The Higgs: Above and Beyond

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Presented at SMU
Department Colloquium
April 7, 2014

Programme

- The Higgs – what do we think we know?
- Above the Higgs – what do we want to know?
- Beyond the Higgs – what else should we know?

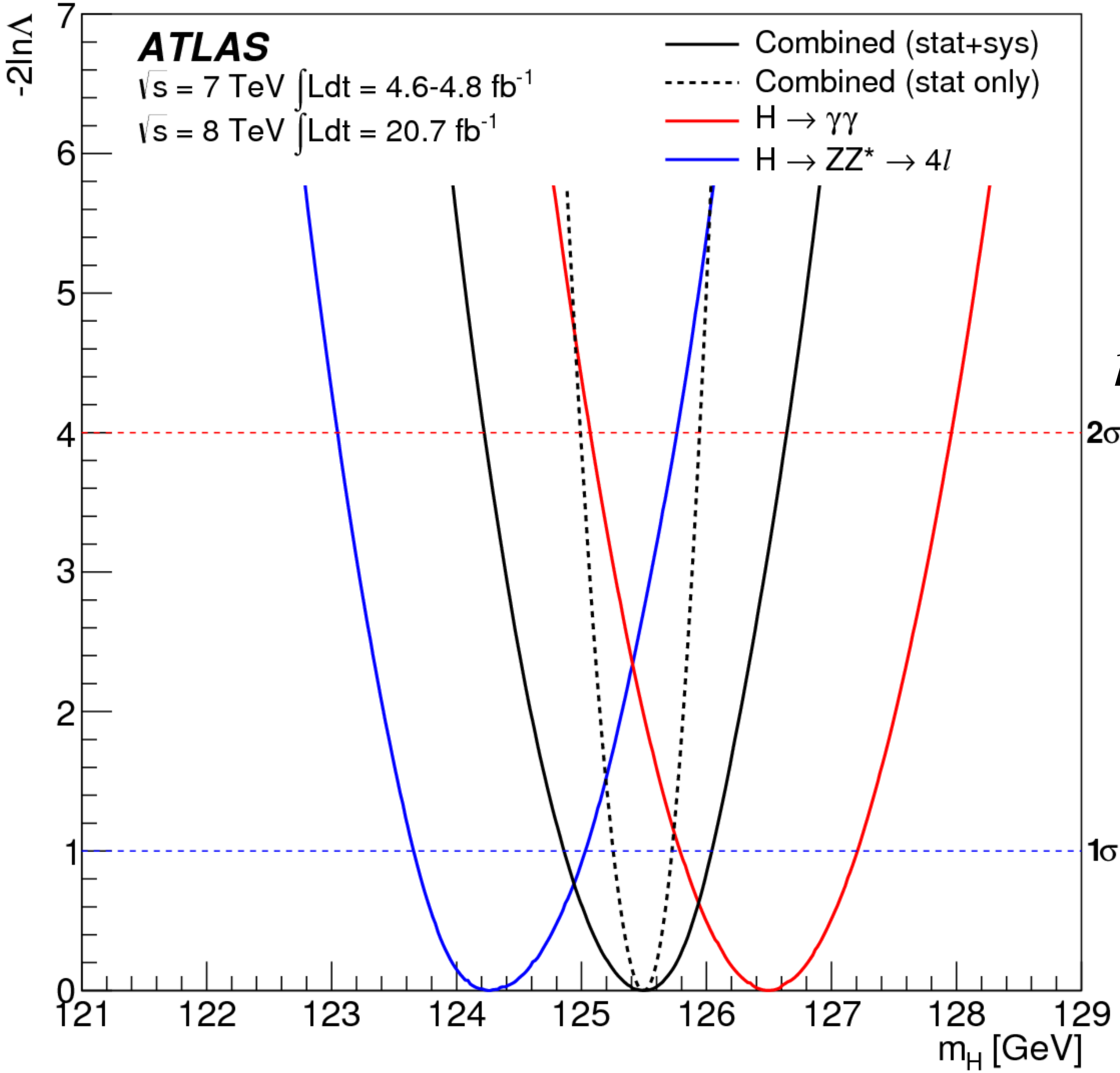
What We Think We Know

Photo credit: Horia Varlan

The Particle Checklist

- Mass – – – – – – – – – – – – – – – –
- Charge – – – – – – – – – – – – – – –
- Spin – – – – – – – – – – – – – – – – –
- Parity – – – – – – – – – – – – – – – –
- Couplings – – – – – – – – – – – – – –

Mass



Phys. Lett. B 726 (2013), pp. 88-119

[in GeV]

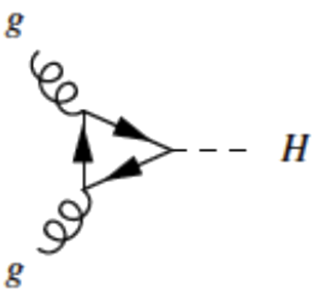
$$m_H = 125.5 \pm 0.2\ (\text{stat.})\ ^{+0.5}_{-0.6}\ (\text{syst.})$$

"Signal Strength"

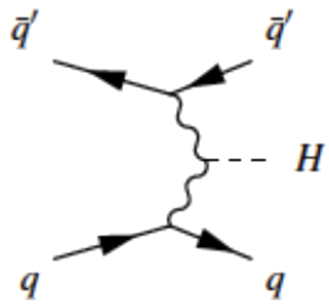
Production cross-section...

Decay branching ratio...

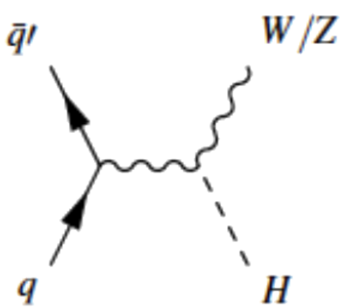
$$\mu_i \equiv \frac{\left(\sigma \times BR_i\right)_{\text{measured}}}{\left(\sigma \times BR_i\right)_{\text{predicted}}}$$



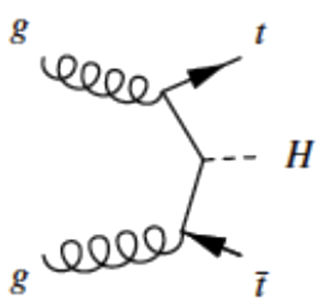
(a) $gg \to H$



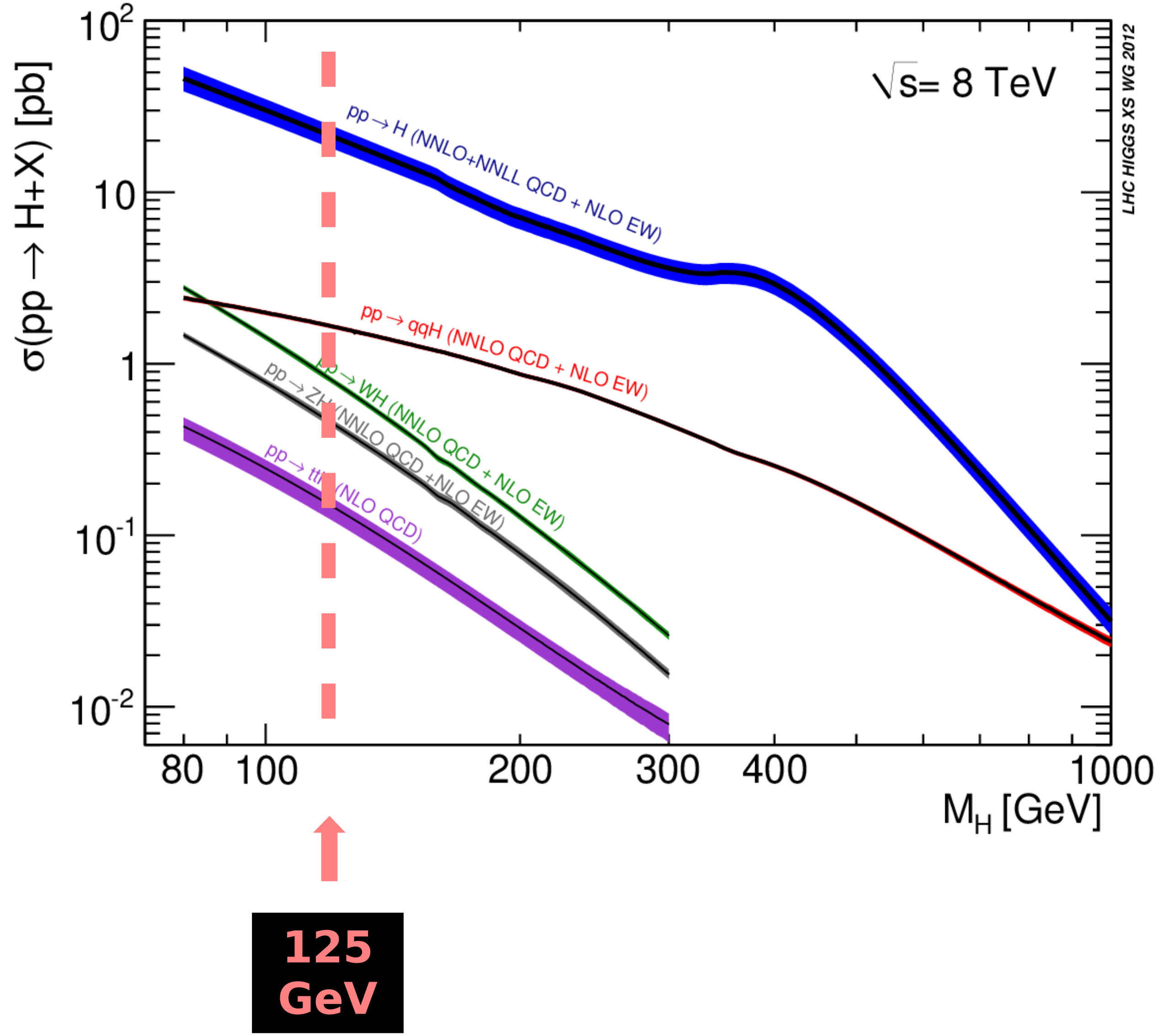
(b) VBF

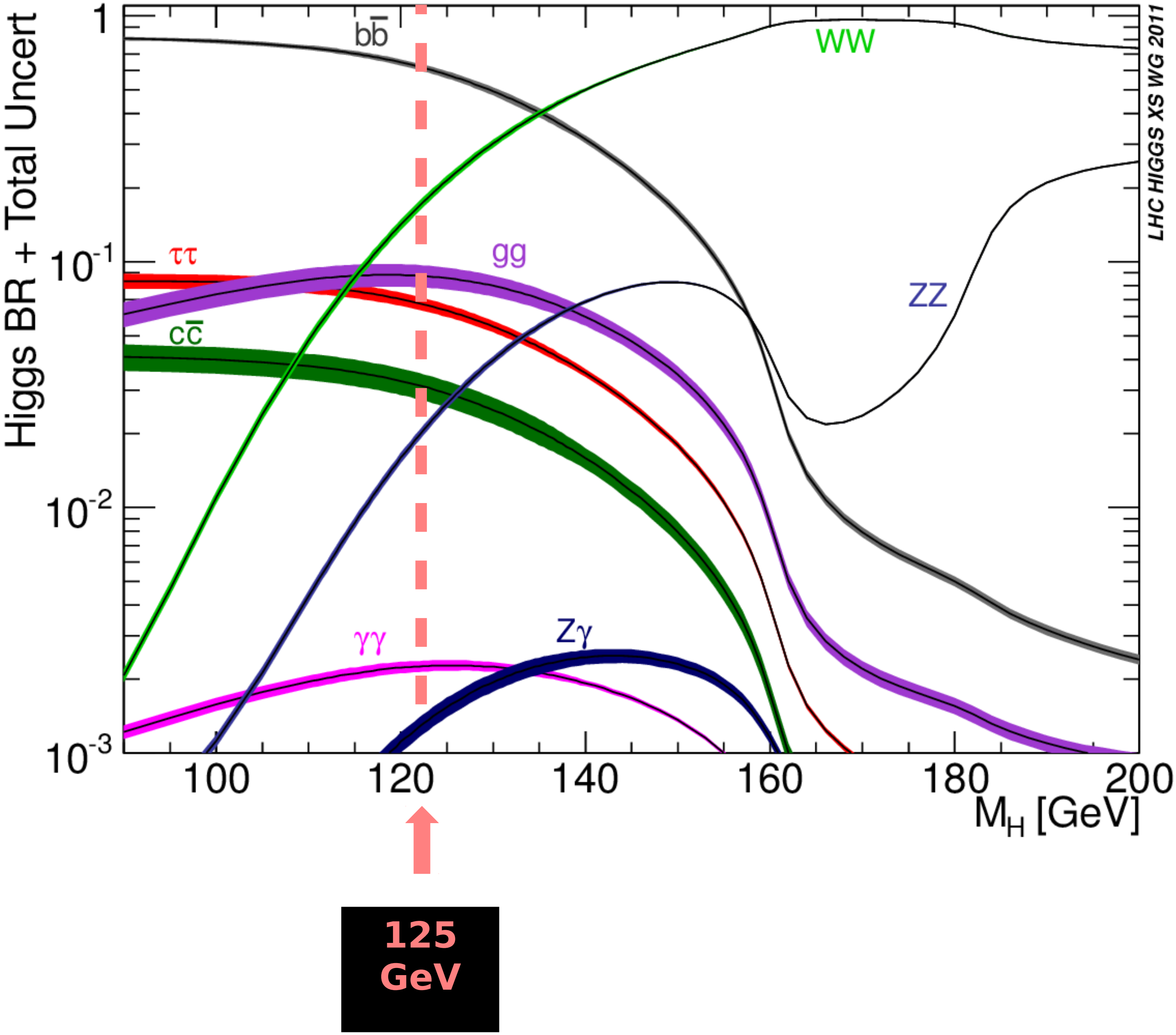


(c) VH



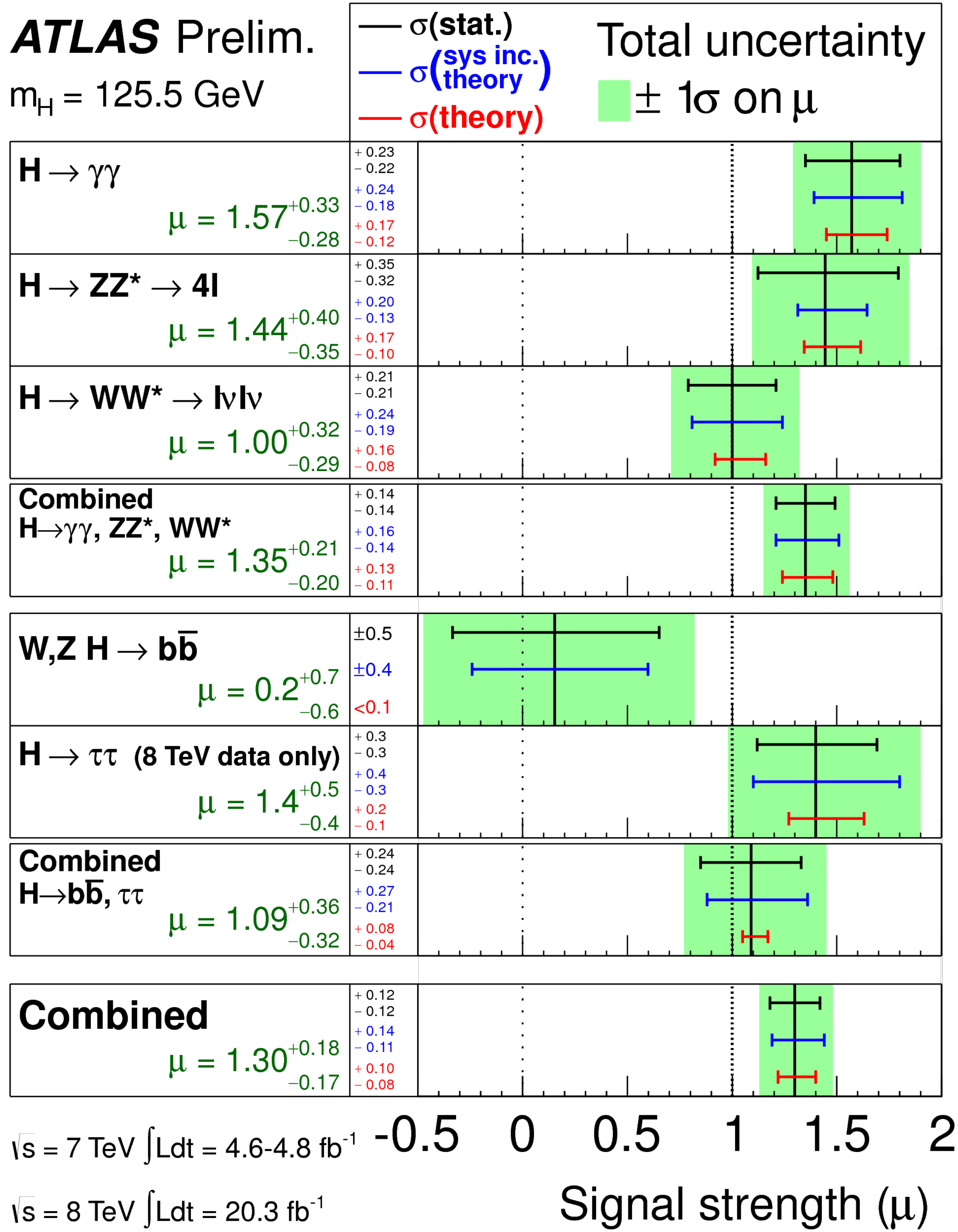
(d) $t\bar{t}H$



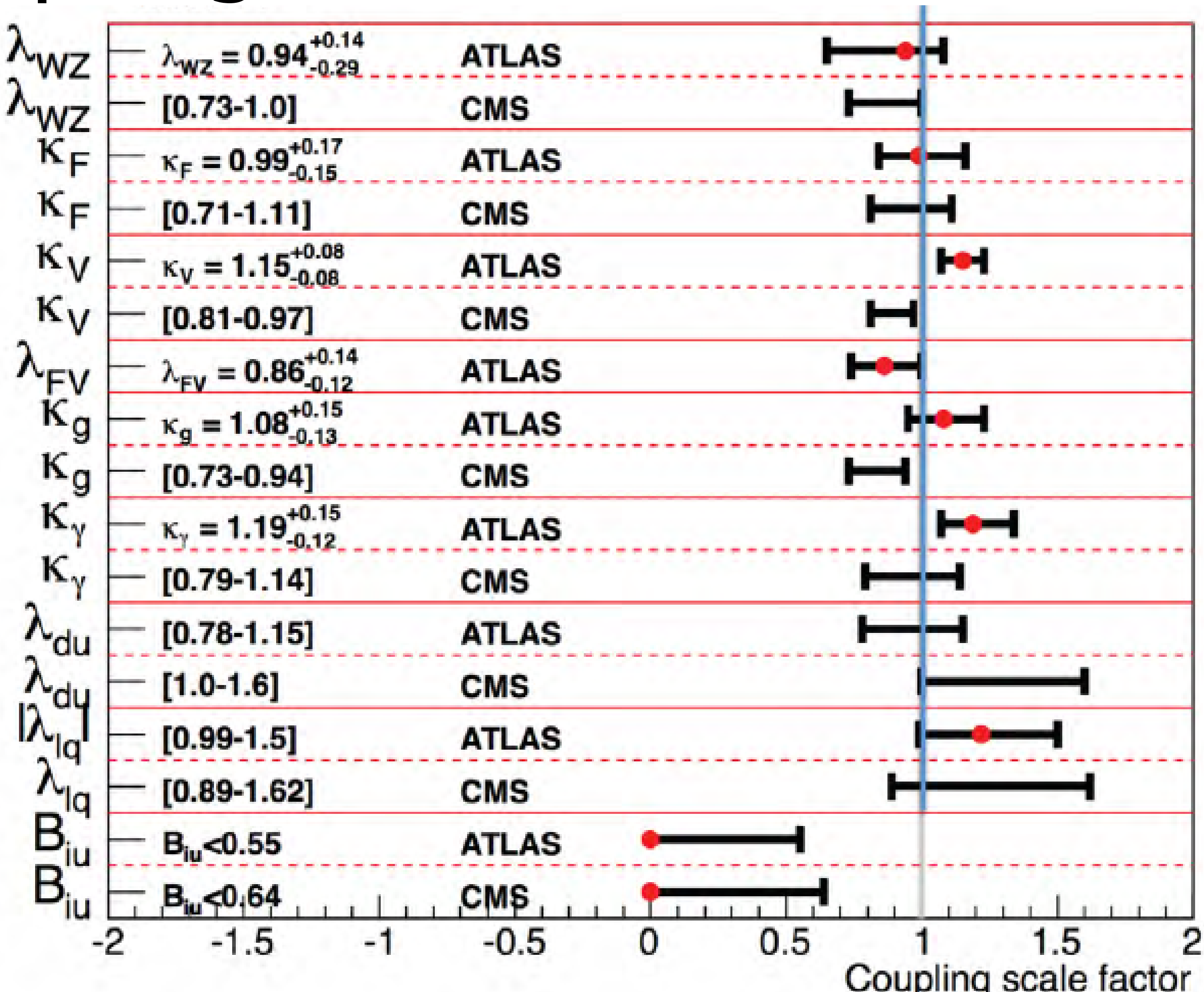


Higgs BR + Total Uncert
$b\bar{b}$
WW
$\tau\tau$
gg
$c\bar{c}$
ZZ
$\gamma\gamma$
$Z\gamma$
LHC HIGGS XS WG 2011
1
10^{-1}
10^{-2}
10^{-3}
100
120
140
160
180
200
M_H [GeV]
125 GeV

