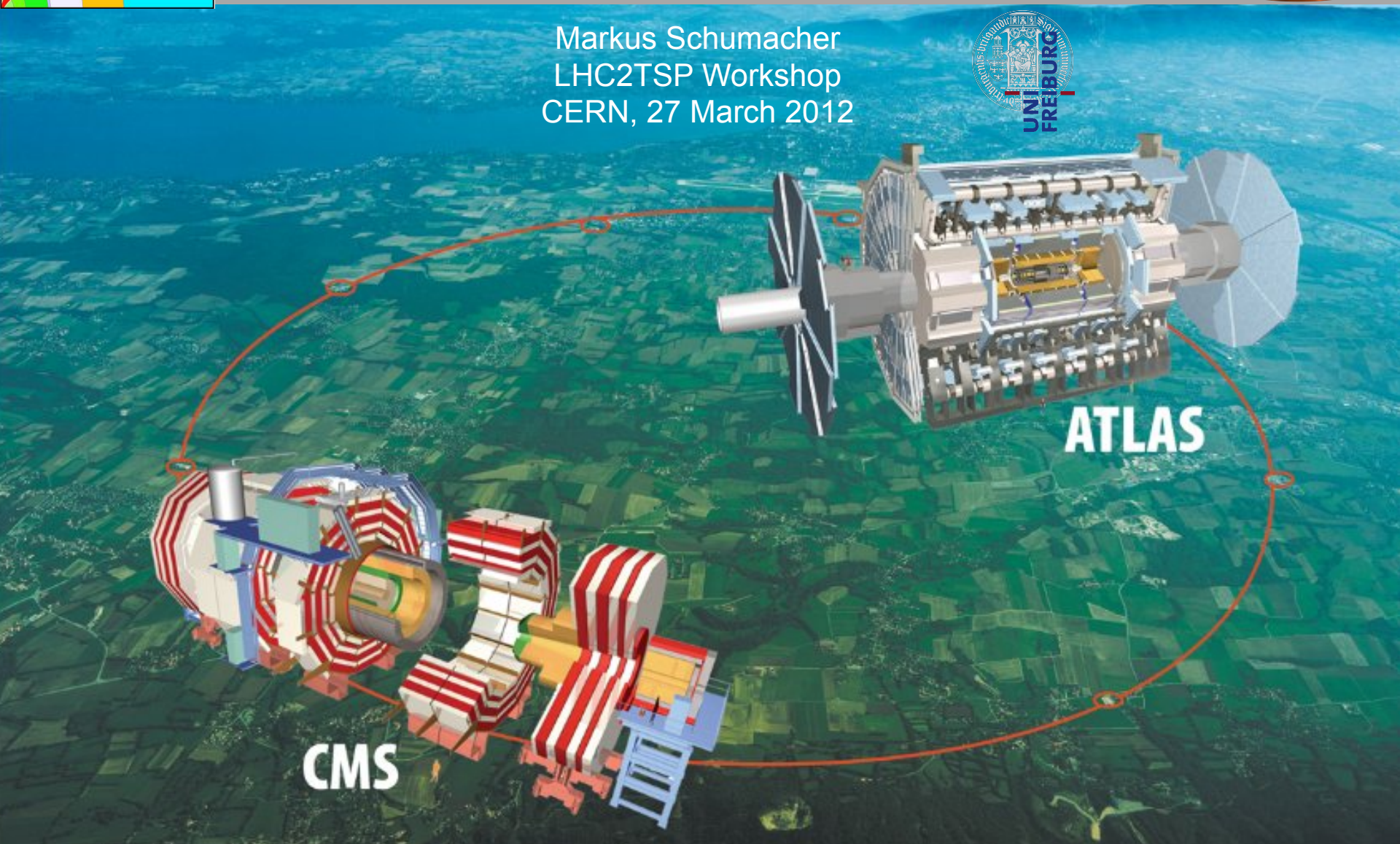
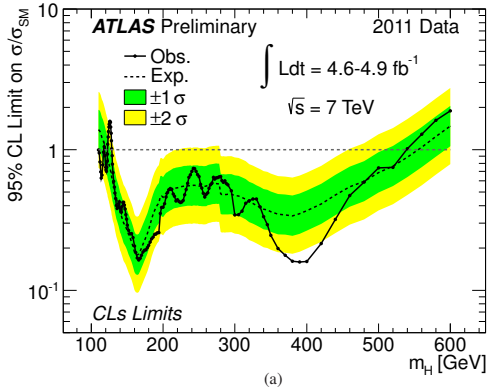
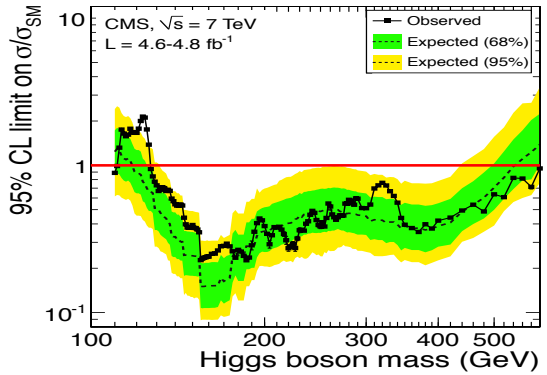
Search for Higgs Bosons beyond the Standard Model at the LHC

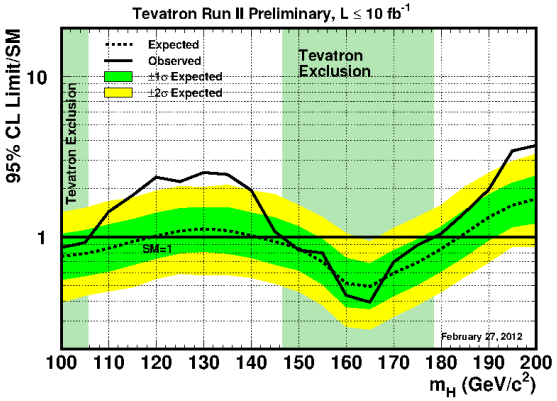
Markus Schumacher
LHC2TSP Workshop
CERN, 27 March 2012

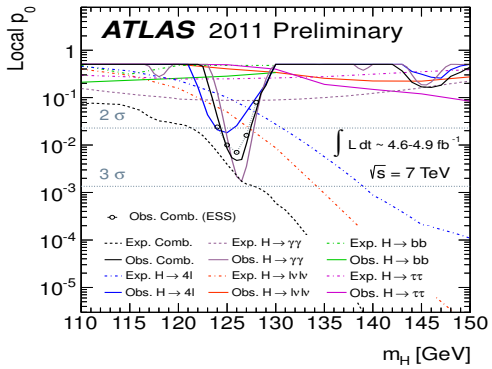


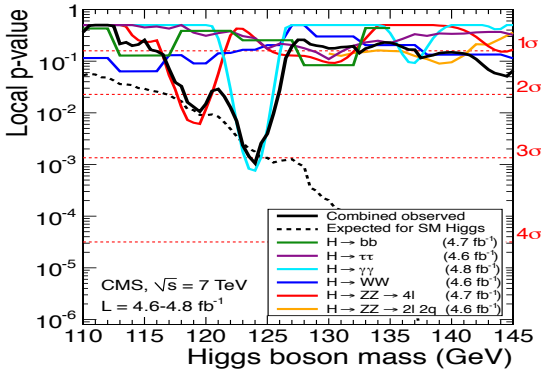
Status of SM Higgs boson searches in nutshell

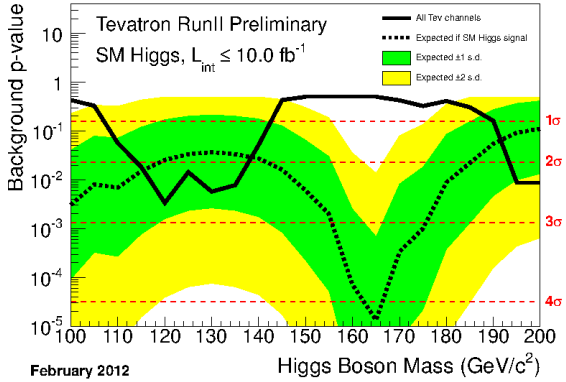












in SM: only small mass intervall unexcluded

what is the situation in BSM?

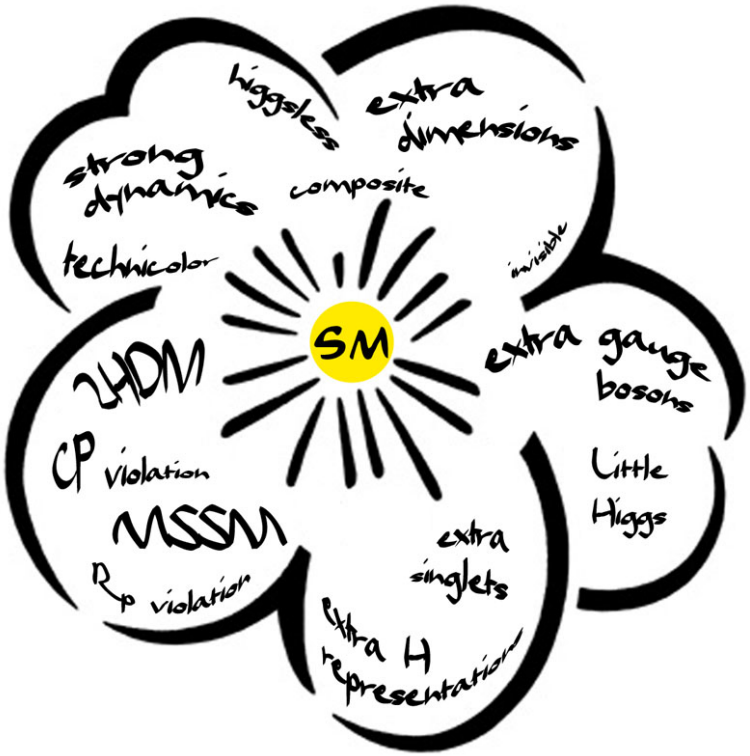
interesting deviations from backgr.-only-hypothesis, not incompatible with H_{SM}

also compatible with BSM Higgs?

additional deviations?

Keep your mind open ...

despite the interesting observation of deviation from backgr.-only-hypothesis (whether hint for new (Higgs) particle or not, whether SM-like Higgs or not)) there might be Higgs bosons realized with diff. properties in other places

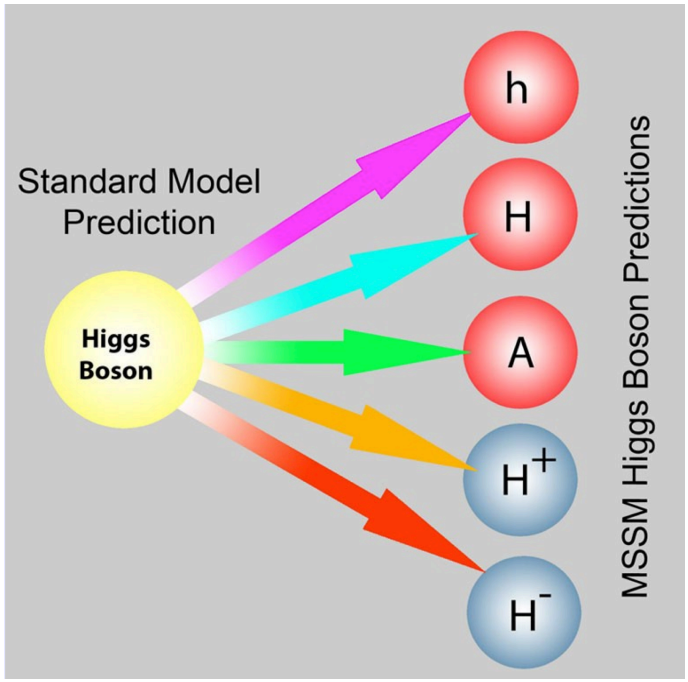


S. Kraml et al., CERN-2006-009, hep-ph/0608079

Examples from BSM Higgs boson searches

$H \to \tau\tau$	(2 HDM, MSSM)
$H^+ \to \tau\nu$ (cs)	(2HDM, MSSM)
Fermiophobic Model	
4th Generation „SM“	
$a \to \mu\mu$	(extra singlet, NMSSM)
$H^{++} \to l^+l^+$	(Higgs Triplett, Little Higgs)
Long lived H	(Hidden Valley, R-Par-Vio. SUSY, NMSSM)

2HDM and MSSM Signatures



so far only: SM-like production kinematics

interpretation in terms of limits on:
- cross section x BR
- in MHMAX scenario

we know: acceptances might be changed
e.g. - effect of b-loop in gluon fusion
- SUSY-QCD and -EW corrections

see arXiv:1201.3084v1 **Handbook of LHC Higgs cross sections: 2. Differential Distributions**

other scenarios need some more work

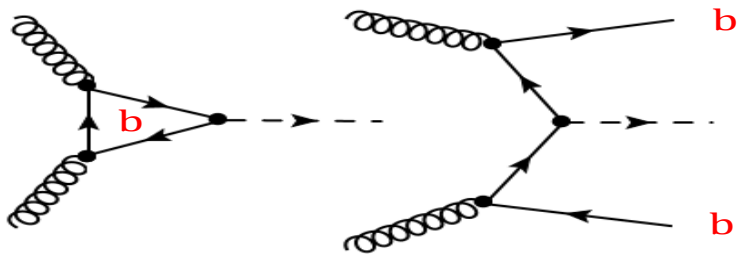
no completely model independent limits possible

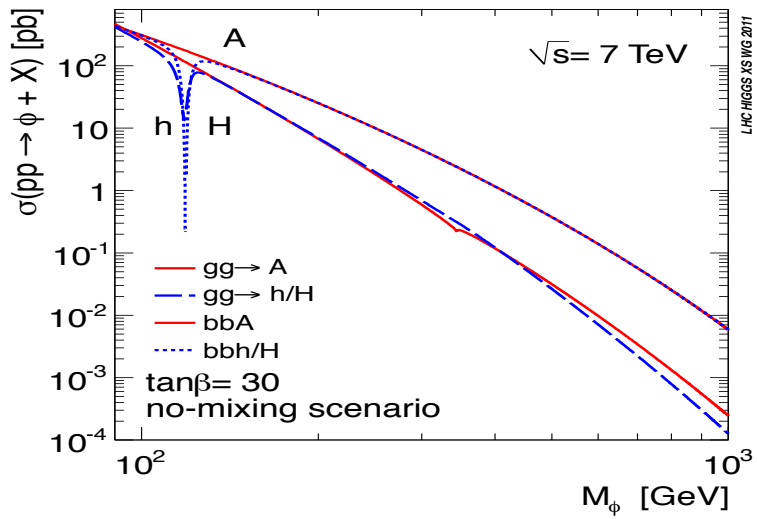
limits on σxBRxacceptance (if neglect influence on shape of final. discriminant)

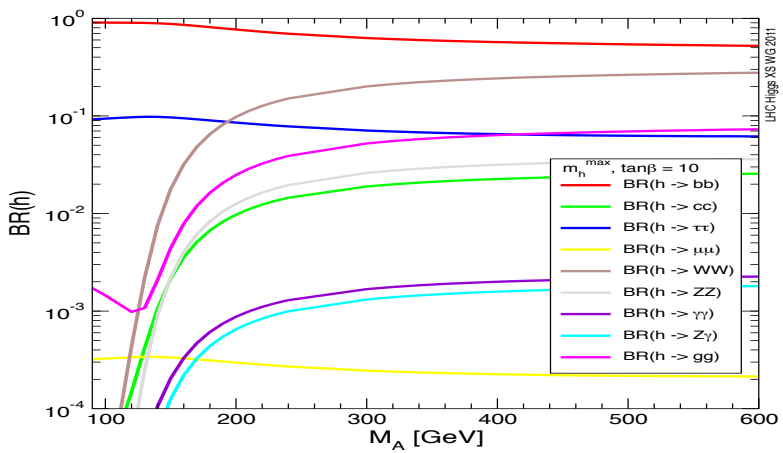
for discovery: wrong acceptance and signal model dilute sensitivity

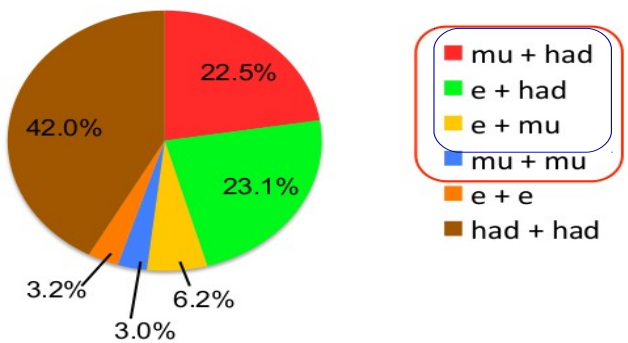
H→ττ in MSSM

enhanced coupling to $I_{W,3}$= -1/2 fermions





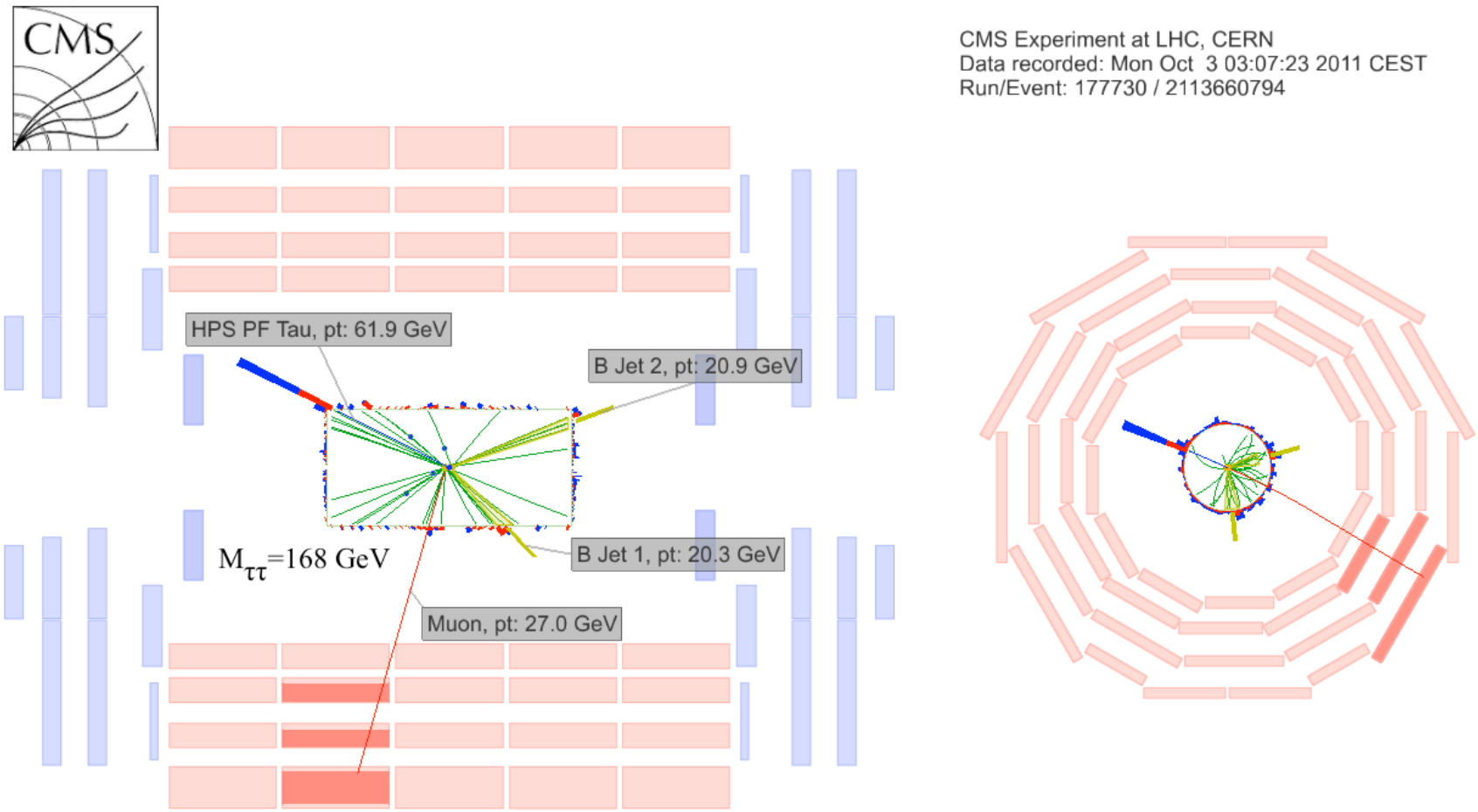




CMS (4.7 fb^{-1}): $e\tau_{had}3\nu$, $\mu\tau_{had}3\nu$. $e\mu4\nu$ and now also $\mu\mu4\nu$ (54%)
analysis optimisation: at least 1 b-tagged or no-btagged jet

ATLAS (1.1 fb^{-1}) $e\tau_{had}3\nu$, $\mu\tau_{had}3\nu$, $e\mu4\nu$, $\tau_{had}\tau_{had}2\nu$ (91%)
only inclusive analysis published

CMS: H→ττ with 4.6 fb^{-1} (CMS PAS HIG-11-029/-12-029)



b-tag category: ≤ 1 jet with p_T > 30 GeV, ≥ 1 b-jet with p_T>20 GeV

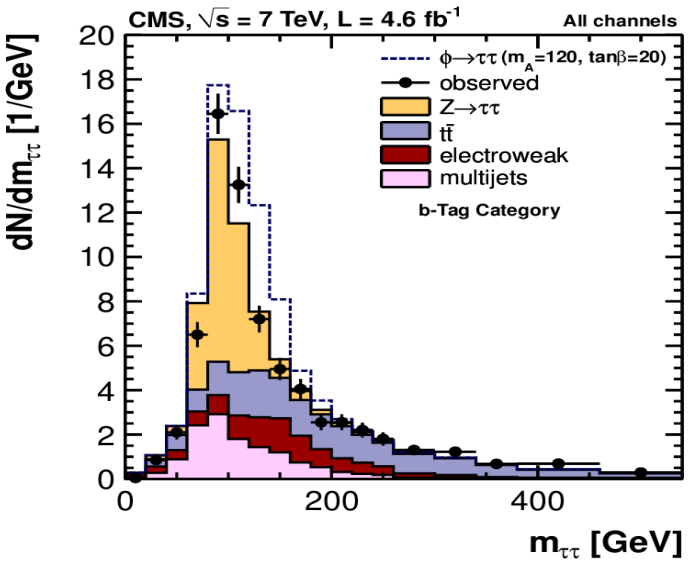
non b-tag category: ≤ 1 jet with p_T>30 GeV, no b-jet with p_T>20 GeV

