Alexander von Humboldt Stiftung/Foundation

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BSM Higgs: experimental results

Will Davey
on behalf of the LHC and Tevatron experiments

LHCP 2014

ATLAS CMS LHCb DØ CDF II

Outline

- 2HDM/MSSM:
  - Neutral
  - Charged
  - Cascades
- NMSSM:
  - Light Neutral
  - Charged cascade
- Exotic Decays:
  - Decay to Invisible
- Not discussed:
  - Decay to Long-lived
  - Doubly Charged
  - Fermiophobic

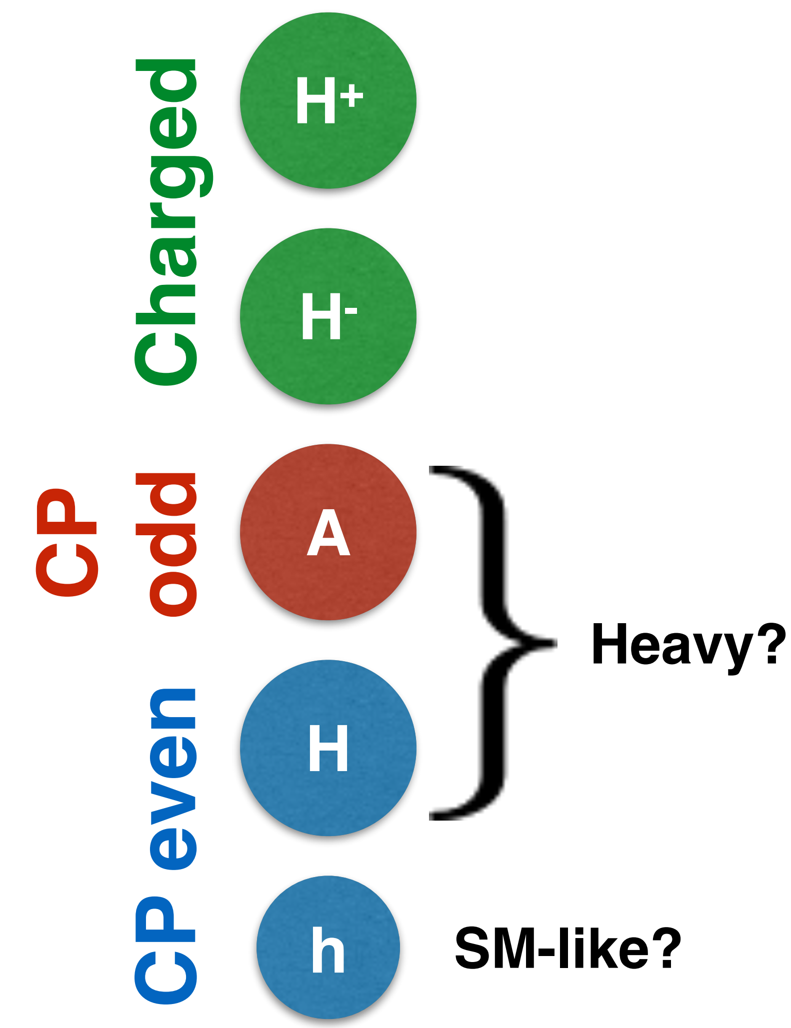
2HDM/MSSM

(Two Higgs Doublet Model)

(Minimal Supersymmetric Standard Model)

2HDM/MSSM Phenomenology

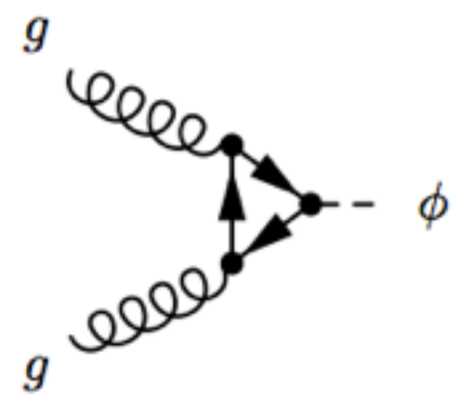
- 2 Higgs doublets → 5 Higgs bosons
- Type I (ϕ_V, ϕ_f), Type II (ϕ_u, ϕ_d) and more…
- MSSM (Type II):
  - 2 parameters: m_A, $\tan\beta = \langle\phi_d\rangle / \langle\phi_u\rangle$
  - for $\tan\beta > 1$ **coupling to b and τ enhanced**
- Search channels:
  - $H \to \tau\tau/bb$ ($\mu\mu$)
  - $H^+ \to \tau\nu/cs$ ($H^+ \to tb$)



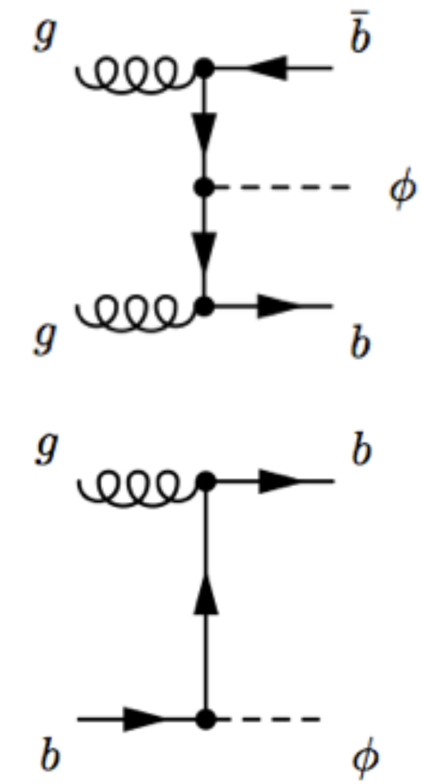
MSSM A/H/h→fermions

- ττ and bb final states most sensitive
- take advantage of presence or absence of b-quarks in signal production modes

gluon fusion

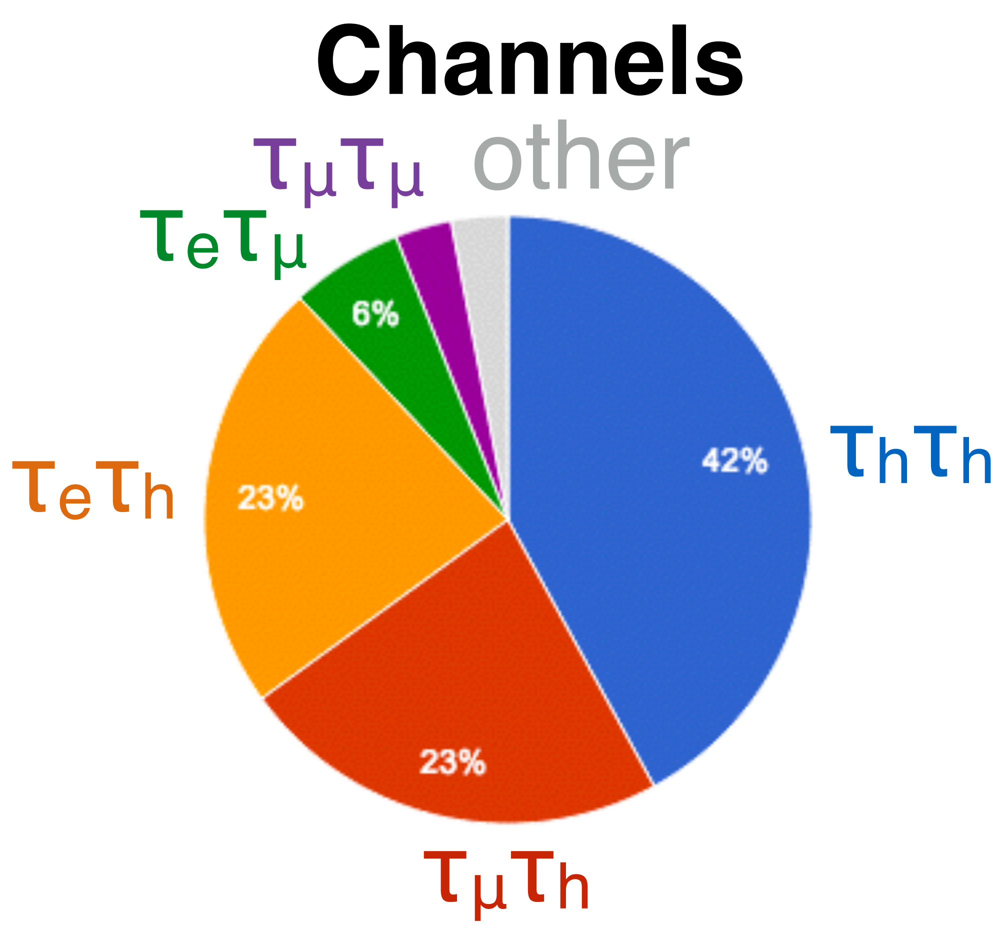


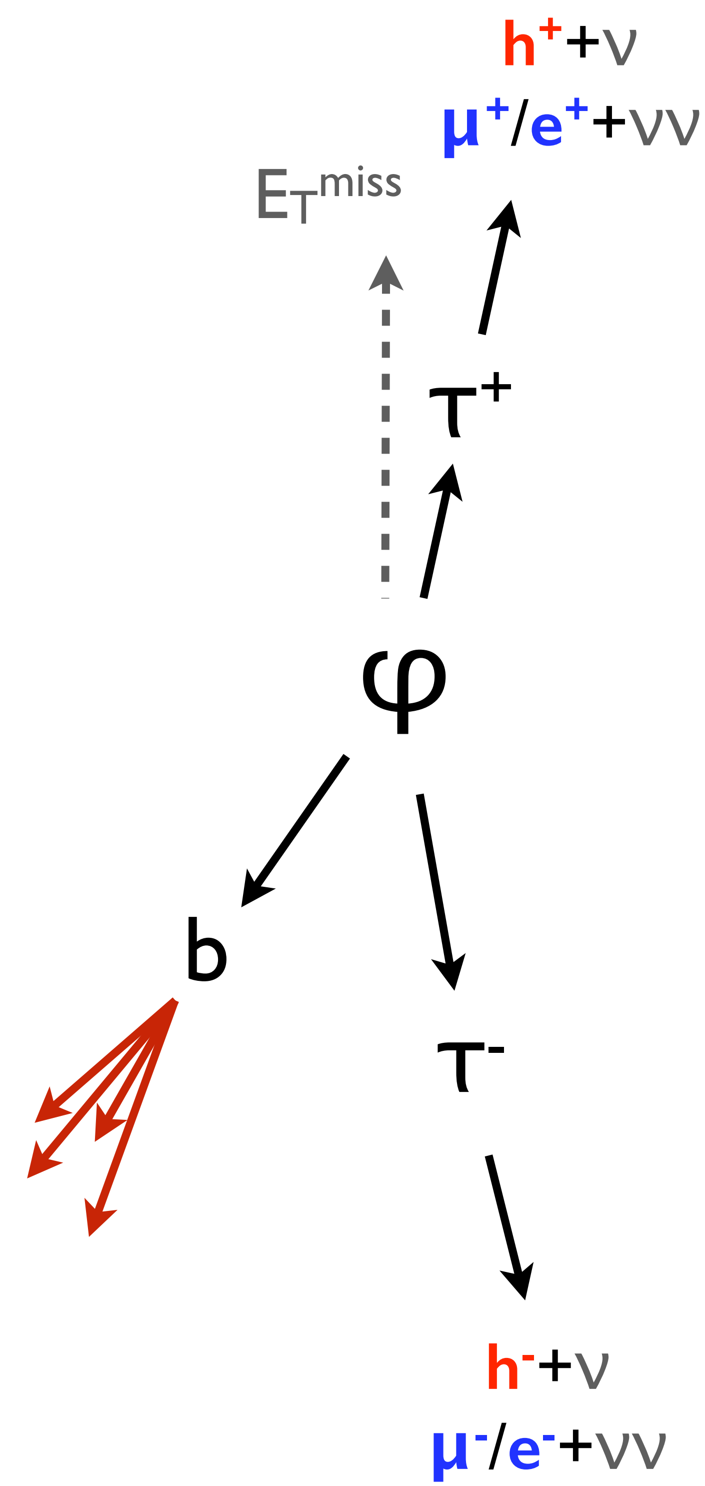
b-quark associated



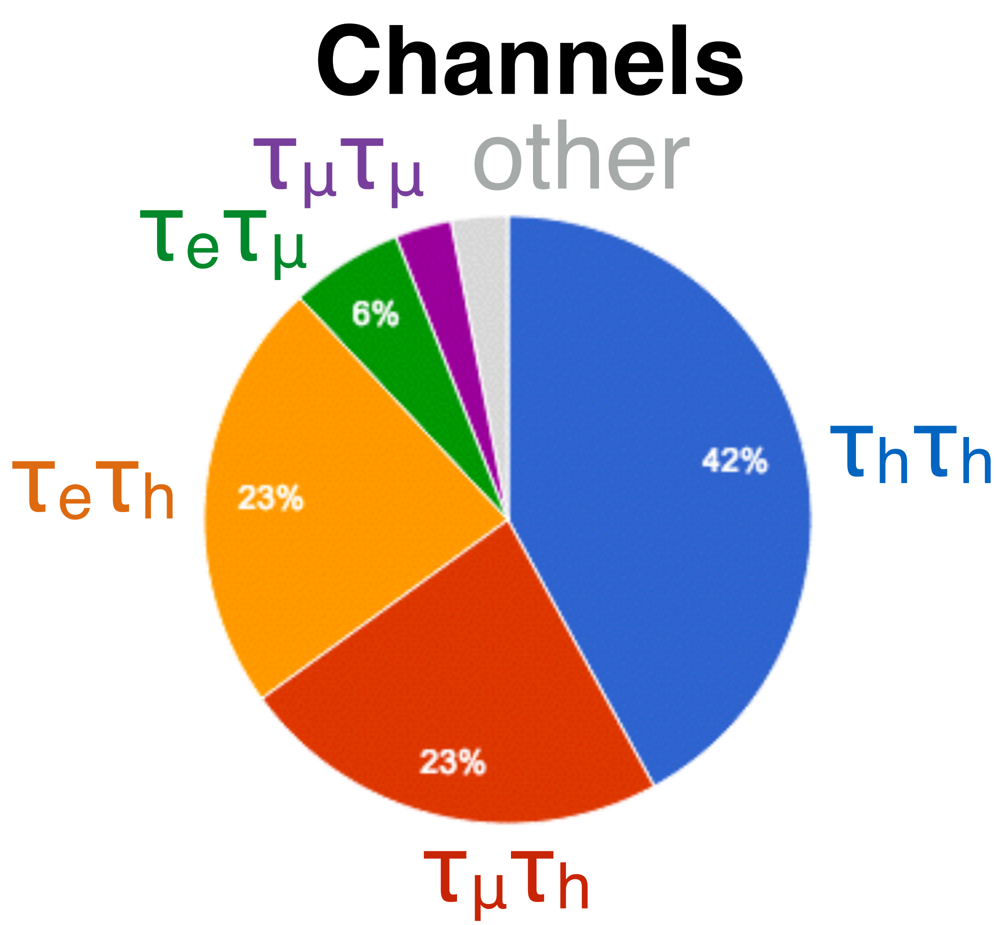
Coll.	Channel	Dataset	Cite
CMS	**ττ**	**25fb-1(7+8TeV)**	**CMS-PAS-HIG-13-021**
ATLAS	ττ/μμ	5fb-1(7TeV)	JHEP02(2013)095
LHCb	ττ	1fb-1(7TeV)	JHEP05(2013)132
D0	ττ+bb	5-7fb-1(2TeV)	PLB 710, 569 (2012)
D0+CDF	**bb**	**3-5fb-1(2TeV)**	**PRD 86, 091101 (2012)**
CMS	**bb**	**3-5fb-1(7TeV)**	**PLB 722, 207 (2013)**

CMS: A/H/h→ττ

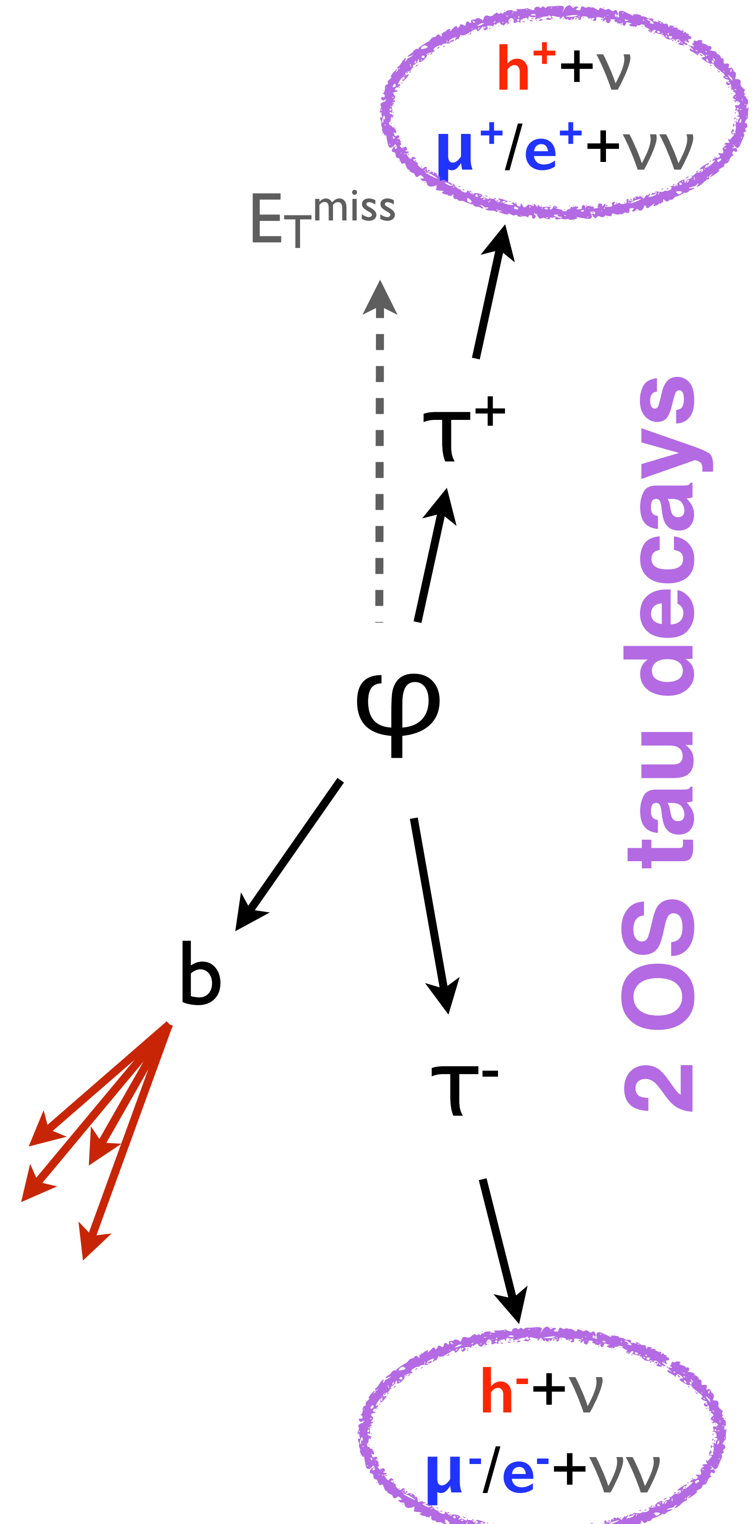

Channels
τμτμ
other
τeτμ
6%
τeτh
23%
42%
τhτh
23%
τμτh


h+ +ν
μ+/e+ +νν
ET miss
τ+
φ
b
τ-
h- +ν
μ-/e- +νν

CMS: A/H/h→ττ

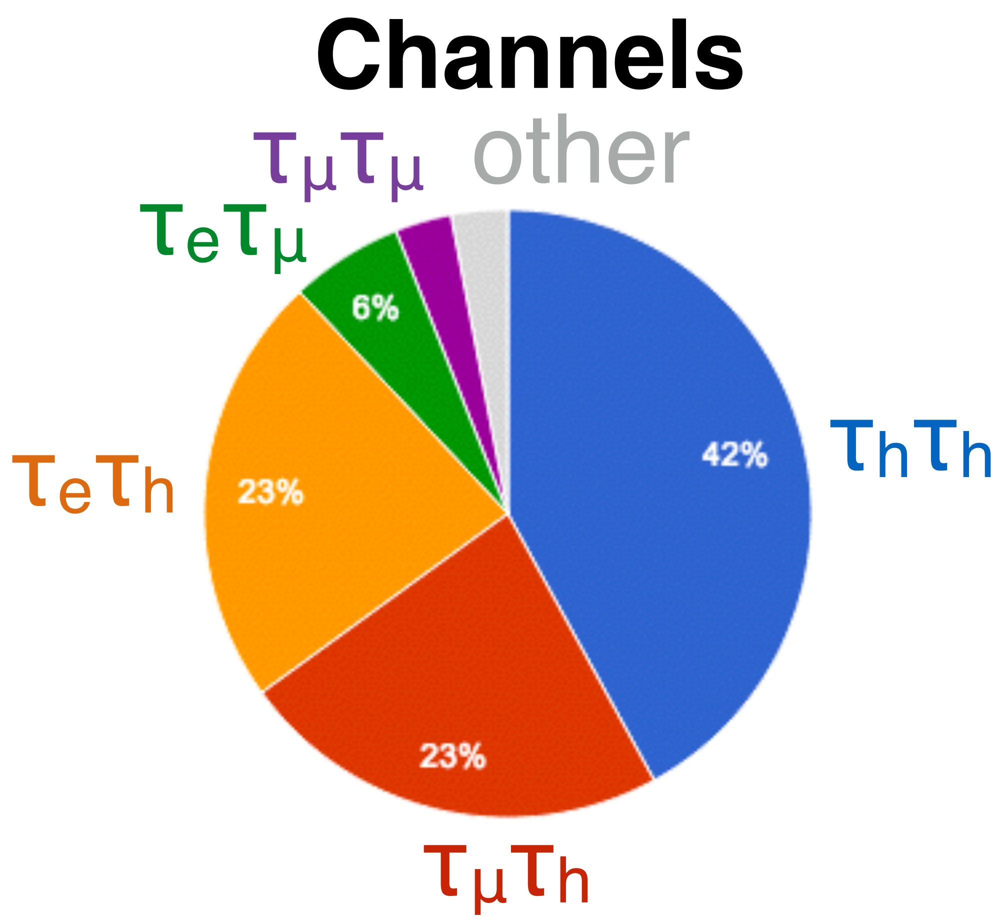


Channels
τμτμ
other
τeτμ
6%
τeτh
23%
42%
τhτh
23%
τμτh

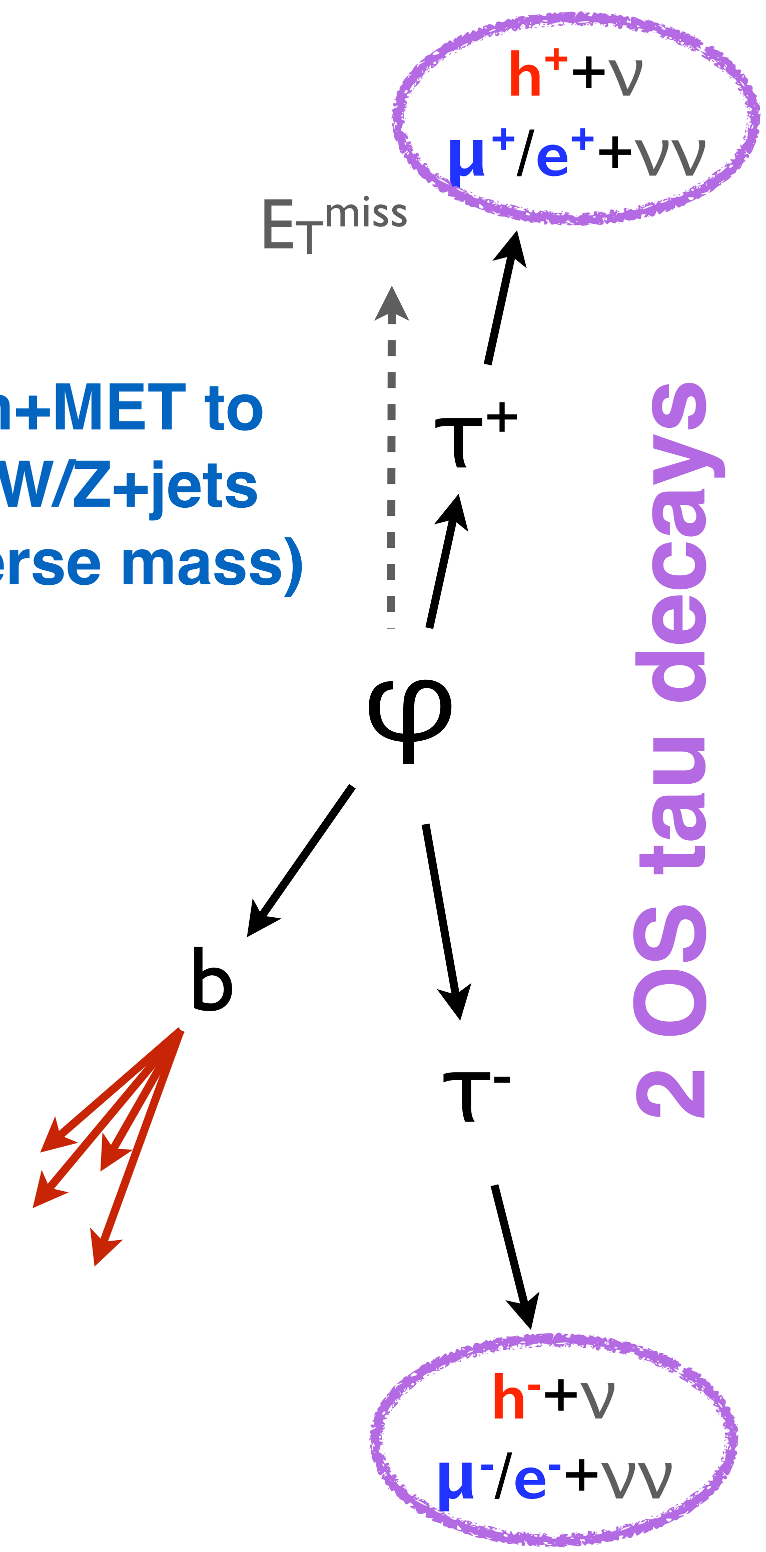


h+ +ν
μ+/e+ +νν
ET miss
τ+
φ
b
τ-
2 OS tau decays
h- +ν
μ-/e- +νν

CMS: A/H/h→ττ

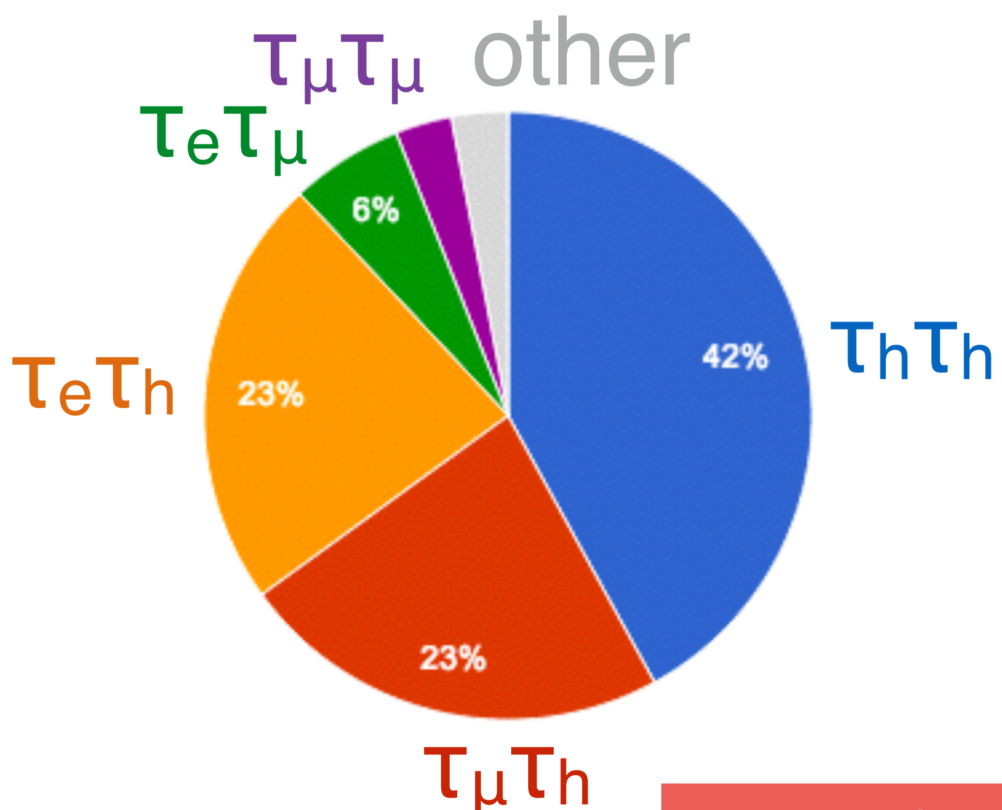


Use lepton+MET to suppress W/Z+jets (eg. transverse mass)



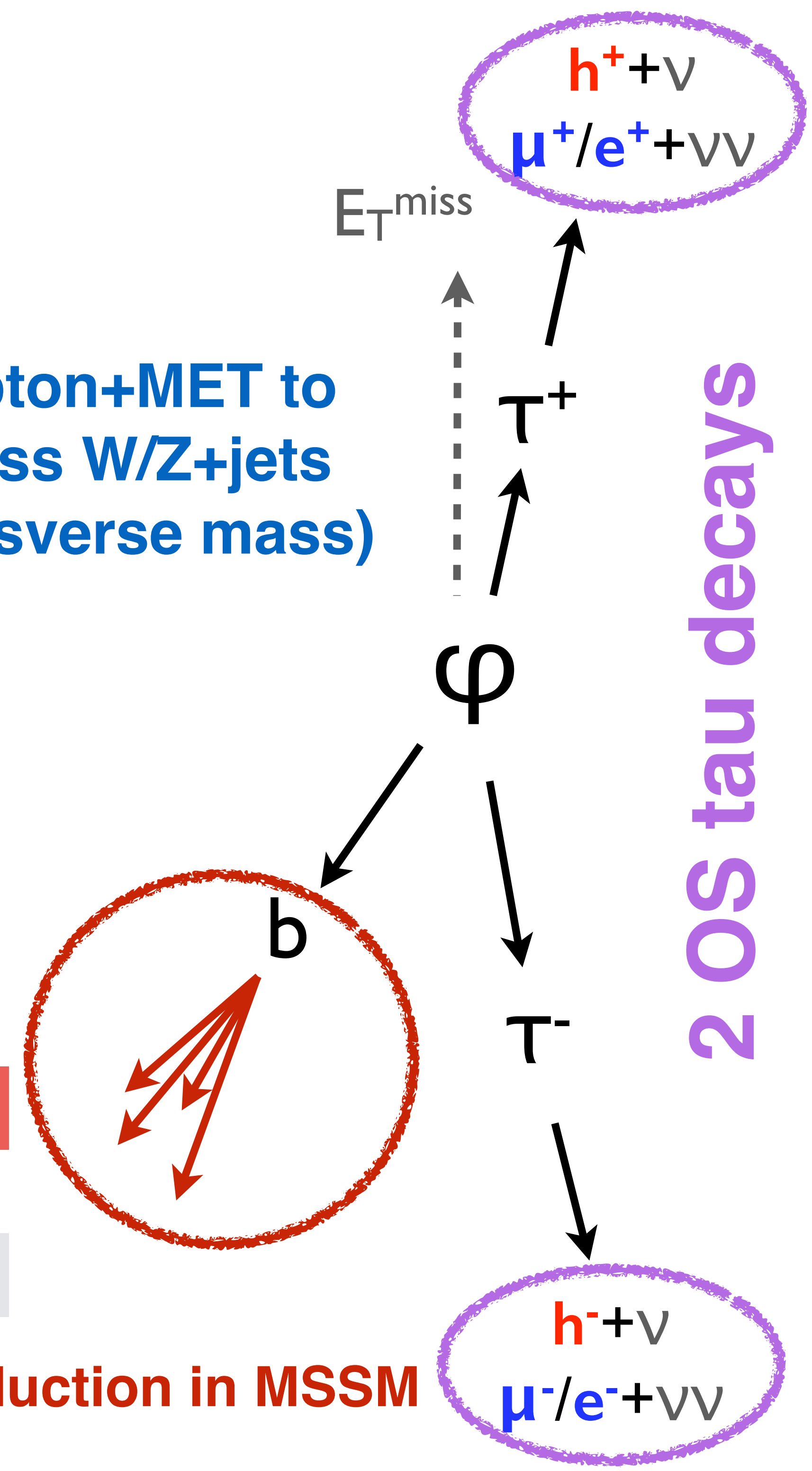
CMS: A/H/h→ττ

Channels



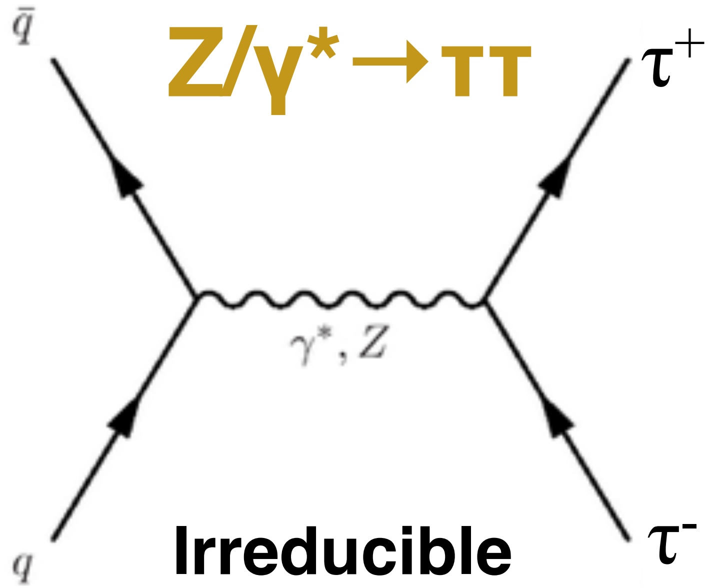
Use lepton+MET to suppress W/Z+jets (eg. transverse mass)

Categorise	
B-Tag	≥1 b-jet
No B-Tag	0 b-jets



Exploit enhanced b-quark associated production in MSSM

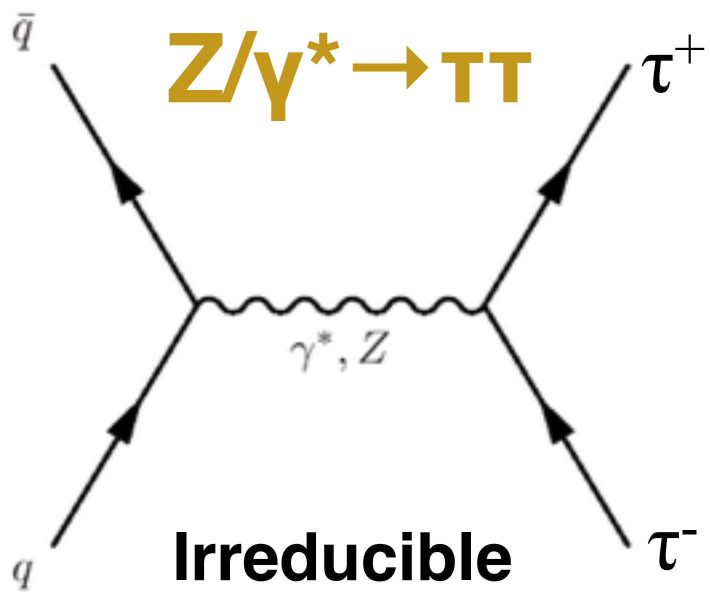
CMS: Backgrounds



Estimated using $Z \rightarrow \mu\mu$ embedding

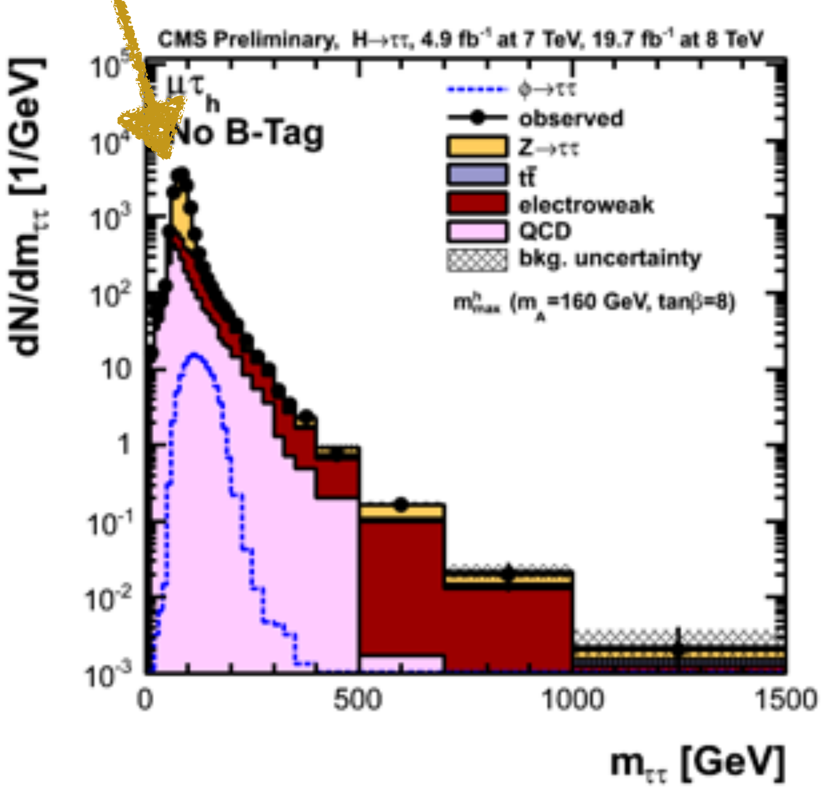
CMS: Backgrounds

Z/γ* → ττ



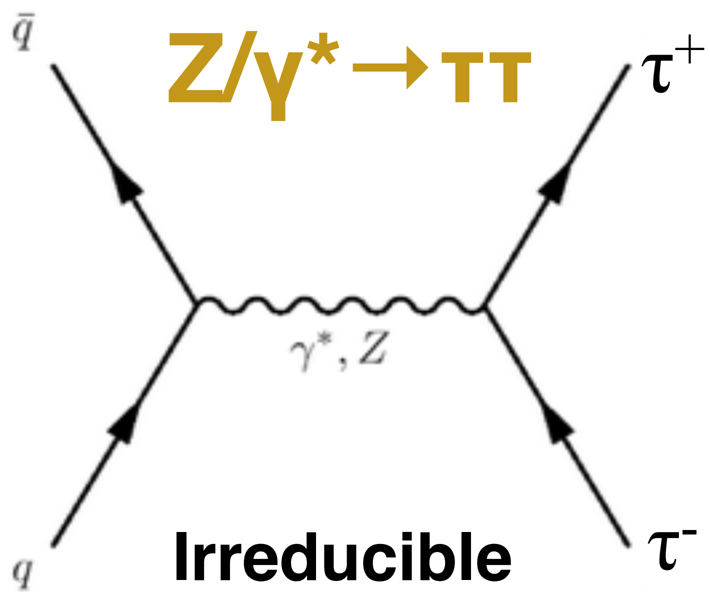
Irreducible

Estimated using Z→μμ embedding



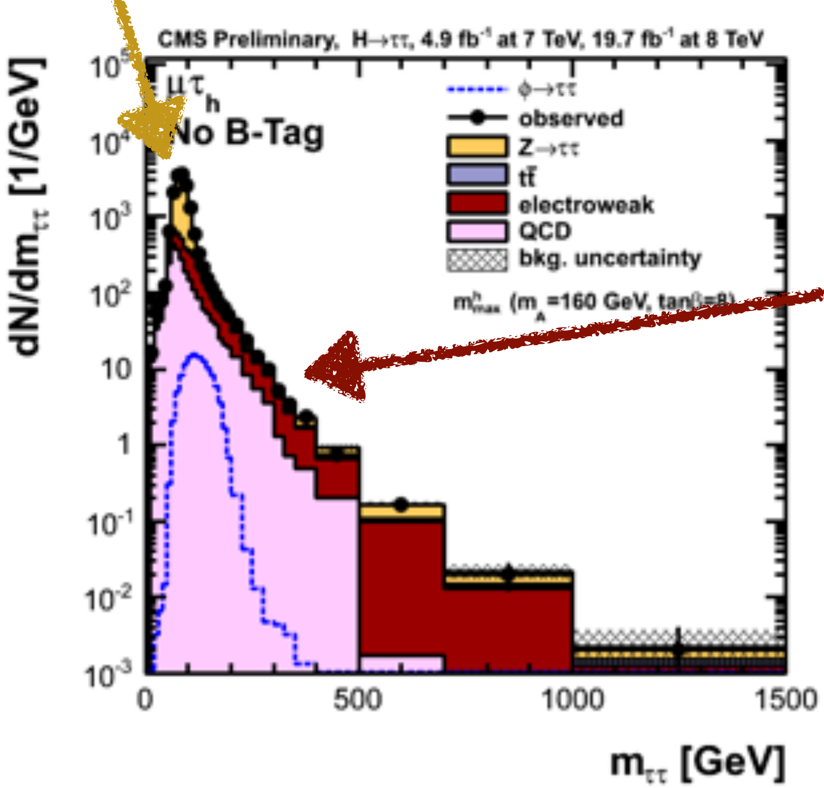
CMS: Backgrounds

Z/γ*→ττ

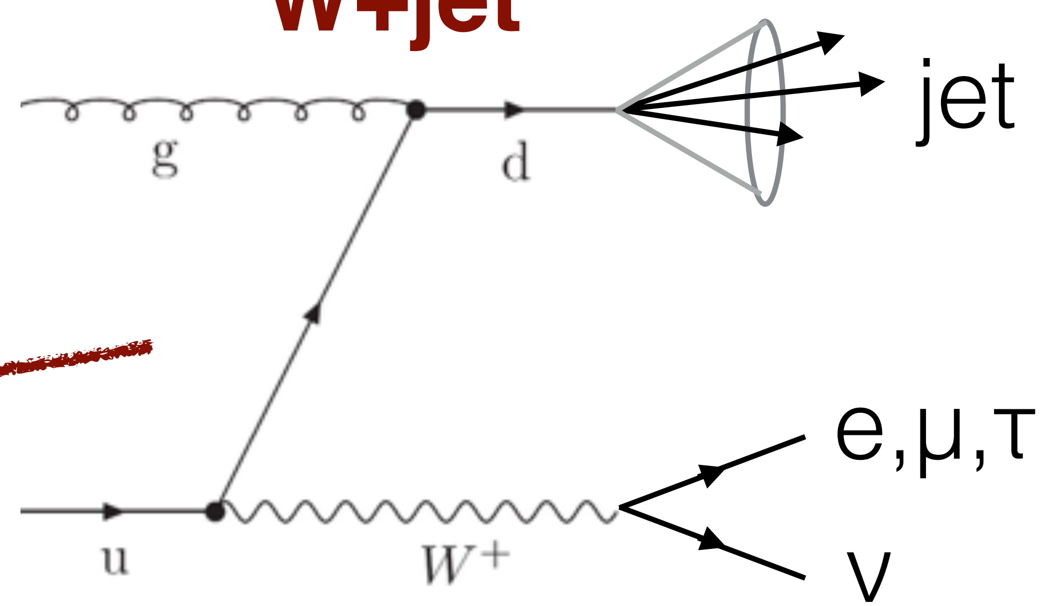


Irreducible

Estimated using Z→μμ embedding



W+jet

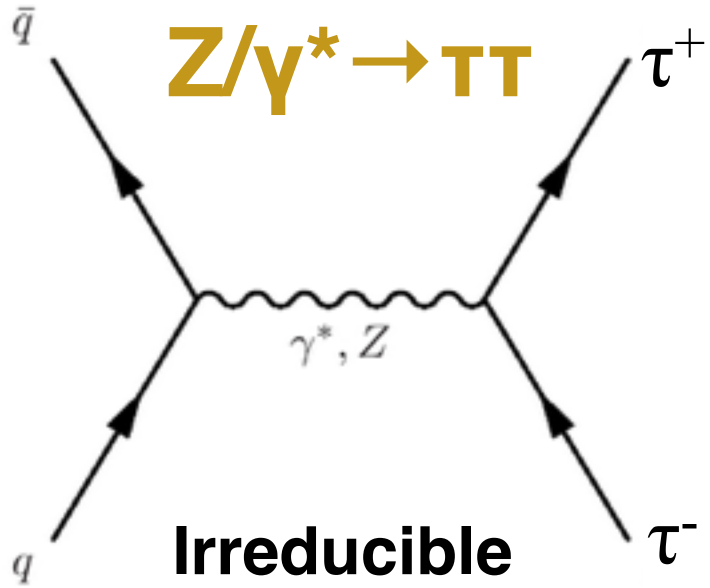


Mimics: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

Estimated using MC + data norm.

CMS: Backgrounds

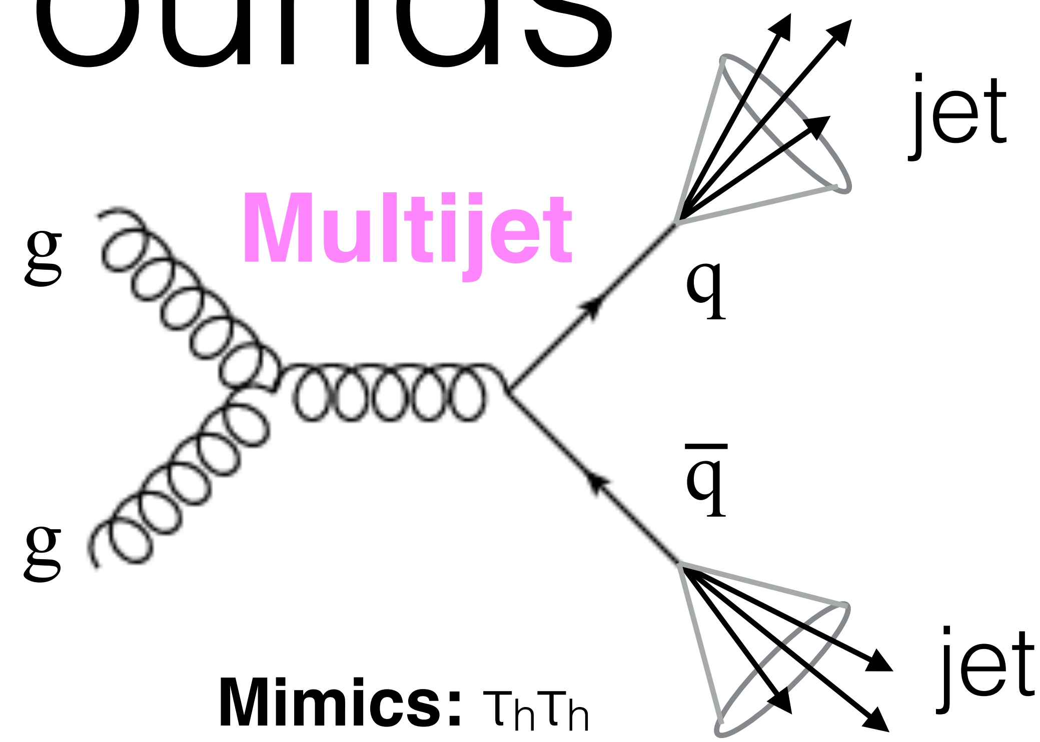
$Z/\gamma^* \to \tau\tau$



Irreducible

Estimated using $Z \to \mu\mu$ embedding

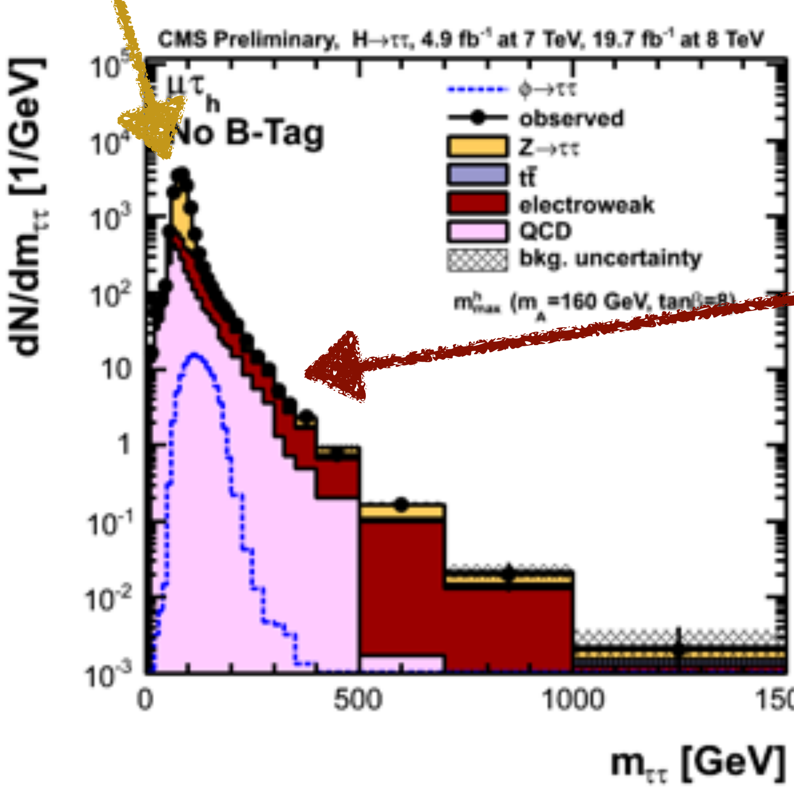
Multijet

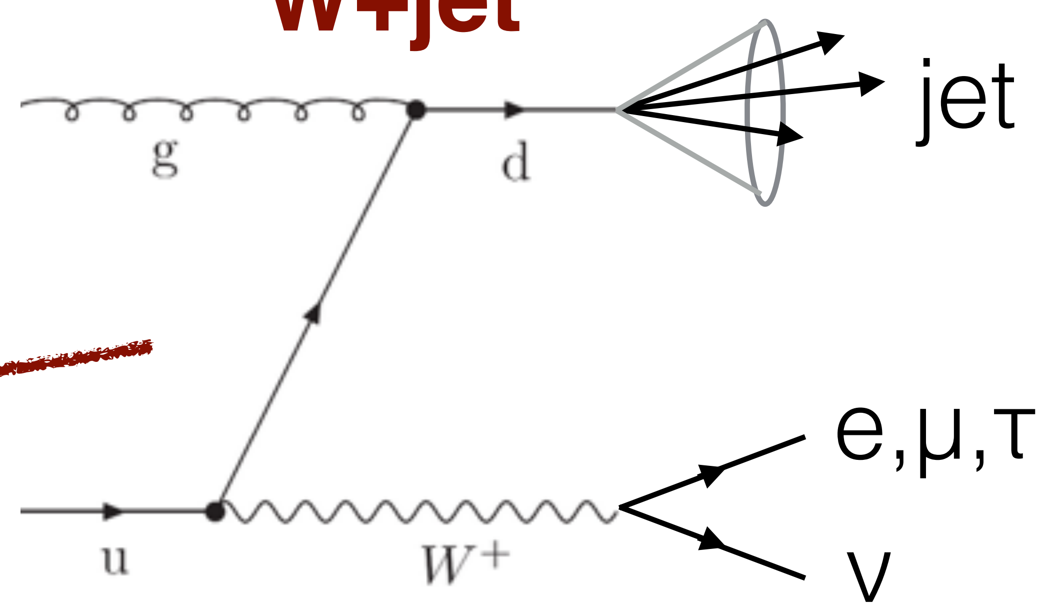


Mimics: $\tau_h\tau_h$

Estimated using tau ID fake-factor

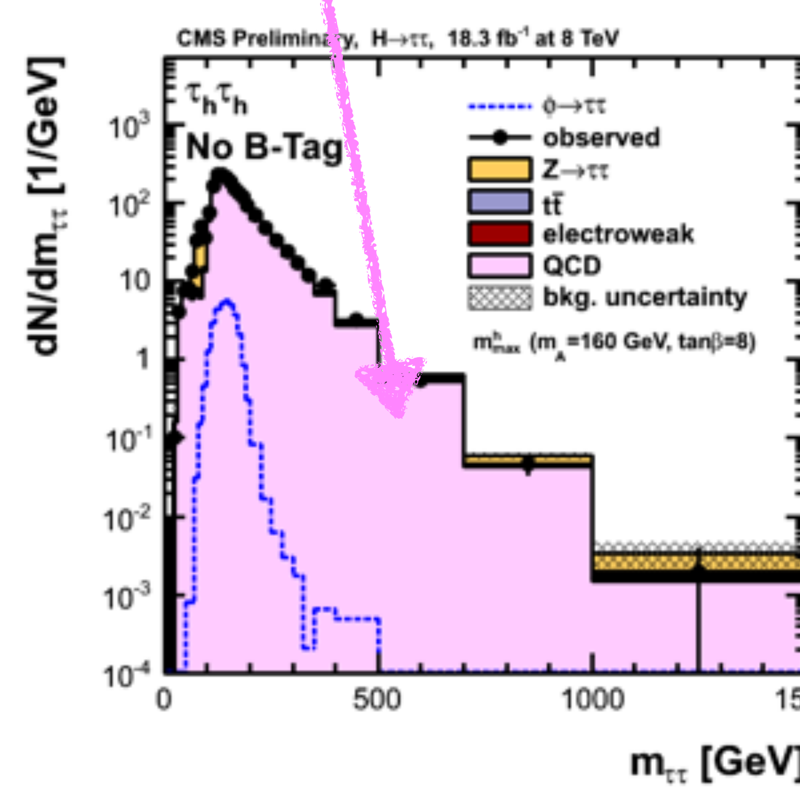
W+jet



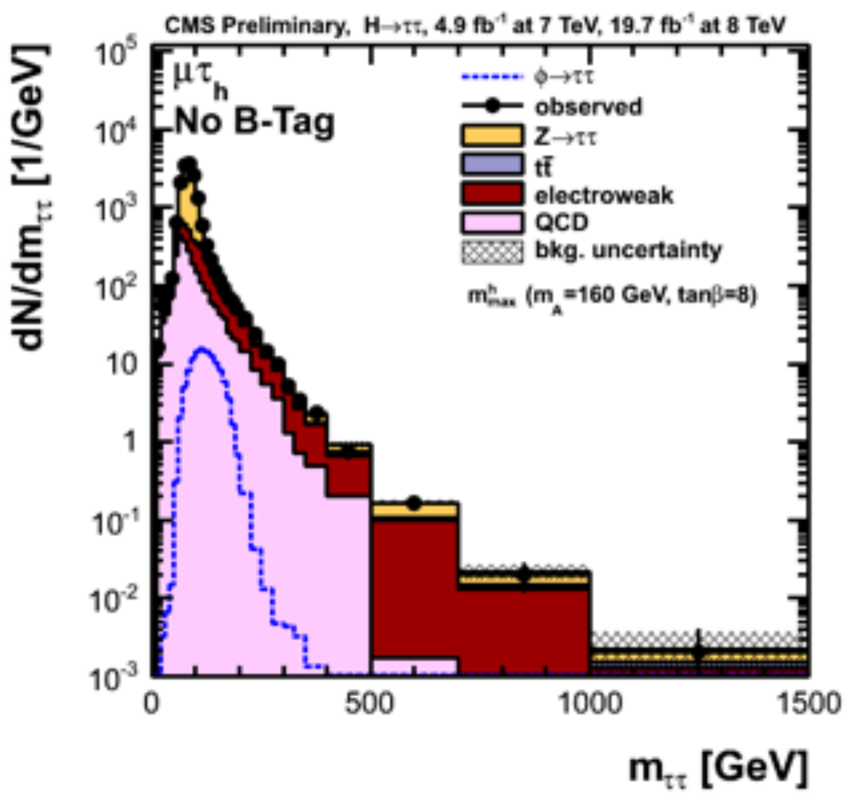


Mimics: $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

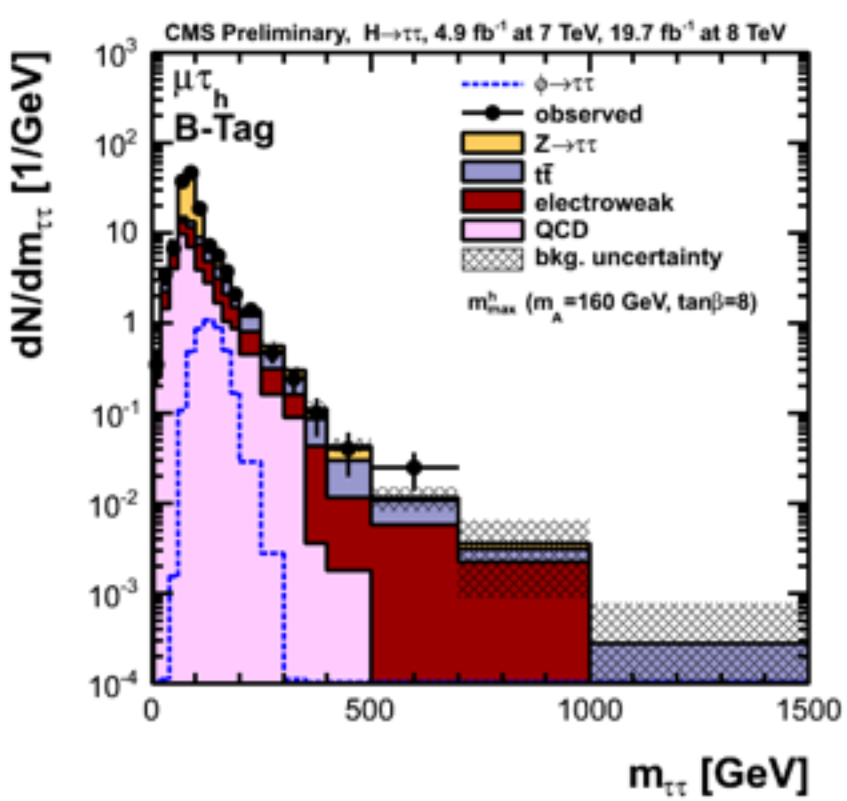
Estimated using MC + data norm.



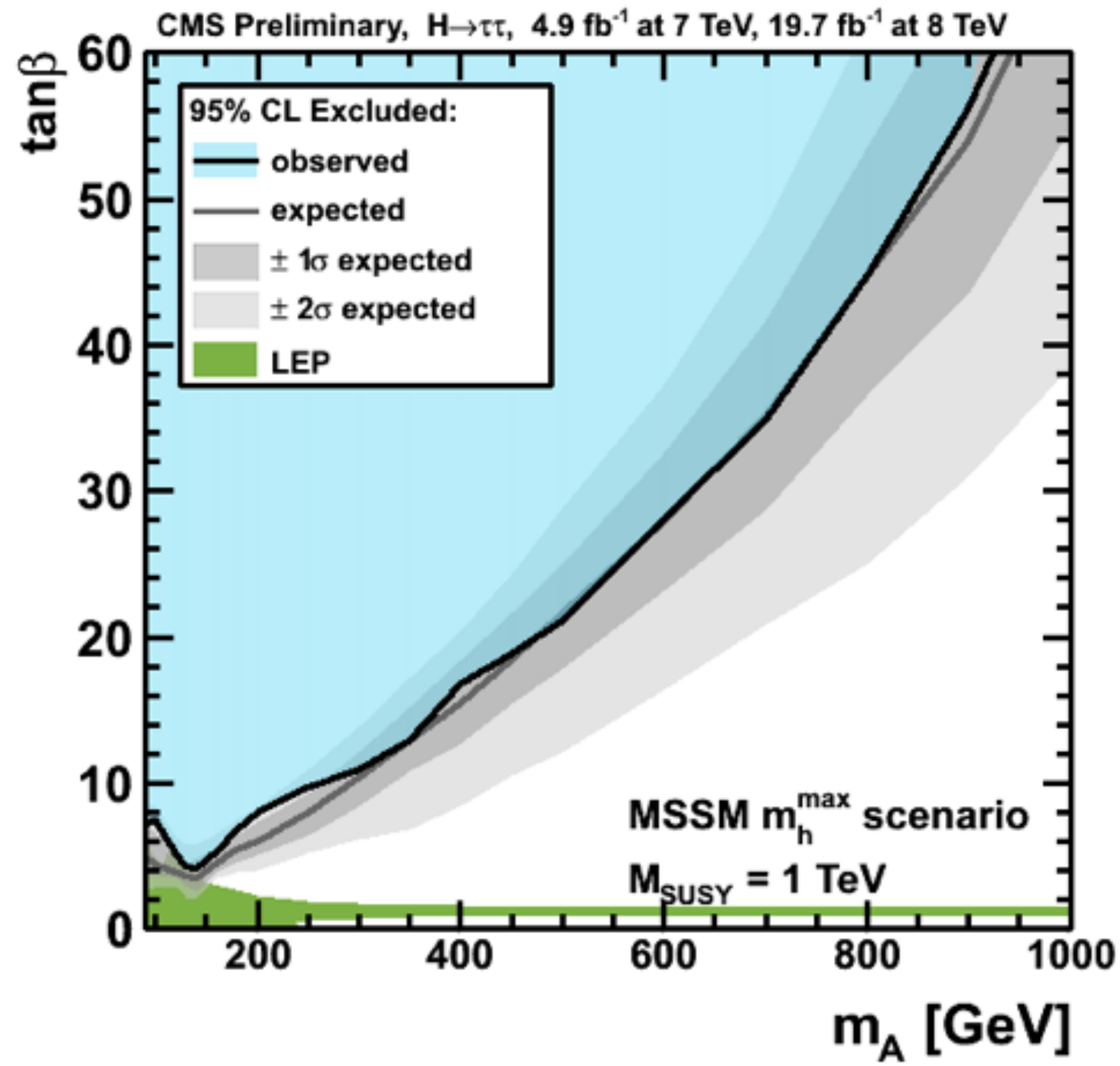
CMS: Results



CMS Preliminary, H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
μτh
No B-Tag
φ→ττ
observed
Z→ττ
tt̄
electroweak
QCD
bkg. uncertainty
dN/dmττ [1/GeV]
mττ [GeV]

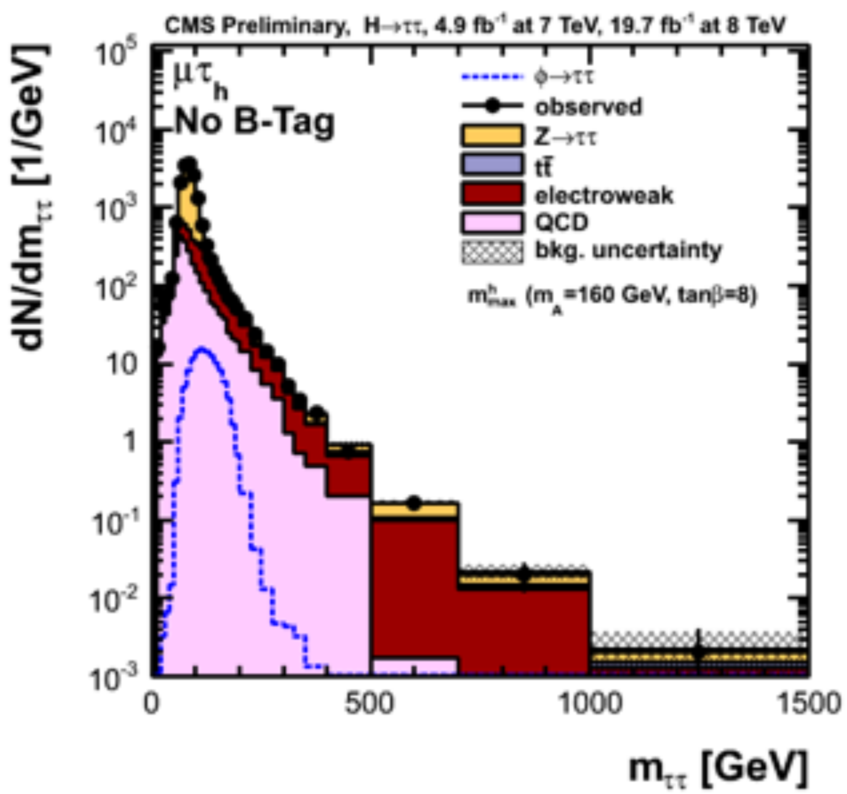


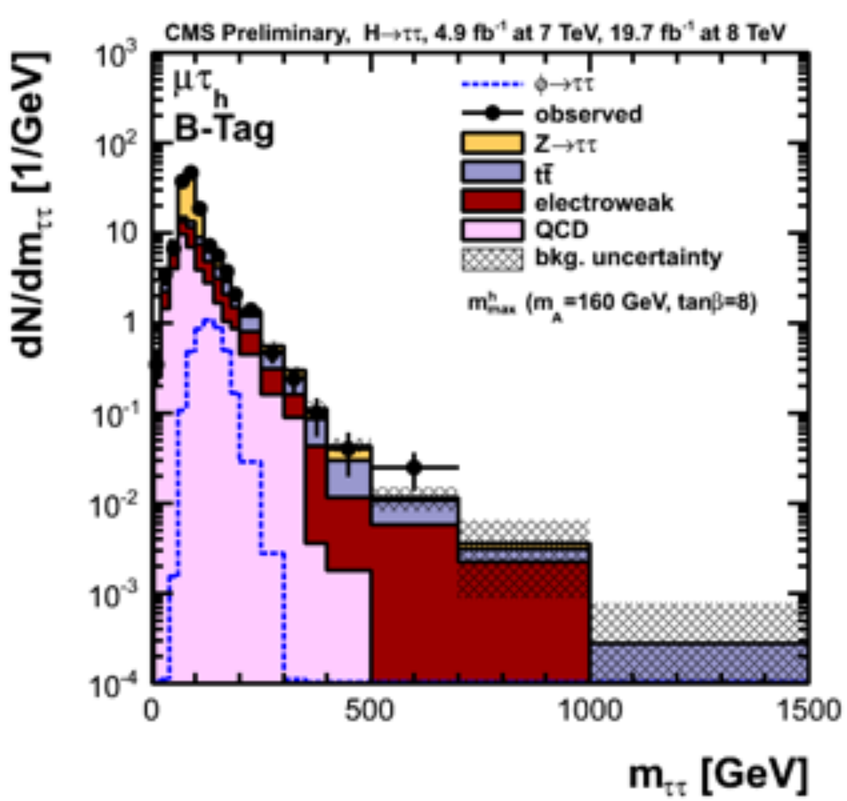
CMS Preliminary, H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
μτh
B-Tag
φ→ττ
observed
Z→ττ
tt̄
electroweak
QCD
bkg. uncertainty
dN/dmττ [1/GeV]
mττ [GeV]

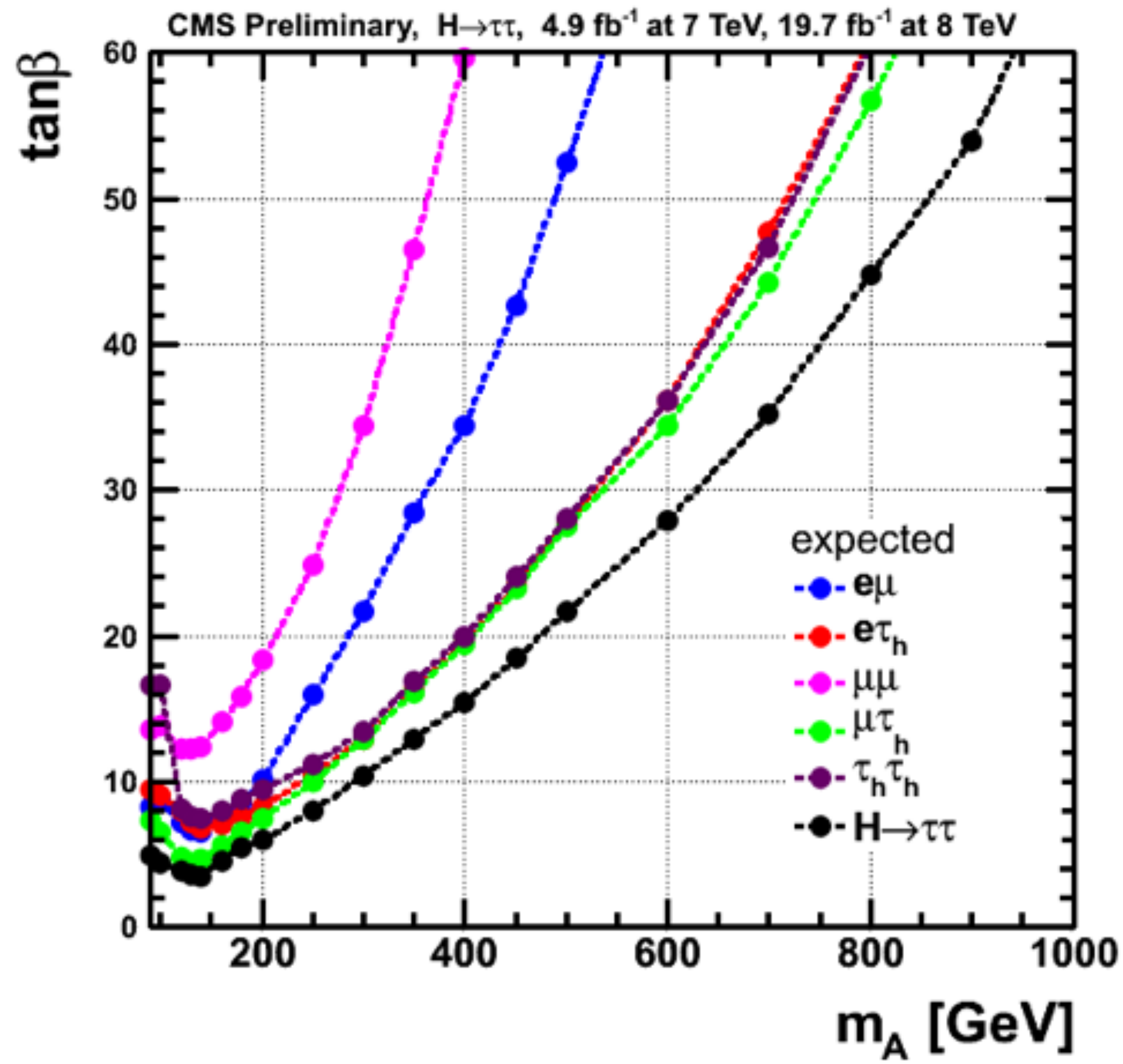


CMS Preliminary, H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
95% CL Excluded:
observed
expected
± 1σ expected
± 2σ expected
LEP
MSSM mhmax scenario
MSUSY = 1 TeV
tanβ
mA [GeV]

CMS: Results


CMS Preliminary, H→ττ, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
μτ_h
No B-Tag
φ→ττ
observed
Z→ττ
tt̄
electroweak
QCD
bkg. uncertainty
m_max^h (m_A=160 GeV, tanβ=8)
dN/dm_ττ [1/GeV]
m_ττ [GeV]

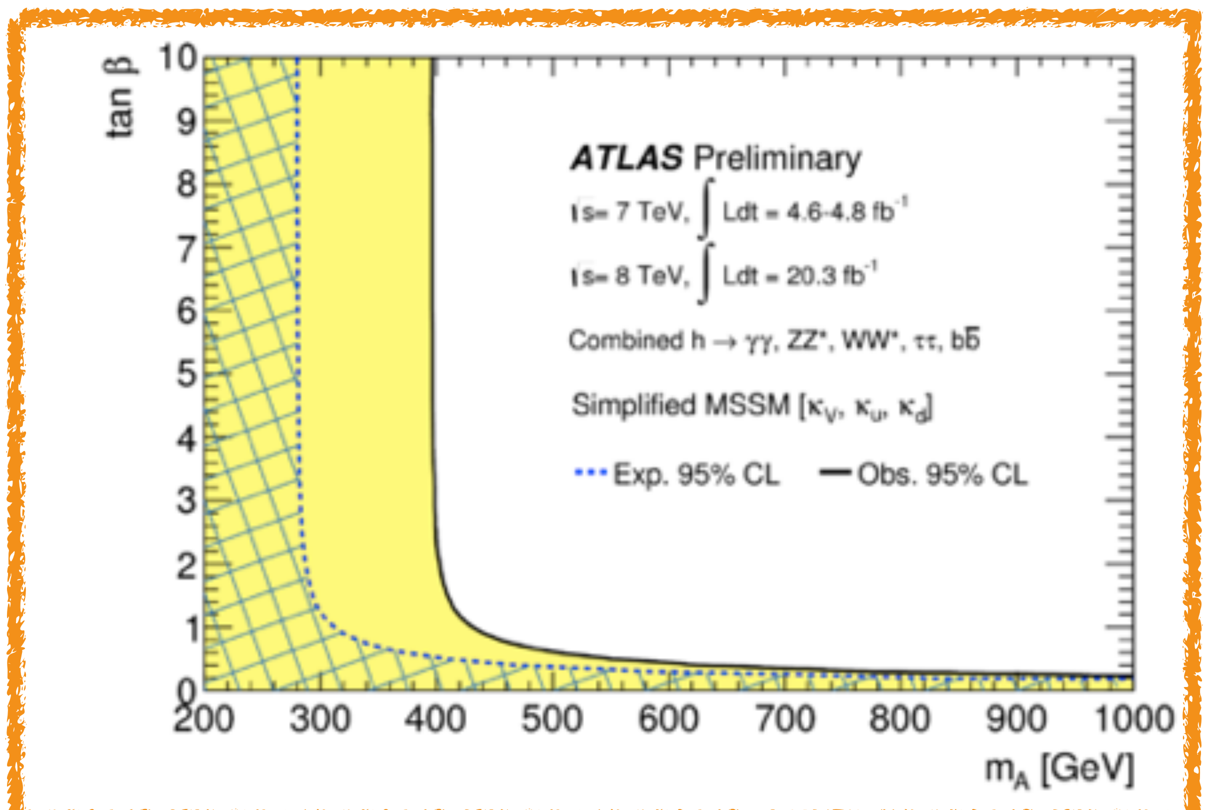

CMS Preliminary, H→ττ, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
μτ_h
B-Tag
φ→ττ
observed
Z→ττ
tt̄
electroweak
QCD
bkg. uncertainty
m_max^h (m_A=160 GeV, tanβ=8)
dN/dm_ττ [1/GeV]
m_ττ [GeV]

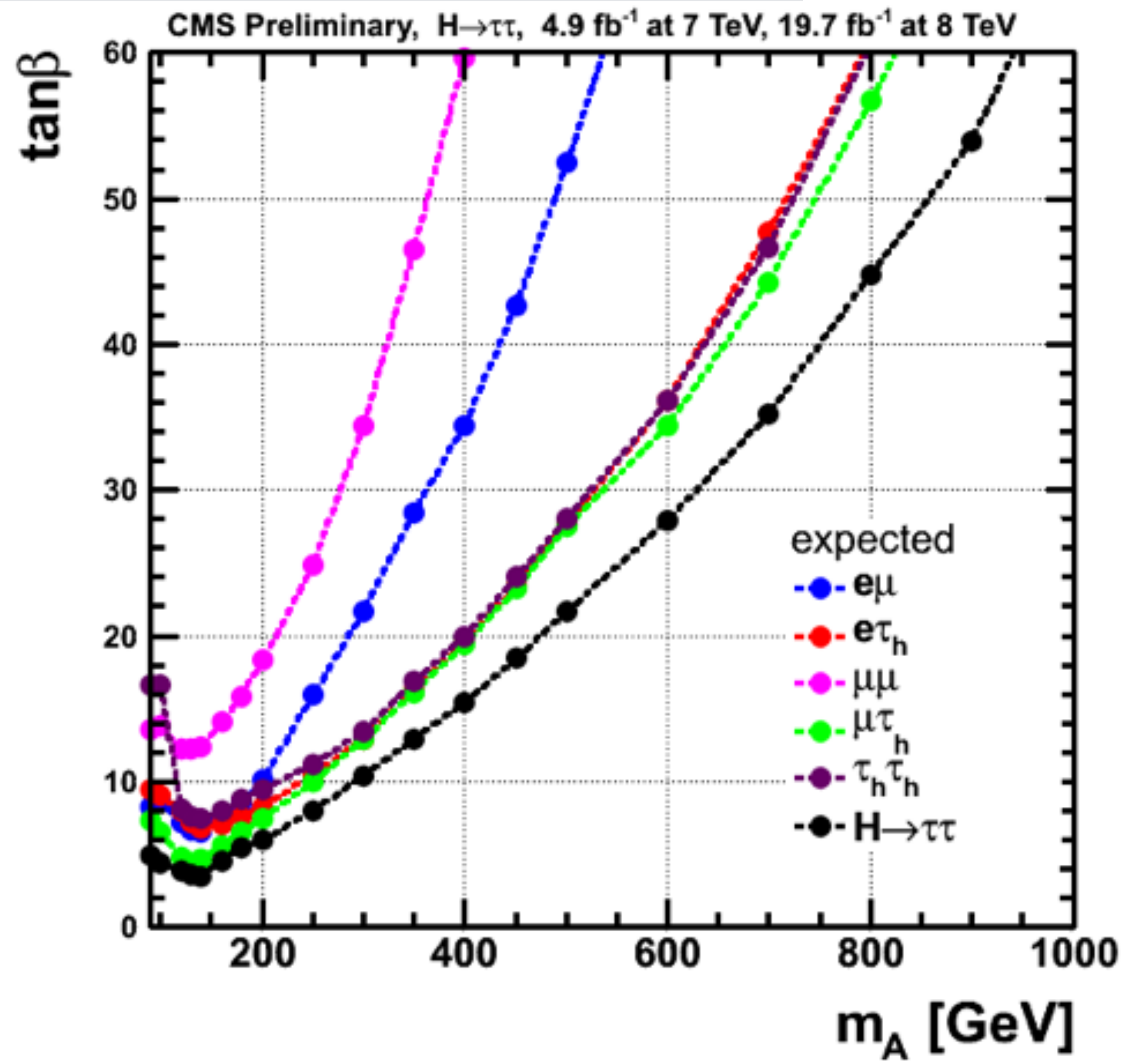

CMS Preliminary, H→ττ, 4.9 fb⁻¹ at 7 TeV, 19.7 fb⁻¹ at 8 TeV
tanβ
expected
eμ
eτ_h
μμ
μτ_h
τ_hτ_h
H→ττ
m_A [GeV]

ATLAS: indirect limits

Coll.	Channel	Dataset	Cite
ATLAS	γγ, ZZ*, WW*, ττ, bb	25fb-1(7+8TeV)	ATLAS-CONF-2014-010
CMS	γγ, ZZ*, WW*, ττ, bb	10fb-1(7+8TeV)	JHEP06(2013)081

- Fit of simplified MSSM to measured H→γγ, ZZ*, WW*, ττ, bb rates.

