36th International Symposium on Physics in Collision (PIC 2016)

13–17 September 2016, Quy Nhon (Vietnam)

Search for additional Higgs Bosons

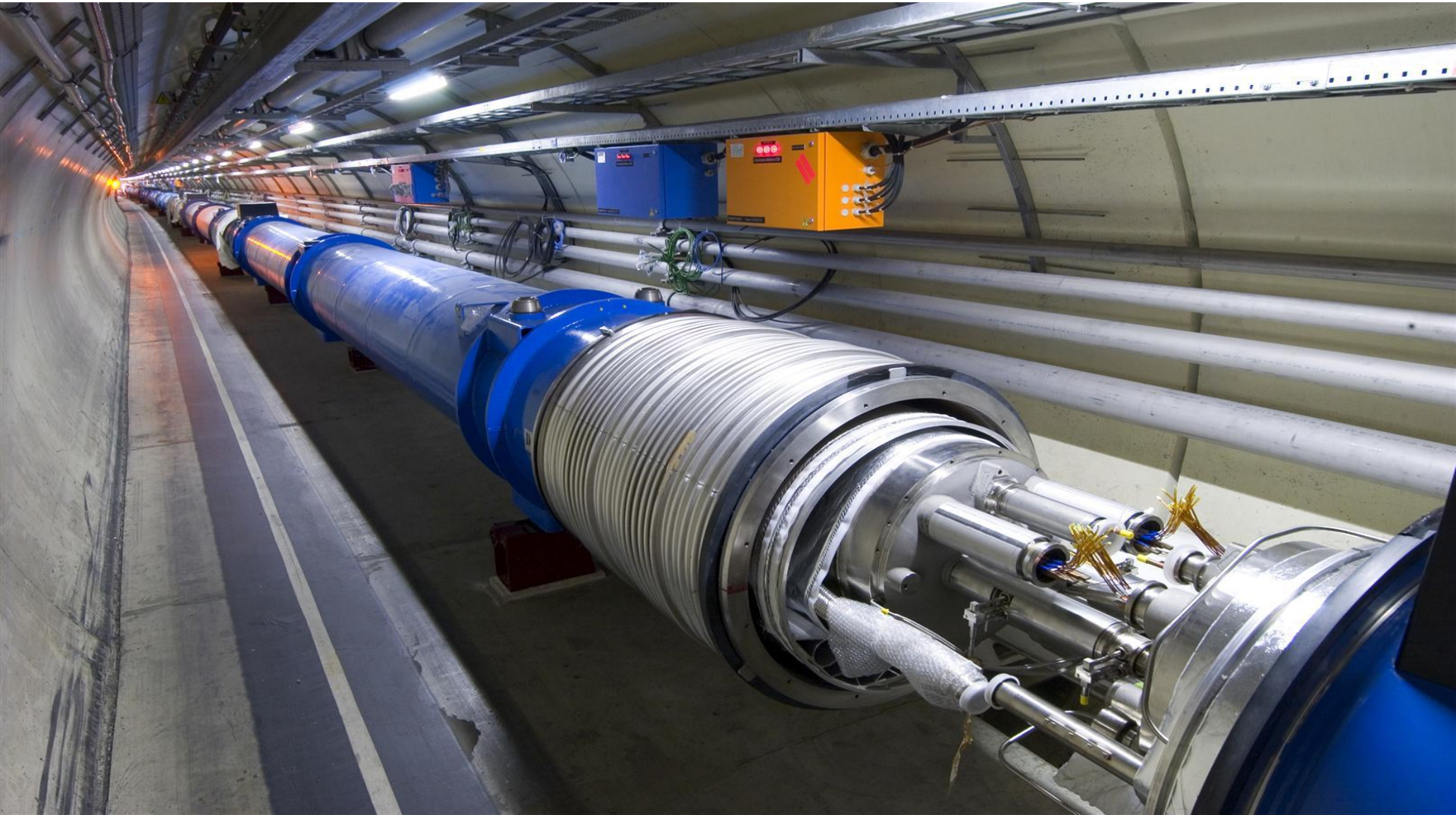
Somnath Choudhury

(for the ATLAS and CMS collaborations)

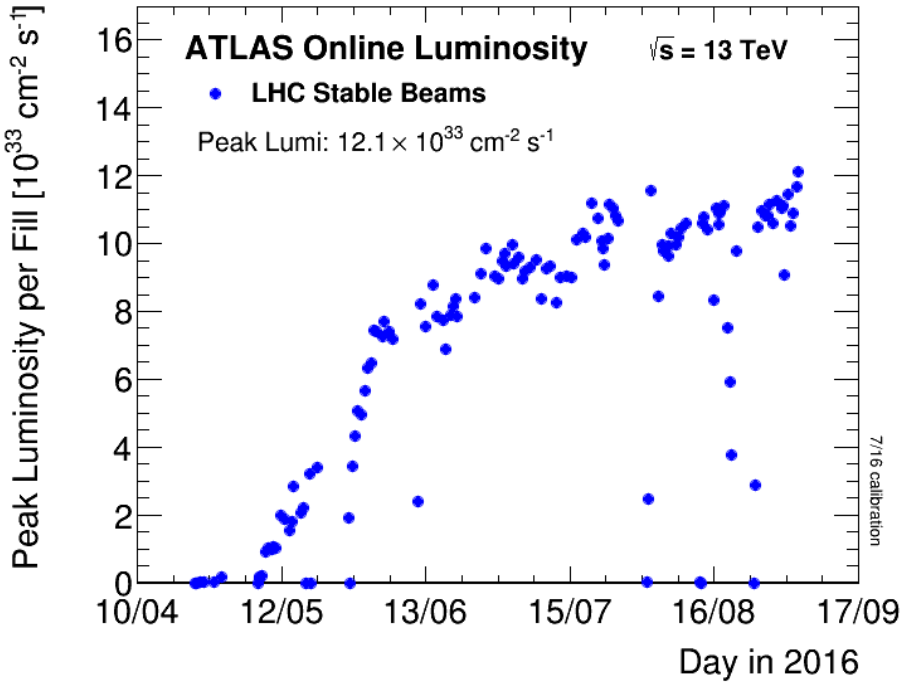
Outline – Run 1 and Run 2 Results

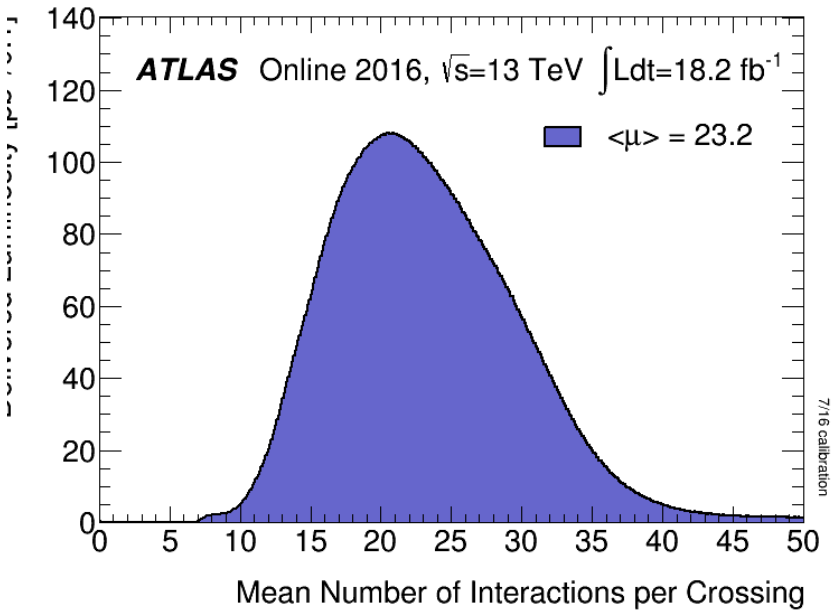
- LHC & the detectors
- BSM Higgs Searches
  - MSSM Neutral Higgs
  - MSSM Charged Higgs
  - Light NMSSM Higgs
  - Heavy Higgs searches
  - LFV Higgs decay
  - Invisible Higgs decay
- Summary & Outlook

The Large Hadron Collider



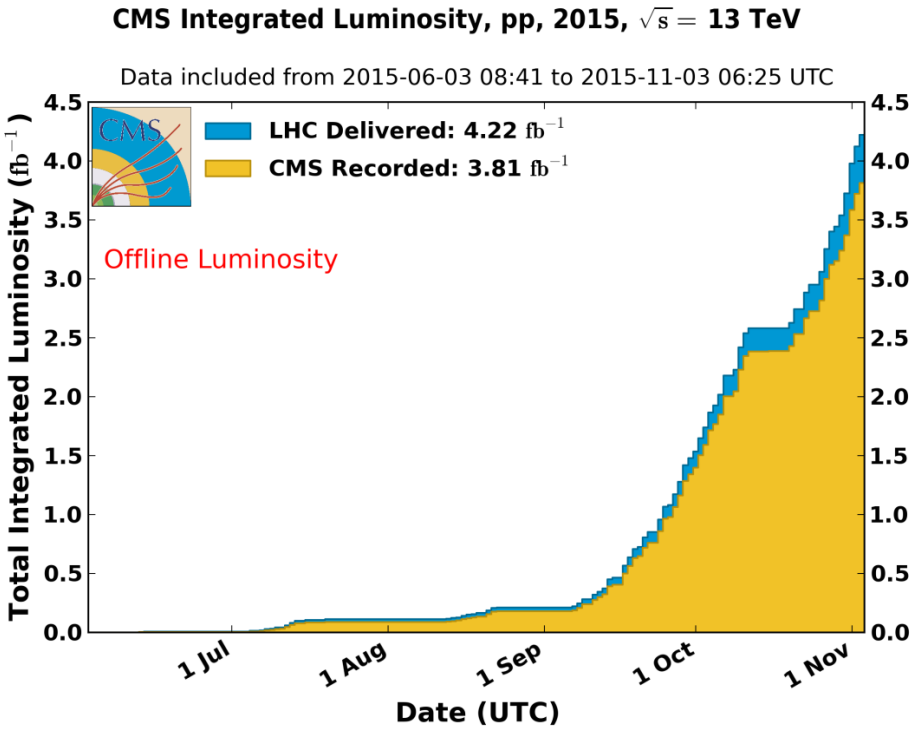
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

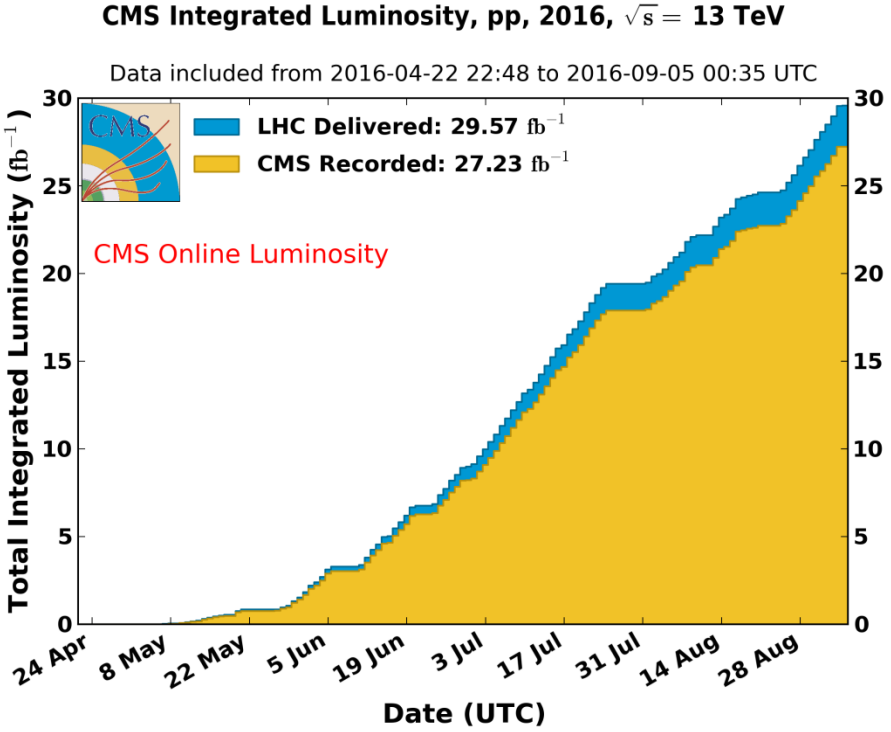




ATLAS luminosity is determined using counting rates measured by the luminosity detectors, and is based on preliminary analysis of van-der-Meer beam-separation scans in 2016

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults



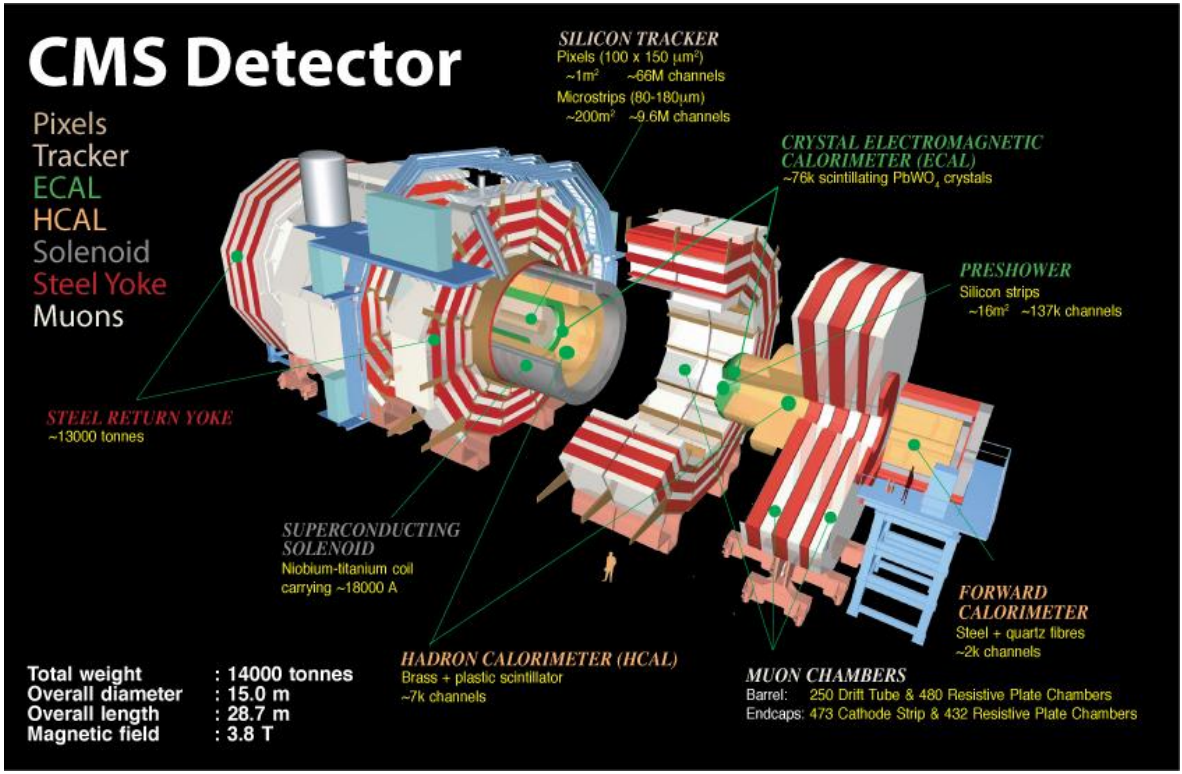


So far in 2016, LHC has delivered **1.2 times nominal instaneous lumi**
Already at 30 fb^{-1} with few more weeks of running left in 2016…
If LHC continues at the same pace, could deliver **over 40 fb^{-1} in 2016**

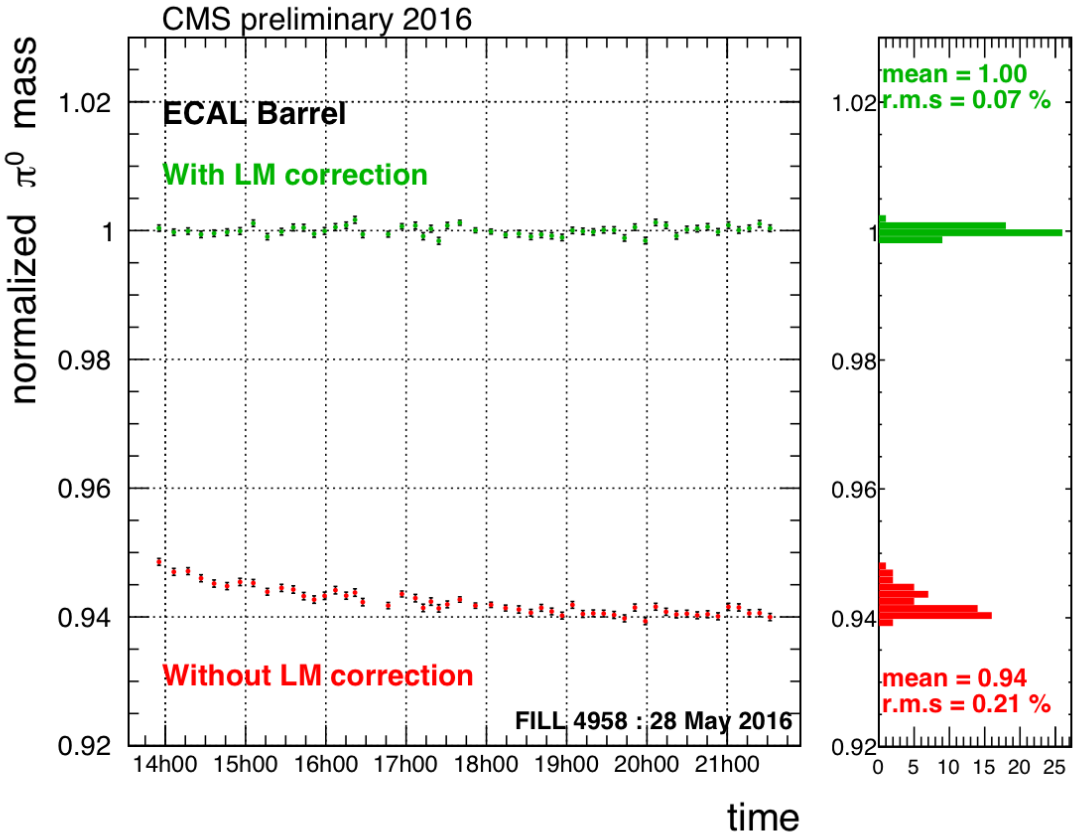
The Detectors

3.8 T superconducting solenoid envelop:

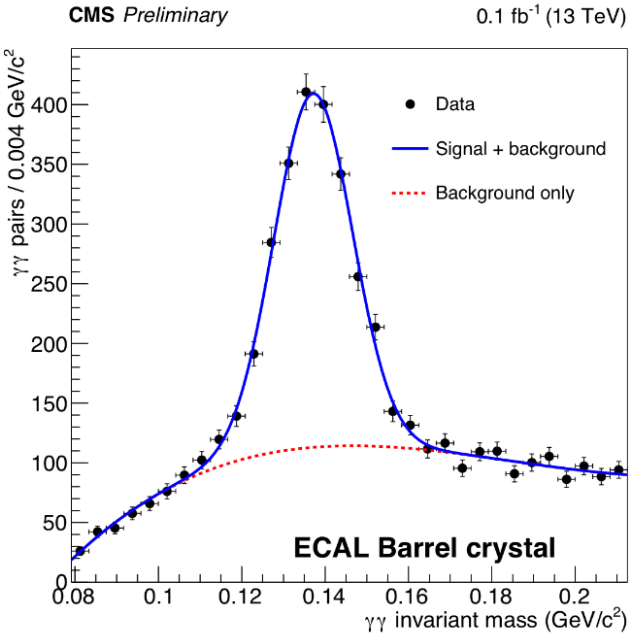
- Tracker (silicon pixel and strip detectors) $|\eta| < 2.5$
- ECAL ($PbWO_4$ crystals)
- HCAL (brass/scintillator samplers)
  Barrel $|\eta| < 1.48$
  Endcap $1.48 < |\eta| < 3.0$
- Muon system – gas ionization detectors embedded in steel return yoke outside the solenoid, $|\eta| < 2.4$
  Drift Tubes, Cathode Strips and Resistive Plate Chambers