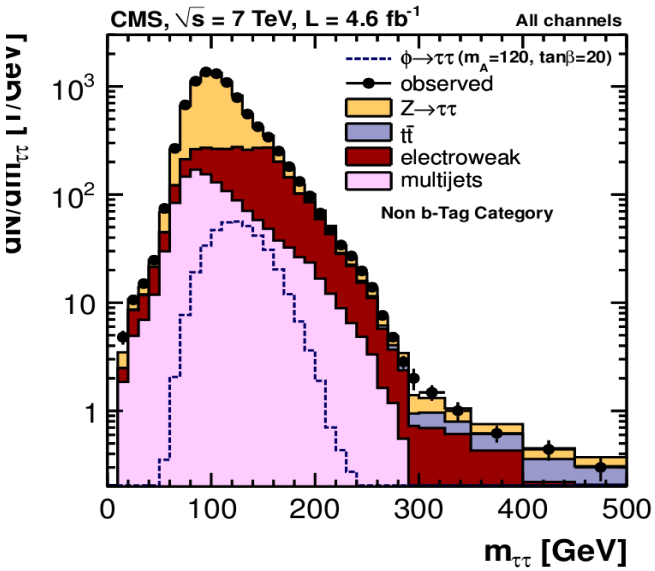
CMS: H→ττ with 4.6 fb^{-1} (CMS PAS HIG-11-029/-12-029)

$e\tau_{had}3\nu$, $\mu\tau_{had}3\nu$. $e\mu4\nu$

cut based

final discriminat: $m_{\tau\tau}$



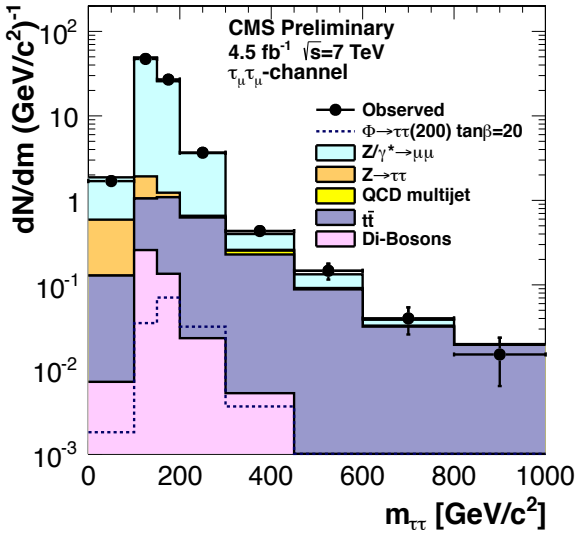


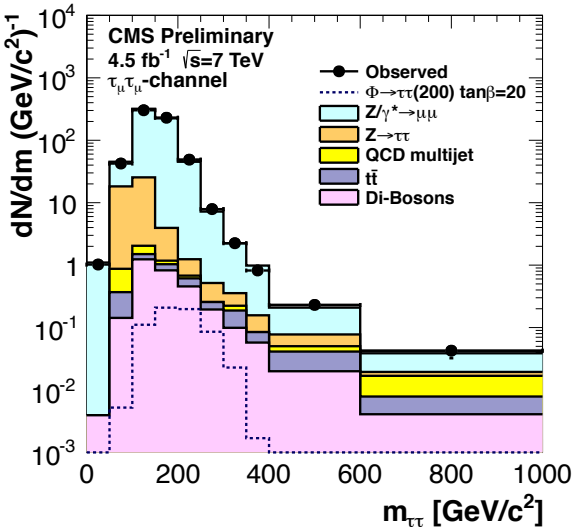
$\mu\mu4\nu$

multivariate analysis

extract sensitivity
2-dim fit in
$m_{\mu\mu}$ and $m_{\tau\tau}$

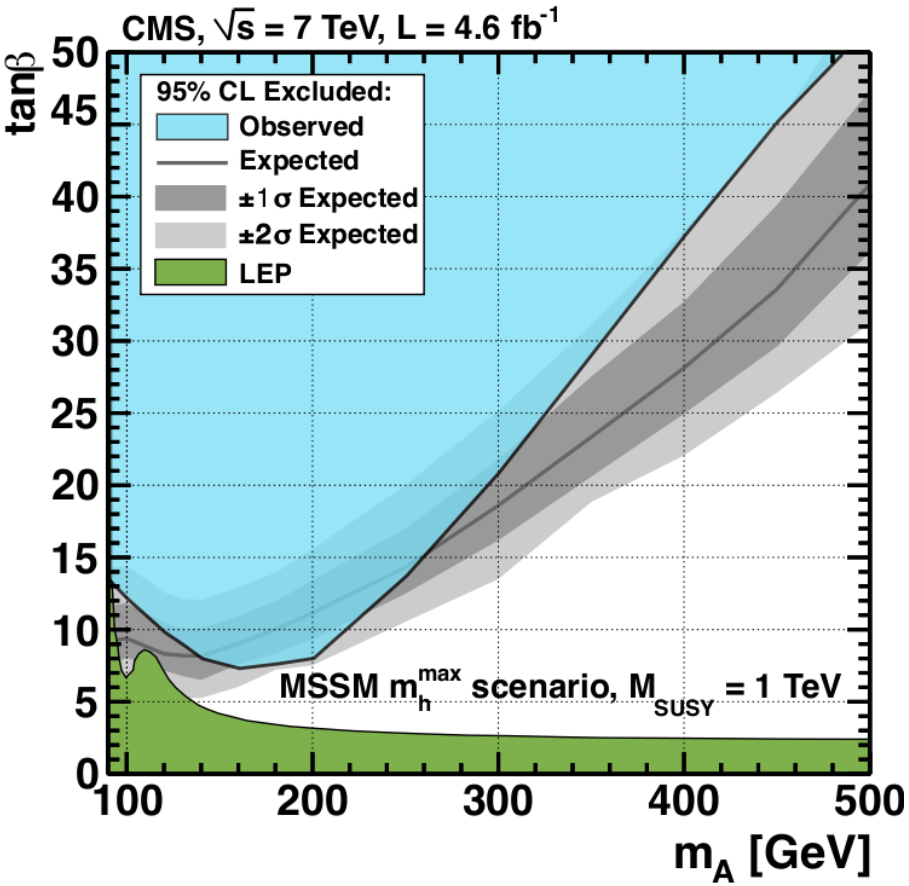
(MET and $m_{\tau\tau}$ for non b-tagged and M>250 GeV)



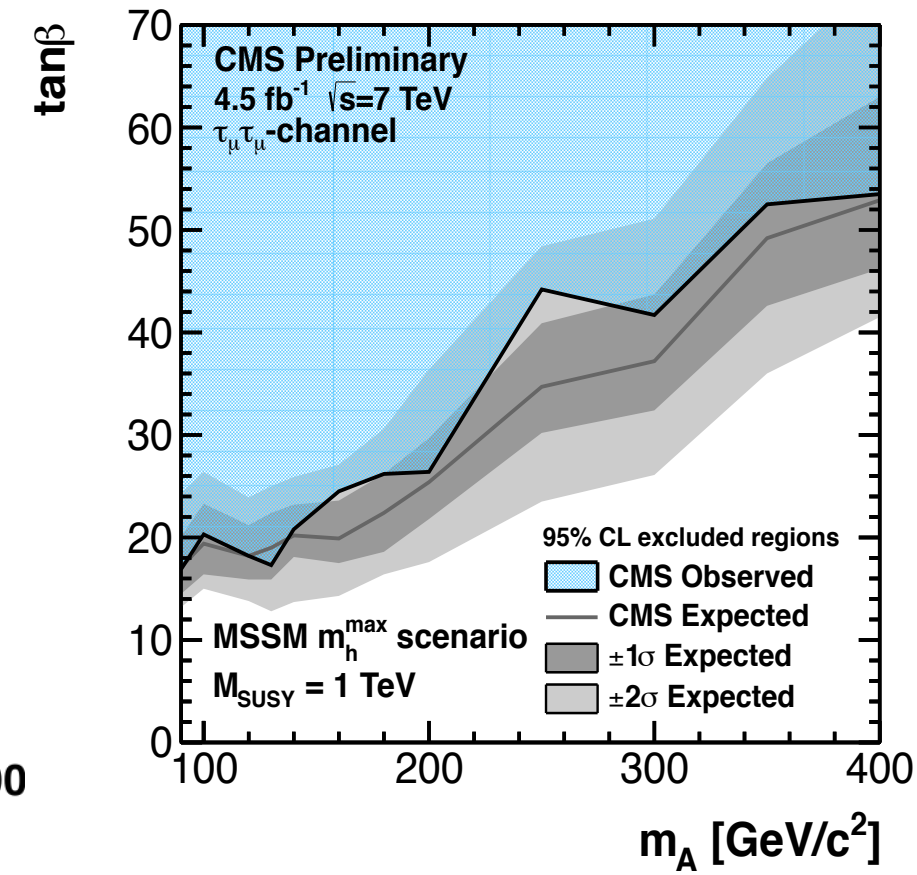


CMS: Exclusion limits in MHMAX scenario

$e\tau_{had}\ 3\ \nu$, $\mu\tau_{had}\ 3\ \nu$ $e\mu$ 4ν



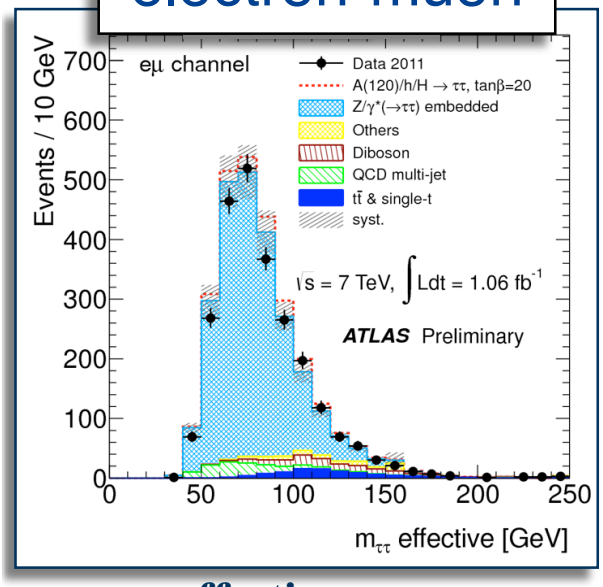
$\mu\mu 4\nu$



my opinion: unfortunately no limits on σ x BR in recent publication

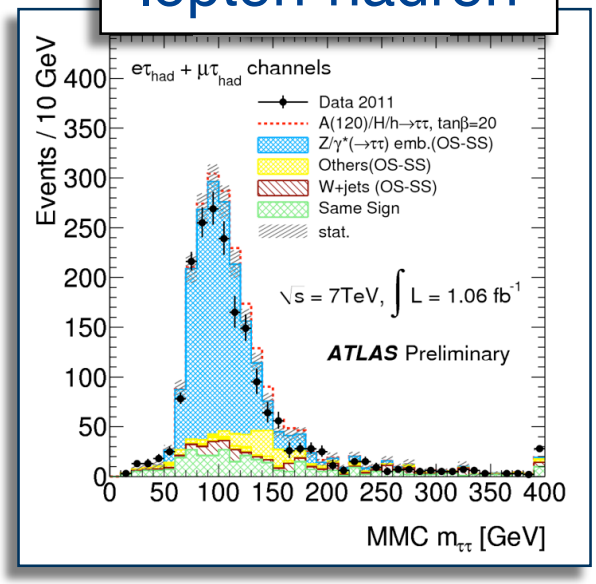
ATLAS: Incl. Analysis with 1.1 fb-1 (ATLAS-CONF-2011-132)

electron-muon



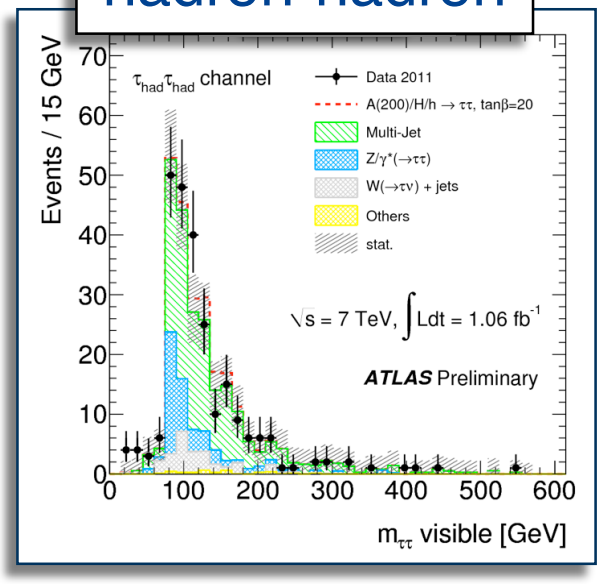
effective mass

lepton-hadron



MMC mass

hadron-hadron

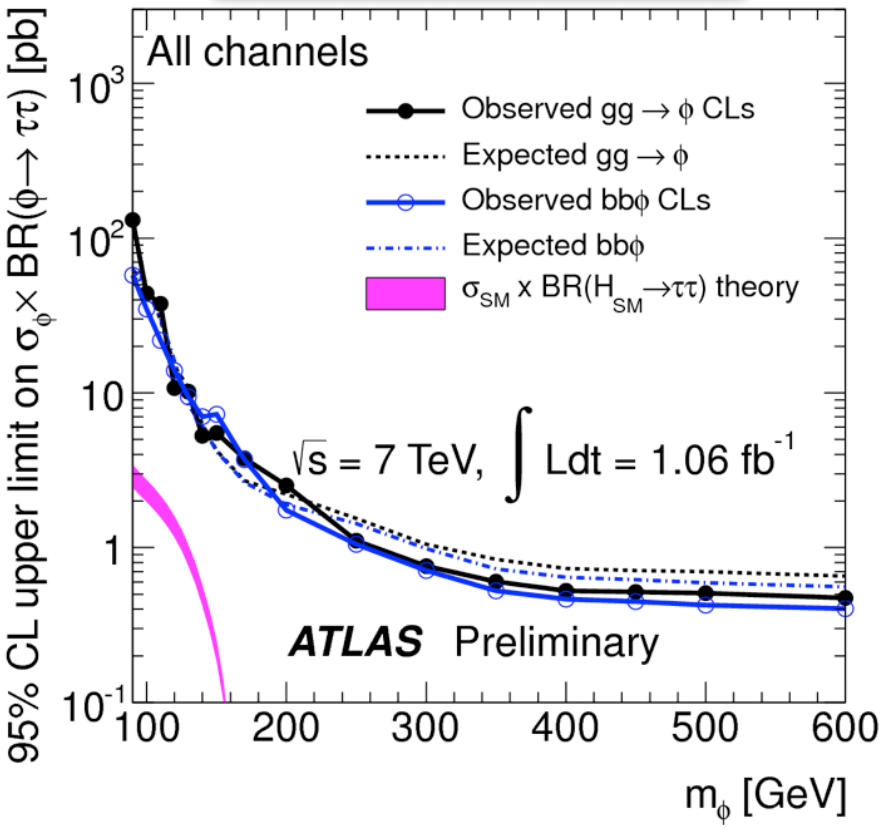


visible mass

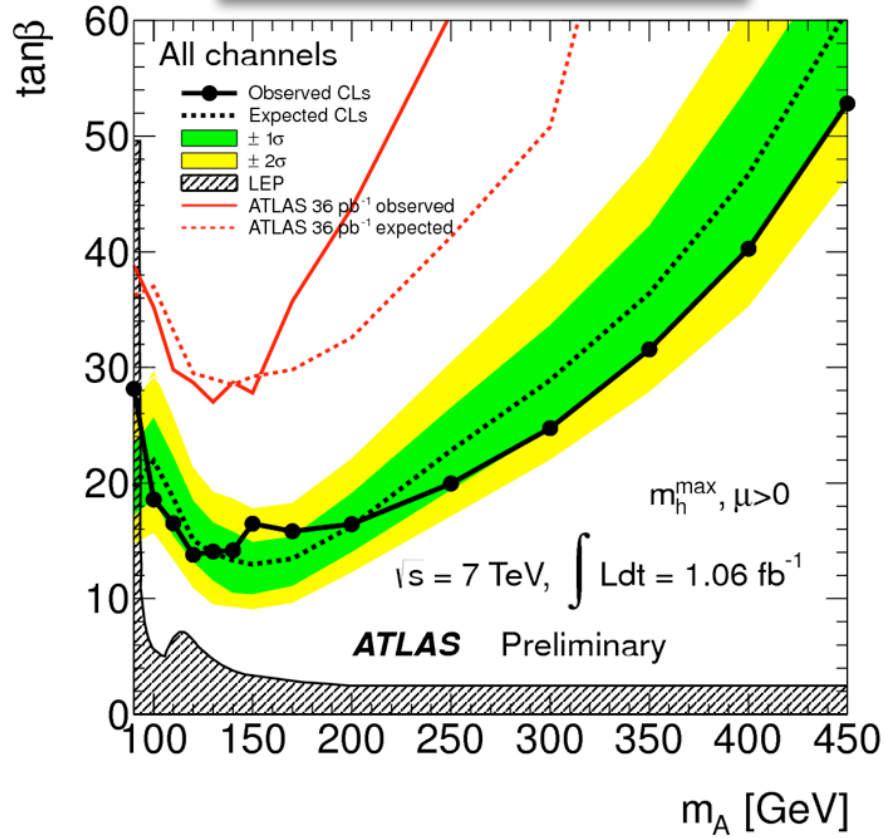
Final state	Exp. Background	Data
$e\mu$	$(2.6 \pm 0.2) \times 10^3$	2472
$\ell\tau_{had}$	$(2.1 \pm 0.4) \times 10^3$	1913
$\tau_{had}\tau_{had}$	$233\ ^{+44}_{-28}$	245
Sum	$(4.9 \pm 0.6) \times 10^3$	4630

ATLAS: Incl. Analysis with 1.1 fb-1

cross section x BR

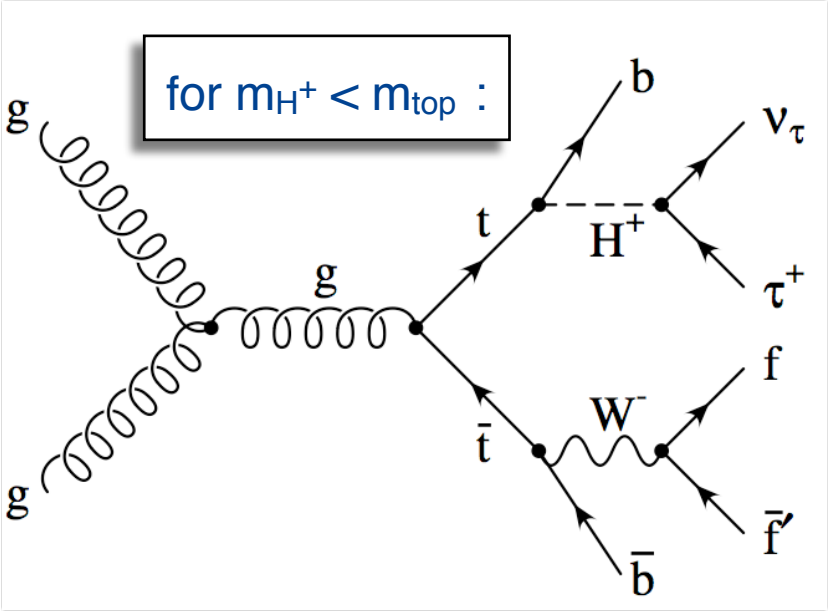


tanβ-m_A plane

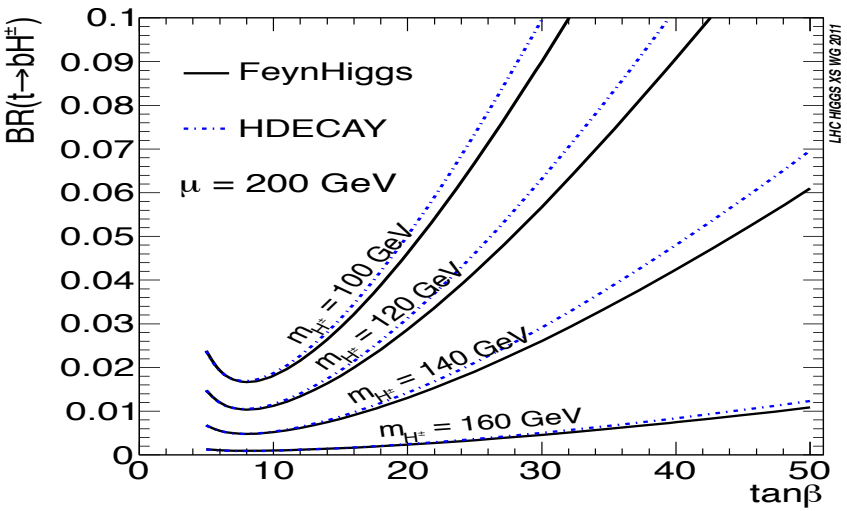


my opinion: show cross section limits for each production mode
maybe also publish: acceptances A or limits on σxBRxA?

