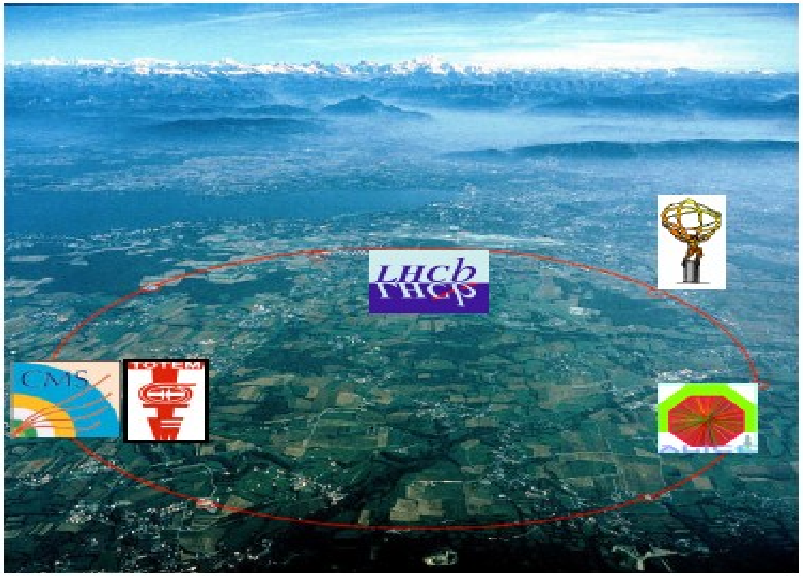
Physics Program
of the experiments at
Large Hadron Collider



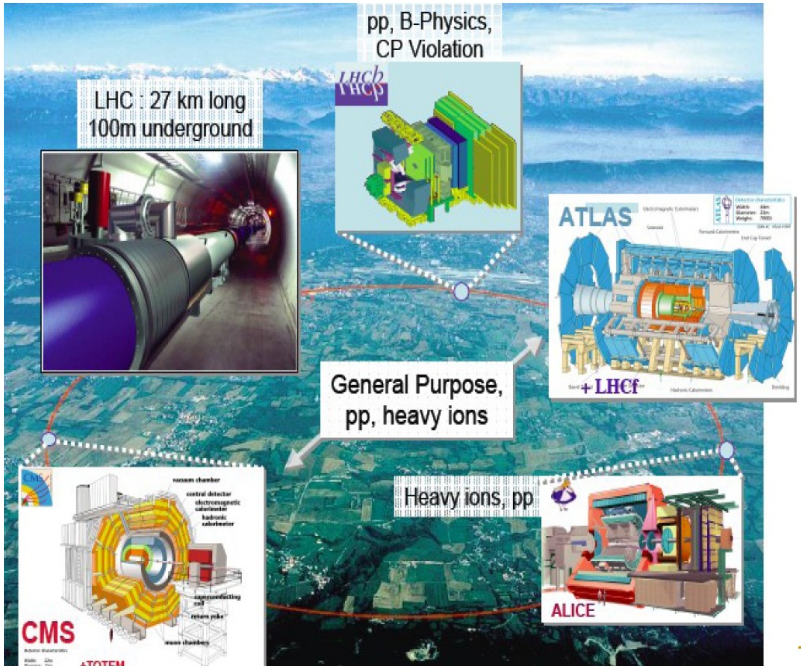
SM and MSSM Higgs boson

Latest news

Tomorrow: CERN Council open session

http://indico.cern.ch/conferenceDisplay.py?confId=221631

Living in incredibly exciting time for fundamental partcile physics!



Latest news

The first LHC proton-proton run is essentially finished:

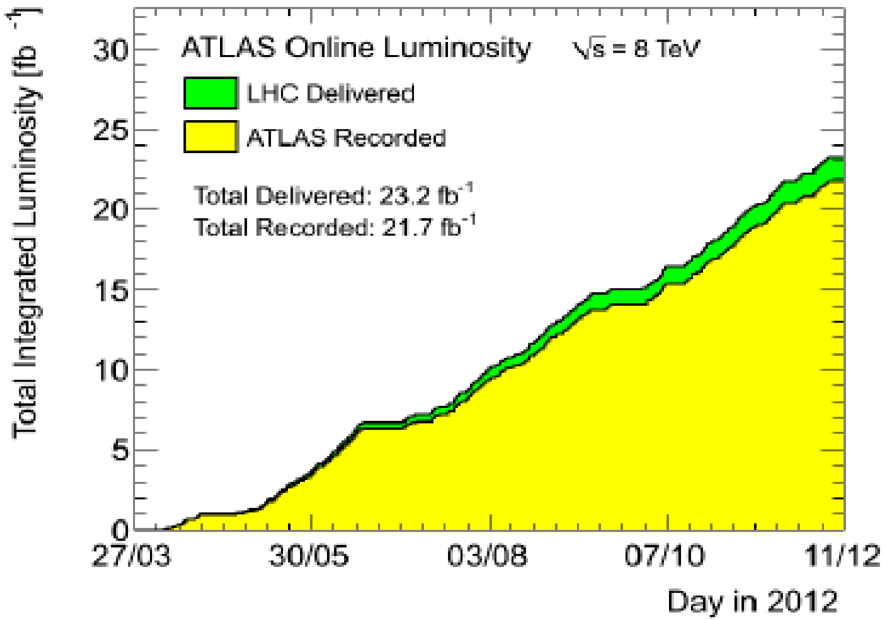
28.6 fb^{-1} delivered in total by the LHC (2010-2012)
26.9 fb^{-1} recorded by ATLAS

→we have ~ 25 fb^{-1} (taking into account DQ) for physics results based on "Run 1"

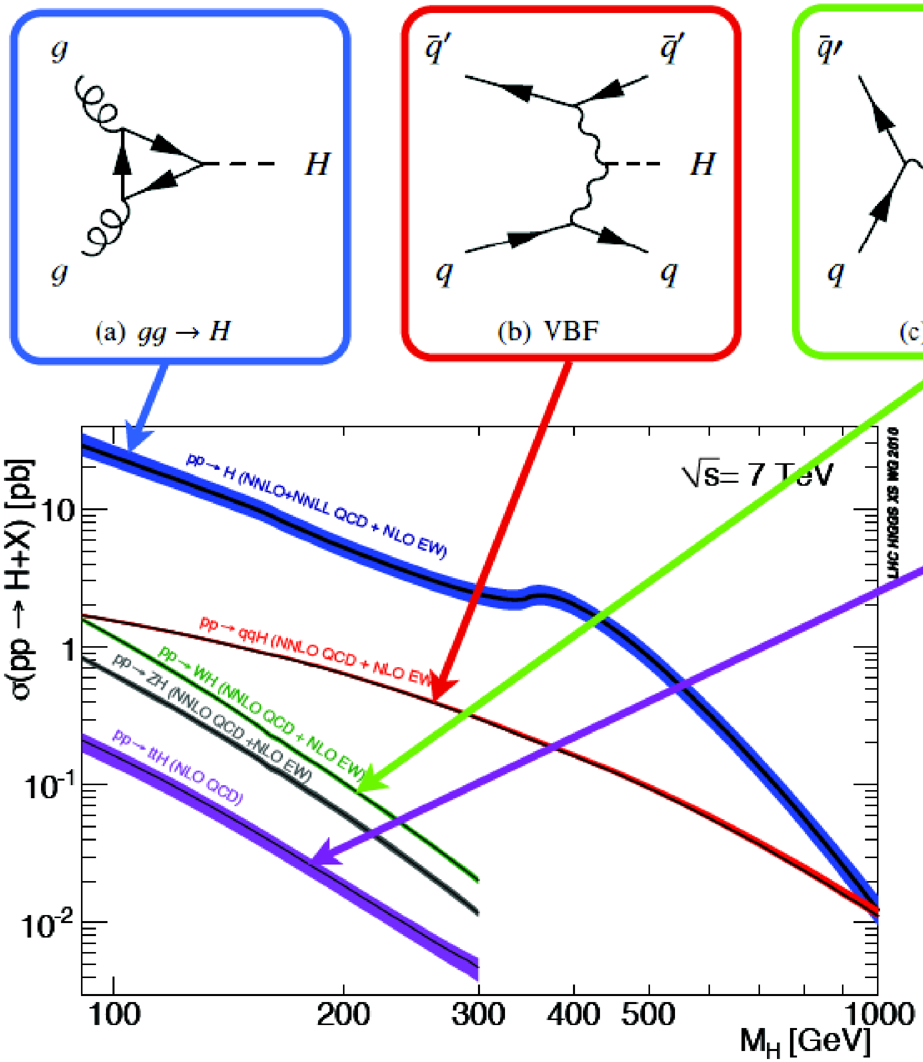
2012: passed 23 fb^{-1} delivered lumi line

Recorded in 2012: **21.7 fb^{-1}**, similar to CMS

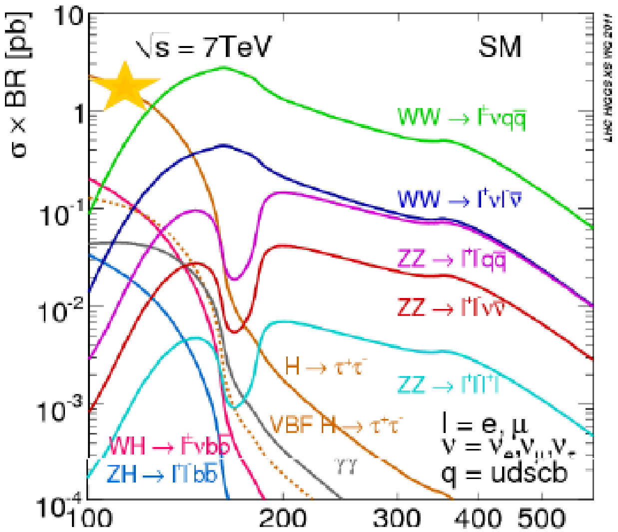
Week 49: ~440 pb^{-1} added, 6 short fills with relatively moderate peak luminosity



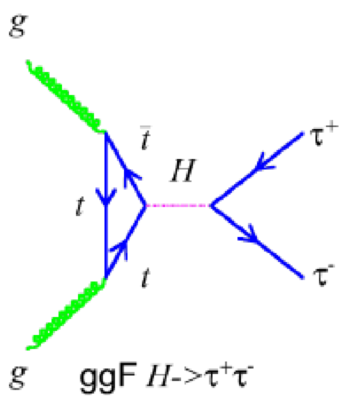
SM Higgs production at the LHC



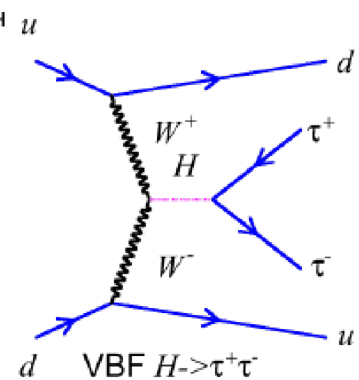
Higgs decay to tau lepton pairs



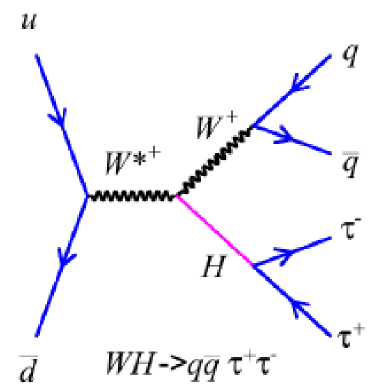
- $H \to \tau\tau$ is one of the leading decay modes for m_H = 125 GeV
- Very important to establish the couplings to the fermions
- The search is performed across various Higgs production processes
- VBF has the highest sensitivity thanks to its signature (2 high-p_T jets with high $\Delta\eta_{jj}$ and high m_{jj})



ggF $H \to \tau^+\tau^-$

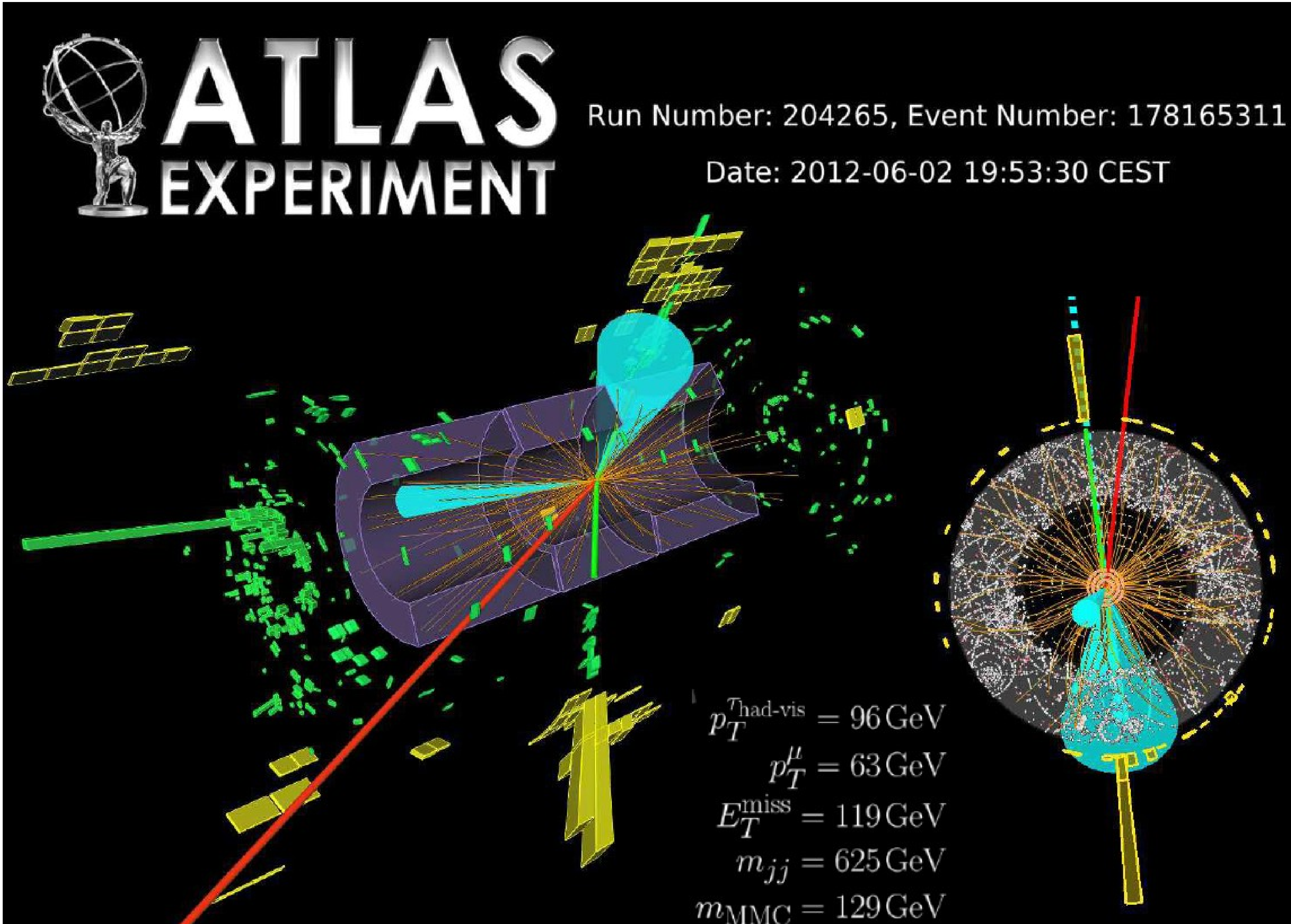


VBF $H \to \tau^+\tau^-$

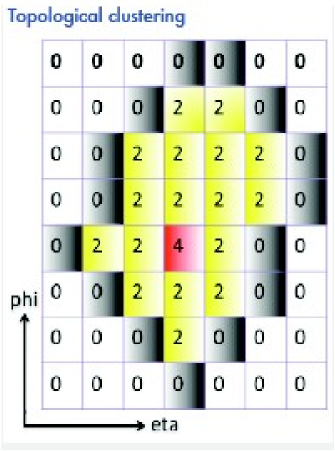


$WH \to q\bar{q}\,\tau^+\tau^-$

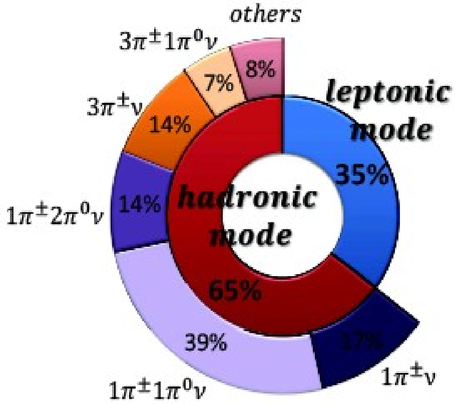
We select only hadronic decays of V

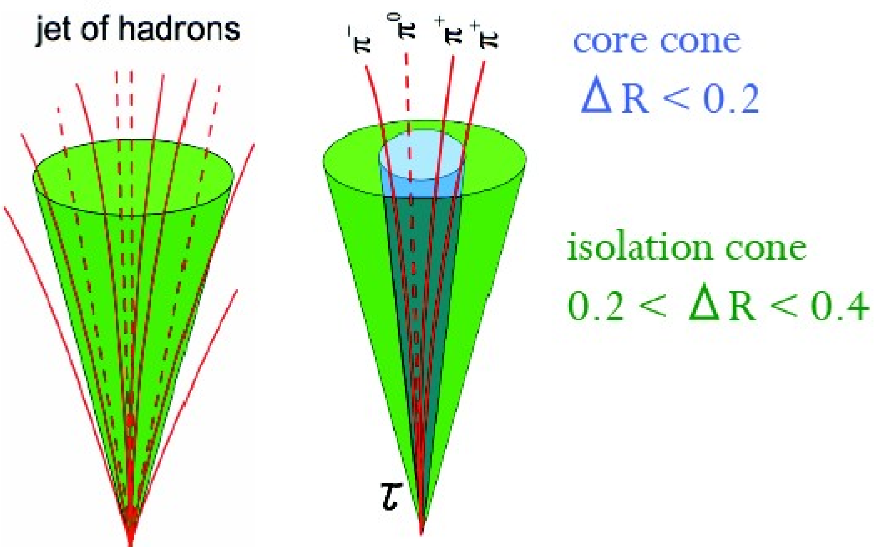

ATLAS EXPERIMENT
Run Number: 204265, Event Number: 178165311
Date: 2012-06-02 19:53:30 CEST
$p_T^{\tau_{\text{had-vis}}} = 96\,\text{GeV}$
$p_T^{\mu} = 63\,\text{GeV}$
$E_T^{\text{miss}} = 119\,\text{GeV}$
$m_{jj} = 625\,\text{GeV}$
$m_{\text{MMC}} = 129\,\text{GeV}$