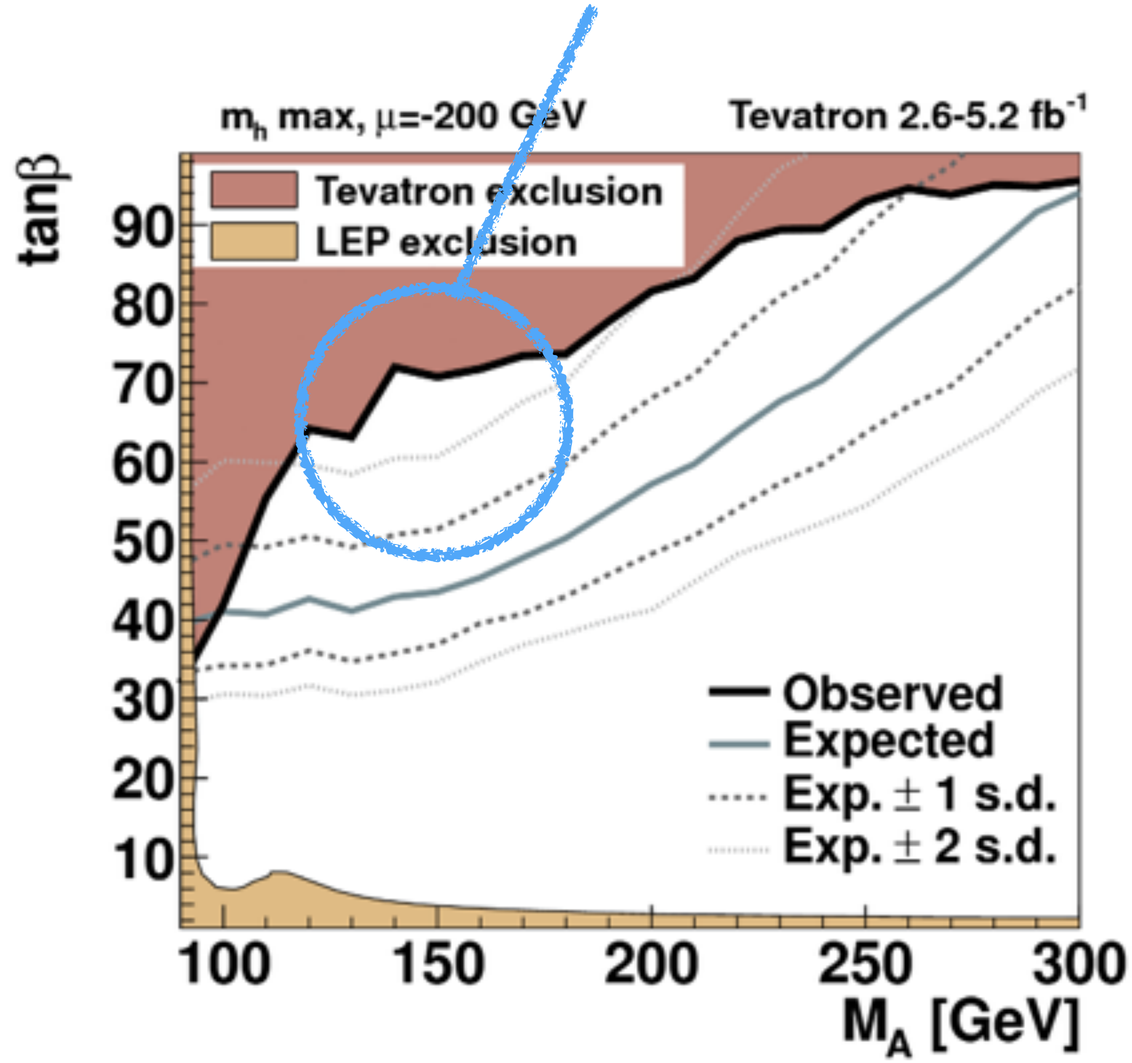




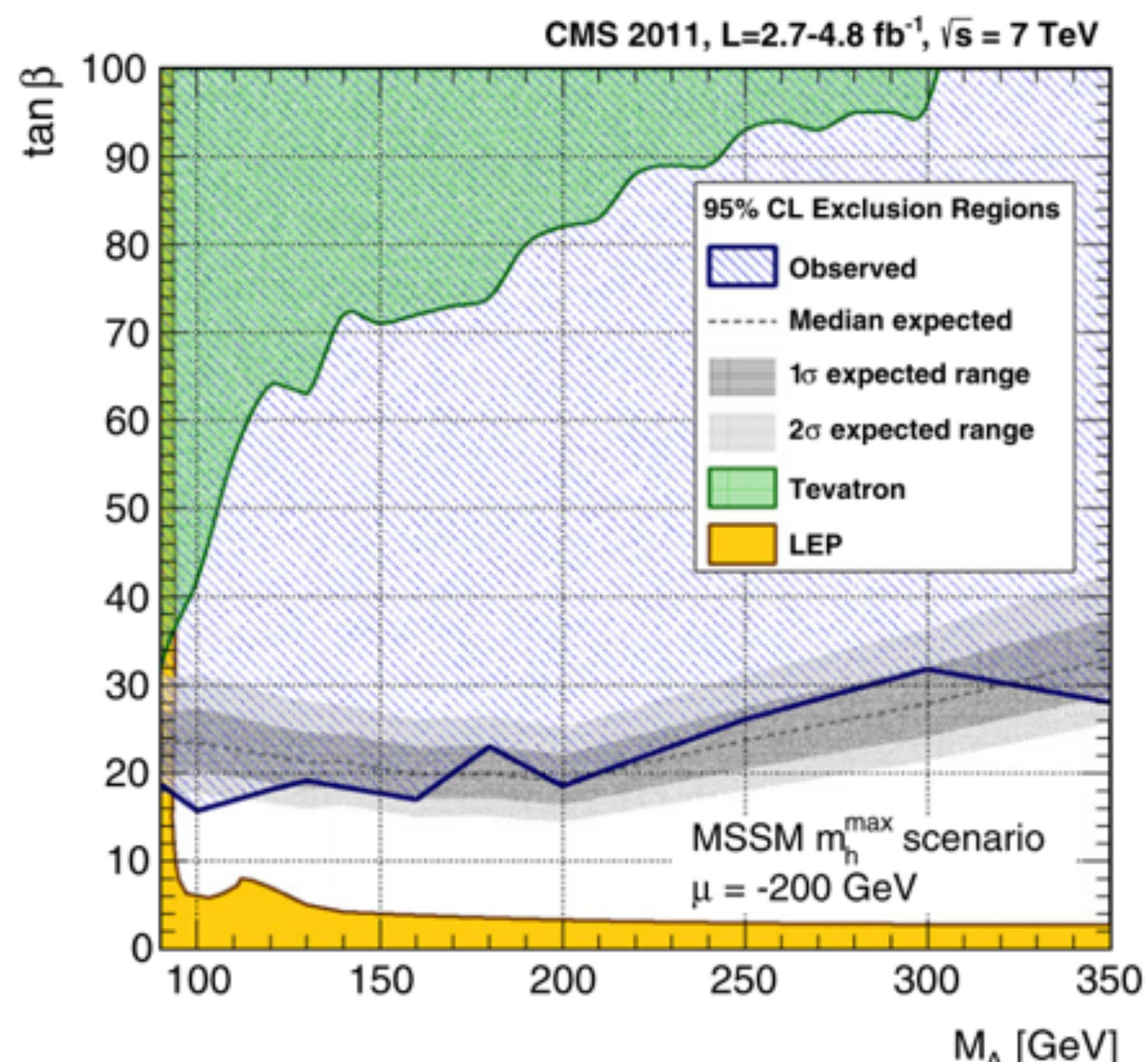
D0+CDF/CMS: bA/H/h→bbb

- Search for bump in mass distribution of leading b-jet pair

Tevatron ~2σ excess

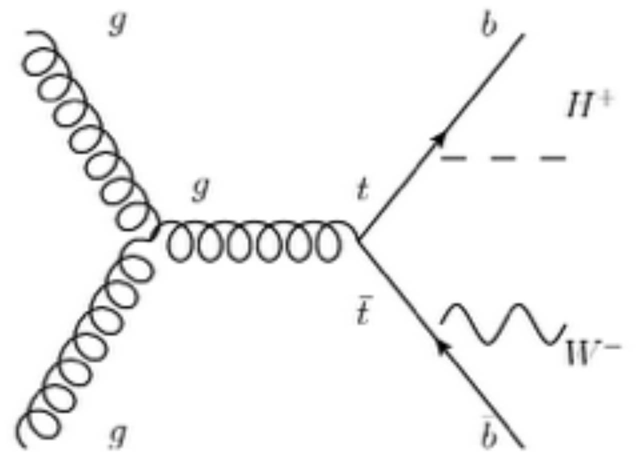


Excluded by CMS

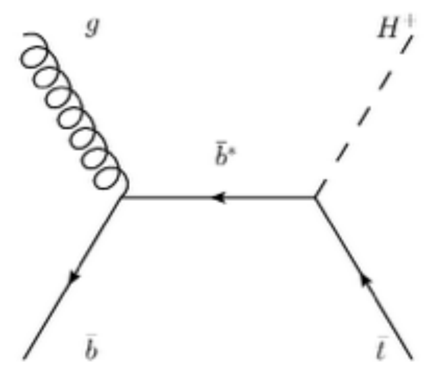


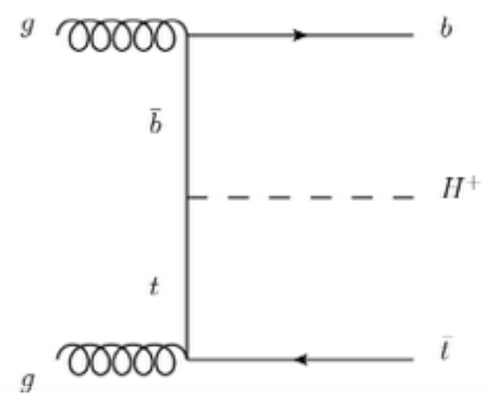
Charged Higgs

- Light ($m_{H+}<m_t$):
  - **tanβ>3: B(H$^+$→τν)~90%**
  - tanβ<1: B(H$^+$→cs)~70%



- Heavy ($m_{H+}>m_t$):
  - H$^\pm$→tb dominant
  - H$^\pm$→τν can be sizeable

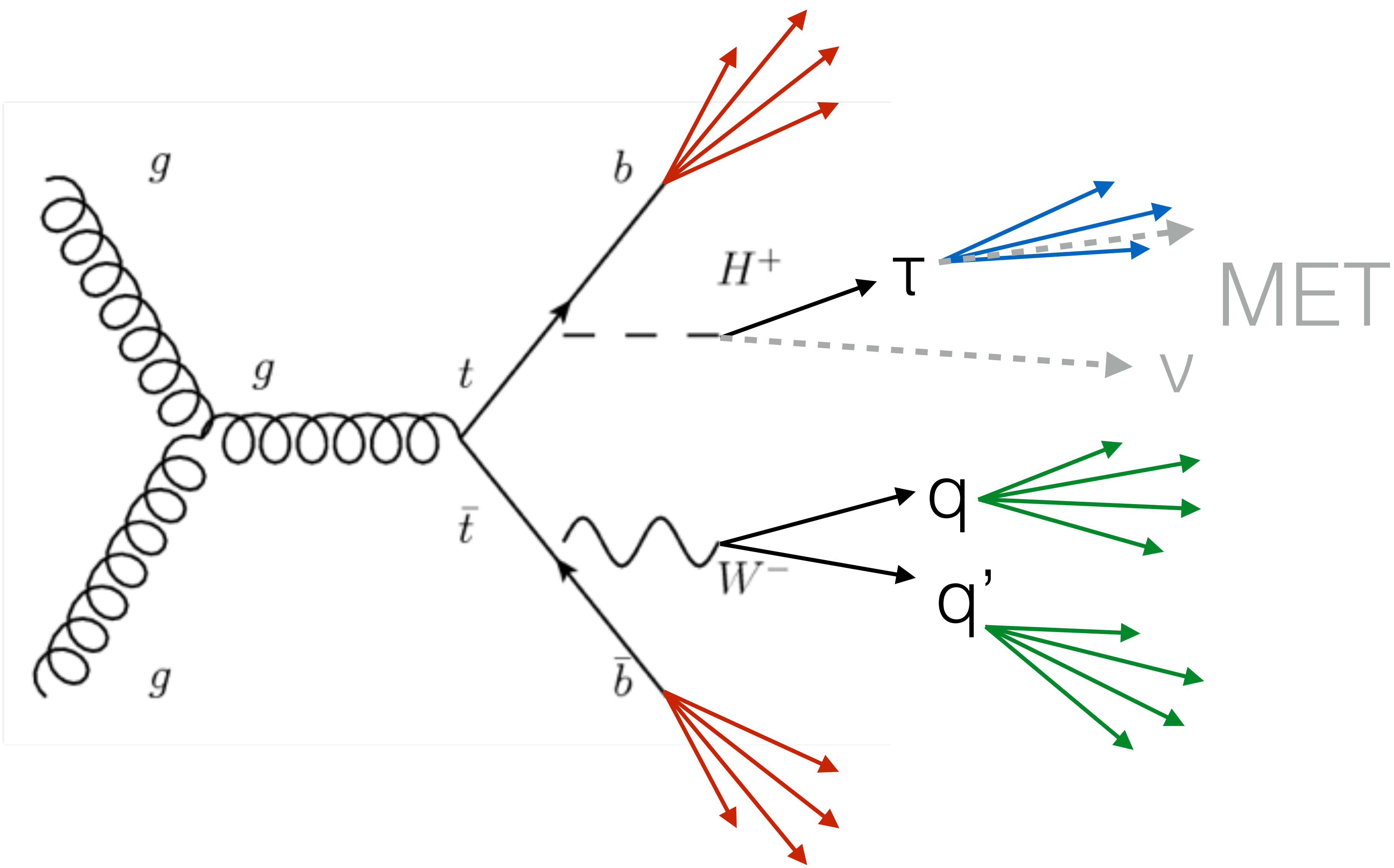




Coll.	Channel	Dataset	Cite
ATLAS	**τν+jets**	**20fb-1(8TeV)**	**ATLAS-CONF-2013-090**
ATLAS	τν+lep	5fb-1(7TeV)	JHEP03(2013)076
ATLAS	cs	5fb-1(7TeV)	EPJC 73 6 (2013) 2465
CMS	τν+lep/jet	5fb-1(7TeV)	CMS-PAS-HIG-12-052
CDF	cs	2fb-1(2TeV)	PRL 103, 101803 (2009)
D0	tb	1fb-1(2TeV)	PRL 102, 191802 (2009)

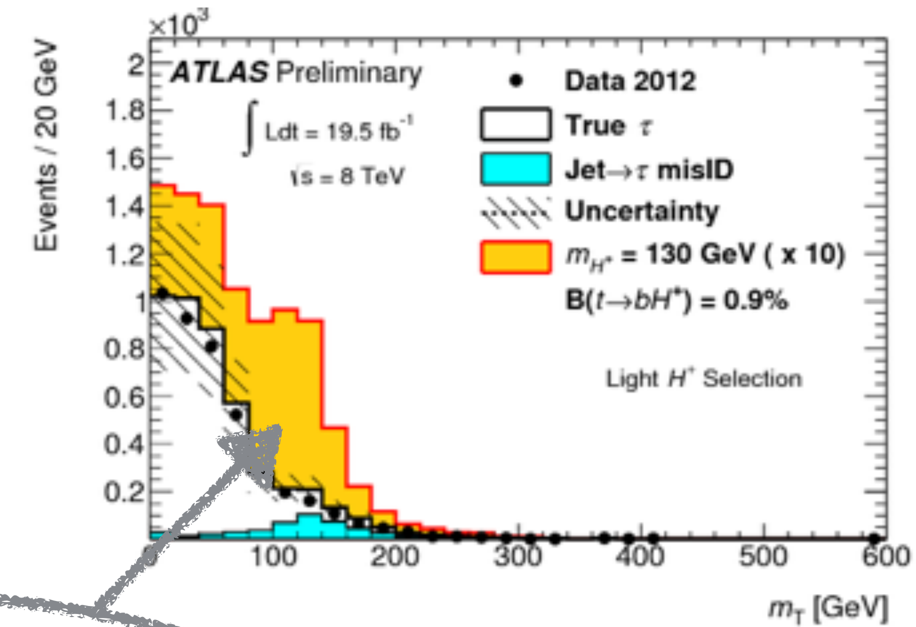
ATLAS: H+→τν+jets

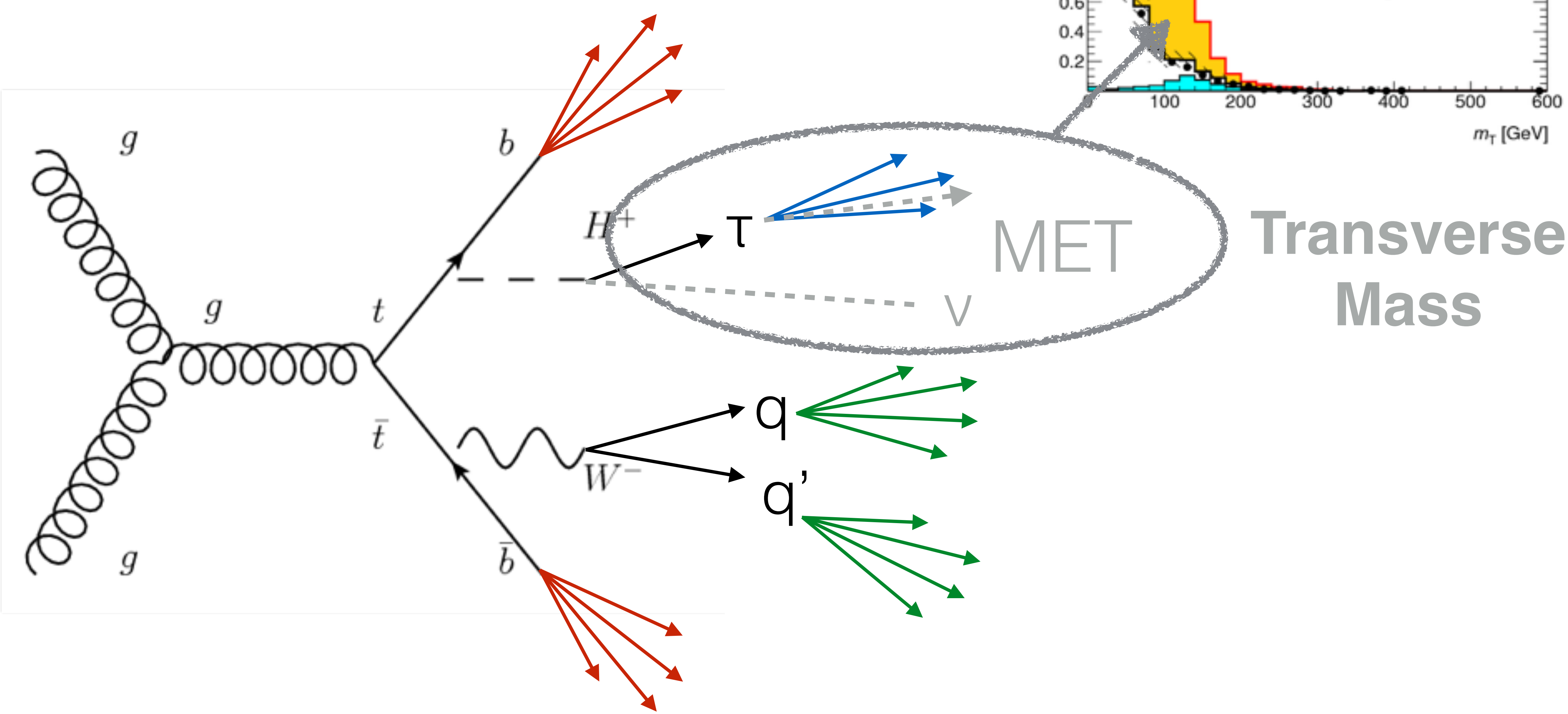
- 1τ, ≥4 jets (≥1 b-jet), no leptons, large MET



ATLAS: H+→τν+jets

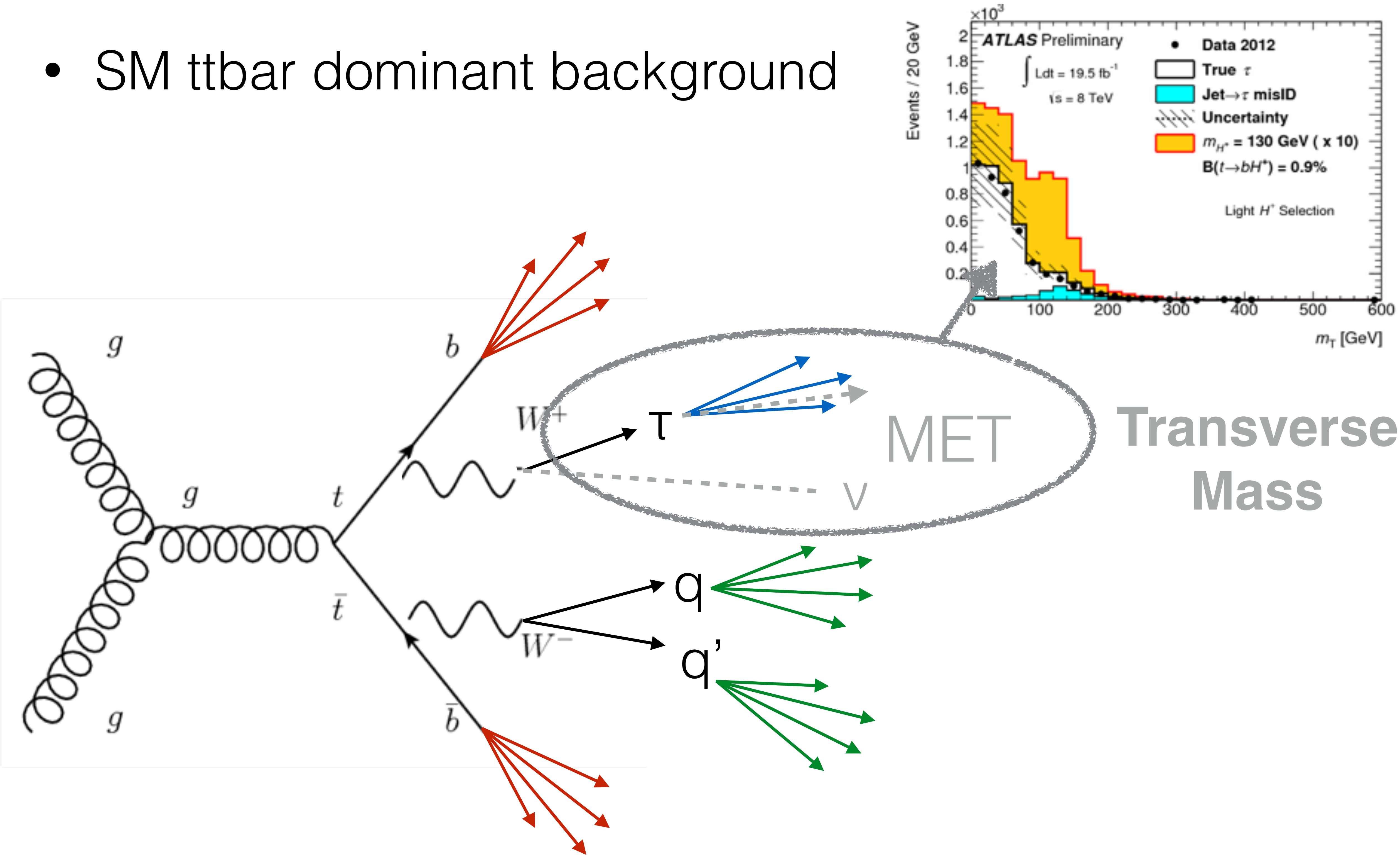
- Look for excess in τ-MET transverse mass distribution





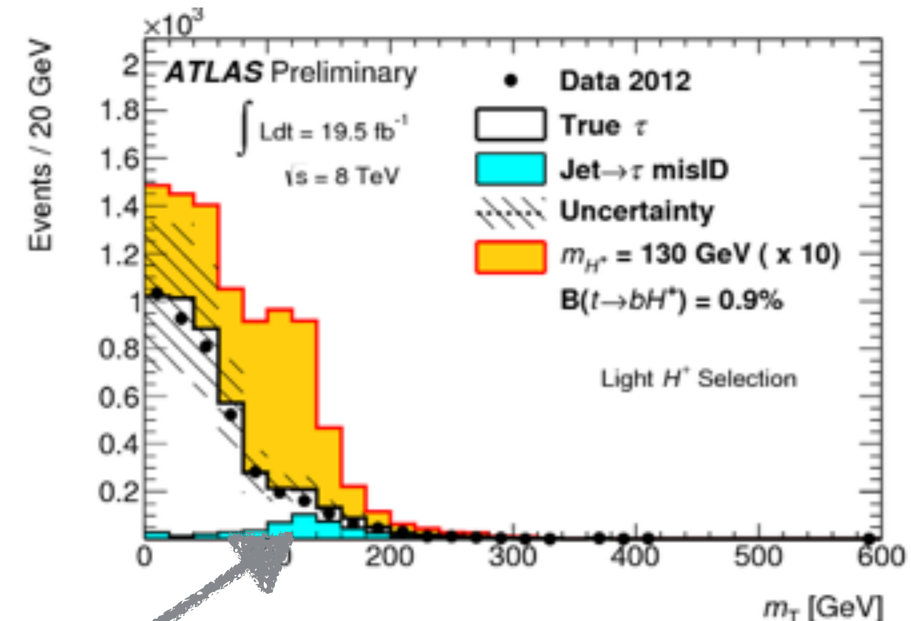
ATLAS: True τ background

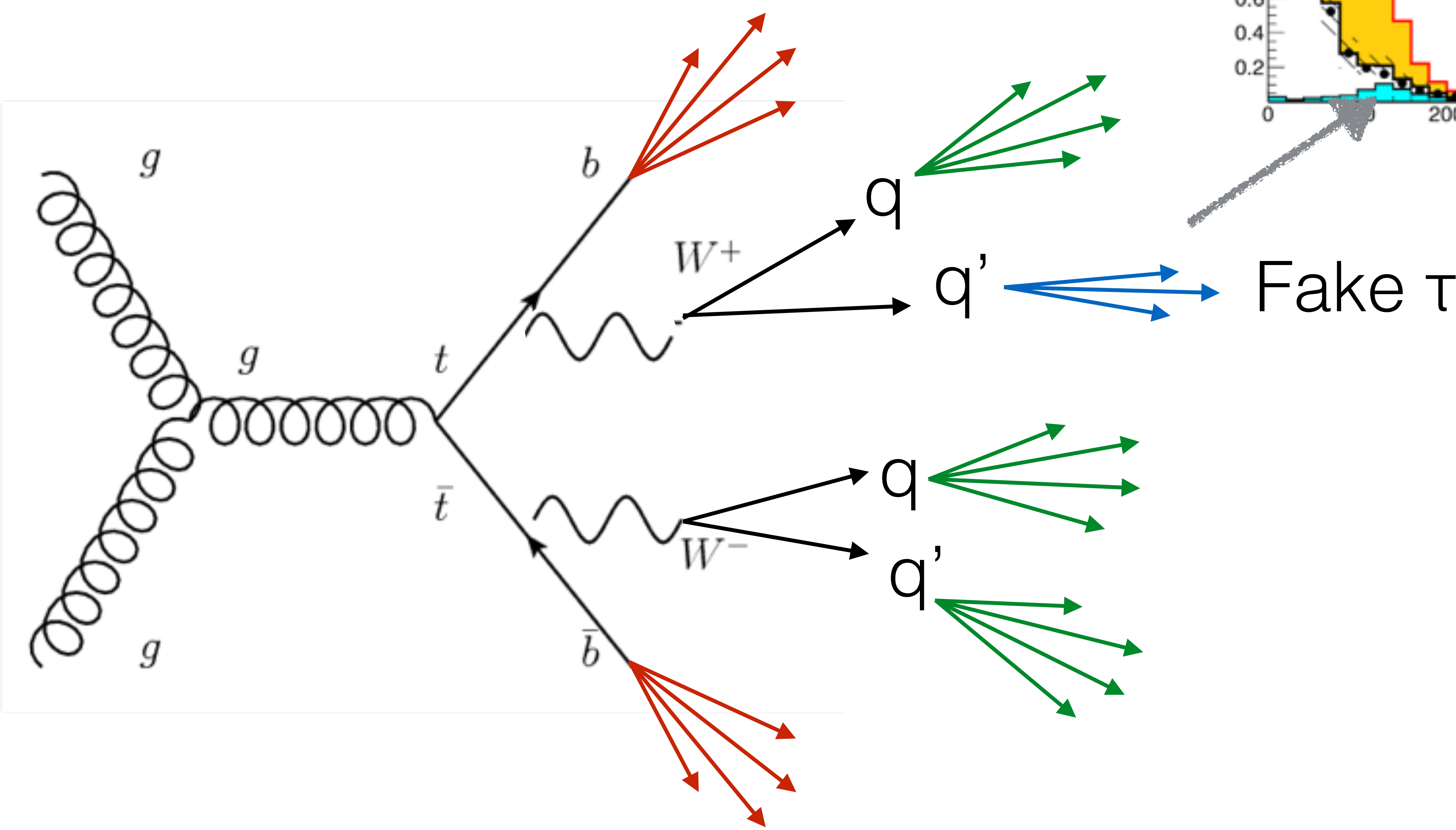
- SM ttbar dominant background



ATLAS: Fake τ background

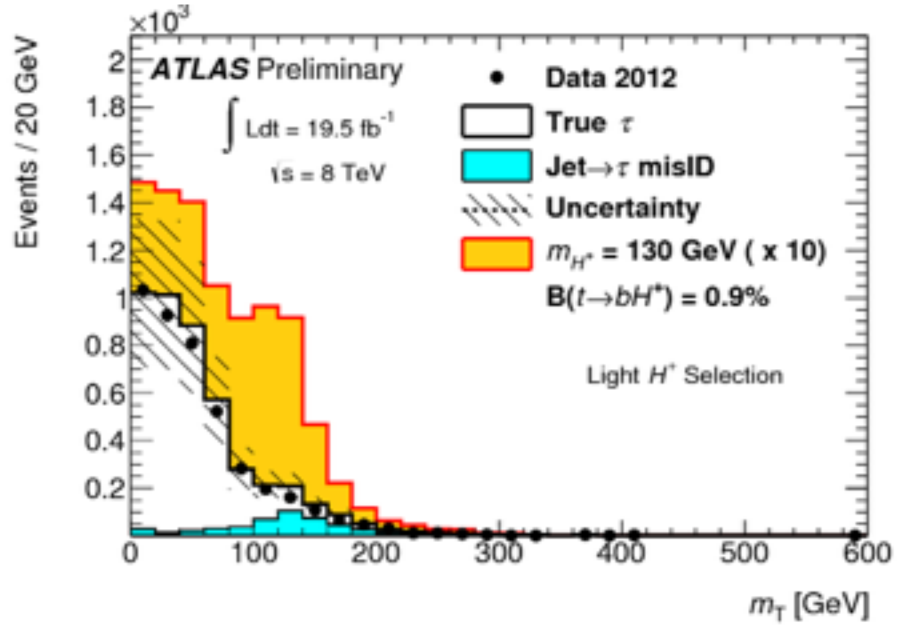
- Estimate by scaling data in loose τ ID control region by loose→tight transfer factor

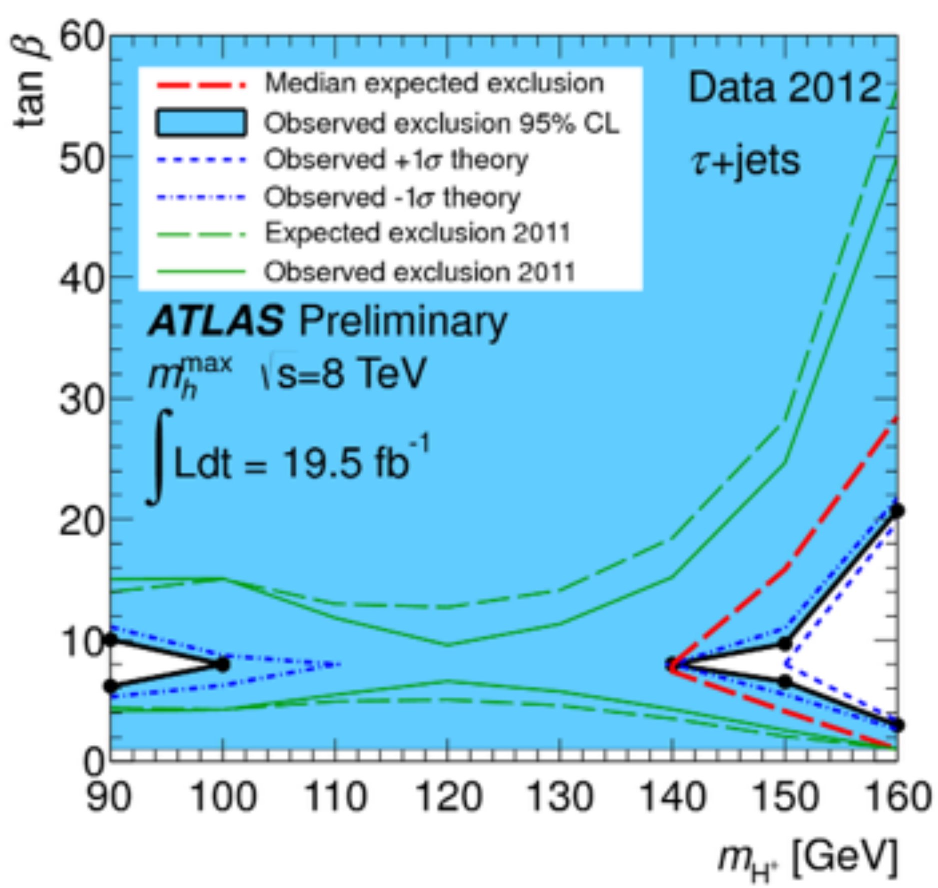




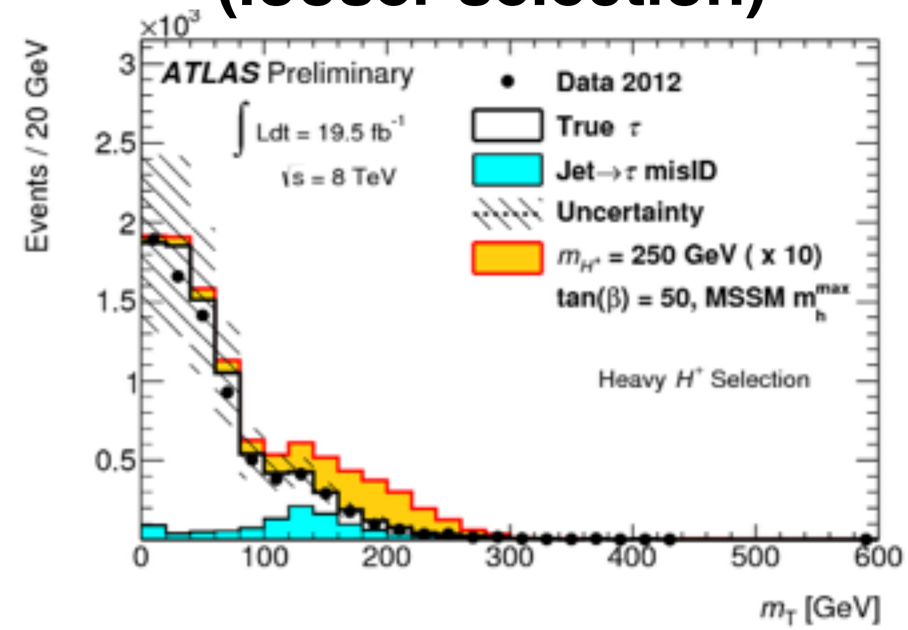
ATLAS: Results

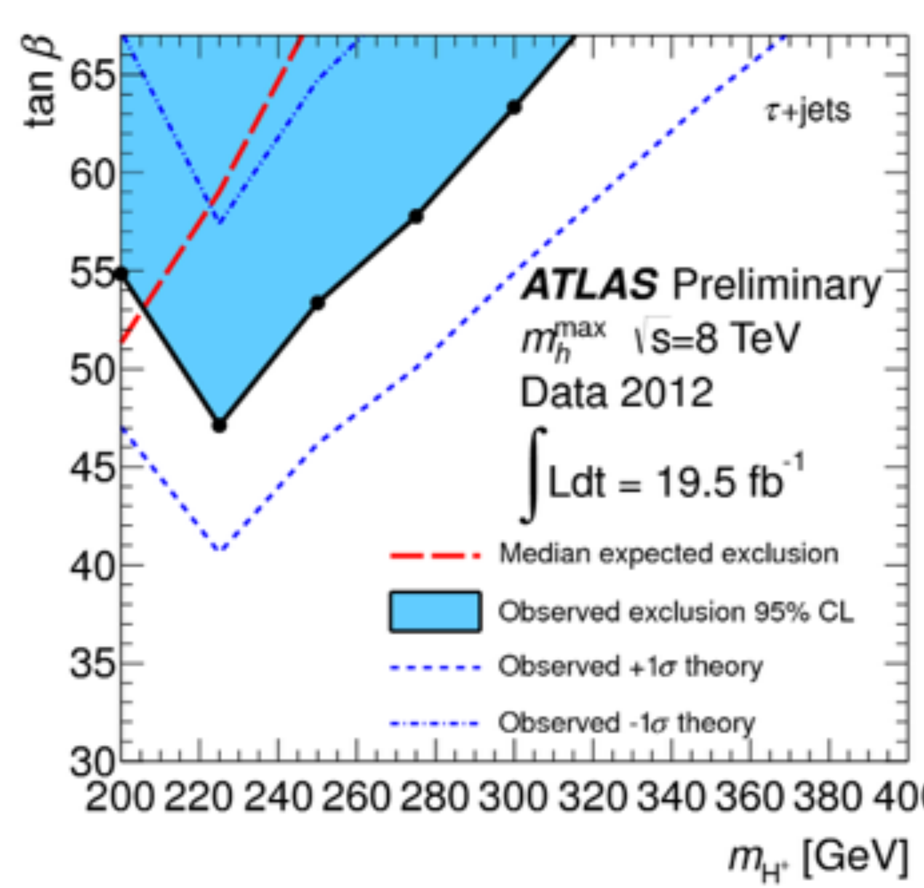
Low mass ($m_{H+} < m_t$)





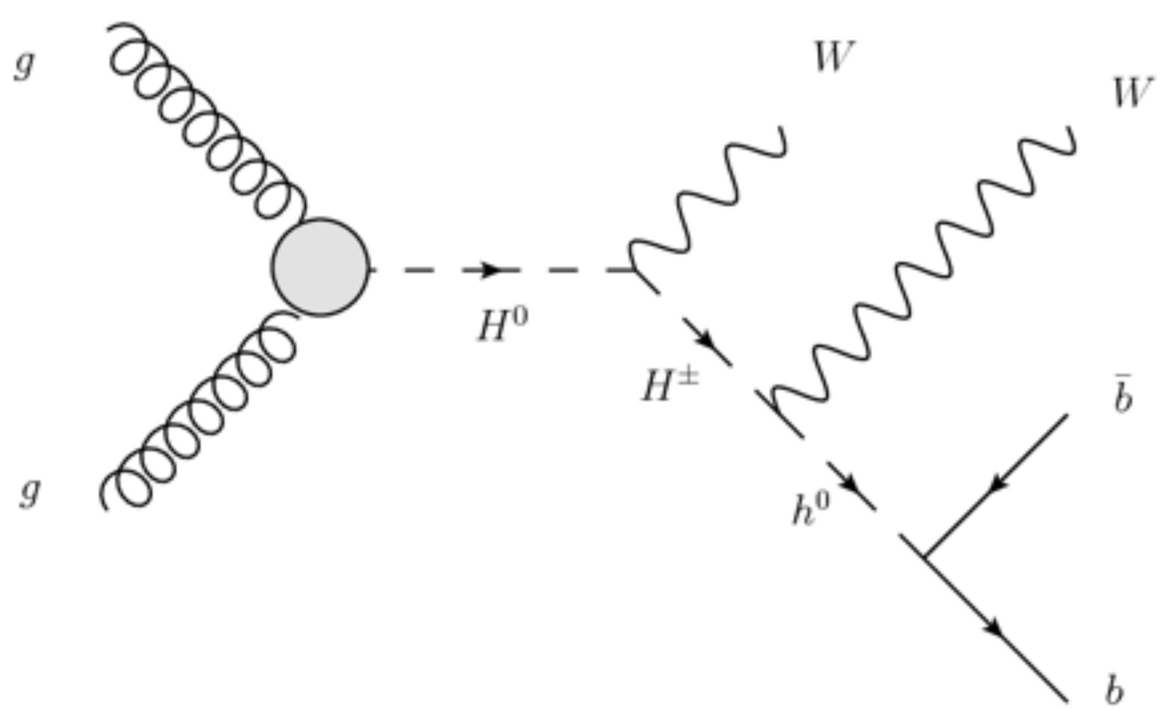
High mass ($m_{H+} > m_t$)
(looser selection)



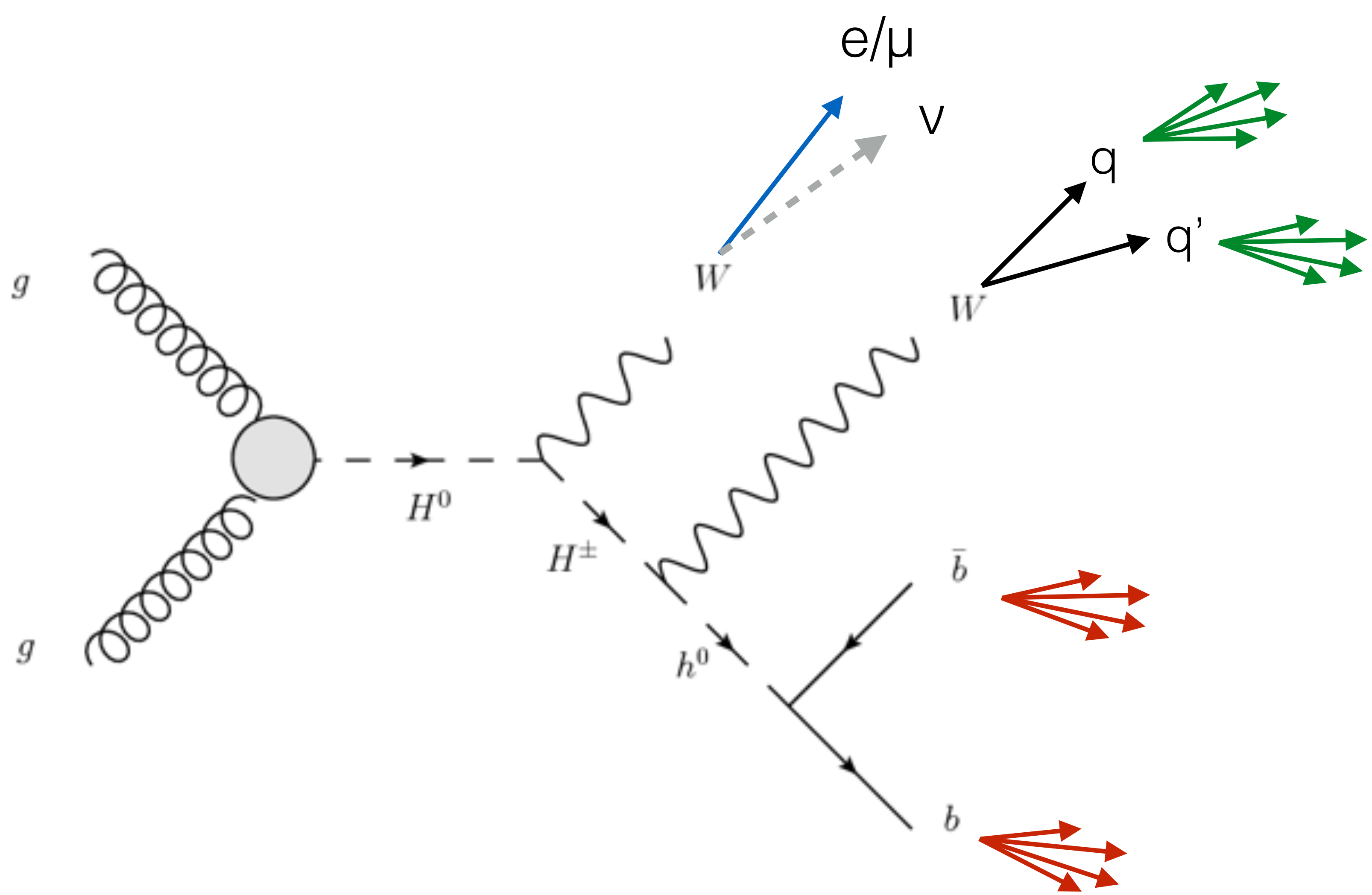


ATLAS: Higgs Cascade

Coll.	Dataset	Cite
ATLAS	**20fb-1(8TeV)**	**PRD 89, 032002 (2014)**
CDF	9fb-1(2TeV)	PRL 110, 121801 (2013)



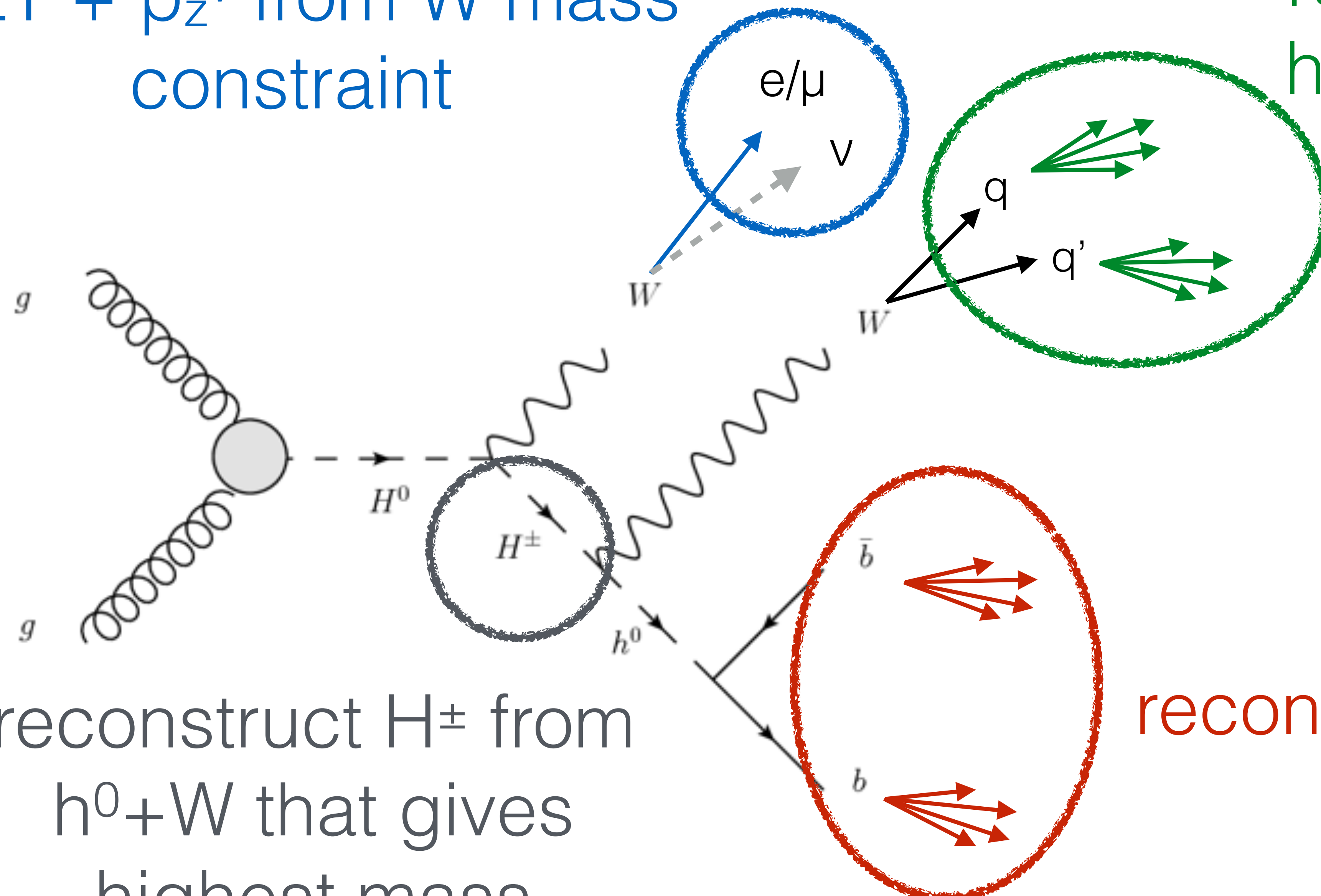
ATLAS: Higgs Cascade



ATLAS: Higgs Cascade

reconstruct leptonic W, MET + p_z^{ν} from W mass constraint

reconstruct hadronic W

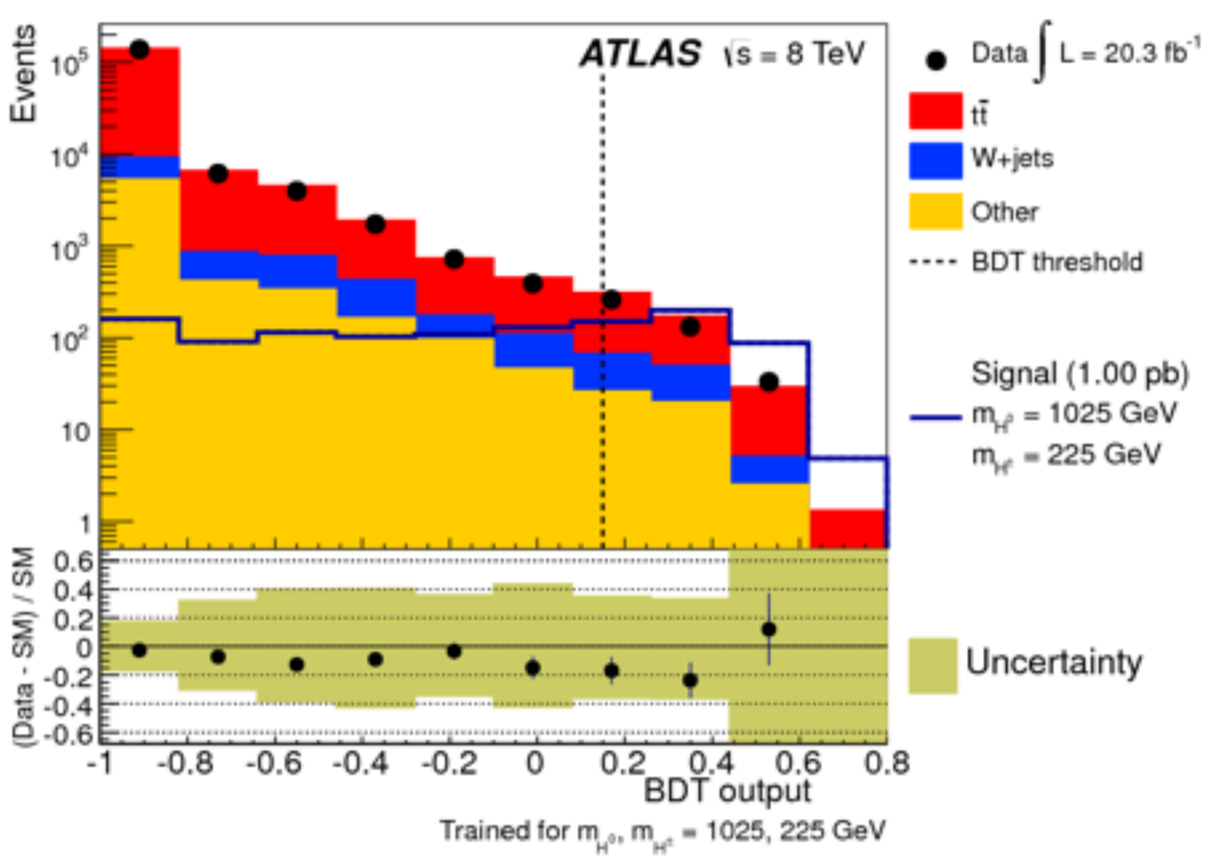


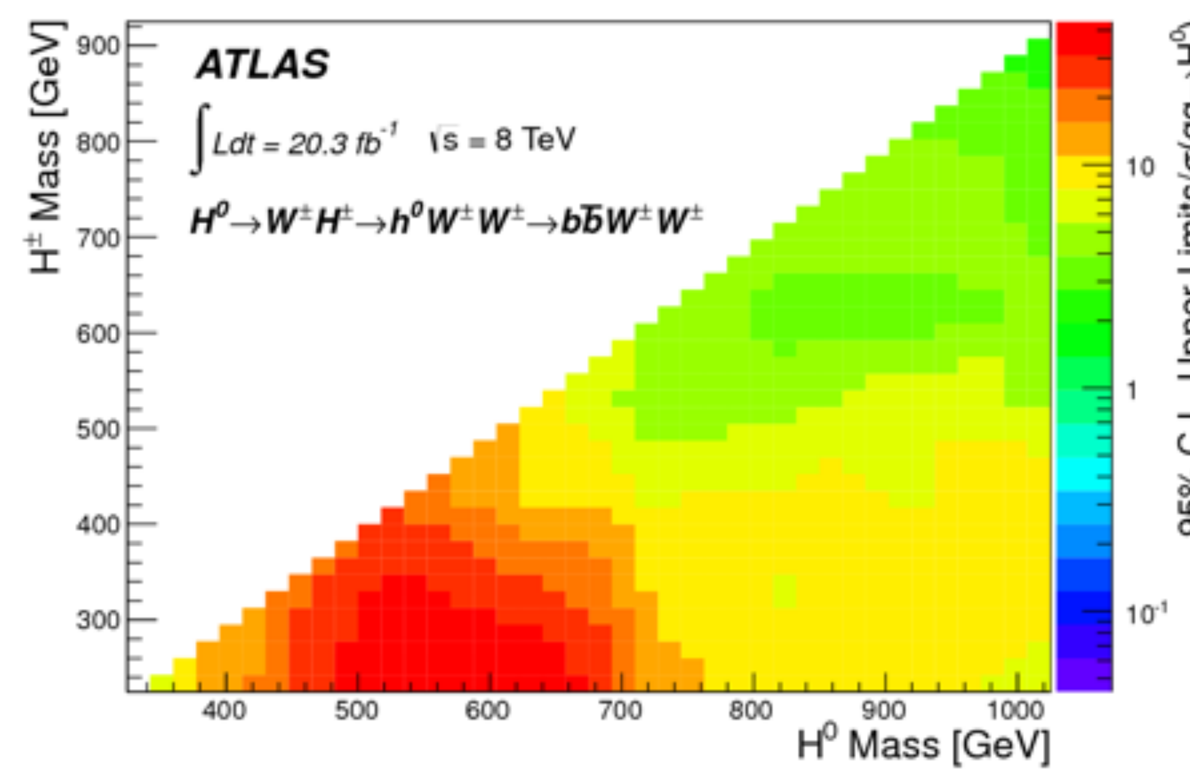
reconstruct h^0

reconstruct $H^\pm$ from h^0+W that gives highest mass

ATLAS: Higgs Cascade

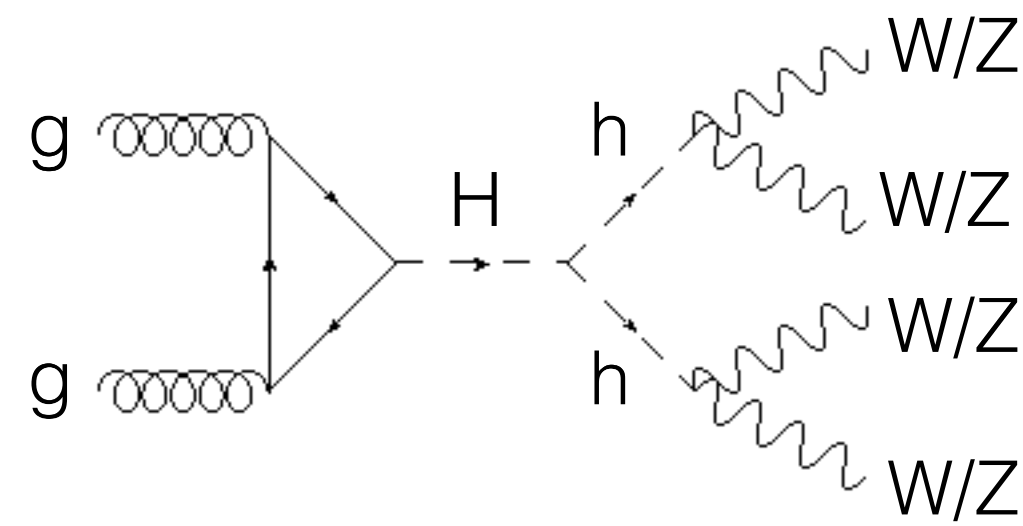
- BDT to discriminate against ttbar using event kinematics
- Dominant Systematics: b-tag eff., jet energy, ttbar norm.
- Almost sensitive to SM-strength production

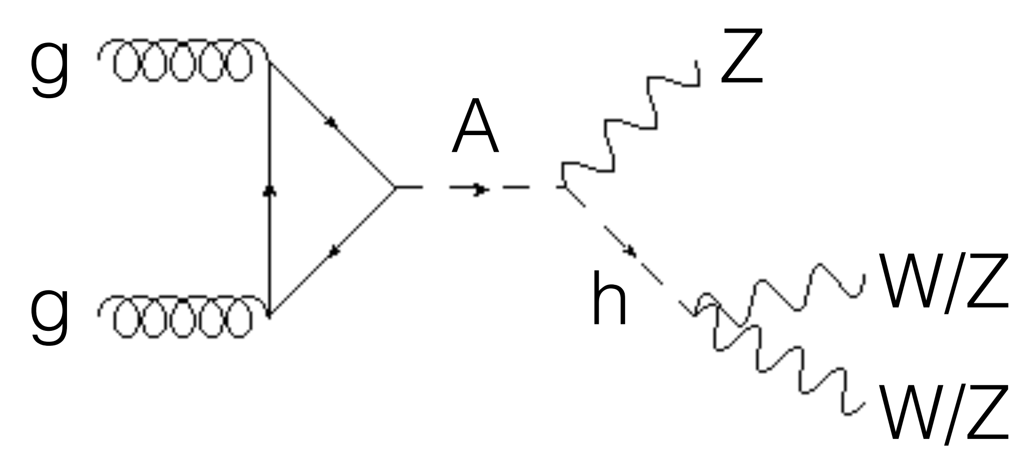




CMS: H→hh / A→Zh

- Assume m_h=126 GeV
- If m_H >2m_h, then H→hh possible
- If 2m_h<m_A<2m_t, A→Zh dominant
- Search for:
  - **Multileptons: ≥3 leptons (≤1 τ)** (estimate fake leptons/conversions with lepton fake-factors, others MC +corrections)
  - **Diphotons: 2γ + 1/2 leptons** ($m_{\gamma\gamma}$ side-band fit)
  - Counting experiment in **categories:** number of τs, b-jets, OSSF pairs, on/off Z, MET

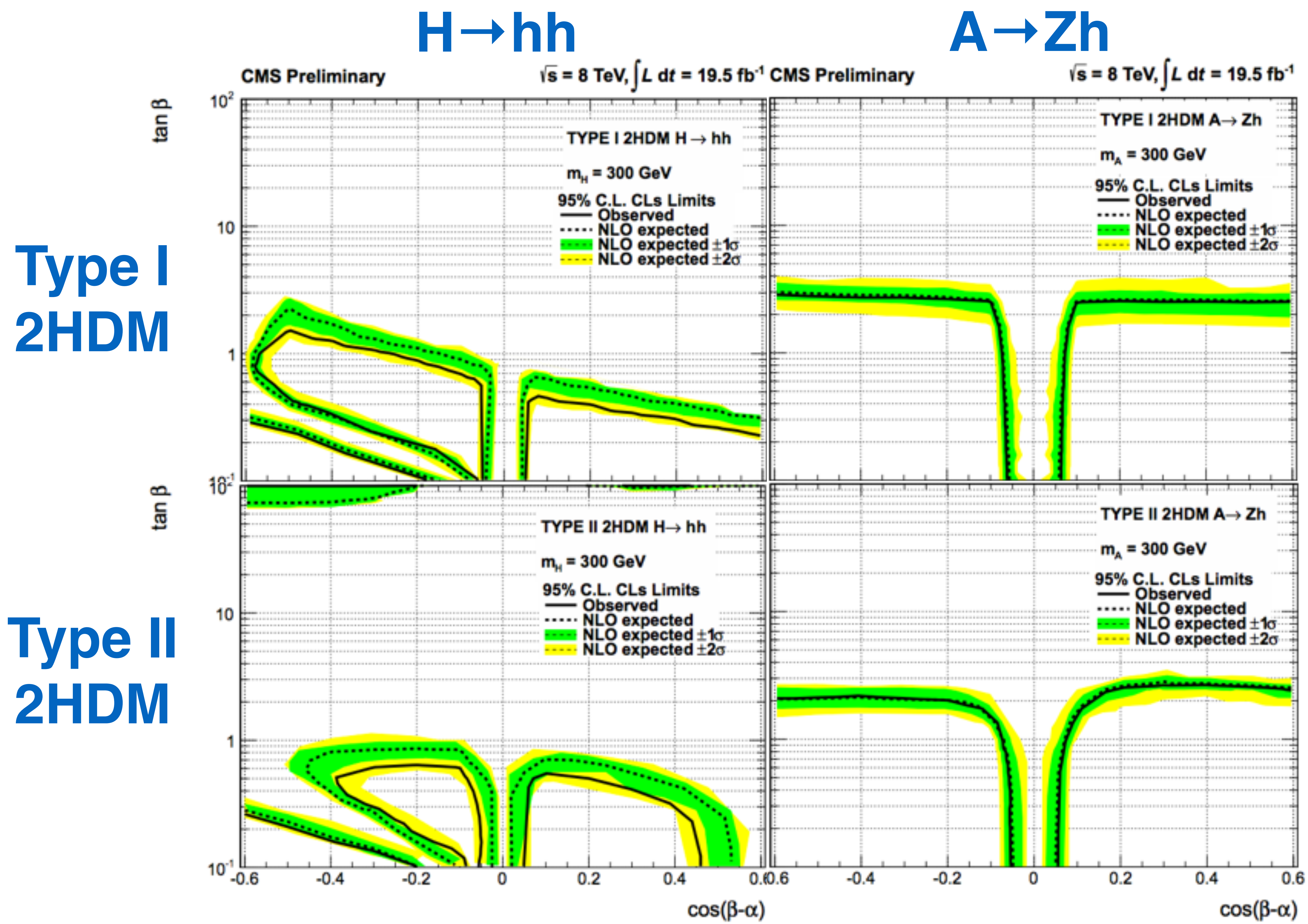




Note: h→WW/ZZ or γγ

Coll.	Dataset	Cite
CMS	20fb-1(8TeV)	CMS PAS HIG-13-025

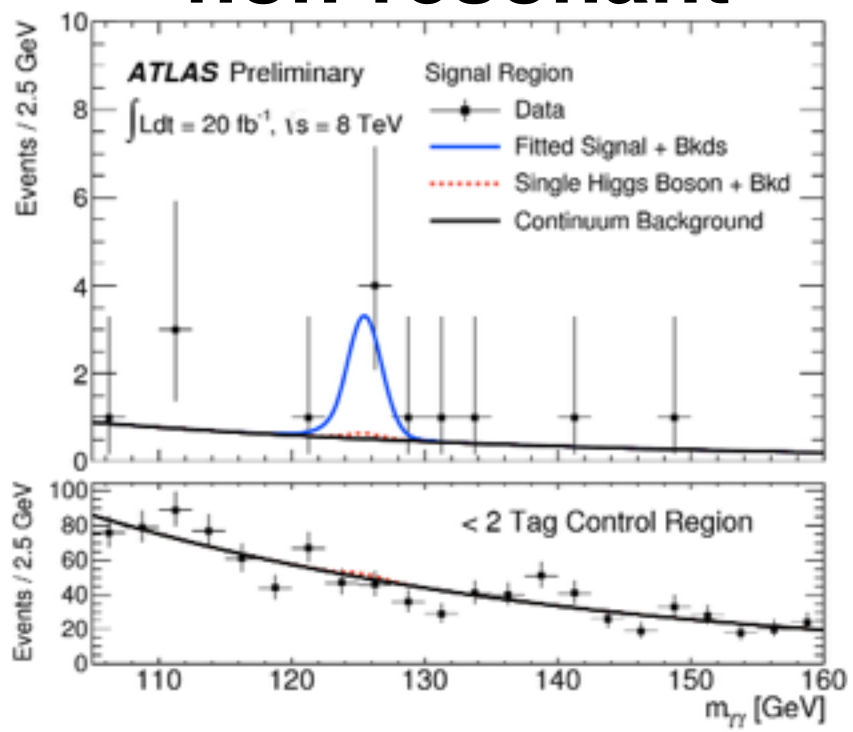
CMS: Results



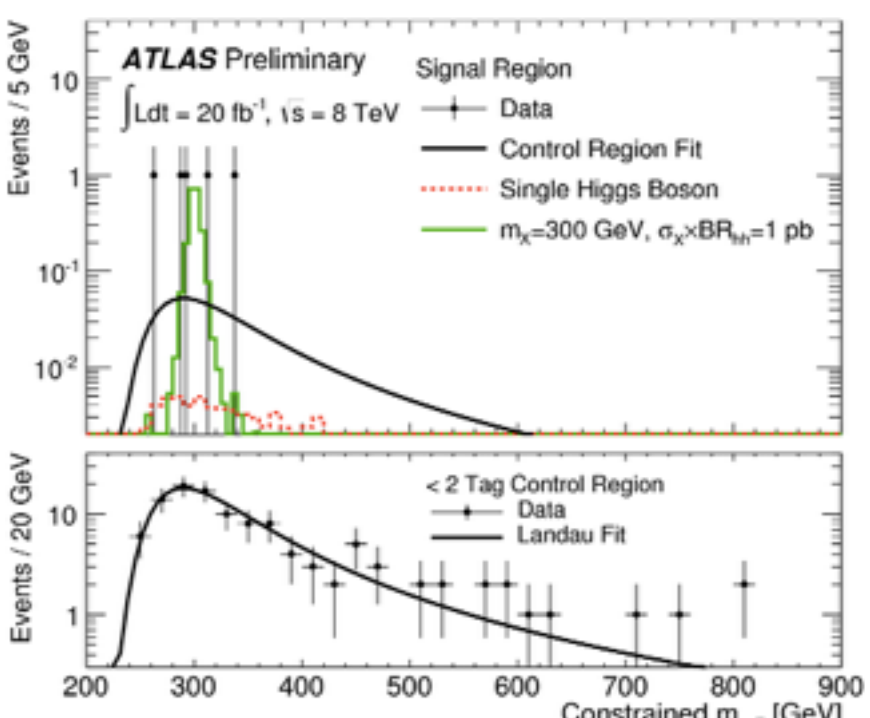
α is H-h mixing angle…

ATLAS: X→hh→γγbb

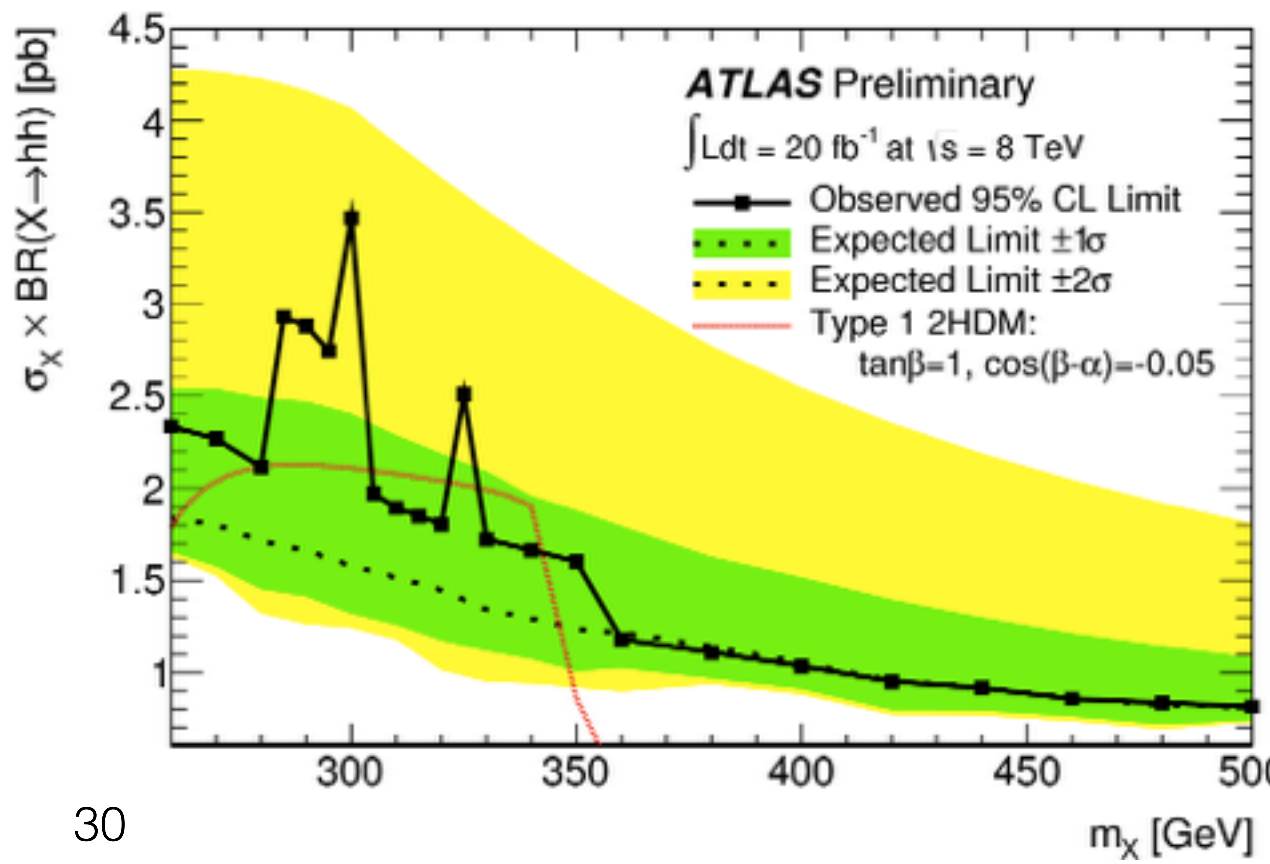
non-resonant



resonant



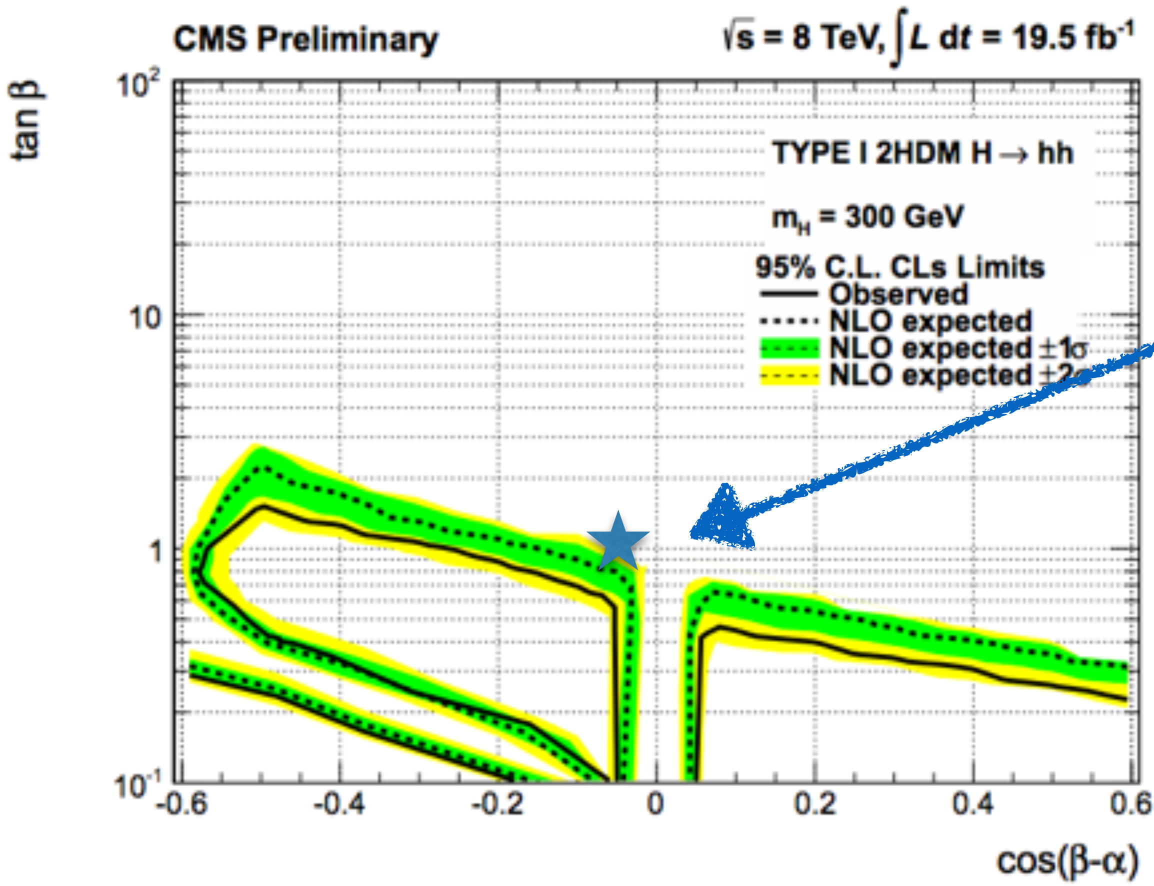
Coll.	Dataset	Cite
ATLAS	**20fb-1(8TeV)**	**HIGG-2013-29**
CMS	20fb-1(8TeV)	CMS-PAS-HIG-13-032

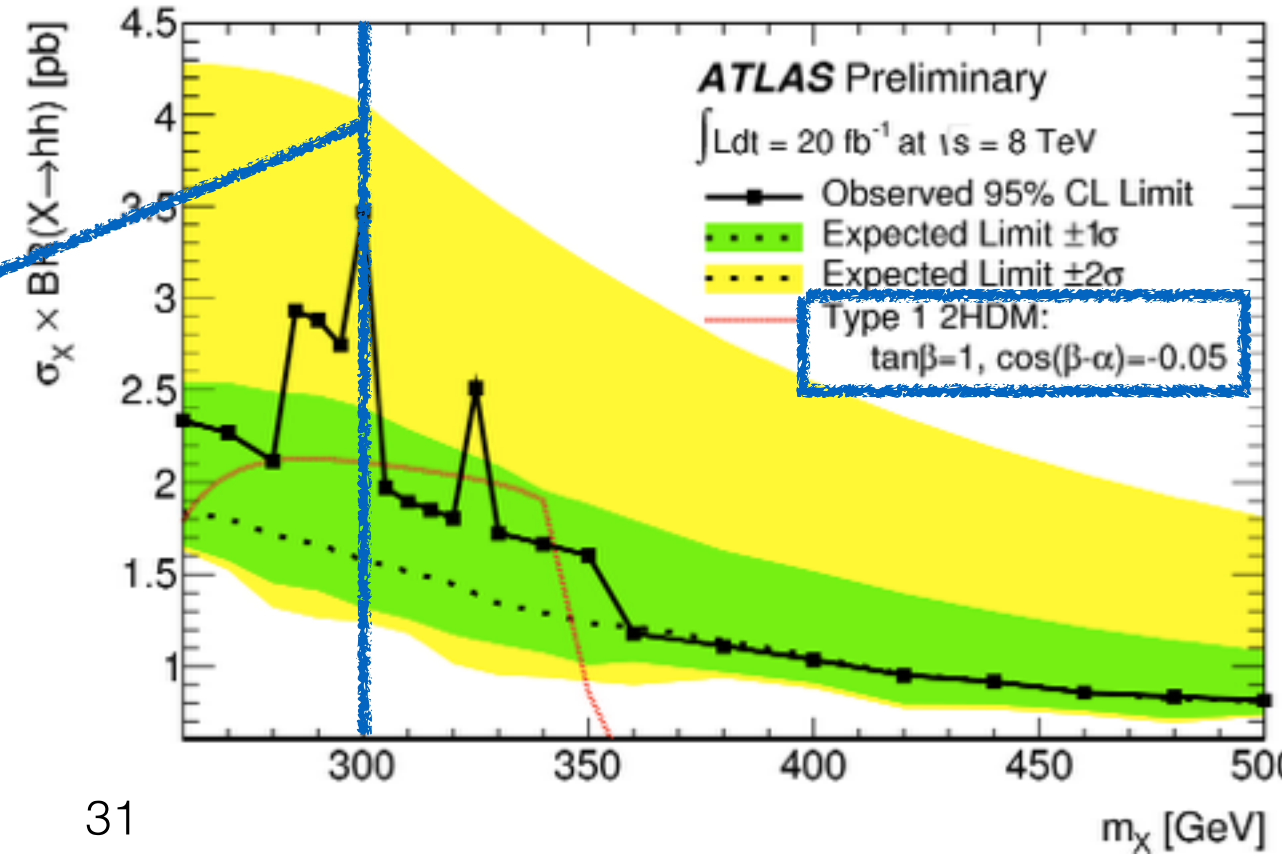


ATLAS: X→hh→γγbb

HOT OFF THE PRESS

Coll.	Dataset	Cite
ATLAS	**20fb-1(8TeV)**	**HIGG-2013-29**
CMS	20fb-1(8TeV)	CMS-PAS-HIG-13-032





t→Hc

- FCNC highly suppressed by GIM in SM, but can be larger in BSM models.

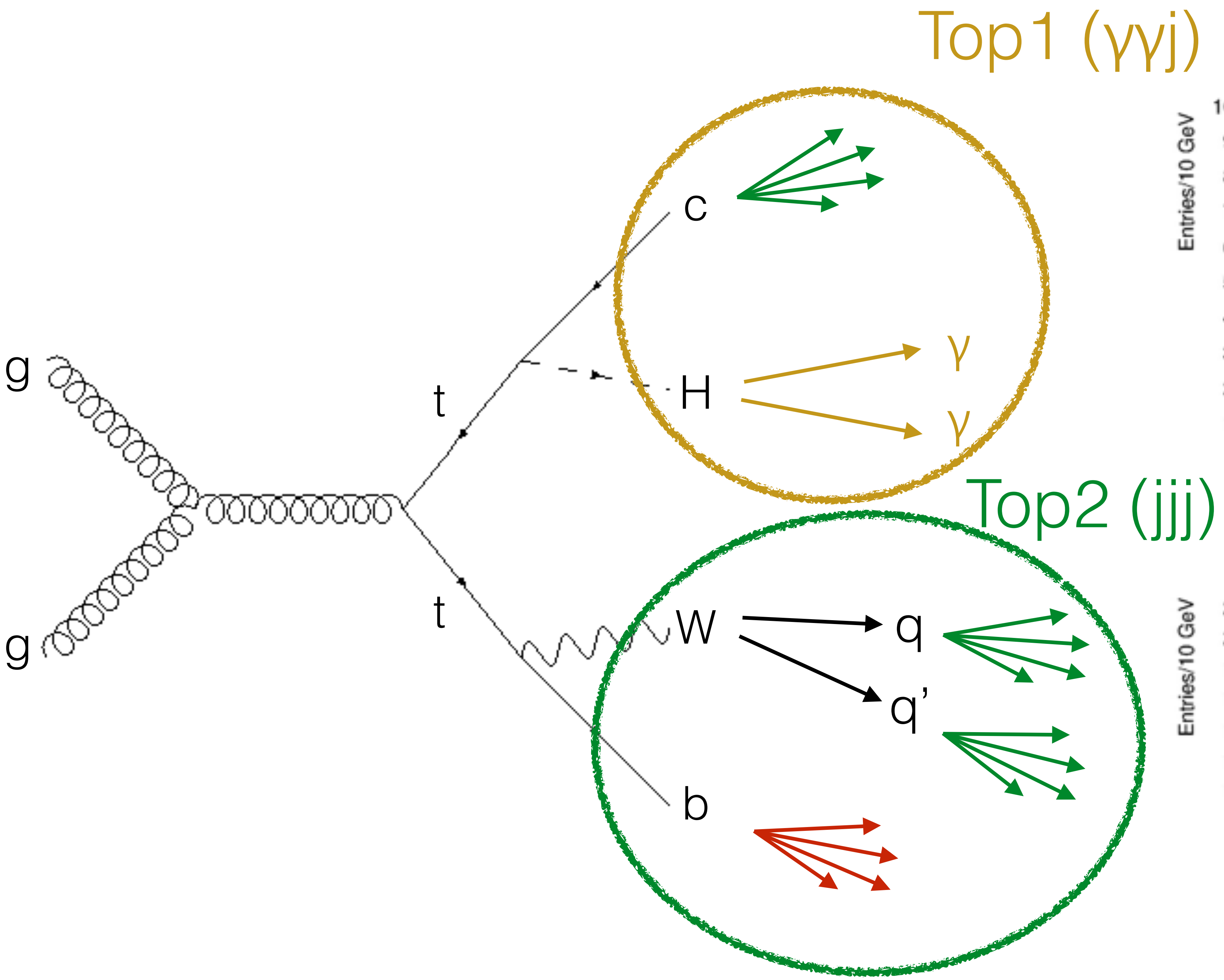
- B(t→c(u)Z) < 0.07% from CMS

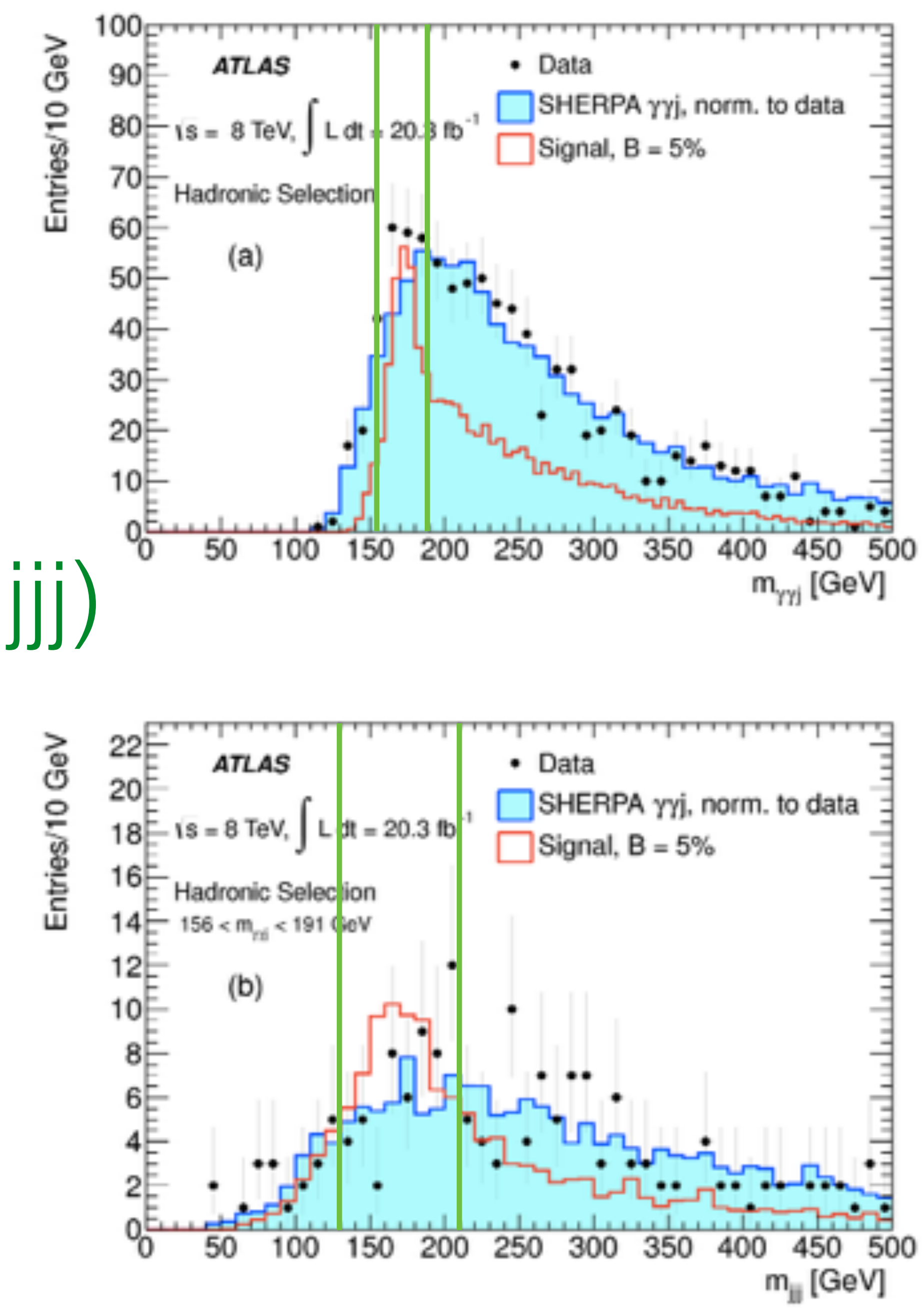
Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

Coll.	Dataset	Cite
ATLAS	**25fb-1(7+8TeV)**	**arXiv:1403.6293 [hep-ex]**
CMS	20fb-1(8TeV)	CMS-PAS-HIG-13-034

ATLAS: tHc search

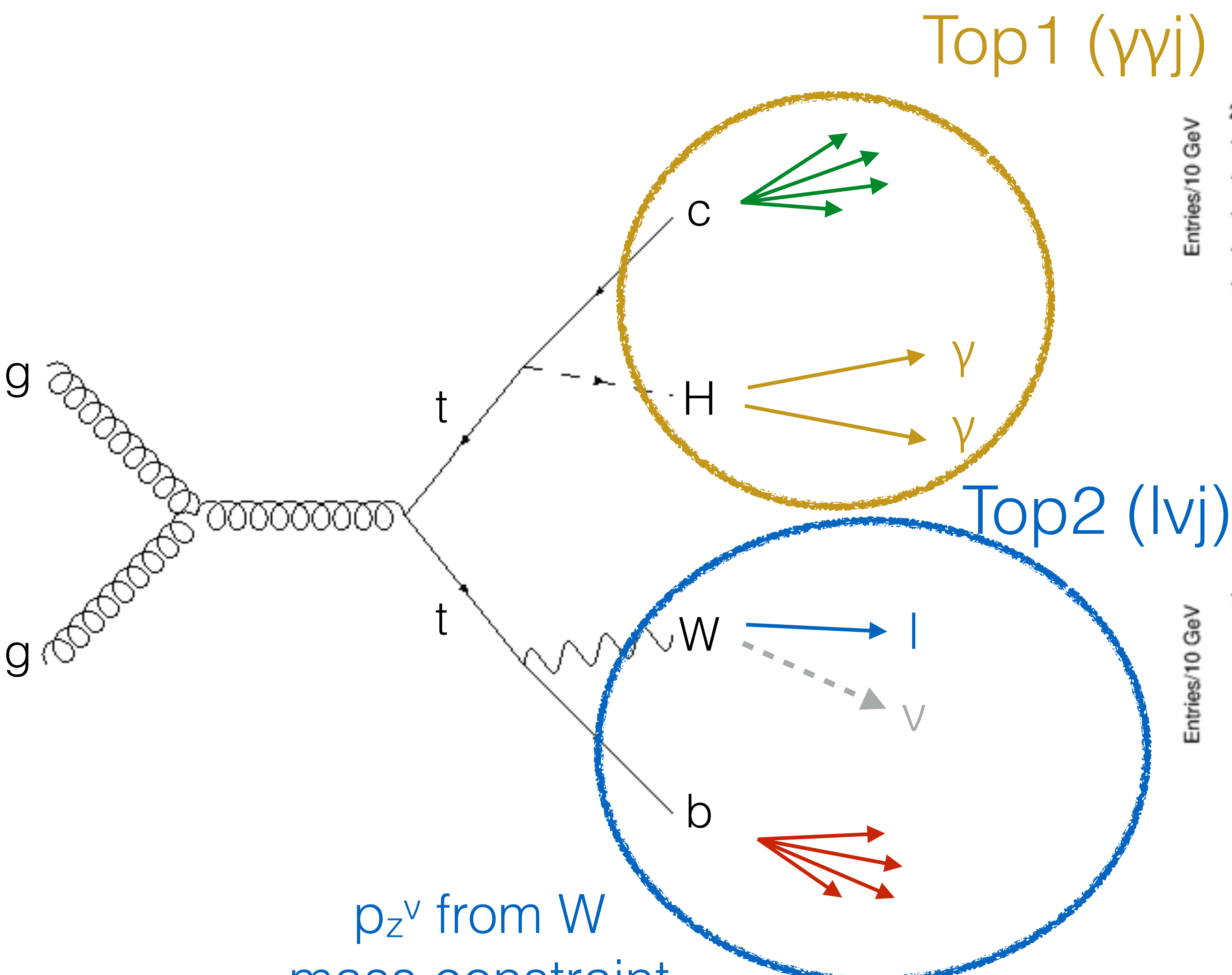
Hadronic Channel



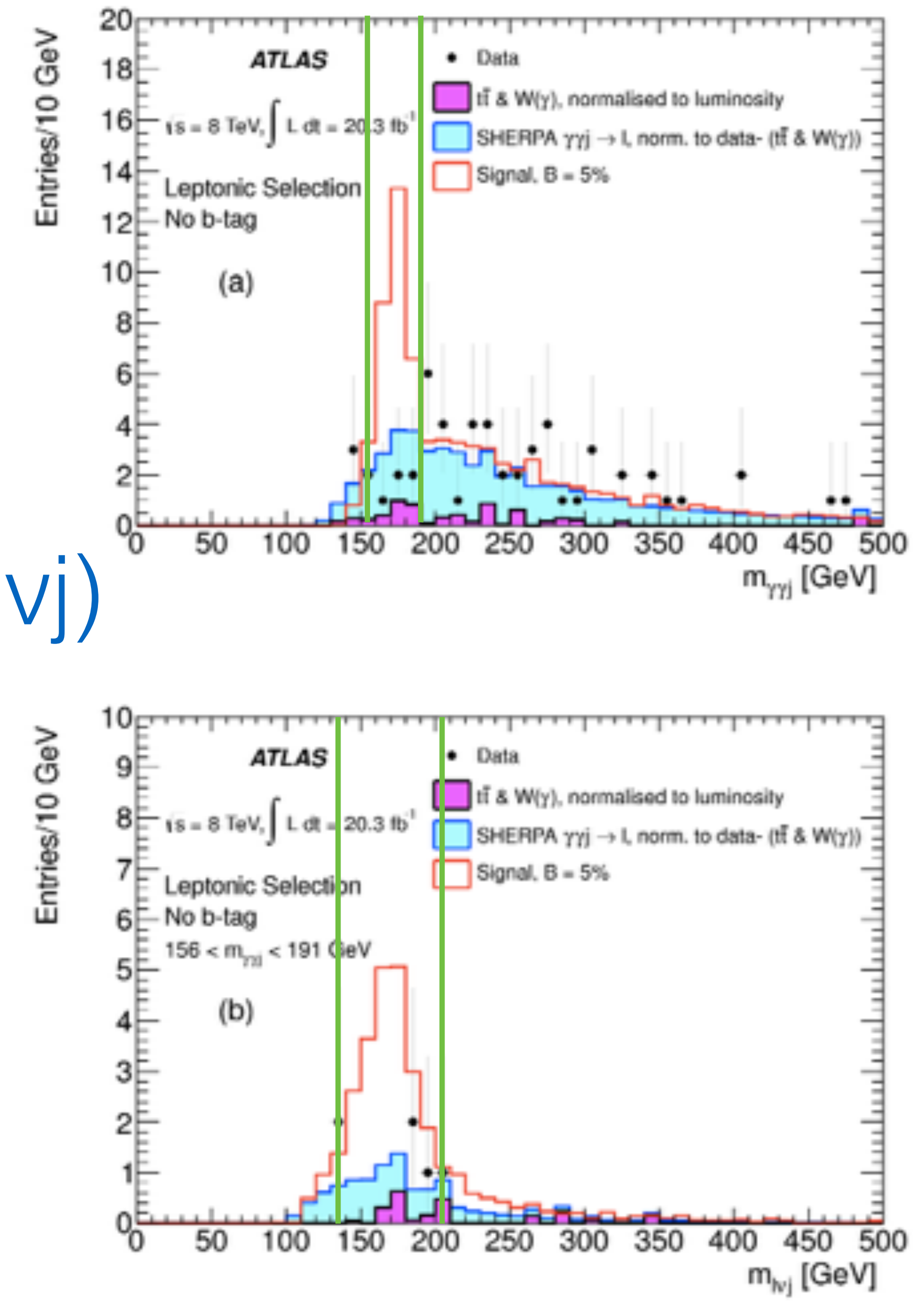


ATLAS: tHc search

Leptonic Channel

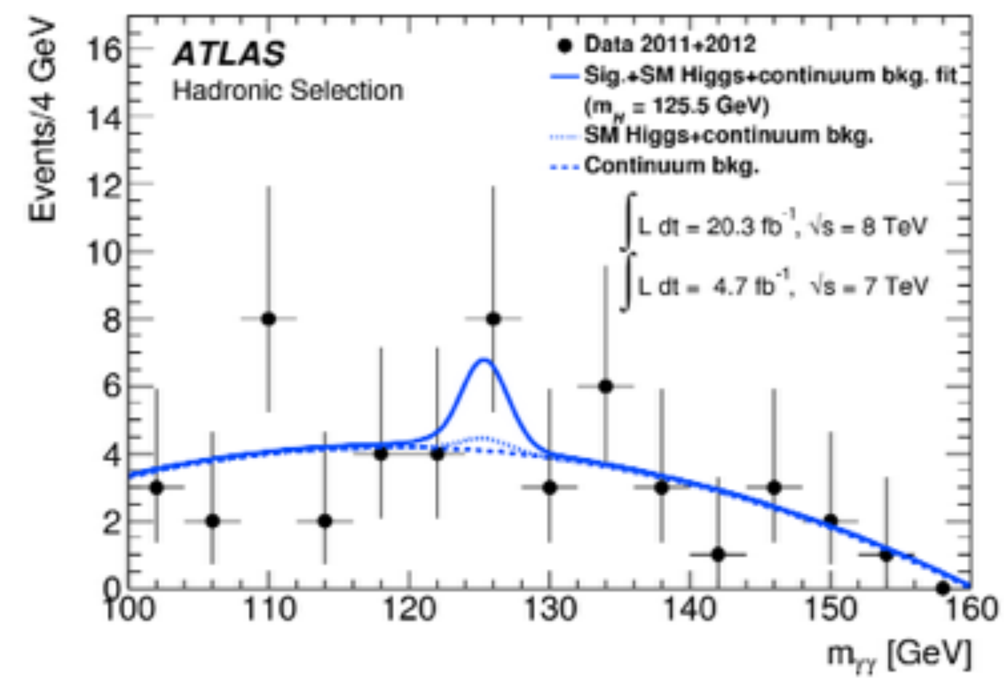


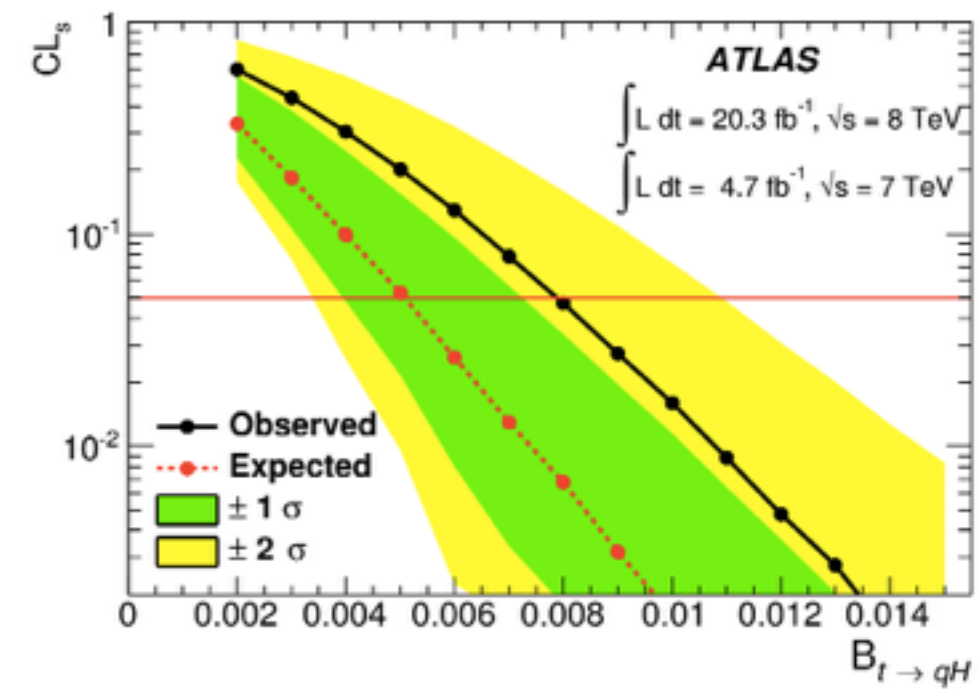
p_Z^ν from W
mass constraint



ATLAS/CMS: Results

- Search for excess in diphoton mass spectrum:
  - **B(t→Hc)< 0.83%** (0.53%)
  - $\lambda_{tHc/u}$ < 0.17 (0.14)
- CMS reinterpretation of diphoton+multileptons searches:
  - **B(t→Hc)<0.56%** (0.65%)
  - $\lambda_{tHc/u}$ < 0.14



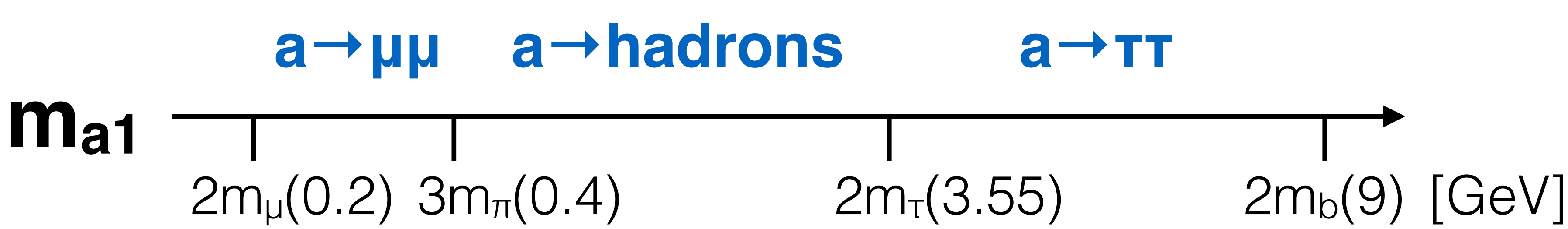


NMSSM

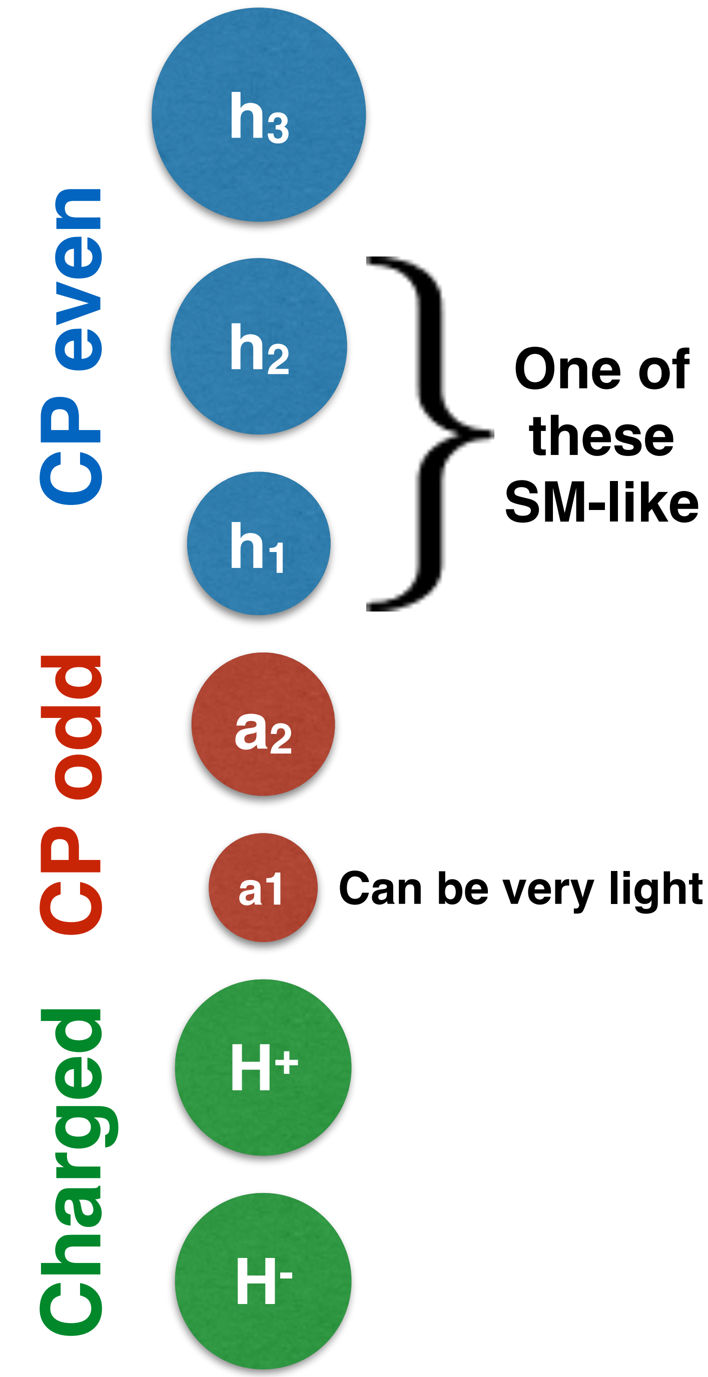
(Next-to-MSSM)

NMSSM

- 2 Doublets (H_u,H_d) **+ 1 Singlet (S)** - alleviates μ-problem of MSSM
- $h \to a_1 a_1$ dominant ($h \to bb$ greatly reduced)



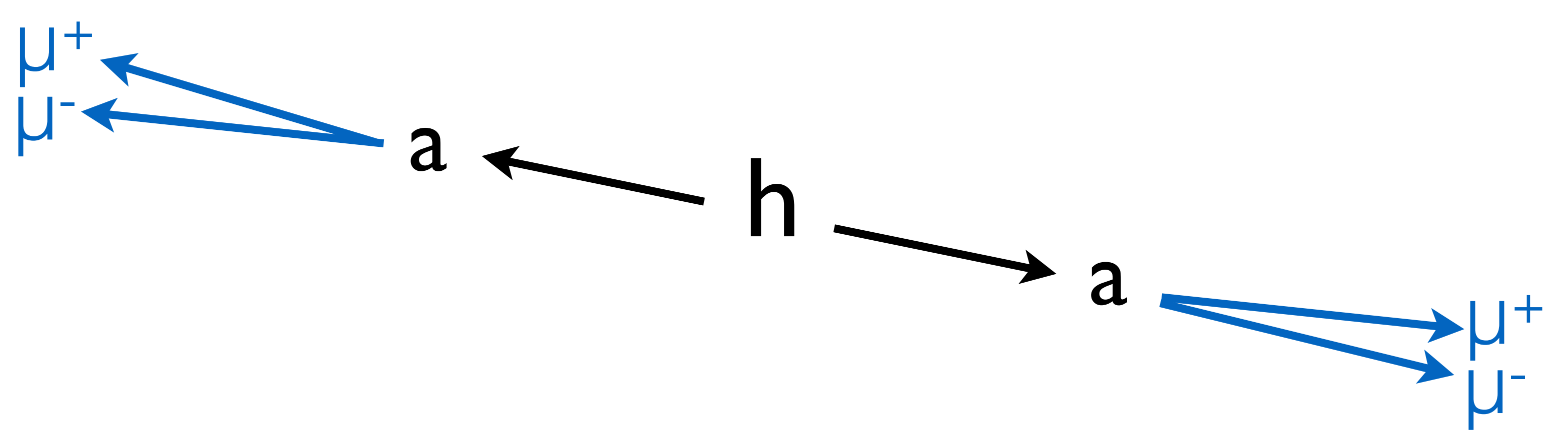
Coll.	Channel	m_a range [GeV]	Dataset	Cite
CMS	**$h \to 2a \to 4\mu$**	**0.25 - 3.55**	**21fb-1(8TeV)**	**CMS-PAS-HIG-13-010**
D0	$h \to 2a \to 4\mu/2\mu 2\tau$	0.2 - 20	4fb-1(2TeV)	PRL 103, 061801 (2009)
ATLAS	$h \to 2a \to 4\gamma$	0.1 - 0.4	5fb-1(7TeV)	ATLAS-CONF-2012-079
CMS	$a \to 2\mu$	5.5 -14	1fb-1(7TeV)	PRL 109, 121801 (2012)
CDF	$t \to H + b \to Wa(\to \tau\tau)b$	4 - 9	3fb-1(2TeV)	CDF Note 10104



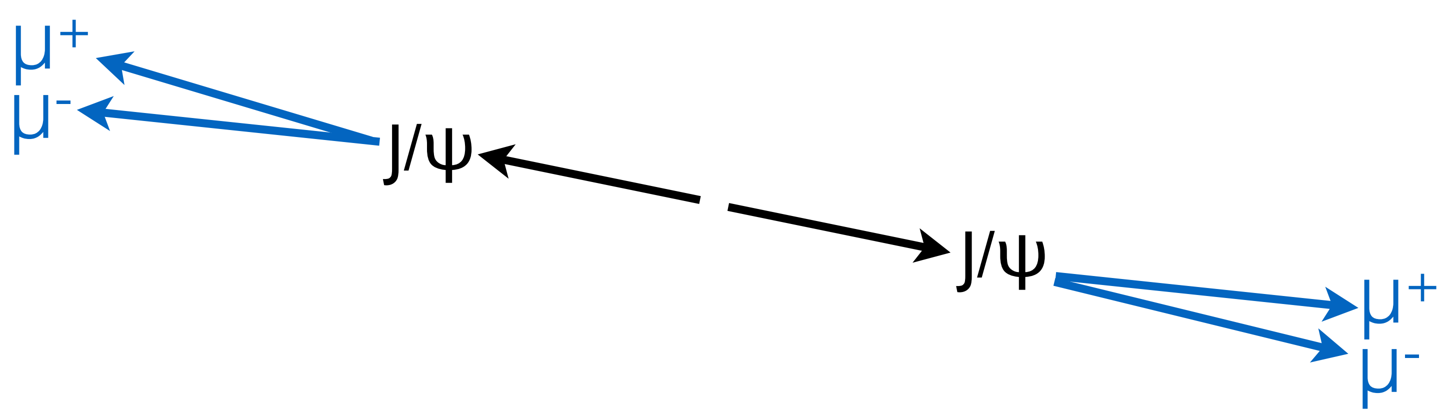
CMS: $h \to 2a \to 4\mu$

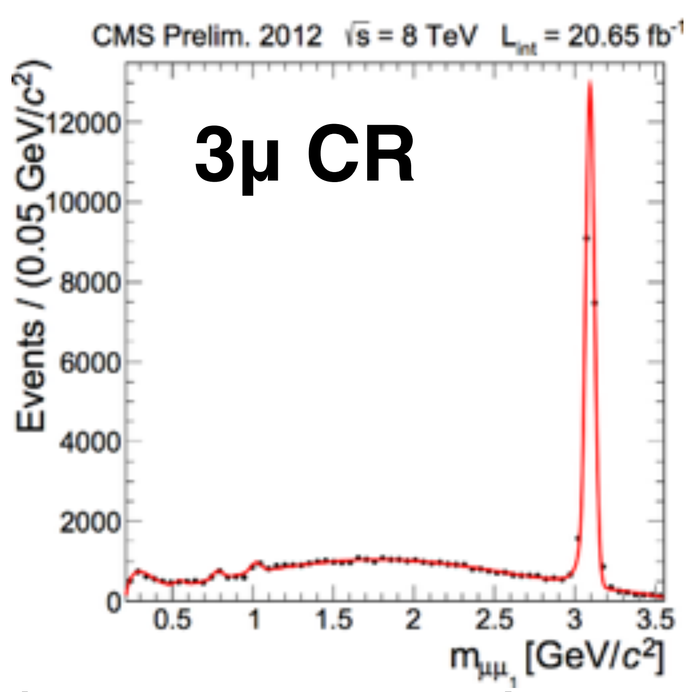
- 2 Isolated OS muon pairs with compatible masses

Signal



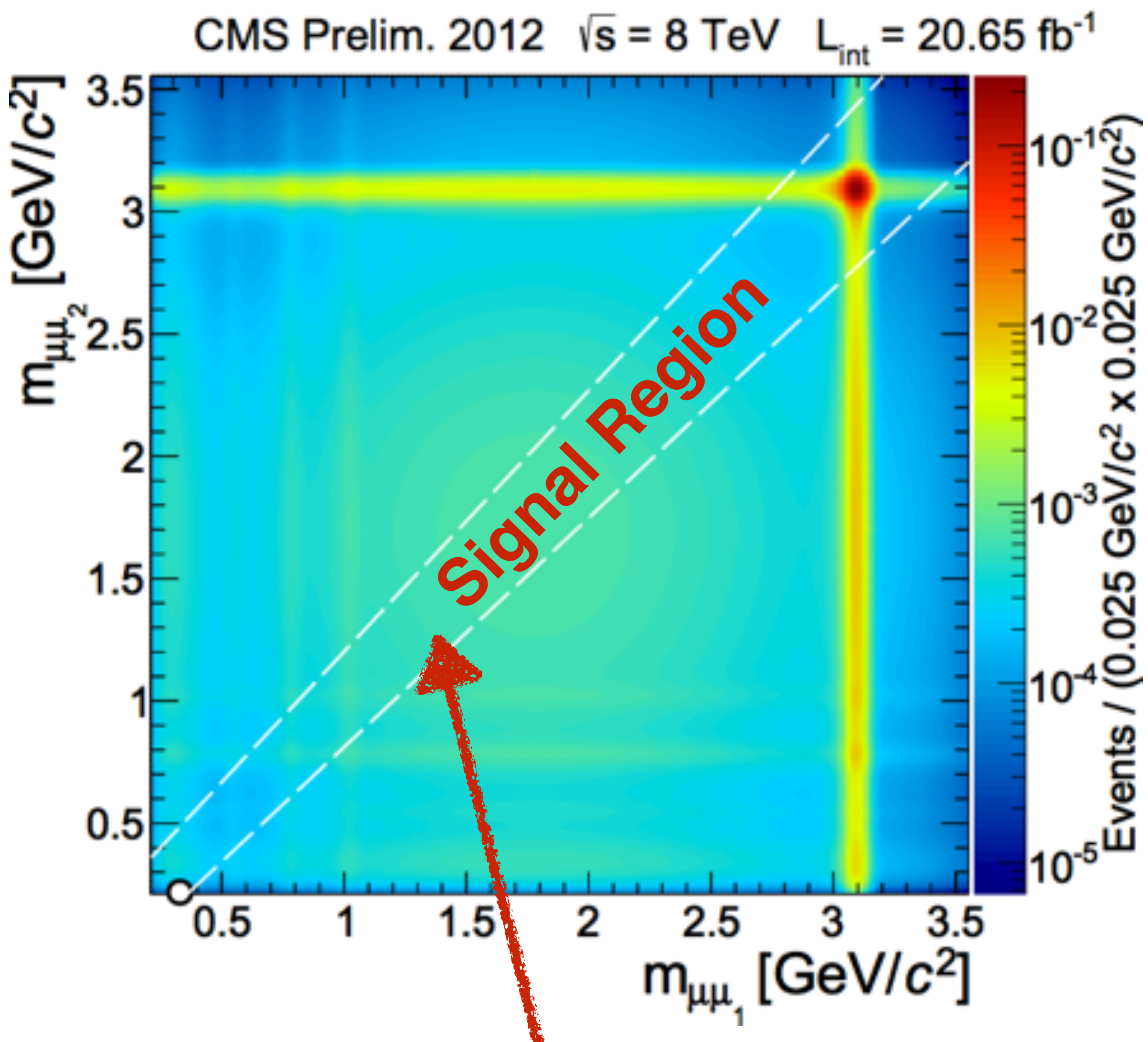
Background: B and J/ψ pair production

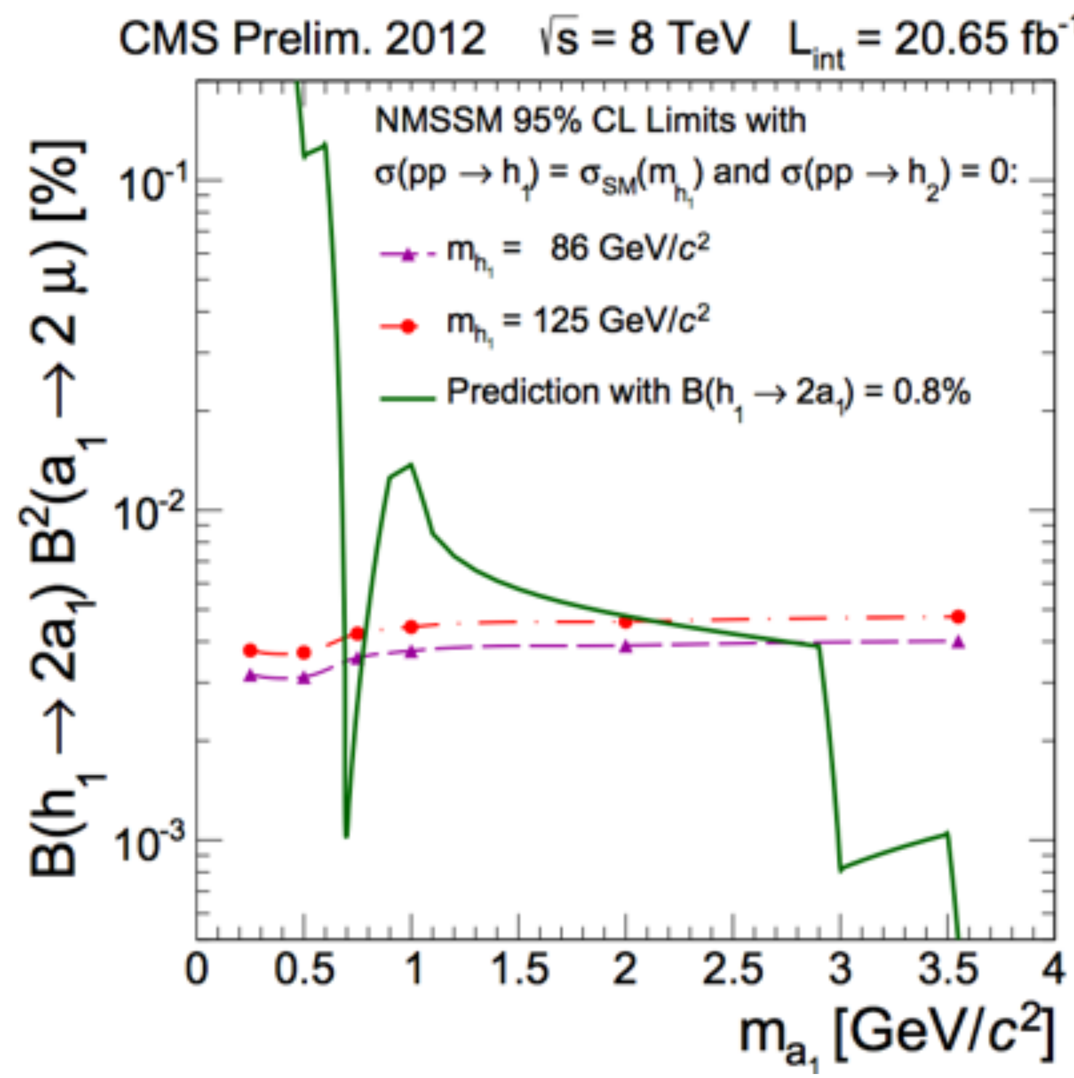




Estimation: BB from 3μ CR, J/ψ from MC+data correction

CMS: Results



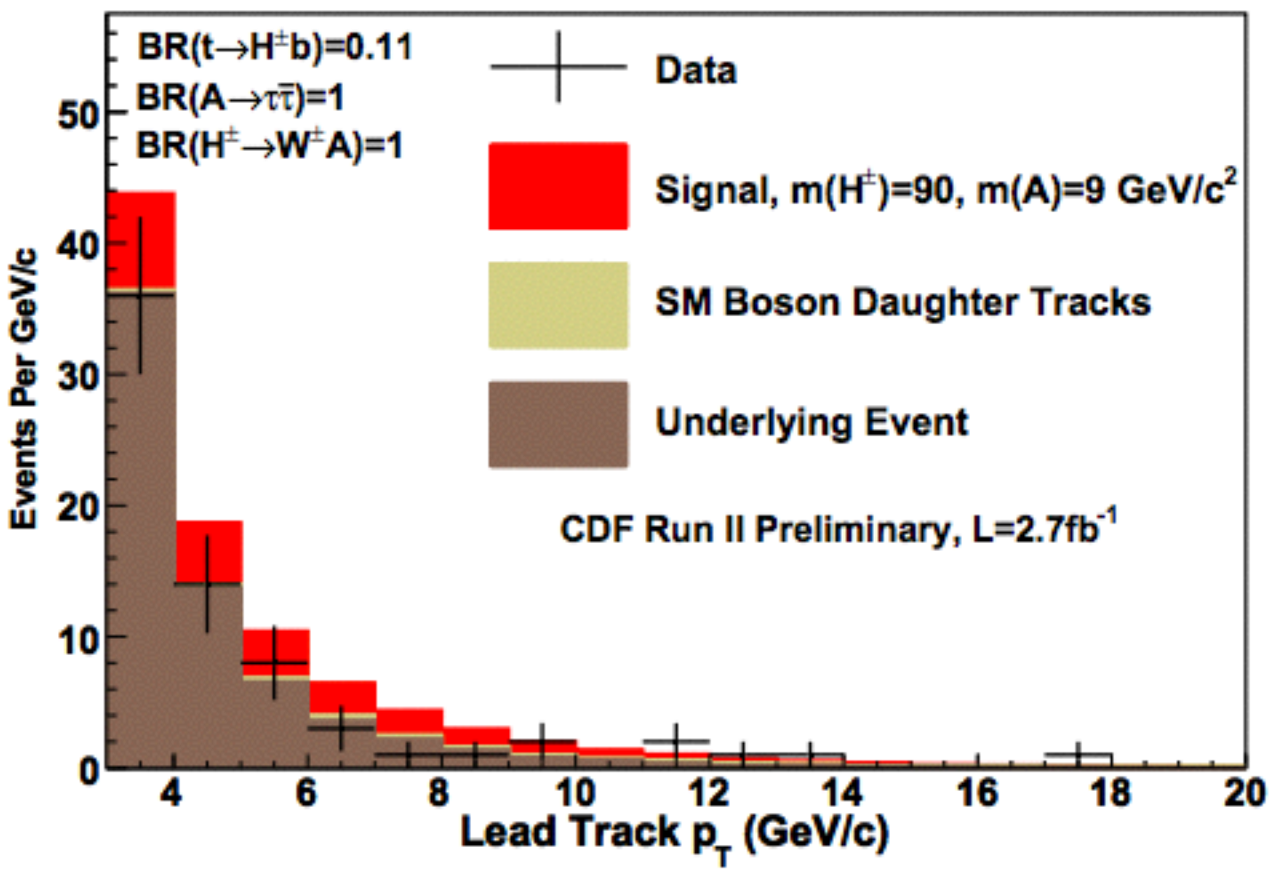


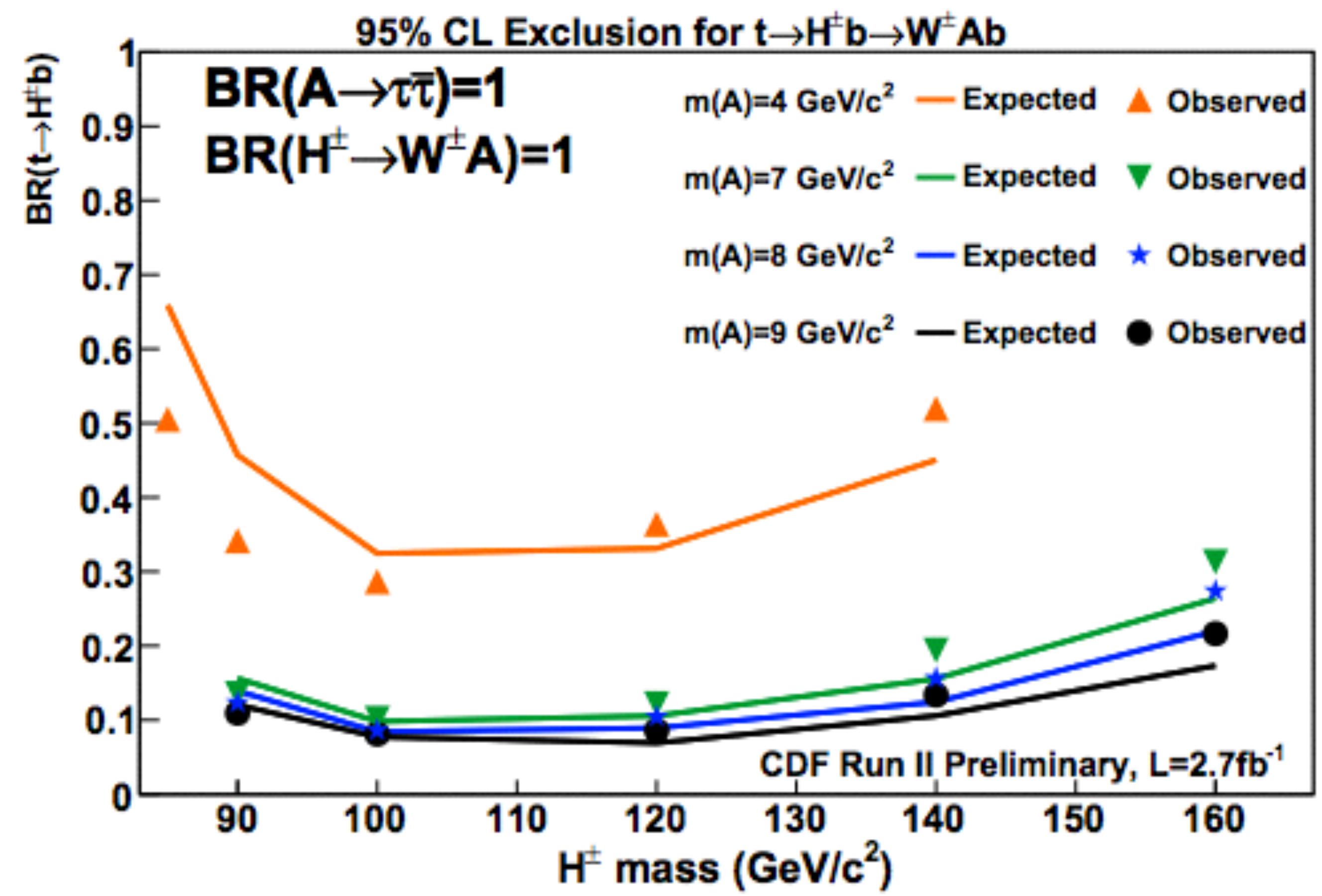
Expected: 3.8±2.1
Observed: 1

Also sensitive to Dark SUSY…

CDF: t→bH⁺→bW⁺a(→ττ)

- $m_a<2m_b$ not experimentally excluded
- First limits on this decay mode



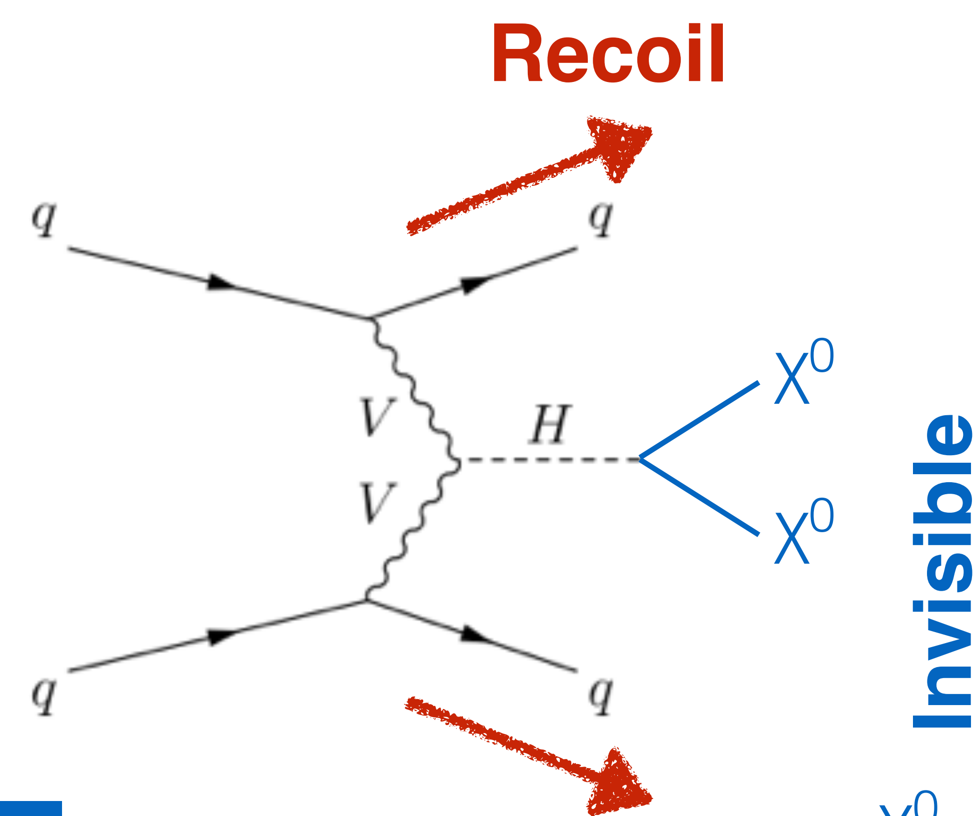


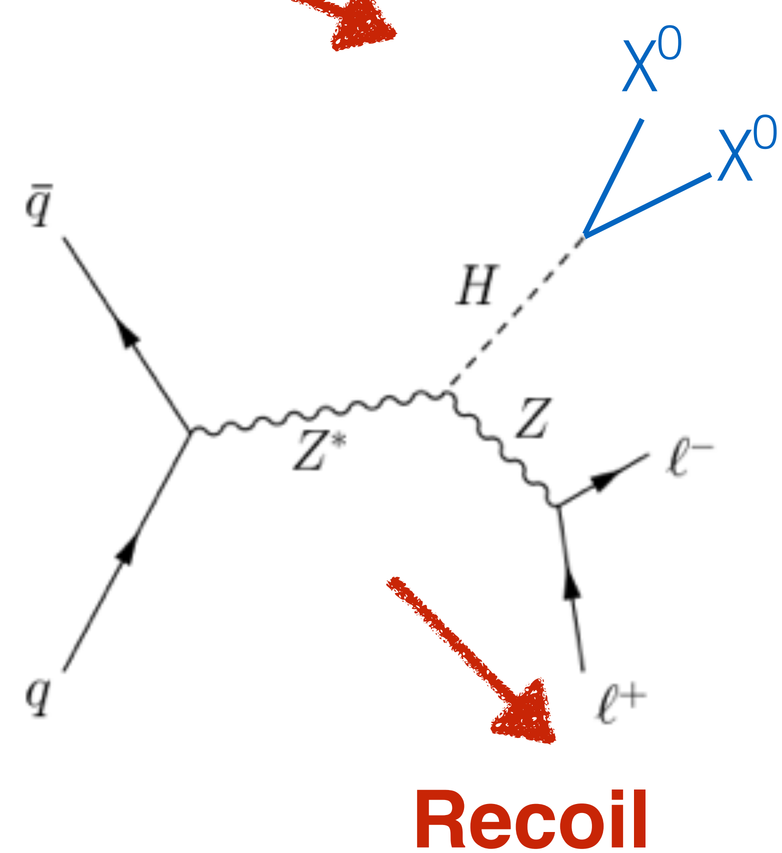
Exotic Higgs Decays

Invisible Higgs

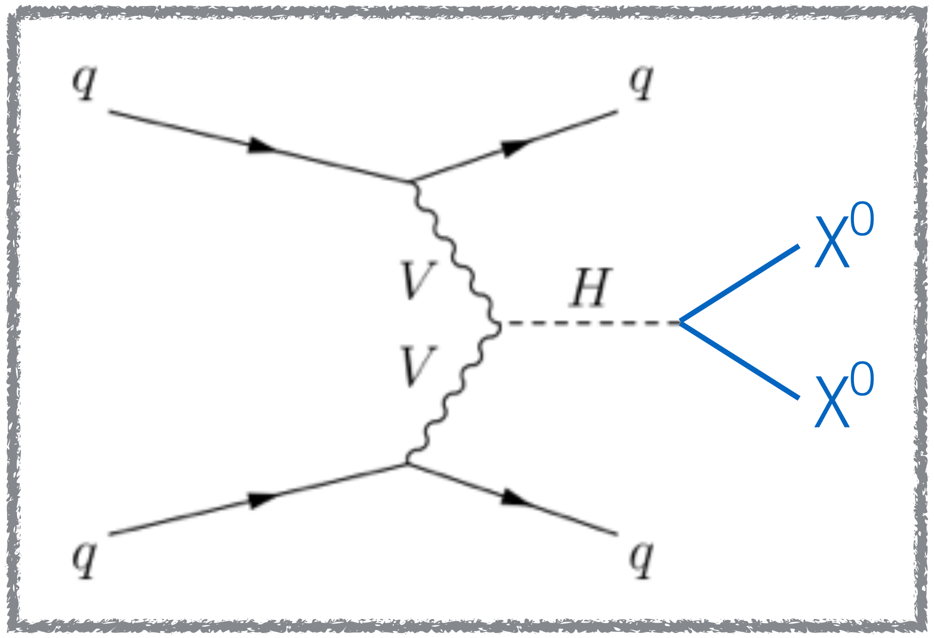
- Search for Higgs decaying into **new weakly interacting particles**
- SM B(H→inv.)~1.2E-3 (H→ZZ→4ν)
- **Indirect Limits**: from vis. decay modes **ATLAS 60%, CMS 64%**

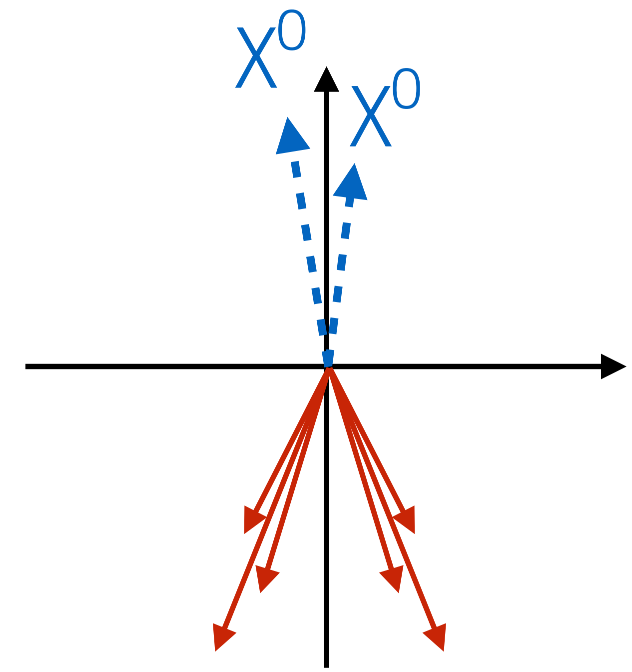
Direct Searches			
Coll.	**Channel**	**Dataset**	**Cite**
CMS	**VBF**	**20fb-1(8TeV)**	arXiv:1404.1344 [hep-ex]
CMS	Z(→ll)H	25fb-1(7+8TeV)	
CMS	Z(→bb)H	19fb-1(8TeV)	
CMS	Comb.	19-25fb-1	
ATLAS	Z(→ll)H	25fb-1(7+8TeV)	arXiv:1402.3244 [hep-ex]
CDF	Z(→ll)H	10fb-1(2TeV)	CDF Note 11068

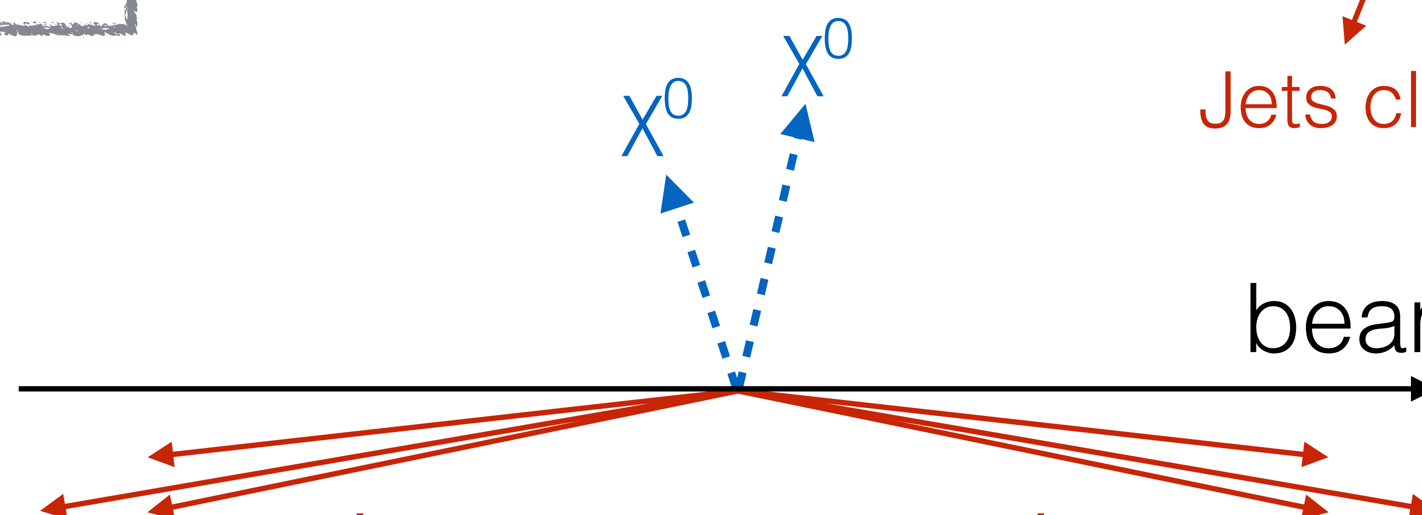




CMS: VBF Invisible

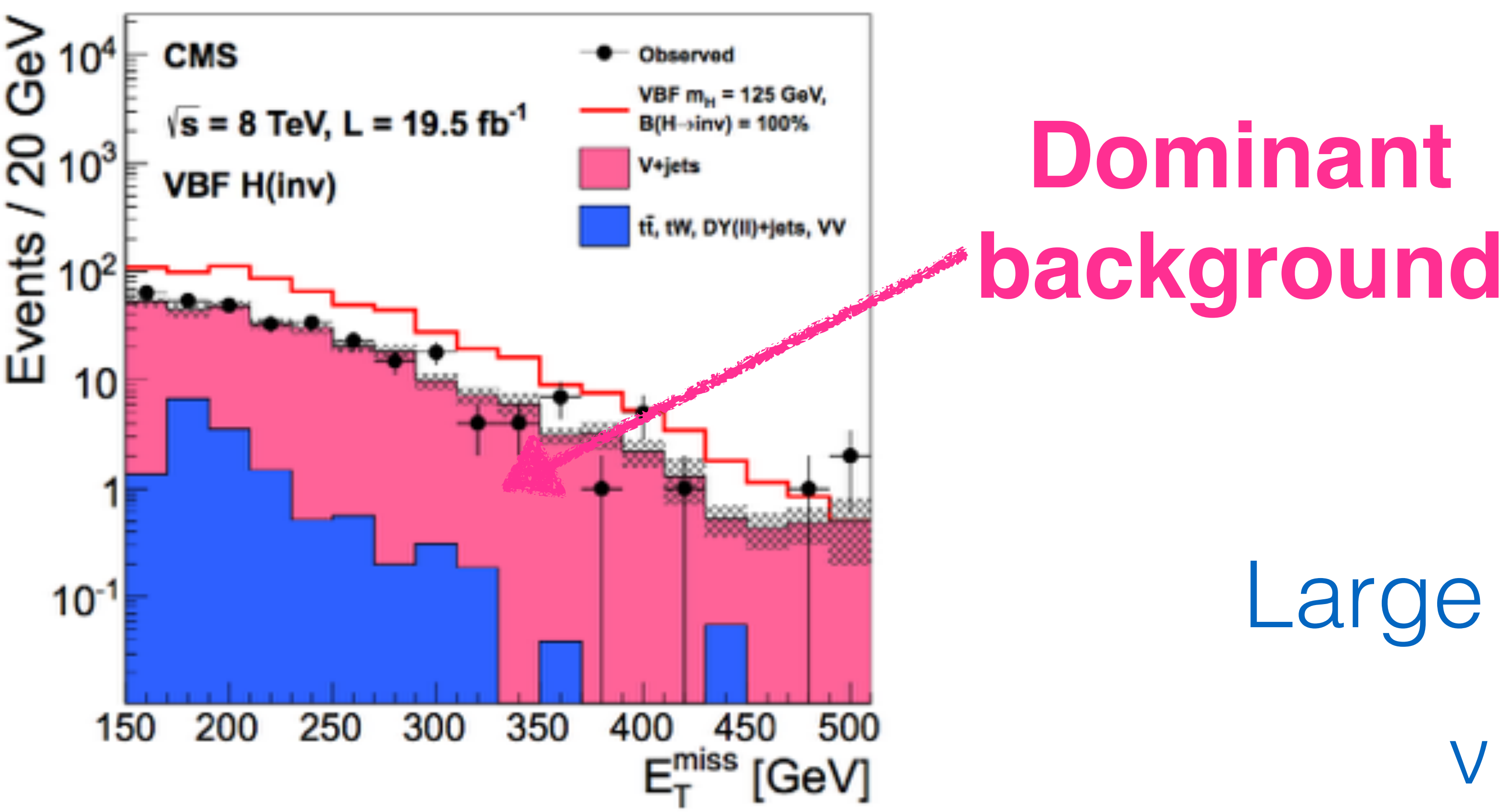


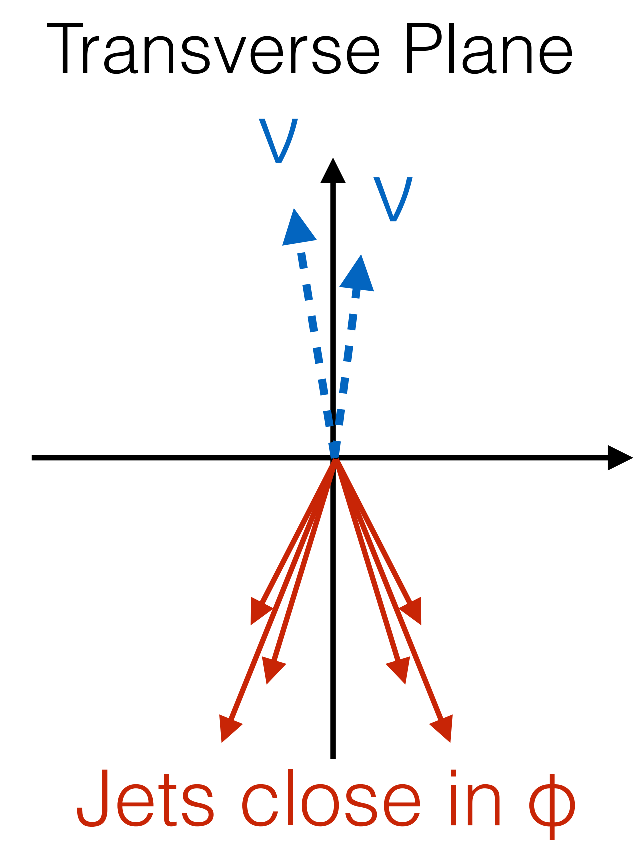


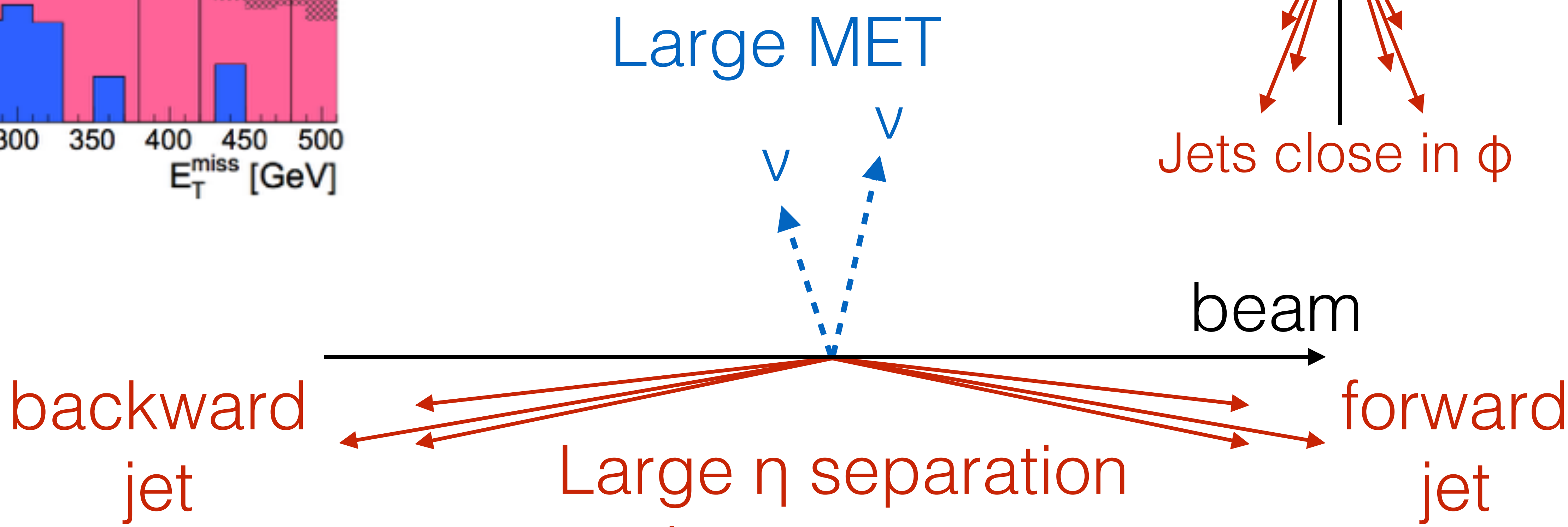


Large η separation
Large mass
No jets in-between
No Leptons

CMS: Z(→νν)+2 jet background



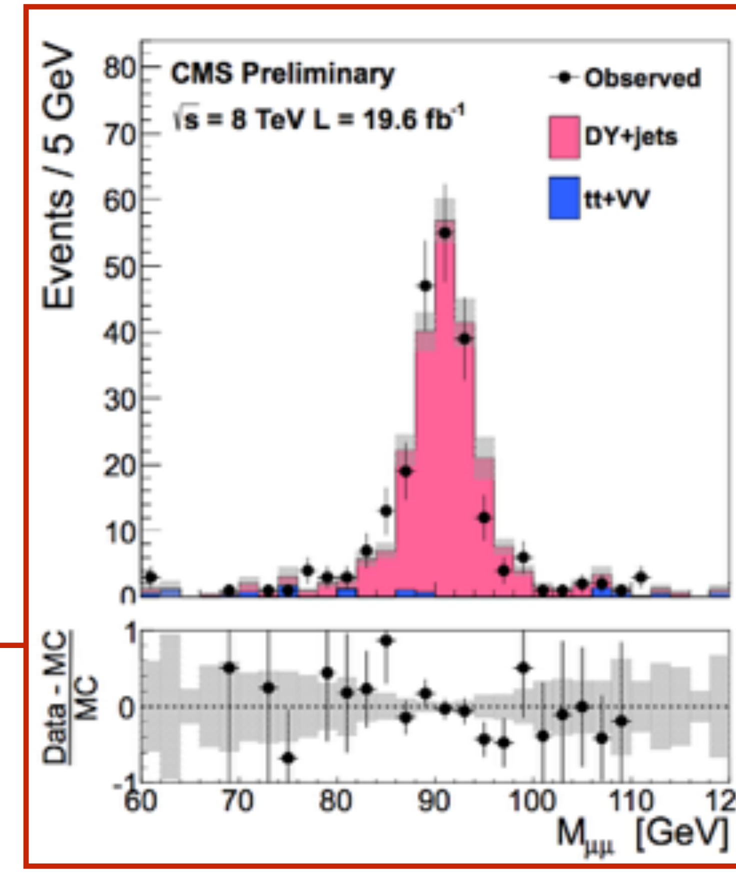


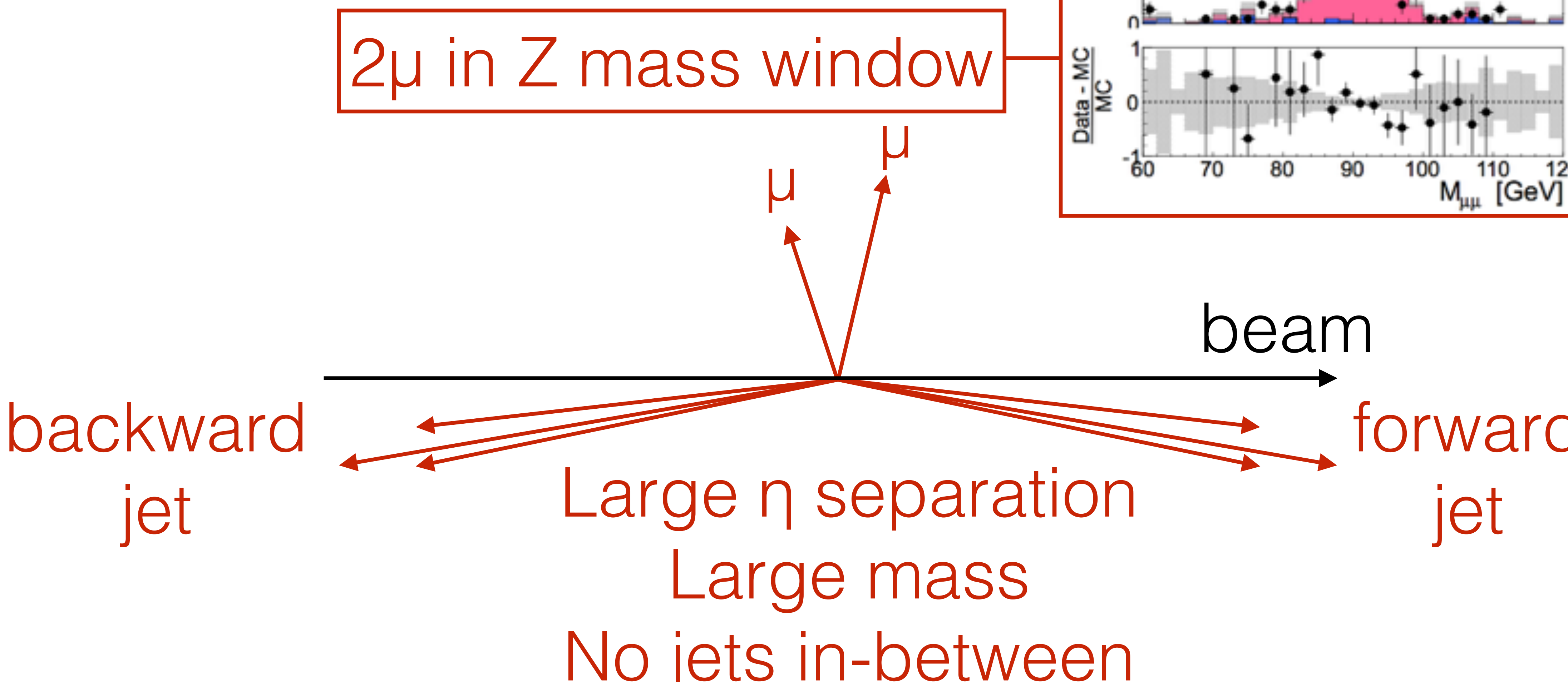


Large η separation
Large mass
No jets in-between
No Leptons

CMS: Z→μμ to Z→νν embedding

- Estimate Z→νν using Z(→μμ)+2 jet
- Remove muon from event and recalc. MET
- Scale by σ.ε ratio (Z→νν/Z→μμ)

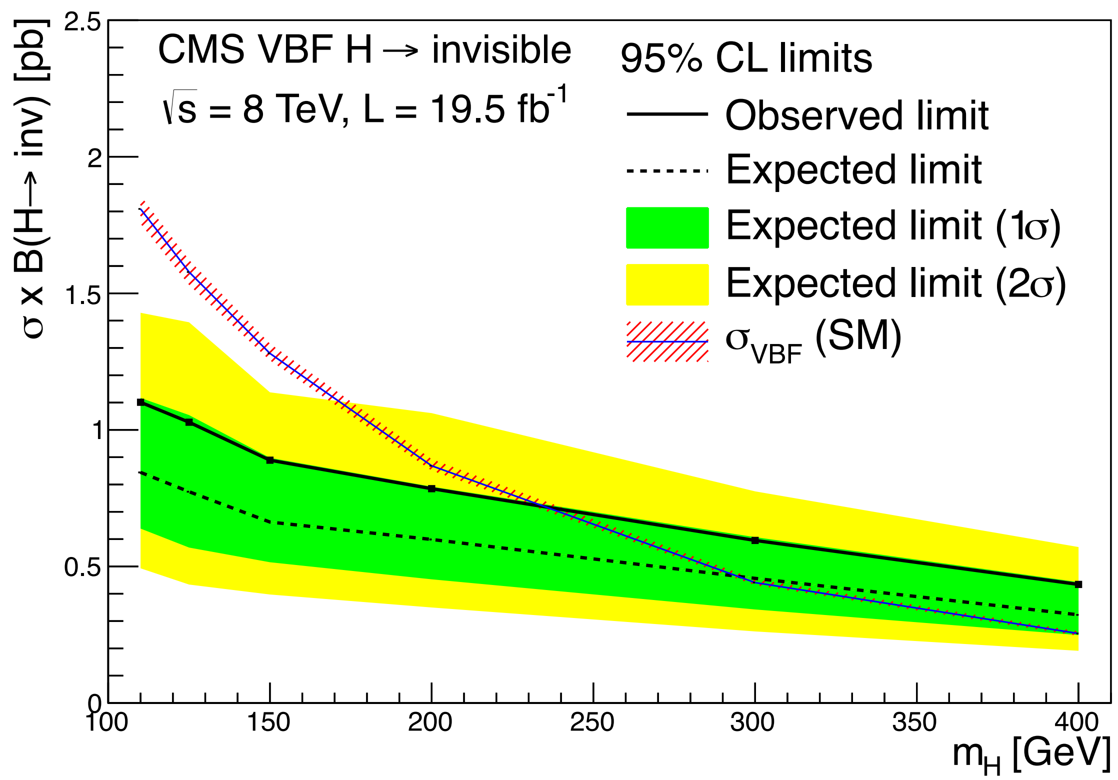




CMS: Results

Events	
Bkg.	339±36(stat.) ±50(sys.)
Sig.	208 (ε~0.67%)
Obs.	390

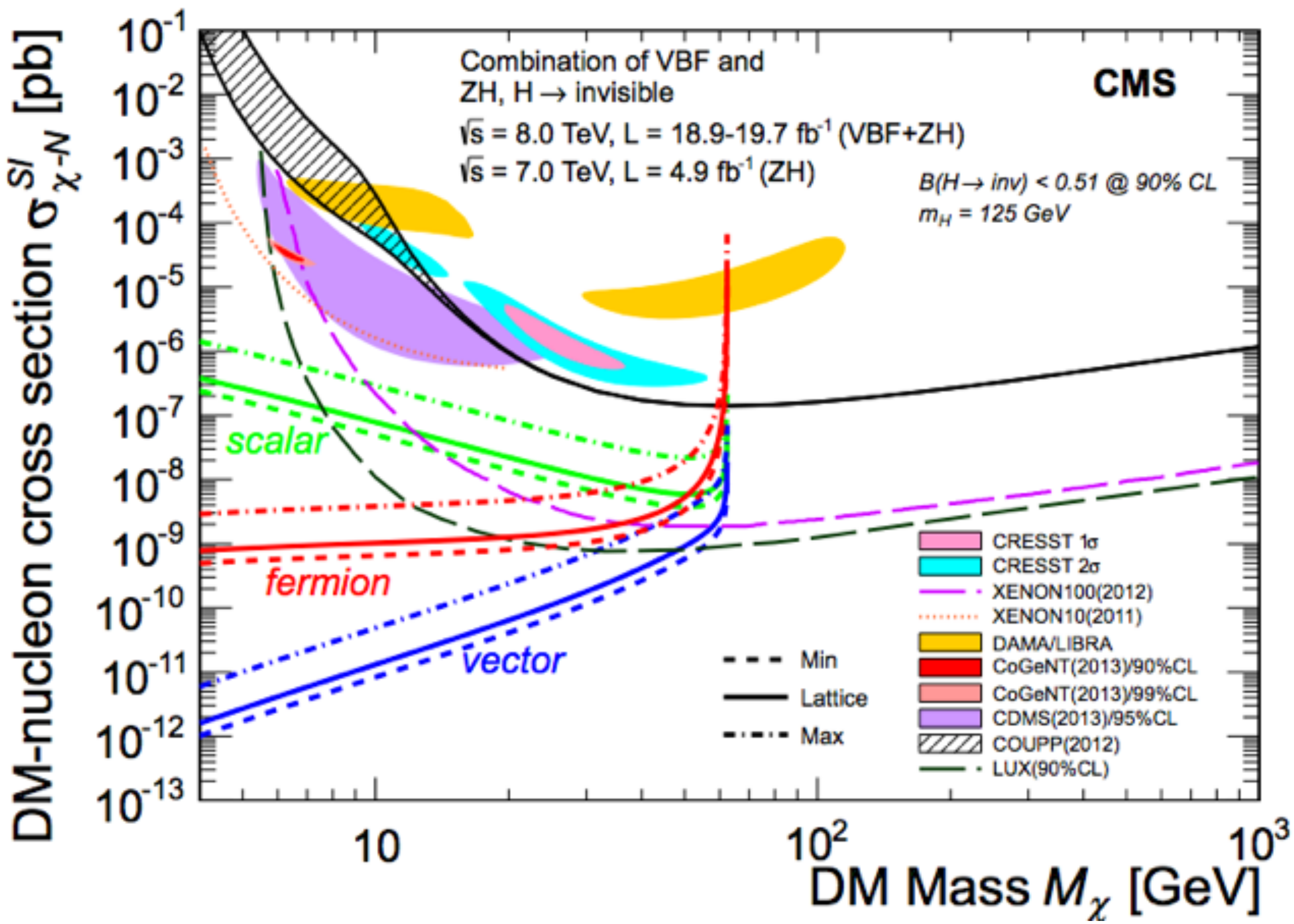
Dominant Systematic	
Zμμ emb. stat.	± 30 events



Summary of Direct Searches		
Coll.	Channel	Limit B(H→inv.)
CMS	**VBF**	**69% (53%)**
CMS	Z(→ll)H	75% (91%)
CMS	Z(→bb)H	(1.8 x σSM)
CMS	**Comb.**	**58% (44%)**
ATLAS	Z(→ll)	65% (62%)

Comparison to direct dark-matter detection

- B(H→inv.) limits constrain DM-nucleon scattering in Higgs portal models.



Summary

- Active searches cover a large range of BSM Higgs boson signatures
- We're ready to find something in LHC Run 2!

References

Neutral MSSM

Coll.	Channel	Dataset	Cite
CMS	**ττ**	**25fb-1(7+8TeV)**	**CMS-PAS-HIG-13-021**
ATLAS	ττ	5fb-1(7TeV)	JHEP02(2013)095
LHCb	ττ	1fb-1(7TeV)	JHEP05(2013)132
D0	ττ+bb	5-7fb-1(2TeV)	PLB 710, 569 (2012)
D0+CDF	**bb**	**3-5fb-1(2TeV)**	**PRD 86, 091101 (2012)**
CMS	**bb**	**3-5fb-1(7TeV)**	**PLB 722, 207 (2013)**

Charged MSSM

Coll.	Channel	Dataset	Cite
ATLAS	**τν+jets**	**20fb-1(8TeV)**	**ATLAS-CONF-2013-090**
ATLAS	τν+lep	5fb-1(7TeV)	JHEP03(2013)076
ATLAS	cs	5fb-1(7TeV)	EPJC 73 6 (2013) 2465
CMS	τν+lep/jet	5fb-1(7TeV)	CMS-PAS-HIG-12-052
CDF	cs	2fb-1(2TeV)	PRL 103, 101803 (2009)

NMSSM

Coll.	Channel	Dataset	Cite
CMS	**h→2a→4μ**	**21fb-1(8TeV)**	**CMS-PAS-HIG-13-010**
D0	h→2a→4μ/2μ2τ	4fb-1(2TeV)	PRL 103, 061801 (2009)
ATLAS	h→2a→4γ	5fb-1(7TeV)	ATLAS-CONF-2012-079
CMS	a→2μ	1fb-1(7TeV)	PRL 109, 121801 (2012)
CDF	**t→H+b→Wa(→ττ)b**	**3fb-1(2TeV)**	**CDF Note 10104**

2HDM Cascade

Coll.	Dataset	Cite
ATLAS	**20fb-1(8TeV)**	**PRD 89, 032002 (2014)**
CDF	9fb-1(2TeV)	PRL 110, 121801 (2013)
CMS	**20fb-1(8TeV)**	**CMS PAS HIG-13-025**
ATLAS	**20fb-1(8TeV)**	**HIGG-2013-29**

t→Hc FCNC

Coll.	Dataset	Cite
ATLAS	**25fb-1(7+8TeV)**	**arXiv:1403.6293 [hep-ex]**
CMS	20fb-1(8TeV)	CMS-PAS-HIG-13-034

Invisible

Coll.	Channel	Dataset	Cite
CMS	**VBF**	**20fb-1(8TeV)**	**arXiv:1404.1344 [hep-ex]**
CMS	Z(→ll)H	25fb-1(7+8TeV)	
CMS	Z(→bb)H	19fb-1(8TeV)	
CMS	**Comb.**	**19-25fb-1**	
ATLAS	Z(→ll)	25fb-1(7+8TeV)	arXiv:1402.3244 [hep-ex]
CDF	Z(→ll)H	10fb-1(2TeV)	CDF Note 11068

Indirect Limits

Coll.	Channel	Dataset	Cite
ATLAS	γγ,ZZ*,WW*,ττ,bb	25fb-1(7+8TeV)	ATLAS-CONF-2014-010
CMS	γγ, ZZ*, WW*, ττ,	10fb-1(7+8TeV)	JHEP06(2013)081

Uncovered Material

Coll.	Analysis	Cite
CDF+D0	Fermiophobic	PRD 88, 052014 (2013)
ATLAS	Fermiophobic	EPJC (2012) 72:2157
CMS	Fermiophobic	PLB 725, 36 (2013)
ATLAS	H→WW (high-mass)	ATLAS-CONF-2013-067
ATLAS	H→WW (2HDM)	ATLAS-CONF-2013-027
CMS	H→WW/ZZ (high-mass)	EPJC 73 (2013) 2469
CMS	H++	EPJC 72 (2012) 2189
ATLAS	H++	PRD 85, 032004 (2012)
D0	H++	PRL 108, 021801 (2012)
CDF	H++	CDF Public
LHCb	Long-lived	LHCb-CONF-2012-014
D0	Long-lived	PRL 103, 071801 (2009)
CDF	Long-lived	CDF Note 10356
CDF	Long-lived	CDF Note 10526

[Title Slide]

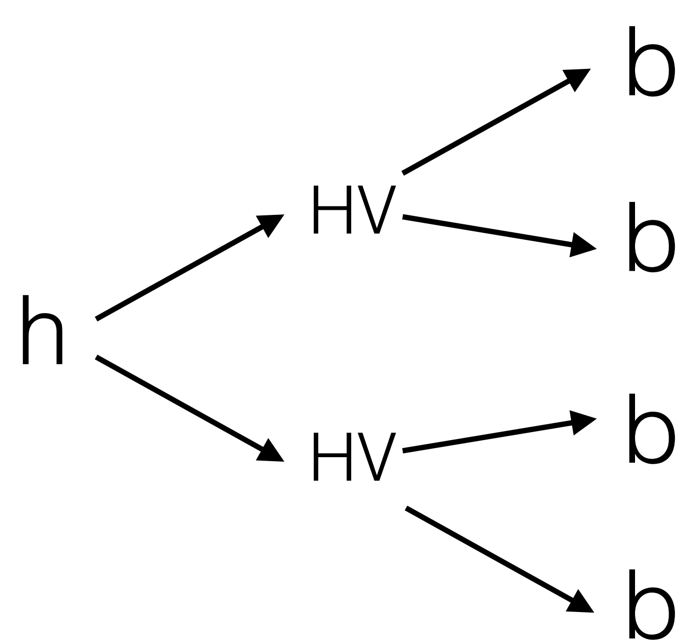
Backup

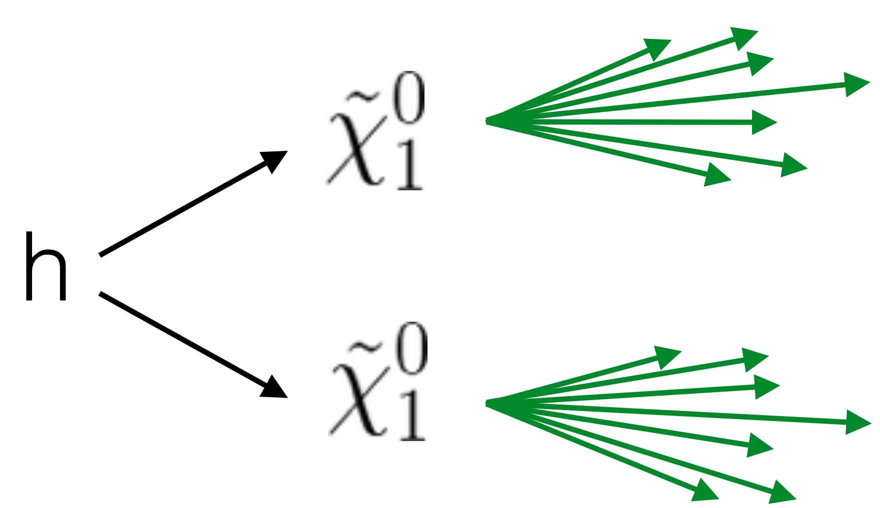
Contents

Long-lived Exotics

- Hidden Valley: new confining gauge group weakly coupled to SM:
  - v-hadrons (HV) couple preferentially to b-quarks due to helicity suppression.
  - Cosmological constraint: $\tau_{HV} \ll 1$ second
- RPV SUSY: LSP unstable (τ = 3 - 25 ps) and decays to 3 quarks

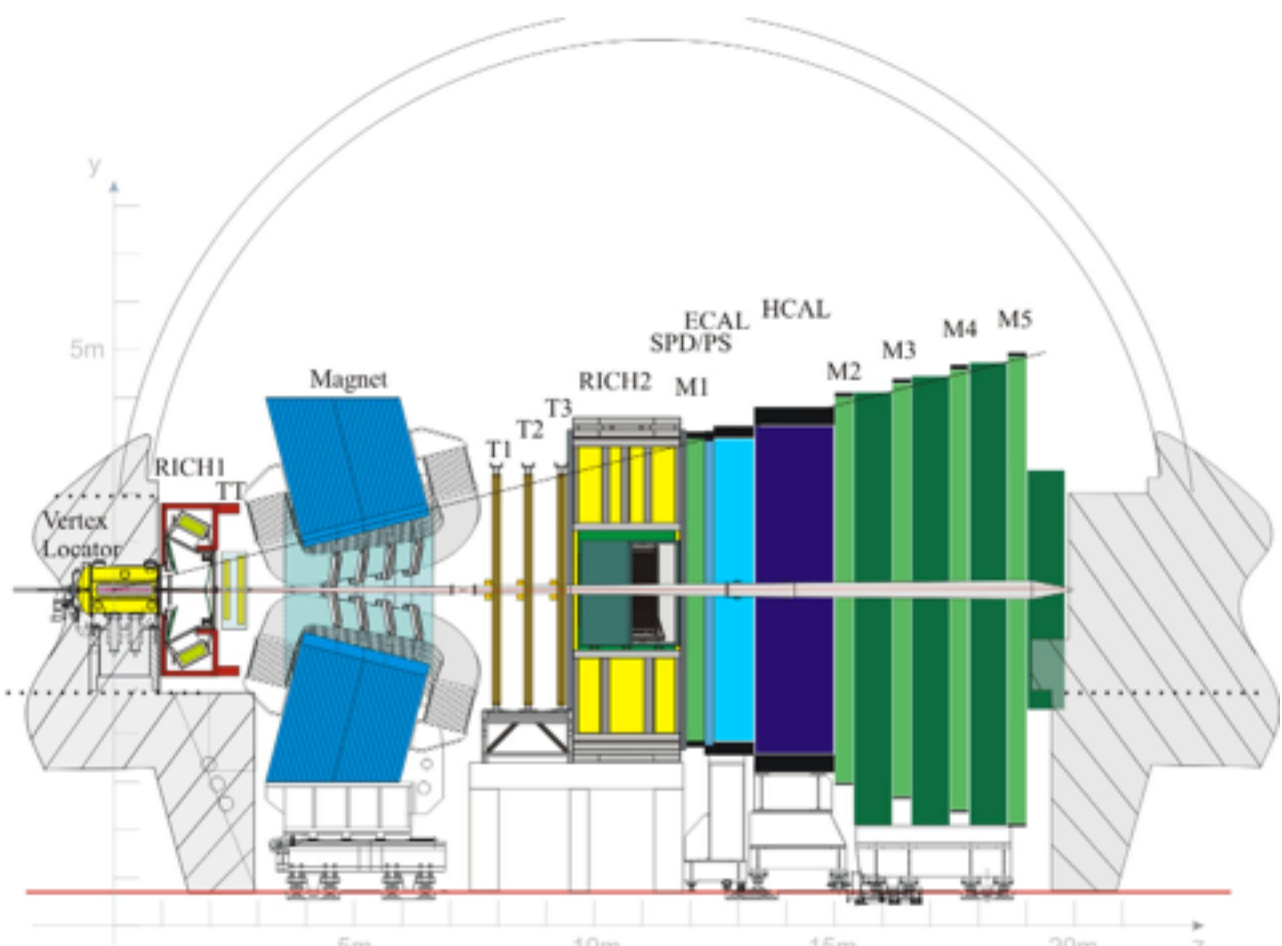
Coll.	Dataset	Cite
LHCb	**36pb-1(7TeV)**	**LHCb-CONF-2012-014**
D0	**3.6fb-1(2TeV)**	**PRL 103, 071801 (2009)**
CDF	6fb-1(2TeV)	CDF Note 10356
CDF	5fb-1(2TeV)	CDF Note 10526



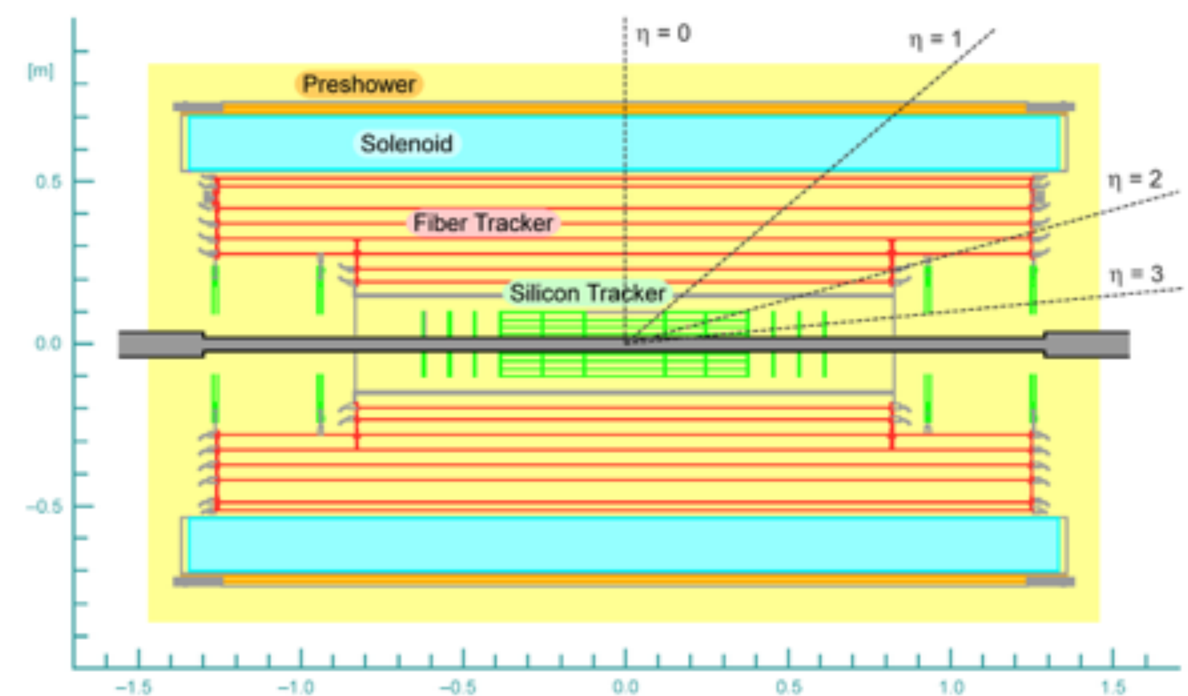


LHCb/D0: Detectors

LHCb

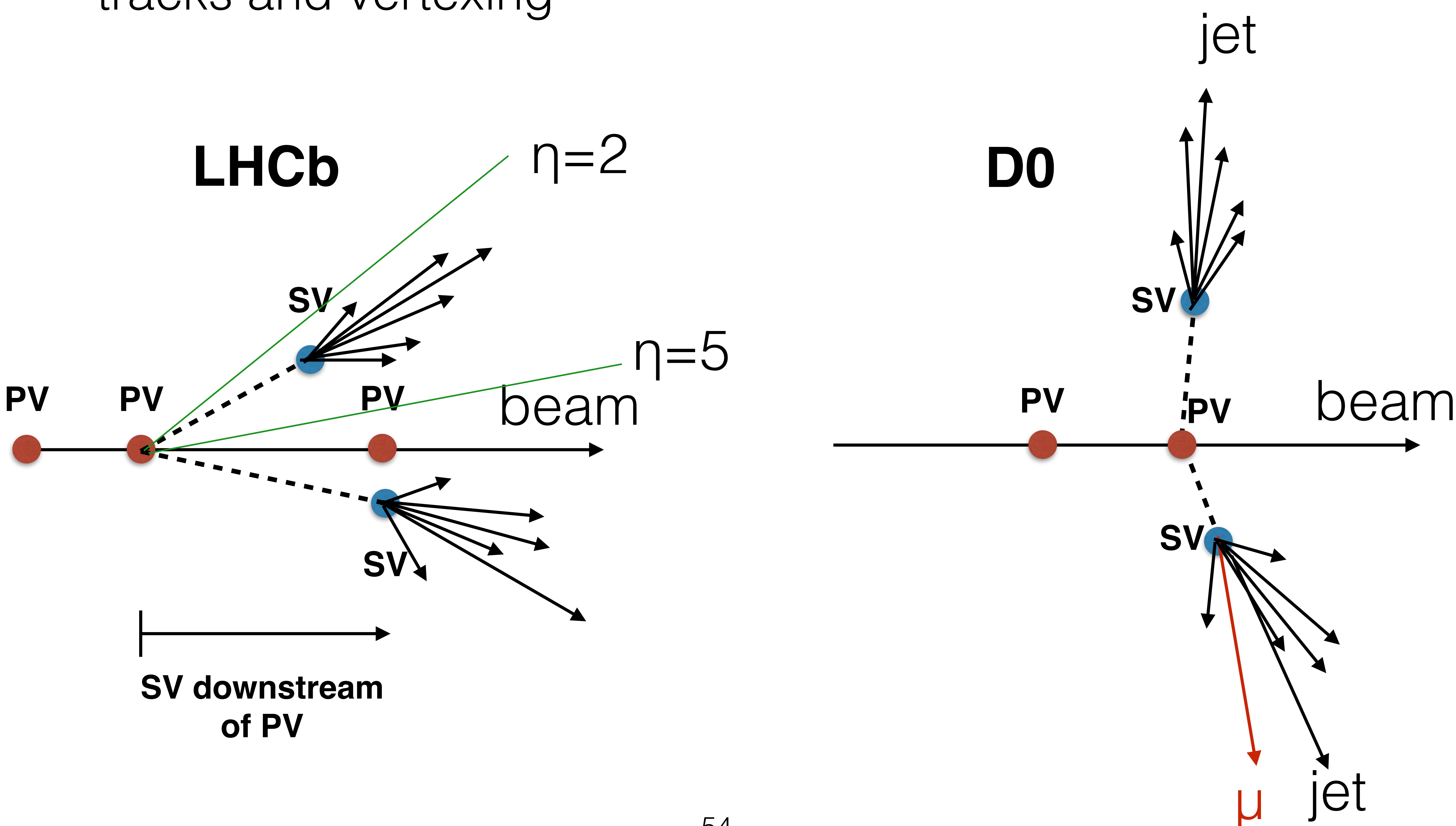


D0



LHCb/D0: Signature

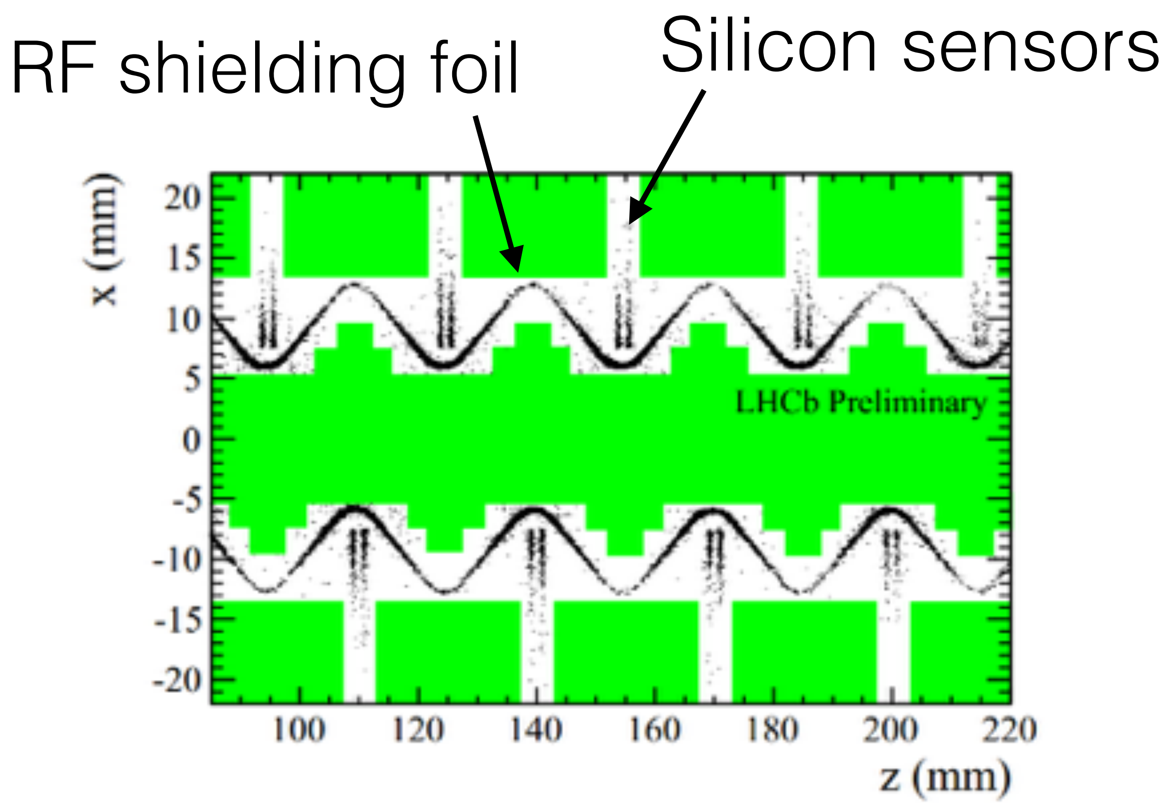
- 2 Secondary Vertices (SV) with tight requirements on tracks and vertexing



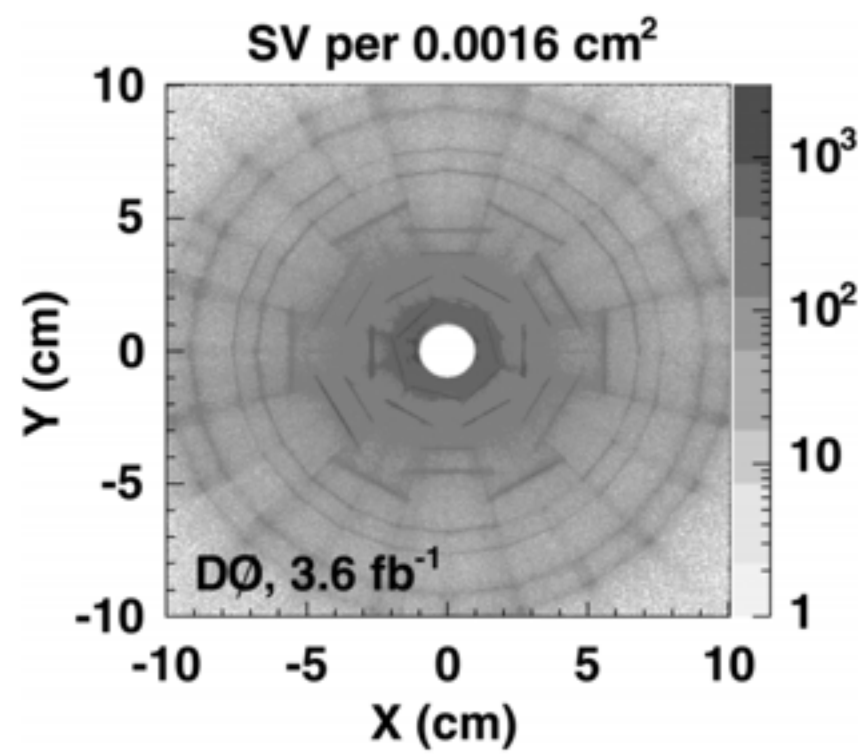
LHCb/D0: Background SVs

- Remove background SVs from interaction with detector

LHCb



D0



LHCb/D0: Results

LHCb BV Limits

BV model scan (τ_{LLP}=10 ps)

m_{LLP} [GeV]	30	35	40	48	55
m_{h^0} [GeV]	[pb]				
100	101	58	44	58	
105	100	75	44	39	
110	132	75	56	34	
114	128	91	47	32	46
120	148	93	58	34	31
125	179	90	61	41	29

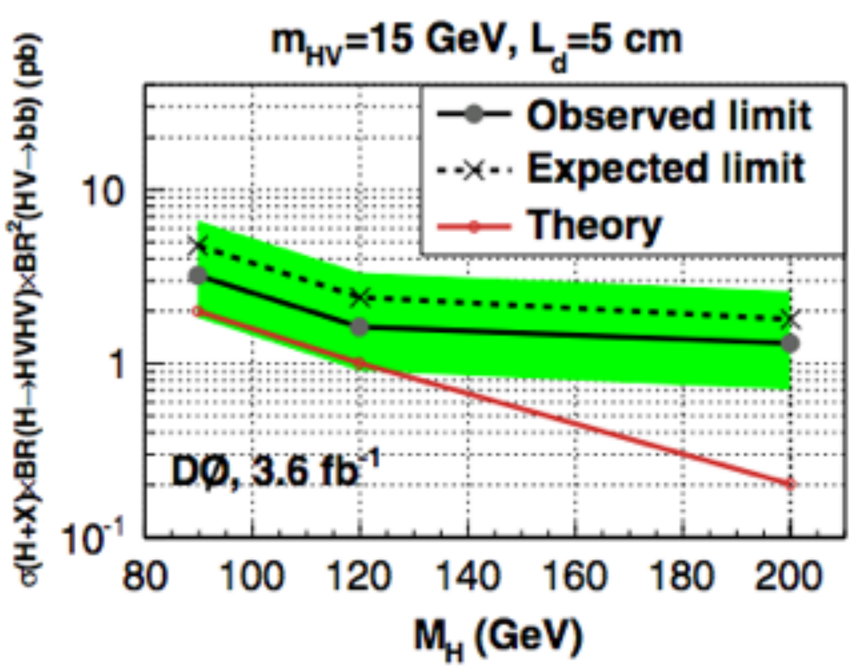
heavier = better →

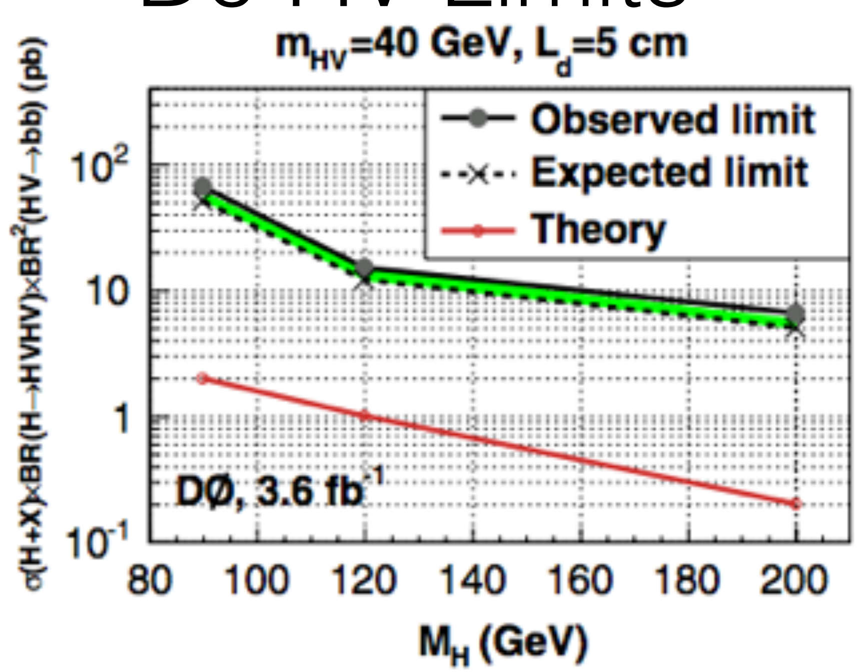
BV model scan (m_h=114 GeV)

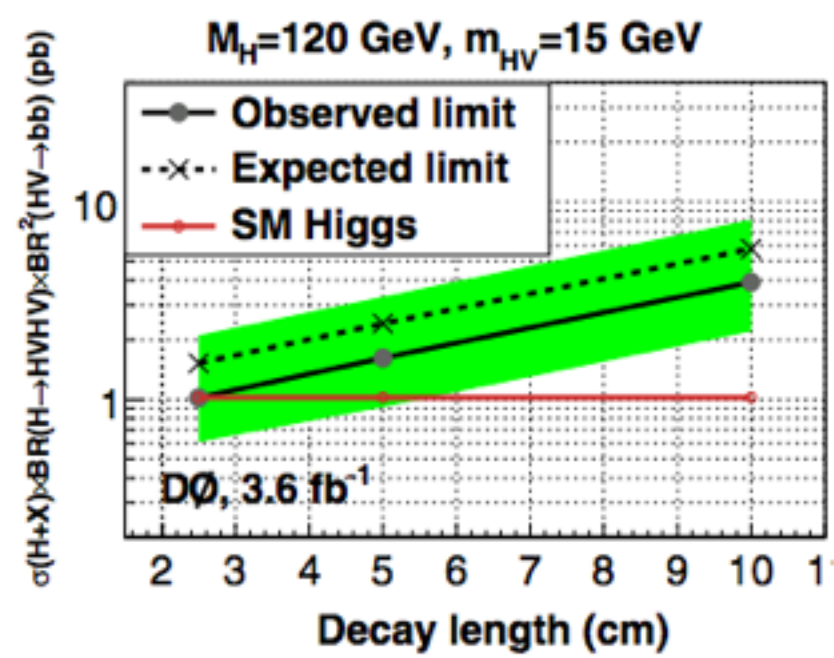
m_{LLP} [GeV]	30	35	40	48	55
τ_{LLP} [ps]	[pb]				
3	210	156	136	168	410
5	145	101	68	58	137
10	129	91	47	32	46
15	155	90	49	31	33
20	131	93	63	32	31
25	142	100	61	34	25

long life = better ↓

D0 HV Limits







Neutral MSSM

CMS: MSSM $H \to \tau\tau$

"Search for MSSM Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions" CMS-PAS-HIG-13-021

CMS: MSSM H→ττ (selection)

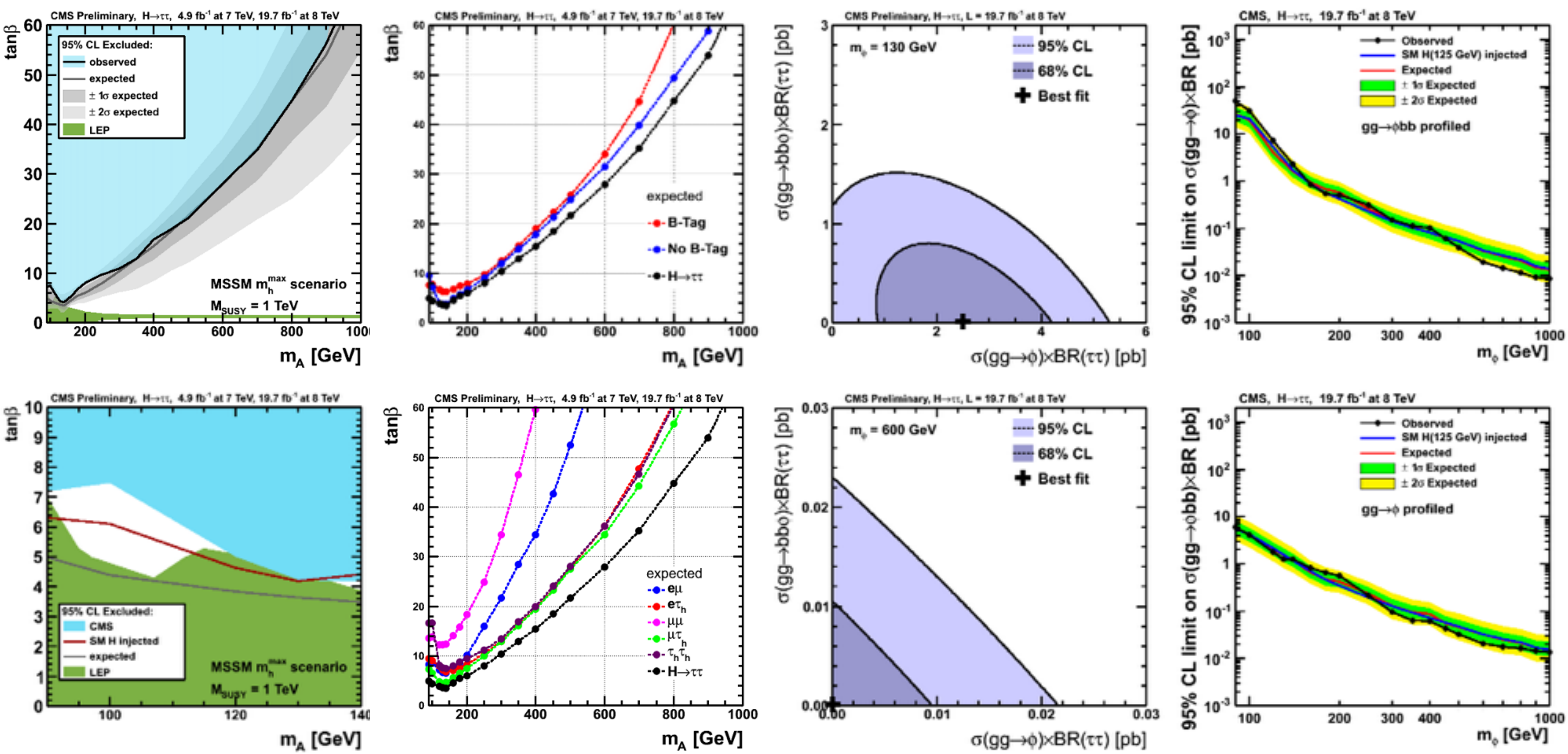
- **ehad/muhad:**
  - trigger: lepton+tau
  - ≥ 1 μ (20 GeV) or e (24 GeV)
  - 1 OS τ (20 GeV)
  - Z veto (reject events with OSSF lepton pair (15 GeV, loose isolation)
  - mT(MET,lep)<30 GeV
  - MET>25 (e-had only)
- **emu/mumu:**
  - trigger: dilepton
  - OS lepton pair (2nd pT>10 GeV)
  - eμ: $p_\zeta - 1.85\, p_\zeta^{vis} > -20$ GeV
  - μμ: BDT to reject Z→μμ
- **hadhad:**
  - trigger: ditau
  - OS tau pair (tau pt>45 GeV)
- Categorise:
  - **b-tagged:** ≥1 b-jet (20 GeV), <2 jets (30 GeV)
  - **no b-tag:** no b-jet (20 GeV)

CMS: MSSM H→ττ (bkg)

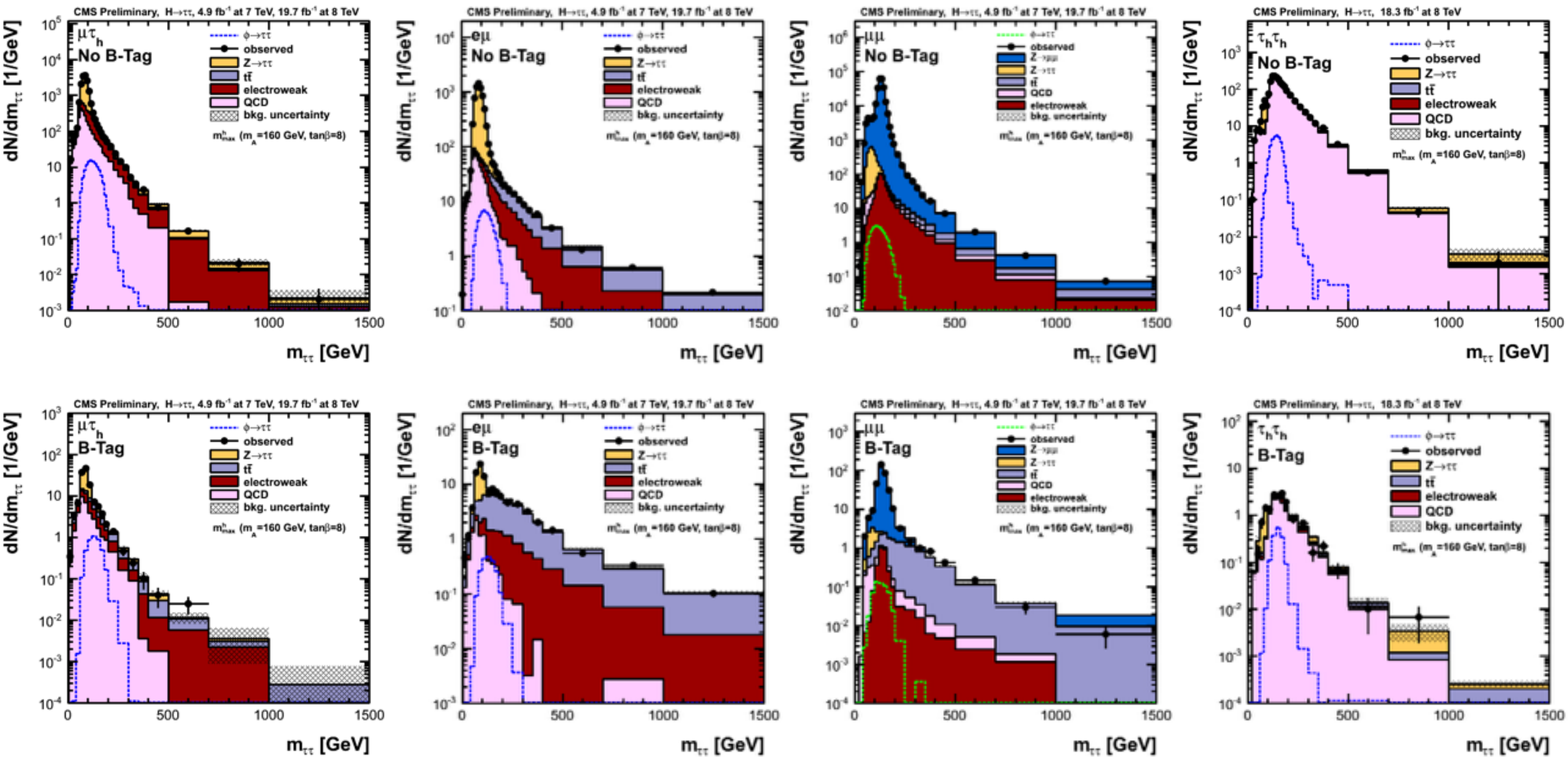
- Z->tautau: embedding
- had-had:
  - Multijet: tau ID fake-factor (caveat denom=fail+pass)
- lep-had:
  - Multijet: SS
  - W+jet: normalise in high mT
- e-mu:
  - W+jet+Multijet: lepton fake-factor (measured in multijet CR)
  - ttbar+Diboson: normalised in CRs

CMS: MSSM H→ττ (results)

- extract limit from binned max likelihood fit to $m_{\tau\tau}$ (SVFit) spectrum (2D $m_{\tau\tau}$, m_{vis} for μμ channel).



CMS: MSSM H→ττ (figs.)



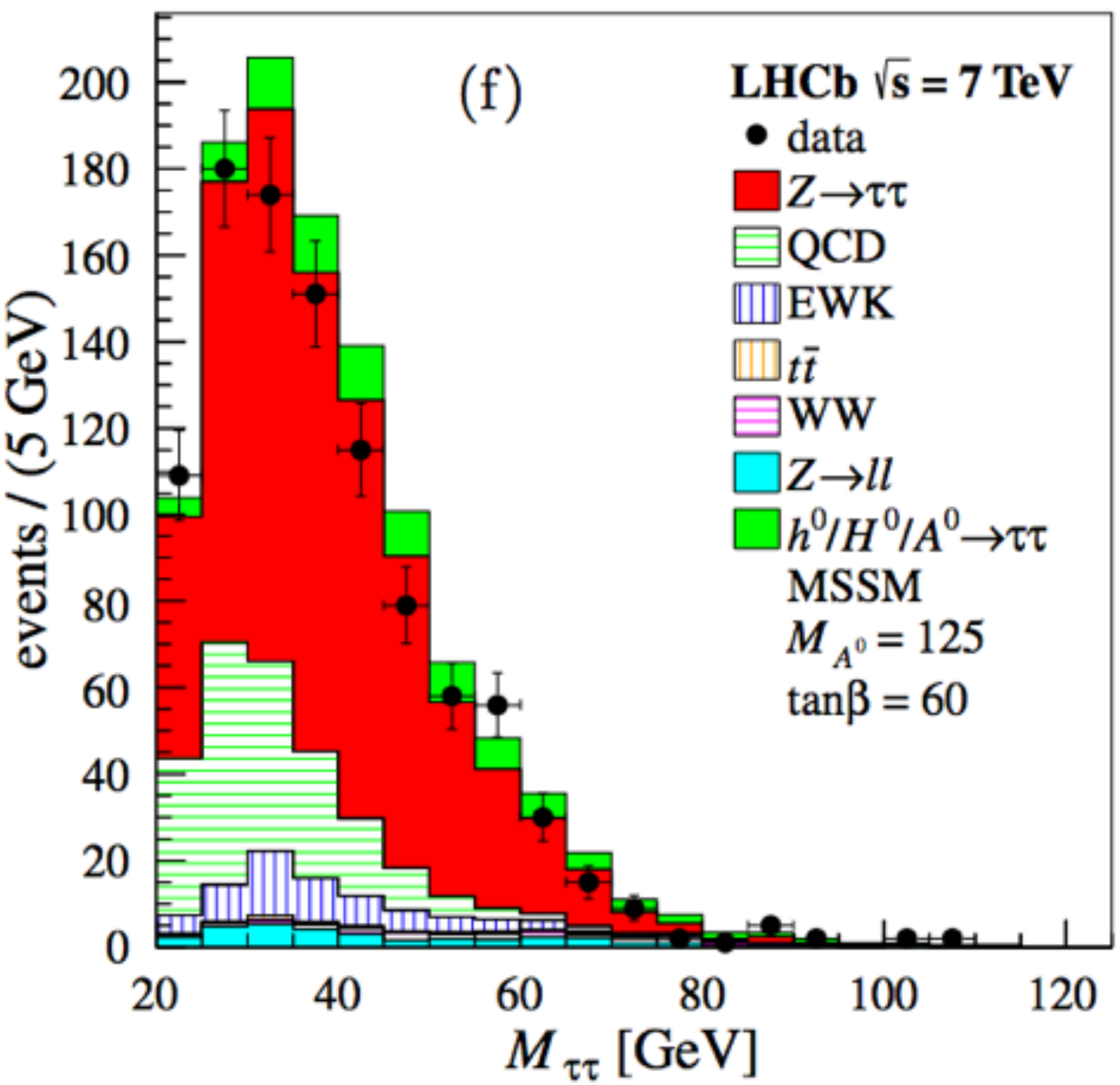
LHCb: MSSM $H \rightarrow \tau\tau$

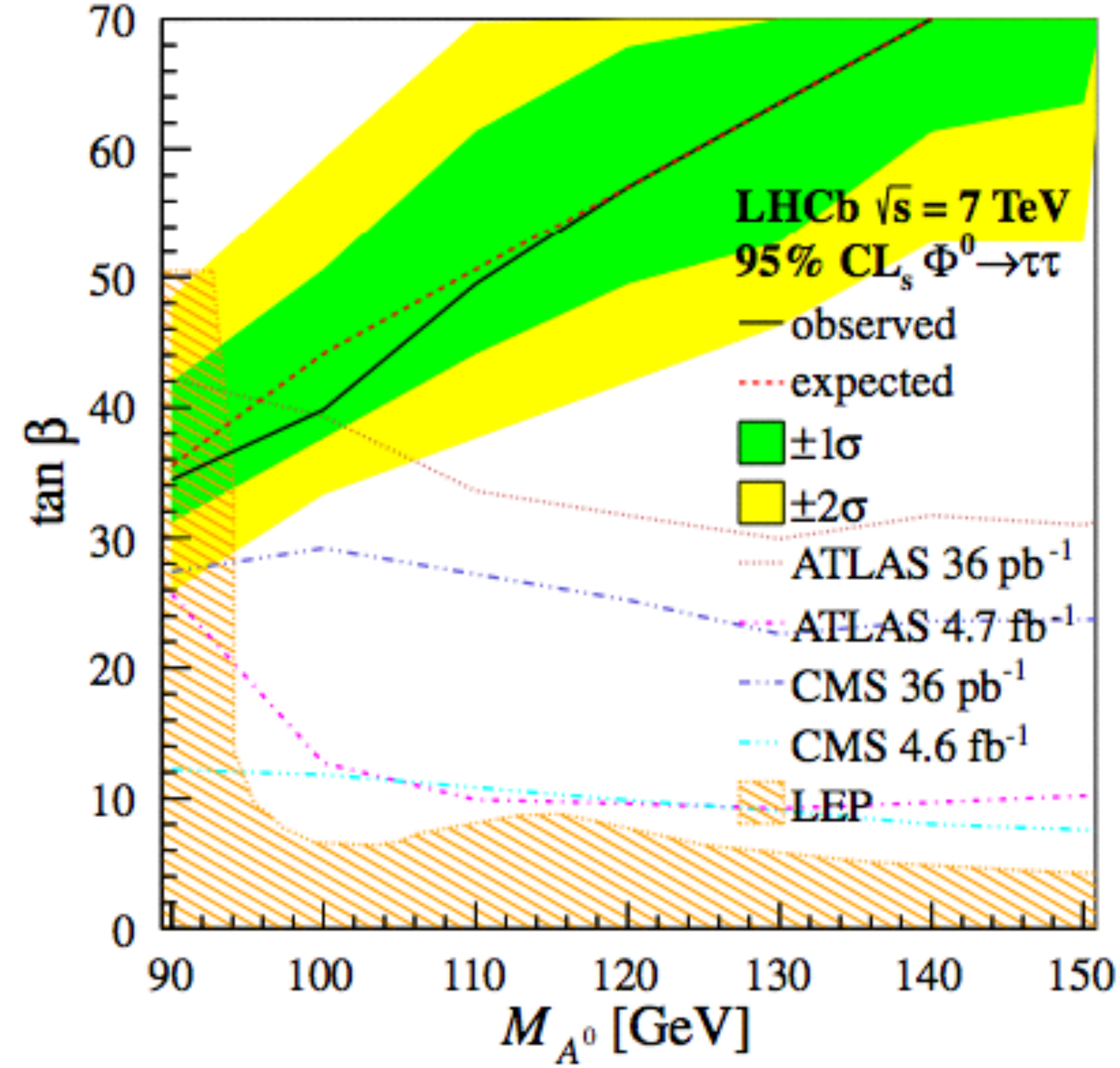
"Limits on neutral Higgs boson productio nin the forward region in pp collisions at sqrt(s) = 7 TeV" JHEP05(2013)132

LHCb: MSSM $H \rightarrow \tau\tau$ (details)

- Search in range $2<\eta<4.5$
- Channels: $\mu\mu,\mu e,e\mu,\mu\tau,e\tau$
- Selection:
  - isolated τ_1 (20 GeV) + τ_2 (5 GeV) ($2<\eta<4.5$)
  - $\Delta\phi(\tau_1,\tau_2)\sim\pi$
  - tracks from displaced vertex ($\mu\mu,\mu\tau,e\tau$ channels)
  - Z-mass veto ($\mu\mu$ channel)
- Backgrounds:
  - Multijet: SS
  - EW: MC+CR norm.
  - $H/Z \rightarrow \tau\tau$: MC with eff. +mass resolution corrections from data.
- Dominant Systematic: stat. on data-driven $Z \rightarrow \tau\tau$ eff.
- Fit mass distribution

LHCb: MSSM H→ττ (figs)





D0: MSSM H→ττ/bb

“Search for Higgs bosons of the minimal supersymmetric standard model in ppbar collisions at sqrt(s)=1.96 TeV” PLB 710, 569 (2012)

D0: MSSM $H \to \tau\tau/bb$ (details)

- channels: $\tau\tau$(μ-had), $b\tau\tau$(μ-had), bbb
- Tau types:
    - type 1 - 1p0n
    - type 2 - 1pXn
    - type 3 - 3p

D0: MSSM H→ττ/bb (selection)

- **ττ channel:**
  - trigger: single μ/jet/τ and μ+jet/τ
  - exactly 1 isolated μ (15 GeV)
  - exactly 1 OS τ (10 GeV) (sum track pt > 7/5/10 GeV for decay types 1/2/3)
  - $d_{z0}(\tau,\mu) < 2$ cm (vertex consistency)
  - mT(μ,MET) < 60 GeV (100 for tau type 2)
  - **No b-tag (inclusive ττ):**
    - no b-jet (NN_b>0.25)
    - Tighten tau pt and sum track pt thresholds (pT_τ>12.5 (15 for type 3), pT_{trk}>12.5/7/15)
    - mT(μ,MET)<40 GeV
    - Mhat>40 GeV ("minimum centre-of-mass energy" see note for definition)
  - **b-tagged (bττ):**
    - ≥1 b-jet (NN_b>0.25)
    - D_{MJ}>0.1 (MV disc. against multi jets)
    - D_{tt}>0.1 (MV disc. against ttbar)
    - combine NN_b, D_{MJ}, D_{tt} to make D_f (final disc. used for limit setting)
- **bbb channel:**
  - trigger: ≥ 3 b-jets
  - ≥ 3 b-jets (2x25+1x15 GeV, NN_b>0.775)
  - categorise 3/4 jet events.
  - cut on D_{bbb} (MV disc.)
  - M_{bb} final discriminant for limit setting

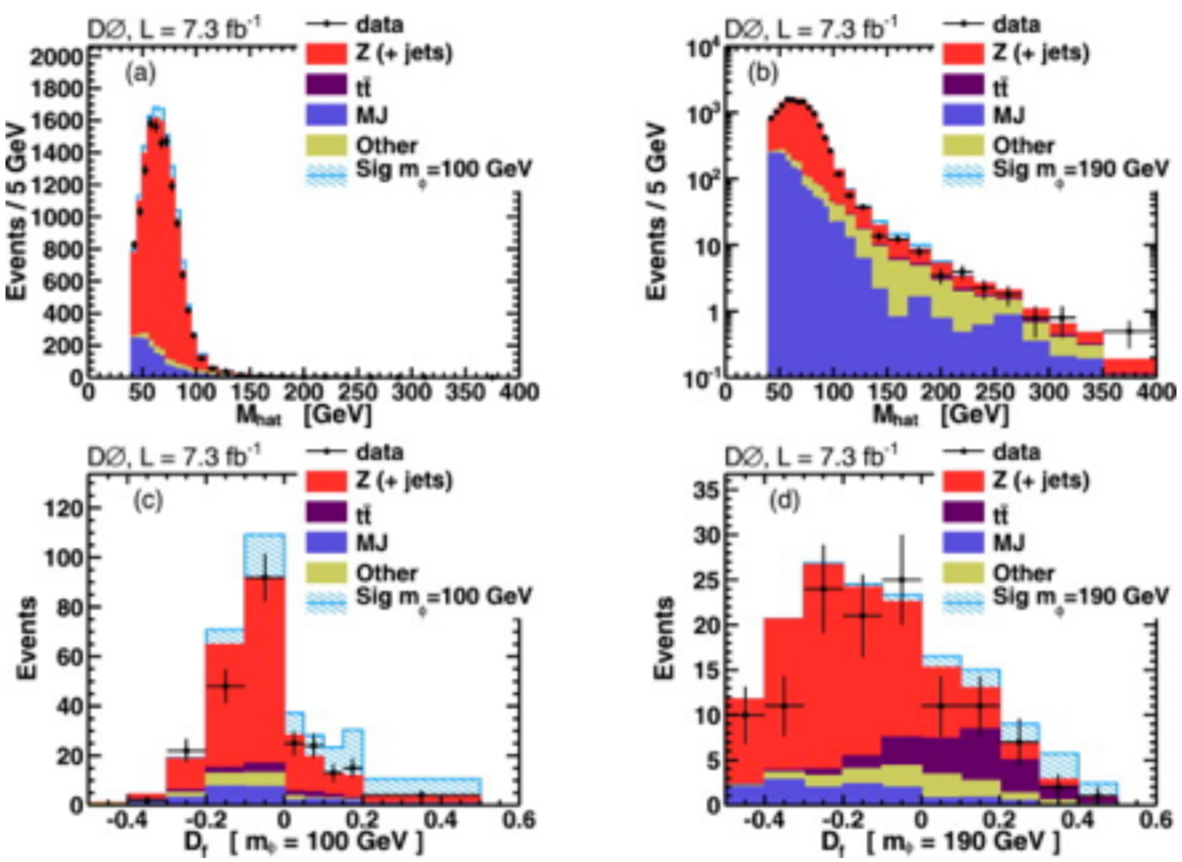
D0: MSSM H→ττ/bb (bkg.)

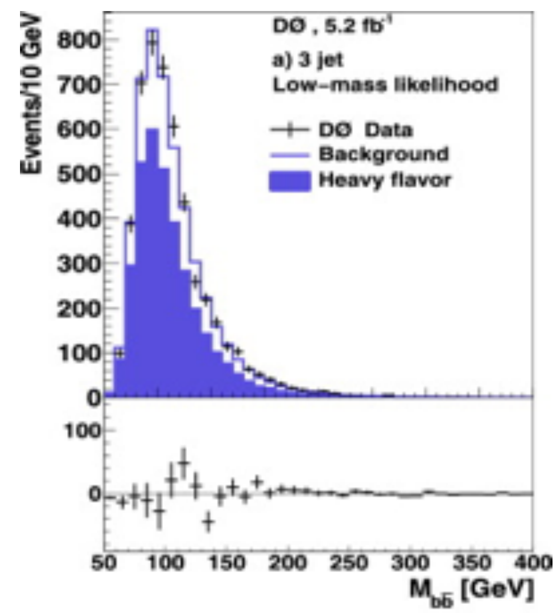
- **ττ channel:**
  - Ztautau: MC + reweight jet kin. in Njet bins using Z→μμ CR
  - W+jet: MC + normalised to data in Njet bins using W CR.
  - Multijet:
    - no-btag: OS/SS
    - b-tagged: lepton isolation fake-factor
    - systematics evaluated by using alternate method
- **bbb channel:**
  - Multijet: relative fractions determined from data. Very similar to a fake-factor on the 3rd b-jet. Essentially take events in data that have only 2 b-jets. Do 2D reweight of M_{bb} and D_{bbb} based on ratio of 3 and 2 b-jet events in simulation.

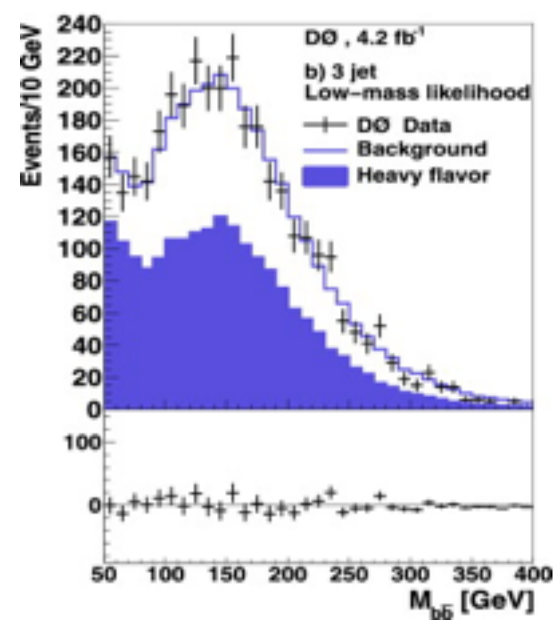
D0: MSSM $H \to \tau\tau/bb$ (results)

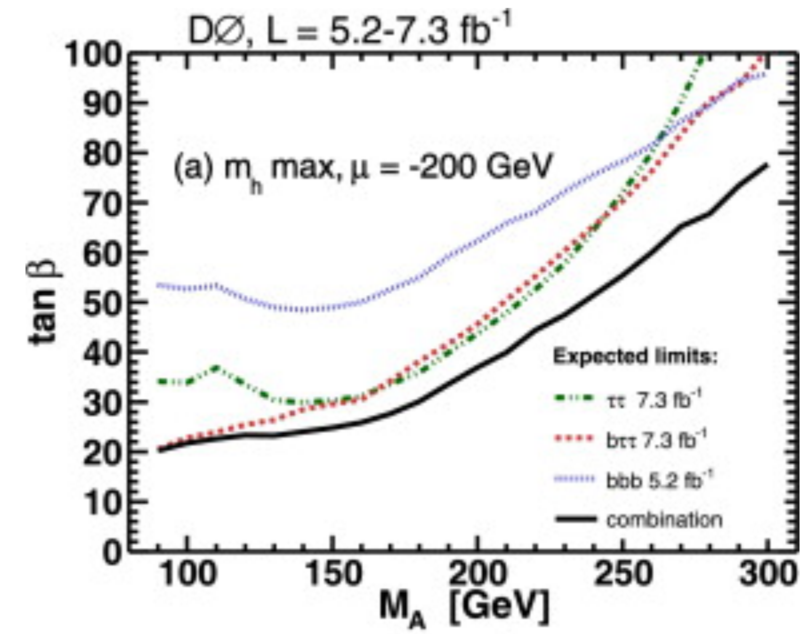
- Use CLs
- $b\tau\tau$ dominates at low mass
- $b\tau\tau+\tau\tau$ similar in intermediate mass
- bbb can help at high mass (but is very model dependent, eg. helps for mu=+200 GeV, but useless for mu=-200 GeV).
- limits no better than tanb~20, comparable to 36pb-1 results from LHC in low-mass range.

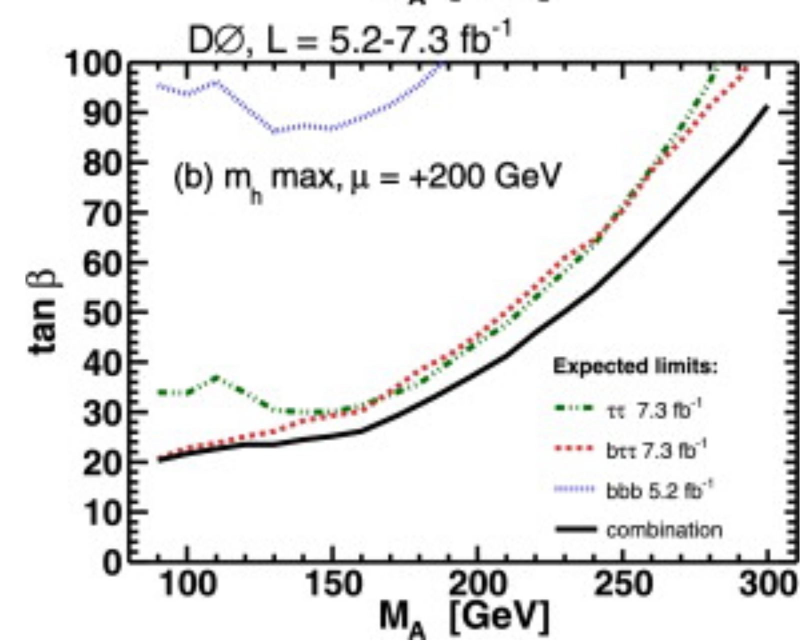
D0: MSSM H→ττ/bb (figs.)











D0+CDF: MSSM H→bb

"Search for Neutral Higgs bosons in events with multiple bottom quarks at the Tevatron" PRD 86, 091101

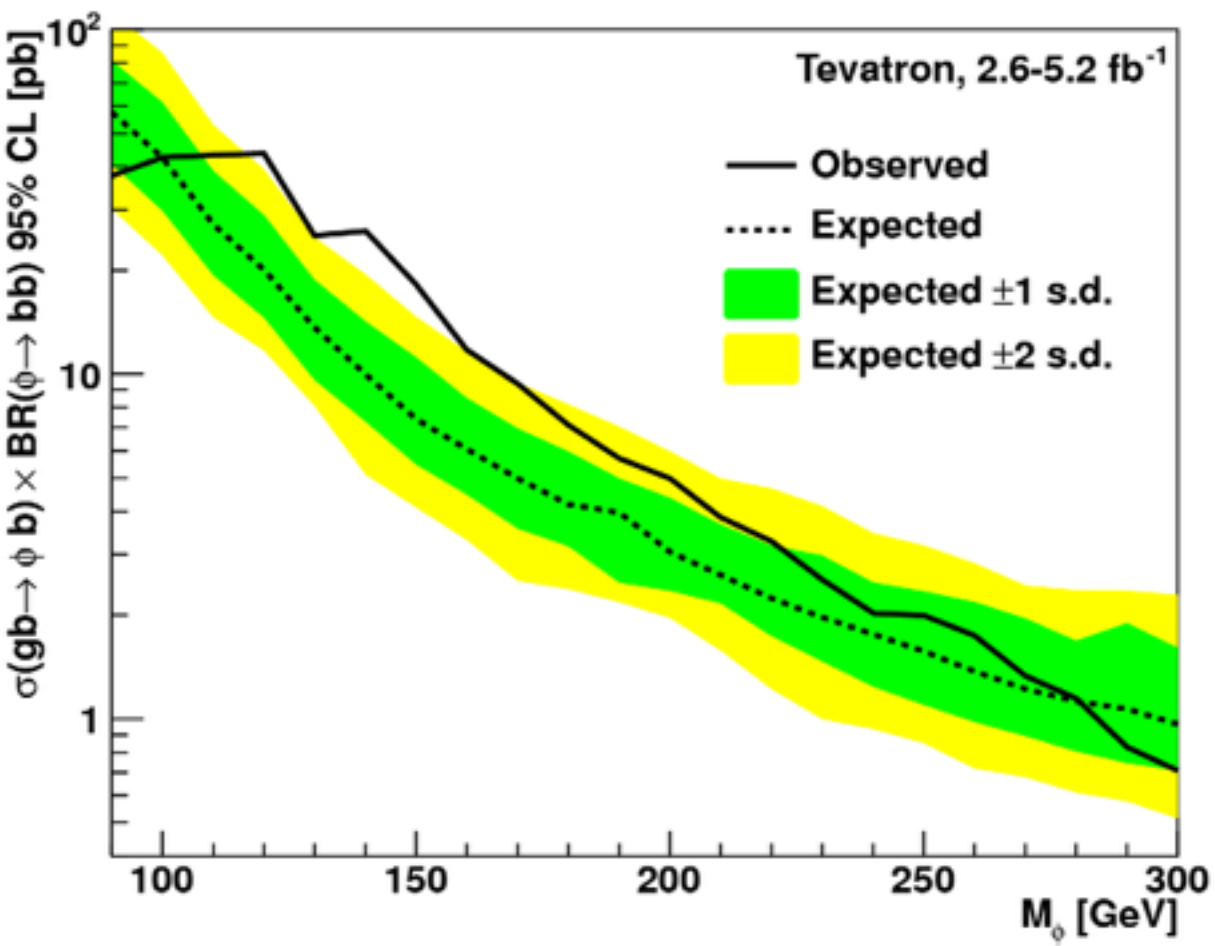
D0+CDF: MSSM H→bb (details)

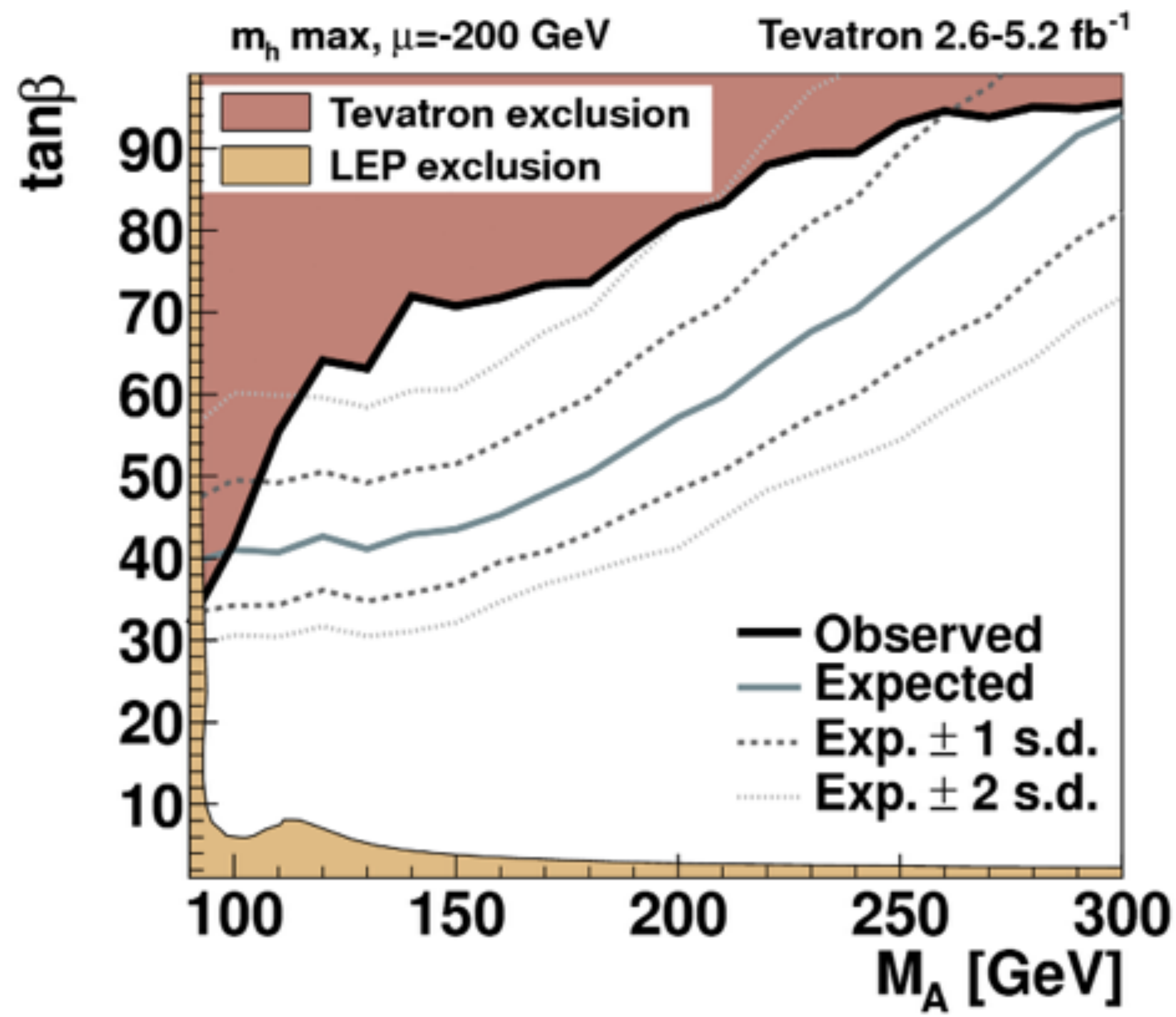
- While searches for H->tautau are relatively insensitive to higher order radiative corrections due to cancellations between the production and decay processes, this is not the case for H->bb. Thus information from decays to bb together with stringent limits from decays to tautau can constrain higher-order effects and yield additional information about electroweak symmetry breaking, supersymmetry or other new physics beyond the SM with similar final states such as pair production of colour octet scalars.

D0+CDF: MSSM H→bb (analysis)

- **Selection:**
  - trigger: 2/3 jets with b-tagging
  - ≥ 3 b-jets
- **Backgrounds:**
  - CDF:
    - m_{j1j2} templates categorised into jet type and kinematics
    - constructed from **2 b-jet CR** with weights applied for 3rd b-jet
  - D0:
    - **2 b-jet CR** with SR/CR transfer factor from MC
- **Dominant Uncertainties:**
  - bkg: b-tag eff. and light-jet cont.
  - sig: b-tag eff.
- **Results:**
  - template fit of sig/bkgs in SR (bkg. completely floating)
  - combination better than D0 alone by 25% at low mass, steadily falling to negligible at 300 GeV.
  - excesses at 120 (2.5σ) and 140 (2.6σ) GeV, driven by excesses:
    - CDF: 150 GeV (2.8σ)
    - D0 : 120 GeV (2.5σ)
  - **2σ excess** in combined analysis.

D0+CDF: MSSM H→bb (figs.)





CMS: MSSM $H \rightarrow bb$

“Search for a Higgs boson decaying into a b-quark pair and produced in associated with b quarks in proton-proton collisions at 7 TeV” PLB 722, 207 (2013)

CMS: MSSM H→bb (details)

- dominant background Multijet with ≥2 real b-jets
- categories: “all-hadronic” and “semi-leptonic”
- strategy: look for peak in leading dijet mass spectrum in events with 3 b-jets.

CMS: MSSM H→bb (selection)

- **All Hadronic:**
  - trigger: 2/3 jet (≥2 b-jets), 3 cats: low-pt (1,3), high-pt (2)
  - Low-mass analysis (m_H<180 GeV): triggers 1+3 (2.7 fb-1)
  - Medium-mass analysis (180≤m_H≤350 GeV): triggers 1+2 (4.0 fb-1):
  - ≥3 b-jets (diff. pT thresholds for low/med mass analyses)
- **Semi-leptonic:**
  - trigger: 1μ + 1/2 central jets and 1/2 b-jets (4.8 fb-1)
  - 1μ (15 GeV)
  - ≥3 b-jets (ΔR>1 jet separation)
  - μ in 1 of 2 leading jets

CMS: MSSM H→bb (bkg./ana.)

- **All Hadronic:**
  - 2D templates: M_{j1j2} vs X_{123} (event b-tag weight).
  - split for diff. jet types/combinations (Qbb, Cbb, Bbb, bQb, bCb, bBb, bbQ, bbC, bbB)
  - create by weighting j3 in 2 b-tag CR with tagging probability
  - merge similar templates to leave only 5
  - fit bkg only vs bkg+sig templates in SR (no constraints on bkg norm.)
- **Semileptonic:**
  - 2 methods (statistically combined):
    - fake-factor on 3rd b-jet.
    - another interesting method (should read if have time)
  - rem. ovl. events from had. sample (~2.7%) and fit M_{j1j2} in SR.
- **Dominant systematic:** b-tag efficiency

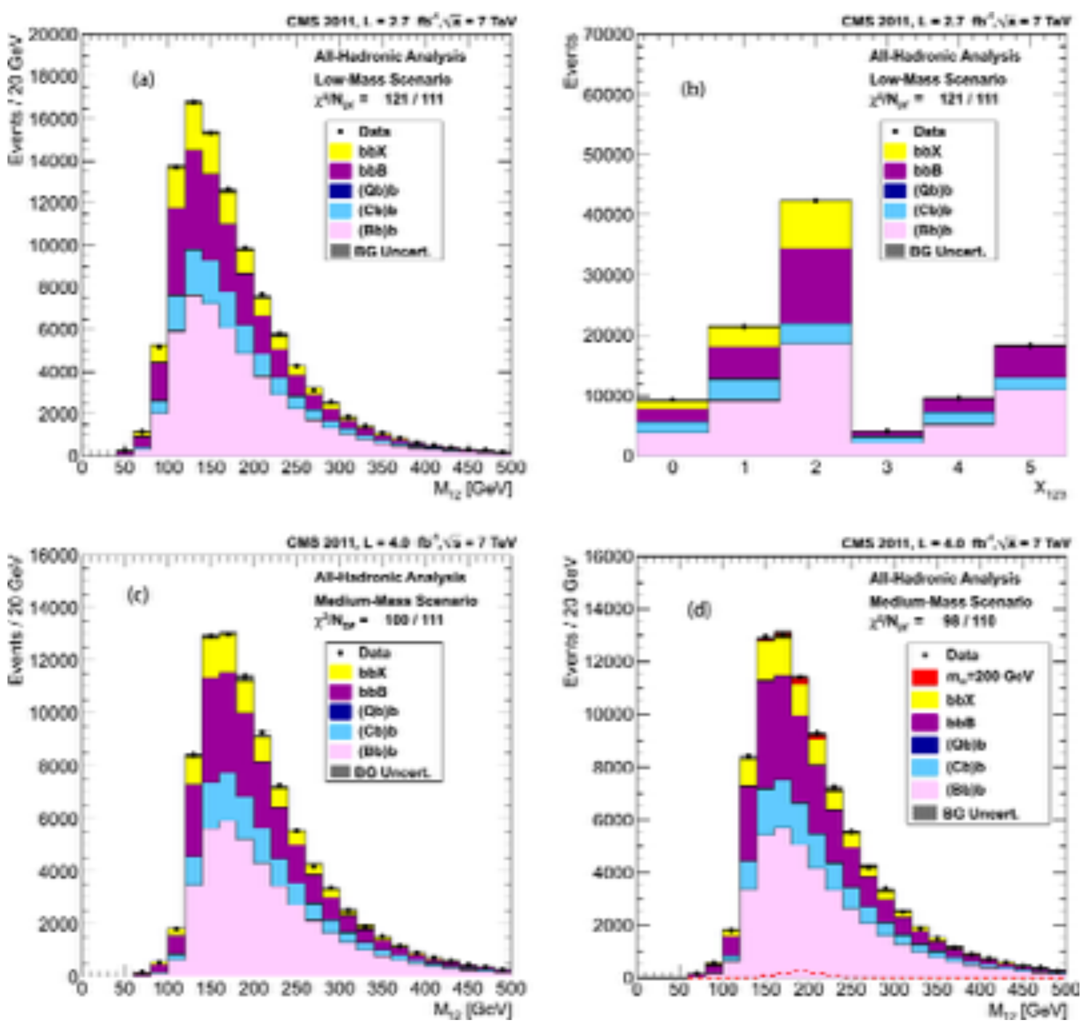
CMS: MSSM H→bb (results)

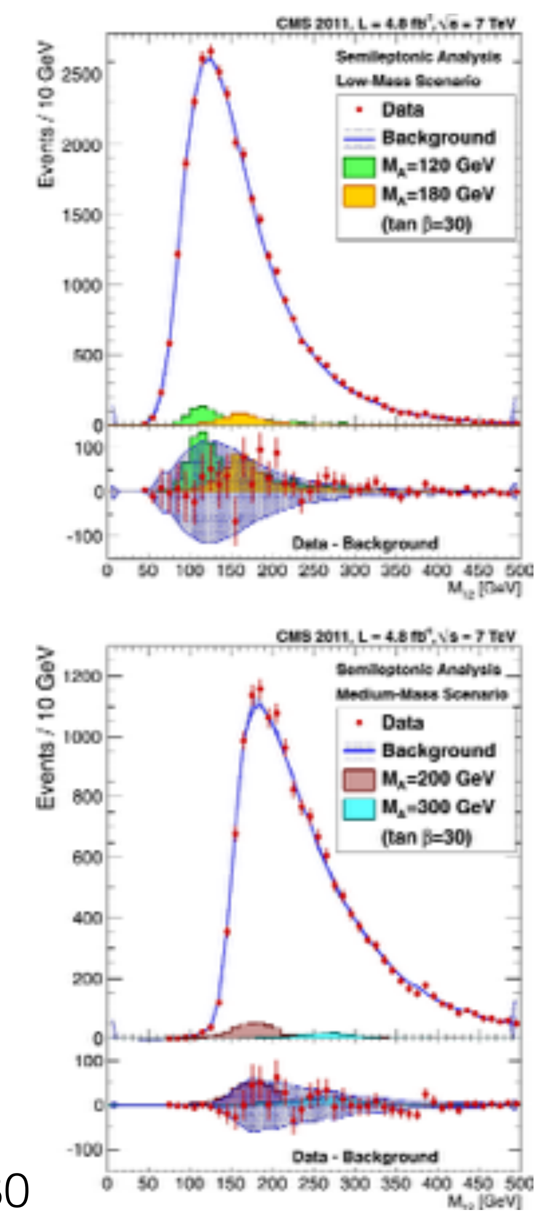
- all hadronic has generally larger signal efficiency but requires high jet thresholds, so both come out with similar sensitivity.

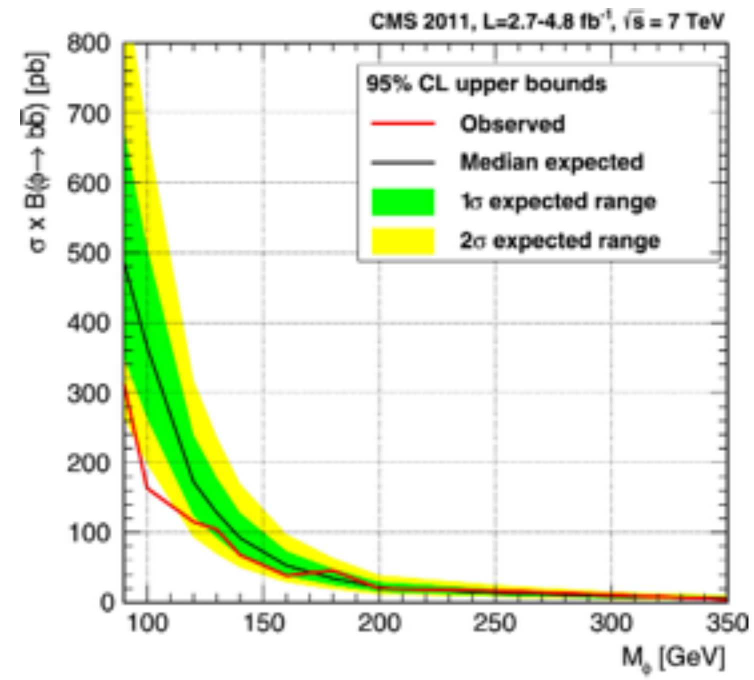
- excludes 2σ excess from Tevatron.

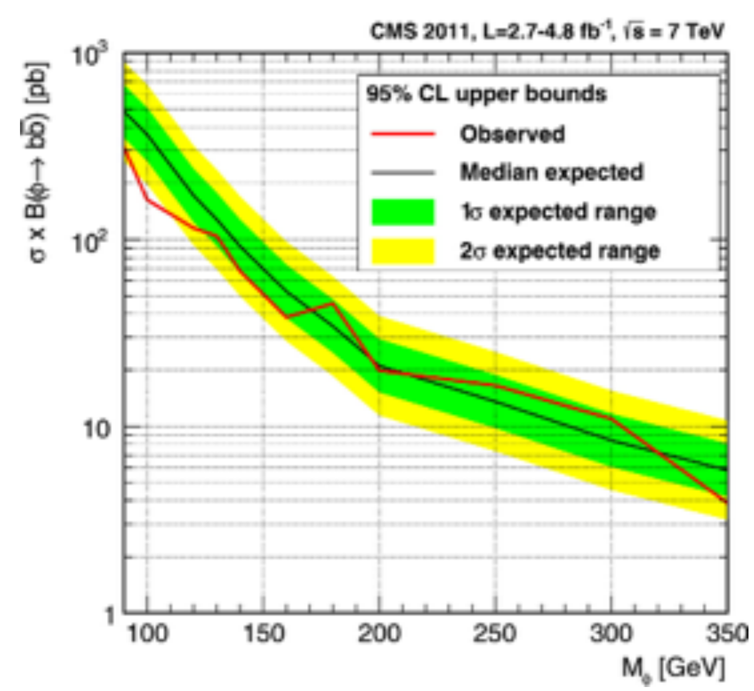
Semileptonic

All Hadronic



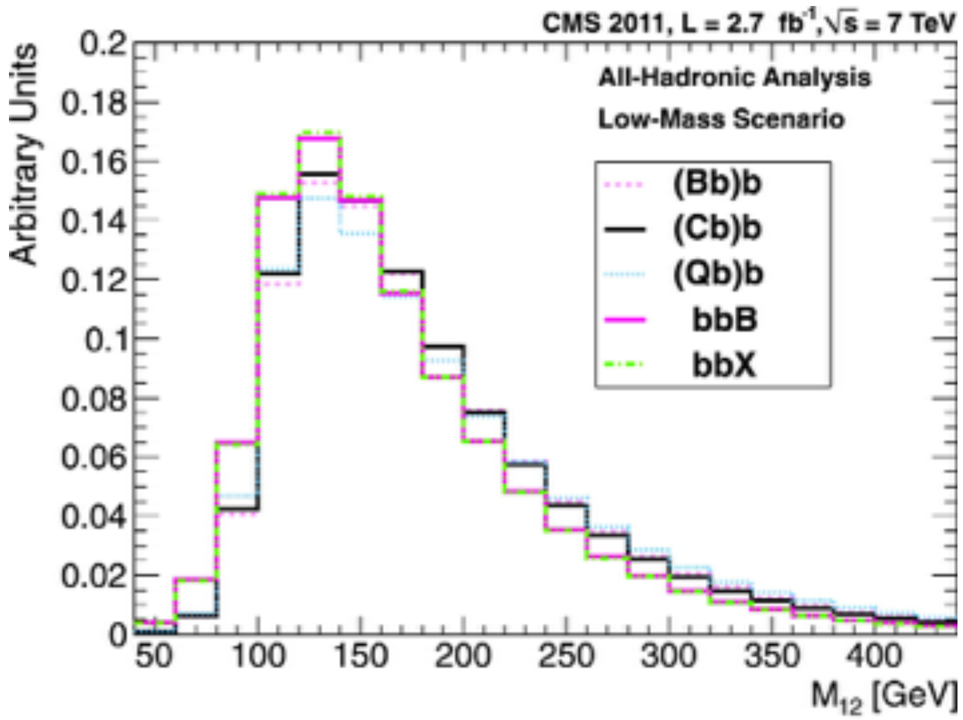


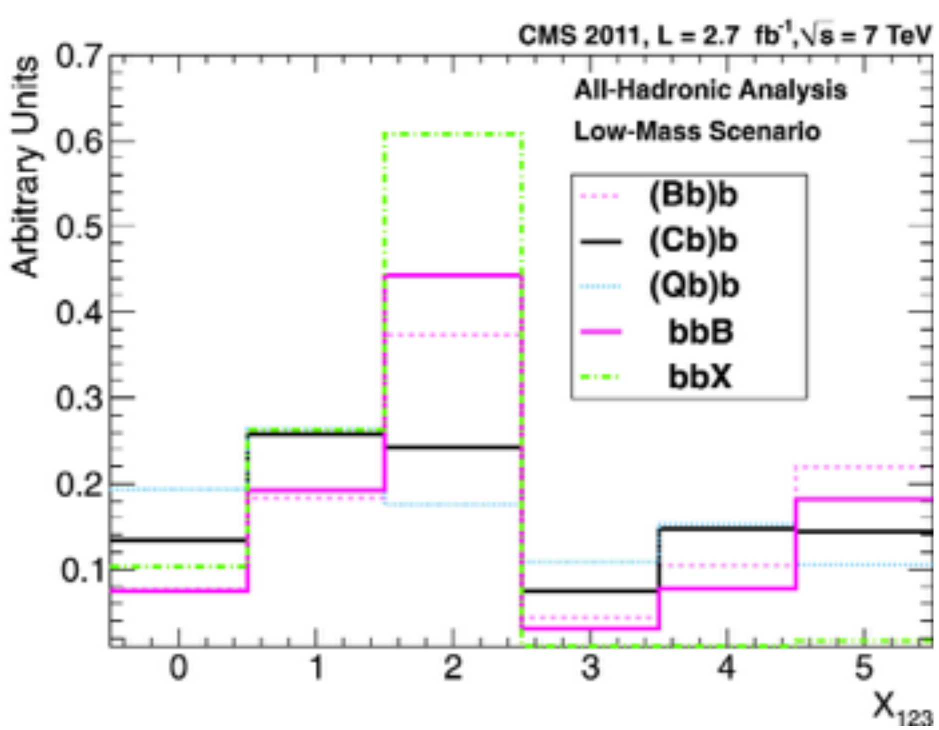




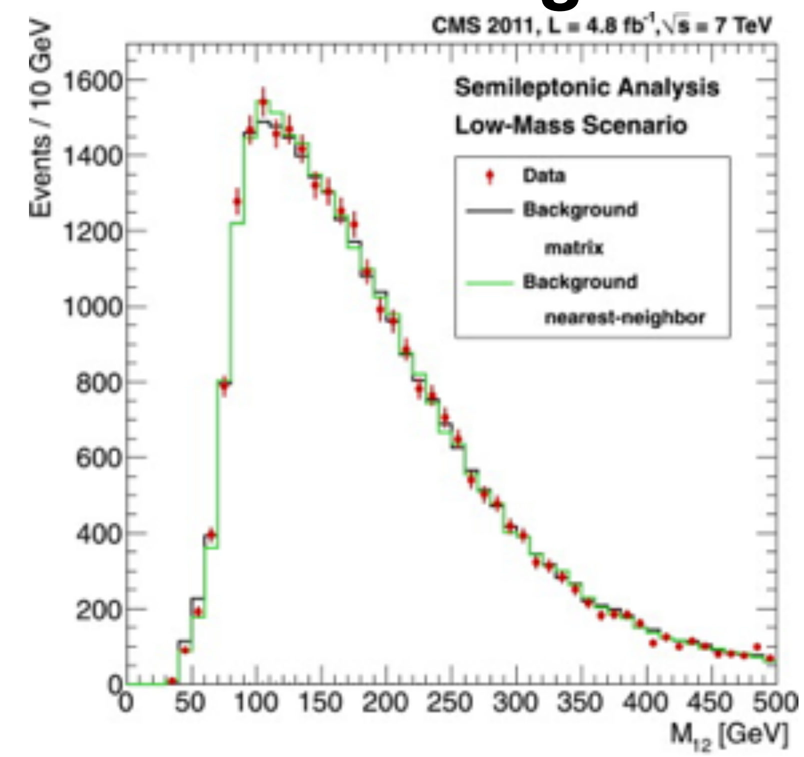
CMS: MSSM H→bb (figs)

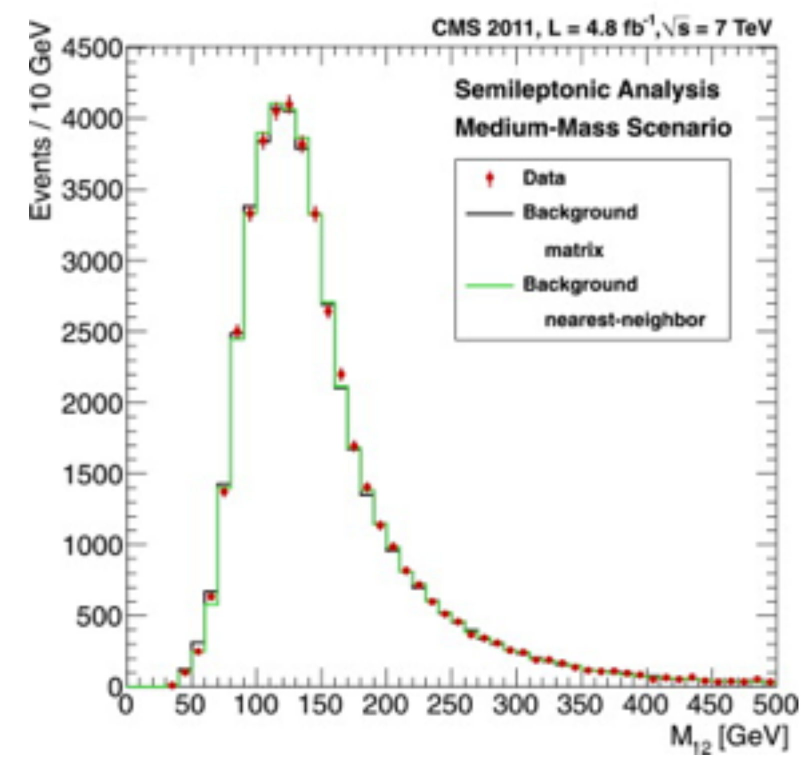
Multijet templates





Control region





Charged

ATLAS: $H^{\pm} \rightarrow \tau\nu$+jets

"Search for charged Higgs bosons in the tau + jets final state with pp collision data recorded at sqrt(s)=8 TeV with the ATLAS experiment" ATLAS-CONF-2013-090

ATLAS: $H^{\pm} \rightarrow \tau\nu$ (details)

- Charged Higgs in extended higgs sectors (eg. Higgs triplets or 2HDMs)
- $m_{H+} < m_t$ and $\tan\beta > 3$ and: $H^{\pm} \rightarrow \tau\nu$ dominates
- $m_{H+} > m_t$, $H^{\pm} \rightarrow \tau\nu$ CAN be sizeable (but not necessarily).
- **Find out more details on top/high mass searches**

ATLAS: $H^{\pm} \rightarrow \tau\nu$ (selection)

- Trigger: τ (29 GeV) + MET (40 GeV)
- ≥4 jets (≥1 b-tagged)
- exactly 1 τ (40 GeV)
- no additional τ (25 GeV)
- no e/μ (25 GeV)
- MET > 65 GeV
- σ(MET) > 13 (√GeV) (*)

- alterations for high-mass analysis:
  - 3 jets
  - MET>80 GeV
  - σ(MET) > 12 (√GeV)
- Final discriminant $m_T(\tau, MET)$

- (*) $\sigma(MET) = MET / 0.5\sqrt{\Sigma p_{T,trk}}$, trk PV matched

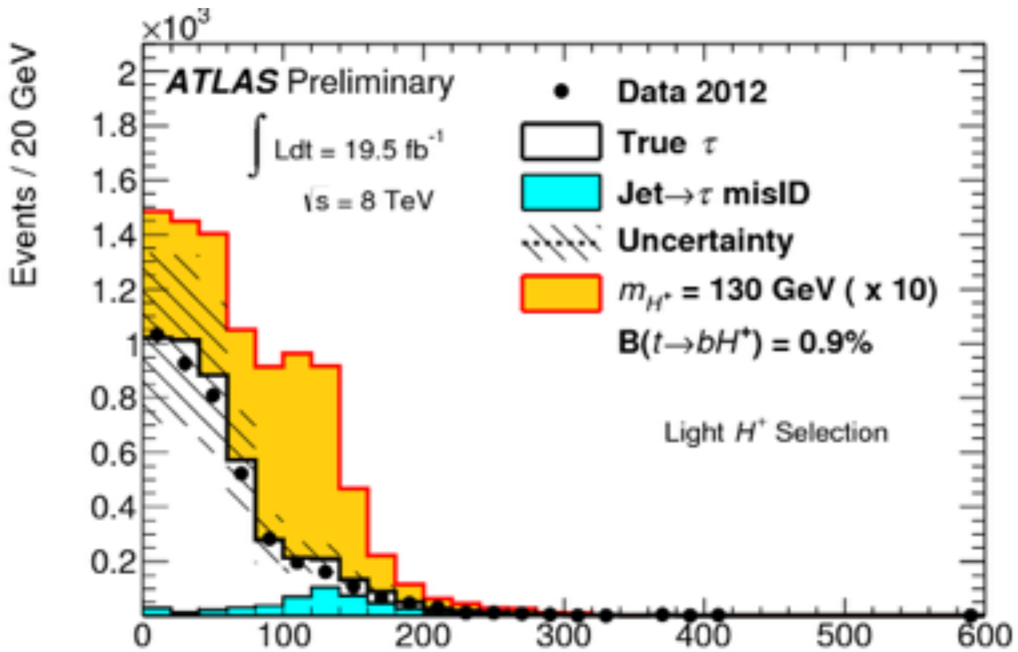
ATLAS: $H^{\pm}\rightarrow\tau\nu$ (bkg./sys.)

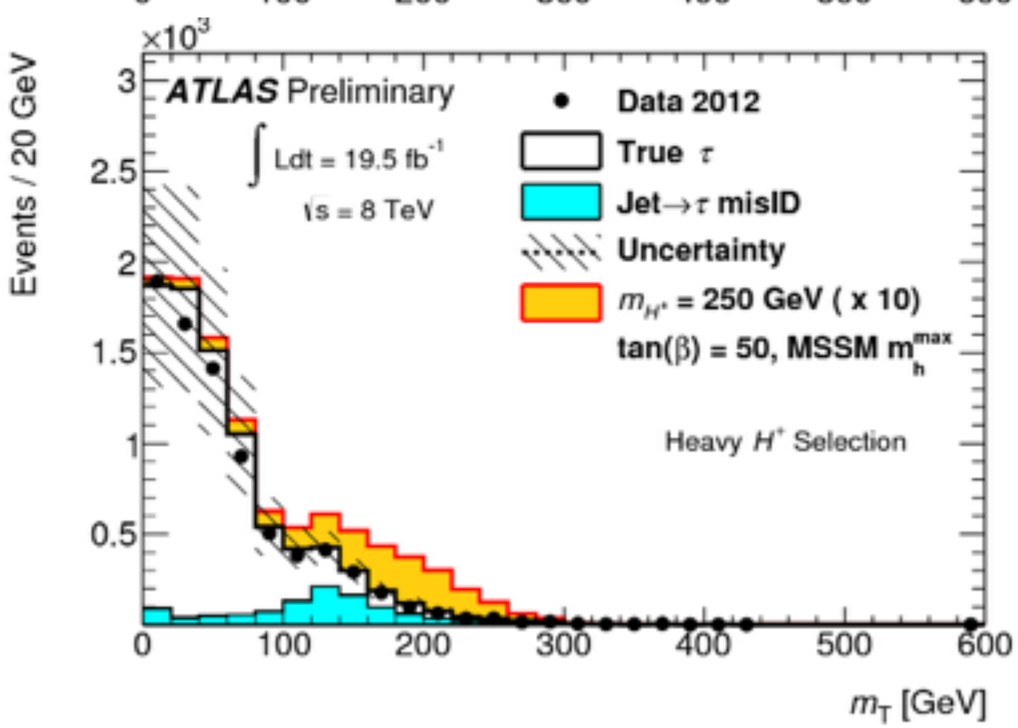
- Dominant bkg: ttbar
- Real τ component from MC
- jet→τ fakes (fake-factor):
  - Pseudo fake-factor method with inclusive denominator
  - Weight both loose and tight taus using function of ID eff. and fake-rate (*)
  - fake-rate binned in: prongs, pT, η and number of isolation tracks
  - Fake-rate measured in W+jet CR, with contam. from real τ and lepton fakes subtracted
  - Multijet CR for systematics
  - Checked in 2 CRs:
    - Top quark CR: heavy higgs selection + 2 bjets
    - Zero b-jet CR: heavy higgs selection + 0 bjets
- Systematics:
  - Sig: JES, b-tag eff., TES, Tau ID, pileup
  - MC BKG: JES, b-tag eff, TES and TauID
  - Data BKG: fake-rate stat., jet comp., Tau ID (from subtraction).
  - tau+MET trig. eff. measured in house

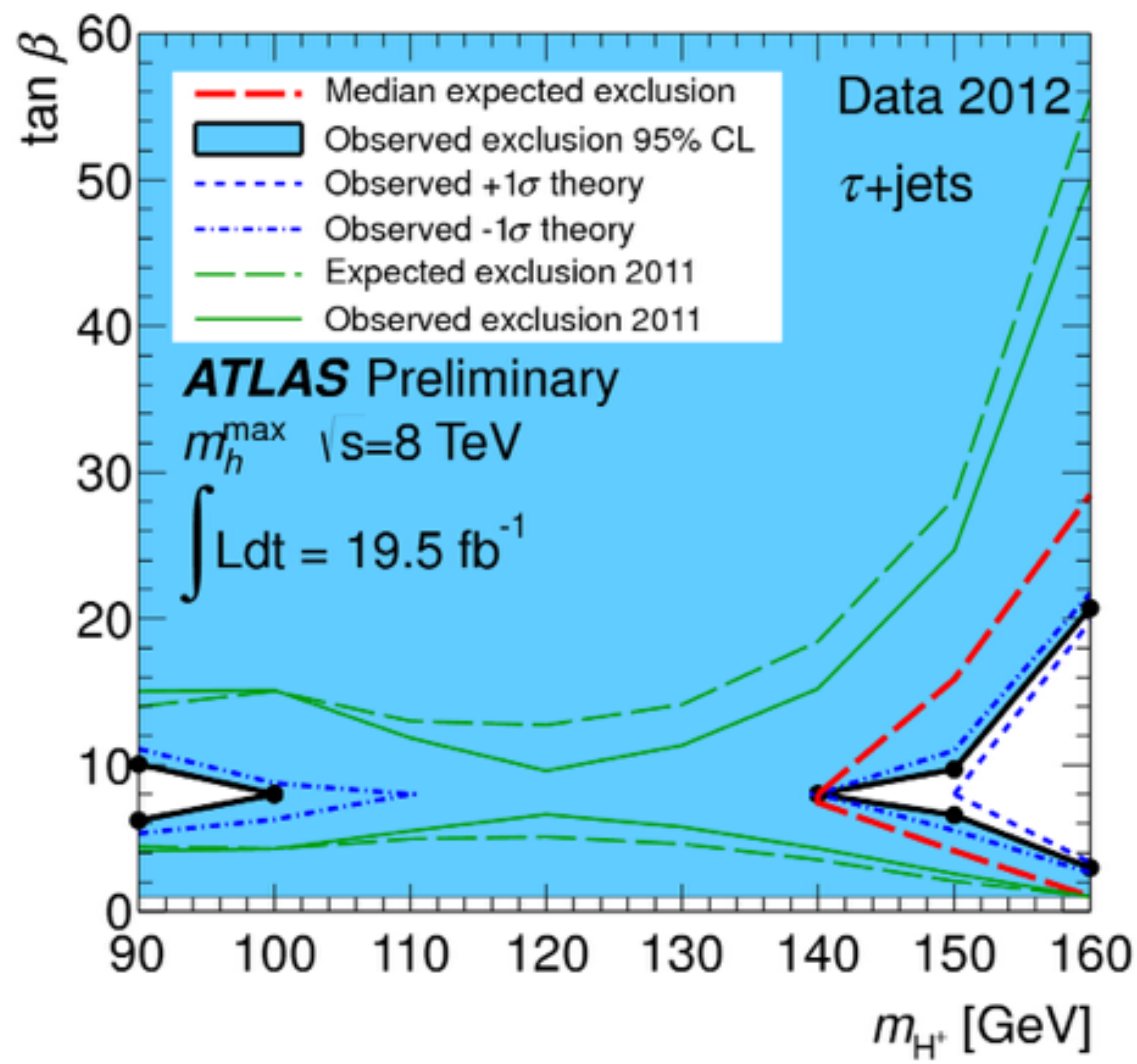
- (*) to account for real tau contribution, rather than subtracting directly from denominator - although, in the end this is very similar

ATLAS: $H^{\pm} \rightarrow \tau\nu$ (results)

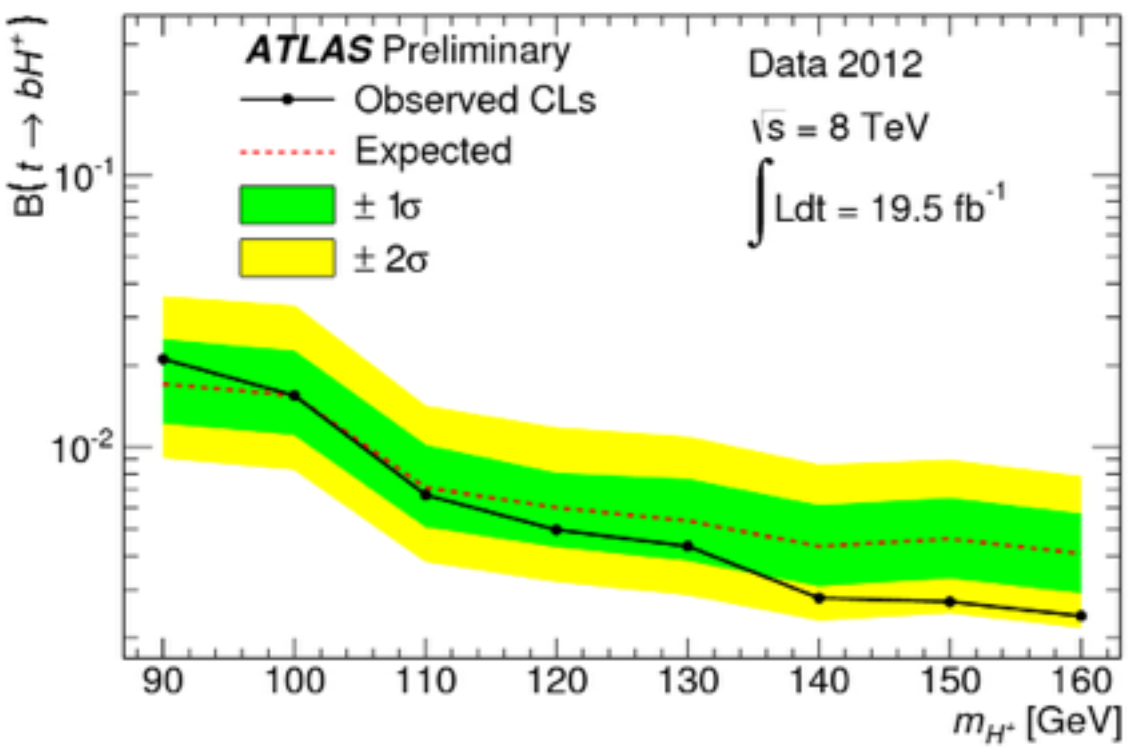
- Fit $m_T(\tau, MET)$ to data
- Assume $BR(H^{\pm} \rightarrow \tau\nu) = 100\%$
- low-mass: $BR(t \rightarrow H^{\pm} b) < 0.24\text{-}2.1\%$
- high-mass: $\sigma(pp \rightarrow t(b)H^{\pm}) < 0.017$ - 0.90 pb

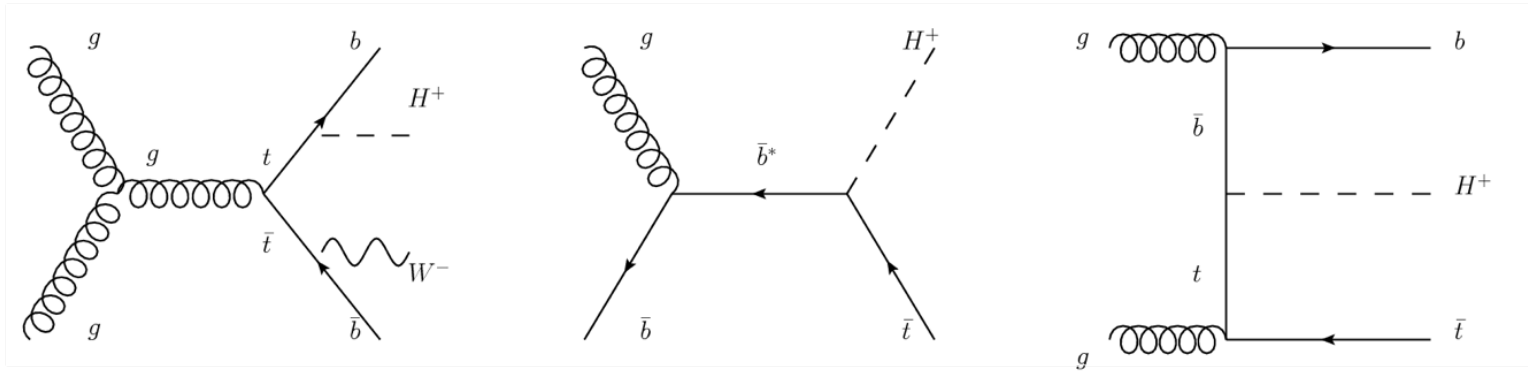


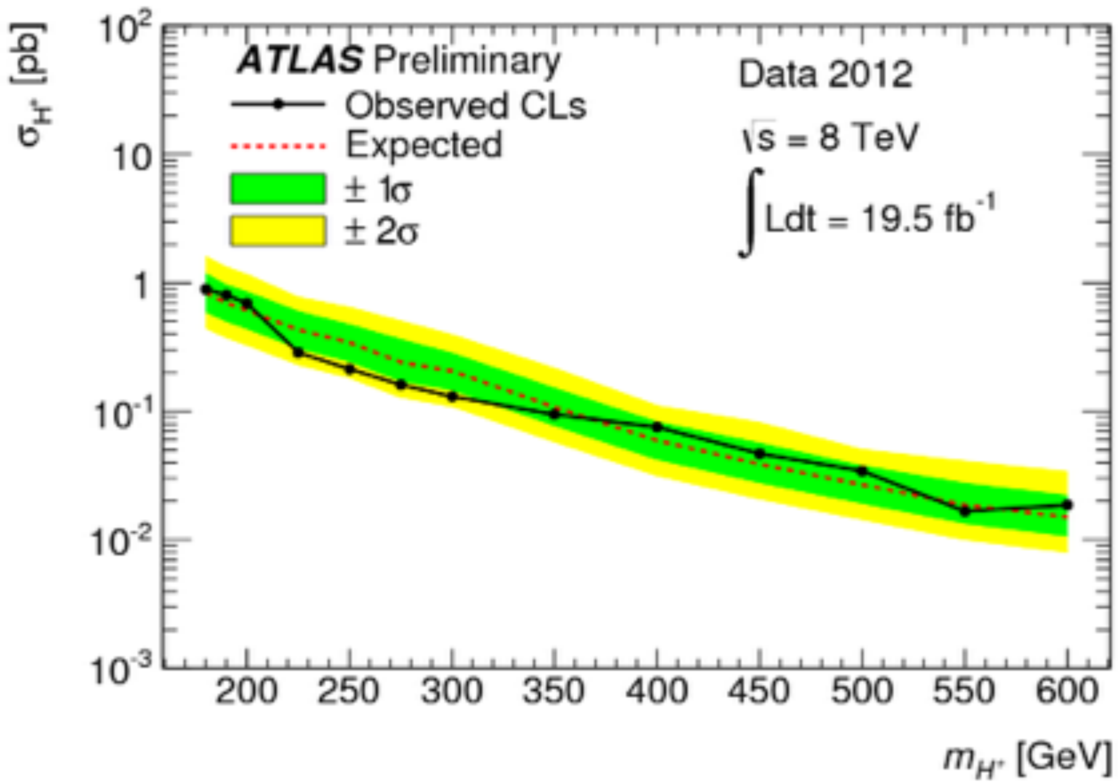


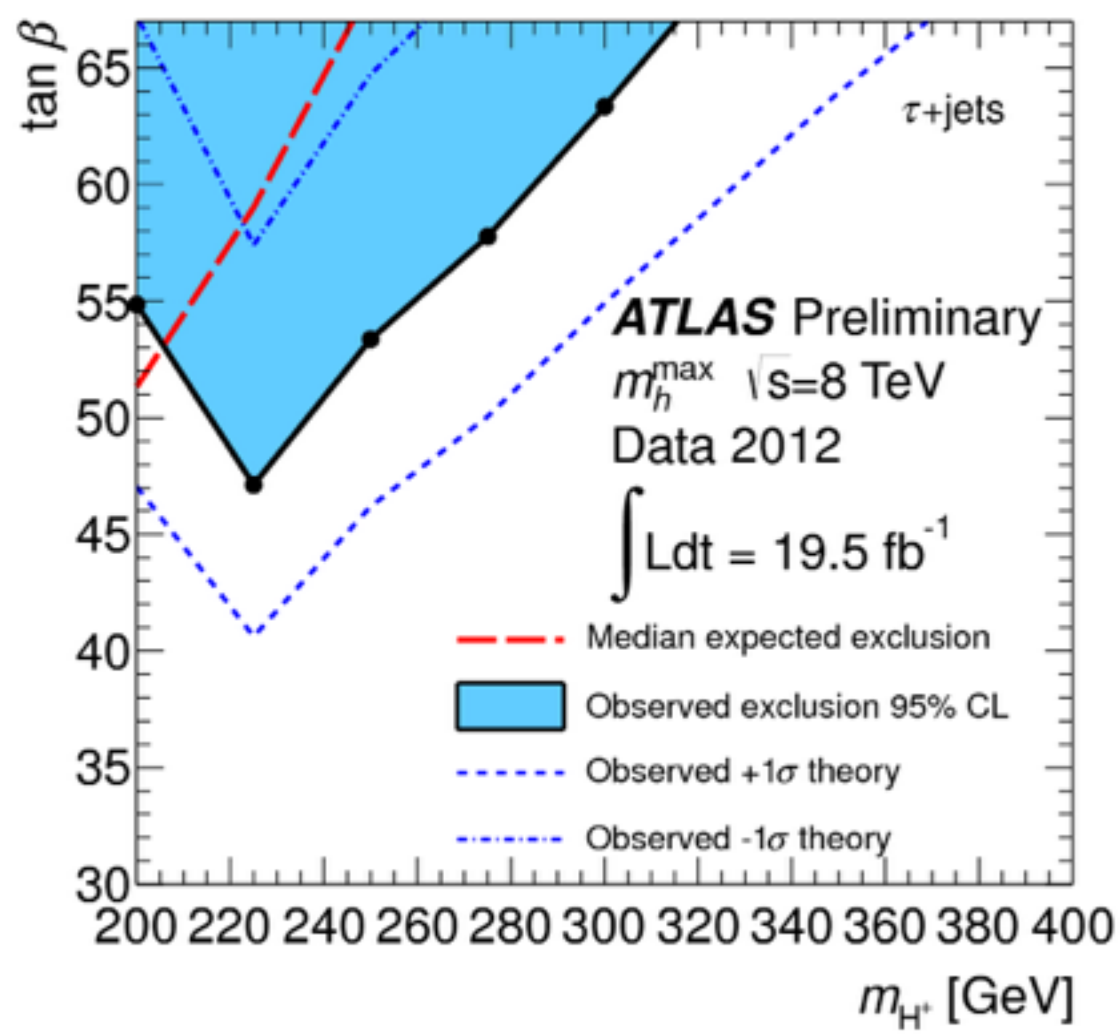


ATLAS: H± → τν (figs.)



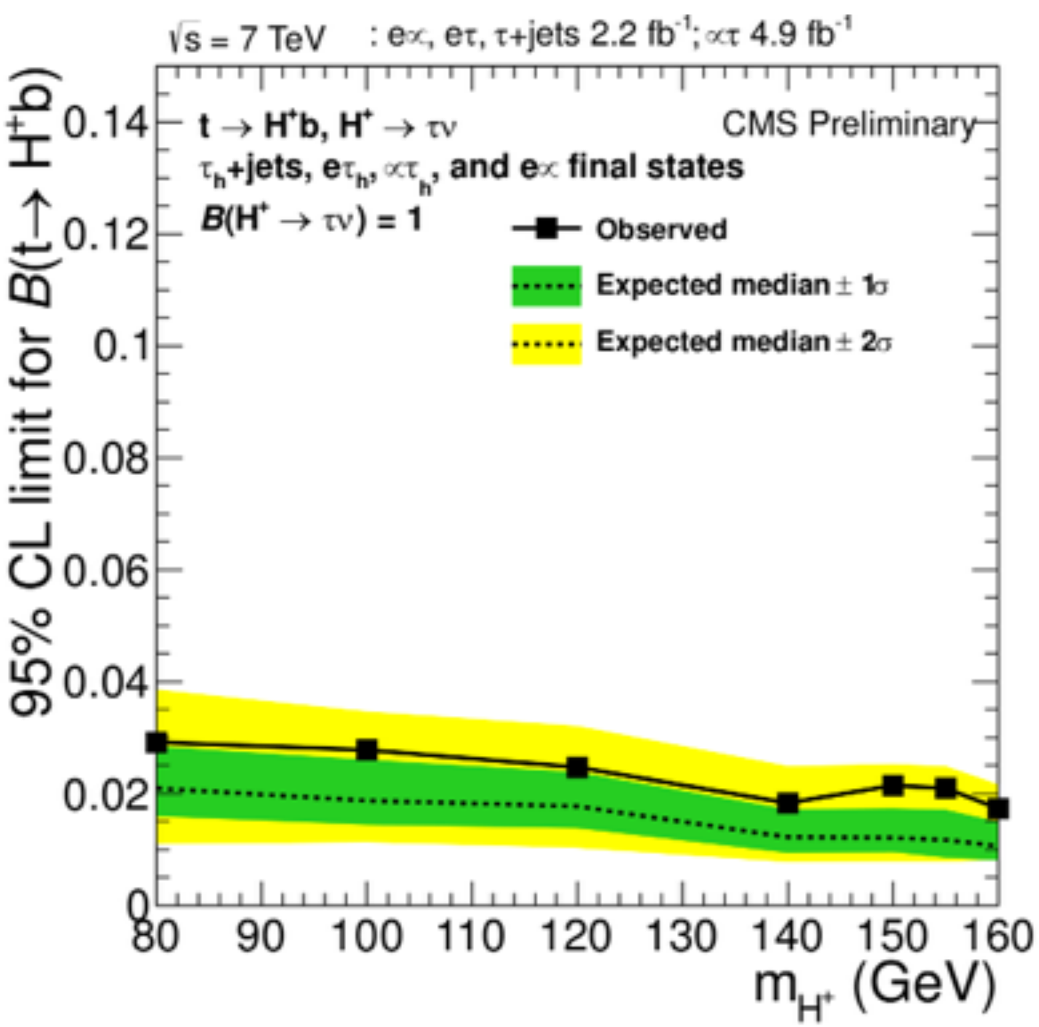




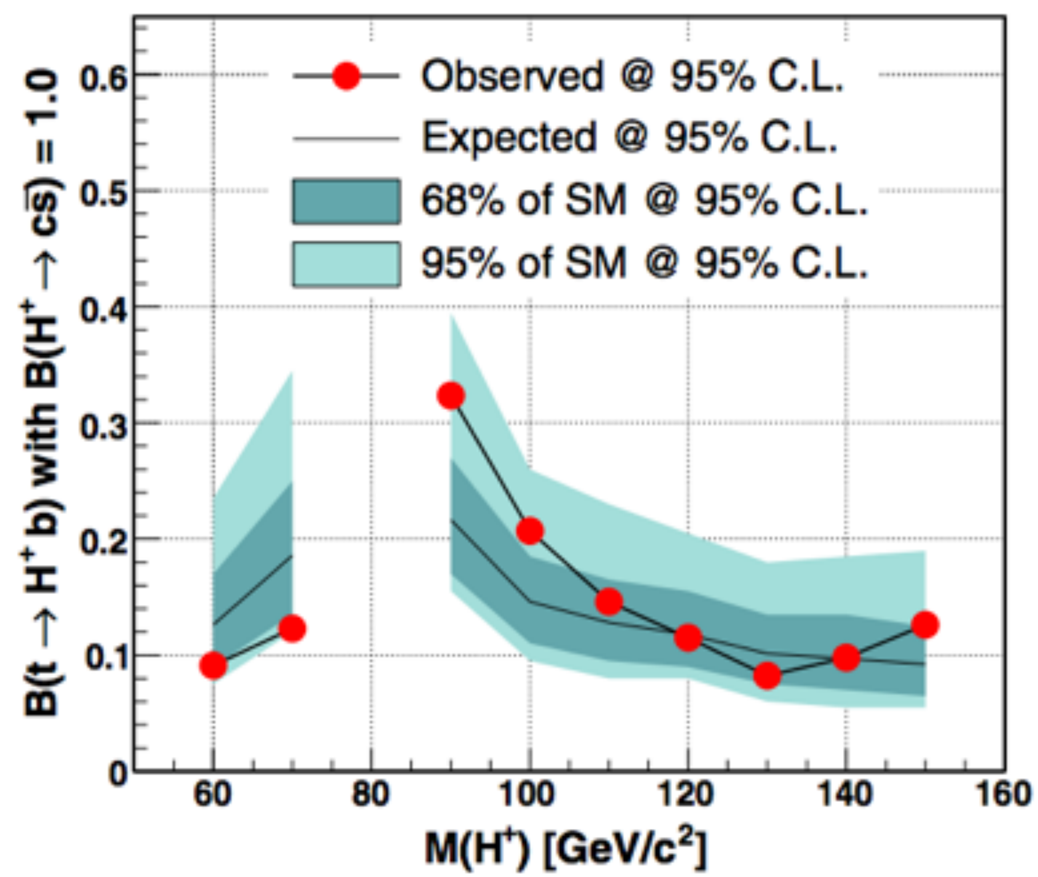


H+ other experiments

CMS Combined



CDF H→cs

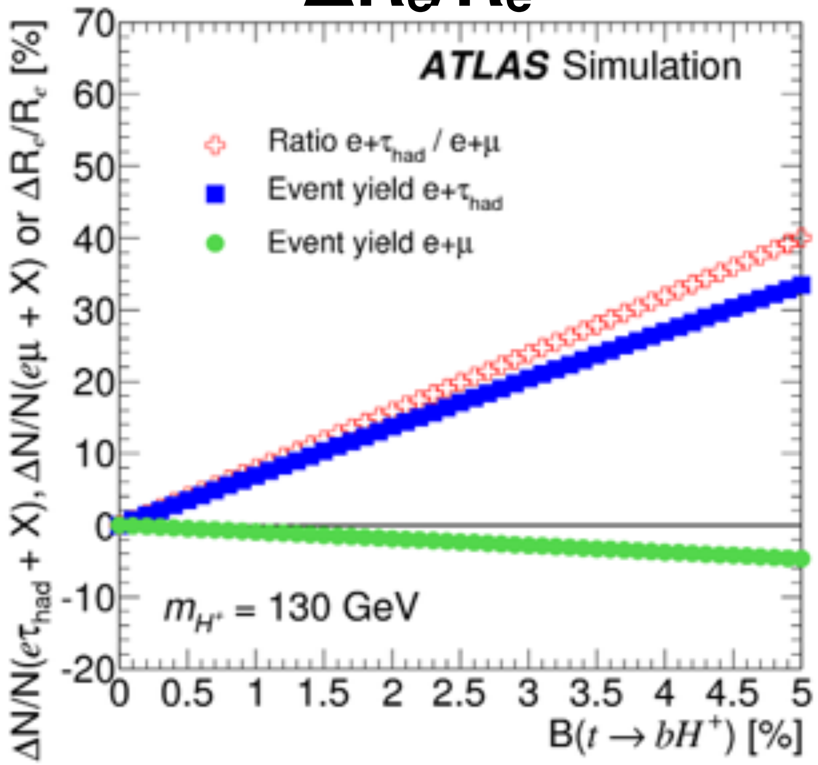


ATLAS: $H^{\pm}\to\tau\nu$ (Ratio Method)

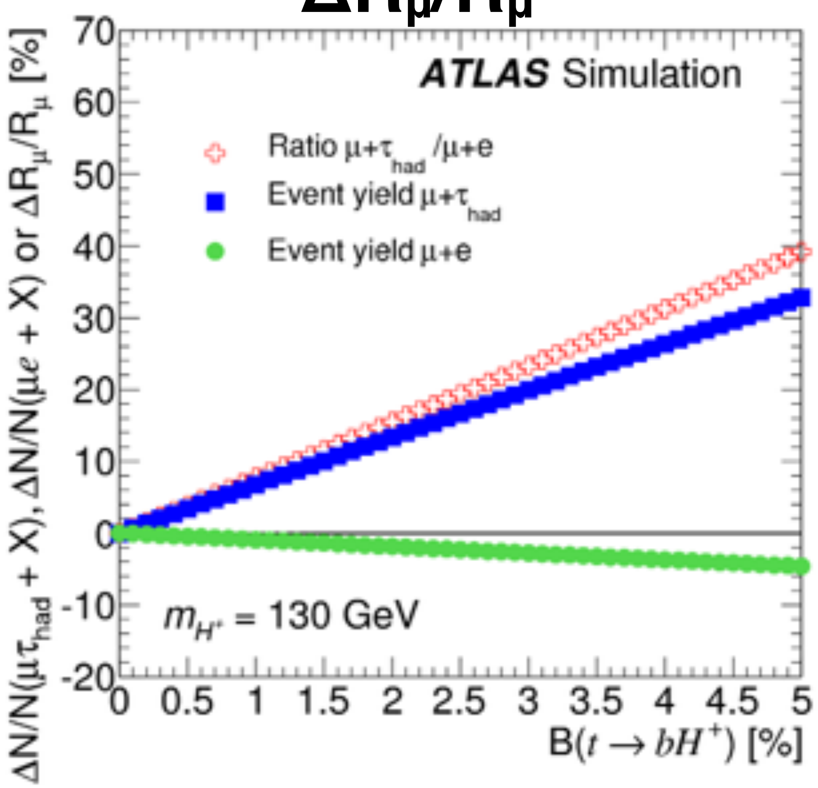
- "Search for charged Higgs bosons through the violation of lepton universality in ttbar events using pp collision data at sqrt(s) = 7 TeV with the ATLAS experiment" JHEP03(2013)076
- Improvement of lepton+tau analysis
- Use ratio of ll' to lτ ttbar events to place limits on H
- **Selection:**
  - Trigger: single e/μ
  - ≥2 jets (20 GeV, exactly 2 b-tagged)
  - MET>40 GeV
  - channel:
    - eμ: 1e+1μ (25 GeV)
    - lτ: 1τ+1e/μ (25 GeV)
  - m_{T2}^{H} >0 (physical)
- **Backgrounds:**
  - mainly from MC
  - lepton fakes: pseudo lepton fake-factor
  - MC jet→τ fake-rate corrected using W+>2j CR
  - OS-SS subtraction
- Define ratios:
  - R_e=N(eτ)/N(eμ), R_μ=N(μτ)/N(μe)
  - sensitivity determined by how R_e and R_μ change with B(t→bH)
- Dominant systematics: τ and ttbar sim.
- Limit: B(t→bH) <~3%
- Improvement of ~2 over non-ratio method (dominated by uncertainties on lepton and tau fakes)

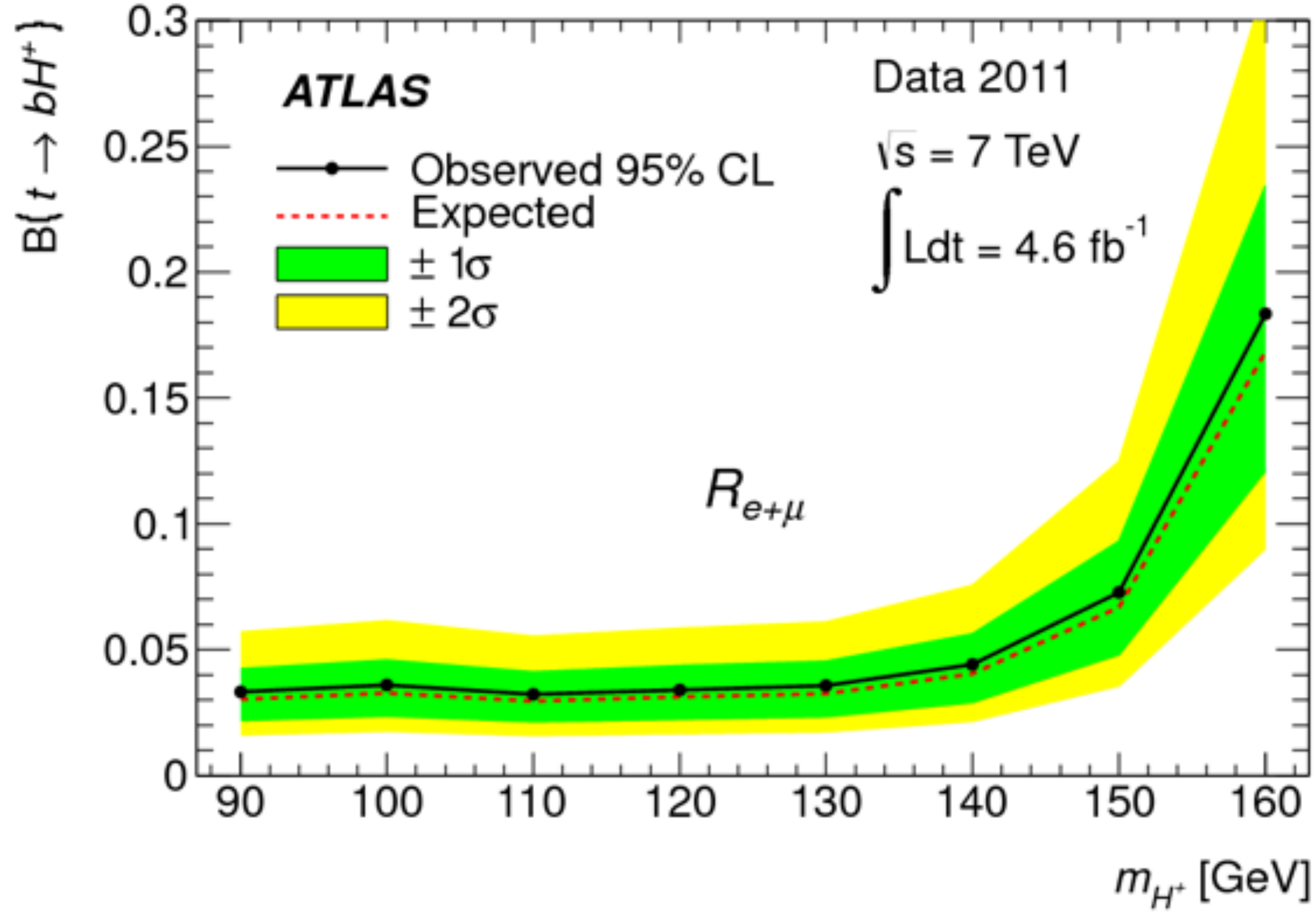
ATLAS: $H^{\pm} \to \tau\nu$ (Ratio Method)

$\Delta R_e / R_e$



$\Delta R_\mu / R_\mu$





ATLAS: $H^{\pm} \rightarrow \tau\nu$ (Ratio Method)

"Assuming that the boson recently discovered at the LHC is one of the neutral MSSM Higgs bosons, only a certain region in the m_{H+}-tanb plane is still allowed for a given scenario. If the new boson is the lightest neutral MSSM Higgs boson (h^0), it would imply tanb>3 and m_{H+}>155 GeV. However, the allowed region depends strongly on MSSM parameters which, on the other hand, do not affect the charged Higgs boson production and decay significantly. Thus, by adjusting these MSSM parameters, the region in which the Higgs boson mass can take a value of about 125 GeV can be changed significantly, while the ATLAS exclusion region shown here is relatively stable with respect to these changes. Should the recently discovered boson instead be the heavier CP-even Higgs boson (H^0), the additional constraint from m_{H0}~125 GeV only leads to an upper omit of roughly m_{H+}<150 GeV, with suppressed couplings for h^0. If the recently discovered particle is an MSSM Higgs boson, excluding a low-mass charged Higgs boson would thus imply that it is the lightest neutral state h^0."

ATLAS: $H^{\pm} \rightarrow cs$

"Search for a light charged Higgs boson in the decay channel $H^{+} \rightarrow$csbar in ttbar events using pp collisions at sqrt(s) = 7 TeV with the ATLAS detector"
EPJC 73 6 (2013) 2465

ATLAS: H±→cs (details)

- In MSSM:
  - $H^+ \rightarrow cs/bbW/\tau\nu$ dominant ($m_{H+} < m_t$)
  - tanβ<1: $B(H^+ \rightarrow cs) \sim 70\%$ ($m_{H+} \sim 110$ GeV)
  - tanβ>3: $B(H^+ \rightarrow \tau\nu) \sim 90\%$
  - $H^+ \rightarrow bbW$ important for higher masses and low tanβ
- Limits:
  - LEP 75-91 GeV (dep. on BRs)
  - Tevatron: $B(t \rightarrow H^+ b) <$ 10-30% with $B(H^+ \rightarrow cs) = 100\%$
  - SM Higgs is a weak constrain on many 2HDMs

ATLAS: H±→cs (selection)

- Trigger: single μ/e (18-22 GeV)
- Exactly 1 μ/e (20 GeV)
- ≥4 jets (25 GeV, ≥2 b-tagged)
- e channel: MET>30 GeV, mT>30 GeV
- μ channel: MET>20 GeV, MET +mT>60 GeV

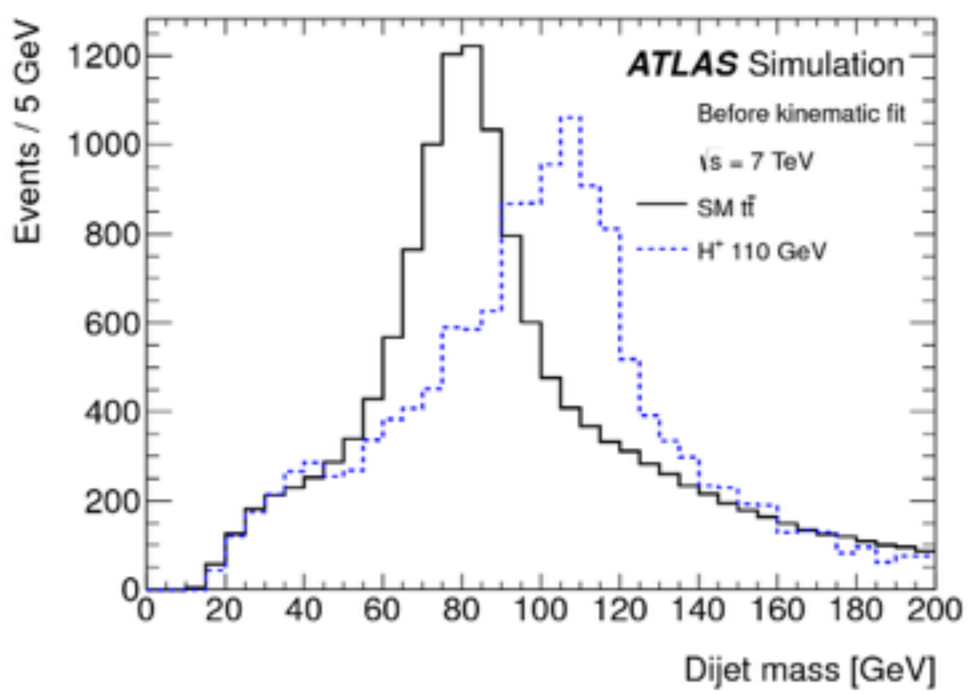
- **Kinematic Fitter to reco H^+ dijet mass:**
  - assume ttbar topology: blv, bjj
  - $p_z(v)$ from W mass constraint
  - priors: object p_T resolutions, top mass
  - require $\chi^2<10$ (63% sig eff.)
  - improves dijet mass res. 20-30%

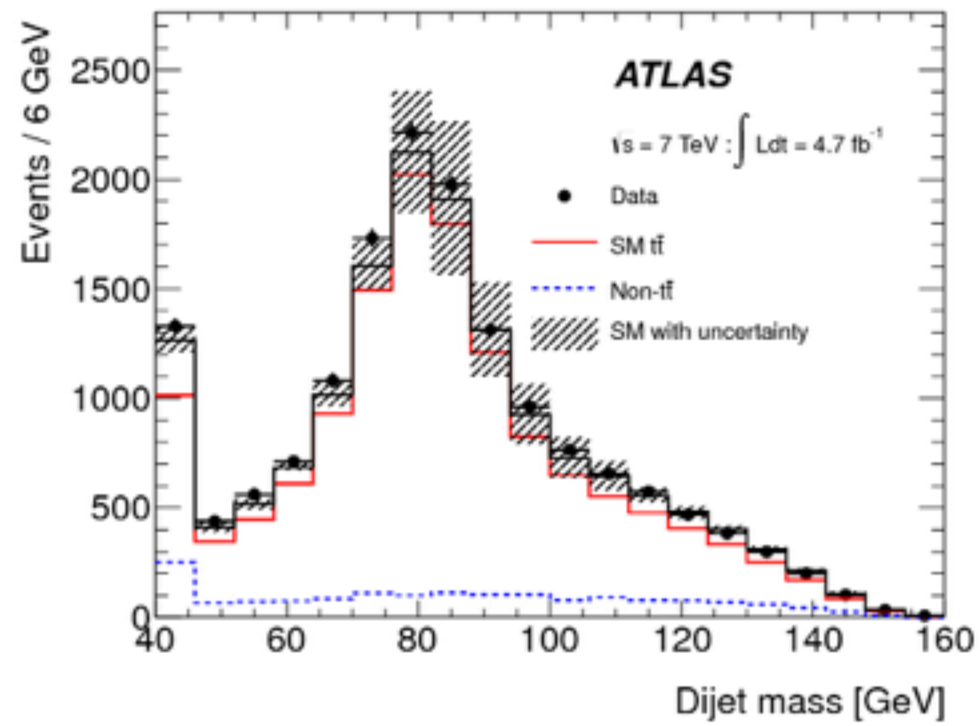
ATLAS: H± → cs (analysis)

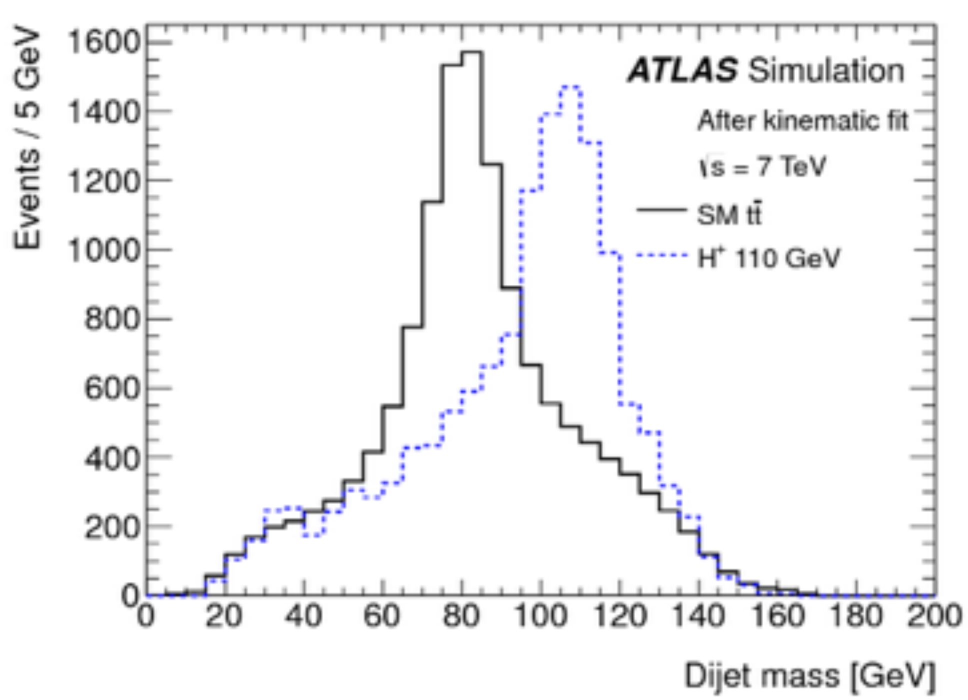
- Dominant bkg: ttbar (MC)
- Multijet: shape from loose lepton CR, norm. from MET templ. fit.
- W+jet: MC + data corrections
- Systematics: JES, ISR/FSR, b-tag eff., σ_{tt} ~10% each

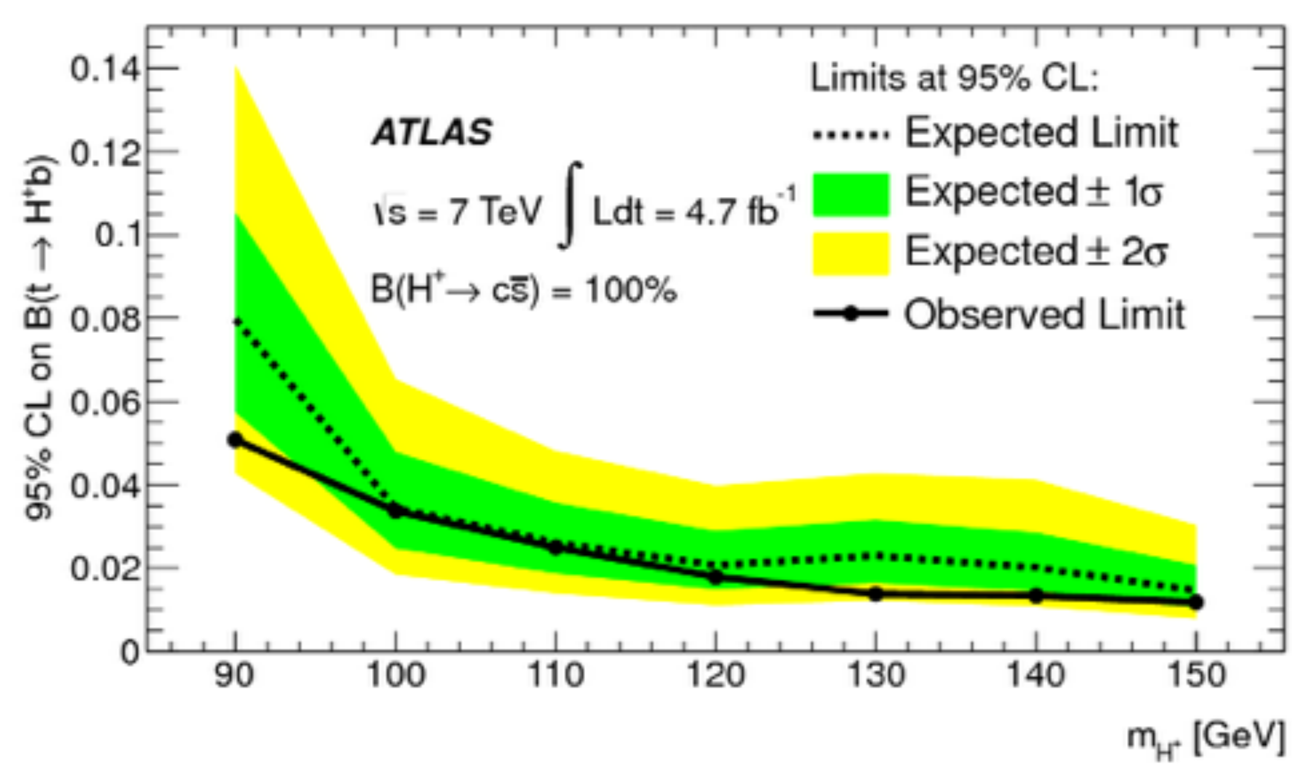
- Fit dijet mass distribution
- Limit: B(t→Hb)<1-5% with B(H→cs)=100%
- Note: they state tt→HbHb does not contribute since it doesn't produce leptons, but this is only because B(H→cs)=100% is assumed

ATLAS: H±→cs (figs.)









Cascades

ATLAS:
$H \rightarrow WH^{+} \rightarrow WWh$

"Search for a multi-Higgs-boson cascade in WWbb events with the ATLAS detector in pp collisions at sqrt(s) = 8 TeV" PRD 89, 032002

ATLAS: Cascade (selection)

- Signature:
  - No particular model assumed
  - $m(h_0)$ = 125 GeV
  - CP-odd (A) too heavy to participate in decay chain
  - Only consider gluon fusion production
- Selection:
  - single lepton triggers
  - exactly one iso muon or electron
  - ≥ 4 jets, 25 GeV, 2 tagged as b-jets
  - electron channel: MET>30 GeV, mT(l,nu) > 30 GeV
  - muon channel: MET>20 GeV, mT(l,nu) > 60 GeV
- Decay chain reconstruction:
  - neutrino p_z from W mass constraint
  - h_0 from 2 b-jets
  - hadronic W from remaining 2 jets closest to W-mass
  - H+ from h_0 and W that gives highest mass
- MVA:
  - 7 vars: m_{bb}, m_{bbW}, m_{bbWW}, dR(b,b), $m_{t\text{-leptonic}}$, $m_{t\text{-hadronic}}$, $|m_{t\text{-lep}}-m_{t\text{-had}}|$
  - trained separately for each signal mass hypothesis
  - optimise cut on BDT to give highest sensitivity then extract limits.

ATLAS: Cascade (notes)

- Background validation in control regions:
  - CR1: no b-jets (W +jets)
  - CR2: 1 b-jet (ttbar)
  - CR3: 2 b-jets, m_{bb}>150 GeV (ttbar)
- Dominant Systematics:
  - b-tag efficiency
  - jet energy
  - ttbar normalisation
- Limits:
  - not stringent enough to exclude models with SM-like production rates or 2HDM
  - tighter bounds than CDF
  - limits weakest at low mass due to poor ttbar separation

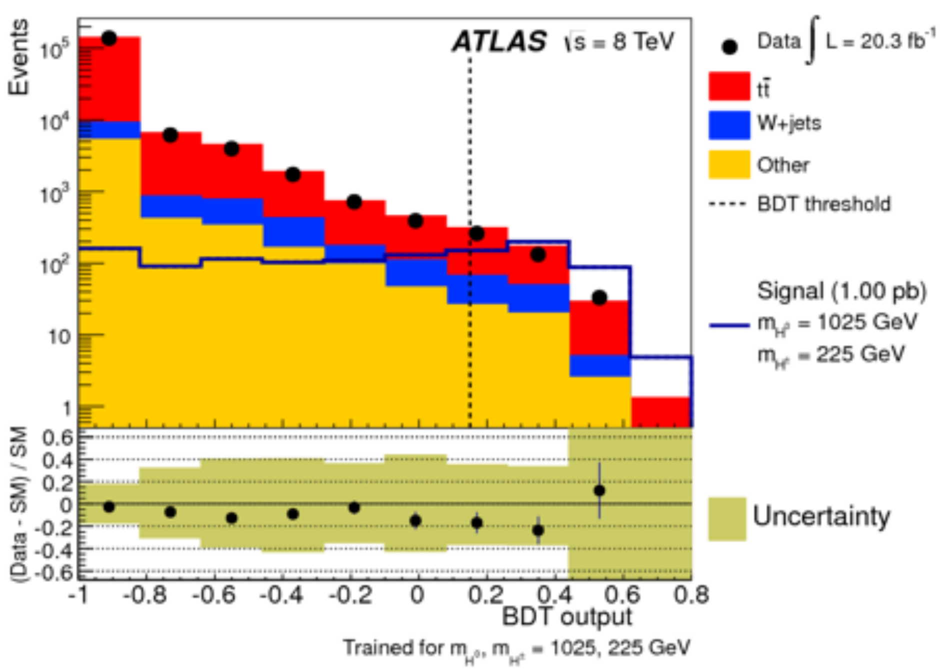
ATLAS: Cascade (tabs.)

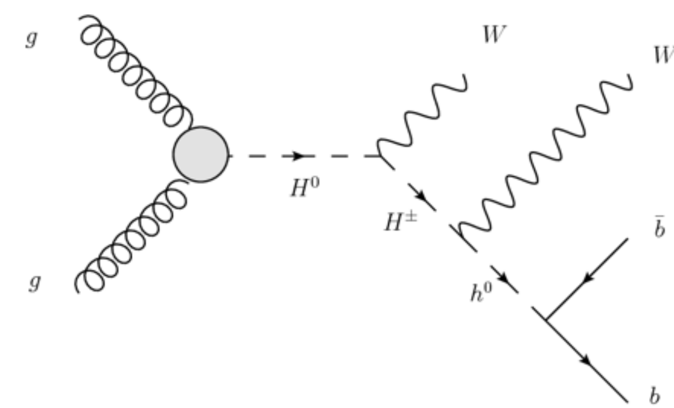
TABLE IV: Interpretation of the results in some type-II 2HDM parameter space choices. For each value of $m_{H^0}, m_{H^\pm}$, where at least one valid point is found, sample points in the space of the parameters ($\tan(\beta)$, $\sin(\beta-\alpha)$, m_A, and $\mathcal{M}^2_{12}$) which satisfy potential stability, unitarity and perturbativity constraints and give the smallest ratio of excluded to predicted cross section are shown.

m_{H^0} [GeV]	$m_{H^\pm}$ [GeV]	$\tan(\beta)$	$\sin(\beta-\alpha)$	m_A [GeV]	$\mathcal{M}^2_{12}$ [TeV^2]	$\sigma(H^0)$ [pb]	BF($H^0 \to h^0 W^+ W^-$)	Excl/Pred
325	225	15	0.99	303	$6.9 \cdot 10^{-3}$	28	0.222	2.1
425	225	20	0.99	439	$8.9 \cdot 10^{-3}$	2	0.404	41
425	325	10	0.99	486	$1.8 \cdot 10^{-2}$	10	0.288	14
525	325	10	0.99	384	$2.7 \cdot 10^{-2}$	3	0.436	39
525	425	10	0.99	384	$2.7 \cdot 10^{-2}$	5	0.136	34
625	325	10	0.99	549	$3.9 \cdot 10^{-2}$	1	0.501	20
625	425	10	0.99	693	$3.9 \cdot 10^{-2}$	2	0.607	4.1
625	525	10	0.99	693	$3.9 \cdot 10^{-2}$	3	0.219	7.7
725	325	1	0.99	675	$5.9 \cdot 10^{-2}$	0.3	0.009	664
725	425	10	0.99	731	$5.2 \cdot 10^{-2}$	1	0.643	3.5
725	525	10	0.99	731	$5.2 \cdot 10^{-2}$	1	0.659	1.1
725	625	10	0.99	396	$5.2 \cdot 10^{-2}$	1	0.002	440
825	525	1	0.99	788	$1.3 \cdot 10^{-1}$	0.3	0.024	76
825	625	1	0.99	788	$1.3 \cdot 10^{-1}$	0.3	0.021	41
825	725	10	0.999	807	$6.8 \cdot 10^{-2}$	1	0.168	4.1
925	725	1	0.999	921	$2.4 \cdot 10^{-1}$	0.2	0.003	530
1025	825	1	0.999	920	$3.4 \cdot 10^{-1}$	0.1	0.003	243

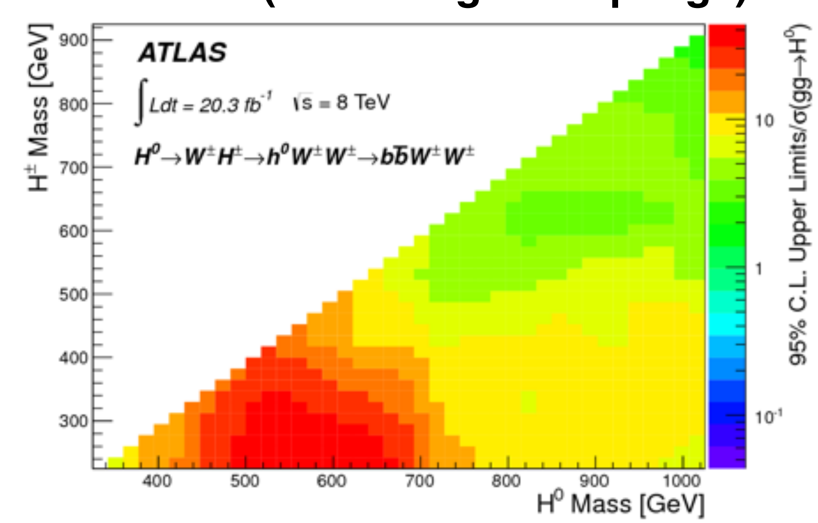
ATLAS: Cascade (figs)

SR (BDT Score)

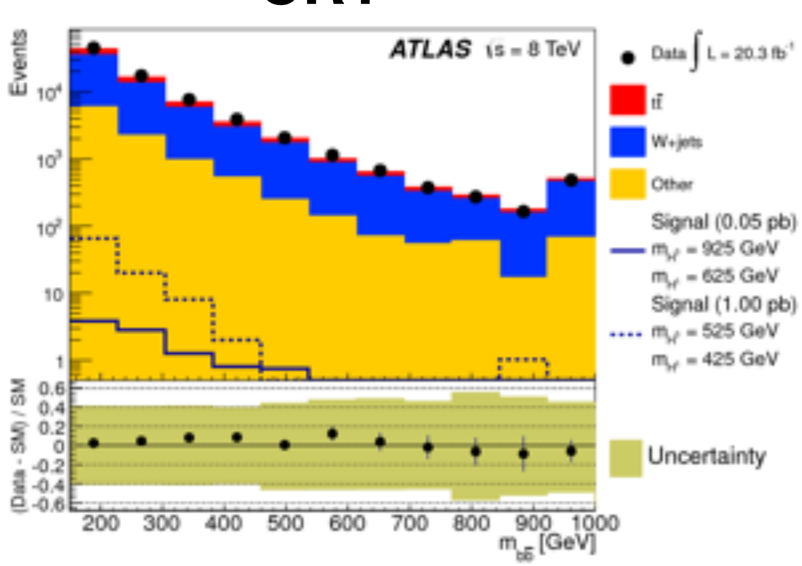




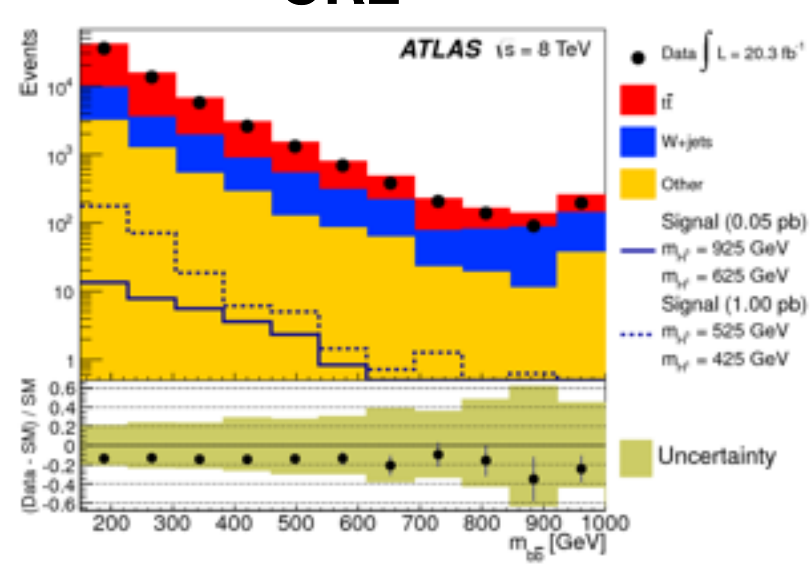
mu limit (SM strength couplings)



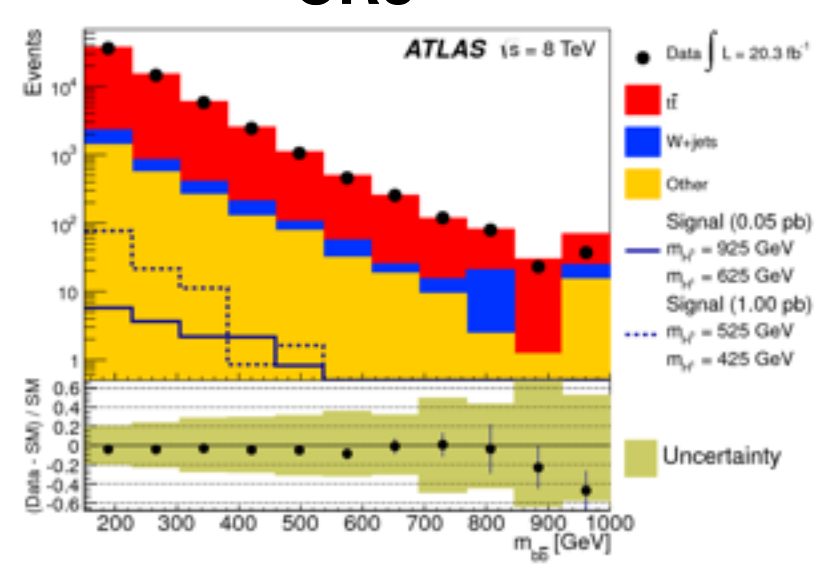
CR1



CR2



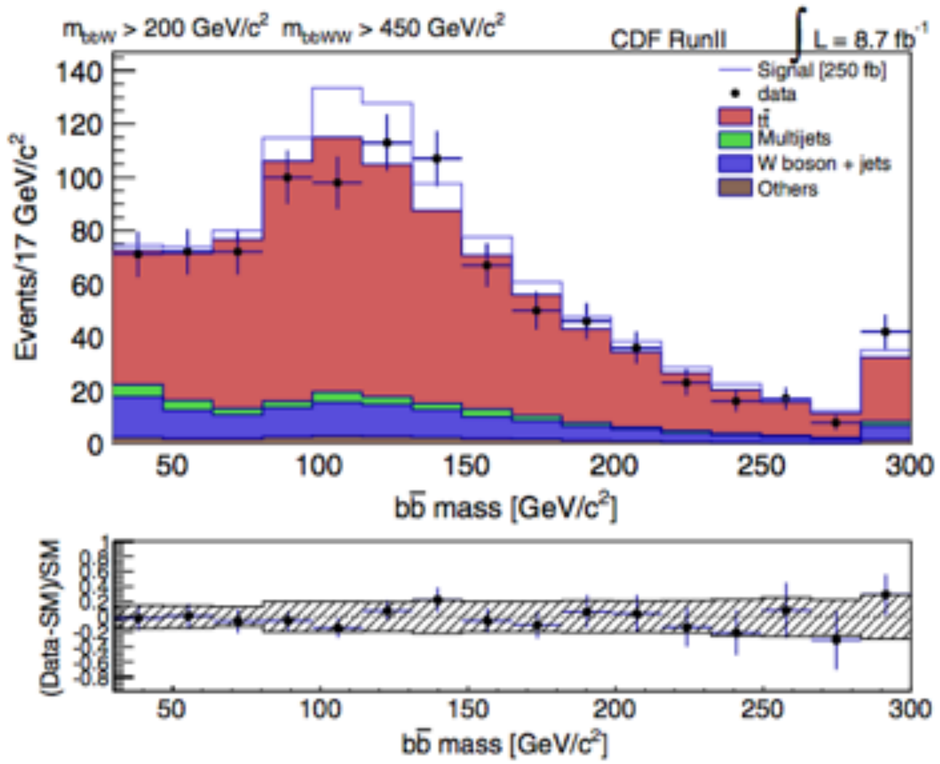
CR3

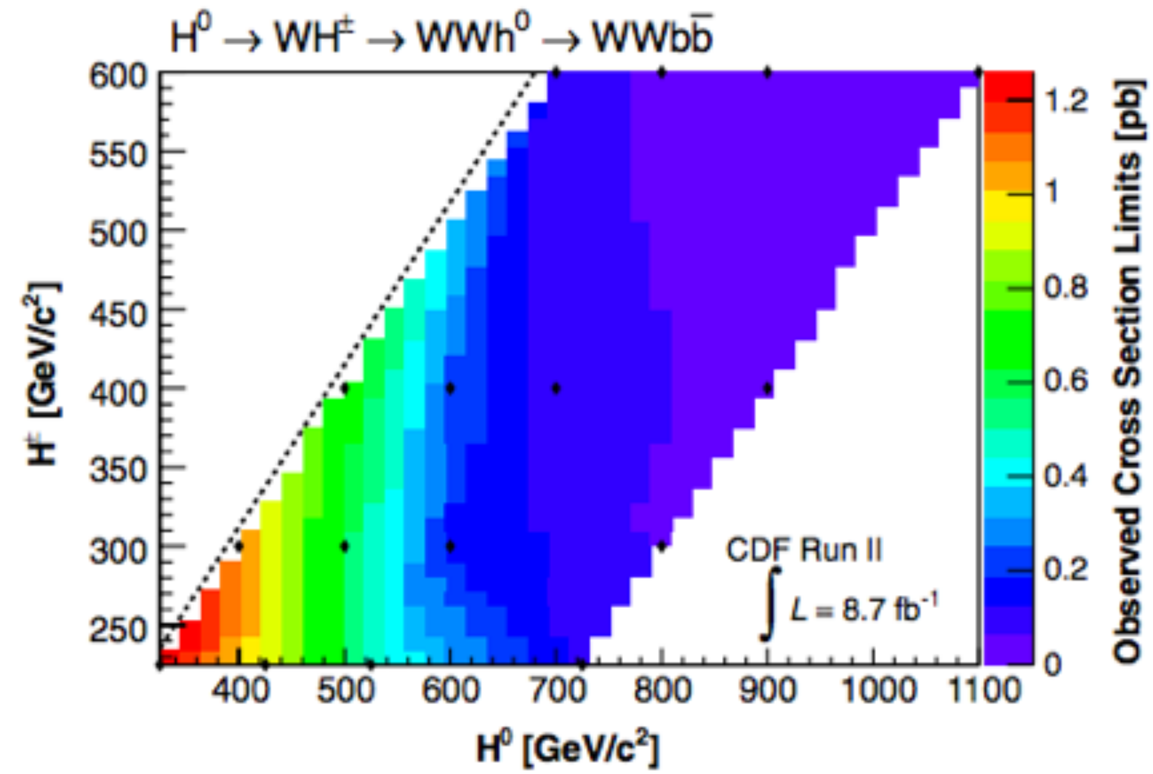


CDF: Cascade

"Search for a Two-Higgs-Boson Doublet Using a Simplified Model in ppbar Collisions at sqrt(s) = 1.96 TeV" PRL 110, 121801

CDF: Cascade





$(m_{H^0}, m_{H^\pm})$ (GeV/c^2)	$m_{H^\pm}$ (GeV/c^2)	m_{H^0} (GeV/c^2)	Expected (Observed) Limit (fb)	Theory (fb)
325, 225	>175	>275	1100 (1300)	34
400, 300	>225	>325	960 (1100)	18
425, 225	>200	>375	900 (960)	13
500, 300	>200	>450	470 (590)	3.9
500, 400	>350	>450	510 (700)	3.9
525, 225	>100	>500	420 (460)	2.5
600, 300	>200	>550	200 (180)	0.76
600, 400	>350	>550	210 (250)	0.76
700, 400	>325	>650	90 (100)	0.15
700, 600	>450	>650	10 (96)	0.15
725, 225	>425	>700	90 (120)	0.10
800, 300	>275	>750	50 (51)	3×10^{-2}
800, 600	>475	>725	43 (46)	3×10^{-2}
900, 400	>450	>775	28 (36)	6×10^{-3}
900, 600	>475	>800	24 (29)	6×10^{-3}
1100, 600	>475	>975	13 (15)	2×10^{-4}

CMS: $H \rightarrow hh$, $A \rightarrow Zh$

"Search for extended Higgs sectors in the H->hh and A->Zh channels in sqrt(s) = 8 TeV pp collisions with multi leptons and photons final states." CMS PAS HIG-13-025

CMS: $H \rightarrow hh$, $A \rightarrow Zh$ (outline)

- L = 19.5 fb-1 @ sqrt(s) = 8 TeV
- multilepton events with or without diphoton candidates.
- Signals:
  - 2HDM
  - if m_H ~2m_h(126), then H->hh is possible (in addition to decays to SM particles)
  - if $2m_h < m_A < 2m_{top}$, A->Zh dominant decay mode.
  - gluon fusion H production
  - **multilepton,** hh has 7 possible decays: WWWW, WWZZ, WWtautau, ZZZZ, ZZtautau, ZZbb, tautautautau.
  - **+diphoton:** $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\tau\tau$ are useful.
- Triggers: ee, $\mu\mu$, μe, $\gamma\gamma$

CMS: H→hh, A→Zh (selection)

- **Multilepton Channels**:
  - At least 3 leptons, max 1 tau
  - reject m_{ll}<12 GeV
  - reject events in low MET bins that don't have on-Z OSSF pair but do have 3-body Z candidate ($m_{lll(')}$) to reject conversions.
  - **Categories**: number of **leptons**, number of **OSSS pairs**, number of **taus**, presence of **b-jets**, on/off **Z peak** (75 - 105 GeV) (light leptonic decays only), amount of **MET**
  - Selection of categories depends on signal model.
  - **H->hh**: most sensitivity comes from h decays to Ws or taus. **Pick channels without on-Z OSSF pair** (suppress Z)
  - **A->Zh**: best channels **with on-Z OSSF pair** with **moderate MET** (suppress Z)
- **Diphoton Channels**:
  - exactly 2 photons + 1 or 2 leptons
  - **Categories**: number of **taus**, amount of **MET**
  - no signal dependent category selection

CMS: H→hh, A→Zh (bkgs)

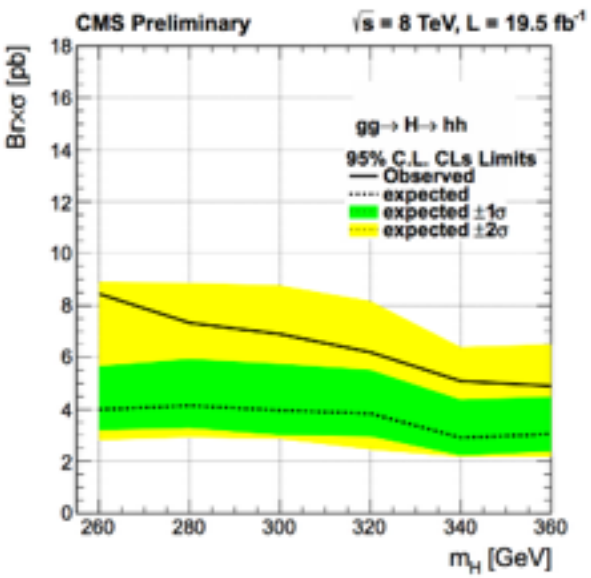
- **Background Est. Multilepton**:
  - Background from **non-prompt leptons/taus**:
    - Predominantly Z+jet (jet->lepton or jet->tau)
    - **lepton/tau fake-factor** (as in SUSY multi-lepton analysis)
    - Weight events with 2 ID leptons and 1 fail ID lepton with Fake-factor on fail ID lepton measured in CR such as low-MET or low-HT
    - Light lepton fake-factors parameterised vs impact parameter to account for dependence on heavy quark fraction.
    - Tau fake-factors 30% uncertainty from variation in various jet dominated samples
  - **ttbar**:
    - **MC** plus **lepton efficiency corrections** (as in SUSY multi-leptons)
    - **Reweight Njets** in dilepton CR
  - **Diboson**:
    - **MC** plus **lepton efficiency** and **MET** corrections (as in SUSY multi-leptons)
    - **MET resolution smearing** as a function of **Nvtx** (higher = worse MET resolution), **HT** (higher = larger tails due to jet misconstruction), modelled as **sum of Rayleigh distributions**.
  - Backgrunds from asymmetric **photon conversions**: **$\gamma \rightarrow l$ fake factor** (as in SUSY multi-leptons)
- **Background Est. Diphoton**: m_{ll} **sideband fit** (50% uncertainty)

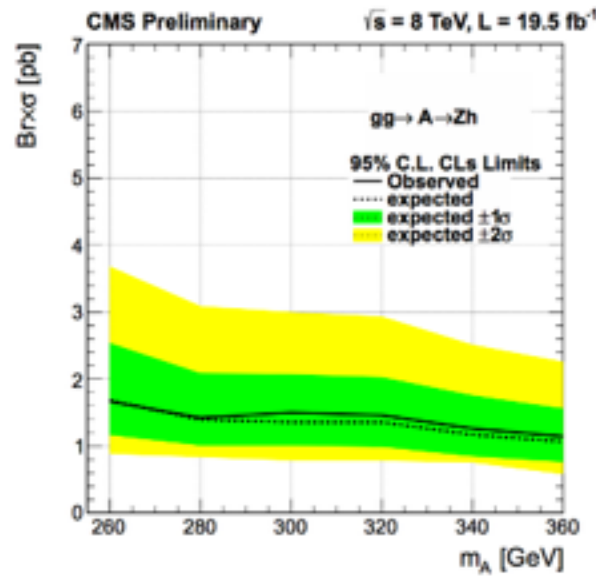
CMS: H→hh, A→Zh (results)

- **Results**:
  - counting experiment, pick only most sensitive channels
  - dominant systematics: lumi, lepton efficiencies and background estimation
  - Limits:
    - **σ(gg→H→hh) < ~7 pb** (in range 260 < m_H < 360)
    - **σ(gg→A→Zh) < ~ 2 pb** (in range 260 < m_A < 360)
  - discrepancy between observed and expected limits comes mainly from excess in the 3lep+tau, no b-jet and off-Z channels. But consistent with the fluctuation you would expect when considering all channels.

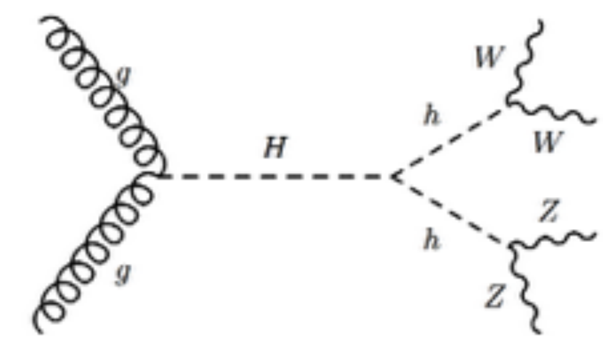
- **Notes on 2HDM couplings**:
  - gg->H->hh (Type I and II 2HDM):
    - drop in gg->H->hh cross section at cos(b-a)=0 and low tan(b) is because HVV coupling goes to 0 and vector couplings dominant in this region, suppressing the vector loop for gluon fusion. At higher tan(b) and low |cos(a-b)|, fermion couplings dominate, so the loop is not significantly suppressed.
    - suspect the line at -ve cos(b-a) and low tan(b) might be at sin(a) = 0, which would suppress fermion couplings, but not 100% confident.
  - gg->A->Zh (Type I and II 2HDM):
    - no AVV coupling
    - don't understand why cross section goes to 0 at cos(b-a)=0. At cos(b-a)=0, |b-a| = pi/2. If tan(b) is low, cos(b) not near 0, i.e. b not near pi/2, b ~ 0 or pi, a ~ pi/2..........hmmmmmm.

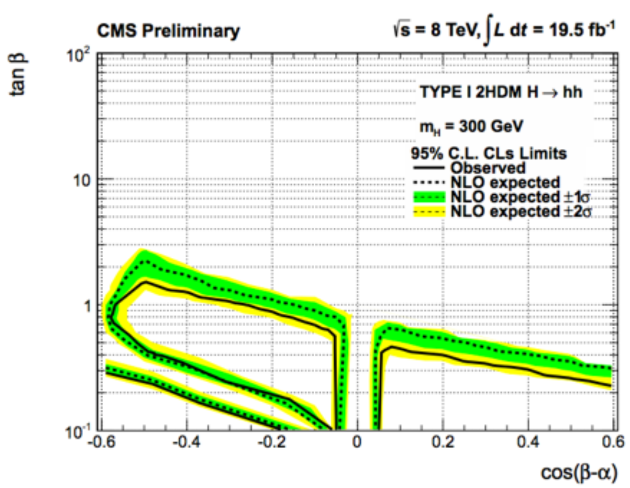
CMS: H→hh, A→Zh (figs.)

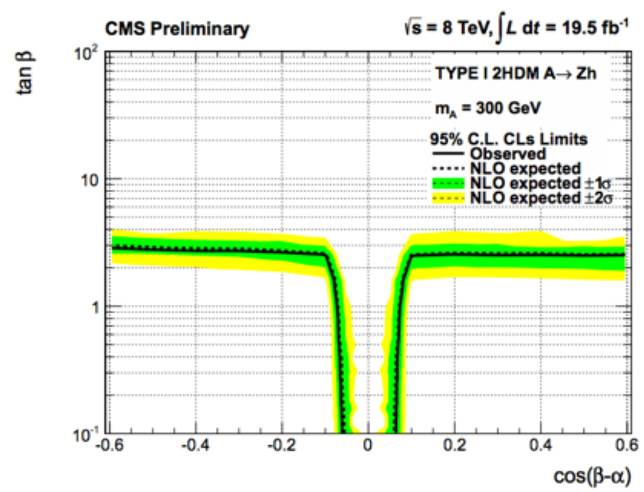


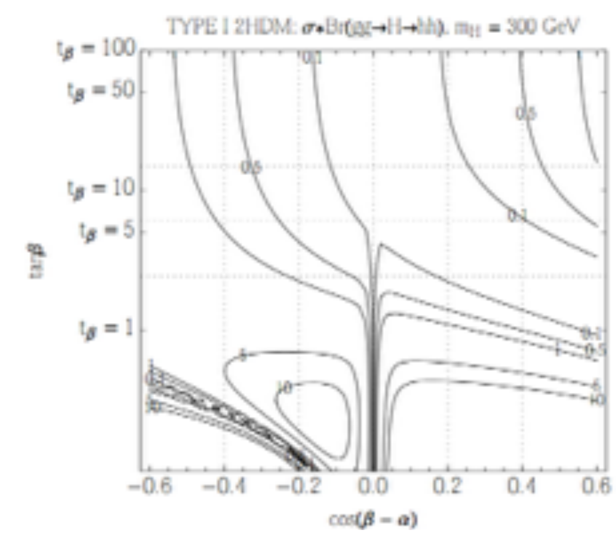


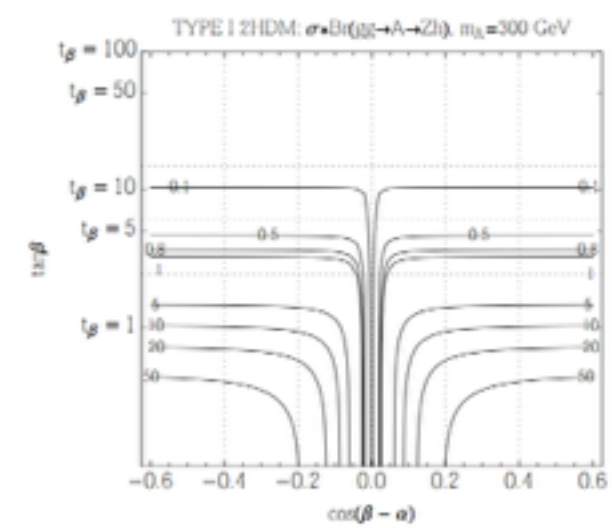
1	2HDM I	2HDM II
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
AVV	0	0
AQu	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$

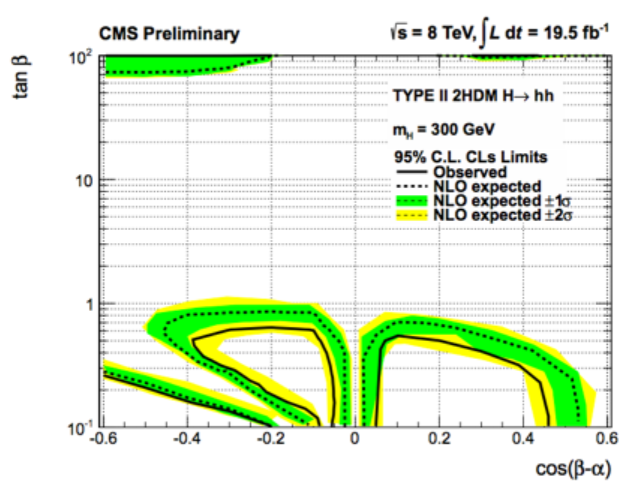


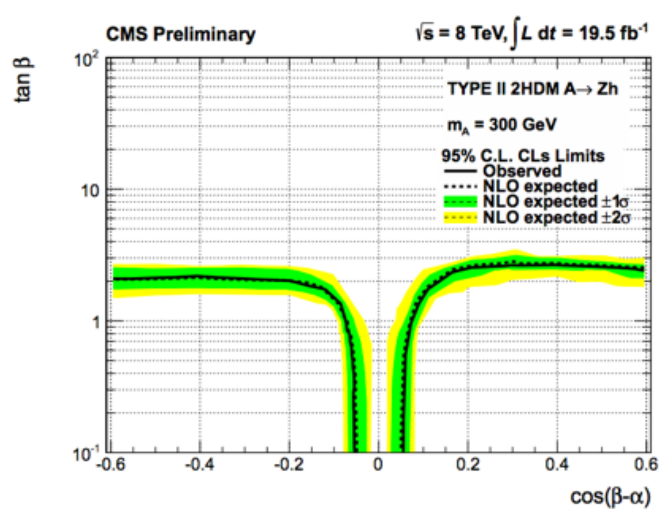


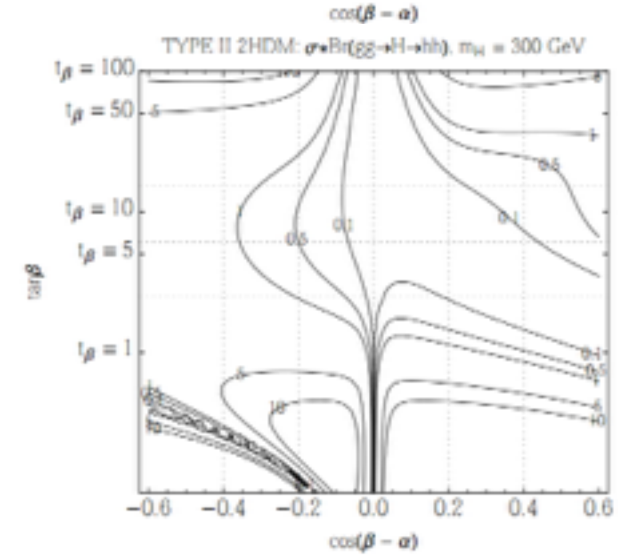


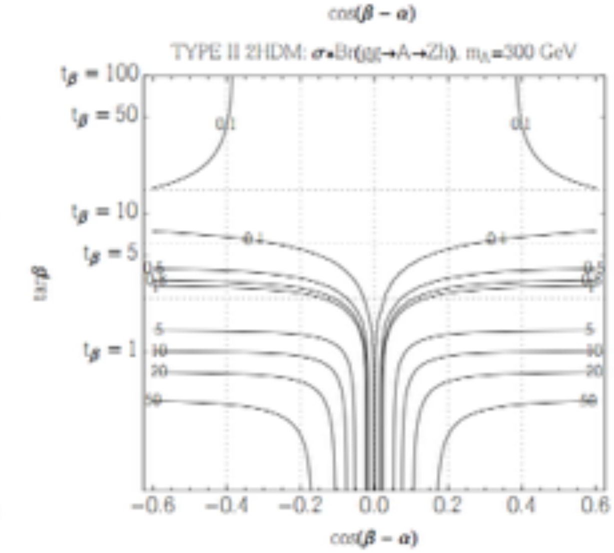












ATLAS: $X \to hh \to \gamma\gamma bb$

“Search for Higgs boson pair production in the $\gamma\gamma bb$ final state using pp collision data at $\sqrt{s}$ = 8 TeV from the ATLAS detector” HIGG-2013-29

ATLAS: $X \to hh \to \gamma\gamma bb$

- Rate for SM hh production too low to observe in Run 1 dataset.
- Search for resonant and non-resonant hh production
- Good in range 260 < mX < 500 where 4b and 2b2τ backgrounds large.
- Selection:
    - Trigger: diphoton
    - 2 γ (isolated)
    - $p_T(\gamma_1)/m_{\gamma\gamma}>0.35$, $p_T(\gamma_2)/m_{\gamma\gamma}>0.25$
    - $105 < m_{\gamma\gamma} < 160$ GeV
    - ≥ 2 b-jets: $95<m_{jj}<135$
- Non-resonant analysis:
    - Simultaneous fit $m_{\gamma\gamma}$ in SR and ≤2 b-jets CR
- Resonant analysis:
    - $|m_{\gamma\gamma}-m_h|<2\sigma_{\gamma\gamma}$
    - correct m_{bb} to m_h
    - $m_{\gamma\gamma bb}$ window

t ➞ Hc

ATLAS: $t \rightarrow Hc$

"Search for flavour changing neutral currents in top quark decays $t \rightarrow cH$, with $H \rightarrow \gamma\gamma$, and limit on the tcH coupling with the ATLAS detector at the LHC."

arXiv:1403.6293 [hep-ex]

ATLAS: tHc (overview)

- 20 fb-1 @ sqrt(s) = 8 TeV + 5 fb-1 @ sqrt(7)
- search for t->cH FCNC, with H->γγ
- t->c(u)Z has been searched for, best limit 0.07% from CMS.
- GIM suppression can be relaxed in BSM models.
- Loop diagrams mediated by new bosons max contribute, yielding effective couplings orders of magnitude larger than those of the SM.
- Examples:
    - quark-singlet model
    - Type I 2HDM with explicit flavour conservation
    - Type II 2HDM (eg. MSSM)
    - 2HDM without explicit flavour conservation (Type III)
- Largest FCNC is t->cH in Type III 2HDM.

ATLAS: tHc (analysis)

- At least 2 photons (pick 2 lead).
- In 7 TeV all events in hadronic channel.
- **<u>Hadronic Channel (no leptons):</u>**
  - At least 4 jets, ≥1 b-tagged (pick 4 lead)
  - If jet 4 not b-tagged but jet 5 or 6 are, swap them. (happens about 6% of time)
  - <u>Combine photons and jets into top candidates:</u>
    - Top 1 (γγj), M1 in [156,191] GeV
    - Top 2 (jjj), M2 in [130,210] GeV
    - 4 combinations per event
  - Fit the diphoton mass spectrum:
    - Same signal shapes as SM H->γγ
    - Sherpa γγj distribution used as a reference when fitting the diphoton mass distribution (smoothed using RooKeysPdf)

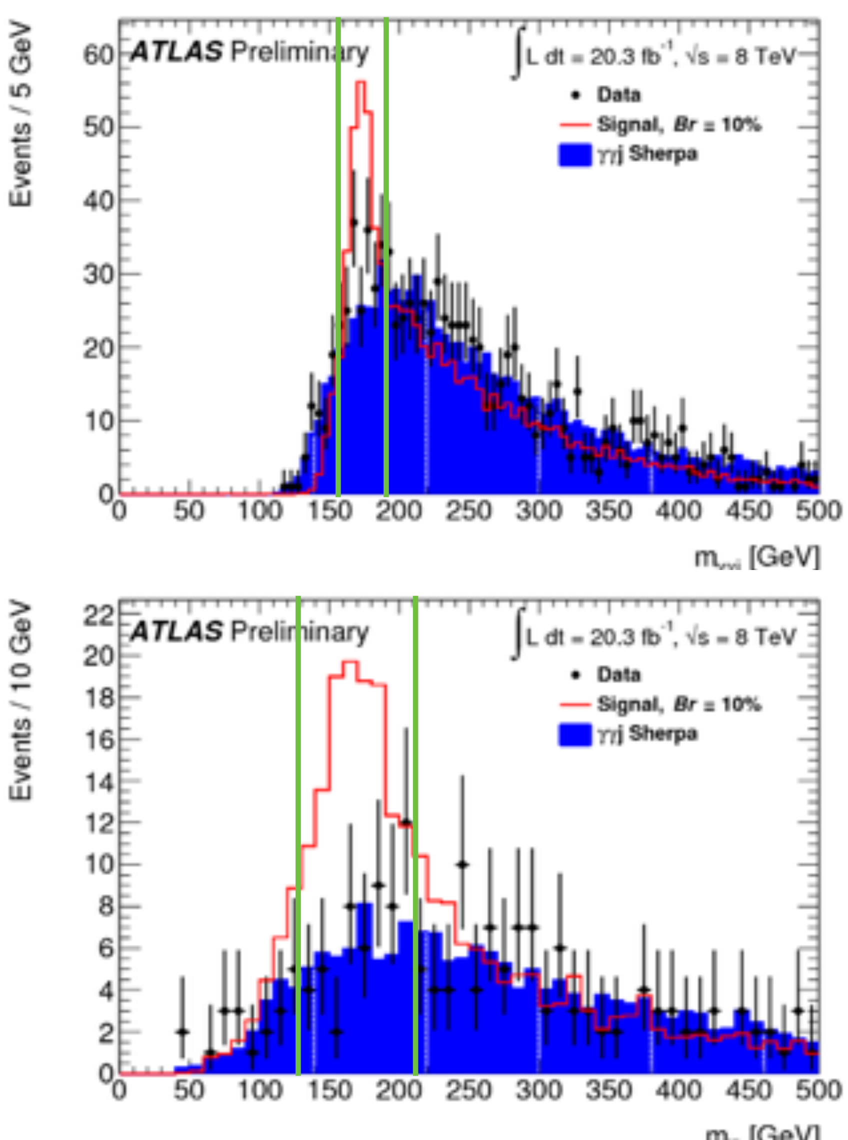
- **<u>Leptonic Channel (exactly one lepton):</u>**
- mT(lep,MET)>30 GeV
- at least 2 jets, ≥1 b-tagged (pick 2 lead and repl. 2 with 3 or 4 if b-tagged ~9%)
- <u>Combine lep/MET/photons/jets into top candidates:</u>
  - Top1 (γγj), M1 in [156,191] GeV (tail to high mass due to wrong combination of final state objects - QUESTION, why not in hadronic channel?)
  - Top 2 (lνj), M2 in [135,205] (pz of neutrino from W mass constraint)
- Event counting in 2 γγ mass bins: SR [123,129], CR [100,123].
  - Estimate background normalisation in SR from CR.
  - Sherpa γγj sample normalised to data in range [0,500] GeV. Replace jet with lowest pt with a lepton to help low stats

ATLAS: tHc (results)

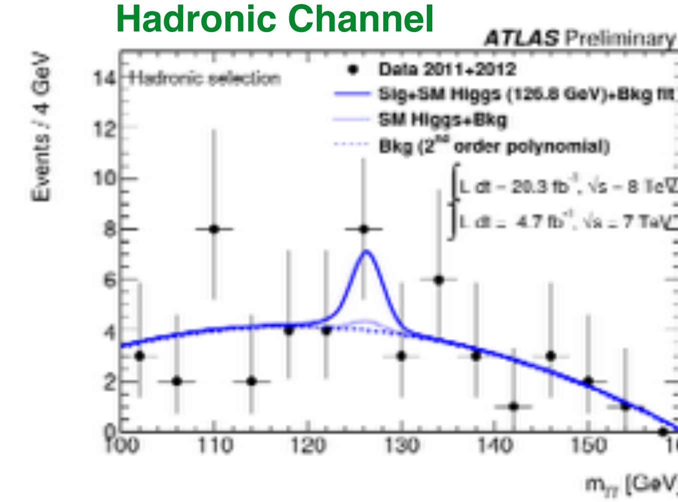
- **B(t->Hc)< 0.83%** (0.53% exp.) for m_h = 126.8 GeV.

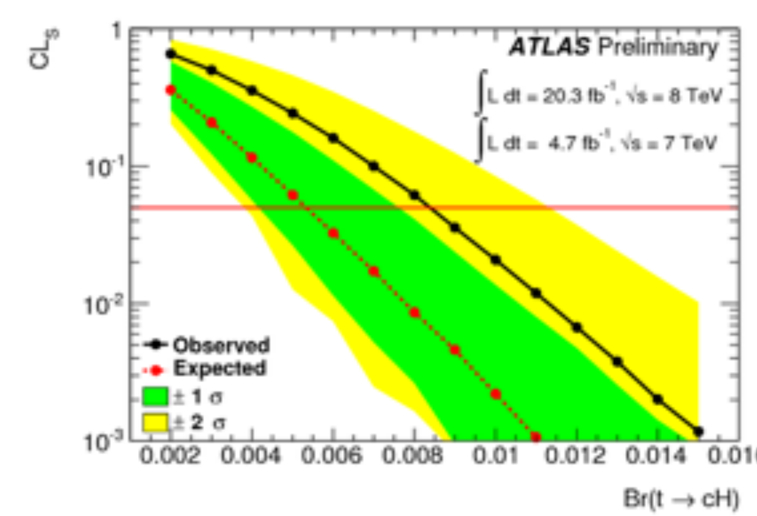
- g_{tHc} < 0.17 (0.14 exp.)

Hadronic Channel | Leptonic Channel



Hadronic Channel





CMS: tHc

“Combined $t \rightarrow cH$ limit from multi-lepton and di-photon analyses” CMS PAS HIG-13-034

CMS: t→Hc

- Use:
  - Diphoton from CMS: H→hh, A→Zh (CMS PAS HIG-13-025)
  - Multilepton from CMS PAS SUS-13-002 (arXiv to PRD)
- Combine most sensitive categories for statistical interpretation
- Signal mainly populates channels with 3 leptons, no tau, a b-tag and no on-Z OSSF pair.
- Result:
  - **B(t->cH)<0.56%** (0.65% exp.)
  - gtHc < 0.14

NMSSM

CMS: $h \rightarrow 2a \rightarrow 4\mu$

“Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states” CMS-PAS-HIG-13-010

CMS: h→2a→4μ (details)

- Signature: h→2a + X →4μ + X
- Designed to be model independent
- **NMSSM sector:**
  - 3 CP even (h_1,h_2,h_3)
  - 2 CP odd (a_1,a_2)
  - h_1/h_2 → 2a_1 allowed
  - h_1 or h_2 SM like (ie. 125 GeV Higgs)
  - B(a1→μμ) substantial if $2m_\mu < m_{a1} < 2m_\tau$
  - most stringent limits on Higgs sector of NMSSM come from LEP and WMAP.
- **Dark-SUSY:**
  - motivated by observed positron excess in satellite experiments.
  - light massive dark photons
  - weak coupling to SM particles through kinetic mixing with photon
  - lightest neutralino (n_1) decays
  - lack of anti-proton excess in measurements of cosmic ray spectrum constrains **$m_{\gamma D} \leq O(1\text{GeV})$**
  - B(γ_D→μμ) can be up to 45%, depending on $m_{\gamma D}$ (assuming decay only to SM particles).

CMS: $h \to 2a \to 4\mu$ (selection)

- Trigger: dimuon
- **≥4μ** (8 GeV), ≥1μ (17 GeV, $|\eta|<0.9$) (*)
- Exactly 2 OS μμ pairs with:
    - no shared muons
    - same vertex
    - vertex fit χ^2 prob>1% OR $\Delta R(\mu,\mu)<0.01$
    - $m_{\mu\mu} < 5$ GeV
- Isolated μμ pairs: $I_{\mu\mu}<2$ GeV (**)

- μμ pair mass compatibility:
    - $|m_1-m_2|<0.13$ GeV + $0.065*(m_1+m_2)/2$
    - m_1 is pair with (17 GeV μ)
    - corresponds to ≥5σ on core resolution
    - signal inefficiency ~5% (FSR)

- (*) ~20% signal acceptance loss. Eliminates significant model dependence due to the reduced trigger performance for collimated dimuons in the forward region.)
- (**) scalar sum track-pt in dR<0.4 around dimuon direction excluding dimuons. Rejection factor 50 against bbbar with 20% signal efficiency loss.

CMS: $h \rightarrow 2a \rightarrow 4\mu$ (bkg./sys.)

- **bbbar:**
  - 2D PDF of μμ masses: $B_{17+8}(m_1)$ x $B_{8+8}(m_2)$
  - shapes from 3μ CR (dimuon + orphan μ)
  - B_{8+8}: orphan has p_T>17
  - B_{17+8}: dimuon contains p_T>17
  - validate shape in non-isolated 4μ events
  - 1.8±0.6 events in SR
- **J/ψ pair production:**
  - 7 TeV MC scaled to 7 TeV Data, scaled by ratio of 8TeV/7TeV cross section
  - 2.0±2.0 events in SR

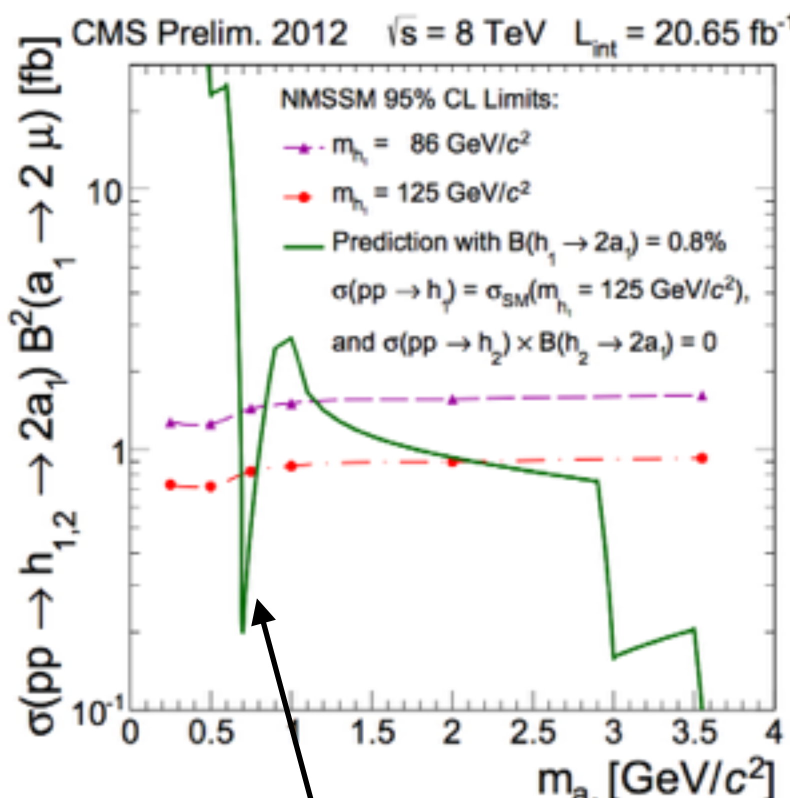
- **Total Events in SR:**
  - Expected: 3.8±2.1
  - Observed: 1

Signal Systematics	
Systematic	**Uncertainty**
muon eff.	4%
muon trig.	3.8%
μμ overlap	3.5%
μμ mass shape	1.5%
lumi	4%
PDF/α	3%
Total	8.4%

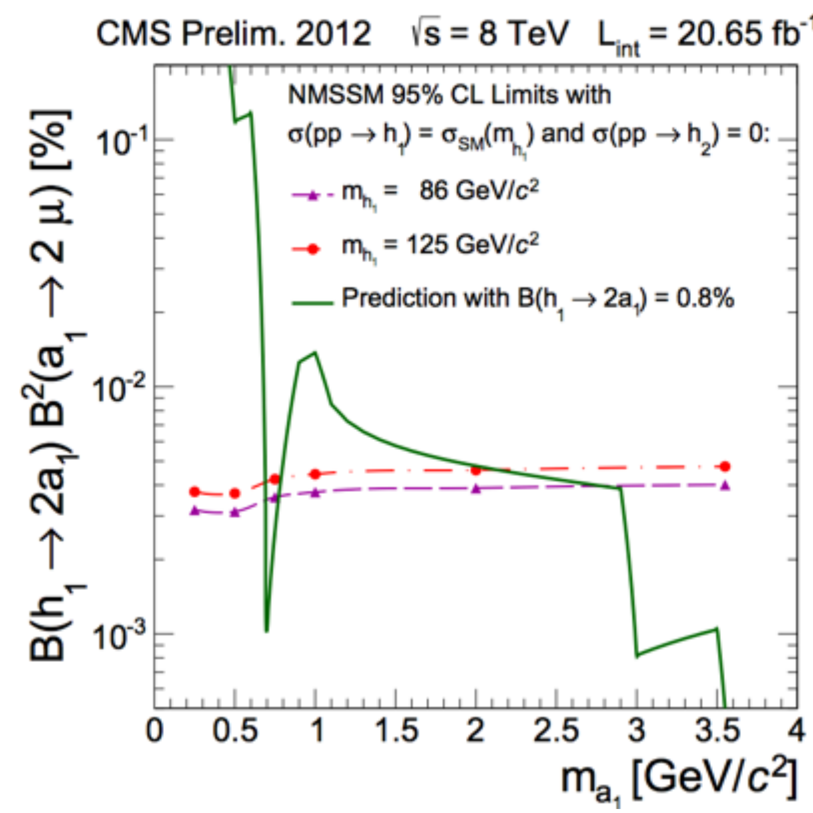
CMS: h→2a→4μ (limits)

- quasi model independent, applicable to models with:
    - 2 μμ pairs
    - from 2 bosons of same type
    - m_a in [0.25,3.55] GeV
    - bosons isolated, spatially separated and have no substantial lifetime.
- limits on σ.BR in NMSSM and Dark-SUSY
- in both cases, BR(h->2a_1) chosen to be large enough so theory ~ experimental limits

lim on σ



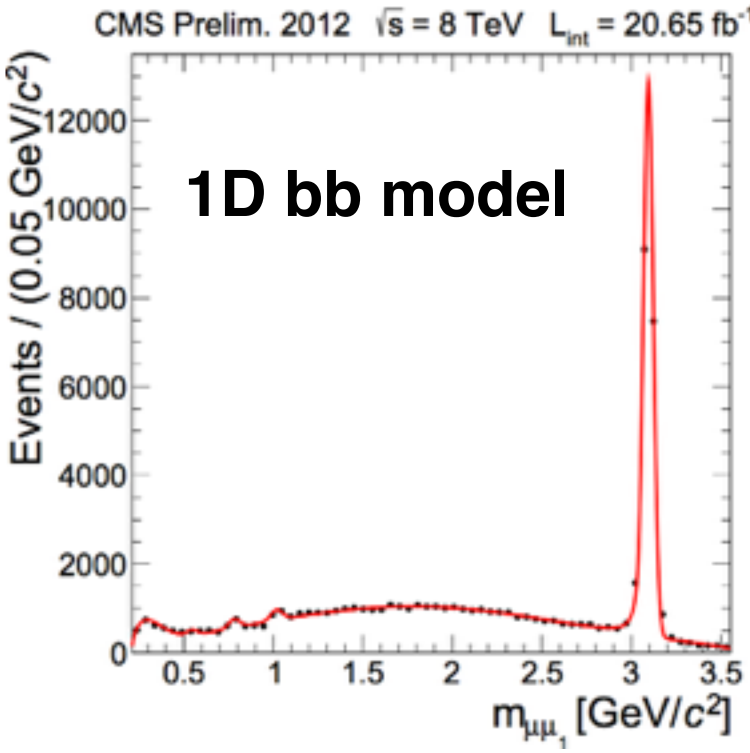
lim. on BR assuming σ_{SM}

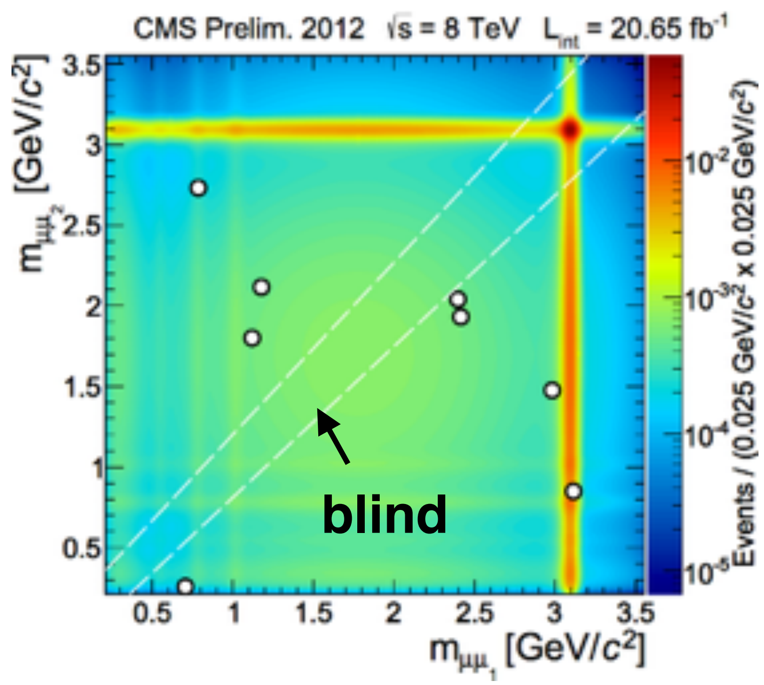


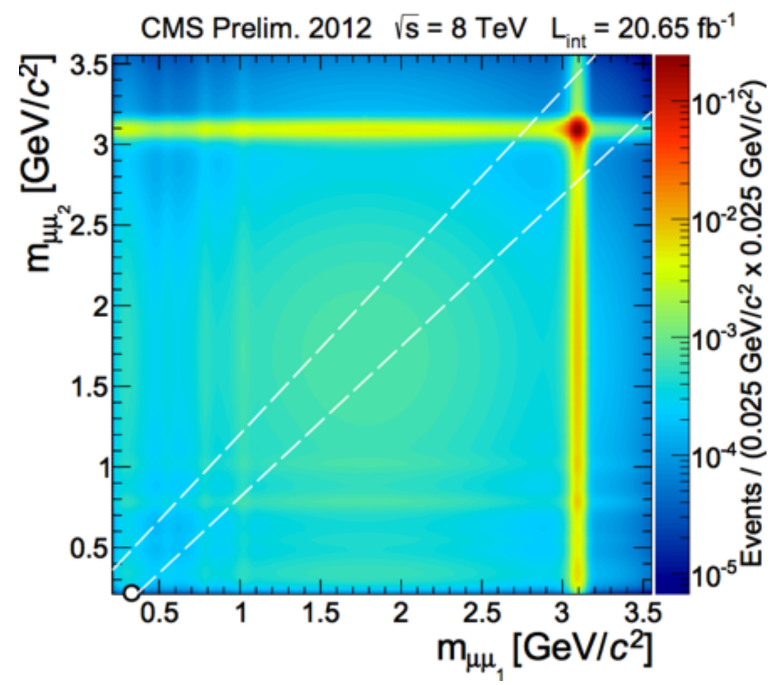
a_1→ss

other large drops are from a1→gg as m_{a1} crosses internal quark loop thresholds

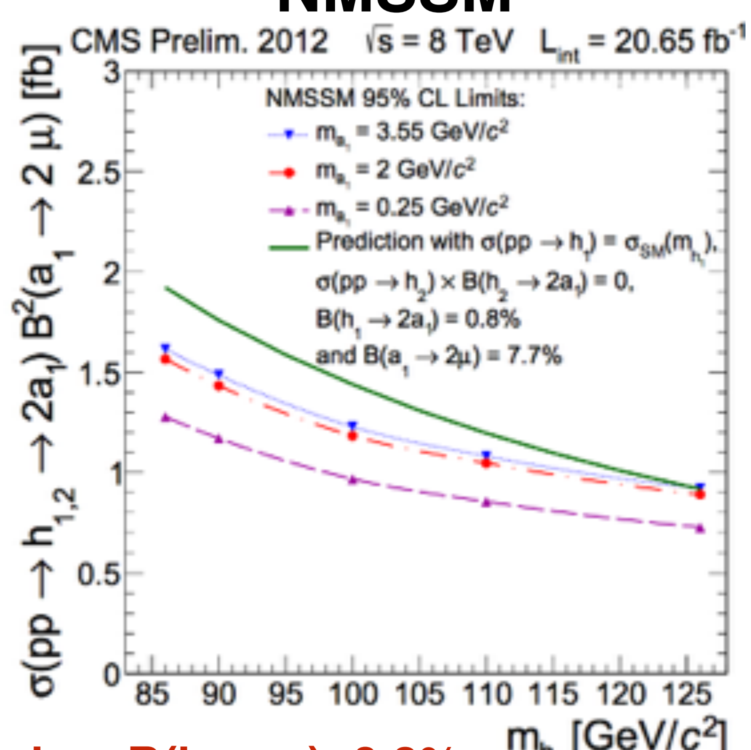
CMS: h→2a→4μ (figs.)



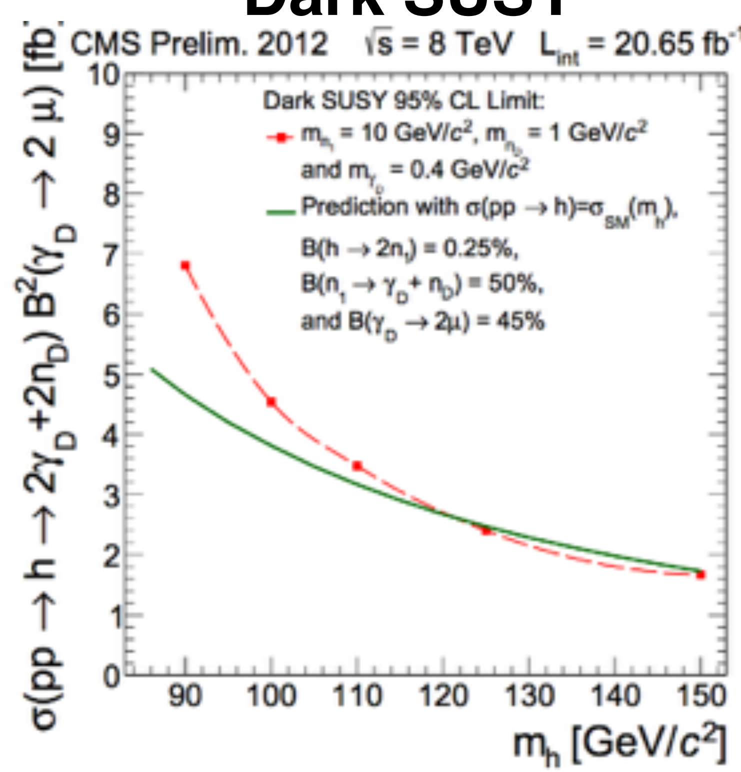




NMSSM

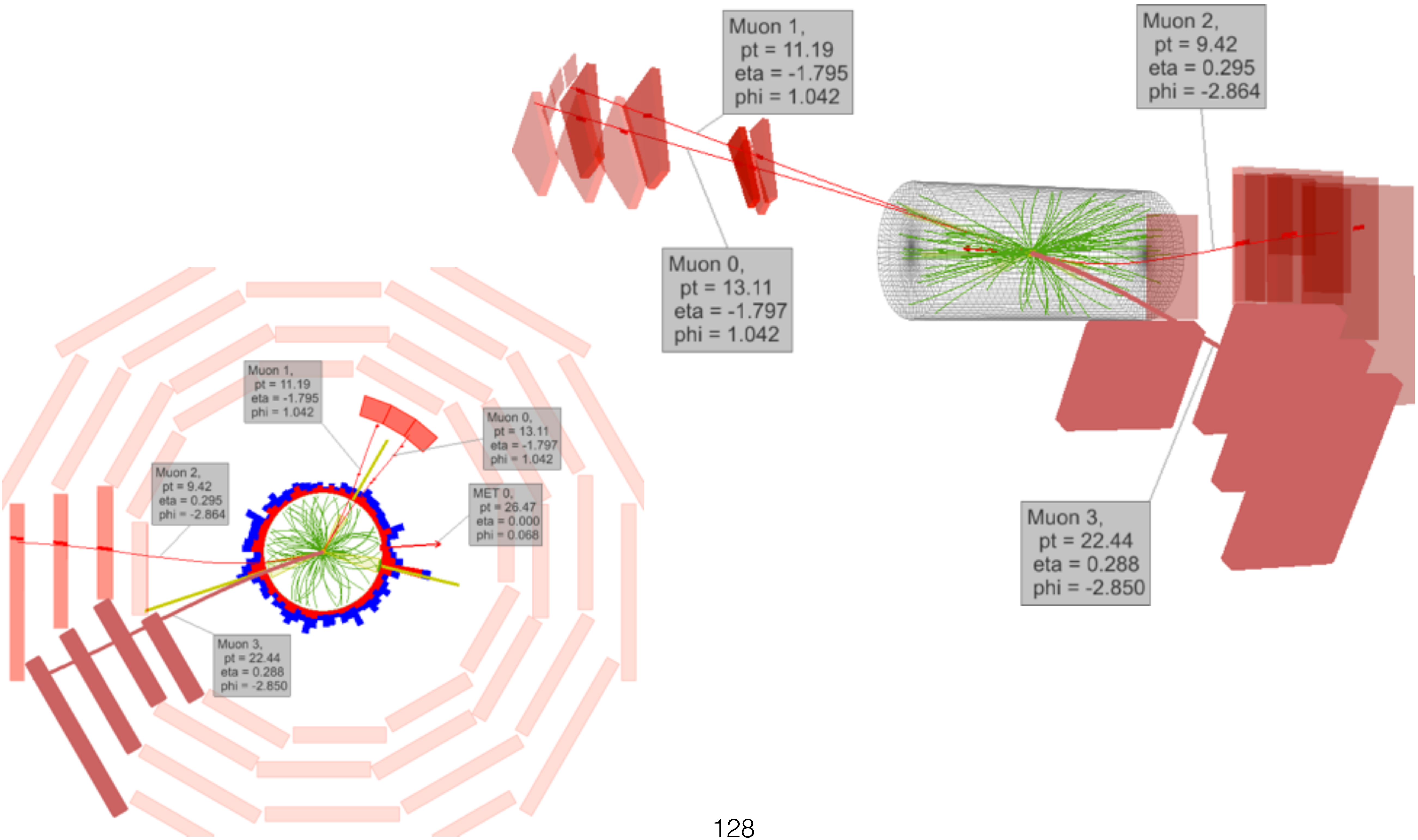


Dark SUSY



Note: prediction has $B(h \rightarrow aa)=0.8\%$

CMS: h→2a→4μ (figs.)



D0: $h \rightarrow 2a \rightarrow 4\mu/2\mu2\tau$

"Search for Next-to-Minimal Supersymmetric Higgs Bosons in the $h \rightarrow aa \rightarrow 4\mu$, $2\mu2\tau$ Channels Using ppbar Collisions at sqrt(s)=1.96 TeV" PRL 103, 061801

D0: $h \rightarrow 2a \rightarrow 4\mu/2\mu 2\tau$ (details)

- NMSSM alleviates fine tuning of MSSM to push m_h above LEP limit (m_h-max)
- $h \rightarrow aa$ dominant ($h \rightarrow bb$ greatly reduced)
- helicity suppression forces a to decay to heaviest possible daughters:
  - $B(a \rightarrow 2\mu) \sim 100\%$ for $2m_\mu < M_a < 3m_\pi$
  - hadronic modes start to dominate above $3m_\pi$
  - $B(a \rightarrow 2\tau)$ dominates for $2m_\tau < M_a < 2m_b$
- dimuon excess reported by "HyperCP Collaboration" suggests searching for $h \rightarrow aa$ with $a \rightarrow$ mumu. Check out cites!
- $h \rightarrow aa \rightarrow 4$tau too difficult, but try searching for $2\mu 2\tau$
- Note: also limits from B factories in $Y \rightarrow a+\gamma$
- Signature:
  - 4μ channel: 2 pairs of collinear muons
  - $2\mu 2\tau$ channel: 1 pair of collinear muons + (MET/μ/e)

D0: $h \to 2a \to 4\mu/2\mu2\tau$ (selection)

- ≥2μ (10 GeV), no trigger
- **4μ channel** (select a muon from each a decay):
  - select largest mass muon pair
  - M(μ,μ)>15 GeV, ΔR(μ,μ)>1.0
  - each muon must have companion track (4 GeV, ΔR<1.0, closest track)
  - muon-companion pair calo+track isolation
- **2μ2τ channel** (select 2 muons from one a decay):
  - select largest pt muon pair
  - M(μ,μ)<20 GeV, ΔR(μ,μ)<1
  - $pT_1+pT_2>35$ GeV
  - muon pair calo+track isolation (plus self-energy veto)
  - tighten muon track quality to improve MET
- $p_T(\mu) < 80$ GeV
- $N_{jets} < 5$ (15 GeV)
- MET < 80 GeV
- Sub-selection to pick e/mu/had(*) taus:
  1. **0 jets**, lead non-μ track 4 GeV + Δϕ(track,MET)<0.7
  2. **>0 jets**, lead jet **(j_1) ≤ 4-tracks**, Δϕ(j_1,MET)<0.7, MET > 20 GeV
  3. **>0 jets**, **j_1 >4 tracks OR Δϕ(j_1,MET)>0.7 + MET>35 GeV**
  4. NOT 1-3, **3rd μ (4 GeV)** + Δϕ(μ,MET)<0.7
  5. NOT 1-4, **ele (4 GeV)** + Δϕ(e,MET)<0.7, N_{jet}<3, MET>10 GeV, MET+p_T(e)>35 GeV
- (*) had called "MET"

D0: $h \rightarrow 2a \rightarrow 4\mu/2\mu2\tau$ (bkg./sys.)

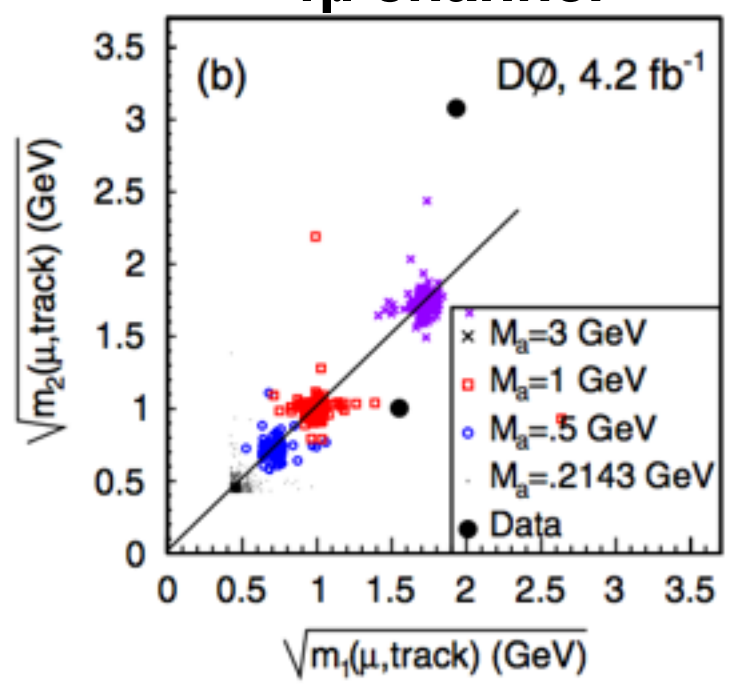
- **Backgrounds:**
    - Dominant: multijet, $Z(\rightarrow ll)$+jets
    - 4μ channel:
        - multijet: non iso. CR
        - $Z(\rightarrow \mu\mu)$+jets: CR missing 1 or 2 companion tracks
    - 2μ2τ channel:
        - Multijet+γ*:
        - cat 1-3: low MET CR
        - cat 4+5: non iso. CR
        - tot. bkg. norm. in M(μ,μ) sideband

- **Systematics:**
    - 4μ channel:
        - Sig: compan. track eff. (50%)
        - Bkg: multijet CR stats. (50%)
    - 2μ2τ:
        - Sig: μ eff. and final sel. (20%)
        - Bkg: stat. in CR (<20%)

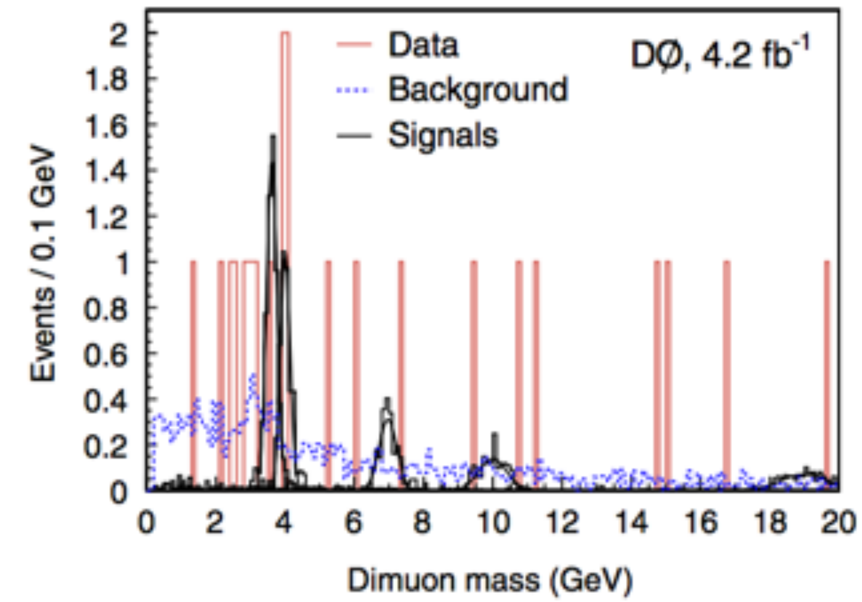
D0: h→2a→4μ/2μ2τ (results)

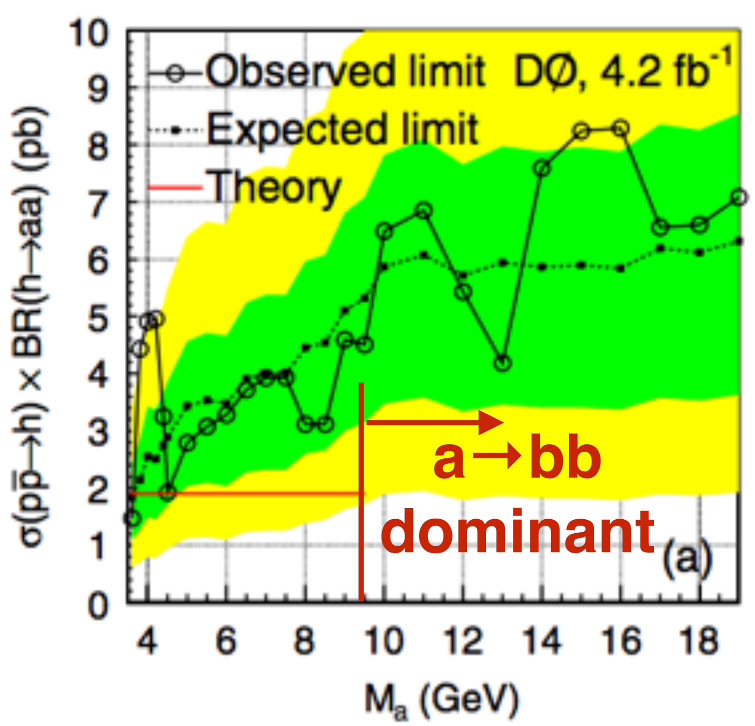
- Events:
  - 4μ channel: Expect 0, Observe 0 (all mass wins.)
  - 2μ2τ channel: expect 0.6-2, observe 1-4
- Limit: B(a→μμ)<7%, assuming:
  - σ(pp→h+X)=1.9pb (m_h=100 GeV)
  - large B(h→aa):
  - severely constrain NMSSM for $m_a < 2m_\tau$
- for $m_a > 2m_\tau$, limits factor 1-4 larger than expected xsec.

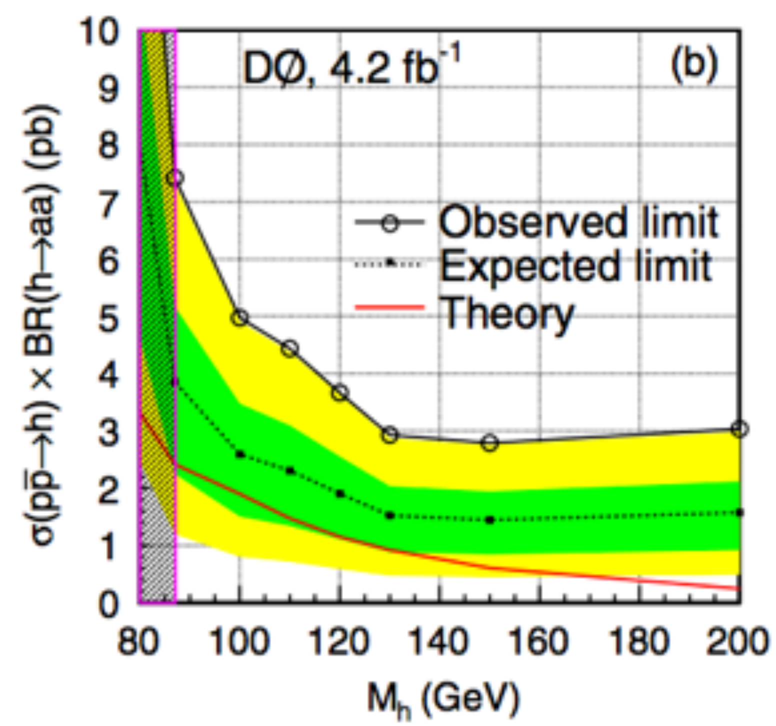
4μ channel



2μ2τ channel







"Theory" has B(h→aa)=100%

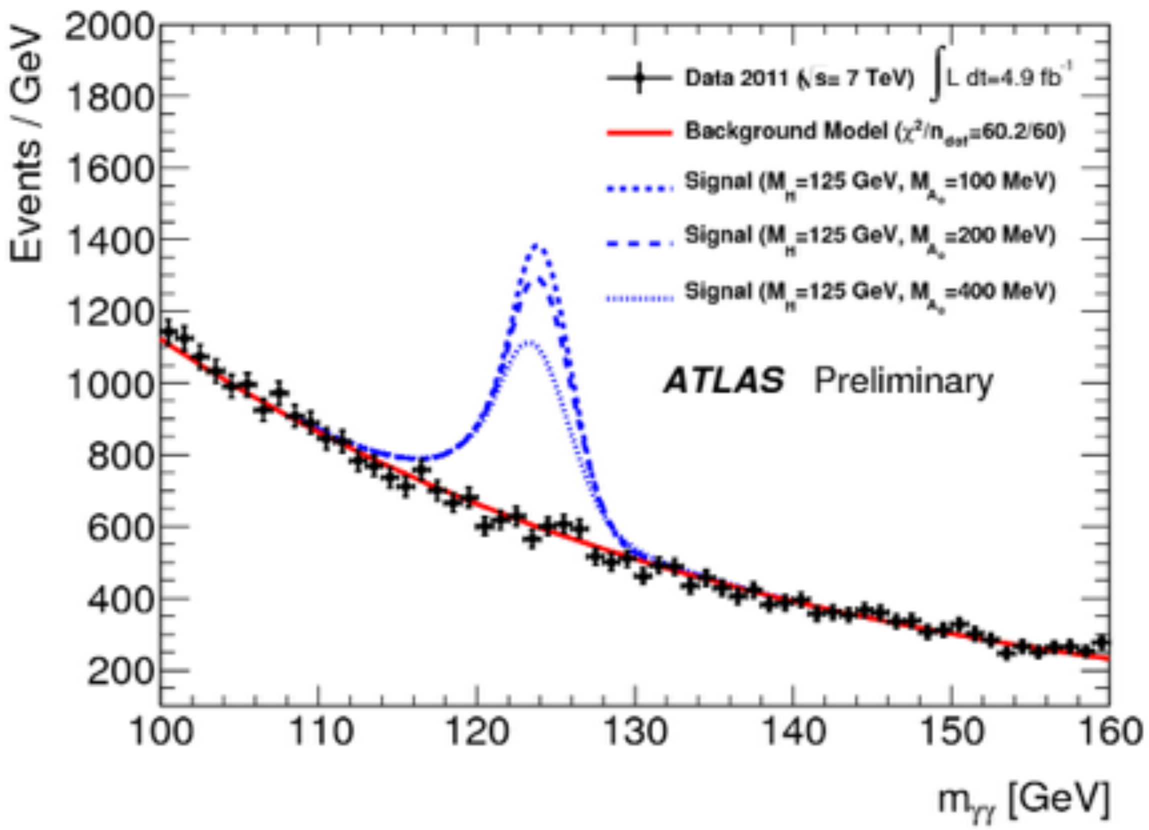
ATLAS: $H \rightarrow 2a \rightarrow 4\gamma$

"Search for a Higgs boson decaying to four photons through light CP-odd scalar coupling using 4.9 fb^{-1} of 7 TeV pp collision data taken with ATLAS detector at the LHC" ATLAS-CONF-2012-079

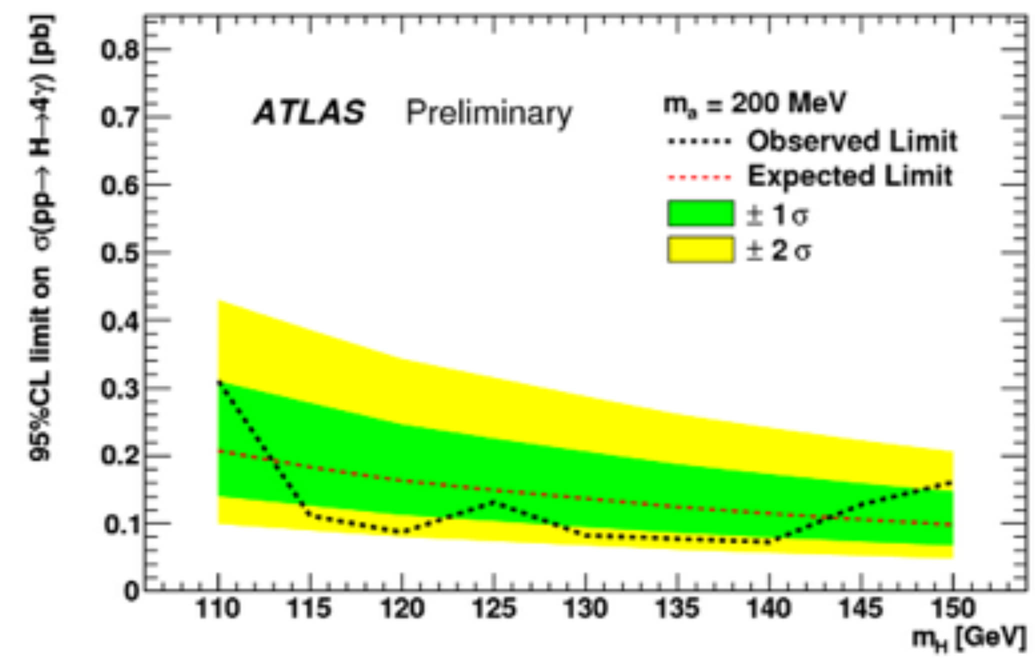
ATLAS: H→2a→4γ (details)

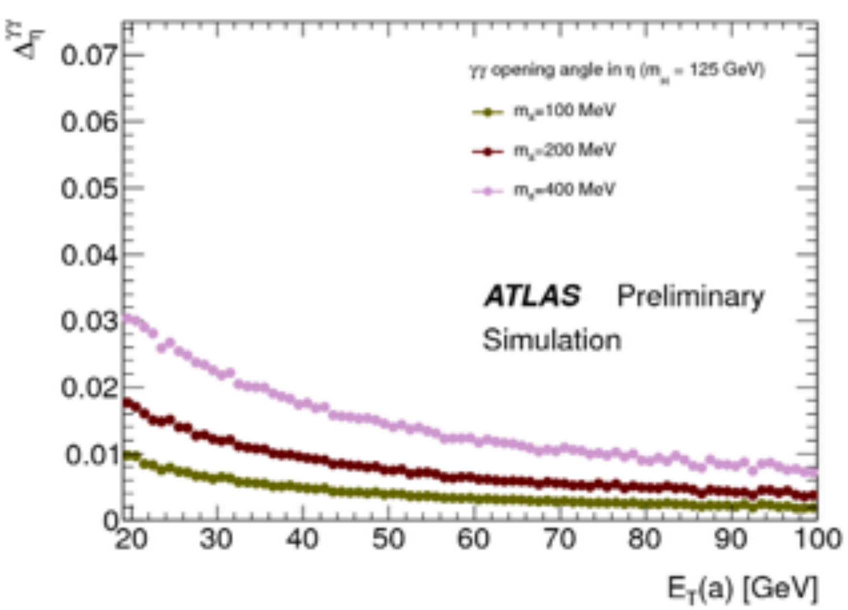
- m_a [100,400] MeV (lower decay outside detector, higher decay to hadrons dominates)
- m_H [110,150] GeV
- $c\tau_a$<0.5m (decay in detector)
- B(a→γγ) enhanced if $m_a < 3m_{\pi 0}$
- Signature H→2a→2γ+2γ (boosted 2γ reco. as 1γ)
- Selection:
  - SM H→γγ analysis
  - Remove π^0 discriminating variables from photon ID (*)
  - Remove diphoton categories.
- Dominant sys: γ eff. 10% (per γ)
- **Limit: σ(H→2a→4γ)< ~0.3 pb** (comparable to D0 4μ sensitivity)
- (*) 2γ π_0 similarity leads to large sig. eff. loss. esp. for large m_a.

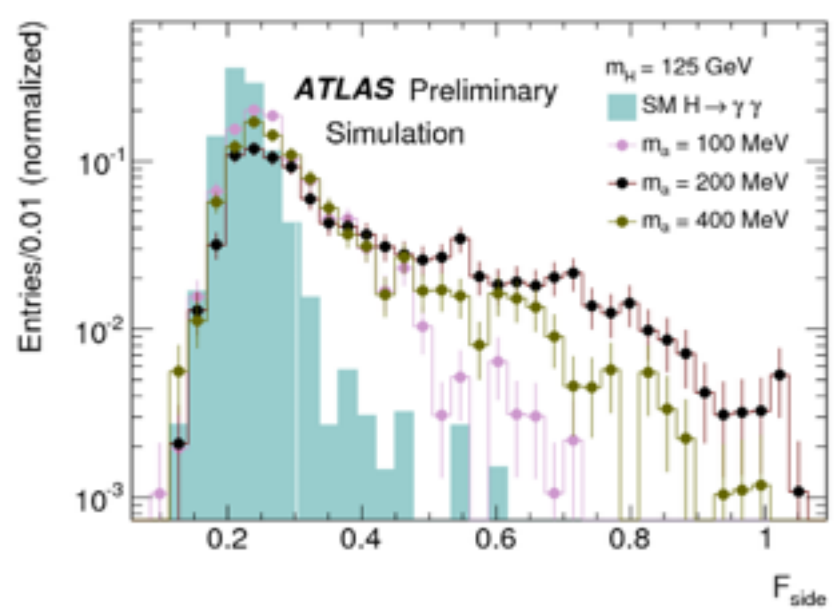
ATLAS: H→2a→4γ (figs.)

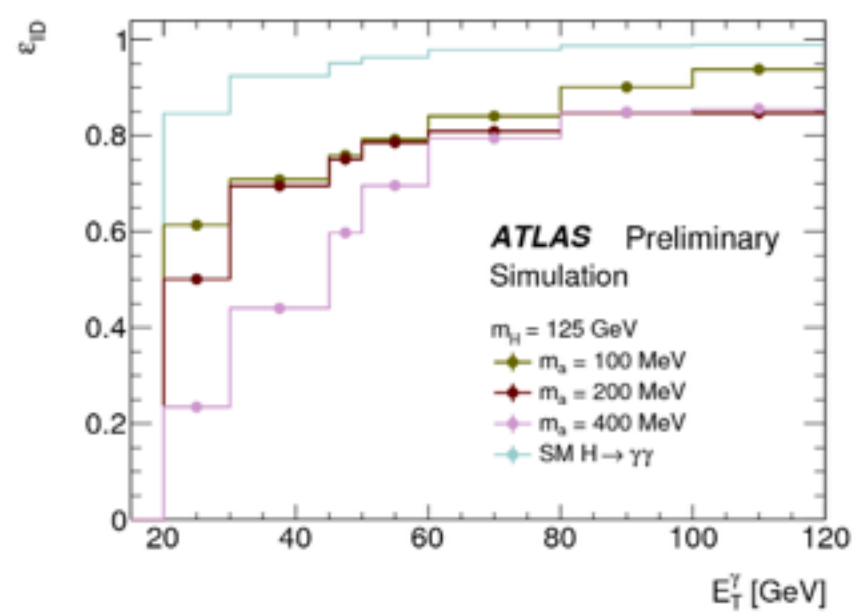


m_a = 200 MeV





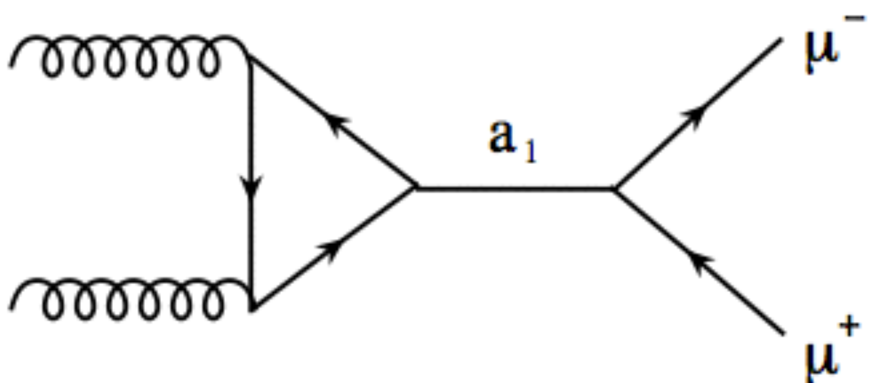




CMS: $gg \rightarrow a1 \rightarrow \mu\mu$

"Search for a Light Pseudoscalar Higgs Boson in the Dimuon Decay Channel in pp Collisions at s√=7 TeV" PRL 109, 121801

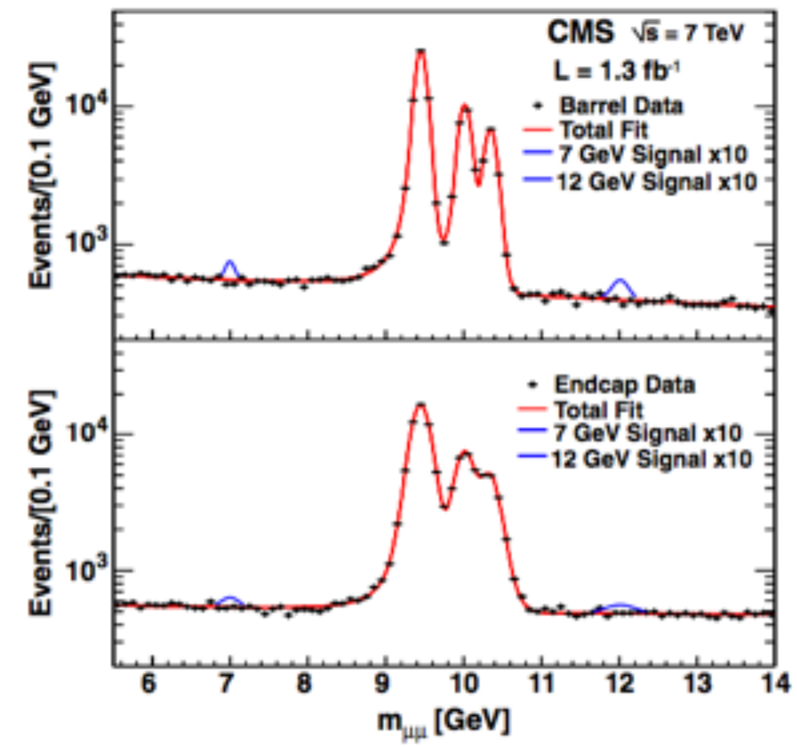
NMSSM

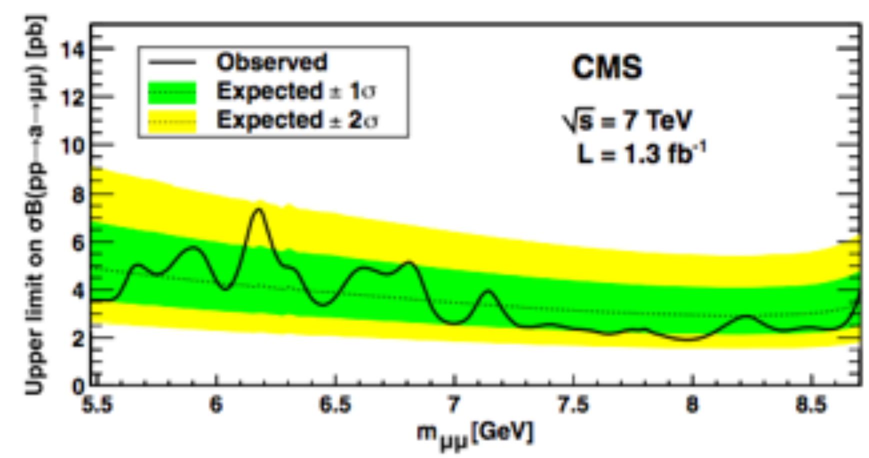


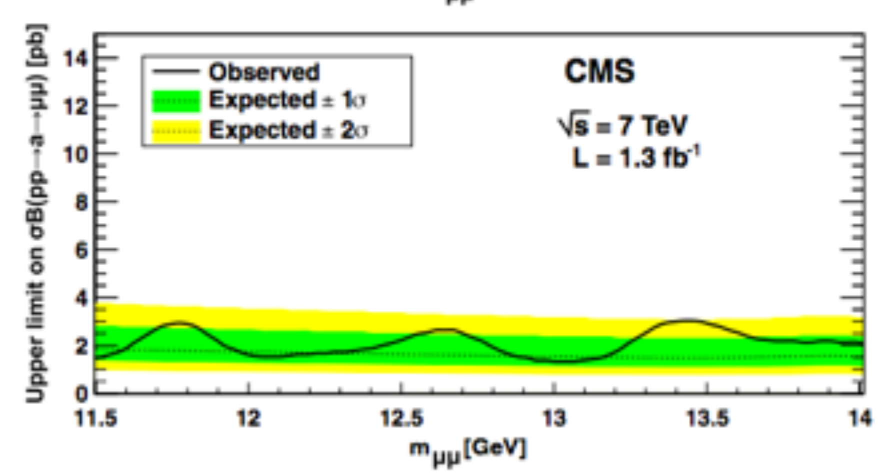
- **NMSSM**: introduces a **singlet scalar field** to solve μ problem
  - 3 CP-even scalars (h_1,h_2,h_3)
  - 2 CP-odd scalars (a_1,a_2)
  - 2 Charged (H^+,H^-)
- a_1 can be **very light**: $m_{a1}<2m_B$

Analysis

- Search for narrow resonance in di-muon invariant mass distribution between 5.5 and 14 GeV (not including Υ region)
- Require opposite-sign isolated di-muons
- Pick best di-muon comb. using vertex info
- Set limits by **fitting to mass spectrum**







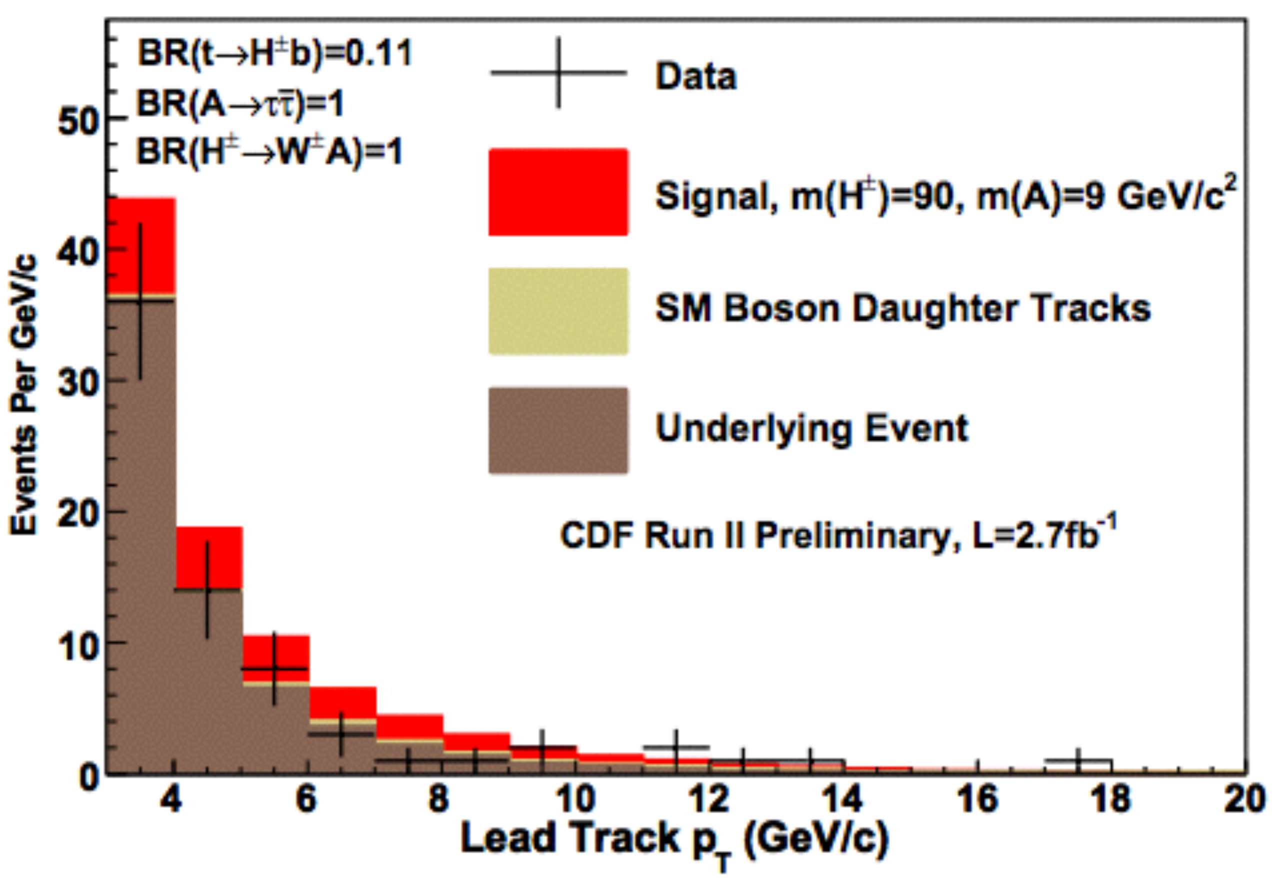
CDF: NMSSM

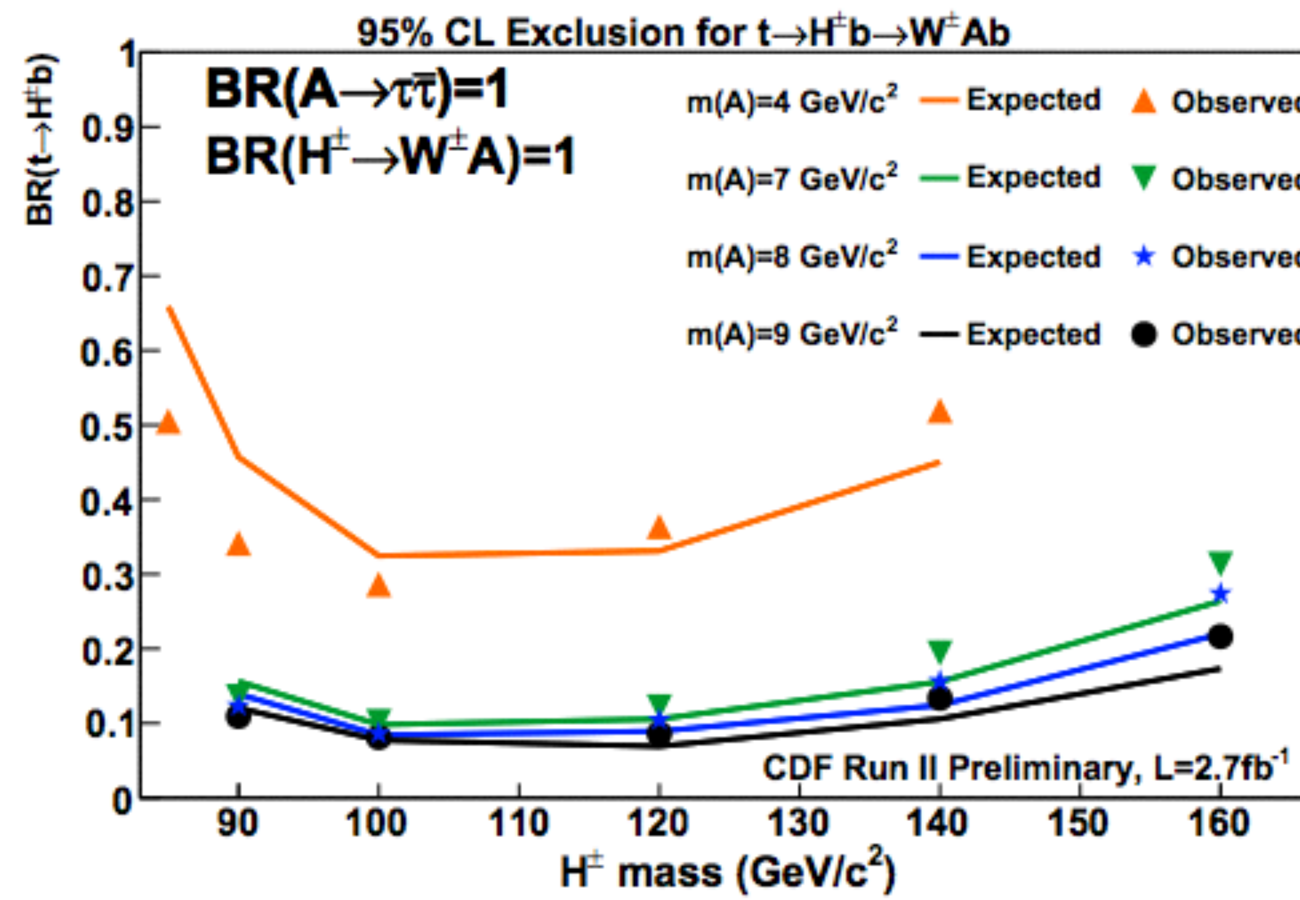
$t \rightarrow H^{+} b \rightarrow W a (\rightarrow \tau\tau) b$

"Search for Light Higgs Boson from Top Quark Decays" CDF Note 10104

CDF: NMSSM $t \to H^+ b \to Wa(\to \tau\tau)b$

- Assume $m_a < 2m_b$ (not experimentally excluded)
- This is the first limits on this decay mode





Invisible

CMS: Invisible VBF

"Search for invisible Higgs decays in the VBF channel"

CMS-PAS-HIG-13-013

CMS: Invisible VBF (outline)

- SM B(H→inv.)~1.2E-3 (H→ZZ→4ν)
- **Indirect Limits**: from vis. decay modes **ATLAS 60%, CMS 64%**
- Direct Limits:
  - H→inv. searches rely on associated production, where recoil against visible system can be measured.
  - **CMS Z(→ll)H(→inv)**: B(H→inv)<**75%** (91%) (CMS-PAS-HIG-13-018)
  - **ATLAS Z(→ll)H(→inv)**: B(H→inv)<**65%** (62%) (PRL)
  - **CMS Z(→bb)H(→inv)**: 1.8σ_{SM} with B(H→inv)=100% (CMS-PAS-HIG-13-028)
  - **CMS Combination**: B(H→inv)<**58%** (44%) (CMS-PAS-HIG-13-030)

CMS: Invisible VBF (strategy)

- 19.6 fb-1 @ 8TeV
- VBF higher cross section than ZH.
- **VBF signature**: **2** final state quark **jets** separated by **large rapidity gap** and **high invariant mass**
- search for:
  - 2 jets + large MET
  - use VBF signature to distinguish signal from background
- Main Backgrounds: $Z \rightarrow \nu\nu$, $W \rightarrow l\nu$
- Limit **B(H→inv)<69%** (53% exp) @95% CL

CMS: Invisible VBF (selection)

- VBF trigger:
  - forward/backward jet pair (40 GeV)
  - $|\eta_{j1} - \eta_{j2}| > 3.5$
  - $M_{jj} > 800$ GeV
  - MET > 65 GeV
- no e or μ (10 GeV)
- pick 2 lead jets (50 GeV, $|\eta|<4.7$):
- $\eta_{j1}.\eta_{j2}<0$
- $|\eta_{j1} - \eta_{j2}| >4.2$
- $M_{jj} > 1100$ GeV
- MET > 130
- central jet veto (30 GeV and $\eta_{j1}<\eta<\eta_{j2}$)
- $\Delta\phi(j1,j2) < 1.0$ (trans. boosted VBF system)

CMS: Invisible VBF (bkg.)

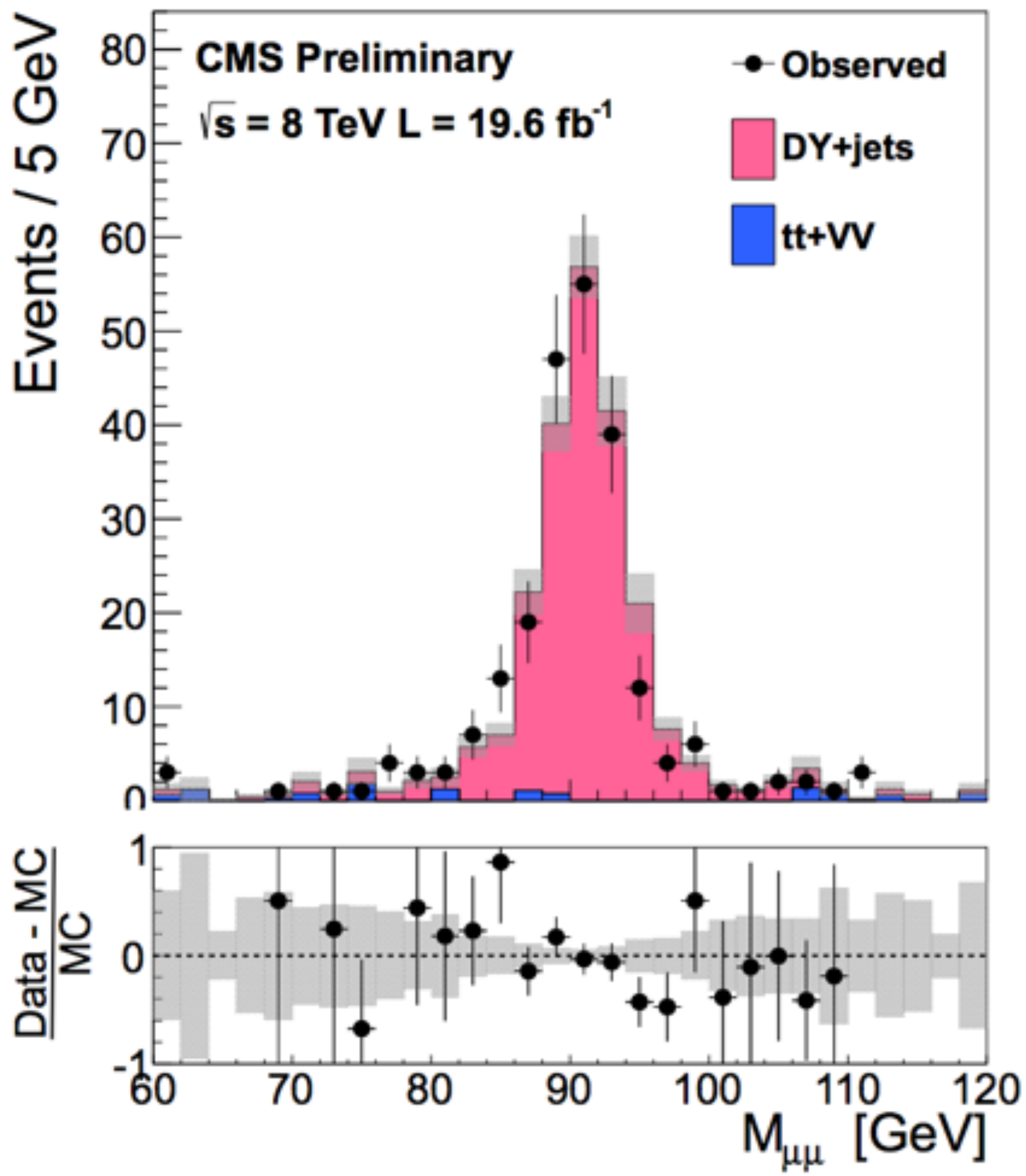
- **Z→νν (Z→μμ embedding):**
  - replace lepton veto with Z→μμ requirement: exactly 2 muons, 60 < $m_{\mu\mu}$ < 120 GeV
  - recompute MET with muons removed
  - scale by Z→μμ/Z→νν eff.*Xsec ratio
  - big problem σ(Z→νν)/σ(Z→μμ) ~ 5.6 so you extrapolate from smaller CR.
    - N_{CR}(obs.) = 12 events
    - N_{SR}(est.) = 102 ±30 (stat.) ±14 (sys.) events
- **W→lν (sideband):**
  - CR with 1 selected lepton
  - for W→μν recalc. MET with muon removed (imitating losing a muon)
  - transfer back using MC N_{CR}/N_{SR}
  - similar or more events in CR (better than Z→νν)
  - systematically limited by MC transfer factor
- **W→τν:** sideband (sim. but looser than W→lν)
- **Multijet:** ABCD

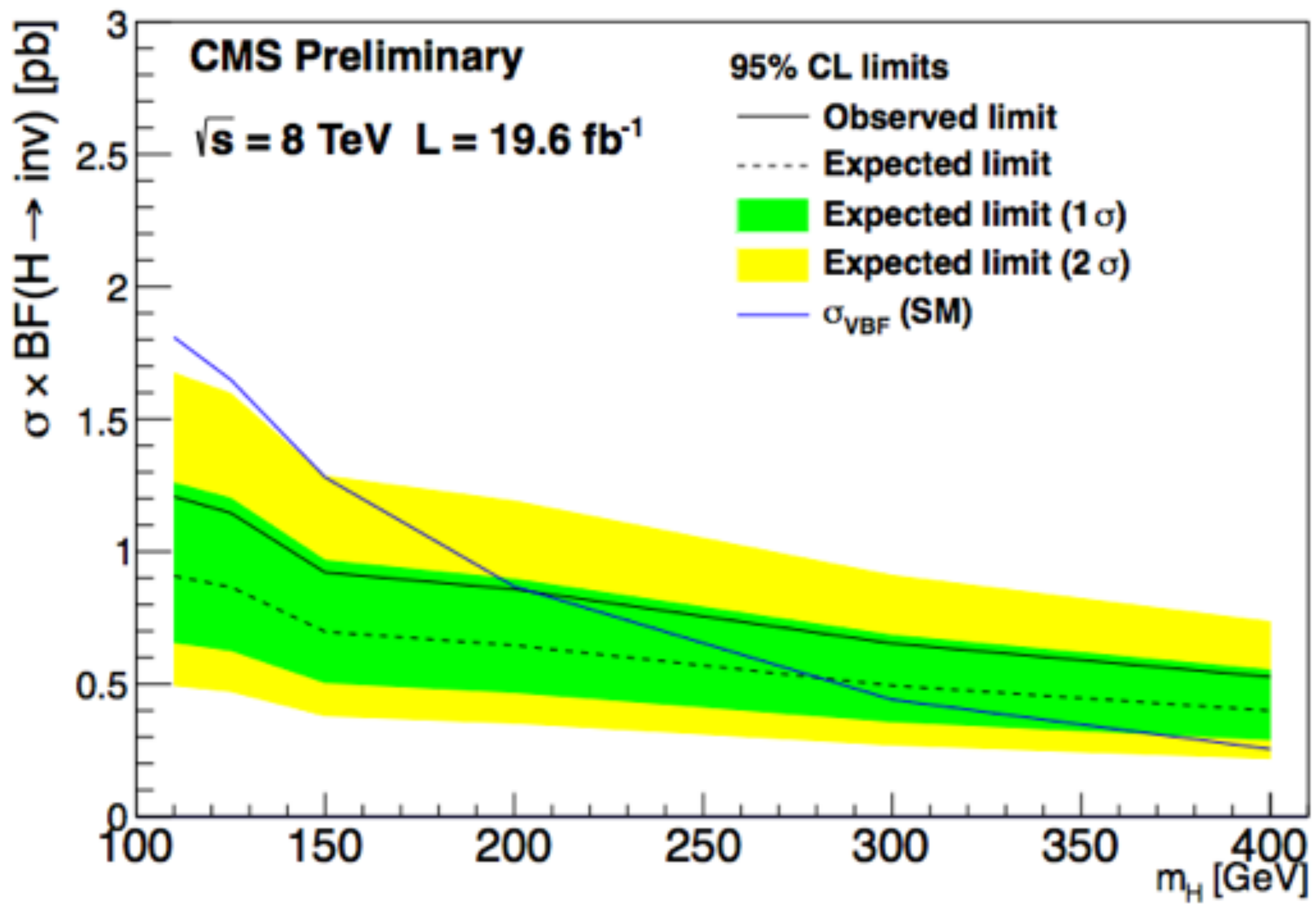
CMS: Invisible VBF (results)

- Largest uncertainty: stat. from $Z \to \mu\mu$ CR ($Z \to \nu\nu$ bkg.)
- N(bkg) = 339 +- 36 (stat.) +- 50 (sys.)
- N(sig) = 208 (ε_{sig}~0.67%)
- N(obs) = 390
- **B(H->inv.)<69%** (53% exp.) (assuming SM VBF production xsec)
- interesting interpretation on DM-nucleon xsec. from ATLAS search.

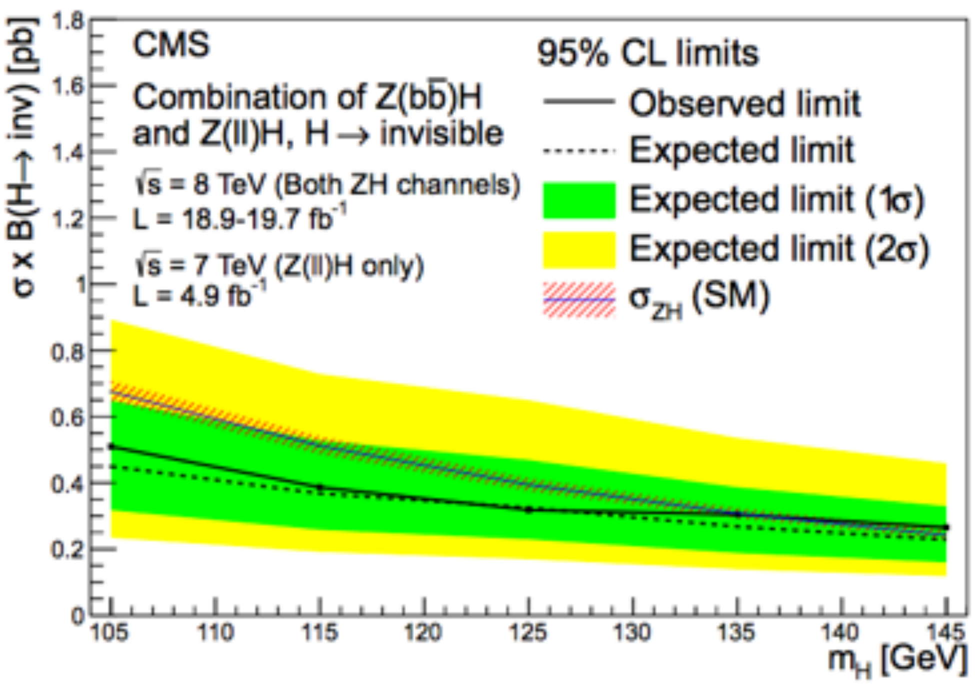
CMS: Invisible VBF (figs.)

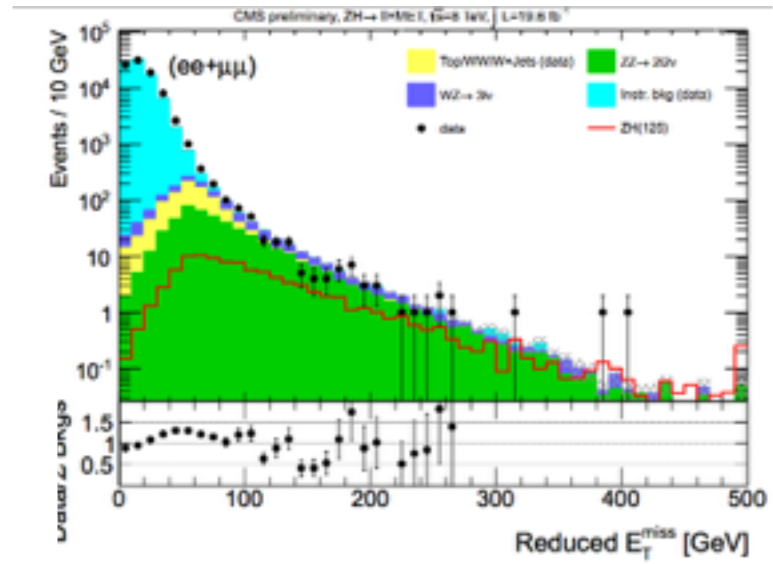
Zμμ CR

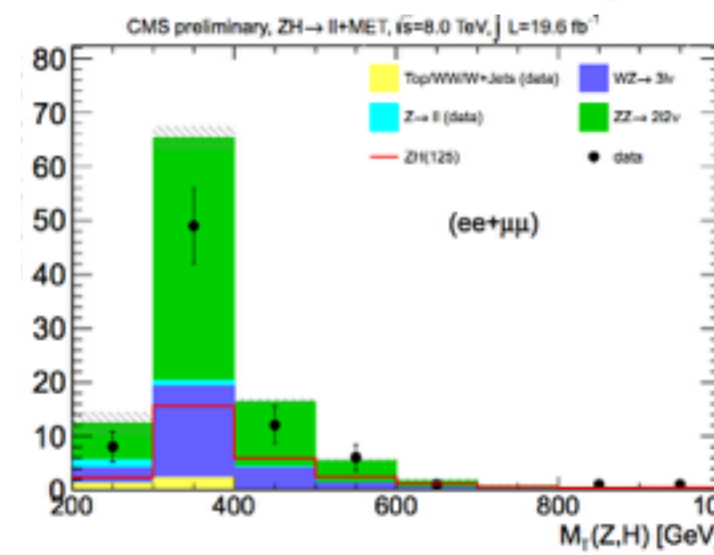


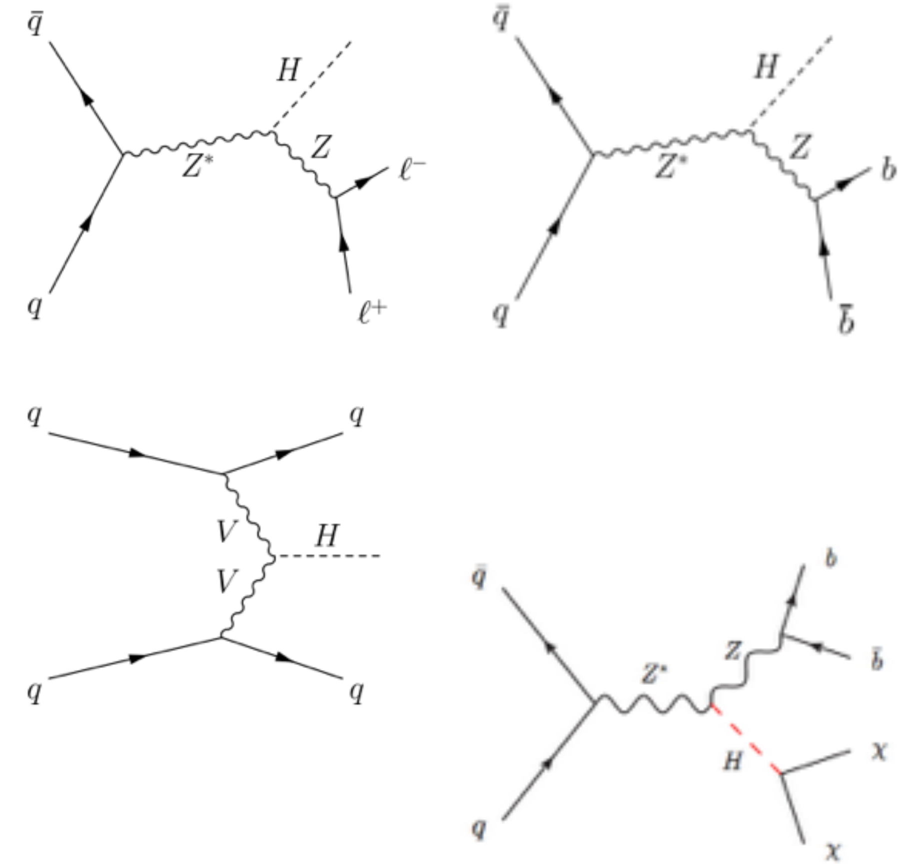


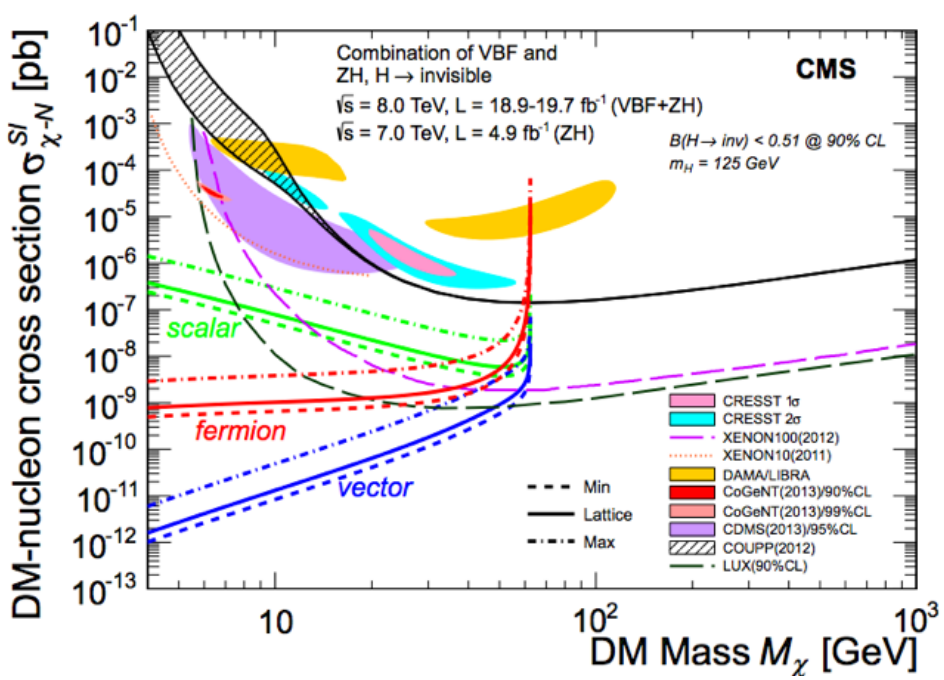
CMS: Invisible combination

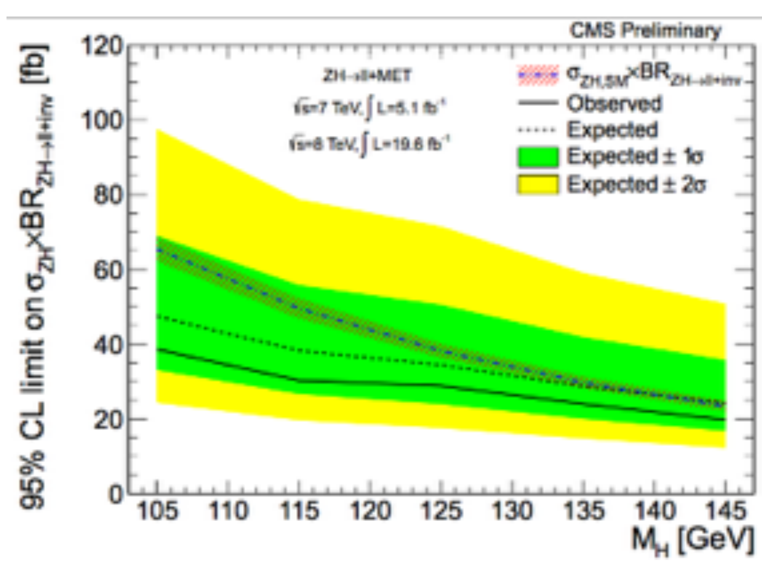


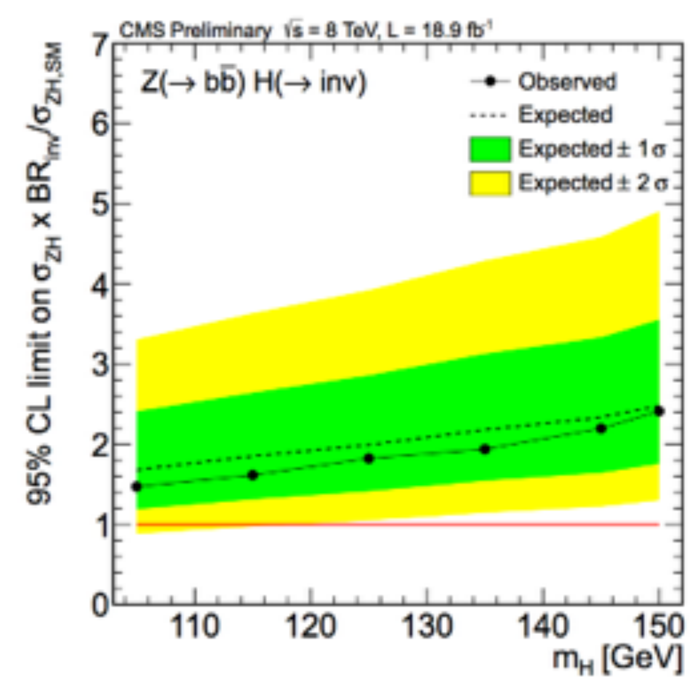












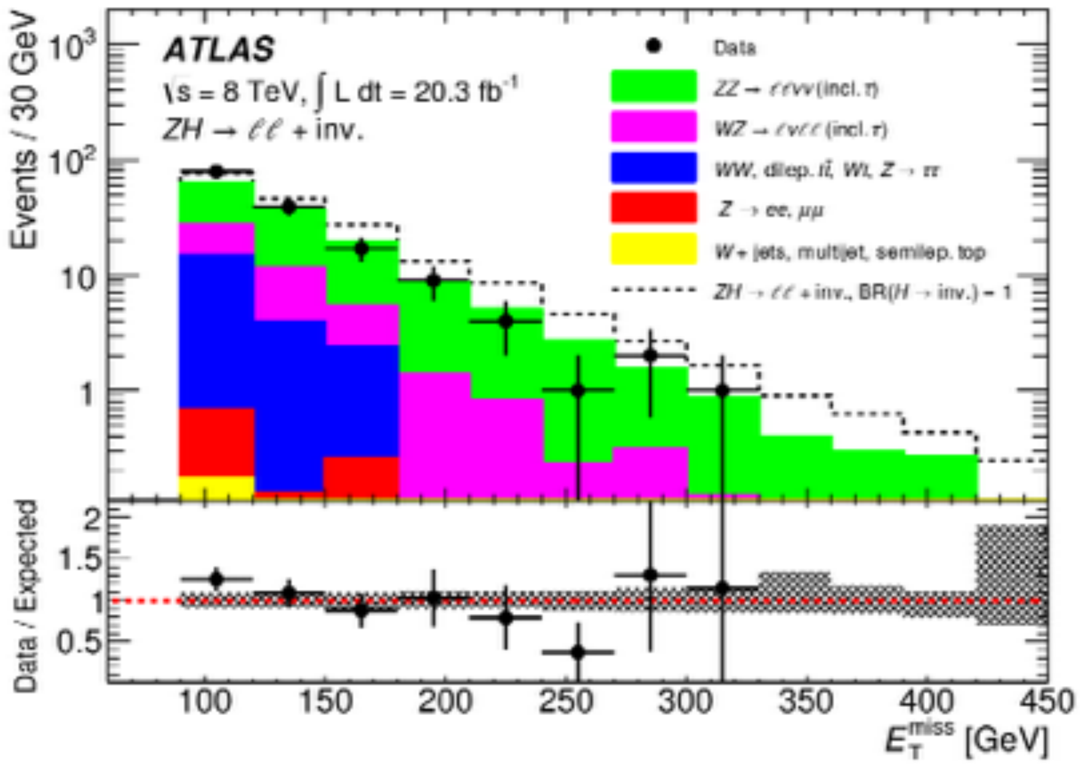
ATLAS: Invisible ZH

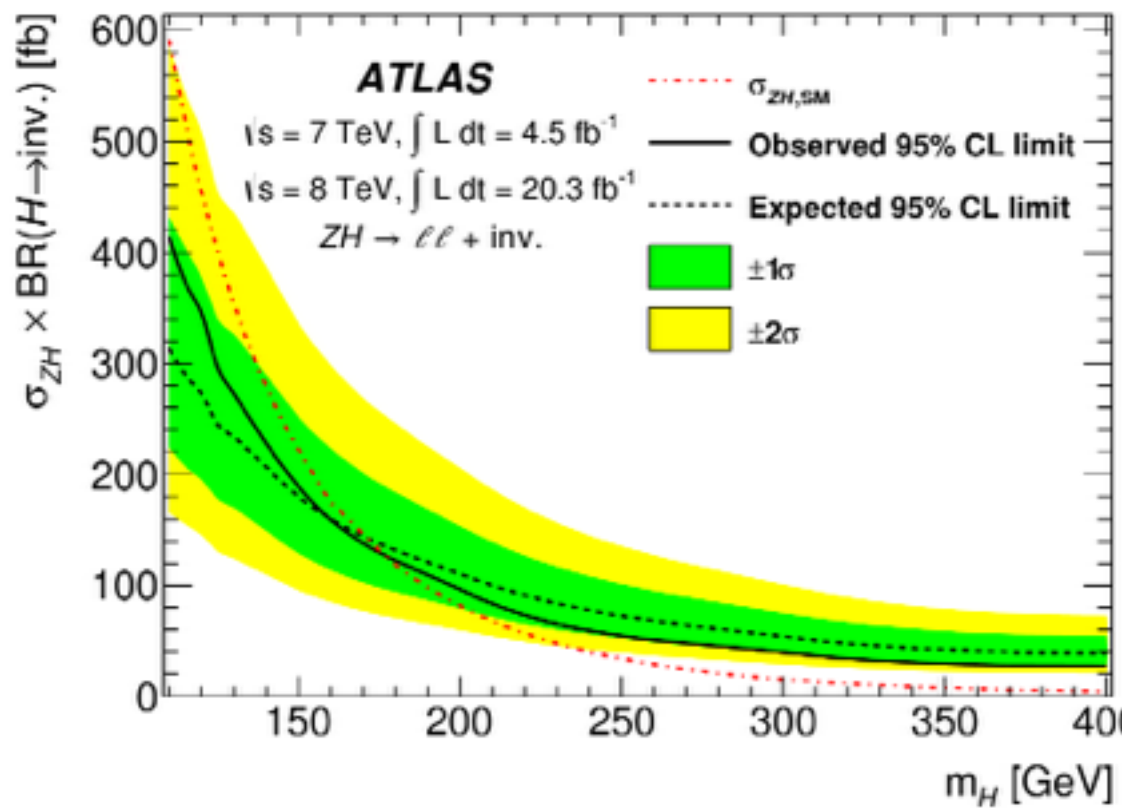
“Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS” arXiv:1402.3244 [hep-ex]

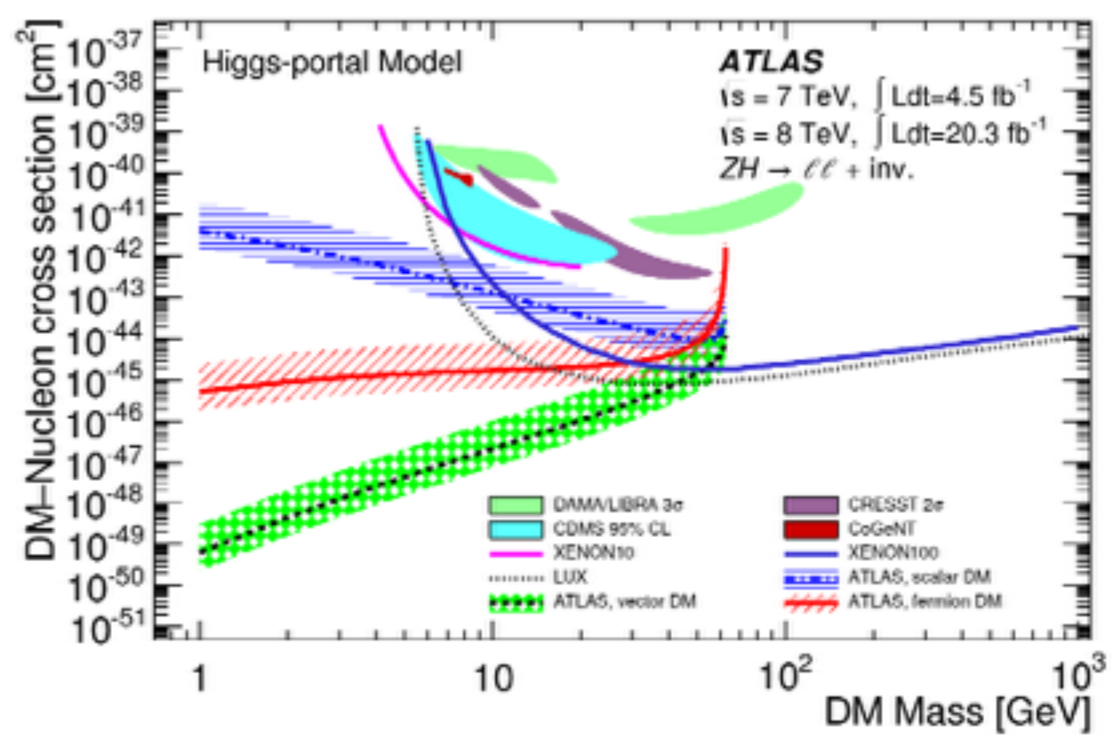
ATLAS: Invisible ZH

- **Selection:**
  - trigger: single- or di-lepton
  - 2e or 2μ (20 GeV, isolated), no add. e/μ (7 GeV)
  - $76 < m_{ll} < 106$ GeV
  - MET > 90 GeV
  - $\Delta\phi$(MET,track MET) < 0.2 (avoid fake MET from calo.)
  - $\Delta\phi(p_{T,ll}$, MET) > 2.6 (balance of inv./vis. systems)
  - $\Delta\phi(l,l) < 1.7$
  - $|\text{MET}-pT_{ll}|/pT_{ll} < 0.2$ (balance)
  - no jets (25 GeV, |eta|<2.5)
- **Backgrounds:** main backgrounds (ZZ,WZ) from MC.

ATLAS: Invisible ZH (figs.)







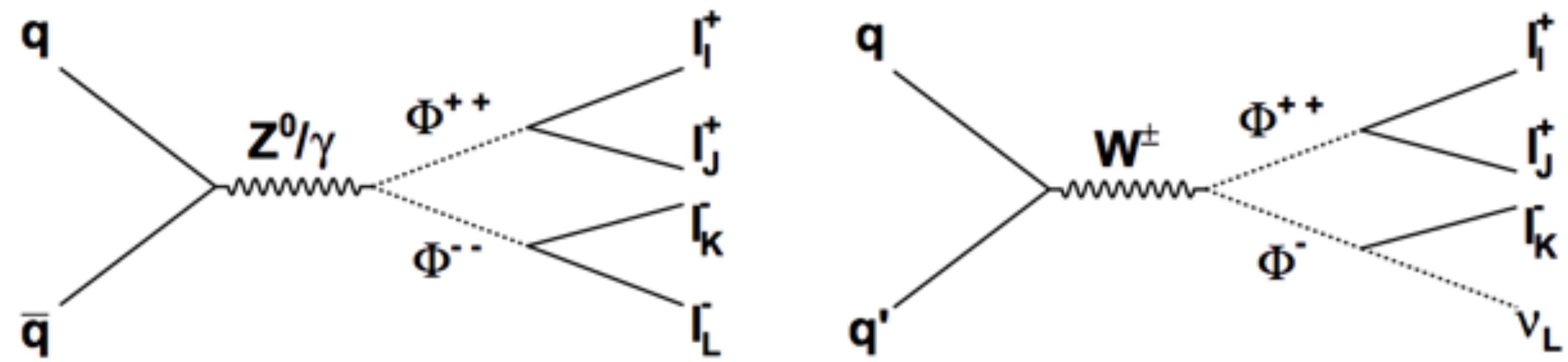
Doubly Charged

CMS: H++

"A search for a doubly-charged Higgs boson in pp collisions at $\sqrt{s}$=7 TeV" EPJC 72 (2012) 2189

Doubly Charged Higgs

- Minimal type II neutrino see-saw model has one Higgs triplet, Φ
- Contains $\Phi^{\pm\pm}$
- Observation of $\Phi^{\pm\pm}$ would make type II see-saw most promising framework for neutrino mass generation.



Assumptions:
- $\Phi^{\pm\pm}$ and $\Phi^{\pm}$ degenerate in mass
- $\Phi^{\pm\pm} \rightarrow WW$ suppressed

No other assumptions on $\Phi^{\pm\pm}$ branching fractions.

Construct benchmark models with different leptonic branching fractions

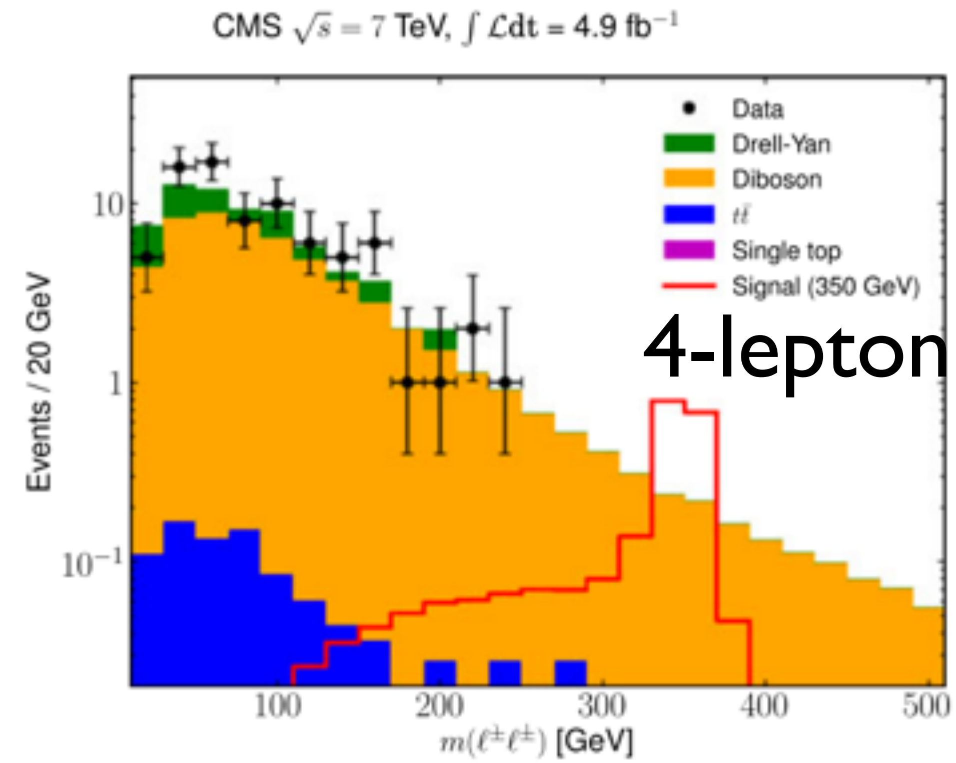
Branching fractions

Benchmark point	ee	eμ	eτ	μμ	μτ	ττ
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	0.50	0	0	0.125	0.25	0.125
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

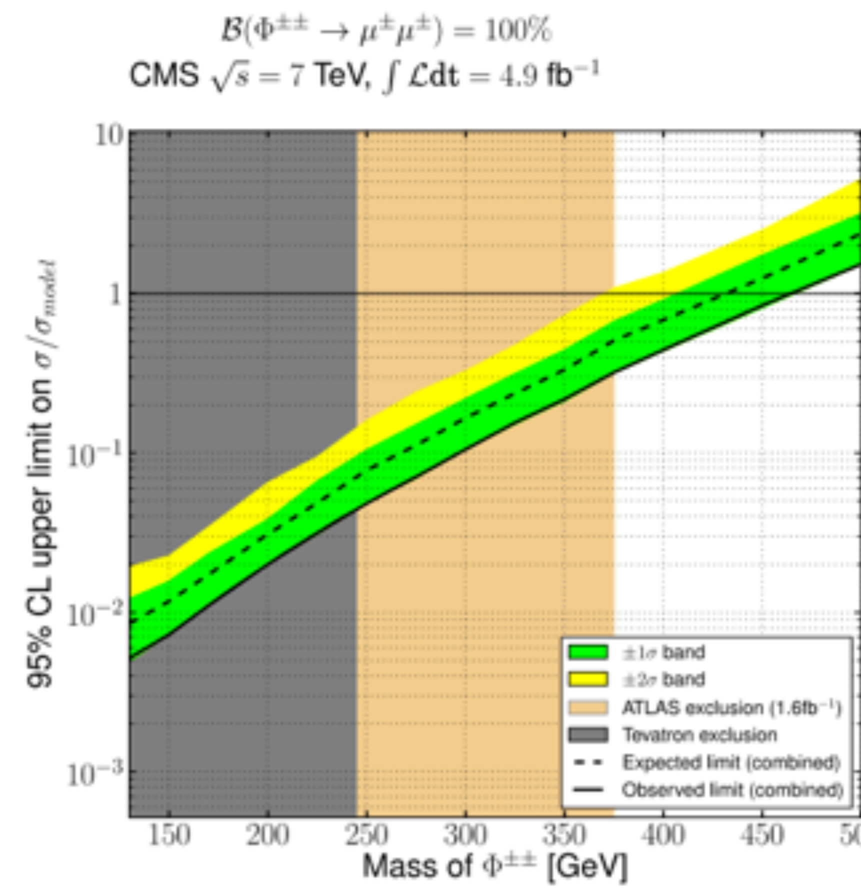
Analysis (CMS)

Selection

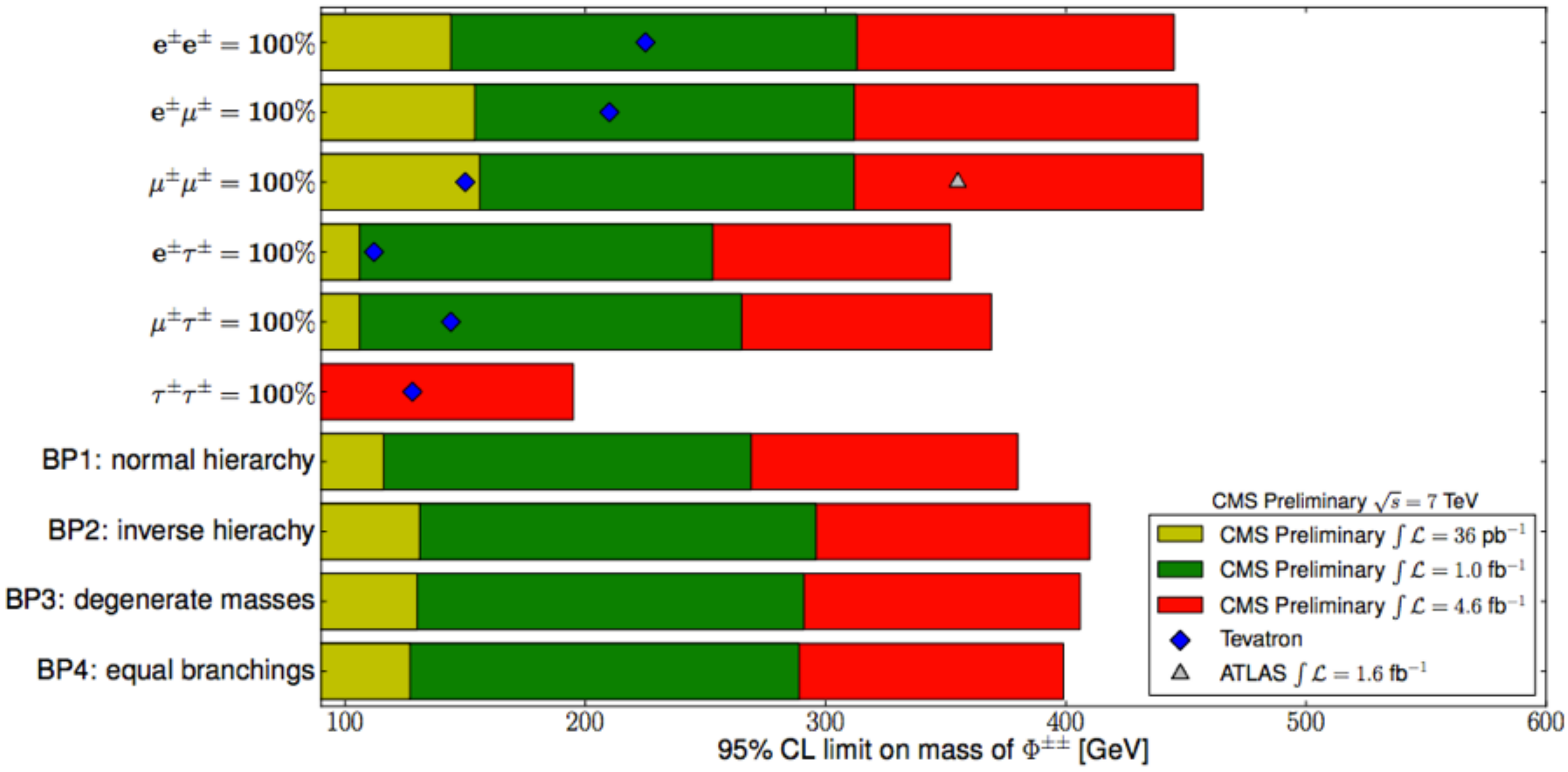
- At least 2 leptons
- Discard pairs at low mass or near Z peak
- Large Σp_T
- Same-sign leptons not back-to-back
- Moderate EtMiss (tau channels)



- Analyse both 3 and 4-lepton final states with:
  - $\Phi^{\pm\pm} \rightarrow ee, e\mu, \mu\mu, e\tau, \mu\tau, \tau\tau$
- Limits extracted by counting events in mass window
- Background in light-lepton channels estimated from mass side-band fit
- Background in tau channels estimated using 2D-sideband, defined with tauID and mass (3τ) or Σp_T (4τ)



Doubly Charged Higgs Limits



D0: H^{++}

“Search for doubly charged Higgs boson pair production in ppbar collisions at sqrt(s)=1.96 TeV” PRL 108, 021801

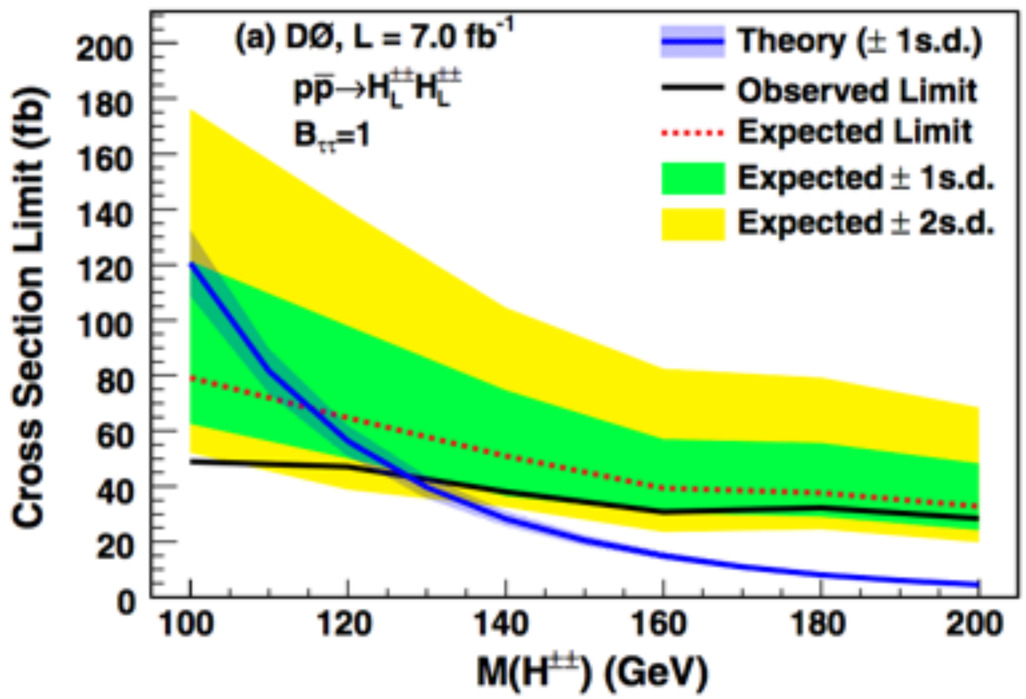
D0: H^{++} (details)

- Models with H++:
  - little higgs
  - LR symmetric models (contain both LH and RH H++)
  - SU(3)c x SU(3)L x U(1)Y
- decays to like-charge lepton pairs violates lepton flavour number conservation
- $\sigma(LH) \sim 2\sigma(RH)$ (b/c Z/γ^* coupling).
- Search for qqbar$\rightarrow H^{++}H^{--}$ with $H^{++}\rightarrow \tau\tau, \mu\tau, \mu\mu$

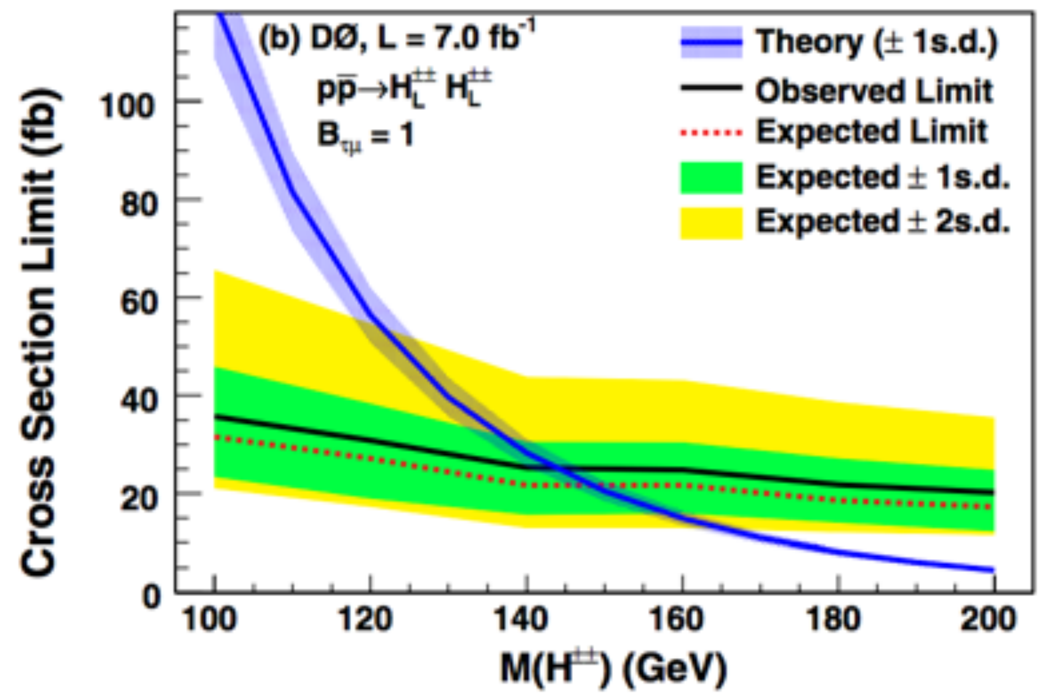
D0: H^{++} (selection)

- Selection:
  - ≥1 μ (15 GeV, |η|<1.6, isolated)
  - ≥ 2 τ (12.5 GeV, |η|<1.5) (additional can be |η|<2)
  - |Q(μ,τ,τ)|=1
  - Categories
    - 1 μ, 2 τ: (OS/SS taus)
    - 1 μ, 3 τ
    - 2 μ, 2 τ
- Background:
  - dominant: Z→ττ, diboson
  - Multijet: ABCD, 2 methods (one or both taus fail ID, Q= ±3 i.e. OS/SS)
- Results:
  - fit $m_{\tau\tau}$ distribution
  - **m_{H++}>128 GeV** ($BR_{\tau\tau}$=1, LH)
  - **m_{H++} > 144 GeV** ($BR_{\mu\tau}$=1)
  - **m_{H++}>130 GeV** (BRττ=BRμτ=BRμμ=1/3)

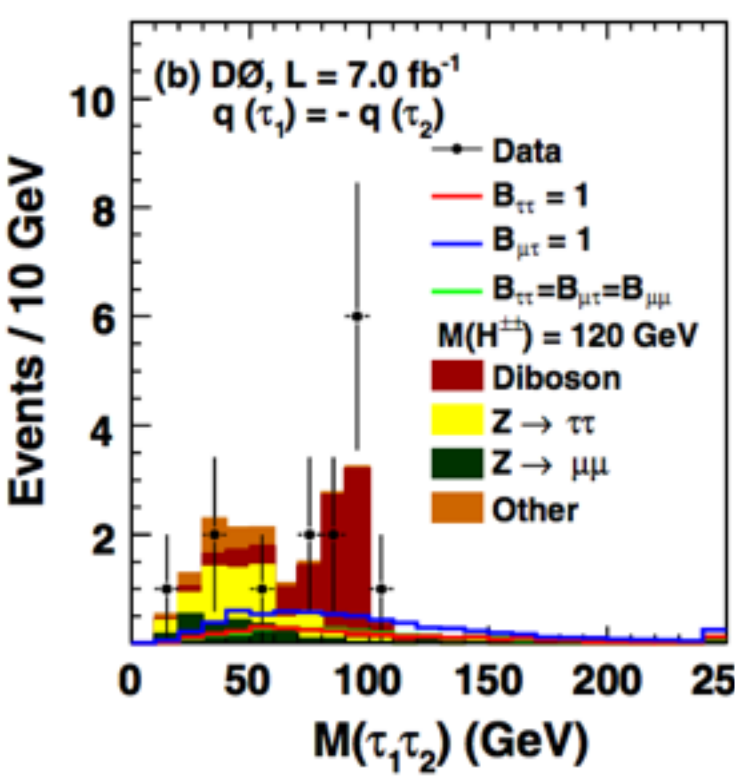
D0: H++ (figs.)



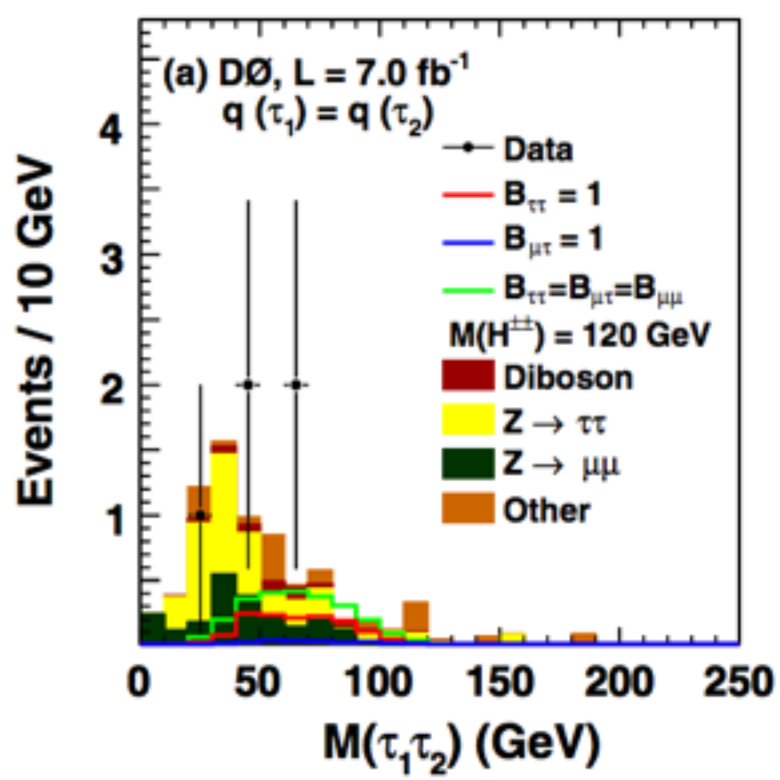
(a) DØ, L = 7.0 fb^{-1}
$p\bar{p} \rightarrow H_L^{\pm\pm} H_L^{\pm\pm}$
$B_{\tau\tau}$=1
Theory (± 1s.d.)
Observed Limit
Expected Limit
Expected ± 1s.d.
Expected ± 2s.d.
Cross Section Limit (fb)
M(H$^{\pm\pm}$) (GeV)



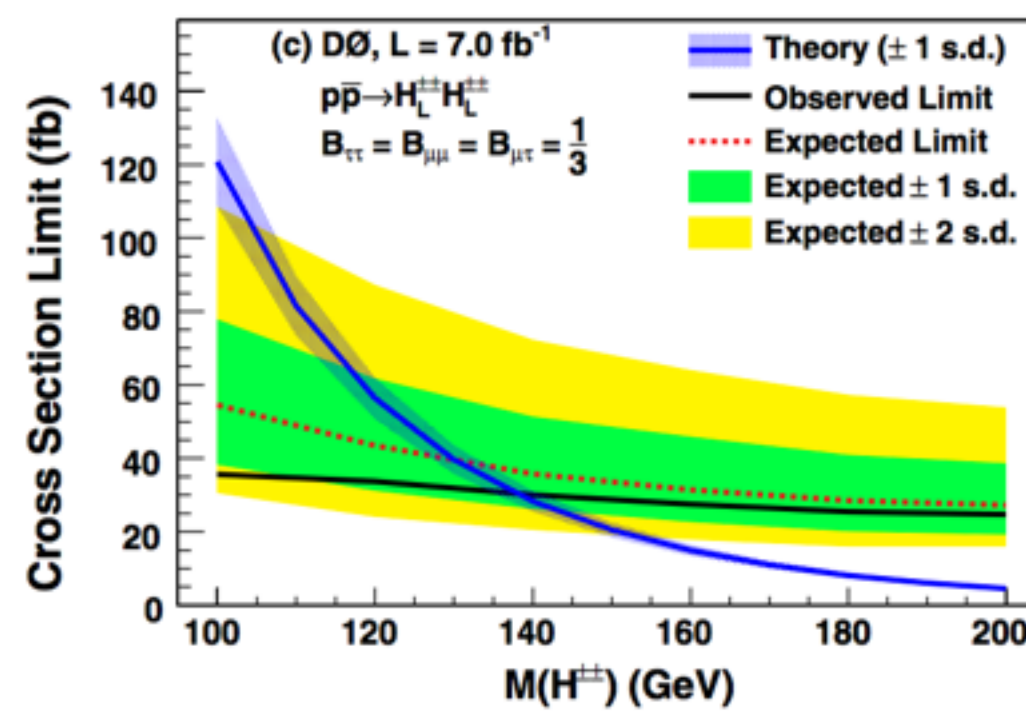
(b) DØ, L = 7.0 fb^{-1}
$p\bar{p} \rightarrow H_L^{\pm\pm} H_L^{\pm\pm}$
$B_{\tau\mu}$ = 1
Theory (± 1s.d.)
Observed Limit
Expected Limit
Expected ± 1s.d.
Expected ± 2s.d.
Cross Section Limit (fb)
M(H$^{\pm\pm}$) (GeV)



(b) DØ, L = 7.0 fb^{-1}
q (τ_1) = - q (τ_2)
Data
$B_{\tau\tau}$ = 1
$B_{\mu\tau}$ = 1
$B_{\tau\tau}=B_{\mu\tau}=B_{\mu\mu}$
M(H$^{\pm\pm}$) = 120 GeV
Diboson
Z → ττ
Z → μμ
Other
Events / 10 GeV
M($\tau_1\tau_2$) (GeV)



(a) DØ, L = 7.0 fb^{-1}
q (τ_1) = q (τ_2)
Data
$B_{\tau\tau}$ = 1
$B_{\mu\tau}$ = 1
$B_{\tau\tau}=B_{\mu\tau}=B_{\mu\mu}$
M(H$^{\pm\pm}$) = 120 GeV
Diboson
Z → ττ
Z → μμ
Other
Events / 10 GeV
M($\tau_1\tau_2$) (GeV)



(c) DØ, L = 7.0 fb^{-1}
$p\bar{p} \rightarrow H_L^{\pm\pm} H_L^{\pm\pm}$
$B_{\tau\tau} = B_{\mu\mu} = B_{\mu\tau} = \frac{1}{3}$
Theory (± 1 s.d.)
Observed Limit
Expected Limit
Expected ± 1 s.d.
Expected ± 2 s.d.
Cross Section Limit (fb)
M(H$^{\pm\pm}$) (GeV)

Long-Lived

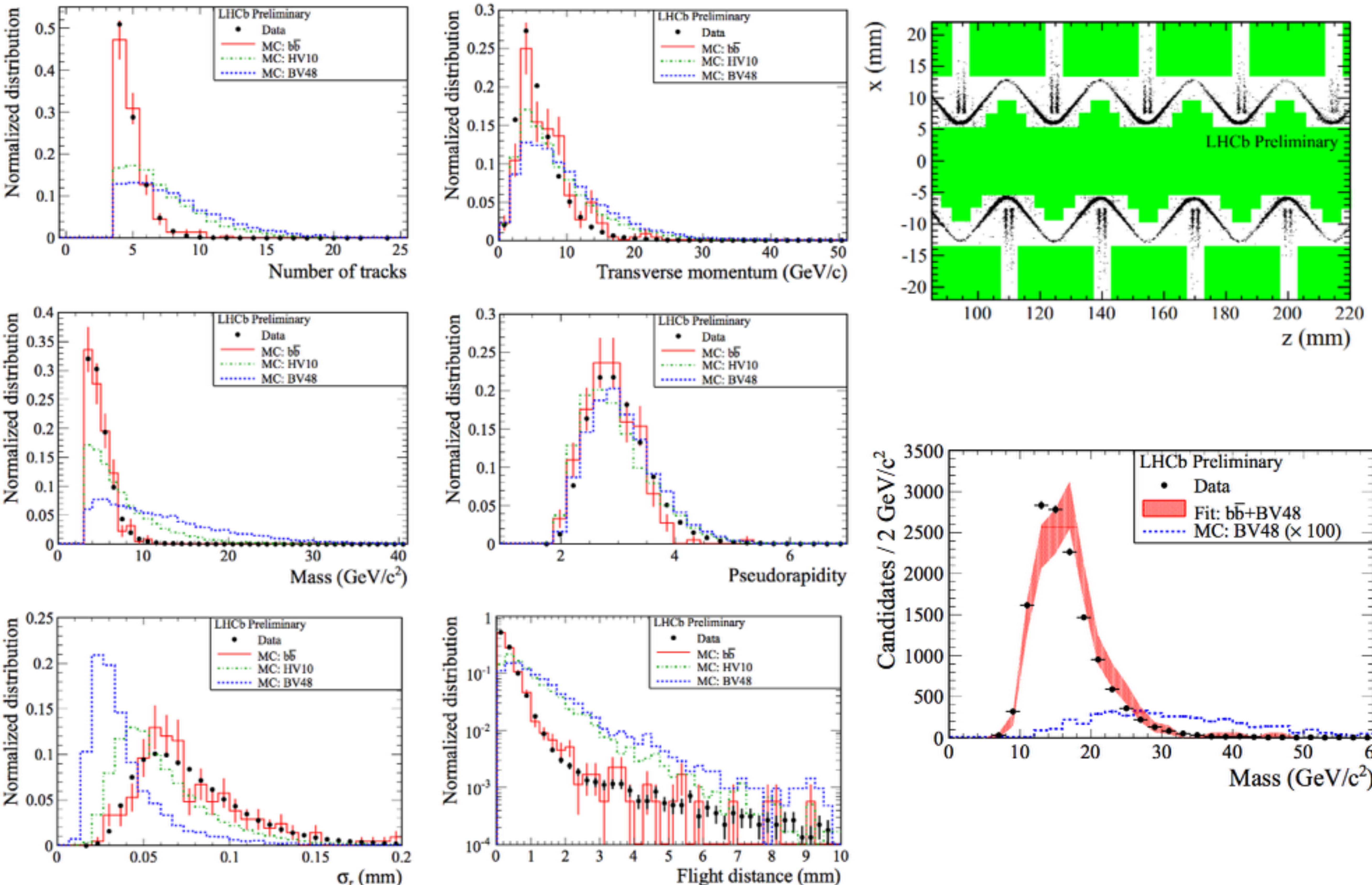
LHCb: Long-lived particles

“Seawrch for Higgs-like bosons decaying into long-lived exotic particles” LHCb-CONF-2012-014

LHCb: Long-lived particles (analysis)

- Vertexing:
  - PV: R<0.3mm, ≥10trk (≥1fwd, ≥1bkwd)
  - SV: any non-PV
  - LLP: SV, ≥4trk (0 bkwd), m>3GeV, R>0.4mm
- Selection:
  - Designed to kill all SM bkg. (v. tight)
  - Trigger: 2 SV: ≥4 trk, m>1.5 GeV
  - ≥1 PV, ≥2 SV: $z_{SV}>z_{PV}$, fiducial vol.
  - $|\Delta\phi(LLP_1,LLP_2)|>2.8$
  - LLP: ≥6 trk, m>6GeV, $\sigma_r<0.05$mm, $\sigma_z<0.24$mm
- Results:
  - Obs/Exp 0 events.
  - Exp 2 BV48 events (ε=0.38% - lower for HV)
  - σBV<25-410 pb for m_h[100,125]GeV, m_{LLP}[30,55]GeV, τ_{LLP}[3,25]ps
  - higher m_h and m_{LLP} better but not too close to $m_h=2m_{LLP}$
  - higher τ_{LLP} better

LHCb: Long-lived particles (figs.)



LHCb: Long-lived particles (tabs.)

Specific model limits

Model	τ_{LLP} ps	m_{LLP} GeV/c^2	m_{h^0} GeV/c^2	ϵ (%)	σ_{UL} pb
BV48-5	5	48	114	0.184 ± 0.011	66
BV48	10	48	114	0.384 ± 0.017	32
BV48-15	15	48	114	0.418 ± 0.017	29
BV20-10	10	20	114	0.010 ± 0.003	1425
BV35-10	10	35	114	0.146 ± 0.010	84
BV48-mh100	10	48	100	0.190 ± 0.013	64
BV48-mh125	10	48	125	0.293 ± 0.019	42

Uncertainties

Source	%
Integrated luminosity	4
Trigger	15
Track reconstruction	7
p_T and mass calibration	6
Vertex reconstruction	12
Fiducial volume	4
Beam line position	1
Total	22

BV model scan (τ_{LLP}=10 ps)

m_{LLP} [GeV] / m_{h^0} [GeV]	30	35	40	48	55
100	101	58	44	58	
105	100	75	44	39	
110	132	75	56	34	
114	128	91	47	32	46
120	148	93	58	34	31
125	179	90	61	41	29

BV model scan (m_h=114 GeV)

m_{LLP} [GeV] / τ_{LLP} [ps]	30	35	40	48	55
3	210	156	136	168	410
5	145	101	68	58	137
10	129	91	47	32	46
15	155	90	49	31	33
20	131	93	63	32	31
25	142	100	61	34	25

D0: Long-lived

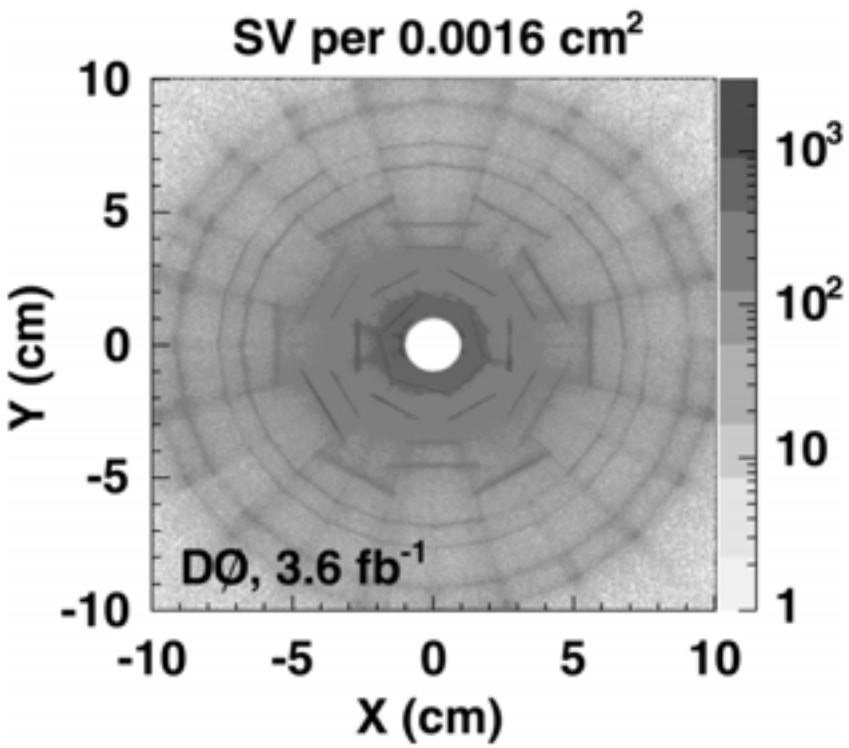
Search for Resonant Pair Production of Neutral Long-Lived Particles Decaying to bbbar in ppbar Collisions at sqrt(s) = 1.96 TeV PRL 103, 071801

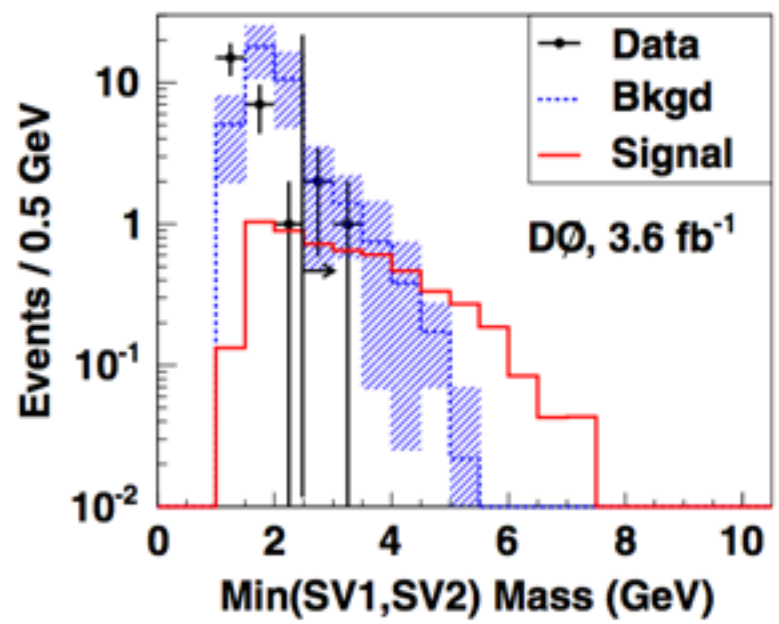
D0: Long-lived (details)

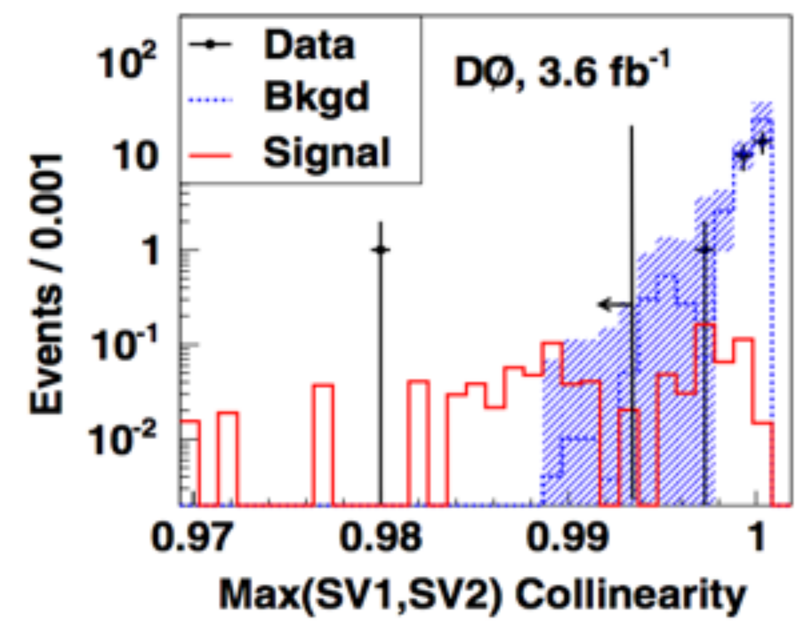
- Hidden Valley:
  - New confining gauge group weakly coupled to SM (HV quarks → v-hadrons)
  - SM Higgs decay to v-hadrons through mixing with HV Higgs.
  - v-hadrons may couple preferentially to heavy SM particles due to helicity suppression.
  - Cosmological constraint $\tau_{\text{v-hadron}}$ << 1 second (Big-band nucleosynthesis)
- Selection:
  - Trigger: any (mostly μ+jet)
  - **≥2 jets** (10 GeV), **≥1 μ** (4 GeV, ΔR(μ,jet)<0.7), **<4 PV**
  - **≥2 SV**: ≥4trk, R>1.6 cm, σ_{flight}>5, point away from PV, **not in high-SV-density region**, $\Delta R(SV_1,SV_2)>0.5$
- Final selection on:
  - m_{HV}<20 GeV: $\text{Min}(m_{SV1},m_{SV2})>2.5$ GeV
  - m_{HV}>20 GeV: $\text{Max}(C_{SV1},C_{SV2})<0.9937$, SV collinearity - $\cos\Delta\theta(p_{SVtrk},p_{SV,PV})$
- Background: correct Multijet MC in 1SV CR (corr. also applied to signal MC)
- Dom. Sys.: Sig (**trig eff.** 13-17%), Bkg (trk. reco. eff 28%).
- **Limits: ~1-10 x σ_{SM}** with $B(h\to\pi_{HV}\pi_{HV})=1$ and $B(\pi_{HV}\to bb)=1$

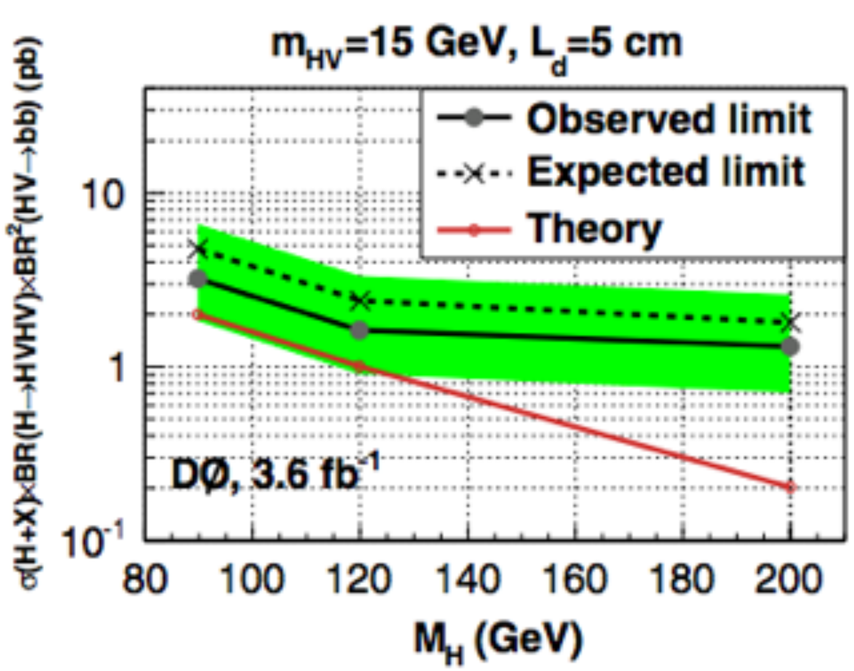
M_H	m_{HV}	L_d	N_{bkgd} ± stat ± sys	N_{sig} ± stat ± sys	N_{data}	Efficiency	SM Higgs (pb)	Limit obs. [exp.] (pb)
90 GeV	15 GeV	5 cm	4.8 ± 1.0 ± 1.7	3.3 ± 0.3 ± 0.5	3	0.06%	2.0	3.2 [4.7]
120 GeV	15 GeV	5 cm	4.8 ± 1.0 ± 1.7	3.6 ± 0.3 ± 0.5	3	0.13%	1.1	1.6 [2.4]
120 GeV	15 GeV	2.5 cm	4.8 ± 1.0 ± 1.7	5.7 ± 0.3 ± 0.7	3	0.21%	1.1	1.0 [1.5]
120 GeV	15 GeV	10 cm	4.8 ± 1.0 ± 1.7	1.5 ± 0.2 ± 0.3	3	0.06%	1.1	3.9 [5.7]
200 GeV	15 GeV	5 cm	4.8 ± 1.0 ± 1.7	0.8 ± 0.1 ± 0.1	3	0.16%	0.2	1.3 [1.8]
90 GeV	40 GeV	5 cm	0.07 ± 0.07 ± 0.02	0.15 ± 0.07 ± 0.03	1	0.003%	2.0	67 [51]
120 GeV	40 GeV	5 cm	0.07 ± 0.07 ± 0.02	0.38 ± 0.07 ± 0.06	1	0.01%	1.1	16 [12]
200 GeV	40 GeV	5 cm	0.07 ± 0.07 ± 0.02	0.16 ± 0.03 ± 0.02	1	0.03%	0.2	6.5 [5.1]

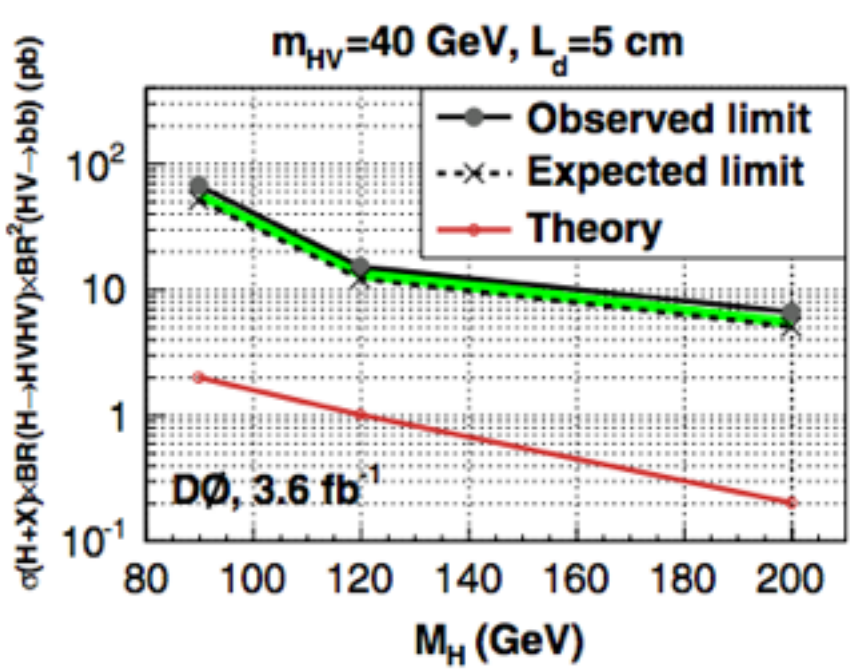
D0: Long-lived (figs.)

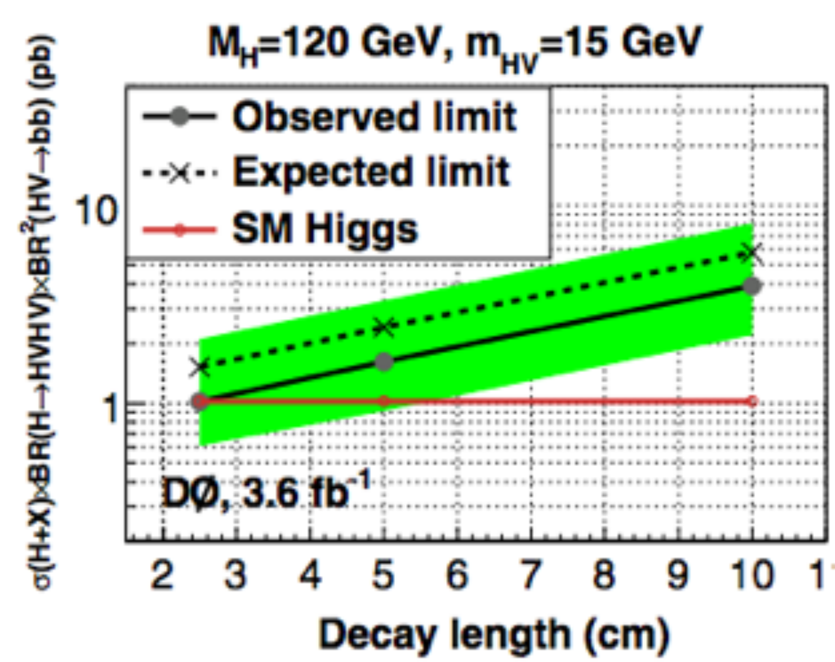












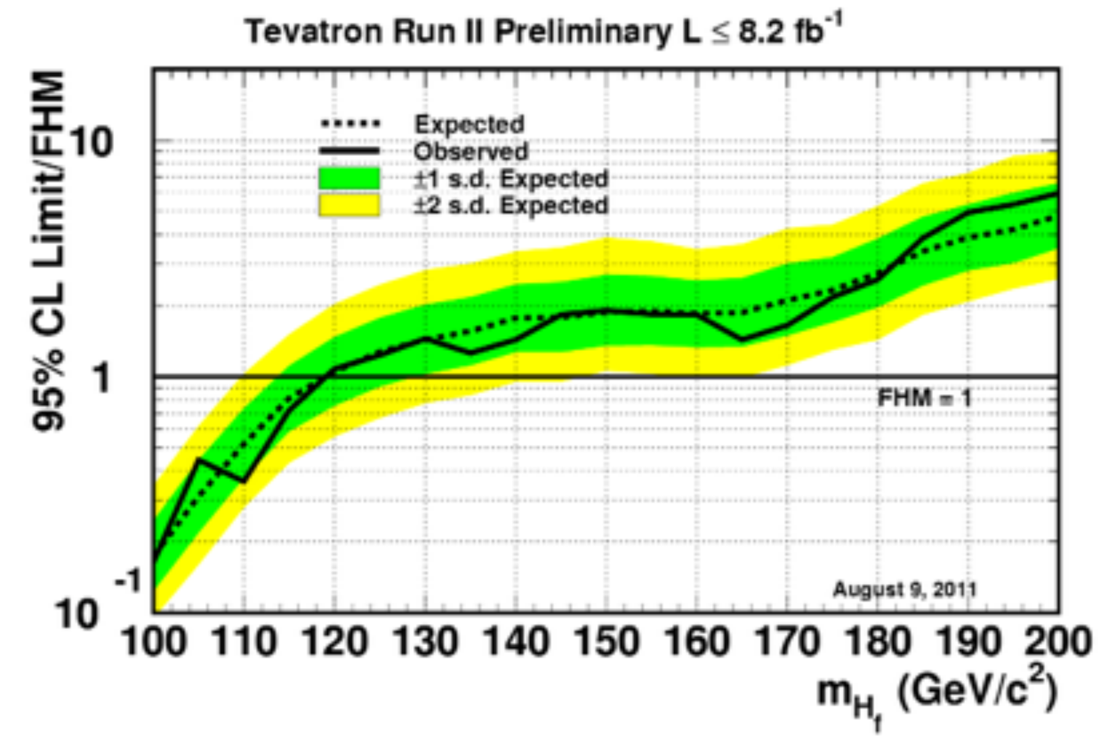
Miscellaneous

CDF+D0: Fermiophobic

"Combined CDF and D0 upper limits on Fermiophobic Higgs Boson Production with up to 8.2 fb^{-1} of ppbar data" arXiv:1109.0576 [hep-ex]

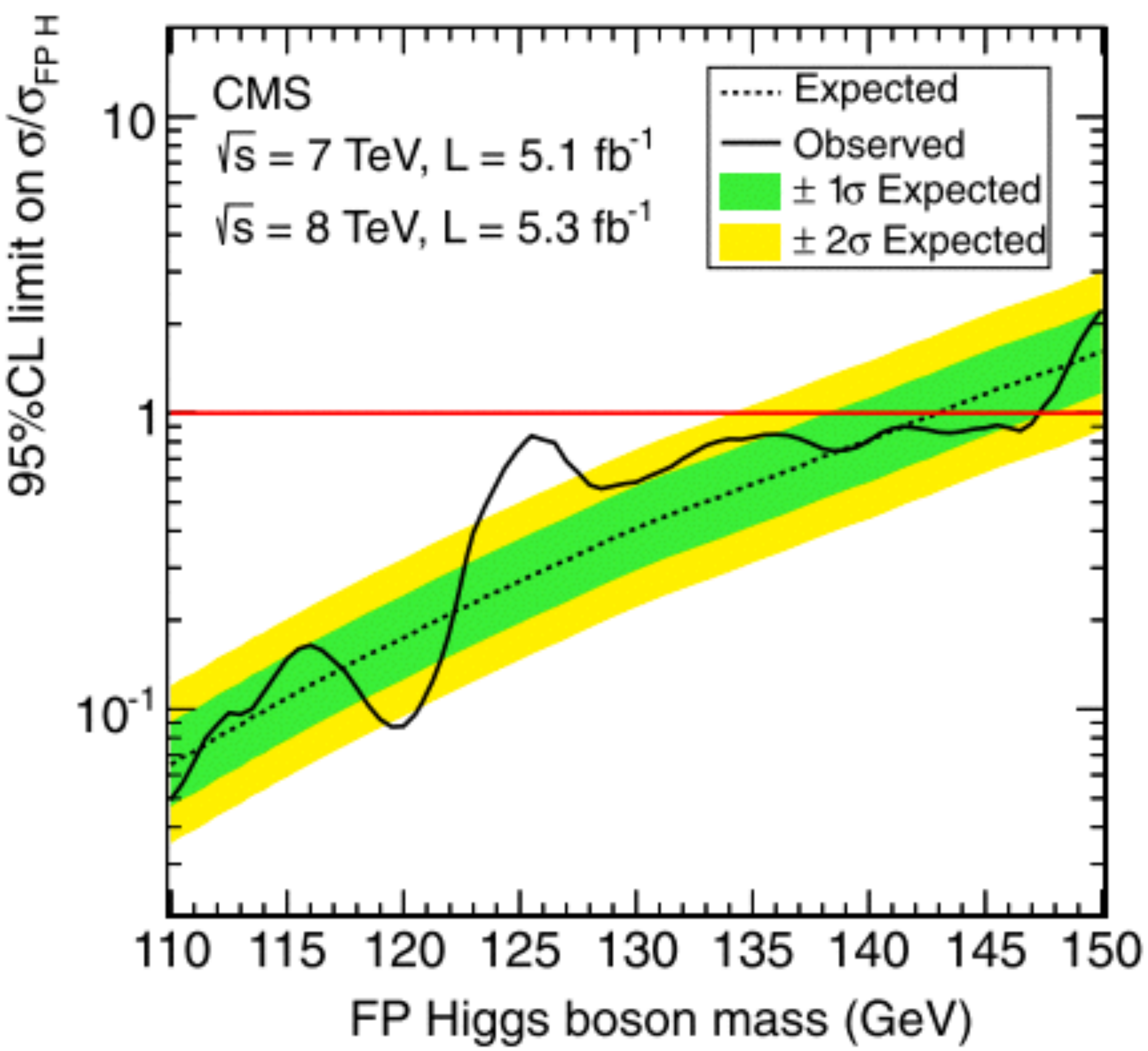
CDF+D0: Fermiophobic

- Model: SM with no Hff couplings
  - gg→H negligible
  - VH and VBF production ~unchanged
  - H→ff forbid. at tree (V loop negl. b/c spin flip)
  - H→**γγ**,**WW**,Zγ,ZZ ~ 100%
  - B(H→WW) dominant for m_H>120 GeV
  - B(H→γγ) greatly enhanced (all m_H) (~all sens. for m_H<120 GeV)
  - p_T(H) slightly different from SM → tweak SM searches
- LEP Limit: m_H>108.2 GeV
- Mods from SM Searches: H→γγ reopt. selection. + diff. analysis channels
- Limit: m_H<119 GeV

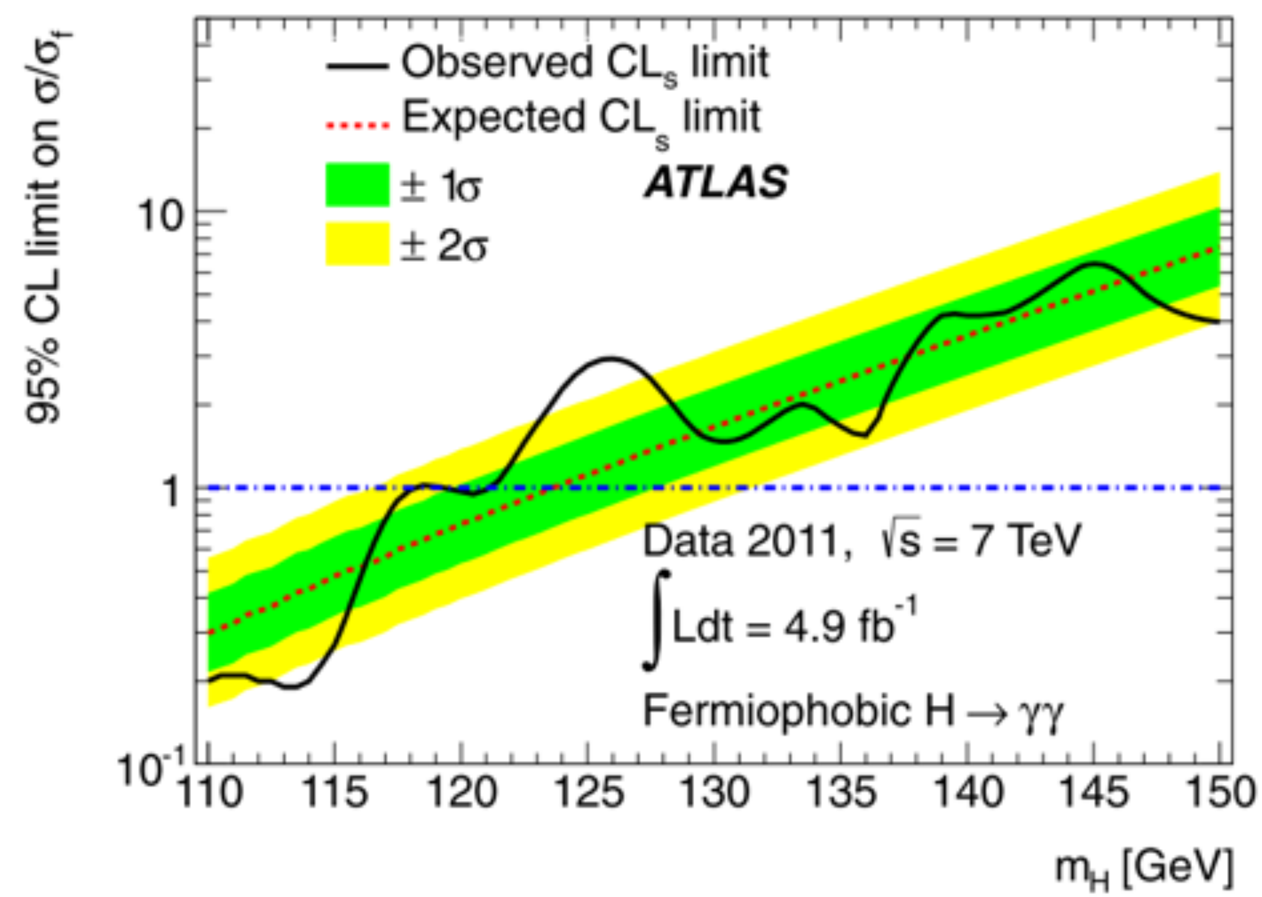


Fermiophobic other experiments

CMS: excl. 110-147 GeV



ATLAS: excl. [110-118] [119.5-121] GeV



ATLAS: H→WW (high-mass)

"Search for a high-mass Higgs boson in the H→WW→lvlv decay channel with the ATLAS detector using 21 fb^{-1} of proton-proton collision data." ATLAS-CONF-2013-067

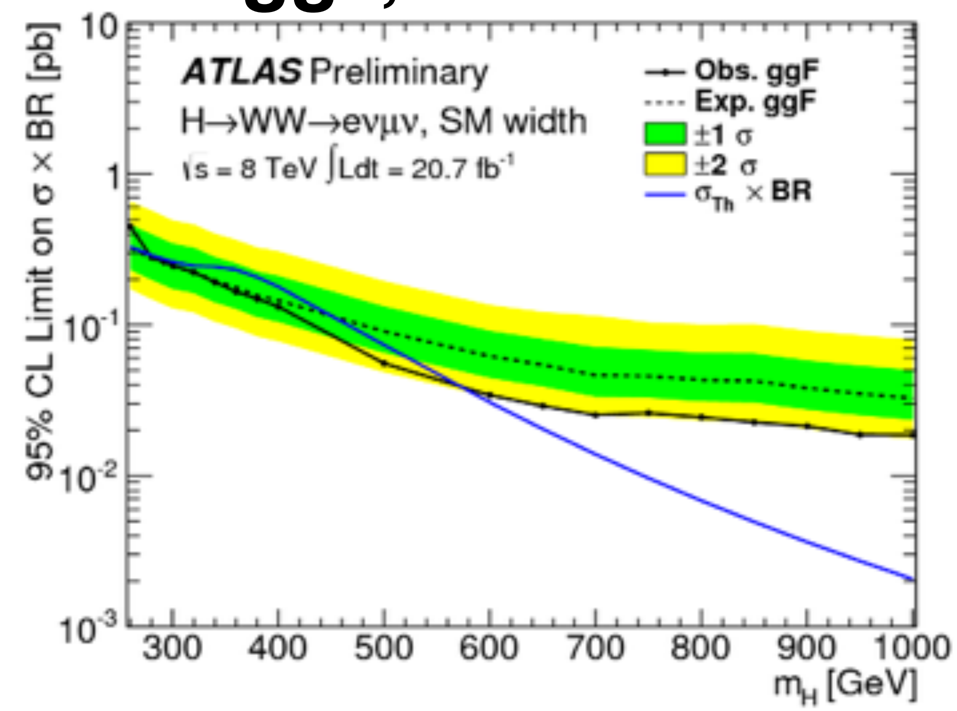
ATLAS: H→WW (selection)

- Very similar to SM analysis.
- Njet≤1: WW (ggH sig.) dominant
- Njet≥2: ttbar (VBF sig.) dominant
- Common selection:
  - Trigger: single e/μ (24 GeV)
  - 1e+1μ (40 GeV, isol., OS)
  - **$m_{e\mu}$>50 GeV, $\Delta\eta_{e\mu}$<1 (high-mass selection)**
- Njet=0 Category:
  - MET_{rel}>25 GeV (*)
  - p_T(ll)>30 GeV, Δϕ(ll,MET)>π/2 (rej. DY and bad reco.)
- Njet=1 Category:
  - MET_{rel}>25 GeV
  - 0 b-jets (rej. ttbar)
  - $|m_{\tau\tau}-m_Z|\geq25$ GeV (rej. Zττ)
- Njet≥2 Category:
  - MET>20 GeV
  - $|\Delta y_{jj}|$>2.8, m_{jj}>500 GeV, cent. jet veto (20 GeV)
  - eμ in VBF jet gap
  - 0 b-jets (rej. ttbar)
  - $|m_{\tau\tau}-m_Z|\geq25$ GeV (rej. Zττ)
  - p_T^{tot} <45 GeV (vec. sum, rej. ttbar)
- (*) MET_{rel} = MET.sinΔϕ(MET,closest e/μ/jet). If |Δϕ|>π/2: MET_{rel}=MET

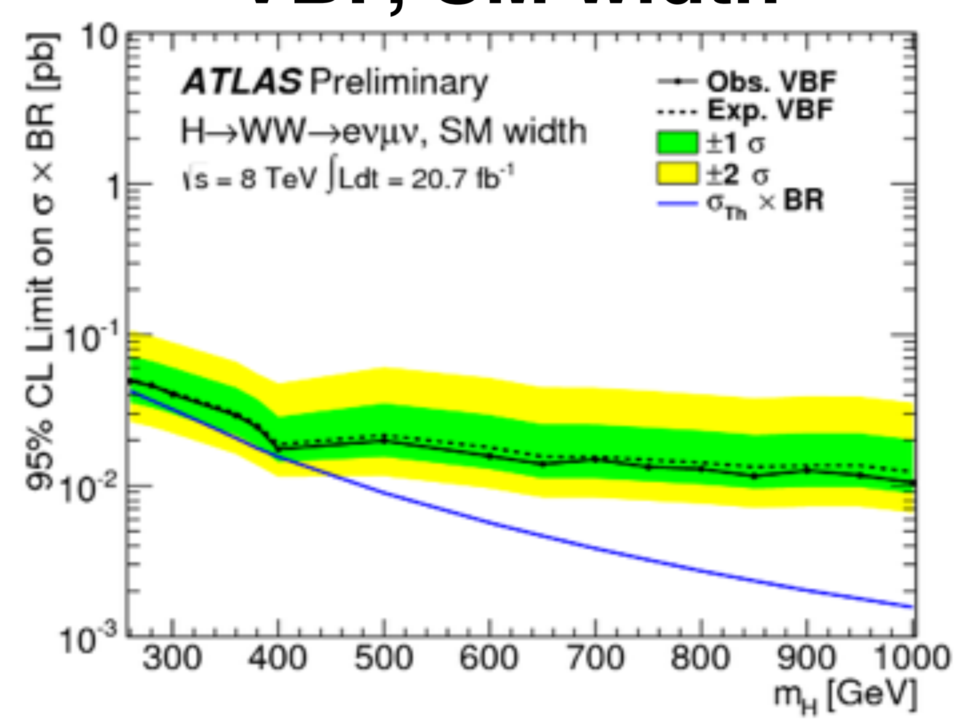
ATLAS: H→WW (results)

- Backgrounds:
  - W+jet: lepton fake-factor
  - top+WW: MC + norm. in CR
- Dominant systematics:
  - Sig: QCD renorm/fact scale ~40%
  - Bkg:
    - $N_{jet} \leq 1$: WW MC ~6%
    - $N_{jet} \geq 2$: b-tag eff.
- Results:
  - Fit m_T(ll,MET).
  - Limit: **260<m_H<642 GeV excluded** for σ_{SM}
  - Results for Narrow/SM width v. similar

ggF, SM width

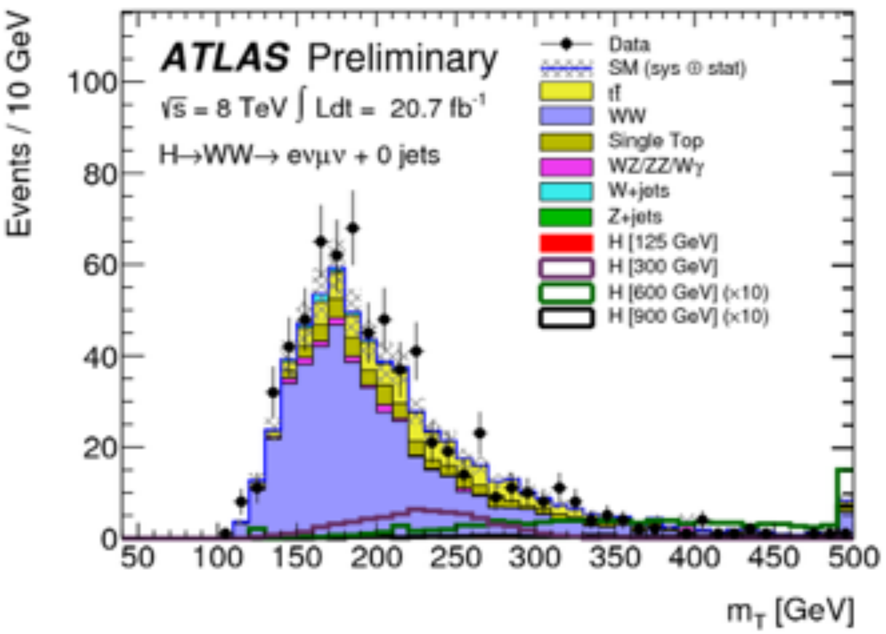


VBF, SM width

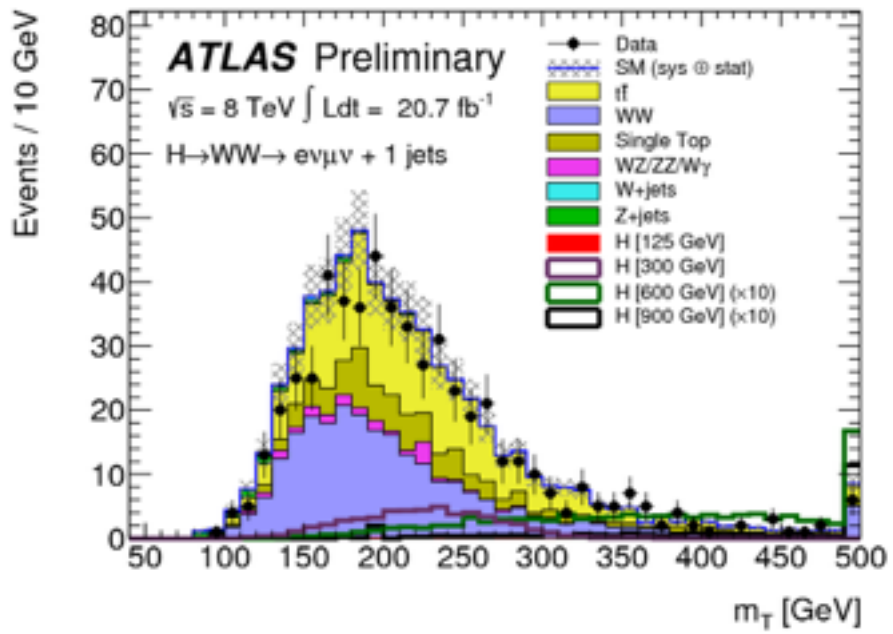


ATLAS: H→WW (figs.)

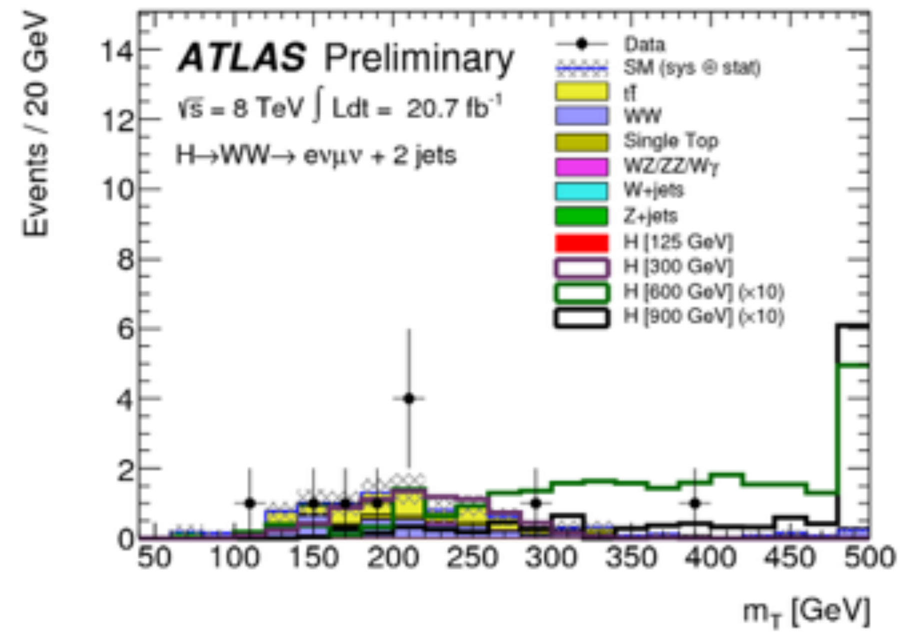
Njet=0 (SR)

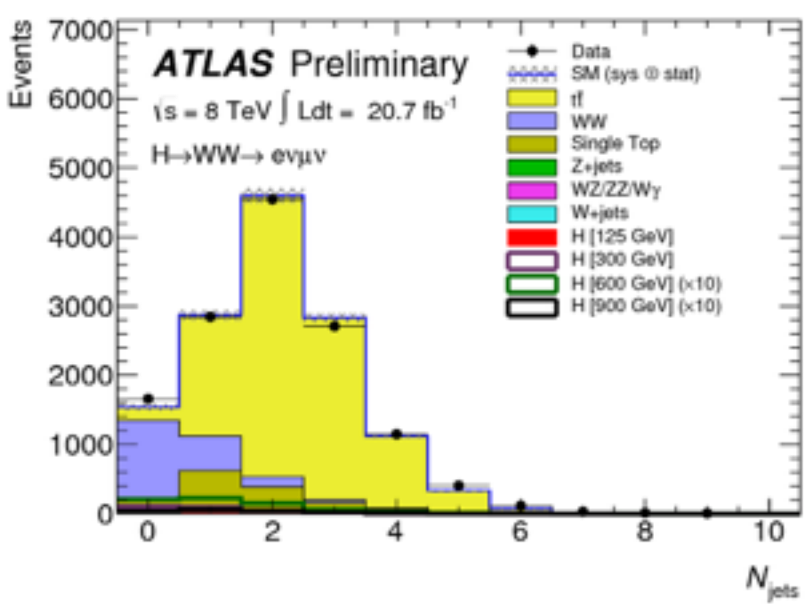


Njet=1 (SR)

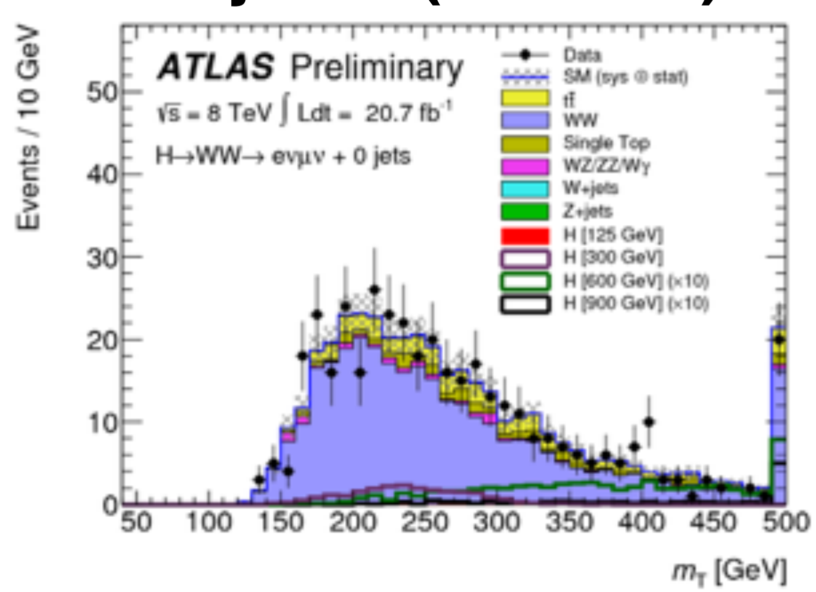


Njet=2 (SR)

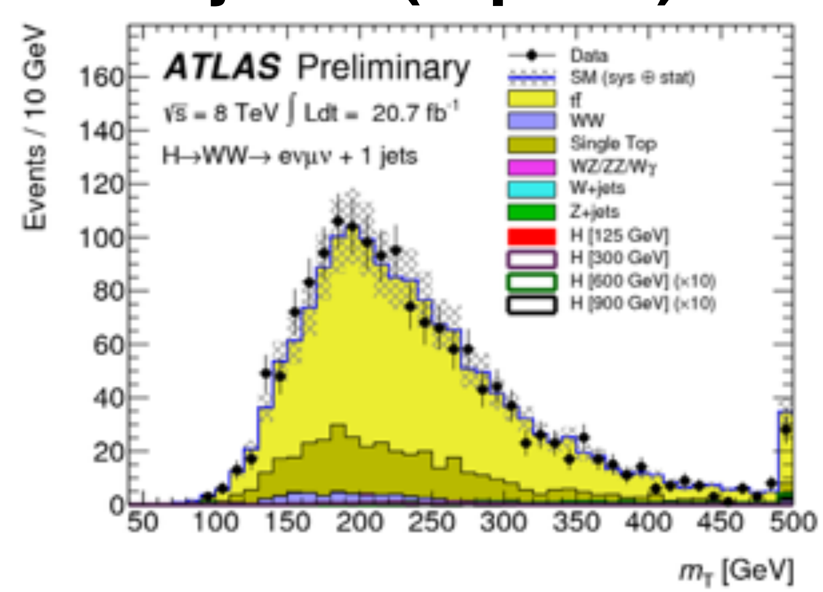




Njet=0 (WW CR)



Njet=1 (top CR)

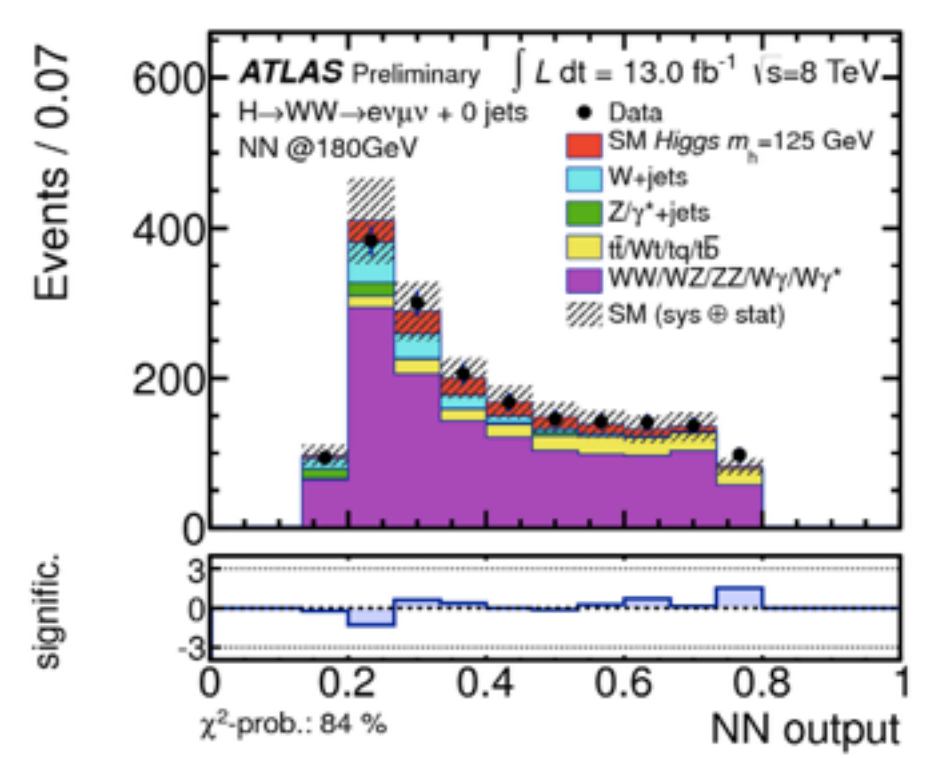


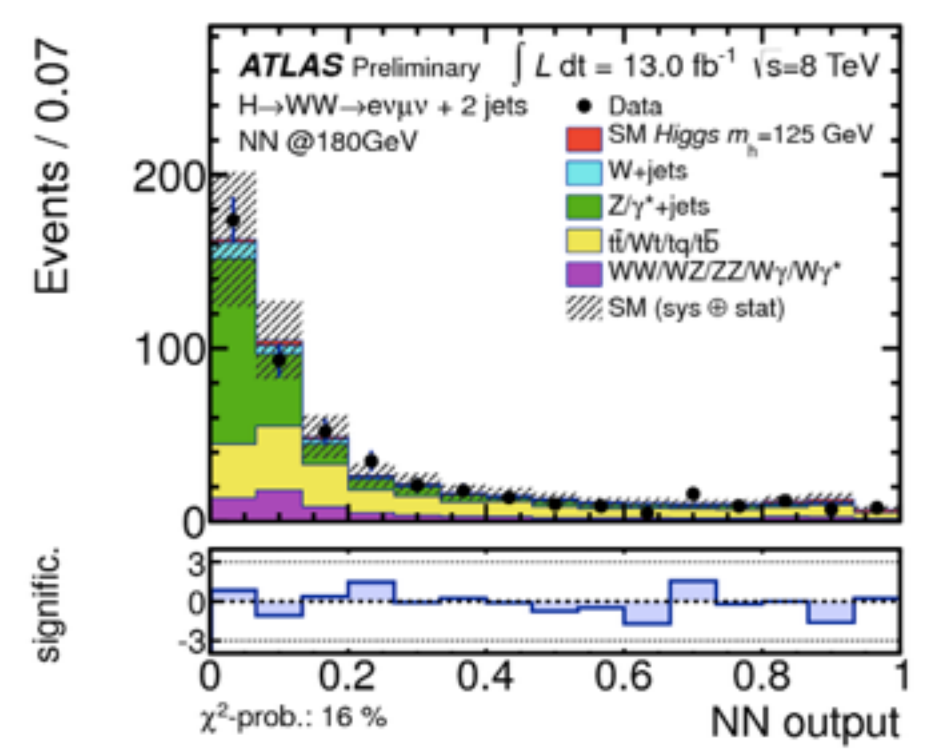
ATLAS: H→WW (2HDM)

“Search for Higgs bosons in Two-Higgs-Doublet models in the H → WW → eνμν channel with the ATLAS detector” ATLAS-CONF-2013-027

ATLAS: H→WW (2HDM) (analysis)

- Assume **h SM-like**, $\mathbf{135<m_H<300}$ GeV
- Same preselection as SM analysis.
- Only use **0-jet** and **2-jet** categories
- Use **NN** to discriminate against background (validated in ttbar and diboson CRs)
- ttbar normalised in CR
- Fit NN to data to determine presence of signal
  - H_0 - **no Higgs**
  - H_1 - **SM-like + heavy Higgs**



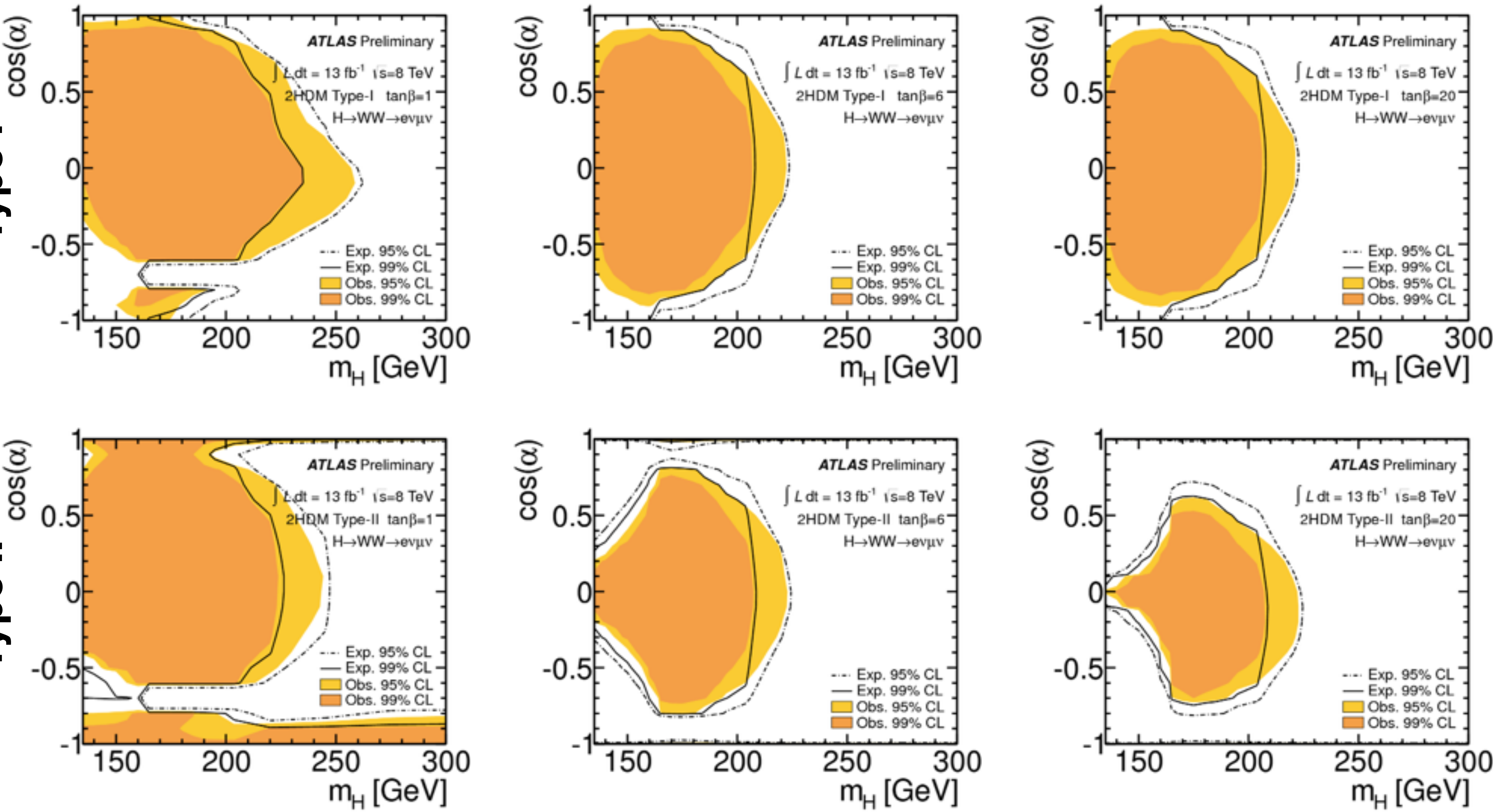


ATLAS: H→WW (2HDM) (limits)

tanβ=1 **tanβ=6** **tanβ=20**

Type I

Type II



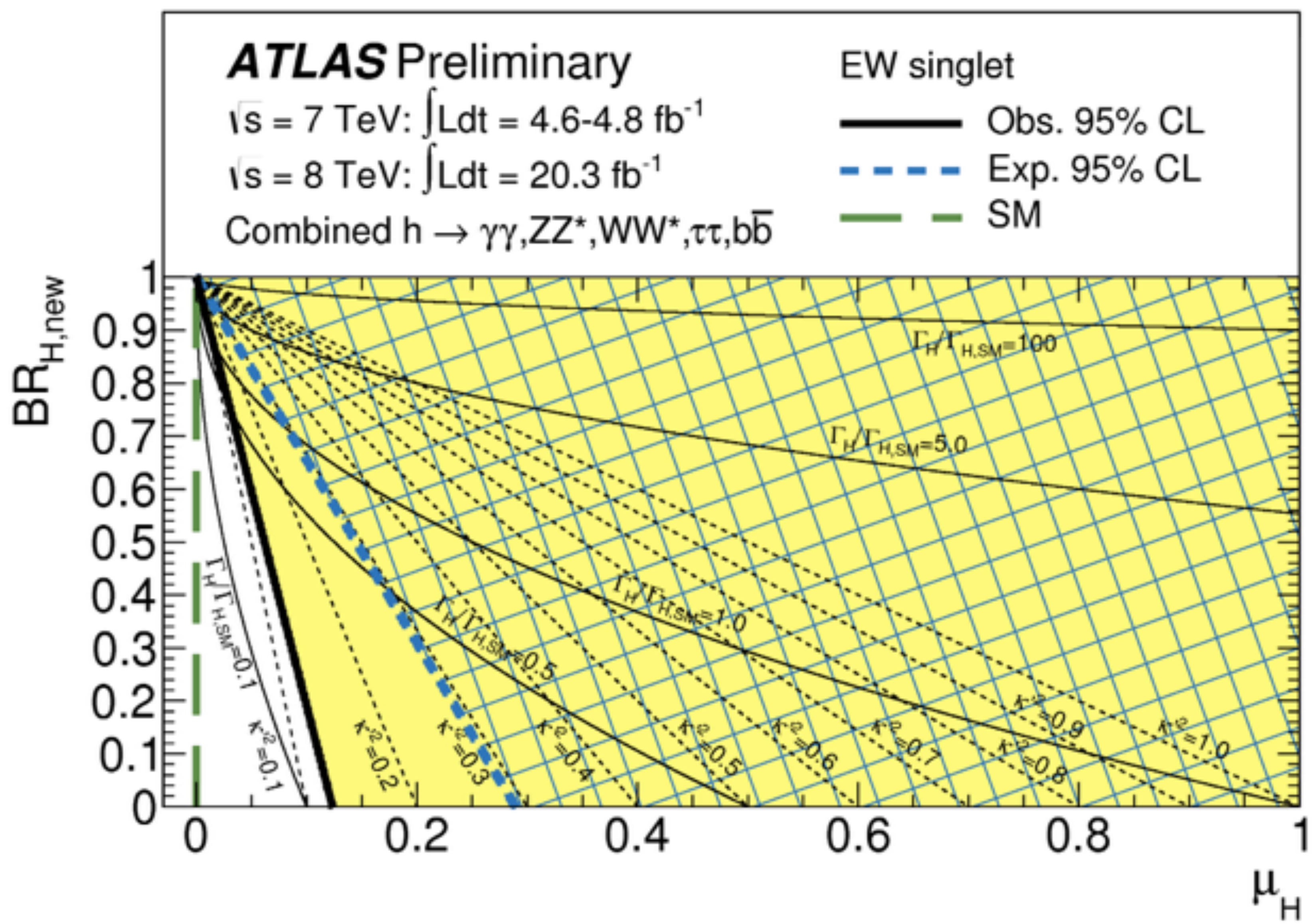
ATLAS: Indirect

"Constraints on New Phenomena via Higgs Boson Coupling Measurements with the ATLAS Detector" ATLAS-CONF-2014-010

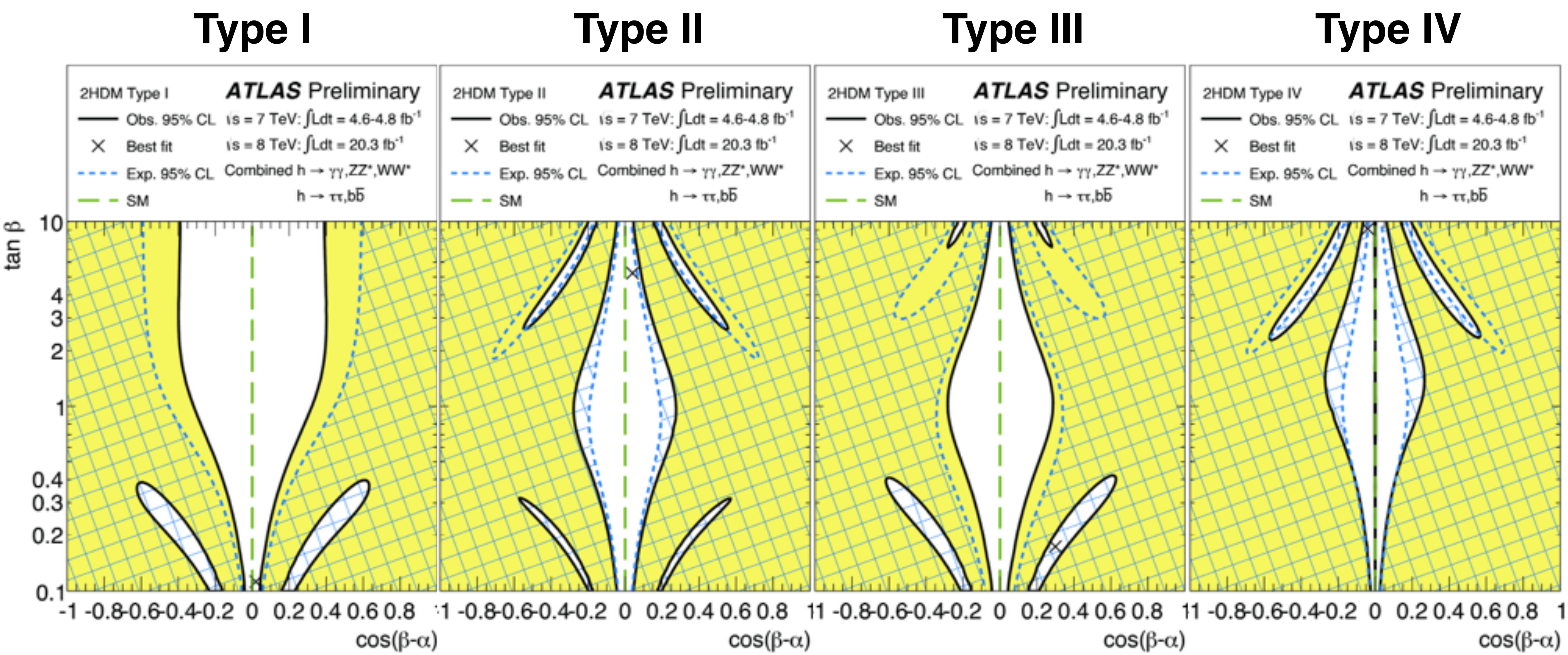
ATLAS: indirect

- Inputs:
  - Higgs rates: $h \rightarrow \gamma\gamma$, ZZ^*, WW^*, $\tau\tau$, bb
  - Higgs mass: $h \rightarrow \gamma\gamma$, ZZ^*
  - $Zh \rightarrow$ll+MET rate
- Parameterise difference in Higgs couplings w.r.t SM
- Assume Higgs decay kinematics not significantly altered
- Fit to variety of models:
  - Minimal Composite Higgs model
  - Additional Electroweak Singlet
  - 2HDM + Simplified MSSM
  - Higgs portal to Dark Matter

ATLAS: indirect (EW singlet)

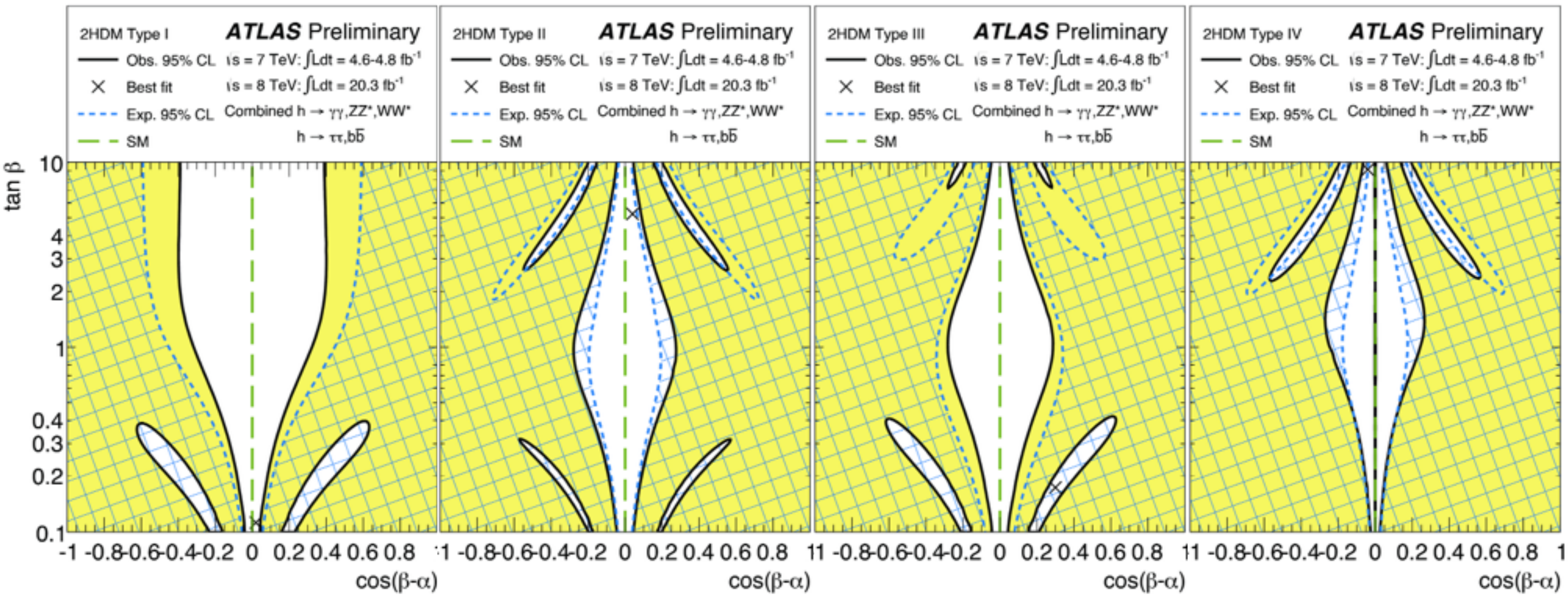


ATLAS: indirect (2HDM)



ATLAS: indirect (2HDM)

Type I **Type II** **Type III** **Type IV**



ATLAS: indirect (portal)