Charged Higgs $H^+ \rightarrow \tau\nu$



so far: light $H^\pm$ ($m_{H\pm} < m_{top}$) produced in top quark decay



$BR(H^\pm \rightarrow \tau\nu) \sim 100\%$ in not excluded parameter space of MHMAX scenario

ATLAS (4.6 fb^{-1}): 3 final states

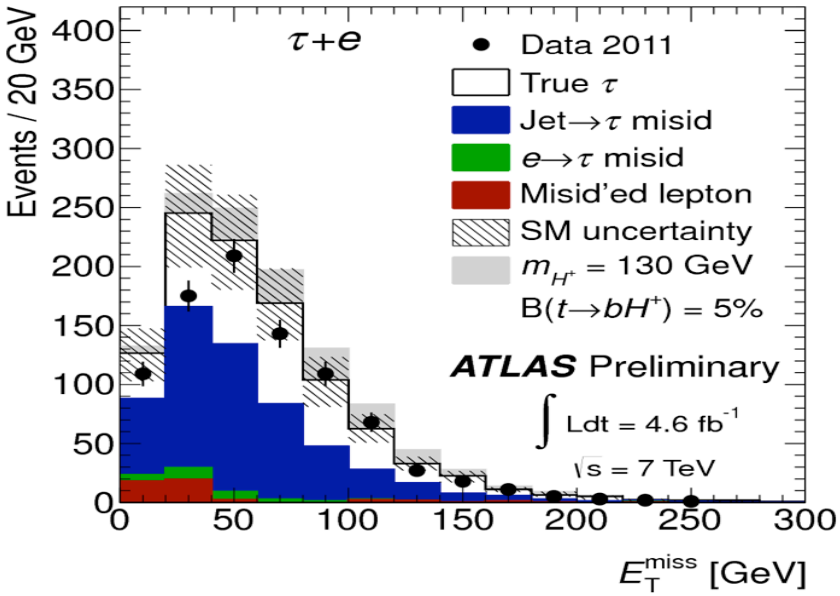
„tau + jets“ $H \rightarrow \tau_{had}\nu$ $W \rightarrow qq$ (44%)
„tau+lepton“ $H \rightarrow \tau_{had}\nu$ $W \rightarrow l\nu$ (13%)
„lepton+jets“„ $H \rightarrow l3\nu$ $W \rightarrow qq$ (24%)

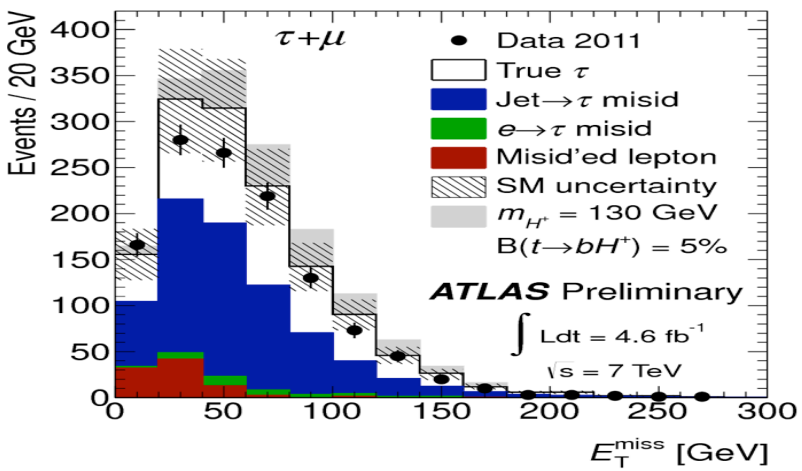
CMS (2.1 fb^{-1}): 3 final states

$H \rightarrow \tau_{had}\nu$ $W \rightarrow qq$ (44%)
$H \rightarrow \tau_{had}\nu$ $W \rightarrow l\nu$ (13%)
$H \rightarrow \mu(e)3\nu$ $W \rightarrow e(\mu)\nu$ (4%)

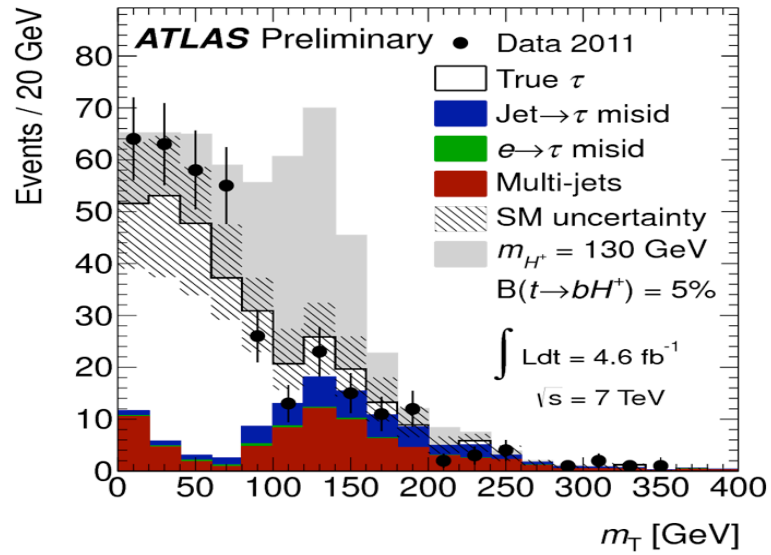
ATLAS: $H^+ \rightarrow \tau\nu$ with 4.6 fb-1 (ATLAS-CONF-2012-011)

Tau + Lepton

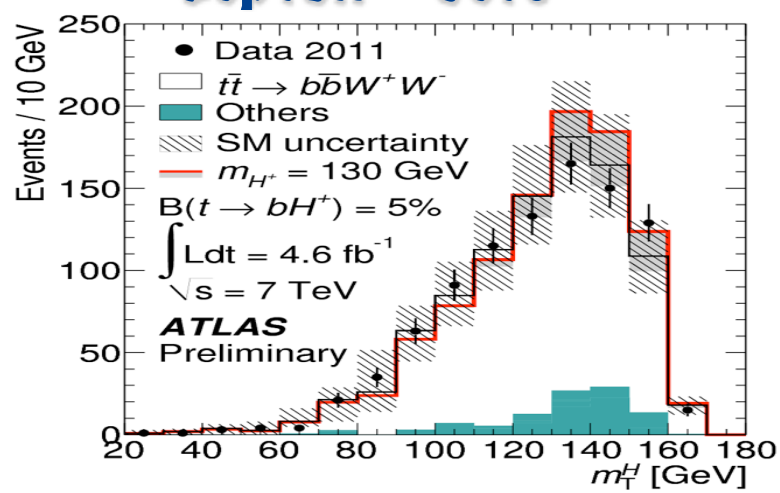




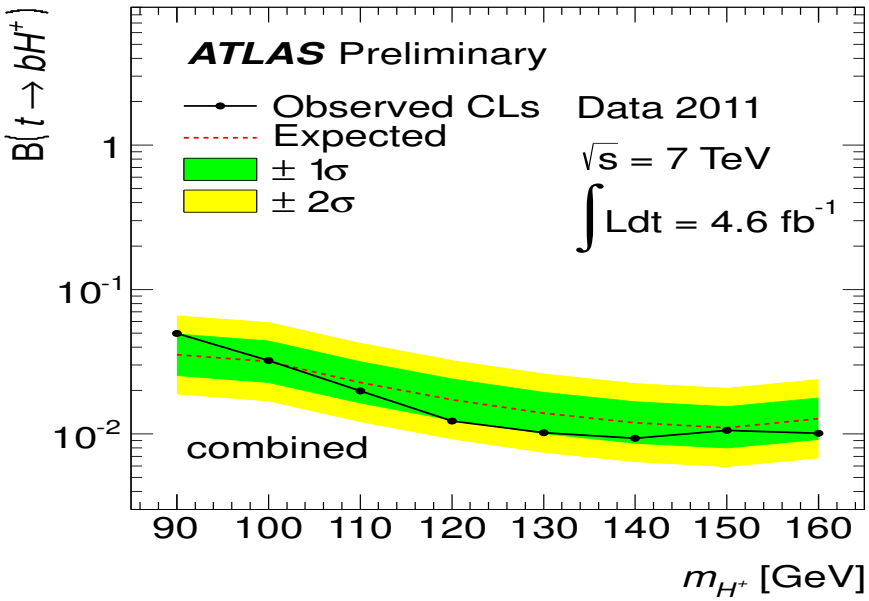
Tau + Jets



Lepton + Jets



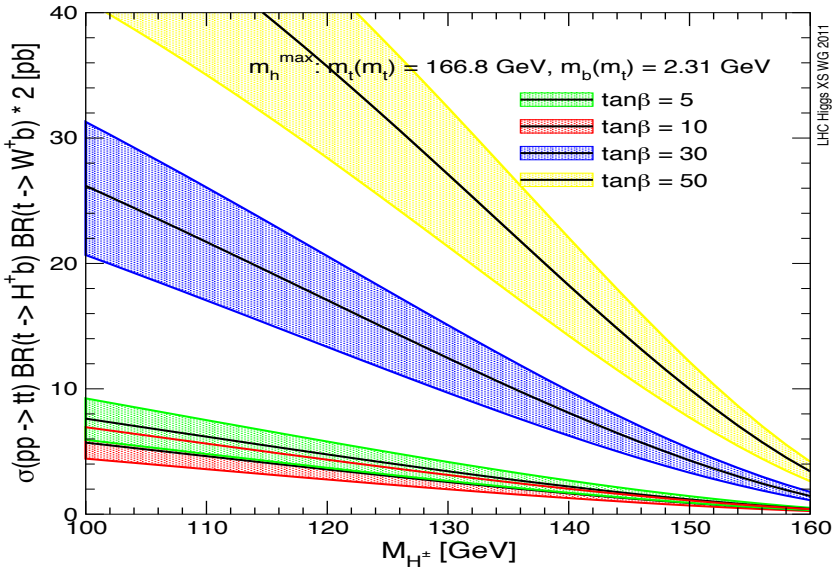
ATLAS: $H^+ \rightarrow \tau\nu$ with 4.6 fb-1 (ATLAS-CNF-2012-011)

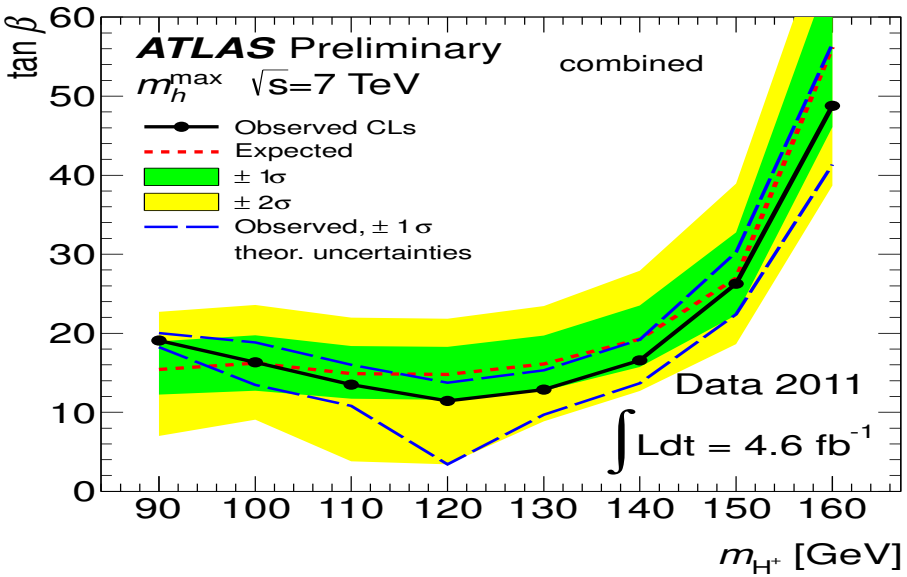


assuming BR($H^+ \rightarrow \tau\nu$)=1

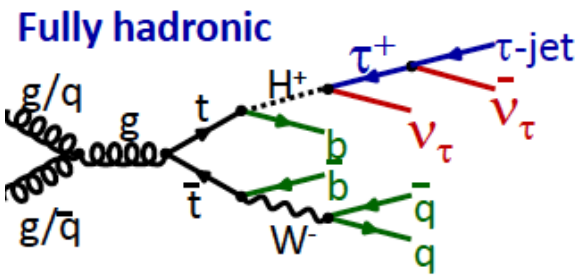
tau+jets most sensitive: 1 to 6%
lepton+jets: 4 to 18%
tau+lepton: 3 to 7%

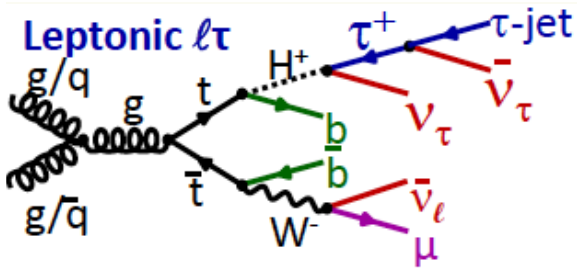
translation in tanβ-vs.-M_{H+} plane
with add.uncertainty on BR($t \rightarrow H^+b$)

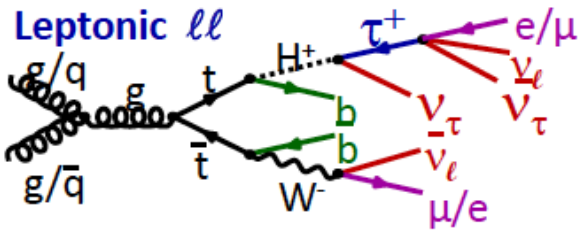


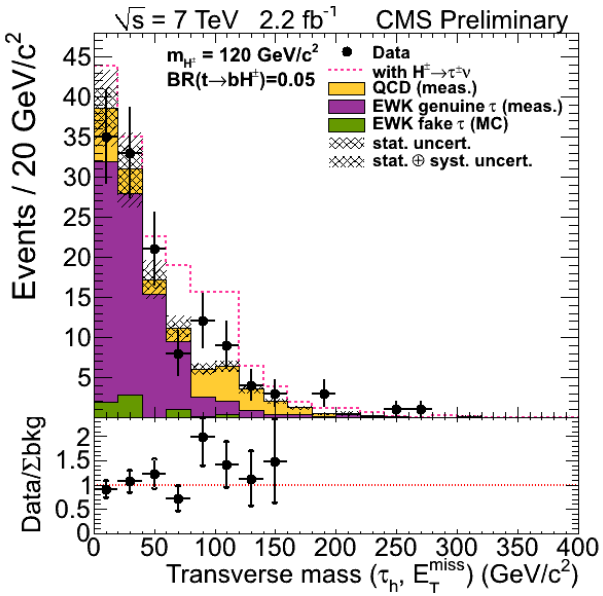


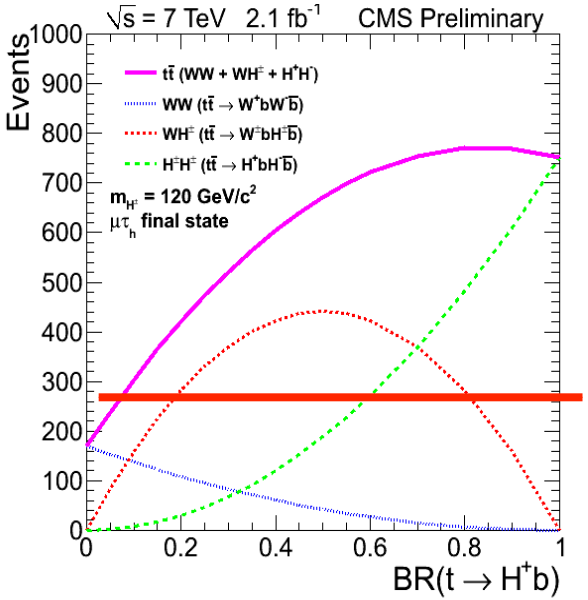
CMS: $H^+ \rightarrow \tau\nu$ with 2.2(1) fb^{-1} (CMS PAS HIG-2012-019)

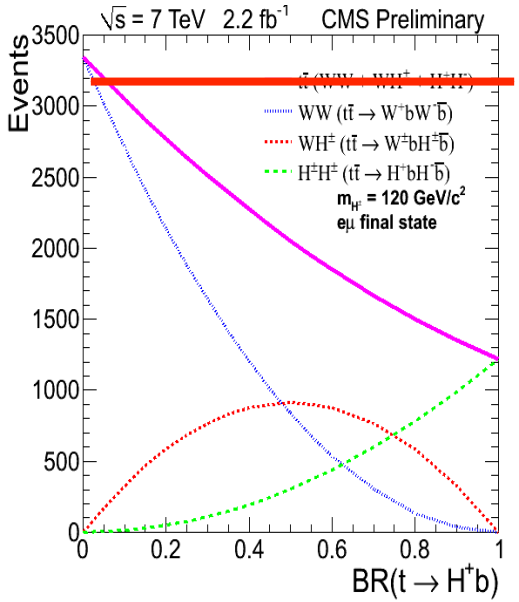








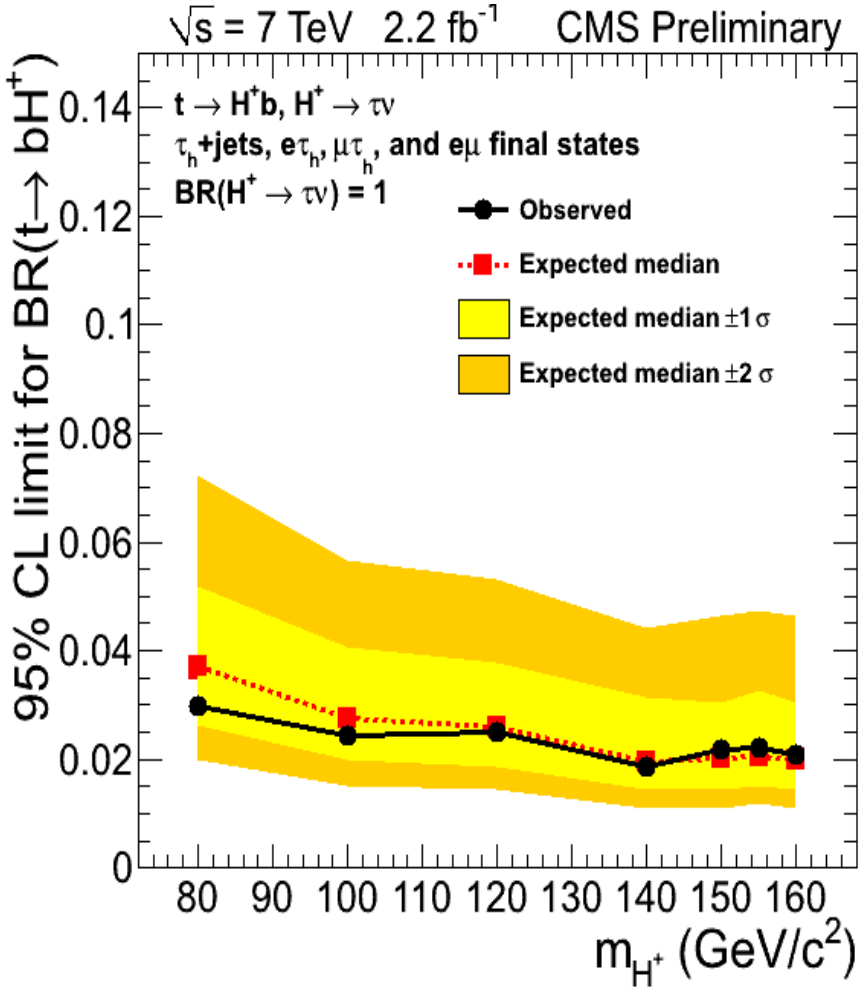


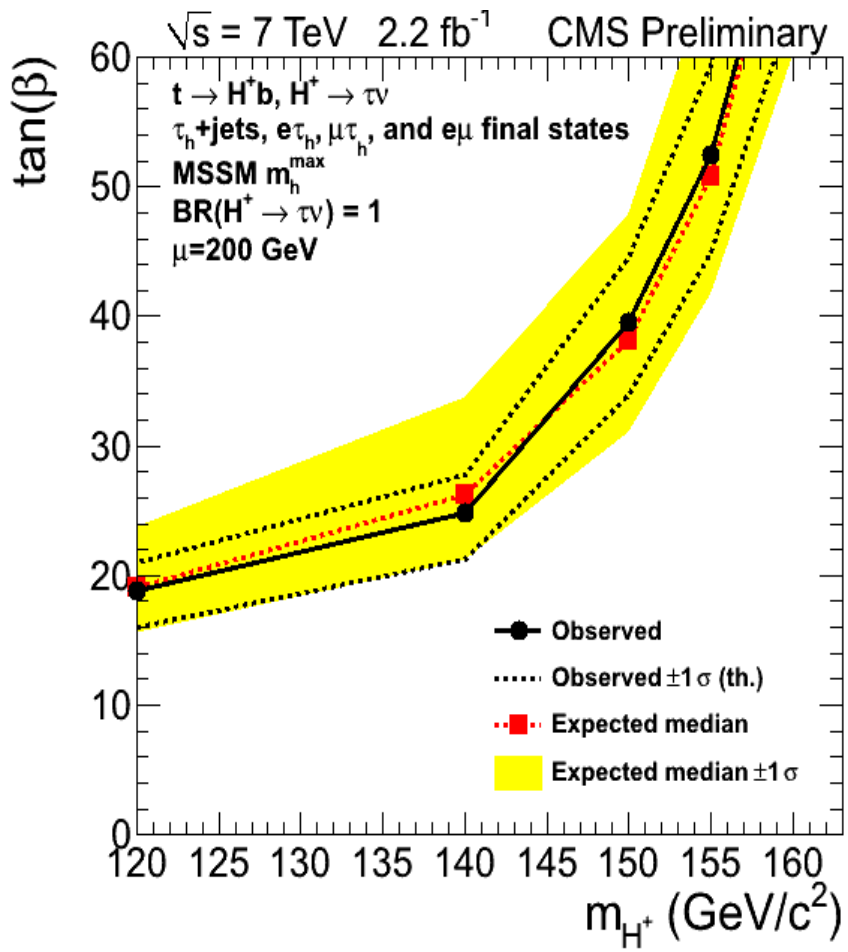


transverse mass distribution

event counting only

CMS: $H^+ \rightarrow \tau\nu$ with 2.2(1) fb^{-1} (CMS PAS HIG-2012-019)





