Beyond-the-Standard Model Higgs Results from ATLAS and CMS

Stephen Sekula
Southern Methodist University
On behalf of the ATLAS and CMS Collaborations

Presented at "The LHC Higgs Signal: Characterization, Interpretation and BSM Model Implications"
University of California - Davis
April 22, 2013

SMU. DEDMAN COLLEGE OF HUMANITIES & SCIENCES


Higgs Boson walks into a church:
Priest: "Get out we don't allow Higgs Boson in here
Higgs Boson: "But without me how can you have mass?"

The Cathedral of Dark Matter

This week: "How, exactly, do I have mass?"

MSSM-Inspired Searches

Important Features

$h^0,\ H^0,\ A^0,\ H^{\pm}$ → Five physical higgs bosons (2 CP-even, one CP-odd, and 2 electrically charged)

$M^2_{H^{\pm}} = M^2_A + M^2_{W^{\pm}}$ → Tree-level mass relationship

$M_A,\ \tan(\beta),\ X_t,\ M_2,\ \mu,\ M_{SUSY}$ → Free parameters

Coupling	Mixing Angle Dependence	Mass Dependence
Huu	sin(α)/sin(β)	m_u
Hdd	cos(α)/cos(β)	m_d
Auu	cot(β)	m_u
Add	tan(β)	m_d
$H^{\pm}$ud	$m_d \tan\beta\ (1 + \gamma_5) + m_u \cot\beta\ (1 - \gamma_5)$	

m_h-max scenario

$$m_t = 174.3 \text{ GeV}, \quad M_{SUSY} = 1 \text{ TeV}, \quad \mu = 200 \text{ GeV}, \quad M_2 = 200 \text{ GeV},$$
$$X_t^{\rm OS} = 2\, M_{SUSY} \text{ (FD calculation)}, \quad X_t^{\overline{\rm MS}} = \sqrt{6}\, M_{SUSY} \text{ (RG calculation)}$$
$$A_b = A_t, \quad m_{\tilde{g}} = 0.8\, M_{SUSY} \ .$$

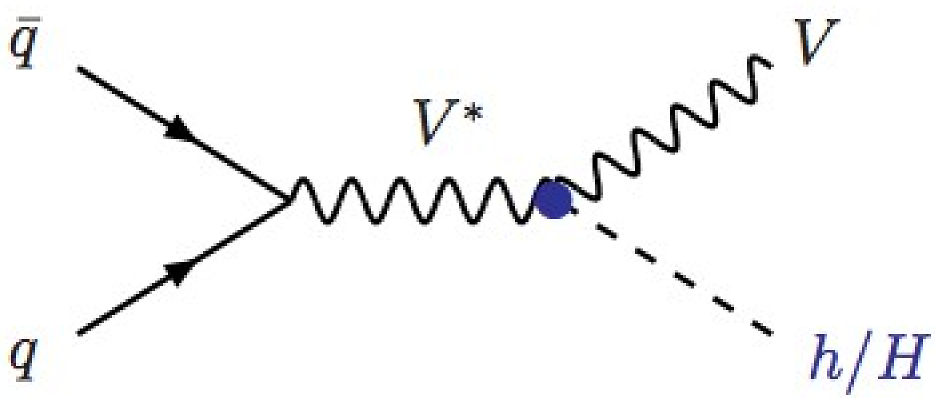
Eur.Phys.J.C26:601-607,2003

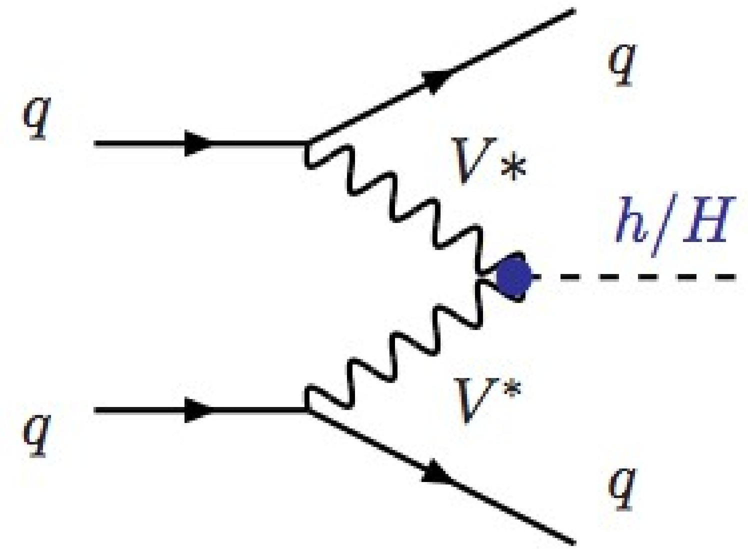
Designed to maximize the SM-like Higgs (h^0) mass ($m_h \sim 135$ GeV).

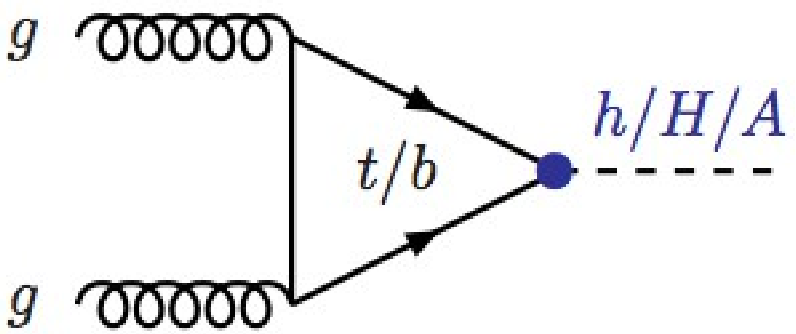
However, we now believe we know the mass of the h^0 (125.5 GeV), so m_h-max is a bit too aggressive.

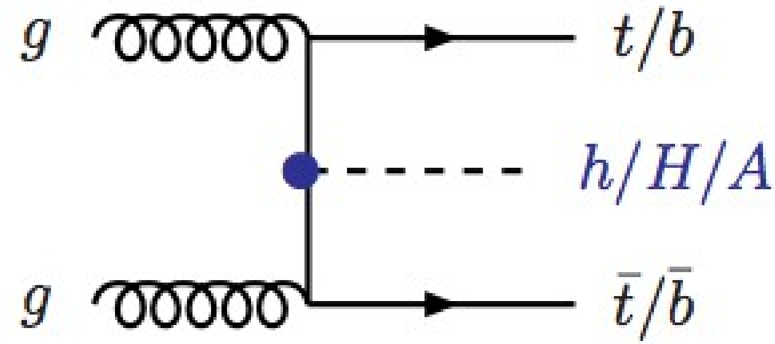
More on this later...

$h^0/H^0/A^0$ Production







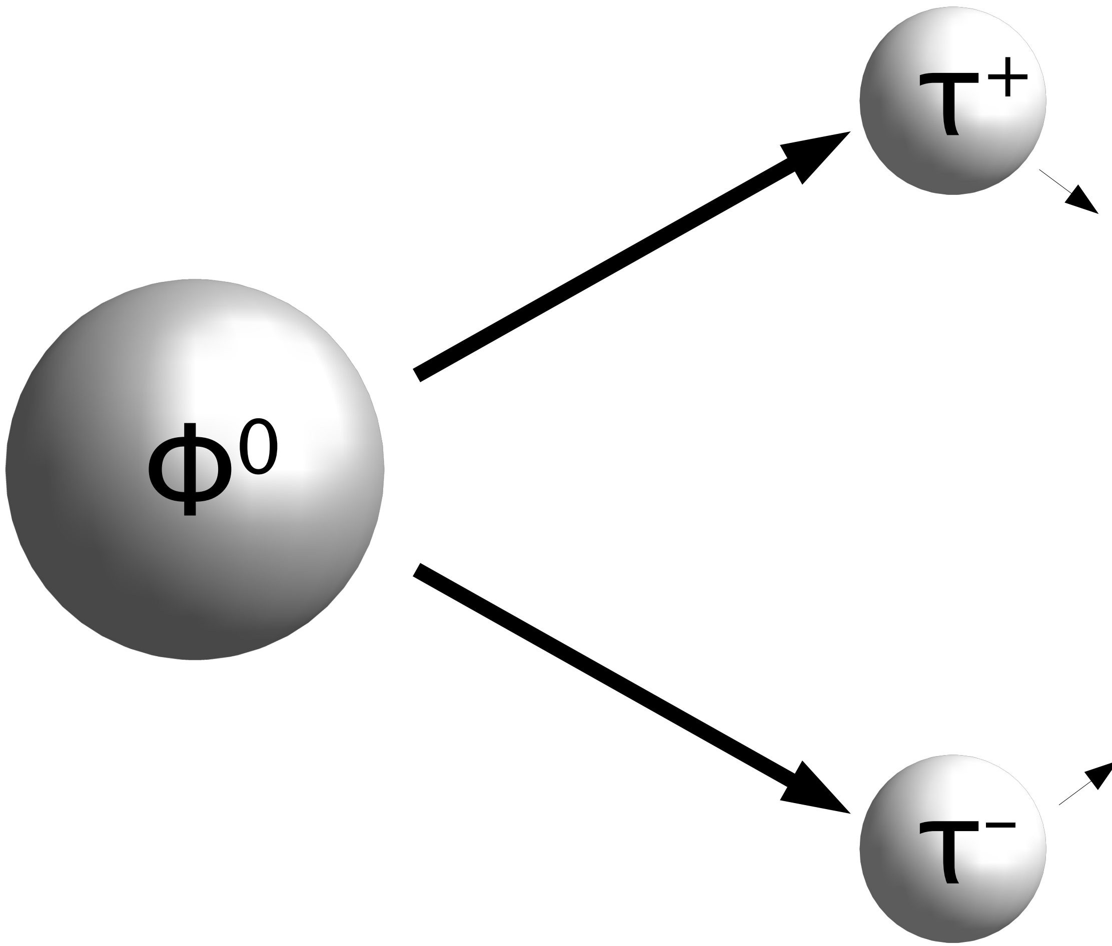


Significant MSSM neutral Higgs production mechanism at any tanβ

b-associated production can be significant at large tanβ

Phys.Rept.457:1-216,2008

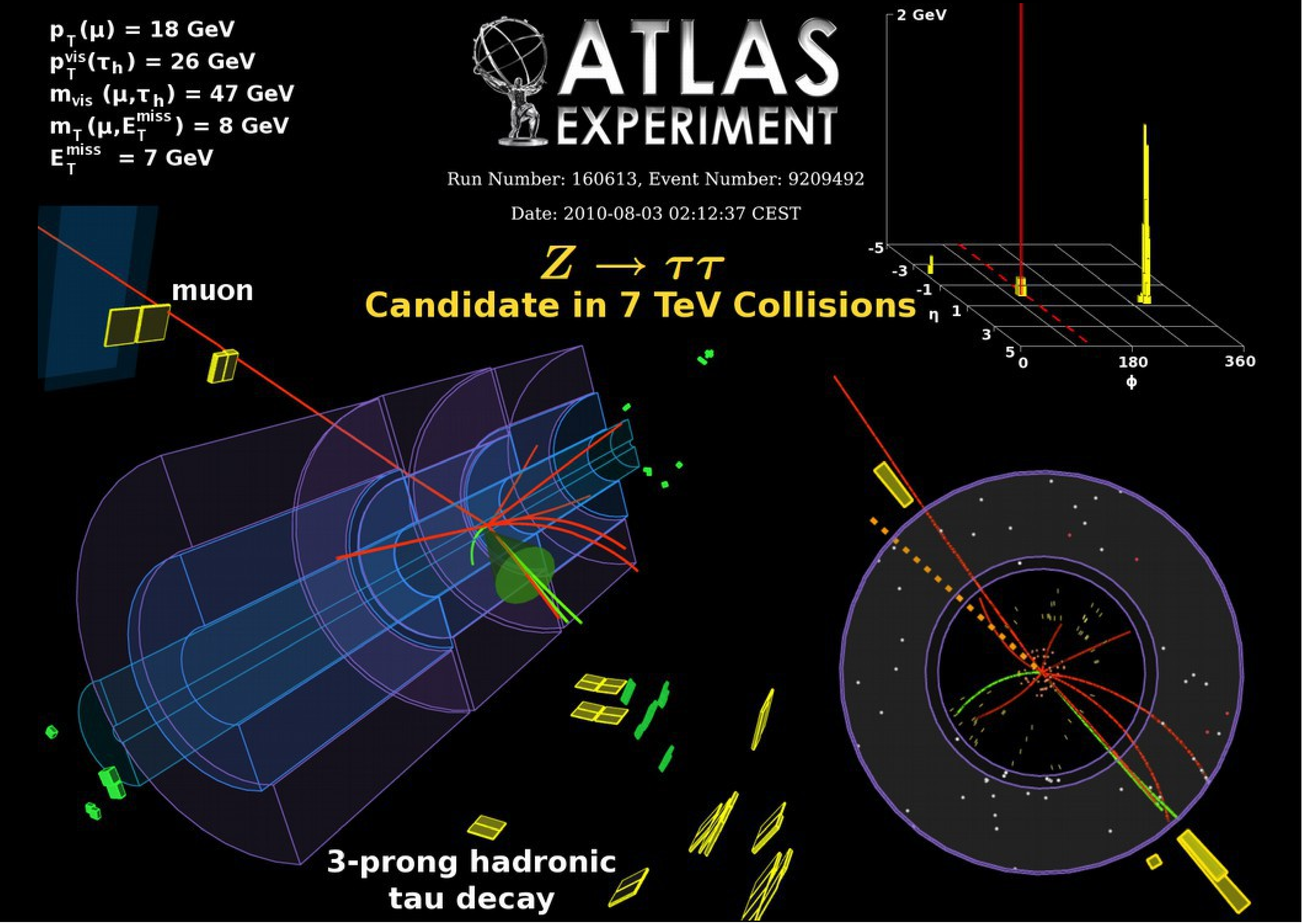
Heavy $H^0/A^0 \rightarrow \tau\,\tau$



Final States

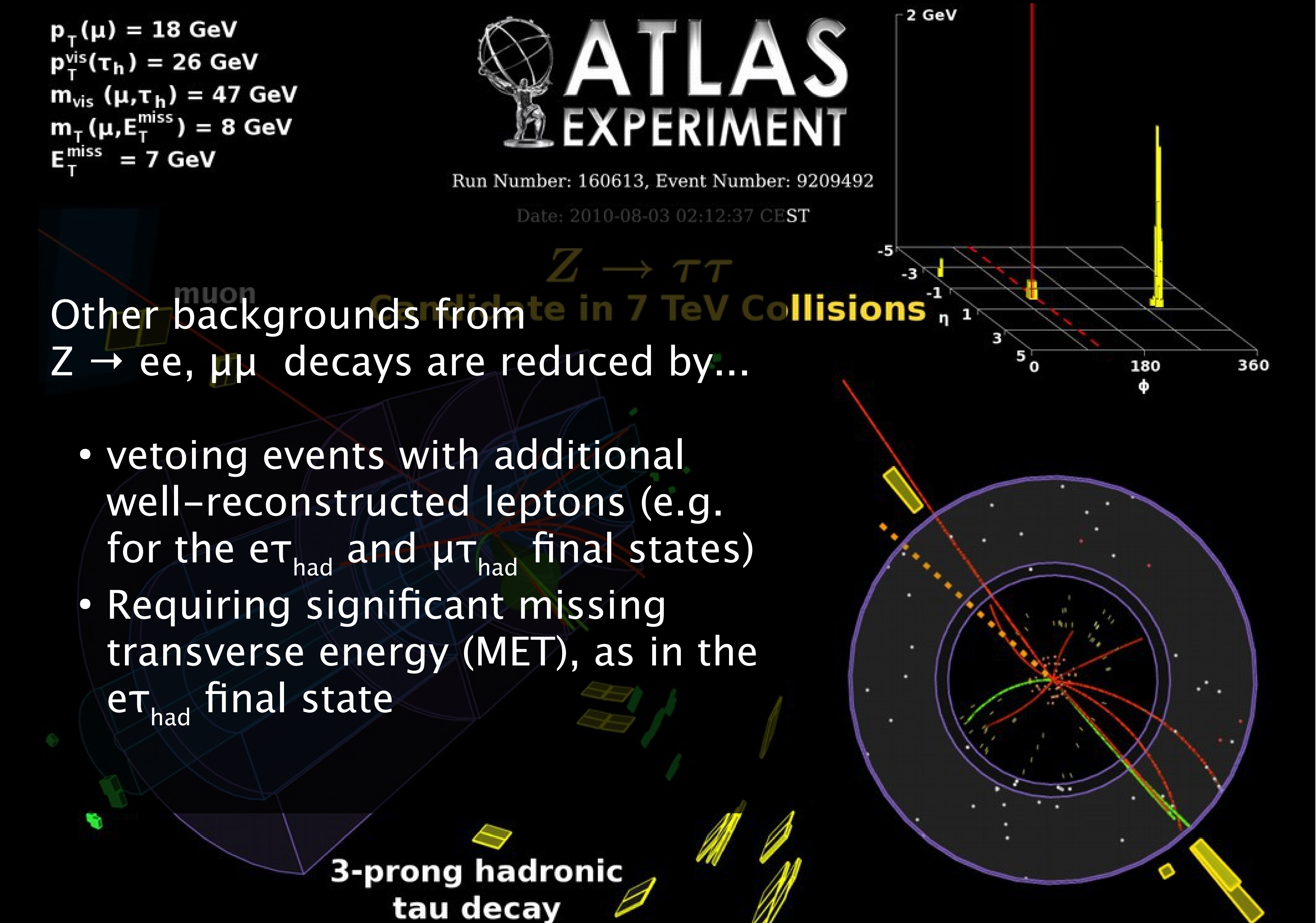
CHANNEL	ATLAS	CMS
$\tau_{had}\ \tau_{had}$	✓	
$e\ \tau_{had}$	✓	✓
$\mu\ \tau_{had}$	✓	✓
$e\ \mu$	✓	✓
$\mu\ \mu$	direct only	✓

Significant MSSM neutral Higgs decay mechanism for $\tan\beta > 1$

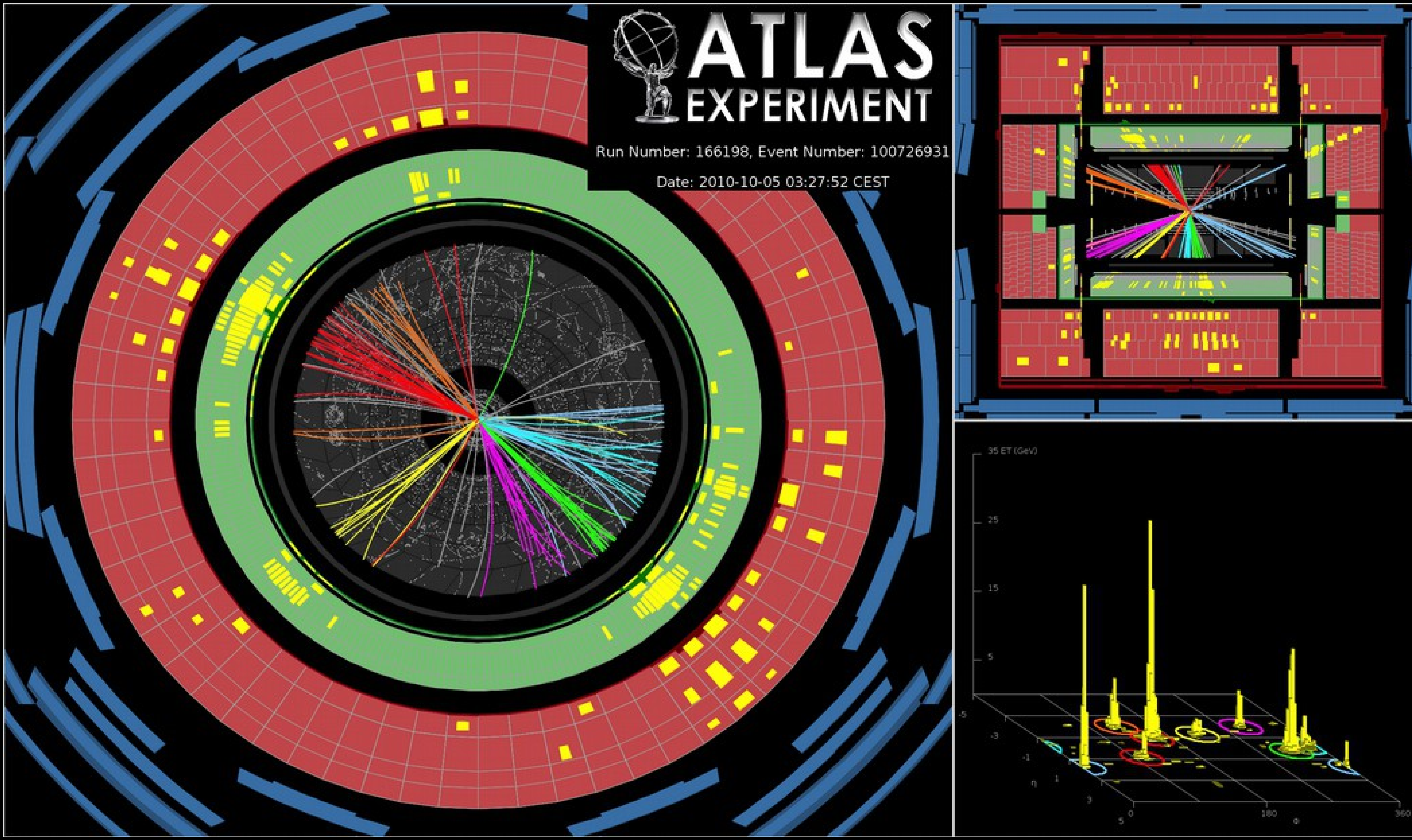

$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
m_{vis} (μ,τ_h) = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \rightarrow \tau\tau$
Candidate in 7 TeV Collisions
muon
3-prong hadronic tau decay
2 GeV
η
φ
-5
-3
-1
1
3
5
0
180
360

Other backgrounds from
$Z \rightarrow ee, \mu\mu$ decays are reduced by...

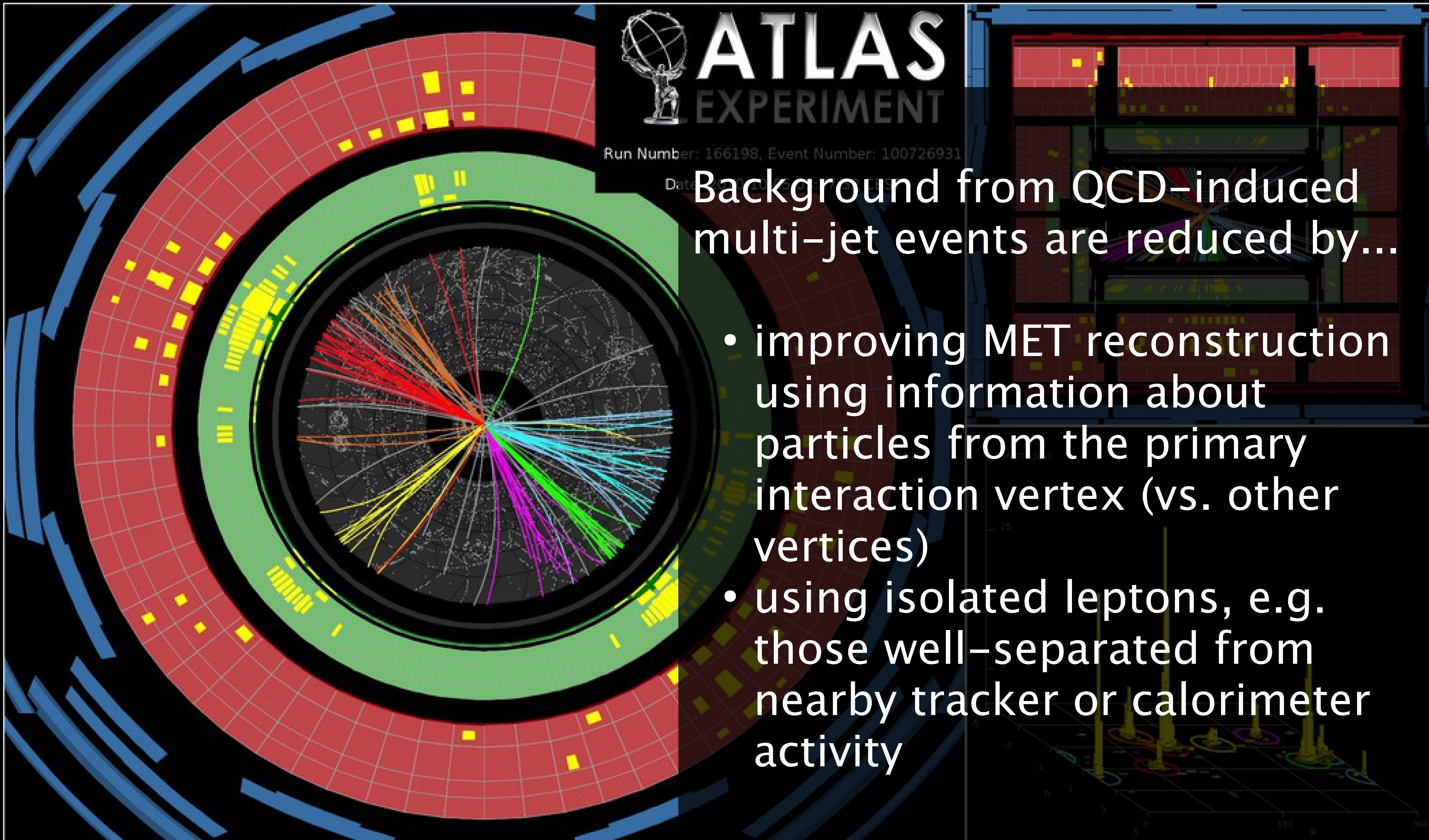
- vetoing events with additional well-reconstructed leptons (e.g. for the $e\tau_{had}$ and $\mu\tau_{had}$ final states)
- Requiring significant missing transverse energy (MET), as in the $e\tau_{had}$ final state



Multi-jet QCD Events

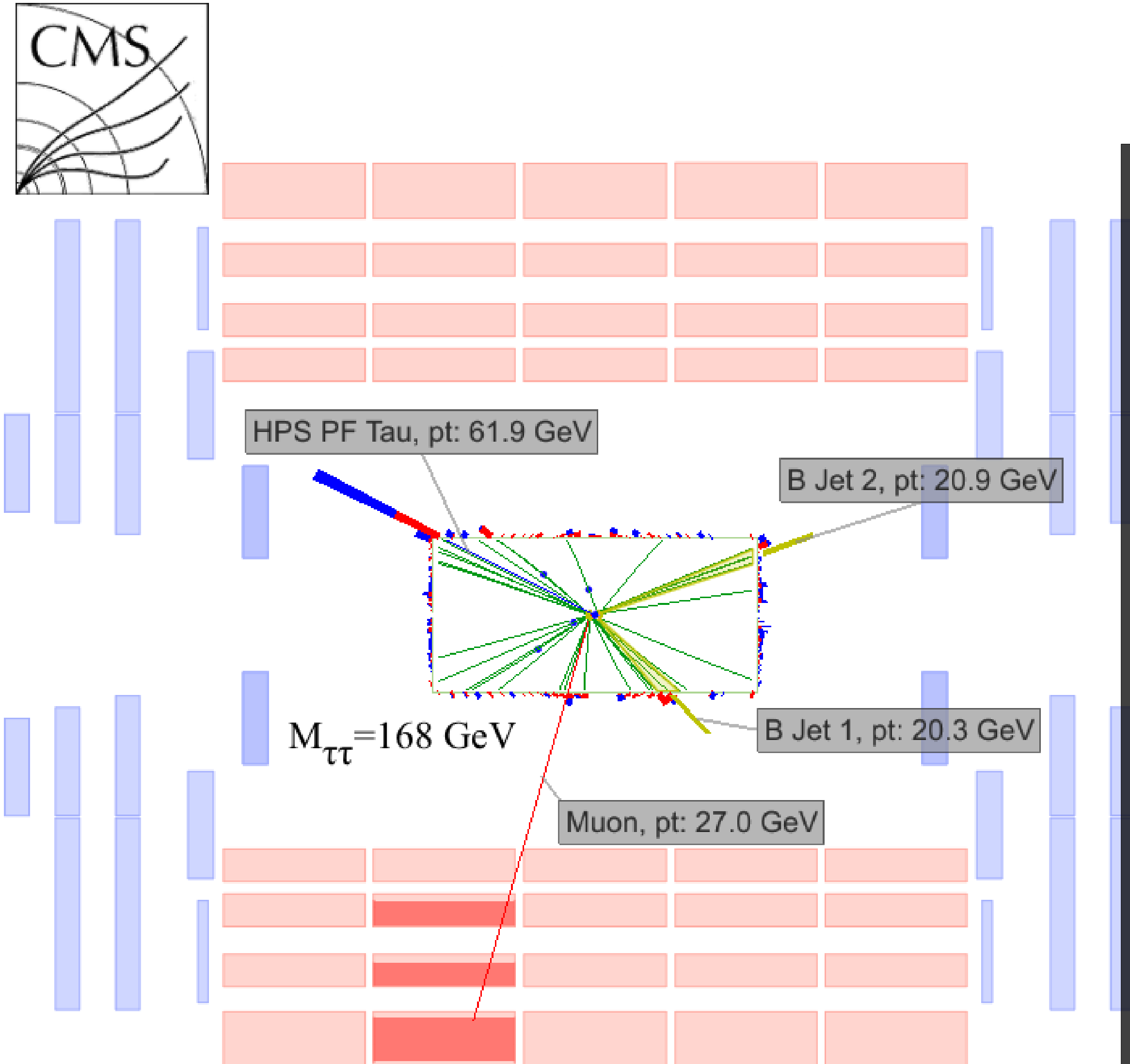


Multi-jet QCD Events



Background from QCD-induced multi-jet events are reduced by...

- improving MET reconstruction using information about particles from the primary interaction vertex (vs. other vertices)
- using isolated leptons, e.g. those well-separated from nearby tracker or calorimeter activity

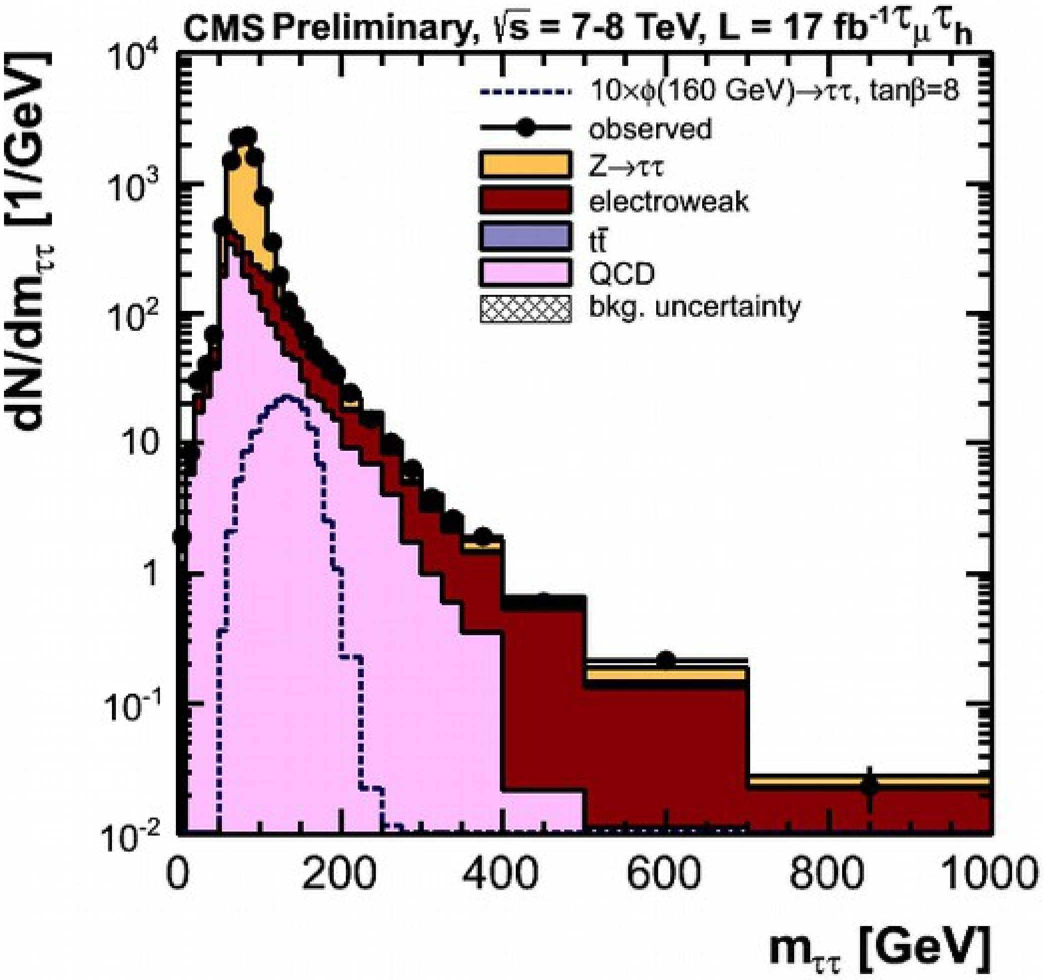


Bottom jet tagging enhances sensitivity to b-quark associated production

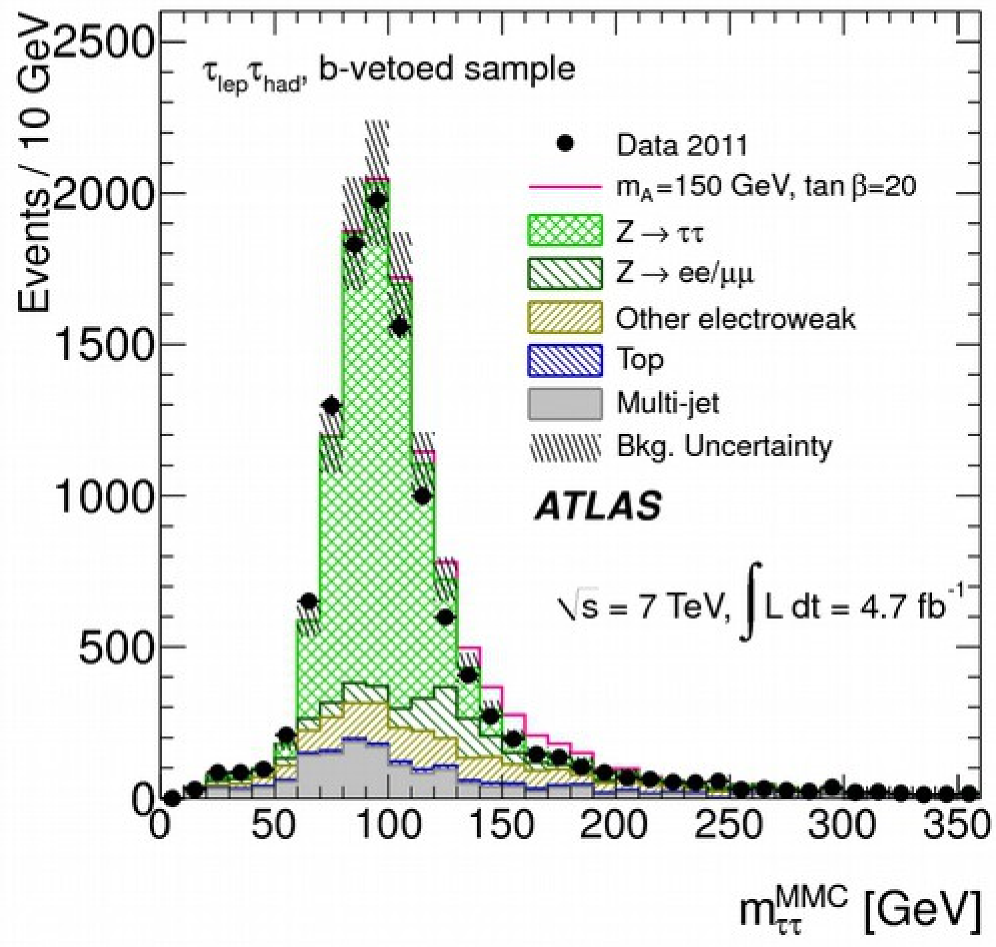
- *b-tagged category:*
  at least 1 b-tagged jet with p_T > 20 GeV
  - CMS: … and not more than 1 jet with p_T > 30 GeV.
  - ATLAS: … and the scalar sum of all jet p_Ts, H_T<100 GeV
- *no-b-tag category:*
  no b-tagged jets with p_T>20 GeV

