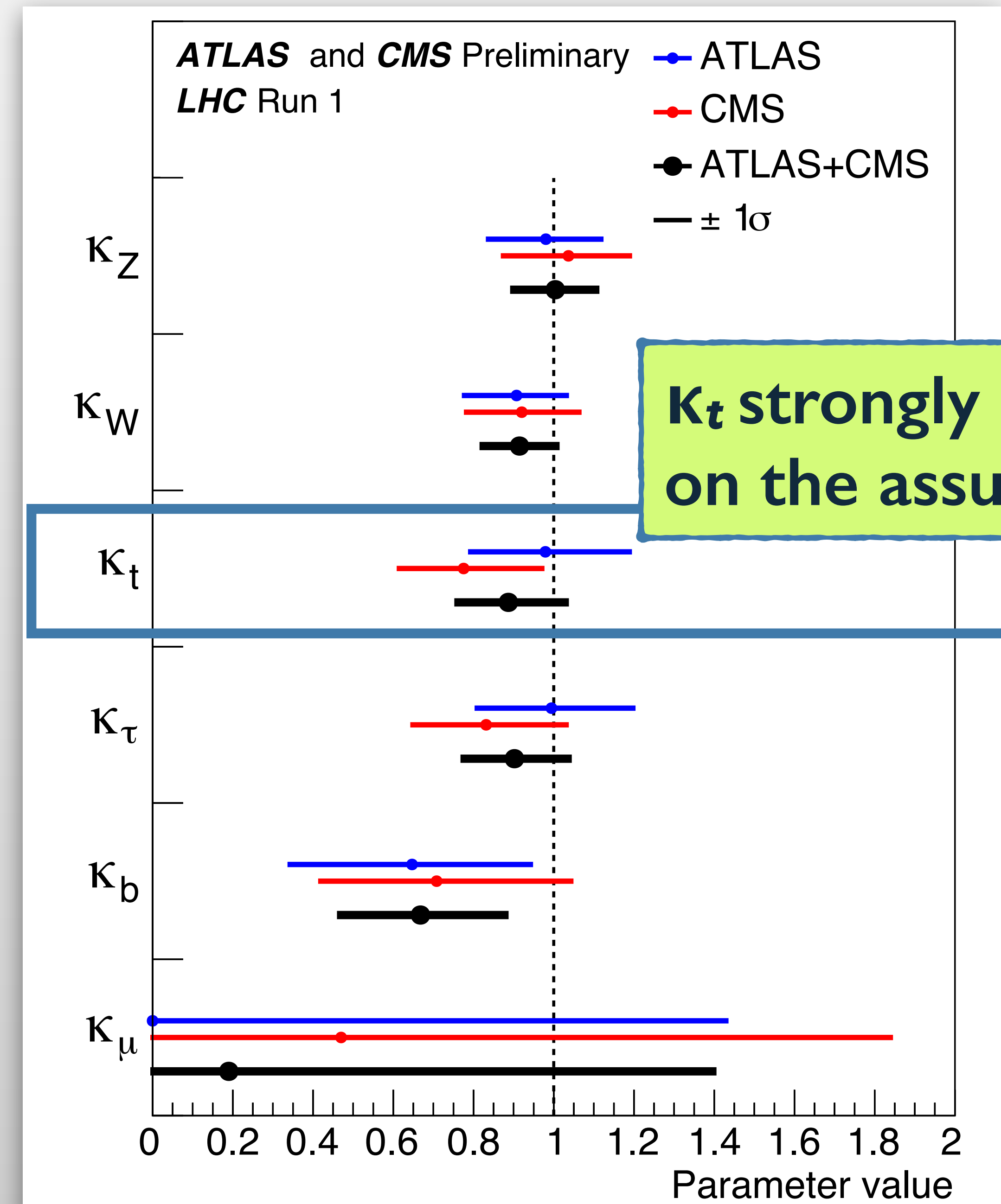
- In case of loop processes κ_x can be expressed as a function of more fundamental κ_y;
- If BSM decays are allowed, scale down all SM decays uniformly.

Tested many scenarios:

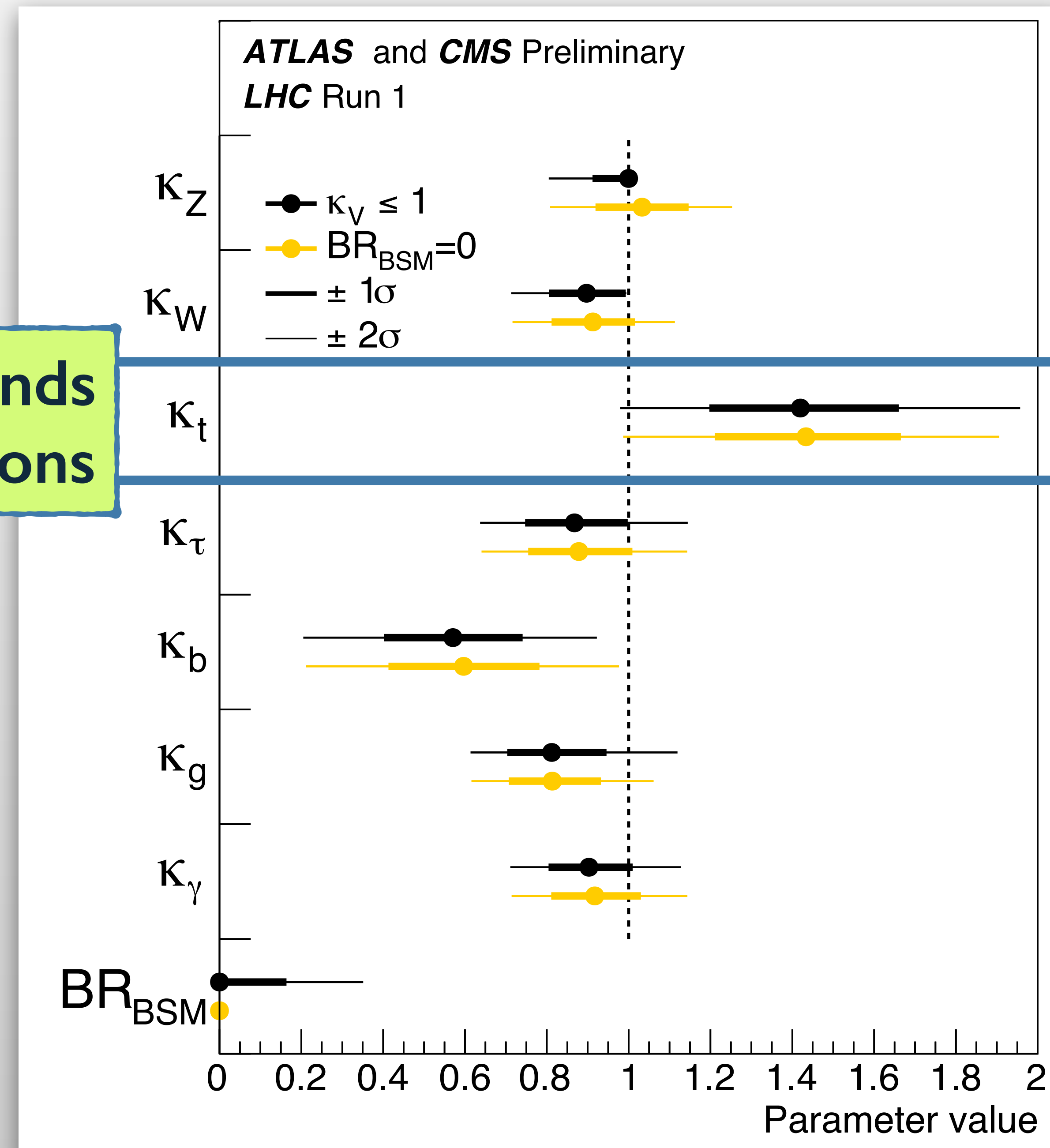
- **Fermion versus vector boson** couplings, up quark VS down quark couplings: also provide constraints on BSM
- **Generic model** - simultaneous fit of all modifiers, etc…

Top Yukawa coupling - ATLAS+CMS Run I

- parameterisation assuming the absence of BSM particles in the loops, $BR_{BSM} = 0$, $\kappa_j > 0$;
- two parameterisations allowing loop couplings, with either $\kappa_{V(W,Z)} \leq 1$ or $BR_{BSM} = 0$;



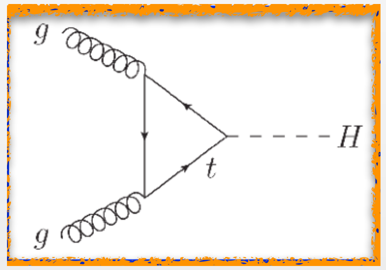
κ_t strongly depends on the assumptions



To resolve the loops or not?

- Sensitivity to κ_t depends strongly on the assumptions on the contributions in the loops;

"Resolved loops" scenario:



- only SM particles contribute to the loop diagrams;
- no new particles that the Higgs boson can decay into (BR_{BSM}=0);
- **Resolving ggF & H→γγ loops pins down κ_t^2 & *sgn* κ_t.**

$$\kappa_t = 0.94 \pm 0.21$$

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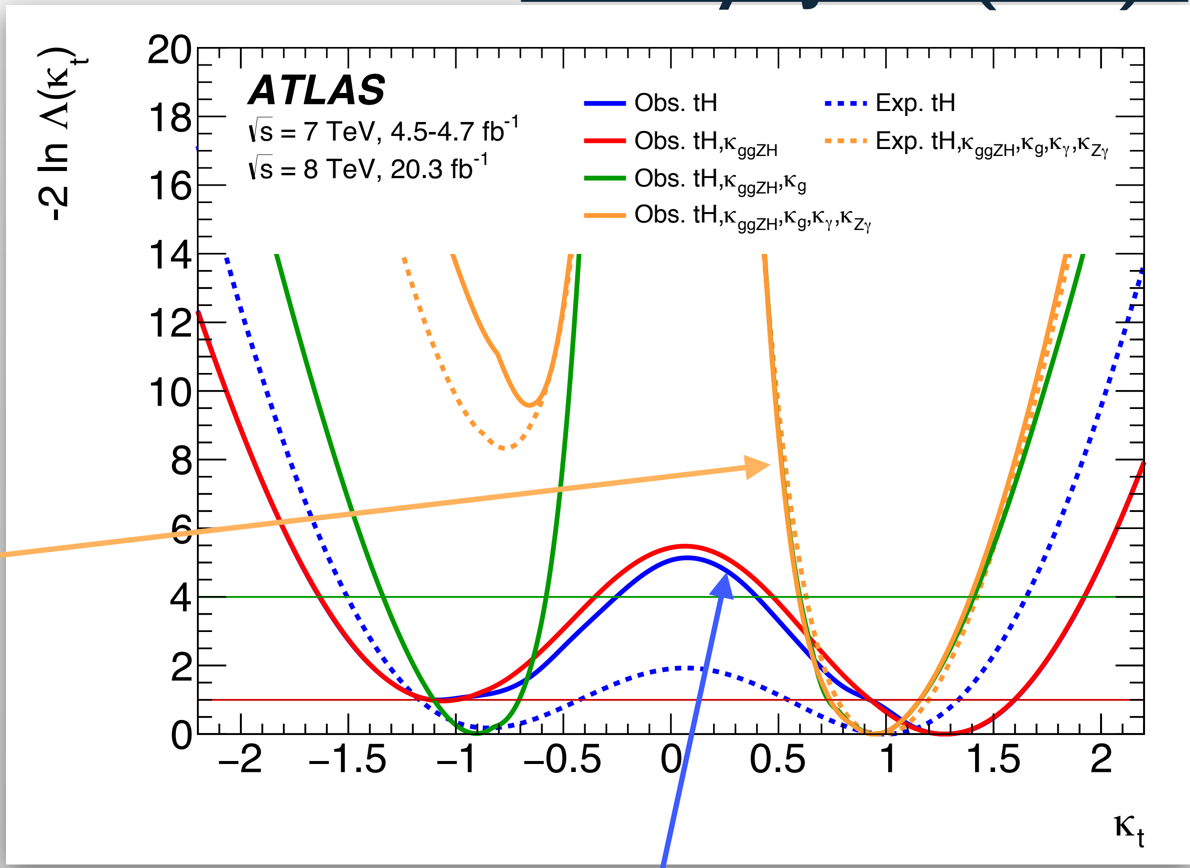
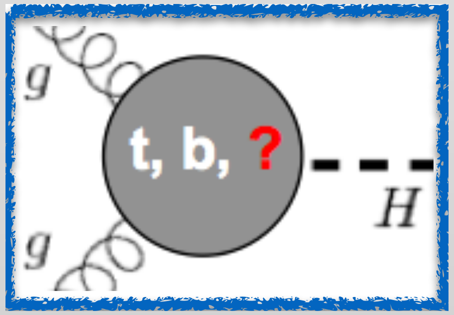


"No resolved loops" scenario:

- allowing BSM effects to modify independently each loop;
- independent κ-modifier for γγ, gg, and Zγ vertices;
- still no new particles the Higgs boson can decay into (BR_{BSM}=0)



➡ **sensitivity on κ_t completely dominated by $t\bar{t}H$ analyses.**

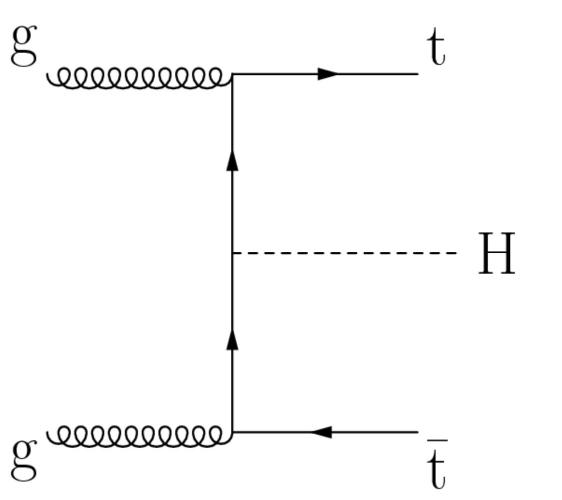
$$\kappa_t \in [-1.12, -1.00] \cup [0.93, 1.60]$$

$t\bar{t}H$ production

$t\bar{t}H$ - final states

Large BR
Large background

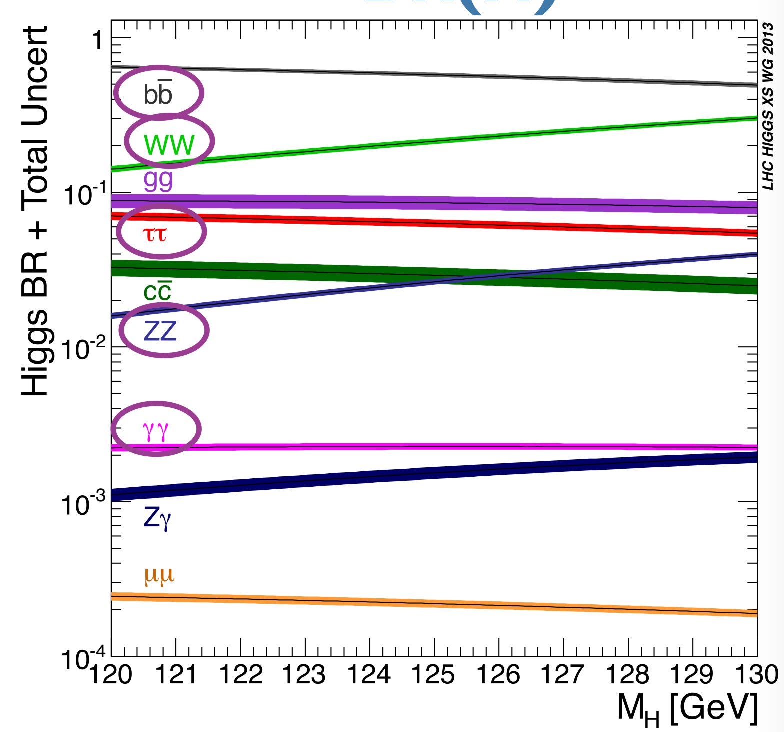
ttH production



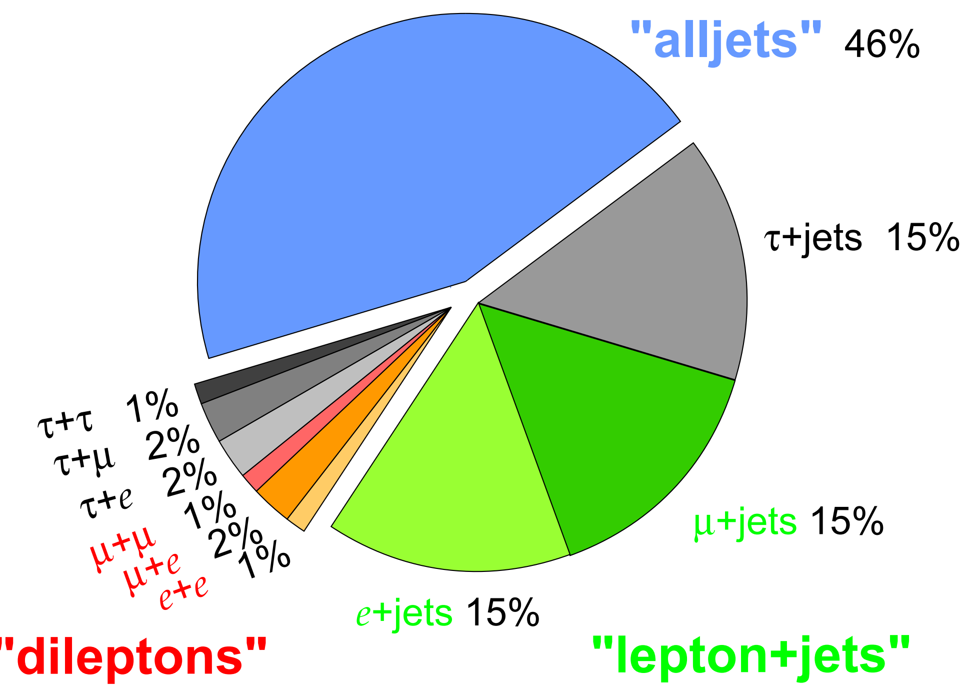
$\sigma(t\bar{t}H) = 507 fb^{-1}$ @ 13TeV

$1\%\sigma(H)$

BR(H)



BR($t\bar{t}$)



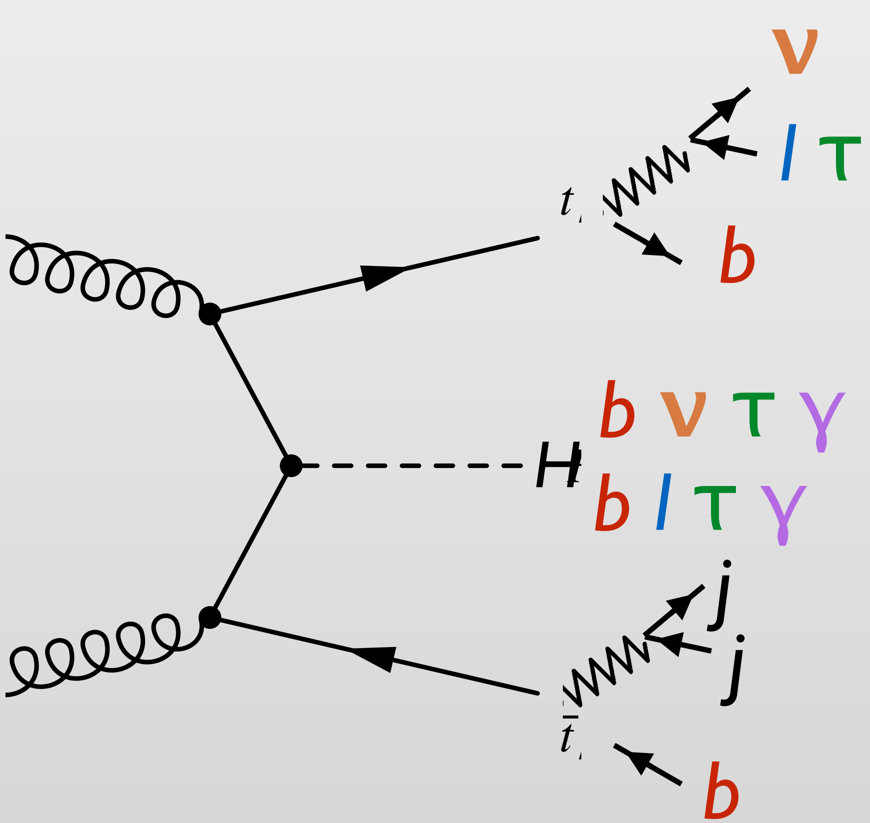
Small BR
Purity and precision

Broad spectrum of analyses covering multiple final states:

- generally combine low BR Higgs decay with high BR $t\bar{t}$ decay and vice-versa;
- $t\bar{t}$ decay products help selection of signal and the reduction of non-$t\bar{t}$ backgrounds, but combinatorics increased when attempting to reconstruct the Higgs boson candidate.