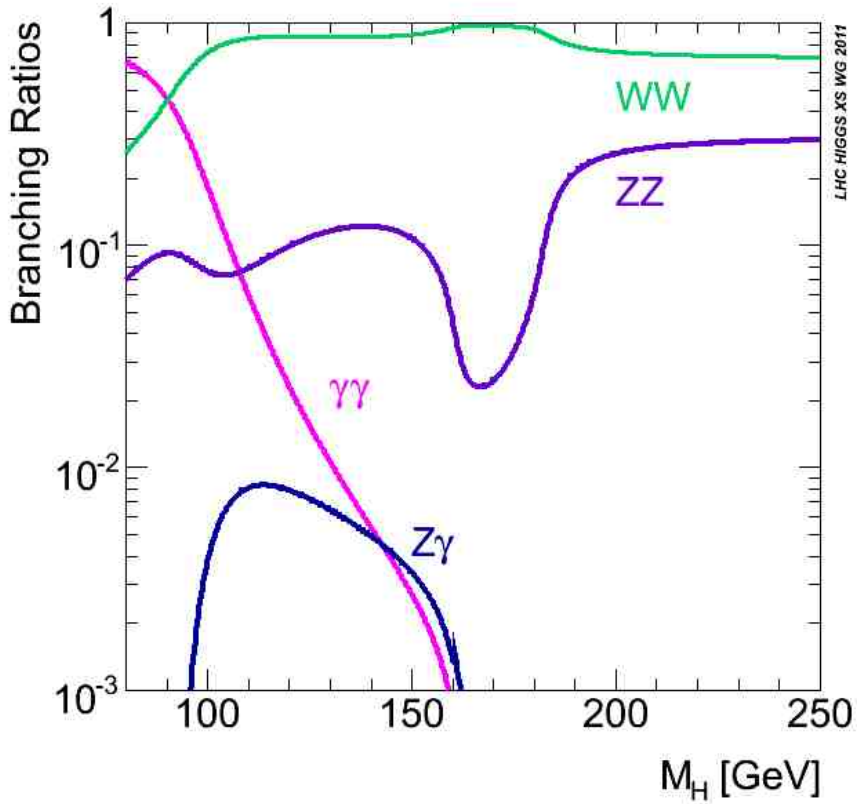
expected exclusion sensitivity on $BR(t \rightarrow H^+b)$

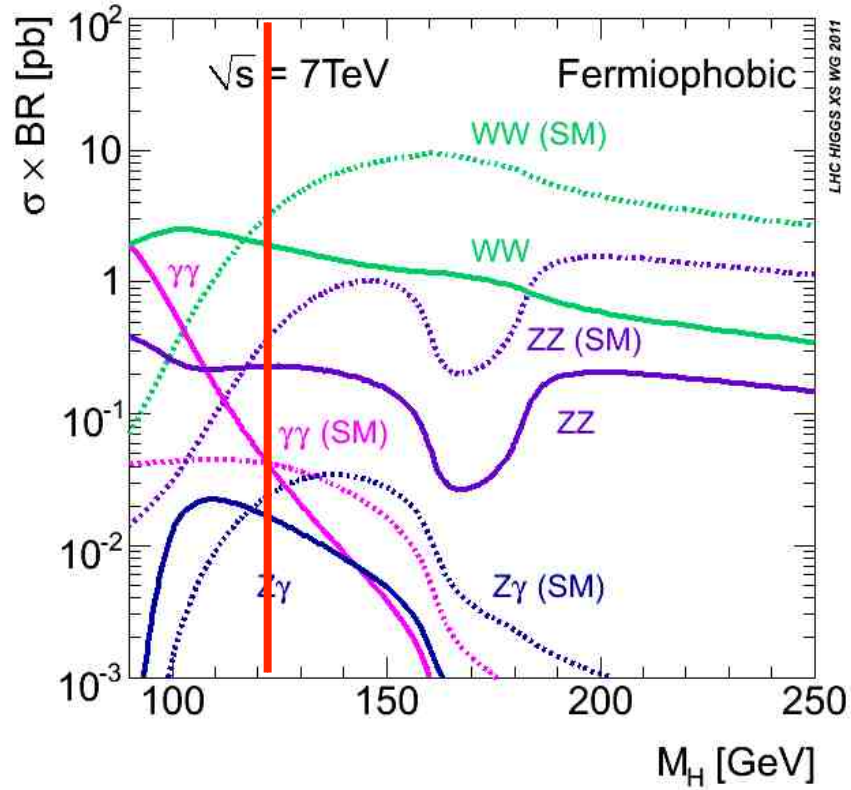
hadronic 2 to 6 % $e\tau_{had}$ 7 to15%

$\mu\tau_{had}$ 6 to 12 % $e\mu$ 20 to 25%

Fermiophobic Higgs Model

simple benchmark: no couplings to fermions (loop induced decays ignored)





enhanced BRs to gauge bosons for low M_H

no production in gluon fusion and ttH

VBF and VH production dominant → larger P_T of Higgs

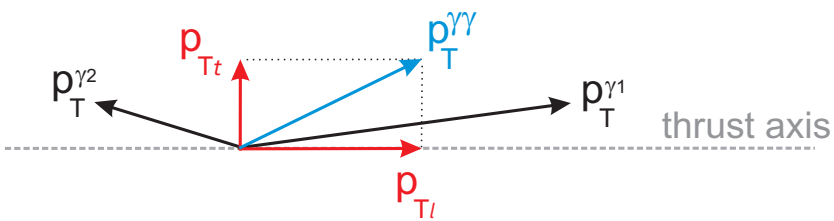
→ optimise sensitivity e.g. for H→2 photons decay mode

LEP: M_H<109 GeV excluded TEVATRON: M_H<119 GeV excluded

ATLAS: H→ 2 γ Fermiophobic (FP) (ATLAS CONF 2012-13)

enhance signal/background ratio and mass resolution by splitting in 9 categories (as in SM):

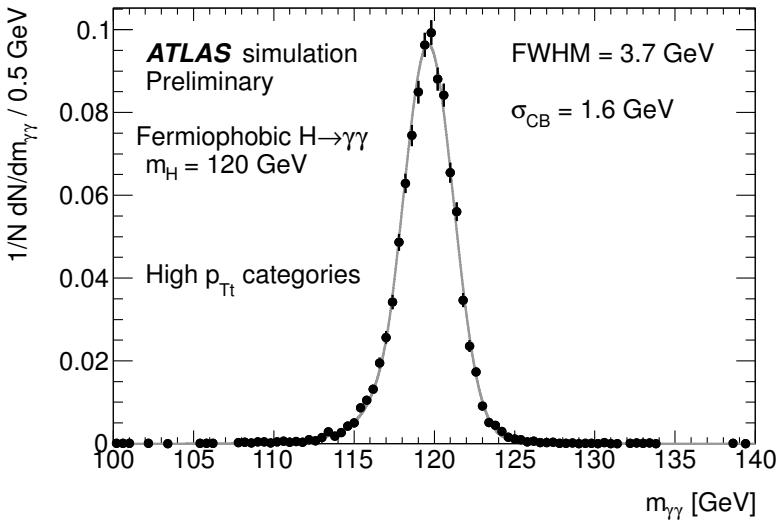
converted/ non converted
central / foward/ transition
low high $p_T^{\gamma\gamma}$ > (≤)40 GeV



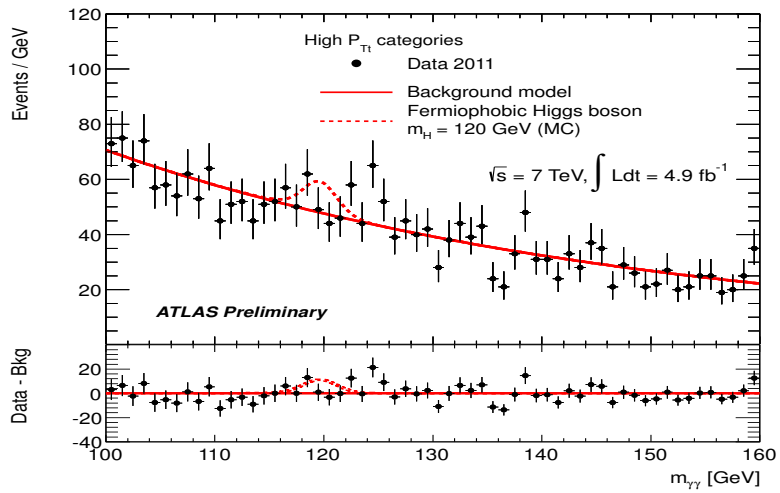
Category	σ_{CB}	FWHM	N_S	N_D	S/B
Unconverted central, low p_{Tt}	1.4	3.3	6.2	1763	0.03
Unconverted central, high p_{Tt}	1.3	3.2	8.6	235	0.37
Unconverted rest, low p_{Tt}	1.7	3.9	12.1	6234	0.02
Unconverted rest, high p_{Tt}	1.6	3.8	16.0	1006	0.13
Converted central, low p_{Tt}	1.6	3.8	4.0	1318	0.02
Converted central, high p_{Tt}	1.5	3.5	5.8	184	0.26
Converted rest, low p_{Tt}	2.0	4.6	11.8	7311	0.01
Converted rest, high p_{Tt}	1.9	4.4	16.1	1072	0.09
Converted transition	2.3	5.8	10.8	3366	0.01
All categories	1.7	3.9	91.2	22489	0.03

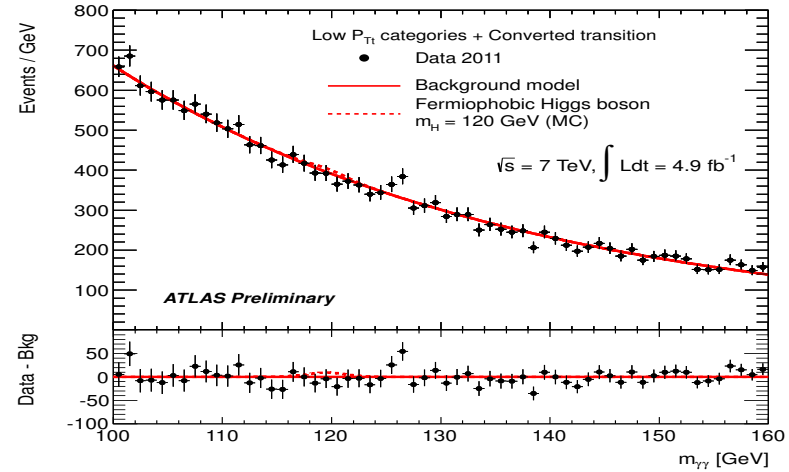
better S/B than in SM for high P_T categories: ~ factor 3:

e.g. uncoverted high p_T
S/B: FP 0.37 SM 0.11

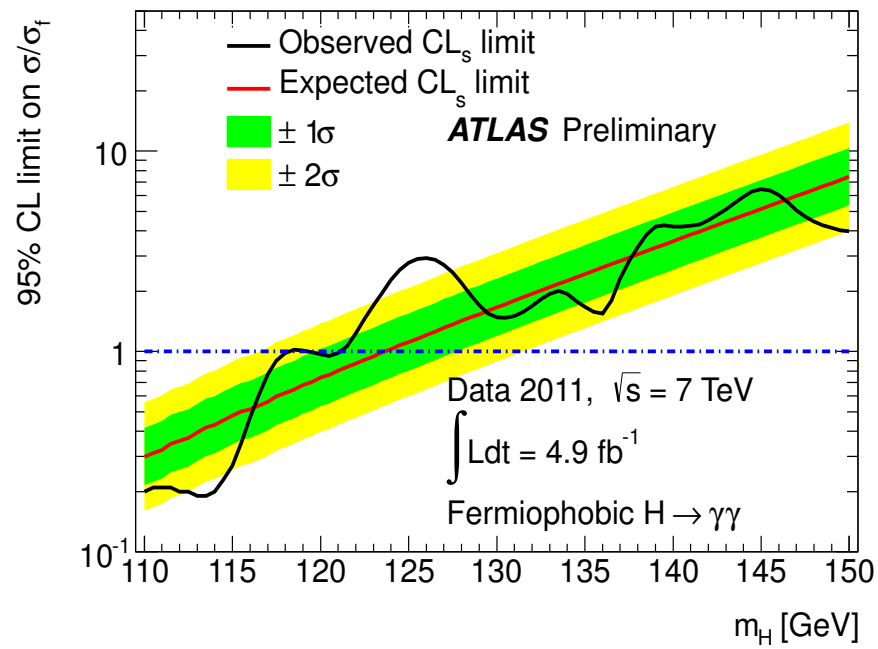


ATLAS: H→ 2 γ: Fermiophobic Analysis



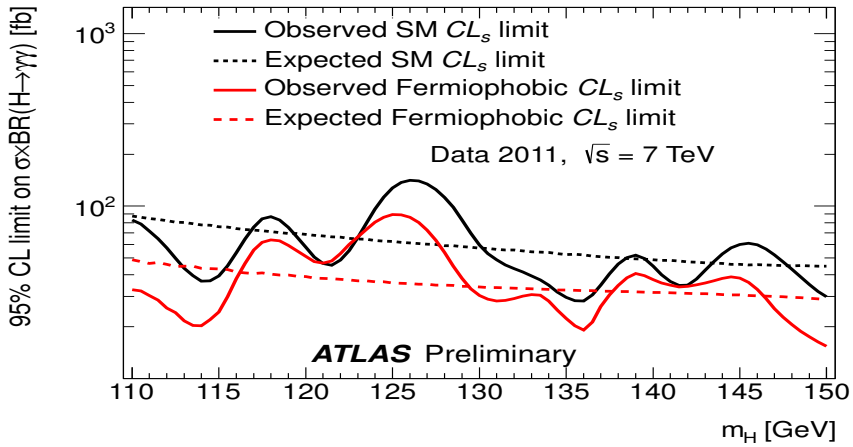


m_H [GeV]	110	115	120	125	130	135	140	145	150
$\sigma \times BR$ [fb]	163	90	53	32	21	13	8.9	5.9	3.9
Signal events	255	149	91	58	38	25	17	12	7.9
Efficiency [%]	32	34	35	37	38	38	39	40	42



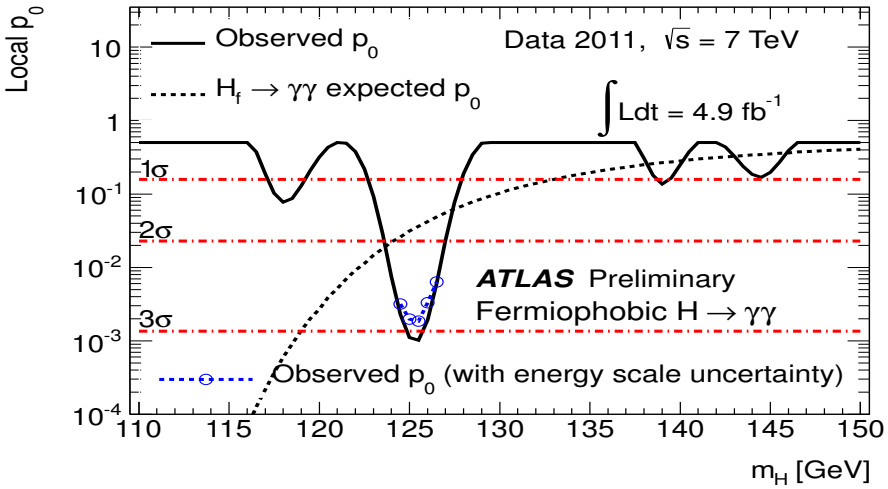
95% CL exclusion:
obs: 110 to 118 and 119.5 to 121.0 GeV
exp: 110 to 123.5 GeV

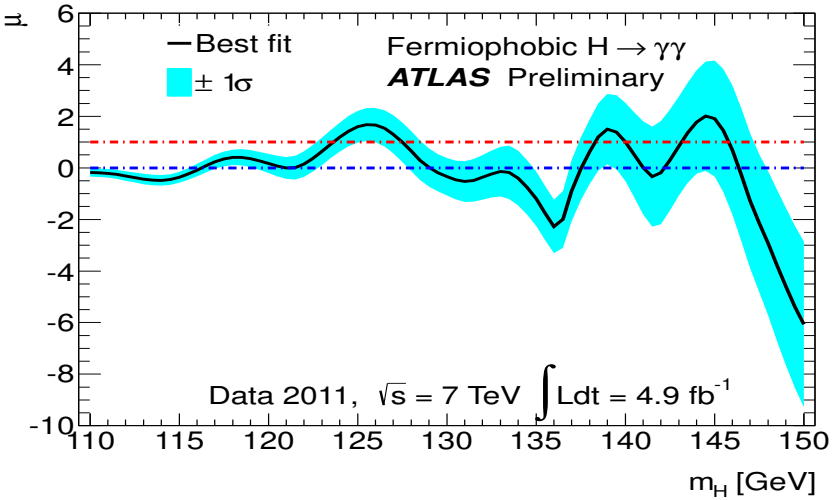
ATLAS H→ 2 γ: Fermiophobic (FP) Analysis



comparison of SM and FP cross sec. x BR limits

increased sensitvity due to other production modes





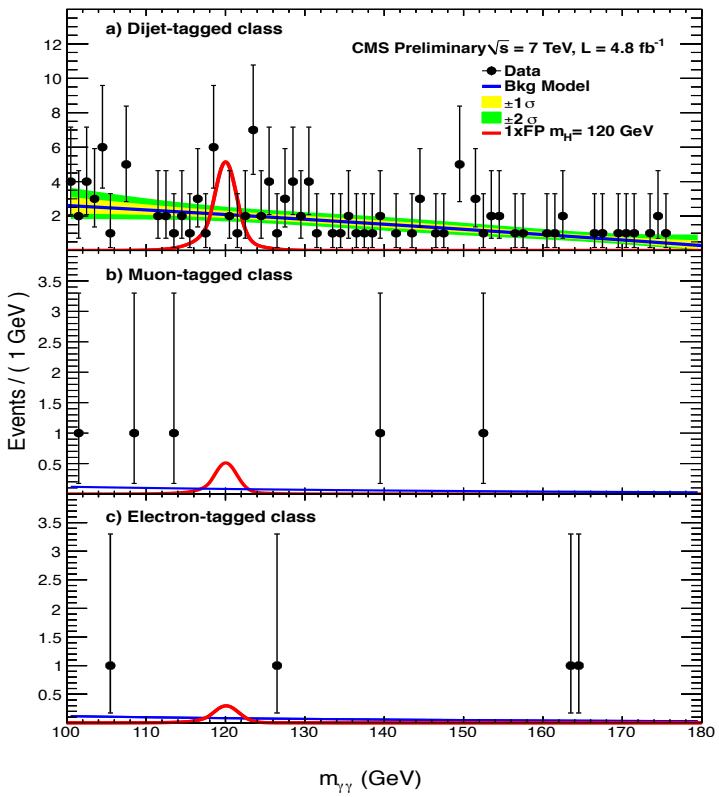
local excess: 3 σ at 125.5 GeV
incl. LEE: 1.6 σ
in SM: 2.8 σ locally

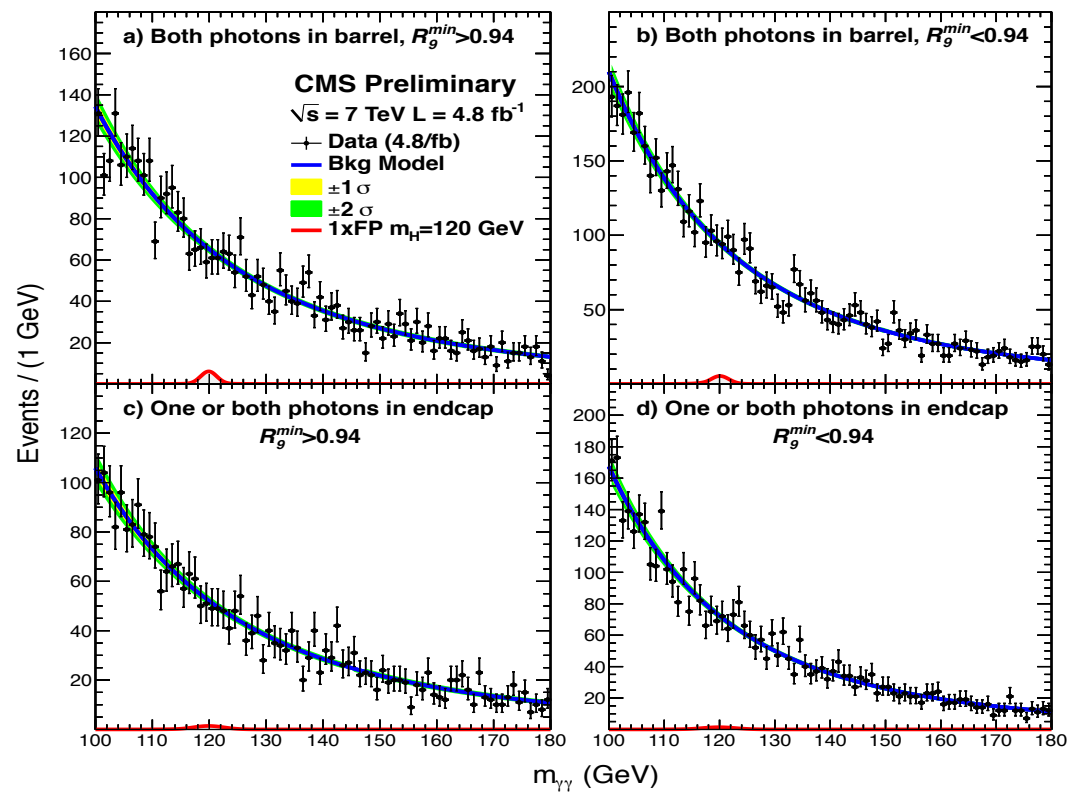
excess compatible with FP Higgs (and SM Higgs)