NO B-TAG ("B-VETOED") CATEGORY

CMS-PAS-HIG-12-050



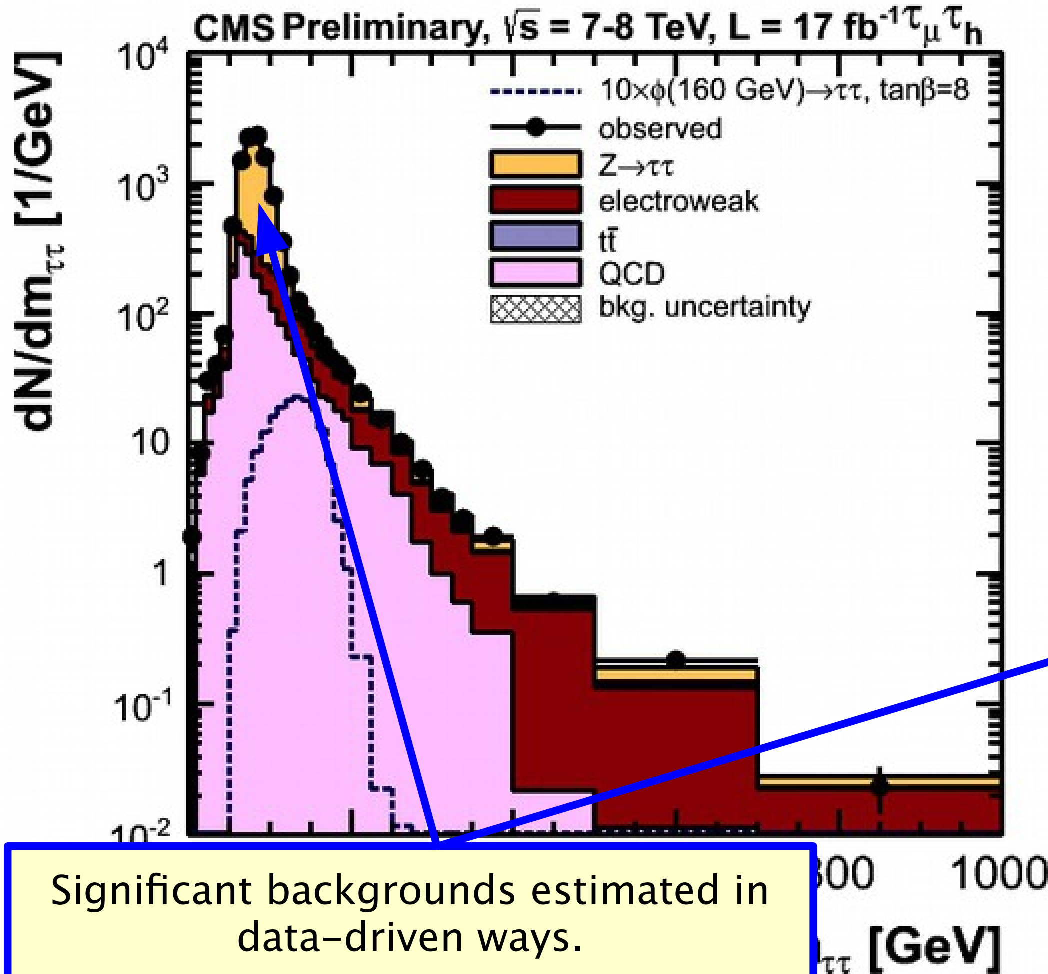
JHEP02(2013)095

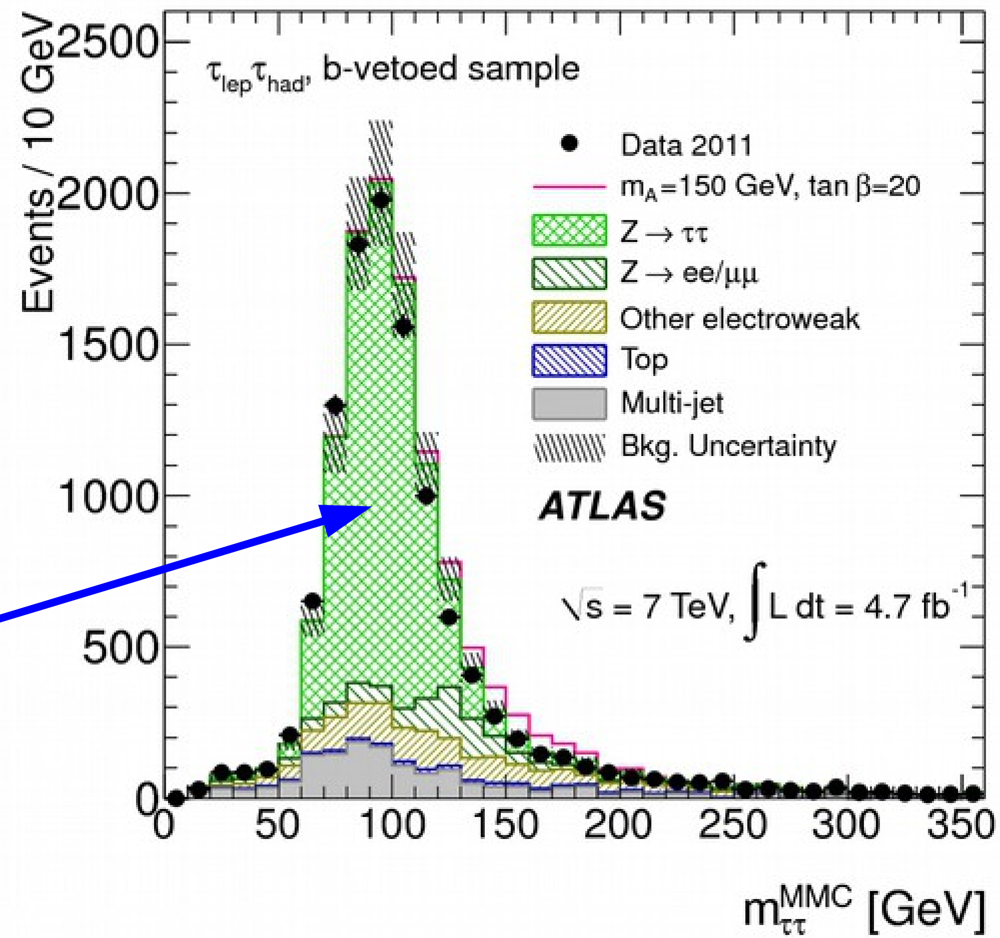


NO B-TAG ("B-VETOED") CATEGORY

CMS-PAS-HIG-12-050

JHEP02(2013)095



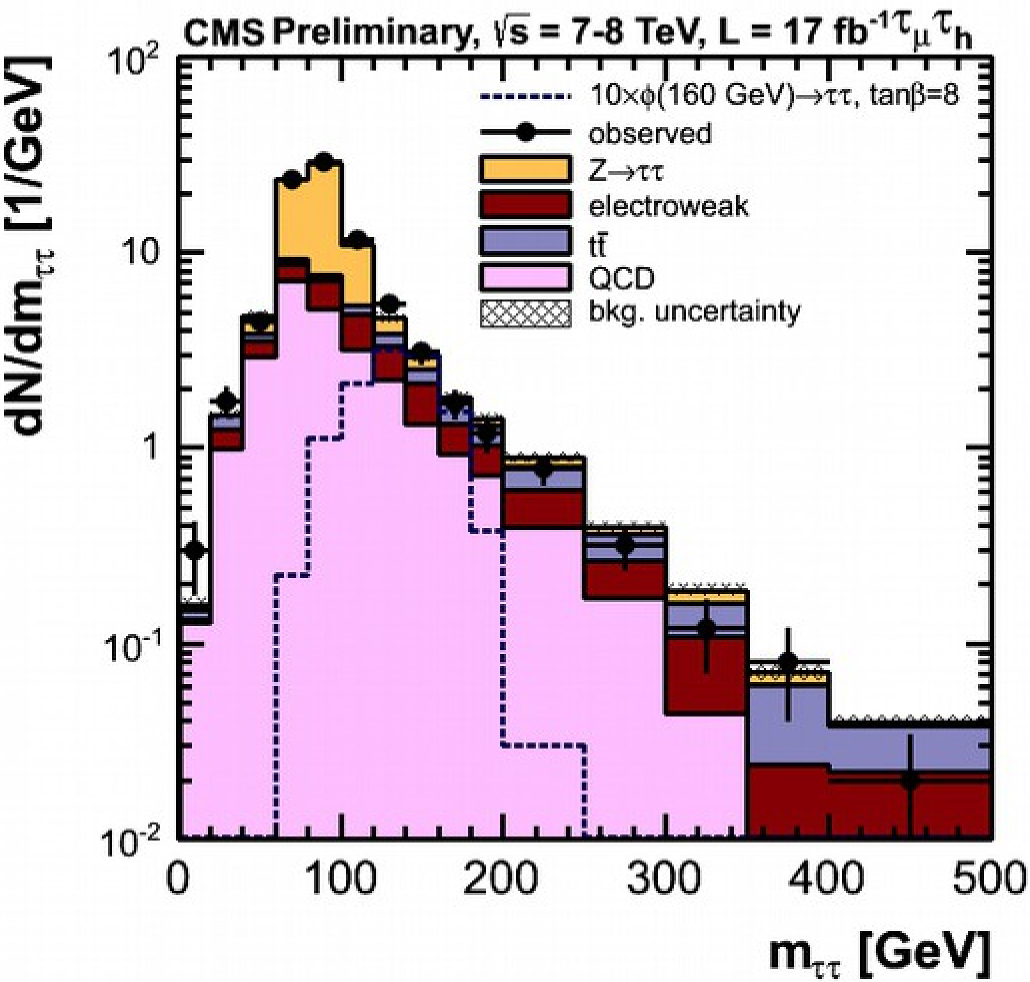


Significant backgrounds estimated in data-driven ways.

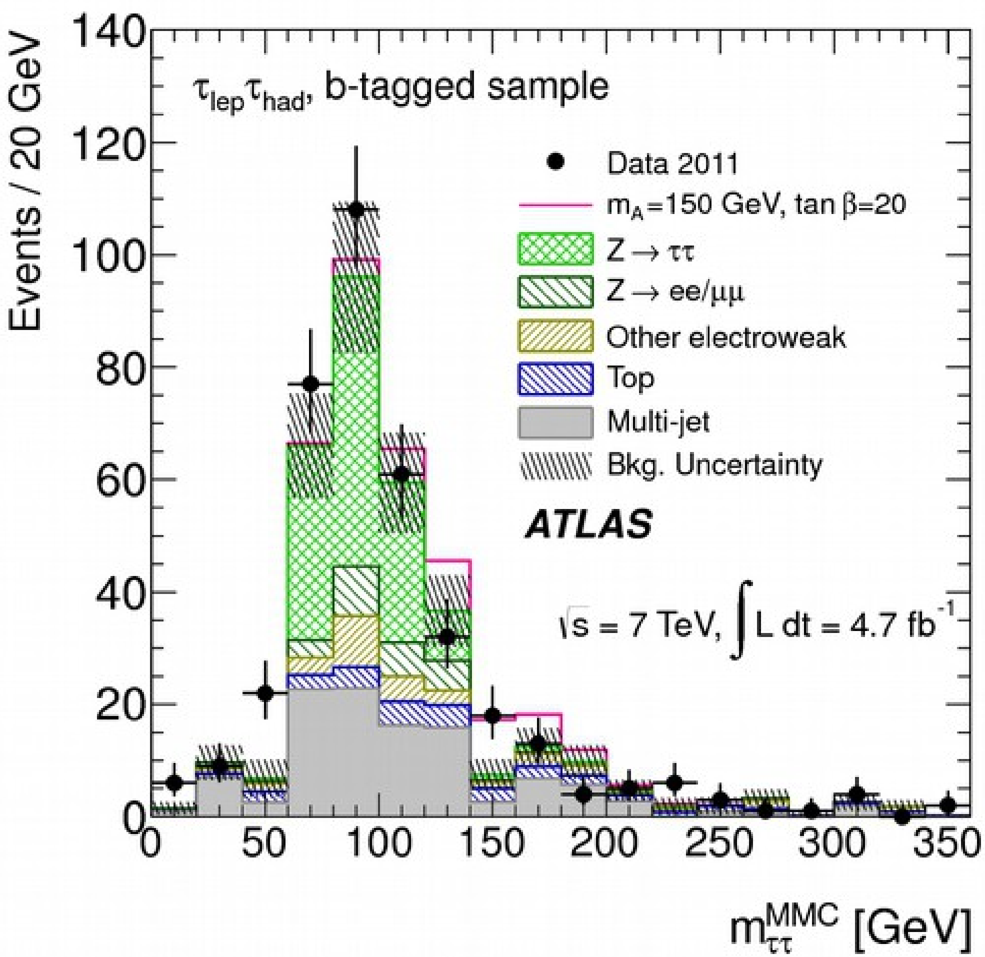
$Z \rightarrow \tau\tau$ estimated using $Z \rightarrow \mu\mu$ events embedded with simulated tau decays.

B-TAGGED CATEGORY

CMS-PAS-HIG-12-050



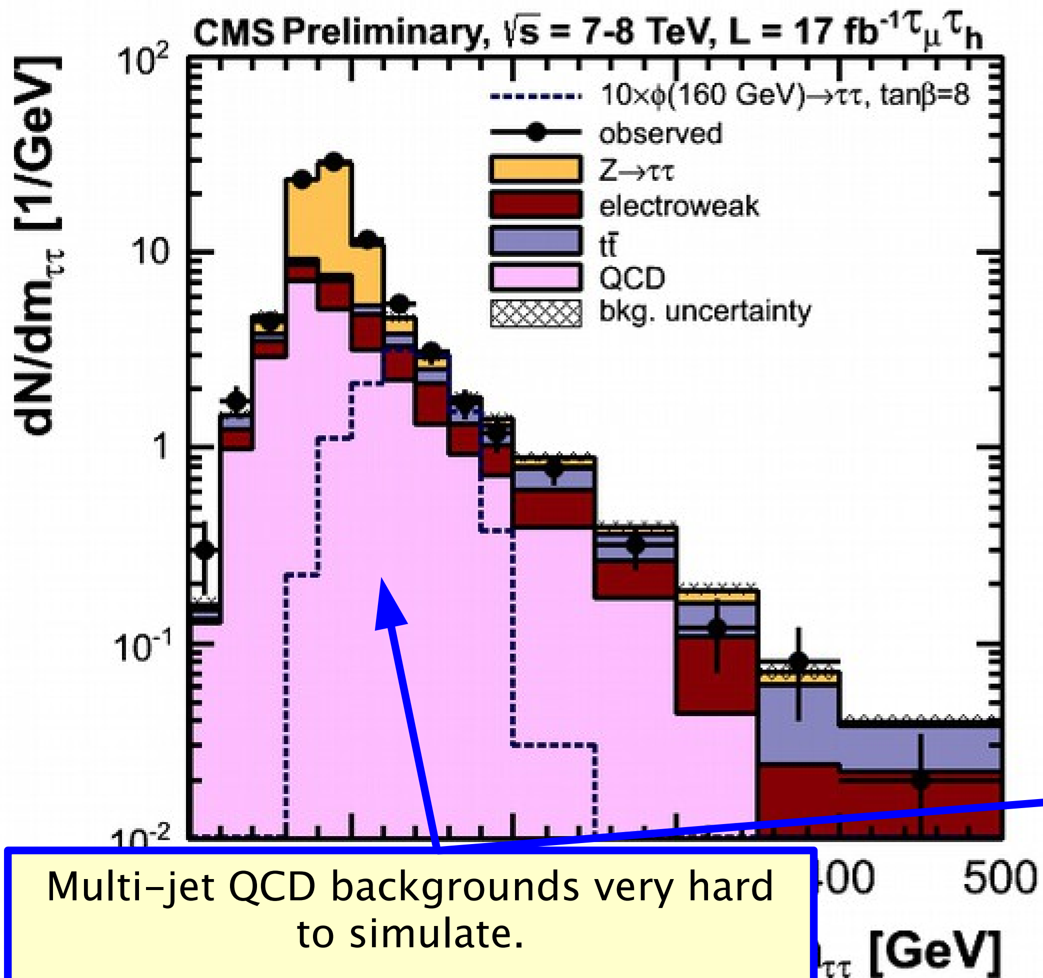
JHEP02(2013)095

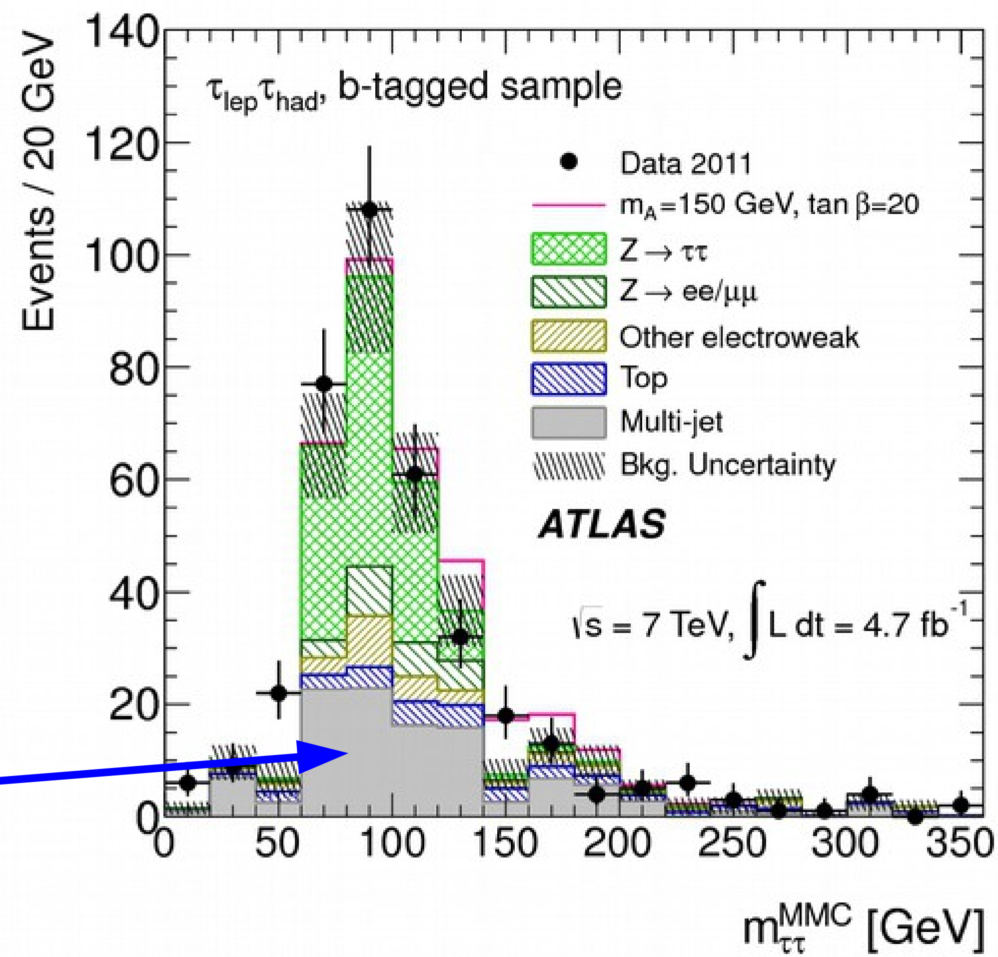


B-TAGGED CATEGORY

CMS-PAS-HIG-12-050

JHEP02(2013)095



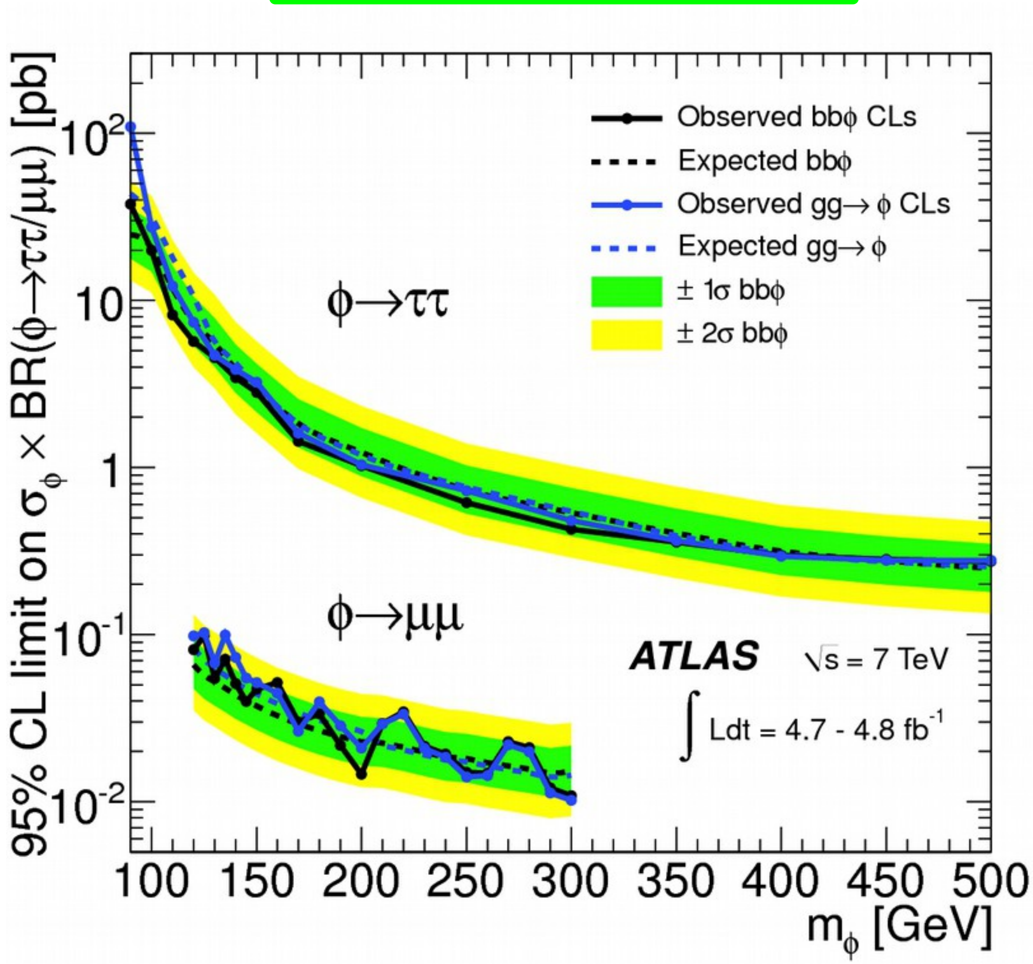


Multi-jet QCD backgrounds very hard to simulate.

Estimated using same-charge leptons in data (CMS) or using sidebands in uncorrelated variable pairs (ATLAS)

Model Independent(*) Results

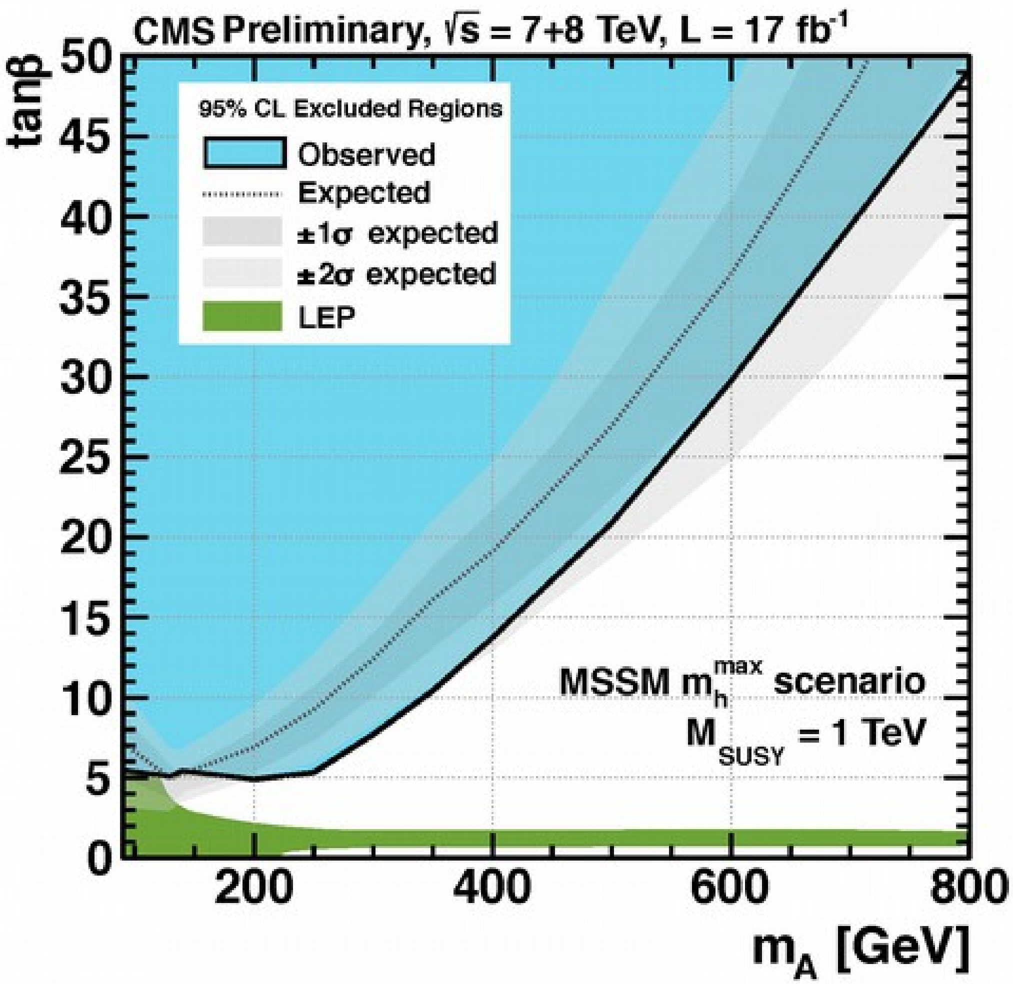
JHEP02(2013)095



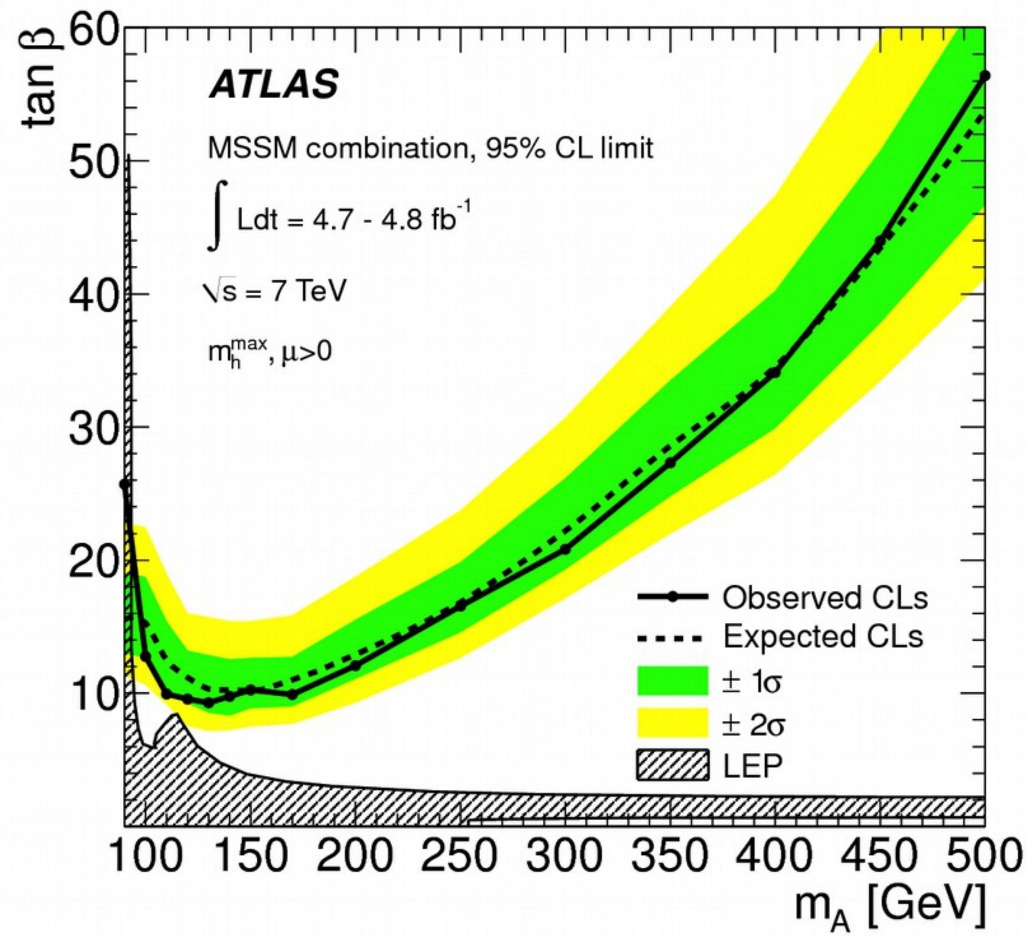
(*) These are almost completely model-independent results except insofar as we assume the production and decay of a *scalar boson**. This comment applies henceforth to results so labeled.*

Model-Dependent(*) Results

CMS-PAS-HIG-12-050

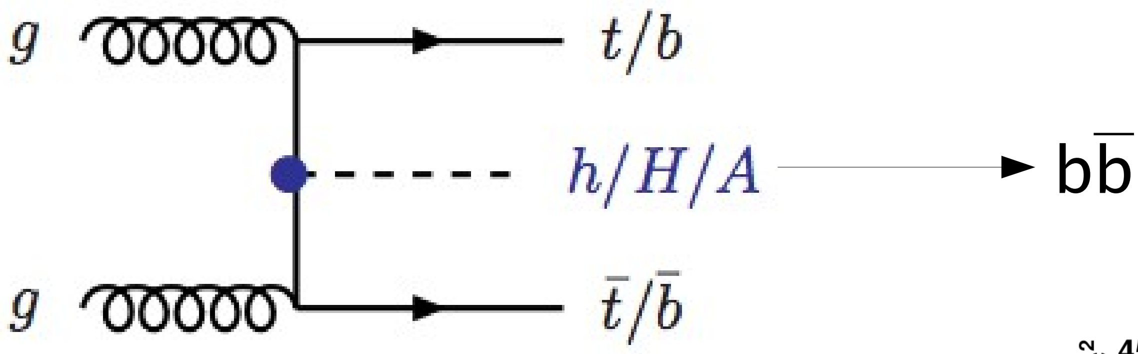


JHEP02(2013)095



(*) It should be noted that if we switch to an alternative MSSM benchmark scenario, like m_h-mod+ or m_h-mod-, we don't expect these constraints to change too much. See slide 50.

$H^0/A^0 \rightarrow b\bar{b}$



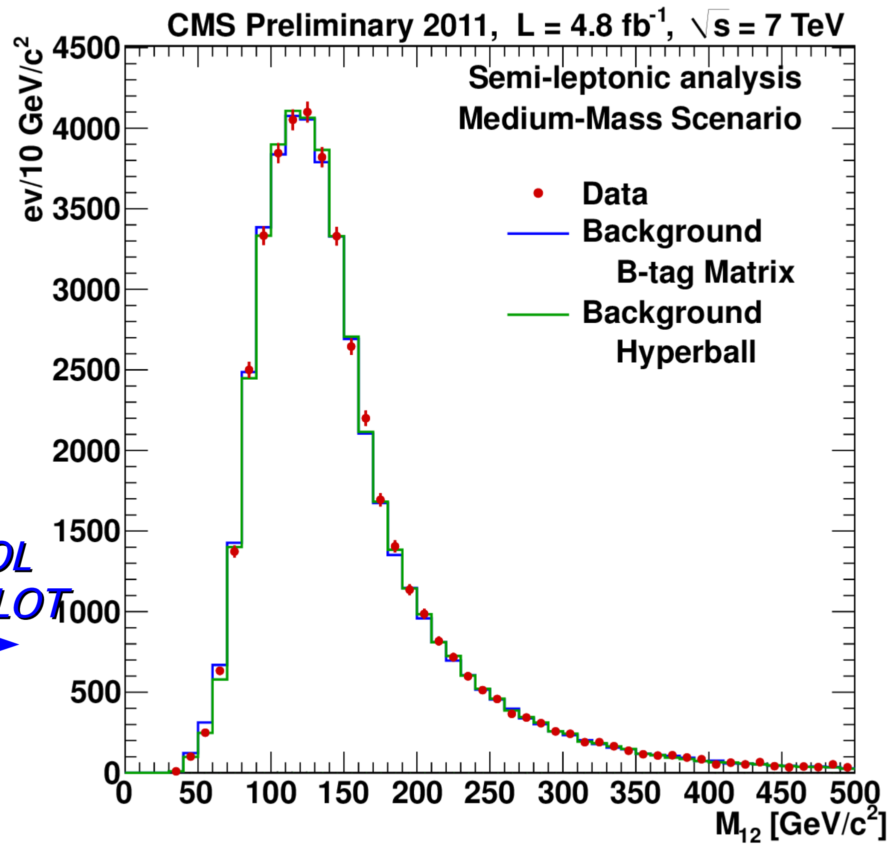
Expected to be a large branching fraction...

Can dominate at large tanβ . . .