ATLAS-CONF-2014-009



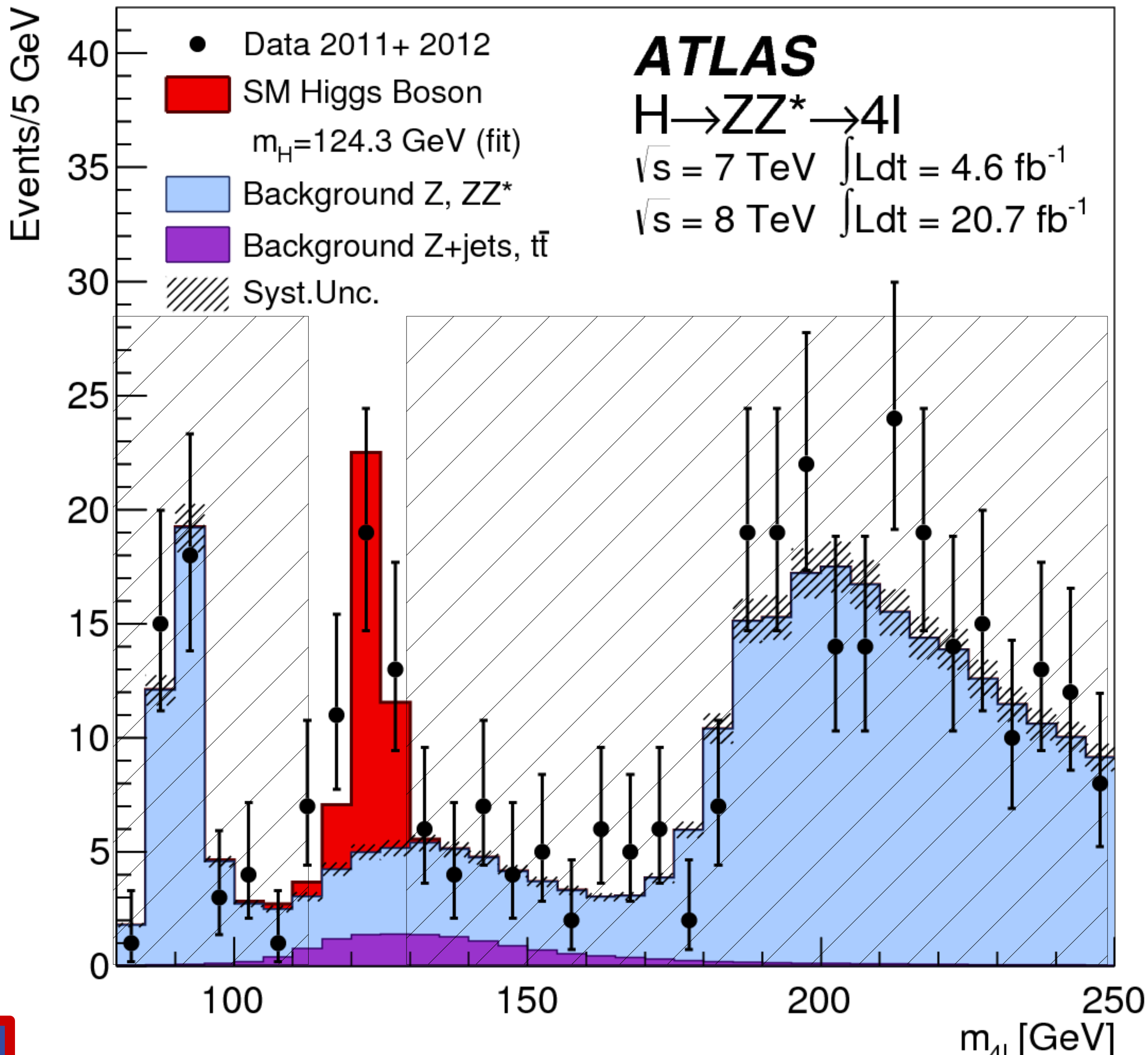
Couplings



K. Einsweiler, Moriond EW 2014

Hypothesis Testing (Quantum Numbers)

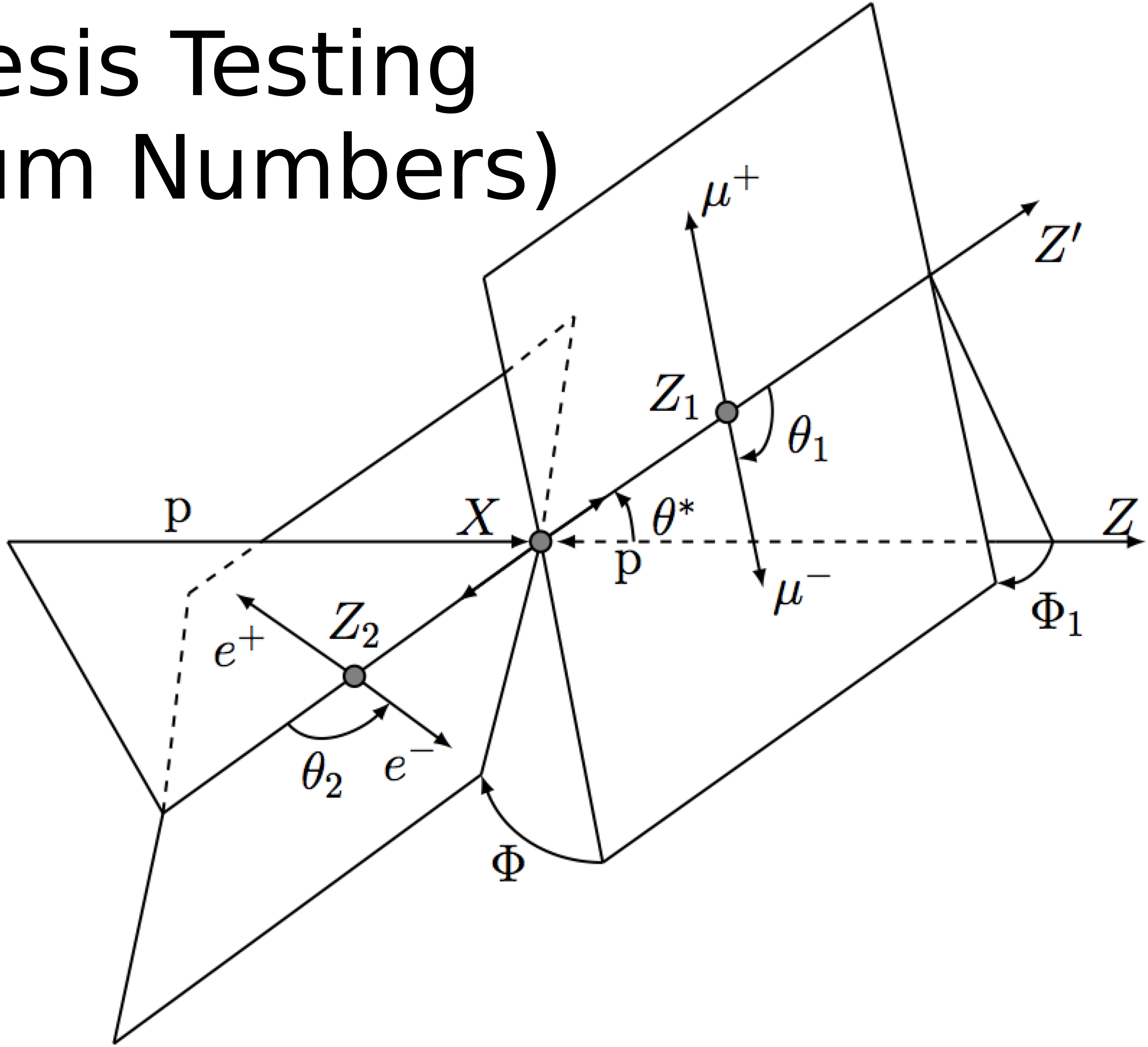
Select events in a highly signal-like region...



Phys. Lett. B 726 (2013), pp. 120-144

Hypothesis Testing (Quantum Numbers)

Construct a discriminant that separates signal from background, but also different signal hypotheses...

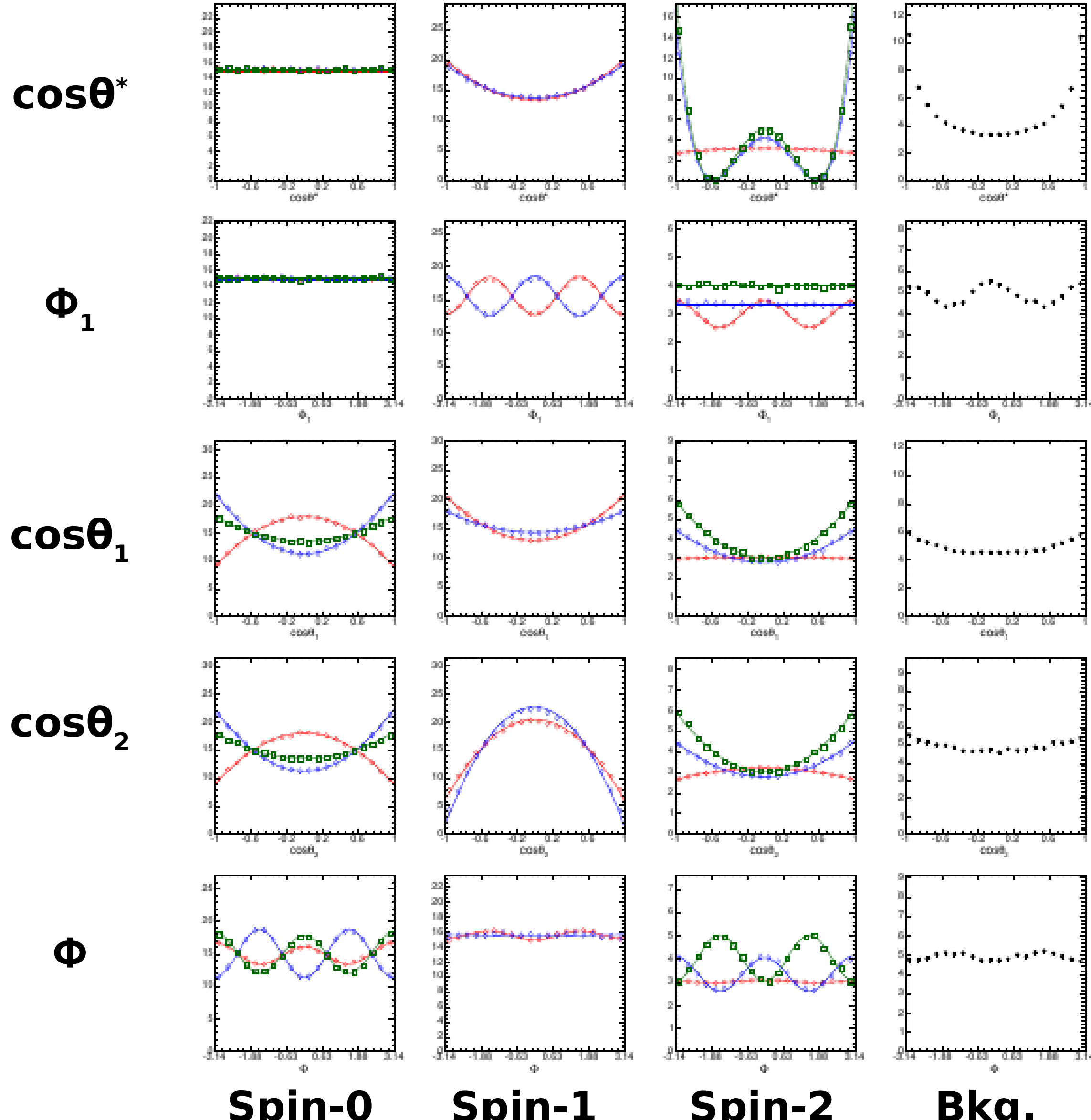


Phys. Lett. B 726 (2013), pp. 120-144

Hypothesis Testing (Quantum Numbers)

Each plot contains multiple Parity hypotheses, where appropriate.

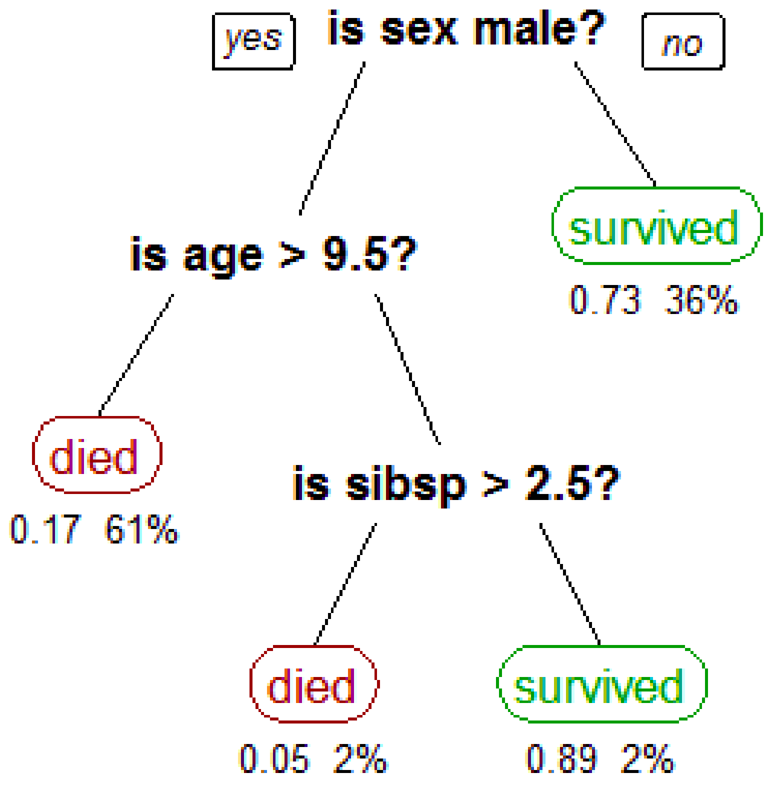
Construct a discriminant that separates signal from background, but also different signal hypotheses...



Physical Review D, vol. 86, no. 9, Nov. 2012.

Hypothesis Testing (Quantum Numbers)

Construct a discriminant that separates signal from background, but also different signal hypotheses...



A simple decision tree (DT). ATLAS used a Boosted DT ("BDT") for the spin-parity analysis. "Boosting" involves increasing the weight of mis-classified events and improving their classification.

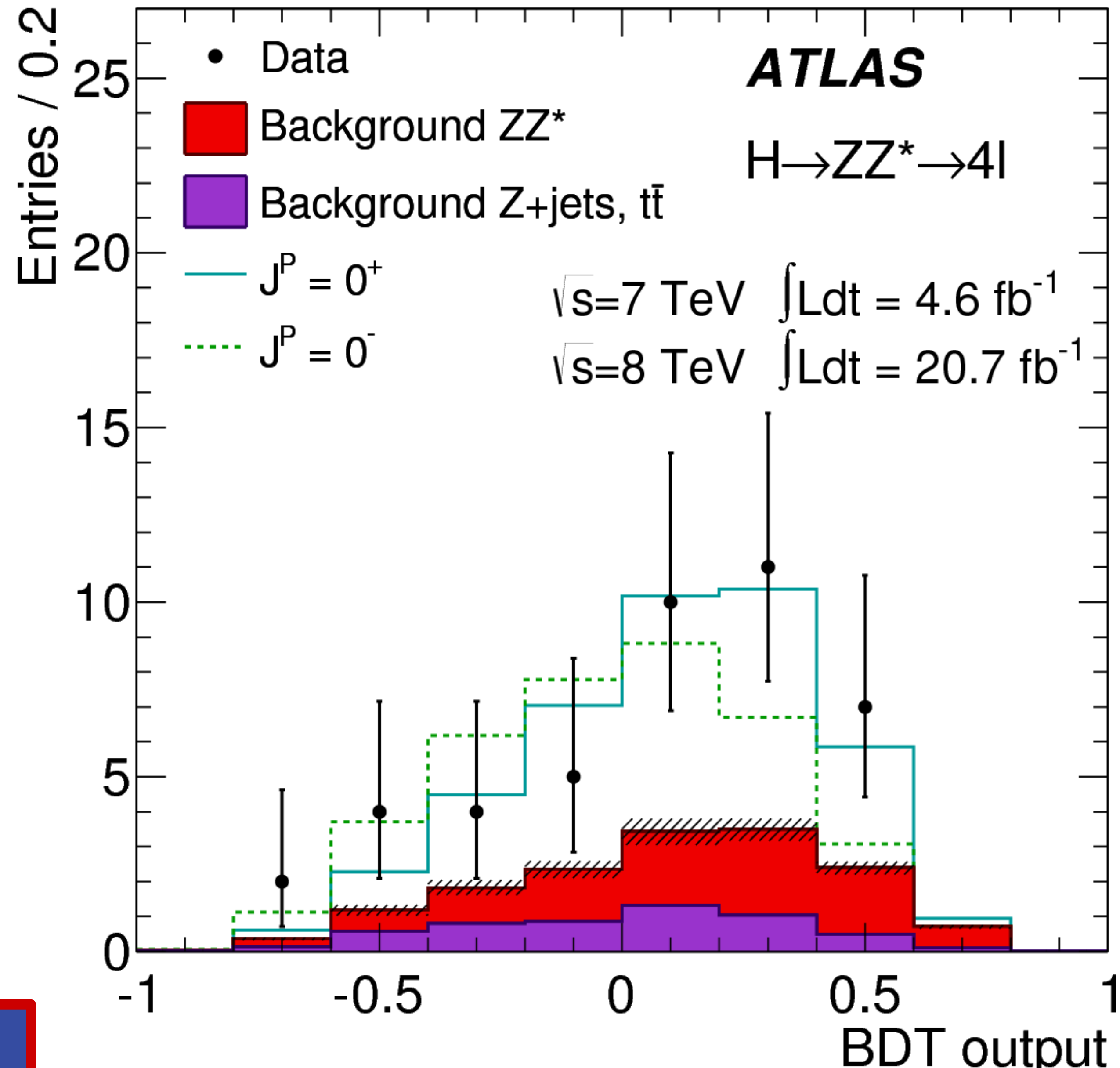
Phys. Lett. B 726 (2013), pp. 120-144

Learn More About Statistical Data Analysis

- Narsky, I and Porter, F. “Statistical Analysis Techniques in Particle Physics: Fits, Density Estimation and Supervised Learning”. Wiley-VCH; 1 edition (December 23, 2013).
- Bevan, A. “Statistical Data Analysis for the Physical Sciences”. Cambridge University Press (June 28, 2013).