CMS H→ 2 γ: Fermiophobic Analysis (CMS PAS HIG-12-002)

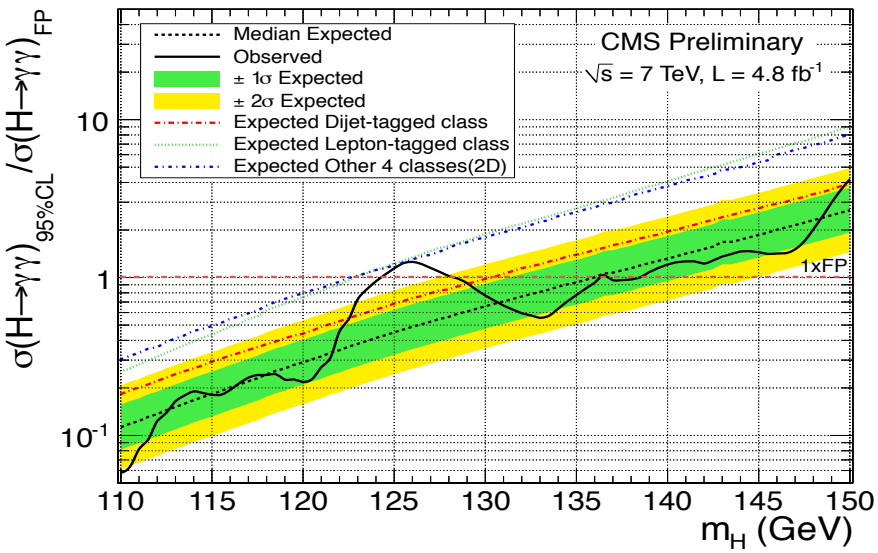
7 event classes: dijet-tagged (VBF), e-tagged μ-tagged (W(Z)H)
4 inclusive (pseudorapidity and isolation of photons)

	Dijet + lepton tag	Both photons in barrel		One or both in endcap	
		R_9^{min} >0.94	R_9^{min} <0.94	R_9^{min} >0.94	R_9^{min} <0.94
FP signal expected	24.7 (27.4%)	22.3 (24.7%)	23.0 (25.5%)	9.5 (10.5%)	10.7 (11.9%)
Data (events)	129 (0.8%)	3740 (22.9%)	5363 (32.9%)	2991 (18.3%)	4090 (25.1%)
σ_{eff} (GeV)	1.72	1.39	1.84	2.76	3.19
FWHM/2.35 (GeV)	1.37	1.19	1.53	2.81	3.18





CMS H→ 2 γ: Fermiophobic (FP) Analysis

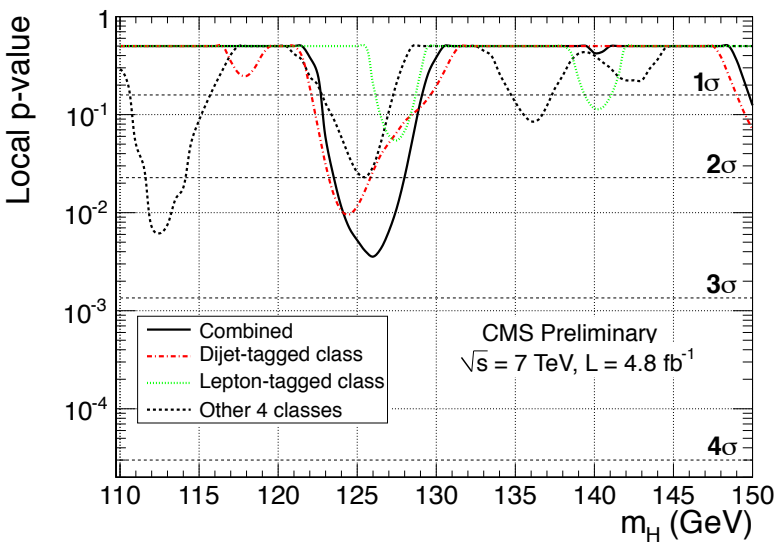


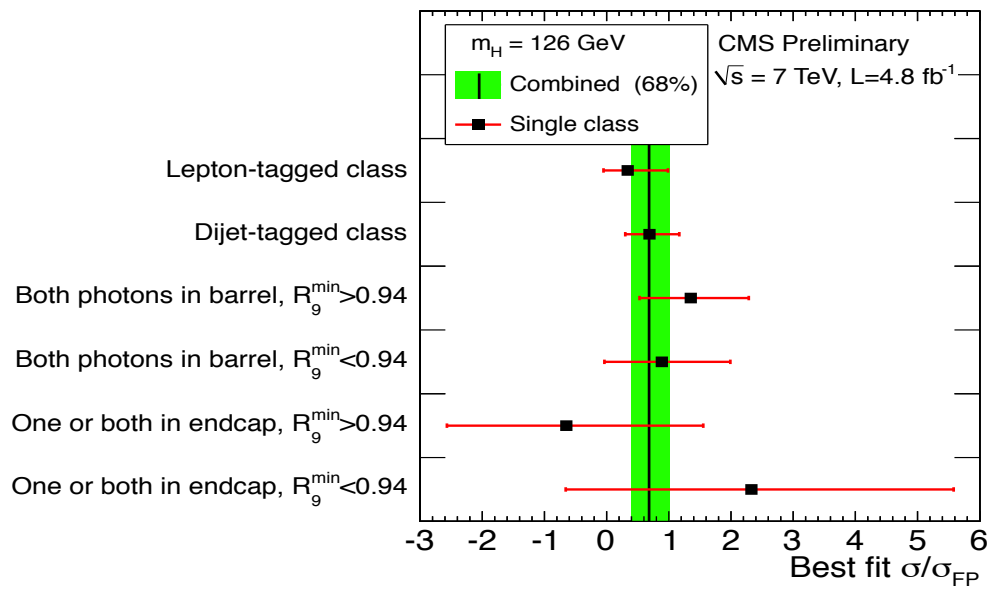
exp. exclusion: 110 to 136 GeV
obs. exclusion: 110 to 124, 128 to 136 GeV

excess at 126 GeV: local 2.7 σ
global 1.2 σ (110 to 150 GeV)
best μ = 0.68+0.31

in SM: local 2.9 σ μ= 1.7+0.7

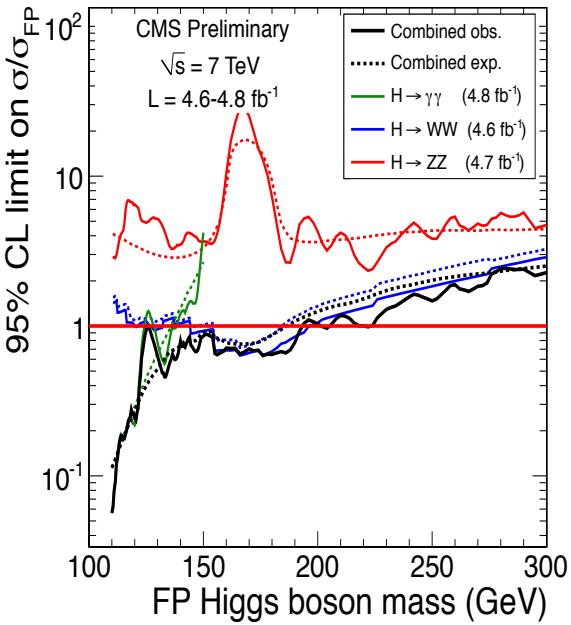
excess also compatible with FP scenario

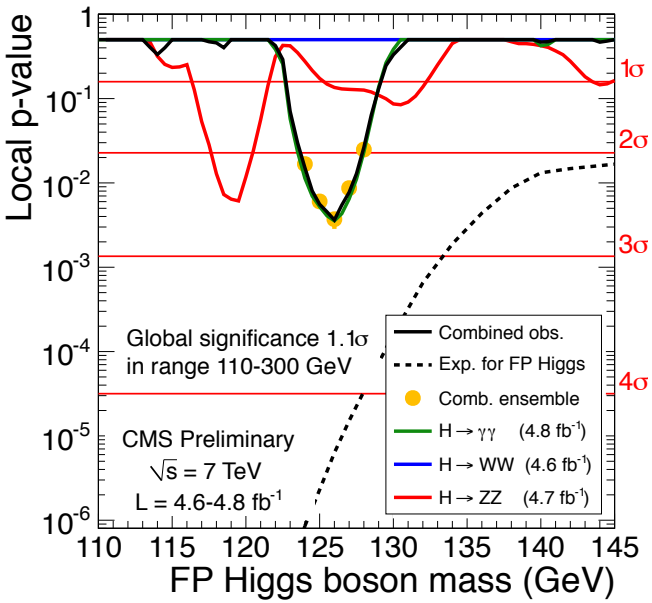


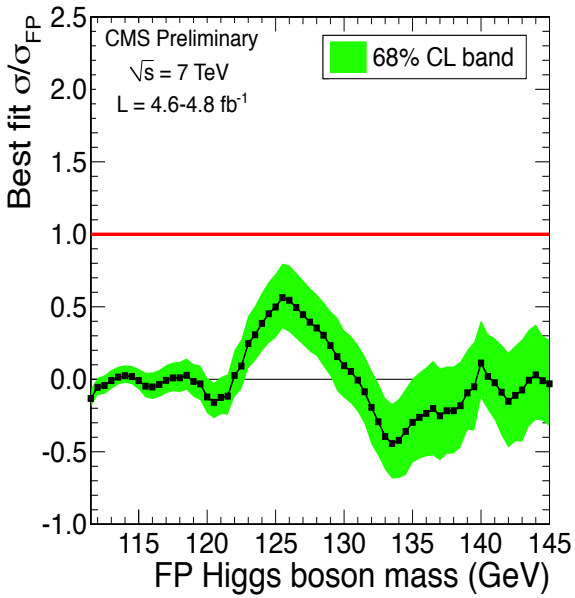


CMS: Interpretation in FP Scenario (CMS PAS 12-008)

reinterpretation of searches for SM Higgs boson + dedicated H→γγ searches
(theo. uncertainties increased by 5%, acceptances as in SM interpretation)







excluded:
95% CL 110 to 192 GeV
99% CL 110 to 188 GeV
not [124.5,128] and
[148,154] GeV

local p-values at M=125 GeV similar to SM result
smaller value for best signal strength w.r.t. SM result (some tension w.r.t. simple FP scenario)

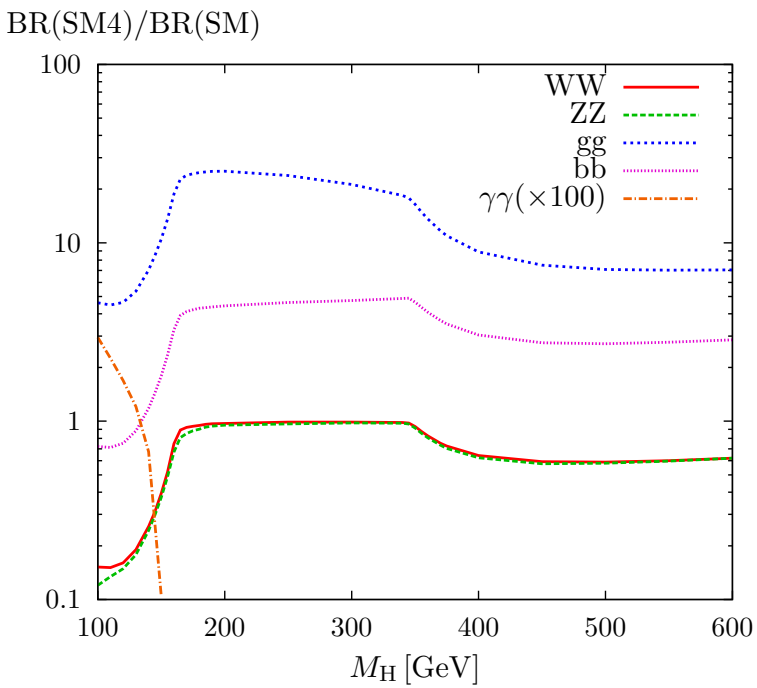
„4th Generation SM“ Scenario

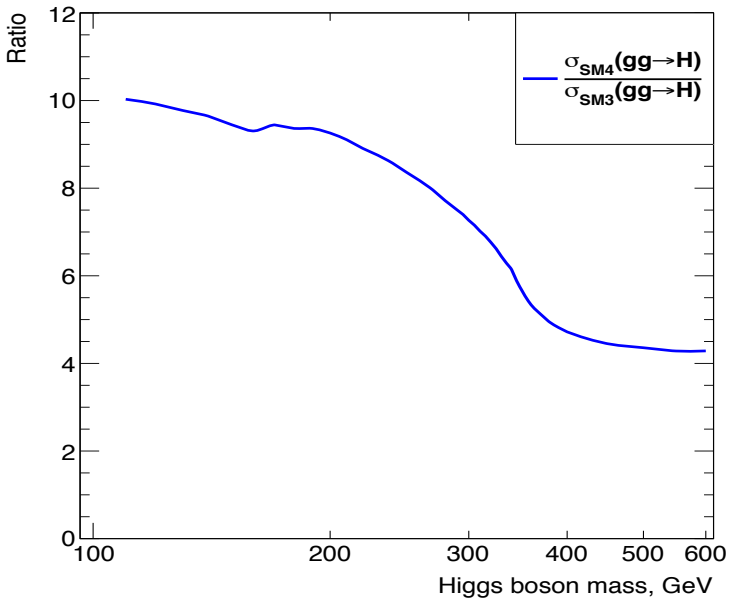
simple benchmark model

(Yukawa coulings derived from mass values)

$$m_{b'} = m_{l'} = m_{\nu_l'} = 600\ \mathrm{GeV},$$

$$m_{t'} = m_{b'} + \left[1 + \frac{1}{5}\ln\left(\frac{M_H}{115\ \mathrm{GeV}}\right)\right] 50\ \mathrm{GeV}$$



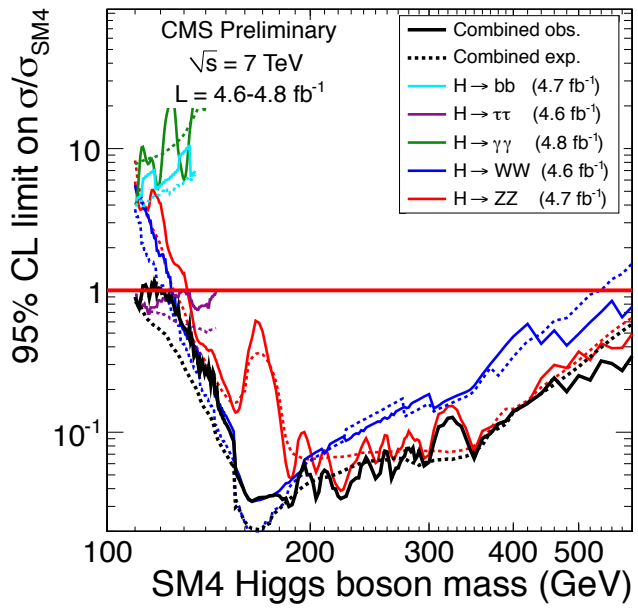


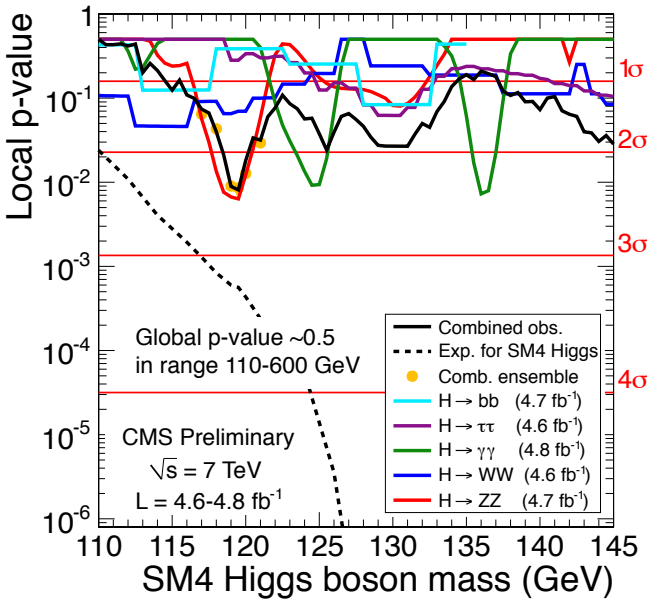
decays in gluons and bb largely enhanced
→ supression of H→ 2 photons and
partially also H→WW and ZZ

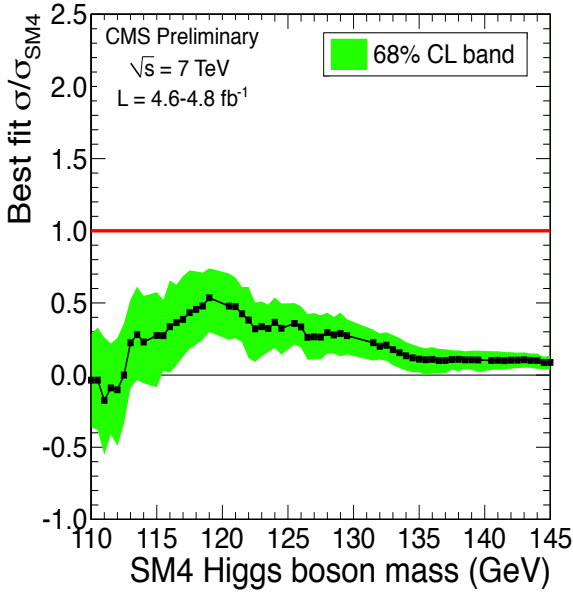
production in gg→H
enhanced by factor 4 to 9

CMS: Interpretation in SM4-scenario (CMS PAS HIG 12-008)

reinterpretation of searches for SM Higgs boson
(using same theo. uncertainties, acceptances as in SM interpretation)







excluded: 120 to 600 GeV

H→ττ most sensitive channel for small M_H

larger combined local p-values and smaller value for best signal strength w.r.t. SM result (inconsistent with simple SM4 scenario)

caused by smaller relevance of H→2 photons anf VBF prduction w.r.t. gluon fusion

CMS: a→μ+μ− at low mass (CMS PAS HIG-12-004)

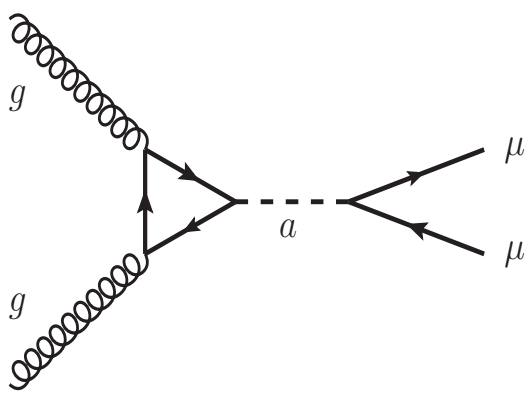
adding a Higgs singlet as e.g. as in the NMSSM

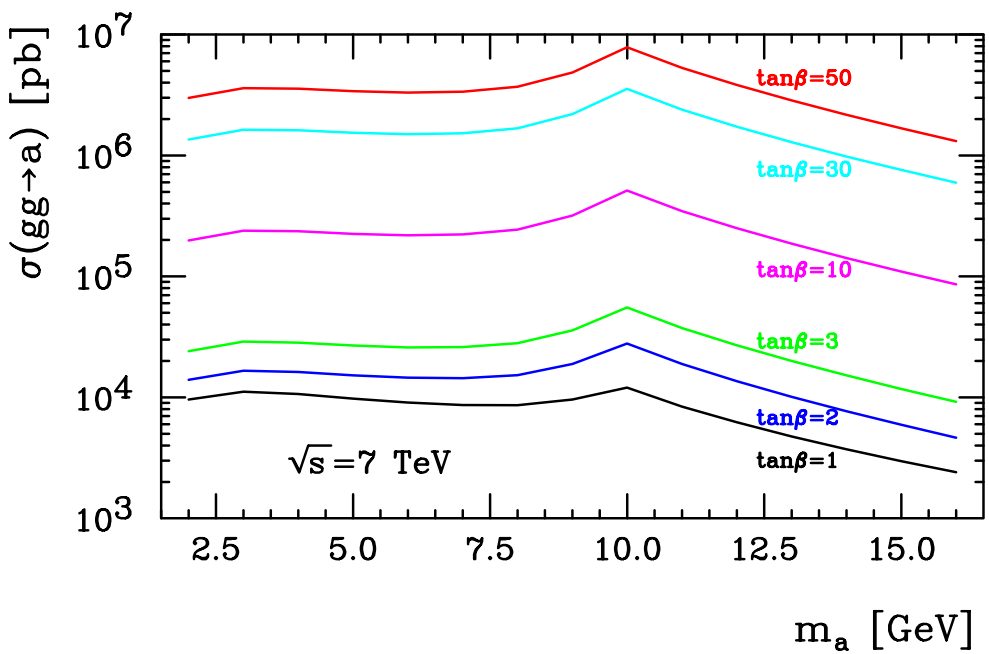
mixing with A of MSSM: $a_1 = \cos\theta_A a_{MSSM} + \sin\theta_A a_S$

coupling to $I_{w,3}$ =-1/2 fermions $C_{a_1 b\bar{b}} = \tan\beta \cos\theta_A$

BR(a→μμ) depends on m_a and tanβ (10^{-3} to 10^{-4} for tanβ=1 to 20)