CMS Electromagnetic Calorimeter



CMS-DP-2016-031

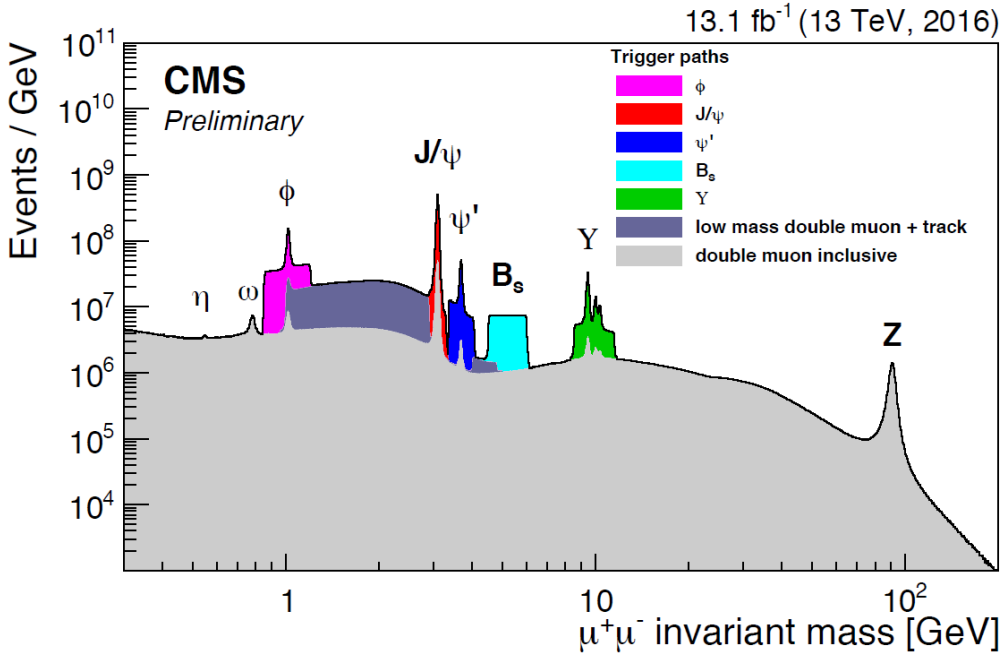


ECAL calibration uses a laser to monitor and correct for transparency loss

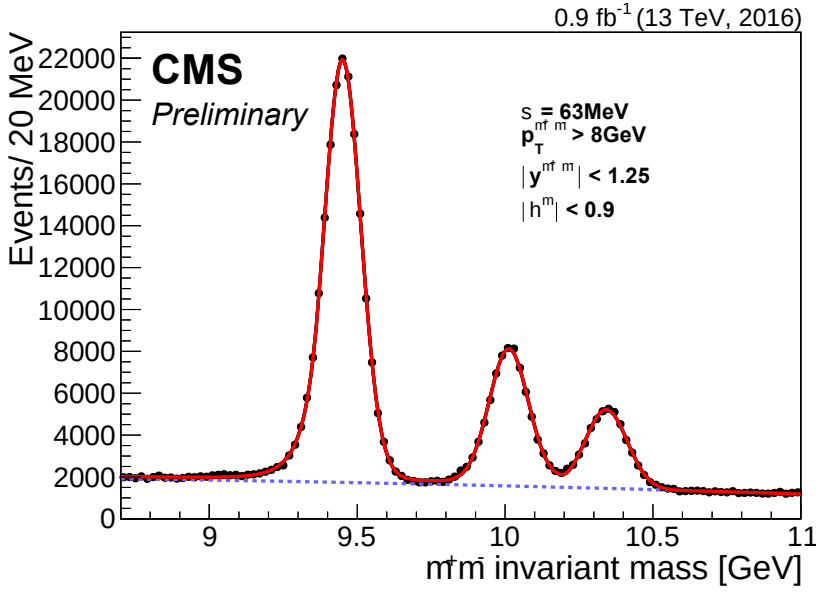
Stability of the relative energy scale measured from invariant mass distribution of $\pi^0 \rightarrow \gamma\gamma$ decays in the ECAL Barrel

CMS Muon Chambers

CMS DP -2016/059



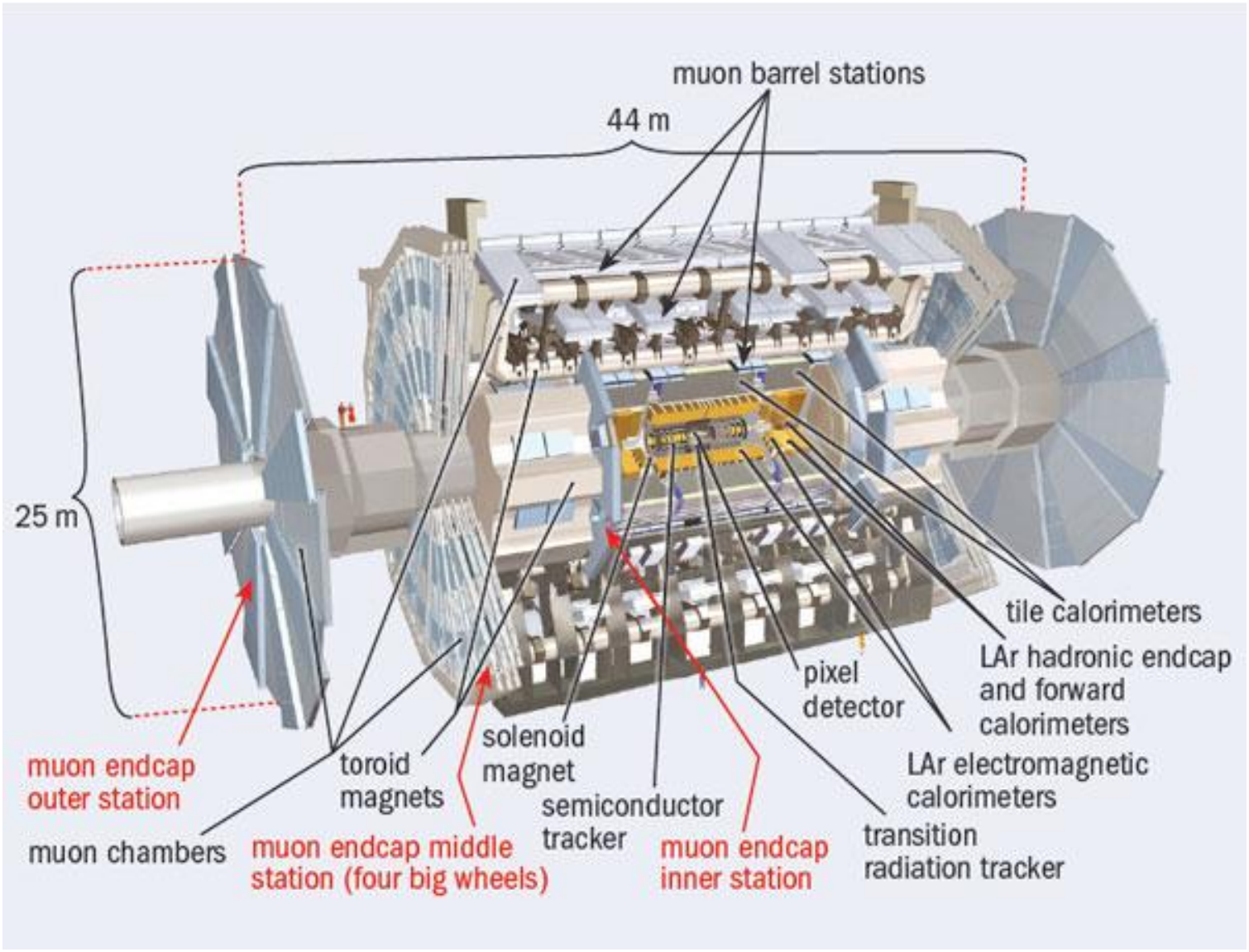
CMS-DP-2016-027



CMS muon detectors cover a wide range of kinematics

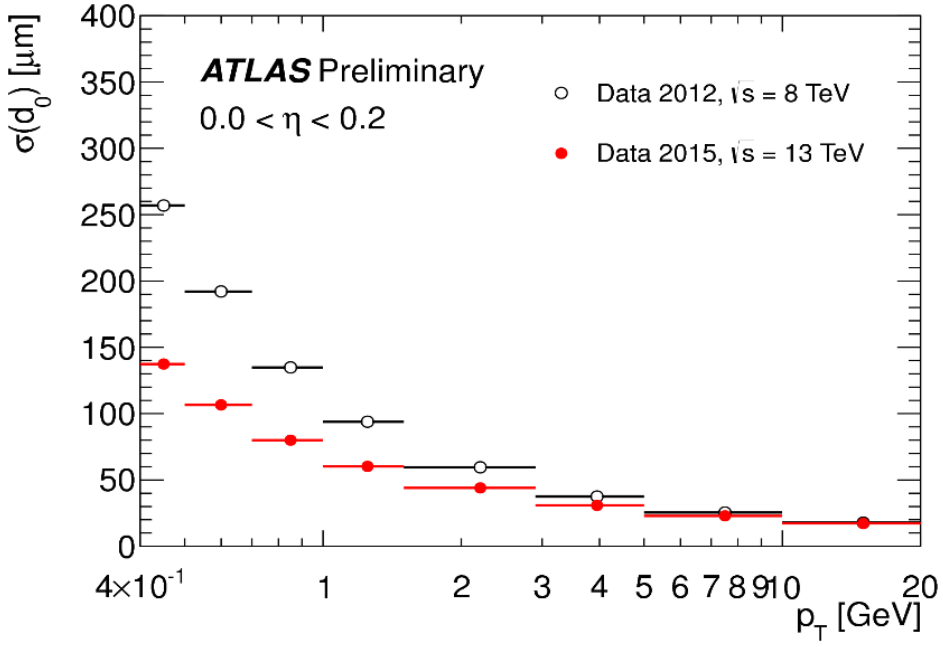
… this comes directly from the High Level Trigger selection of muons "out of the box"…

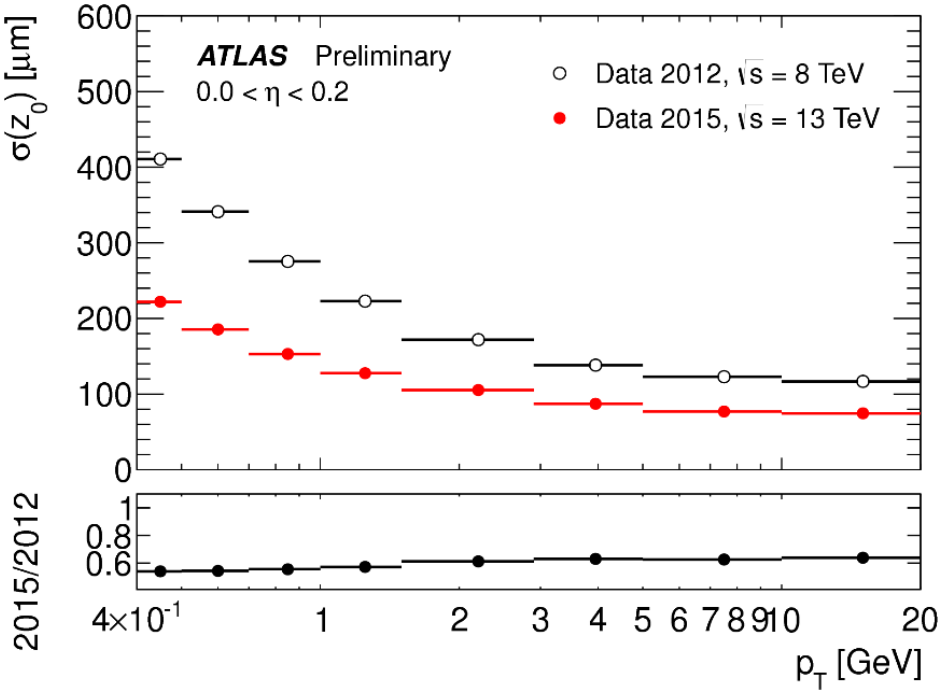
The ATLAS Detector



ATLAS Insertable B-Layer

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2015-007





Insertable 4th pixel layer with planar and 3D sensors; at R=33 mm from the beam line, mounted on the new smaller beam-pipe

Impact parameter significantly improved in Run 2 after IBL– up to a factor 2 at low p_T

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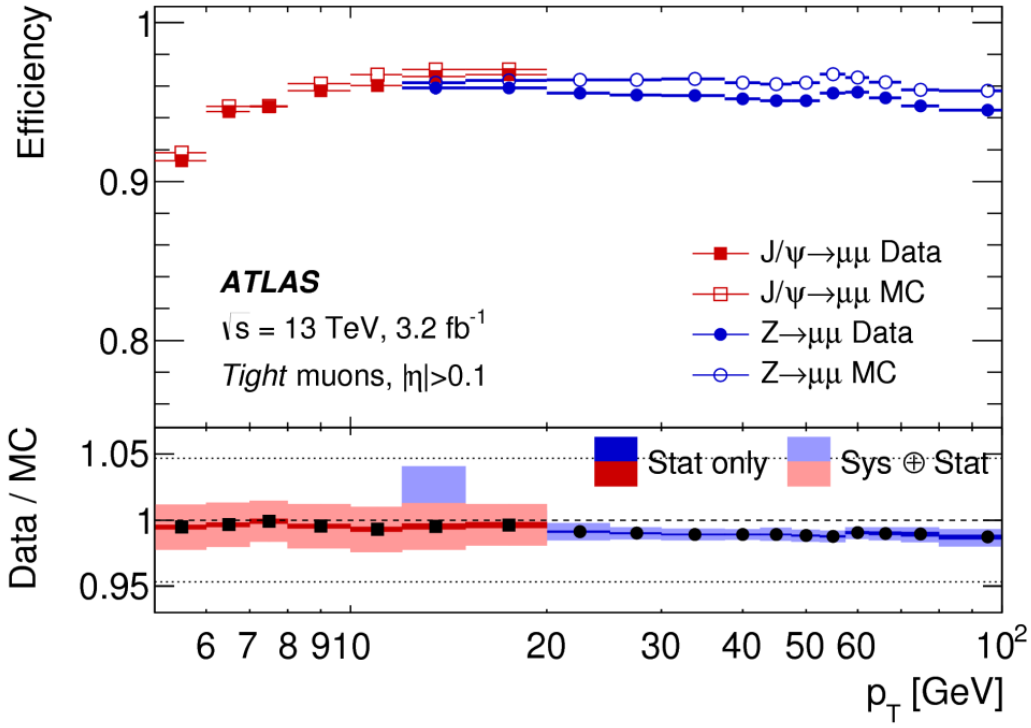
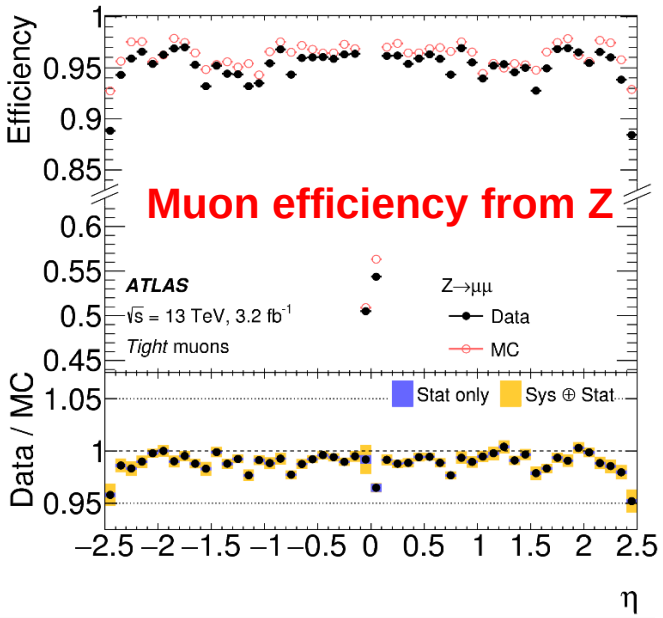
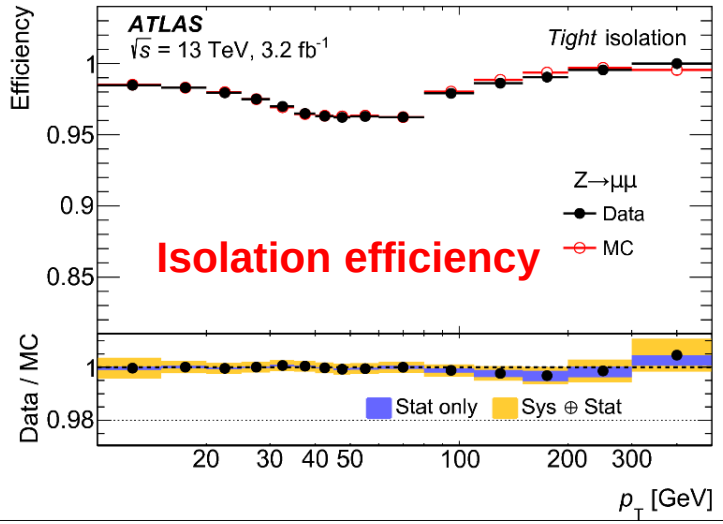
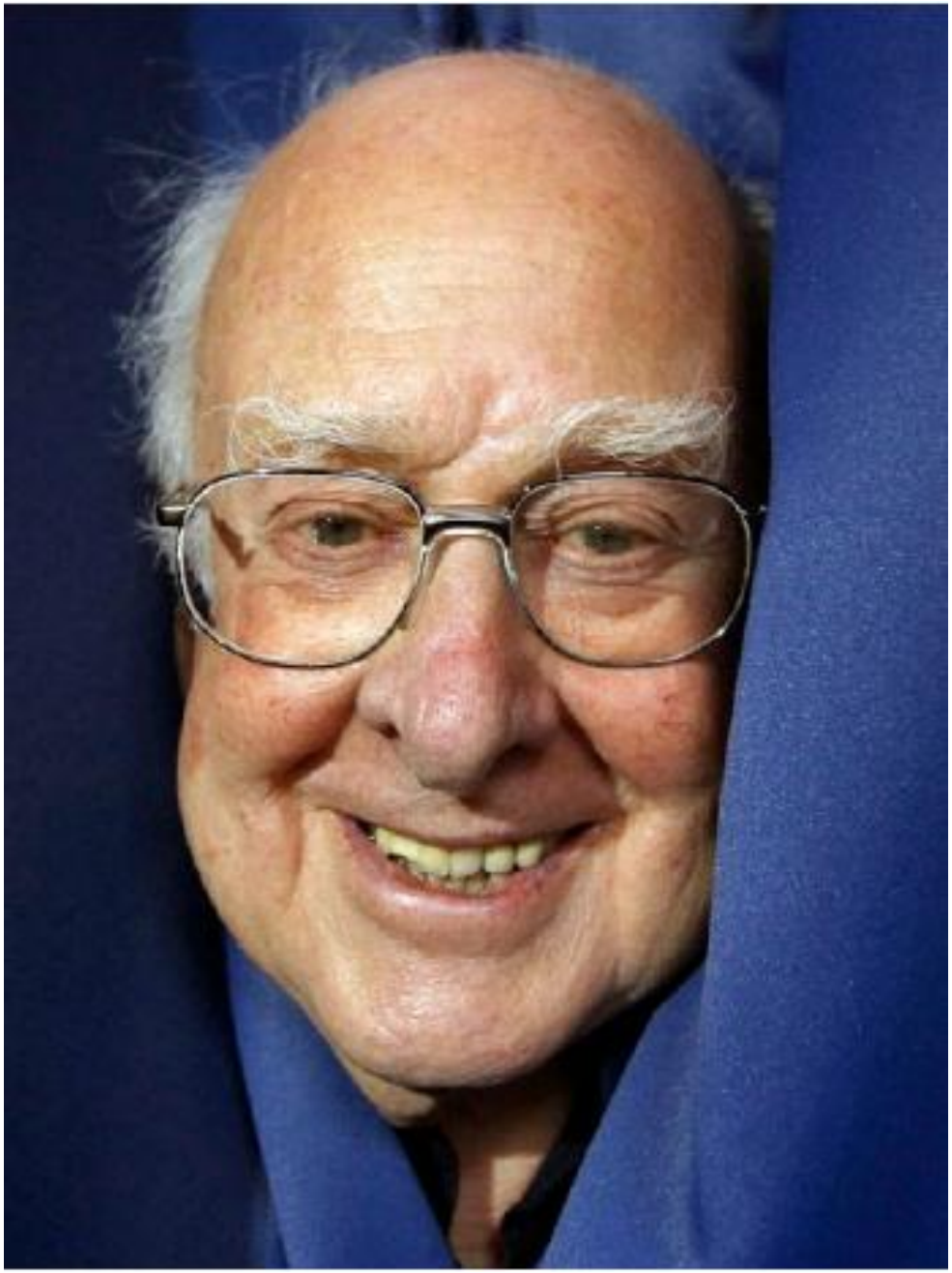
- ATLAS Muon spectrometer running smoothly
- Alignment ~ 50 μm for both barrel and endcap