Experimental challenges

Large variety of final states - good understanding of all reconstructed objects



- **electrons / muons**: precise (sub % level) energy / momentum calibration, understanding of identification efficiency, trigger rate;
- **hadronically decaying taus**: energy calibration, controlling rate from misidentified jets and electrons.
- **photons**: energy calibration, precise identification, direction determination (pointing).
- **jets**: precise calibration (% level), stability in presence of large pile-up.
- **missing transverse energy**: stability in presence of large pile-up
- **b-jets** Good understanding of signal efficiency and misidentification rate.

Analysed final states

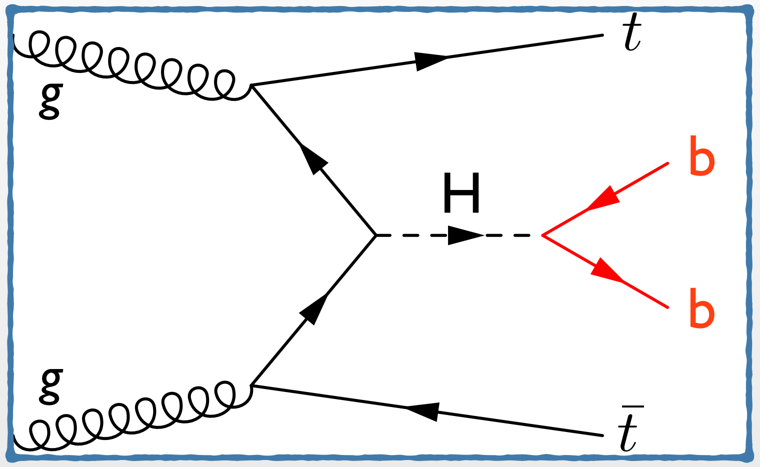
- **Focus on the latest 13 TeV results - ATLAS (13.3fb^{-1}) and CMS (12.9fb^{-1});**
- H→bb: ATLAS-CONF-2016-080 , CMS-PAS-HIG-16-038 (previous 13TeV result) JHEP 05 (2016) 160 - Run 1 all-hadronic channel;
- H→γγ: ATLAS-CONF-2016-067 , CMS-PAS-HIG-16-020 ;
- H→leptons: ATLAS-CONF-2016-058 , CMS-PAS-HIG-16-022 (previous 13TeV result);
- ttH combination: ATLAS-CONF-2016-068.

	H→bb	H→γγ	H→WW* (H→leptons)	H→ττ (H→leptons)	H→ZZ* (H→leptons)
$t\bar{t}$-allhad	Y	Y			
$t\bar{t}$-l+jets	Y	Y	Y	Y	Y
$t\bar{t}$-dilepton	Y	Y	Y	Y	Y

Y - 13 TeV result   Y - 8 TeV result

(The Y for $t\bar{t}$-allhad H→bb is an 8 TeV result; all others are 13 TeV results.)

$t\bar{t}H(bb)$



- Largest BR ~ 58% ☺
- Fermion-only production and decay; ☺
- Multiple b-quarks in the final state - Higgs reconstruction challenging; ☹
- irreducible tt+bb background has large theory unc. ☹

Selection:

- semi-lepton / dilepton tt-decays - events with *1l* / *2l* & ≥*4j* (≥2 btag) / ≥*3j* (≥2 btag).

Categorisation based on N-jet & N-btag;

- High S/B regions - signal-like (S/B~1%-7%), low S/B regions used to control background and systematic uncertainties.

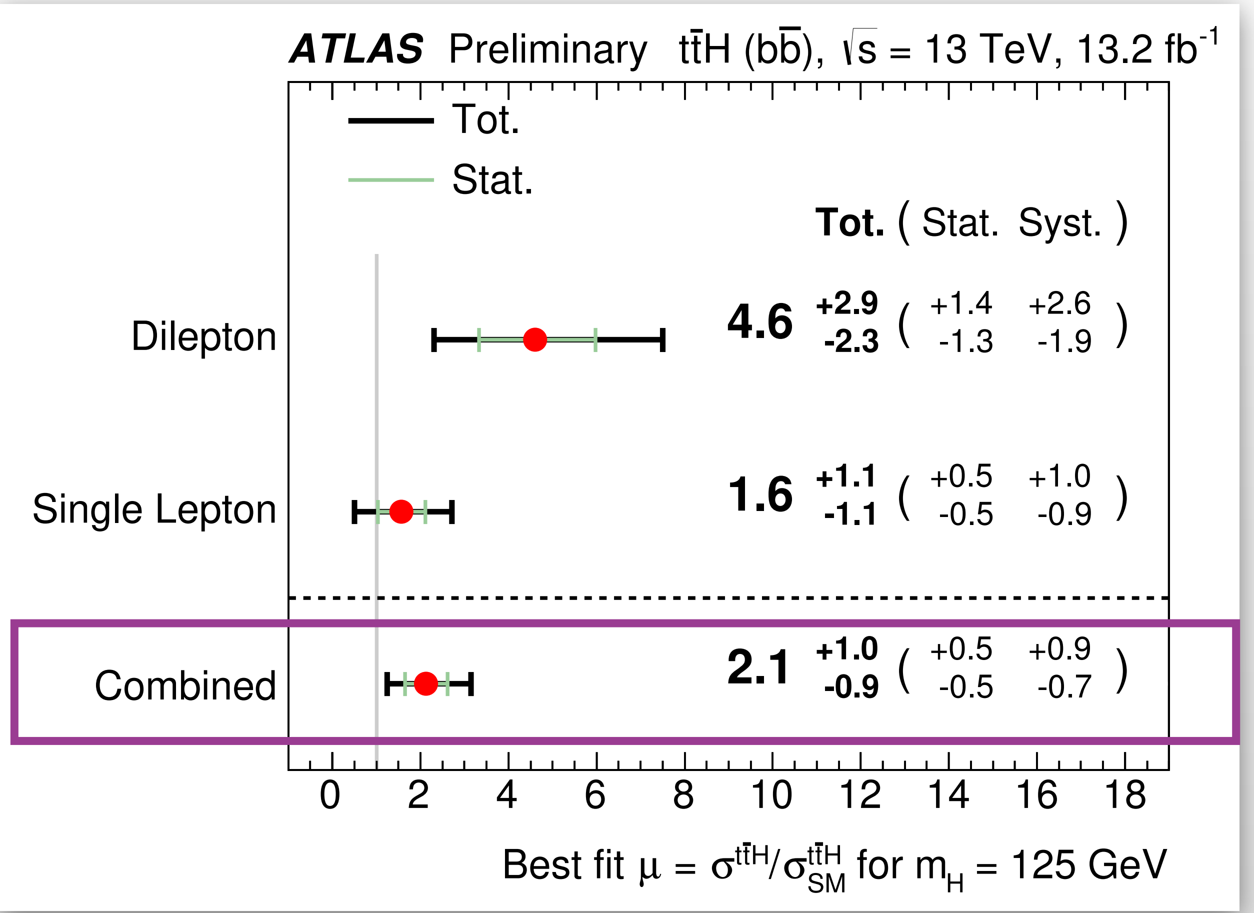
Main background $t\bar{t}$+jets Understanding of the tt+jets(HF) modelling and associated uncertainties requires a huge effort (from the experiments and theorists) - backup;

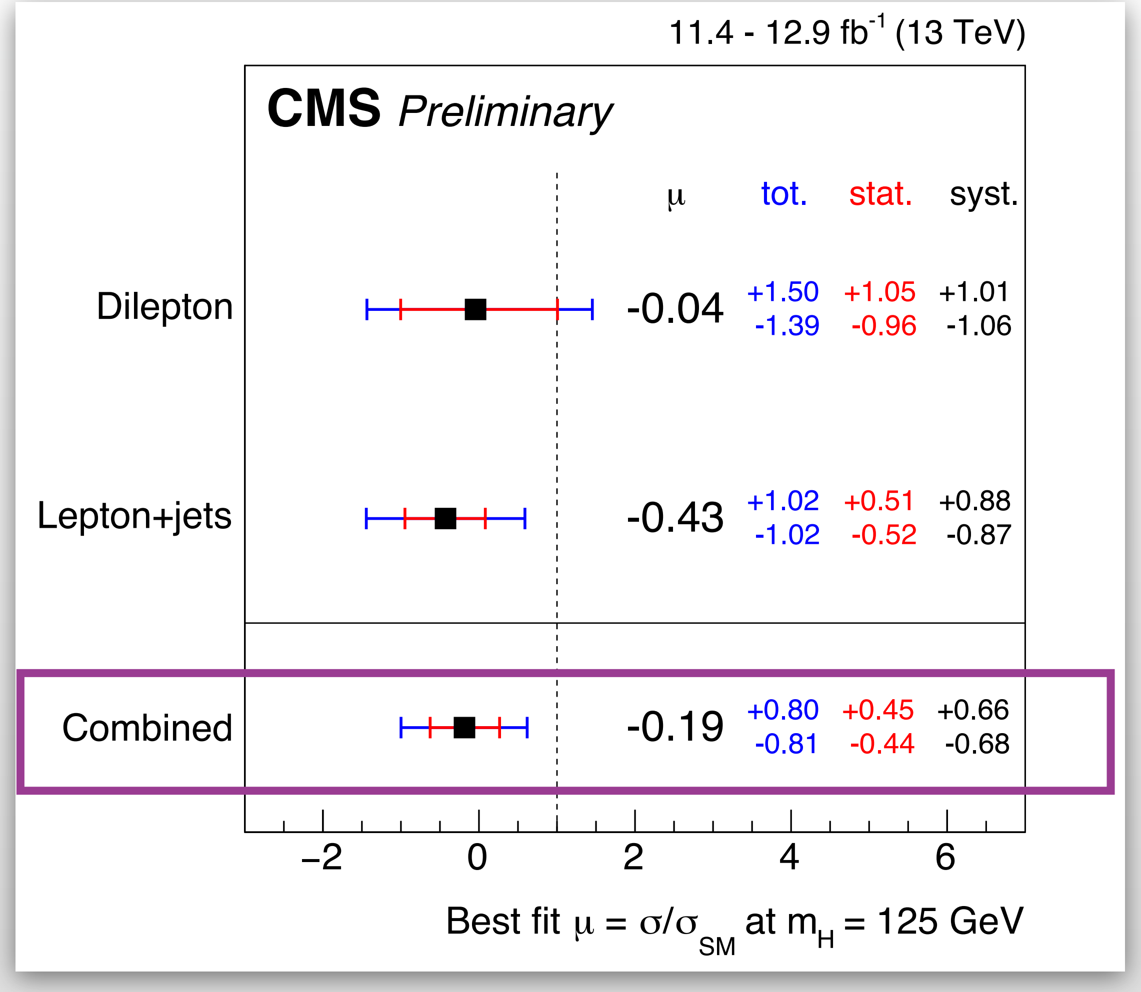
Signal extraction - final discriminant:

1. BDT reconstruction technique or MEM to separate $t\bar{t}H$ vs $t\bar{t}$+bb;
2. Using 1 in combination with BDT that exploits full event kinematics.

BDT - Boosted Decision Tree, MEM - Matrix Element Method

$t\bar{t}H(bb)$





Dominant systematics

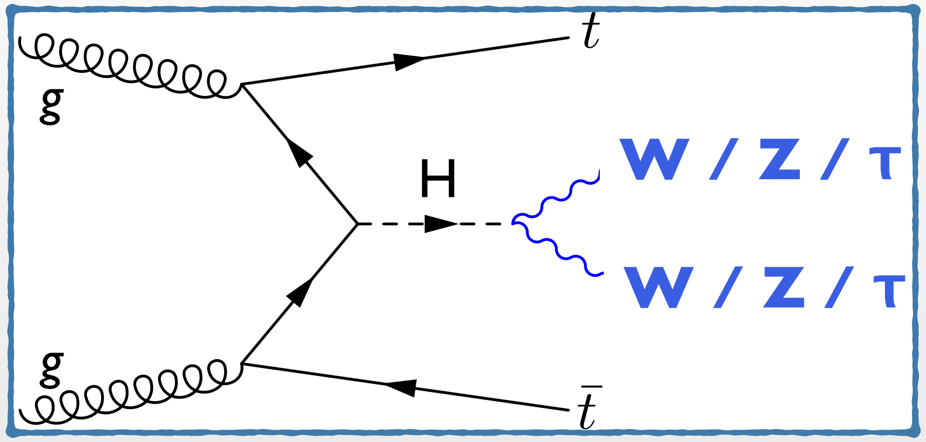
Modelling of $t\bar{t} + \geq 1b$, jet flavour tagging and $t\bar{t}H$ modelling.

95% confidence level upper limit of $\sigma < 4.0 \times \sigma_{SM}$ ($1.9^{+1.4}_{-2.8}$ exp.)

Normalisation of $t\bar{t} + \geq 1$ HF jet processes.

95% confidence level upper limit of $\sigma < 1.5 \times \sigma_{SM}$ ($1.7^{+0.7}_{-0.5}$ exp.)

$t\bar{t}H$(multilepton)



- Significant BR (*WW~20%, ZZ~3%,* ττ*~6%*);
- Distinct multi-lepton signatures from Higgs and top decays;
- Higgs reconstruction is difficult.

- Targeted experimental signatures: **2*l*** (e, μ) **of same charge** OR **≥3*l*** (to reduce $t\bar{t}$).

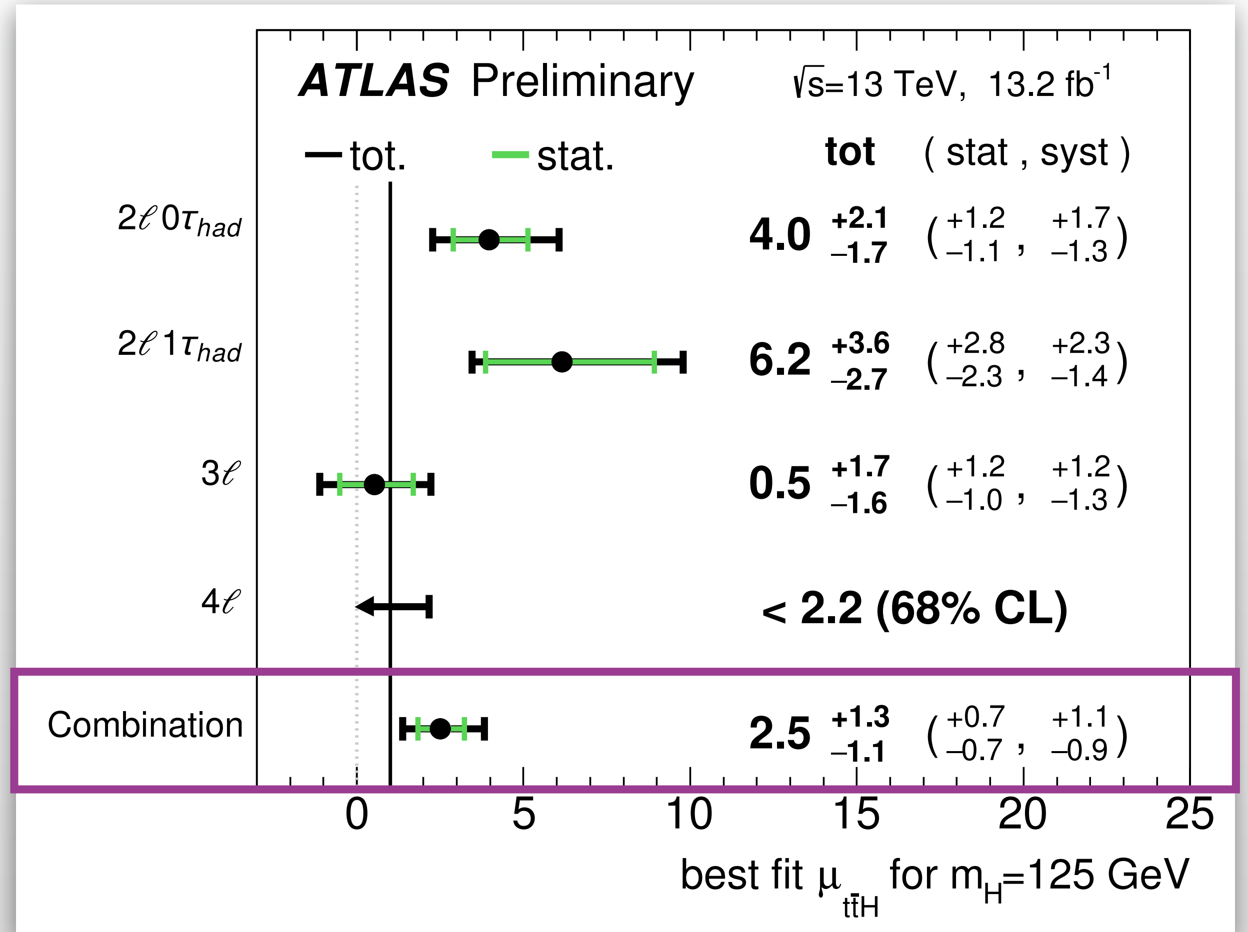
Main background:

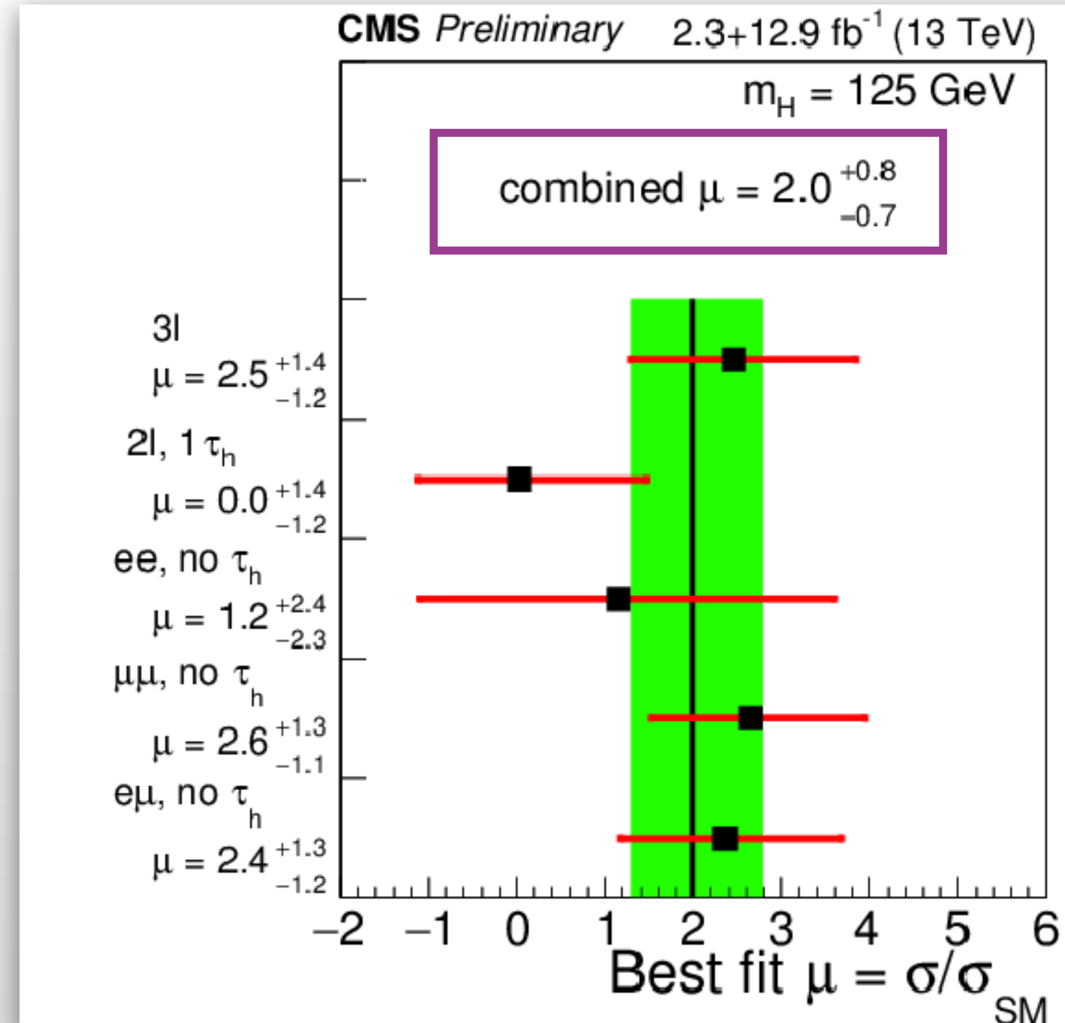
- Irreducible: $t\bar{t}$ +V and VV production - estimated from NLO MC and validated in data.
- Reducible: from non-prompt leptons (primarily from b hadron decays in $t\bar{t}$) and from prompt leptons with misidentified charge - data driven estimate;

Selection and Signal extraction:

- ATLAS: Tight selection → high purity, cut and count analysis;
- CMS: MVA lepton selection, fit 2D BDT: $t\bar{t}H$ vs $t\bar{t}$ & $t\bar{t}H$ vs $t\bar{t}V$ (inc. MEM as input in ≥3l).