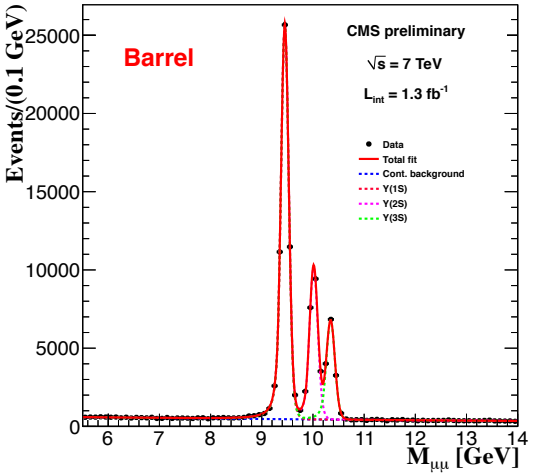
$$\sigma(gg \to a_1) \propto \cos^2\theta_A$$

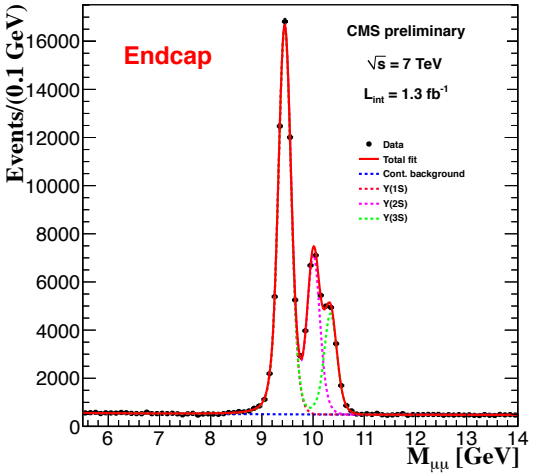




search performed in mass ranges 5.5 to 8.8 GeV and 11.5 to 14 GeV

CMS: a→μ+μ− at low mass

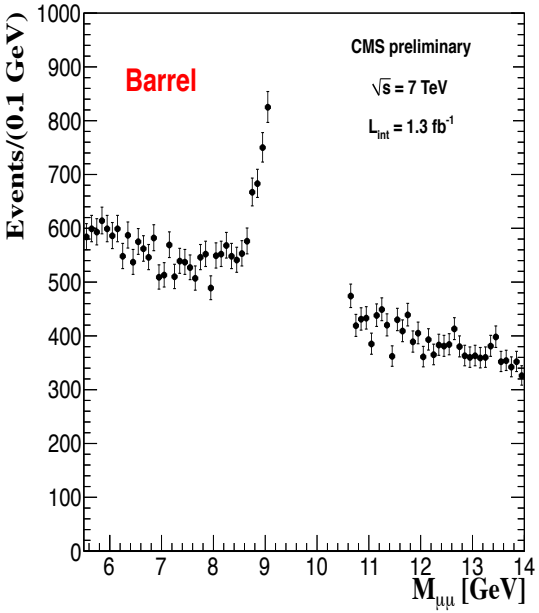


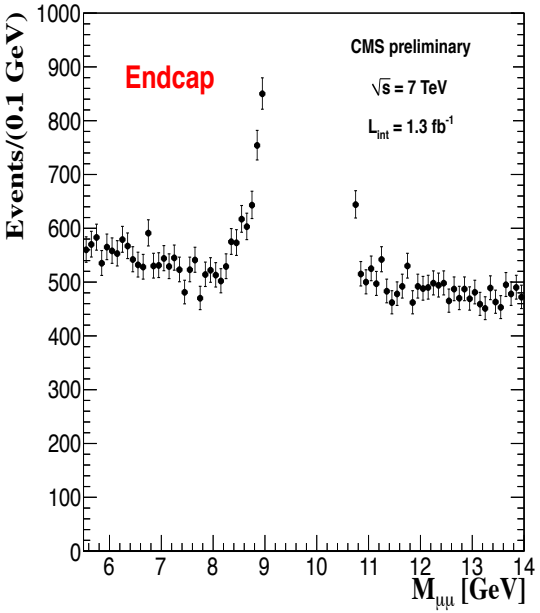


look for mass resonance of two isolated. low p_t muons

background modelling completely data driven

eff. = 1% to 3.5% (M_a 6 to 13 GeV)
σ_M/M = 50 to 190 MeV

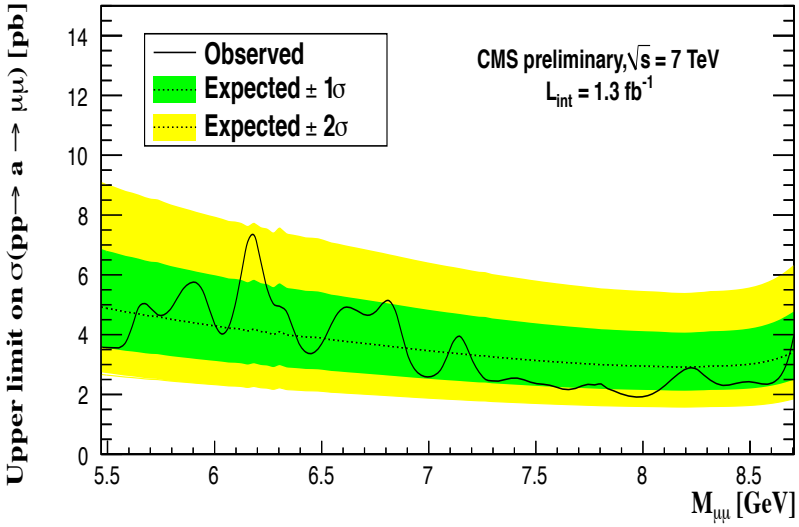


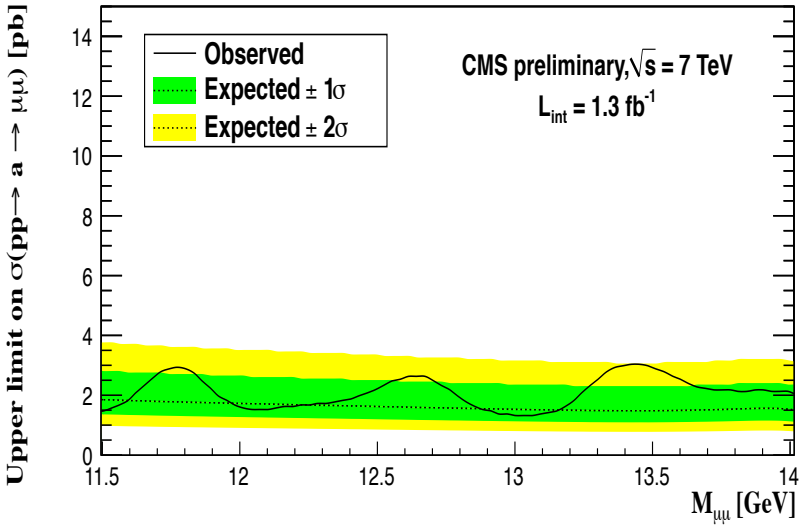


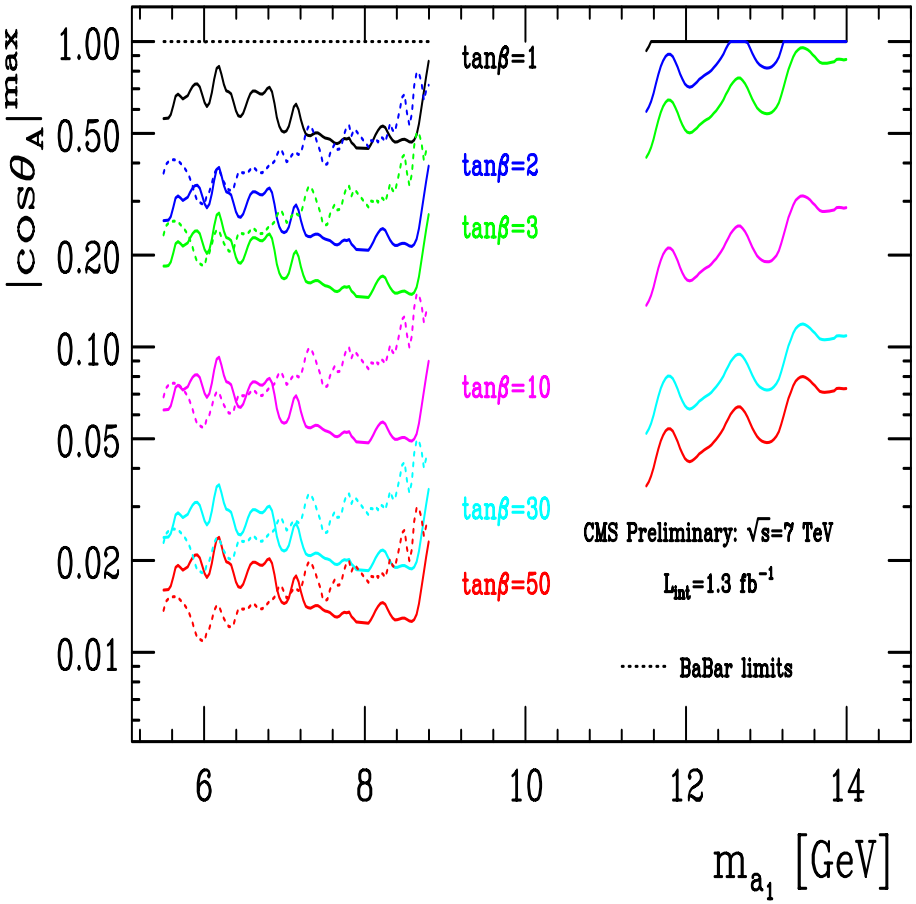
Finally, we note that the *a* modeling lacks a complete MC generator that accurately represents the kinematic of the scalar production and decay. Since no generator is currently considered to be appropriate for this model, at present we do not assign any systematic uncertainty to account for this effect.

no signal acceptance uncertainty assigend

CMS: a→μ+μ− at low mass

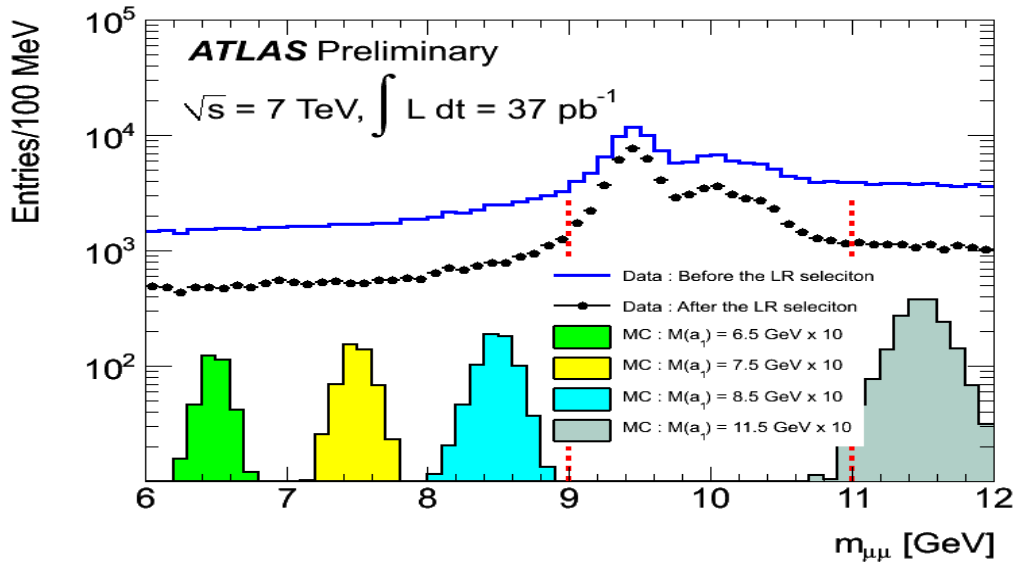




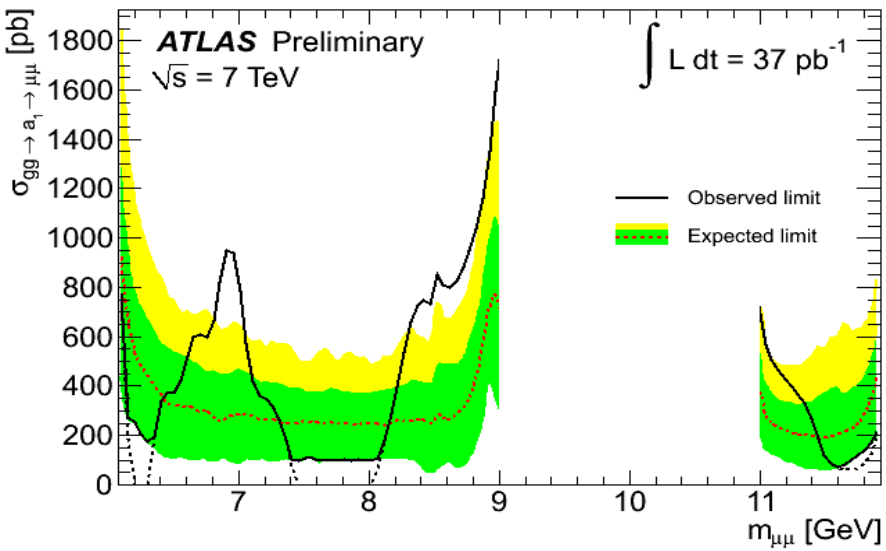


best limits in range 5.5 to 8.8 GeV
and first ones in range 11.5 to 14 GeV

ATLAS: a→μ⁺μ⁻ at low mass

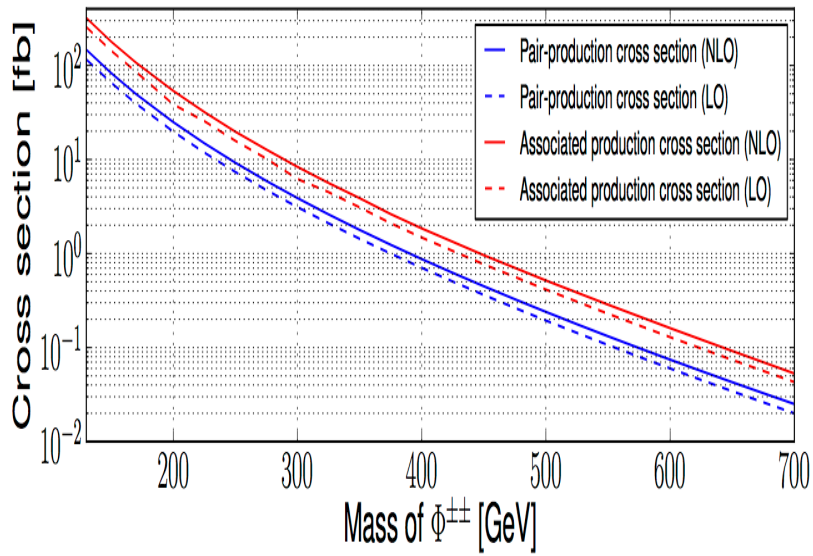


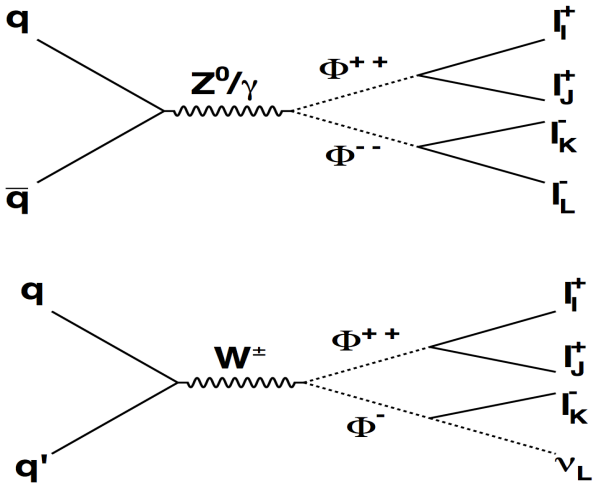
Source	Relative Uncertainty (%) at $m(a_1)$ (GeV) 6.0	6.5	7.0	7.5	8.0	8.5	11.0	11.5
Luminosity	±11							
Pythia vs MC@NLO	±67	±55	±49	±40	±36	±32	±20	±20
Dimuon Efficiency	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+15}_{-14}$	$^{+15}_{-14}$
Trigger Correction	±8							
Trigger MC Stats.	±10	±10	±10	±10	±10	±10	±9	±9
Likelihood Ratio Modeling	±3							
Total (Pythia vs MC@NLO)	±70	±59	±53	±45	±41	±37	±28	±28



recommendation from e.g. LHC XS working group on how to model signal to estimate its uncertainty appreciated

Doubly Charged Higgs $H^{++} \rightarrow l^+ l^+$





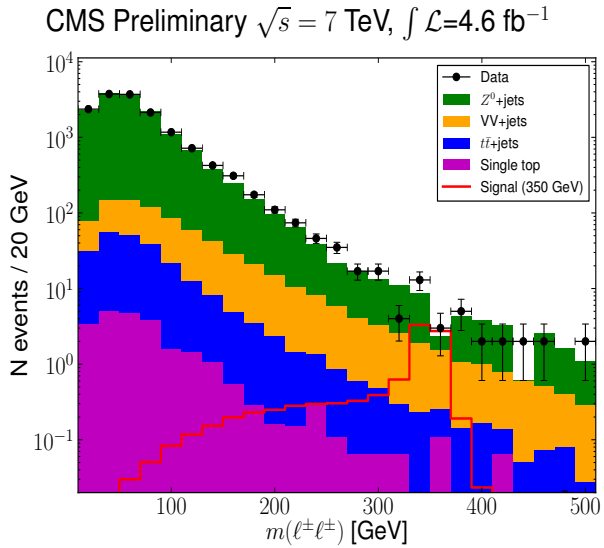
ATLAS: only pair production and $H^{++} \rightarrow \mu^+\mu^+$ with 1.6 fb^{-1}
(right handed only couple to $\gamma \rightarrow \sigma$ smaller by factor 2.5)
assumption: $c\tau$<10 mm and $\Gamma_{H^{++}}/M_{H^{++}}$<1% (exp. resolution ~3%)

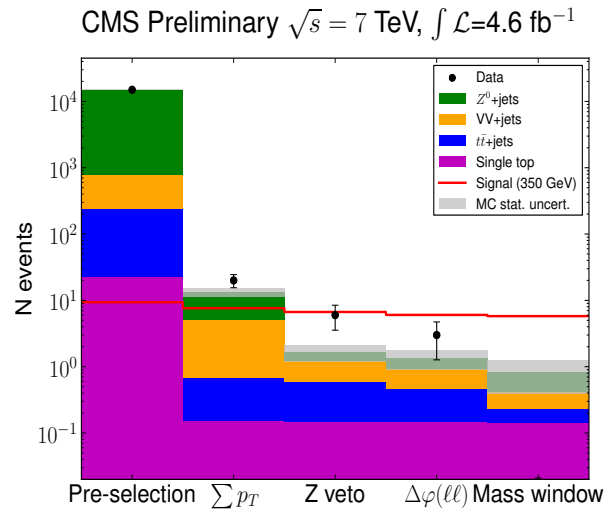
CMS: associated and pair production and $H^{++} \rightarrow l^+ l^-$ (at most 1 τ_{had}) with 4.6 fb^{-1}
model independent and benchmark points of see-saw type II models

Benchmark point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
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

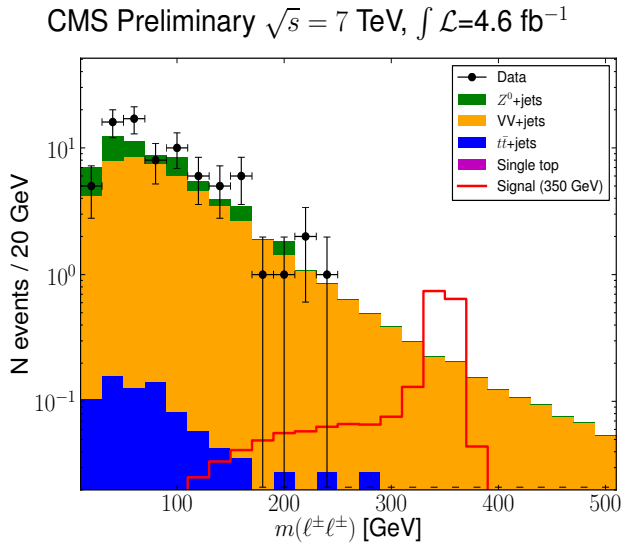
CMS: $H^{++} \rightarrow l^+l^+$ (CMS PAS HIG-12-005)