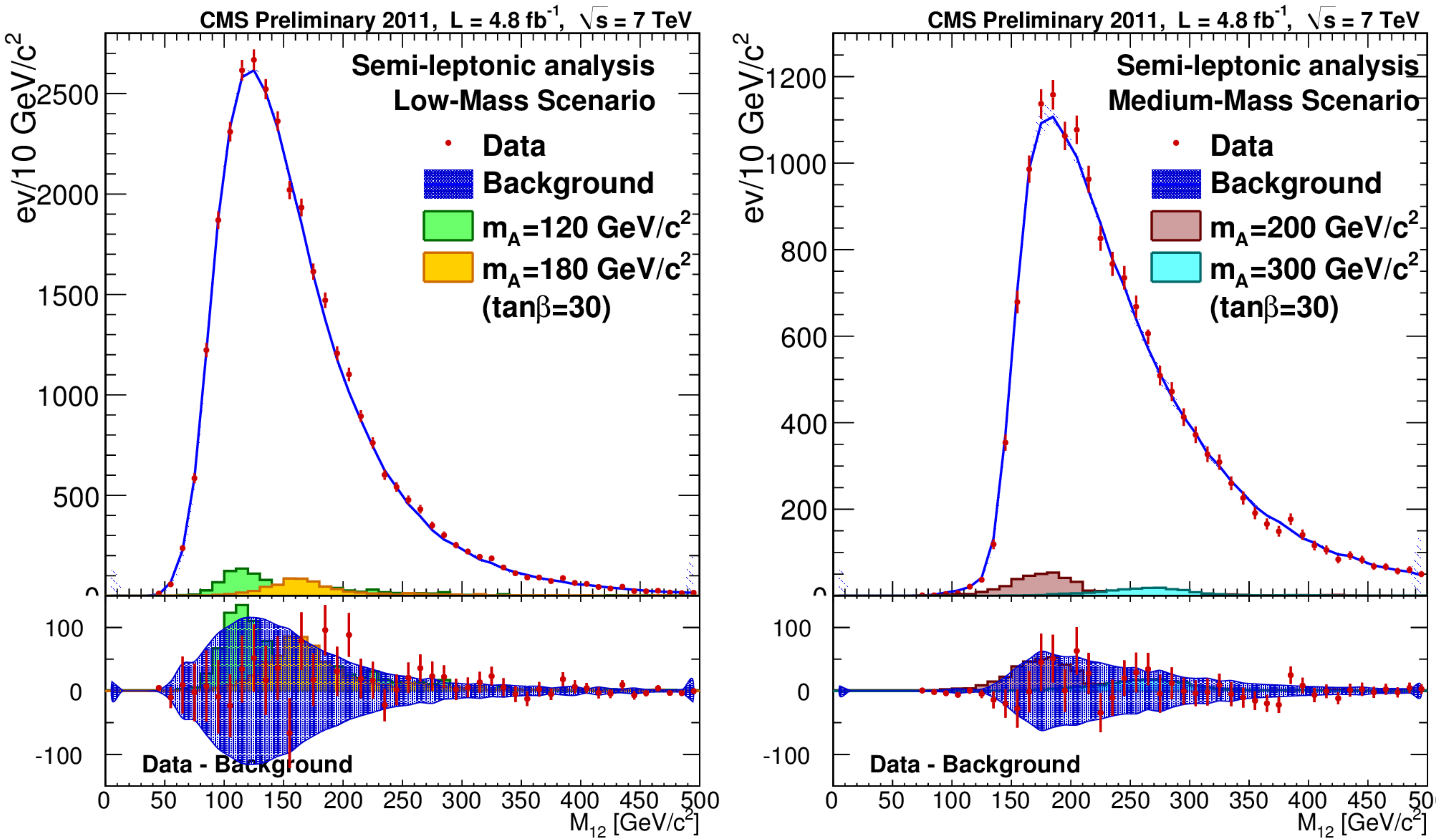
Search for events with at least 1 b-tagged jet in associated with a high-pT b-tagged jet pair.

- low (<180 GeV) and medium mass (>180 GeV) search dependent on multi-jet triggers
- "semi-leptonic": one b-jet contains an identified, non-isolated muon
- "hadronic": no such muon is present.

CONTROL REGION PLOT

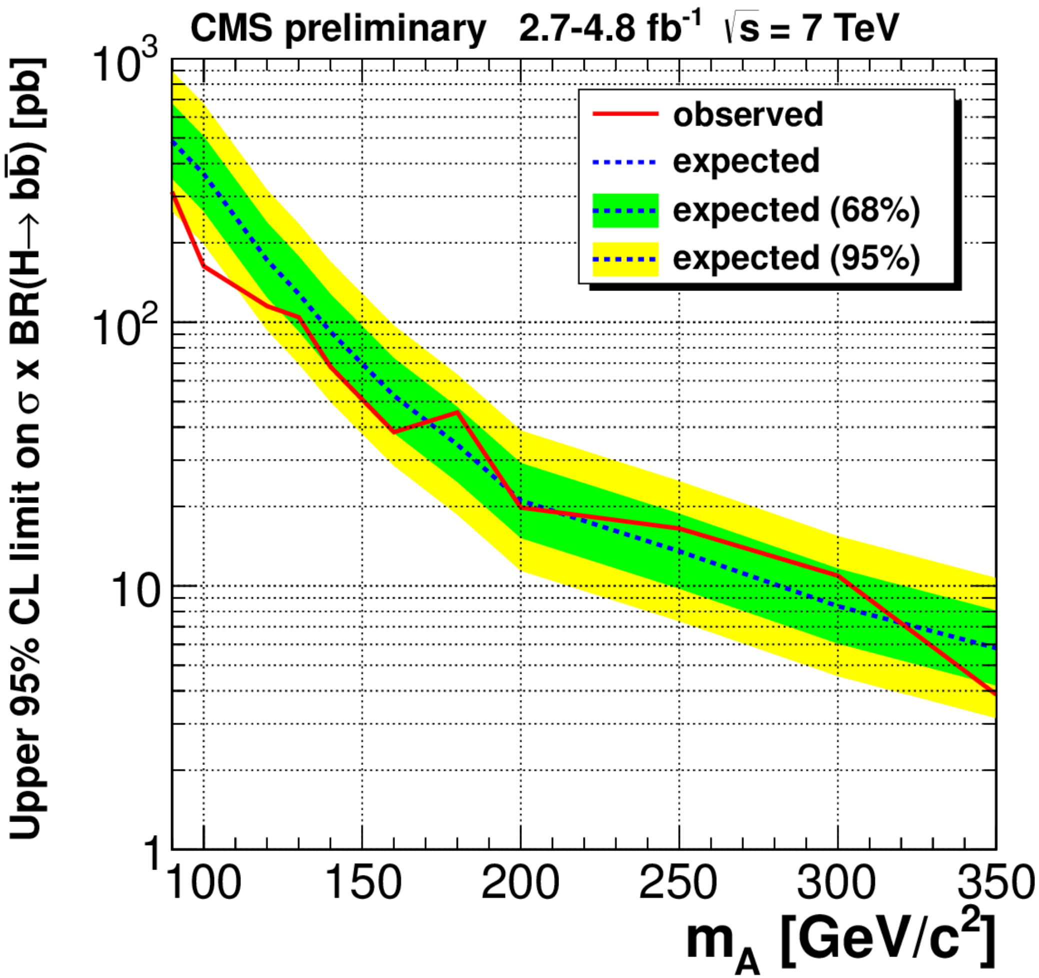


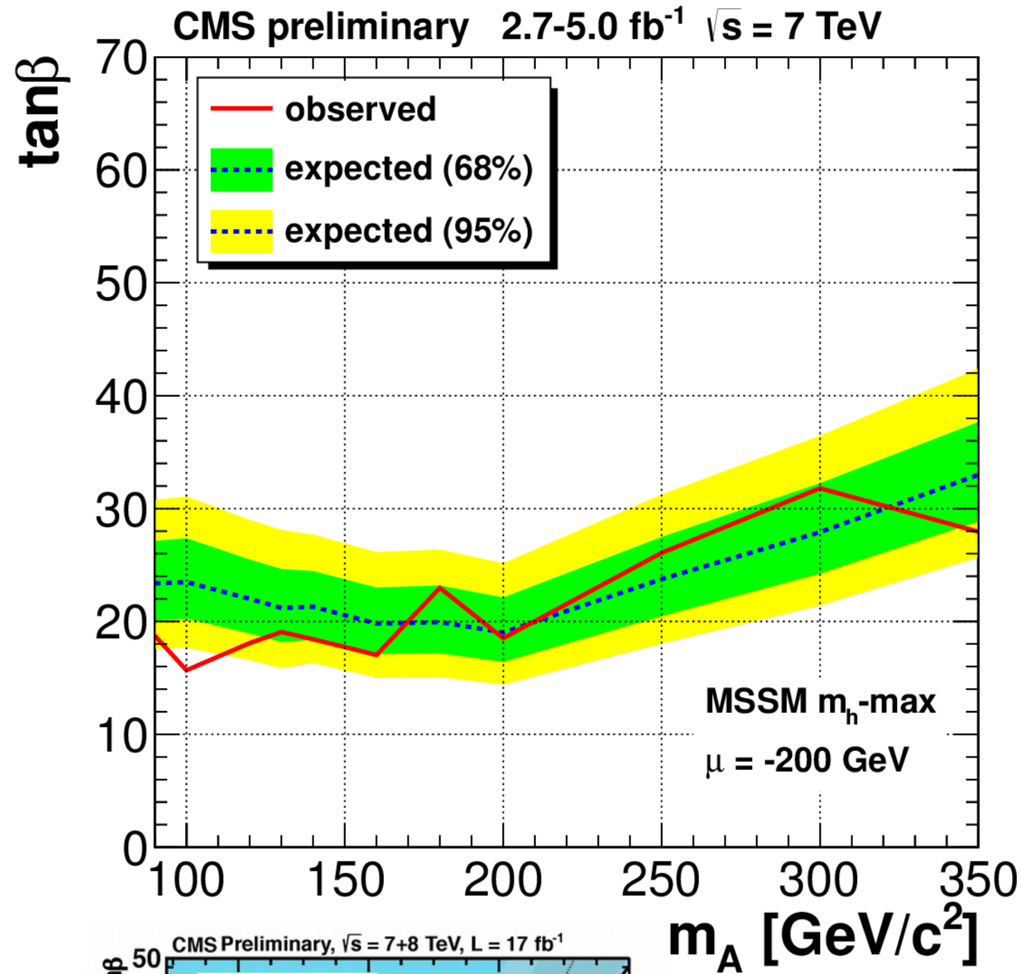
arXiv:1302.2892



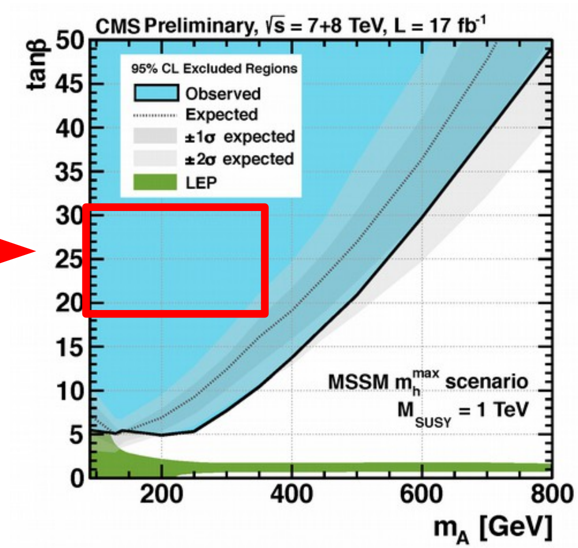
Background estimated by using bbj and bjj samples where 1/2 jets are untagged; samples reweighted by b-tagging/mis-tagging probabilities.

arXiv:1302.2892



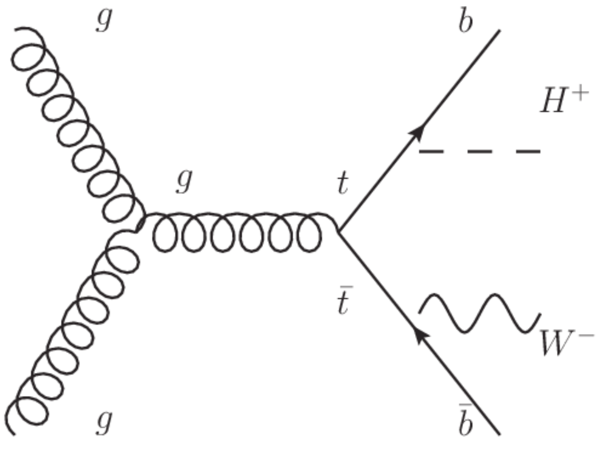


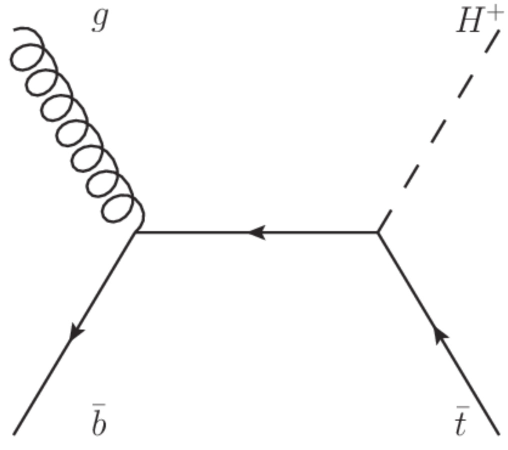
Red box is my own indication on the $H^0/A^0 \to \tau\tau$ MSSM exclusion plot of where this channel contributes independently.

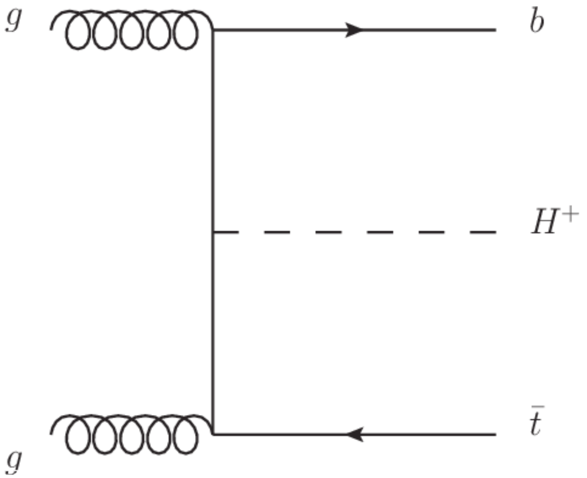


arXiv:1302.2892

H^+ Production



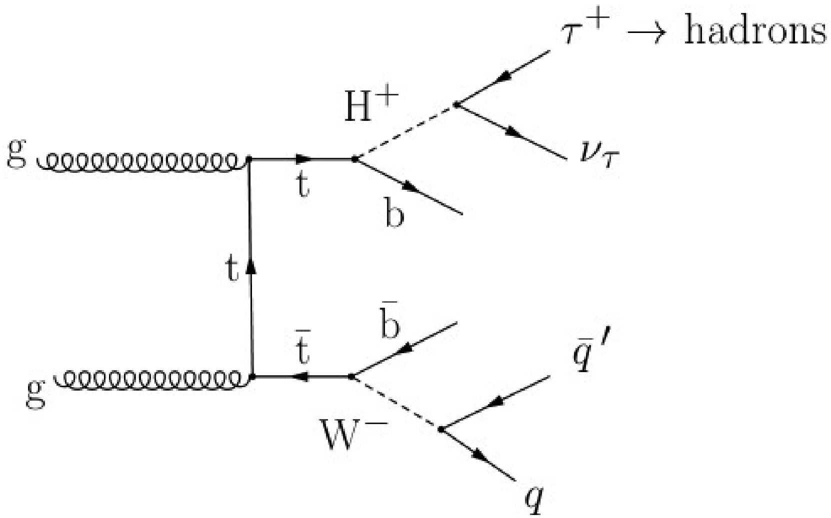


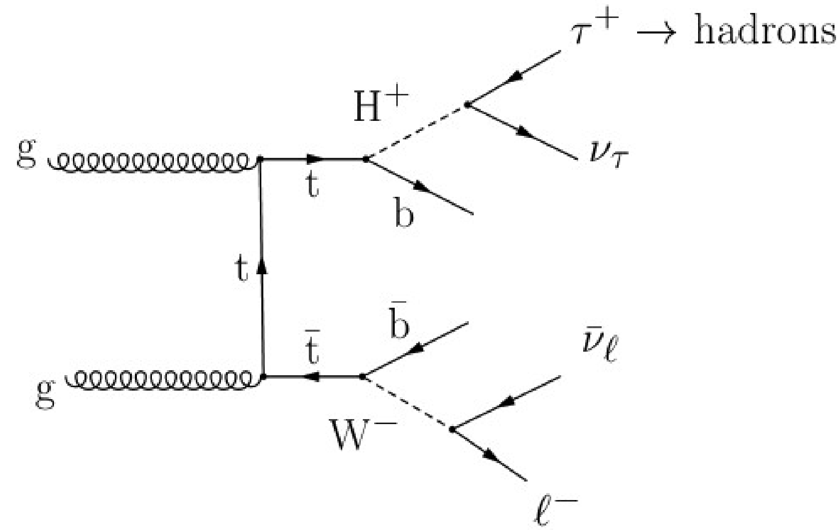


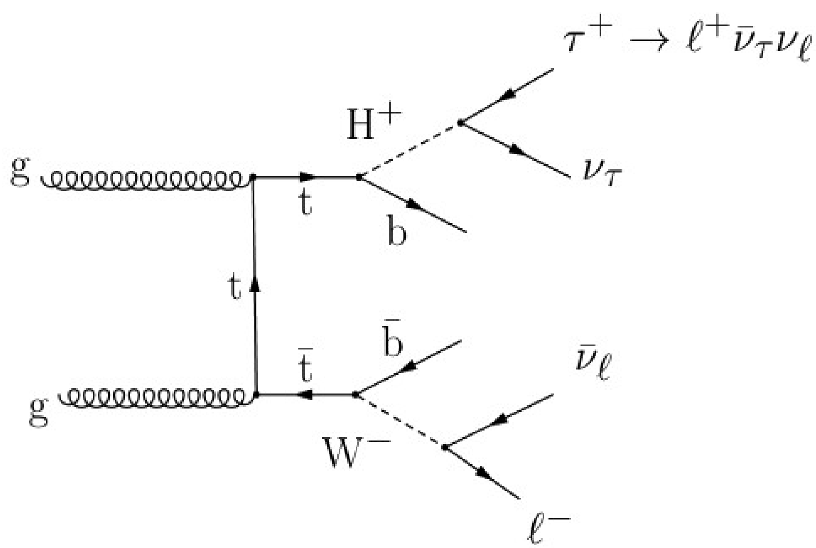
Dominant for masses below $m_t - m_b \approx 169$ GeV

Dominant for larger masses

$H^+ \rightarrow \tau^+ \nu$ ($m_{H+} < m_t - m_b$)





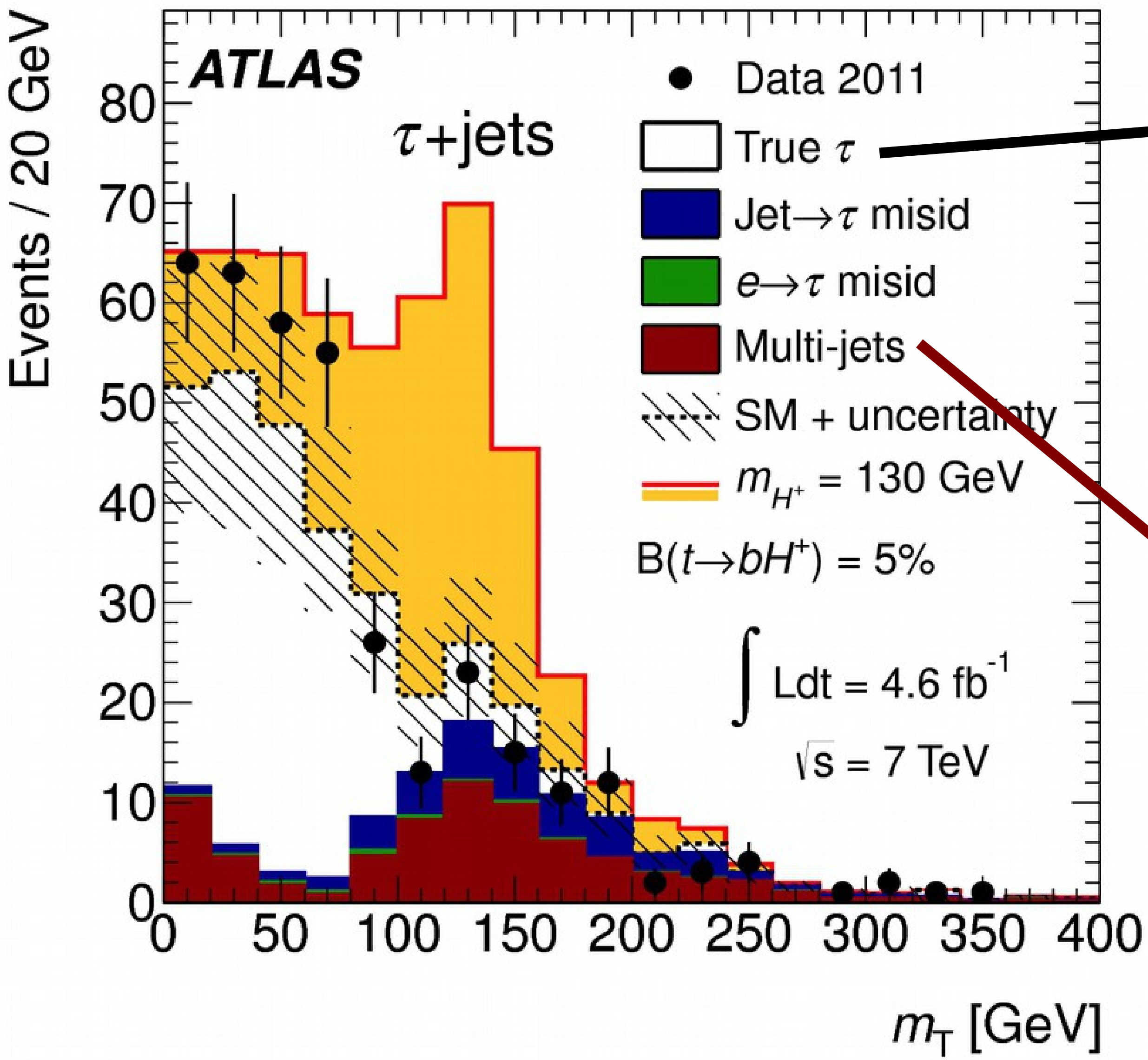


Different experimental approaches are needed for these final states

- hadronic tau decays more prone to QCD backgrounds
- leptonic tau/W decays yield more significant MET and present reconstruction/resolution challenges
- CMS uses e + μ channel directly, while ATLAS uses it in combination with the lepton + τ_{had} channel; ATLAS uses lepton + jets channel; the other two are in common.

CMS-HIG-11-019

$H^+ \to \tau^+ \nu$ Example: τ_{had} +jets



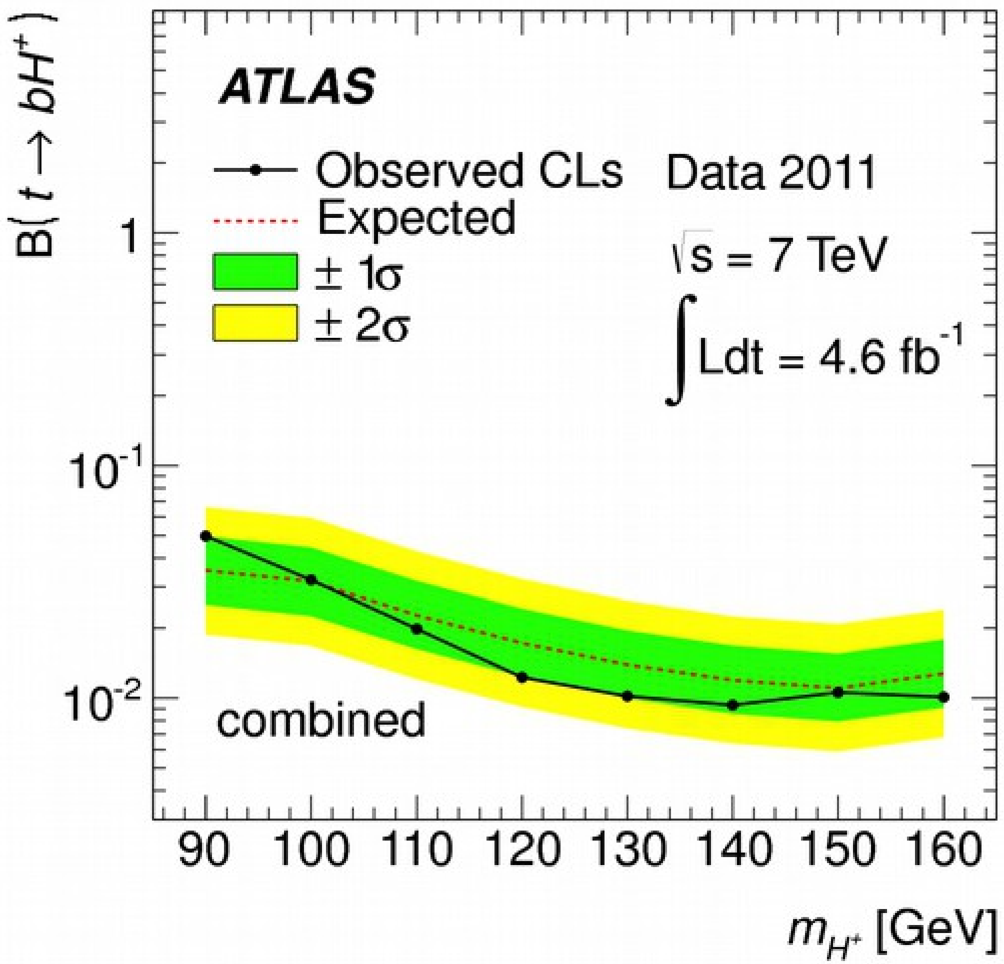
True tau background obtained from data events with muons instead of taus selected, then the muon is removed and a simulated tau is embedded in its place. Fully accounts for pileup effects, etc.

QCD multi-jet measured using data-driven methodology (shape obtained from control region, yield obtained by fitting MET in signal region using shape from control region)