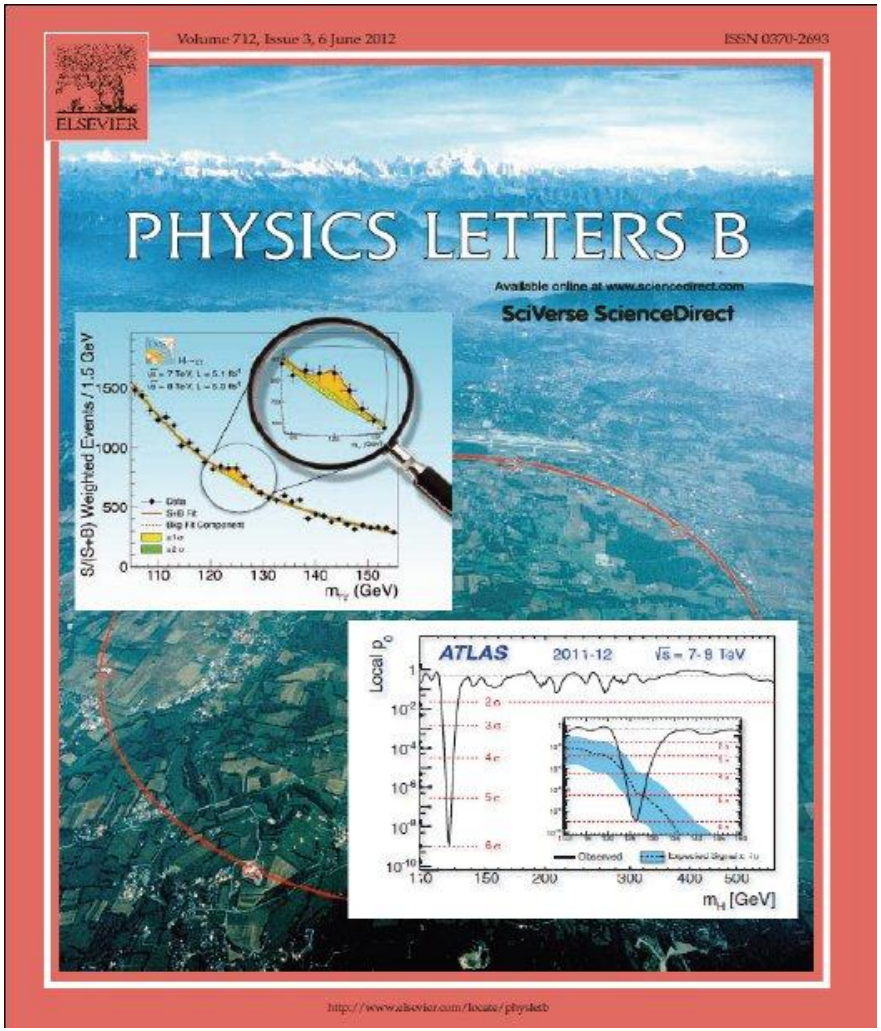


125 GeV Higgs Boson Measurements



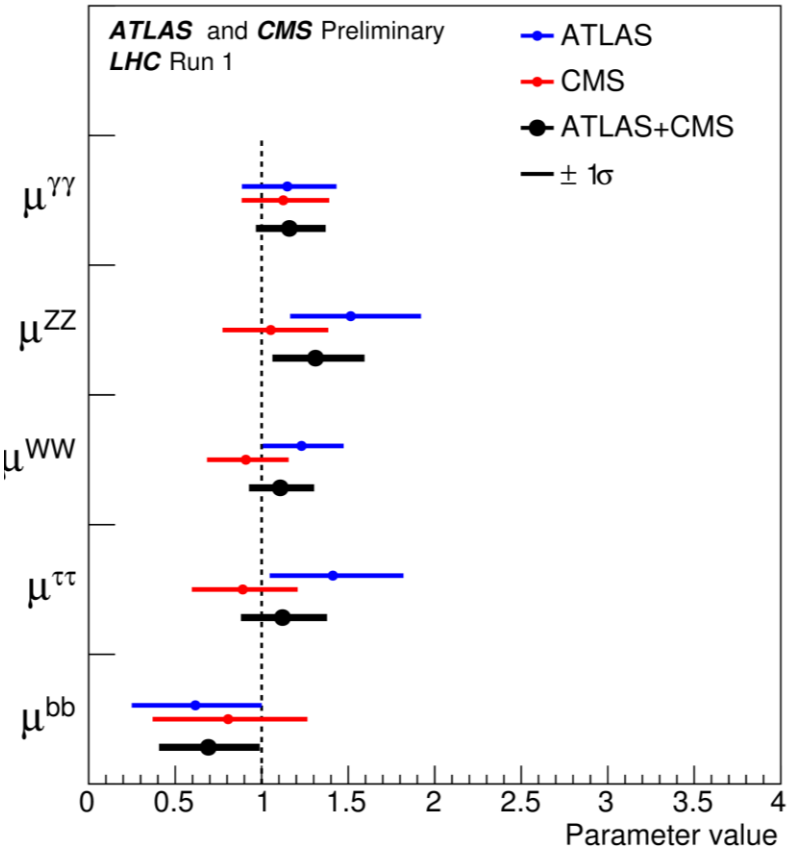
Great Moments!

Great achievement to a four decade long quest
A Higgs-like state pinned down at 125 GeV mass



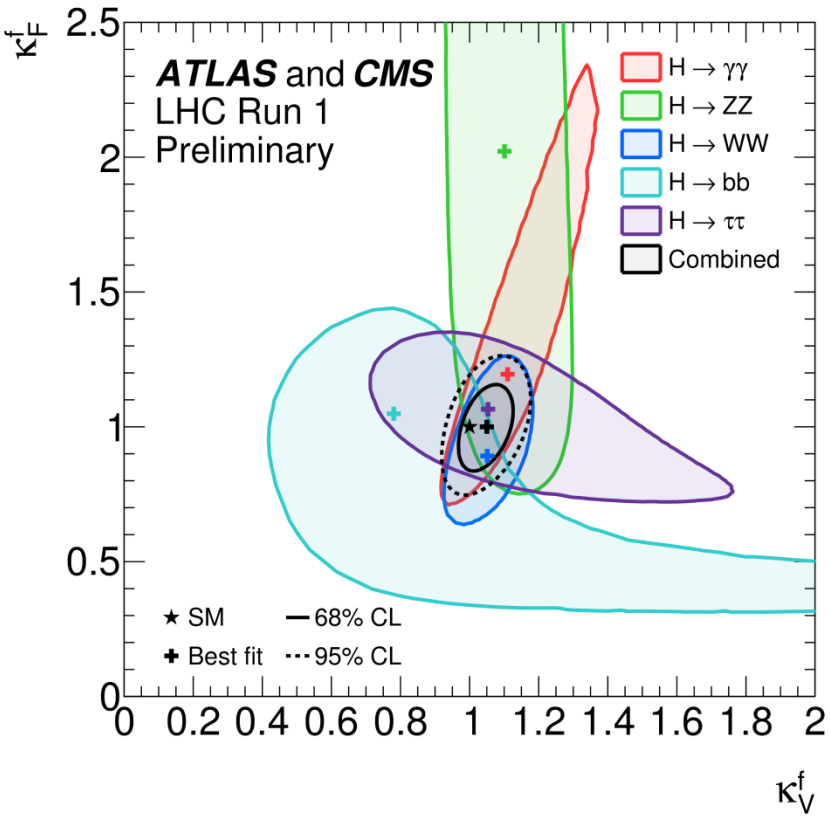
ATLAS + CMS Combination @ Run-1

JHEP 08 (2016) 045

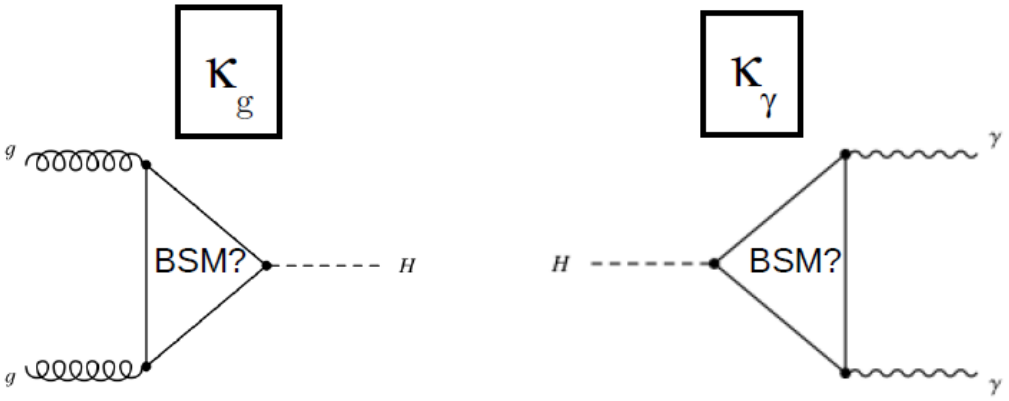


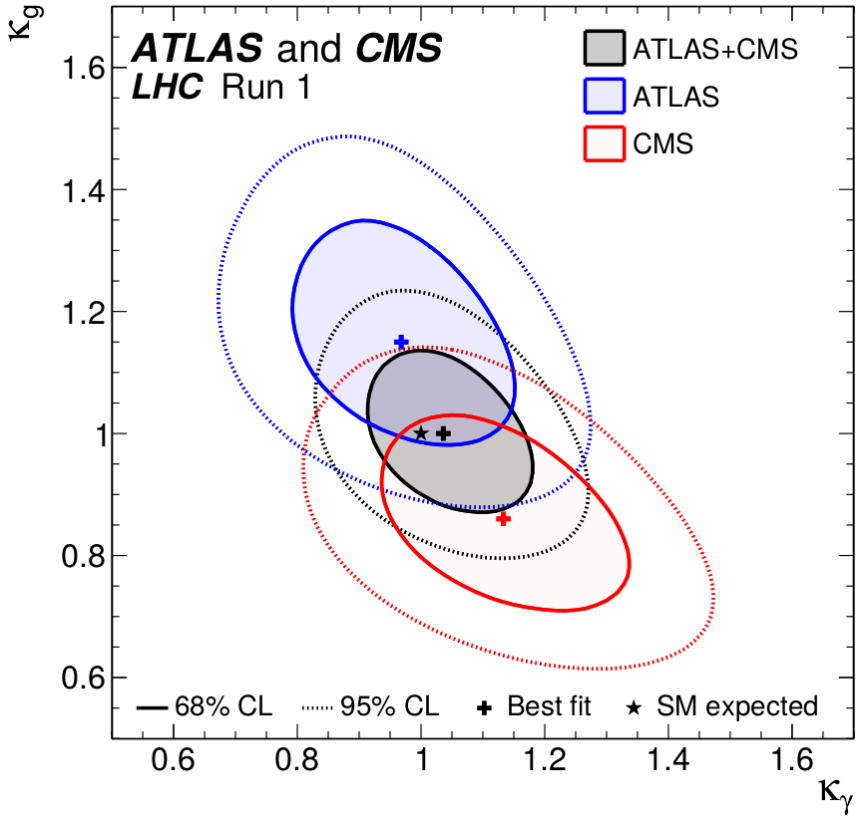
Best-fit results for decay signal strengths for the combination of ATLAS and CMS.

κ_F versus κ_V for the combination of ATLAS and CMS in the individual decay channels as well as their global combination



New Physics could modify the effective Higgs-gluon and Higgs-γ loop induced couplings.

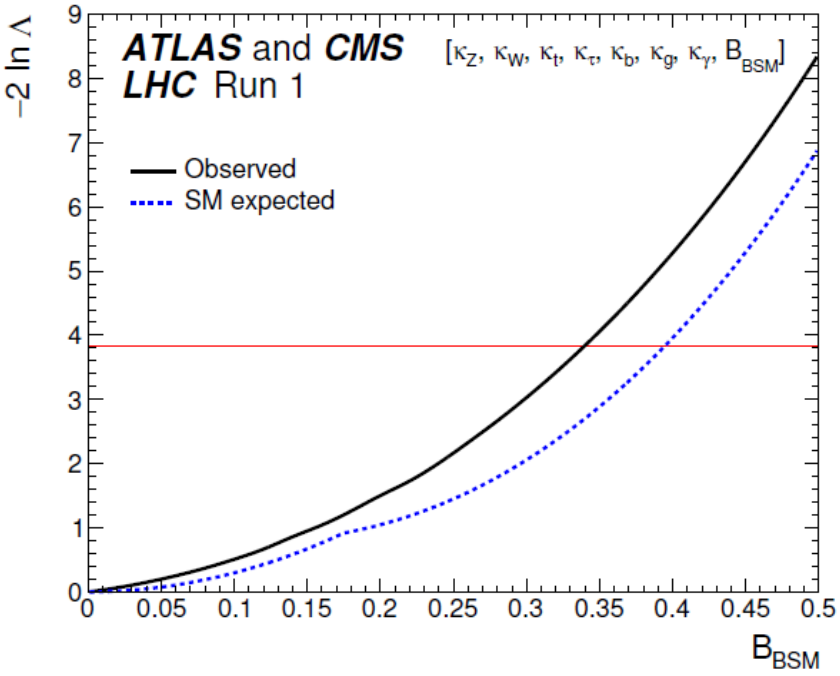


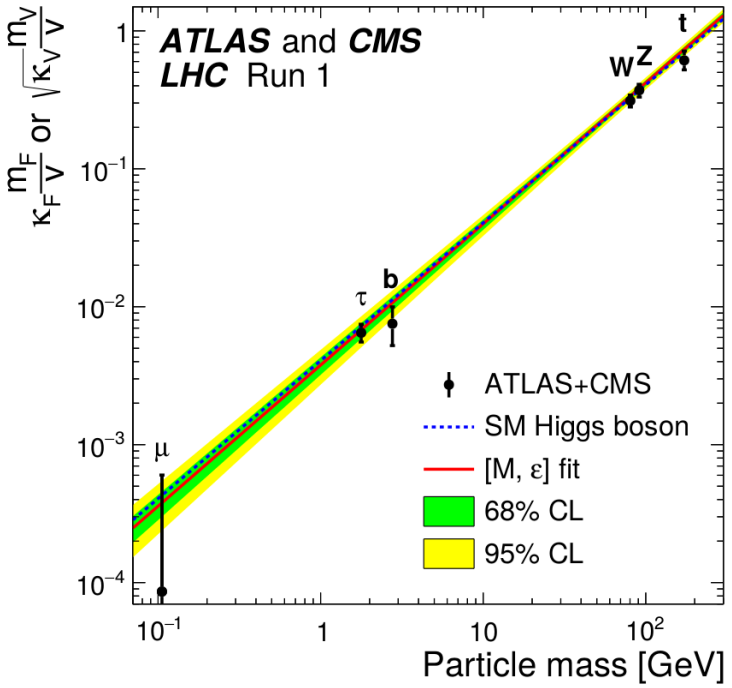


- They have been fitted fixing all the other parameters to the SM prediction.

- Both κγ and κg have been found compatible with SM.

ATLAS + CMS Combination @ Run-1





Results shown for the parameterisation with assumptions $\kappa_V \leq 1$ and $BR_{BSM} \geq 0$

ATLAS and CMS Run-1 measurements/ searches provides indirect constraints:

BR_{BSM} < 0.34 (0.39)% at 95% CL

Dependence of couplings versus particle mass

The observed particle at 125 GeV is indeed a Higgs boson

Question remains: **Is it the Higgs boson of the SM or part of an extended Higgs sector?**

Higgs is a journey,
not a destination

BSM Higgs Physics

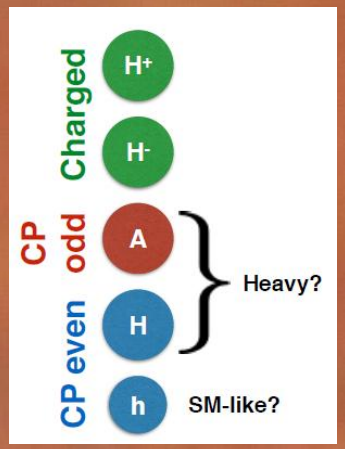
BSM Higgs Results @ Run 1 & 2

- Run I searches covered a large range of BSM Higgs boson signatures
  Run II is continuing the searches
- LHC is the discovery machine
  → the adventure in the TeV energy regime has just begun

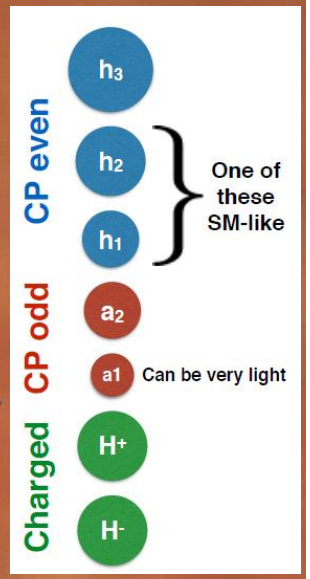
Lepton Flavour Violating Higgs Decays

Invisible Higgs Decays

MSSM / 2 HDM



Next-to-MSSM (NMSSM)