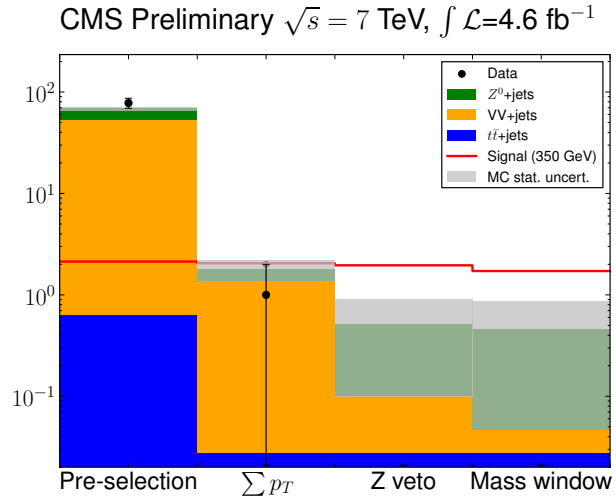
3 lepton final state





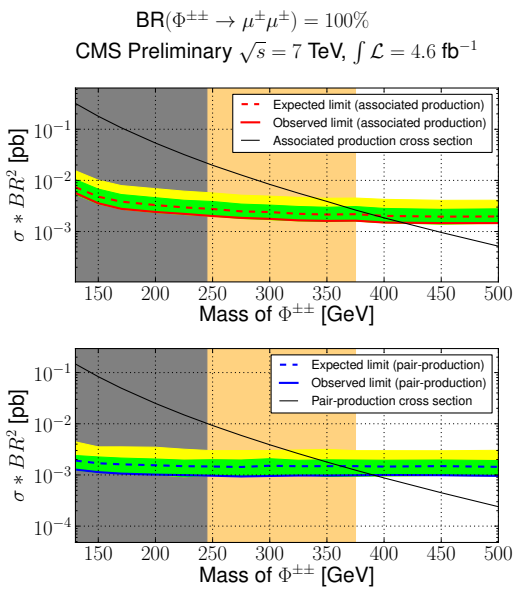
4 lepton final state

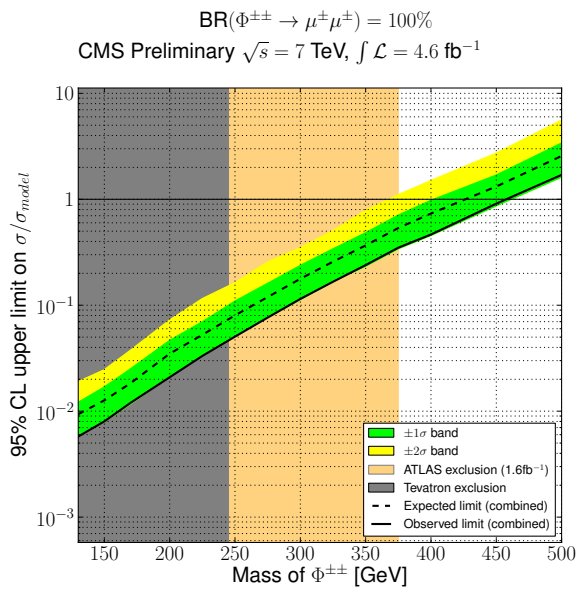




no excess observed

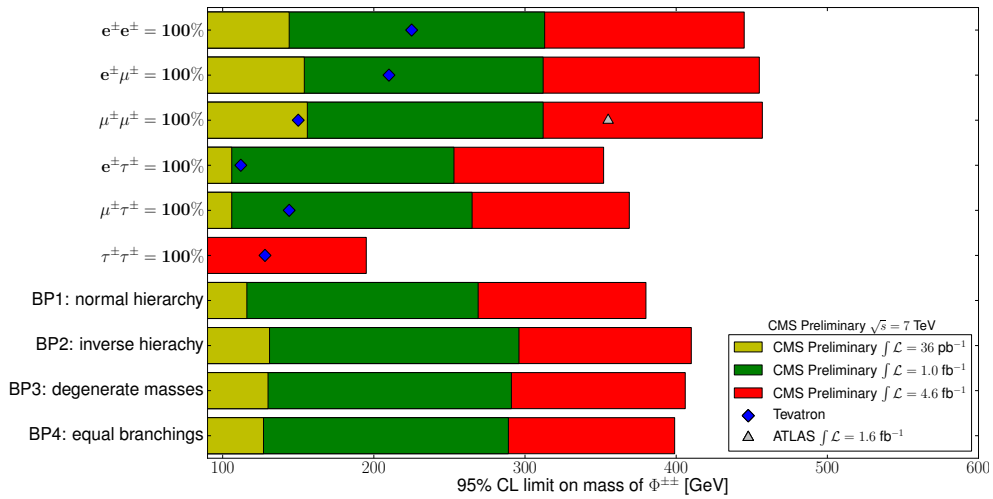
CMS: $H^{++} \rightarrow l^+l^+$ (CMS PAS HIG-12-005)





model independent limit in $H^{++} \rightarrow \mu^+\mu^+$ final state

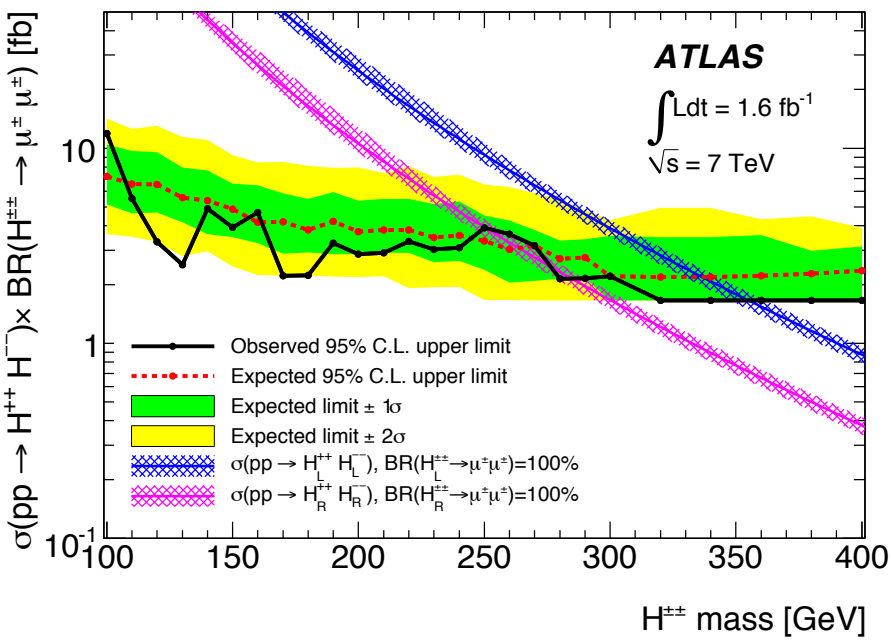
(also derived for all other final states and benchmark points)

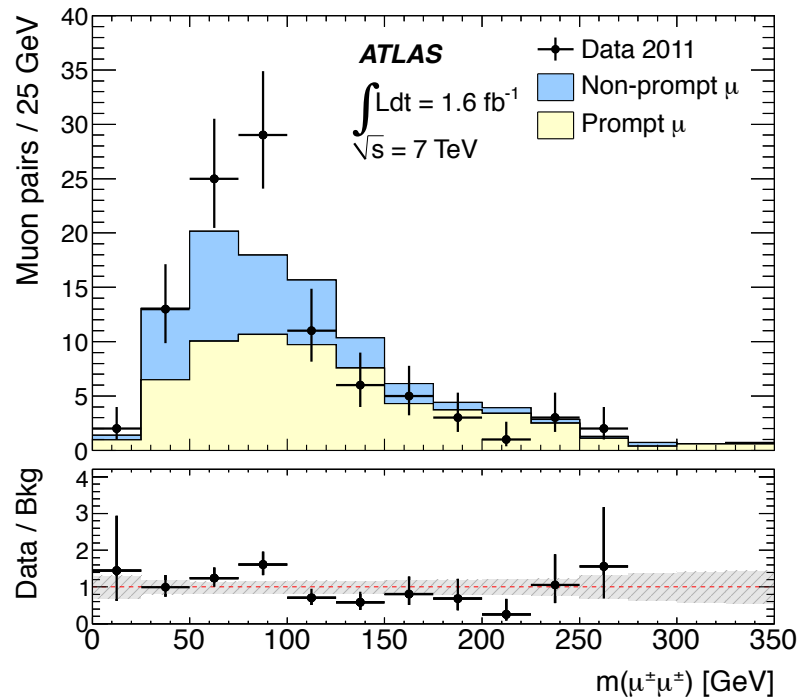


Benchmark point	CMS combined result	CMS result for pair production only
$BR(\Phi^{++} \rightarrow e^+e^+) = 100\%$	445 GeV	387 GeV
$BR(\Phi^{++} \rightarrow e^+\mu^+) = 100\%$	455 GeV	389 GeV
$BR(\Phi^{++} \rightarrow e^+\tau^+) = 100\%$	352 GeV	300 GeV
$BR(\Phi^{++} \rightarrow \mu^+\mu^+) = 100\%$	457 GeV	391 GeV
$BR(\Phi^{++} \rightarrow \mu^+\tau^+) = 100\%$	369 GeV	313 GeV
$BR(\Phi^{++} \rightarrow \tau^+\tau^+) = 100\%$	198 GeV	165 GeV
BP1	380 GeV	326 GeV
BP2	410 GeV	361 GeV
BP3	406 GeV	350 GeV
BP4	399 GeV	353 GeV

ATLAS: H++→μ+μ+ (CERN-PH-EP-2011-219)

Sample	Number of muon pairs with $m(\mu^-\mu^-)$			
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV
prompt muons	21.9 ± 3.0	11.4 ± 1.8	3.04 ± 0.67	0.91 ± 0.32
non-prompt muons	$17.4^{+4.7}_{-5.8}$	6.8 ± 2.4	0.83 ± 0.38	$0.07^{+0.08}_{-0.07}$
charge flip	$0^{+1.3}_{-0.0}$	$0^{+0.5}_{-0.0}$	$0^{+0.34}_{-0.0}$	$0^{+0.30}_{-0.00}$
total	$39.3^{+5.8}_{-6.5}$	18.2 ± 3.0	$3.87^{+0.84}_{-0.77}$	$0.98^{+0.45}_{-0.33}$
data	40	10	1	0





limit on M_{H++}:
left handed coupling
355 (244) GeV for BR=100 (33)%

right handed coupling
251 (209) GeV for BR=100(33)%

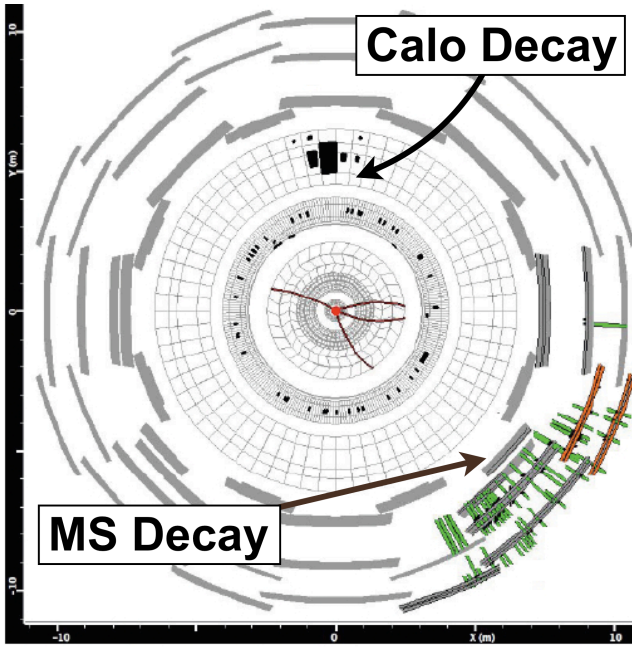
H→ longlived particles

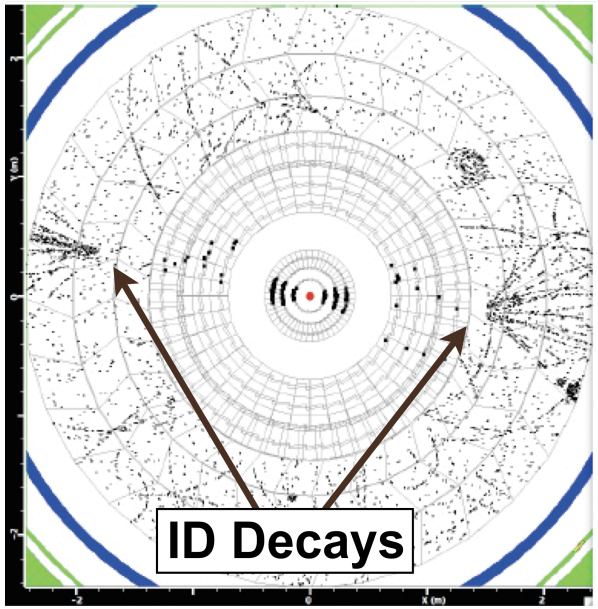
H → longlived particles in Hidden Valleys, R-Parity violating SUSY, NMSSM, ...

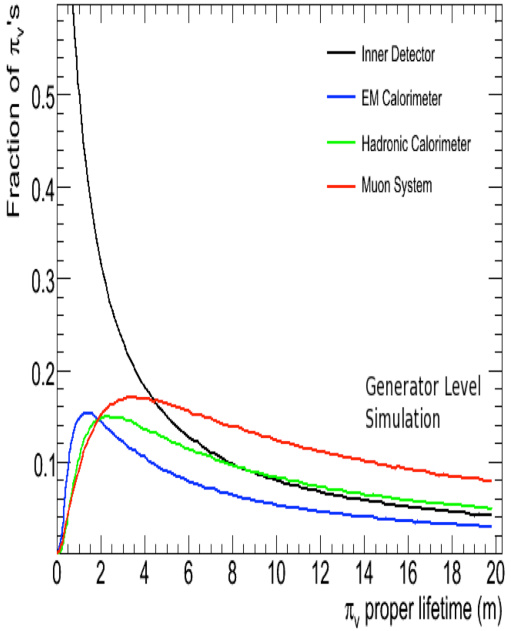
here considered: gg → H→ XX or $\pi_V\pi_V$ X/π_V (pseudo-)scalar particles

ATLAS: π_V→ bb/cc (1.9 fb^{-1})

CMS: X→ee/μμ (1.2(1) fb^{-1})







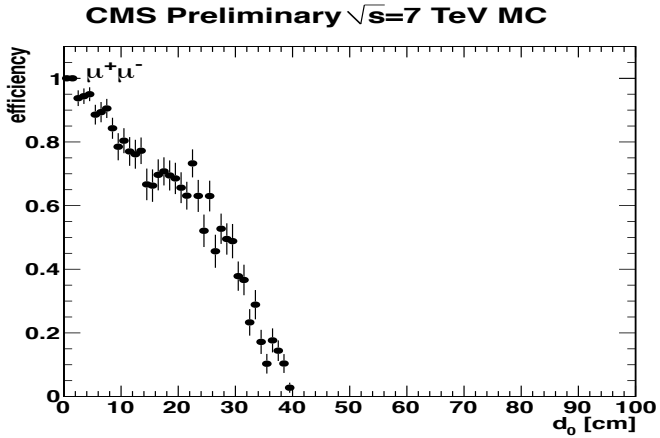
decays in muon spectrometer sensitive to cτ =1 to 35 m

decay in tracking detectors sensitive to cτ = 1mm to 10 m

CMS: H→ XX → 2 (l+l-) CMS PAS EXO-2011-004

search for two displaced vertices with two oppositely charged isolated leptons

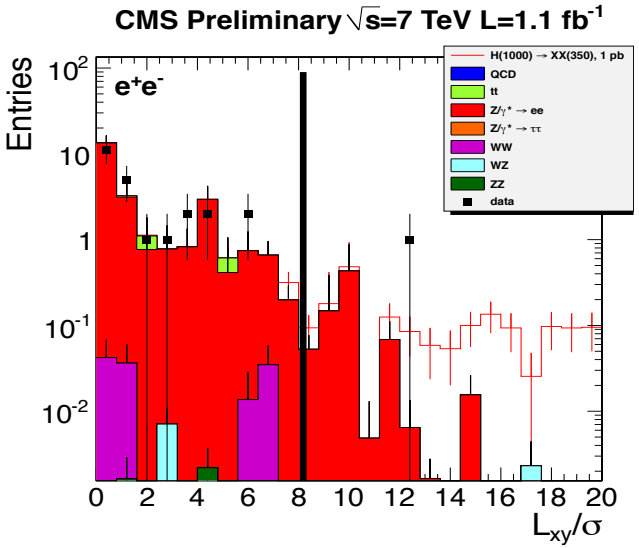
challenge: tracking for displaced tracks

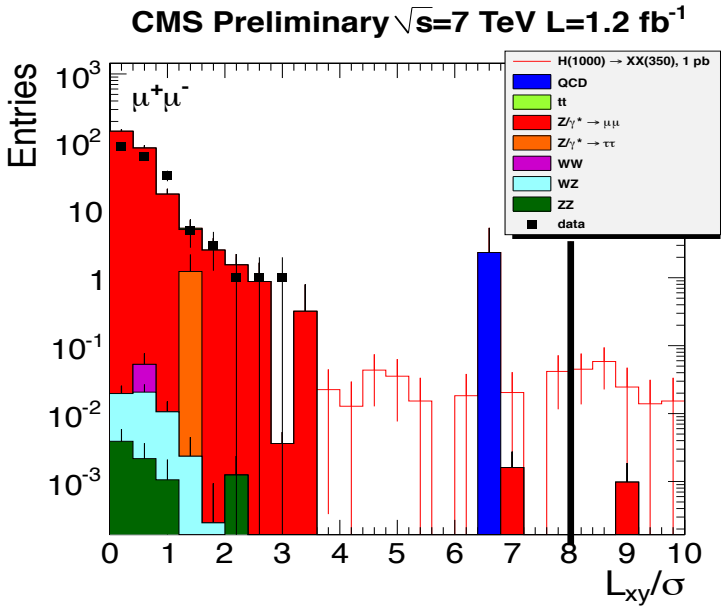


l_{trans} ~ 20 cm

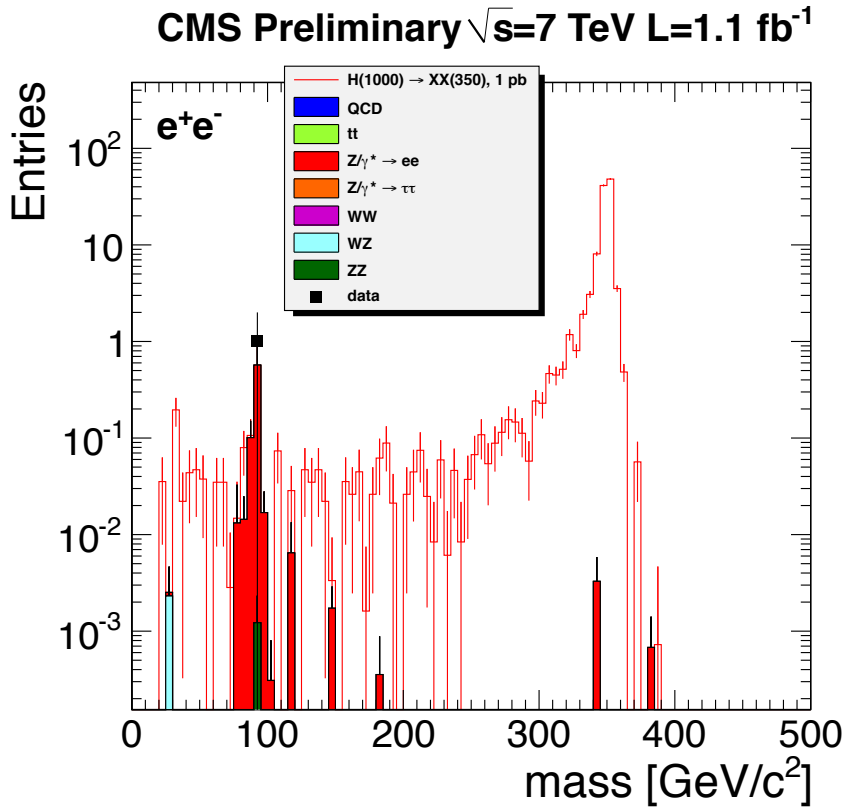
M_{H^0} (GeV/c^2)	M_X (GeV/c^2)	$c\tau$ (cm)
1000	350	35.0
1000	150	10.0
1000	50	4.0
1000	20	1.5
400	150	40.0
400	50	8.0
400	20	4.0
200	50	20.0
200	20	7.0

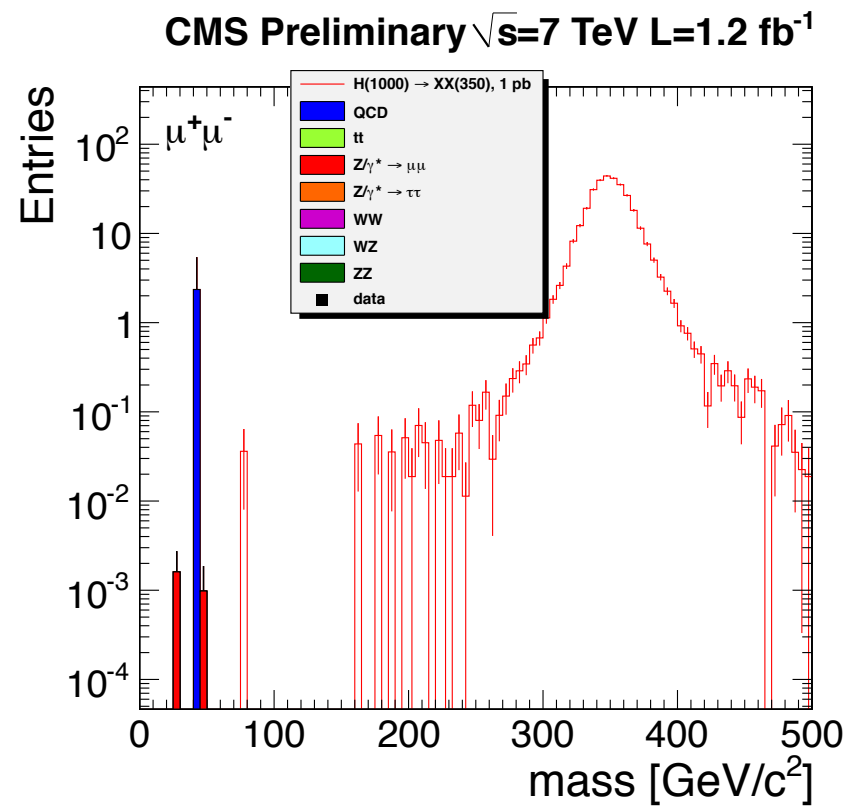
final selection:
transverse
decay length
significance>8