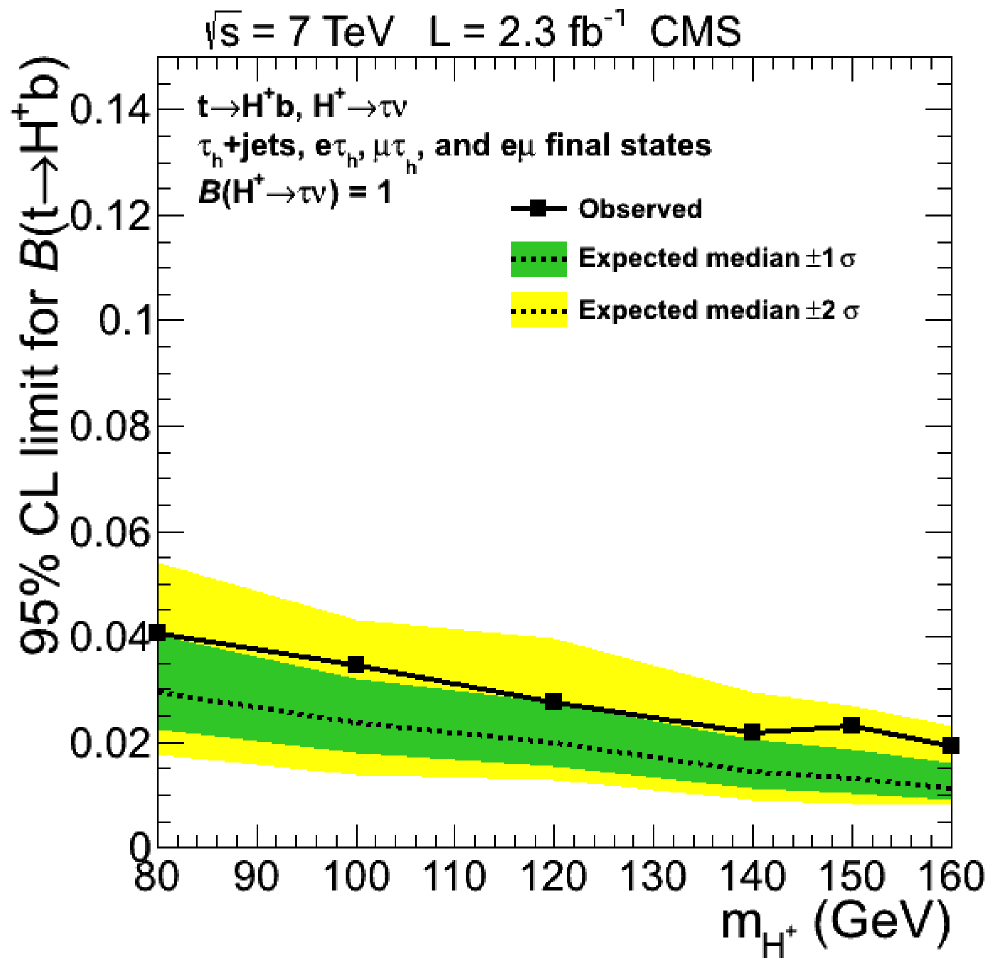
JHEP06 (2012) 039

Model-Independent Results

JHEP06 (2012) 039

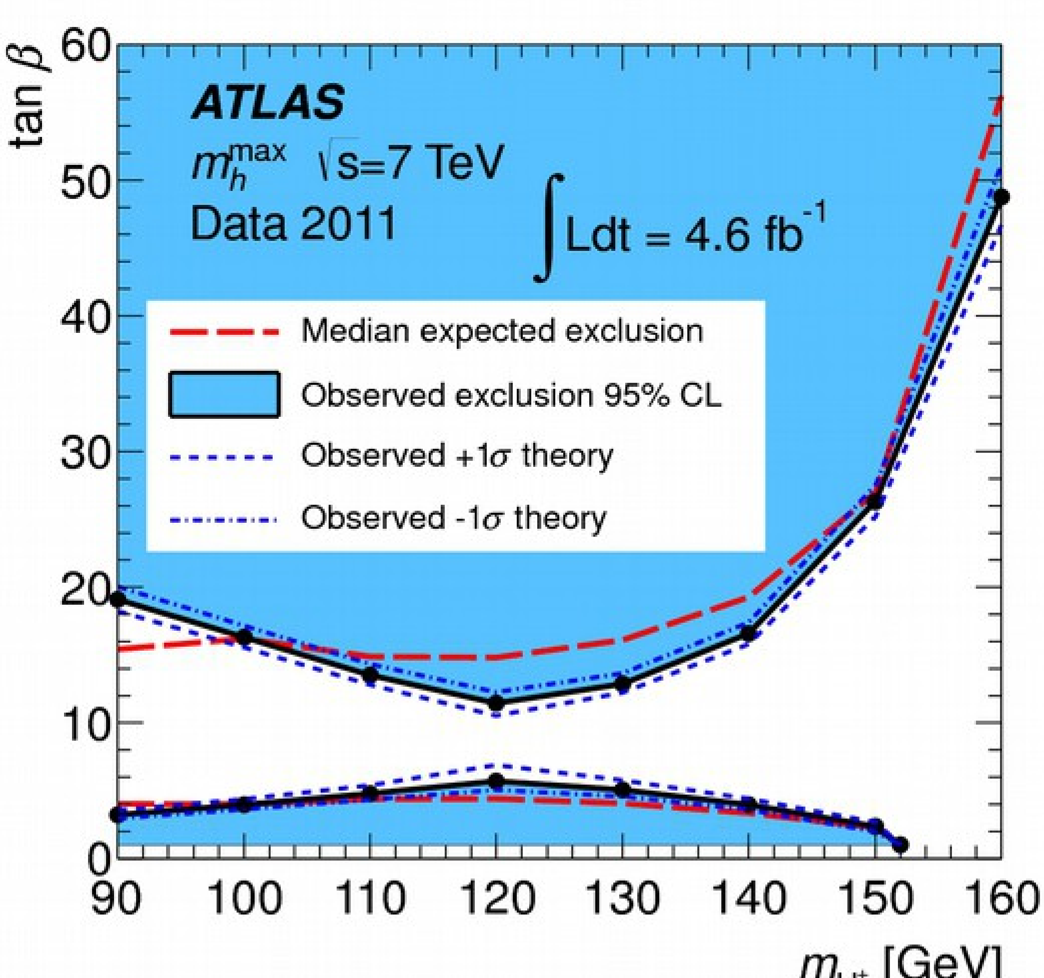


JHEP07 (2012) 143

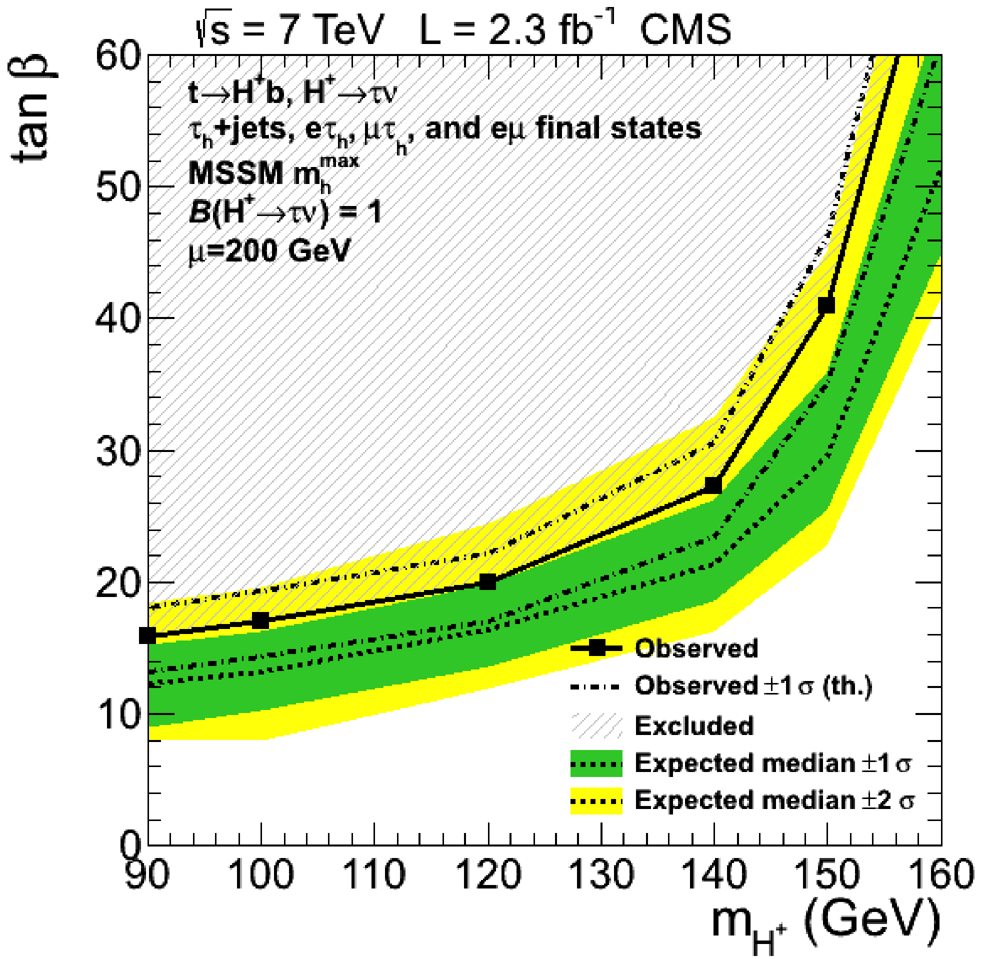


Model-Dependent Results

JHEP06 (2012) 039



JHEP07 (2012) 143

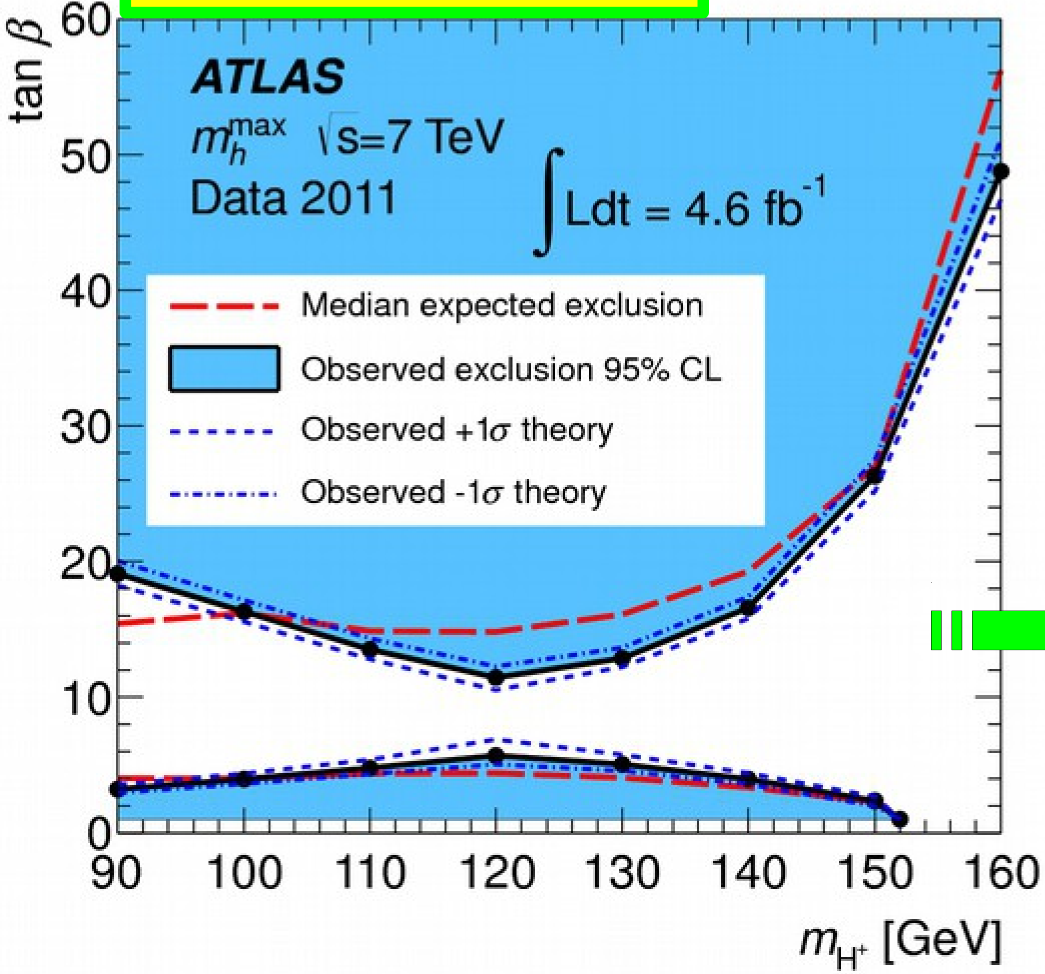


Including Lepton Universality Violation Search

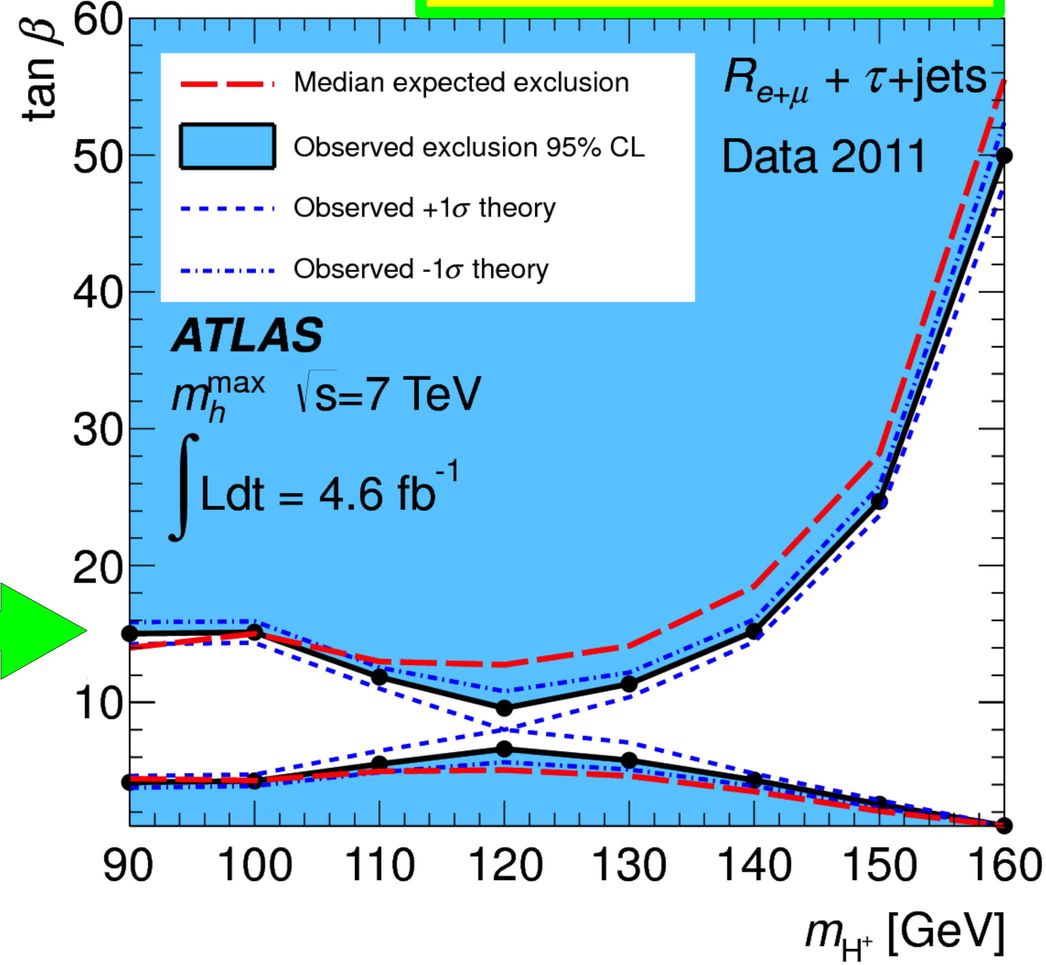
Direct search using three independent final states

$$R_l = \frac{\mathcal{B}(t\bar{t} \to b\bar{b} + l\tau_{\rm had} + N\nu)}{\mathcal{B}(t\bar{t} \to b\bar{b} + ll' + N\nu)}$$

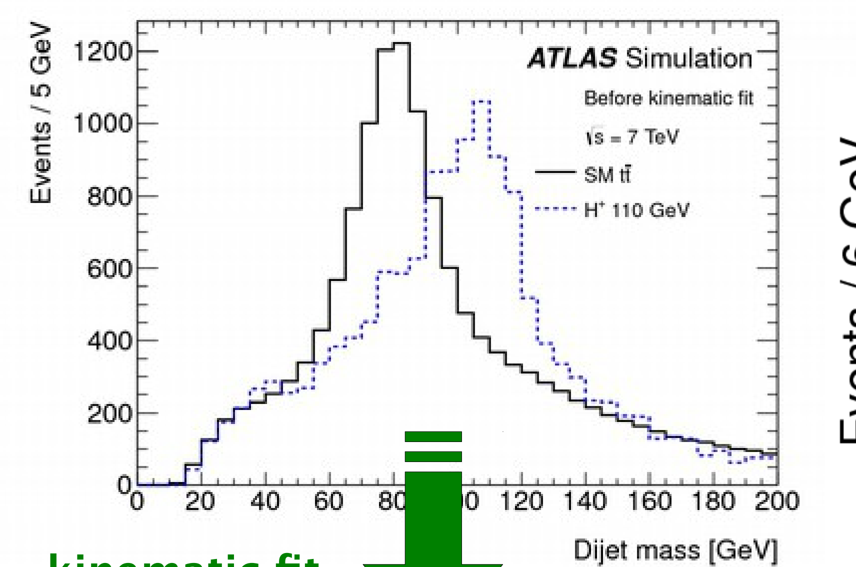
JHEP06 (2012) 039



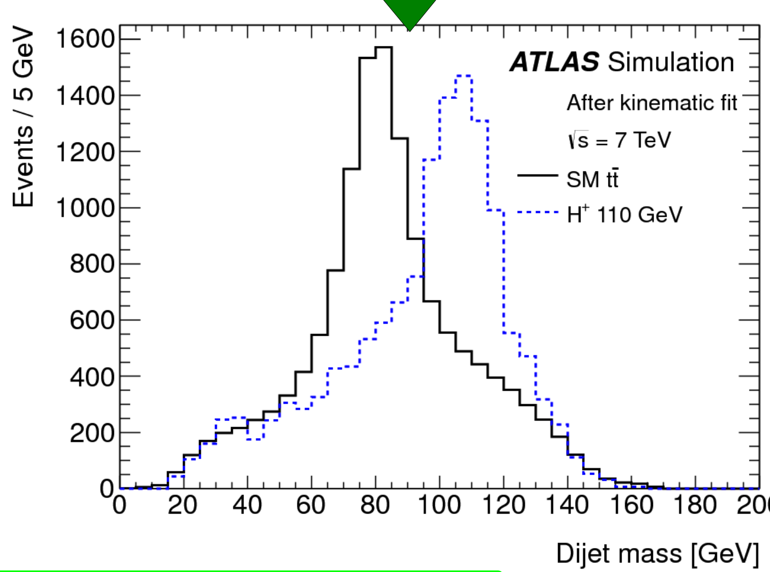
JHEP03 (2013) 076

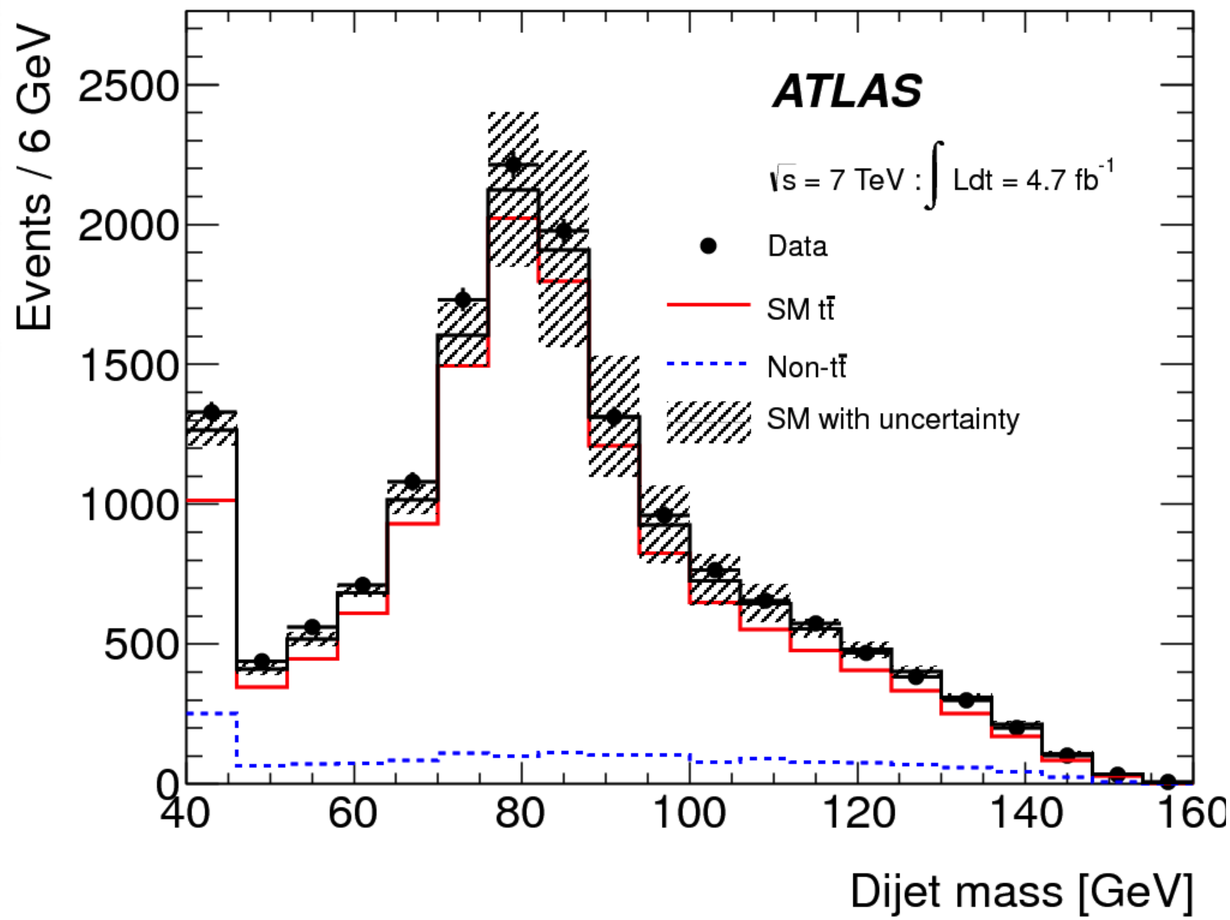


$H^+ \rightarrow cs\ (m_{H+} < m_t - m_b)$



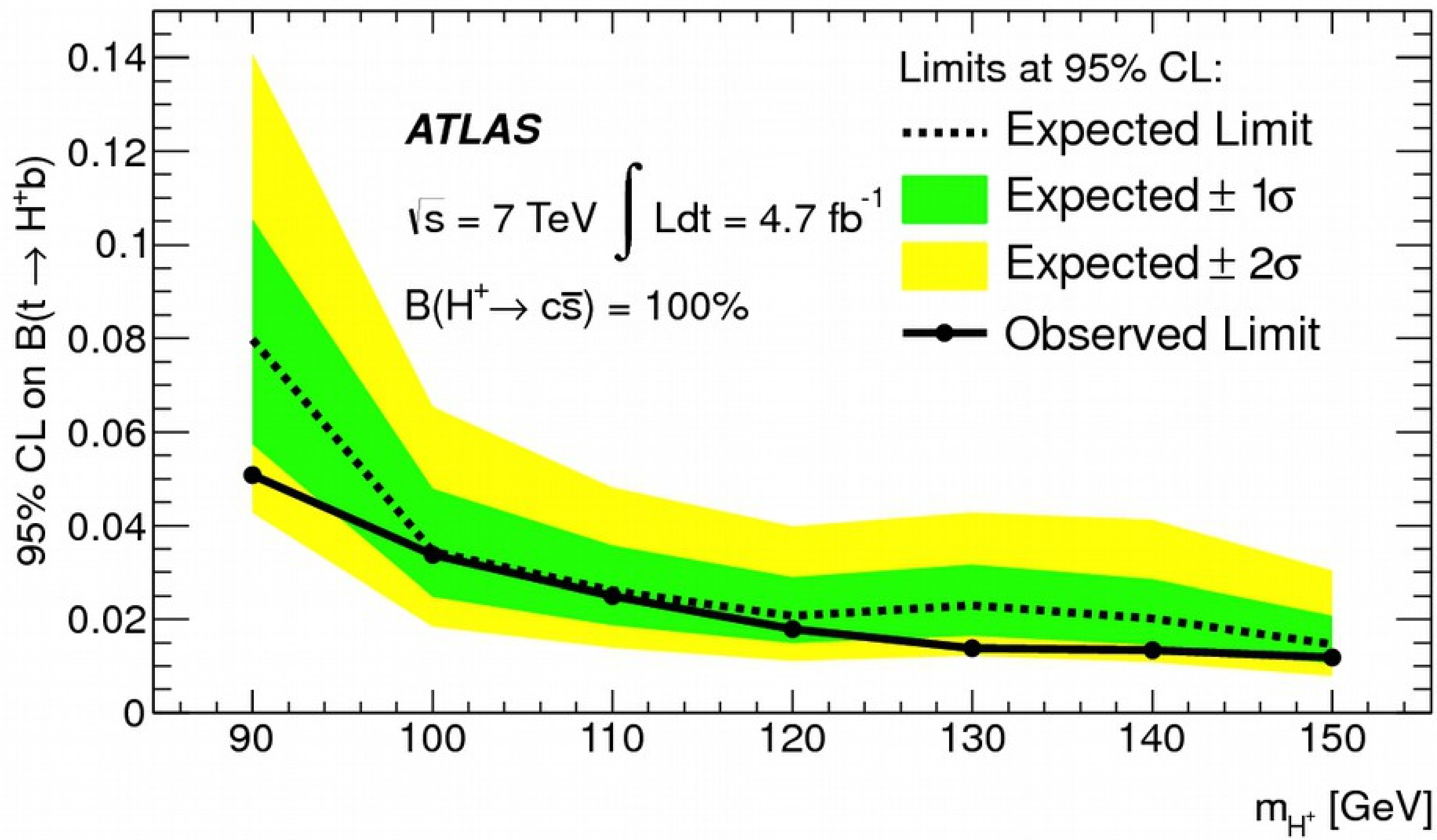
kinematic fit





arXiv:1302.3694

Model-Independent Results



arXiv:1302.3694

2HDM-Inspired Searches

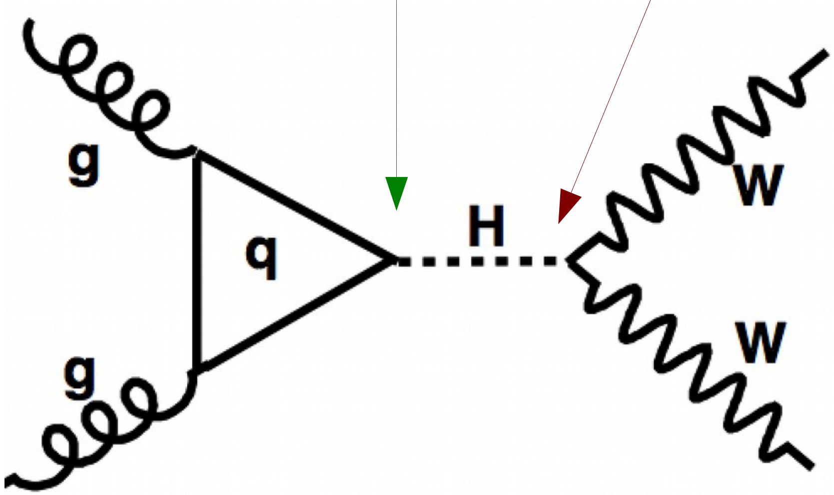
ATLAS-CONF-2013-027

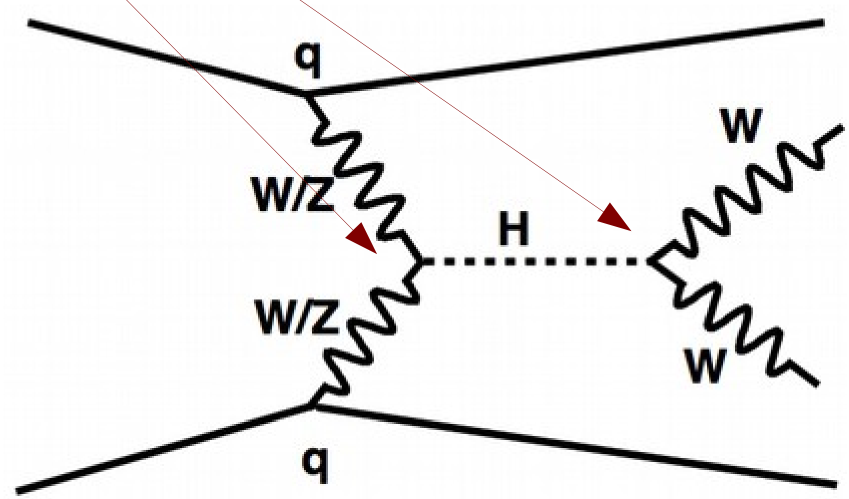
	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^l	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^l	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

SM-like Higgs (h^0) couplings

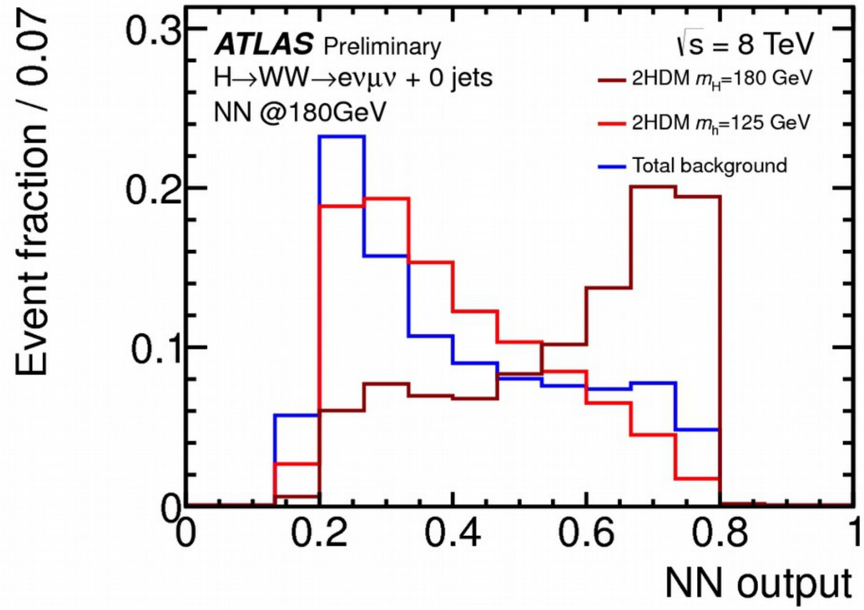
Heavy CP-even Higgs (H^0) couplings

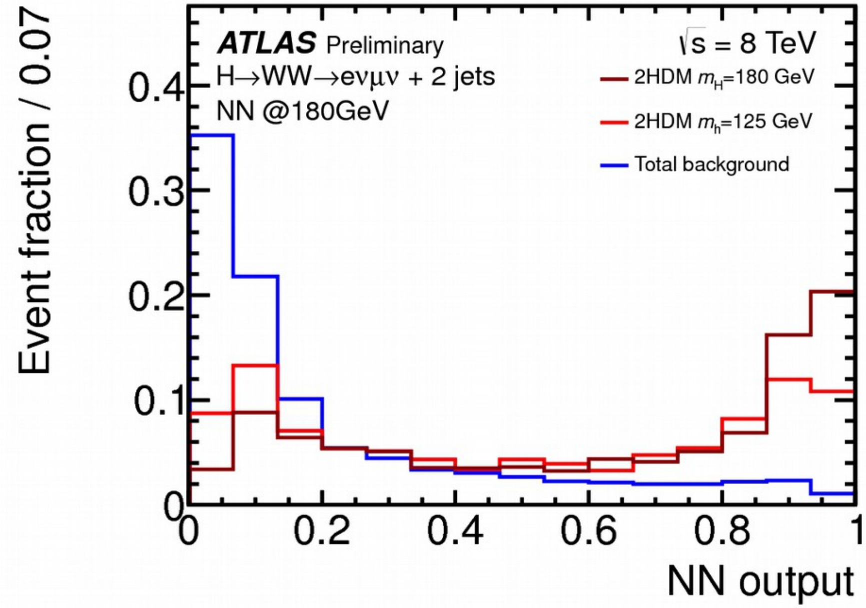
Test the hypothesis that the data contains both of these being produced and decaying via WW



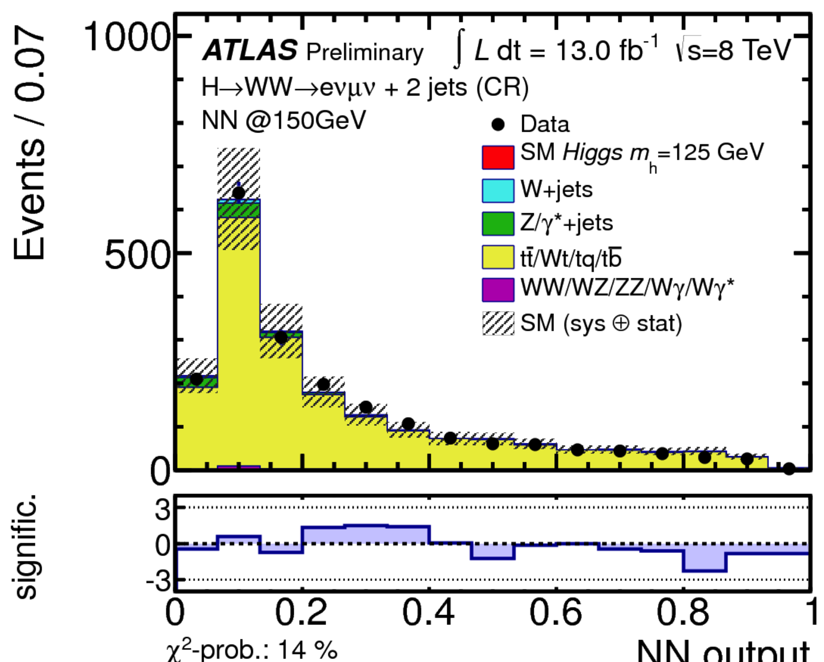


The considered production mechanisms





Enhance sensitivity to heavy Higgs through neural networks (NN)trained at 3 mass points: (150, 180, 240 GeV)



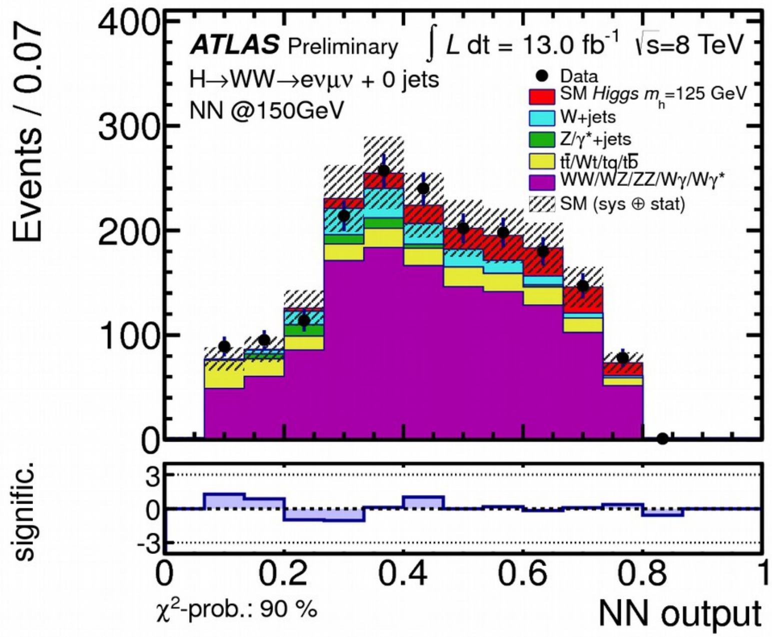
The NN shows good behavior even in samples against which it was not trained. Left is the NN output for the 150 GeV training point in a top-background-enhanced control region.

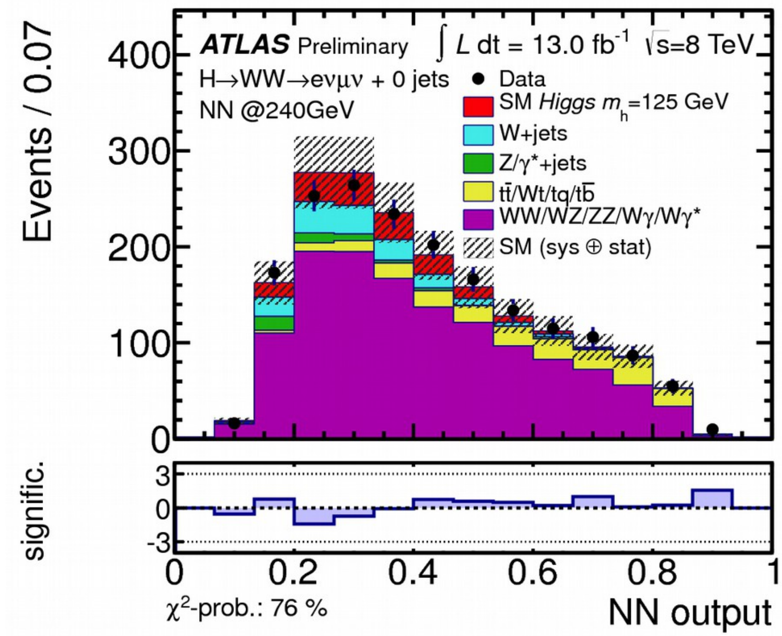
ATLAS-CONF-2013-027

NN trained @150 GeV

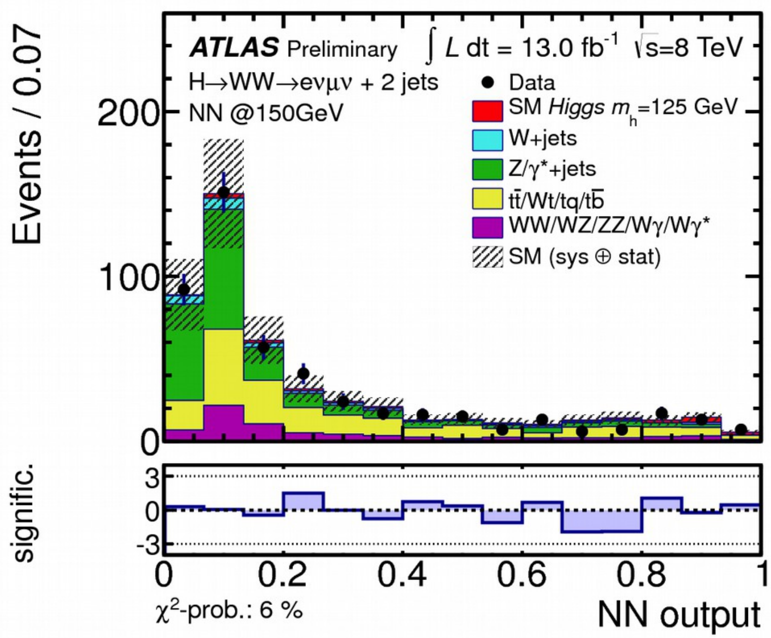
NN trained @240 GeV

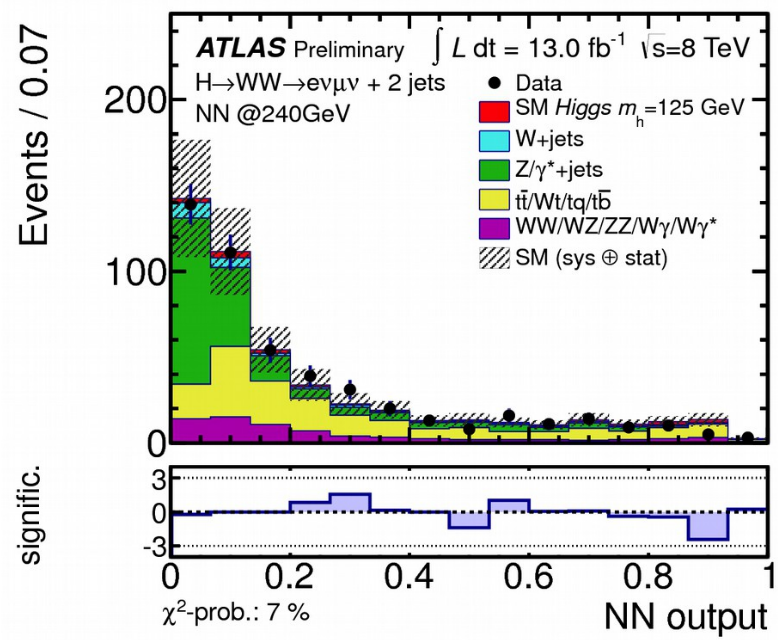
0–jet Events
(enriched in gluon-gluon fusion)





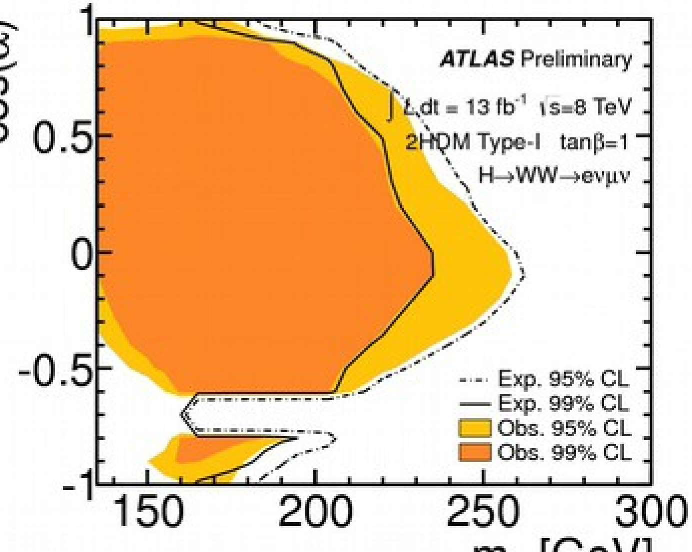
2–jet Events
(enriched in VBF)



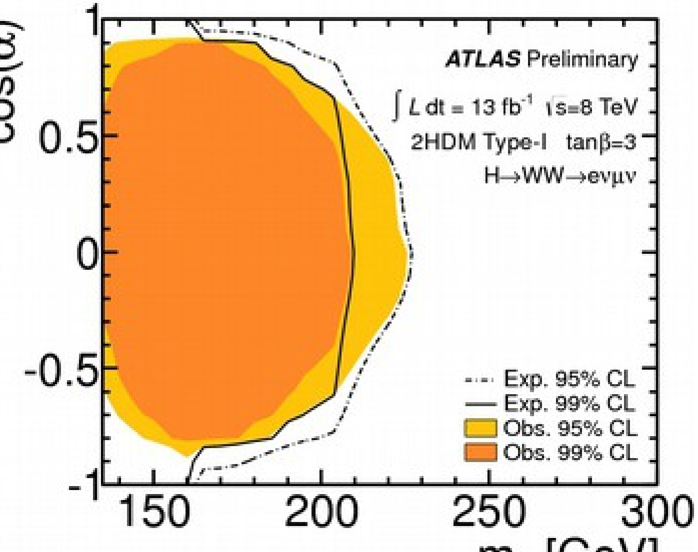


ATLAS-CONF-2013-027

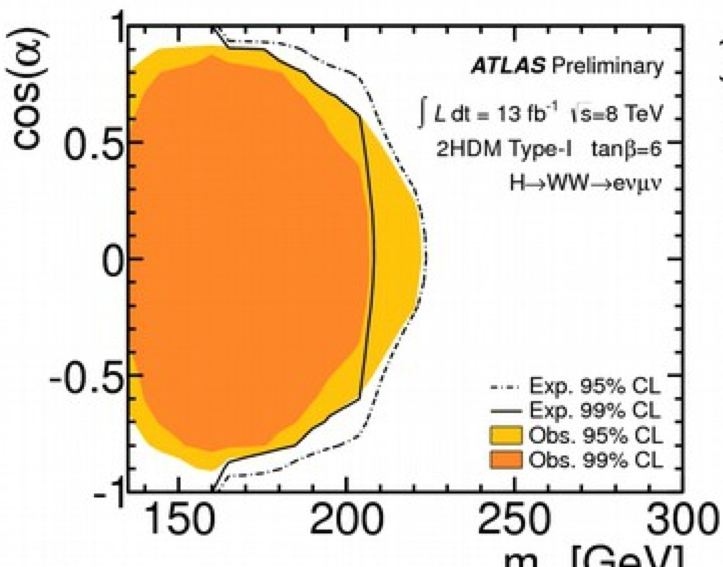
	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^l	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^l	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$