Hadronic tau reconstruction



- Hadronic decays of tau: 65%
- Reconstruction seeded by anti-kt jets(R=0.4)
  - $p_T > 10$ GeV, $|\eta| < 2.5$
  - calibrated 3D topological clusters
  - good quality tracks with $p_T > 1$ GeV
  - discriminating variables
    - combined information from calorimeter and tracking
    - input to multi-variate algorithms



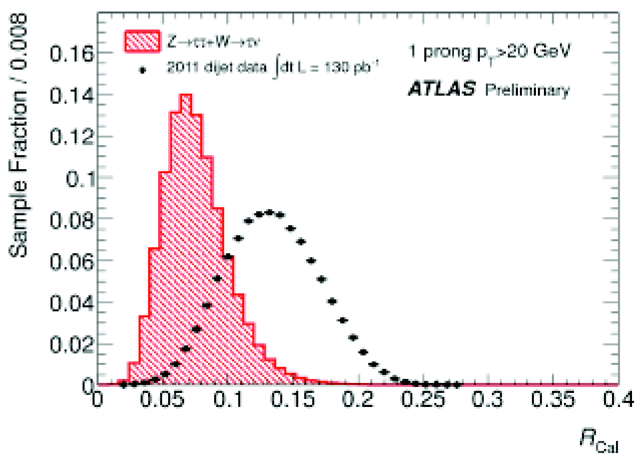


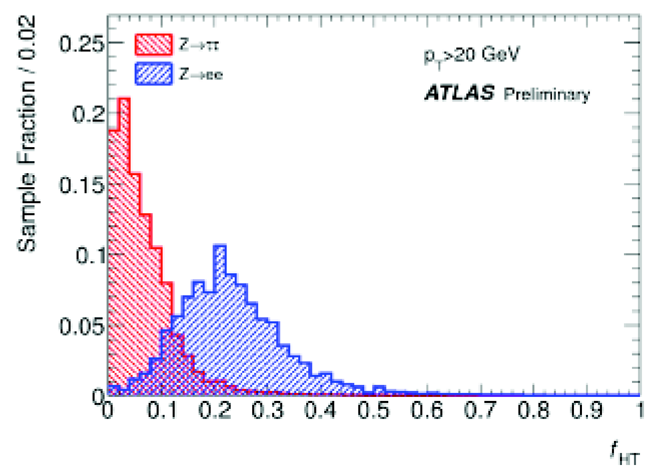
Hadronic tau identification

Decay properties of tau	Detector information used
Collimated decay products	Jet width in tracker and calorimeter
Leading charged hadron	Leading track
No gluon radiation	Isolation
Low invariant mass	Invariant mass of tracks and clusters
Lifetime	Impact parameter, secondary vertex
EM energy fraction different from electrons	Longitudinal position of energy deposits
EM component from π^0	LAr strip
Less transition radiation than electrons	TRT

Discrimination against Jets

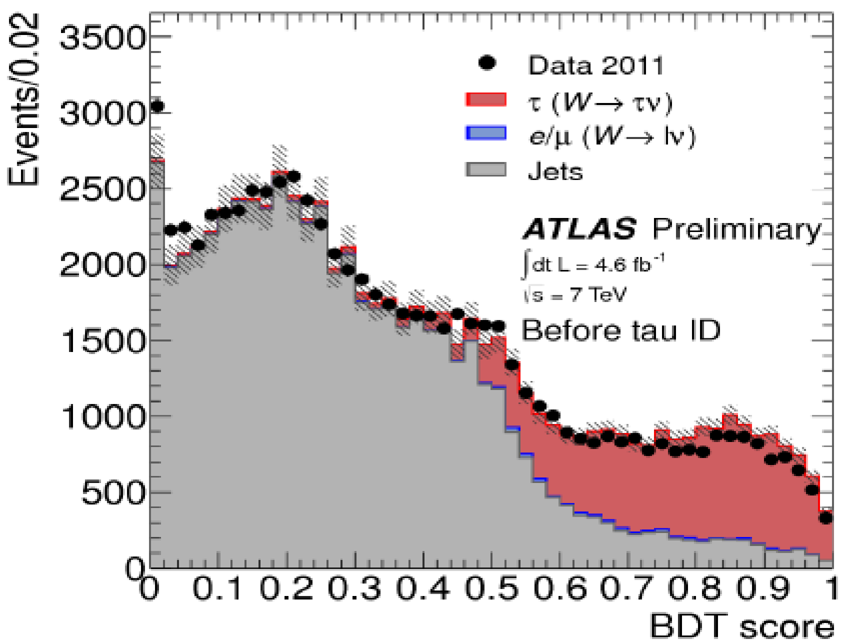
e

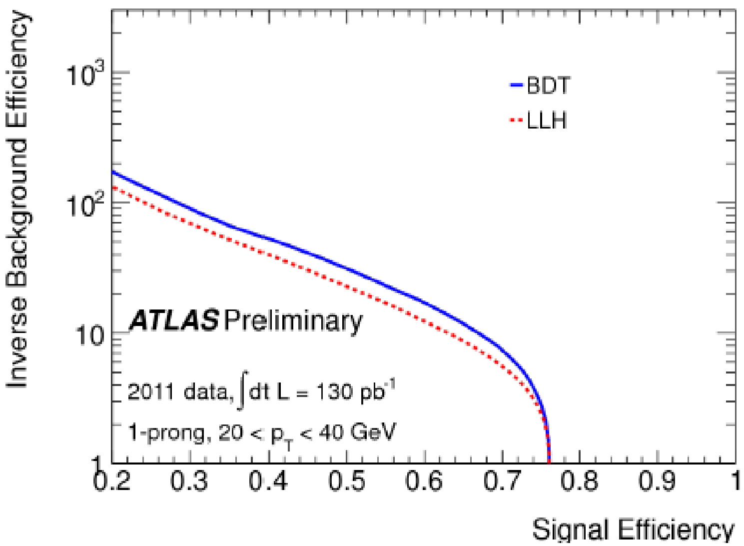


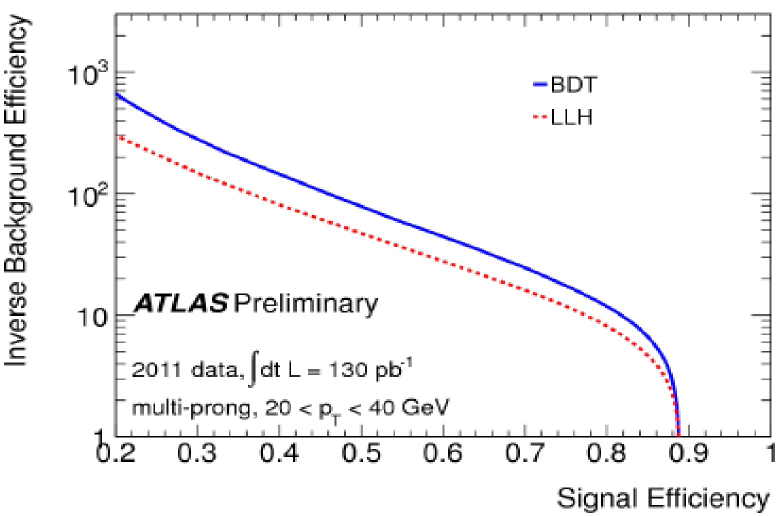


Hadronic tau identification

- seeded by calorimeter jets
- associated tracks within $\Delta R < 0.2$
- combine calorimeter and tracking into multi-variate discriminator
  (BDT/LLH focusing on lateral width and isolation)

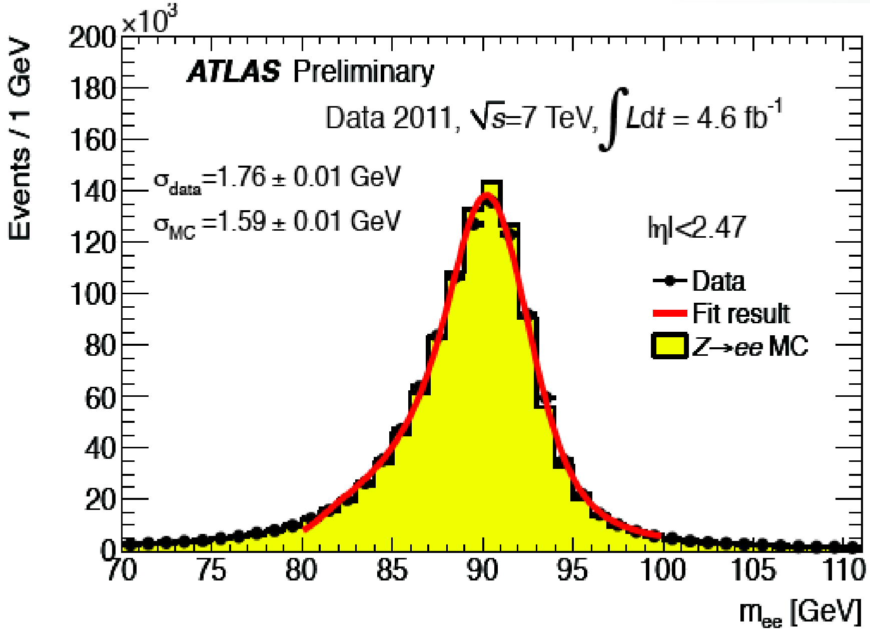


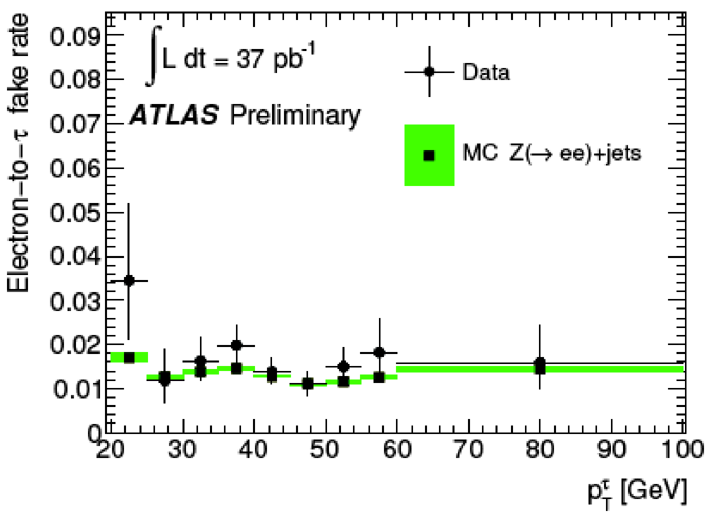


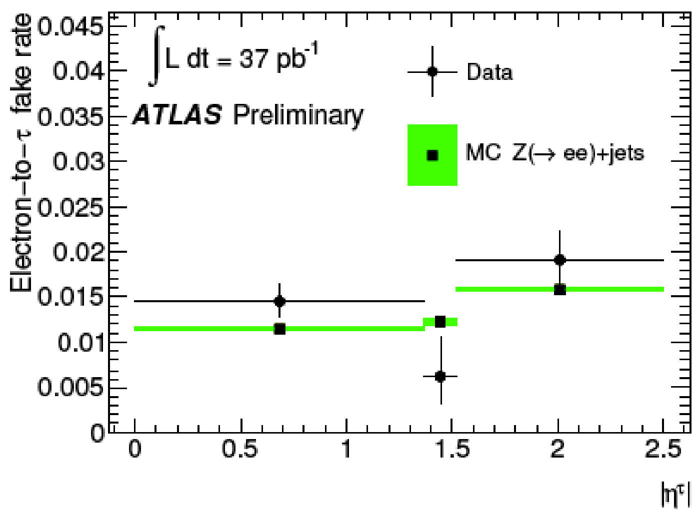


e→τ fakes

- "Tag and probe" method
  - Use clean Z->e^+e^- signal
  - One tight electron to "tag"
  - Other electron to probe the probability to be identified as a τ-jet

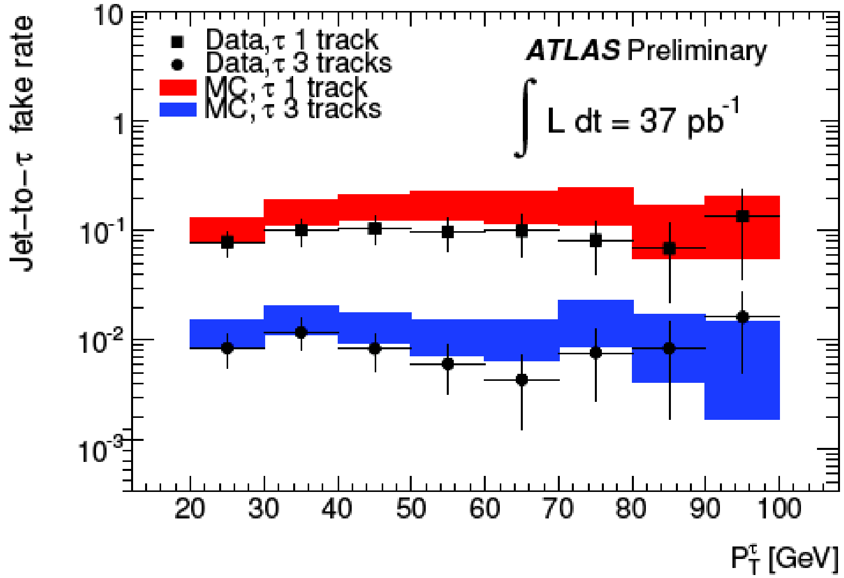






Jets → τ fakes (1) (37pb^{-1} publication only)

- γ+jets event are used. Identified by the γ trigger.
- Binned by the number of tracks in the jet and p_T.



- Systematics include:
  - Contamination (real τ) from processes like QCD and Z,W
  - Control sample uncertainty and correlation to other methods.

Di-tau mass reconstruction

Di-tau invariant mass should be a important discriminating variable from backgrounds. But having 2-4ν in a events.

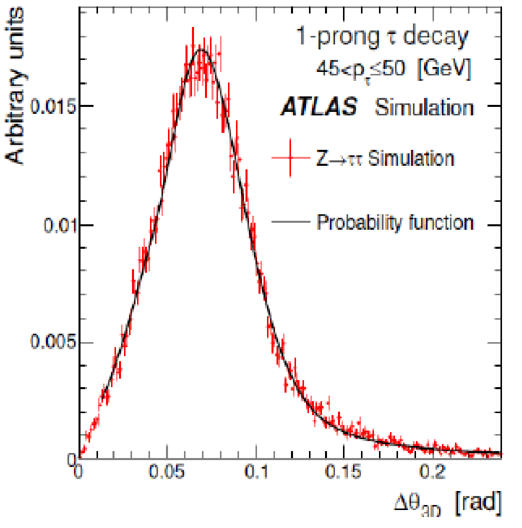
Need…

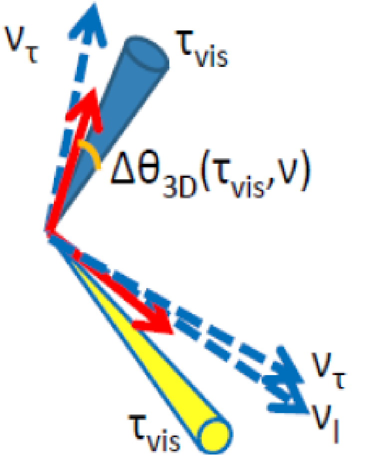
Event by Event estimator of true di-τ mass likelihood.