CMS: H→ XX → 2 (l+l-) CMS PAS EXO-2011-004

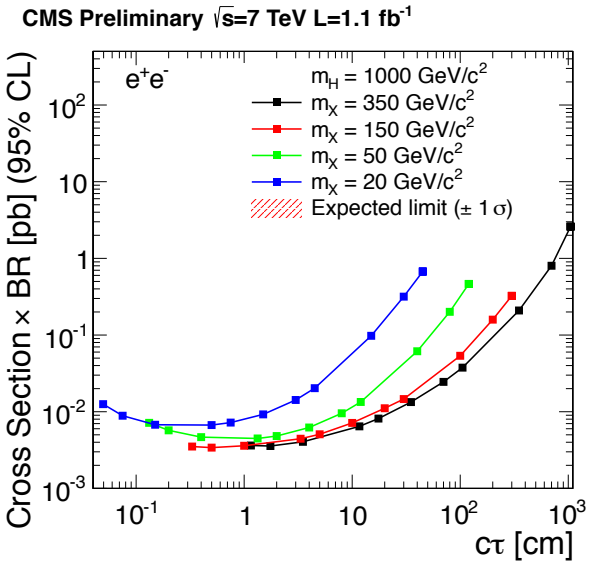


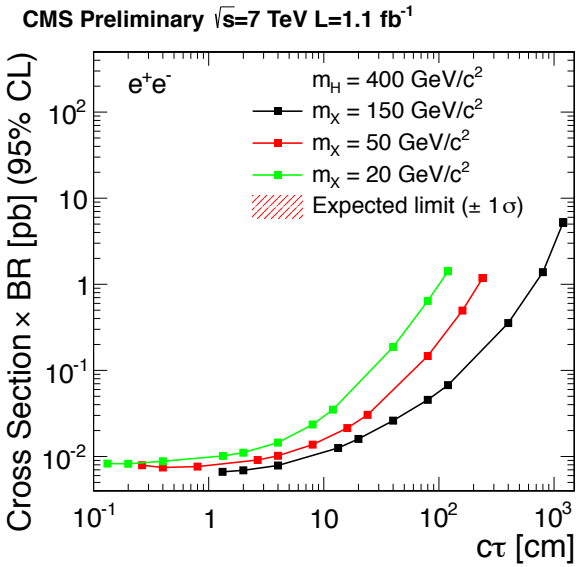


ee exp background 0.79±0.99
observed: 1 at M_Z

μμ expected background 0.02±2.38
observed: 0

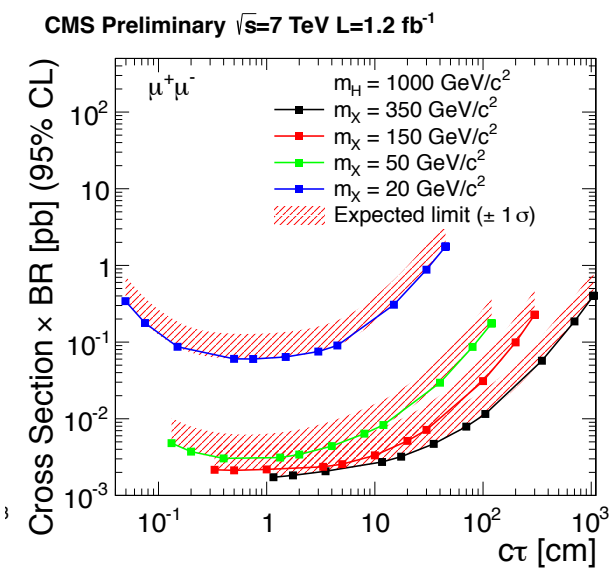
CMS: H→ XX → 2 (l+l-) Results

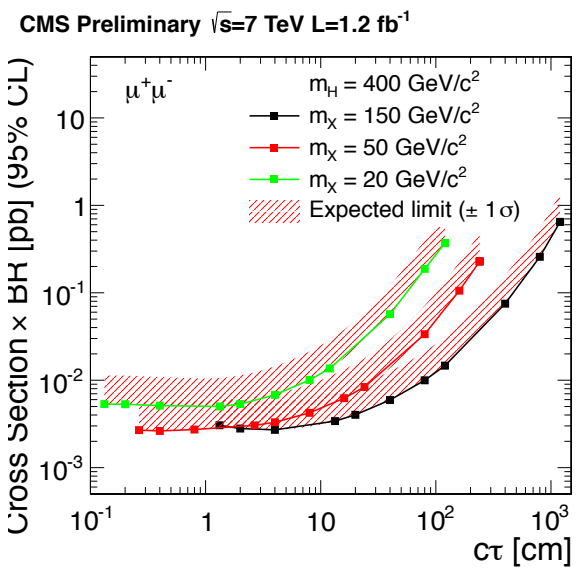


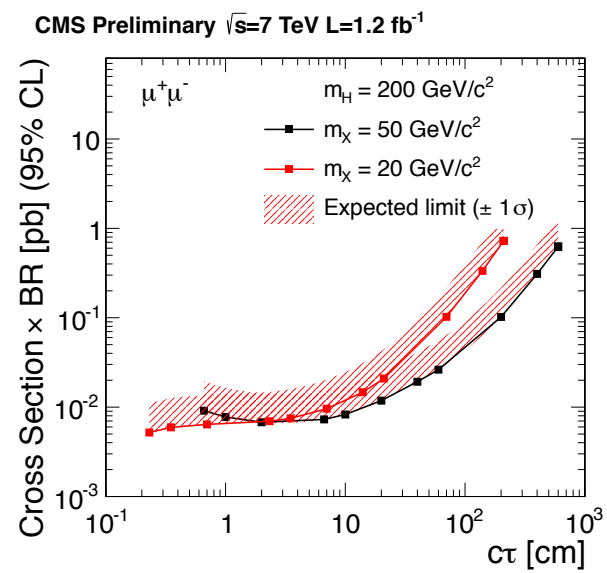


limits on
σ_{prod} x BR(H→XX)
with X→ll

eff. in the range of 10 to 30% depending on masses and final state

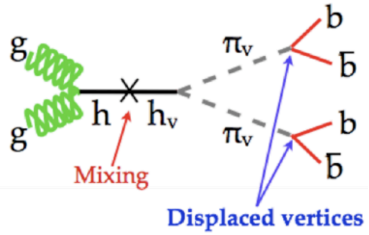


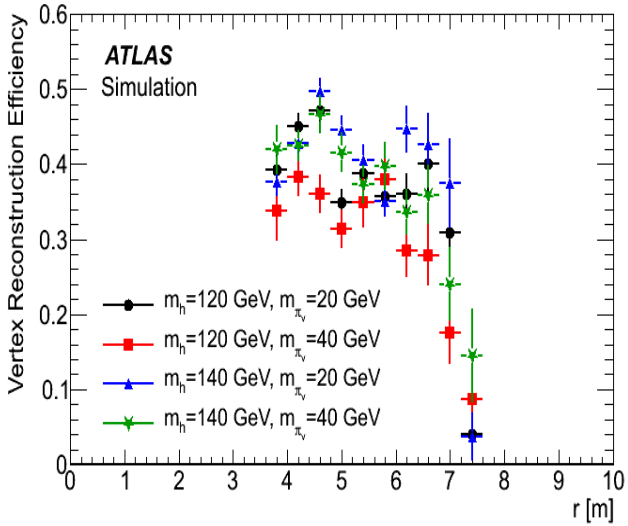


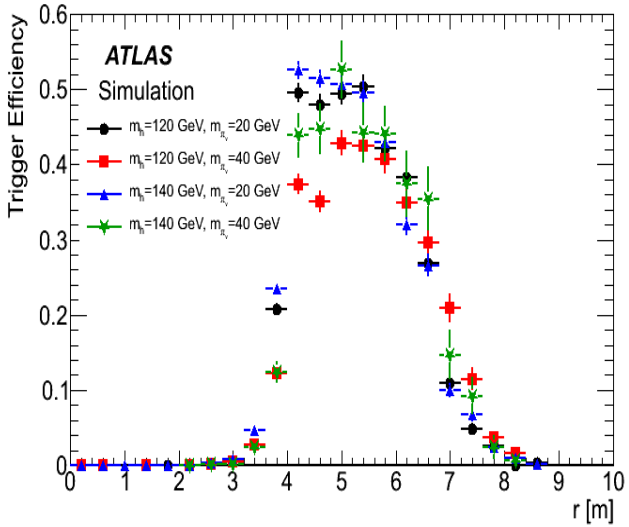


ATLAS: H→ XX → 2 (qq)

search for: two isolated back-to-back decays in muon spectrometer





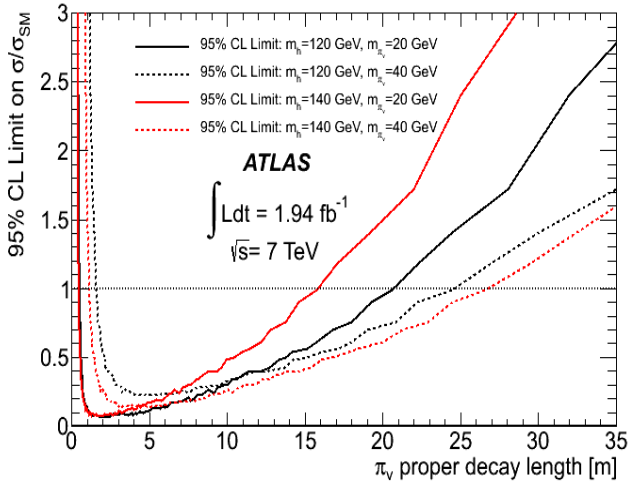


needs dedicated algos for trigger, tracking and vertexing

exp background: 0.02±0.03 0 observed

limits assuming BR(H→$\pi_v\pi_v$)=100%

m_{h^0} (GeV)	m_{π_v} (GeV)	Excluded Region
120	20	$0.50 < c\tau < 20.65$ m
120	40	$1.60 < c\tau < 24.65$ m
140	20	$0.45 < c\tau < 15.8$ m
140	40	$1.10 < c\tau < 26.75$ m



Conlusions and personal remarks

No remarkable excesses observed in specific BSM searches

Several extensions of SM and signatures considered

More to come: e.g charged Higgs bosons for $M_{H+}>M_{top}$, …

What about H→ invisible particles?

What about sensitivity for H→light quarks or gluons?

What about reinterpretation of SM searches in BSM scenarios?

What about extend mass ranges of searches in particular to low M_H (e.g. in H→$\gamma\gamma$,$\tau\tau$,bb but also H→AA→4 fermions)?

Which models to investigate?

How to present results as model independent as possible?

Limits on: 1) σxBR, 2) + A and/or 3) σ x BR xA, …?

For each combination of production and decay and also p-values.

Be careful with reinterpretation in models with different signal!

Conclusions and personal remarks

Despite the exciting observation of interesting deviation from background-only hypothesis, there might be Higgs bosons realized in other places

→ investigate carefully "all interesting" final state topologies

→ determine model parameter space (in)compatible with observations

Dr Watson: I wonder what desperate circumstances could occasion such an appeal.

Sherlock Holmes: I have devised seven separate explanations, each of which would cover the facts as far as we know them.

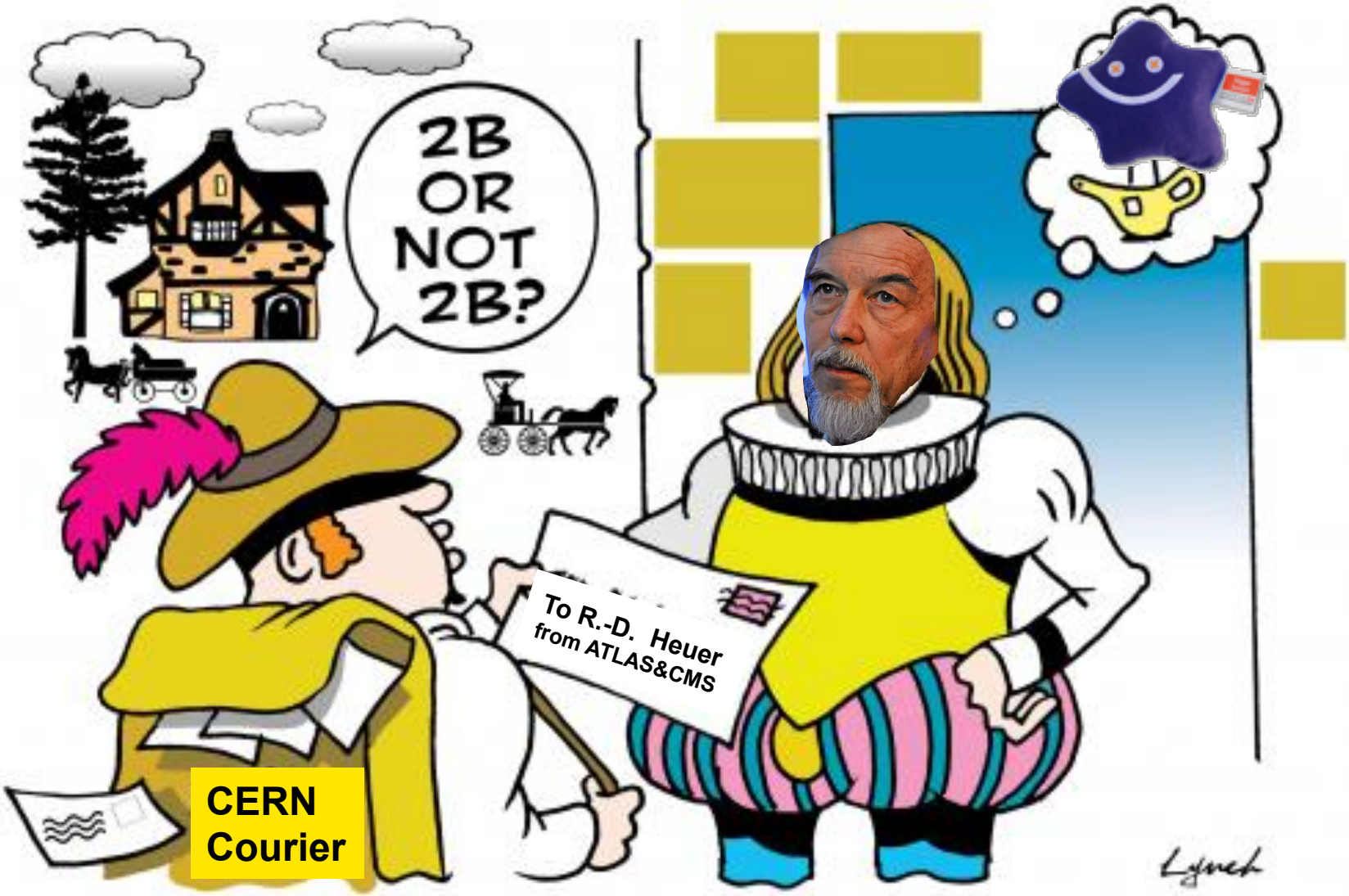
Dr Watson: Oh, and which one do you favour, Holmes?

Sherlock Holmes: At the moment, I have no favourites. Data, data, data! I cannot make bricks without clay!

Dr. Watson: We cannot theorize without data, I'm afraid. (A.C. Doyle "The Copper Beaches")

But we can prepare ourselves to do so in an optimal way
and maybe it is worth discussing whether we have done already

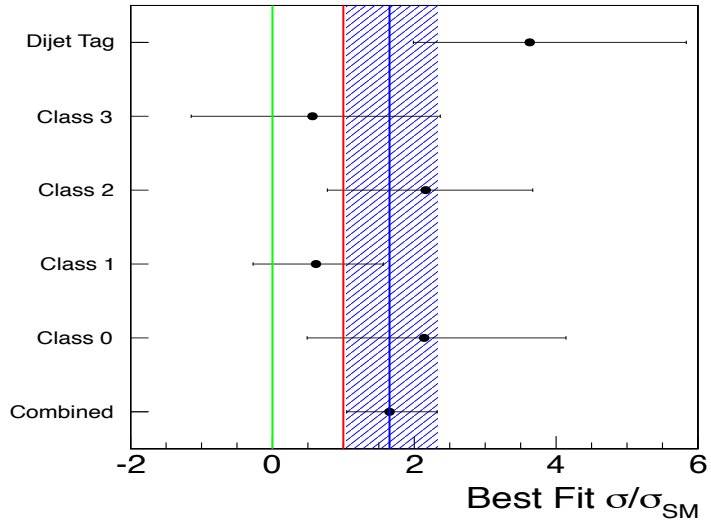
2012: the year of the Higgs boson (or not) …

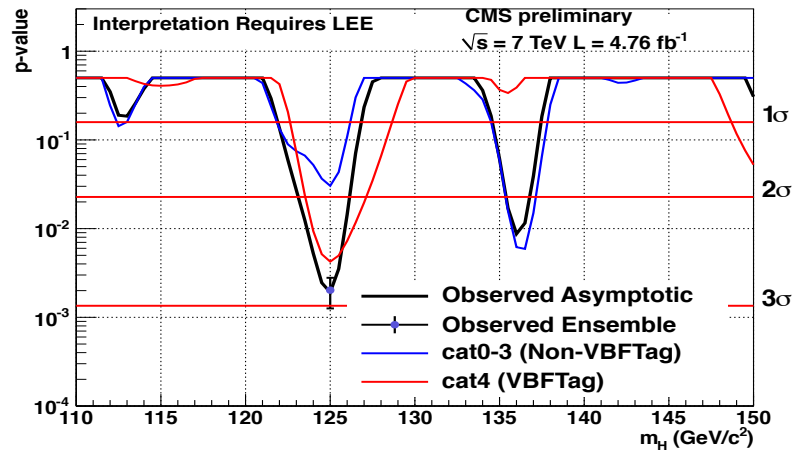


Backup

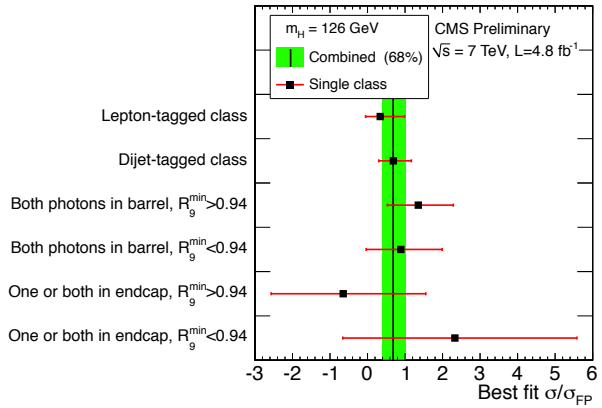
CMS: Comparions of H→ 2 γ Interpretation

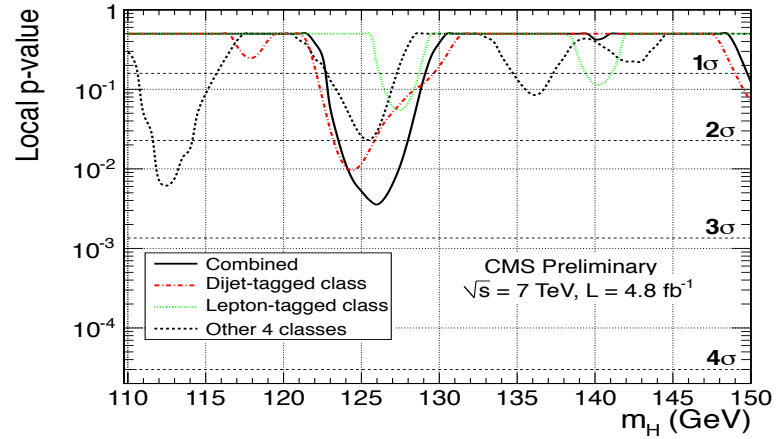
SM: best signal strength 1.65+0.67-0.60 local p-value = 2.9 σ





FP: best signal strength 0.68+0.31 local p-value = 2.7 σ

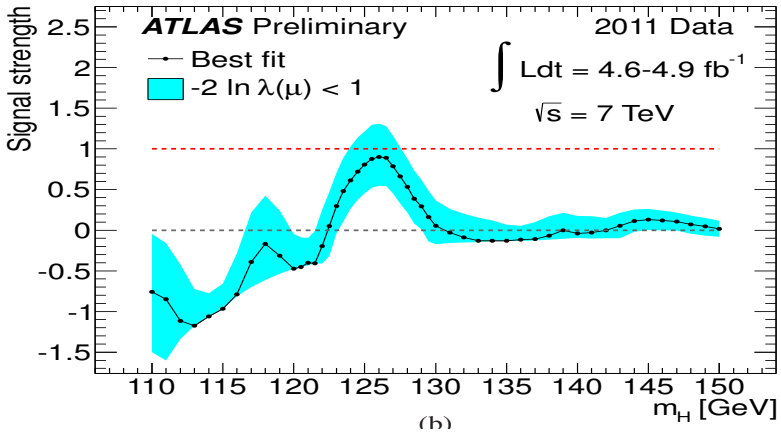




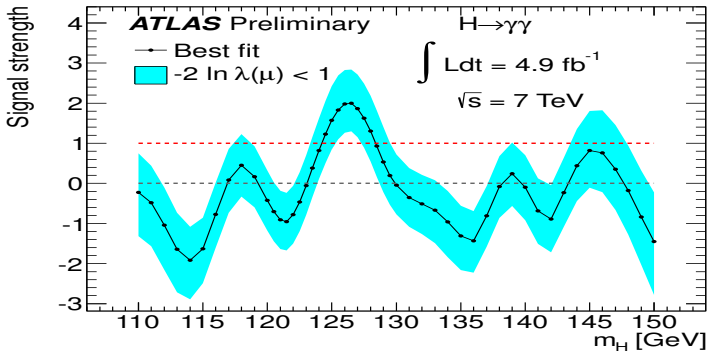
ATLAS: p-values and signal strength in SM

SM: local p-value = 2.5 σ (2.8 σ in $\gamma\gamma$)

$\beta\varepsilon\sigma\tau$ signal strength:



(b)



CMS: p-values and signal strength in SM

SM: local p-value $2.8\ \sigma$

best signal strength: