Bundesministerium
für Bildung
und Forschung

universitätbonn

LHC Higgs results

Bethe Forum:

“Beyond the standard Higgs-system”

Bonn, Nov 2016

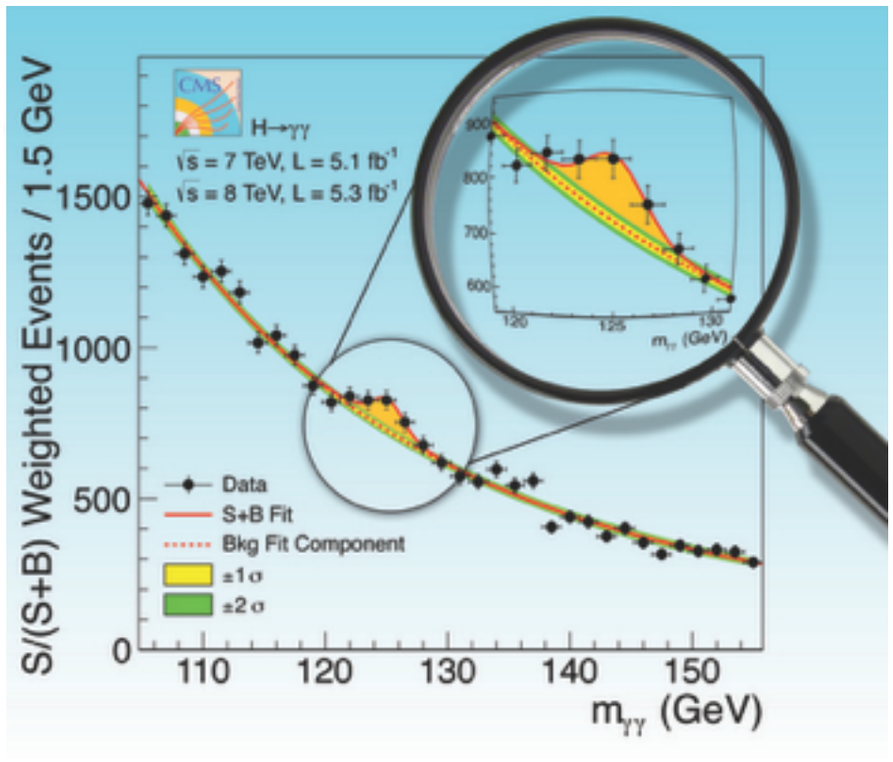
Will Davey

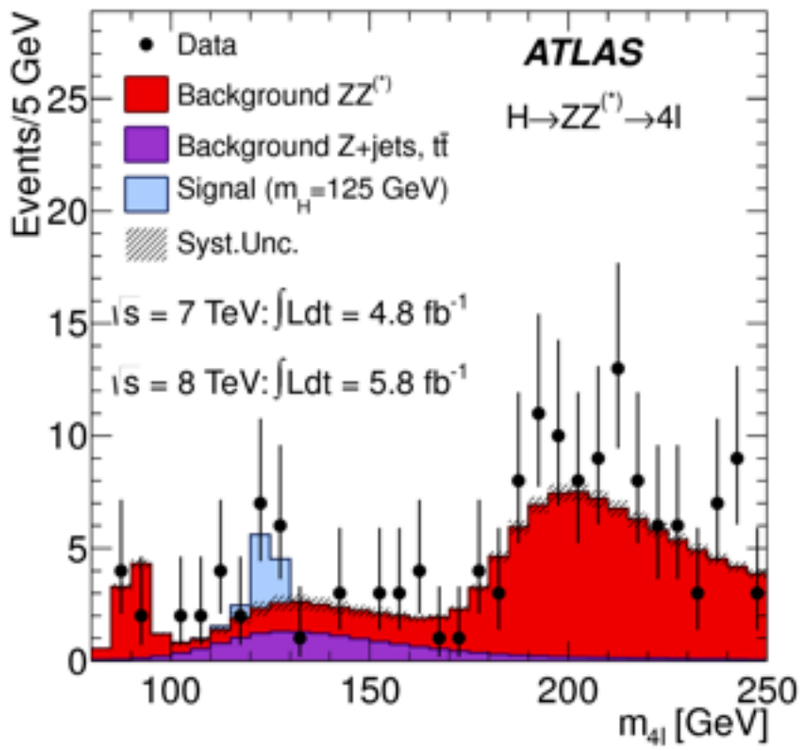
Outline

- Run 1 SM Higgs: discovery and properties
- Run 2 SM Higgs: rare decays, differential measurements, etc…
- BSM Higgs searches (Run1+Run2): MSSM, 2HDM, Di-Higgs, Exotic decays,…

Check out attached pdf with links to all results in this talk

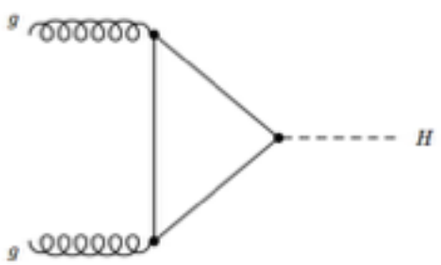
2012 discovery



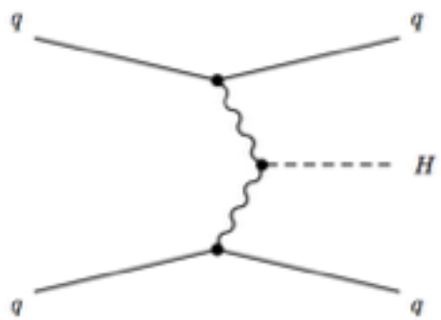


h(125) production

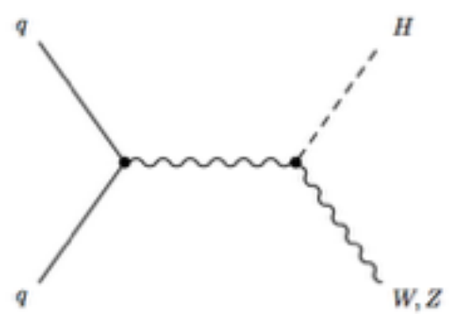
ggF



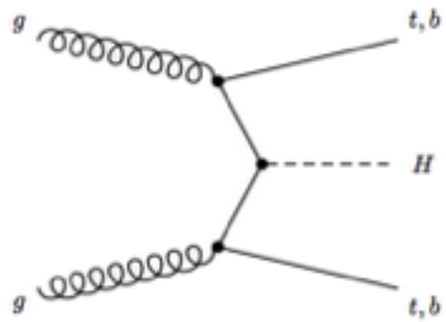
VBF

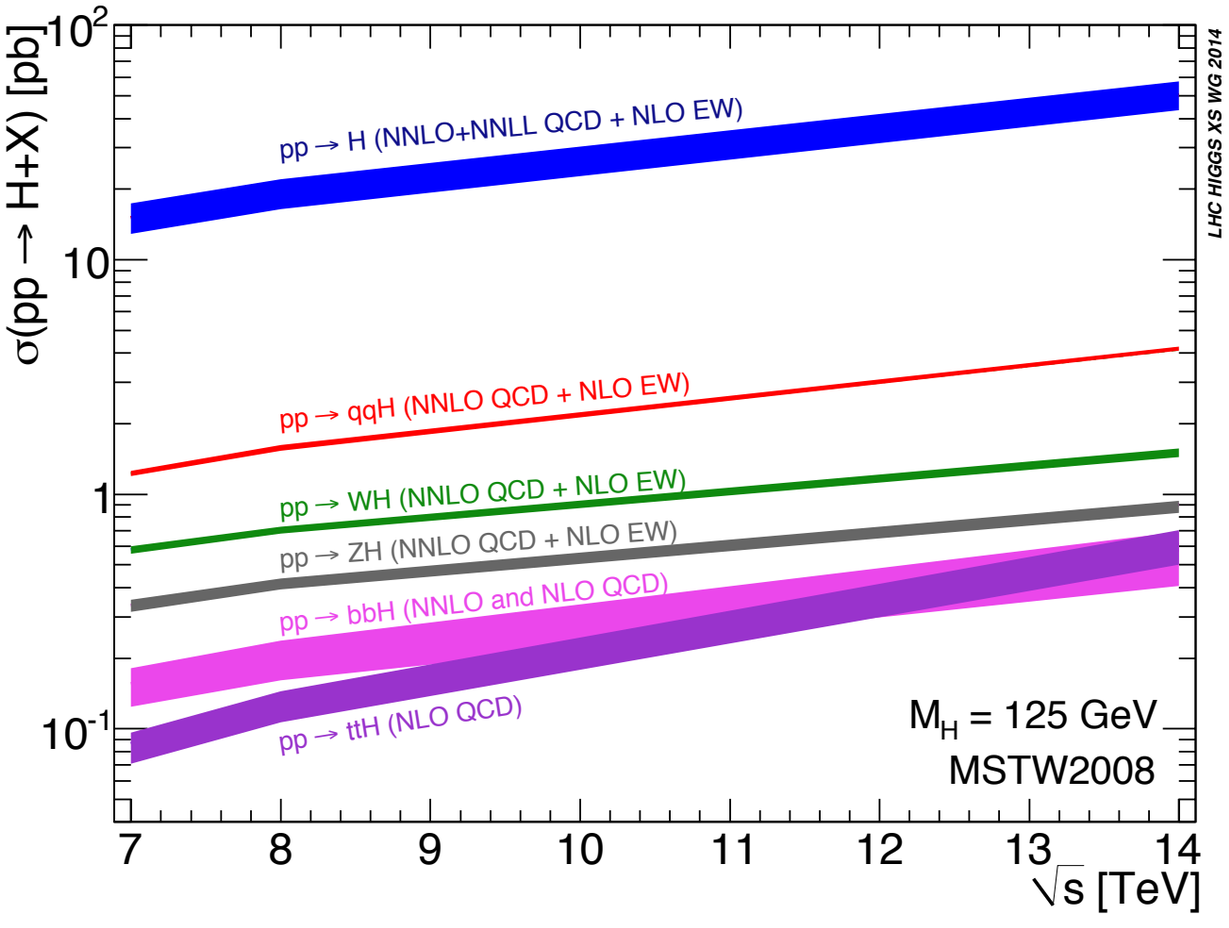


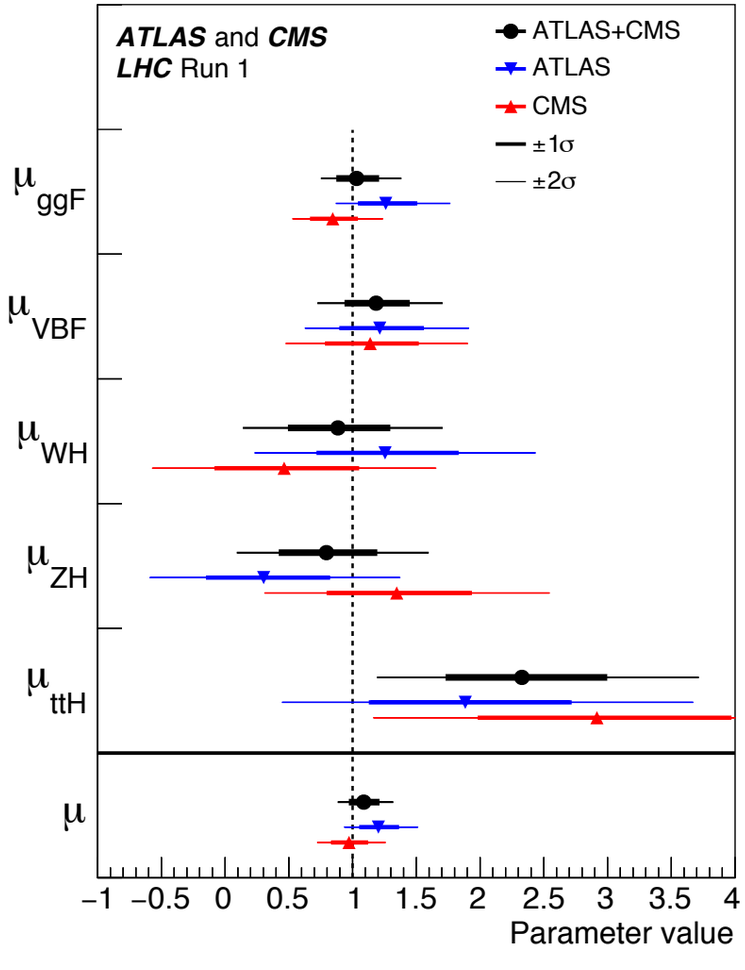
VH



ttH







>5σ

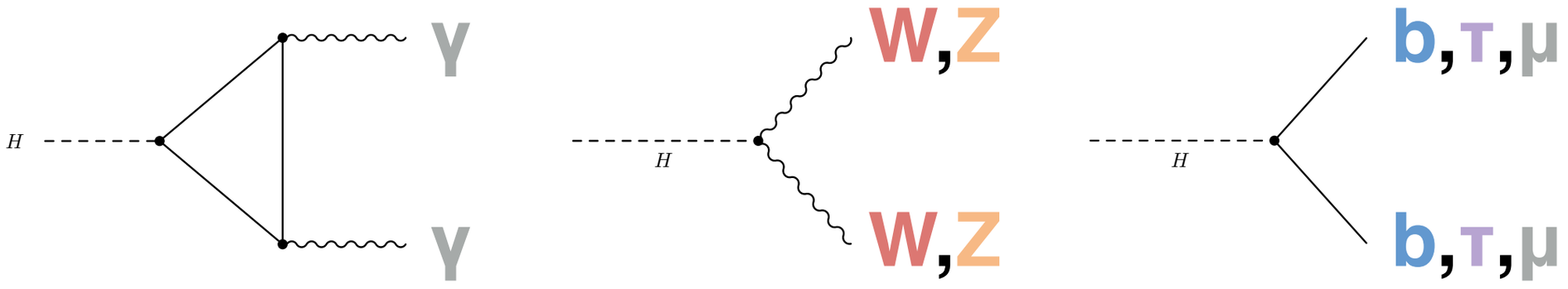
5.4σ

2.4σ

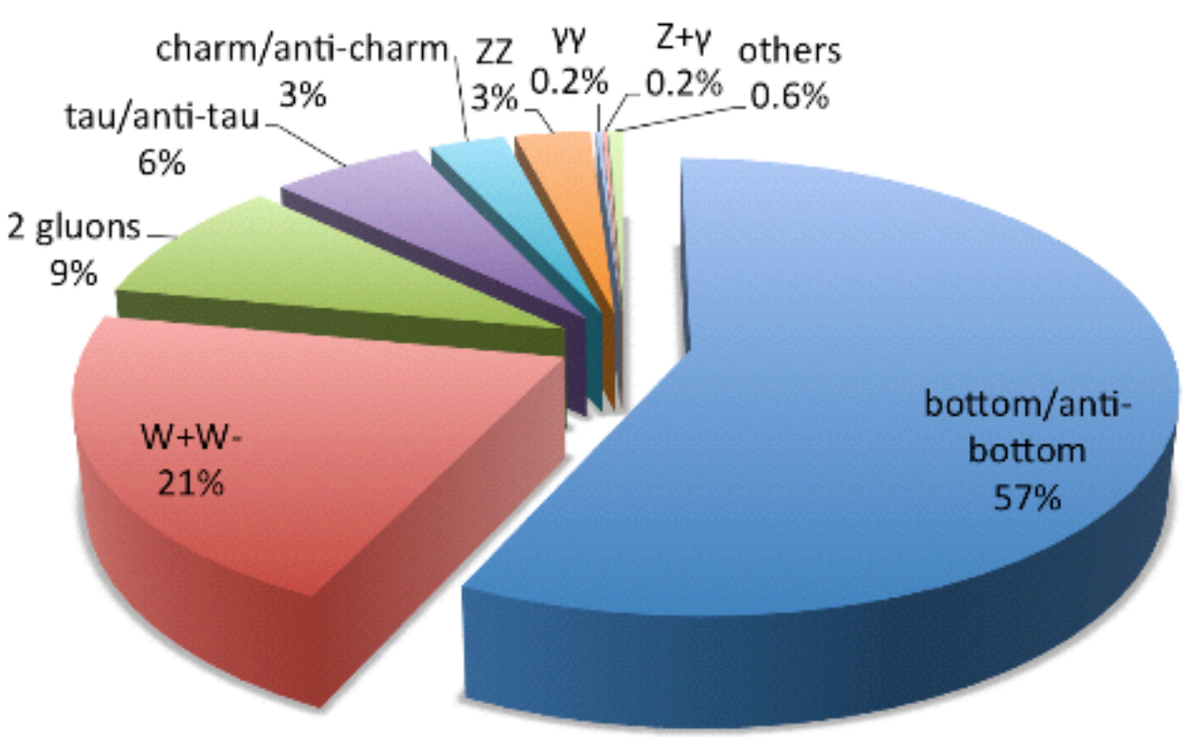
2.3σ

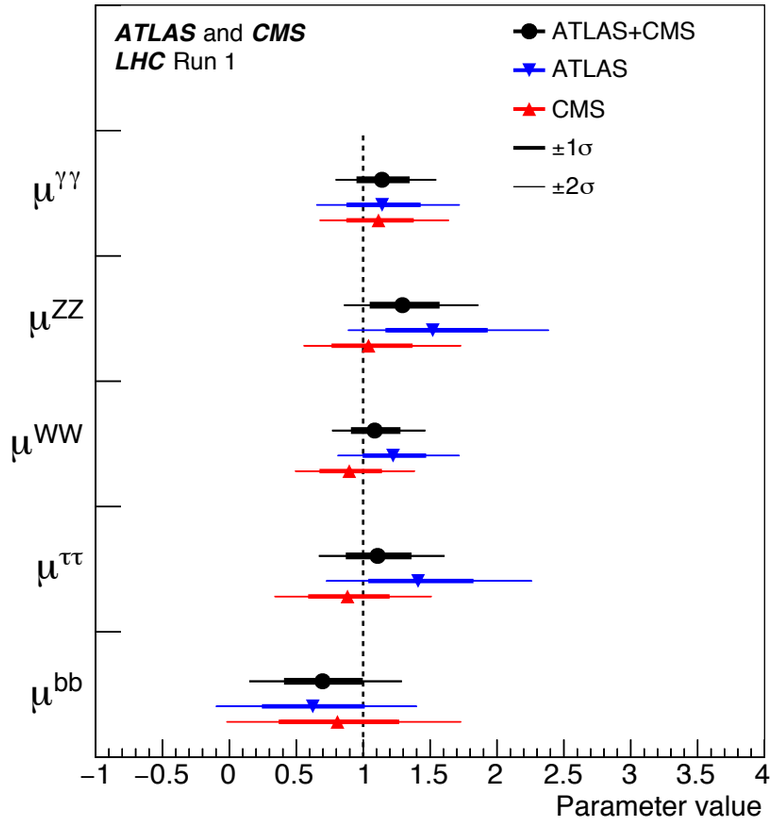
4.4(2.0)σ

h(125) decay



Decays of a 125 GeV Standard-Model Higgs boson

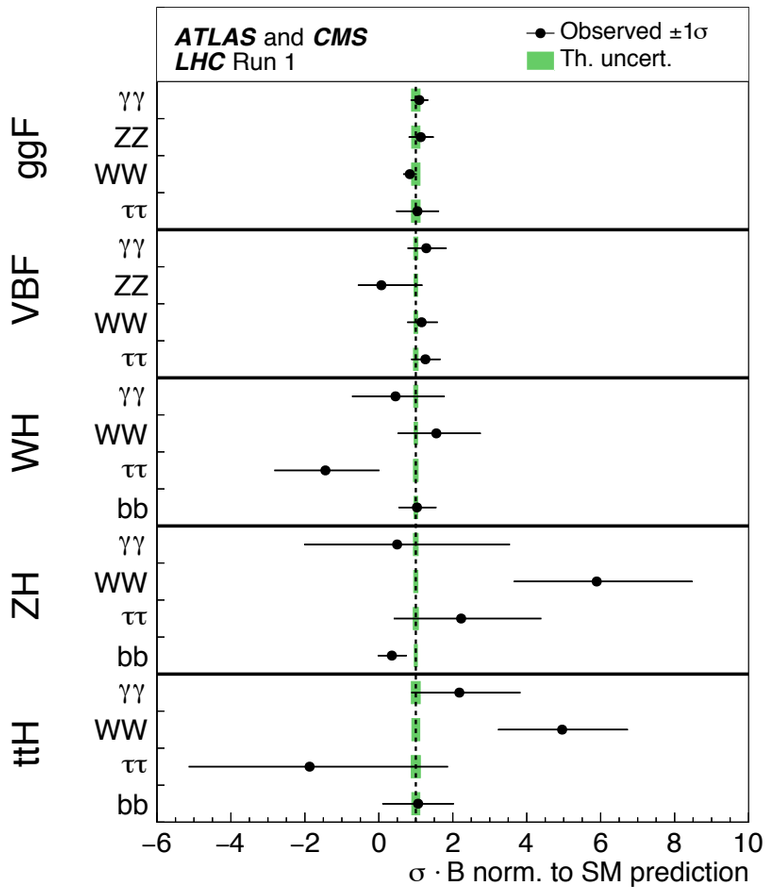


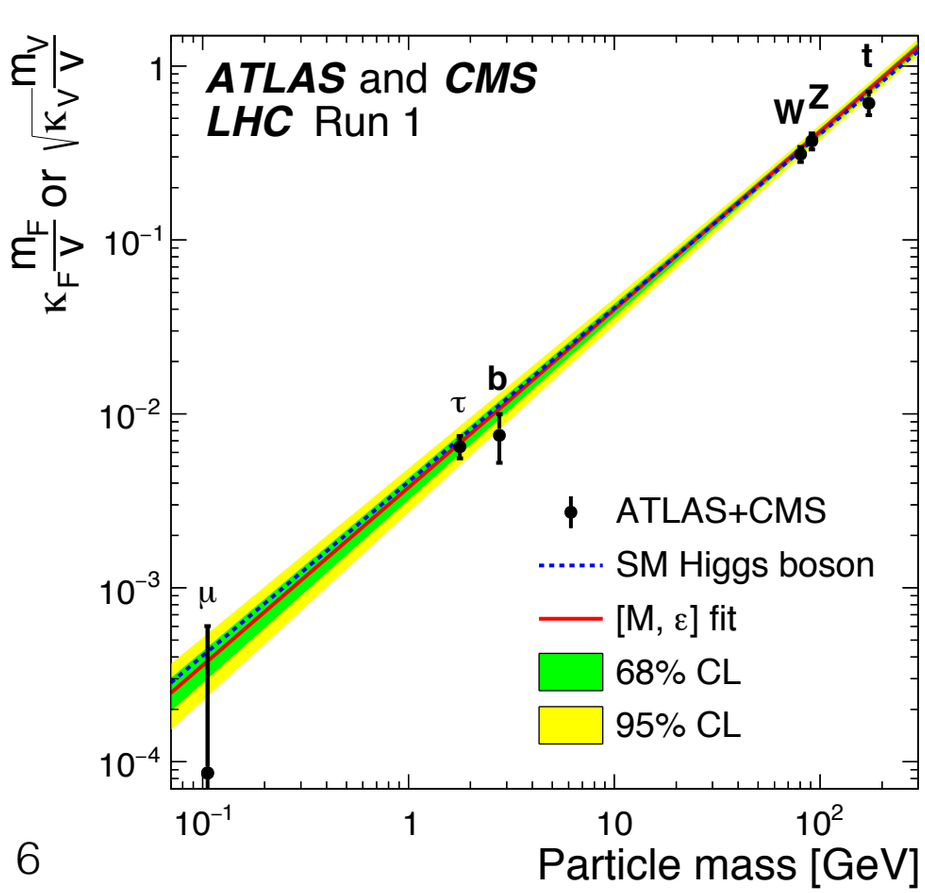


h(125) summary

- Couplings consistent with SM Higgs boson
- m_h = 125.09±0.24 GeV, JP = 0+ strongly favoured

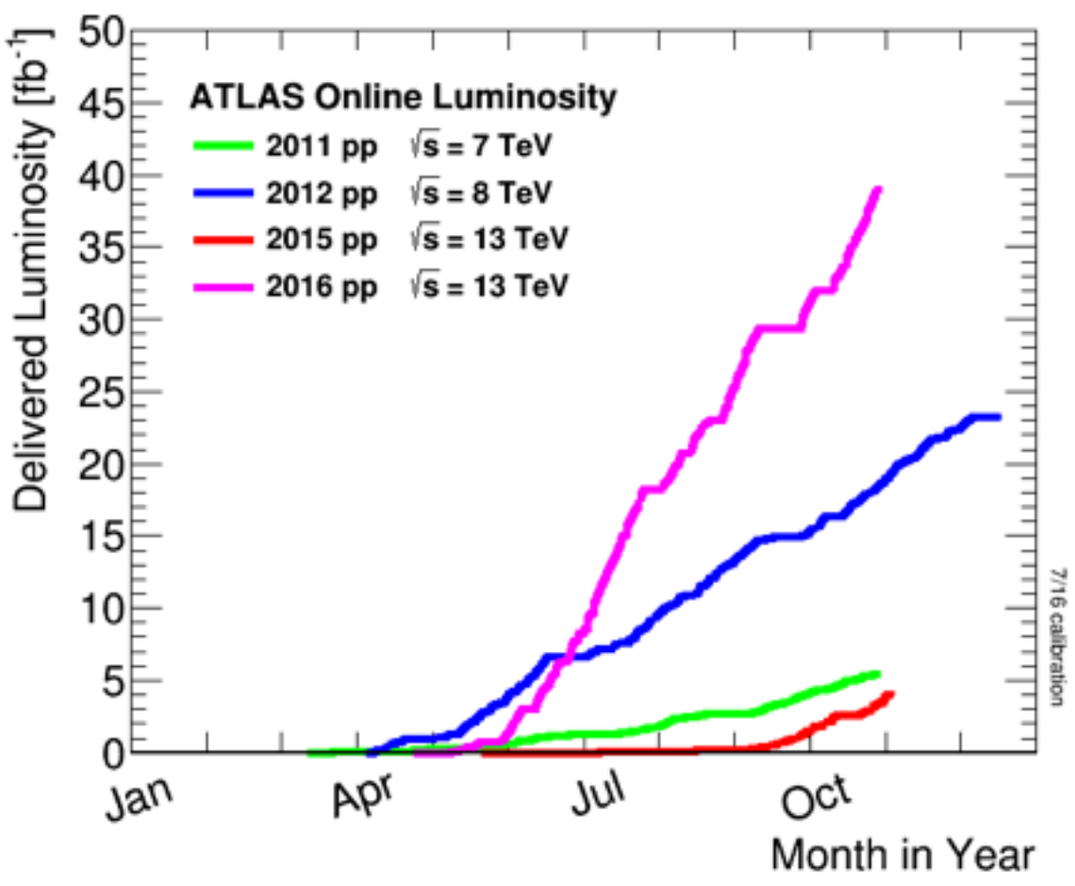
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

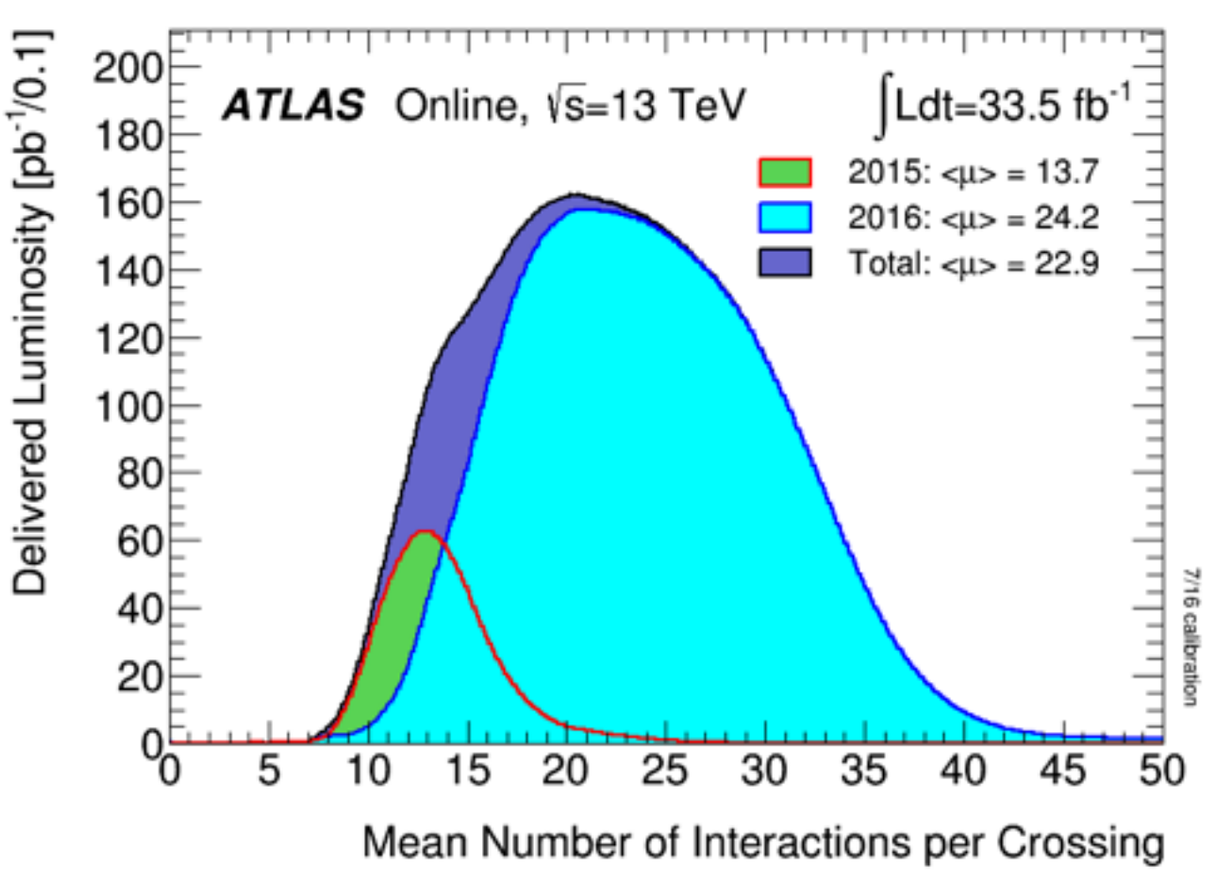




LHC Run 2

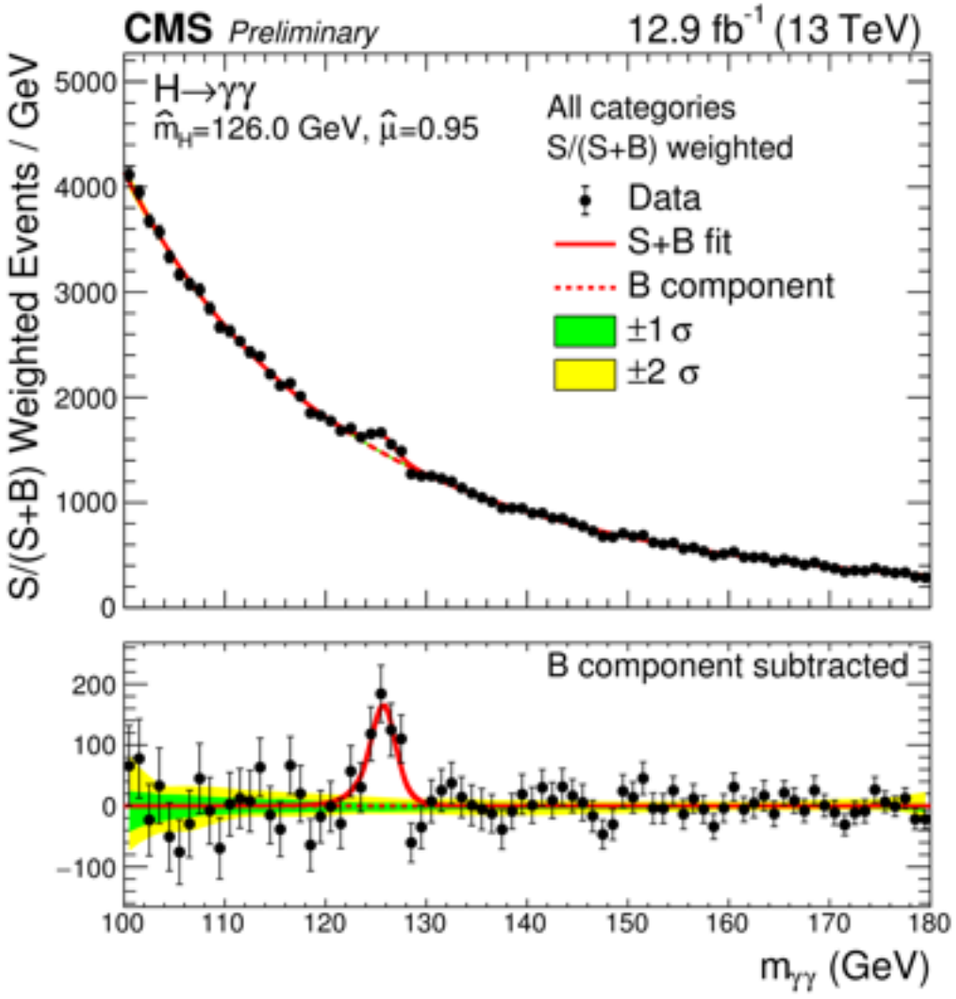

Weasel Halts LHC
LHC run meeting 2016-04-29 slides 9 to 11
Uploaded 7 hours ago
Next Post >
Electrical perturbation
• Affected all accelerators
• Most LHC magnets performed "Fast Aborts"
• Main circuits with earth fault, checked and fine
• Several current leads quenched
• Cryo down everywhere
• RF He purge (standard)

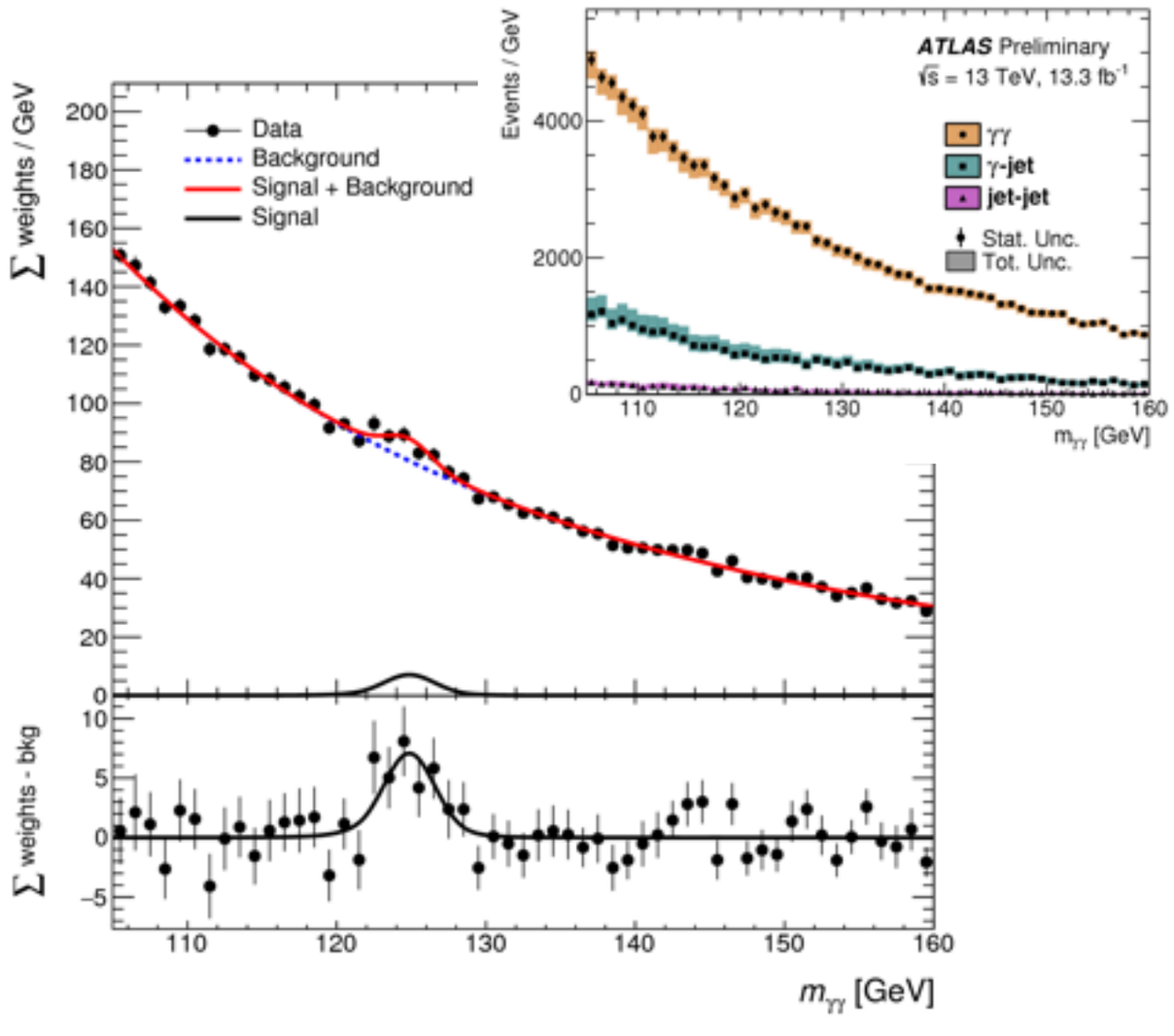

ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
Delivered Luminosity [fb-1]
Jan
Apr
Jul
Oct
Month in Year
7/16 calibration


ATLAS Online, √s=13 TeV
∫Ldt=33.5 fb-1
2015: <μ> = 13.7
2016: <μ> = 24.2
Total: <μ> = 22.9
Delivered Luminosity [pb-1/0.1]
Mean Number of Interactions per Crossing
7/16 calibration

$H \rightarrow \gamma\gamma$

- Fit sharp $m_{\gamma\gamma}$ peak over falling background ($\gamma\gamma$, γj, jj)
- Target ggF, VBF, VH (only ATLAS), ttH modes by categorising events
- Dominant systematics: photon energy, background model choice