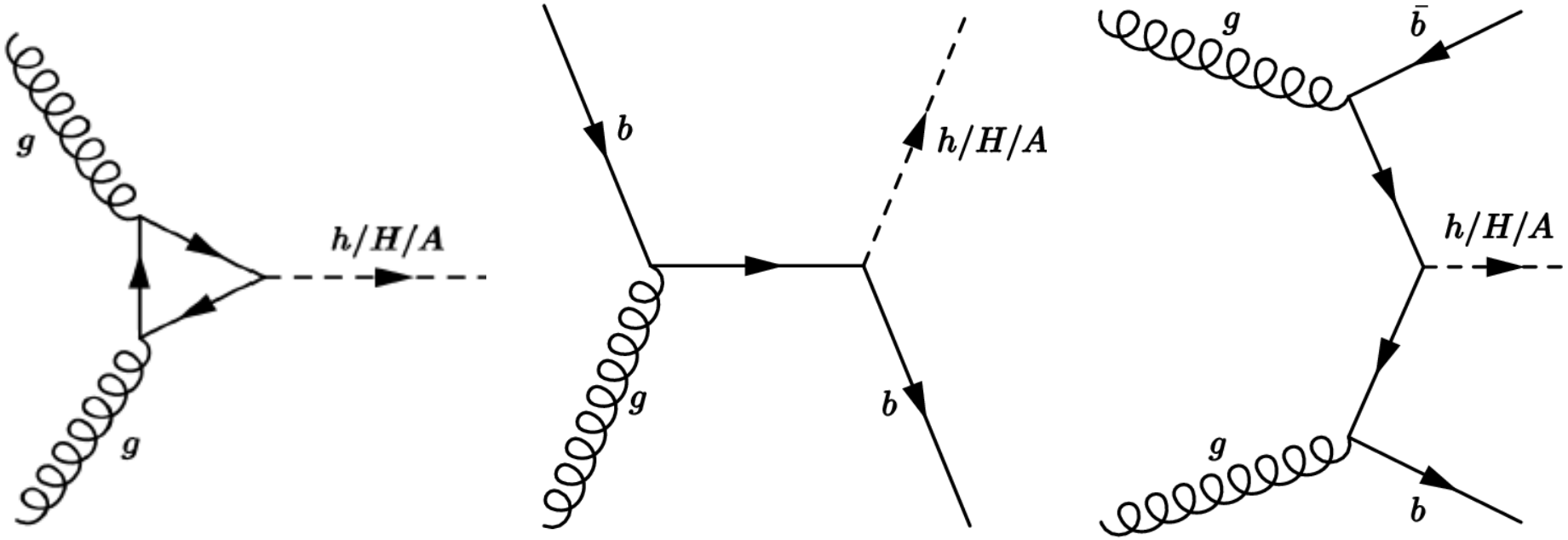
Neutral MSSM Higgs

MSSM Higgs : H→ττ

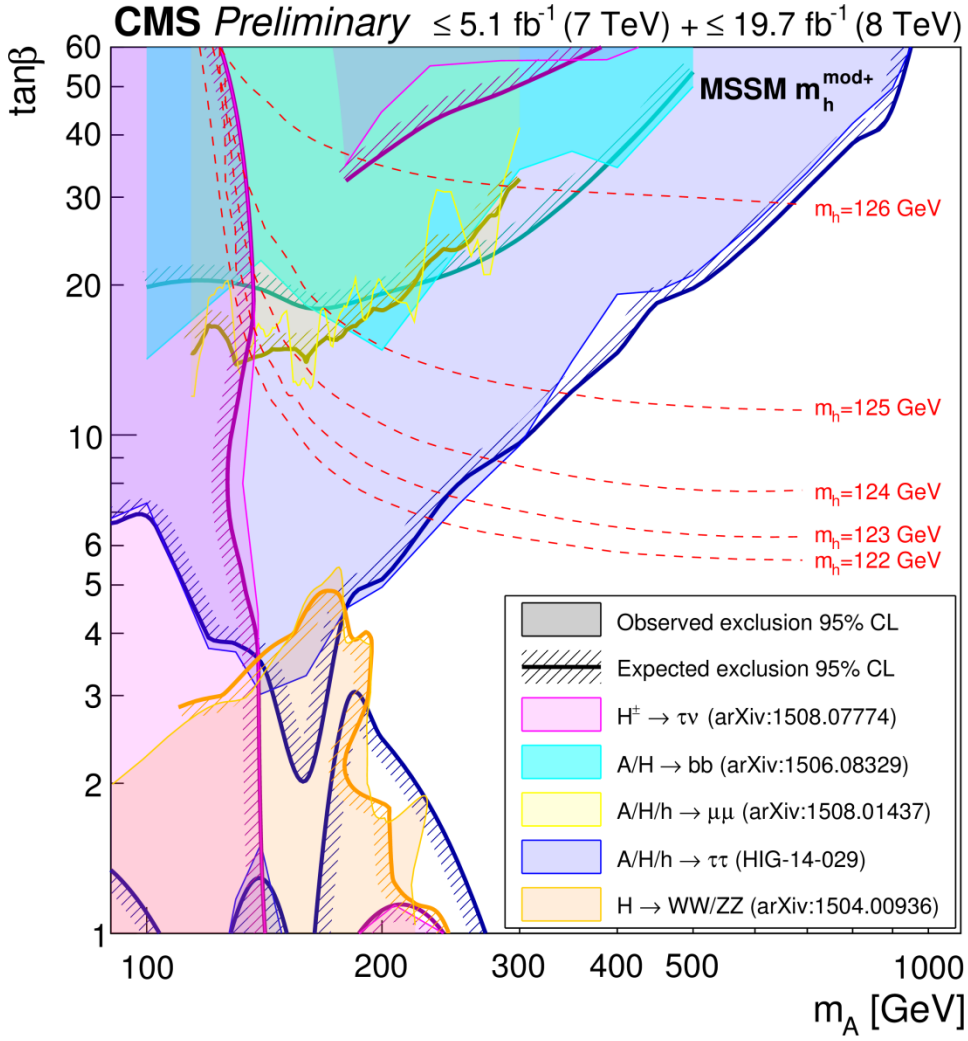
Is 125 GeV Higgs Boson the low mass Higgs in the MSSM sector?

Hadronic decays of tau lepton τ_h and leptonic decays $\tau_{e/\mu}$ exploited
Decay of tau pair final states : **$\mu + \tau_h$, $e + \tau_h$, $\mu + e$, $\tau_h + \tau_h$**

Selected Events analyzed in 2 Categories: b-Tag and non-b-Tag
(to enhance sensitivity of bbΦ coupling)
B-tagging : based on secondary vertex + track-based life-time info



MSSM Higgs Summary @ Run-1



CMS-HIG-16-007

> Interpretation of CMS Run-1 analyses in 2HDM and MSSM models

> Choice of fixed parameters motivated from theory + experimental constraints

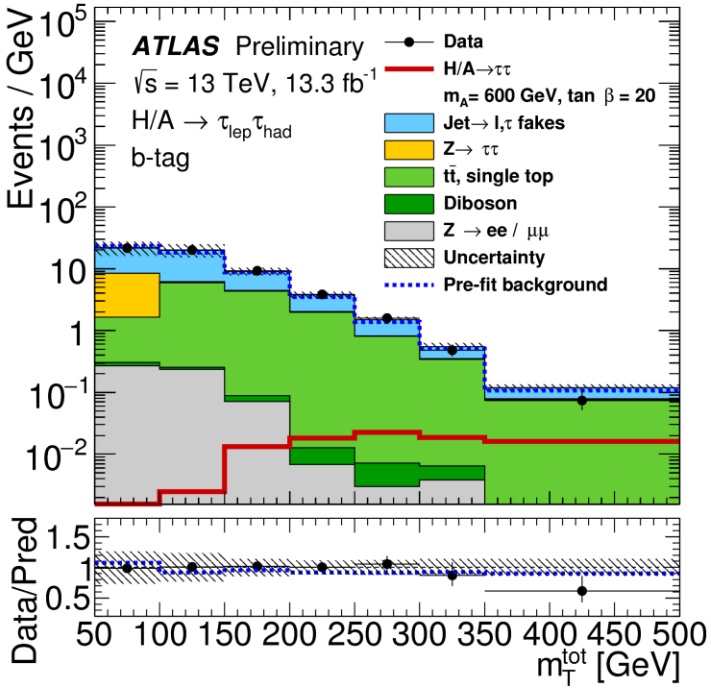
➢ Complementarity of experimental BSM searches explores a large part of the parameter space

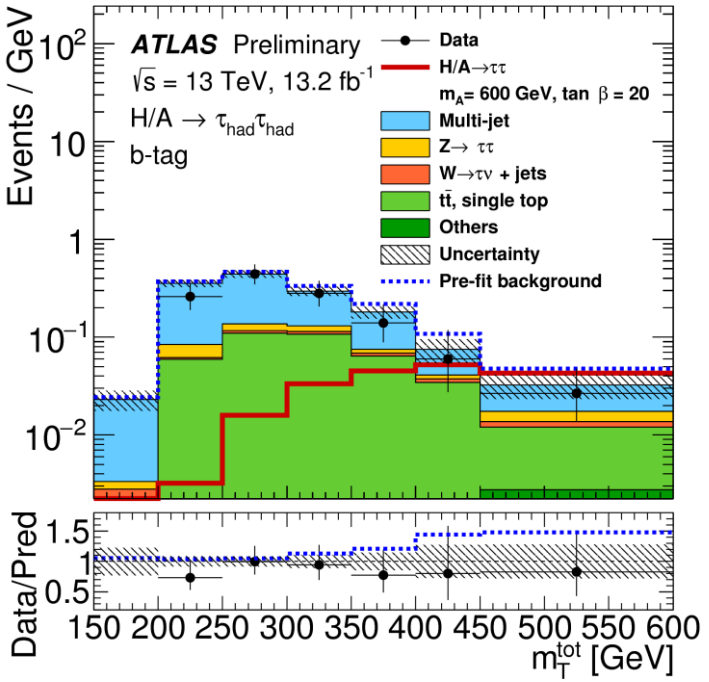
ATLAS-CONF-2016-085

> Gluon fusion and b-associated production

$\tau_{lep}\tau_{had}$ channel: 1 $\tau_{had\text{-}vis}$ and 1 lepton

$\tau_{had}\tau_{had}$ channel: 2 $\tau_{had\text{-}vis}$



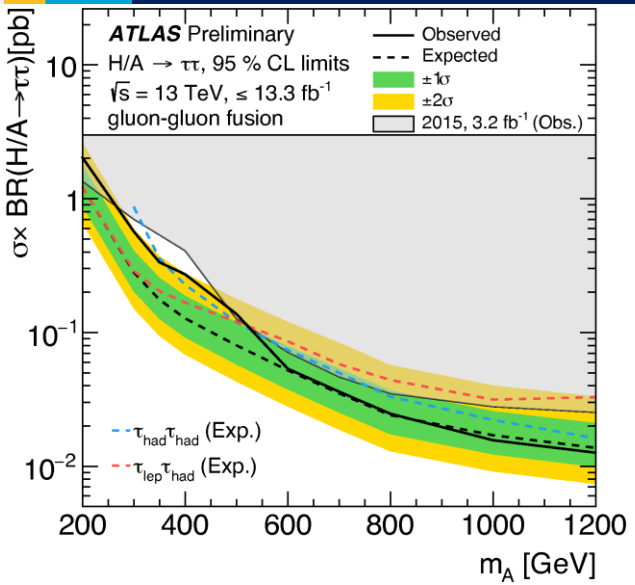


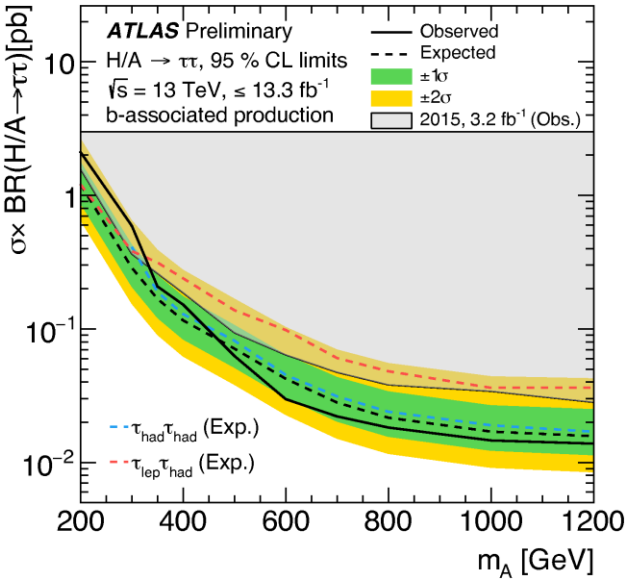
- angular and mass cuts for W/Z background removal
- event categories: presence of b-tagged jets, E_T^{miss}

> Discriminating variable: **transverse mass of di-tau system**

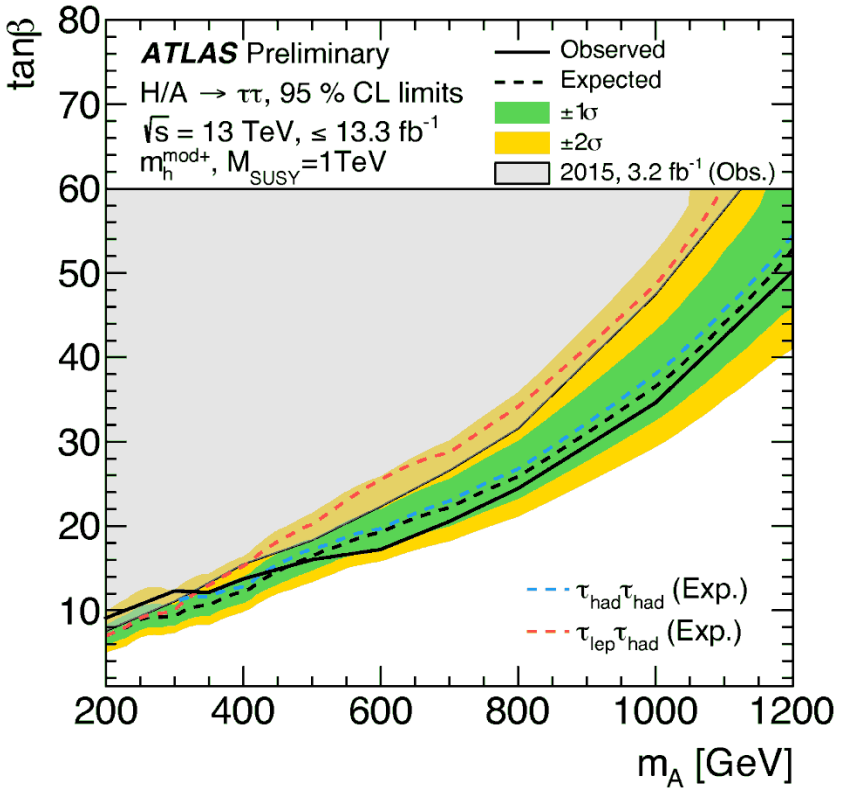
$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}$$

$$m_T(a,b) = \sqrt{2p_T(a)p_T(b)[1 - \cos\Delta\phi(a,b)]}$$





Systematic uncertainties: top background parton shower modelling, τ_{had} energy scale, multijet estimation, etc

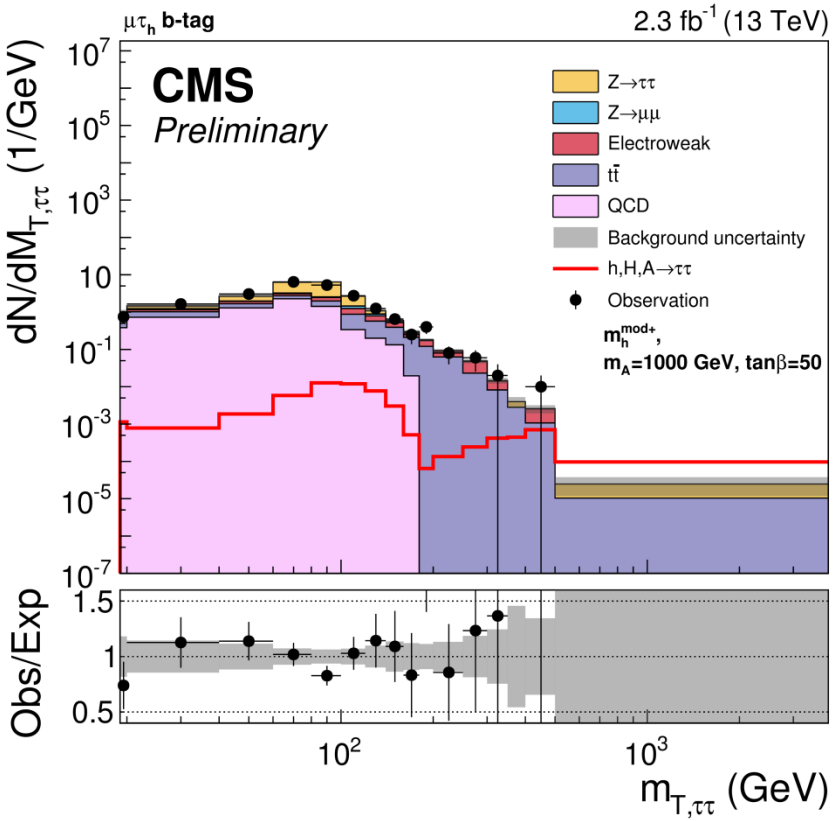


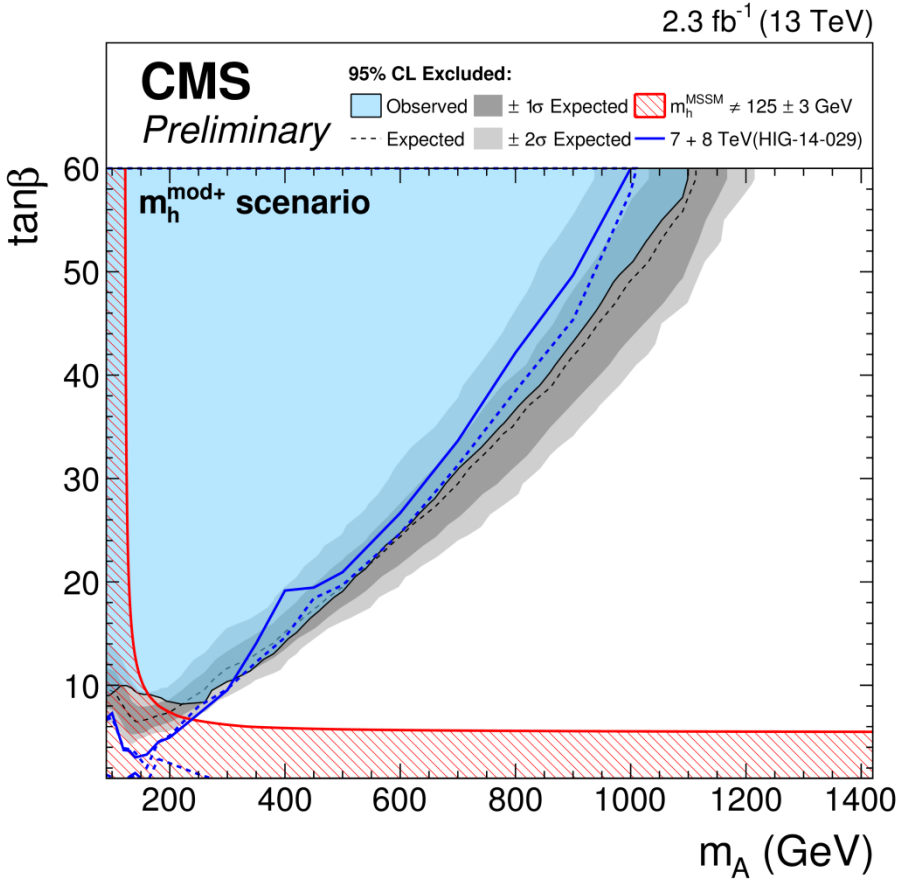
> Gluon fusion and b-associated production

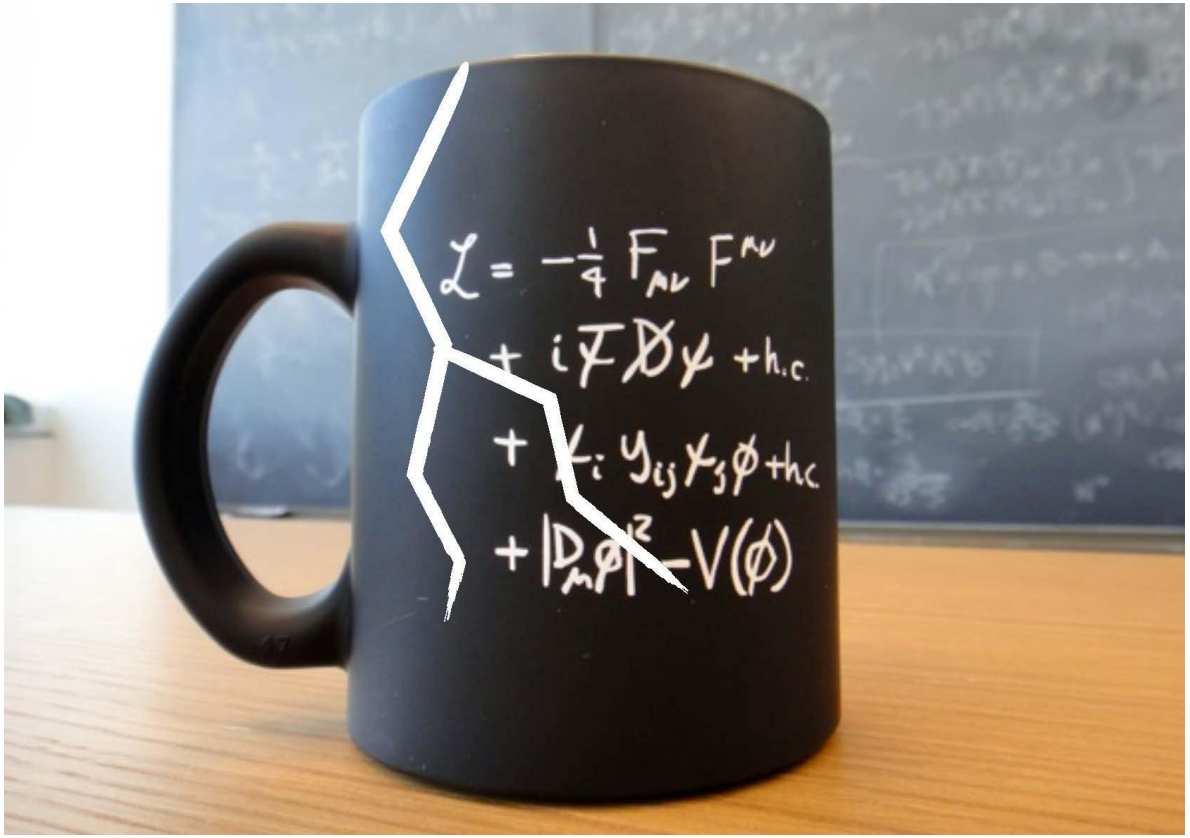
$\tau_\mu\tau_e$, $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_{had}\tau_{had}$ channels

> Discriminating variable: **transverse mass of di-tau system**

CMS-HIG-16-006



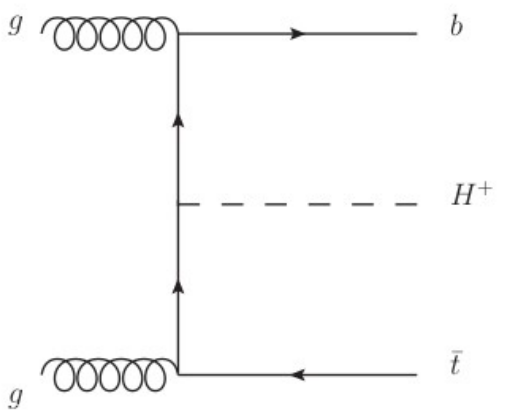


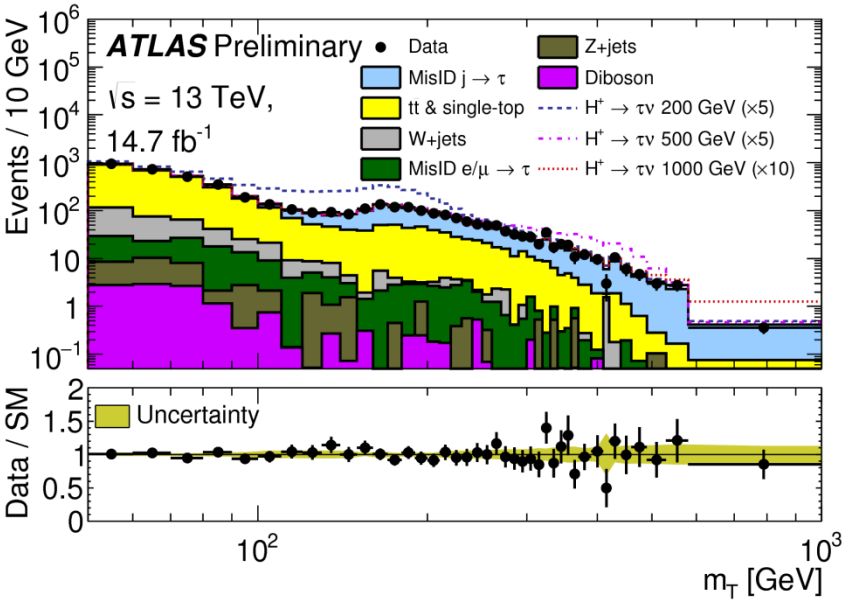


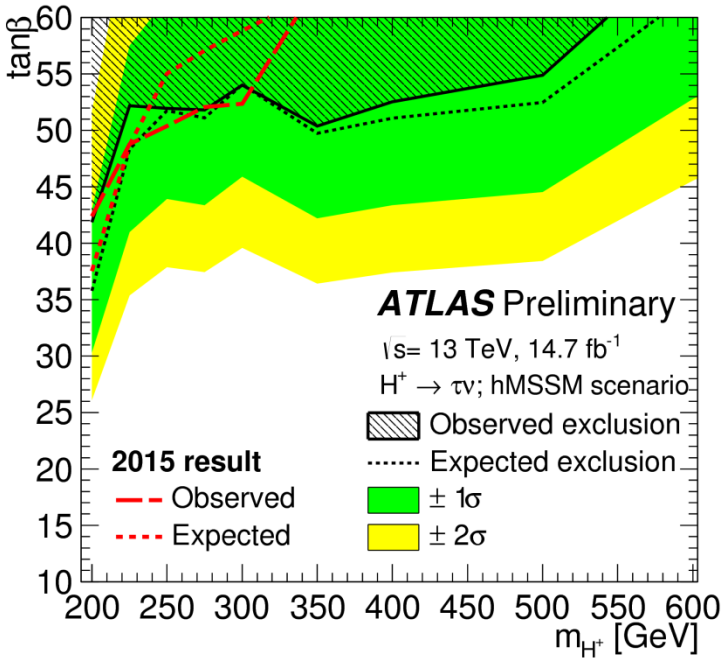
Charged Higgs

ATLAS-CONF-2016-088

- Production of $H^{\pm} \rightarrow \tau\nu$ in association with top quark
- Data-driven background estimation for jets and e/μ identified as τ leptons by applying fake factors from control regions
- Systematic uncertainties: τ identification, b-tagging, energy scale of jets and τ

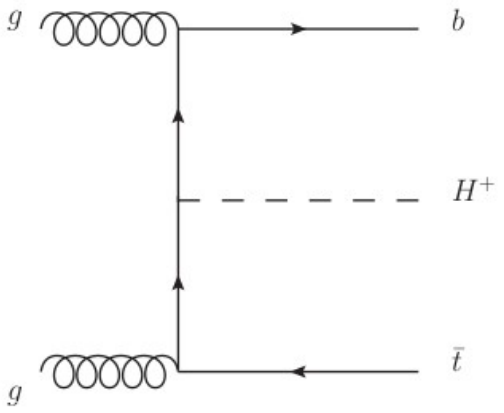






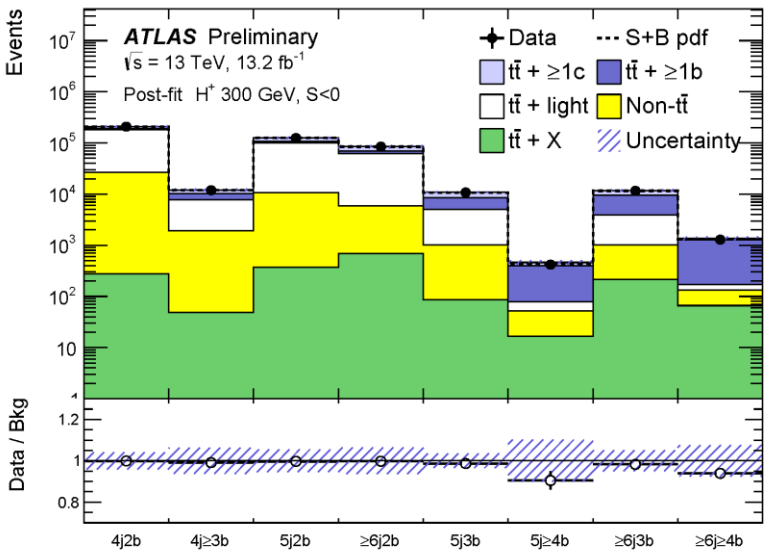
ATLAS-CONF-2016-089

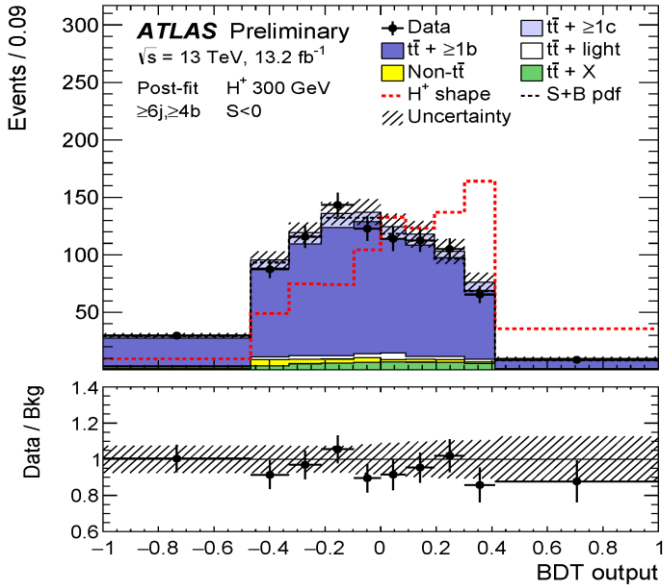
- Production of $H^{\pm} \rightarrow tb$ in association with top quark



1 lepton (electron or muon) ≥4 jets with ≥2 b-tag
Veto events with τ_{had}
4 control regions, 4 signal regions; based on the number of jets and b-tagged jets

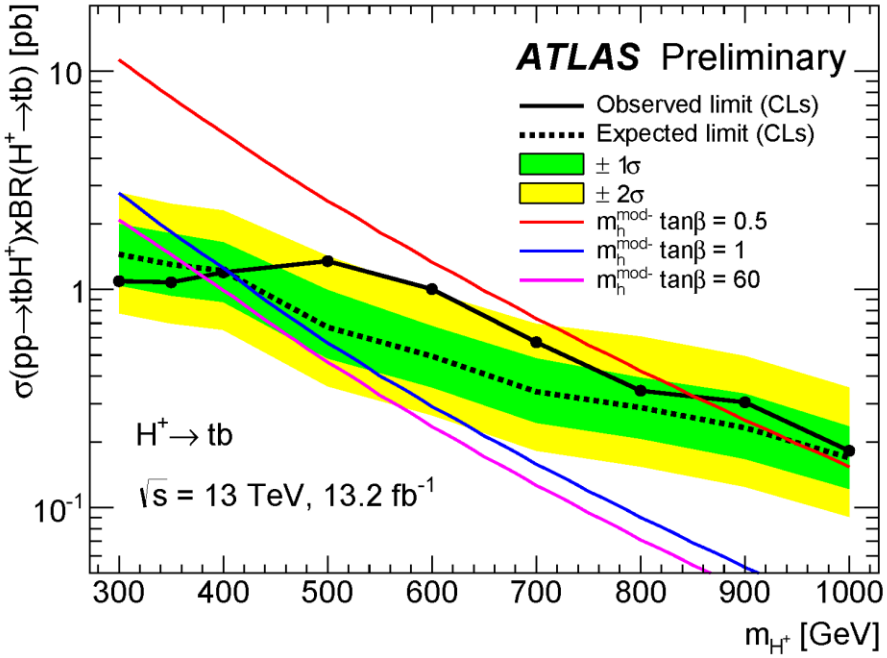
- Discriminating variable in signal region: BDT (leading jet p_T, mass of bb pair, ΔR(lep, bb pair), mass of jet triplet with largest p_T, ...)

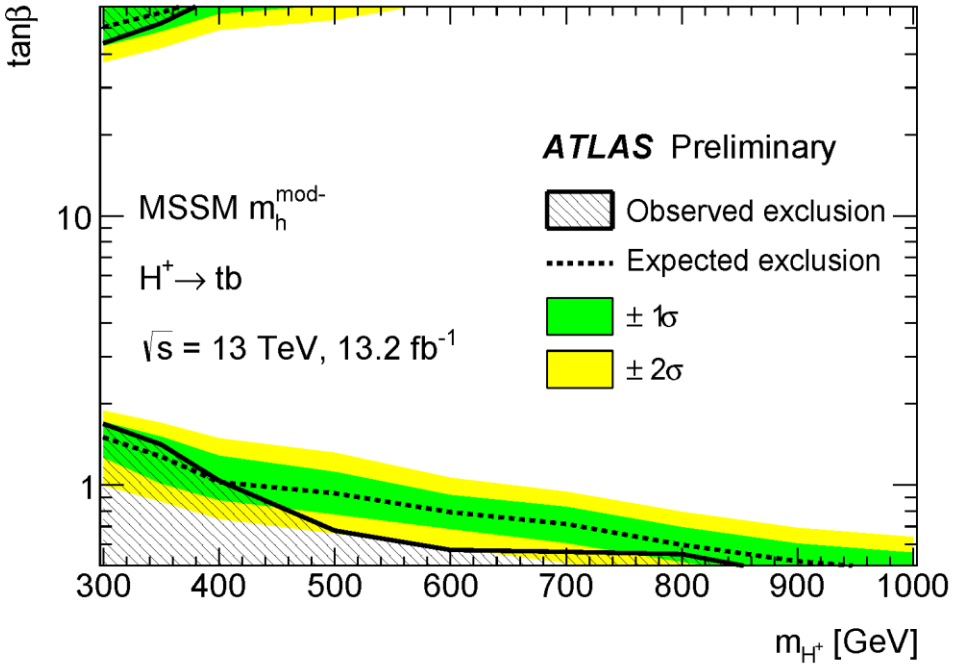




ATLAS-CONF-2016-089

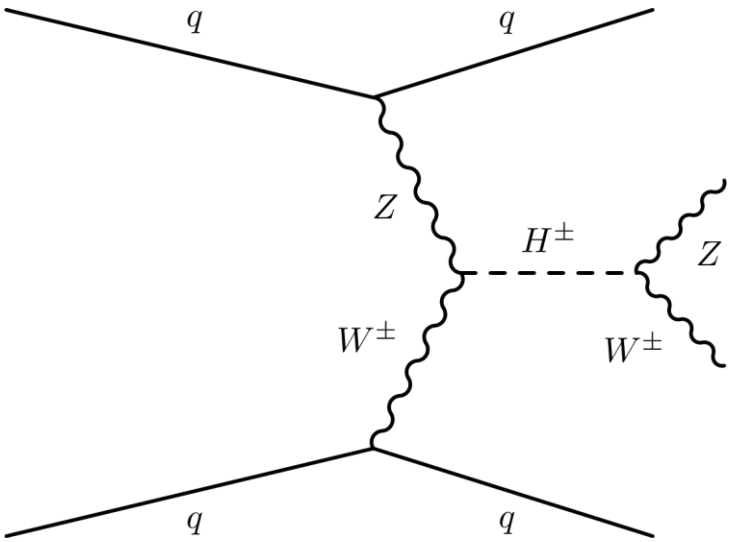
> Systematic uncertainties: tt + ≥ 1b/c modelling, jet flavour tagging, background model statistics, jet energy scale, ...
> Limits on cross section times branching ratio, interpretation in MSSM context



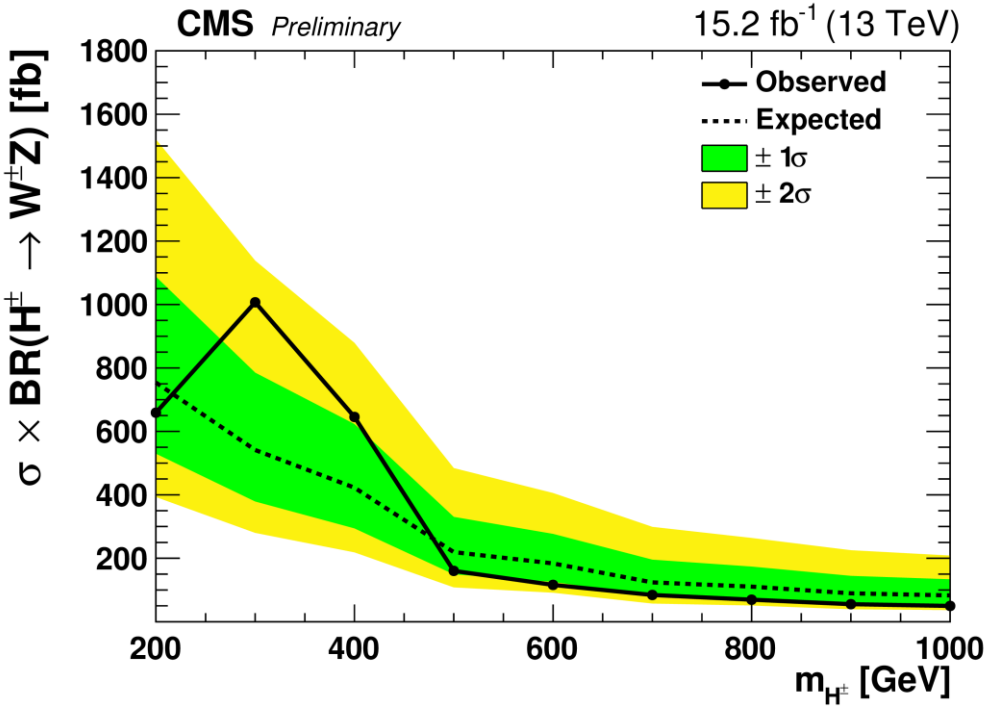


$H^{\pm} \rightarrow WZ$ @ Run-2

CMS-PAS-HIG-16-027



Events selected with three leptons (electron, muon), two jets with large rapidity separation and high dijet mass, and moderate missing E_T



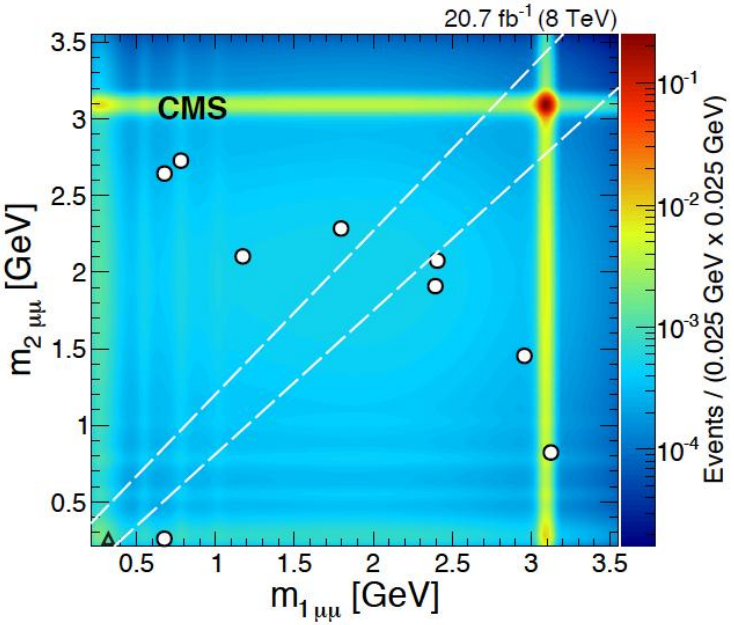
Observation agrees with SM prediction

Limits on the charged Higgs boson cross section times branching fraction given as function of charged Higgs mass

Interpretation in Higgs triplet models.

Light NMSSM Higgs

NMSSM Higgs : H→aa→μμμμ @ Run-1



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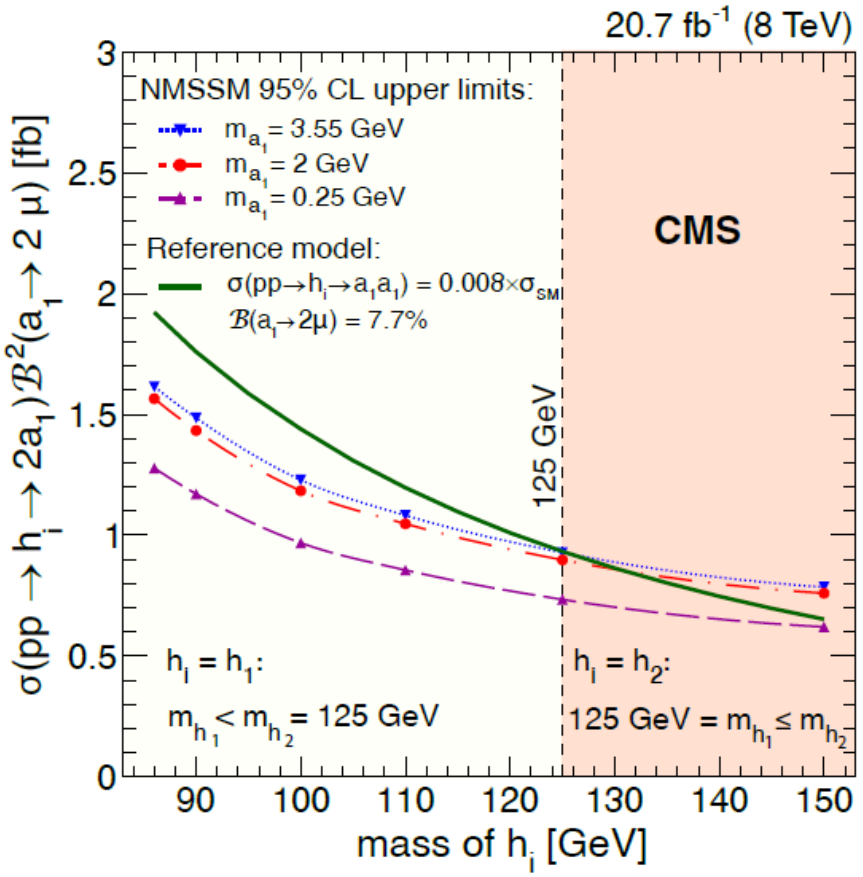
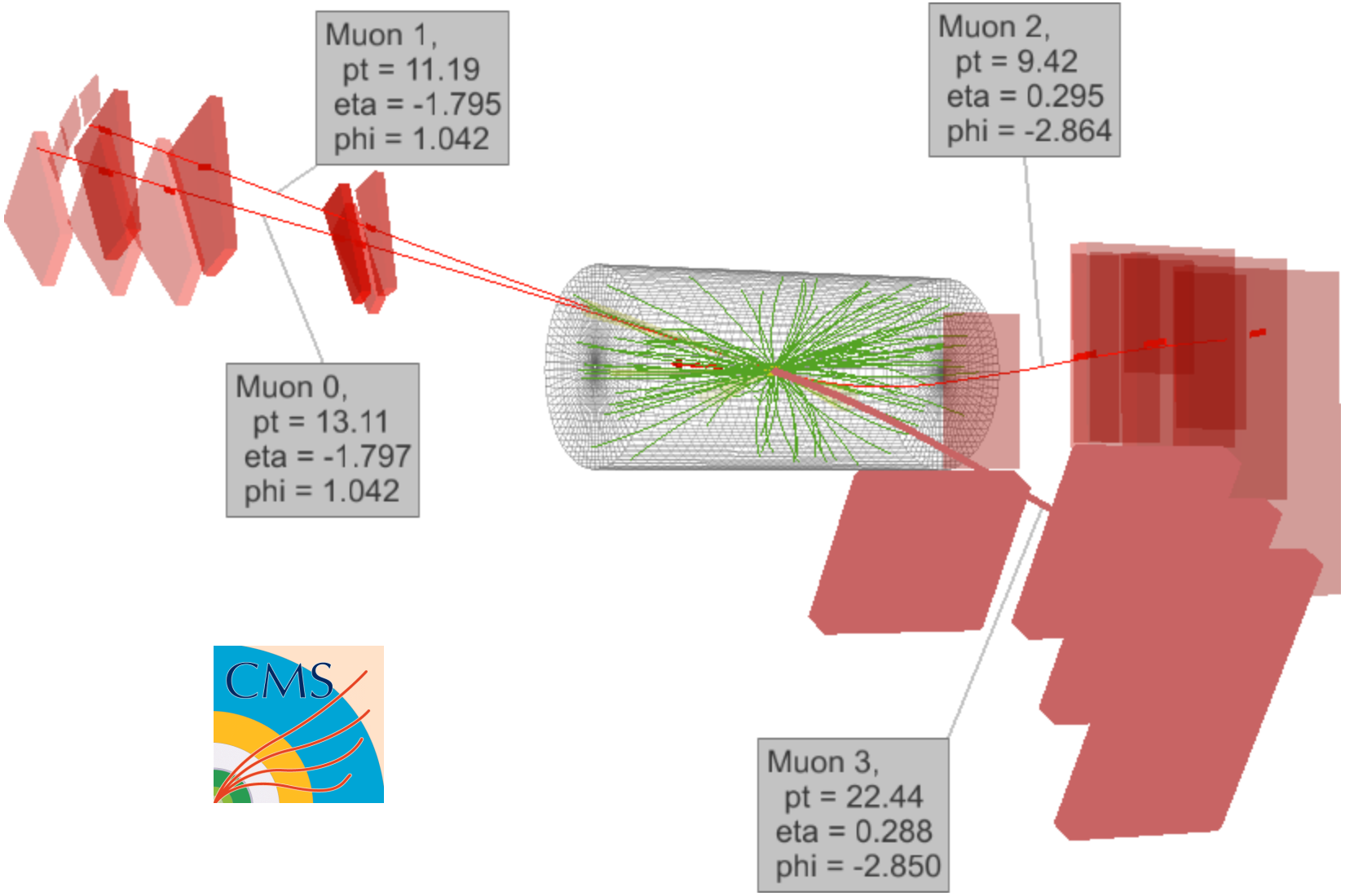


- SM background dominated by bb production, small contributions from the electroweak production of four muons and direct J/ψ pairs
- 1 event is observed in signal region, with 2.2 ± 0.7 events expected from SM backgrounds
- Upper limit at 95% CL on cross section times branching fraction times acceptance obtained for light boson masses in range $2m_\mu < m_a < 2m_\tau$ Result compared in the **NMSSM** scenario

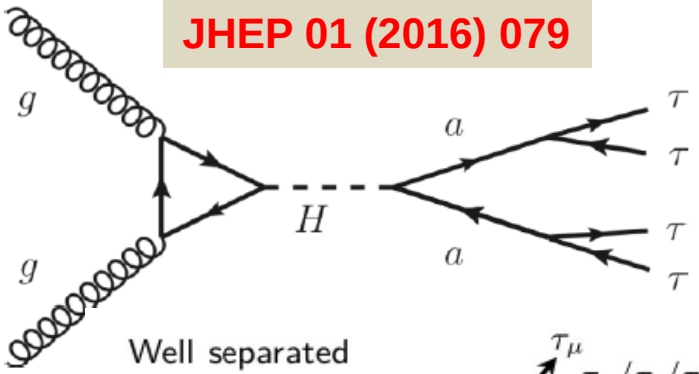
NMSSM Higgs : H→aa→μμμμ



NMSSM Higgs : H(125)→2φ→4τ @ Run-1

Very light **NMSSM** Higgs boson

JHEP 01 (2016) 079



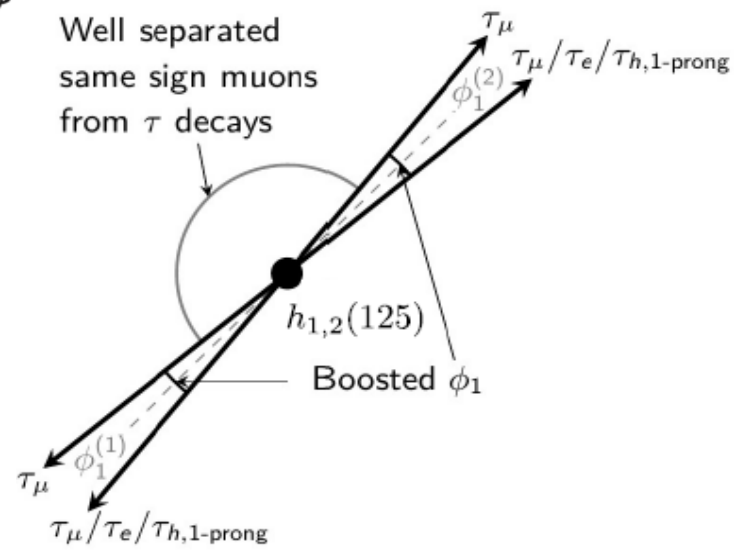
$gg \rightarrow h_{1,2}(125) \rightarrow 2\varphi_1 \rightarrow 4\tau$

Probed masses of the φ_1 state:

$4\ \text{GeV} < m_{\varphi 1} < 8\ \text{GeV}$

considered decays of each φ_1 state : $\varphi_1 \rightarrow \tau_\mu + \tau_{1\text{-prong}}$

require two SS muons ($\mu^{\pm}\mu^{\pm}$) well separated in (η,φ) → suppression of QCD, EWK and top pair backgrounds

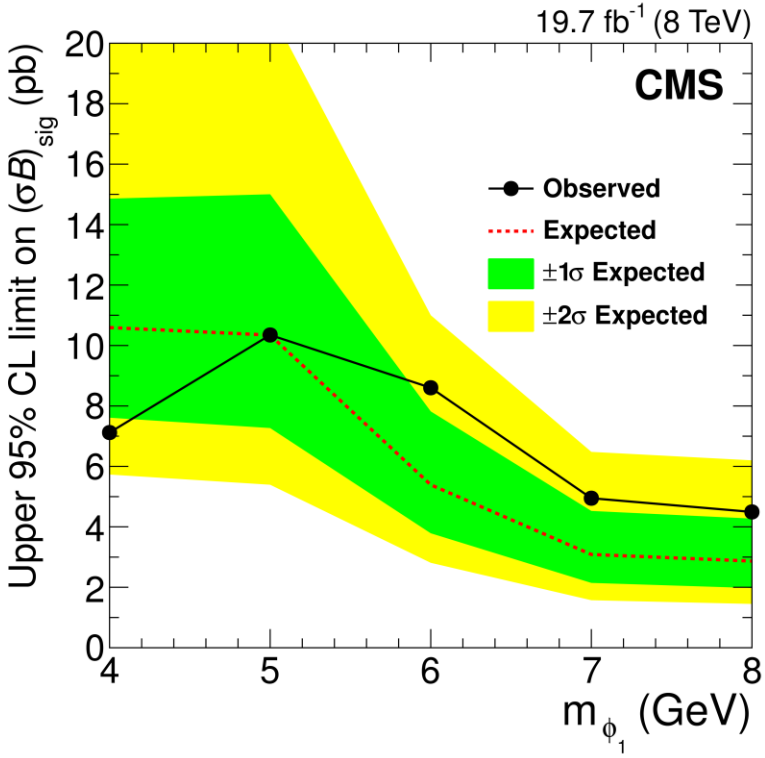


$m_{h(125)} \gg m_{\varphi 1} \rightarrow$ boosted φ_1

- small opening angle between muon and track from 1-prong tau decays
- require each muon to be accompanied by only 1 track (pt>2.5 GeV)

Distribution of muon-track invariant masses used to extract signal

NMSSM Higgs : H(125)→2φ→4τ

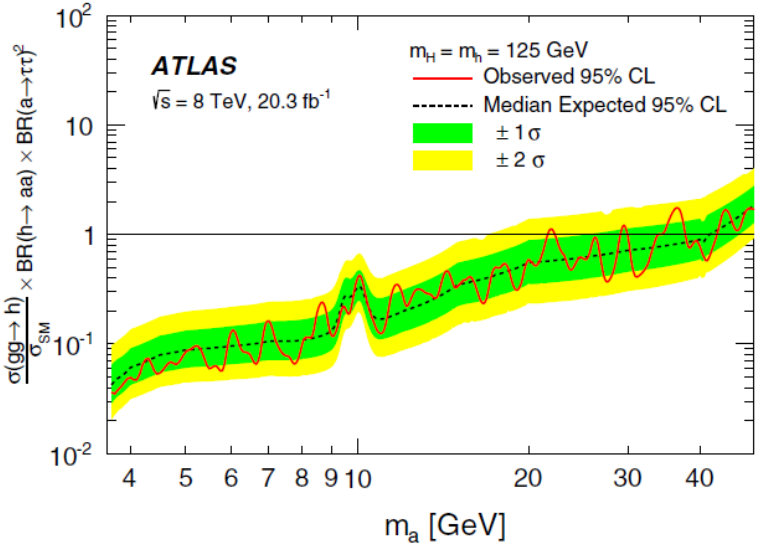


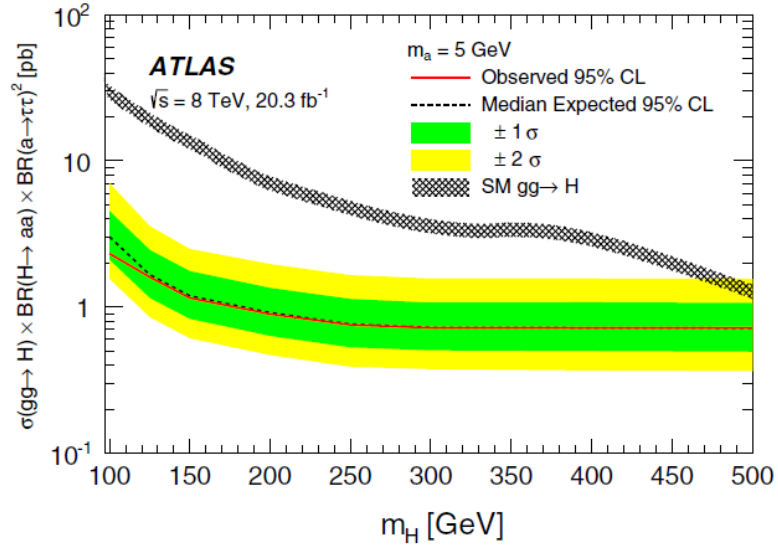
JHEP 01 (2016) 079

No BSM Physics so far in this sector
Looking forward to more 13 TeV data

- factor ~ 2.3 increase of gg → H(125) cross section
- major background is QCD multijets : factor ~2.2 increase in cross section
  → need ~ 9/fb @ 13 TeV to reach sensitivity of Run 1 analysis
  → need ~ 34/fb @ 13 TeV to improve sensitivity by a factor of 2

NMSSM Higgs : H→aa→μμττ @ Run-1





Phys Rev D 92 (2015) 052002

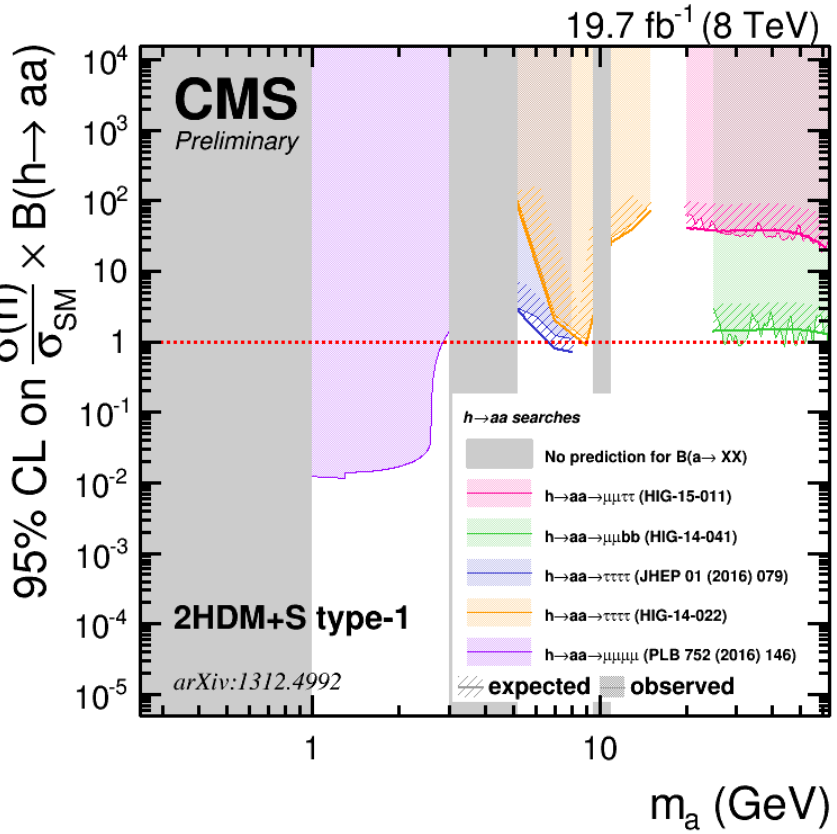
No significant excess observed above expected backgrounds in $m_{\mu\mu}$ range from 3.7 to 50 GeV

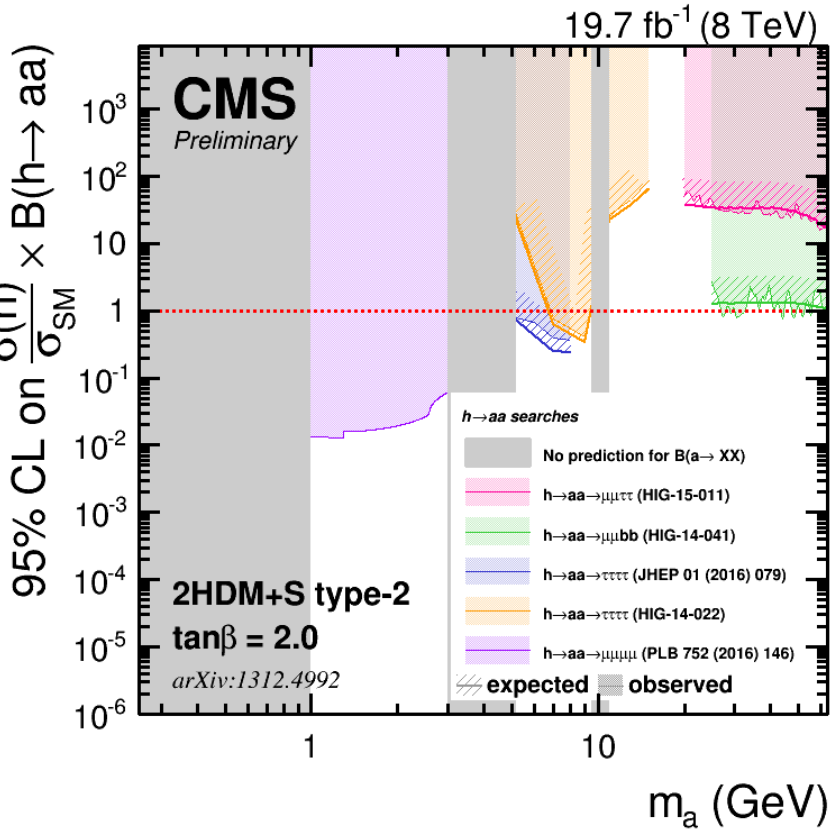
No evidence to support the NMSSM hypothesis, 95% CL limit set on rate relative to SM Higgs gluon fusion as function of m_a with m_H=125 GeV

Upper limits placed on production cross section of H→aa from 2.33 to 0.72 pb, for fixed m_a=5 GeV with m_H ranging from 100 to 500 GeV.

Light Higgs Summary from Run-1

https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/SummaryResultsHIG





✓ Searches performed in several final states

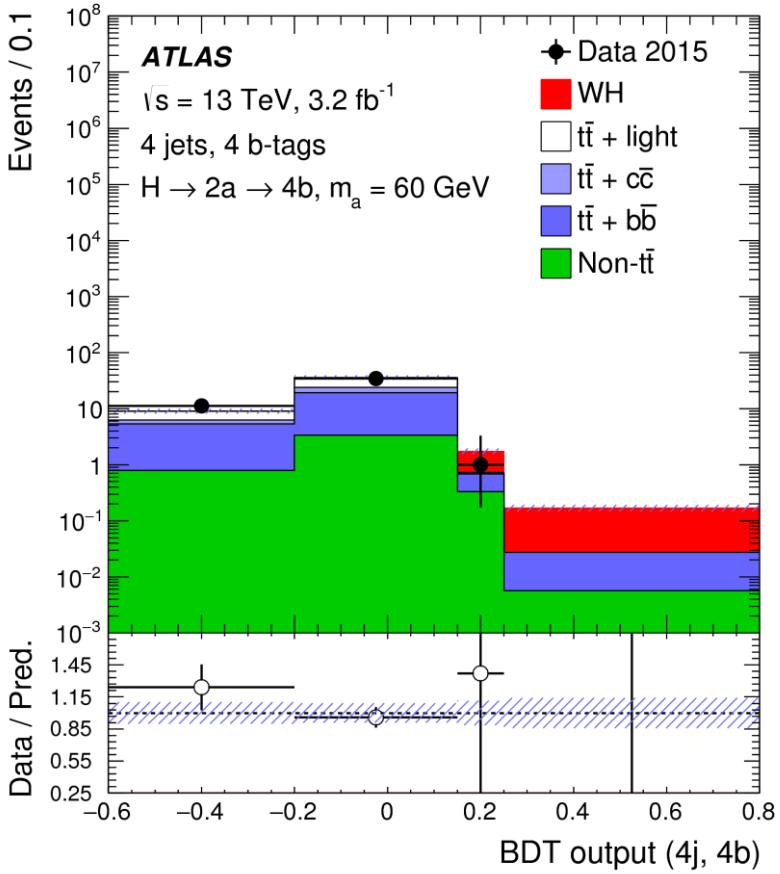
✓ No excess was found and results are interpreted in several 2HDM + S scenarios

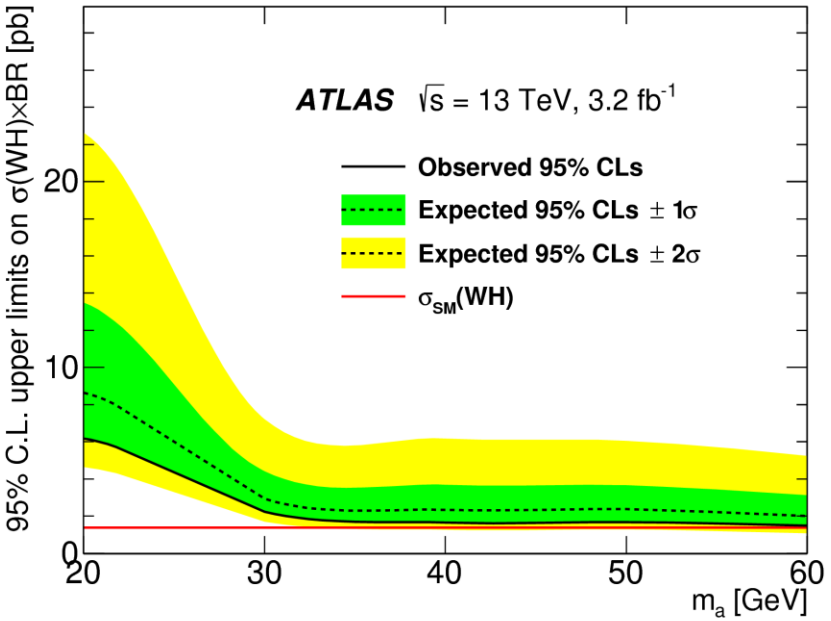
NMSSM Higgs : H→aa→bbbb @ Run-2

arxiv: 1606.08391

Higgs boson produced in association with W boson, giving rise to a signature of a lepton, missing E_T, and multiple jets from b-quark decays.