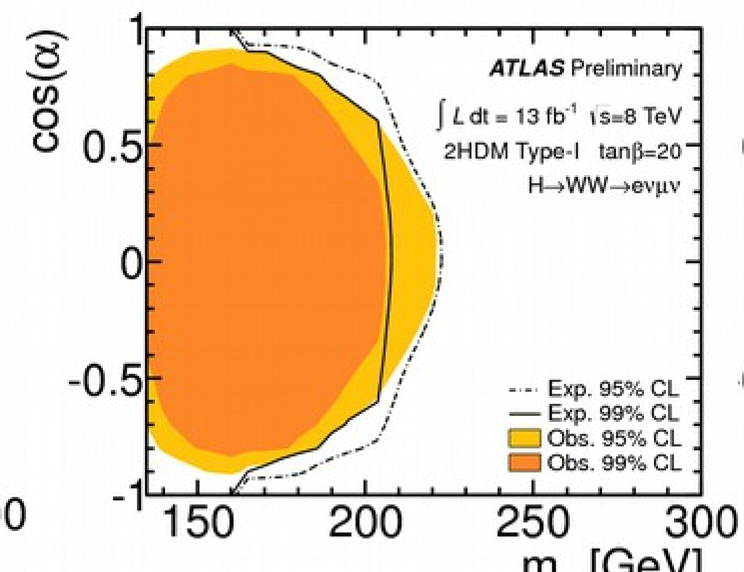
tanβ = 1



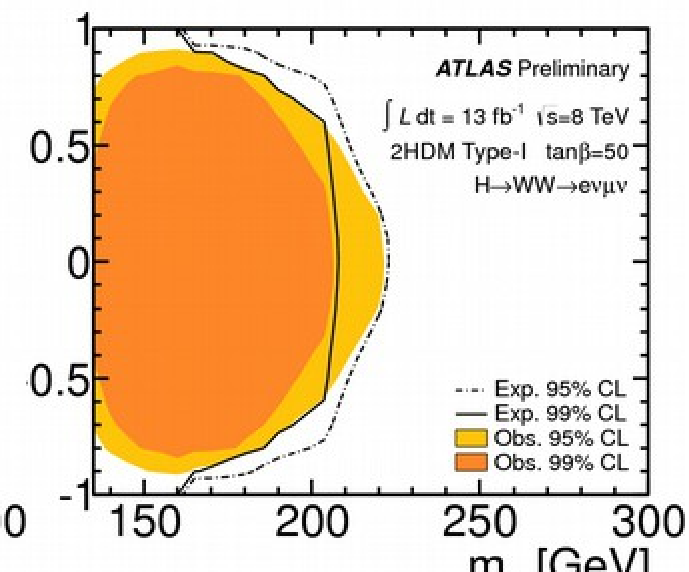
tanβ = 3



tanβ = 6



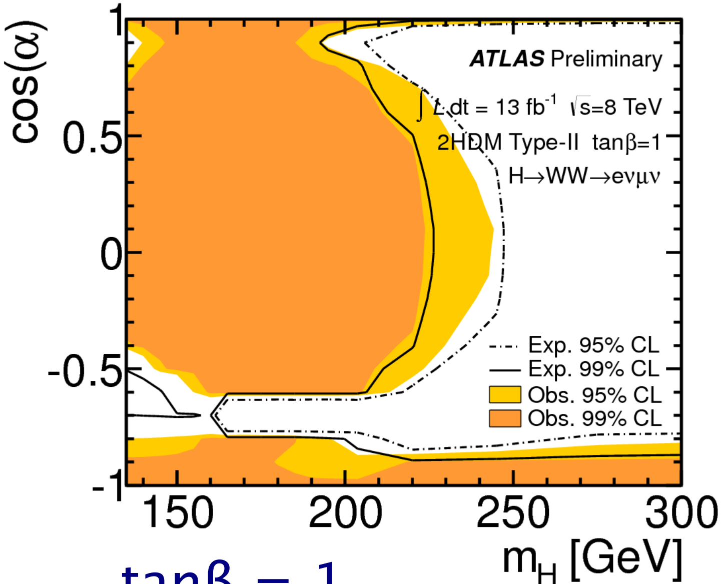
tanβ = 20



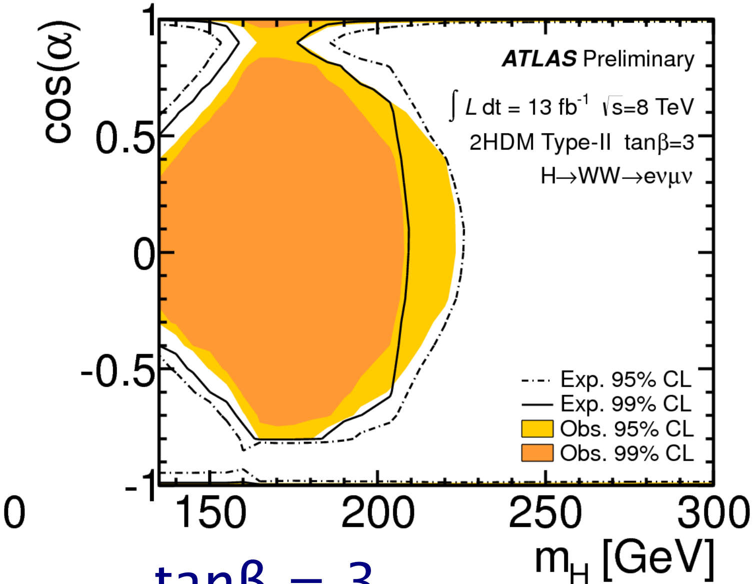
tanβ = 50

ATLAS-CONF-2013-027

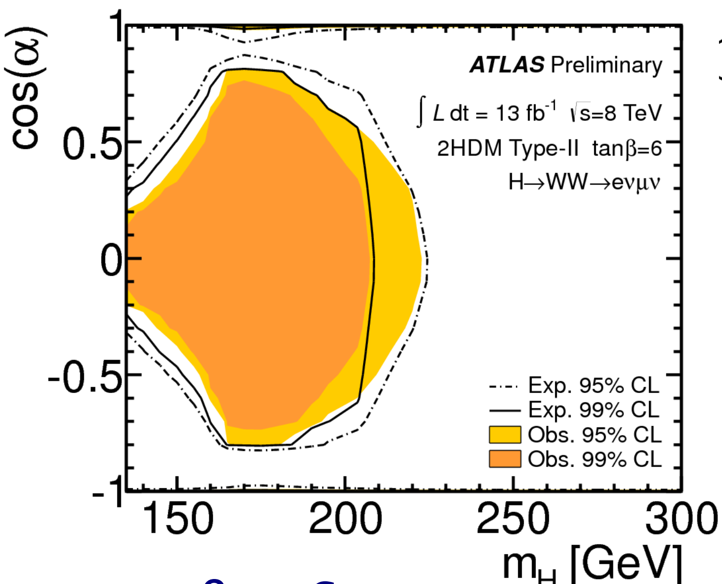
	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^l	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^l	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$



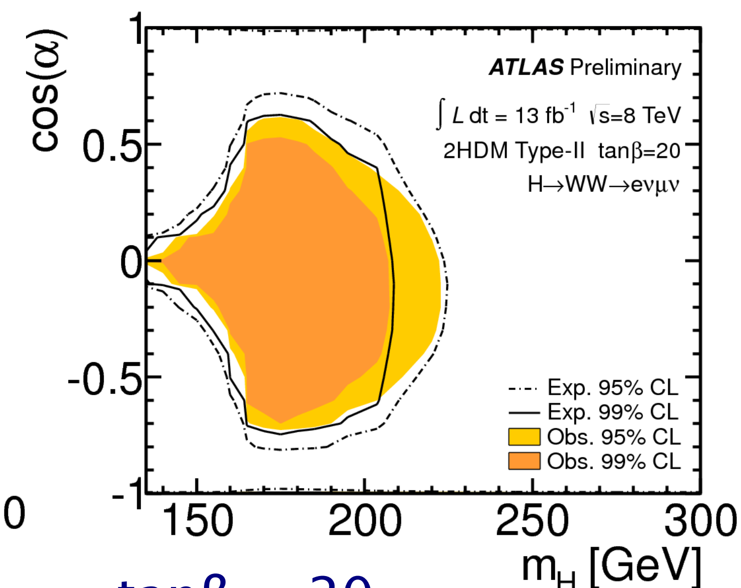
tanβ = 1



tanβ = 3



tanβ = 6



tanβ = 20

Useful feedback from the theory community on this effort has already been received (e.g. show exclusions in cos(β – α) vs. mass instead of what ATLAS has made public so far)

ATLAS-CONF-2013-027

NMSSM-Inspired Searches

Important Features

$H_1^0,\ H_2^0,\ H_3^0,$
$a_1^0,\ a_2^0,\ H^{\pm}$ → 2 Higgs Field Doublets + 1 Singlet

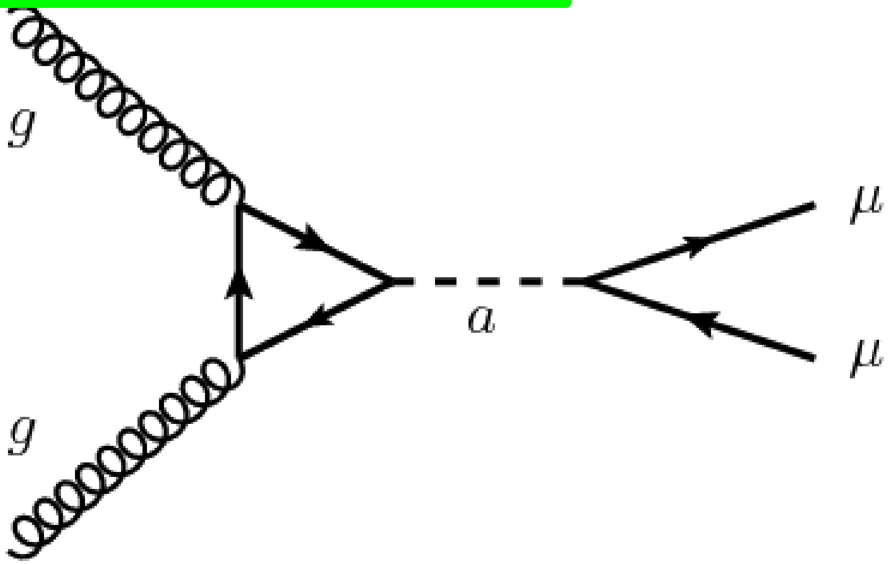
Seven physical higgs bosons (3 CP-even, two CP-odd, and 2 electrically charged)

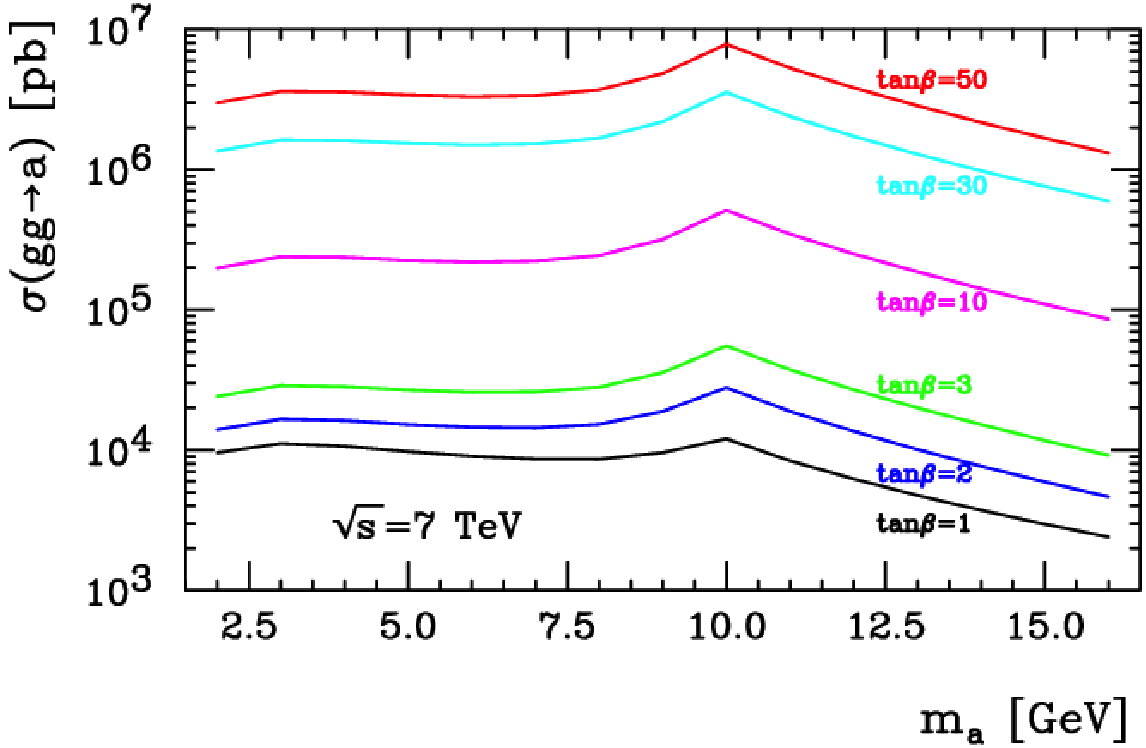
$\cos(\theta_A)$ → Mixing angle between the doublet and singlet pseudoscalars

The mass of the lightest pseudo-scalar could be quite light ($m_{a1} < 2m_B$).

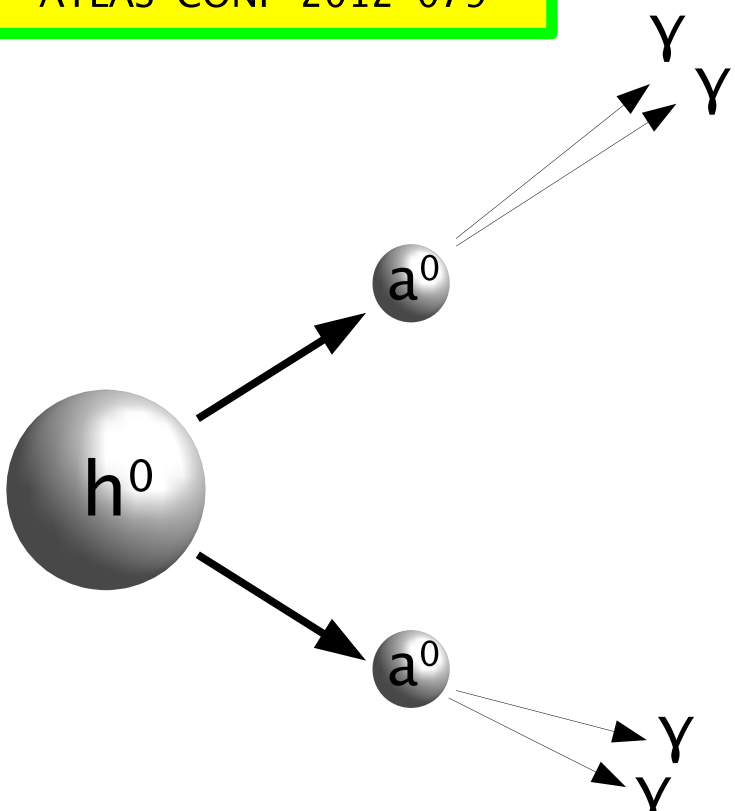
B-factories, LEP, the Tevatron, and now LHC are searching for signatures of this model.

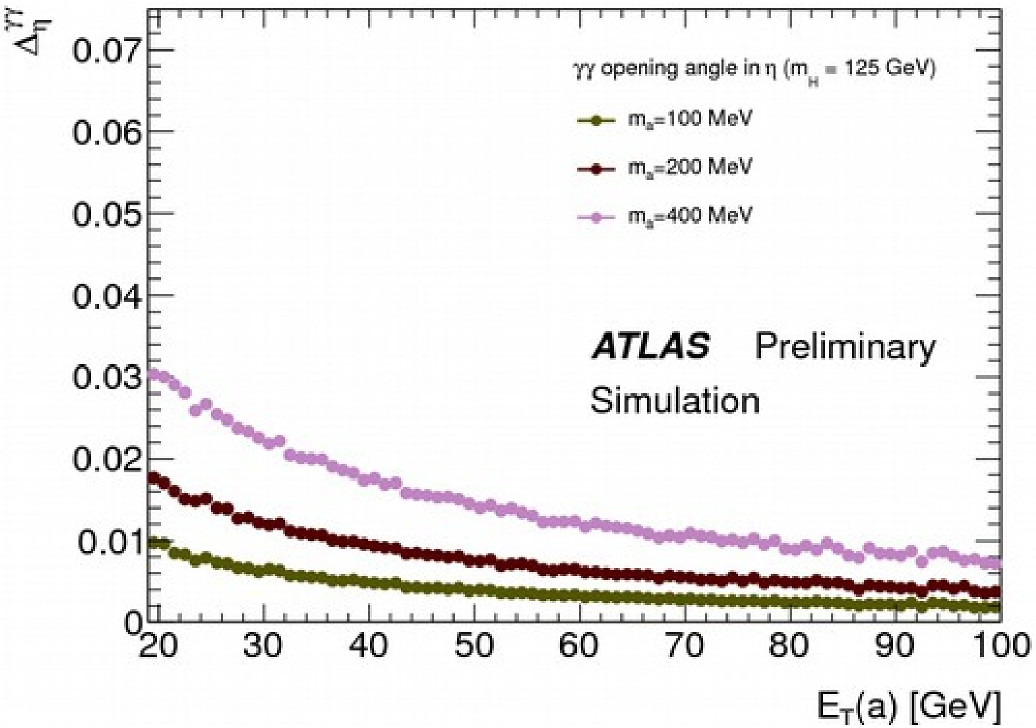
CMS-HIG-12-004

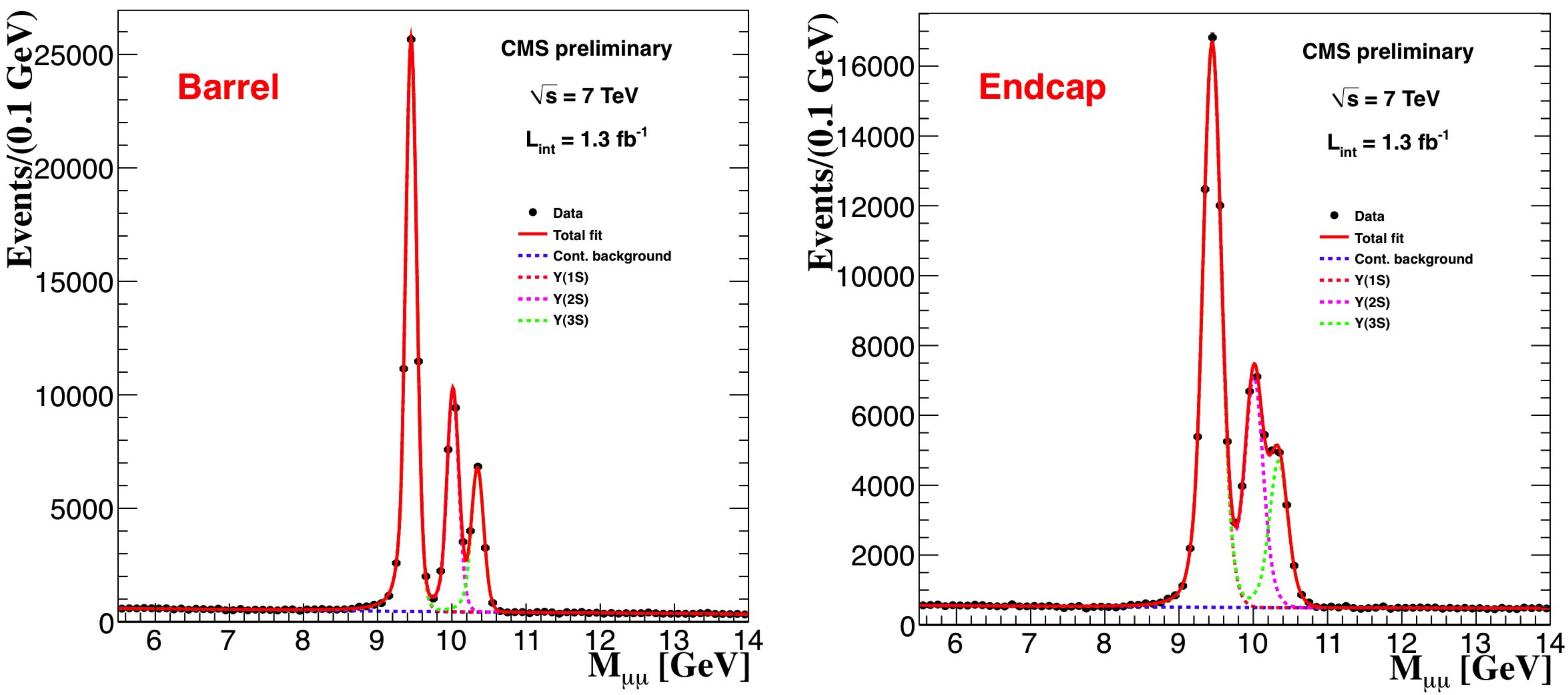




ATLAS-CONF-2012-079



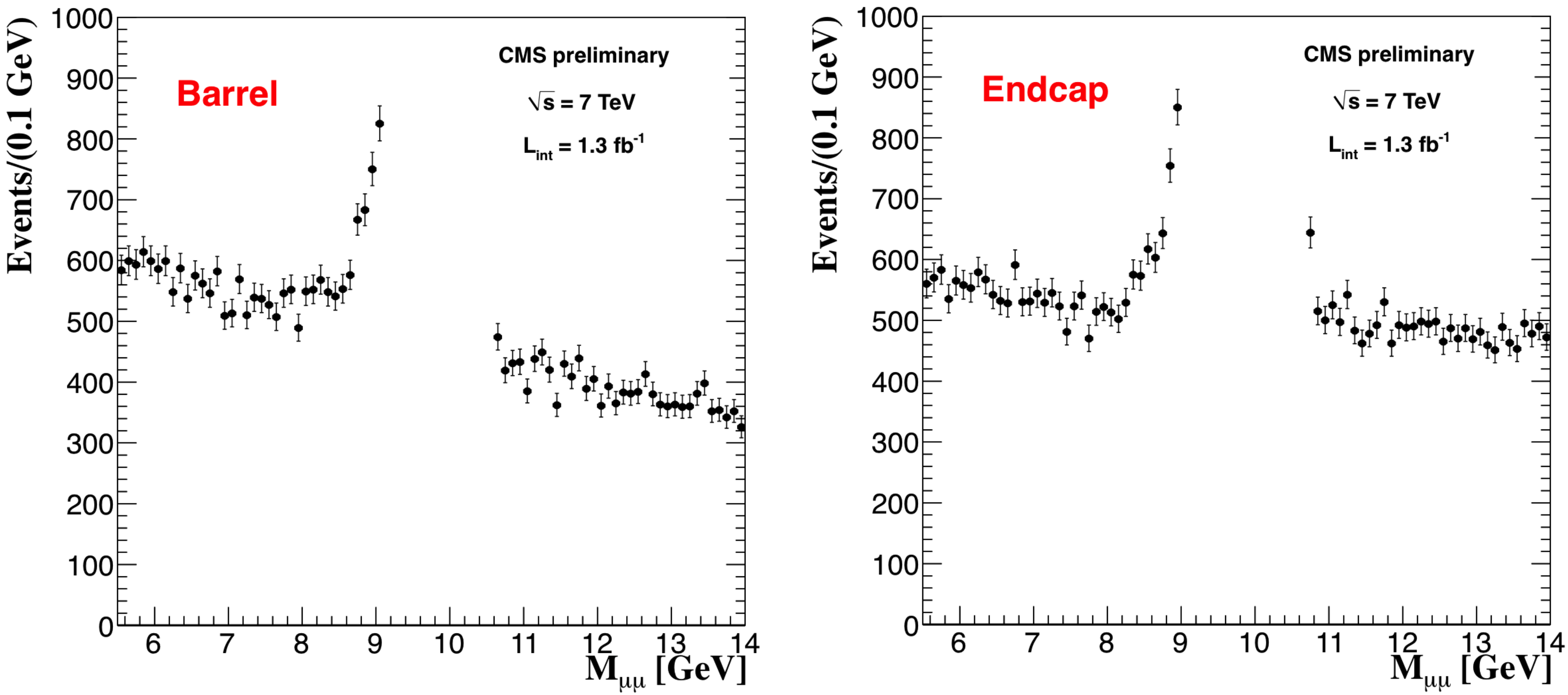




CMS uses the excellent resolution on pairs of muons to search for $pp \to a_1 \to \mu\mu$

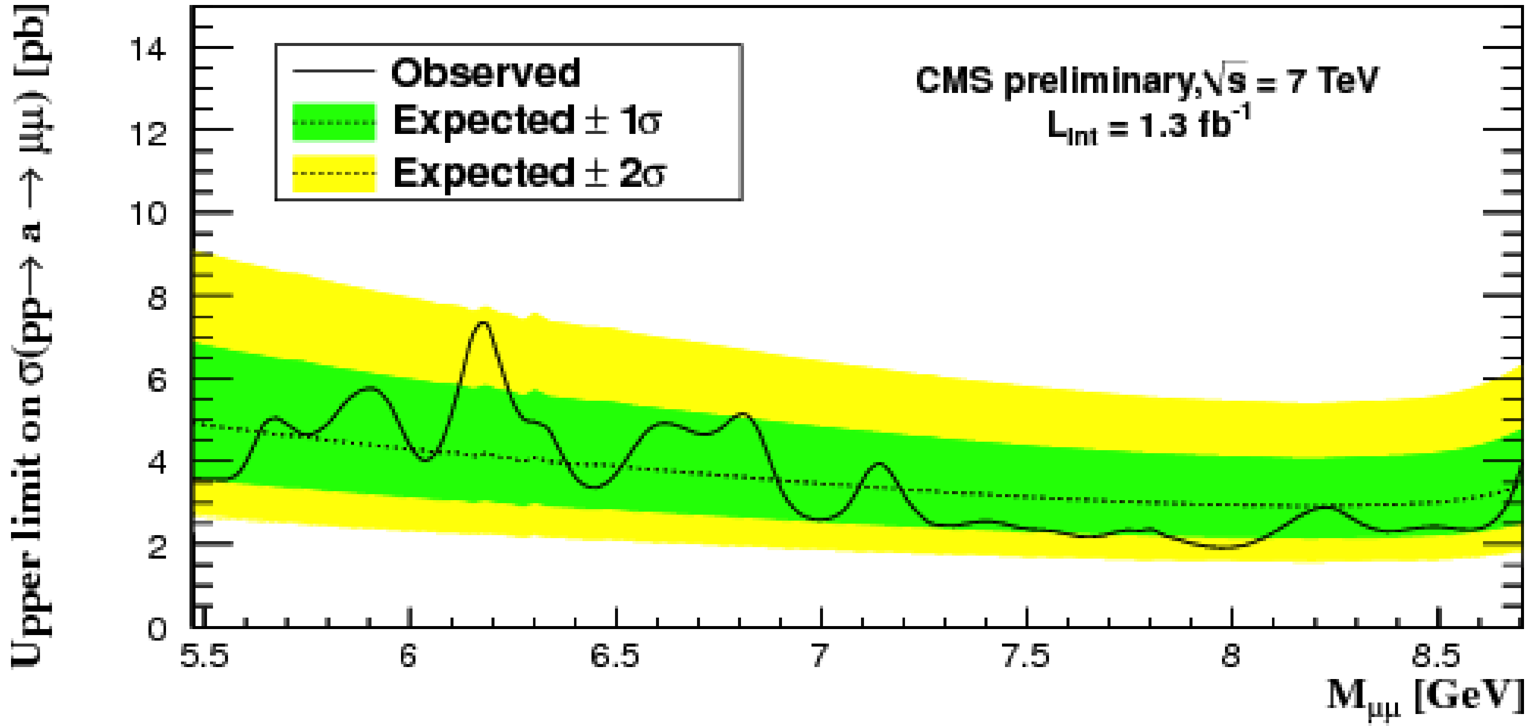
Soft muon p_T is a challenge for triggering, but once triggered we see how smooth the data are and how the Upsilon resonances help to understand resolution in this mass region.

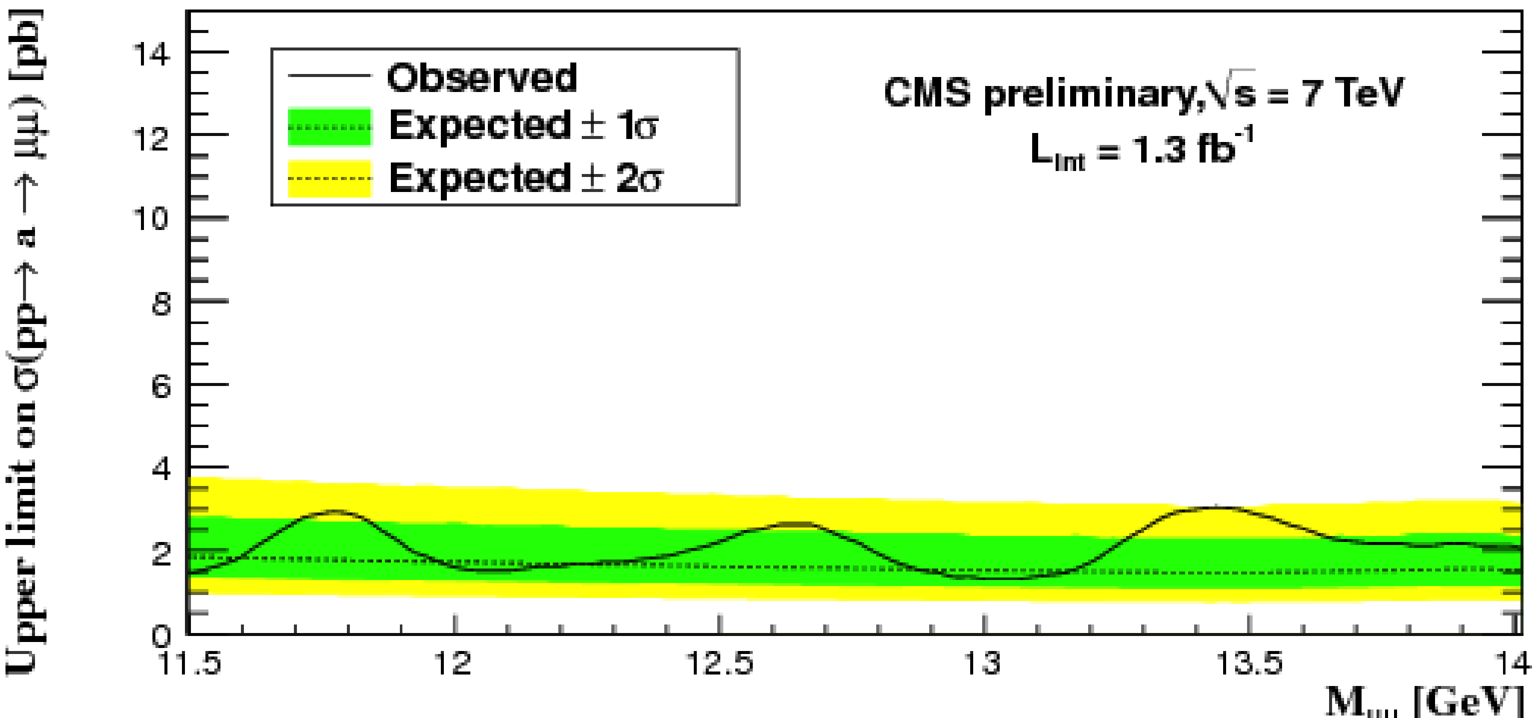
CMS-HIG-12-004



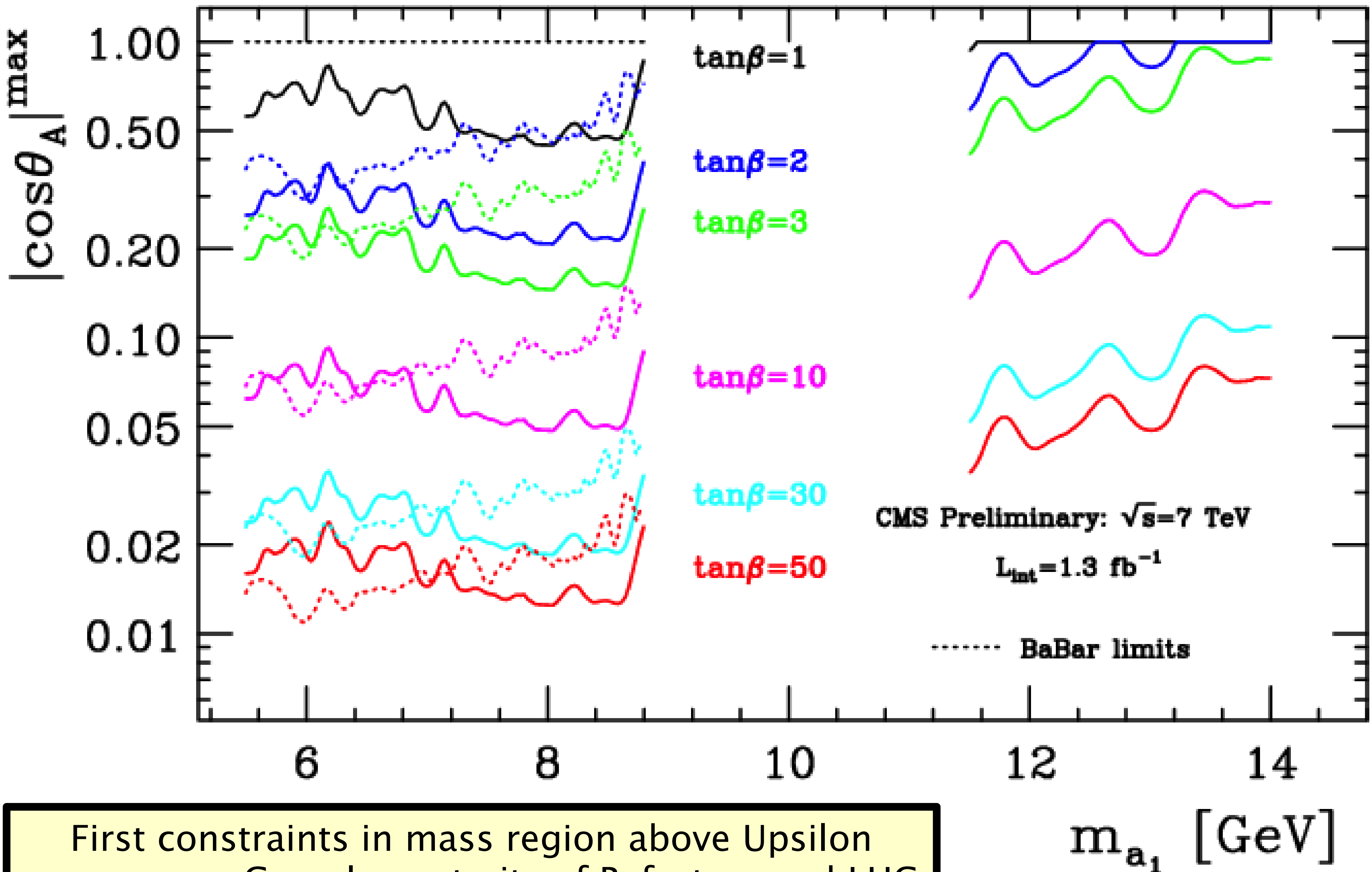
The data, excluding the Upsilon region. We still see the significant tails of the Upsilons, which are a background on the low side.

CMS-HIG-12-004





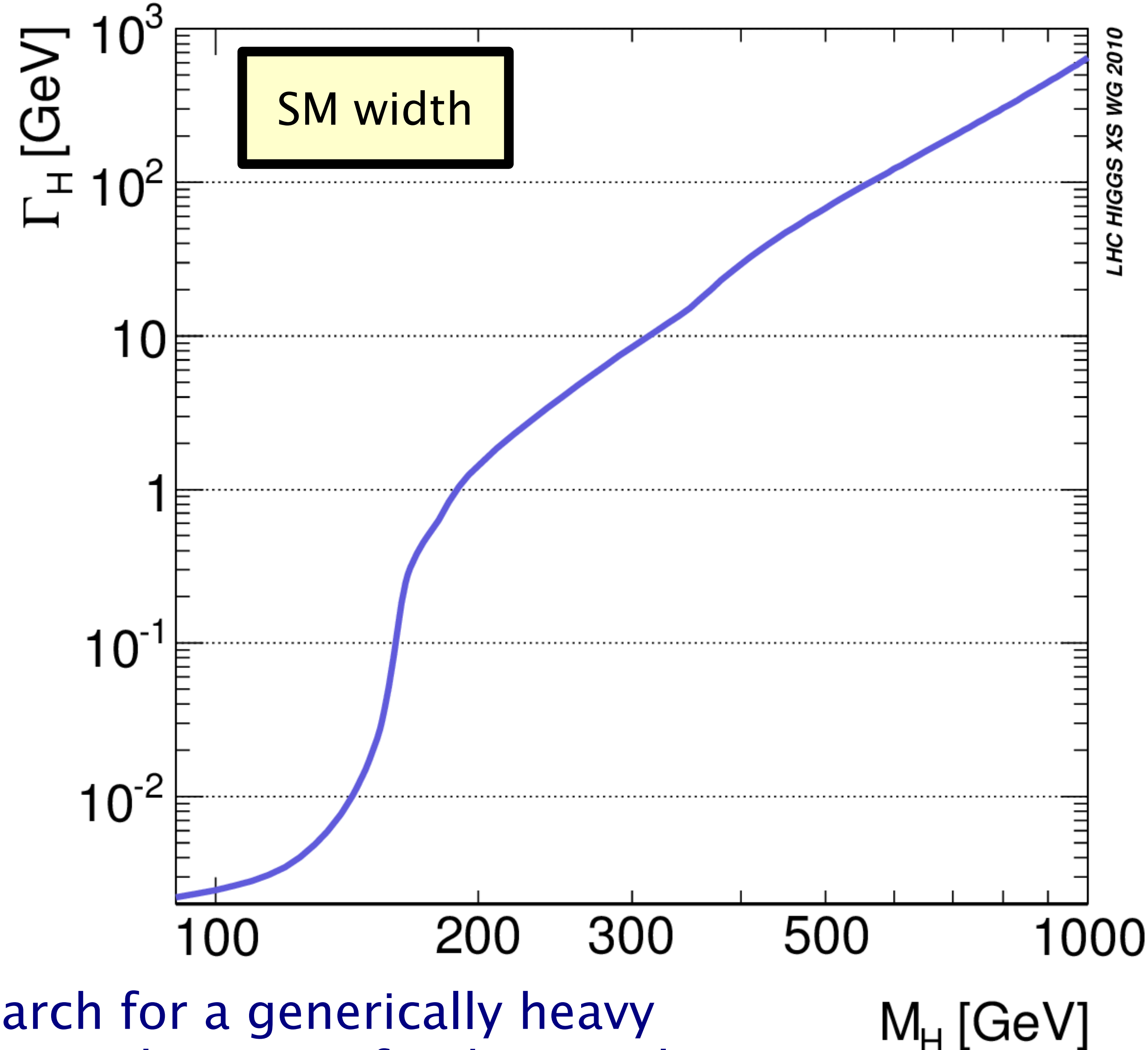
CMS-HIG-12-004



First constraints in mass region above Upsilon resonances. Complementarity of B-factory and LHC is clear for this kind of search.

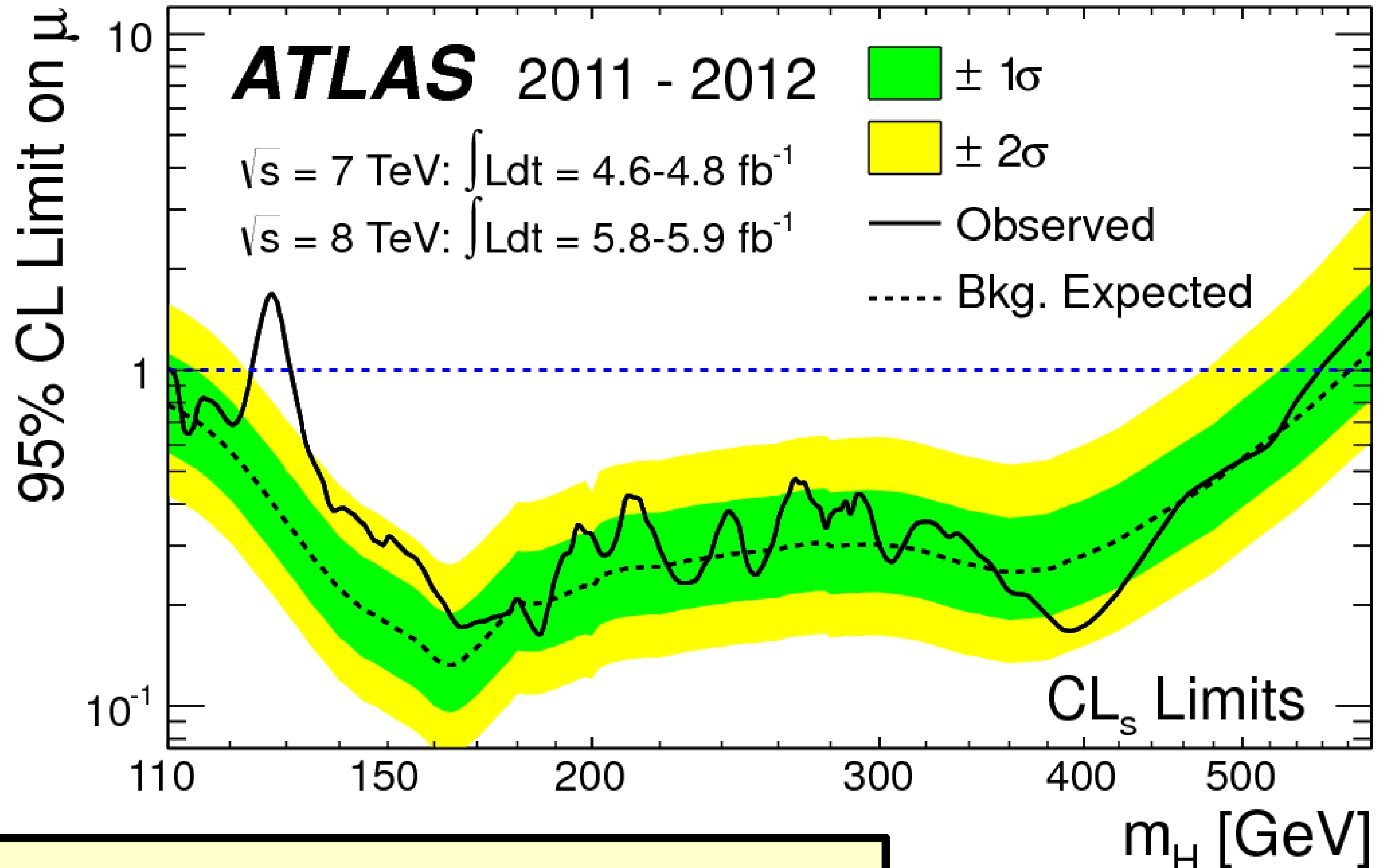
CMS-HIG-12-004

Heavy Higgs Searches



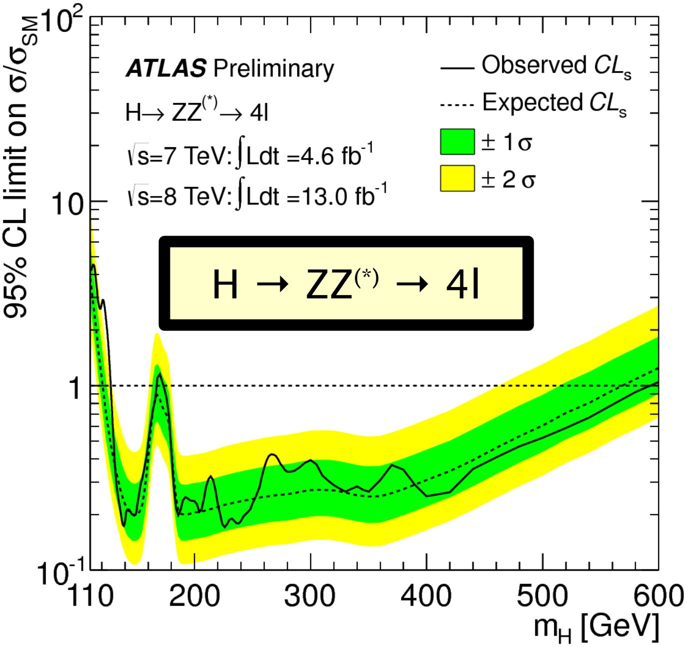
Any search for a generically heavy Higgs has at least one fundamental challenge: modeling the Higgs width

arXiv:1101.0593

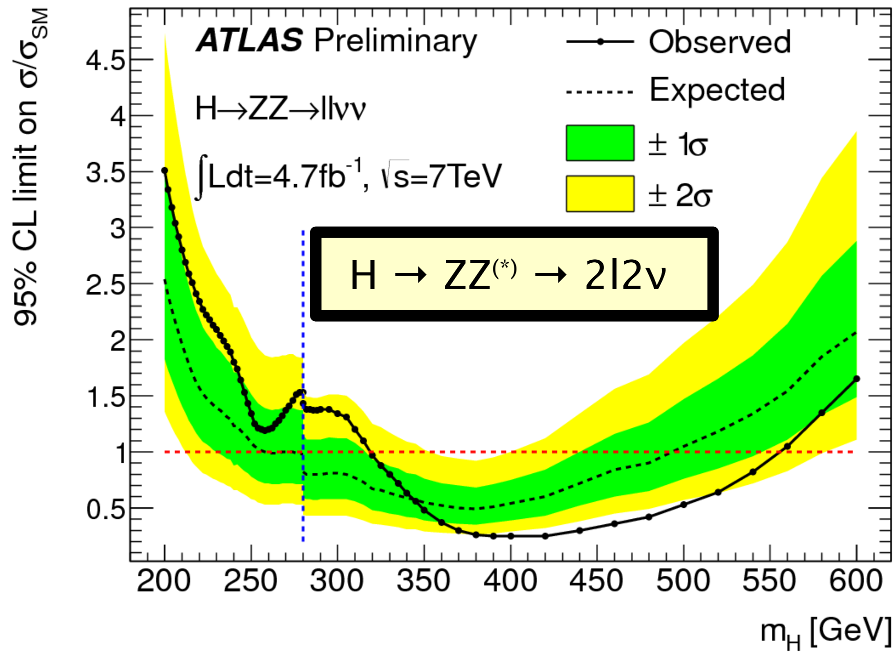


Combined SM-like Higgs search across multiple channels (ca. July, 2012)

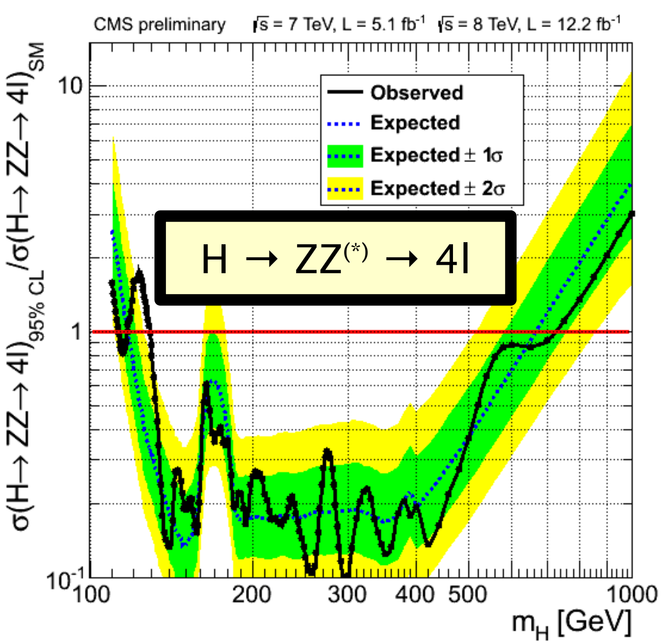
Phys. Lett. B 716 (2012) 1-29



ATLAS-CONF-2012-169

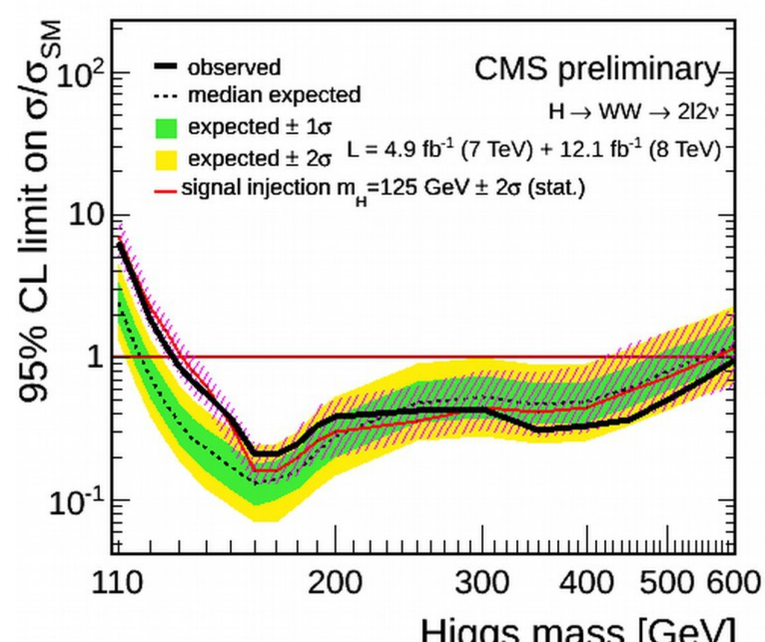


ATLAS-CONF-2012-017



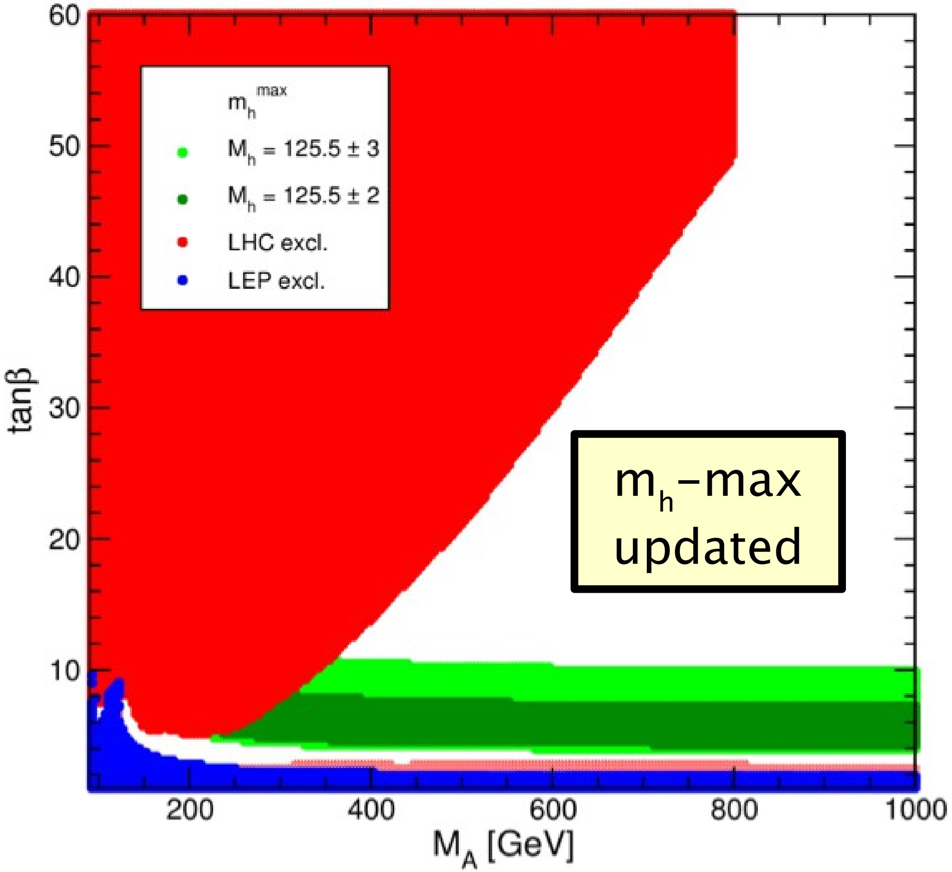
CMS-PAS-HIG-12-041

ATLAS and CMS don't yet have high-mass Higgs searches combined on the full data set



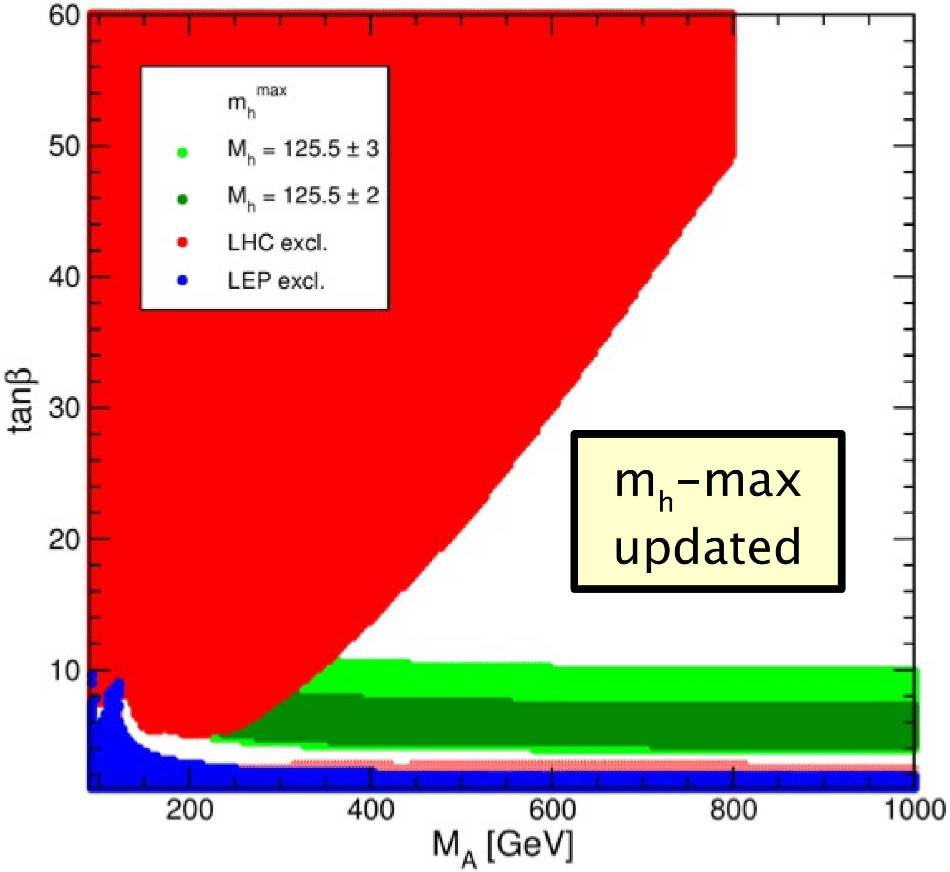
CMS-PAS-HIG-12-042

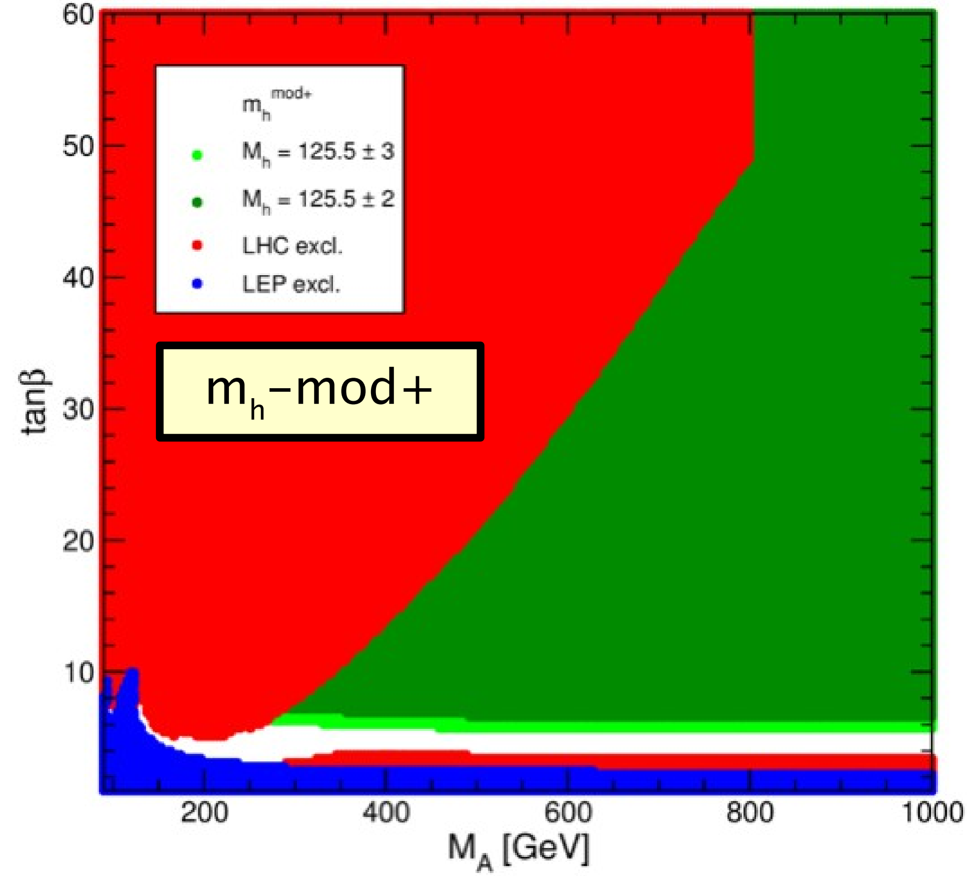
An Experimentalist's View: Theoretical Issues



$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 2\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= \sqrt{6}\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

arXiv:1302.7033





$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= \sqrt{6}\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde g} &= 1500 \text{ GeV}, \\
M_{\tilde l_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

Alter stop mixing

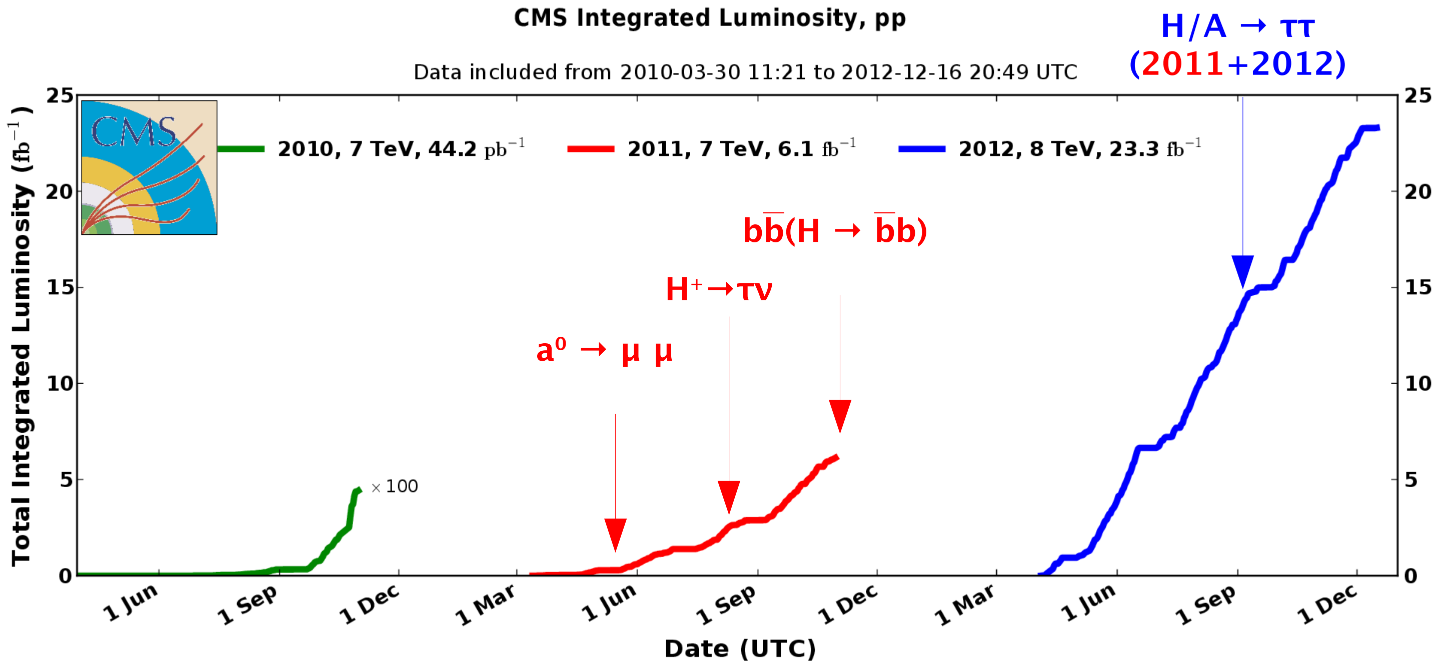
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 1.5\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= 1.6\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde g} &= 1500 \text{ GeV}, \\
M_{\tilde l_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

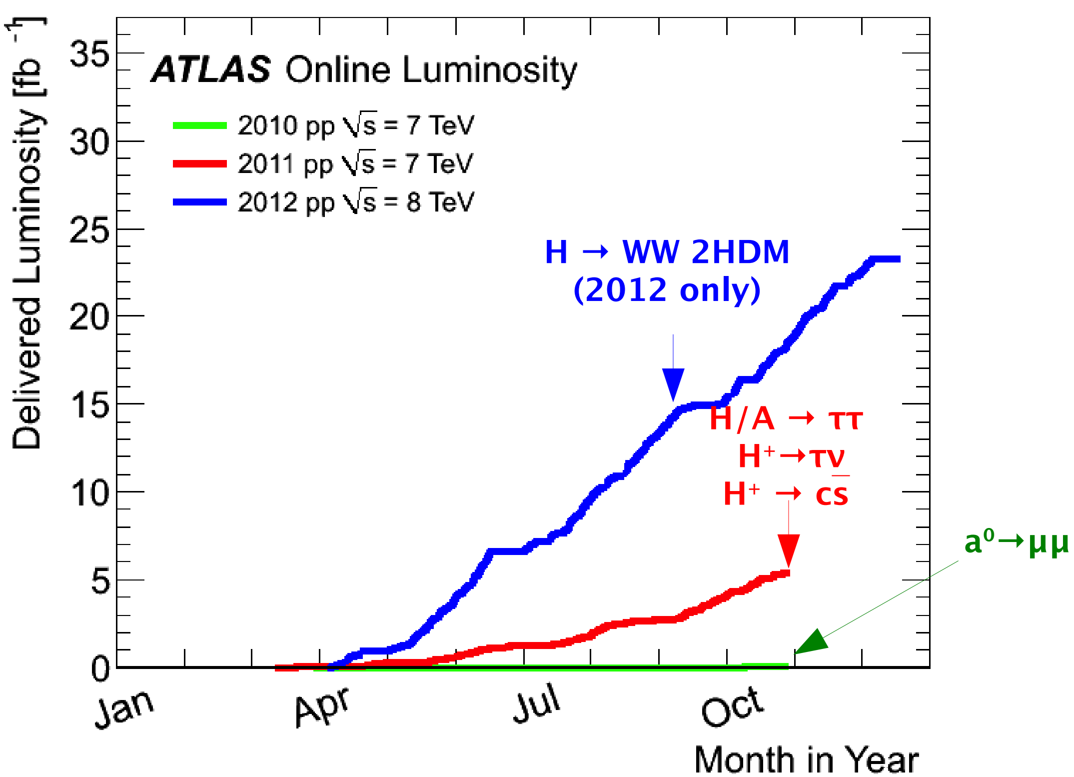
arXiv:1302.7033

- LHC Higgs Cross-Section Working Group anticipates Yellow Report #3 (YR3) soon
  - updated benchmarks for MSSM (c.f. arXiv:1302.7033)
- Other discussions: 2HDM benchmarks
  - parameterization: e.g. $\cos(\beta - \alpha)$ vs. mass instead of $\cos(\alpha)$ vs. mass
  - tools: SusHi[1], 2HDMC[2], etc.
  - are benchmarks in a type-III model possible (motivated by recent $B \to D^{(*)} \tau \nu$ results from BaBar)?
- discussions ongoing about other heavy Higgs search frameworks
  - what scheme is to be used to interpret high mass searches?
- What aren't we doing that we SHOULD be doing?

[1] http://arxiv.org/pdf/1212.3249.pdf
[2] http://arxiv.org/abs/0902.0851

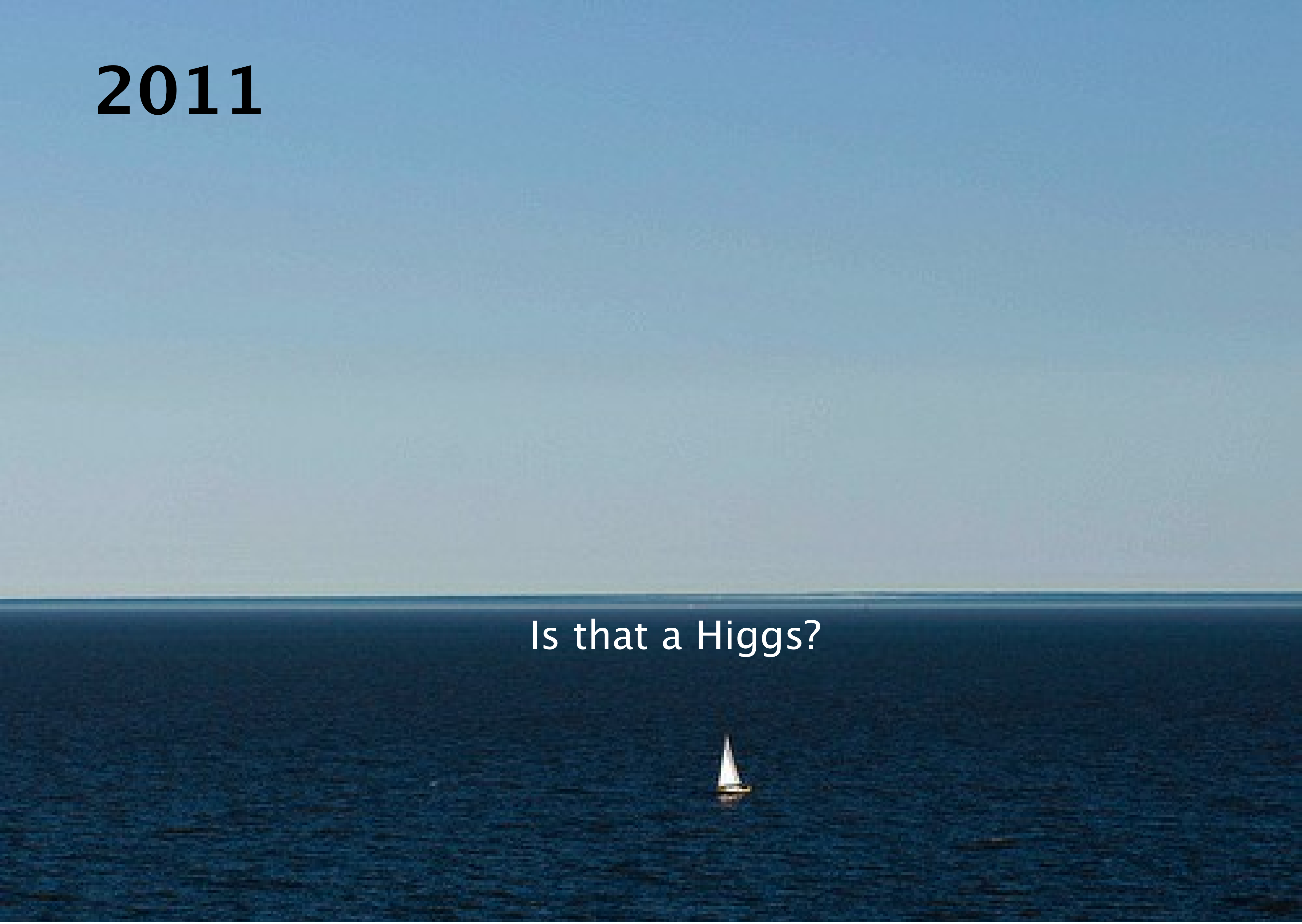
Conclusions and Outlook





Neither experiment has yet used its entire data sample to do any of these analyses.

There is potentially much to be learned from both independent data samples!


2011
Is that a Higgs?

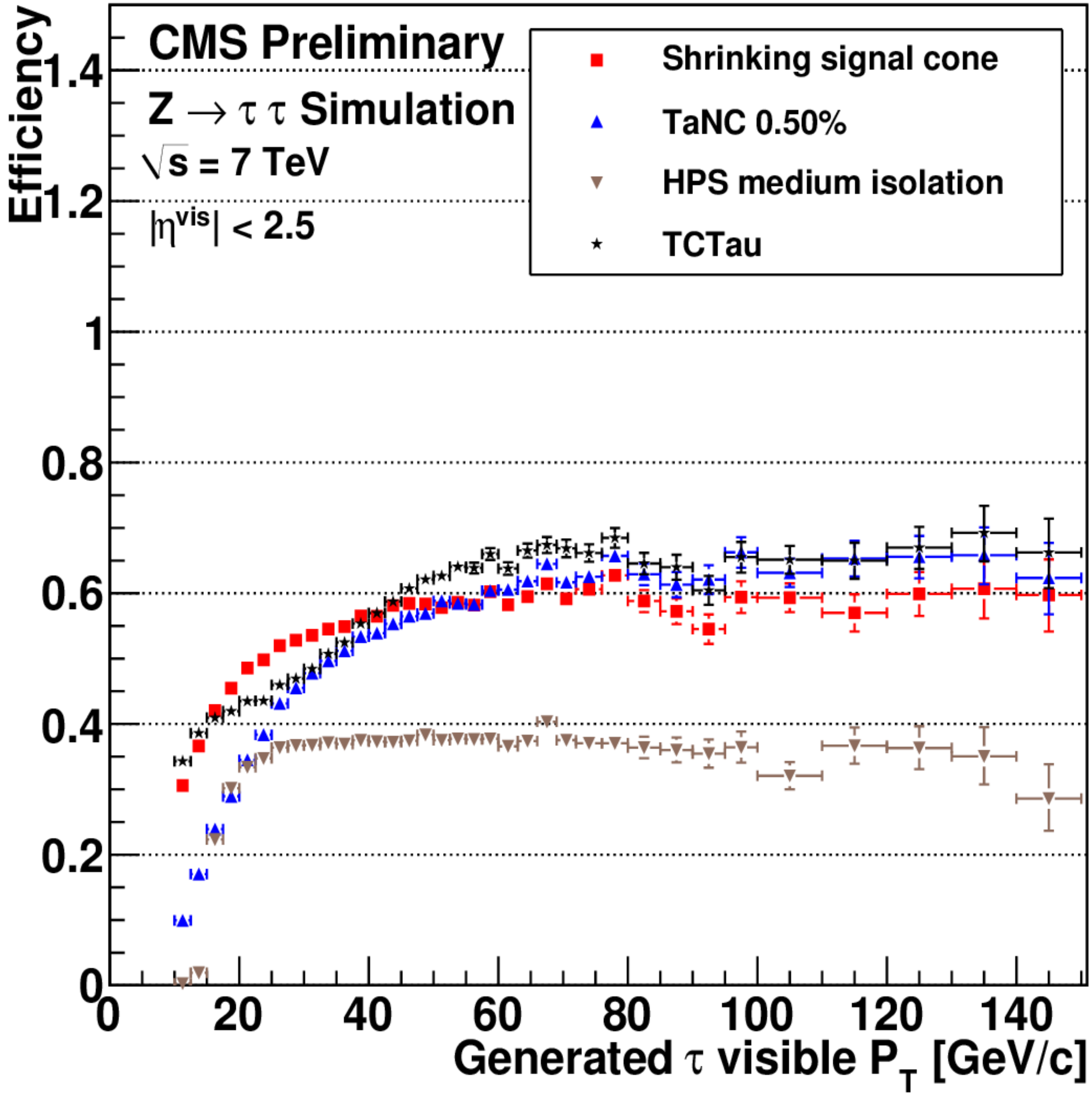
2012

2013 and beyond?

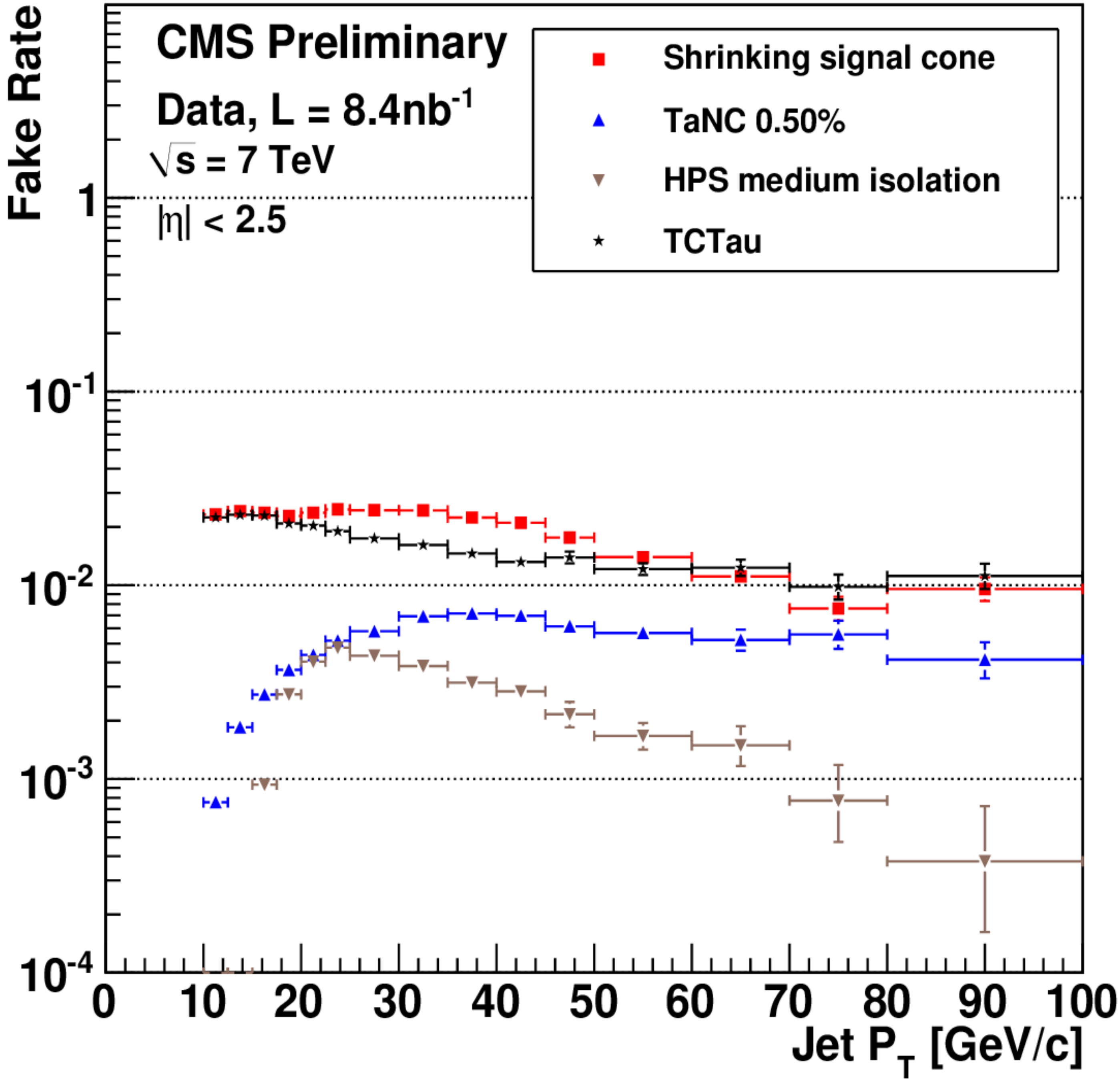
More Higgs(es)?

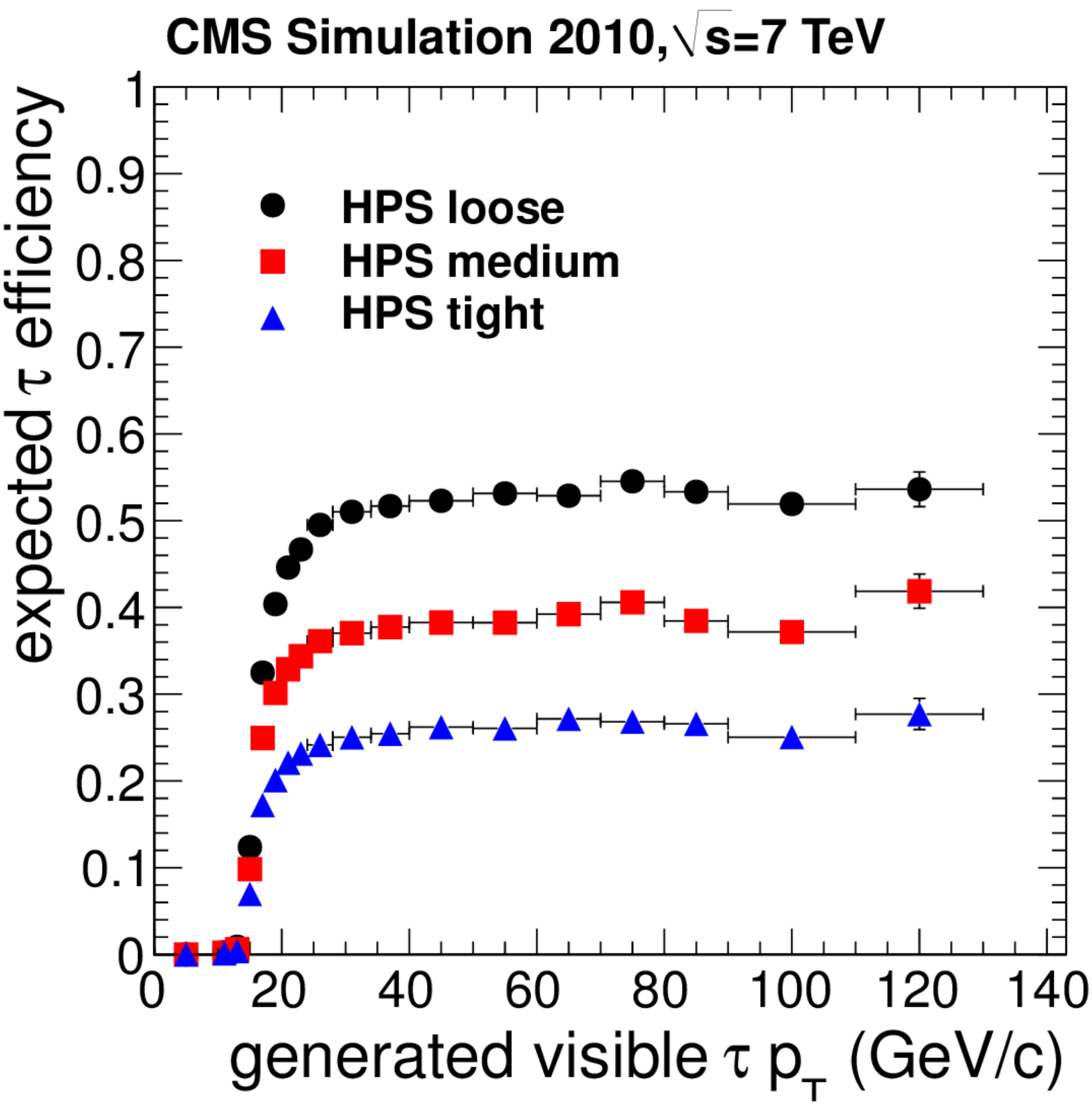
ADDITIONAL MATERIAL

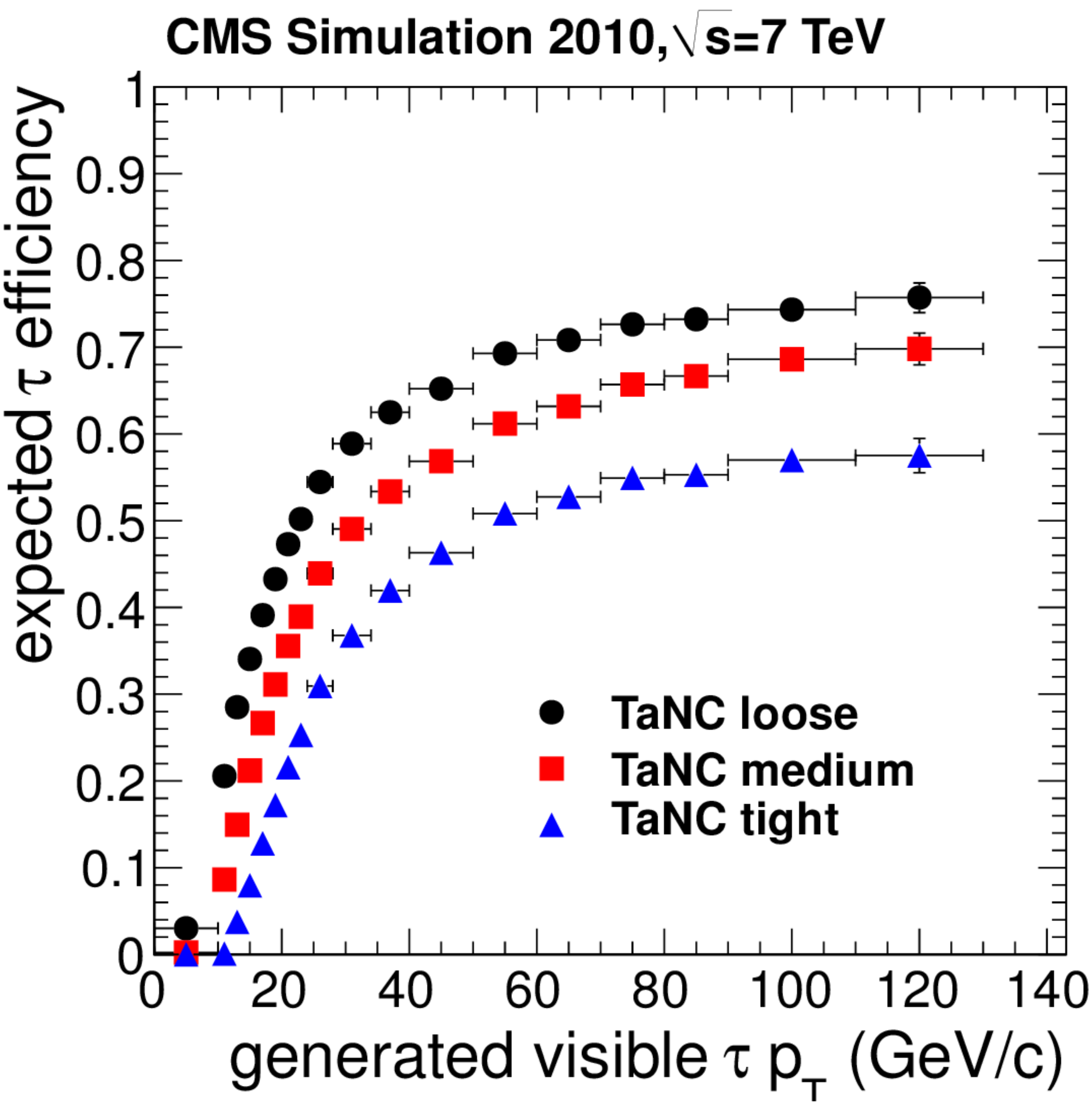
TAU IDENTIFICATION



CMS Preliminary
Z → τ τ Simulation
√s = 7 TeV
|η^vis| < 2.5
Shrinking signal cone
TaNC 0.50%
HPS medium isolation
TCTau
Efficiency
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
20
40
60
80
100
120
140
Generated τ visible P_T [GeV/c]


CMS Preliminary
Data, L = 8.4nb-1
√s = 7 TeV
|η| < 2.5
Shrinking signal cone
TaNC 0.50%
HPS medium isolation
TCTau
Fake Rate
1
10-1
10-2
10-3
10-4
0
10
20
30
40
50
60
70
80
90
100
Jet PT [GeV/c]

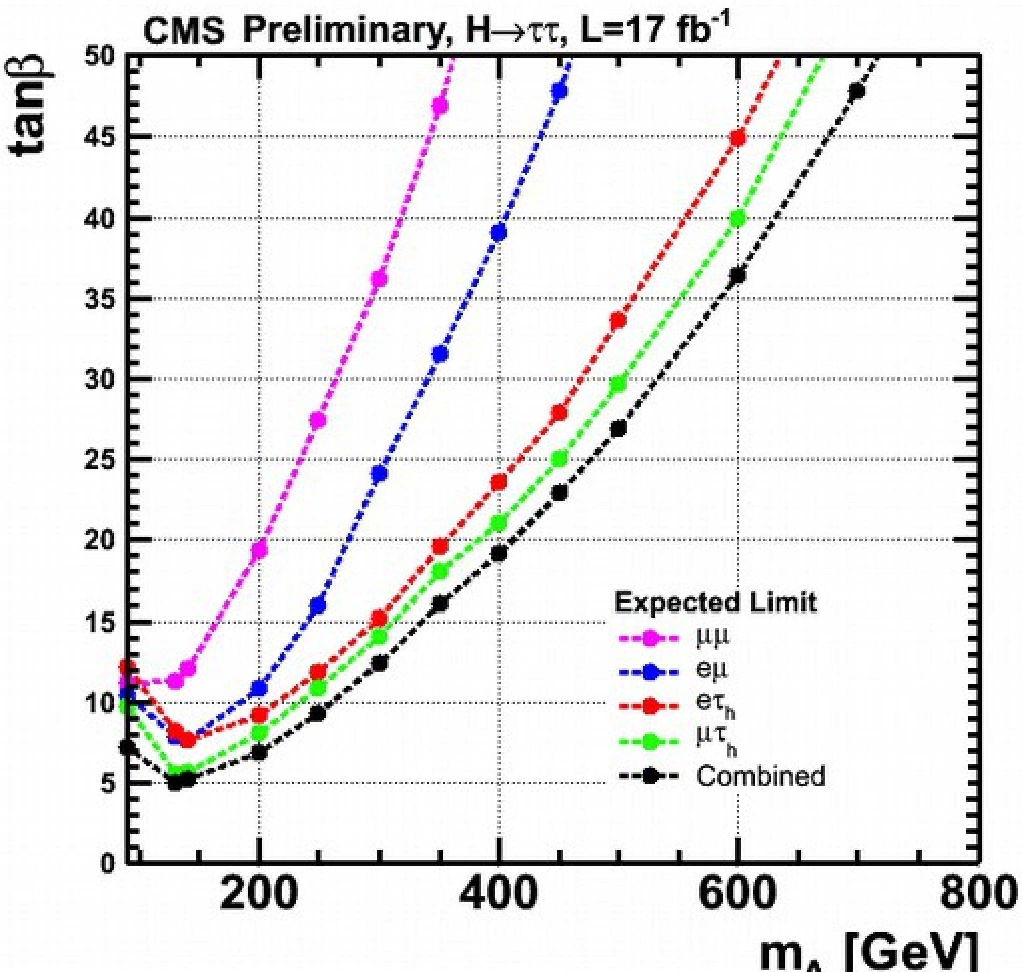

CMS Simulation 2010, $\sqrt{s}$=7 TeV
expected τ efficiency
HPS loose
HPS medium
HPS tight
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
generated visible τ p_T (GeV/c)


CMS Simulation 2010,√s=7 TeV
expected τ efficiency
generated visible τ p_T (GeV/c)
TaNC loose
TaNC medium
TaNC tight
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140

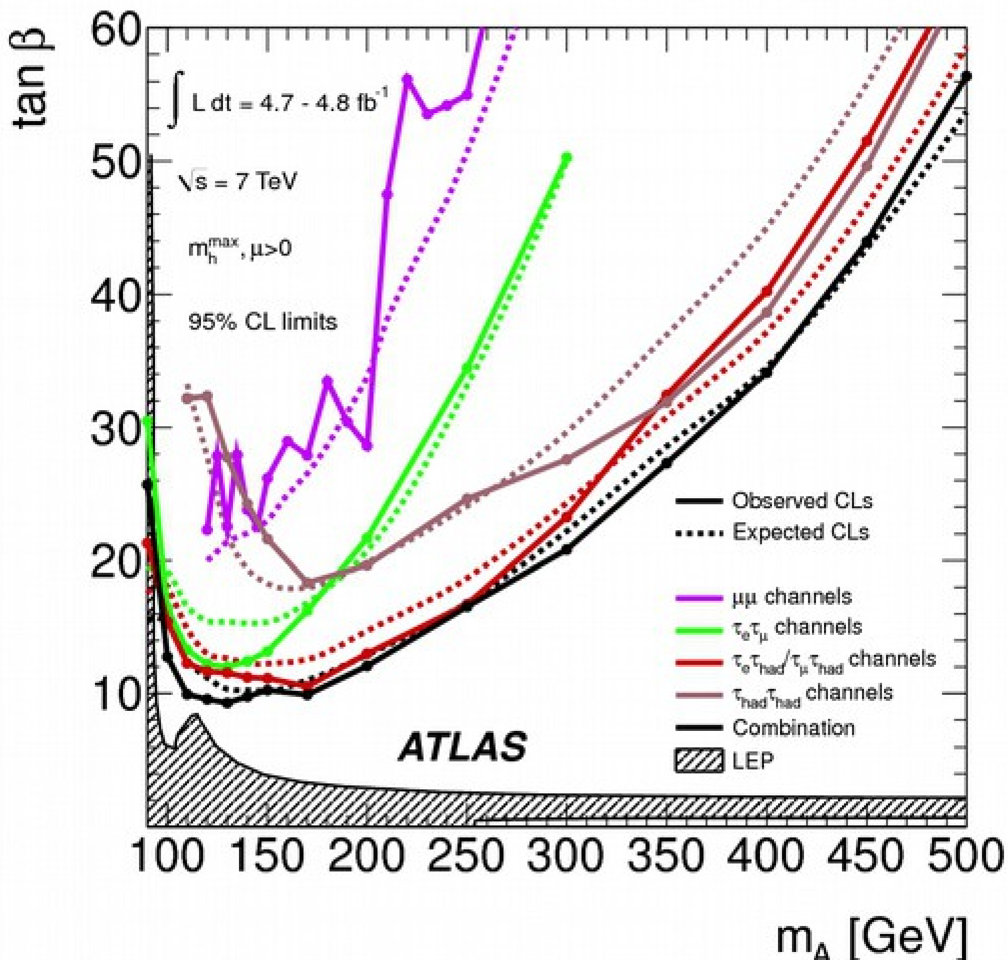
MSSM-INSPIRED $H^0/A^0 \rightarrow \tau^+ \tau^-$

Results by Channel

CMS-PAS-HIG-12-050



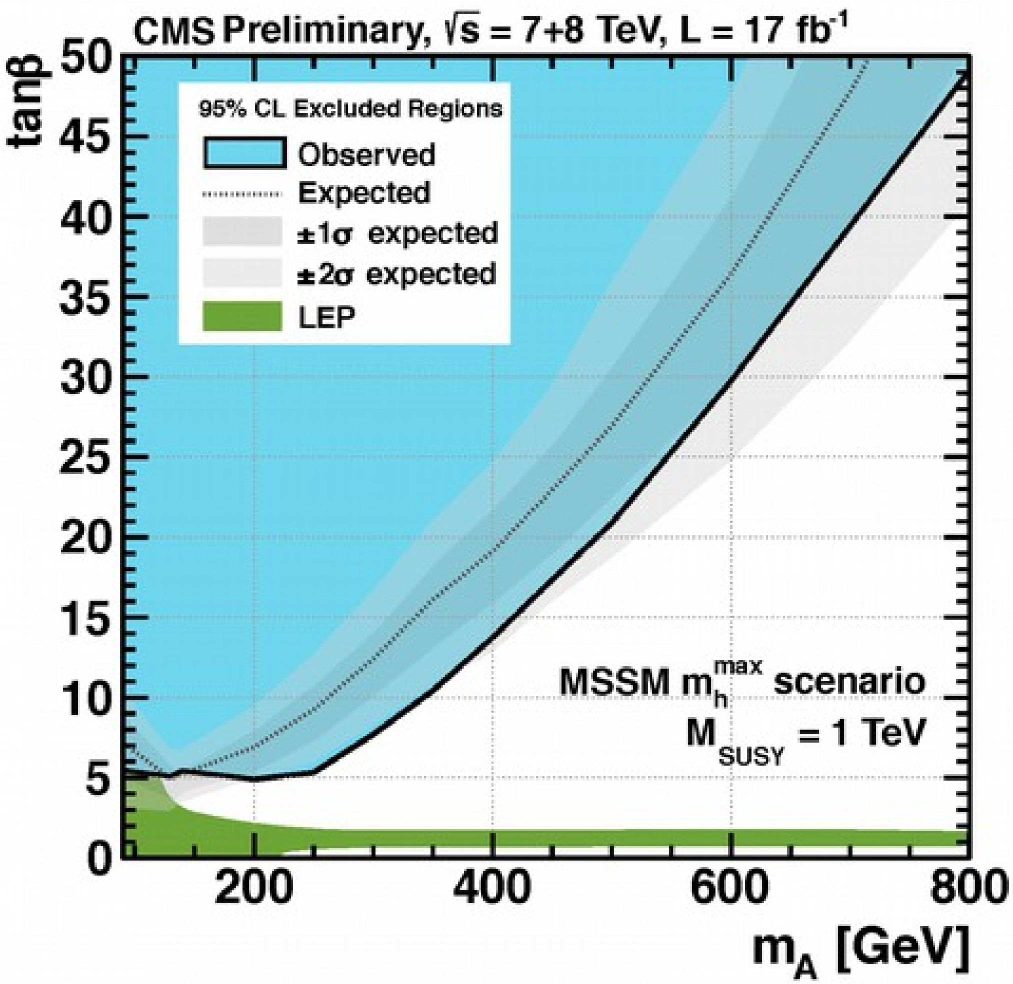
JHEP02(2013)095



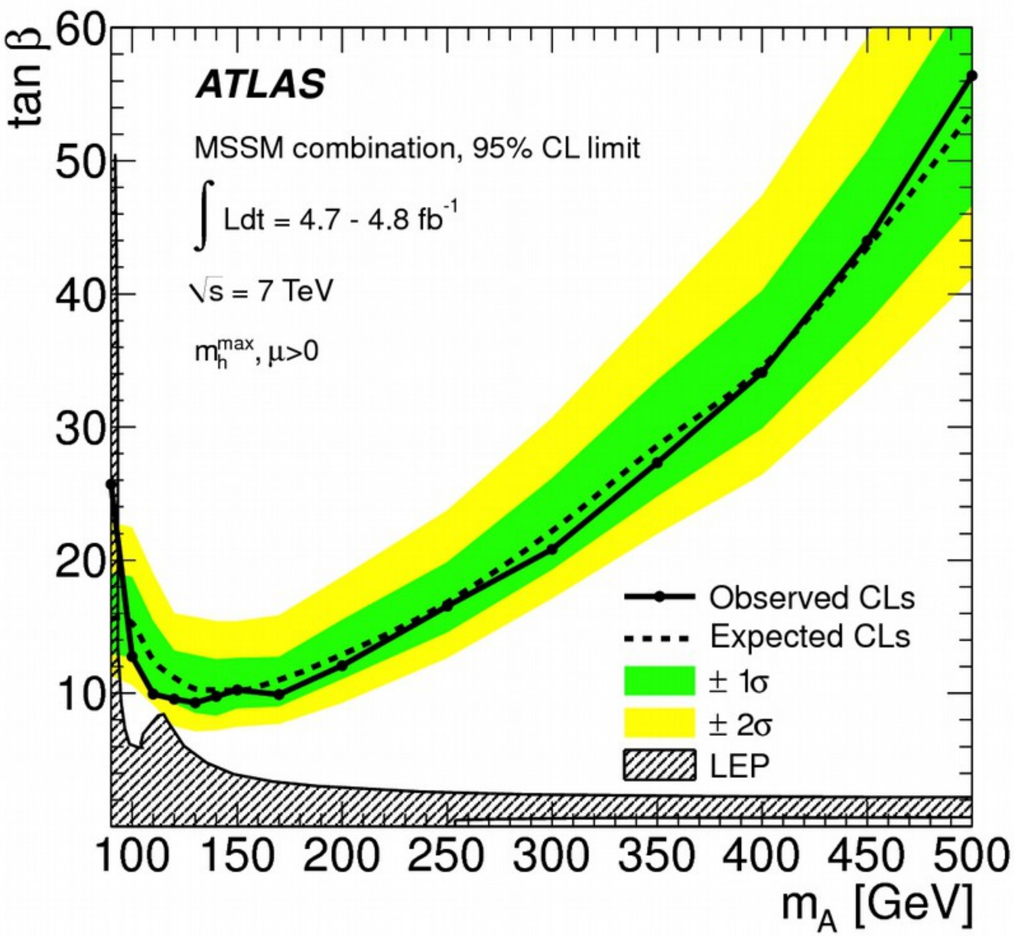
(*) It should be noted that if we switch to an alternative MSSM benchmark scenario, like mh-mod+ or mh-mod-, we don't expect these constraints to change too much.

Model-Dependent(*) Results

CMS-PAS-HIG-12-050



JHEP02(2013)095

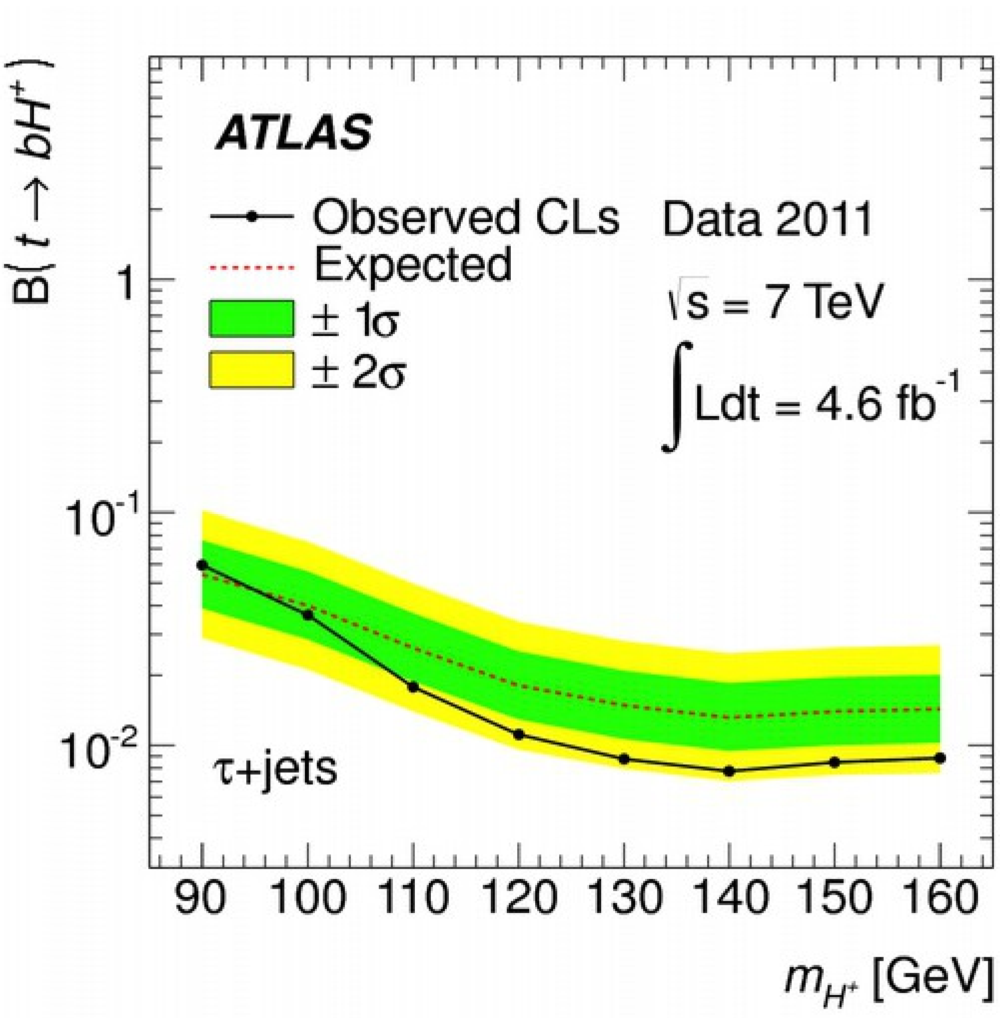


(*) It should be noted that if we switch to an alternative MSSM benchmark scenario, like mh-mod+ or mh-mod-, we don't expect these constraints to change too much.

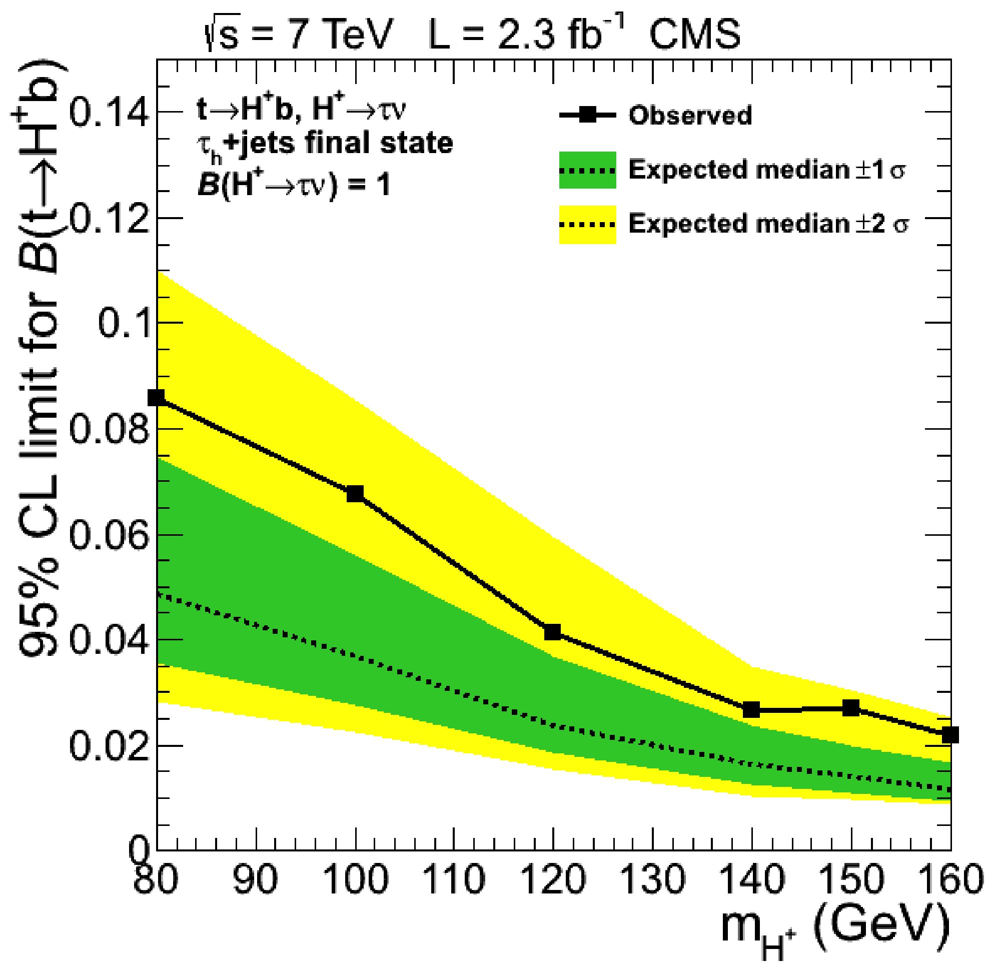
MSSM-INSPIRED $H^+ \rightarrow \tau^+ \nu$

Channel-by-channel

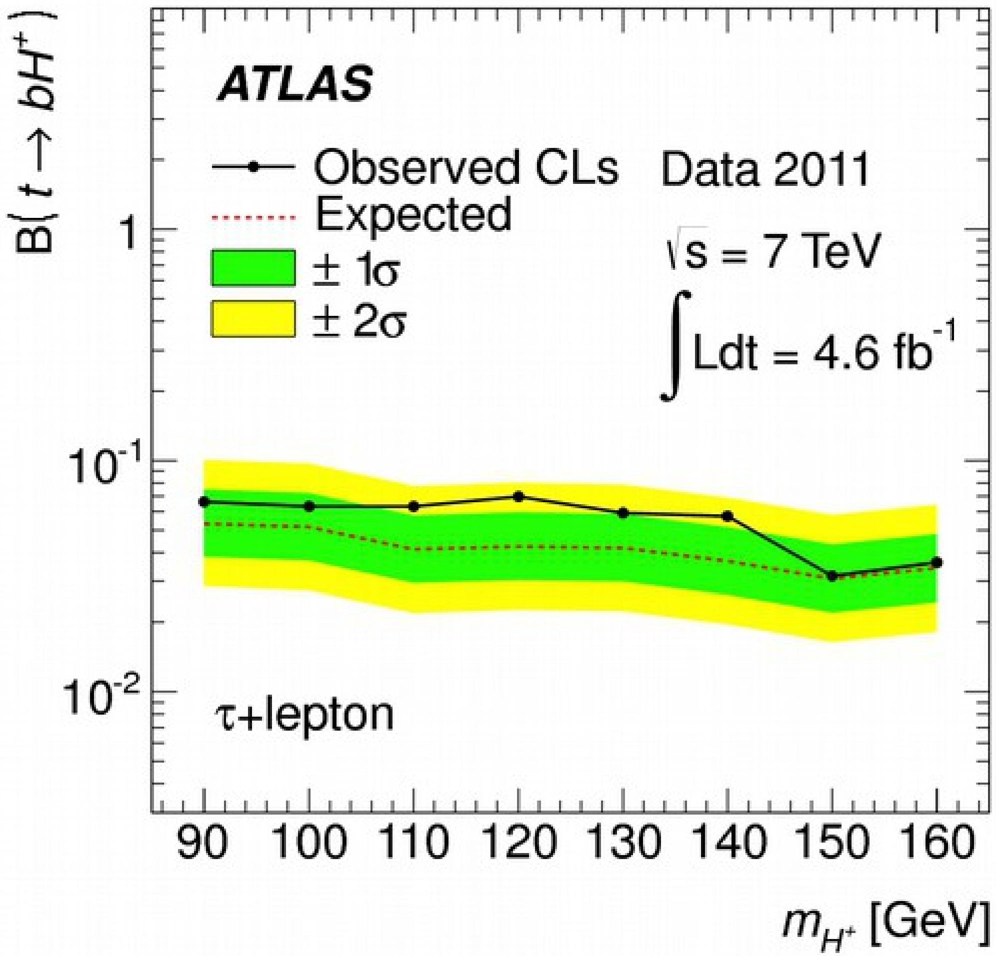
JHEP06 (2012) 039



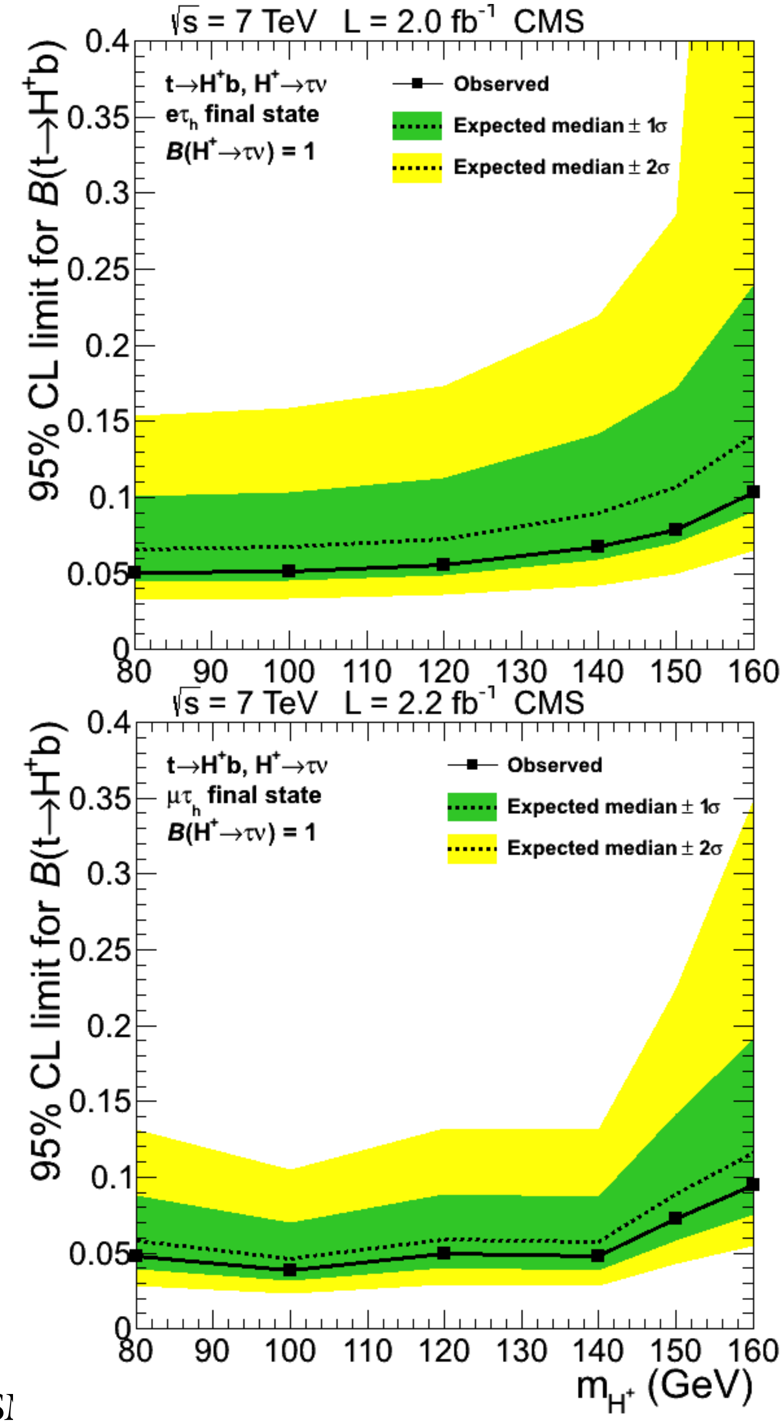
JHEP07 (2012) 143



JHEP06 (2012) 039

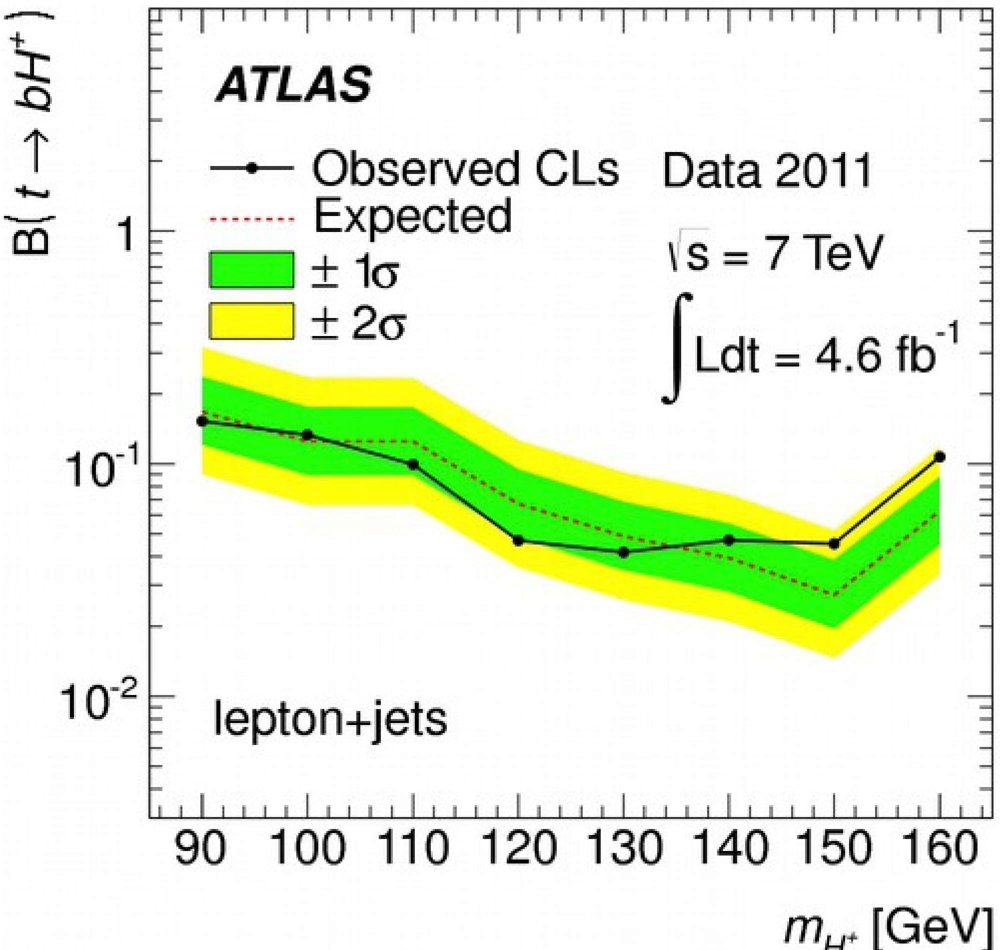


JHEP07 (2012) 143

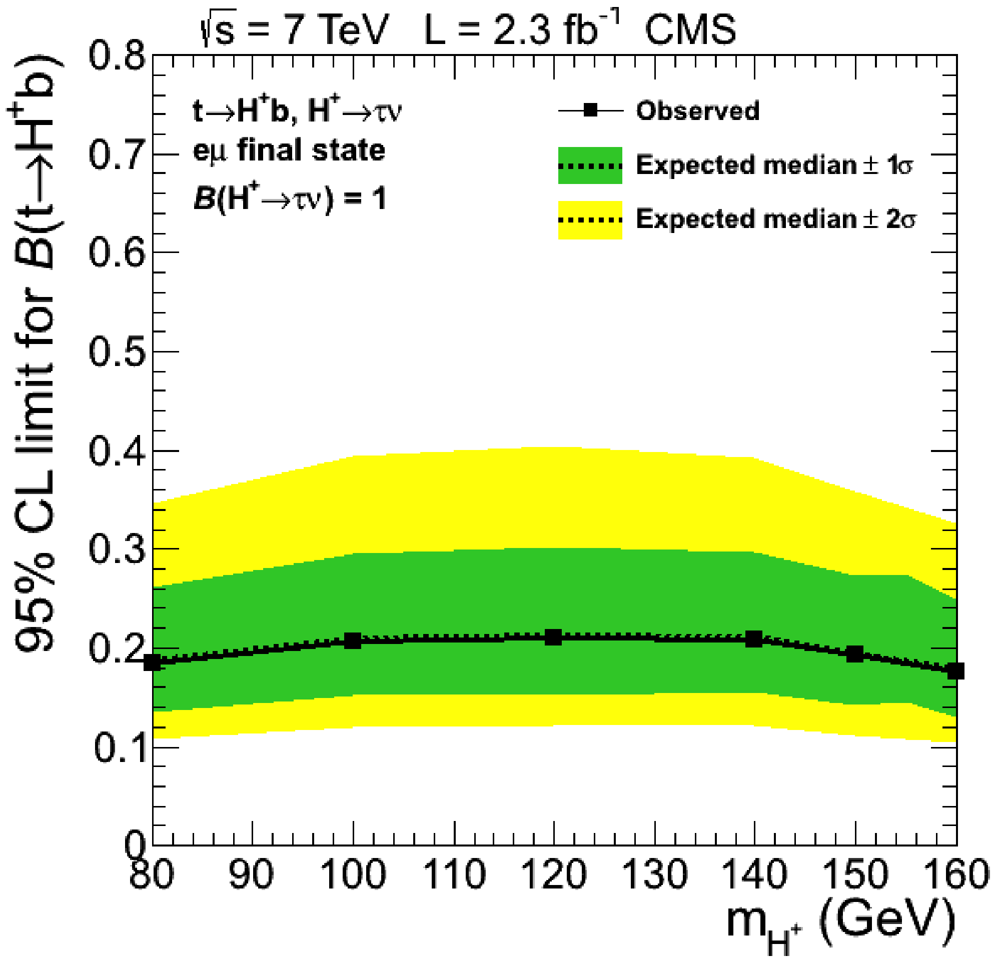


JHEP06 (2012) 039

JHEP07 (2012) 143

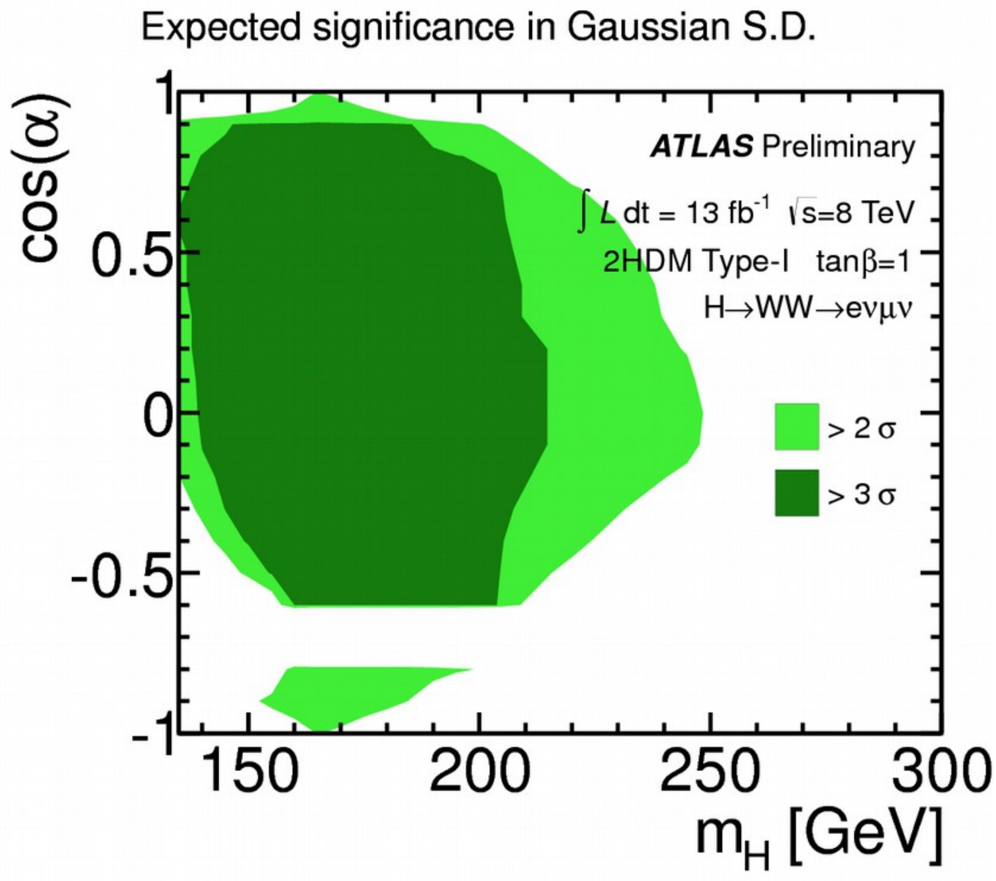


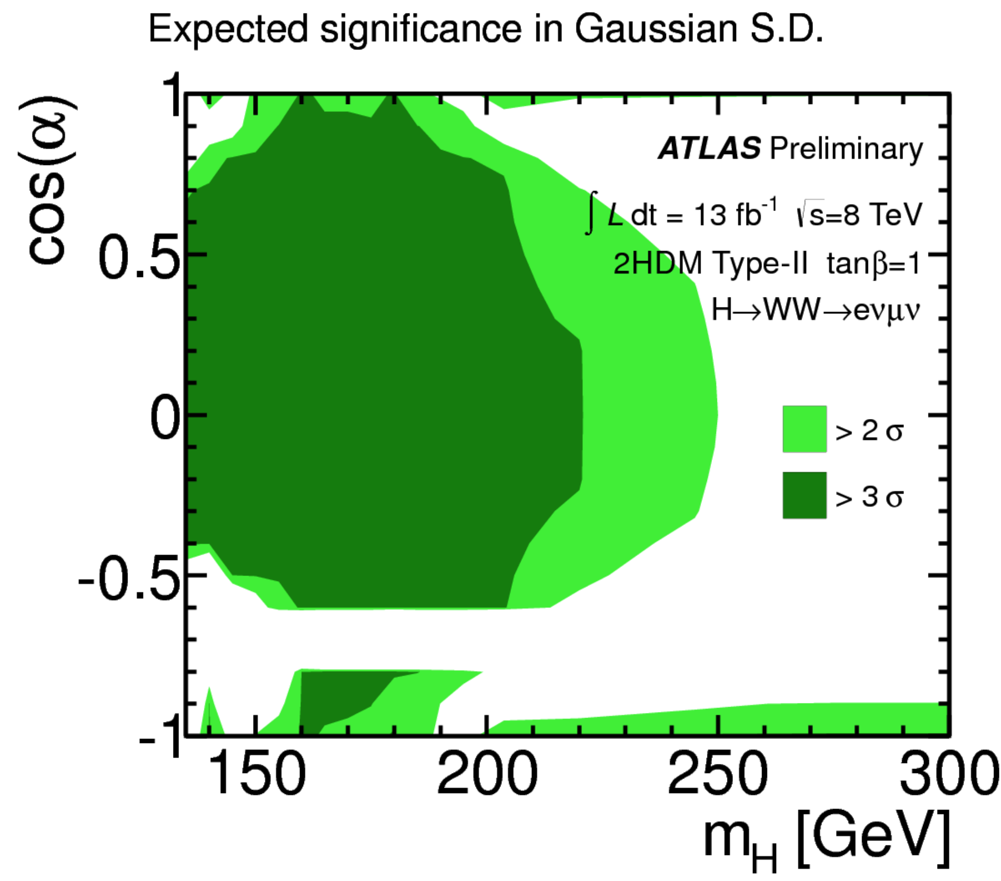
lepton + jets channel
[ATLAS Only]



e + μ channel
[CMS Only]

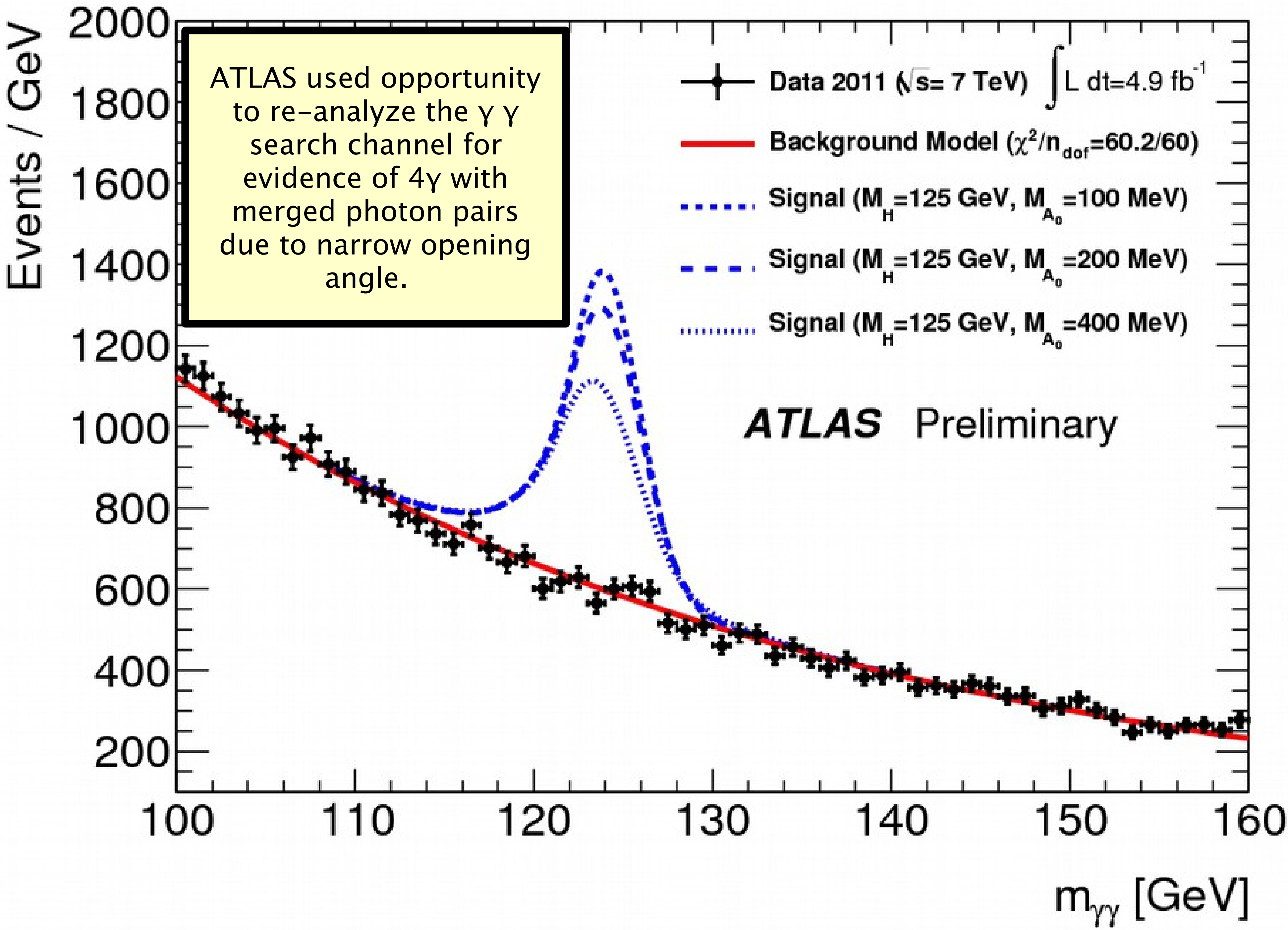
2HDM-Inspired $H^0 \rightarrow WW$

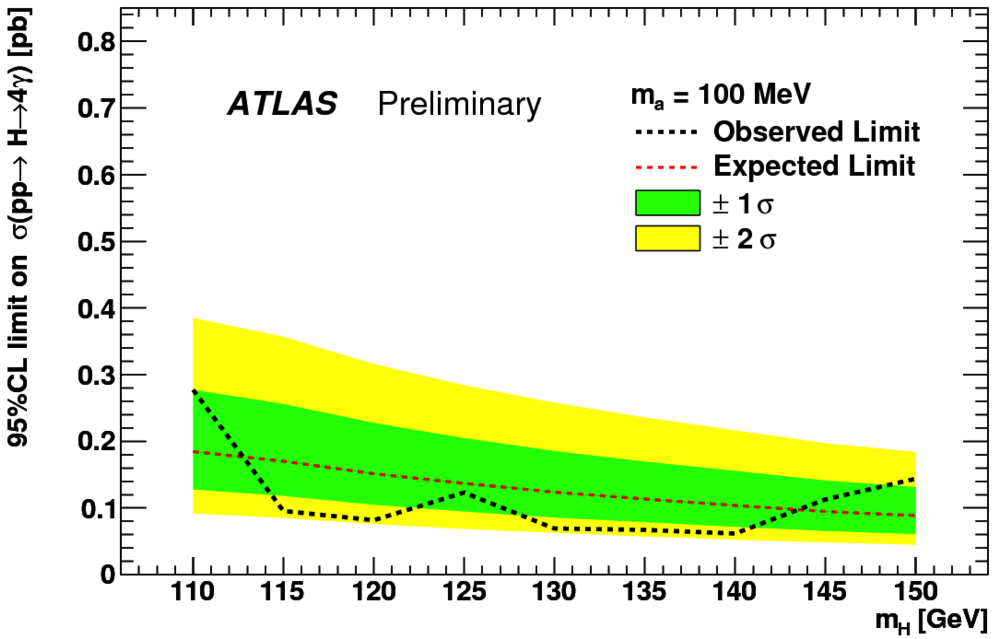

Expected significance in Gaussian S.D.
cos(α)
ATLAS Preliminary
∫ L dt = 13 fb^-1 √s=8 TeV
2HDM Type-I tanβ=1
H→WW→eνμν
> 2 σ
> 3 σ
1
0.5
0
-0.5
-1
150
200
250
300
m_H [GeV]

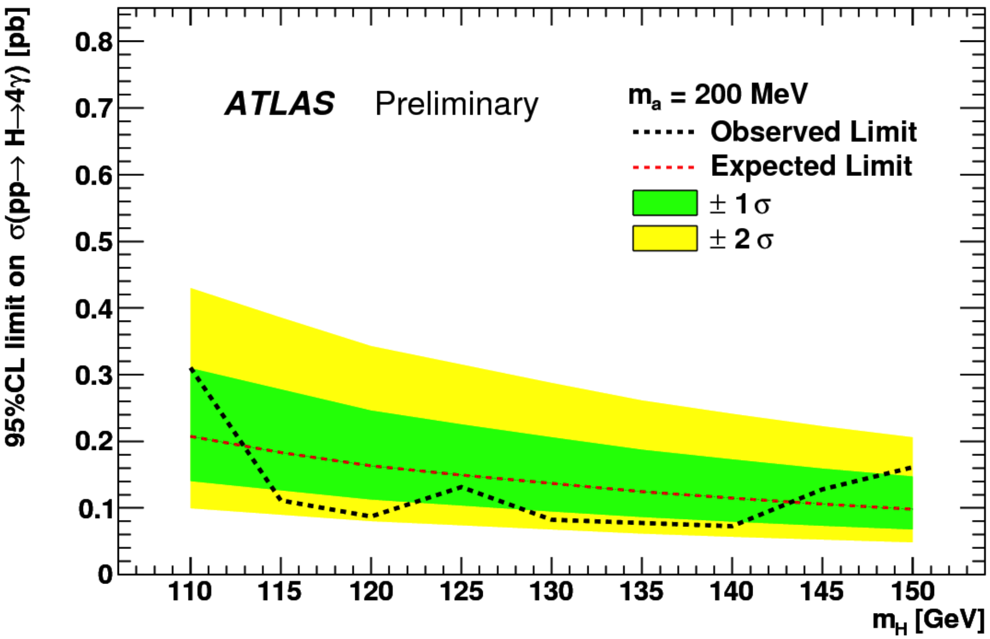

Expected significance in Gaussian S.D.
cos(α)
ATLAS Preliminary
∫ L dt = 13 fb^-1 √s=8 TeV
2HDM Type-II tanβ=1
H→WW→eνμν
> 2 σ
> 3 σ
1
0.5
0
-0.5
-1
150
200
250
300
m_H [GeV]

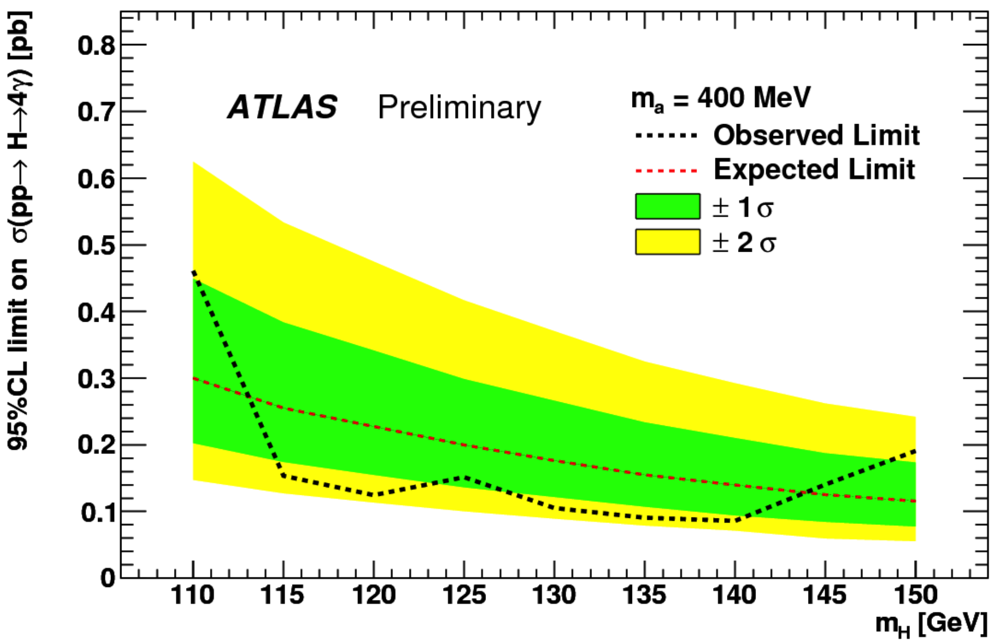
NMSSM-inspired $H_1 \rightarrow 4\gamma$

ATLAS used opportunity to re-analyze the γ γ search channel for evidence of 4γ with merged photon pairs due to narrow opening angle.



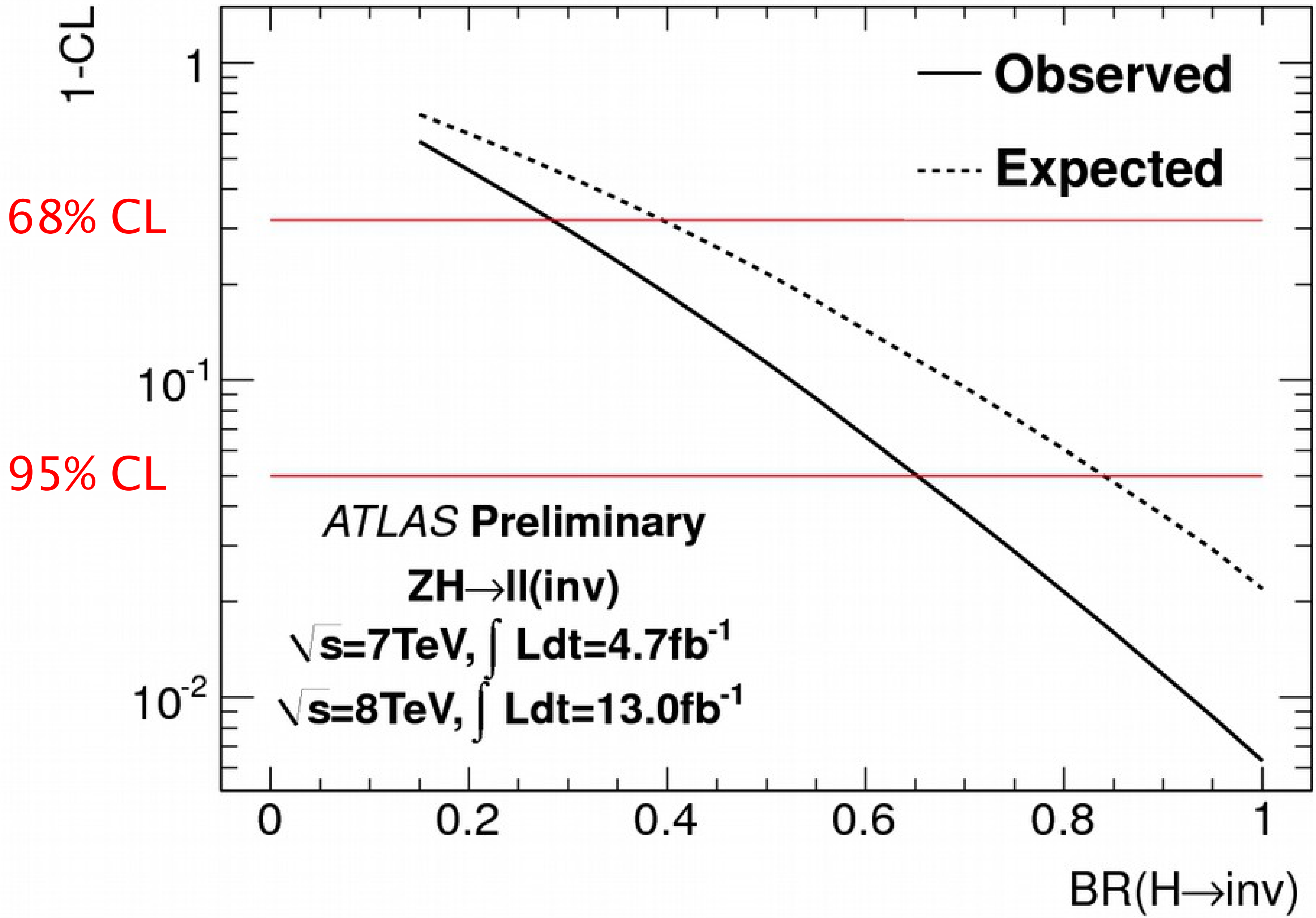




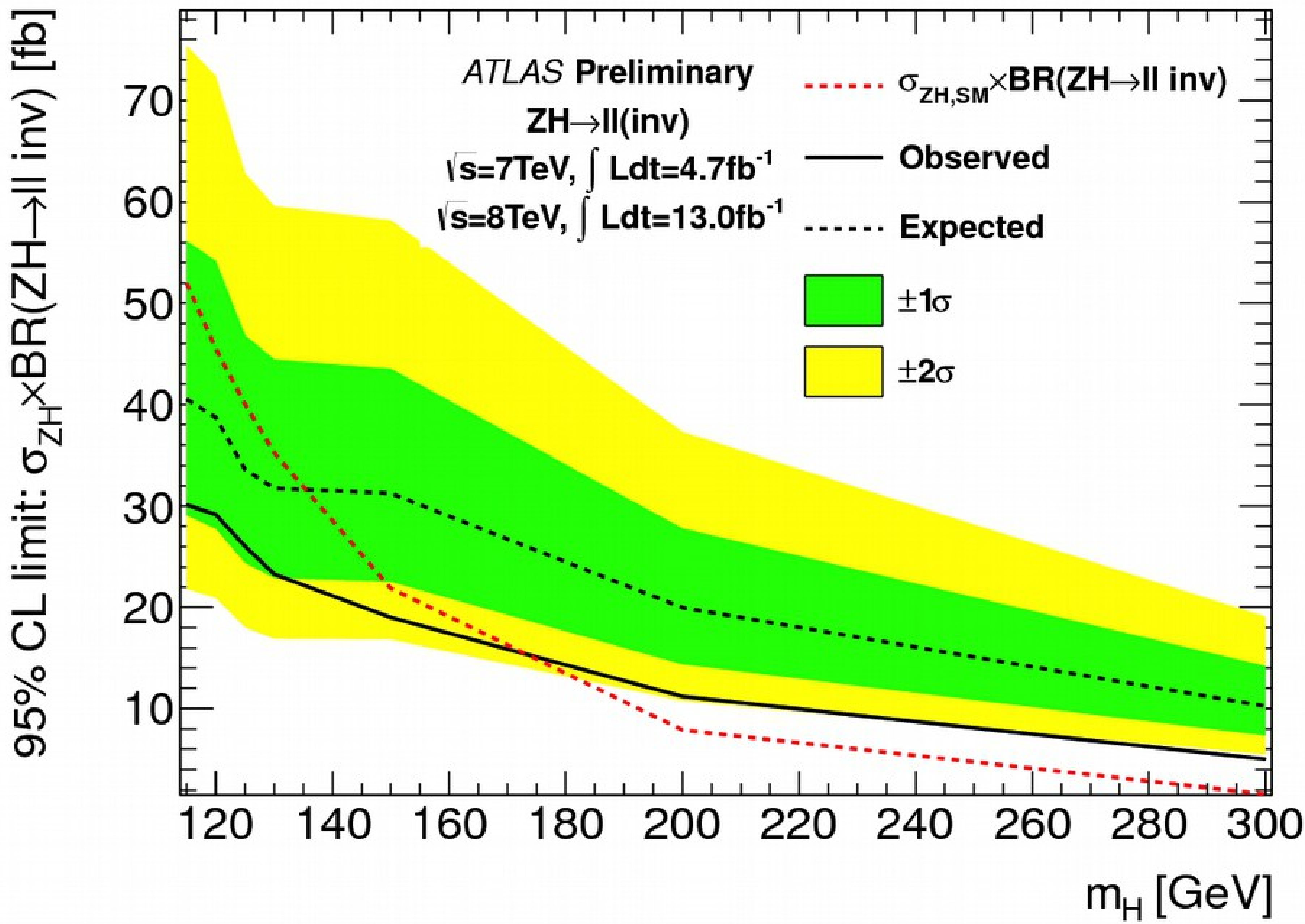


ATLAS-CONF-2012-079

$H^0 \rightarrow$ invisible



68% CL
95% CL
1-CL
1
10^-1
10^-2
Observed
Expected
ATLAS Preliminary
ZH→ll(inv)
√s=7TeV, ∫ Ldt=4.7fb^-1
√s=8TeV, ∫ Ldt=13.0fb^-1
0
0.2
0.4
0.6
0.8
1
BR(H→inv)



ATLAS-CONF-2012-079