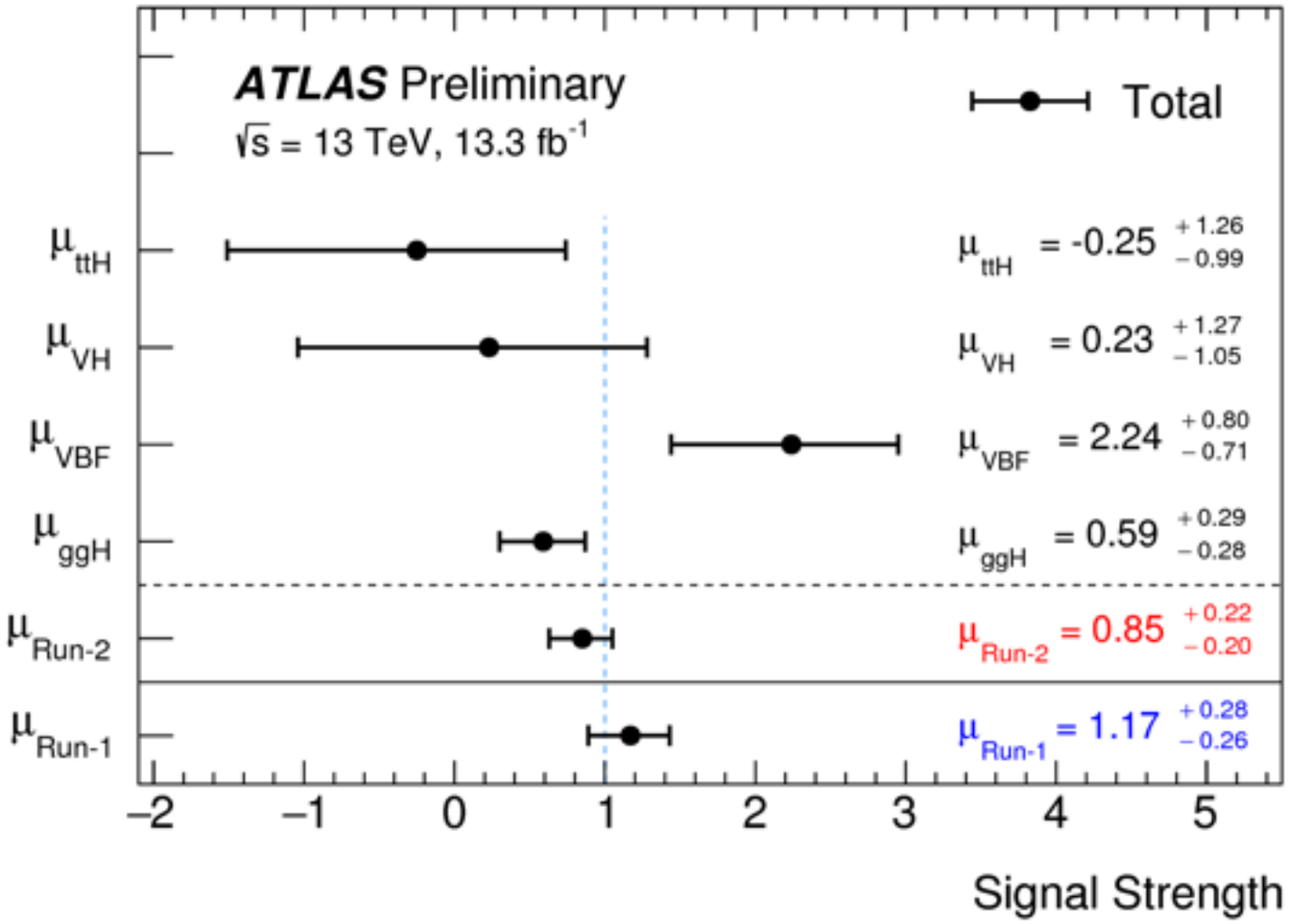


$H \to \gamma\gamma$

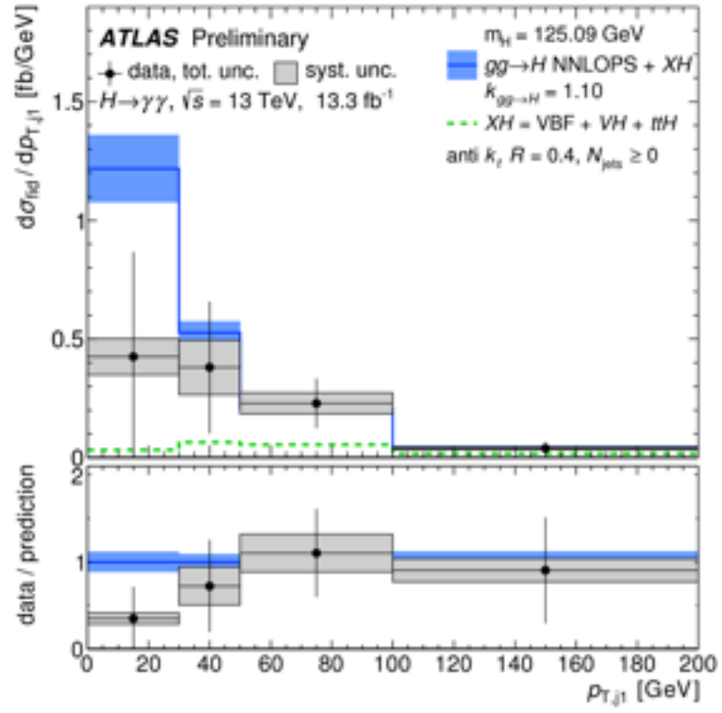
Fiducial cross sections

Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$	$62.8\,^{+3.4}_{-4.4}$	[N^{3}LO + XH]
VBF-enhanced	$4.0 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})$	2.04 ± 0.13	[NNLOPS + XH]
single lepton	$1.5 \pm 0.8\,(\text{stat.}) \pm 0.2\,(\text{syst.})$	0.56 ± 0.03	[NNLOPS + XH]

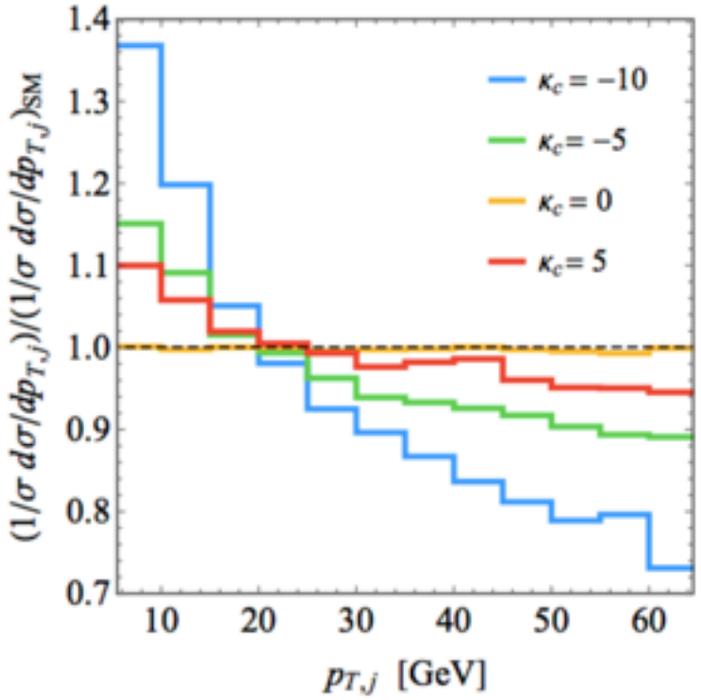
Production strengths



Differential cross sections



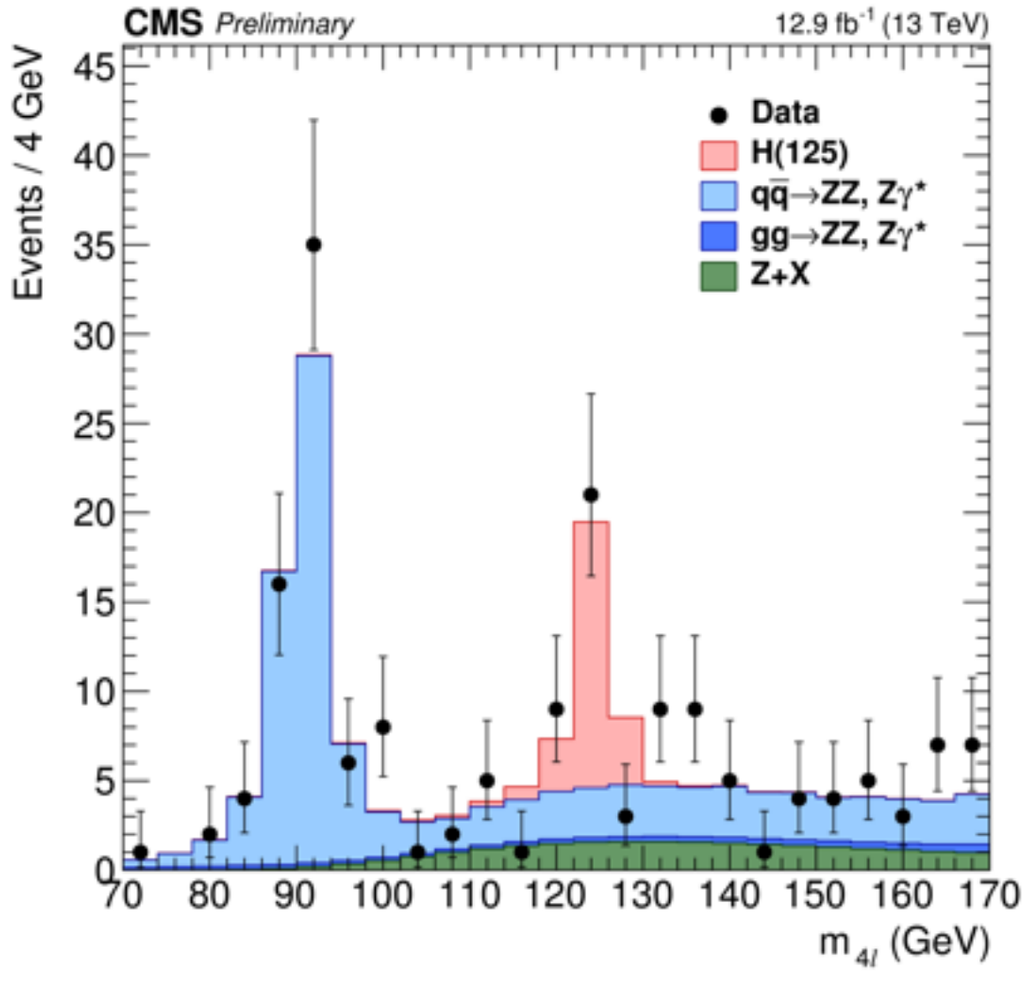
Extracting c-quark coupling?

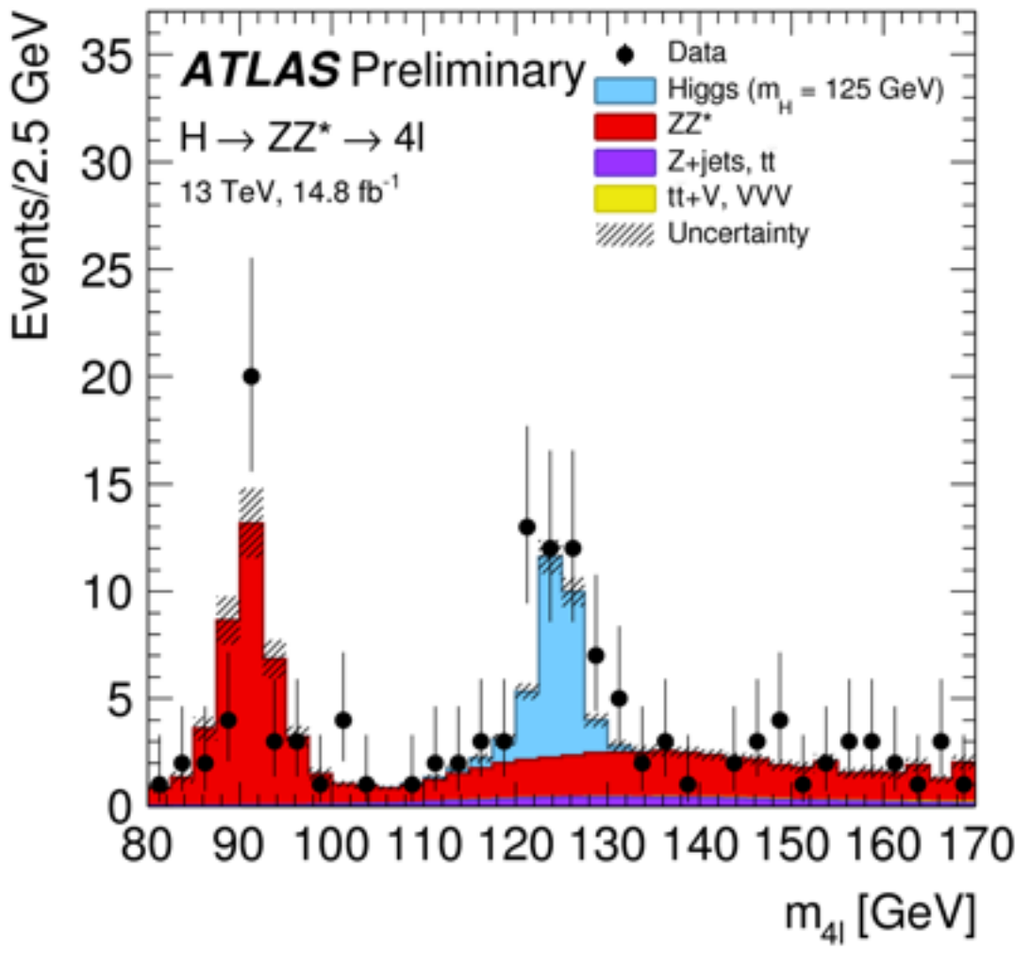


arXiv:1606.09253 [hep-ph]

$H \rightarrow ZZ \rightarrow 4l$

- Fit sharp m_{4l} peak over tiny flat background
- Target ggF, VBF, VH, ttH modes by categorising events
- Dominant systematics: luminosity, lepton efficiency



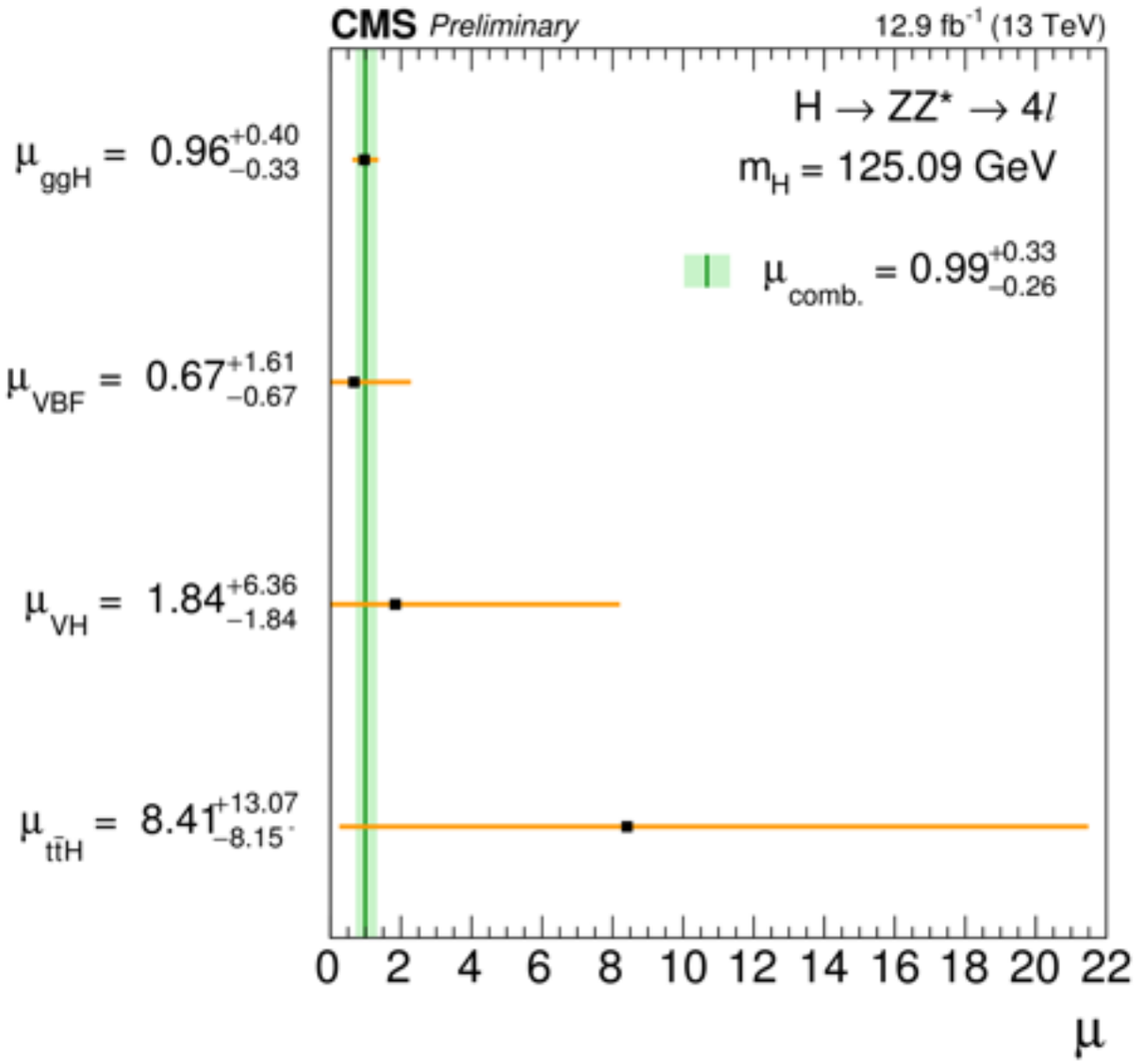


$H \rightarrow ZZ \rightarrow 4l$

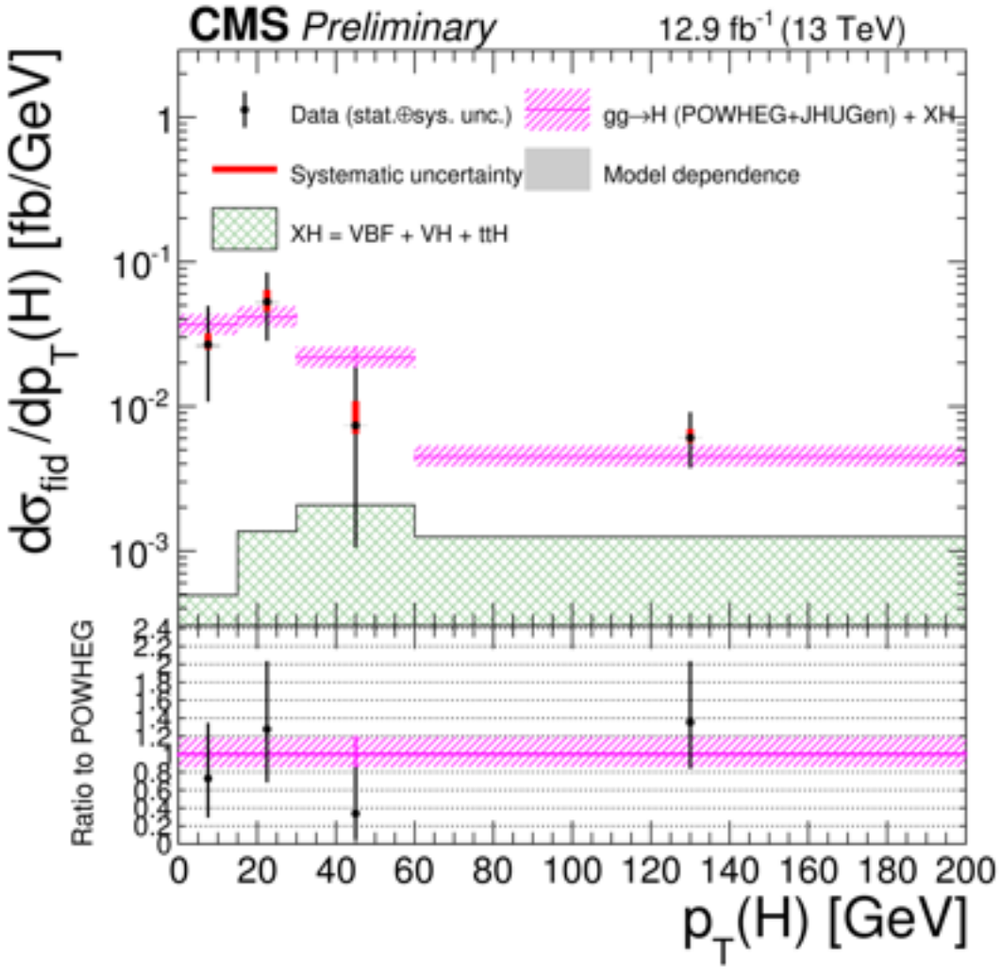
Fiducial cross section

$$\sigma_{\text{fid.}} = 2.29^{+0.74}_{-0.64}(\text{stat.})^{+0.30}_{-0.23}(\text{sys.})^{+0.01}_{-0.05}(\text{model dep.})\ \text{fb} \qquad \sigma^{\text{SM}}_{\text{fid.}} = 2.53 \pm 0.13\ \text{fb}$$

Production strengths



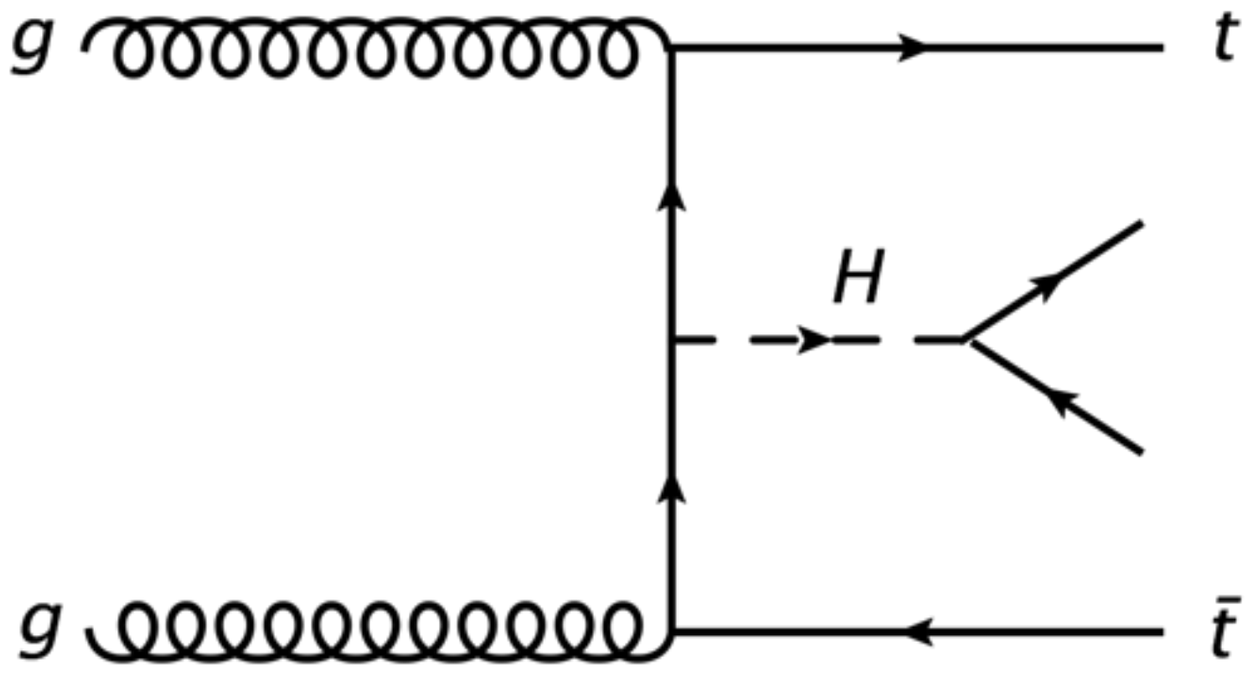
Differential cross sections



ttH

- Direct probe of top Yukawa coupling
  (probes via ggF assume no BSM coupling)

- Small signal cross section, large tt background!



Divide and conquer

Channel	BR [%]
bb	58
WW	21
ZZ	2.6
ττ	6.3
γγ	0.23

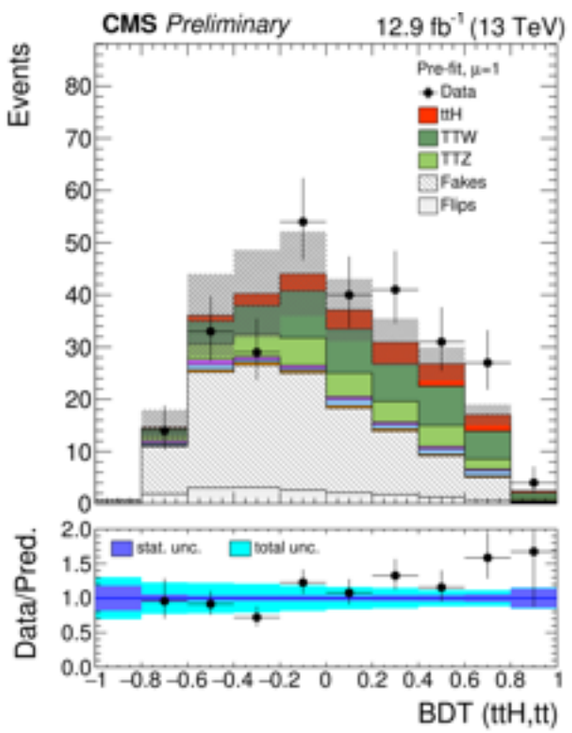
ttH multileptons

Same-sign dilepton
=2 SS leptons (e/μ)
≥4 jets (≥1 b-tag)
moderate MET
Z-mass veto (ee channel)

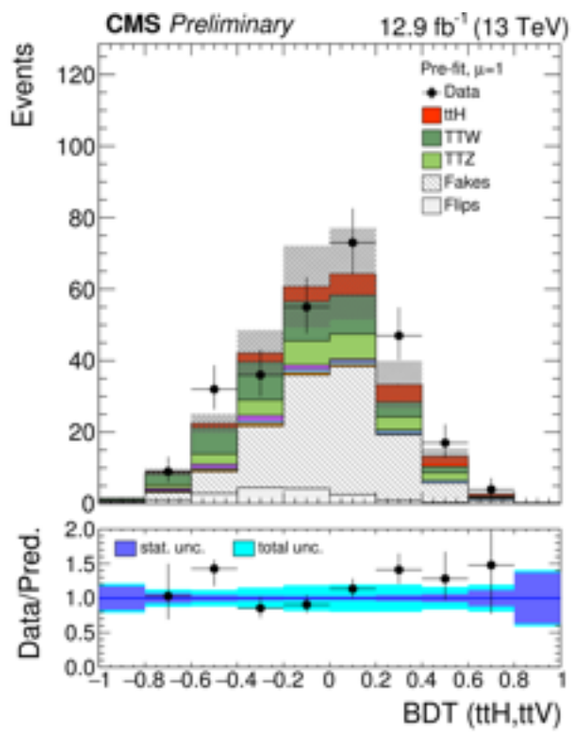
Trilepton
≥3 leptons (e/μ)
≥2 jets (≥1 b-tag)
moderate MET or ≥4 jets
Z-mass veto

Categorise: τ_h presence, b-tag quality, lepton charge sum

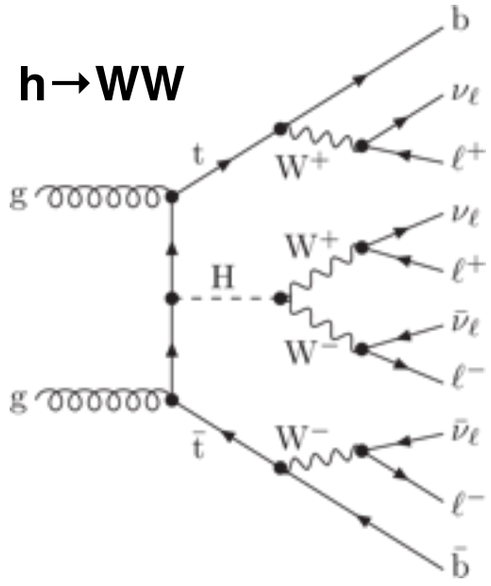
BDT1



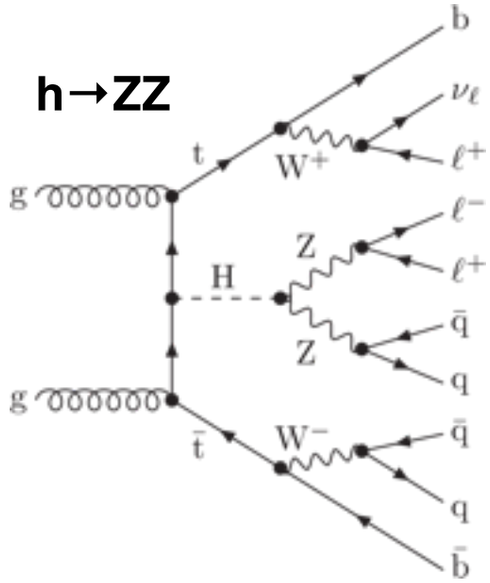
BDT2



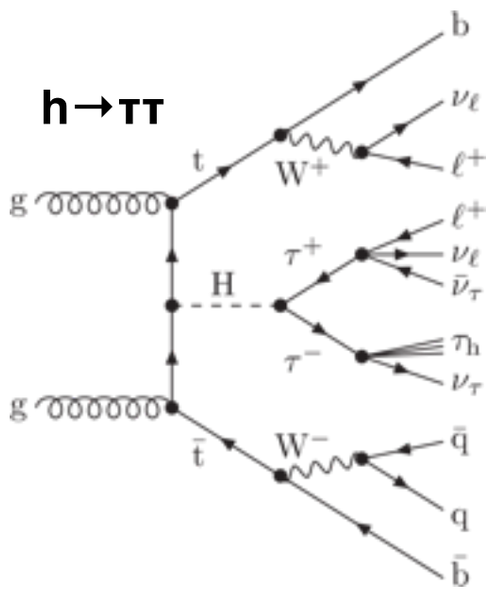
h→WW



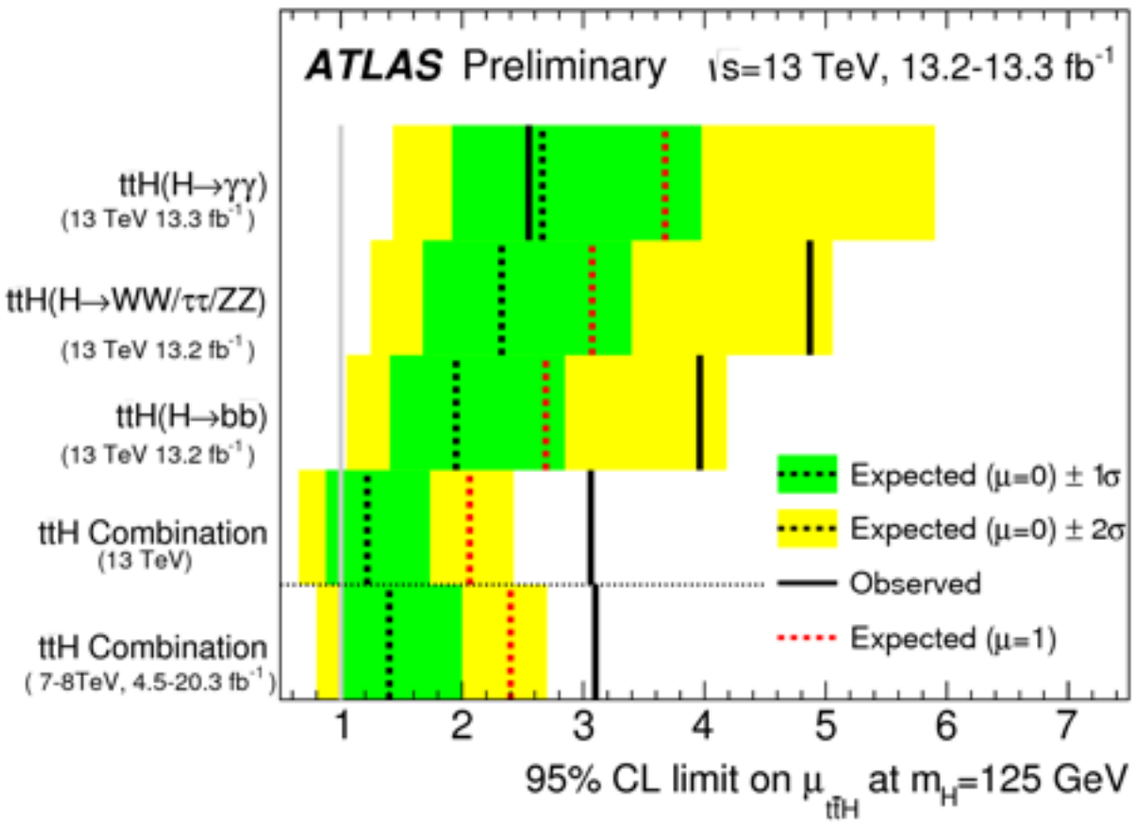
h→ZZ

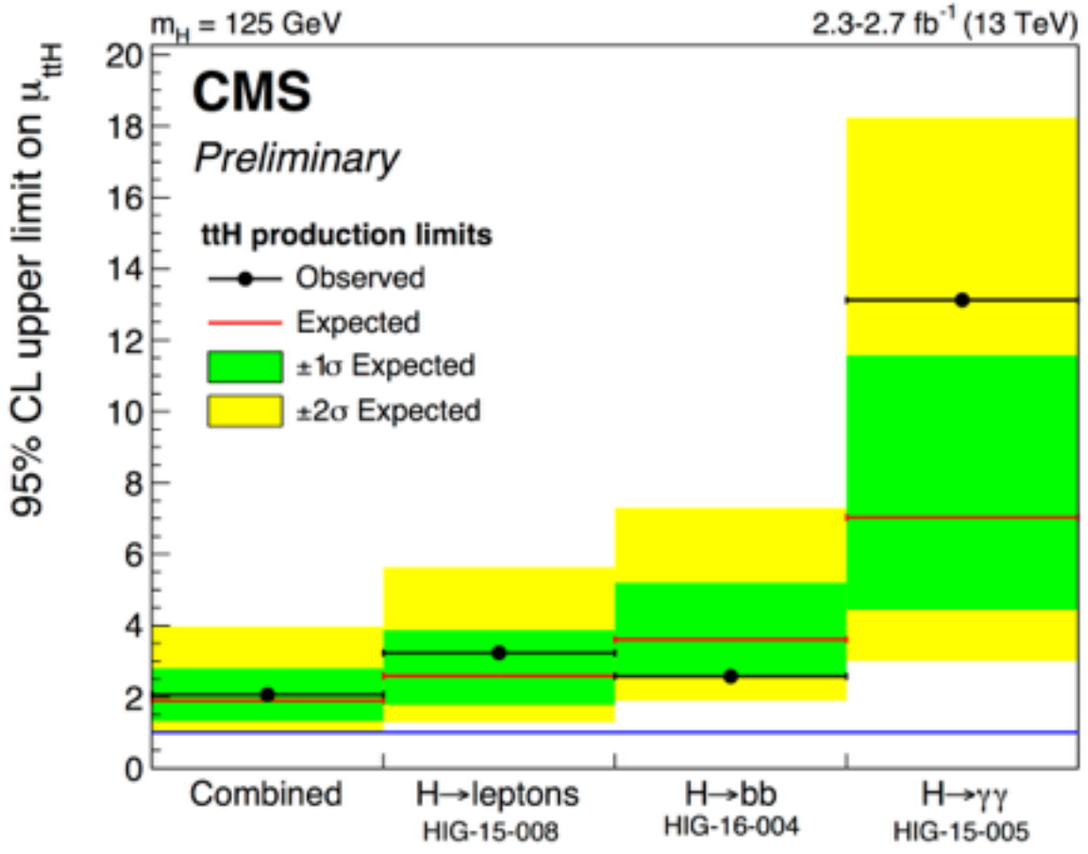


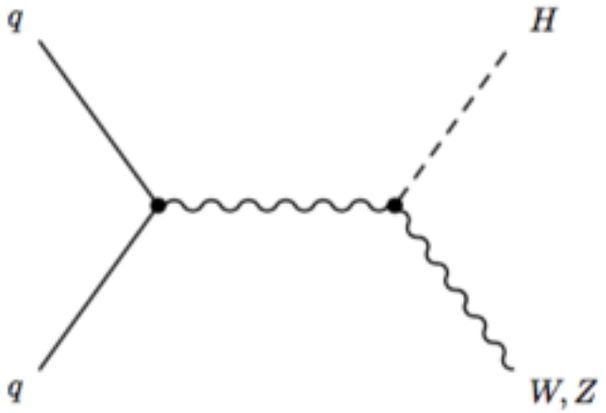
h→ττ



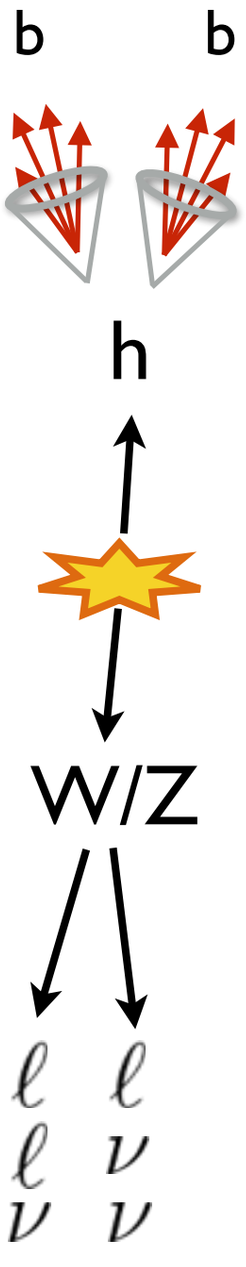
ttH combination







VH(→bb)

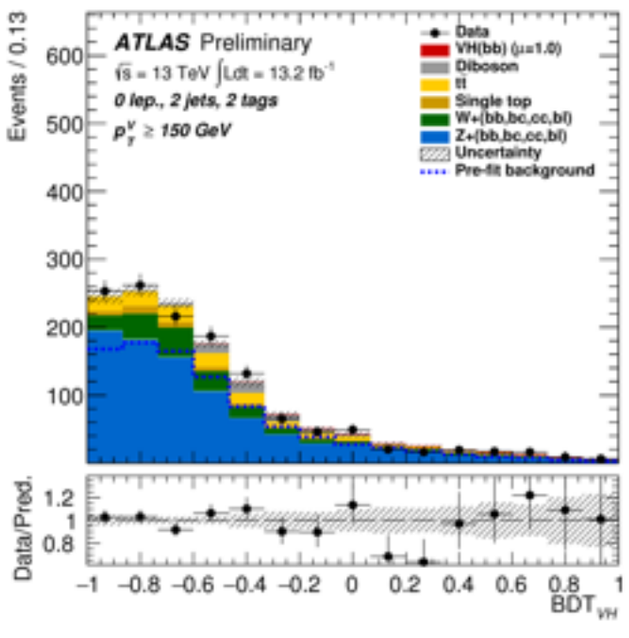


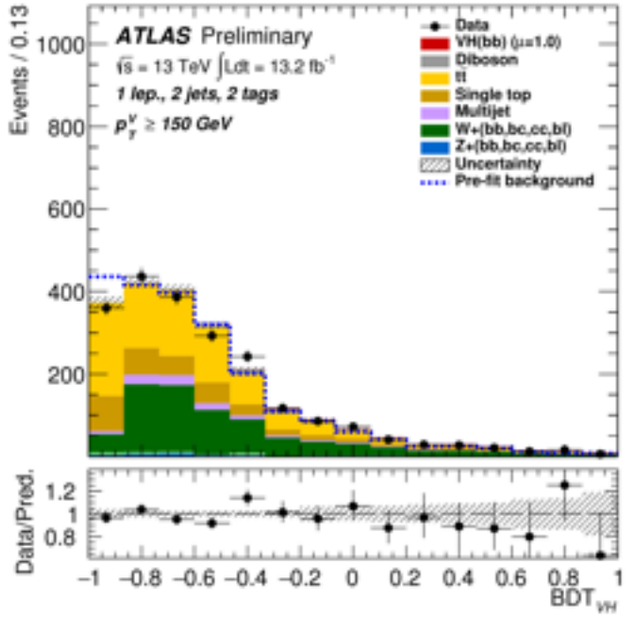
0 lepton
MET>150 GeV
b-jets not back-to-back
b-jets recoil against MET
MET not from jet mismeasure

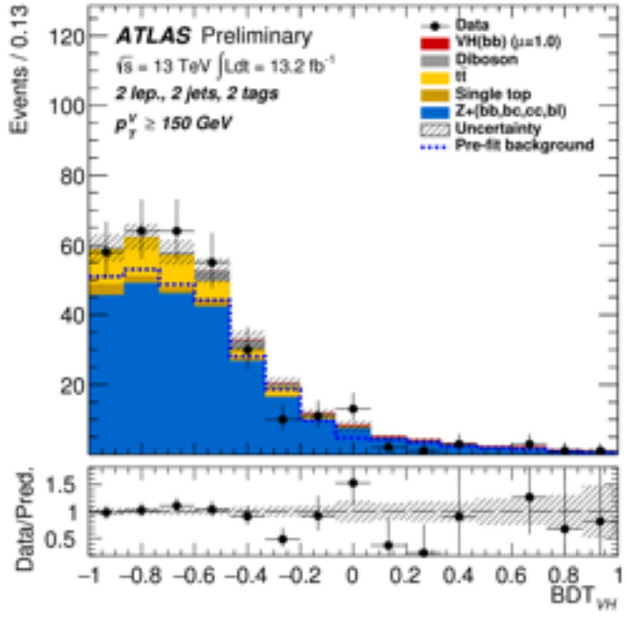
1 lepton
MET > 30 (e-channel)
MET trigger (μ-channel)
$p_T(V) > 150$ GeV

2 lepton
Opposite sign (μ-channel)
Z-mass window
Split: $p_T(V)$ [0, 150] [150, ∞] GeV

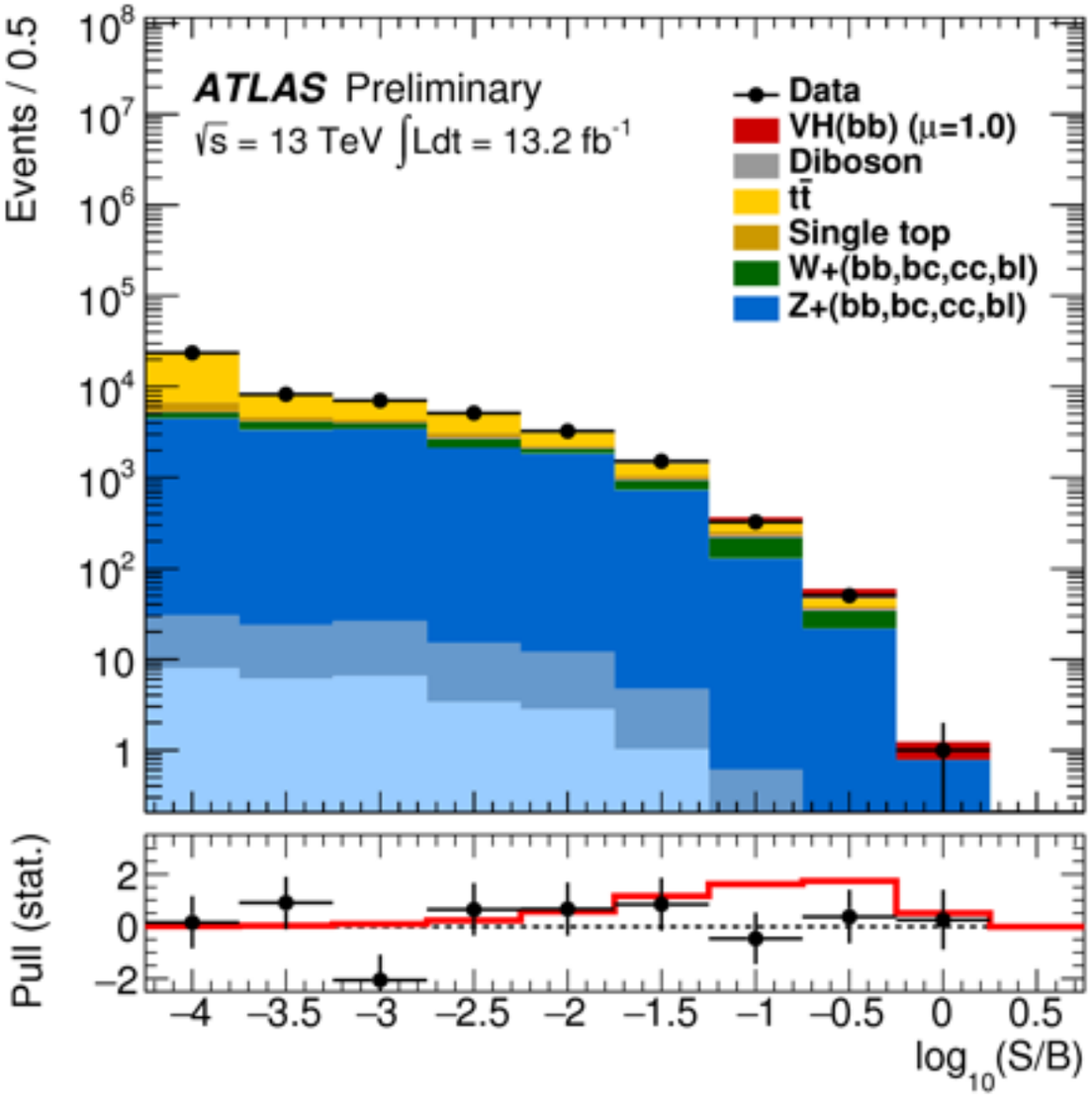
Categorise: presence of additional jets

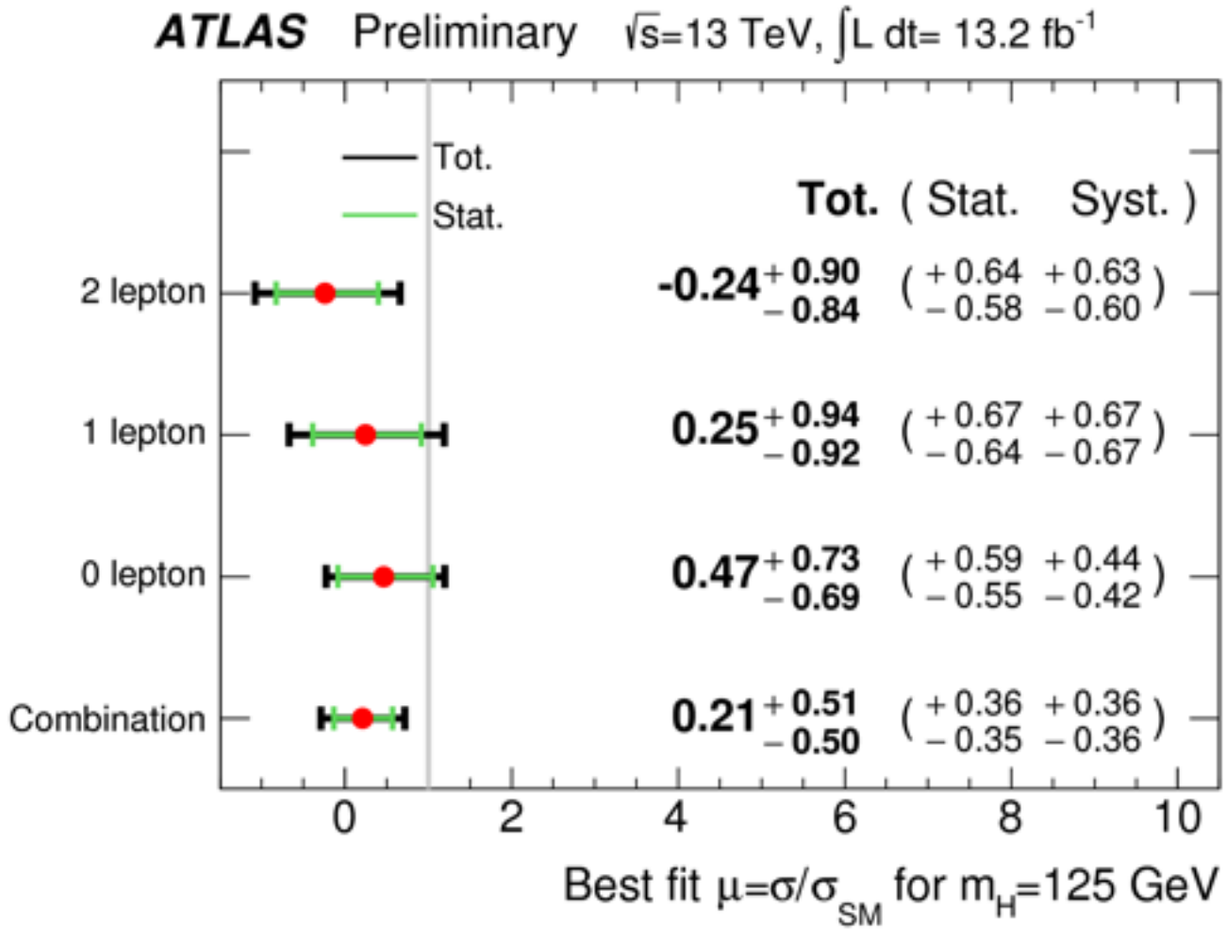






VH(→bb)





Dominant systematics:
b-tagging efficiency
Z+bb normalisation

BSM Higgs

BSM Higgs

- While h(125) compatible with SM, also compatible with many BSM models:
  - **Extended Higgs Sectors:**
    additional light/heavy charged/neutral higgs bosons
    (eg. 2HDM, singlets, triplets…)
  - **Modified Higgs Sectors:**
    invisible/BSM/LFV decays, …
- Can be probed via:
  - **Constraints from h(125)**
  - **Direct searches** (many performed at LHC)

Google: "ATLAS (CMS) public higgs results"

SM like searches

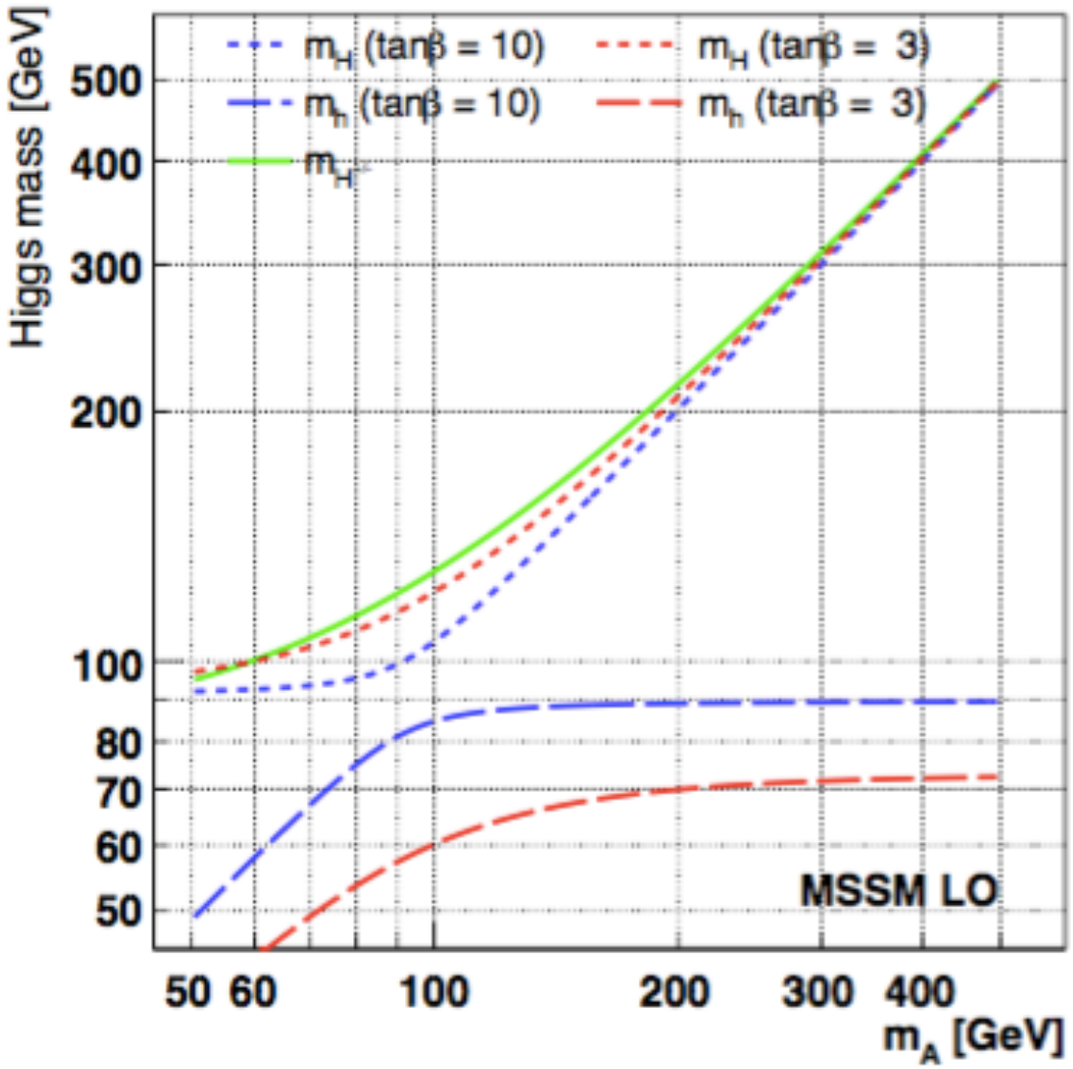
- High-mass SM like searches: WW, ZZ, γγ, bb, ττ
  - In general, techniques very similar to SM searches
  - They show no deviations from SM (X750 in backup)
  - Won't cover in detail
- Exceptions:
  - ττ particularly important for MSSM

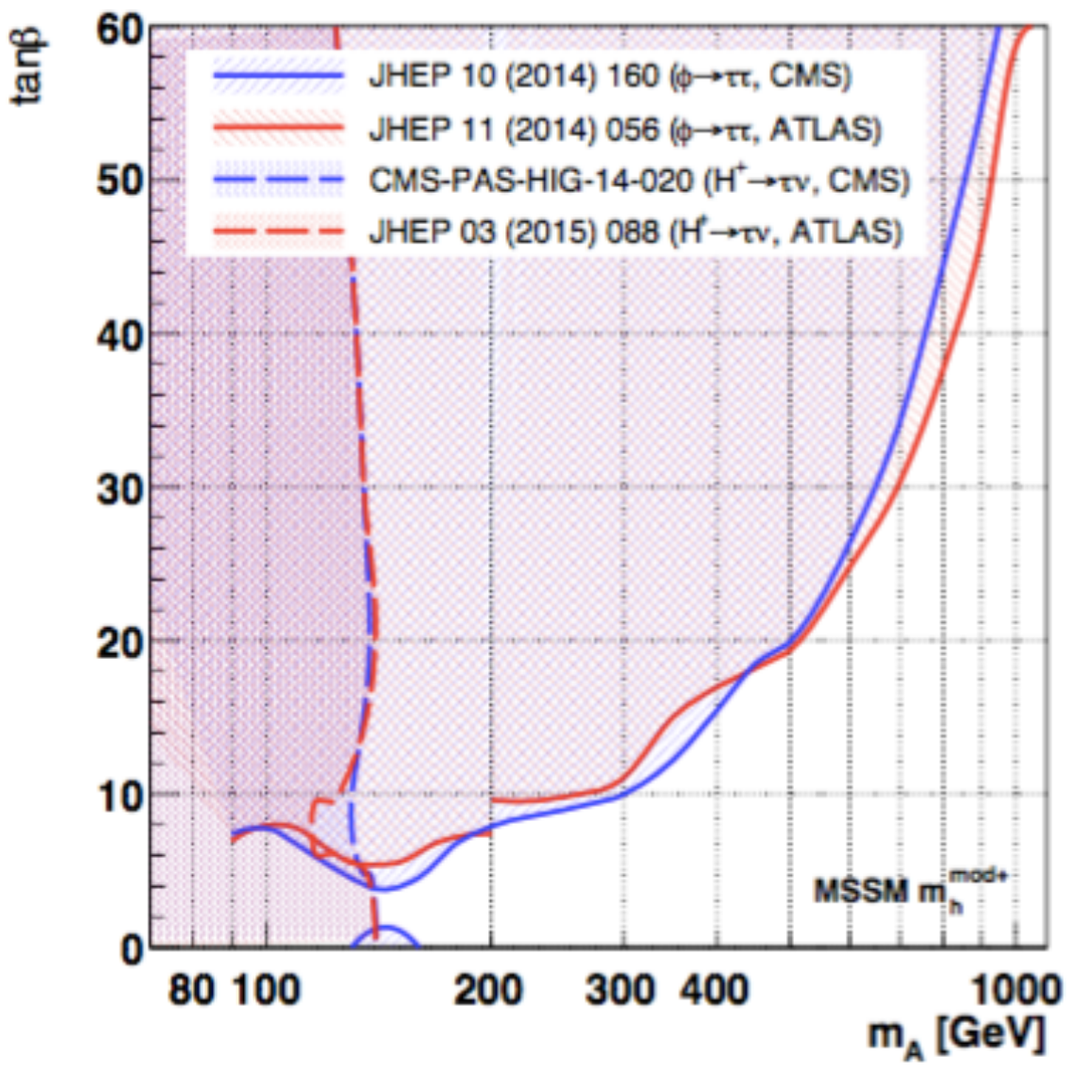
MSSM

CP even **CP odd** **Charged**

h H A H^- H^+

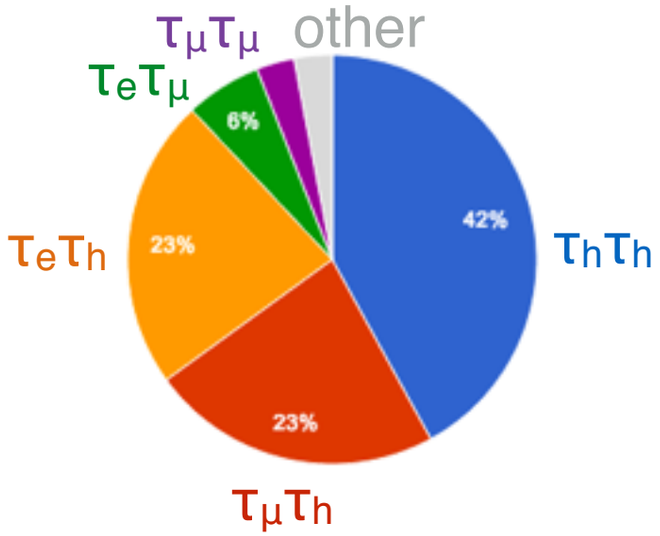
SM-like?





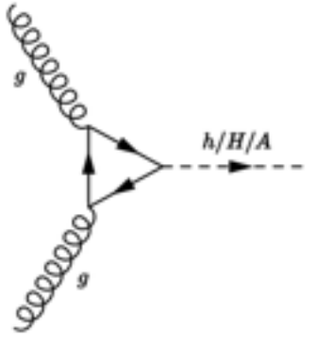
A/H → ττ

Decay channels

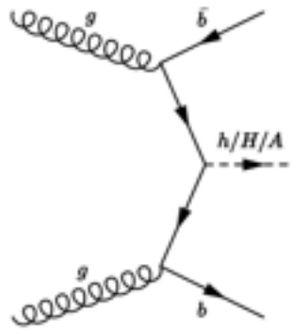


Production modes

ggF

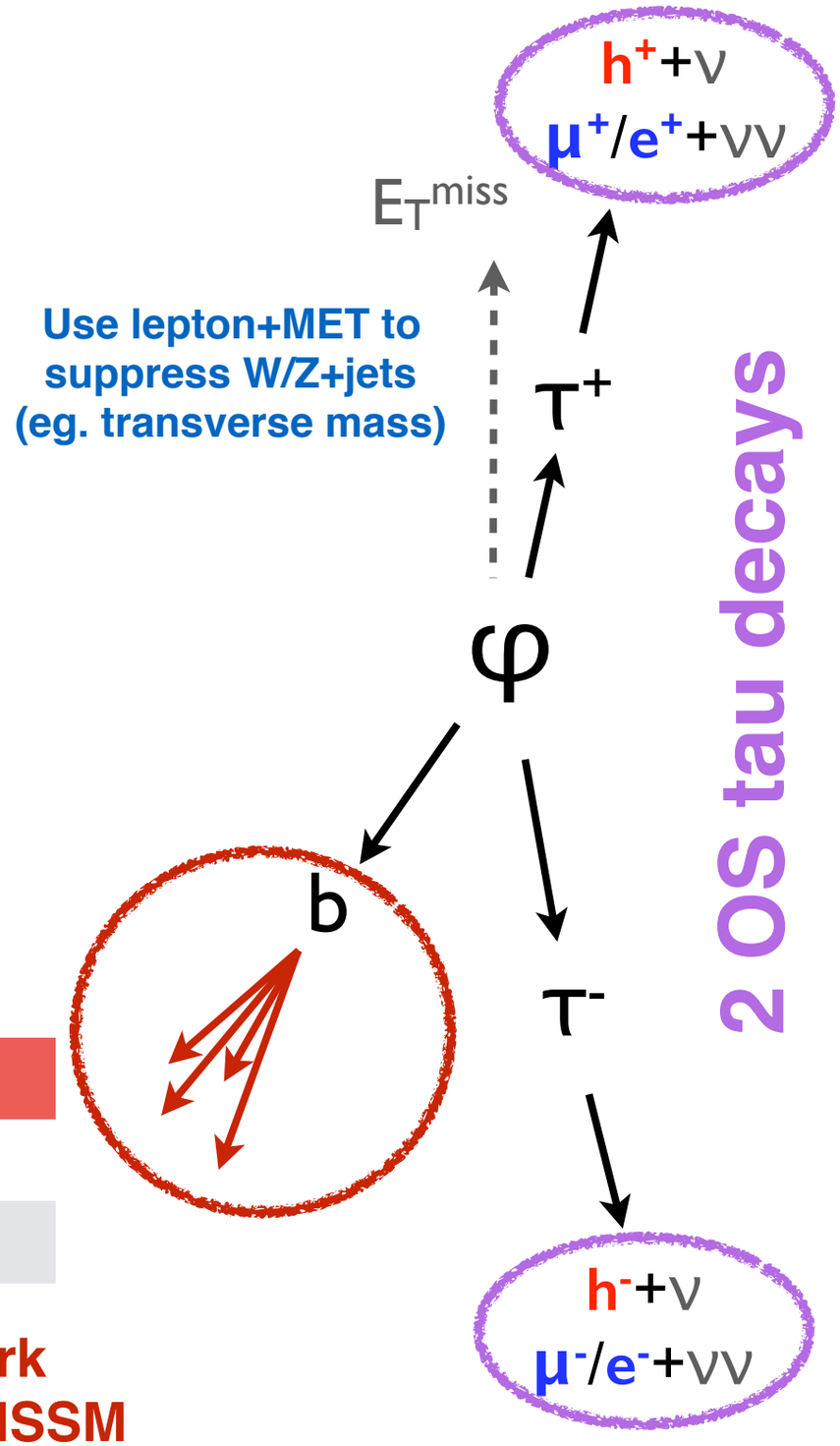


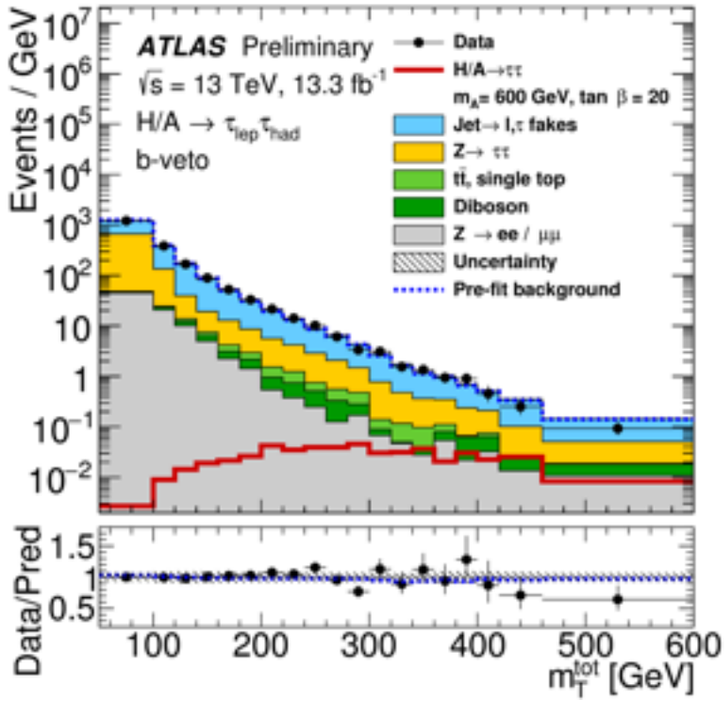
bbA

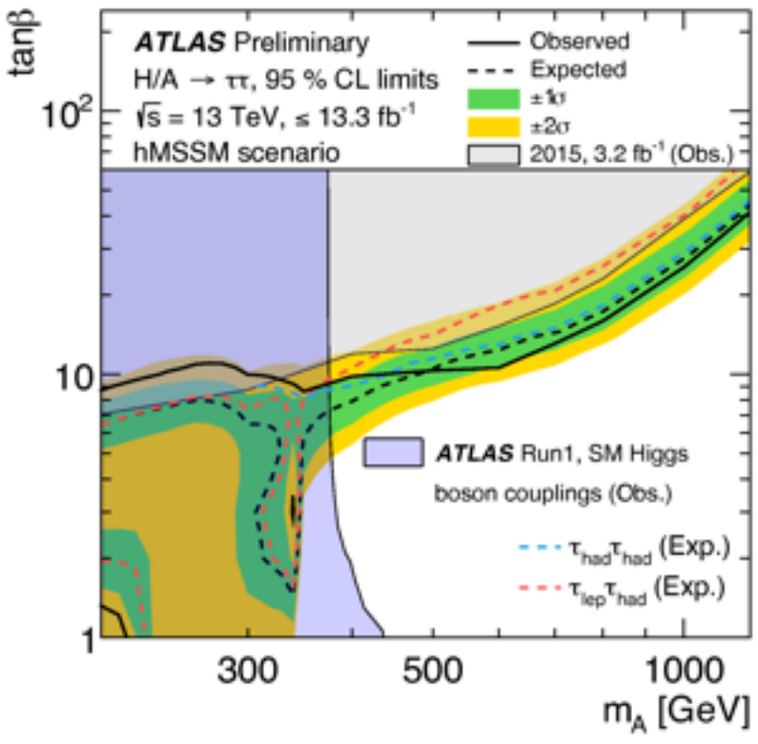


Categorise	
B-Tag	≥1 b-jet
No B-Tag	0 b-jets

Exploit enhanced b-quark associated production in MSSM

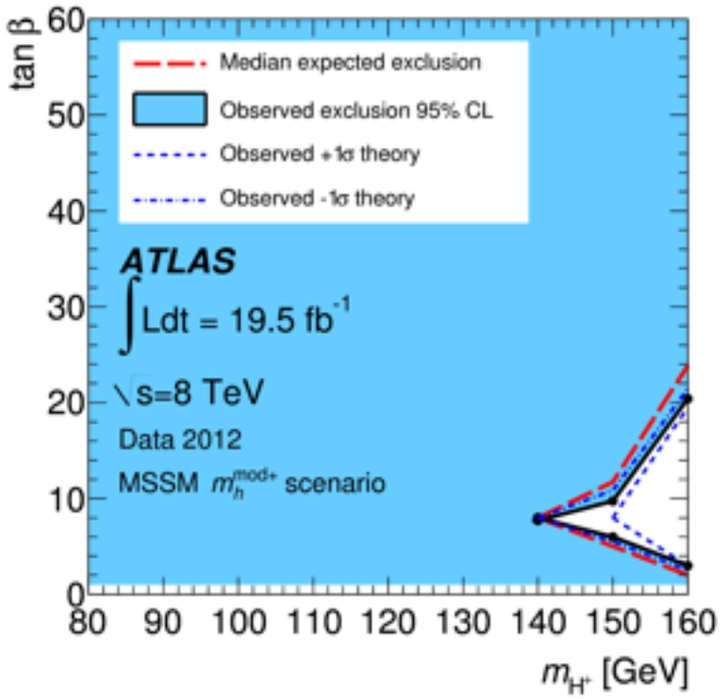




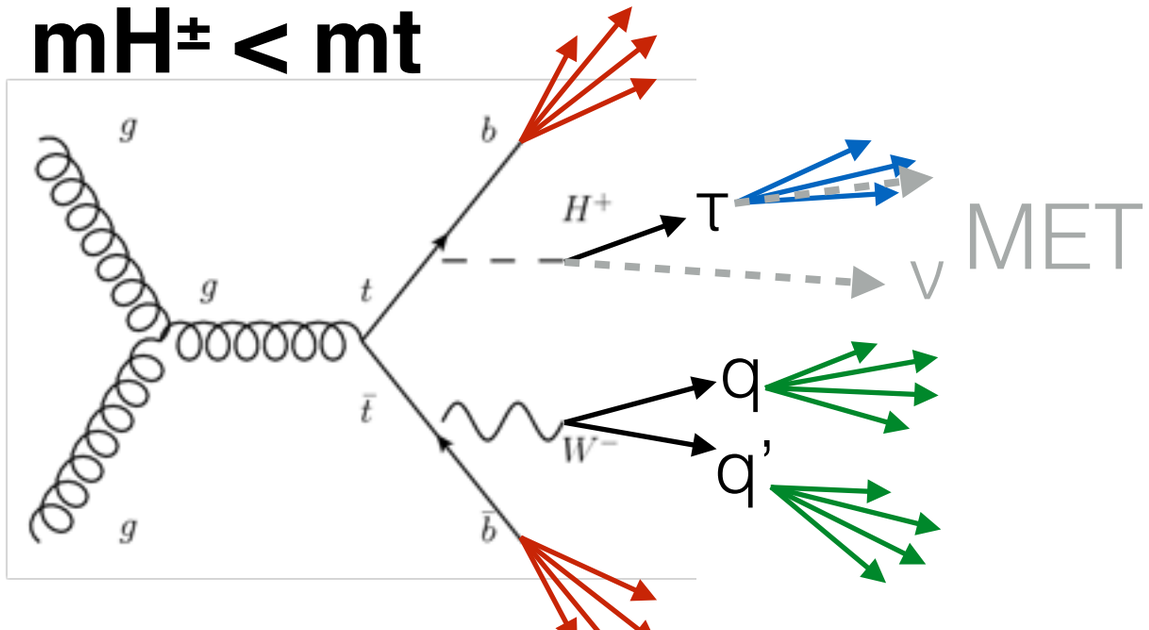


$H^{\pm} \rightarrow \tau\nu$

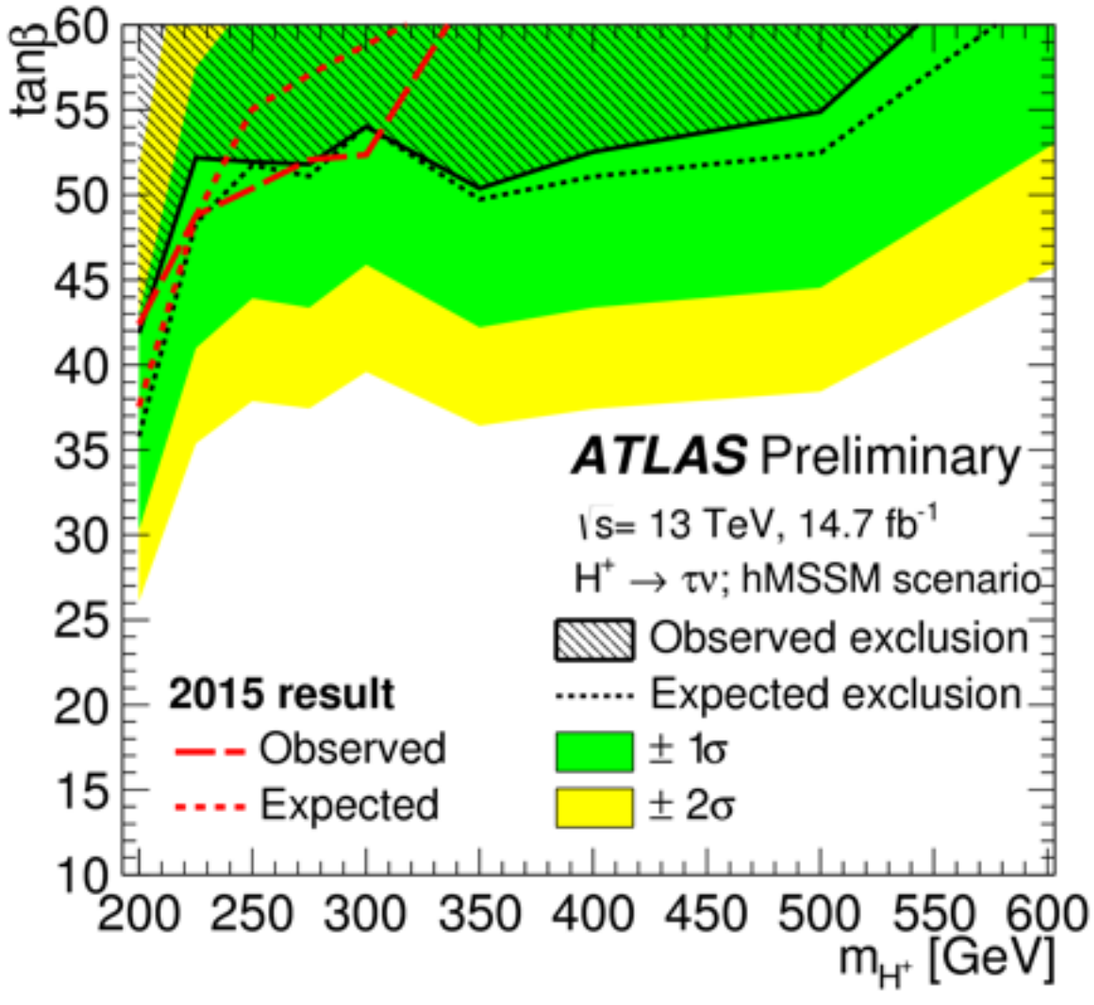
- 1τ, ≥4 jets (≥1 b-jet), no leptons, large MET



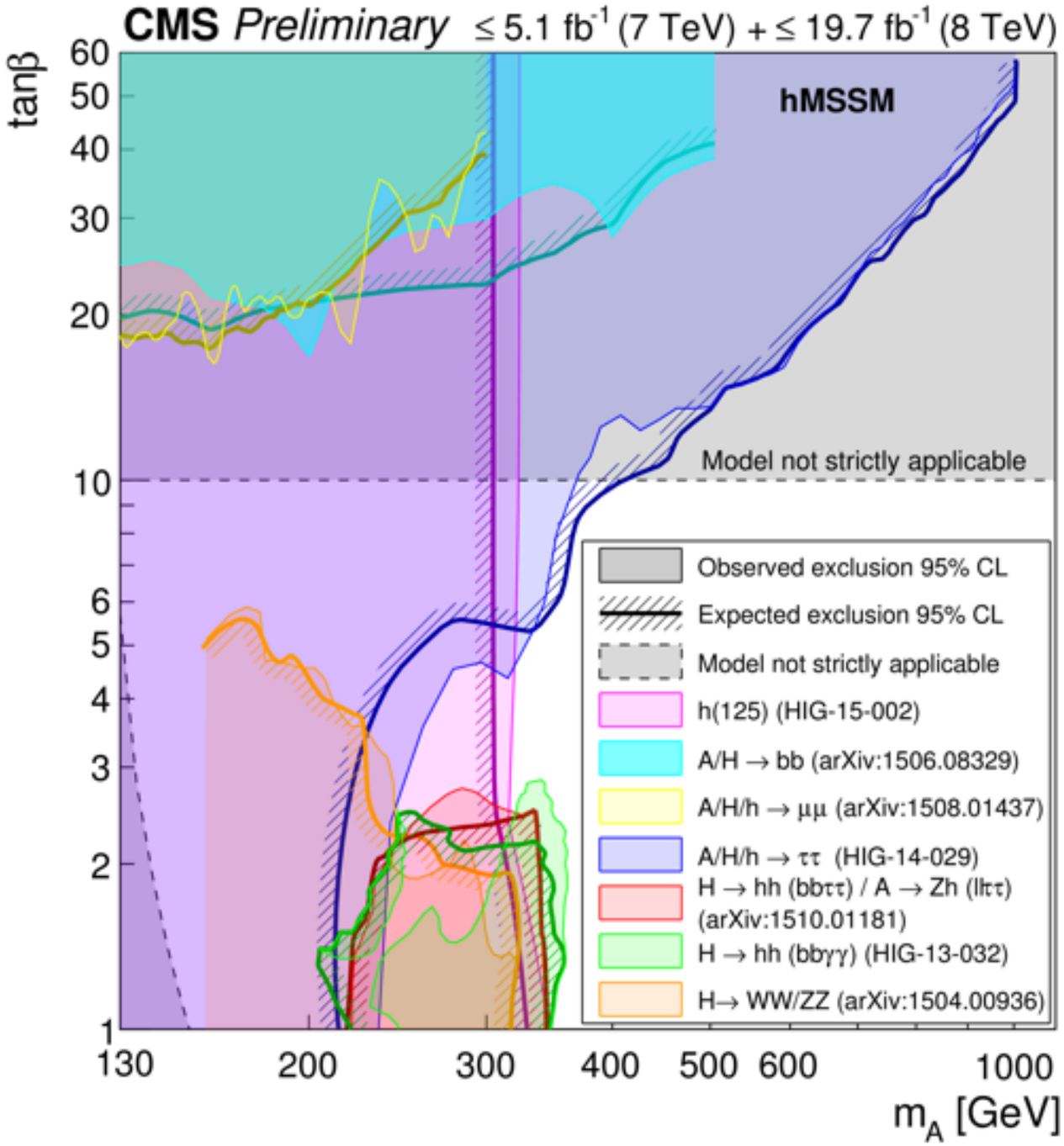
mH± < mt

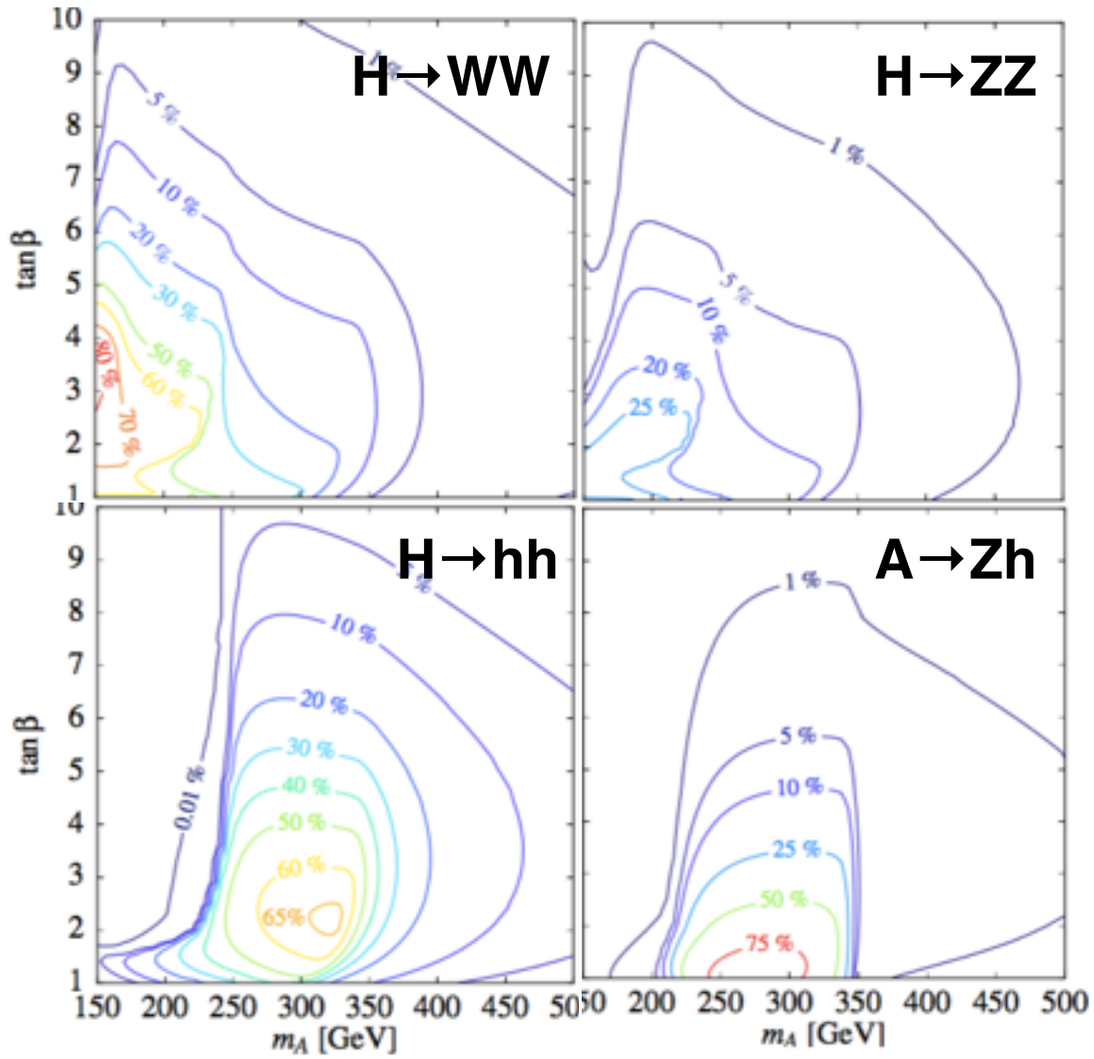


mH± > mt



MSSM (low tanβ)





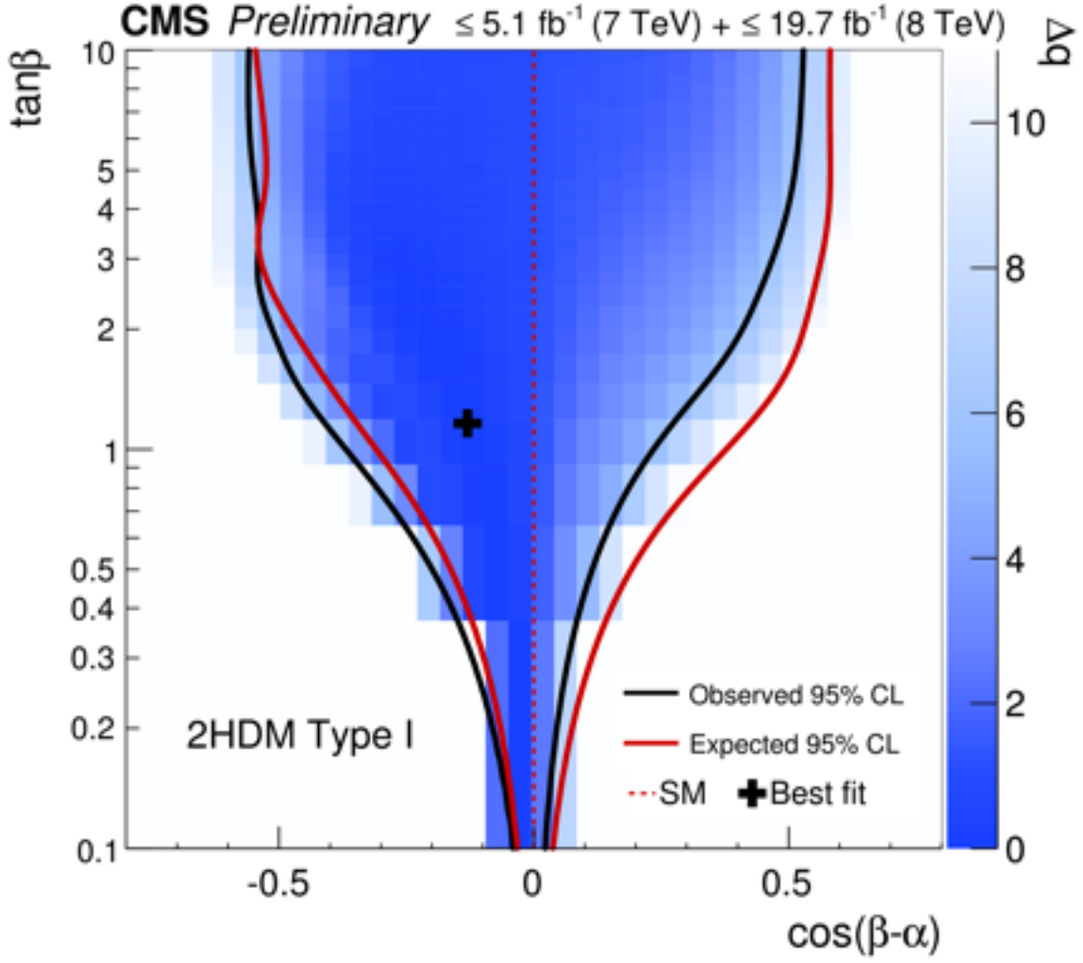
2HDM

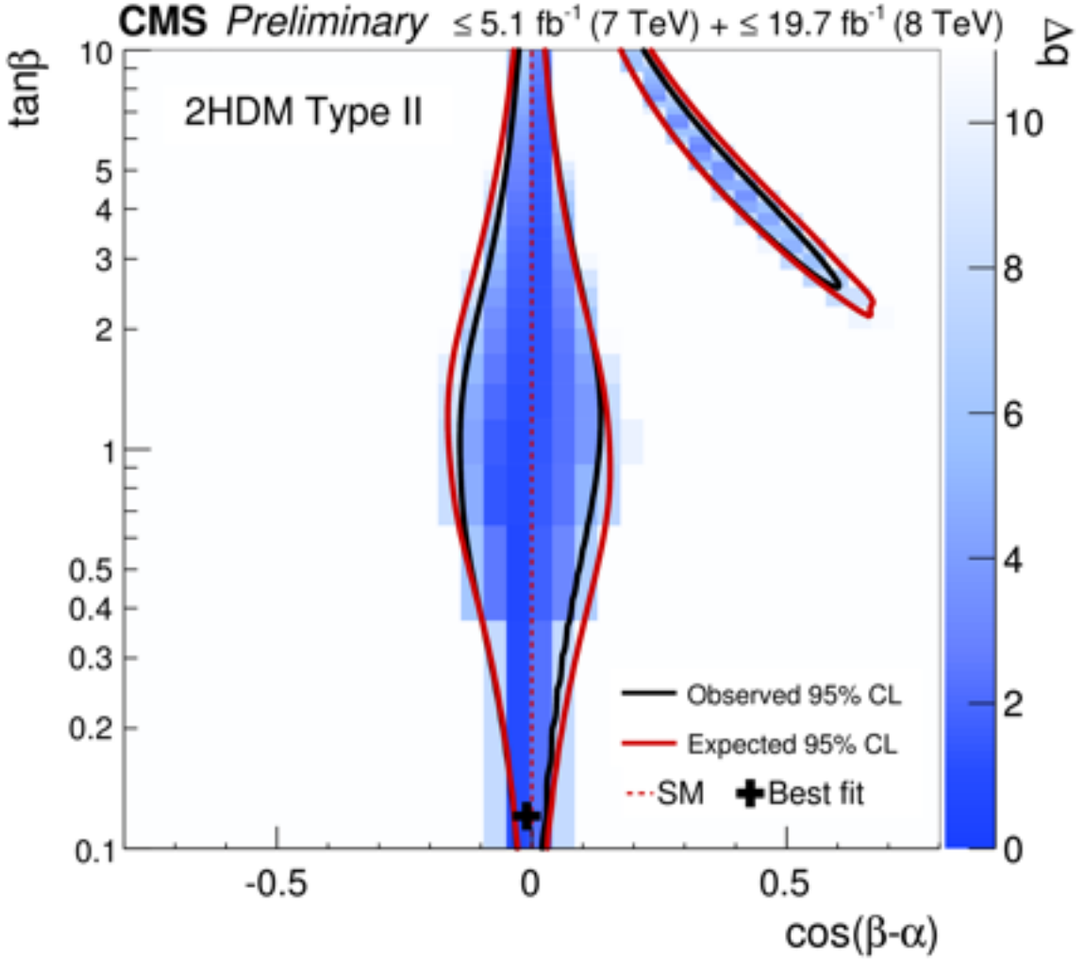
- 14→7 params (avoid CPV):
  m_h, m_H, m_A, $m_{H\pm}$, α, β, m_{12}.

- H, A, H± should be roughly degenerate (pert., unit, vac.)

- h(125) couplings (t,τ) strongly constrain α, β

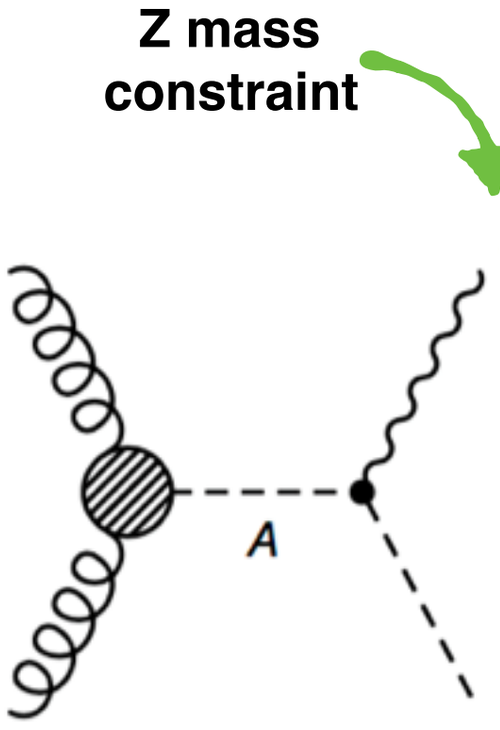
	2HDM		hMSSM
	type I	type II/MSSM	
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\frac{s_d+s_u\tan\beta}{\sqrt{1+\tan^2\beta}}$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$s_u\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$s_d\sqrt{1+\tan^2\beta}$