$t\bar{t}H$(multilepton)



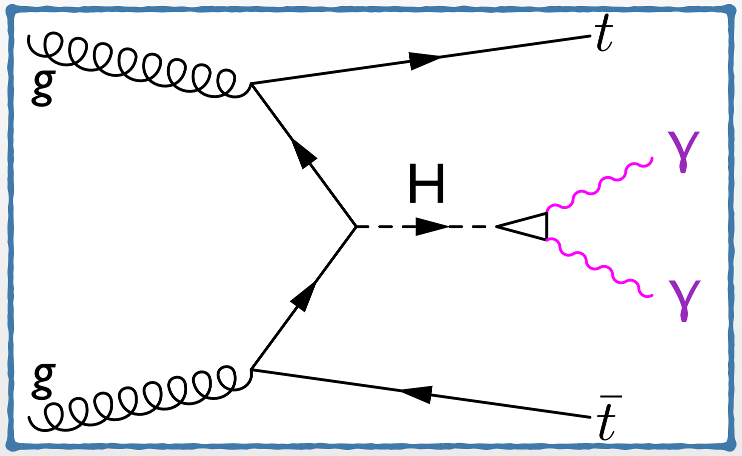


Dominant systematics: Estimation of background from non-prompt leptons

95% confidence level upper limit of $\sigma < 4.9 \times \sigma_{SM}$ ($2.3^{+1.1}_{-0.6}$ exp.)

95% confidence level upper limit of $\sigma < 3.4 \times \sigma_{SM}$ ($1.3^{+0.6}_{-0.4}$ exp.)

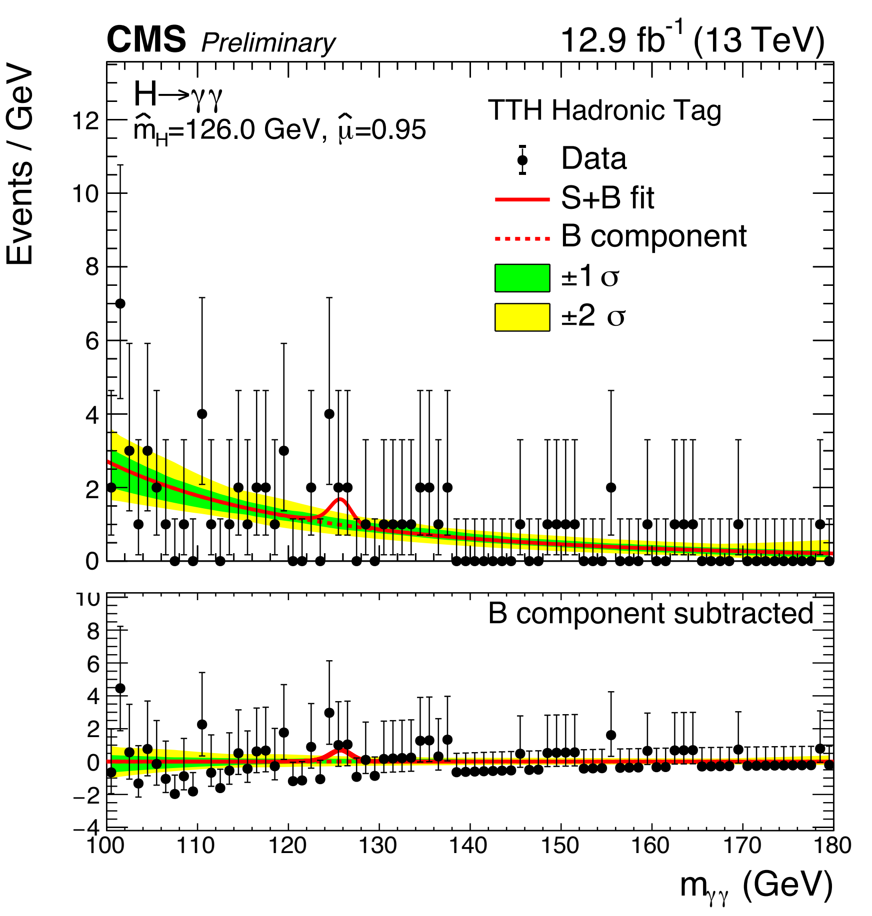
$t\bar{t}H(\gamma\gamma)$



- Small BR ~ 0.2%
- Higgs boson can be reconstructed as a narrow peak
- parametrisable background.

Strategy (a category of the H→γγ couplings analysis):

- look for a bump over a smooth background in the di-photon invariant mass spectrum;
- Categories: Selected 2 photons + ≥ *1l/0l* + additional jet requirements enhancing leptonic / hadronic tt decays;



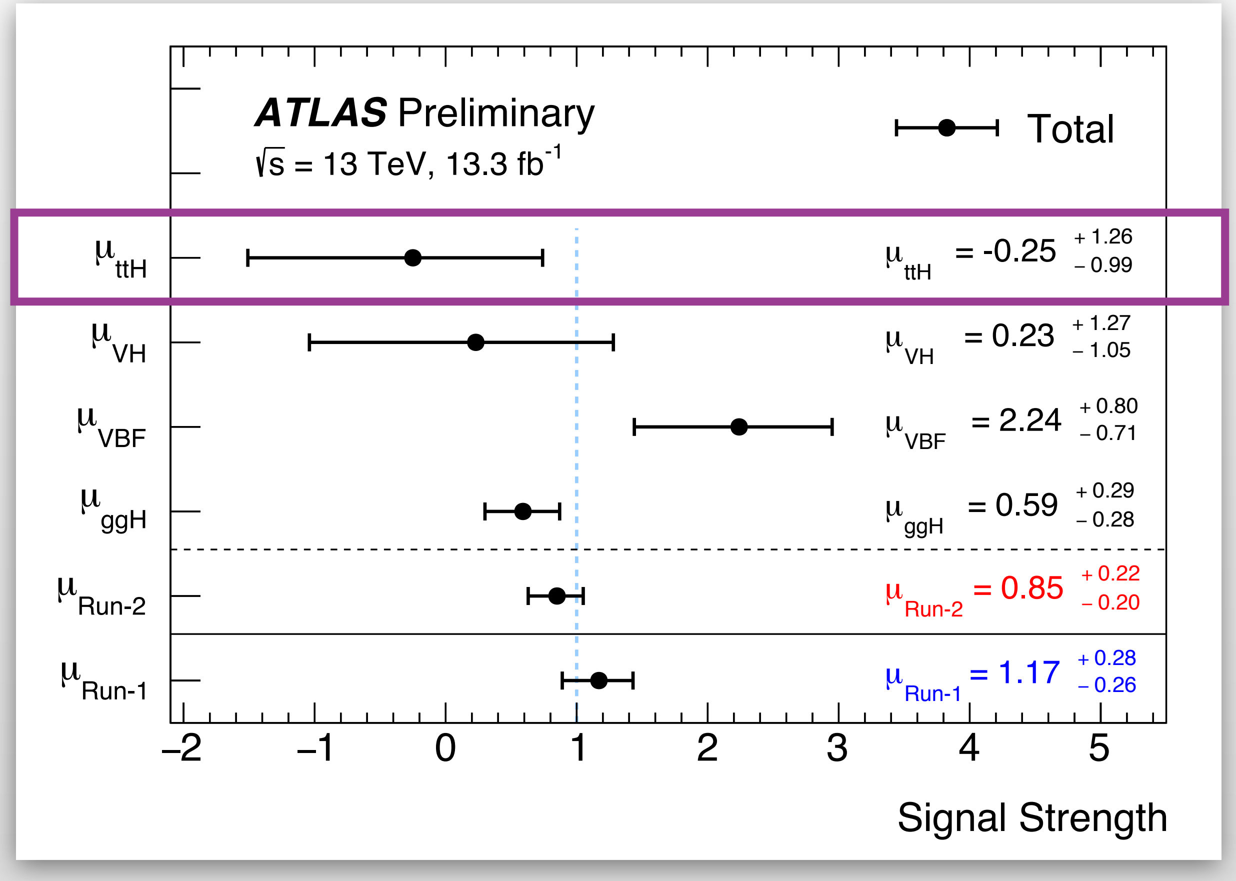
Signal modelling:

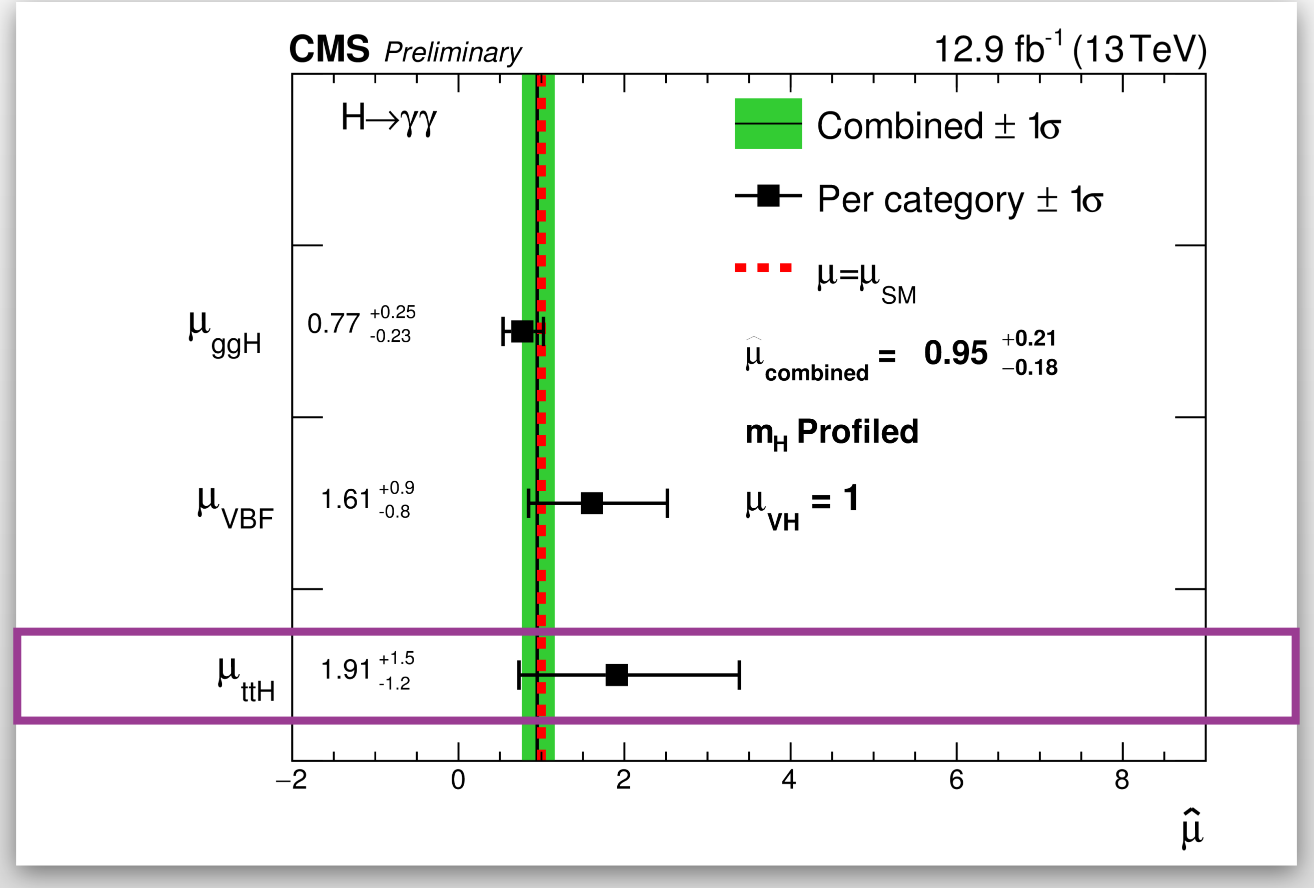
- ATLAS: Double-sided crystal ball function;
- CMS: Sum of Gaussians.

Background modelling:

- ATLAS: exponential function extracted from side bands;
- CMS: Sum of exponentials or power law terms, Laurent series and polynomials;

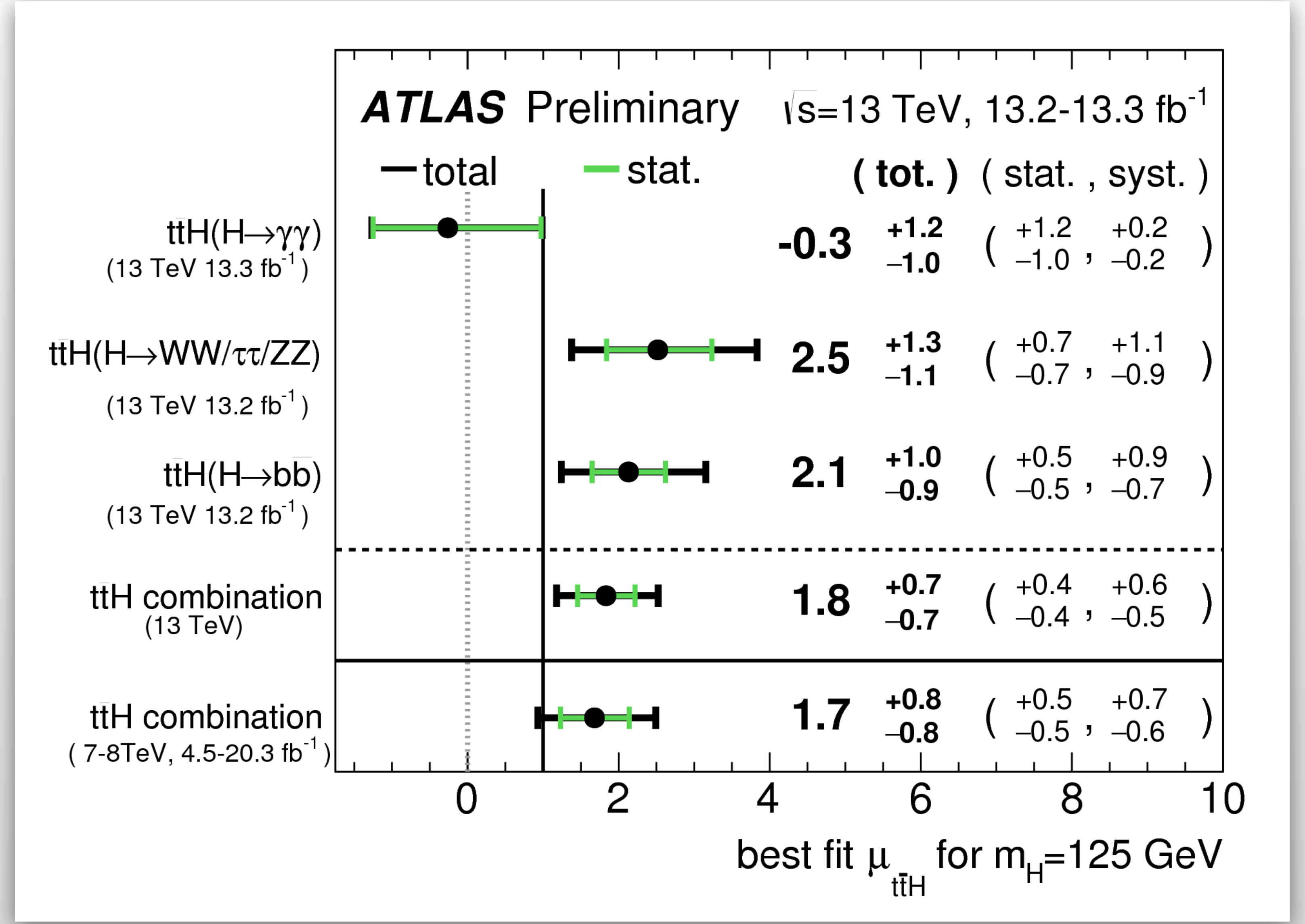
$t\bar{t}H(\gamma\gamma)$





The result is heavily dominated by the statistical uncertainty. By the end of Run 2, we expect to have factor of ~3 reduction in statistical uncertainty.

$t\bar{t}H$ combination and summary

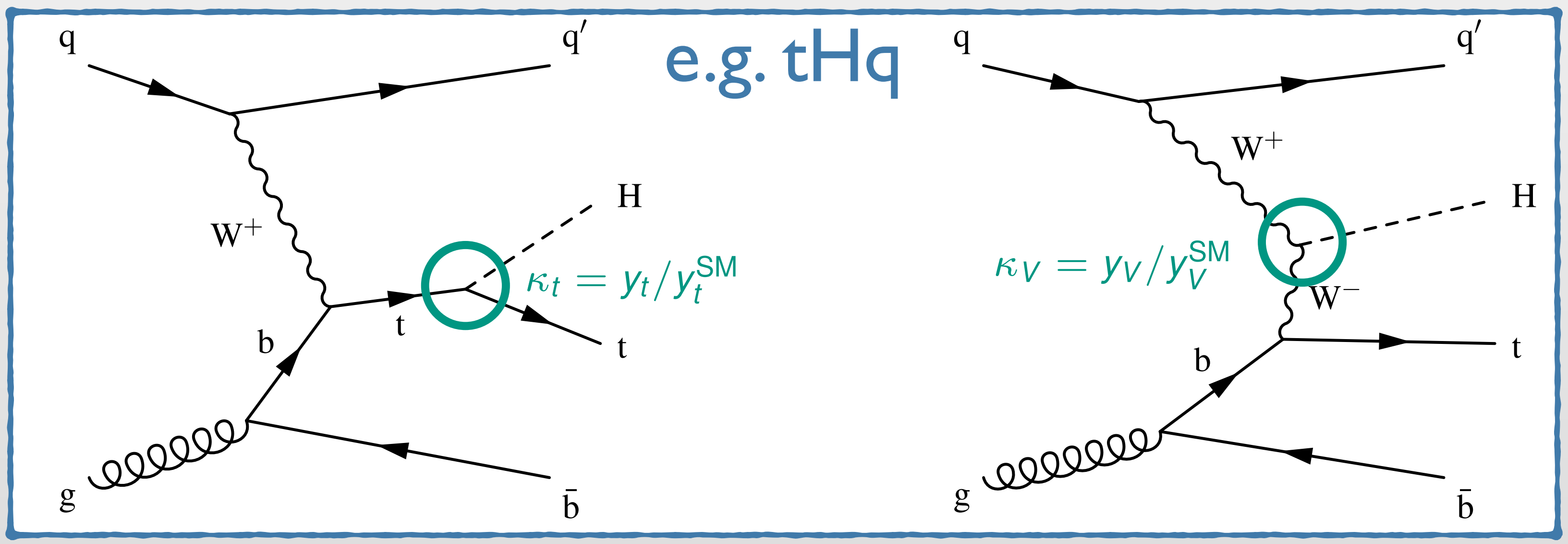


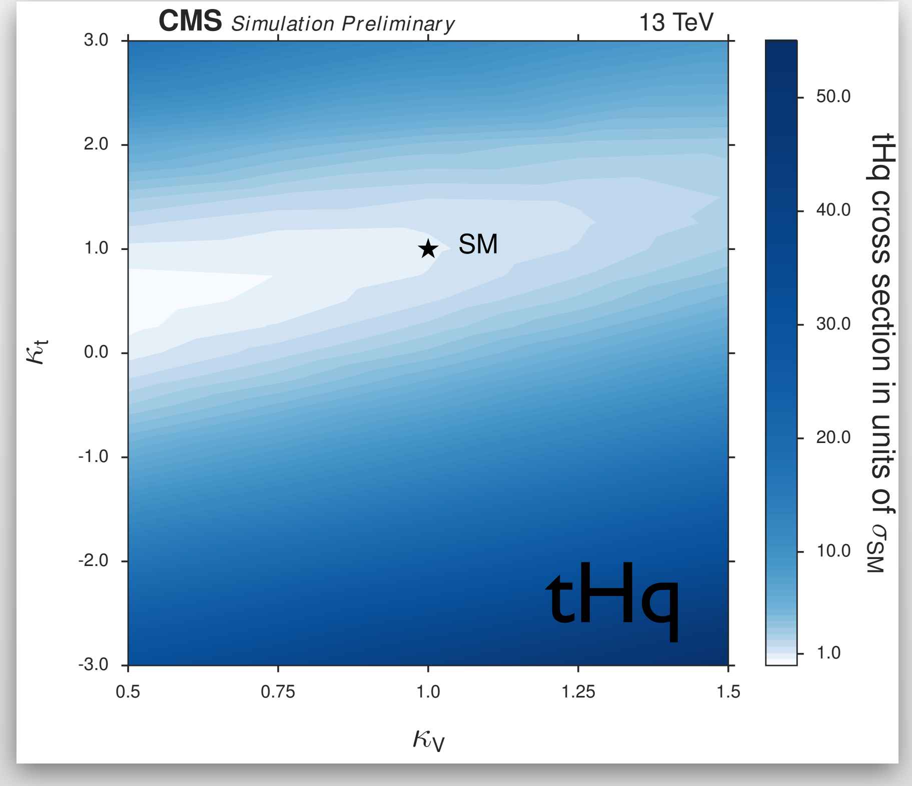
Run1 precision already reached with ~13fb^{-1} of Run 2 data!
No significant deviations from the SM observed at both experiments.
Stay tuned for the new results from CMS and ATLAS using full 2015+2016 statistics ~ 35fb^{-1}

tH production

tH production at the LHC

- CMS Run2: tH(bb) - CMS PAS HIG-16-019, Run1: tH(bb, multi-lepton, γγ) - CMS-HIG-14-027, ATLAS Run 1 indirect constraint in H→γγ - Physics Letters B 740 (2015);
- Both t-channel (tHq) and tW production (tHW) considered;

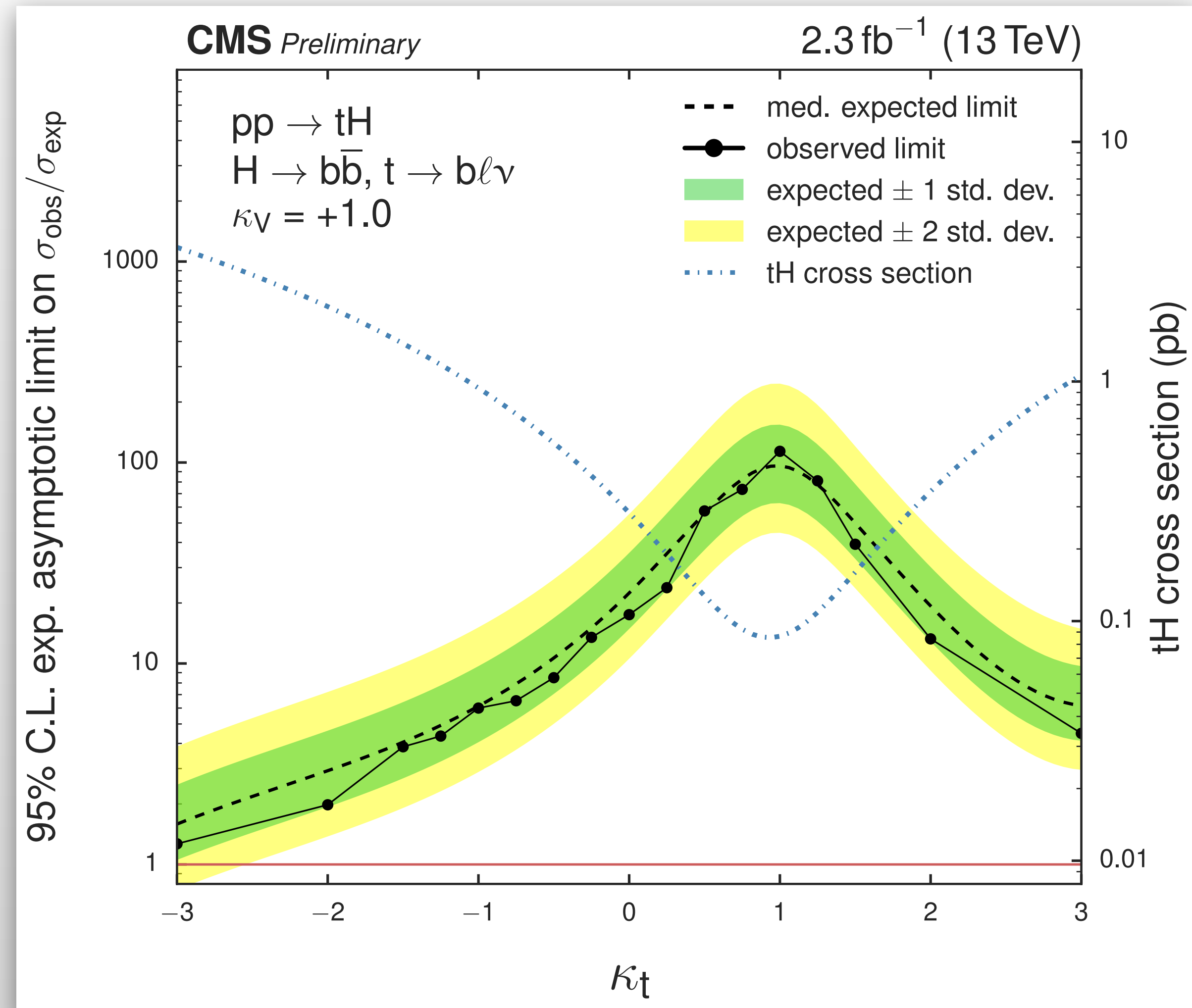




- **tH** - **sensitive to magnitude** and **sign** of **Higgs-top-Yukawa** coupling
  - SM assumption κ_t=*1* - destructive interference, σ_{SM}(tH) ~ 90 fb^{-1};
  - κ_t=-*1* (if BSM contributions allowed in the loops), σ(tH) ~ 10 x σ_{SM};
- Analysis Strategy: Similar to ttH. Benefit from forward jet tag. Dedicated sig. vs bkg BDT for each (κ_t,κ_V) point (in case of tHq event reconstruction for tHq and tt-bkg.).

Results of the direct tH search

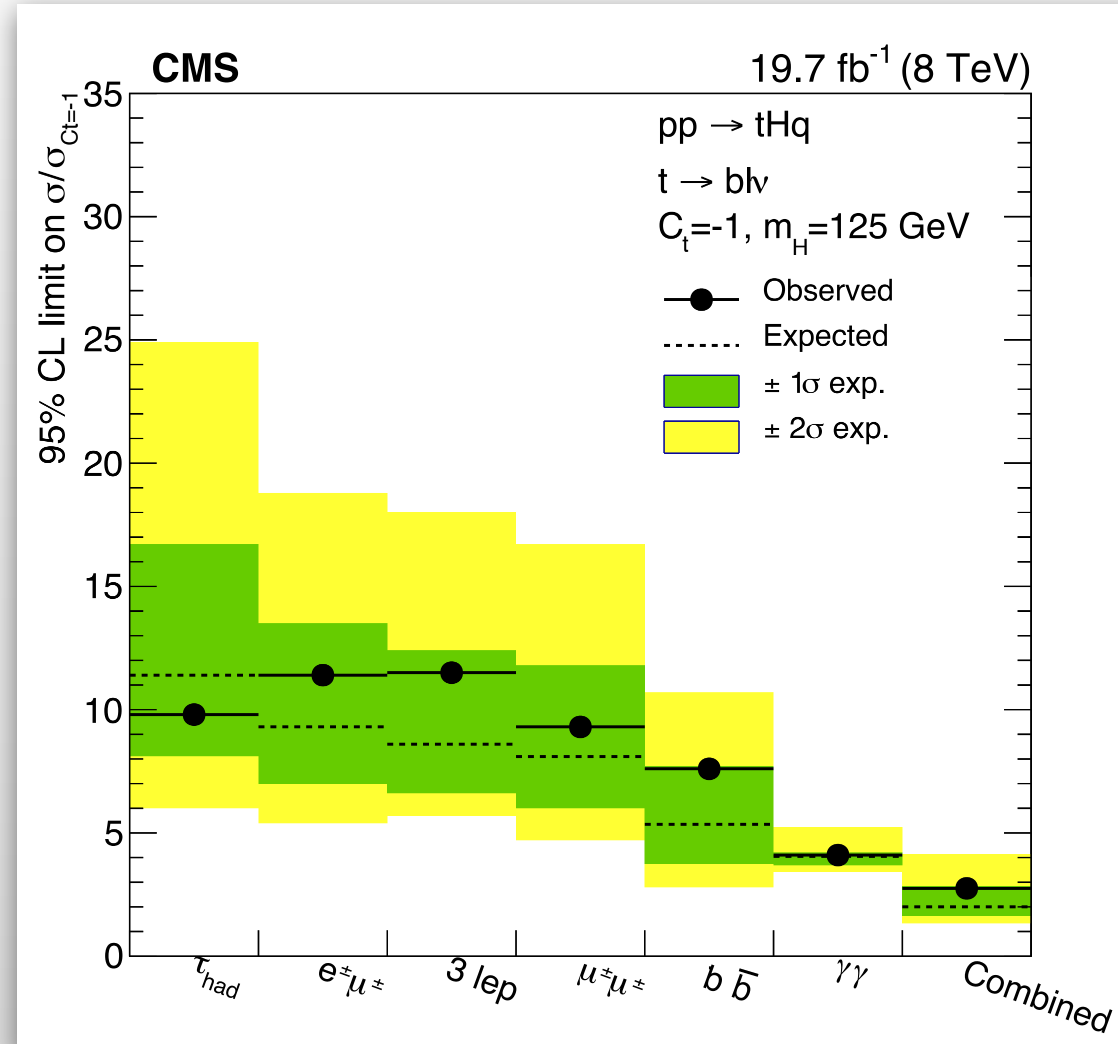
- Run 2 tH(bb) result



Excluding SM tH production above 113.7 (obs.) and 98.6 (exp.) x σ_{SM}

Exclusion at κ_t=-1 6.0 (obs.) and 6.4 (exp.) x $\sigma_{\kappa t=-1}$

- Run 1 tH(bb,ττ,leptons, γγ) result



From all channels combined in Run1 exclusion at κ_t=-1 2.8 (obs.) and 2.0 (exp.) x $\sigma_{\kappa t=-1}$

BSM charged Higgs searches

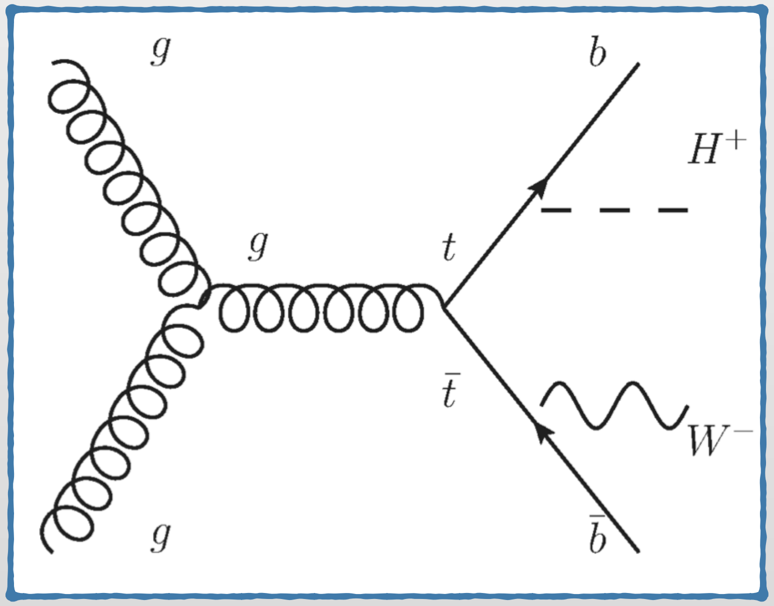
Many extensions of the SM, as well as suppressed SM scenarios, sensitive to Higgs-top interactions:

- Flavour changing neutral current: $t \to qH$
- Vector-like heavy top partner
- Charged Higgs boson searches within the top sector (SUSY, 2HDM,…)
- …

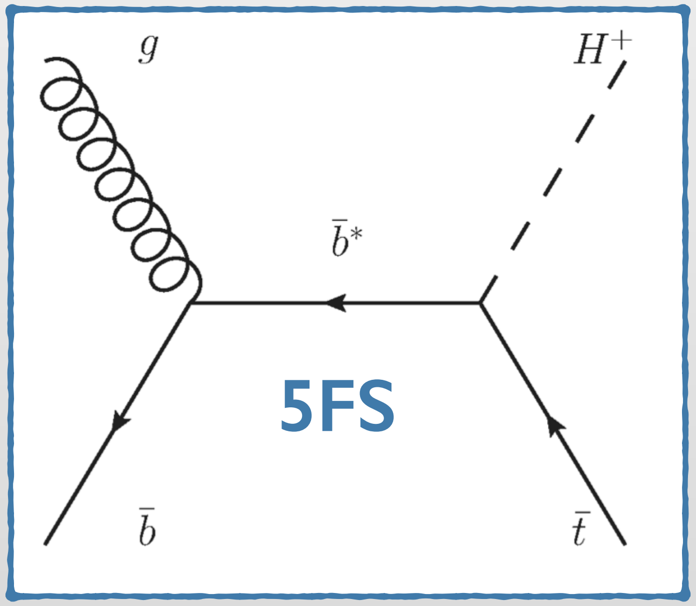
Search for H± within top sector

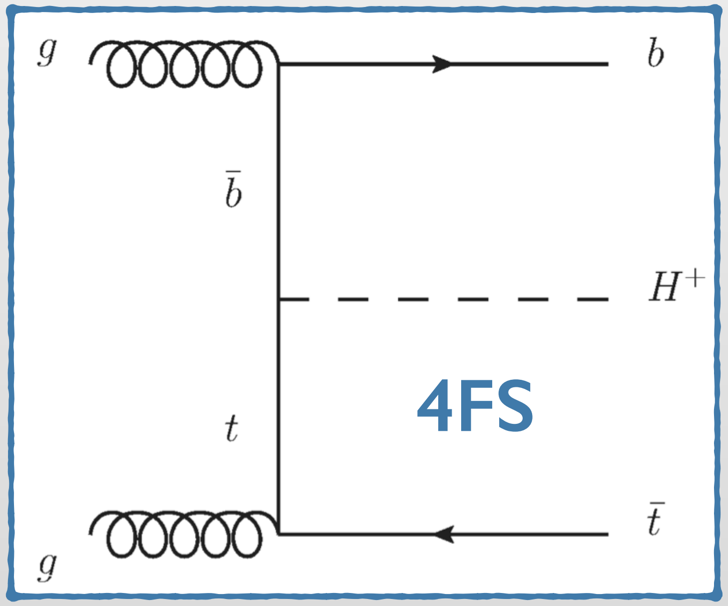
- Charged Higgs bosons can be produced in decays of ($m_{H^\pm} < m_{top}$) or in association with ($m_{H^\pm} > m_{top}$) a top quark
    - Experiments explore several H± decay modes (cs, cb, tb, τν, AW)

Light H± ($m_{H^\pm} < m_{top}$)



Heavy H± ($m_{H^\pm} > m_{top}$)





H± near top mass

- In the region **near the top mass**, finite top-width effects as well as the interplay between top-quark resonant and non-resonant diagrams cannot be neglected
    - **Recent TH development:** Precision computation of the H± production with $m_{H^\pm} \sim m_t$ (Degrande et al., 1607.05291). Opens doors for new searches!

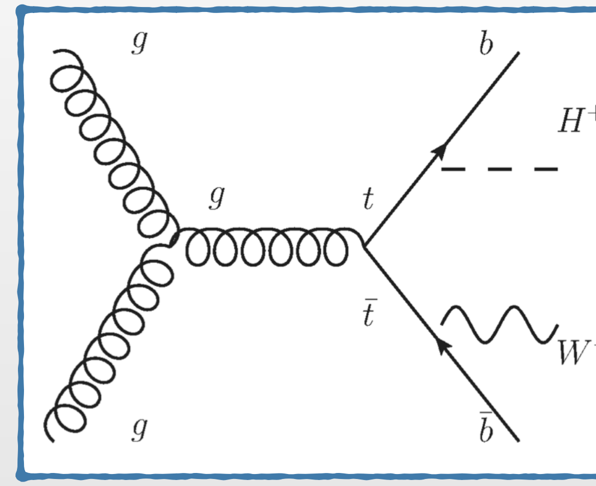
Searches for light H± (top sector)

Many searches also interpreted in SUSY / 2HDM

- Searches based on t → H±b decays
- Zoology of models with different branching ratios
- Searches at Tevatron:

  CDF ***t→H±(AW)b, t→H±(cs)b:***
  CDF note 10104,
  10.1103/PhysRevLett.103.101803

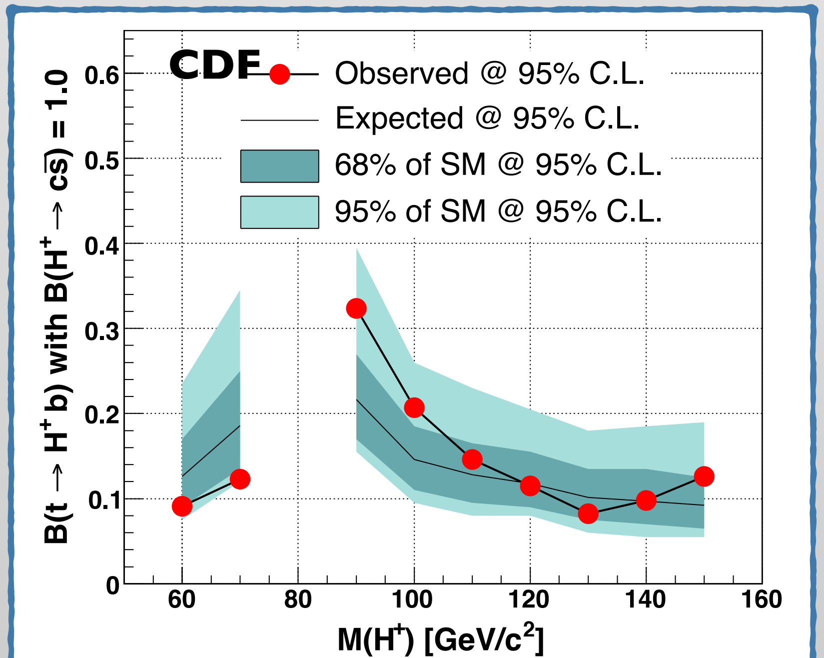
  D0 ***t→H±(τν/cs)b:***
  Phys.Lett.B682:278-286,2009,
  10.1016/j.physletb.2009.11.016



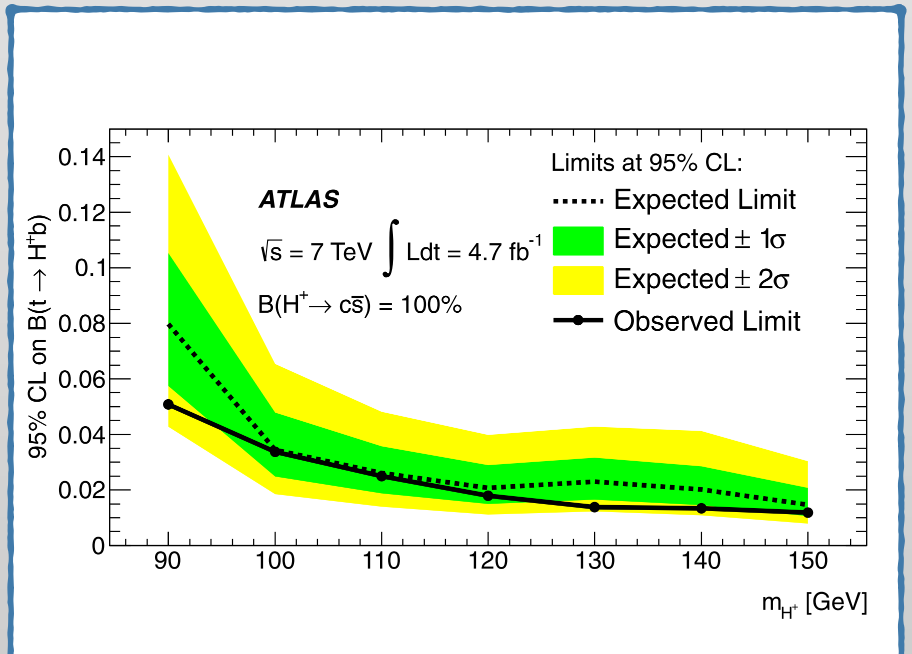
- Searches at LHC:

  CMS ***8 TeV t→H±(cs)b, 8 TeV H± legacy***: ATLAS ***7 TeV t→H±(cs)b***:
  Eur. Phys. J. C (2013) 73, JHEP 11 (2015) 018 Eur. Phys. J. C (2013) 73

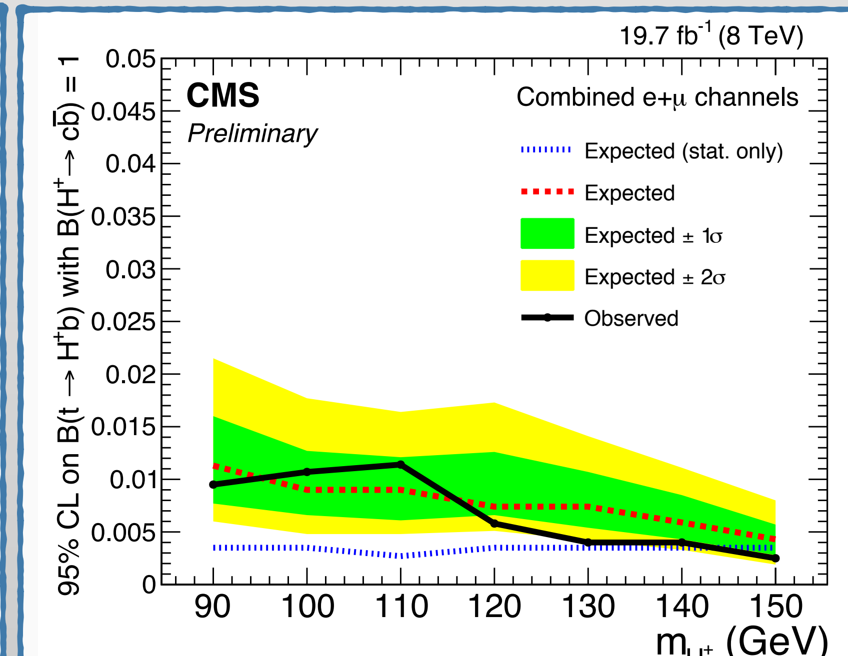
H±→cs



H±→cs



H±→cb



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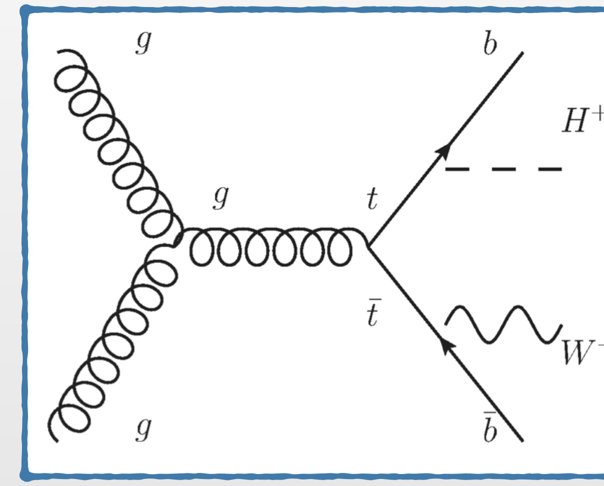
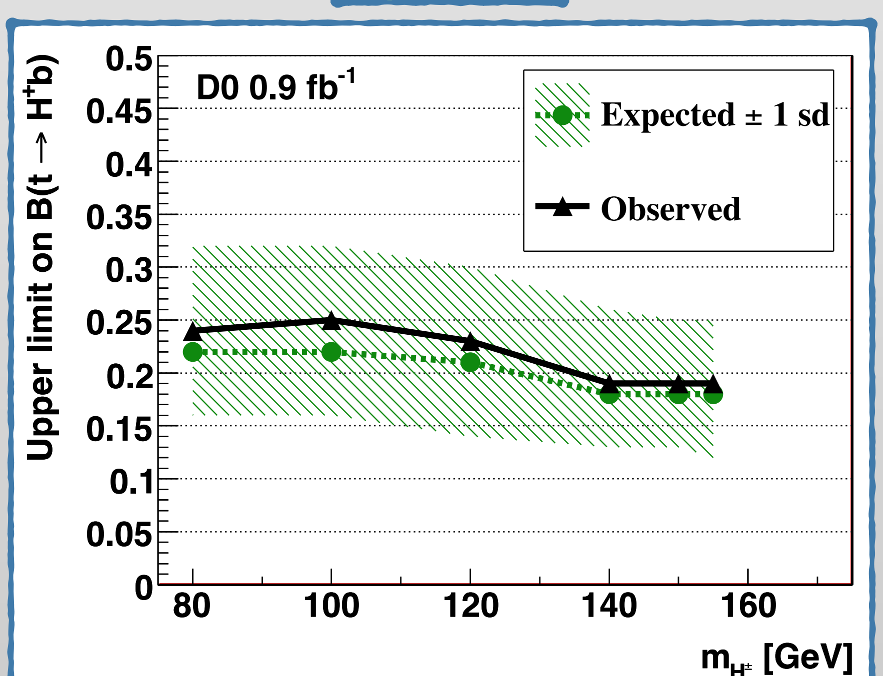
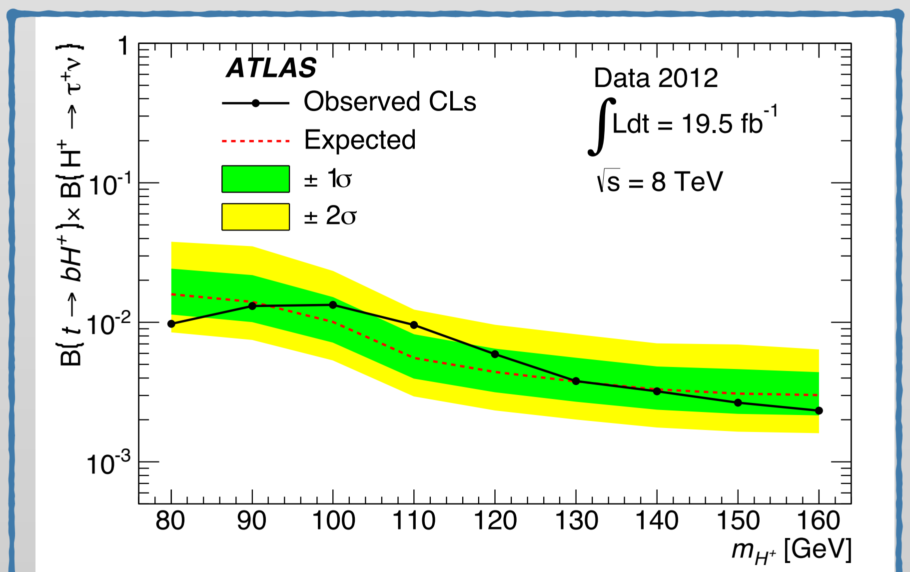


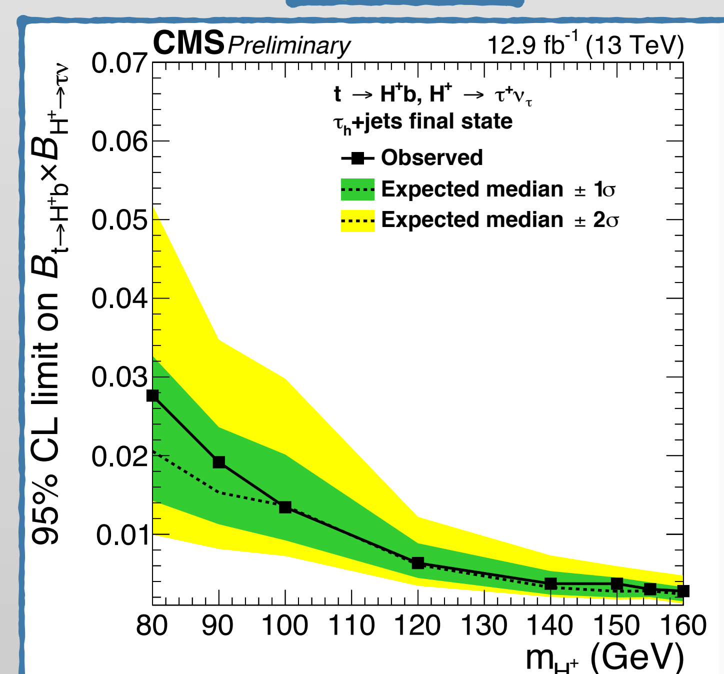
H±→τν



H±→τν



H±→τν



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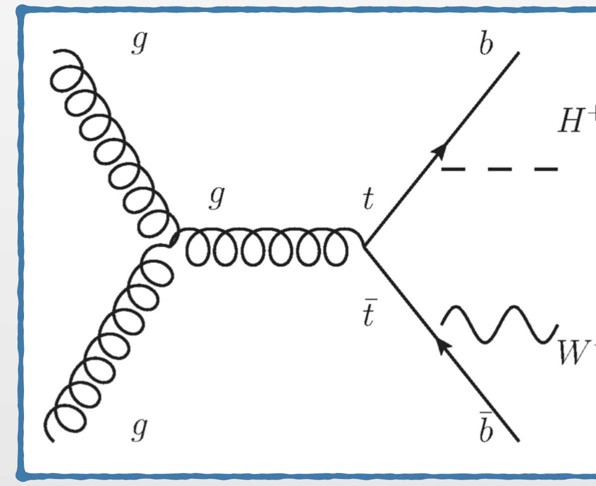

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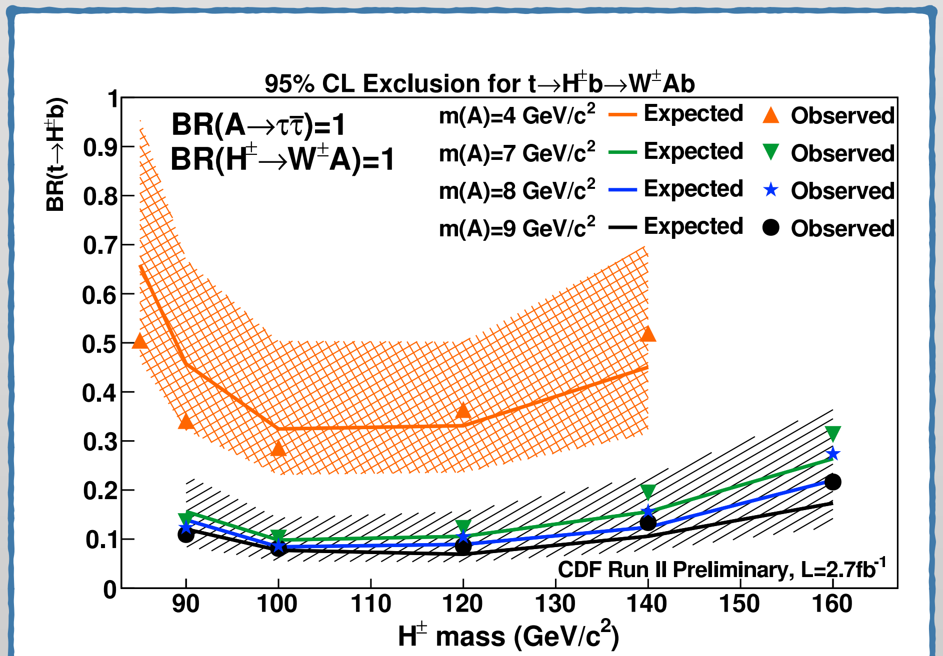
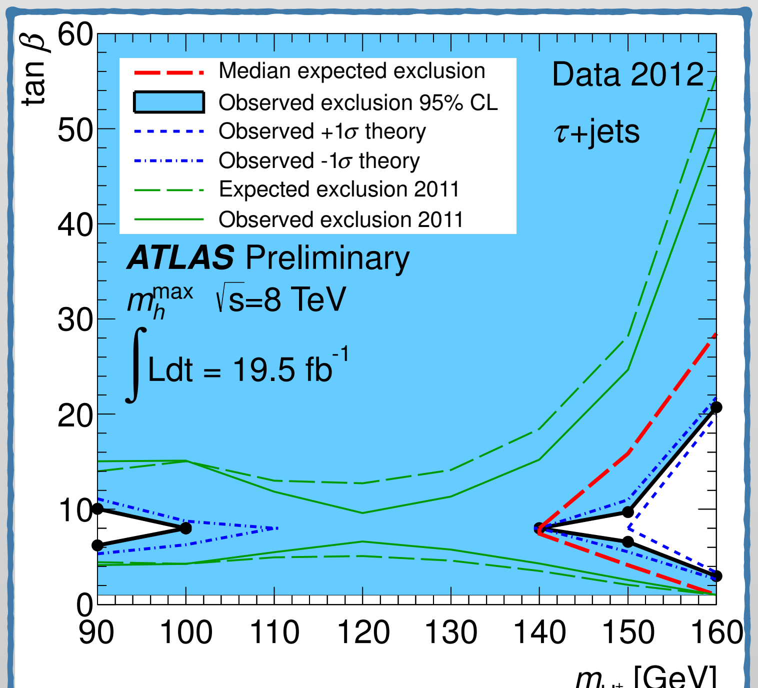
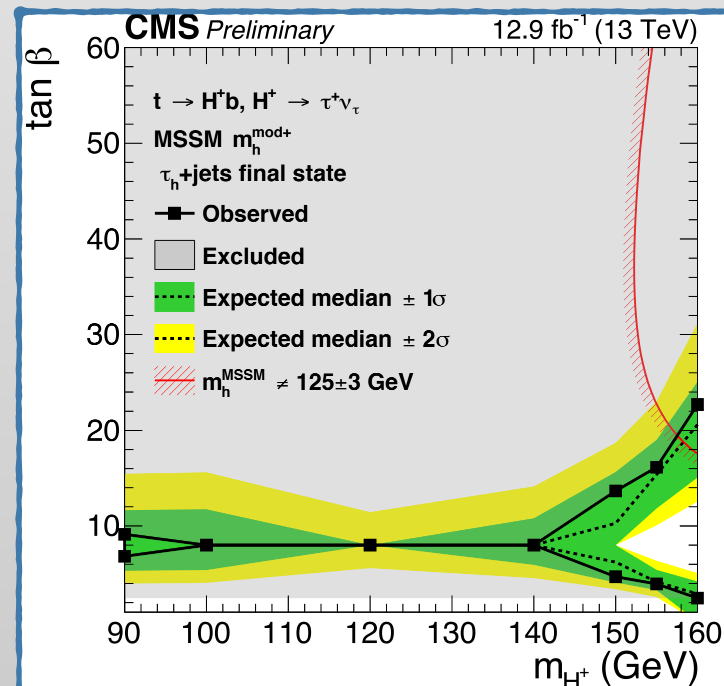
Eur. Phys. J. C (2013) 73

H±→AW

H±→τν







Searches for light $H^{\pm}$ (top sector)

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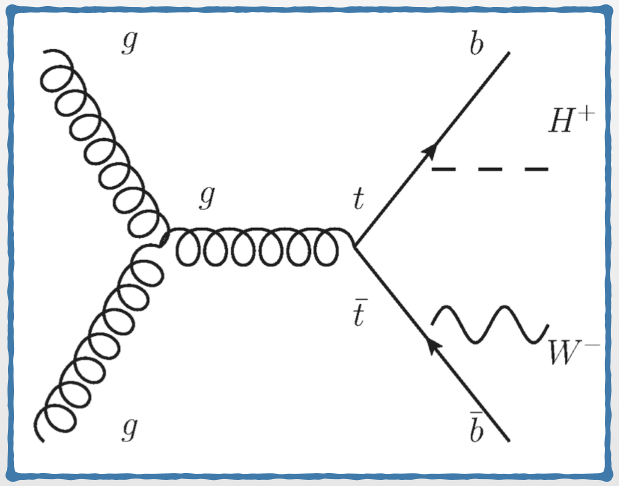
Many searches also interpreted in SUSY / 2HDM



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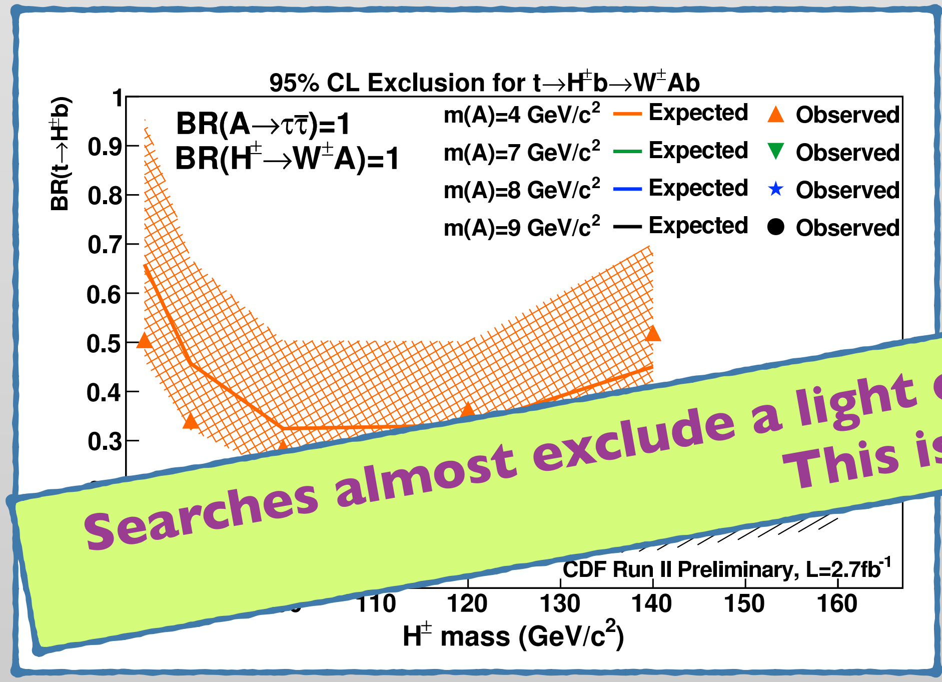
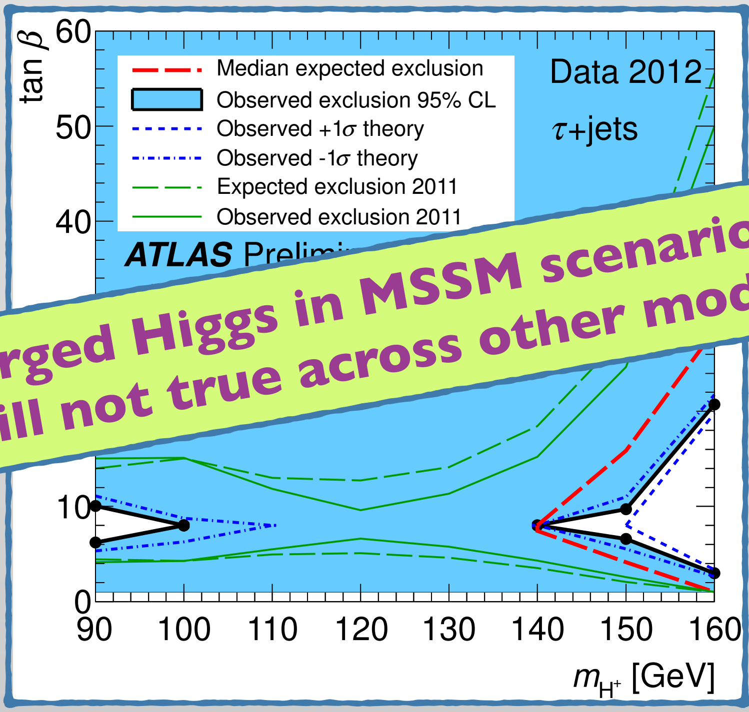
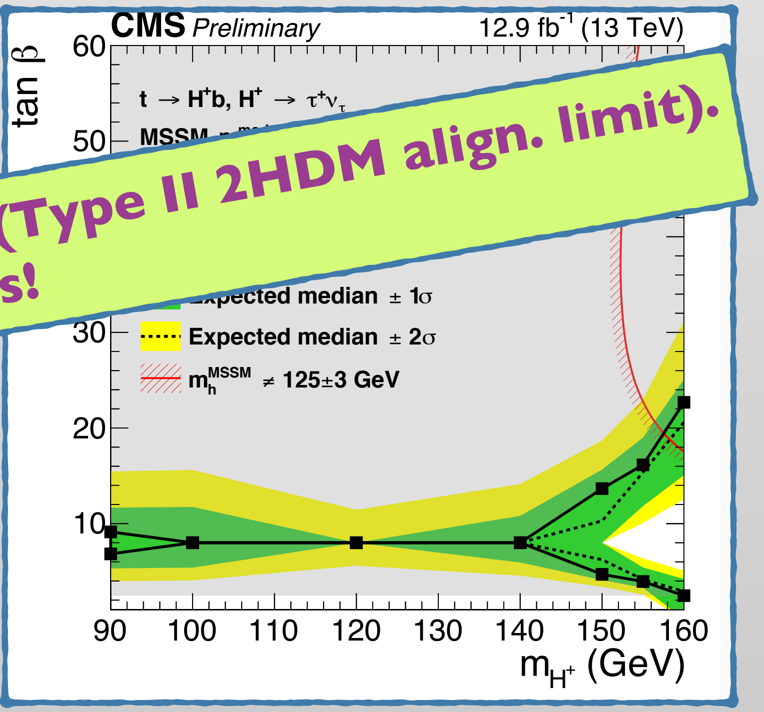
Eur. Phys. J. C (2013) 73

$H^{\pm} \rightarrow AW$

$H^{\pm} \rightarrow \tau\nu$







Searches almost exclude a light charged Higgs in MSSM scenarios (Type II 2HDM align. limit).
This is still not true across other models!

Searches for **heavy** $H^{\pm}$ (top sector)

- Searches based on $H^{\pm}\rightarrow\tau\nu$ decays:

  ATLAS ***13 TeV*** $H^{\pm}\rightarrow\tau\nu$: ATLAS-CONF-2016-088

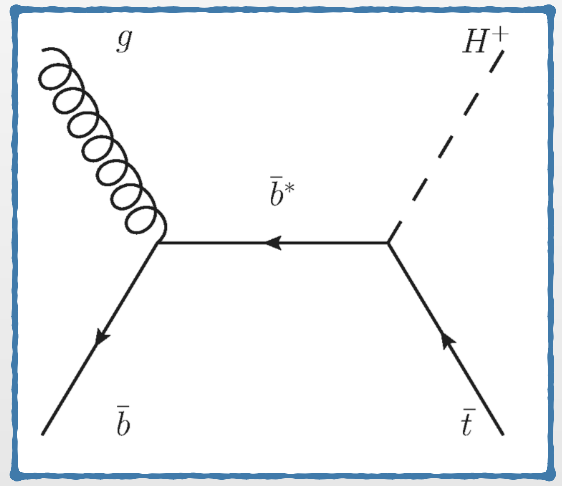
  CMS ***13 TeV*** $H^{\pm}\rightarrow\tau\nu$: CMS-PAS-HIG-16-031

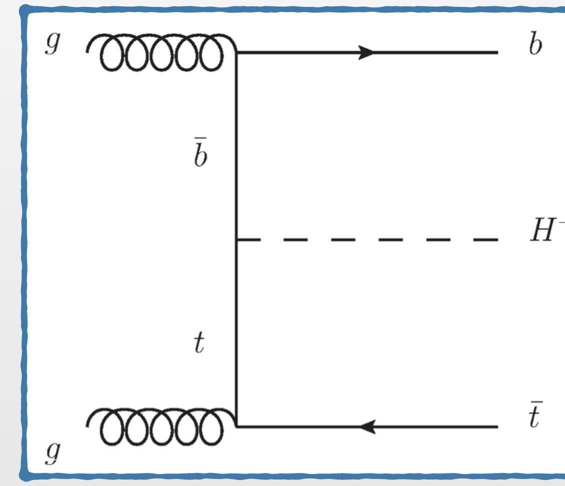
- Searches based on $H^{\pm}\rightarrow tb$ decays:

  ATLAS ***13 TeV*** $H^{\pm}\rightarrow tb$: ATLAS-CONF-2016-089

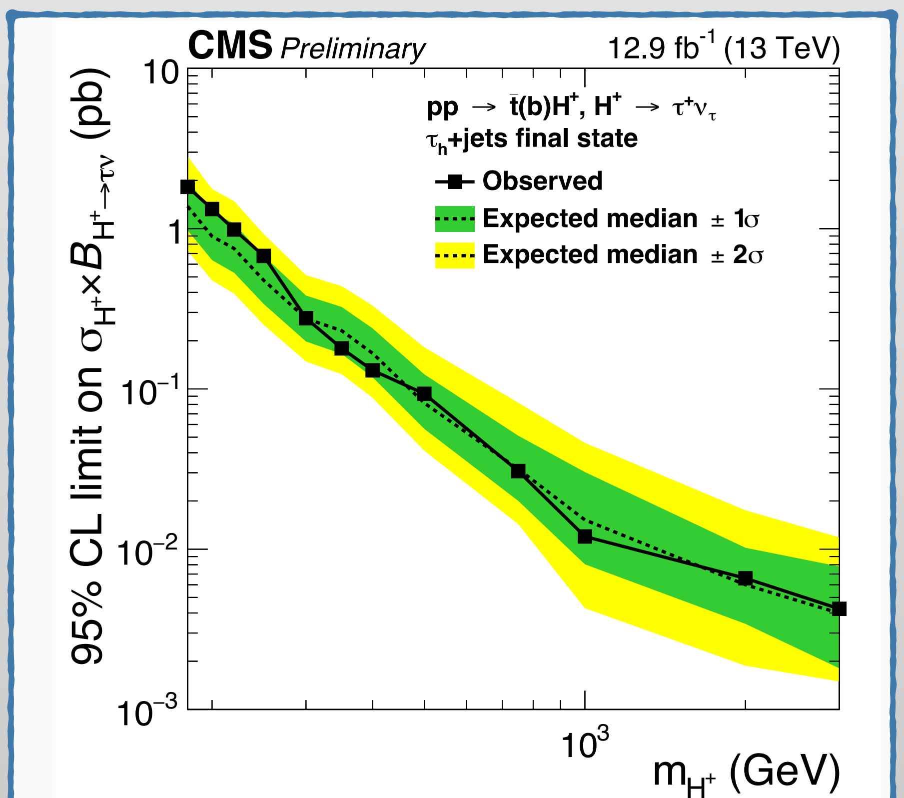
  CMS ***8 TeV*** $H^{\pm}$ ***legacy***: JHEP 11 (2015) 018

Many searches also interpreted in SUSY / 2HDM

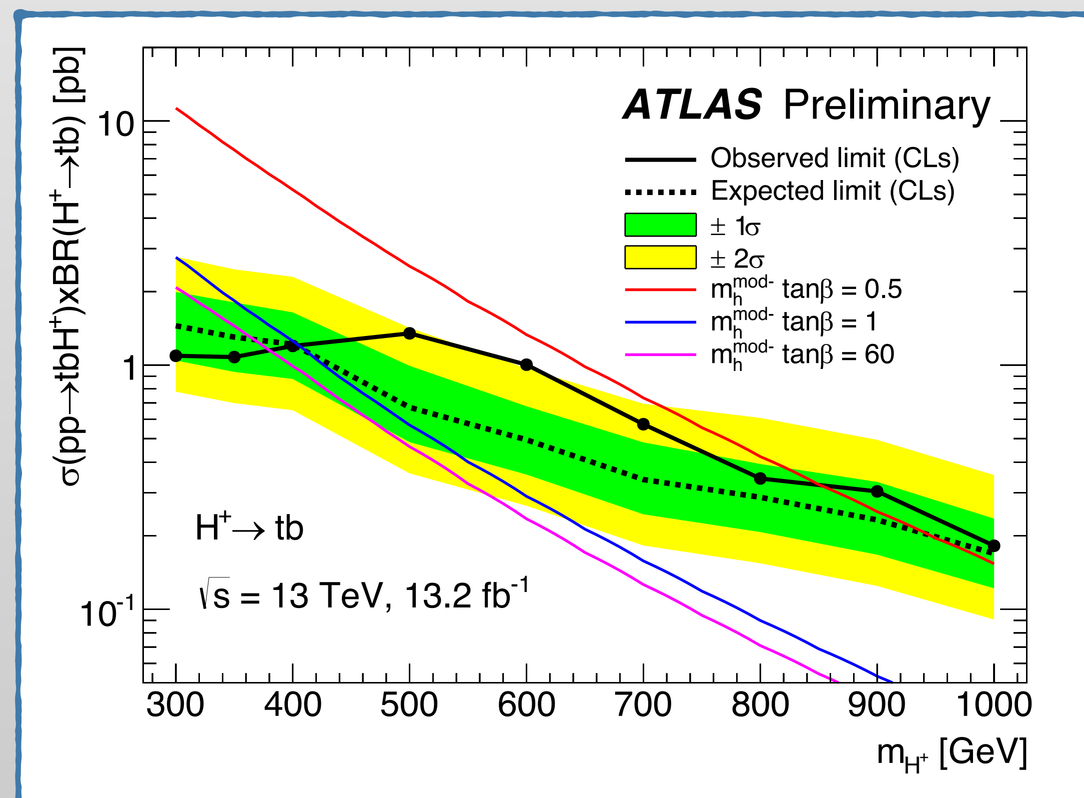




$H^{\pm}\rightarrow\tau\nu$



$H^{\pm}\rightarrow tb$



Searches for **heavy** $H^{\pm}$ (top sector)

TRIUMF

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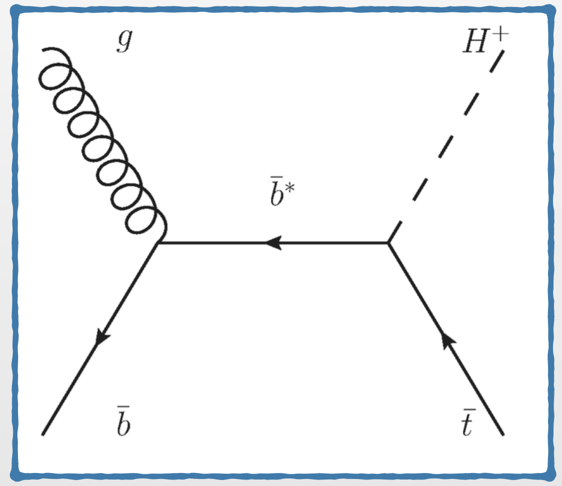

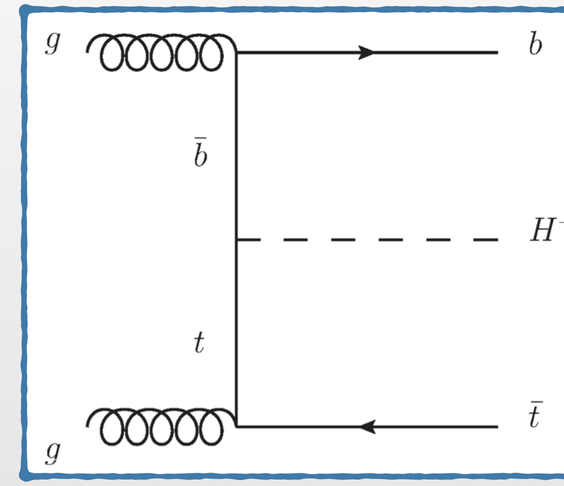

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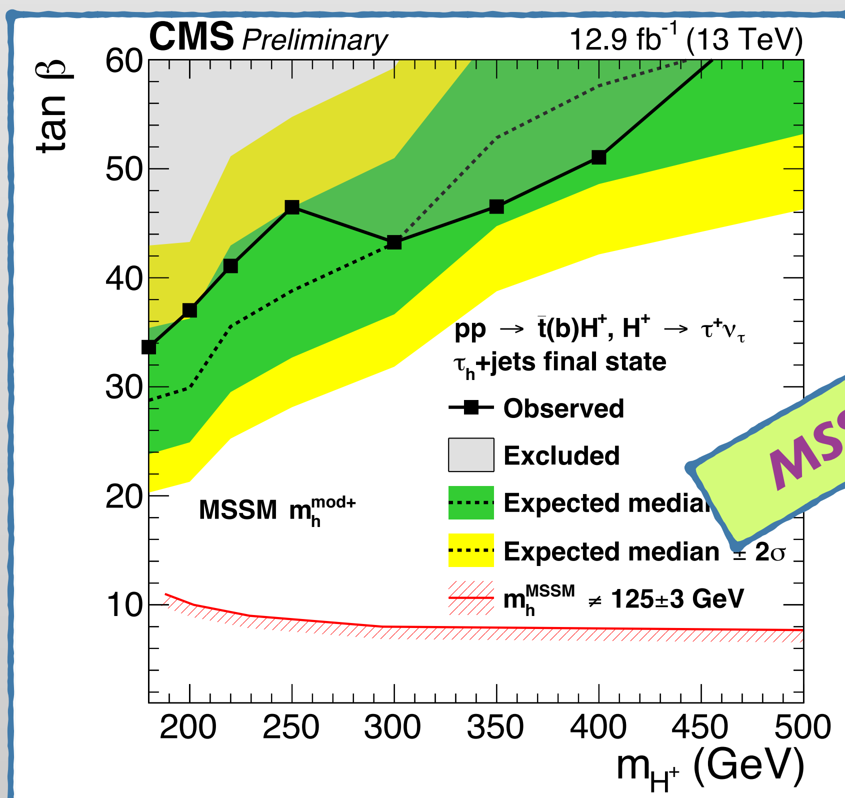
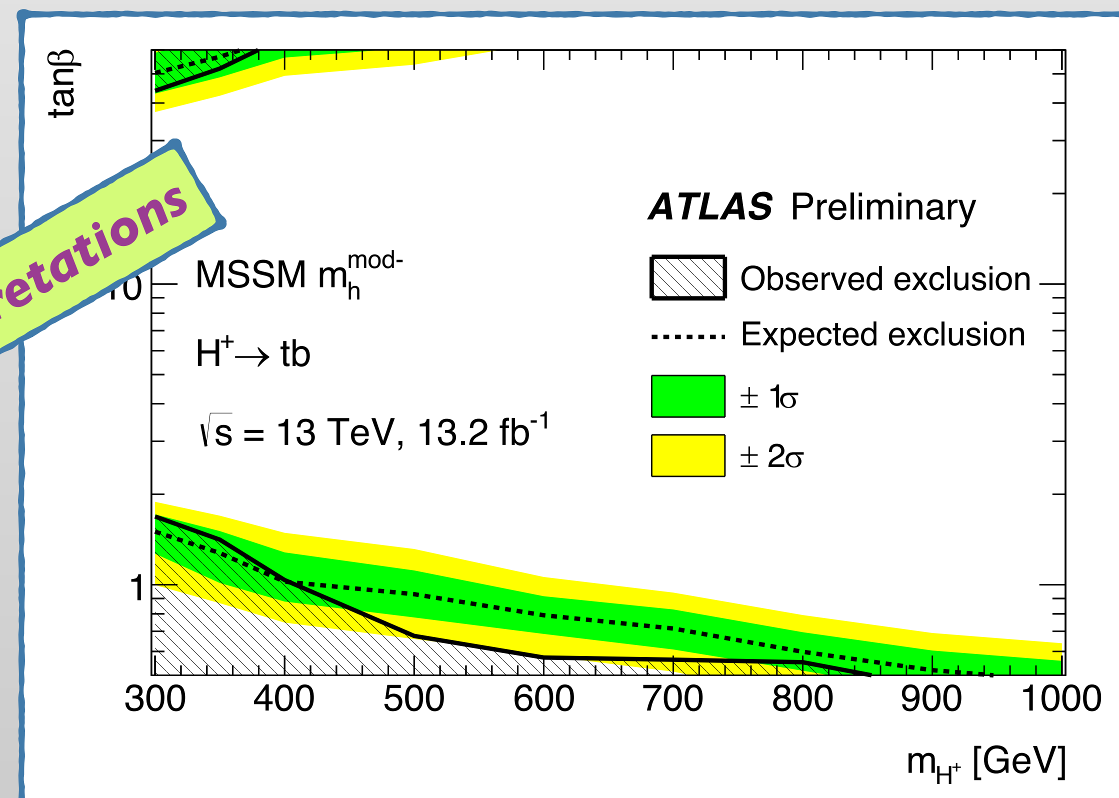
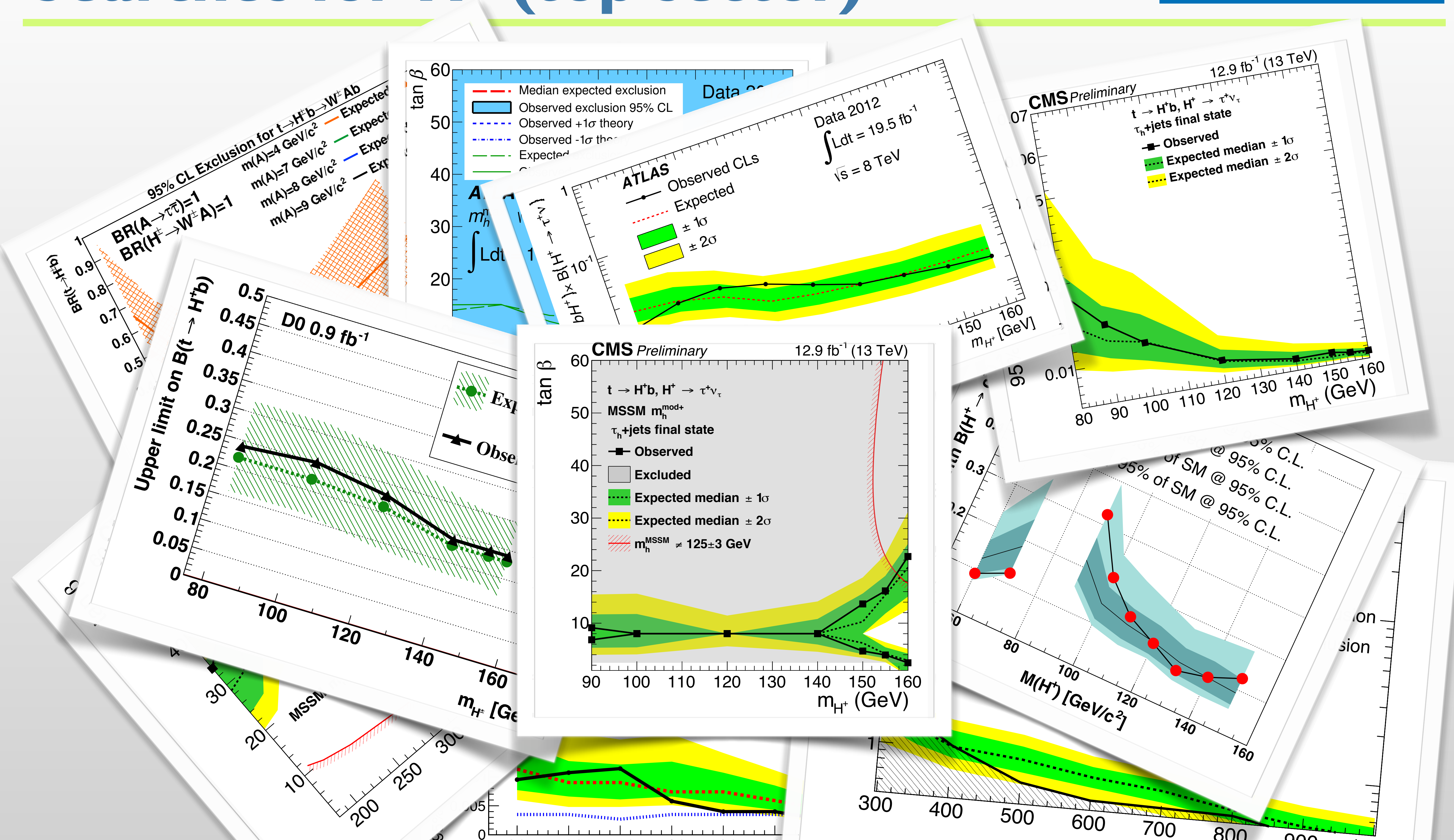


MSSM interpretations

$H^{\pm}\rightarrow tb$



Searches for H± (top sector)



No sign of charged Higgs yet in any of the searches!

Summary

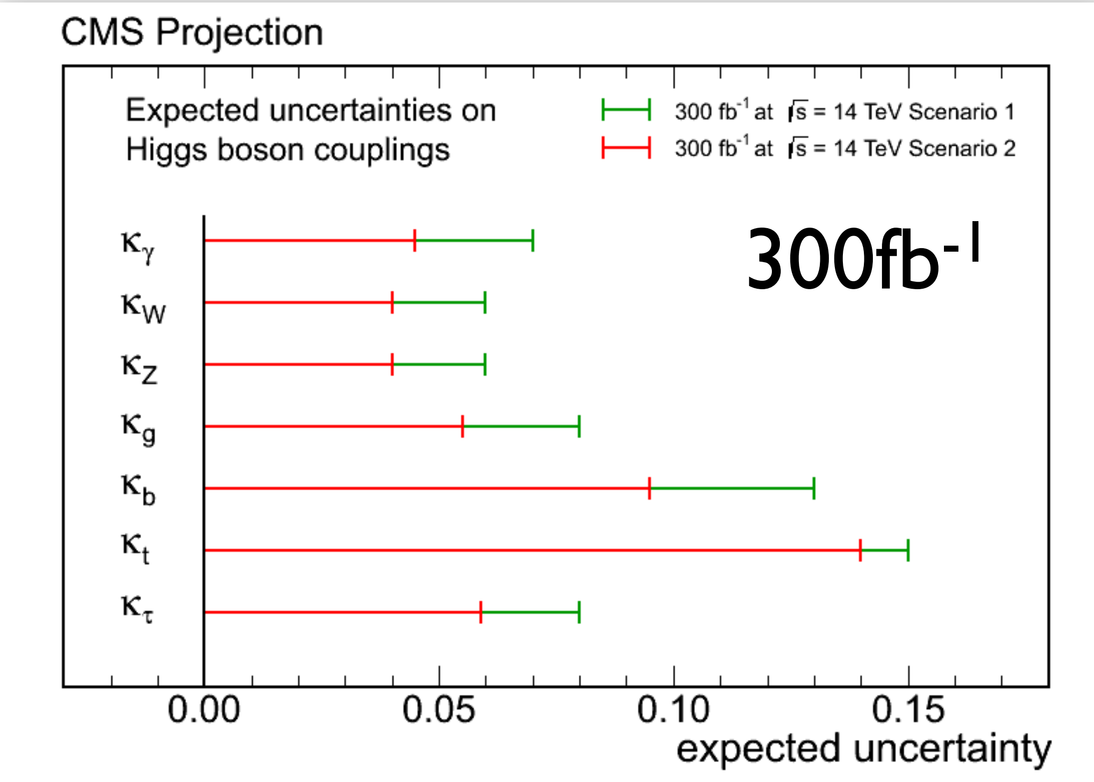
- Higgs and top are here - experiments started to play games with them…
- Interplay between the Higgs and top allows for indirect tests of the consistency of the SM via LEP / Tevatron / LHC measurements
- Limits on Higgs-top couplings from ATLAS & CMS (Run 1):
  - Most precise constraints through parametrisation of all accessible production and decay modes (mainly indirect, via loop diagrams);
- $t\bar{t}H$ measurement in all accessible final states at LHC
  - Most precise direct constraint on Higgs-top Yukawa coupling;
- tH measurement allows constraints on sign of Higgs-top-Yukawa coupling;
- Experiments also actively explore a wide range of BSM models, including those with $H^{\pm}$ that couples to top quark (SUSY, 2HDM, etc.)
  - Searches in both low-mass and high-mass $H^{\pm}$ scenarios;

- **All measurements compatible with SM predictions at current precision.**

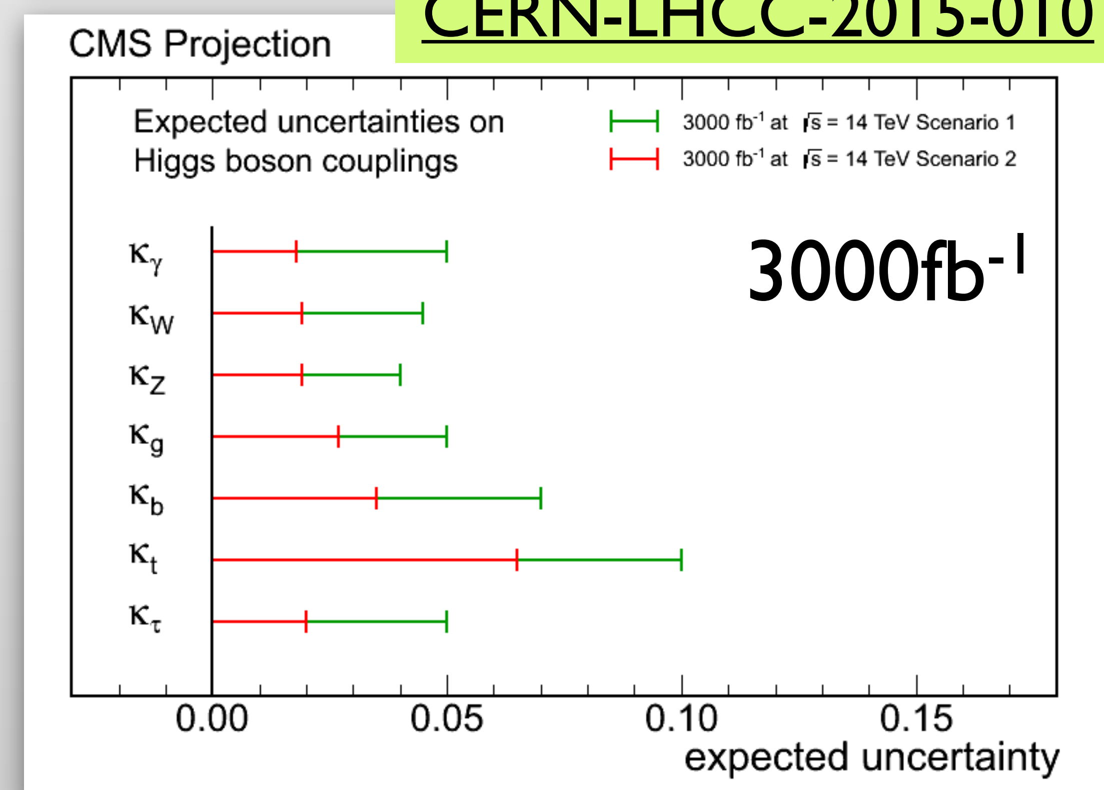
Backup

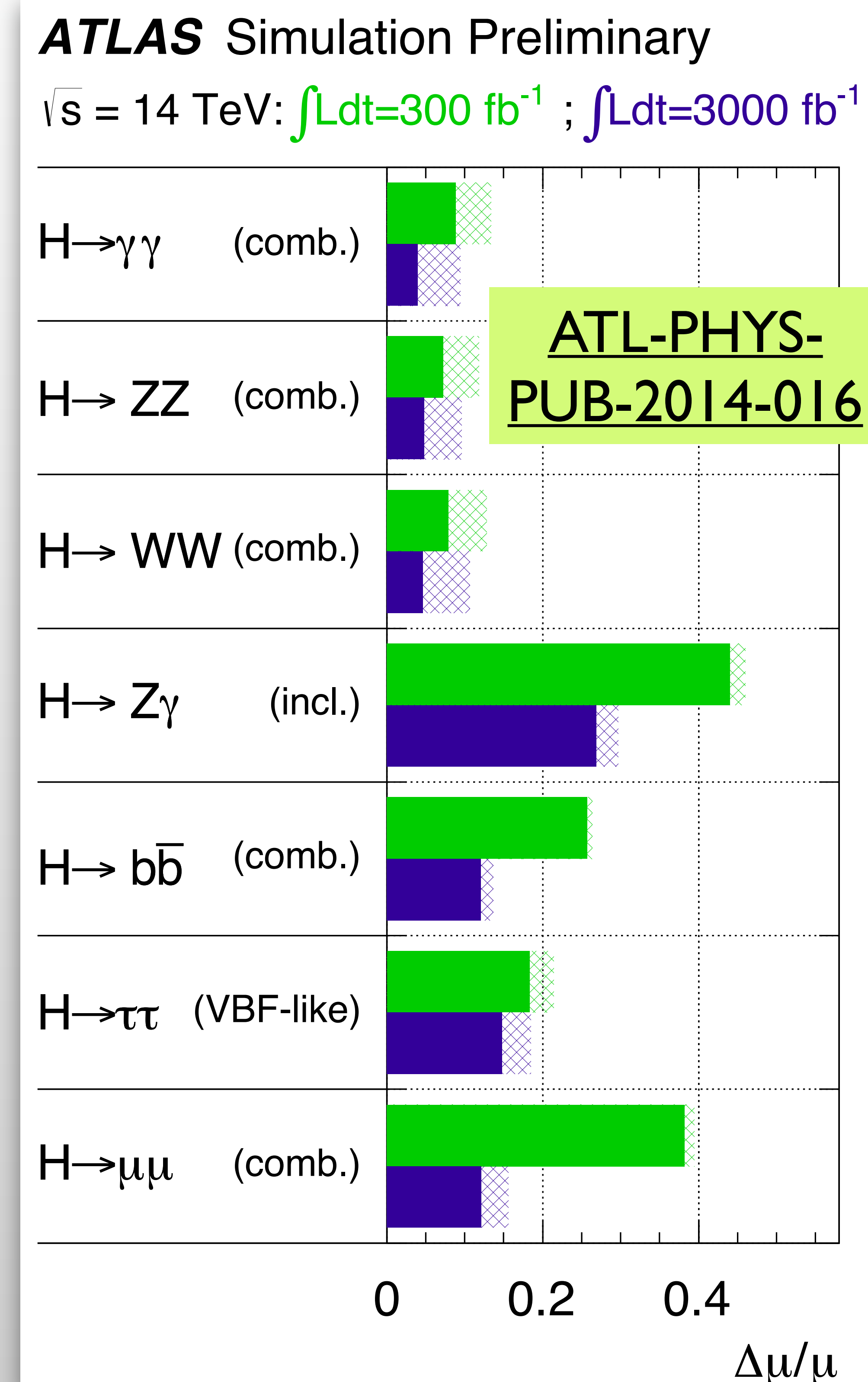
HL-HLC projections

TRIUMF



CERN-LHCC-2015-010





ATL-PHYS-PUB-2014-016

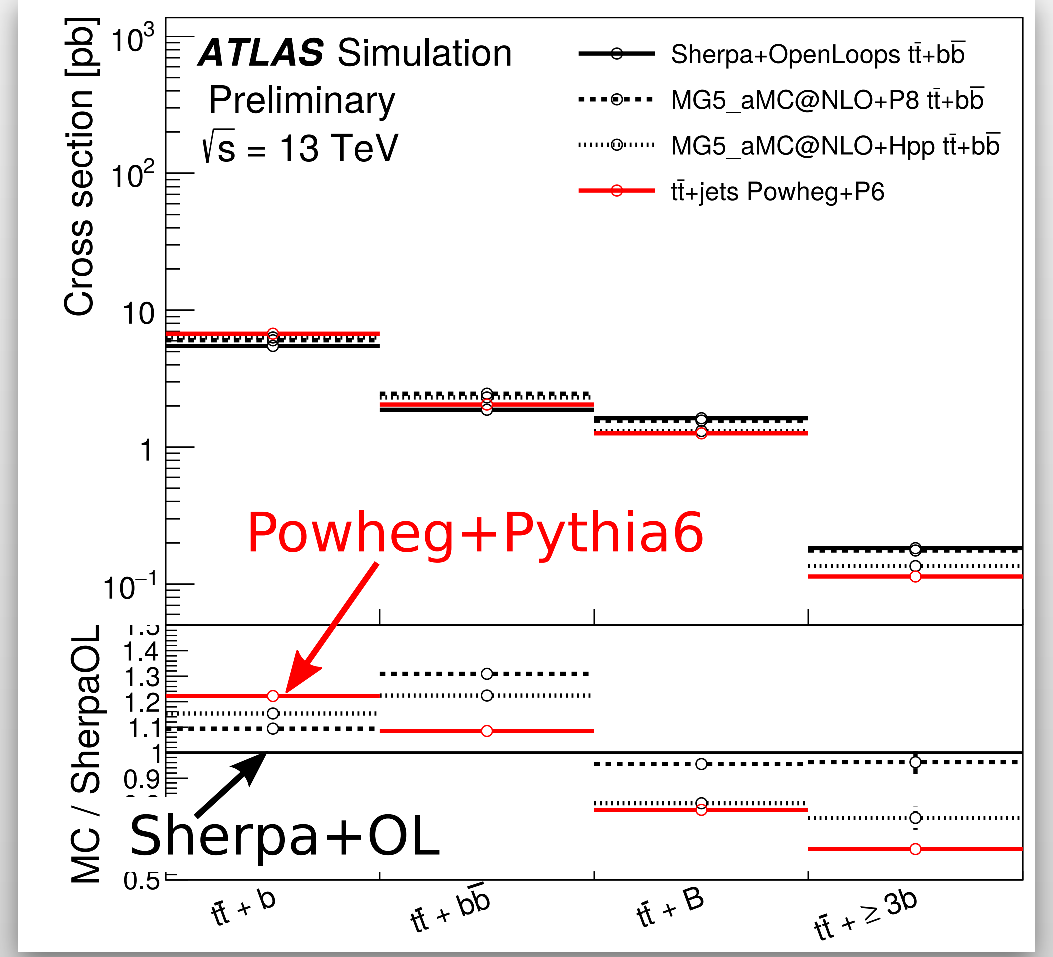
$t\bar{t}$+jets background in $t\bar{t}H(bb)$

CMS:

- Powheg+Pythia8 normalised to NNLO prediction;
- separate templates for $t\bar{t}$+b, $t\bar{t}$+bb, $t\bar{t}$+2b*, $t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1LF$;

ATLAS:

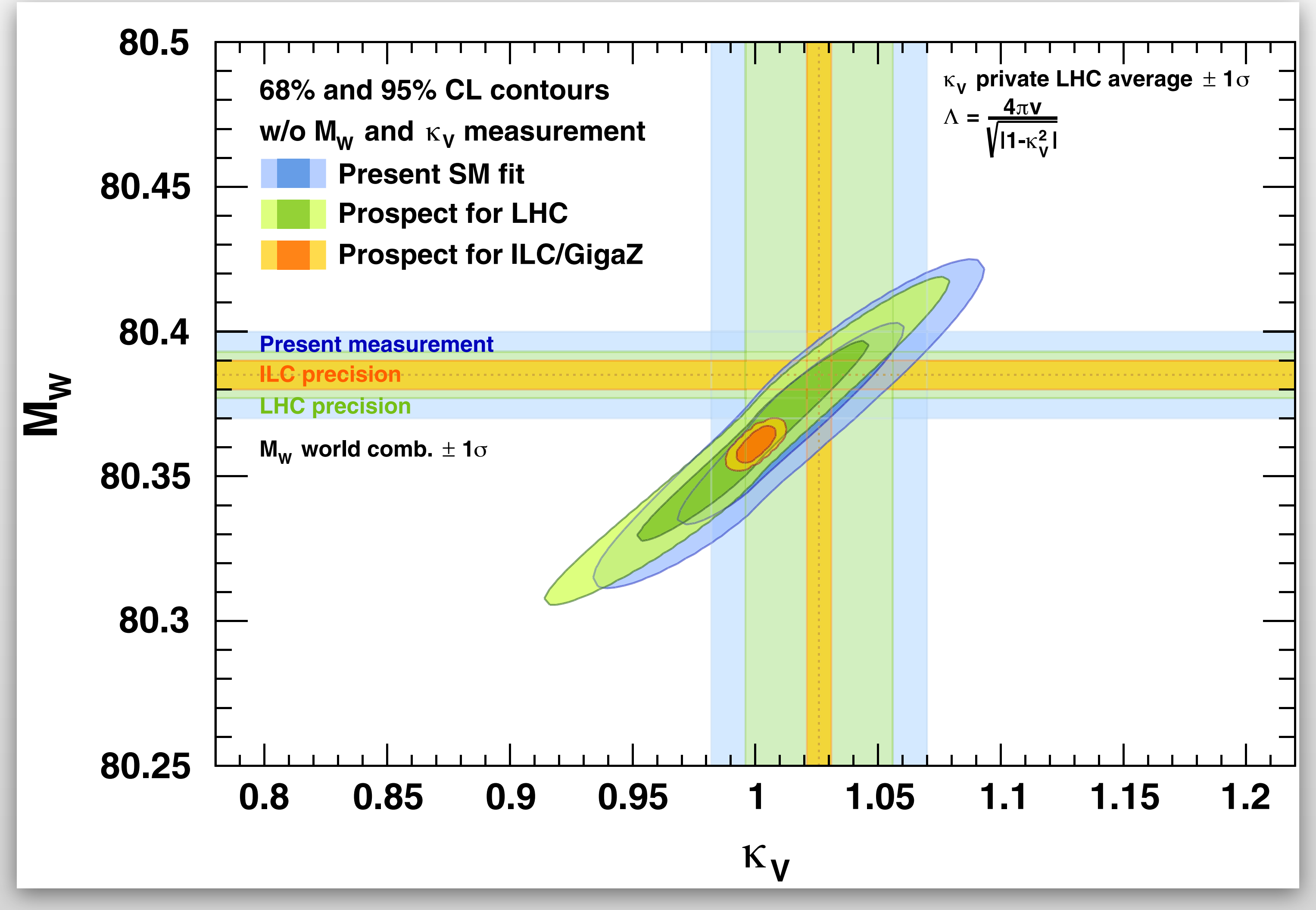
- Powheg+Pythia6 normalised to NNLO prediction;
- $p_T(t)$ & $p_T(tt)$ corrected to NNLO prediction for $t\bar{t}+\geq 1c$ and $t\bar{t}+\geq 1LF$;
- $t\bar{t}$+b, $t\bar{t}$+bb and $t\bar{t}$+B corrected to Sherpa +OpenLoops NLO calculation;
- normalisation for $t\bar{t}+\geq 1b$ and $t\bar{t}+\geq 1c$ free floating in the fit.



* CMS $t\bar{t}$+2b corresponds to ATLAS $t\bar{t}$+B

CMS 13 TeV $t\bar{t}$+bb measurement CMS-PAS-TOP-16-010:
ATLAS 8 TeV $t\bar{t}$+bb measurement: Eur. Phys. J. C (2016) 76:11

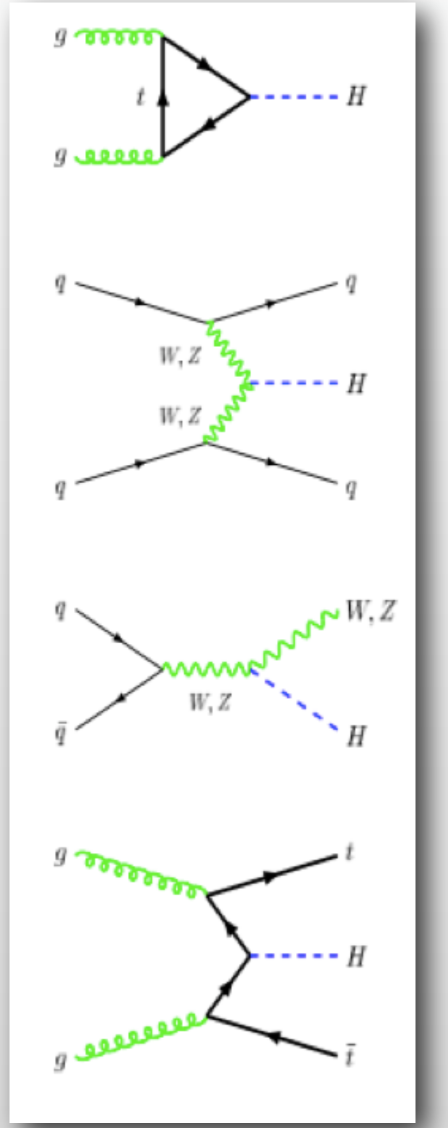
Higgs and top mass - prospects



Eur. Phys. J. C (2014) 74: 3046.

Higgs production at LHC

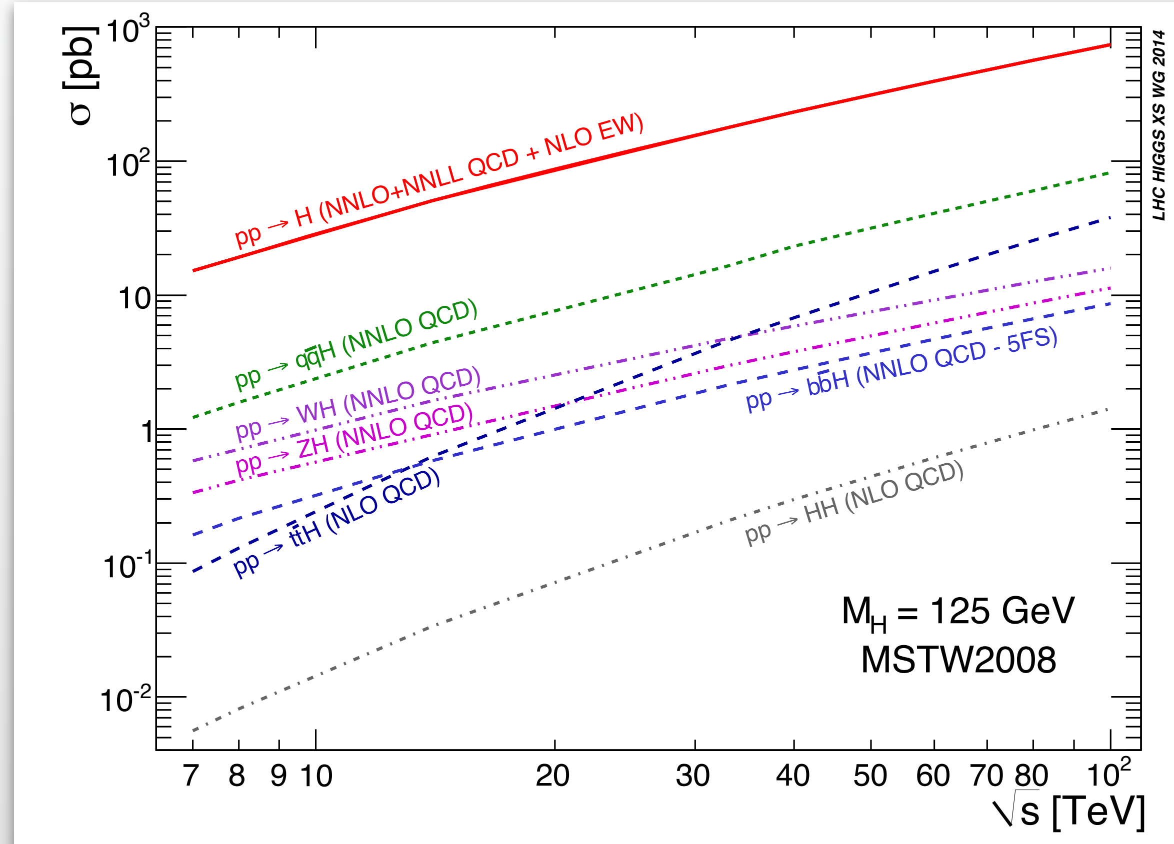
Production mechanisms



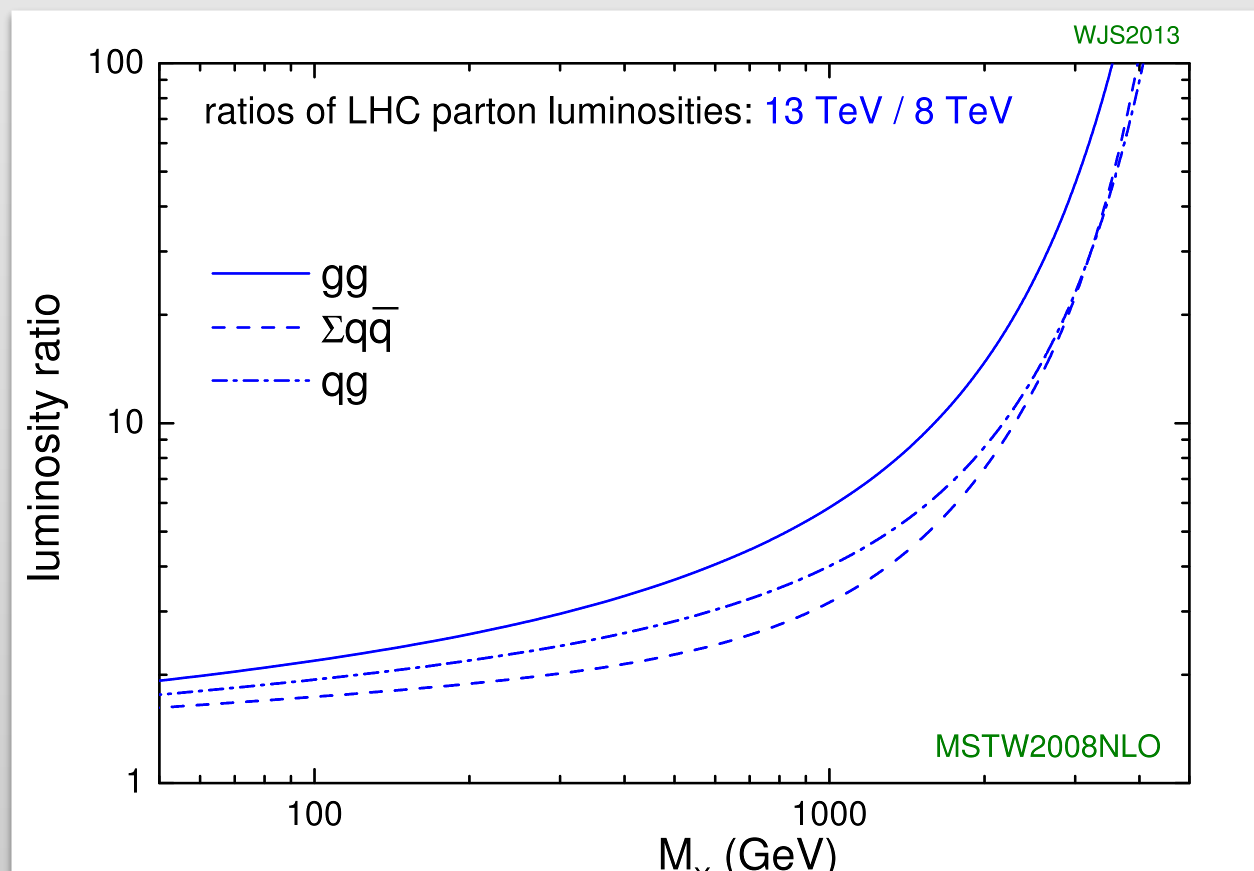
ggF	87%	Largest cross-section, largest theory uncertainties;
VBF	7%	Characteristic signature with 2 jets separated in η;
VH	5%	Reduced QCD multijet backgrounds;
$q\bar{q}H$	1%	Signature characterised by 2 b-jets + additional jets or leptons

ttH production

$$\sigma_{t\bar{t}H}(13TeV) \sim 4 \times \sigma_{t\bar{t}H}(8TeV)$$



Phase space opening
+
$M_X = 2M_t + M_H$ in gg

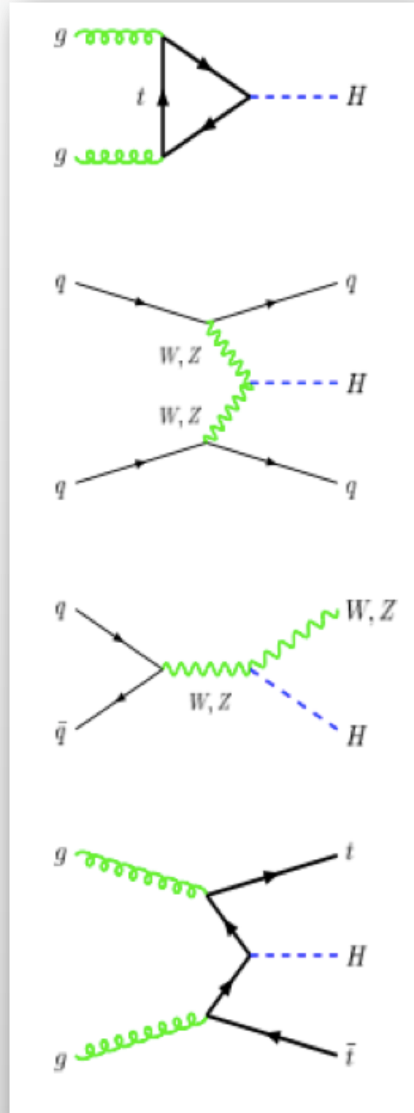


	σ(13 TeV) / σ(8 TeV)
gg→H	~2.3 (M_X=M_H)
qq→H	~2.4 (probes high M_X)
qq→VH	~2.0 (M_X=M_V+M_H)
qq→ttH	~3.9 (phase space + M_X)
tt	~3.3 (gg→tt dominates)

Higgs boson decays

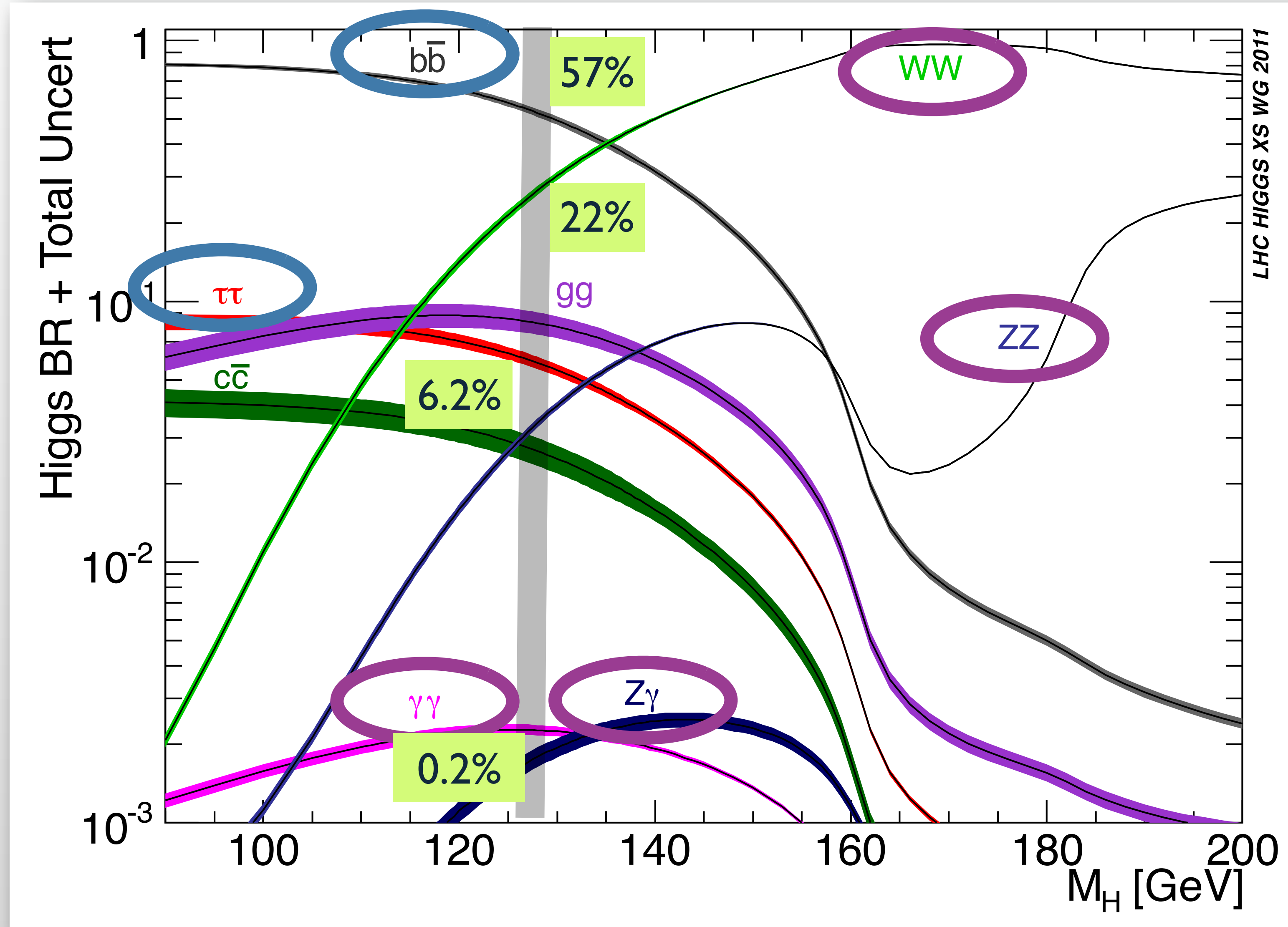
TRIUMF

Production mechanisms



ggF	87%
VBF	7%
VH	5%
ttH	1%

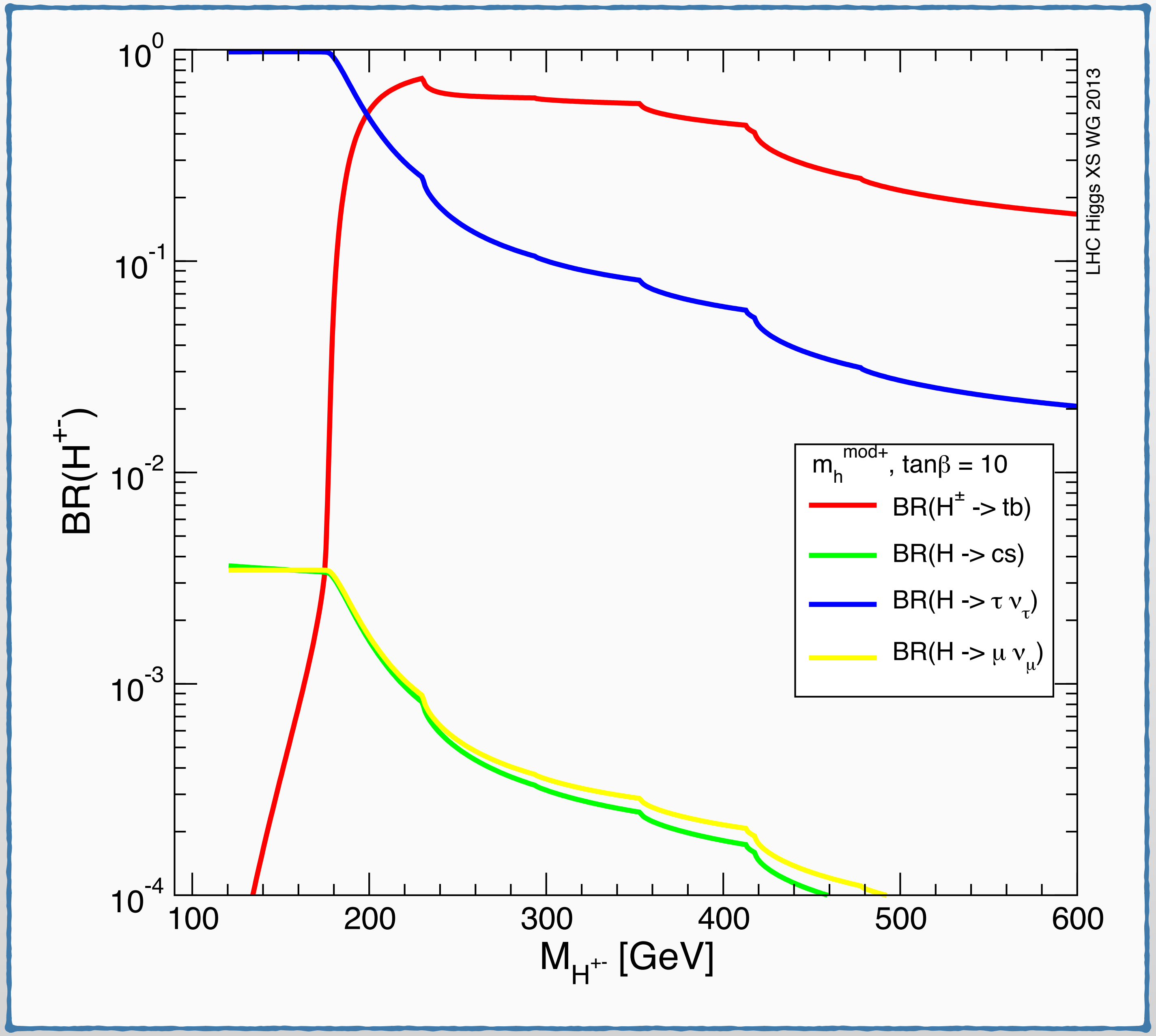
SM Higgs boson decay modes



Many decay modes accessible for m_H = 125 GeV

Bosonic decays: ZZ, WW, γγ, Zγ;
Fermionic decays: $b\bar{b}$, ττ, μμ;

BR($H^{\pm}$)



10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
BR(H^{+-})
100
200
300
400
500
600
$M_{H^{+-}}$ [GeV]
LHC Higgs XS WG 2013
m_h^{mod+}, tanβ = 10
BR($H^{\pm}$ -> tb)
BR(H -> cs)
BR(H -> τ ν_τ)
BR(H -> μ ν_μ)