Upper limit for production cross-section pp→WH times branching ratio for the decay H→aa→4b ranges from 6.2 pb for the light pseudoscalar mass m_a=20 GeV to 1.5 pb for m_a=60 GeV.





Heavy Higgs

Heavy Higgs Searches @ Run-2

Several Heavy Higgs searches performed by both ATLAS and CMS

CMS

Heavy Neutral Higgs Boson:

✓ Higgs → ZZ → 4l	**CMS PAS HIG-16-033**
✓ Higgs → ZZ → 2$l2\nu$	**CMS PAS HIG-16-001**
✓ Higgs → WW → $l\nu l'\nu'$	**CMS PAS HIG-16-023**
✓ Higgs →bb	**CMS PAS HIG-16-025**

ATLAS

Heavy Neutral Higgs Boson:

✓ Higgs → ZZ → 4l	**ATLAS-CONF-2016-079**
✓ Higgs → ZZ → 2$l2\nu$	**ATLAS-CONF-2016-056**
✓ Higgs → WW → $l\nu$qq	**ATLAS-CONF-2016-062**
✓ Higgs → WW → $l\nu l'\nu'$	**ATLAS-CONF-2016-074**
✓ Higgs → VV → llqq/$\nu\nu$qq	**ATLAS-CONF-2016-082**

Heavy Neutral Higgs Boson H→hh (h→γγ, ττ, bb, WW)
(this part will focus on decay to 125 GeV Higgs boson pair)

Heavy Higgs (hh→bbγγ) @ Run-2

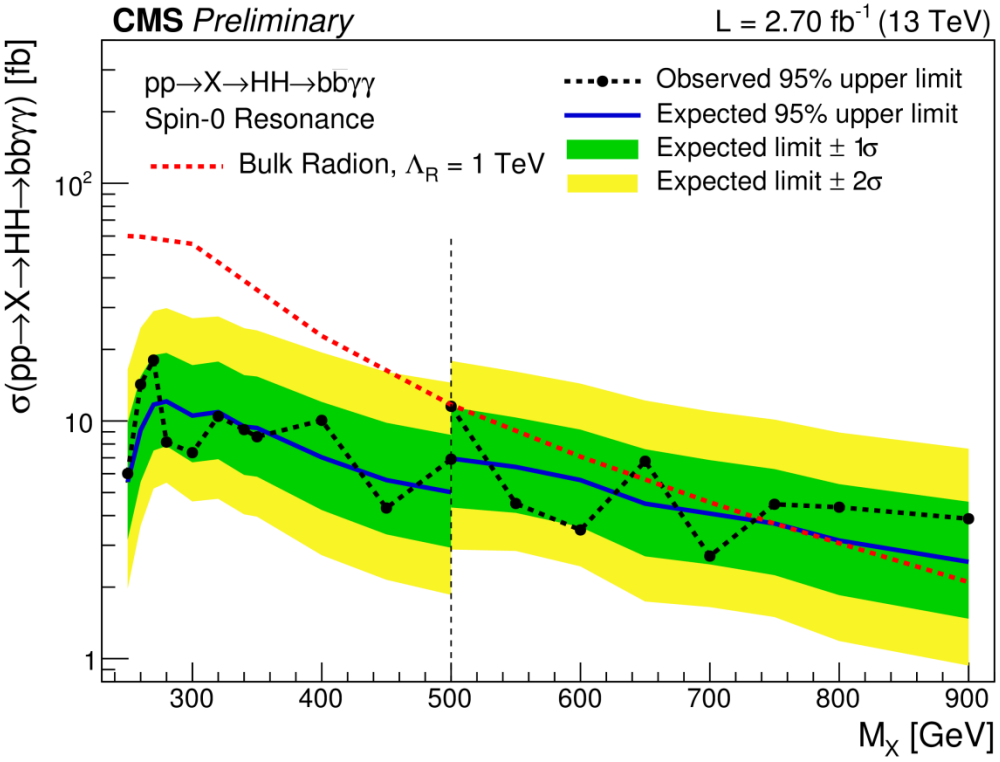
CMS-HIG-16-032

> Search for resonant production of two SM-like h bosons (hh→bbγγ)

≥2 photon candidates
dijet candidate (2 jets with highest b-tag scores)

resonance search: window of mass(jjγγ) depending on signal hypothesis
$M_X = M(jj\gamma\gamma) - M(jj) + 125$ GeV

> Parametric fit of 2D plane defined by diphoton and dijet mass.



>Systematic uncertainties: jet and photon energy scales and resolutions, b-tagging efficiency, ...
>Interpretation as new spin-0 resonance

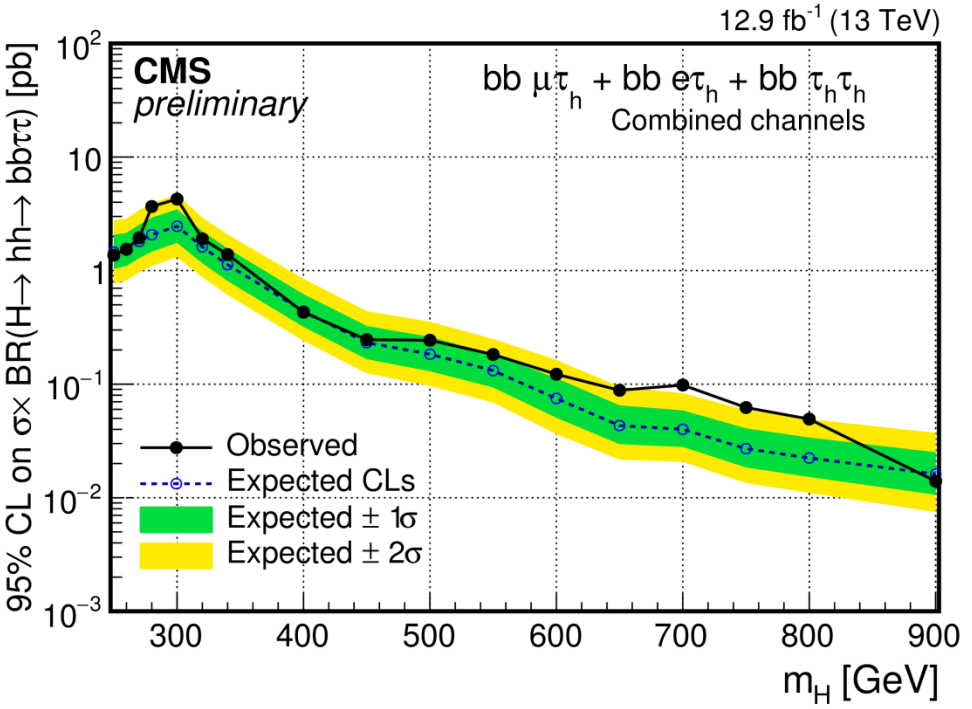
Heavy Higgs (hh→bbττ) @ Run-2

- Resonant production of two SM-like h bosons (h→bb and h→ττ)

$\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_{had}\tau_{had}$ di-tau decay modes

- Distributions of the four-body mass reconstructed with kinematic fit after applying the event selections.
- No excess over the SM background prediction observed
- Model independent upper limit on values of cross section times branching ratio derived for different signal mass hypotheses between 250 and 900 GeV

CMS-PAS-HIG-16-029



Heavy Higgs (hh→bbbb) @ Run-2

arxiv: 1606.04782

- Resonant production of two SM-like h bosons (h→bb)

- **"Resolved" regime**

≥4 b-tagged jets forming 2 dijet systems with small ΔR

m_{4jet} dependent p_T requirements on dijets

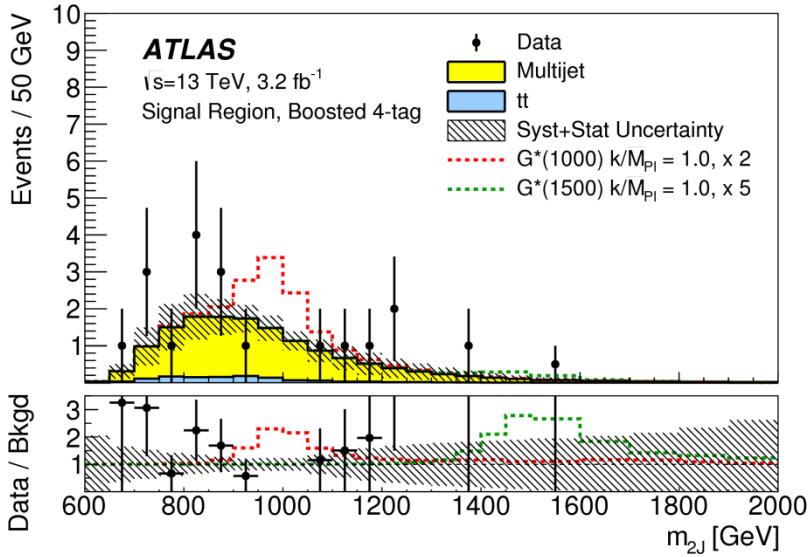
- **"Boosted" regime**

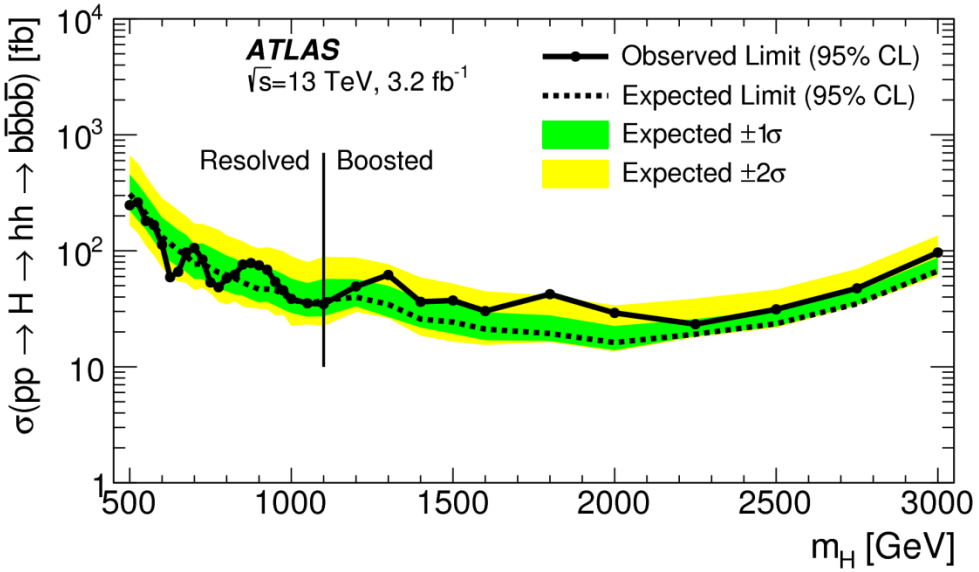
3 or 4 b-tagged jets

≥ 2 large-R jets with ≥ 2 smaller-R track jets associated to each

> Systematics: b-tagging, multijet background, large-R jet mass scale and resolution

> Interpretation as new narrow width Higgs resonance





Heavy Higgs (hh→γγWW) @ Run-2

ATLAS-CONF-2016-071

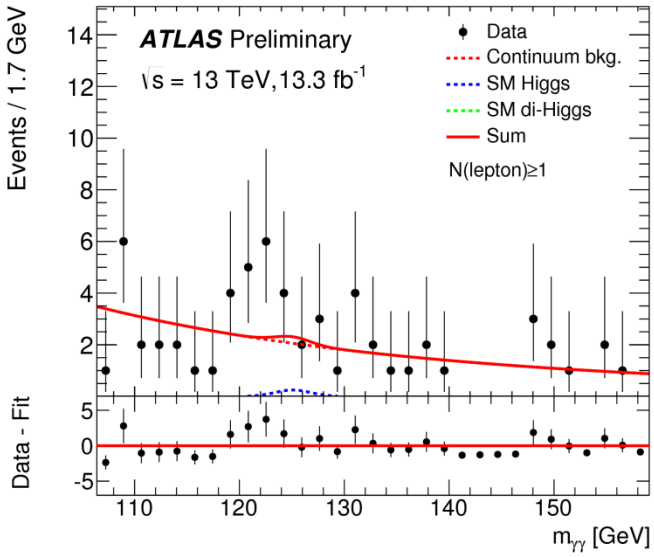
- Search for resonant production of two SM-like h bosons **hh→γγWW(→lνjj)**

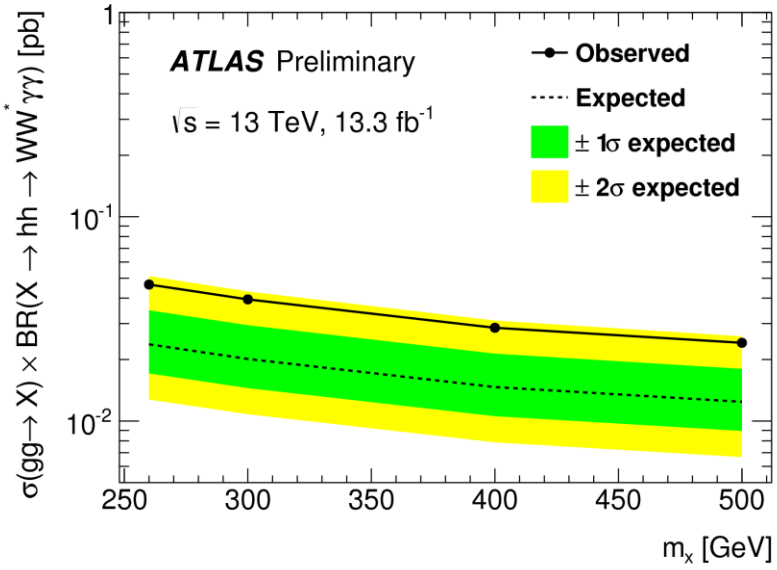
  at least 2 photons, ≥ 2 jets with no b-jet

- Events split into 2 categories according to **lepton multiplicity**: requiring at least one lepton or no lepton

- Final signal region defined in 1-lepton region: with a tight mass window $|m_{\gamma\gamma} - m_h| < 2\sigma_{\gamma\gamma}$

- Observed 95% CL upper limit on resonant production times the branching fraction of X→hh ranges between **47.7pb** and **24.7pb** in the mass range of **260–500 GeV**





Lepton Flavour Violating Higgs Decays

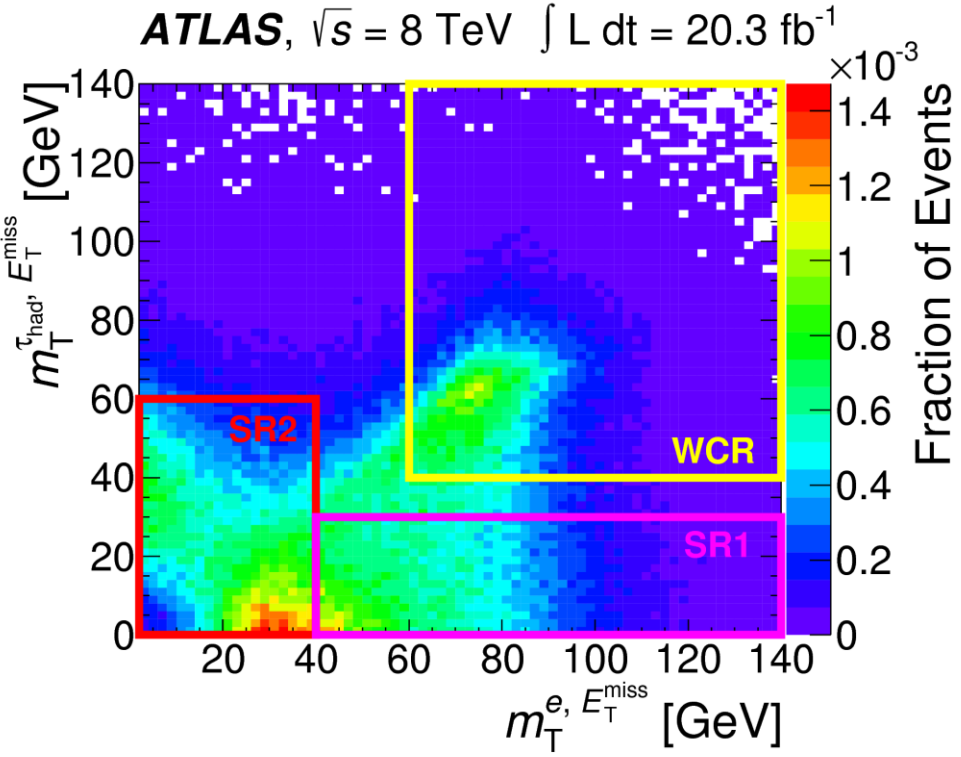
arXiv:1604.07730

Misidentified τ_{had} have much **softer $p_T(\tau_{had})$ spectrum** and a **larger angular separation between the τ_{had} and E_T^{miss}**

Two signal regions are defined using **transverse mass m_T**, of the eE_T^{miss} and $\tau_{had}E_T^{miss}$ systems

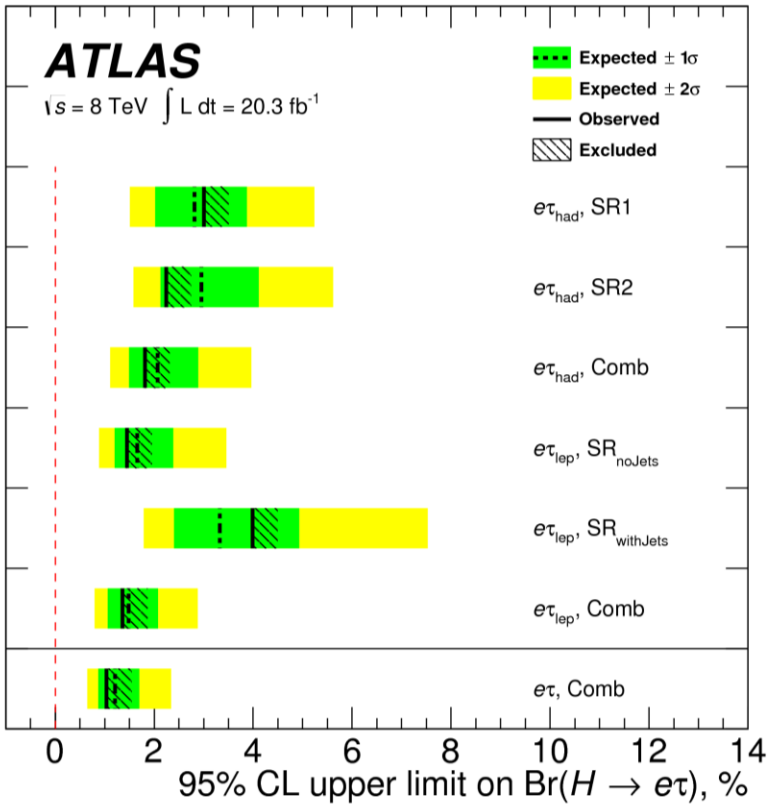
Choice of m_T cut defining signal and control regions motivated by correlations between $m_T(eE_T^{miss})$ and $m_T(\tau_{had}E_T^{miss})$ in signal and major background W+jets and Z events