Hypothesis Testing (Quantum Numbers)

Construct a discriminant that separates signal from background, but also different signal hypotheses...

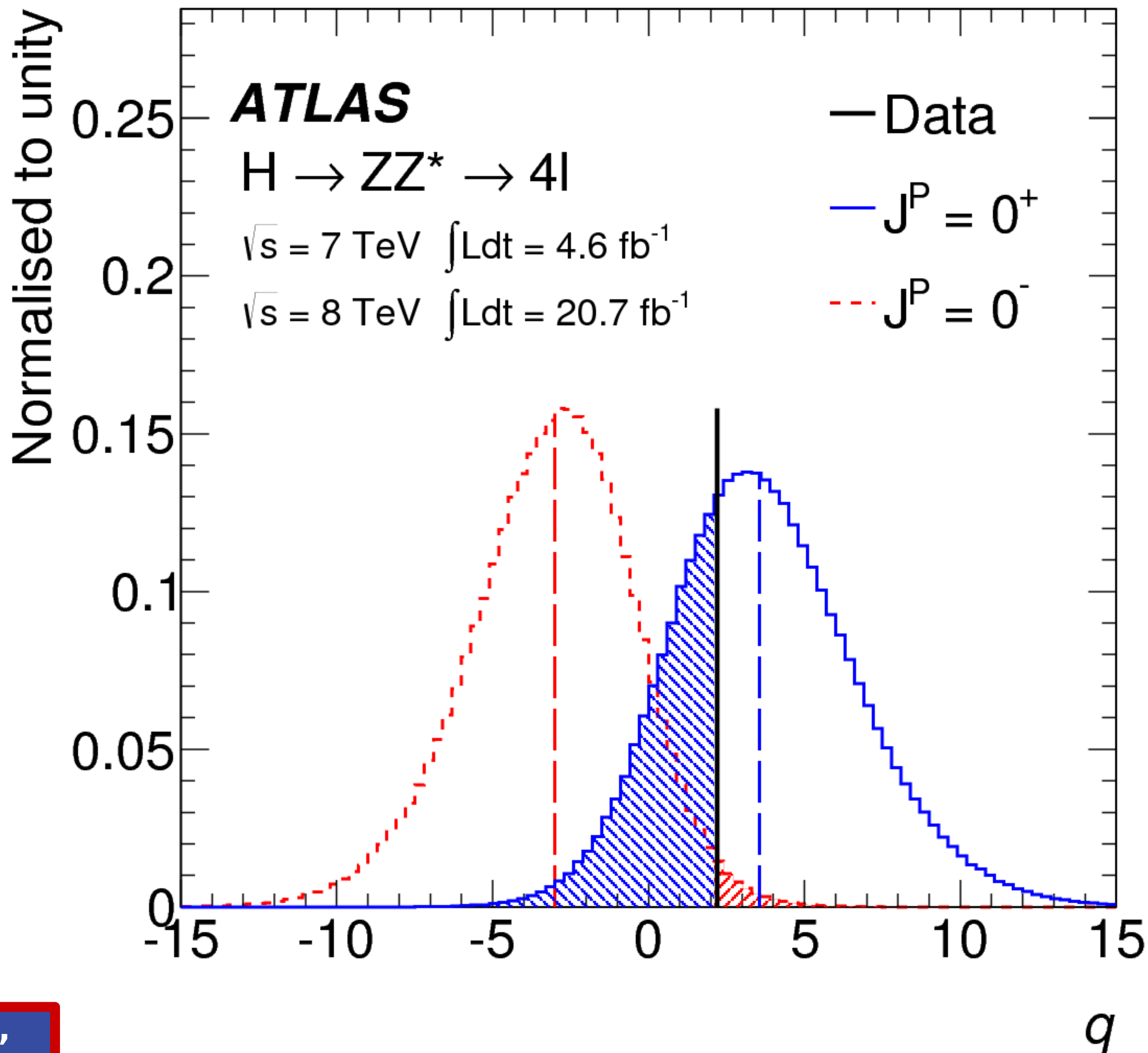


Phys. Lett. B 726 (2013), pp. 120-144

Hypothesis Testing (Quantum Numbers)

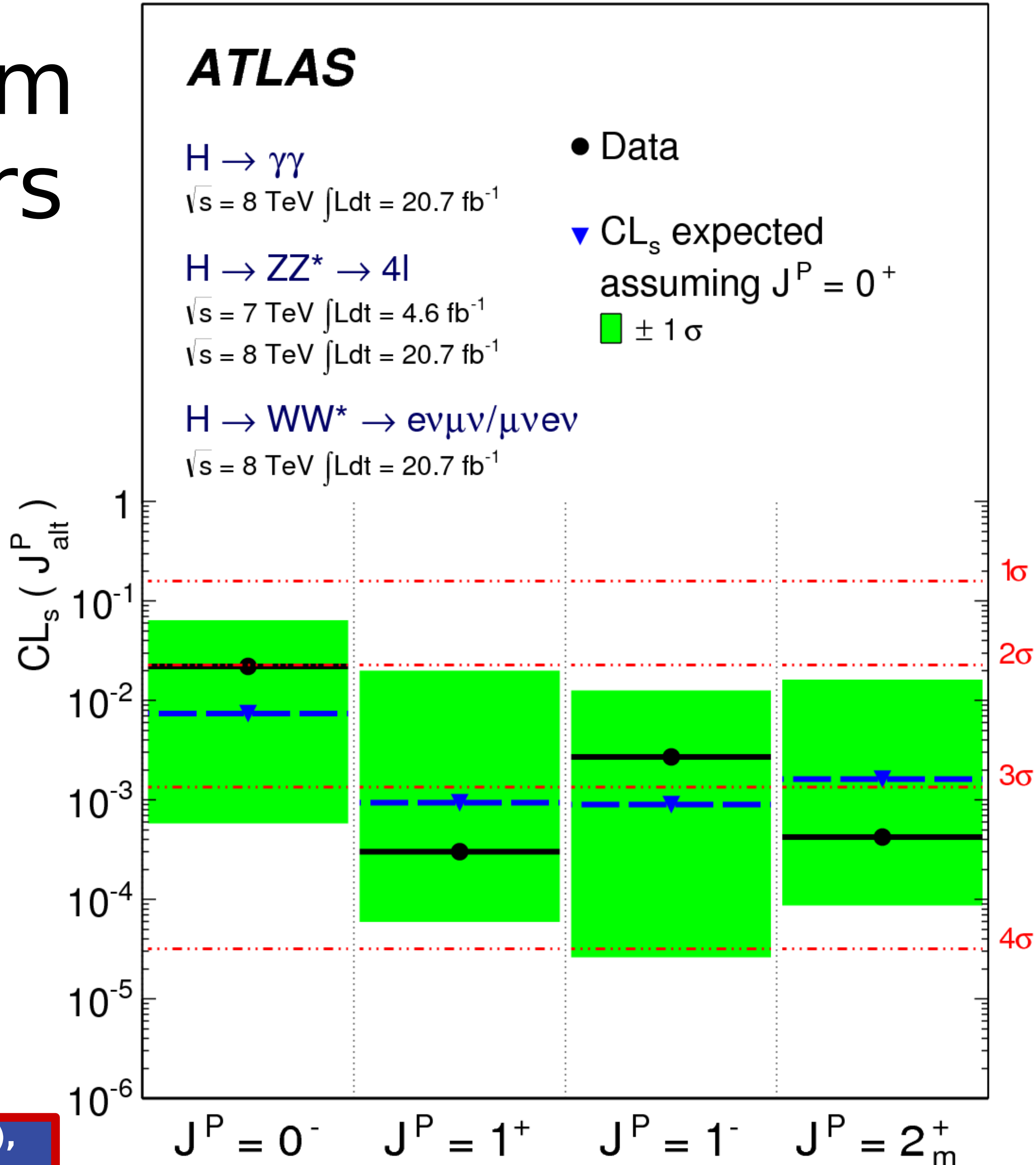
$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$$

Use a statistical test to assess the compatibility of data with different hypothesis pairs...



Phys. Lett. B 726 (2013), pp. 120-144

Quantum Numbers



Phys. Lett. B 726 (2013), pp. 120-144

Above the Higgs: What Do We Want To Know?

Photo credit: Tilemahos Efthimiadis

Wish List
(a multi-decade program)

- The width of the Higgs boson
  - predicted in the Standard Model (~4 MeV)
- The decay modes and spin-parity of the Higgs
  - "Complete" the picture of couplings to bosons with $H \rightarrow Z\gamma$
  - Definitively measure bb and $\tau\tau$
  - Push the couplings and spin-parity uncertainties down
- Probe the Higgs Field directly
  - Try to get the Higgs self-coupling by looking at Higgs pair production
- Determine if this Higgs is "alone"
  - Search for additional Higgs Bosons in nature

Beyond the Higgs: Supersymmetry-Inspired Searches

List continues off-screen...

HSG6 Webpage, Oct. 2013

HSG6 Data Notes:

- In preparation:
  - H+ -> csbar CDS-INT CDS
  - Ratio method CDS-INT CDS SVN-INT SVN-CONF TWiki
  - H+ -> WZ CDS-INT CDS
  - H+ -> a1W CDS-INT CDS

- 5/fb results:
  - Title: **Search for charged Higgs bosons decaying via H+ -> taunu in ttbar events using pp collision data at \sqrt(s) = 7 TeV with the ATLAS detector**
  - Plots JHEP06(2012)039 arXiv:1204.2760 CERN-PH-EP-2012-083 ATLAS-CONF-2012-011 TWiki
  - Supporting documents (internal notes):
    - Limit & combination supporting note: ATL-INT-PHYS-2012-044
    - lep+jets supporting note: ATL-INT-PHYS-2012-045
    - tau+lep supporting note: ATL-INT-PHYS-2012-046
    - tau+jets supporting note: ATL-INT-PHYS-2012-047
- 1/fb results:
  - **Search for a charged Higgs boson decaying via H+ to tau(lep)+nu in ttbar events with one or two light leptons in the final state using 1.03/fb of pp collision data recorded at sqrt(s) = 7 TeV with the ATLAS detector.** CDS-INT CDS-CONF TWiki Plots
  - **Search for Charged Higgs Bosons in the τ+jets Final State in tt̄ Decays with 1.03 fb−1 of pp Collision Data Recorded at sqrt(s)=7 TeV with the ATLAS Experiment** CDS-INT CDS-CONF TWiki Plots
  - **A Search for a light charged Higgs boson decaying to cs̄ in pp collisions at √s = 7 TeV with the ATLAS detector** CDS-INT CDS-CONF Plots
- 35/pb results:
  - **Study of discriminative variables for charged Higgs boson searches in ttbar events with 35pb-1 of data from the ATLAS detector.** CDS-INT CDS-CONF
  - **Data-driven estimation of the background to H+ searches with hadronic-tau final states.** CDS-INT CDS-CONF TWiki

HSG6 Simulation Notes in CDS

- Embedding Technique for the ttbar Background Estimation in Charged Higgs Boson Searches
- Data-driven measurement of the fake tau contribution from light jets and application for the ttbar background estimation in charged Higgs Searches
- Light Charged Higgs Boson Searches for H+ to tau+ nu and H+ to c sbar in Early LHC Data at the ATLAS Experiment
- An ATLAS Search for the NMSSM Ideal Higgs Scenario
- Update on Light Charged Higgs Boson Searches with Early LHC Data at 7 TeV in the ATLAS Experiment

Other Public Results

- Expected Sensitivity in Light Charged Higgs Boson Searches for H+ to tau+nu and H+ to c+sbar...
- Public Plots from ATL-PHYS-PUB-2010-006
- Computing and Software Commissioning (CSC) Book in CDS

HSG6 Webpage, ~Oct. 1, 2012

NaN

(not quite fair – BSM Higgs analysis efforts were distributed among multiple parent HSGx groups. Nonetheless, 2011-2013 was quite a fast ride!)

HSG6 TWiki, ~Oct. 1, 2011

MSSM: 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±ud	$m_d \tan\beta\,(1+\gamma_5) + m_u \cot\beta\,(1-\gamma_5)$	

Embedded in the MSSM is a Type-II Two-Higgs Doublet Model (2HDM)

c.f. Physics Reports, Volume 459, Issues 1–6, 2008, Pages 1–241

2HDMs

	type-I	type-II
ξ_h^u	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$
ξ_h^d	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)\cdot\tan\beta$
ξ_h^l	$\sin(\beta-\alpha)+\cos(\beta-\alpha)/\tan\beta$	$\sin(\beta-\alpha)-\cos(\beta-\alpha)\cdot\tan\beta$
ξ_H^u	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$
ξ_H^d	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)\cdot\tan\beta$
ξ_H^l	$\cos(\beta-\alpha)-\sin(\beta-\alpha)/\tan\beta$	$\cos(\beta-\alpha)+\sin(\beta-\alpha)\cdot\tan\beta$
ξ_A^u	$1/\tan\beta$	$1/\tan\beta$
ξ_A^d	$-1/\tan\beta$	$\tan\beta$
ξ_A^l	$-1/\tan\beta$	$\tan\beta$

Table 1: Yukawa coupling coefficients of the neutral bosons of the type-I and type-II 2HDMs for up-type quarks (u), down-type quarks (d) and charged leptons (l). These coefficients are defined such that the Yukawa Lagrangian terms are $-(m_f/v)\bar{f}f\phi$ and $i(m_f/v)\bar{f}\gamma_5 fA$ where $f=u,d,l$ and $\phi=h,H$.

A Comment on Notation

- h
  - the lightest (lowest-mass) neutral CP-even Higgs in the theory
- H
  - the next-lightest (heavier) neutral CP-even Higgs
- A priori, we don't know which one we've discovered

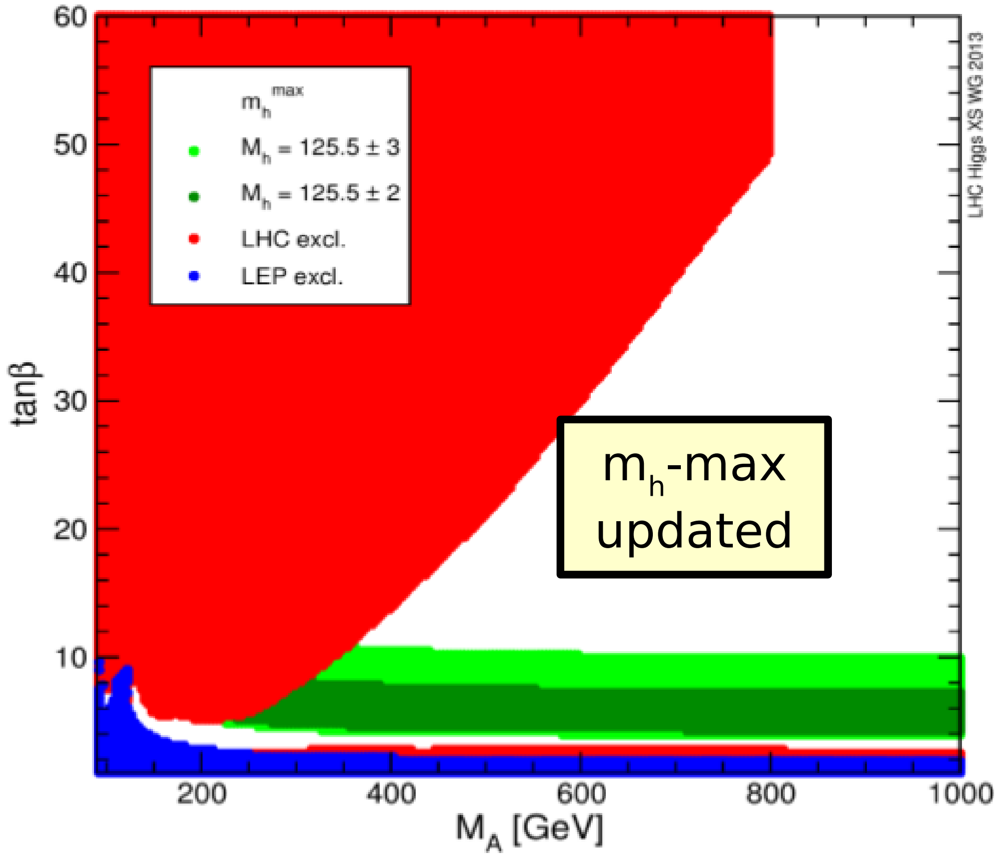
MSSM: m_h-max scenario

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

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

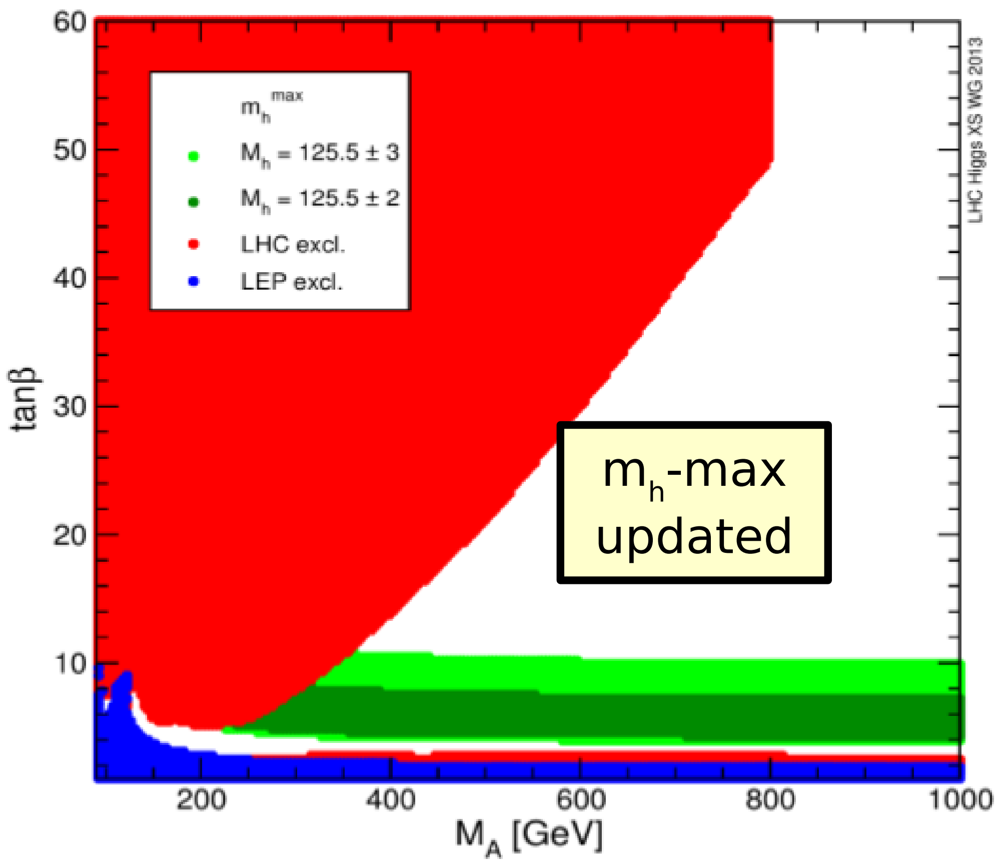
Designed to maximize the SM-like Higgs (h^0) mass ($m_h \sim 135$ GeV).

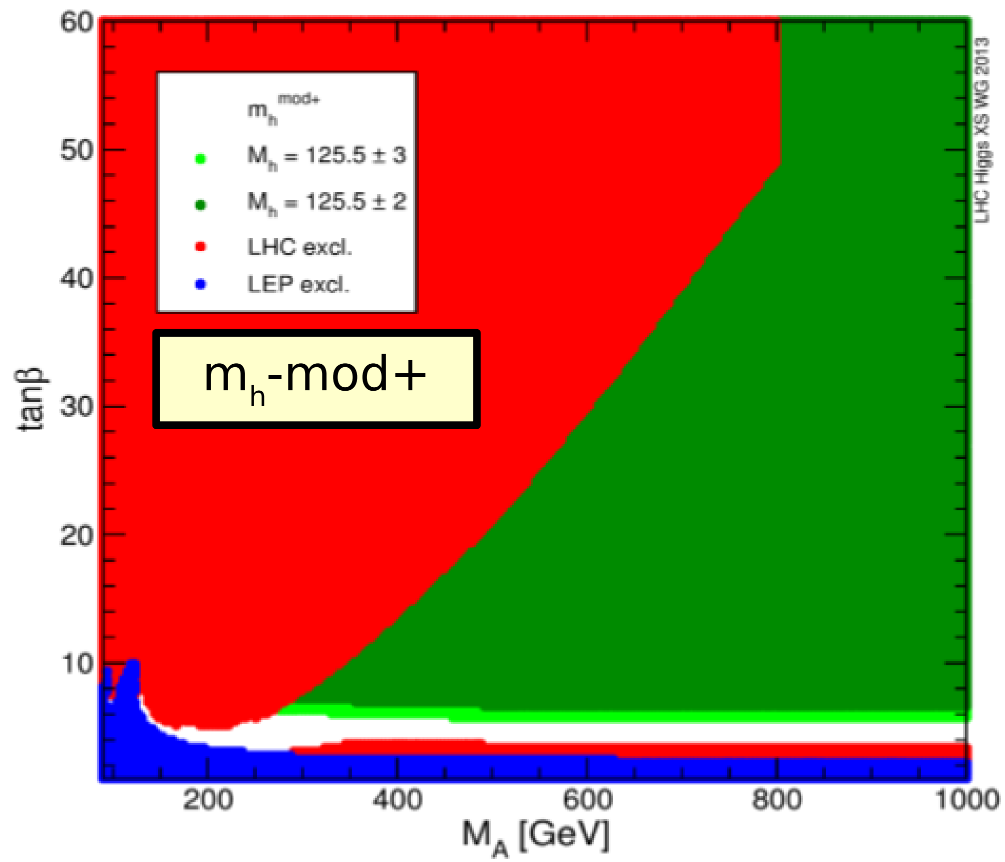
However, we now know the mass of the h^0 (~126 GeV), so m_h-max is a bit too aggressive.



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

arXiv:1307.1347





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

Alter stop mixing

$$\begin{aligned} m_t &= 173.2 \text{ GeV}, \\ M_{\text{SUSY}} &= 1000 \text{ GeV}, \\ \mu &= 200 \text{ GeV}, \\ M_2 &= 200 \text{ GeV}, \\ X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_\tau = A_t, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \\ M_{\tilde{l}_3} &= 1000 \text{ GeV}\,. \end{aligned}$$

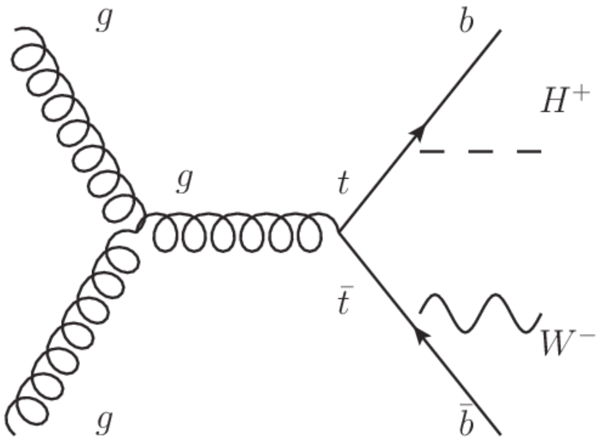
arXiv:1307.1347

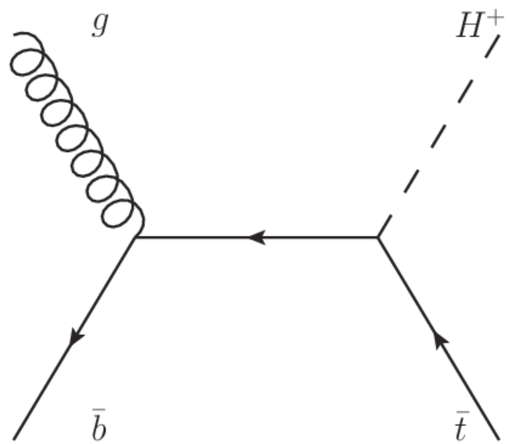
Comments

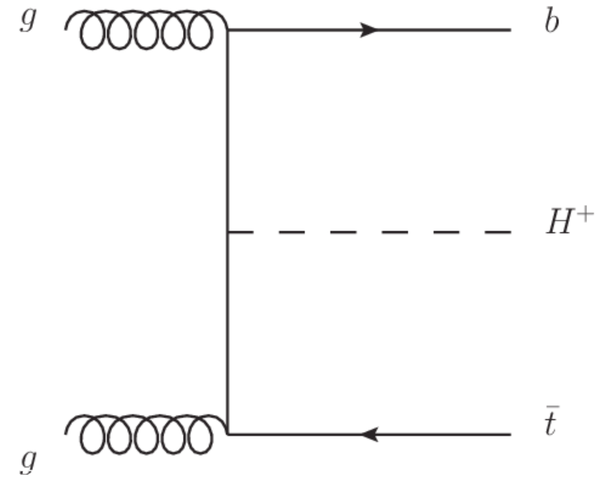
- Many results I show today employ m_h-max
  - this is largely for backward-compatibility of interpretations over the last 1-2 years.
  - LHC Higgs Cross-Section Working Group has looked at the effect on exclusions in tanβ vs. m_{H+} using m_h-max or m_h-mod+
    - no significant differences seen for channels like $A/H \rightarrow \tau\tau$ or $H^+ \rightarrow \tau\nu$
    - in those channels, exclusions in m_h-max are basically transferable to m_h-mod+

Above and Beyond the Higgs: The Search for $H^{\pm}$

H^+ Production



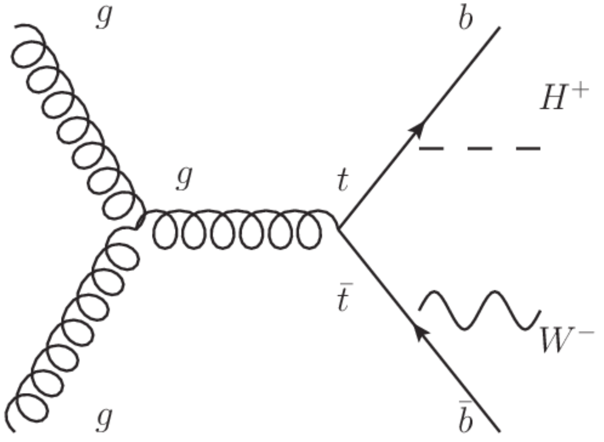


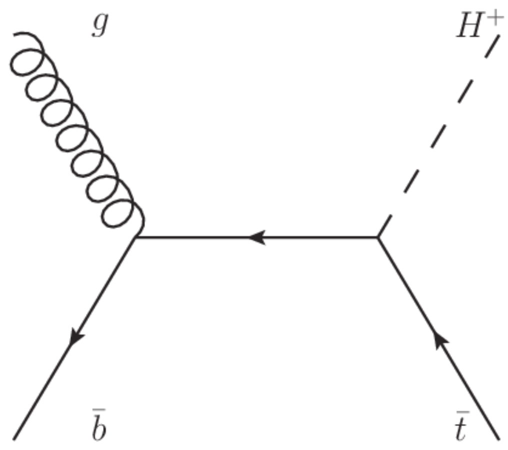


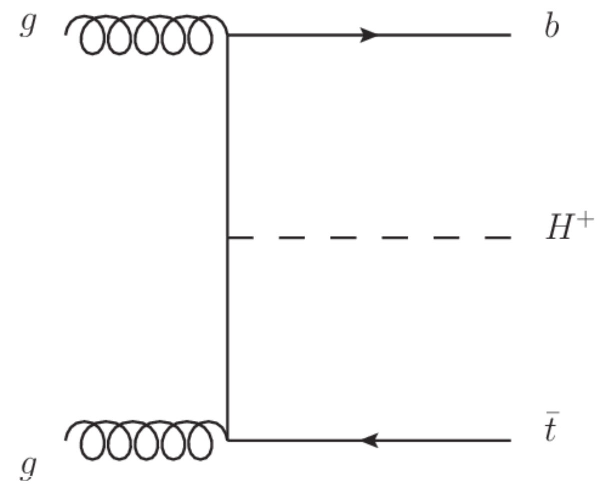
Coupling	Mixing Angle Dependence	Mass Dependence
Huu	sin(α)/sin(β)	m_u
Hdd	cos(α)/cos(β)	m_d
Auu	cot(β)	m_u
Add	tan(β)	m_d
$H^{\pm}ud$	$m_d \tan\beta\,(1+\gamma_5) + m_u \cot\beta\,(1-\gamma_5)$	

Competition between production ($tbH^{\pm}$ vertex) and decay can make us sensitive to low and high tanβ

H^+ Production



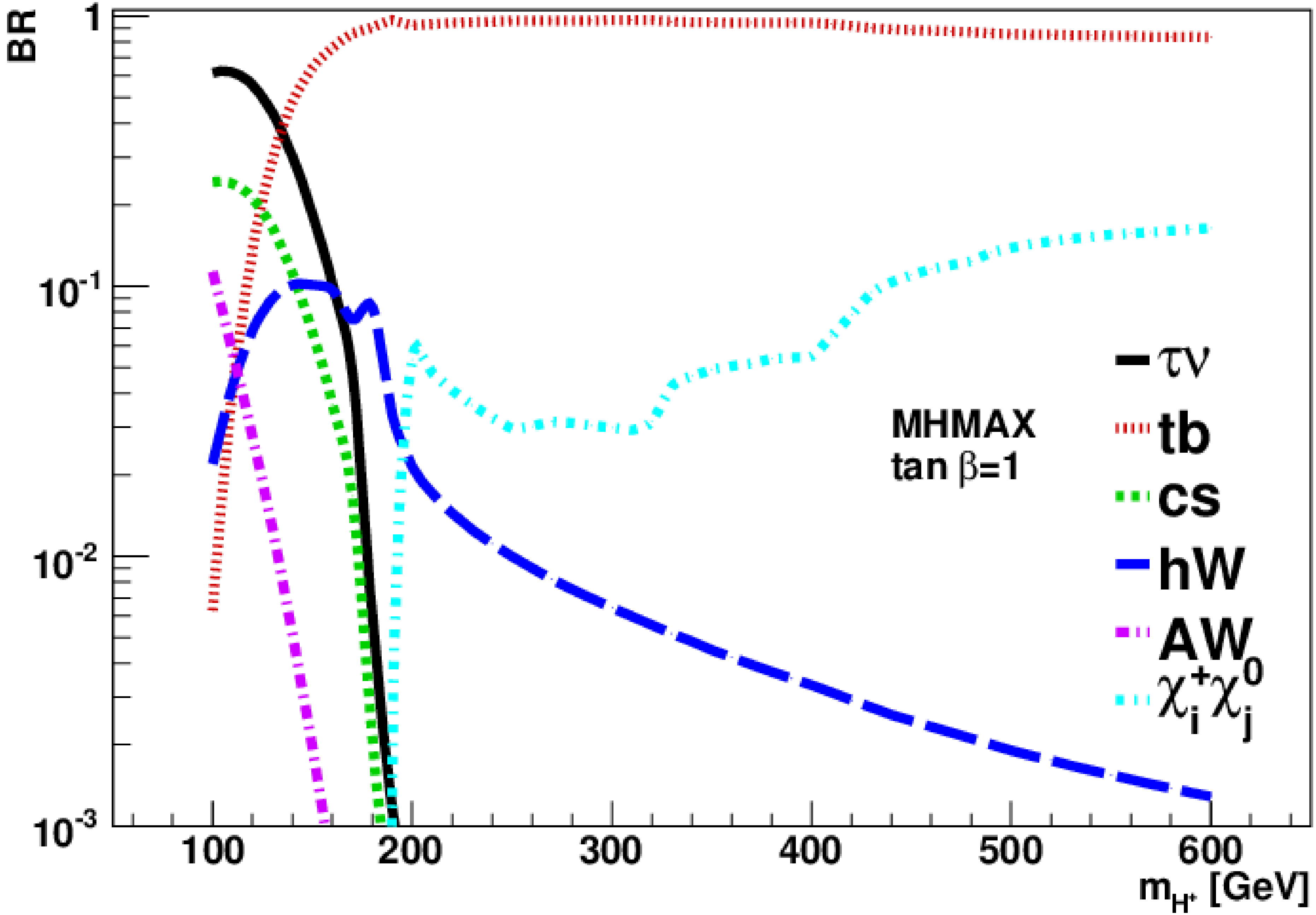




Dominant for masses below $m_t - m_b \approx 169$ GeV

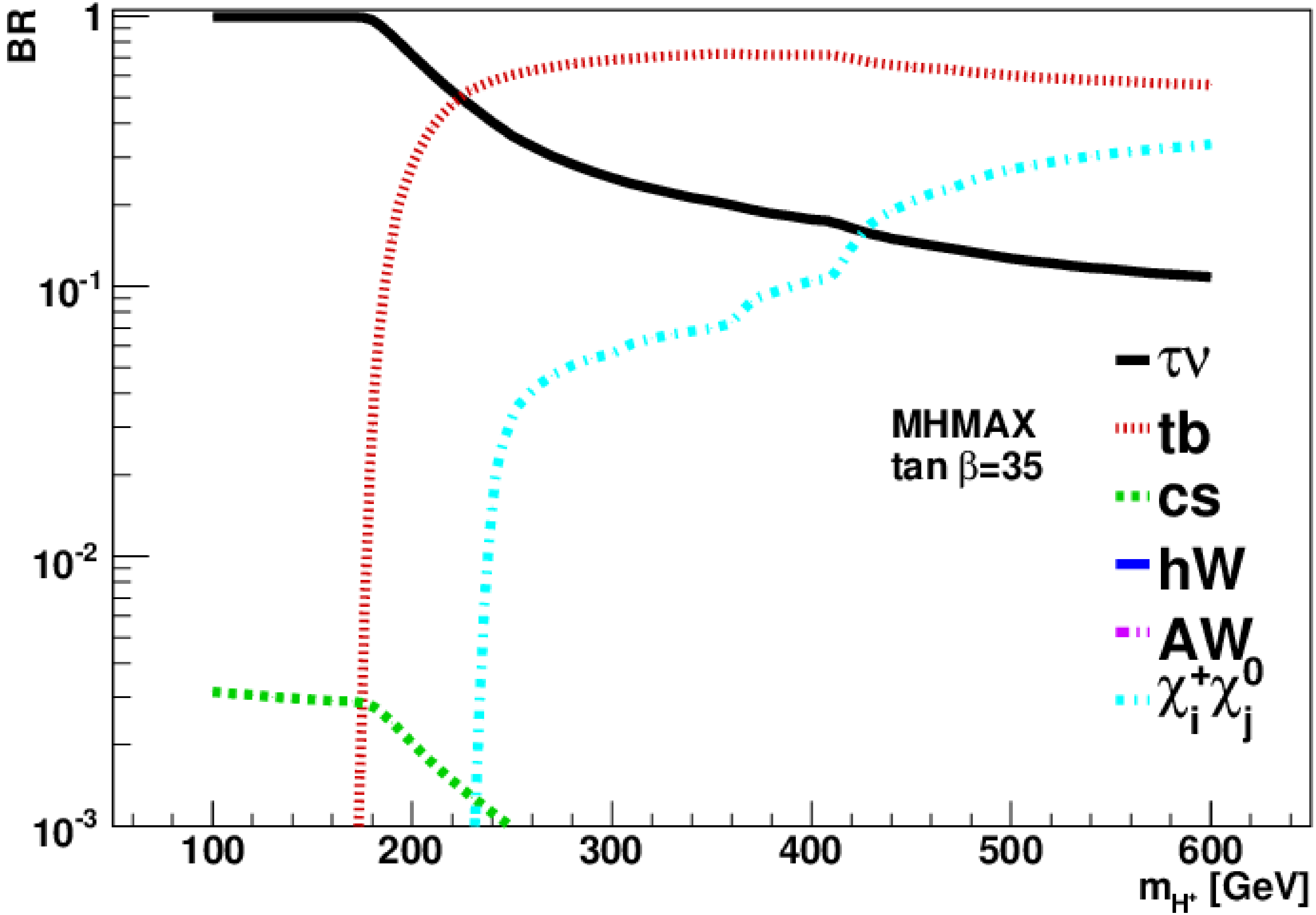
Dominant for larger masses

BR($H^+ \to$ ...)

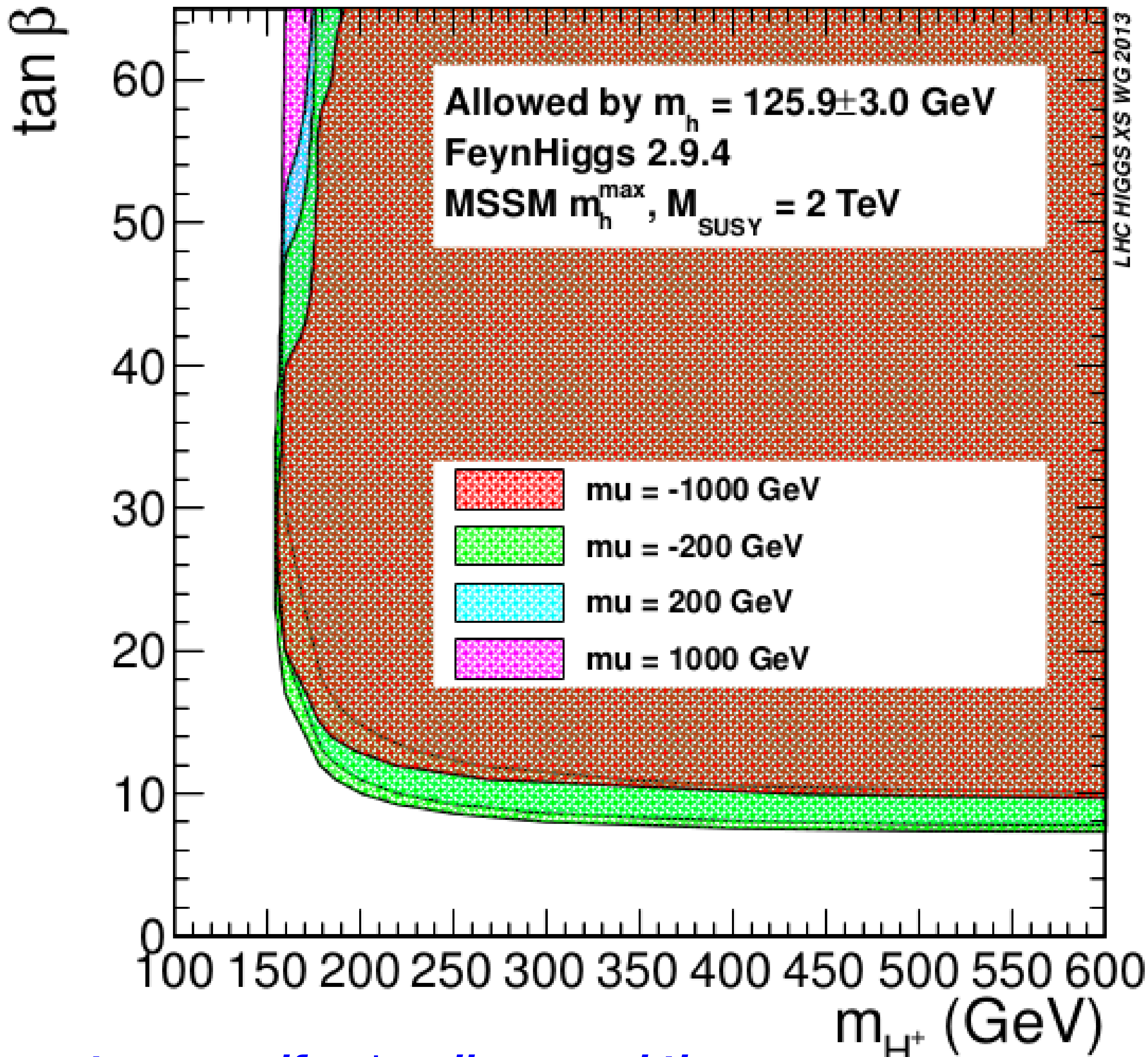


BR
1
10^-1
10^-2
10^-3
100
200
300
400
500
600
m_H+ [GeV]
MHMAX
tan β=1
τν
tb
cs
hW
AW
χ_i^+ χ_j^0

BR($H^+ \to$ ...)

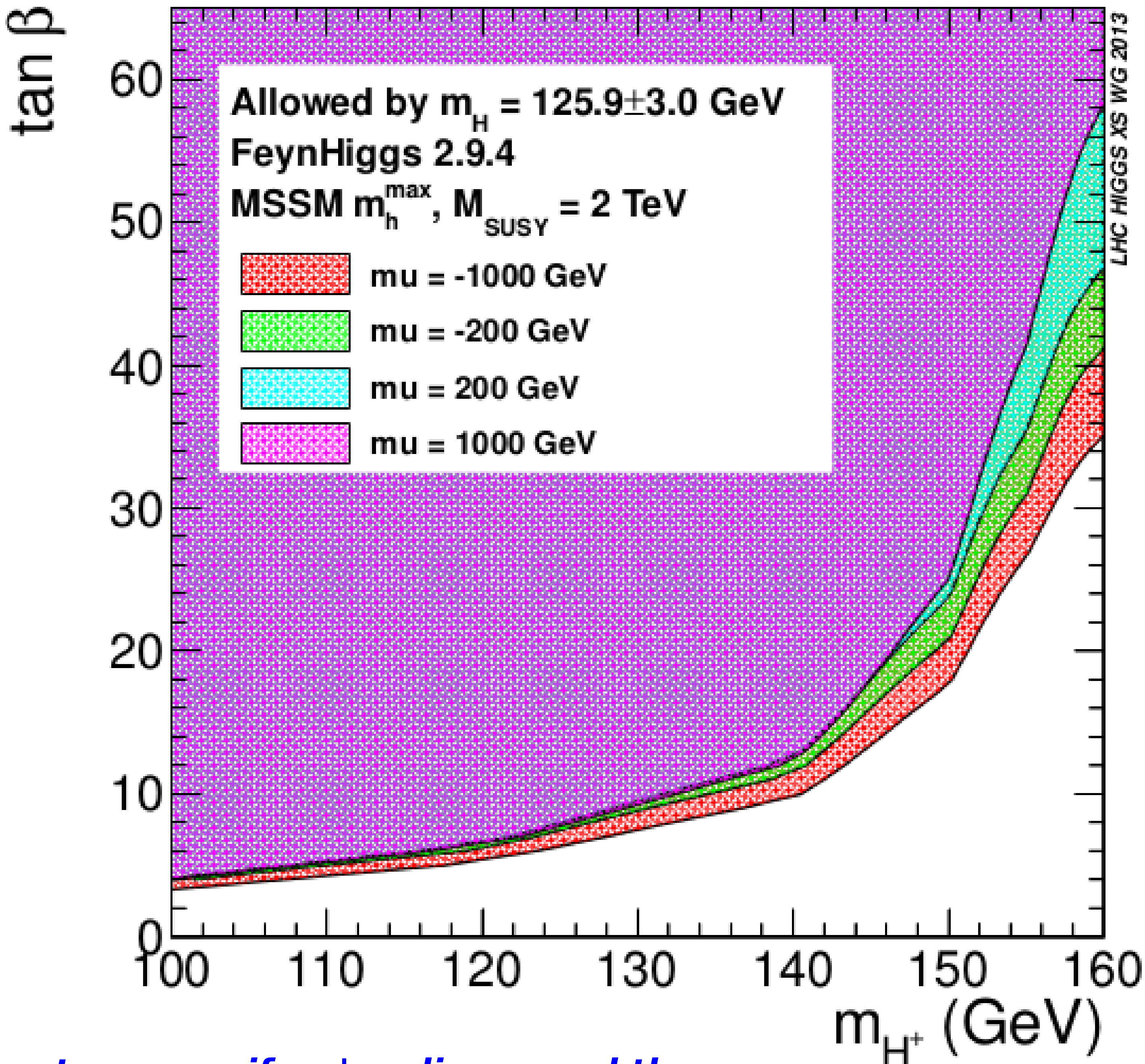


BR
1
10^{-1}
10^{-2}
10^{-3}
100
200
300
400
500
600
m_{H^+} [GeV]
MHMAX
tan β=35
τν
tb
cs
hW
AW
$\chi_i^+\chi_j^0$



Allowed parameter space if we've discovered the lightest neutral MSSM Higgs Boson, h

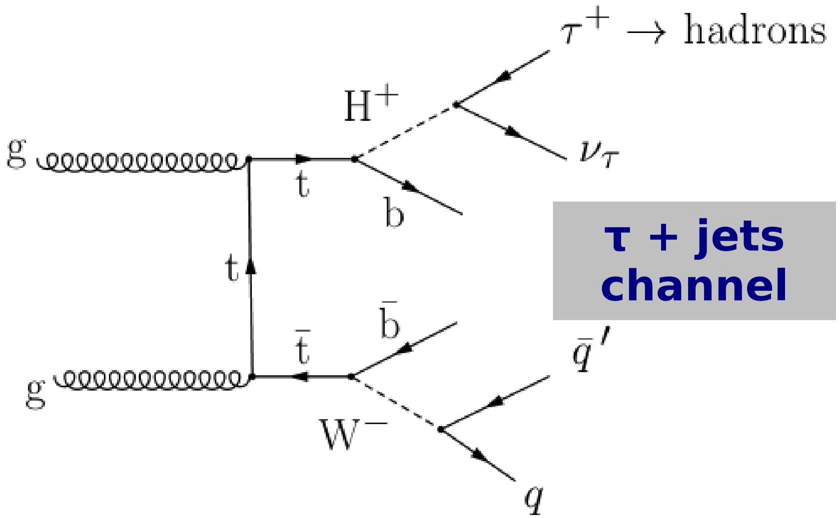
arXiv:1307.1347

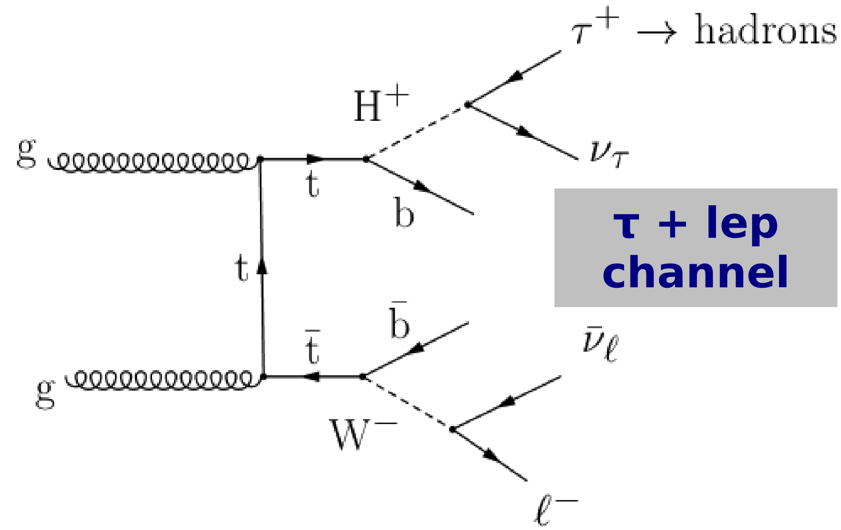


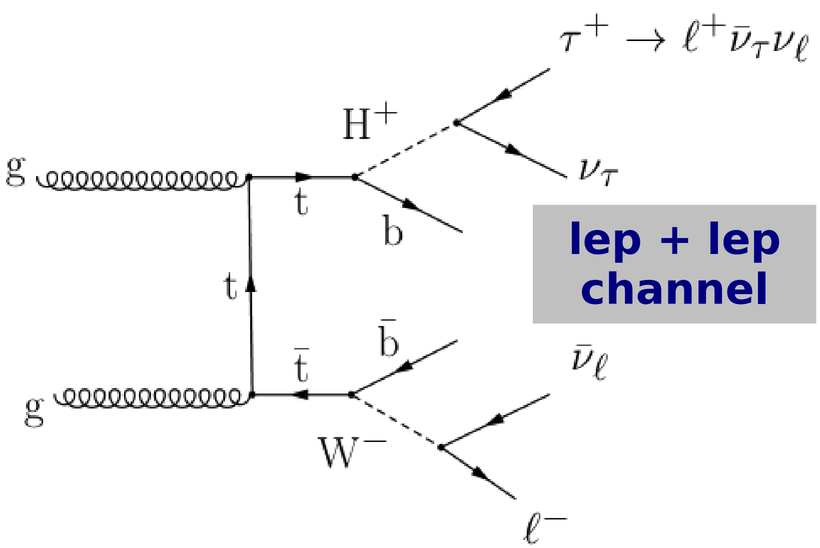
Allowed parameter space if we've discovered the seond-lightest neutral MSSM Higgs Boson, H

arXiv:1307.1347

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





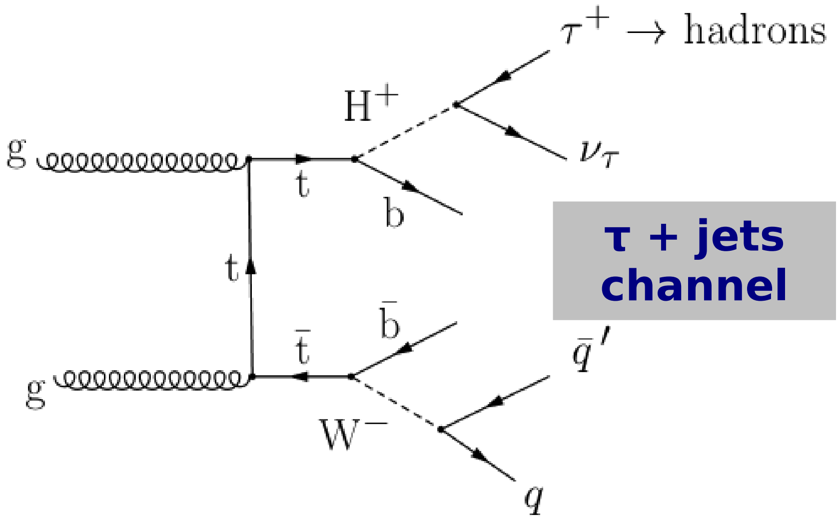


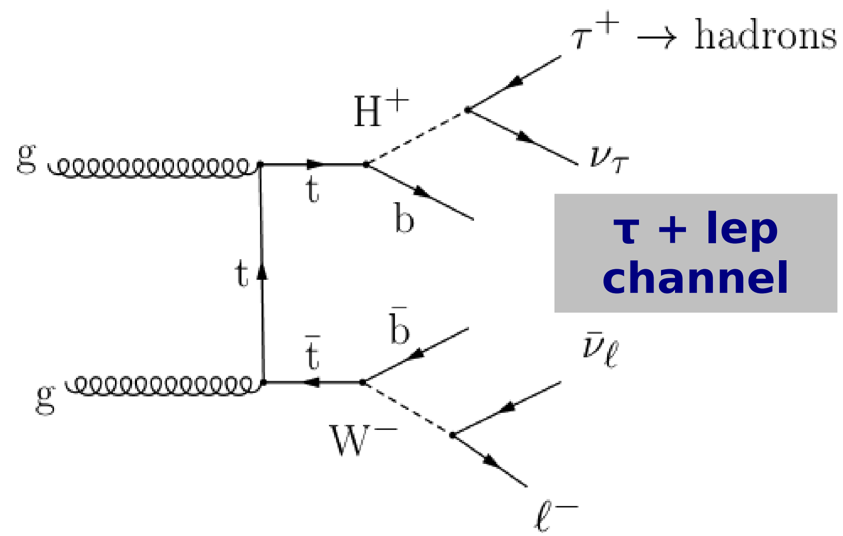
Different experimental approaches are needed for these final states

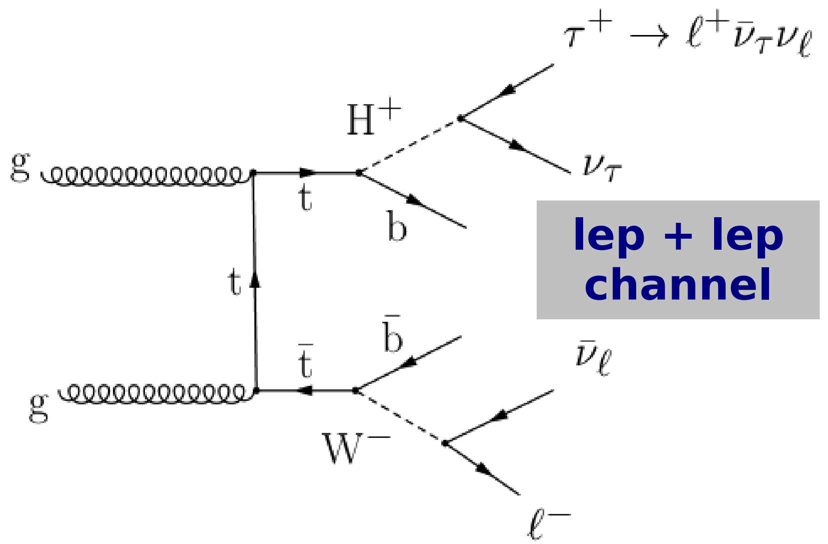
- hadronic tau decays more prone to QCD backgrounds
- leptonic tau/W decays yield more significant MET and present reconstruction/resolution challenges

Figs. from CMS-HIG-11-019

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



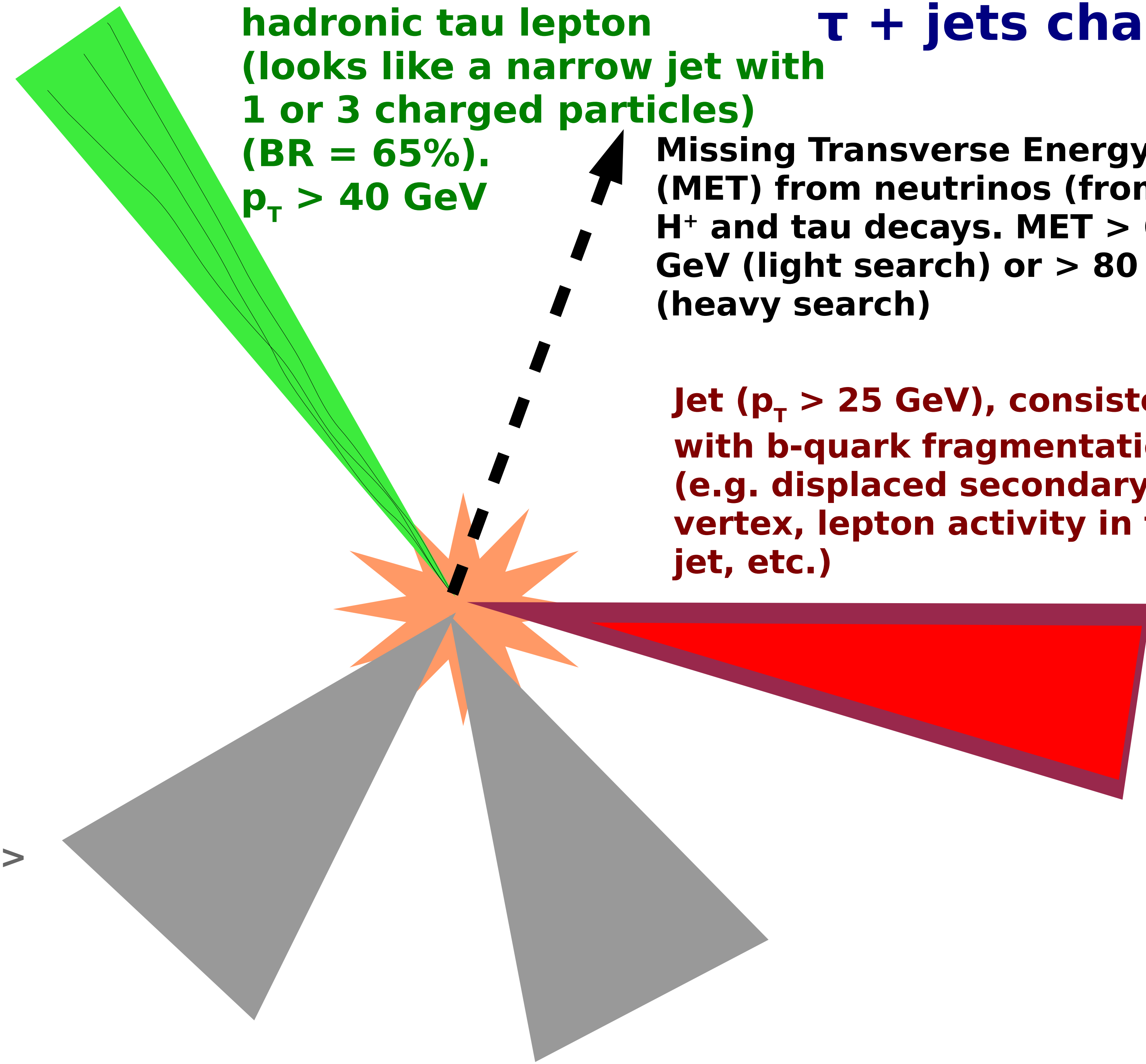




I will focus on the "all-hadronic channel", tau+jets. Here, SMU has made major contributions and it is the most sensitive single search channel.

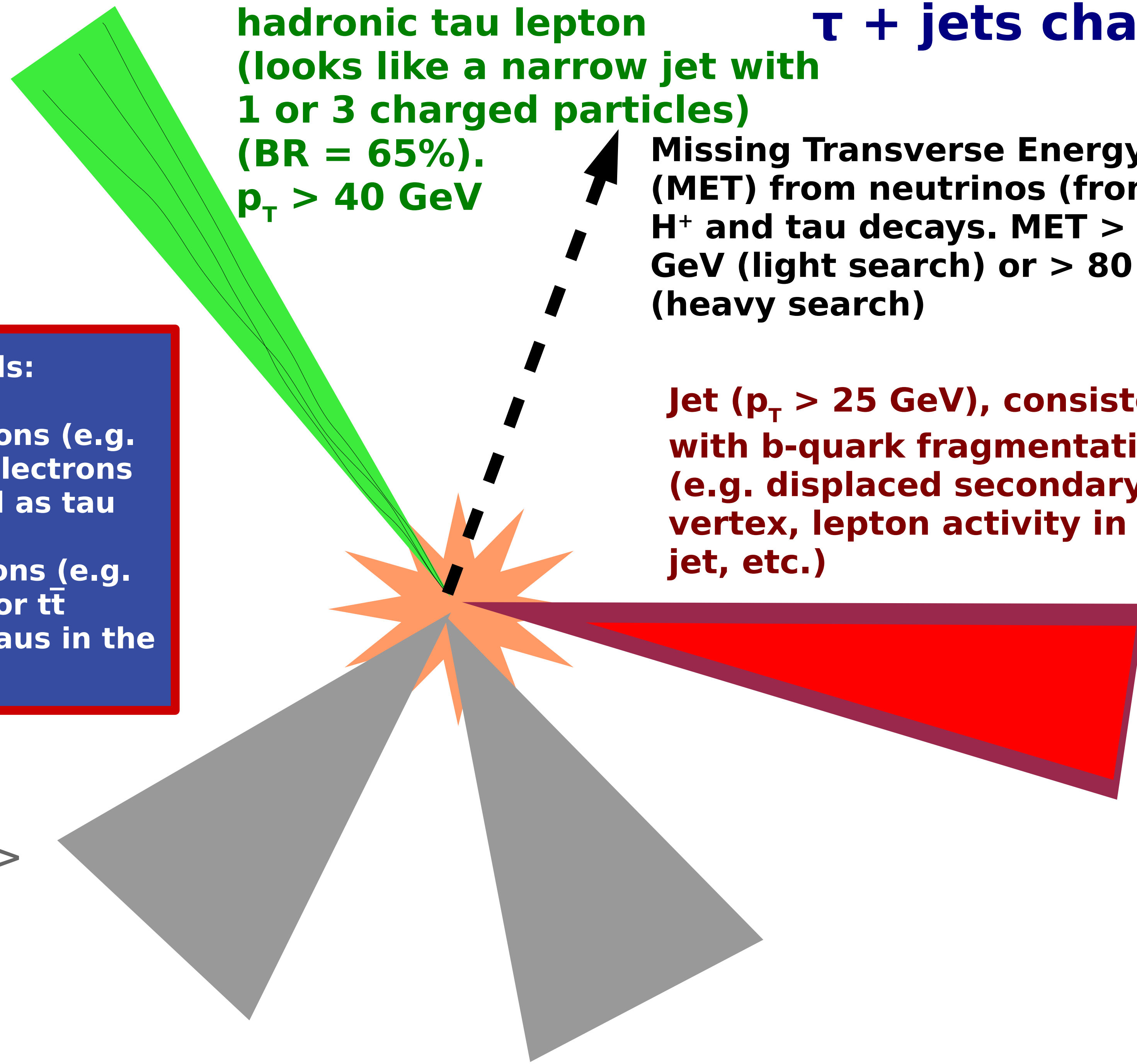
Figs. from CMS-HIG-11-019

τ + jets channel



Cartoon of production and decay in the plane transverse to the proton beams...

τ + jets channel



Major Backgrounds:

- Fake tau leptons (e.g. from jets or electrons mis-identified as tau leptons)
- Real tau leptons (e.g. from W+jets or $t\bar{t}$ events with taus in the final state)

Cartoon of production and decay in the plane transverse to the proton beams...

τ + jets channel

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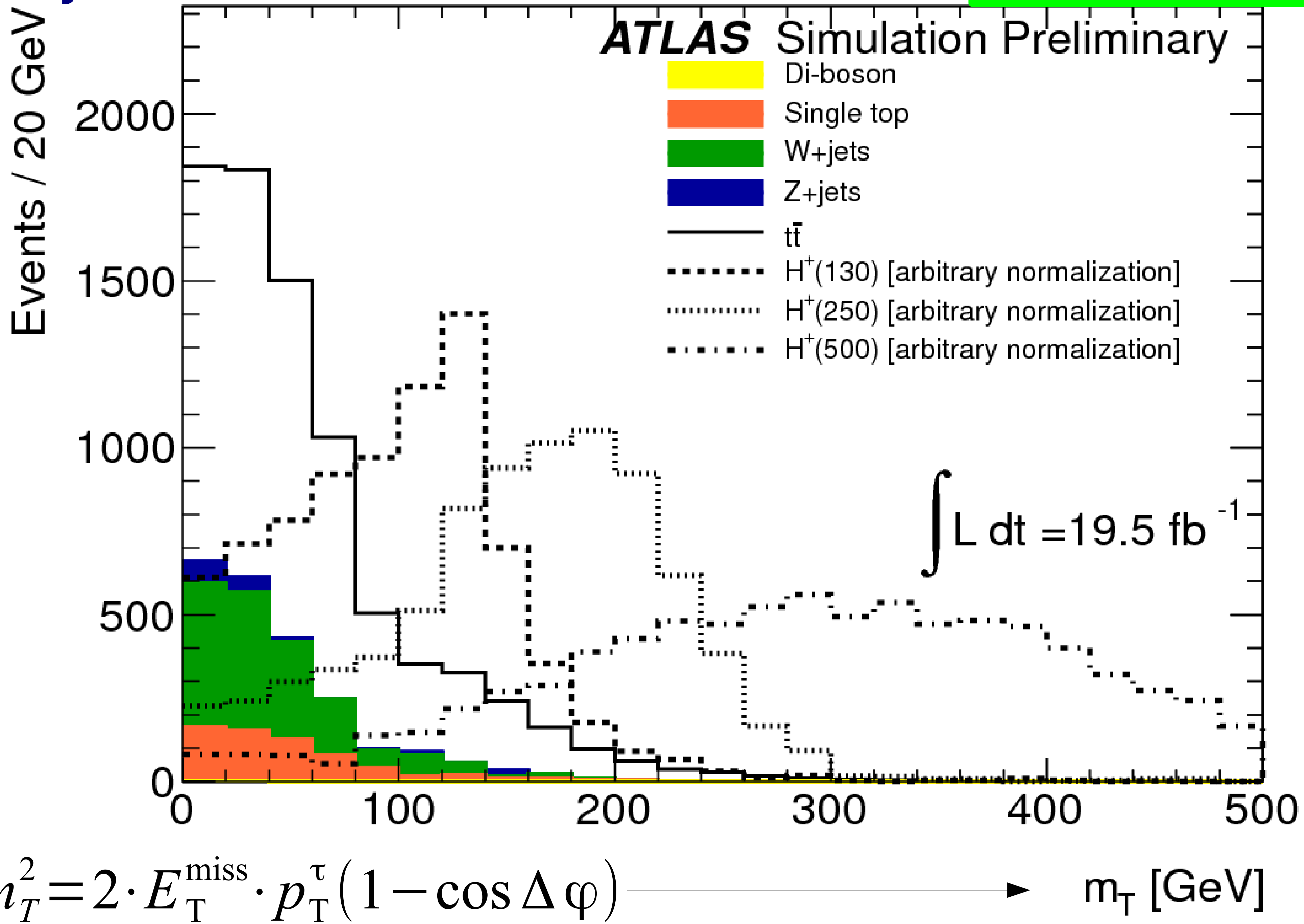


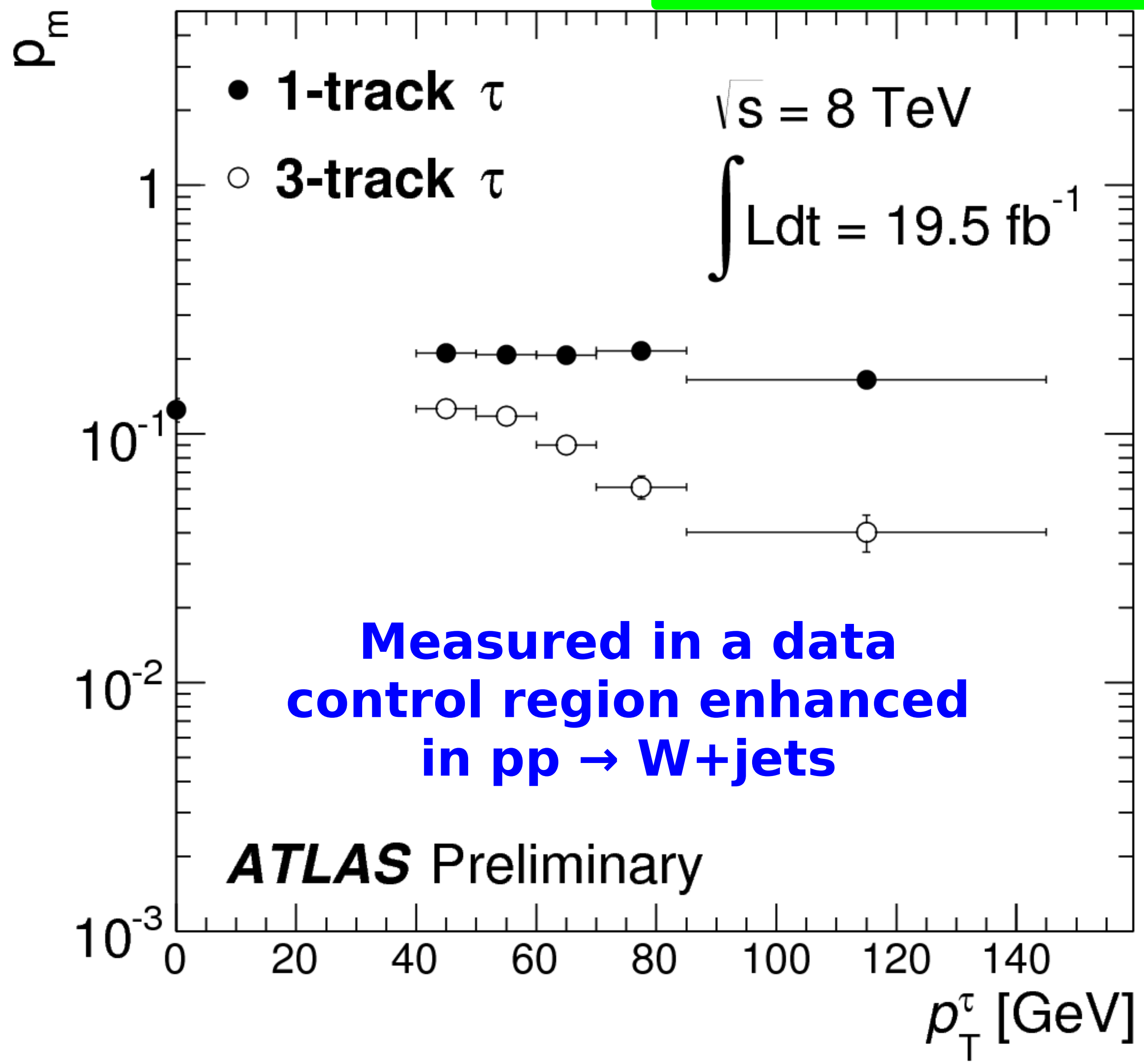
$$m_T^2 = 2 \cdot E_T^{miss} \cdot p_T^{\tau} (1 - \cos \Delta \varphi)$$

Fake Tau Background

$$N_m^T = \frac{p_m}{(p_r - p_m)} p_r N^L - N^T$$

Number of mis-identified, tightly (T) identified tau candidates

p_m is the probability for a mis-identified loose tau candidate to also pass a tighter selection; p_r is the same, but for real taus. We take p_r from MC simulation for now...

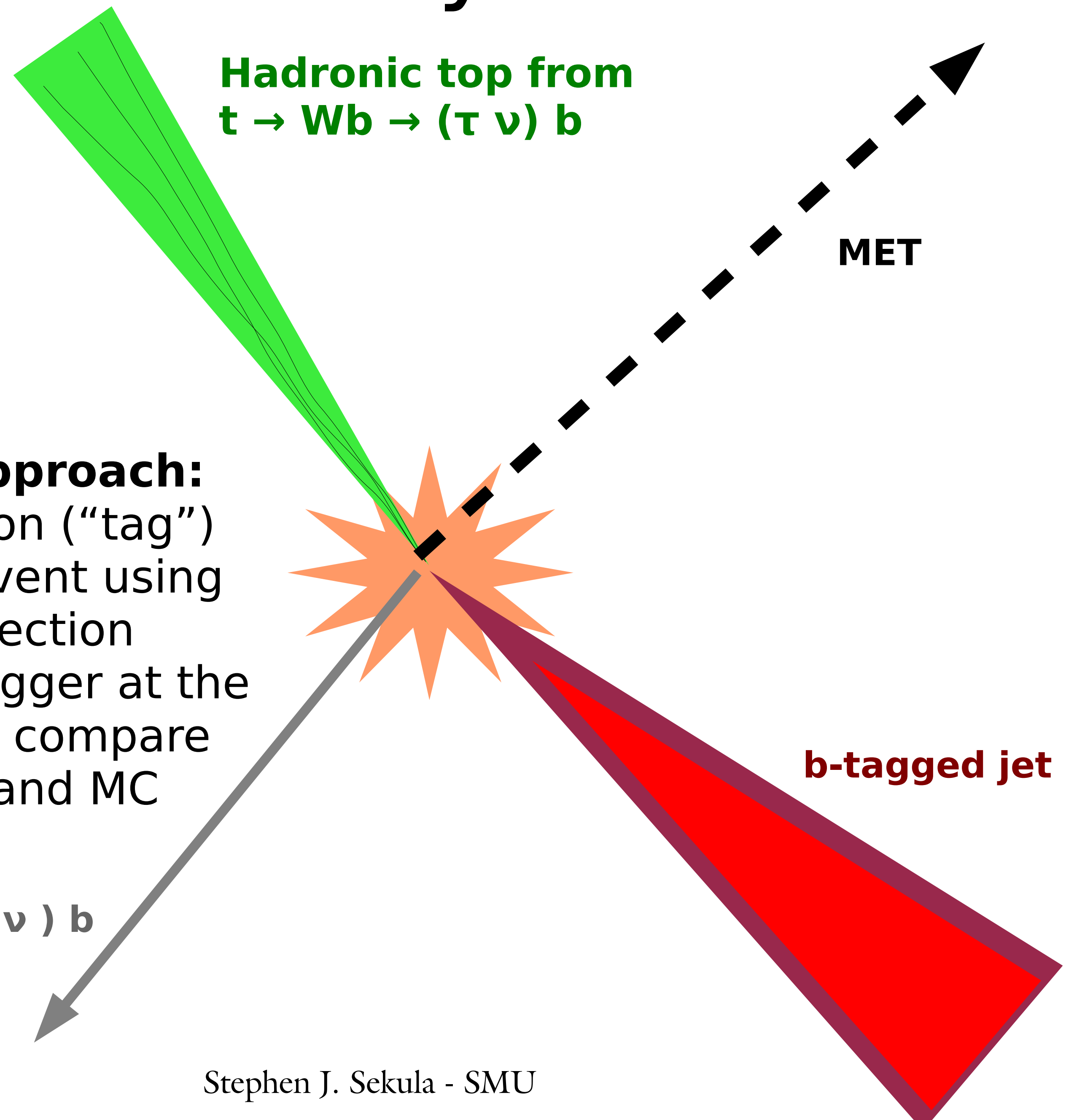


Measured in a data control region enhanced in pp → W+jets

The numbers of events with tightly or loosely reconstructed tau candidates passing our event selection.

Trigger Efficiency Corrections

Technique for this analysis was developed by A. Randle-Conde and S.S.



“Tag and probe” approach:

- Trigger on the muon (“tag”)
- Reconstruct the event using signal analysis selection
- Apply tau+MET trigger at the end (“probe”) and compare efficiency in data and MC simulation

Trigger Systematics

	$p_T^\tau = (40, 70)$ GeV	$p_T^\tau = (70, 500)$ GeV
$E_T^{miss} = (65, 80)$ GeV	$0.94 \pm 0.16 \pm 0.18$	$0.89 \pm 0.14 \pm 0.26$
$E_T^{miss} = (80, 100)$ GeV	$1 \pm 0.1 \pm 0.4$	$1.1 \pm 0.15 \pm 0.24$
$E_T^{miss} = (100, 500)$ GeV	$0.93 \pm 0.09 \pm 0.18$	$0.94 \pm 0.10 \pm 0.31$

The biggest source of systematic uncertainty is due to the effect of kinematic bias – there is more MET, typically, in the control sample than in real signal events. We've learned to deal with this and for the publication we expect to reduce greatly these systematics.

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Jet → τ Fake Rate Systematics

Variation	Shift (±%)	Shift (±%)
	Light H^+ event selection	Heavy H^+ event selection
True τ contamination	3	3
Jet composition	10	10
Statistical uncertainty on p_m	16	14
Statistical uncertainty on p_r	7	8
$\tau_{\text{had-vis}}$ e-veto uncertainty	4	4
$\tau_{\text{had-vis}}$ identification uncertainty	9	11

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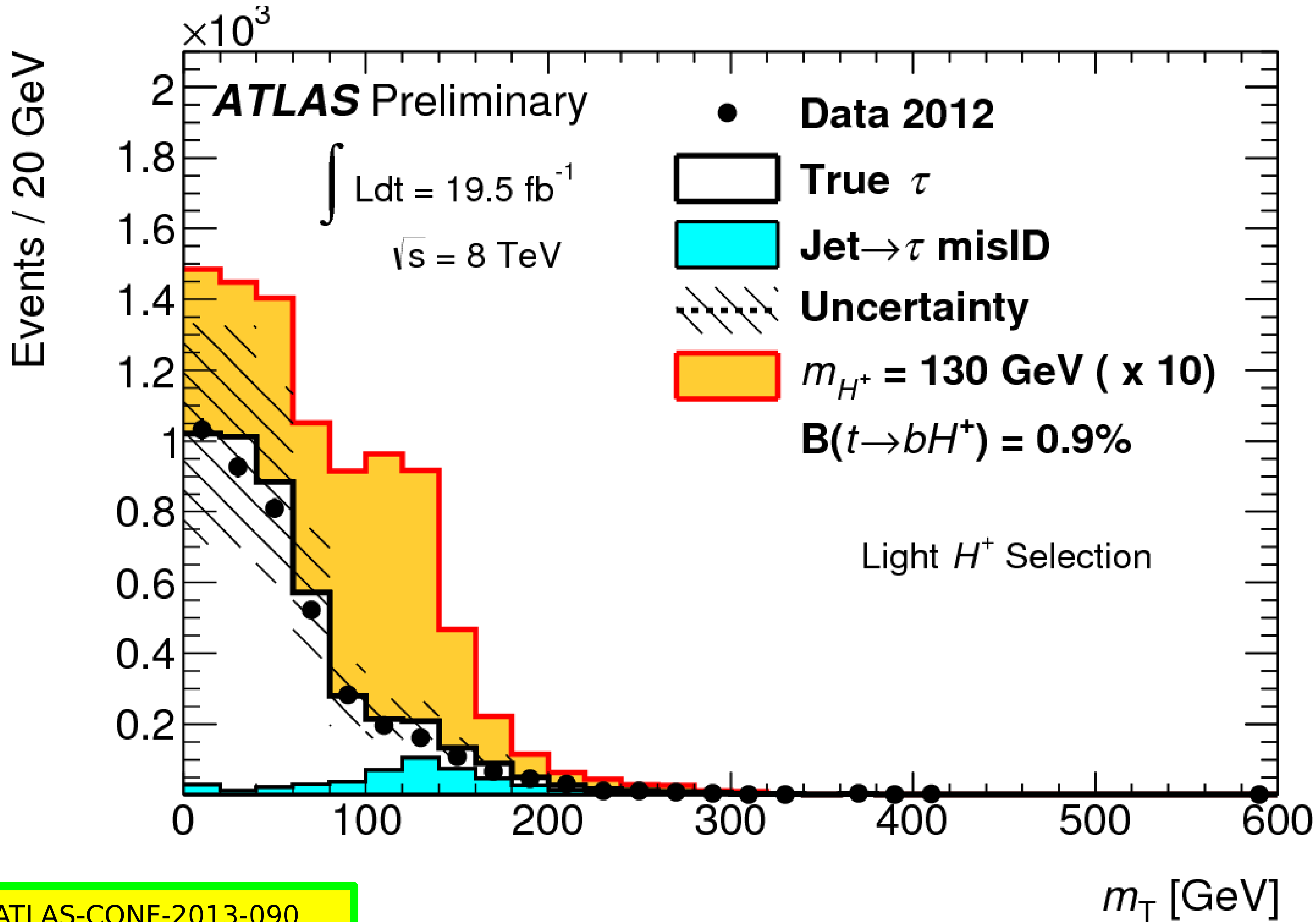
Simulation Systematics

Variation	Shift up (%)	Shift down (%)	Shift up (%)	Shift down (%)
	Light H^+ event selection		Heavy H^+ event selection	
b jet (mis-)tag efficiency uncertainty	3.1	-3.4	2.9	-3.2
Jet energy scale uncertainties	3.7	-4.8	7.1	-6.8
JVF uncertainty	2.2	-1.9	2.2	-2.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties	0.4	0.3	-0.6	-0.2
$\tau_{\mathrm{had-vis}}$ e-veto uncertainty	0.02	-0.02	0.01	-0.01
$\tau_{\mathrm{had-vis}}$ energy scale uncertainty	3.6	-3.8	3.6	-3.8
$\tau_{\mathrm{had-vis}}$ identification uncertainty	3.8	-3.8	3.7	-3.7
Pile-up uncertainties	0.9	-1.5	2.6	-2.1

Theory Systematics

Source of uncertainty	Normalization uncertainty
Light $H^{\pm}$	
Generator model ($b\bar{b}W^{\pm}H^{\pm}$)	9%
Generator model ($b\bar{b}W^{+}W^{-}$)	9%
$t\bar{t}$ cross section uncertainty	10%
Jet production rate (SM and $H^{\pm}$)	11%
Heavy $H^{\pm}$	
Generator model ($H^{\pm}$)	2 – 9%
Generator model (SM)	8%
$t\bar{t}$ cross section uncertainty	10%
Jet production rate ($H^{\pm}$)	4.4 – 11%
Jet production rate (SM)	11%

$H^+ \to \tau^+ \nu$ (τ_{had} +jets)



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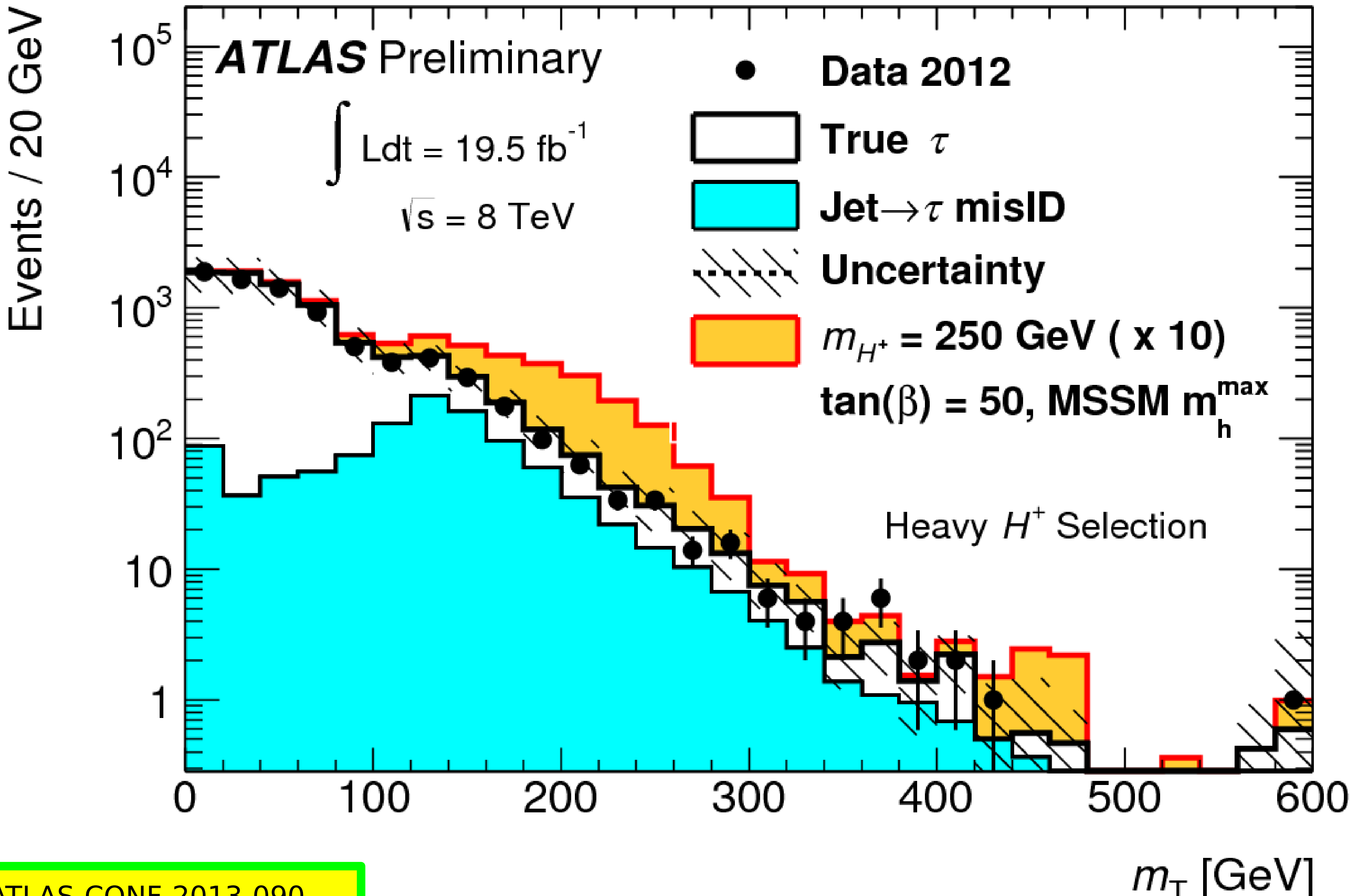
$H^+ \rightarrow \tau^+ \nu$ (τ_{had} +jets)



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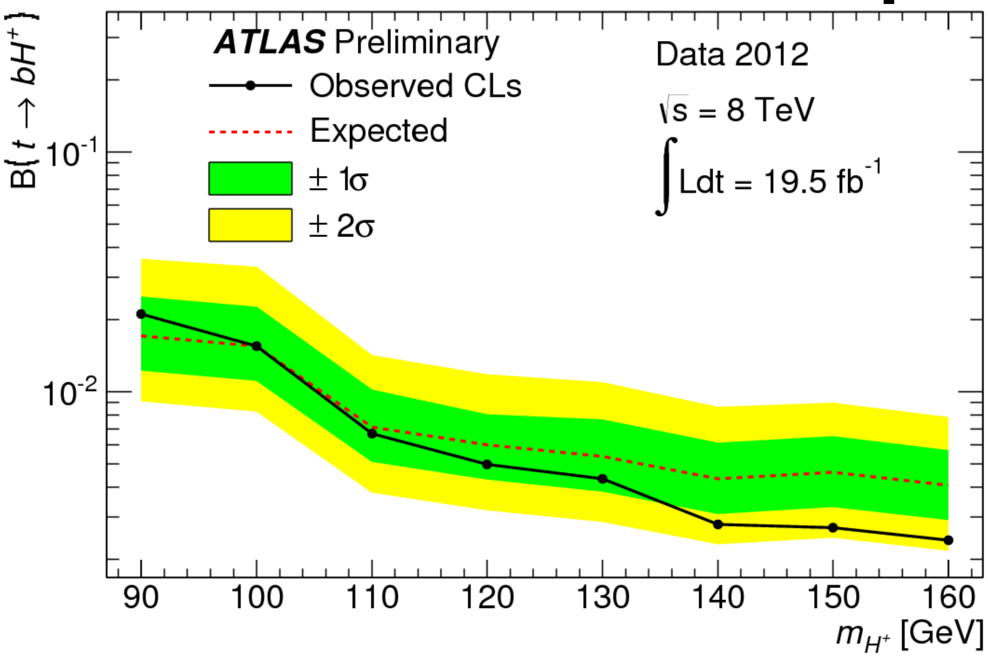
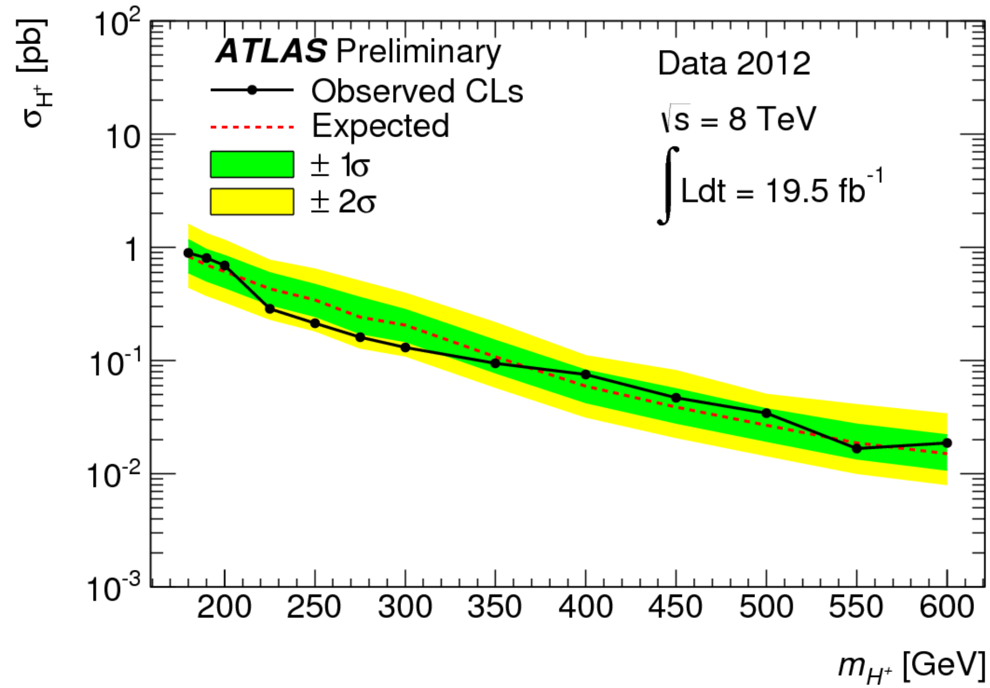
Model-Independent Results





No evidence for a signal, so we set upper limits at the 95% C.L. on . . .

- The branching fraction $B(t \to H^+ b)$ (assuming $H^+ \to \tau \nu$ is 100%) for the low-mass search. Limits range between 0.2-2.1%
- The product $\sigma(pp \to H^+ t (b)) \times B(H^+ \to \tau \nu)$ for the high-mass search. Limits range between 0.01-0.9 pb.

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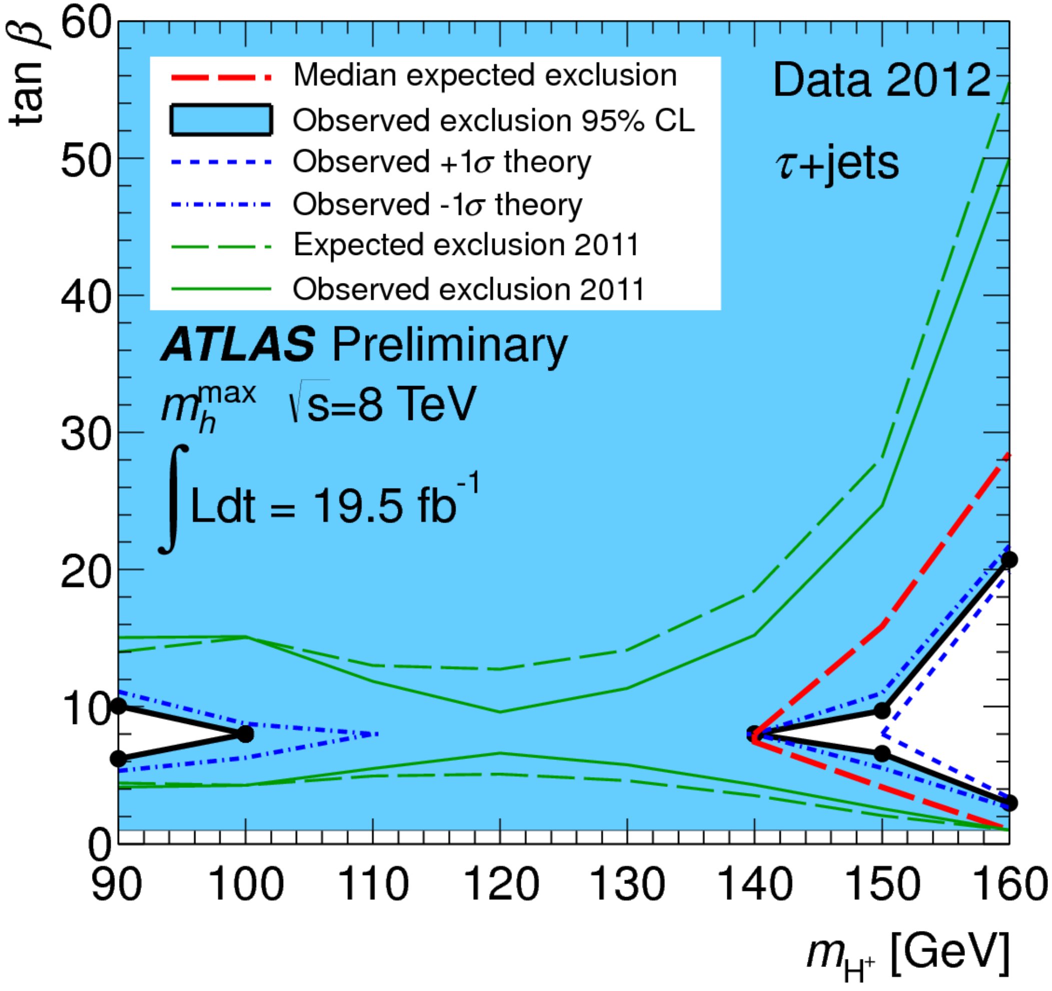
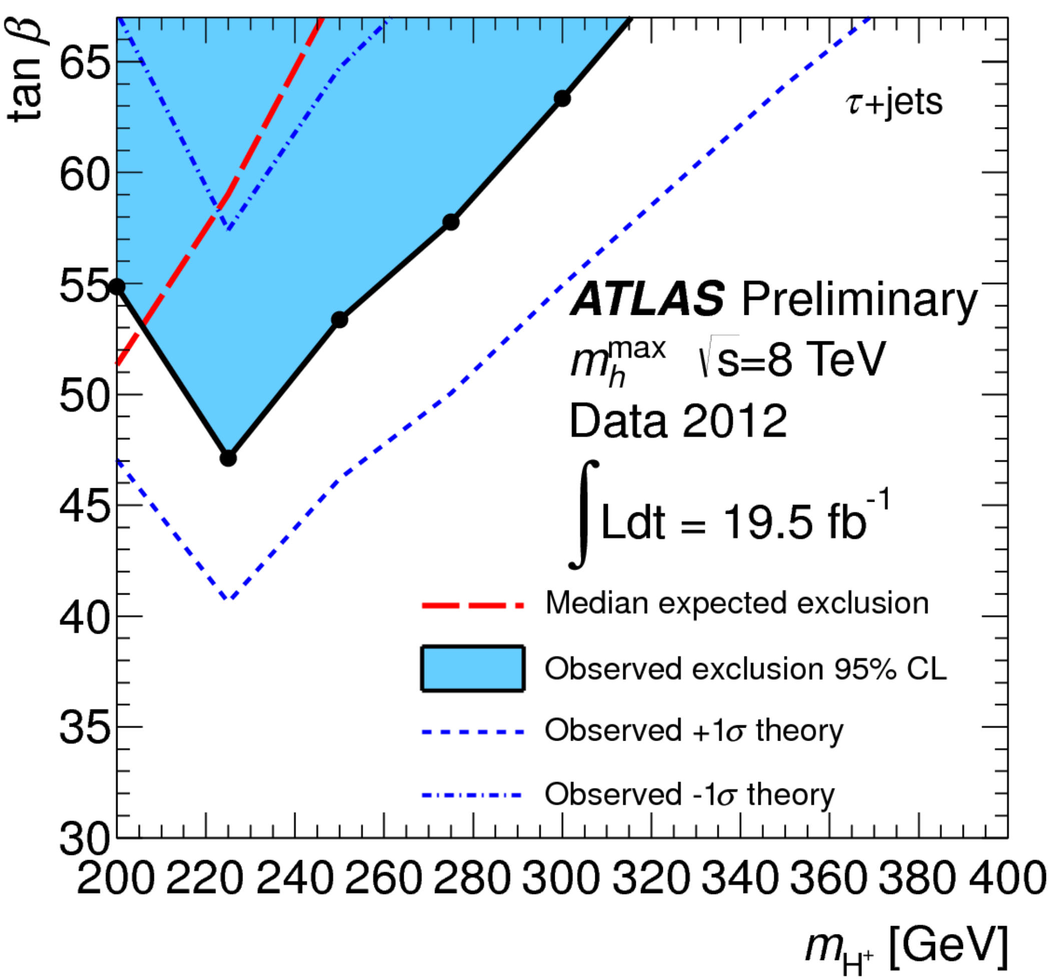
Model-Dependent Results





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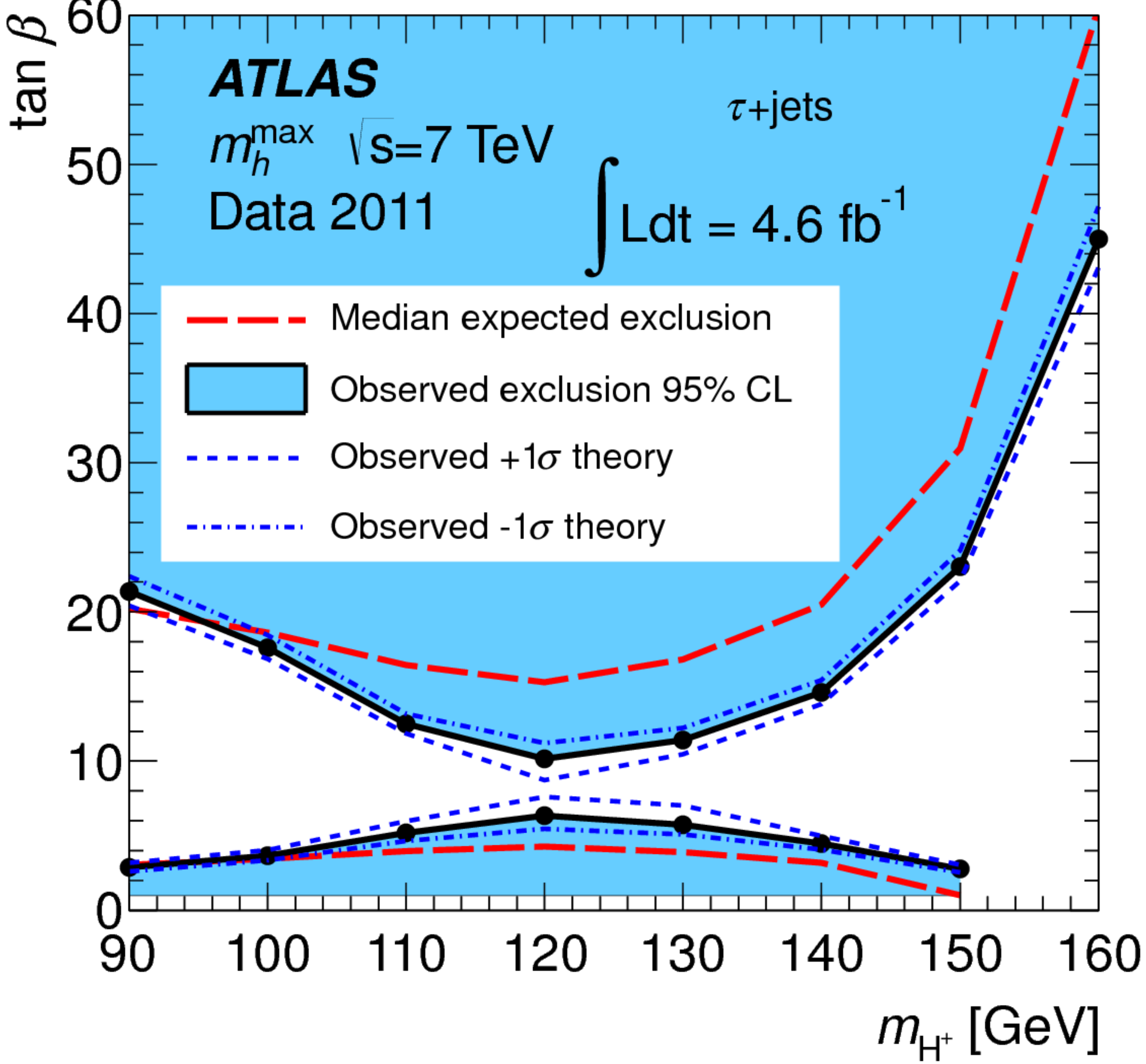
Comparison: 2011 Data



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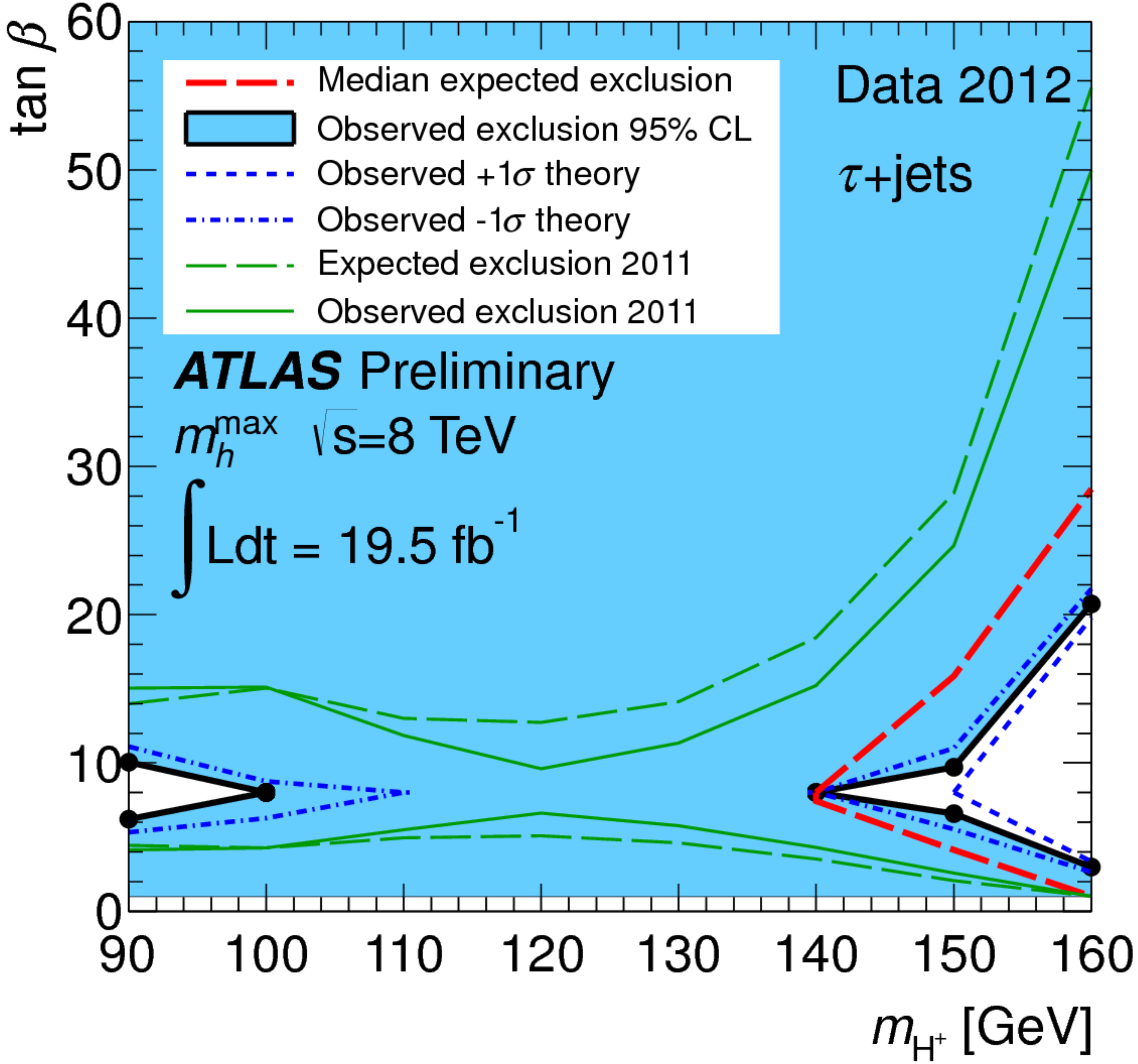
Current: 2012 Data



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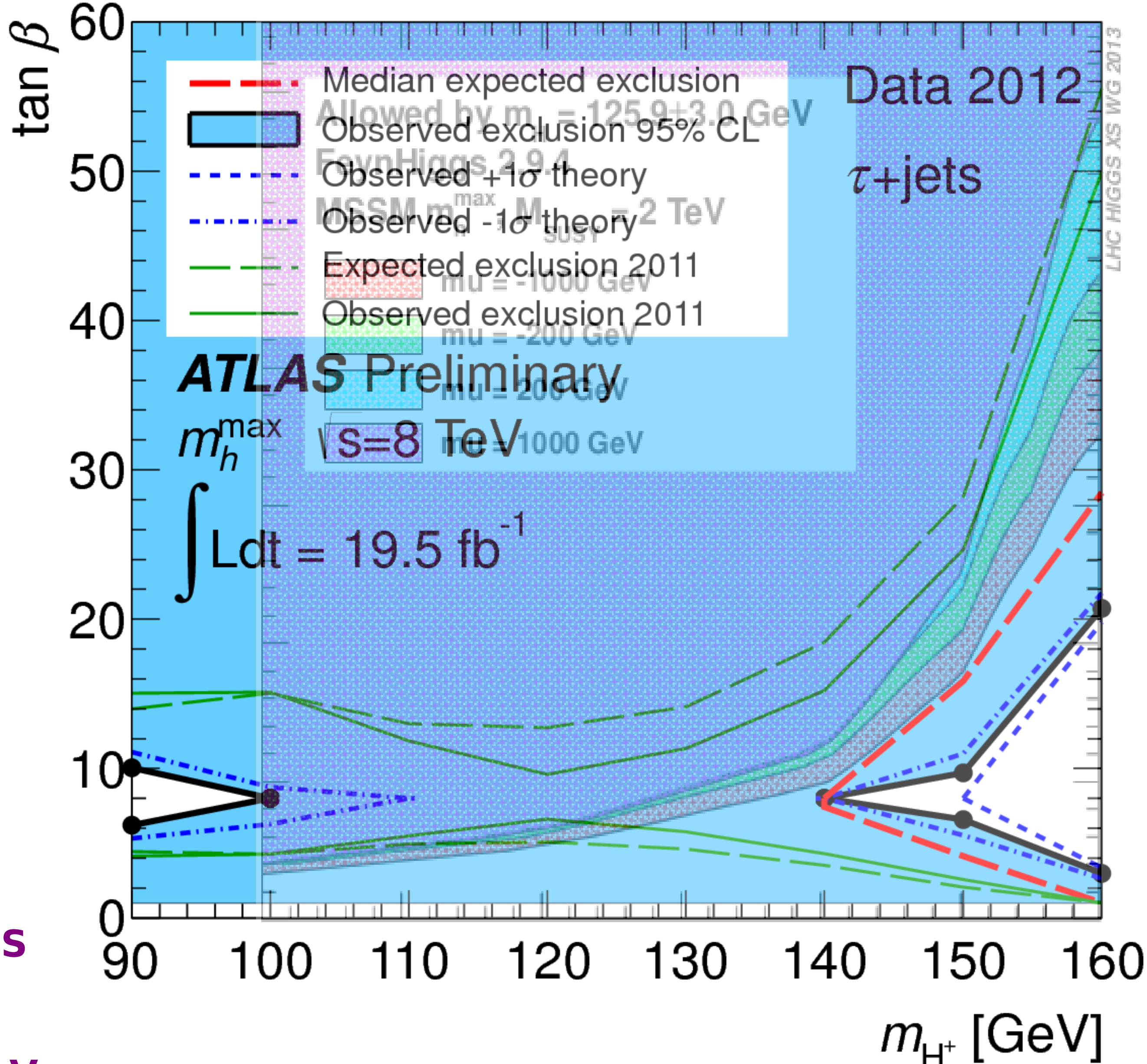
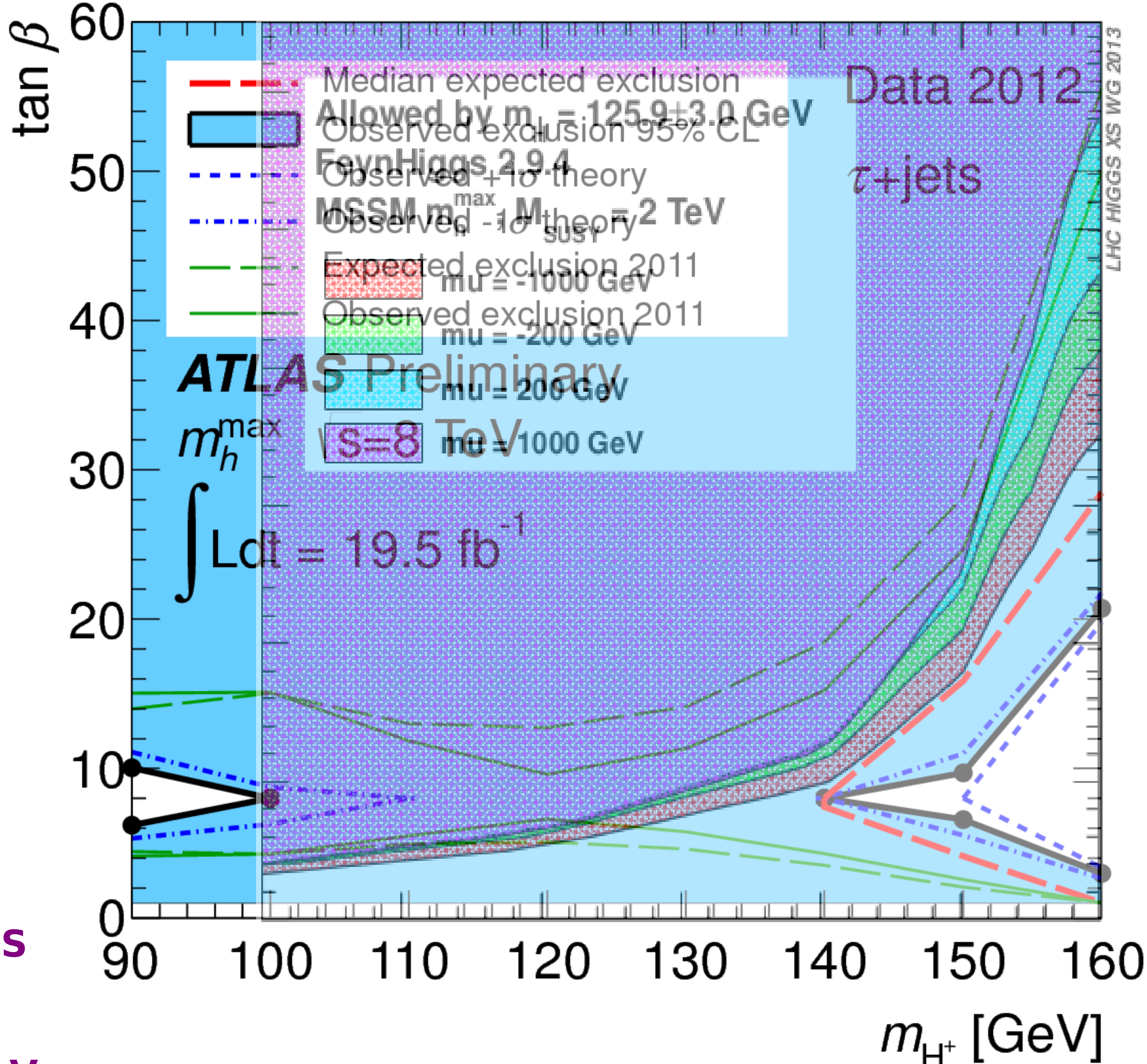
2012 Data



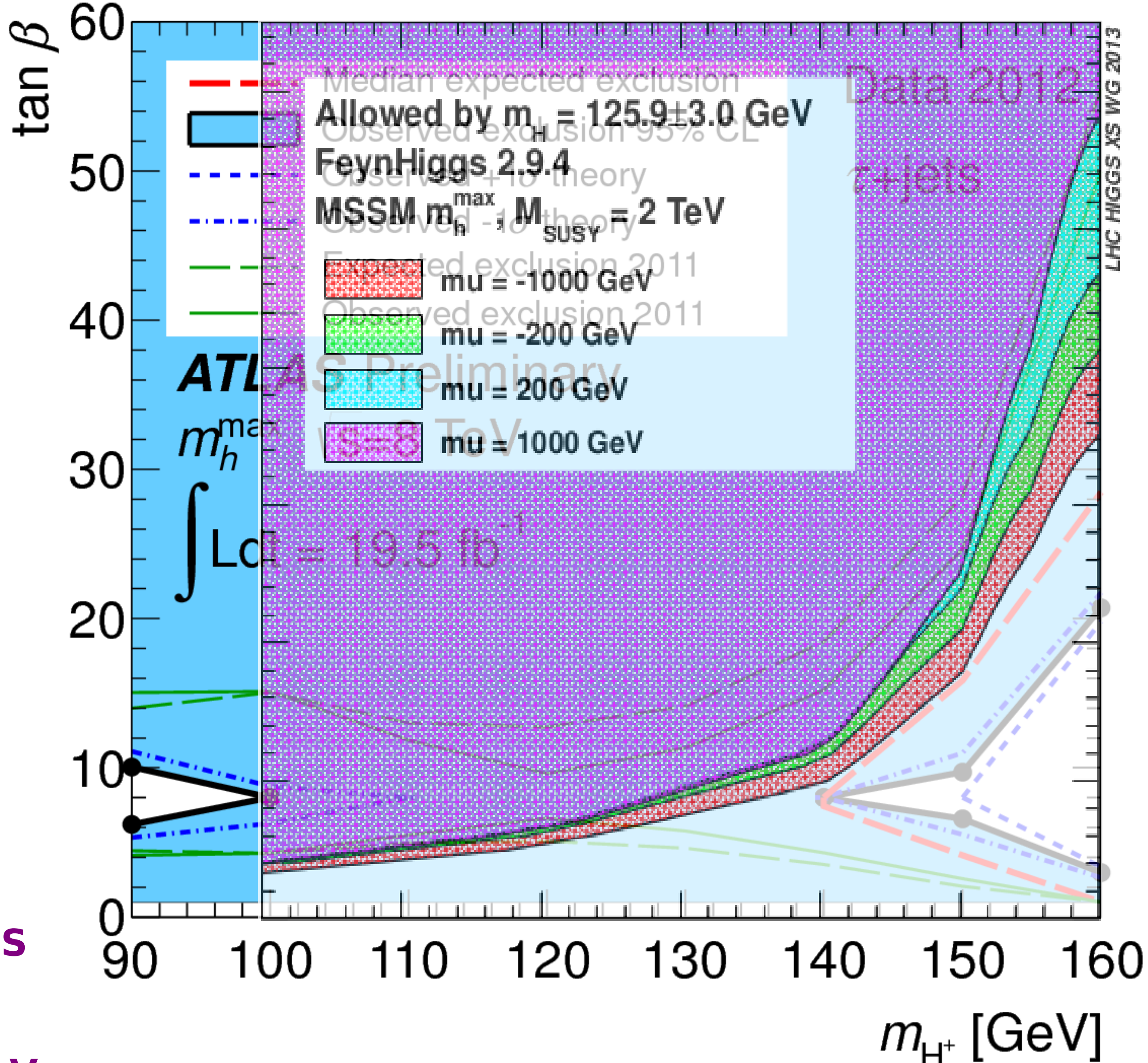
Fade in an overlay of the LHCHXS WG allowed space for mH=125.8 GeV

2012 Data

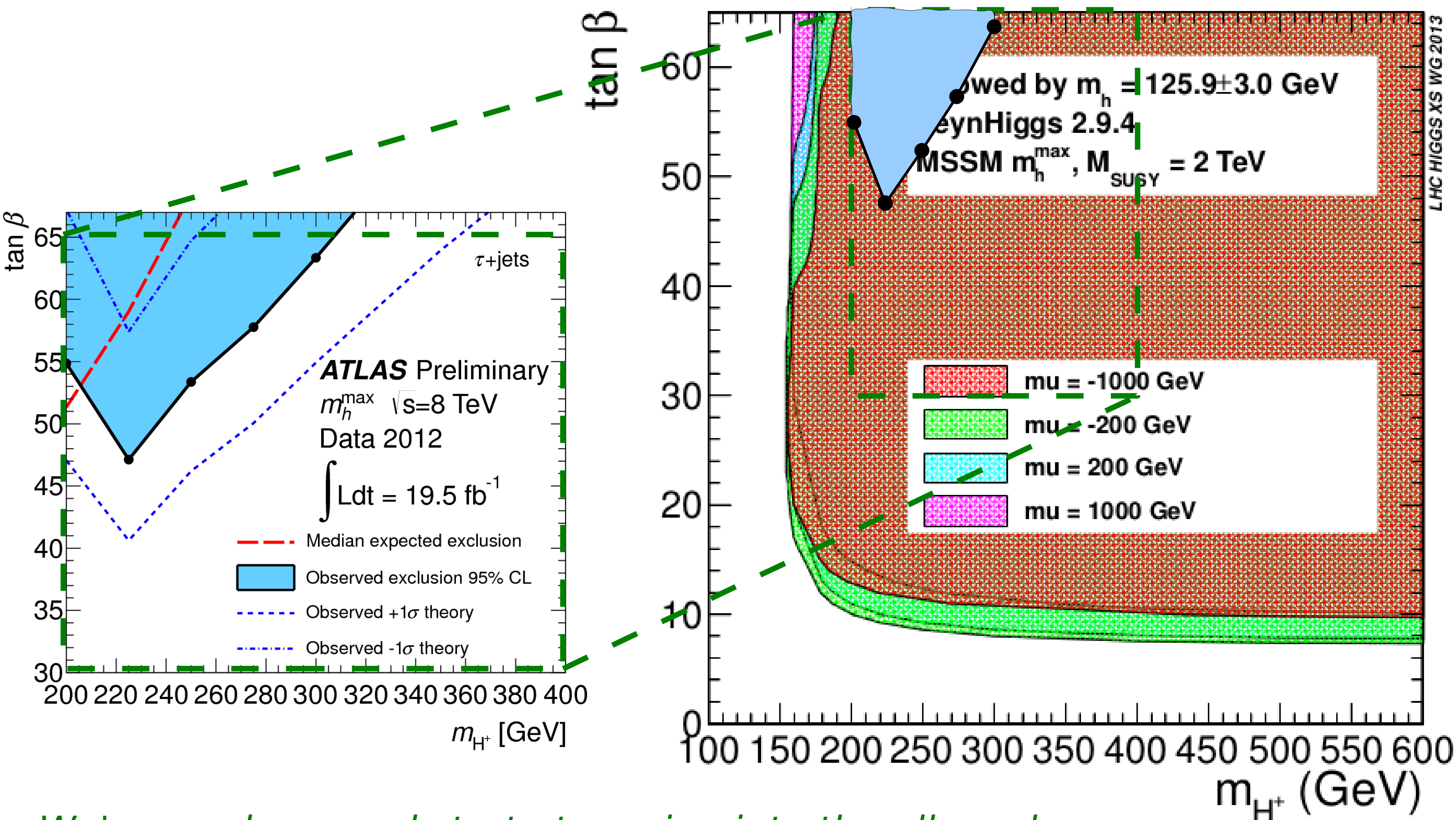


Fade in an overlay of the LHCHXS WG allowed space for mH=125.8 GeV

2012 Data



Fade in an overlay of the LHCHXS WG allowed space for mH=125.8 GeV



We've made a good start at carving into the allowed space for the heavy H⁺ - more channels in 8 TeV and a lot more data and creativity at 14 TeV will push this effort along rapidly!

Conclusions and Outlook

The Road Ahead

- Run 2 – 2015-2017
  - expect to integrate ~100/fb
- Long-Shutdown 2: ~2018-2019
  - “Phase I upgrade”
  - prepare for running at $2x10^{34}/cm^2/s$
- Running – 2019-2021
- Long-Shutdown 3: ~2022-2023
  - “Phase II upgrade”
  - prepare for running at $5x10^{34}/cm^2/s$
- Running – ~2024-…

- Above the Higgs
  - There is much work for Run 2:
    - improved statistics and upgraded detector will allow us to push the statistical uncertainties down on Higgs couplings and quantum numbers, as well as improve access to the fermion (and other) final states.
    - likely that the revisiting of reconstruction and identification efforts will greatly improve systematic uncertainties
- Beyond the Higgs
  - So far, in Run 1, there are no clear direct signs of additional Higgs bosons
  - The MSSM is all but ruled out – if SUSY is real, it's eluded us in Run 1 and if we don't see it in Run 2 well . . . then . . .
  - Let's just be open for surprises . . . !