Full reconstruction of event kinematics.

Missing Mass Calculator(MMC)

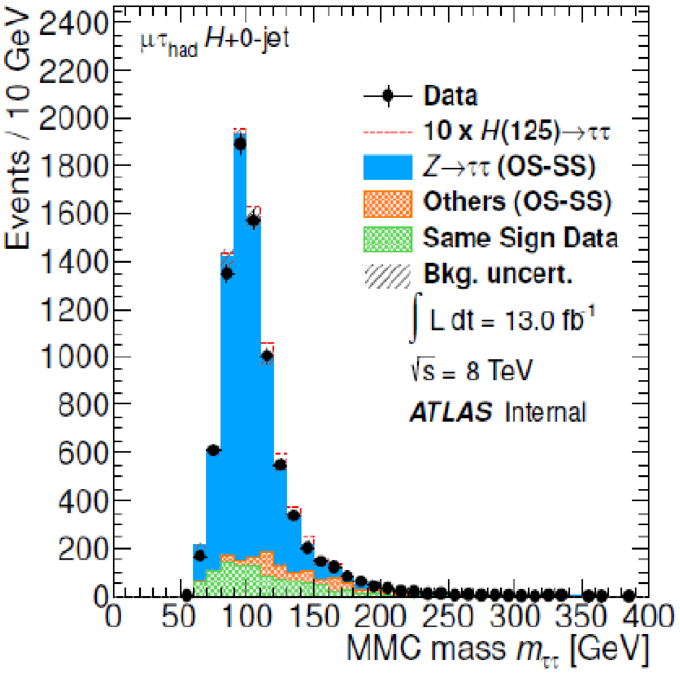
- Solve τ, E_T^{miss} in $\Delta\phi(\tau_{vis},\nu)$ parameter space using $\Delta\theta_{3D}(\tau_{vis},\nu)$ template from simulation as PDF.



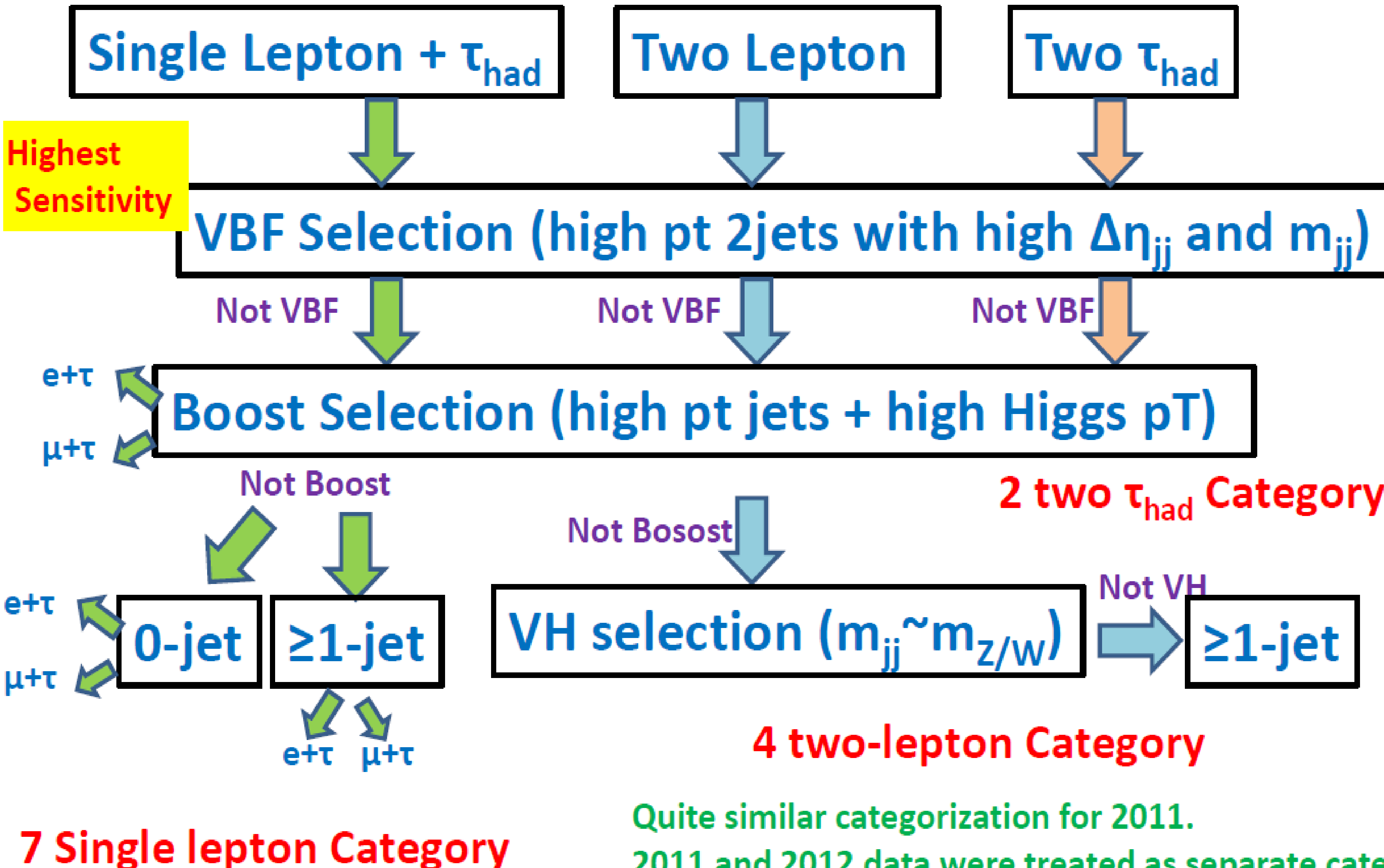


Challenge

- Dominant background is irreducible Z→ττ.
- Signal is on the left shoulder, so need careful validation of Z→ττ shape (right tail).
- MMC mass distribution is calculated based on visible tau decay product and the Missing Momentum.



Analysis categories (8 TeV)

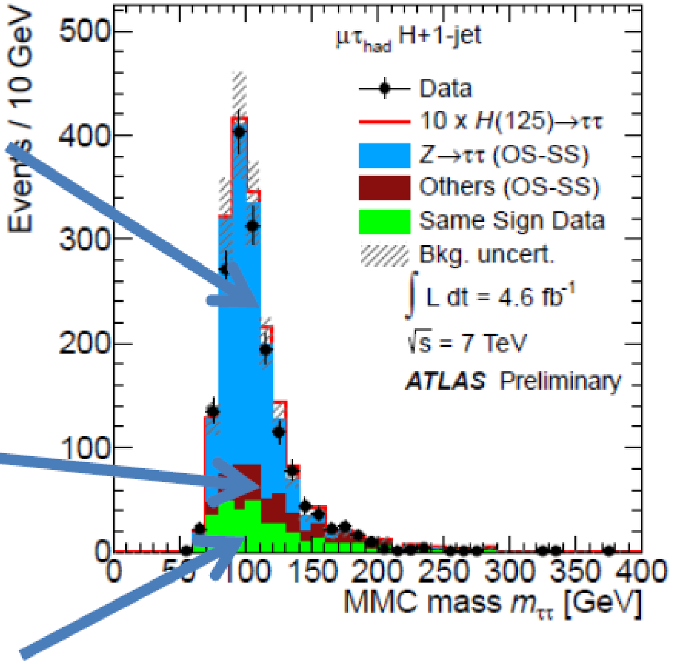


Quite similar categorization for 2011.
2011 and 2012 data were treated as separate categ.

Background estimations

- Opposite sign tau decay products are required.
- High Missing ET and low MT cuts are added.

$Z \rightarrow \tau\tau$ estimated by embedding+MC
-- used $Z \rightarrow \mu\mu$ data and replace μ by full simulated τ, so that all the objects except tau decay product are obtained by real data.
-- Used high statistics MC for VBF channel with correction by data.

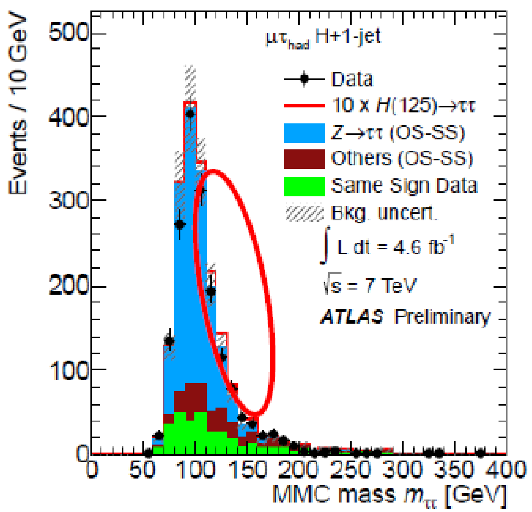


$Z \rightarrow ee/\mu\mu$ + jets, Top, di-boson Estimated by MC with correction.

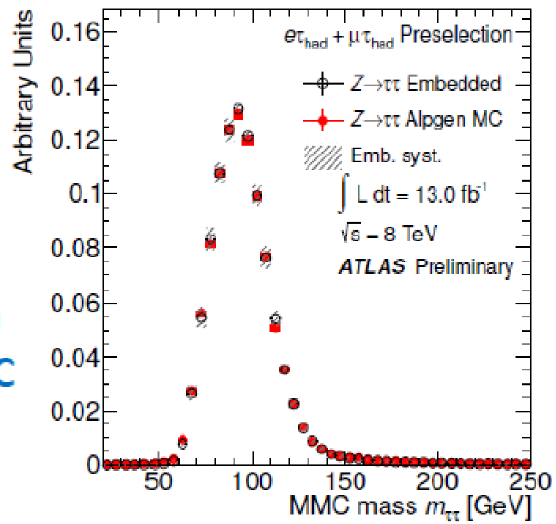
QCD and W+Jets – Estimated from Same Sign events(lephad)
-- Template fit by loose selection (lep-lep,hadhad)

Z(->ττ)+jets modeling validation

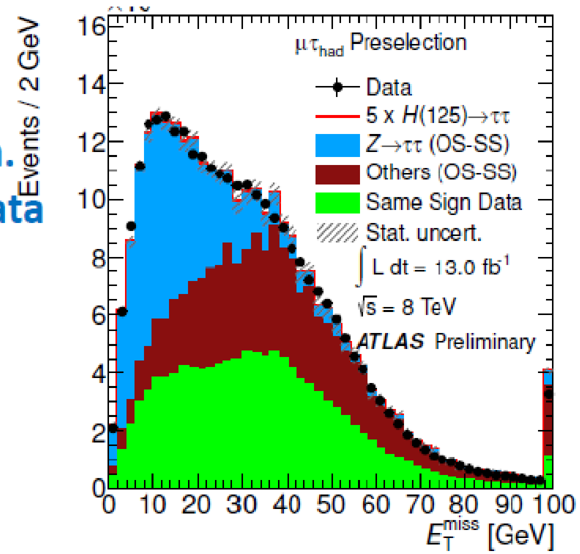
Higgs Signal is on the right hand side tail of Z.
Need carful varidation of the Z→ττ shape.



MMC distribution embedding vs MC



MET distribution. estimation vs data



Non-VBF channel : Embedding

- → Checked with MC sample
- → Assigned systematics by varying condition.

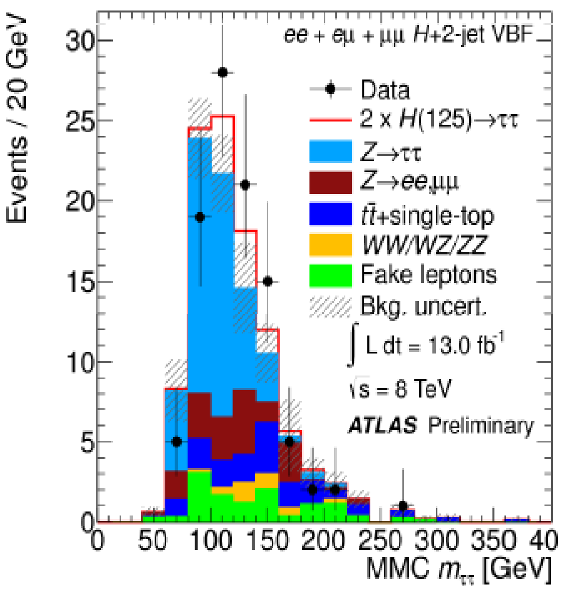
VBF channel : High statistics MC

- → Jet kinematics are validated by Zee/μμ data.
- → Reweighted kinematics for MC mismodeling.

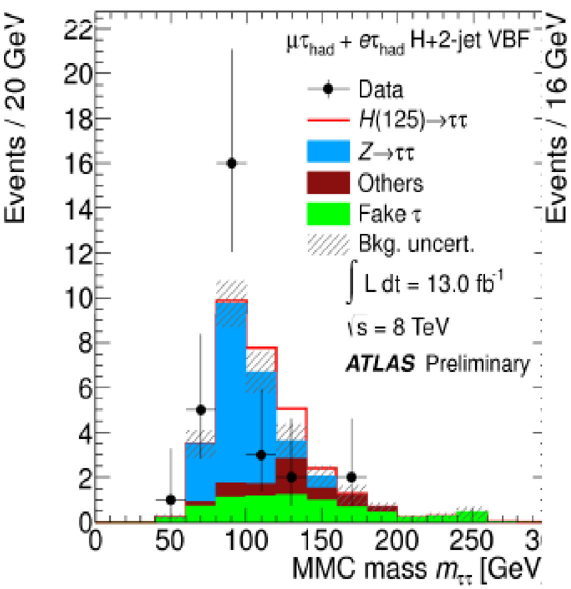
Results for VBF: $m_{\tau\tau}$

- VBF category has the highest sensitivity
- Limited statistics but good S/B ratio
- In this slide: results for 8 TeV data

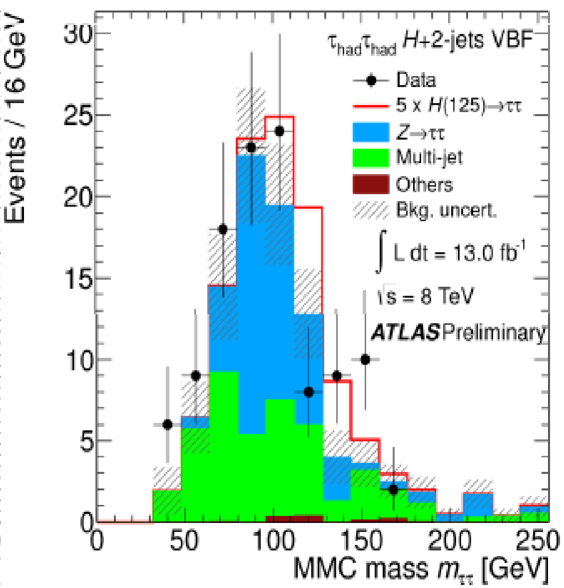
lep-lep



lep-had



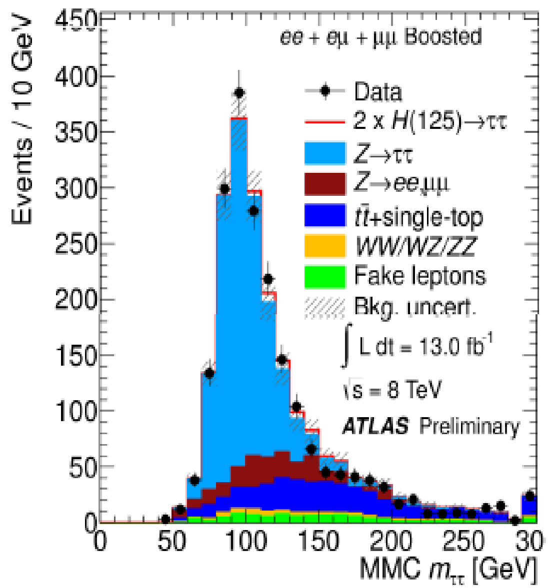
had-had



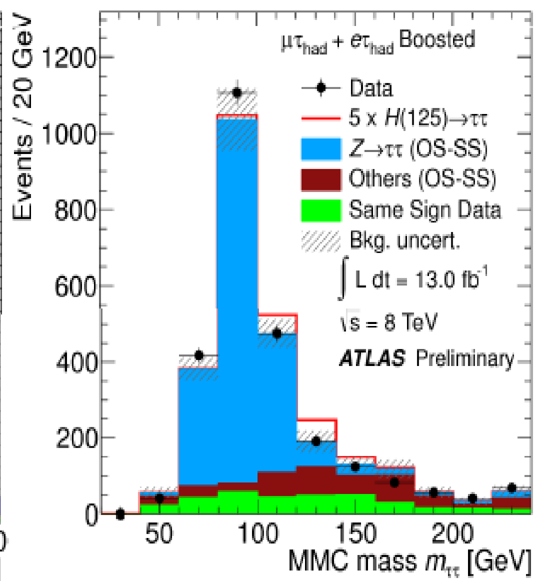
Results for boosted: $m_{\tau\tau}$

- Boosted category has the best sensitivity among non-VBF categories
- The bulk of ggF is in this category
- In this slide: results for 8 TeV data

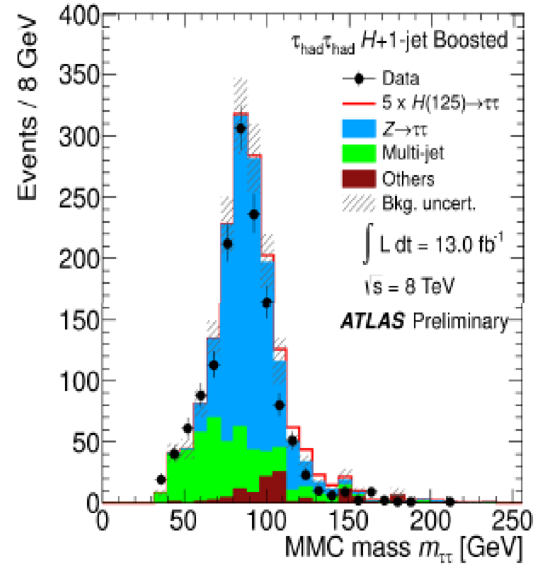
lep-lep



lep-had



had-had



Systematic uncertainties

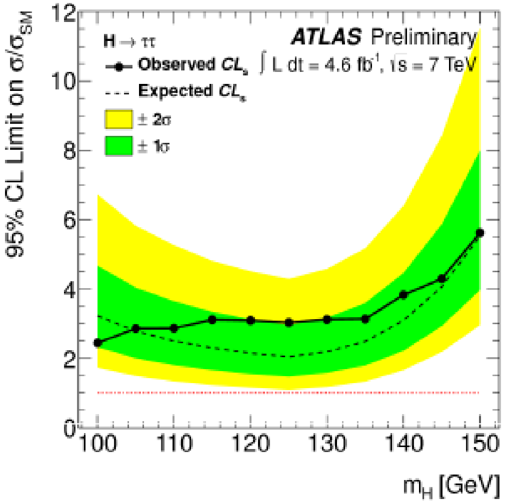
- Main systematic uncertainties for $Z \to \tau\tau$ Background and the Signal
- Dominant systematic : Embedding, τ Energy Scale, Jet Energy Scale

Uncertainty	$H \to \tau_{lep}\tau_{lep}$	$H \to \tau_{lep}\tau_{had}$	$H \to \tau_{had}\tau_{had}$
		$Z \to \tau^+\tau^-$	
Embedding	1-4% (S)	2-4% (S)	1-4% (S)
Tau Energy Scale	-	4-15% (S)	3-8% (S)
Tau Identification	-	4-5%	1-2%
Trigger Efficiency	2-4%	2-5%	2-4%
Normalisation	4.7%	4% (non-VBF), 16% (VBF)	9-10%
		Signal	
Jet Energy Scale	1.0-5.0% (S)	3-9% (S)	2-4% (S)
Tau Energy Scale	-	2-9% (S)	4-6% (S)
Tau Identification	-	4-5%	10%
Theory	7.9-28%	18-23%	3-20%
Trigger Efficiency	small	small	5%

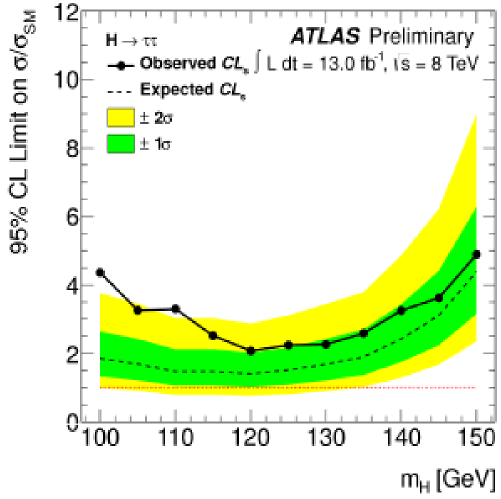
Uncertainties with (S) are also applied bin-by-bin (affect the shape of the final distribution)

Results

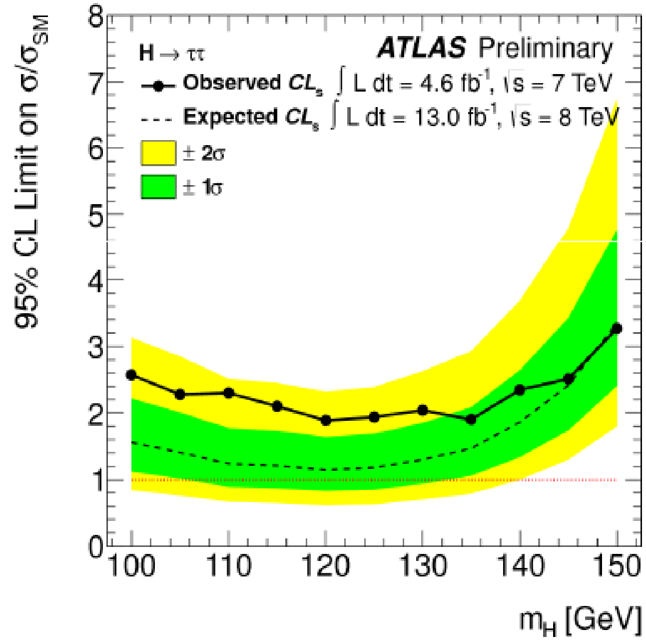
2011



2012



2011 & 2012

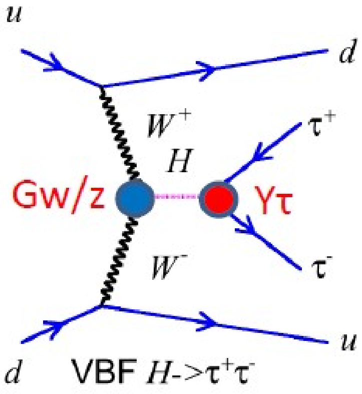


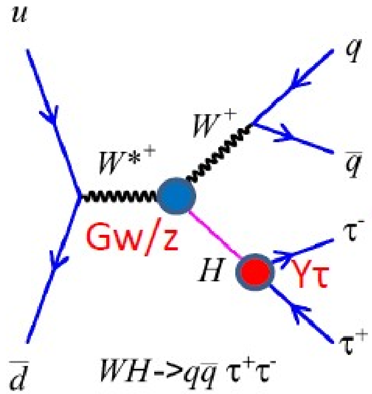
❖ **Combined results (2011&2012):**

- Use standard CLs profiling method
- Fit full $m_{\tau\tau}$ distribution
- Observed (expected) limit at m_H = 125 GeV:

  1.9 (1.2) x SM prediction
- $\sigma/\sigma_{SM} = \mu = 0.7 \pm 0.7$
- No significant excess observed

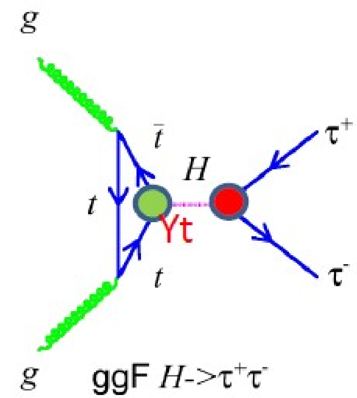
Results



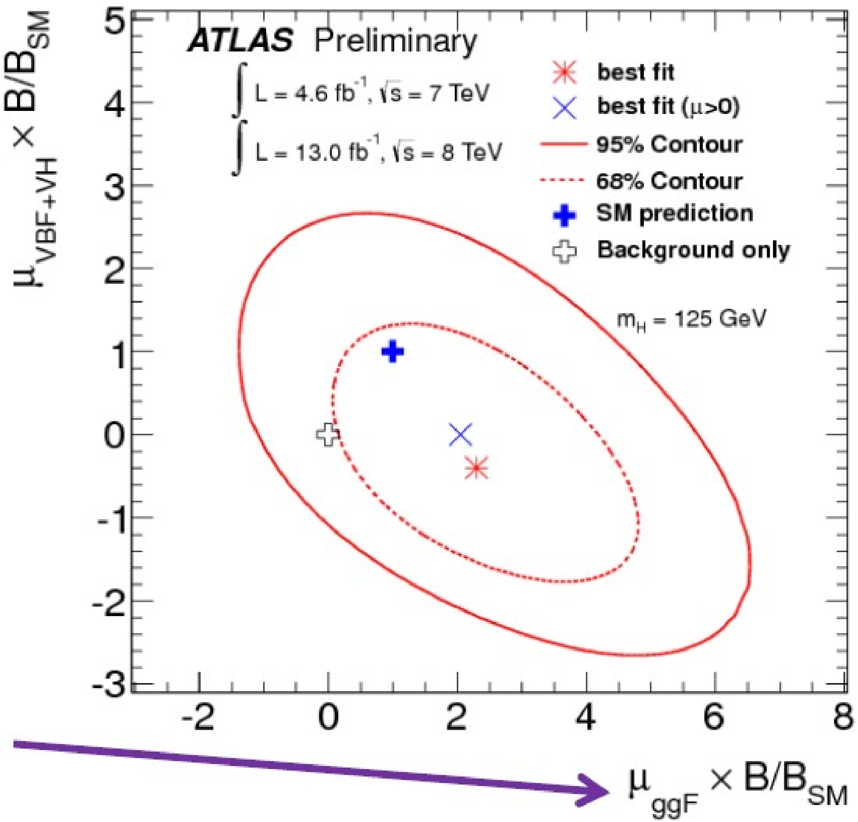


$$\frac{\sigma_{\rm VBF}}{\sigma^{\rm SM}_{\rm VBF}} = \frac{\sigma_{\rm WH}}{\sigma^{\rm SM}_{\rm WH}} = \frac{\sigma_{\rm ZH}}{\sigma^{\rm SM}_{\rm ZH}}$$

$= \mu_{\rm VBF+VH}$



$$\frac{\sigma_{\rm ggH}}{\sigma^{\rm SM}_{\rm ggH}} = \mu_{\rm ggF}$$



Consistent both to SM and bkg only hypothesis with large error.

It is quite important to see where this best fit converged to!

Results

- Analyzed 4.6fb^{-1} 7TeV data and 13fb^{-1} 8TeV data.
- About 50% improvement could be achieved. Still Cut base!!
- Expected sensitivity for the limit is now touching to 1.
- We had first measurement of couplings by production processes, although we need more data to see where the values are converged.

95% CL upper limit : Expected (μ=0) **:1.2xSM**

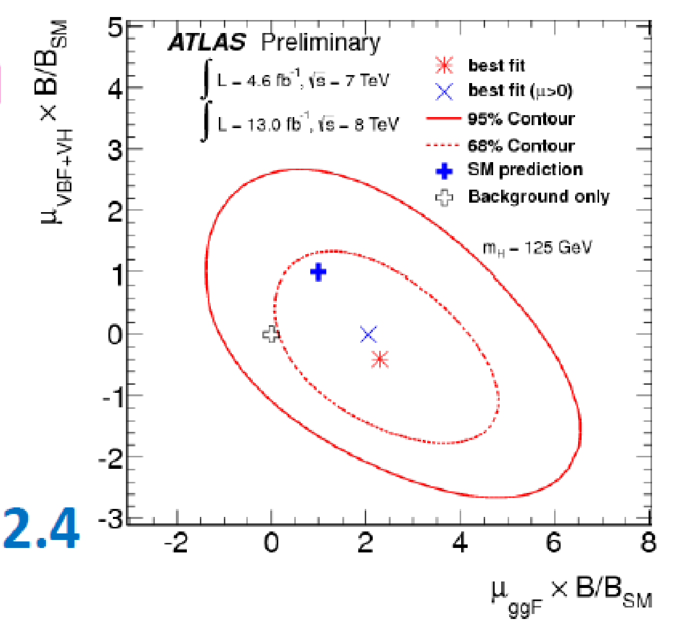
Observed:1.9xSM

Local p0 : Expected (μ=1) **:1.7σ**

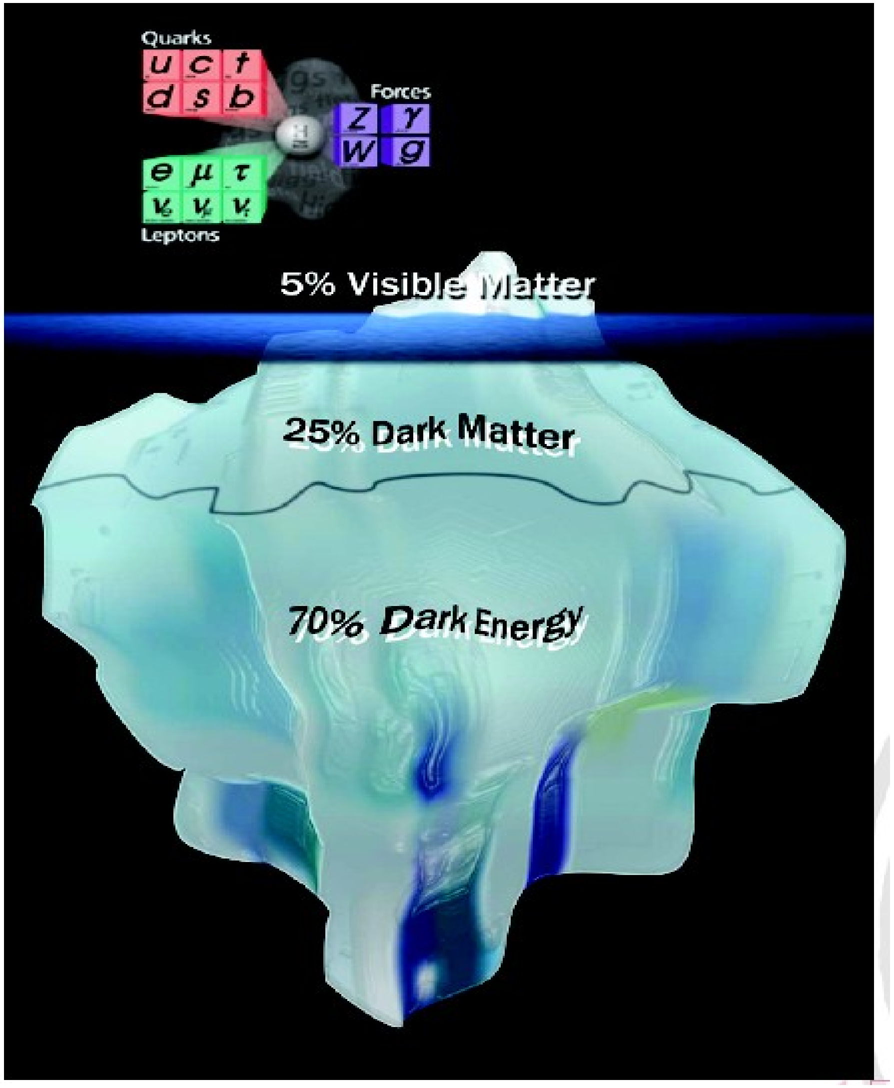
Observed:1.1σ

Signal Strength μ_{best}: 0.7±0.7

Coupling : $\mu^{best}{}_{VBF+VH}$= -0.4 $\mu^{best}{}_{ggF}$= 2.4



Beyond Standard Model

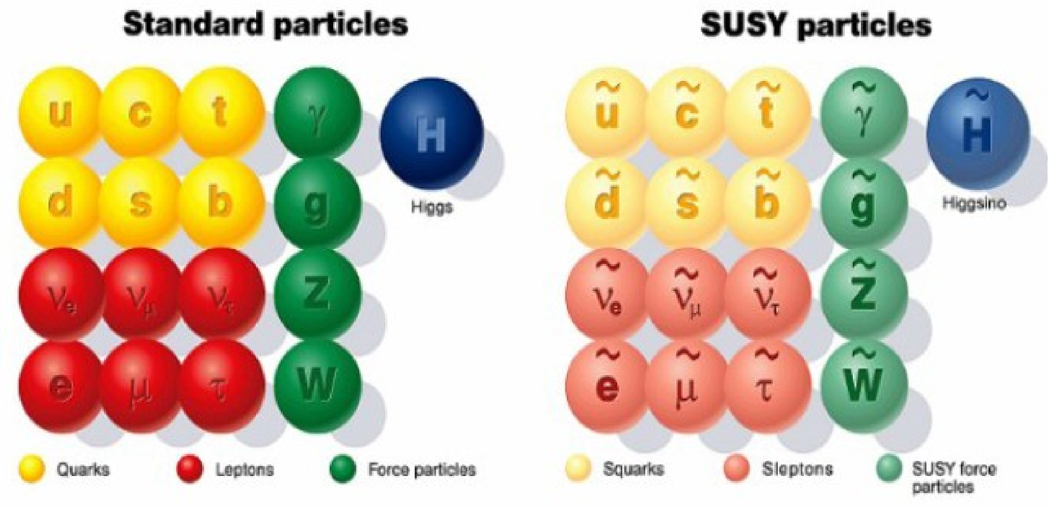


Can the Higgs sector give an indication of new physics, beyond the Standard Model?

Minimal Supersymmetry

Supersymmetry:

- partner particles with same quantum numbers but opposite spin-statistics
- popular framework for beyond-SM models



Advantages:

- consistent with light Higgs boson
- provides dark matter candidate
- reduces fine-tuning in weak scale hierarchy problem
- helps gauge coupling unification

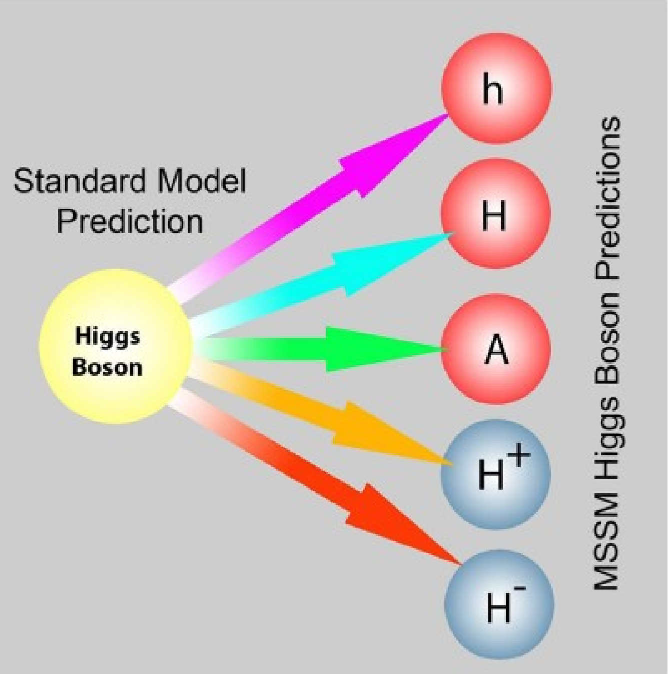
No SUSY particles observed thus far

- supersymmetry a broken symmetry

Minimal Supersymmetric Standard Model

- minimal SUSY particle spectrum
- introduces 105 new parameters

The MSSM Higgs sector



Two-doublet Higgs sector (Y = ±1)

Five Higgs bosons
- h, H: neutral, CP even
- A: neutral, CP odd
- $H^{\pm}$: charged

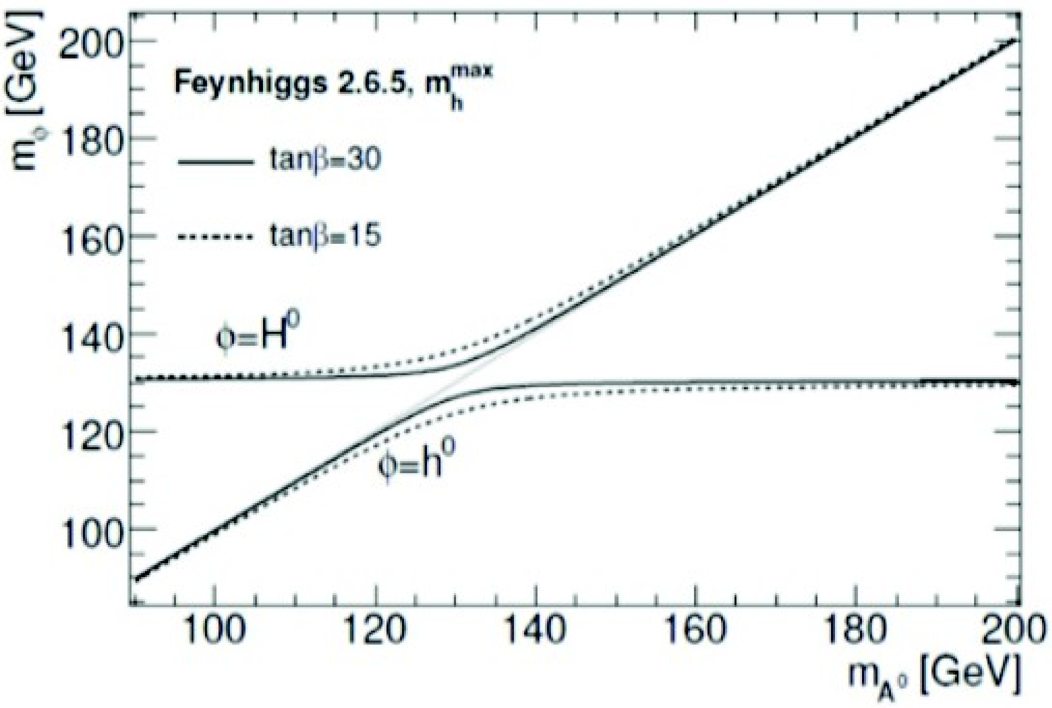
Two free parameters describe couplings (Born level):
- m_A, tanβ

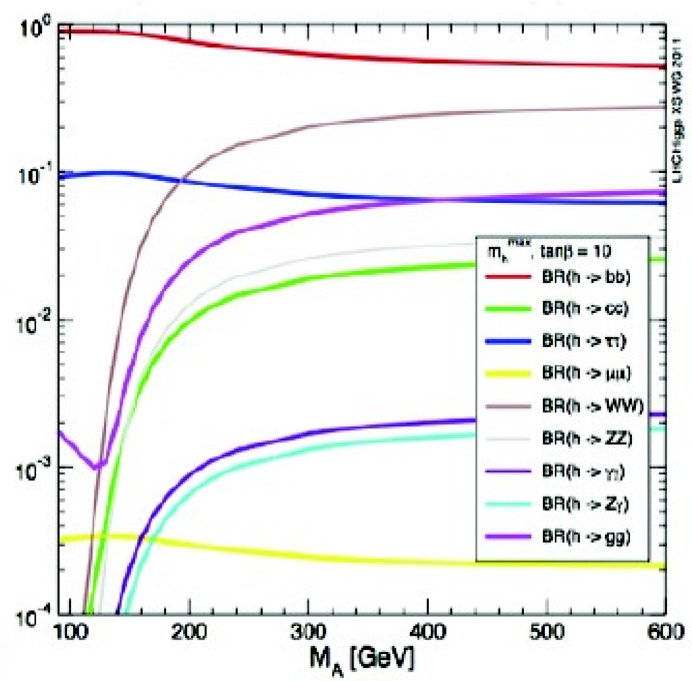
Enhanced couplings of h/H to down-type fermions with high tanβ

focuses on 2011 7 TeV searches for:

- light charged Higgs searches ($m_{H+} < m_{top}$) in $H^{\pm}\to\tau\nu$ decays
- neutral Higgs searches in $h/H/A\to\tau\tau$ and $h/H/A\to\mu\mu$ decays

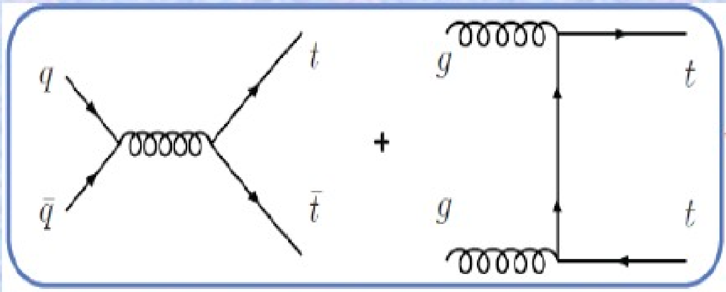
MSSM neutral higgs sector



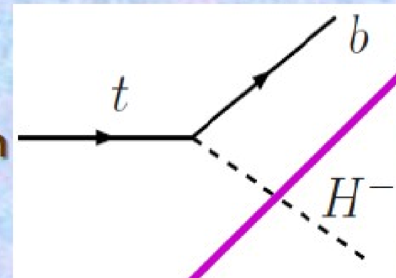


Charged Higgs

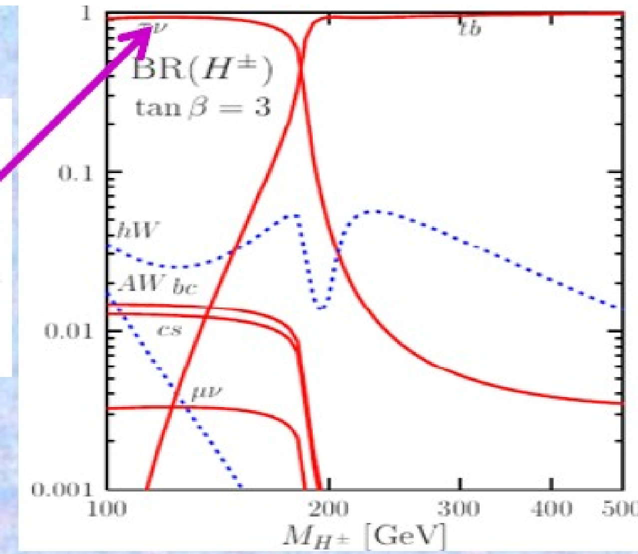
➢ $M_{H+} < m_{top}$: (Standard Model tt production)



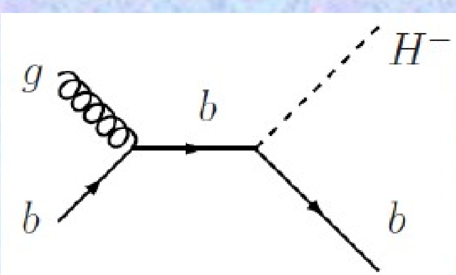
with



Dominant Decay mode: $H^+ \to \tau\nu$



➢ $M_{H+} > m_{top}$:



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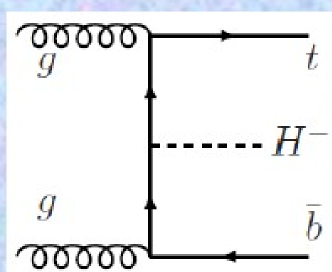
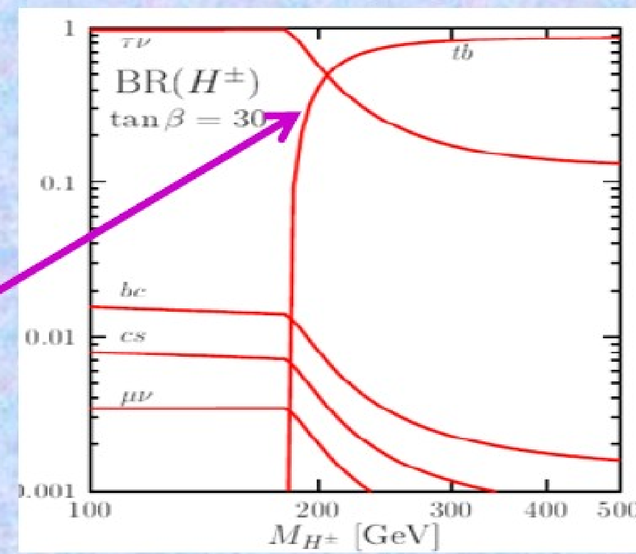
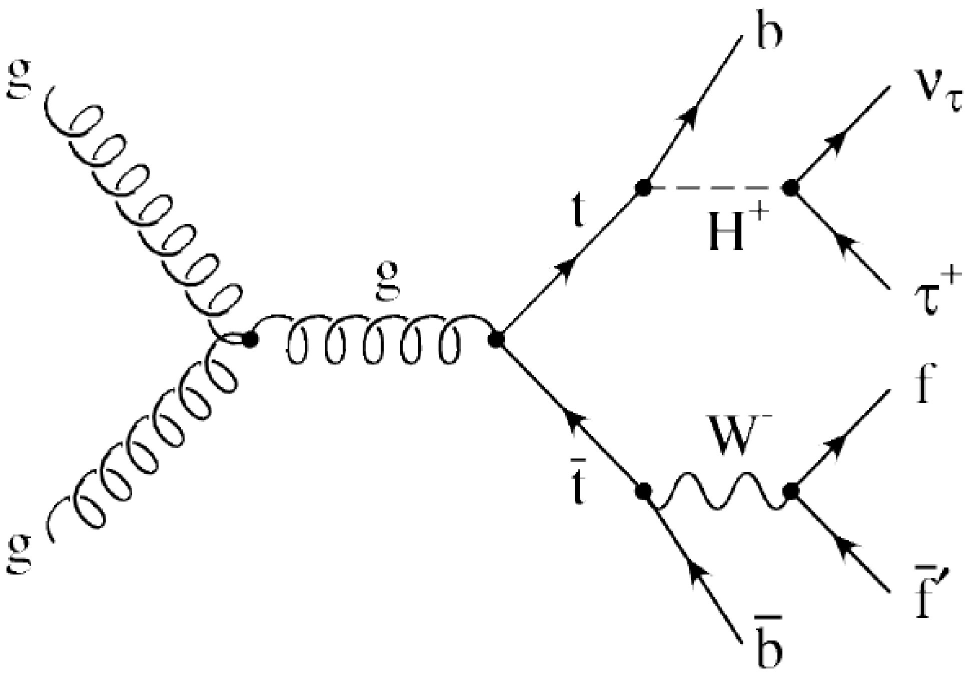


Dominant Decay mode: $H^+ \to$ tb



Charged Higgs searches



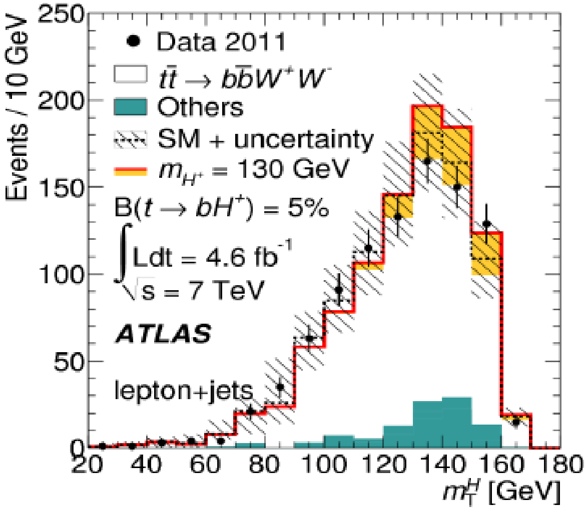
- in MSSM $\tan\beta = v_u/v_d$
- for $\tan\beta>2$, decay $H^{\pm}\rightarrow\tau\nu$ dominates
- for $m_{H\pm} < m_{top}$, primary production mode is through $t\rightarrow H^{\pm}b$

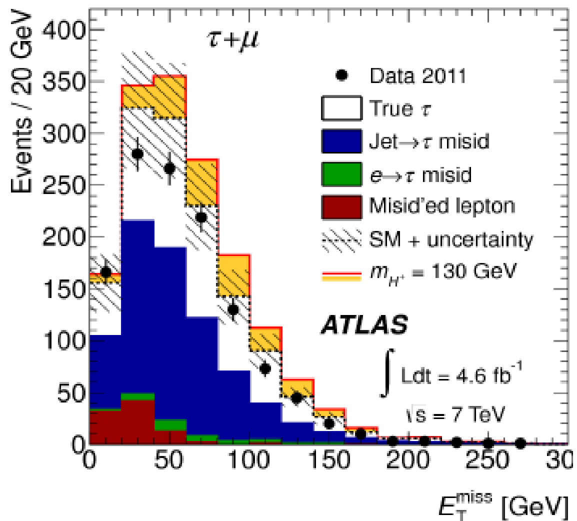
Look for top pair topologies with different enhanced decays from charged Higgs

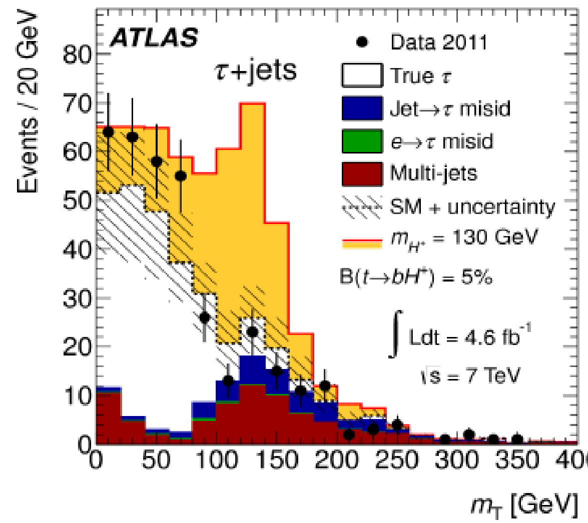
Note: search results can be extended to general Two Higgs Doublet Models

Charged Higgs searches

Searches in bb(qq')(lν), bb(lν)($\tau_h\nu$), bb(qq')($\tau_h\nu$) topologies







- electron or muon (p_T > 25 or 20 GeV)
- two b-tagged jets
- E_T^{miss} > 40 GeV
- top pair kinematics

- usage of $\cos\theta_l^* \alpha\, m_{bl}$
- fake lepton backgrounds determined from data

- electron or muon (p_T > 25 or 20 GeV)
- identified τ_h (p_T > 20 GeV)
- one b-tagged jet

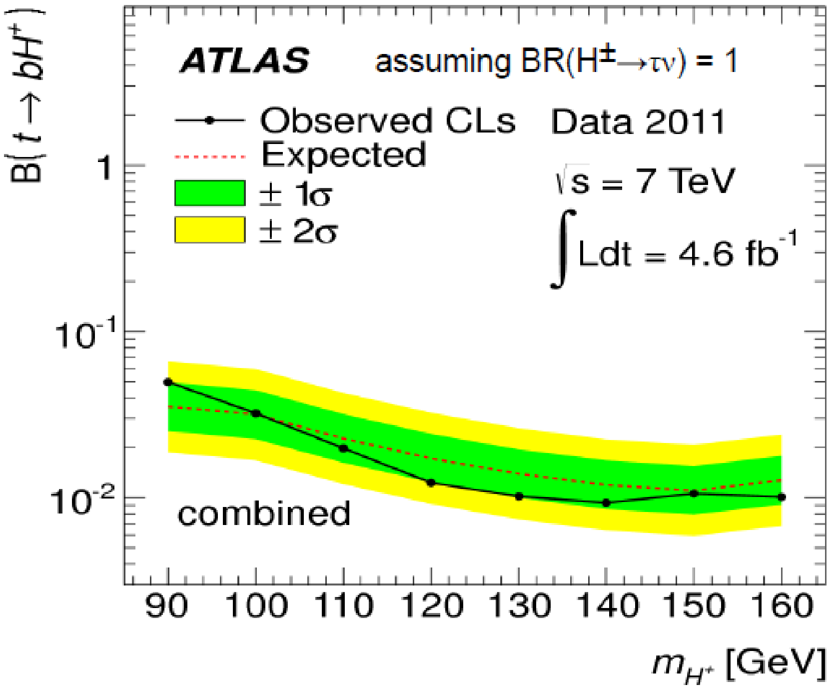
- tau lepton fakes from electrons and jets determined from data

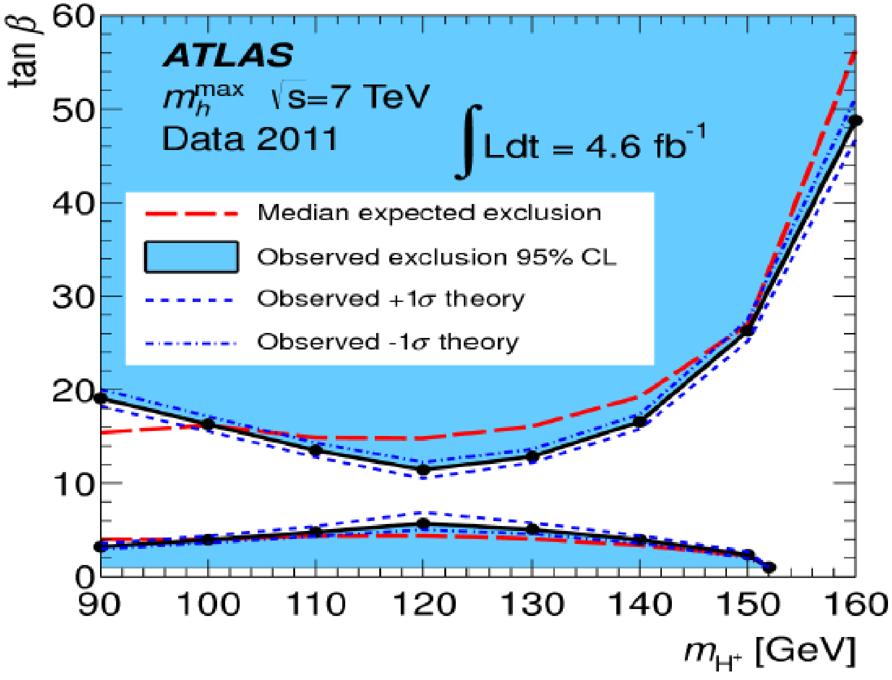
- ≥4 jets, one b-tagged
- identified τ_h (p_T > 40 GeV)
- E_T^{miss} > 65 GeV
- top pair kinematics

- multi-jet background determined from E_T^{miss} template fit

Charged Higgs searches

Combined limits on BR(t→H±b)

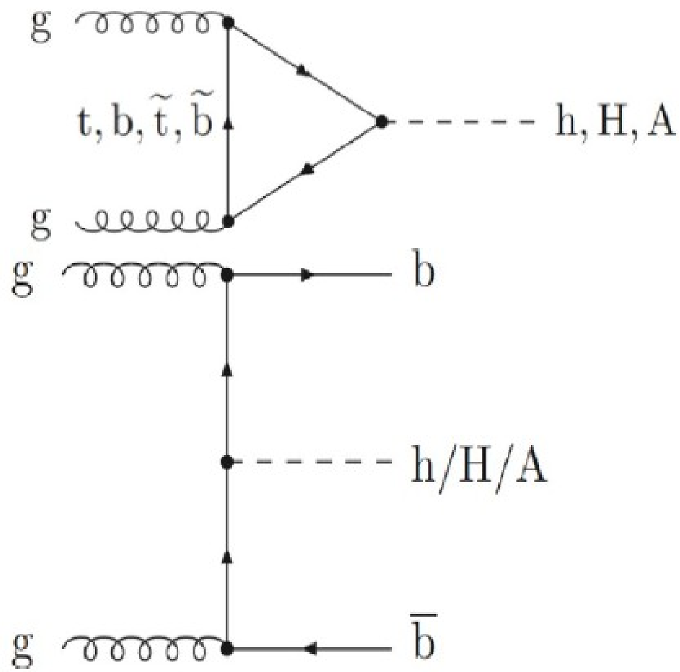




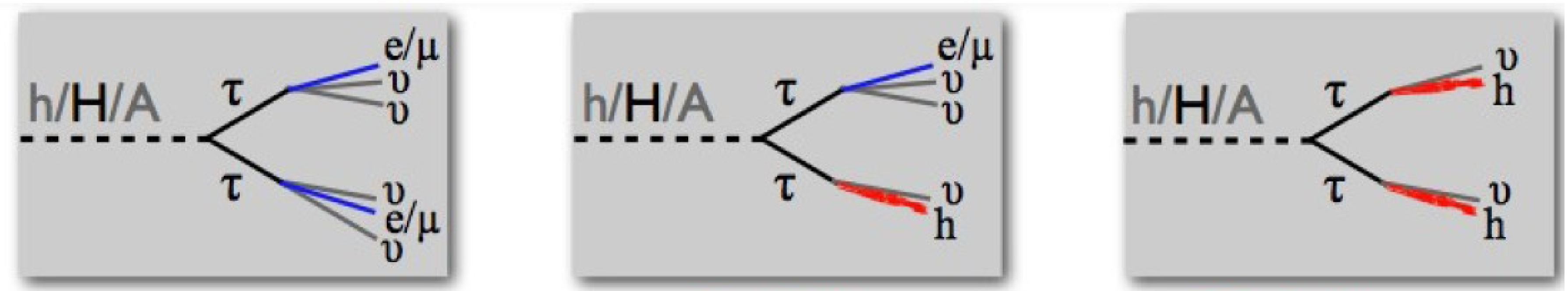
Exclude BR(t→H±b) > 1-5% over $m_{H\pm}$ range

Extensive exclusion of $m_{H\pm}$ vs tan β parameter space at 95% CL (m_h^{max} scenario)

Neutral MSSM Higgs searches



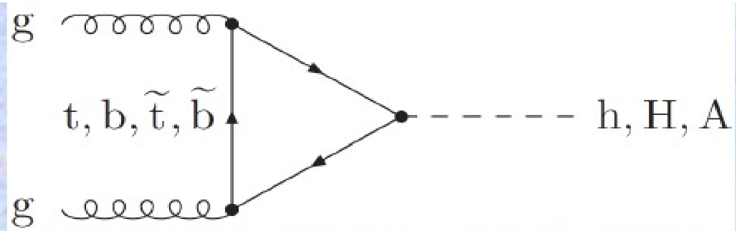
- Higgs couplings to b-quarks and tau-leptons enhanced compared to SM
- gluon-fusion and b-quark associated production most copious production modes
- branching ratios to tau leptons (muons) are approximately 10% (0.04%)
- interpretation presented in m_h^{max} scenario



BR=12.4% BR=45.6% BR=42.0%

Neutral MSSM Higgs searches

Main production mechanisms:
h, H (CP-even, scalars)
A (CP-odd, pseudoscalar)



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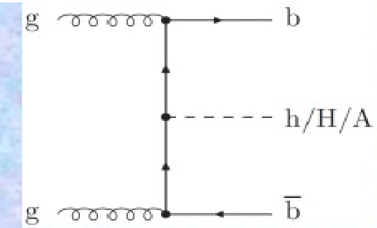
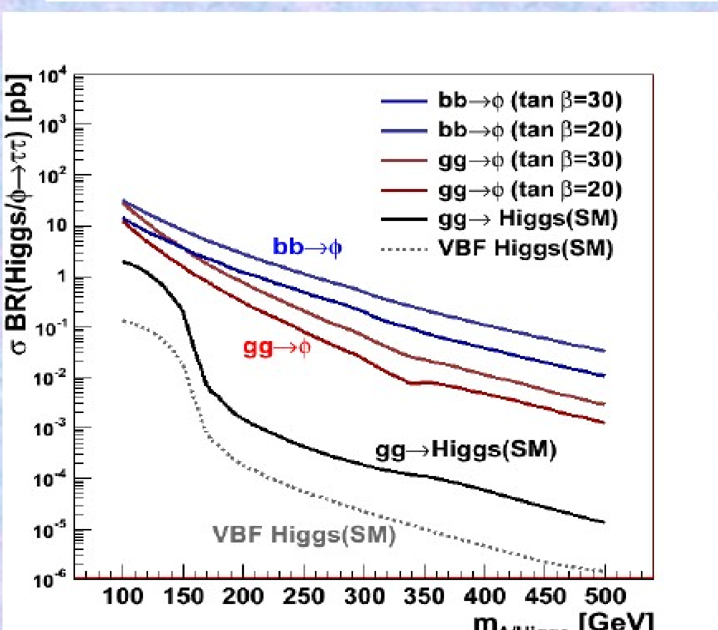
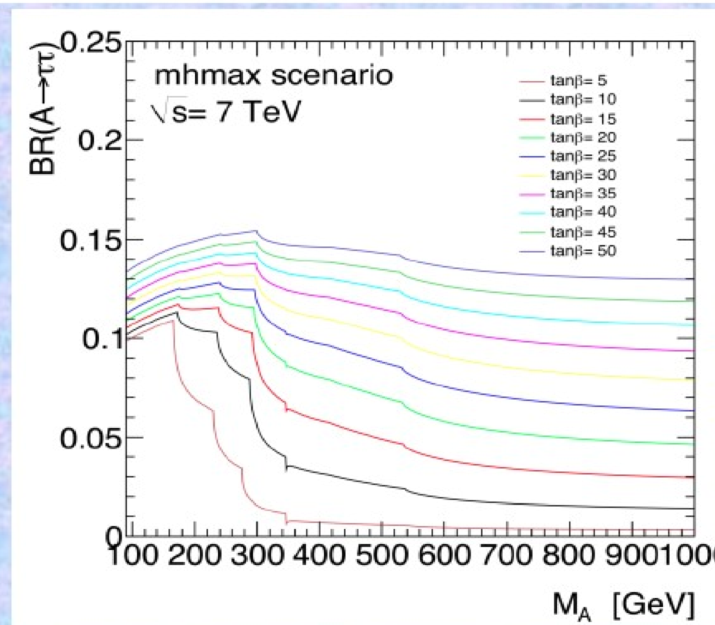


- Production via gluon fusion (b, t loops) and associated b-quark annihillation
- Enhanced coupling to b-quarks and τ-leptons ($g^{MSSM}_{b\bar{b}H} = \tan\beta \cdot g^{SM}_{b\bar{b}H}$ → production rate enhanced × $\tan^2\beta$), b-associated production becomes dominant

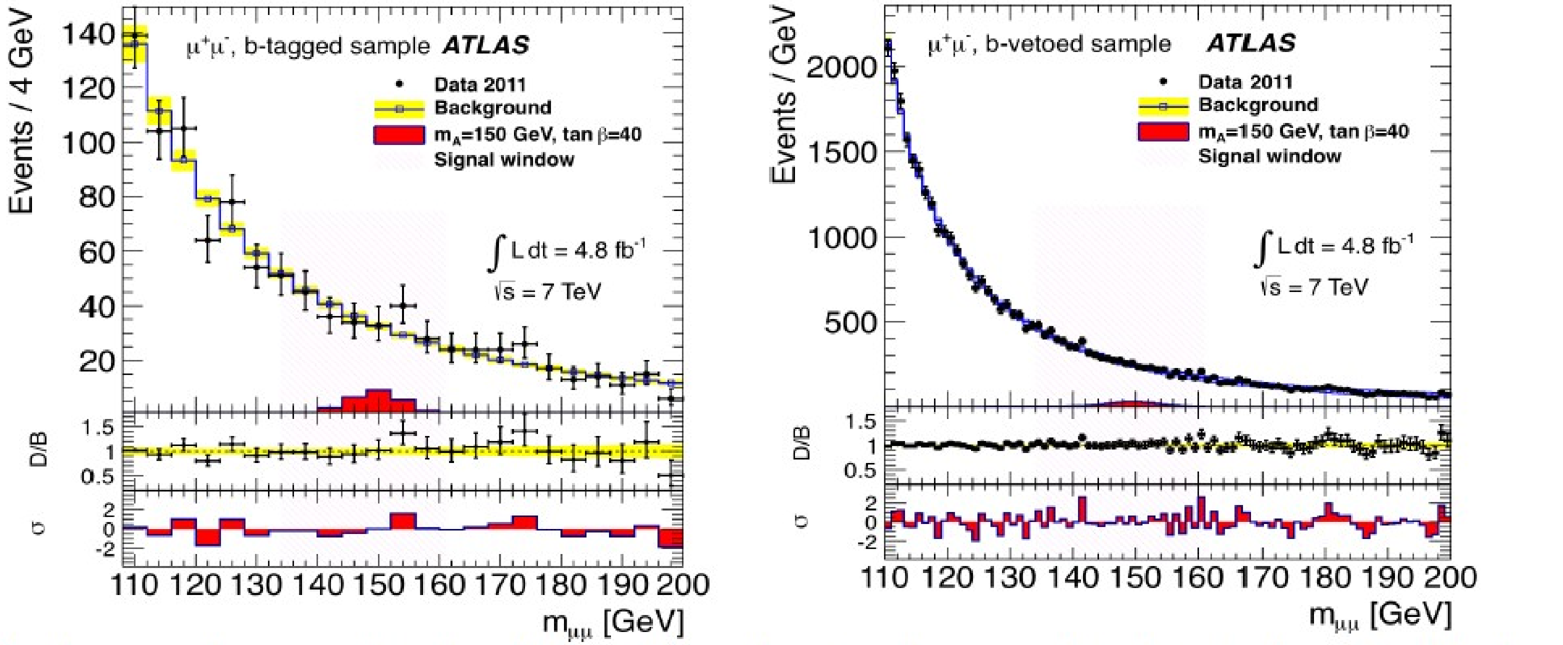




H/A/h → μμ search

Two oppositely-charged muons $p_T > 20(15)$ GeV, $E_T^{miss} > 40$ GeV

Split into b-tagged and b-vetoed categories



Background parametrization fit to sidebands, signal parametrization in (m_A, tan β) plane

Background model:

$$N_B \cdot [f_Z \otimes f_{Gauss}]$$

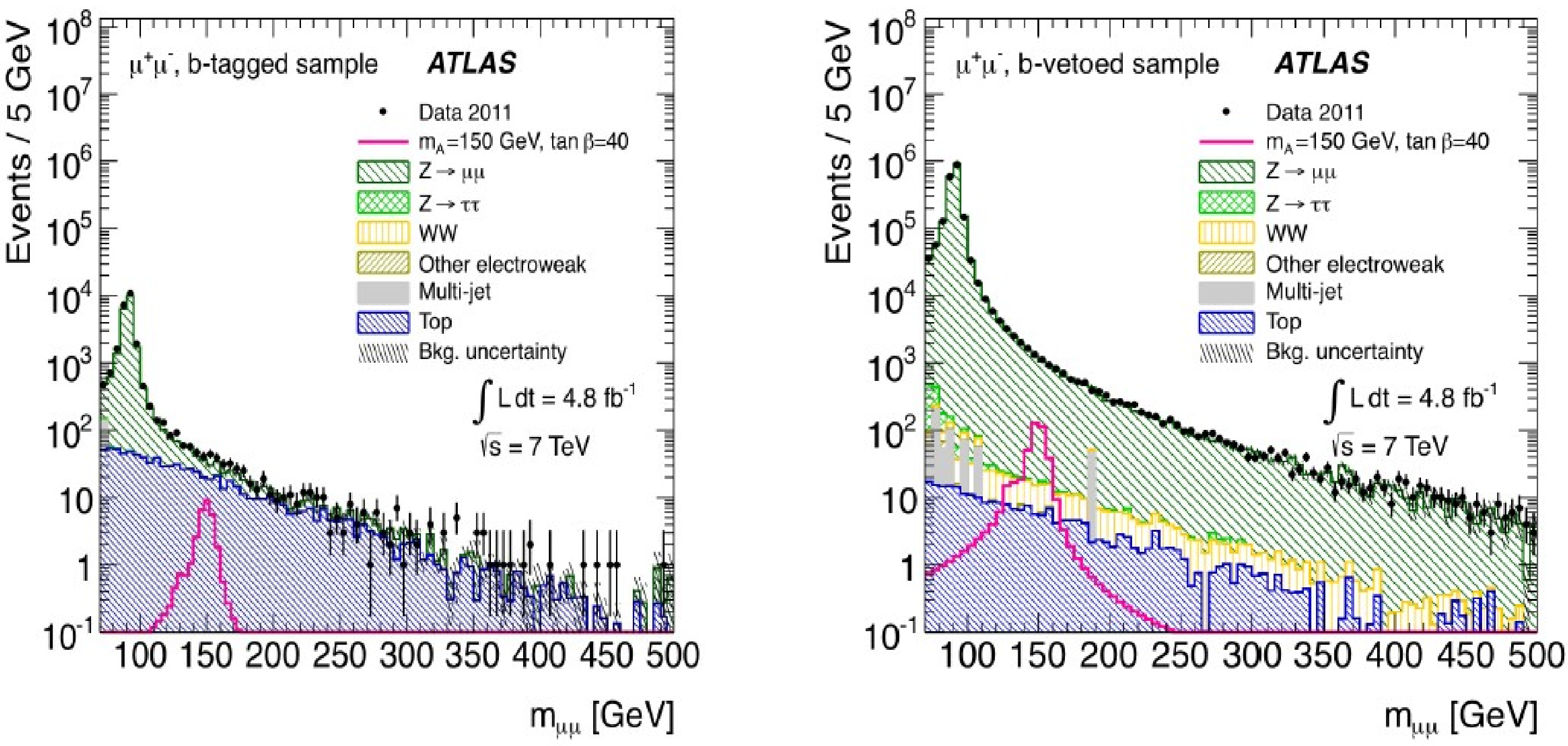
Z/γ^* curve — Resolution

Signal model:

$$N_S \left[\frac{1}{[x^2 - M^2]^2 + M^2 \gamma^2} \otimes f_{Gauss} + c \; f_{Landau} \right]$$

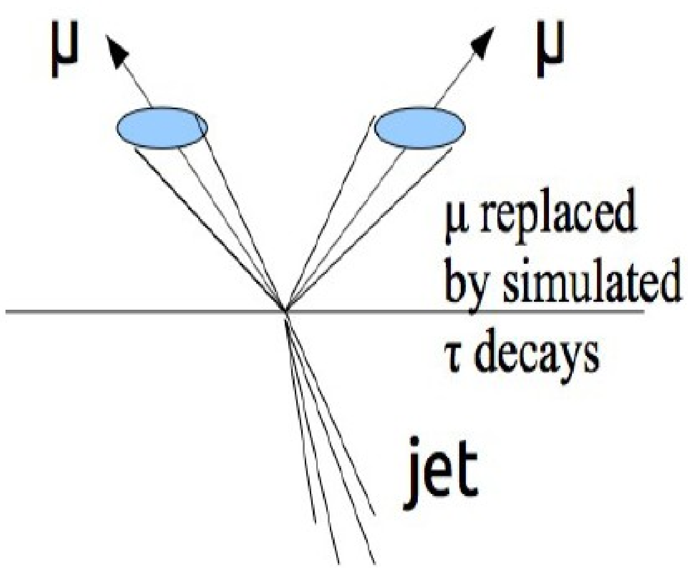
Signal curve — Resolution — Left tail

Dimuon spectrum



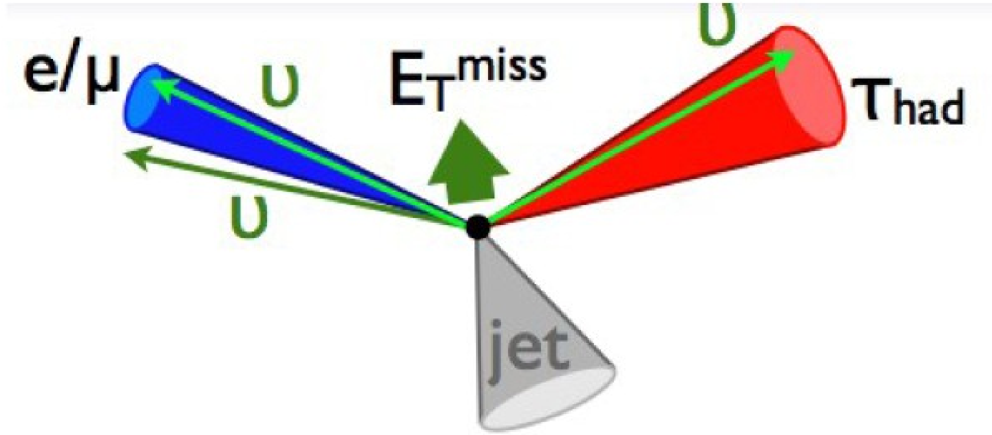
H/A/h → ττ search

Z→ττ + jets: overwhelming irreducible background



Embedding Z→μμ events with simulated taus:
data-driven background estimate

Invariant mass not fully constrained by reconstructed objects (neutrinos appear as E_T^{miss})



Special techniques to estimate invariant mass of the di-tau system

CMS: maximum likelihood mass
- likelihood for free parameters maximized wrt kinematic constraints

ATLAS: missing mass calculator (MMC)
- scan neutrino direction and take most probable value for mass reconstruction

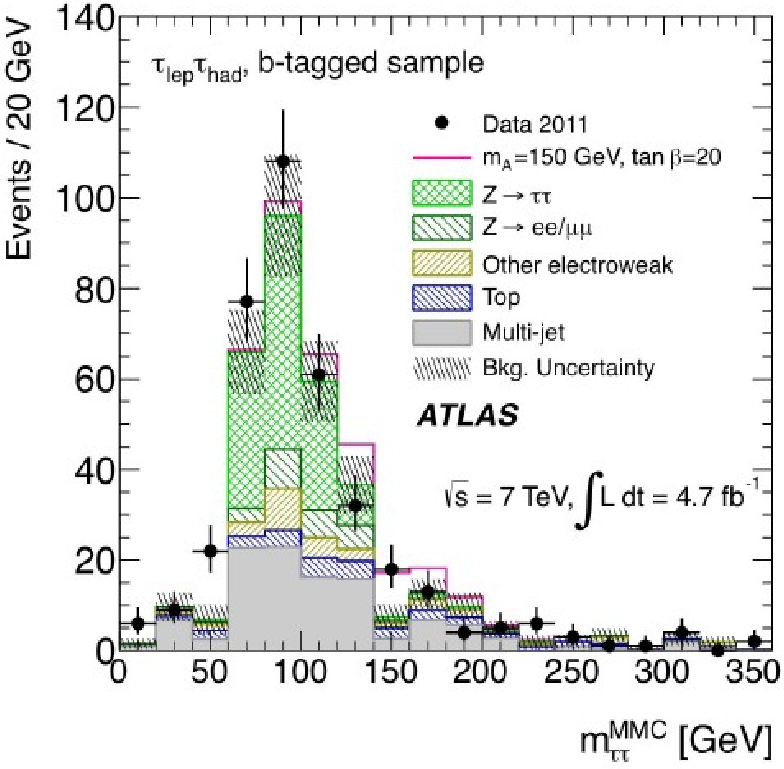
H/A/h → ττ search

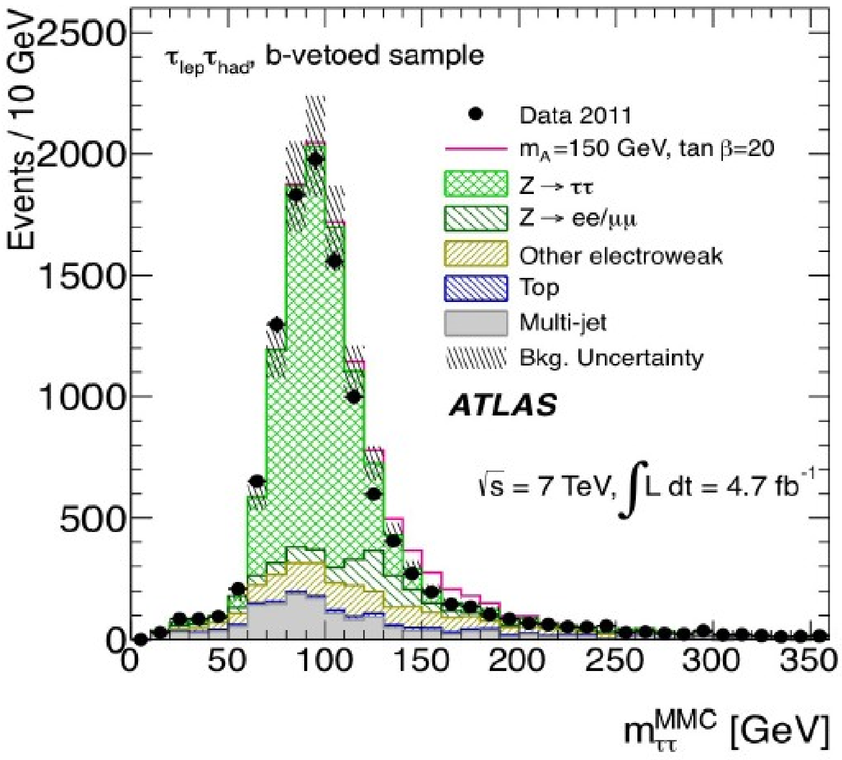
The $\tau_l\tau_h$ selection includes:

- electron or muon with p_T > 25(20) GeV
- tau candidate with p_T > 20 GeV
- m_T(lepton, E_T^{miss}) < 30 GeV
- b-tagged category (20 < $p_T^{b\text{-}jet}$ < 50 GeV)

Estimation of key backgrounds:

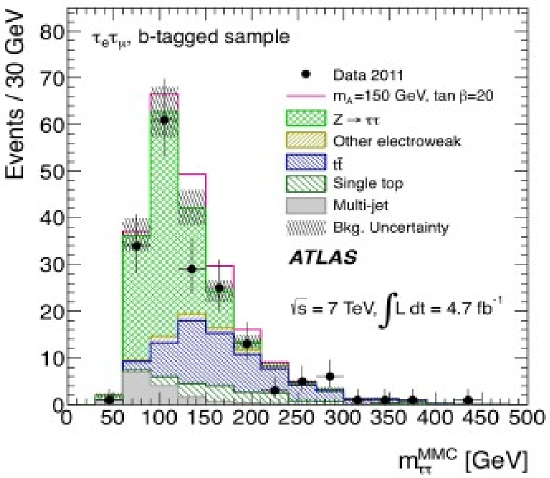
- W+jets: normalized in high m_T region
- top pair production: normalized in b-jet high p_T region

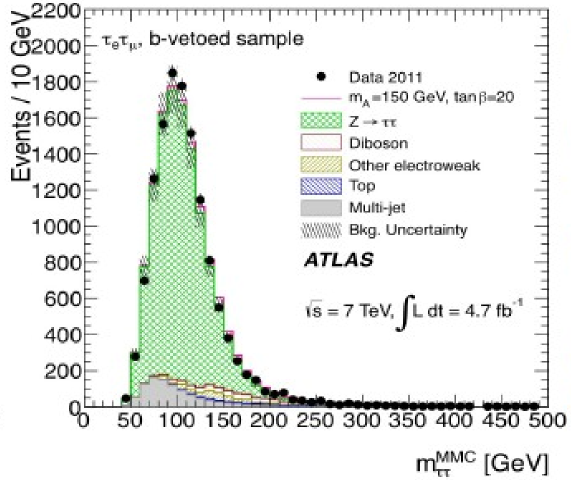




H/A/h → ττ search

Searches in $\tau_e\tau_\mu$, $\tau_h\tau_h$ topologies, b-tagged/b-vetoed categories

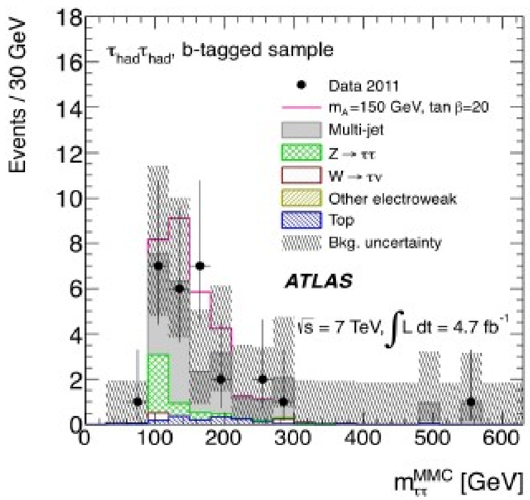


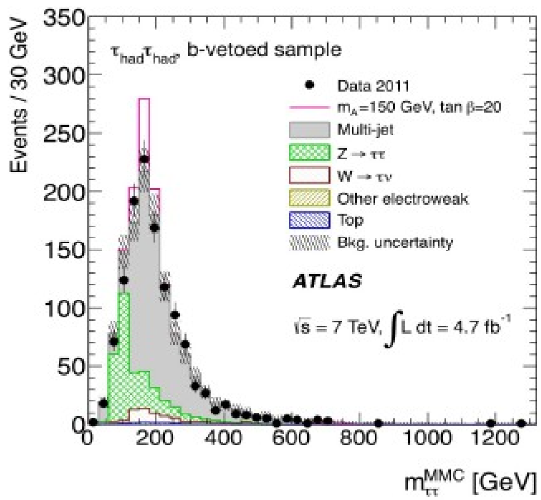


electron + muon with p_T > 15/10 GeV

category dependent cuts on:
$E_T^{miss}+p_T^{e}+p_T^{\mu}$, $\Delta\varphi_{e\mu}$,
Σp_T^{jet}, $\Sigma\cos\Delta\varphi(l, E_T^{miss})$

top backgrounds normalized in region with two b-tagged jets





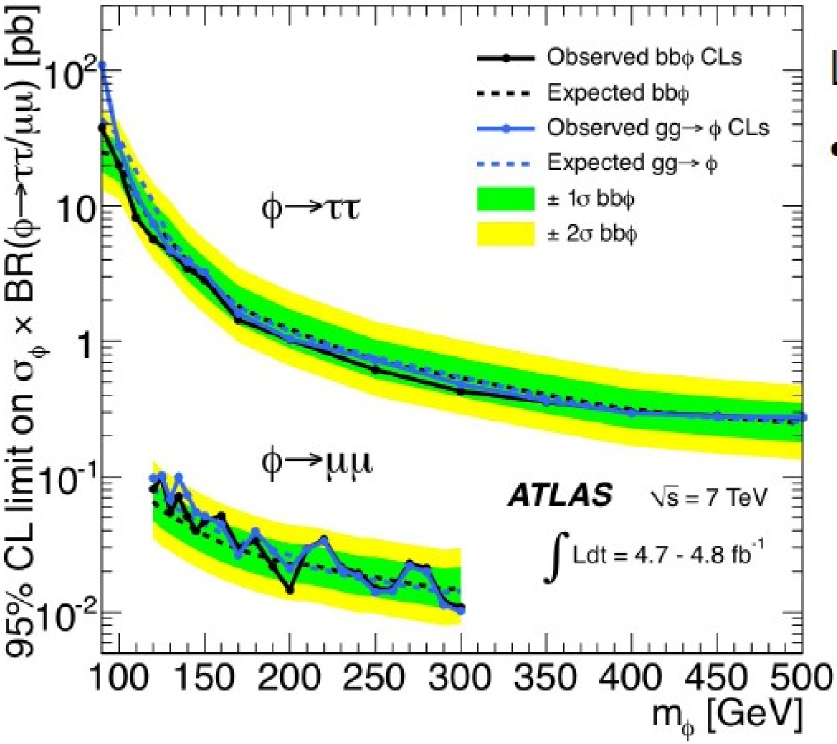
two τ_h with p_T > 45/30 GeV
(60/30 for b-veto cat.)