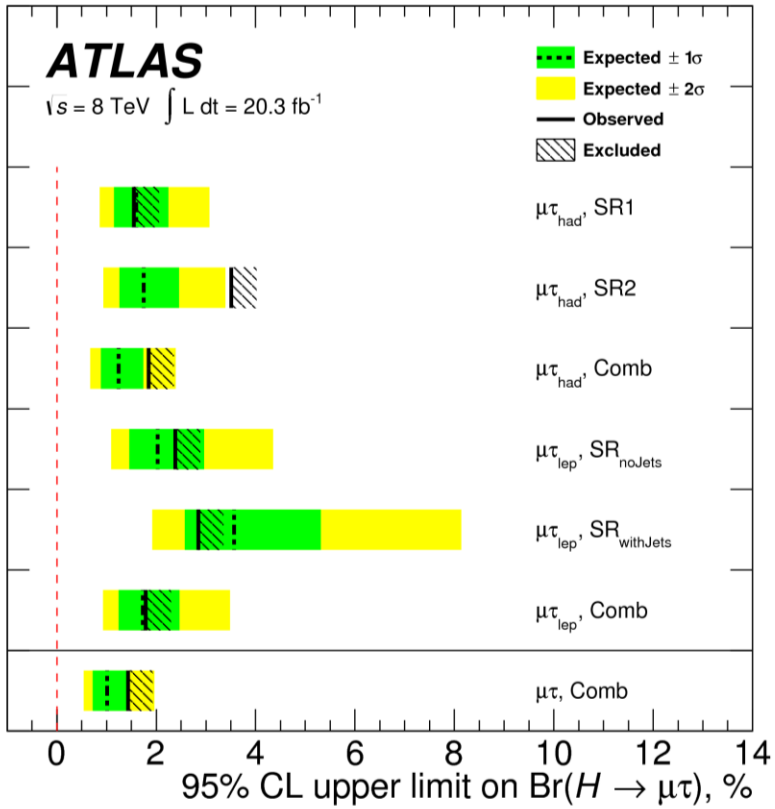
LFV signal is searched by performing a fit to the mass distribution in data



LFV Higgs Decays @ Run-1

Upper limits on LFV Higgs decays in **H →μτ** hypothesis and **H →eτ** hypothesis
Br(H→μτ)<1.43% and Br(H→eτ)<1.04%
Limits computed under the assumption that either Br(H→μτ)=0 or Br(H→eτ)=0



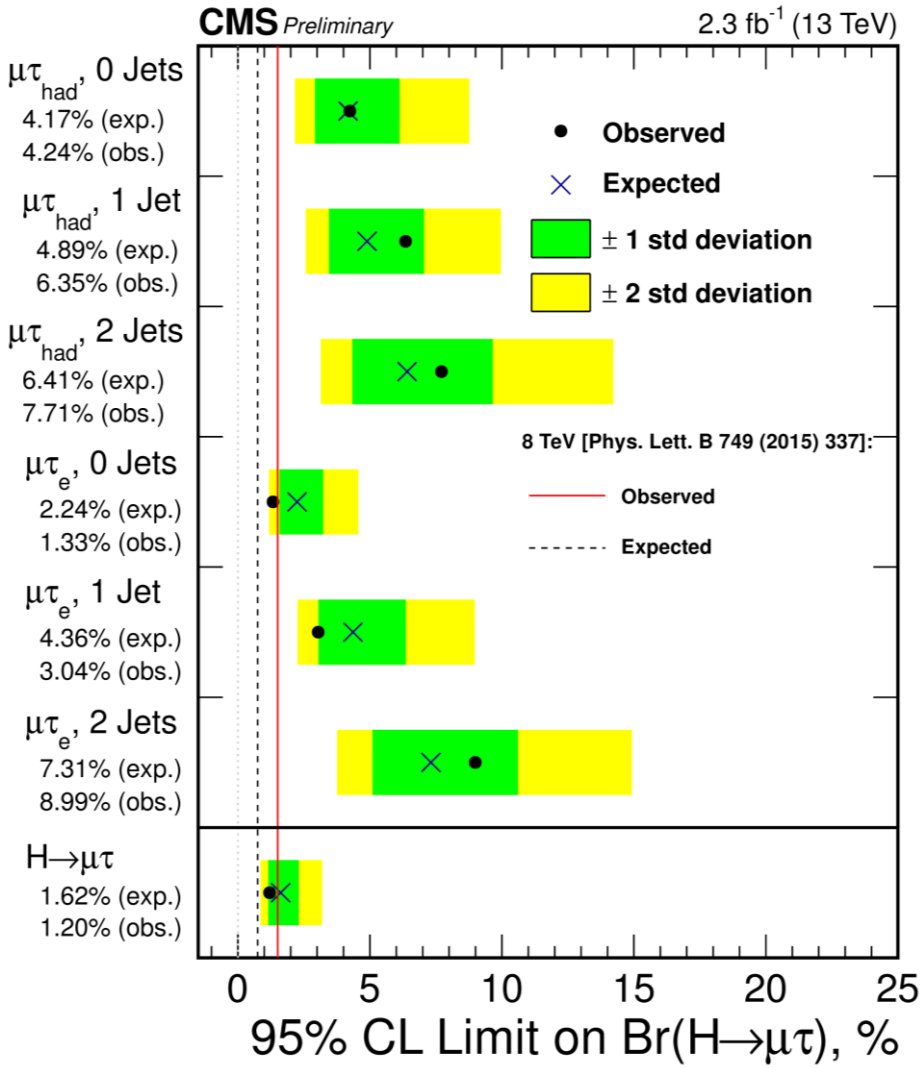


CMS-PAS-HIG-16-005

- Decay modes in $H \rightarrow \mu\tau_e$ and $H \rightarrow \mu\tau_{had}$ channel
- Dominant background in the $H \rightarrow \mu\tau_e$ channel is $Z \rightarrow \tau_\mu\tau_e$
- Dominant background in the $H \rightarrow \mu\tau_{had}$ channel from jets faking taus in W+jets, QCD multi-jet and tt+jets events

At 8 TeV collisions a small excess was observed, corresponding to 2.4σ, with integrated luminosity 19.7 fb^{-1}

More data at 13 TeV required to refine our understanding!



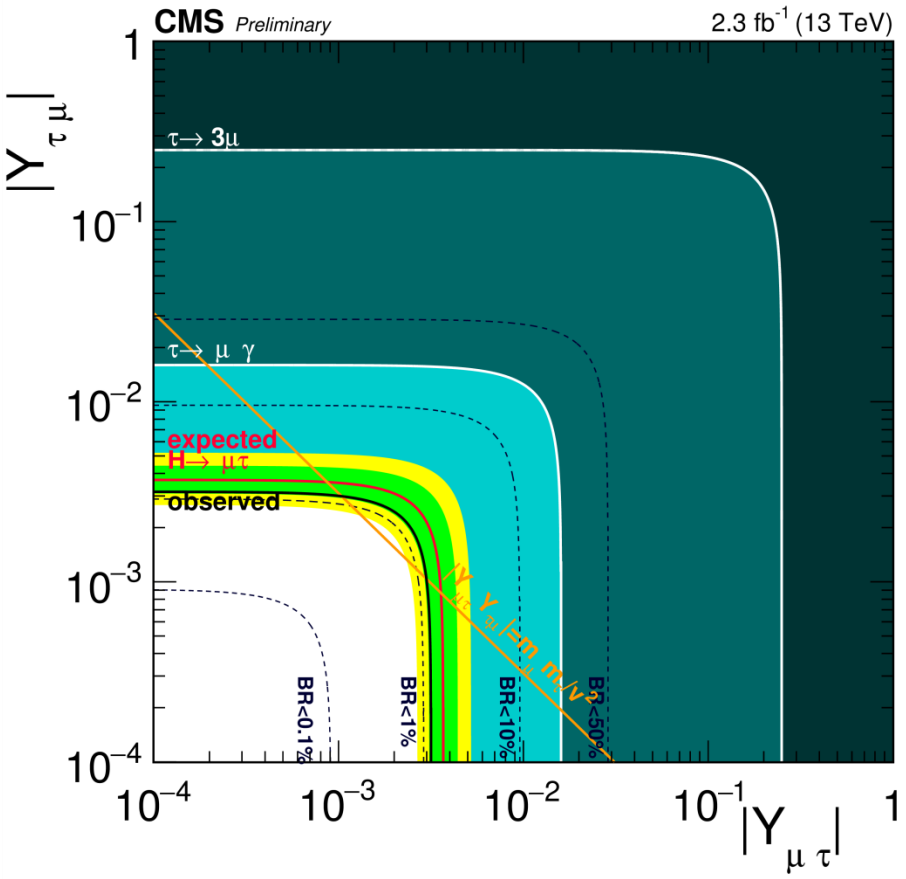
CMS-PAS-HIG-16-005

$$B(H \to l^{\alpha} l^{\beta}) = \frac{\Gamma(H \to l^{\alpha} l^{\beta})}{\Gamma(H \to l^{\alpha} l^{\beta}) + \Gamma_{SM}}$$

$$\Gamma(H \to l^{\alpha} l^{\beta}) = \frac{m_h}{8\pi}(|Y_{l^{\beta} l^{\alpha}}|^2 + |Y_{l^{\alpha} l^{\beta}}|^2)$$

- Constraint placed on B(H →μτ) < 1.2% at 95% CL
- The best fit branching fraction is B(H →μτ) = $(-0.76^{+0.81}_{-0.84})$%
- The limit is subsequently used to constrain the $Y_{\mu\tau}$ Yukawa coupling

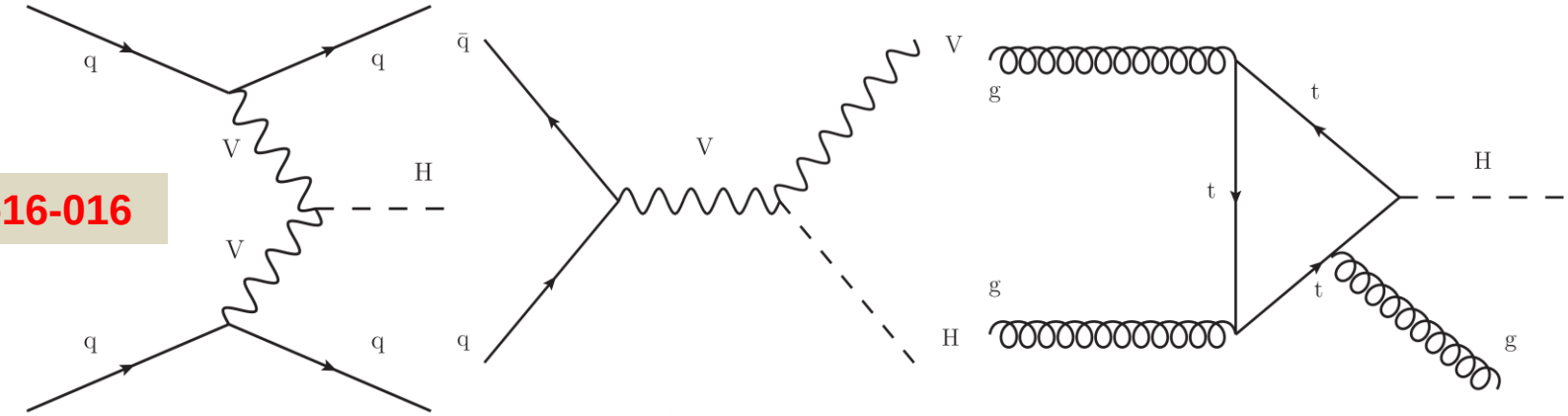
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \times 10^{-3}$$

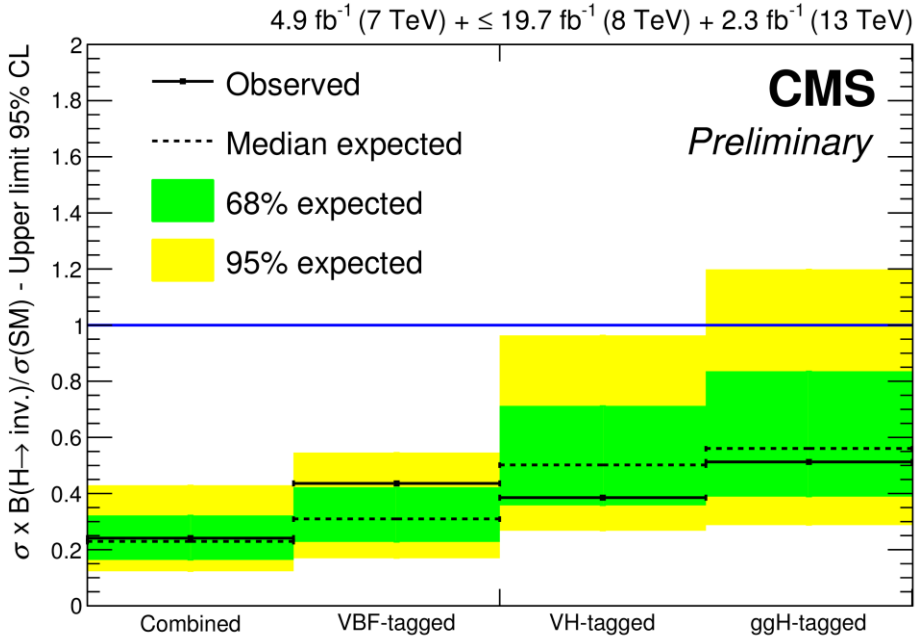


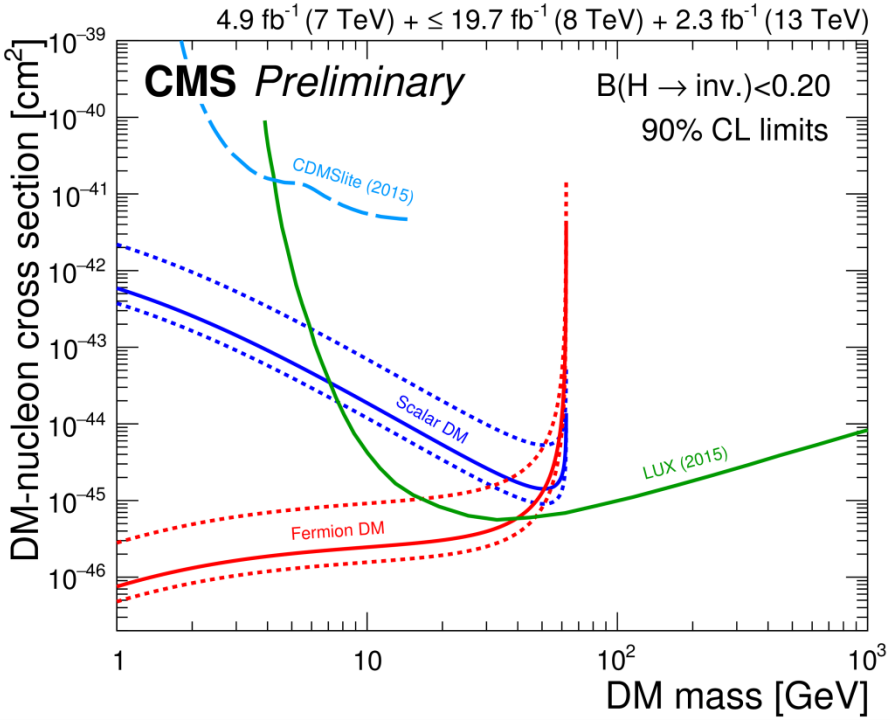
Invisible Higgs Decays

Invisible Higgs Decays

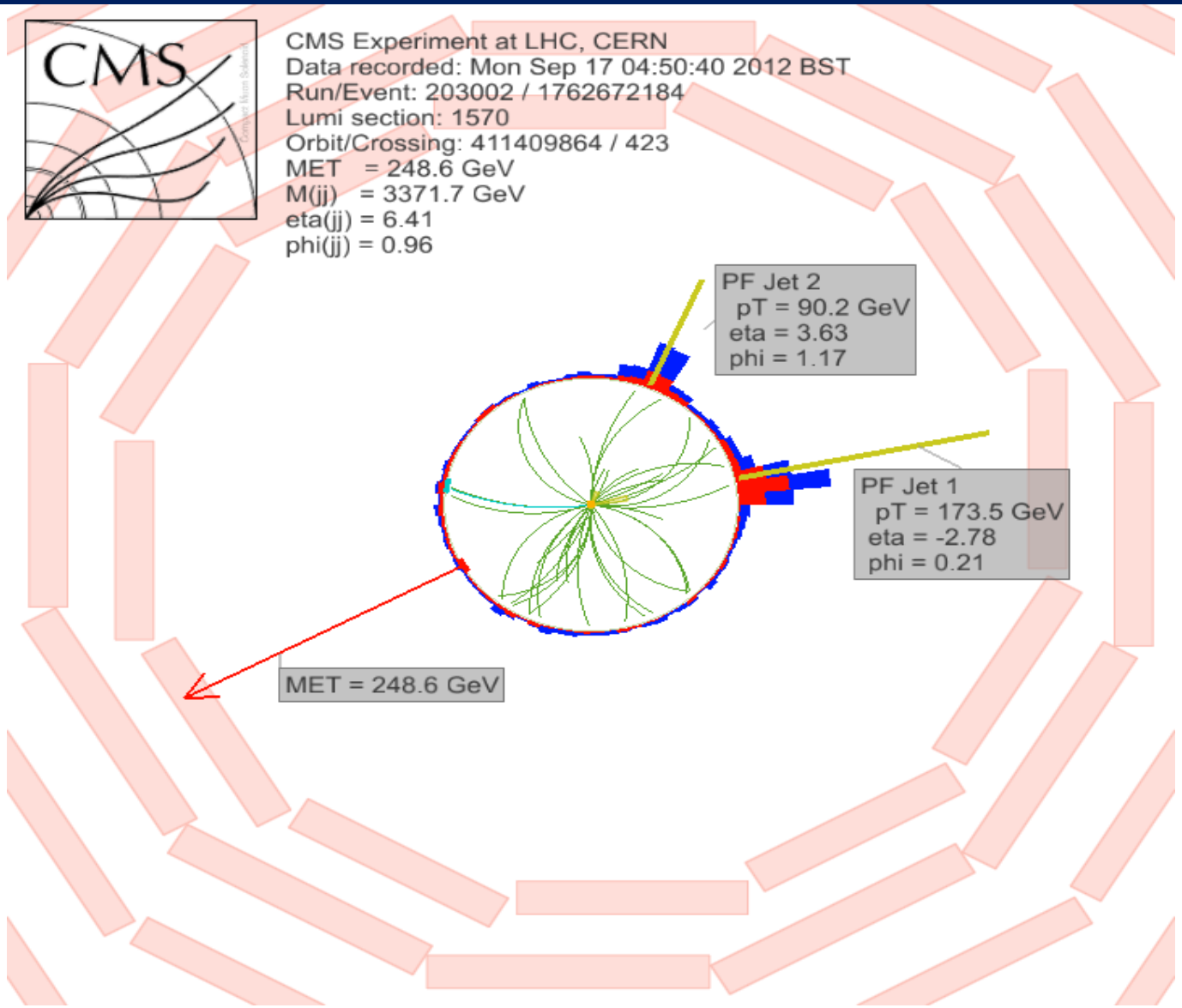
CMS-PAS-HIG-16-016







Invisible Higgs Decays



Moderate Excess @ Run-1

Search	Topology	Excess	Local σ	Global σ	Citation
H→WW	lνJ	700 GeV	2.6	0.5 combination	CMS, 1504.00936
reso→Z+bb	llbb	(m_{bb}, m_{llbb}) = (95,285) GeV	2.6	1.6	CMS, 1603.02991
		(m_{bb}, m_{llbb}) = (575,660) GeV	2.85	1.9	
A→Zh	llbb	560 GeV	2.6	1.1	CMS, 1504.04710
$H^{\pm}$→tb	ttb(b)	200-500 GeV	up to 2.4		ATLAS, 1512.03704
reso→hh	various	300 GeV (γγbb)	2.5		ATLAS, 1509.04670

No evidence or observations, but **interesting channels to follow up at 13 TeV** !

Summary & Outlook

✓ All measured H(125) properties so far found compatible with SM predictions.

Observed Higgs boson at mass 125 GeV may be part of an extended Higgs sector

✓ Many BSM models predicting new scalar, pseudoscalar and charged or neutral Higgs bosons (2HDM, MSSM, NMSSM …) have been explored

No signs for BSM in the Higgs boson sector yet…

✓ but now exploration with larger data sample at an increased energy, also new channels are opening and new searches becoming possible!

✓ Exciting times ahead of us, Run II has just started!