E_T^{miss} > 25 GeV

b-tagged requires 20 < $p_T^{b\text{-}jet}$ < 50 GeV

multijet backgrounds estimated using control regions in data (shape+normalization)

Neutral MSSM Higgs searches

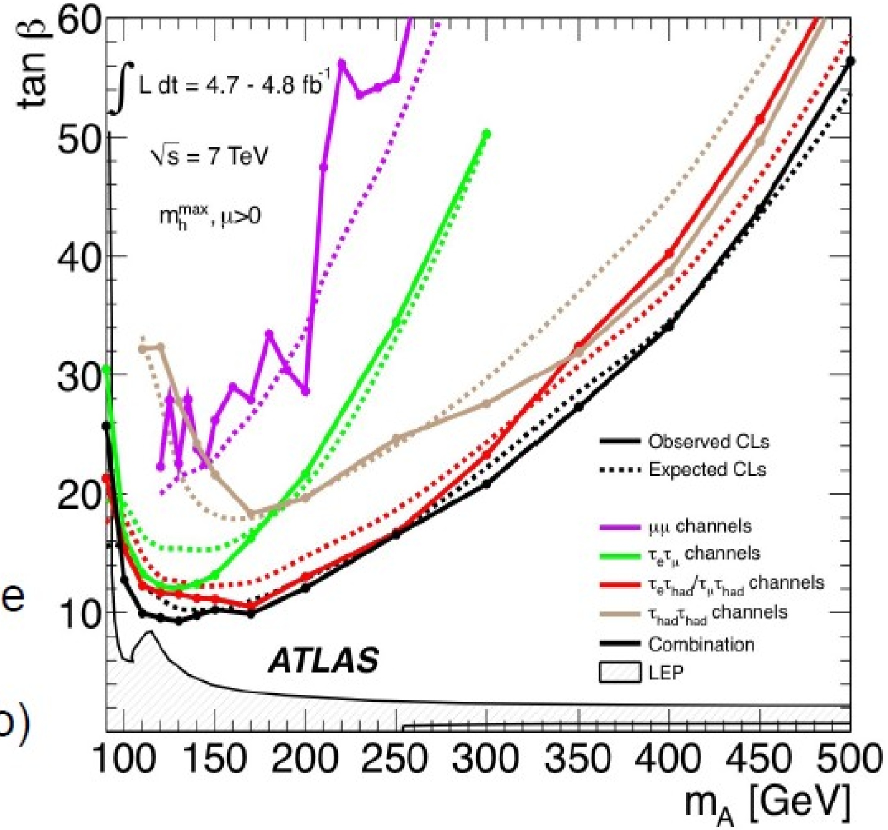


Limits on signal strength for combination:

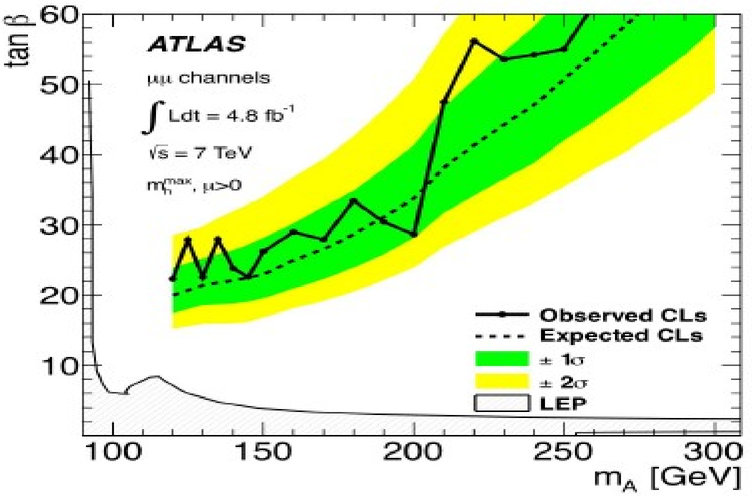
- binned profile likelihood on MMC distributions

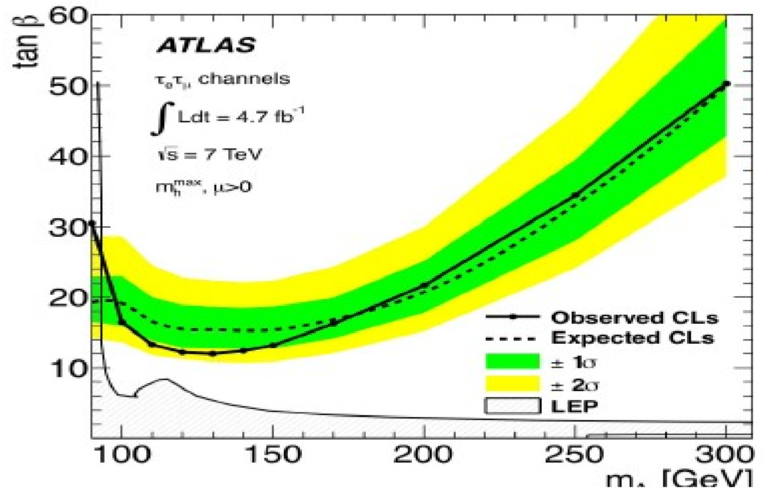
95% CLs exclusions shown in m_A-tanβ plane

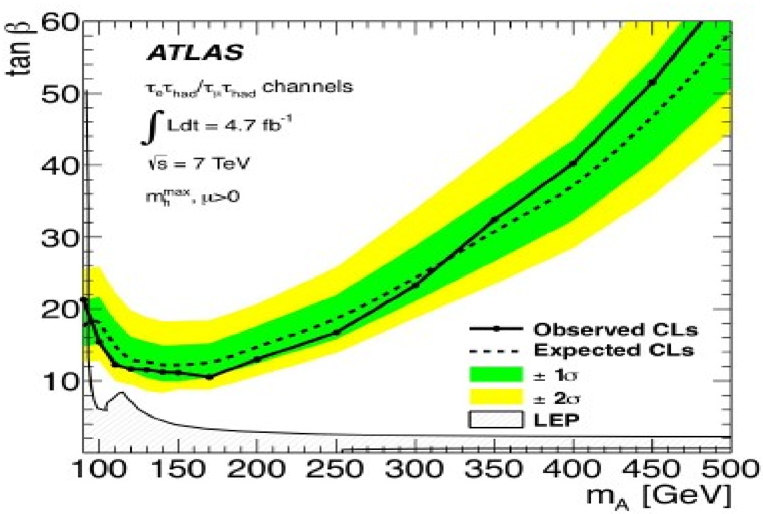
(m_h^{max} scenario)

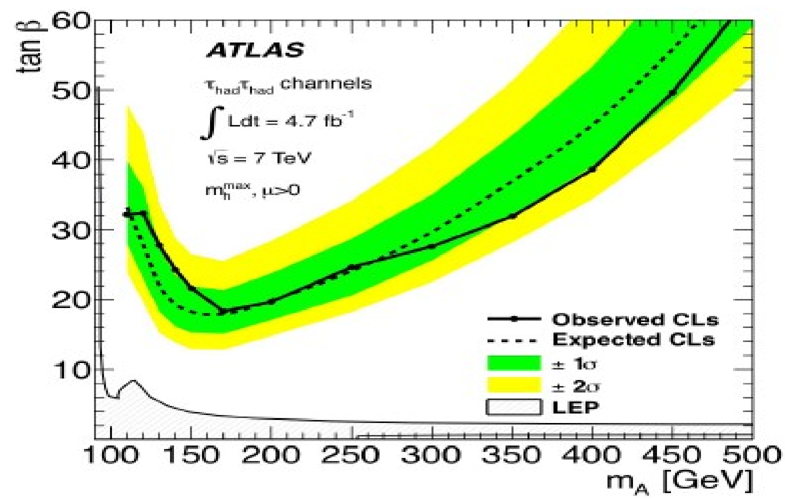


Neutral MSSM Higgs searches





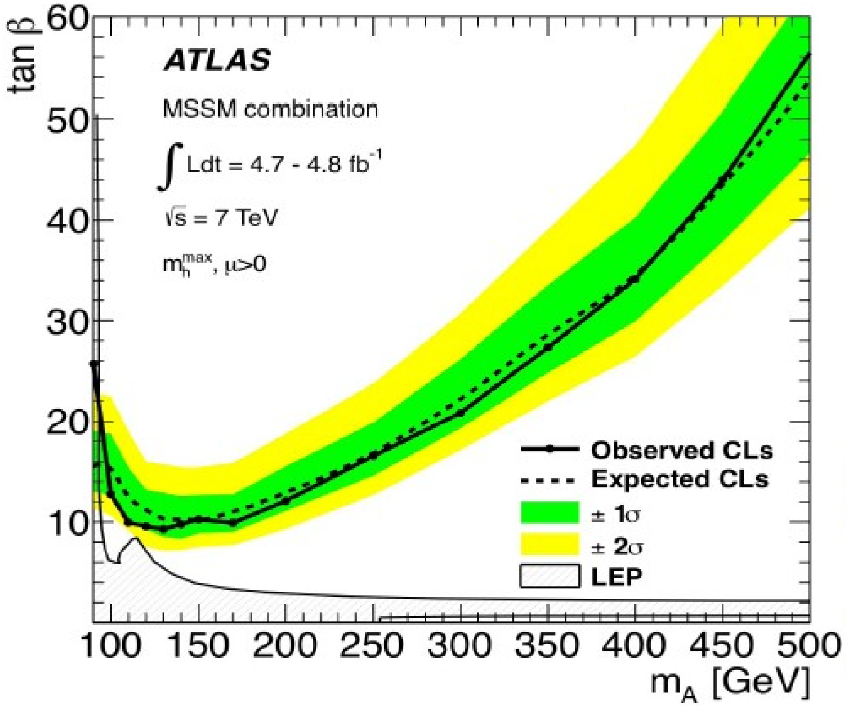


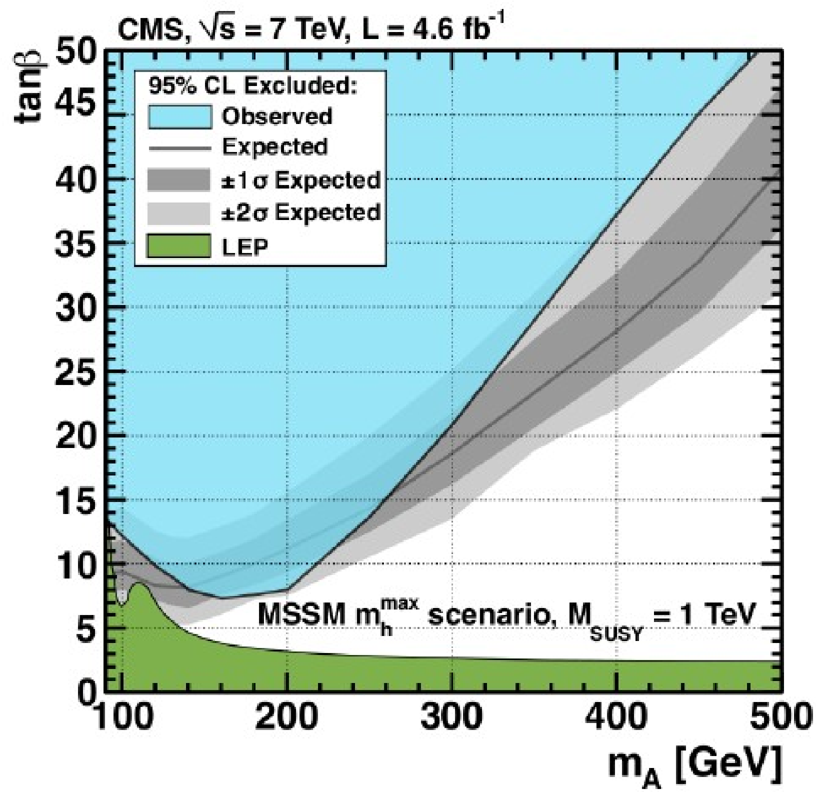


Neutral MSSM Higgs searches

Searches at ATLAS and CMS (7 TeV) for MSSM Neutral and Charged Higgs Bosons (many channels involved)

Large regions of MSSM parameter space excluded at 95% CL



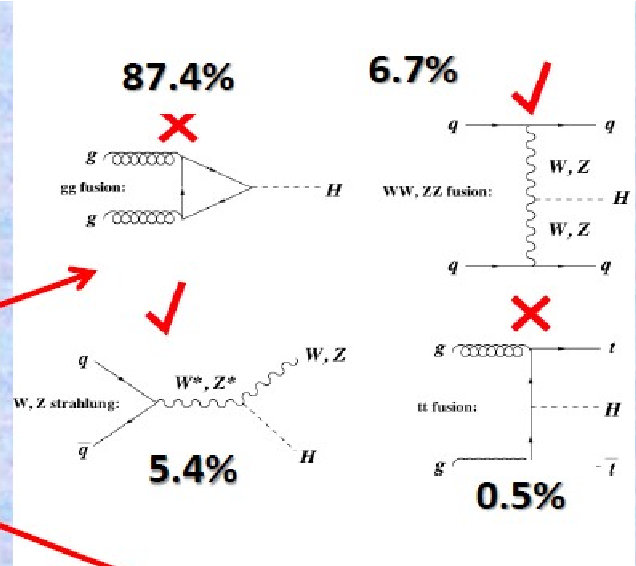


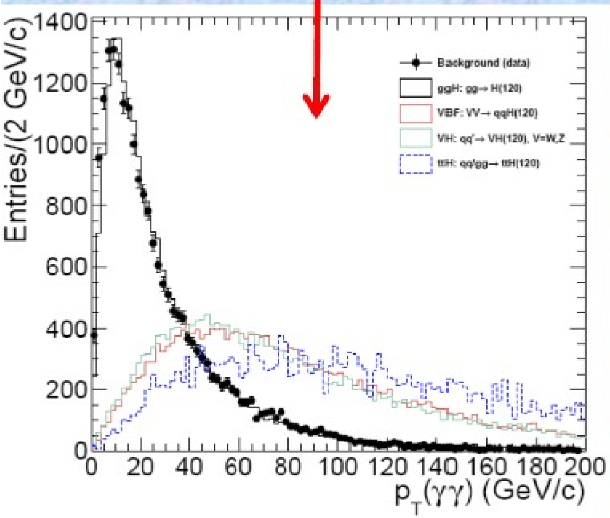
Searches using more data at 8 TeV can further extend exclusions.....but........

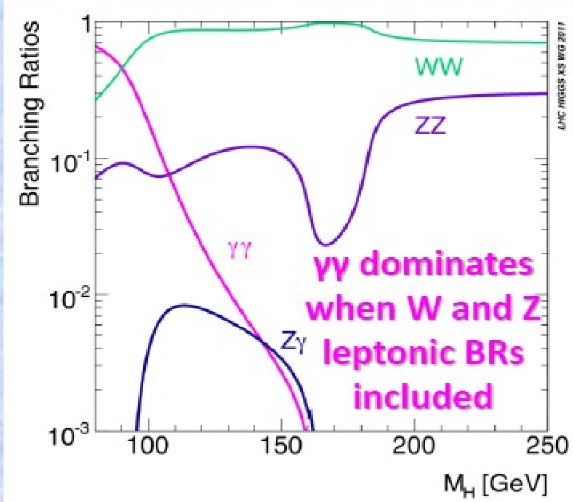
Since we've found one Higgs-like boson, maybe the other four are just around the corner!

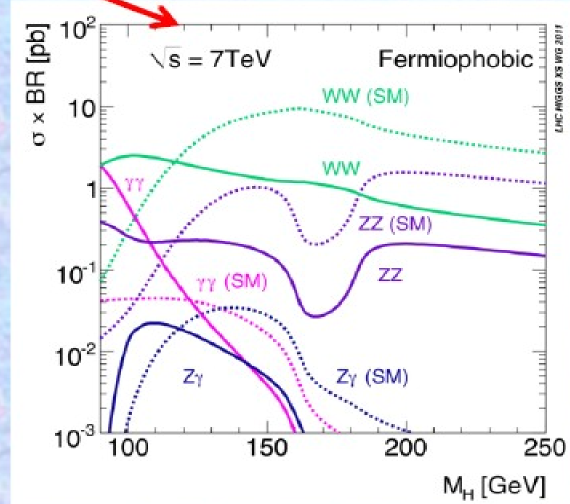
Fermophobic Higgs

- **SM Higgs results are very interesting**
  - No excess in ττ, signal strength in γγ might be too large
- **Interest for beyond the SM scenario of EWSB (2 HDM)**
  - FP is important part of Higgs program - couplings
- **Fermiophobic Higgs**
  - No couplings to fermions (Vector boson fusion (VBF) or associated VH production only)
  - Low mass higgs decays change dramatically
  - Higgs is boosted (exploit presence of two tag jets in forward region or associate W and Z (leptons)









Next topics

- 19.12 - **SUSY**
- 9.1 – other searches for New Physics
- 16.1 - B-physics programme
- 23.1 – heavy ion programme

Definitions:

Global signal strength factor μ:

Scale factor on the total number of events predicted by the SM for the Higgs boson signal:

μ=0 - bgd only hypothesis

μ=1 - SM signal in addition to the bgd

Hypothesised values of μ tested with statistics based on profile likelihood ratio.

Local p_0:

Probability that the background can produce a fluctuation greater than or equal to the excess observed in data. Equivalent in terms of number of standard deviations is called local significance.

95% CLs exclusion:

Value of μ is regarded as excluded at 95%CL when CLs is less than 5%. A SM Higgs boson with mass m_H is conisdered excluded at 95%CL when μ=1 is exluded at that mass.