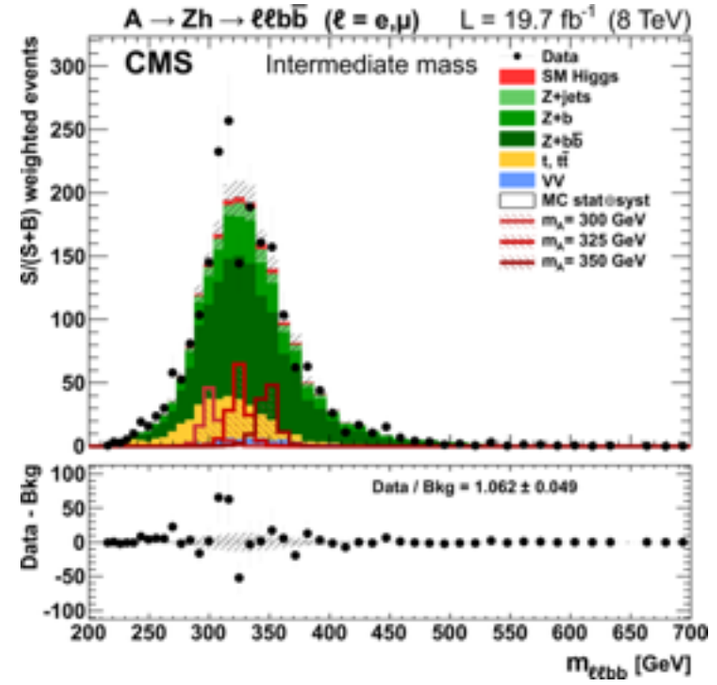


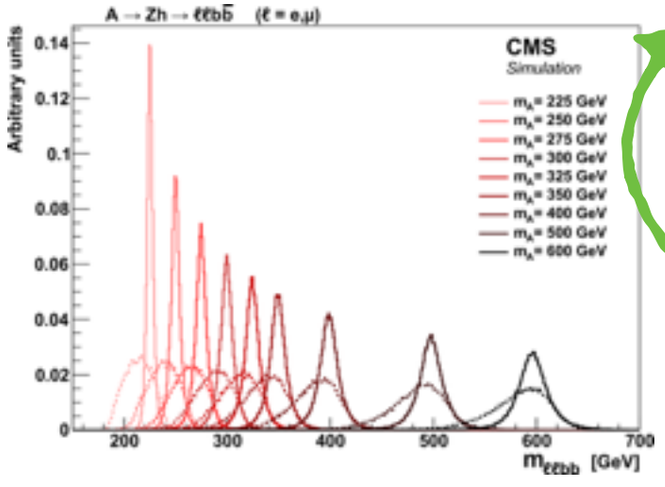


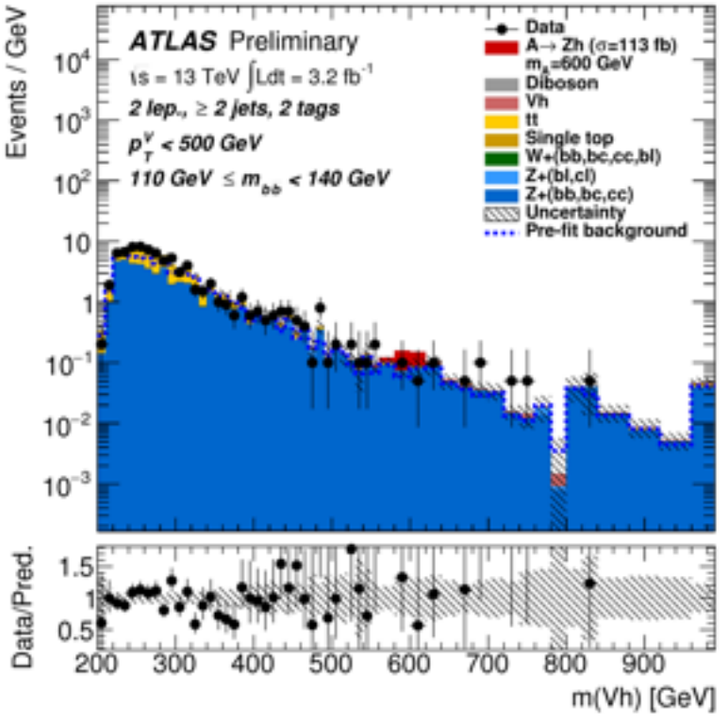
A→Zh

Typically dominant for $m_h+m_Z < m_A < 2m_t$



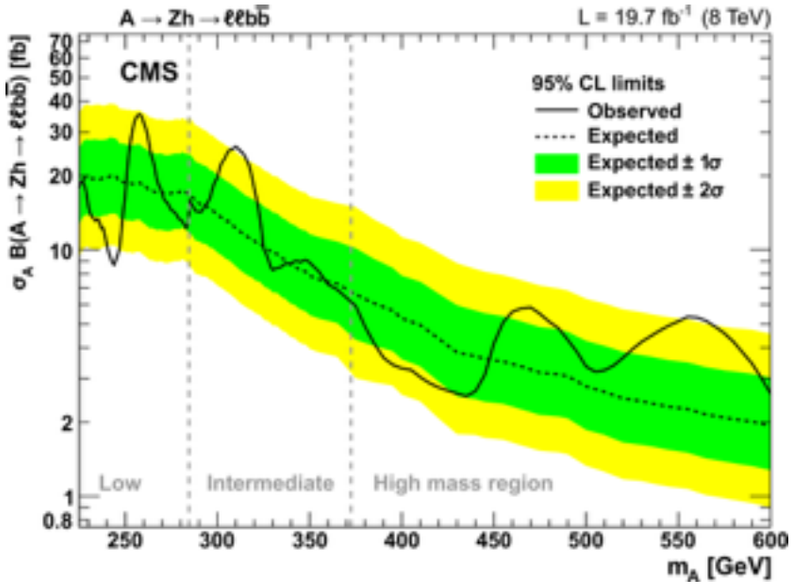


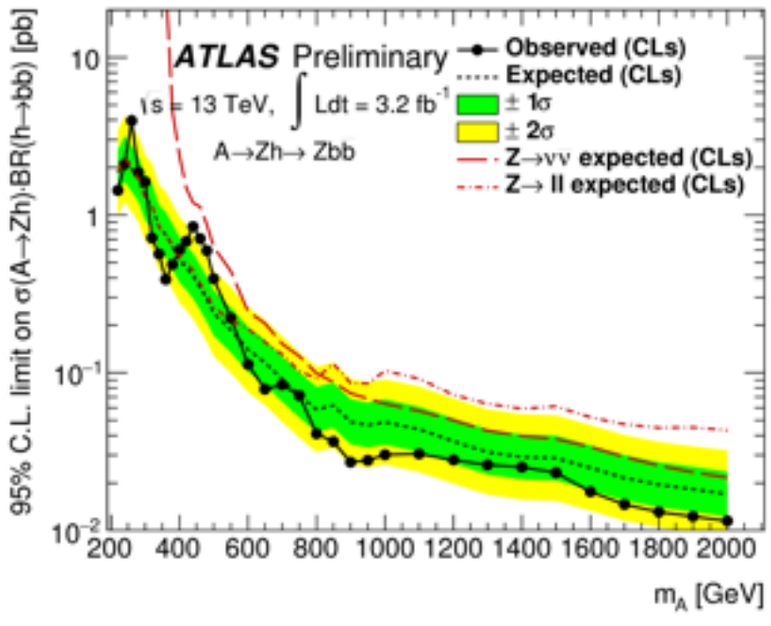




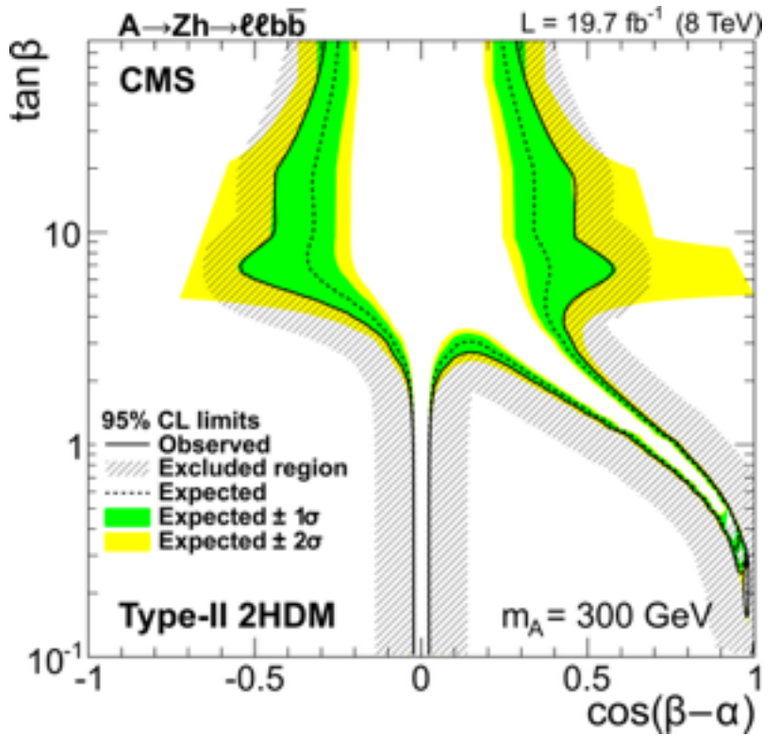
A→Zh

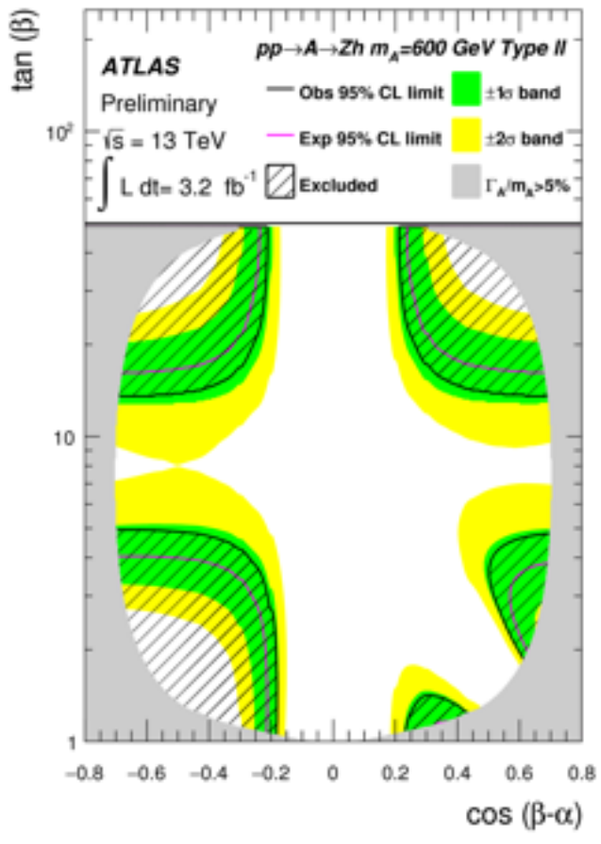
Cross section limits





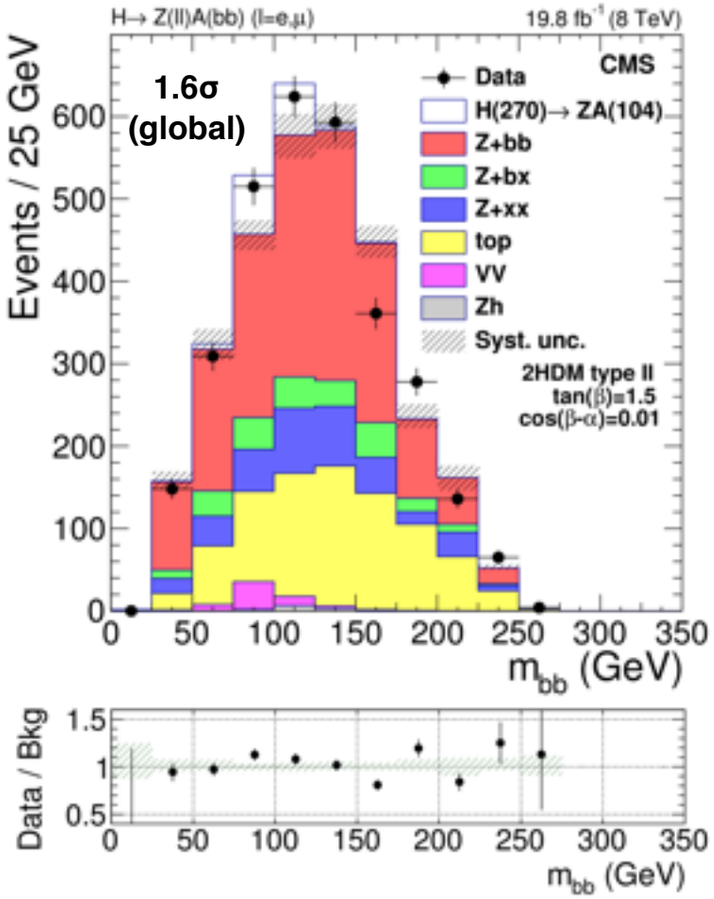
2HDM limits

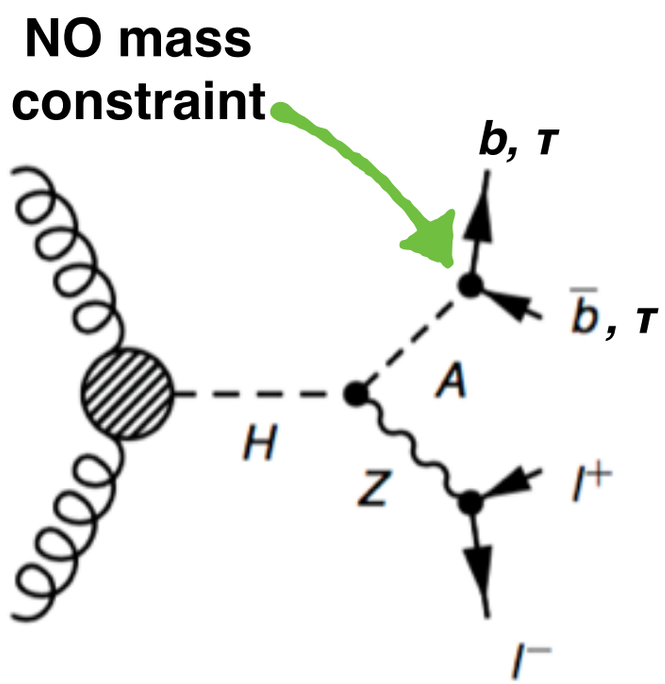


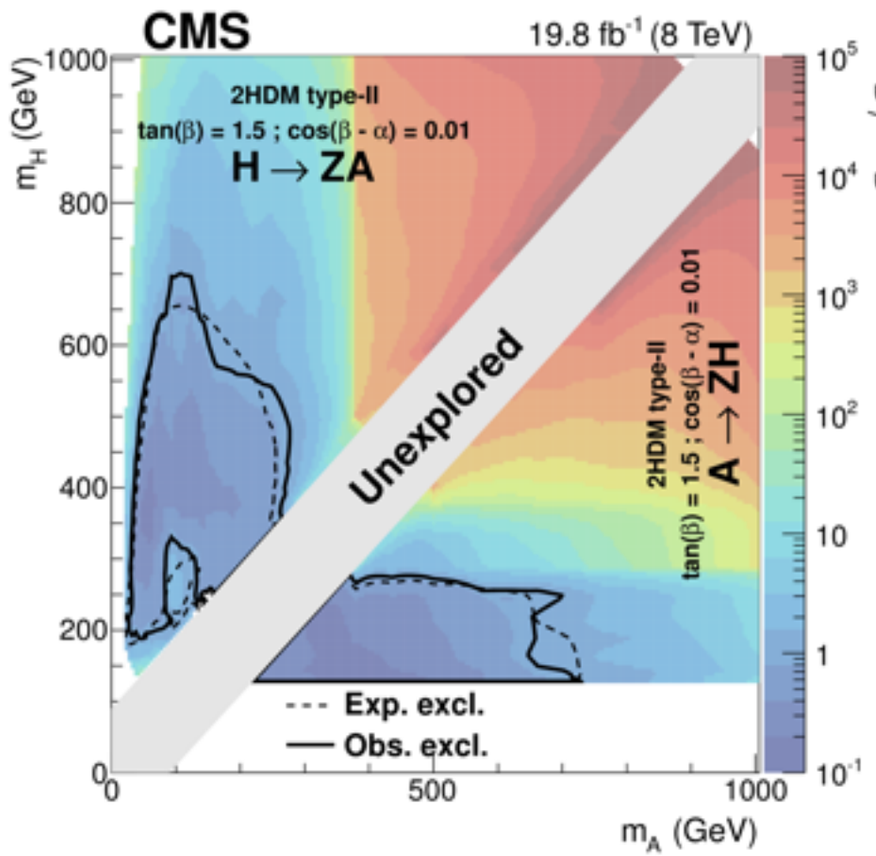


H→ZA

- large H-A mass splitting favour EW phase transition required for baryogengesis
- In this case A→ZH/H→ZA dominant
- Basically proceed as for A→Zh, but drop h(125) mass constrain on m_{bb}.

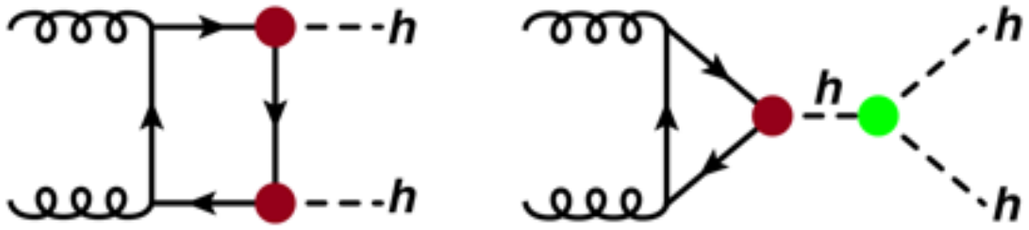




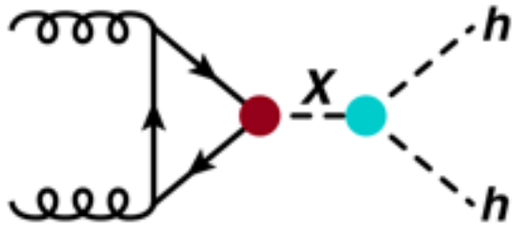


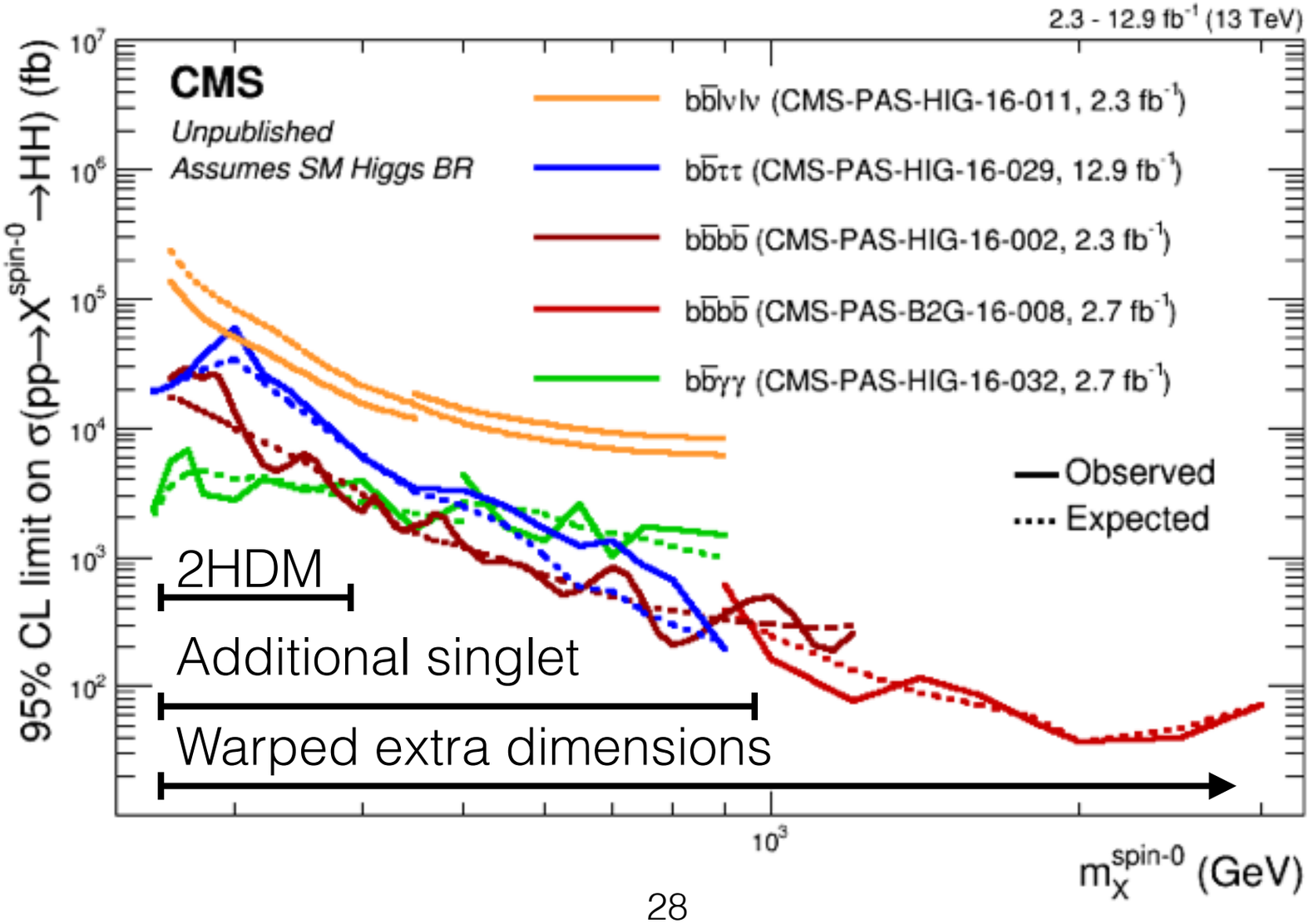
Di-Higgs

SM, non-resonant



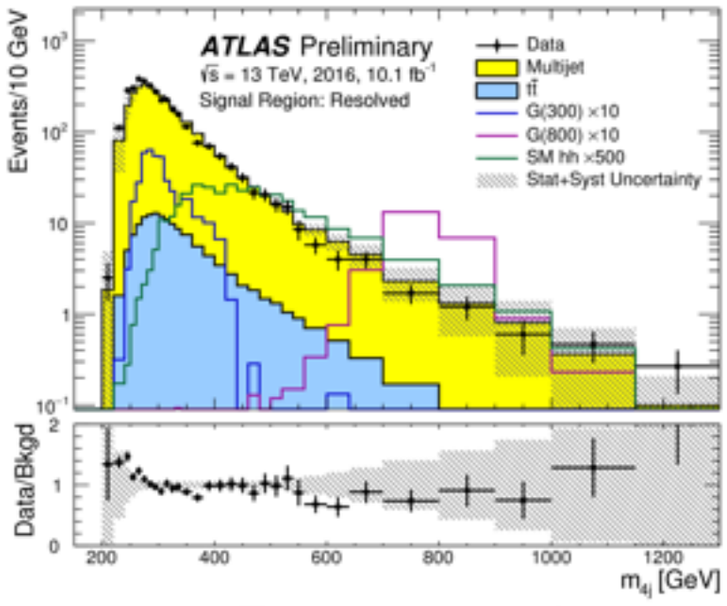
BSM resonant



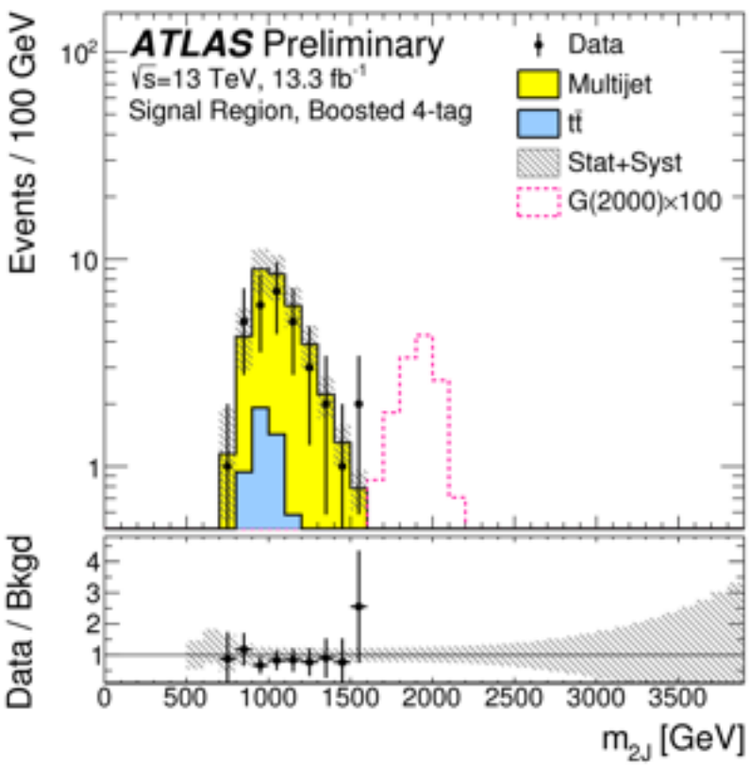


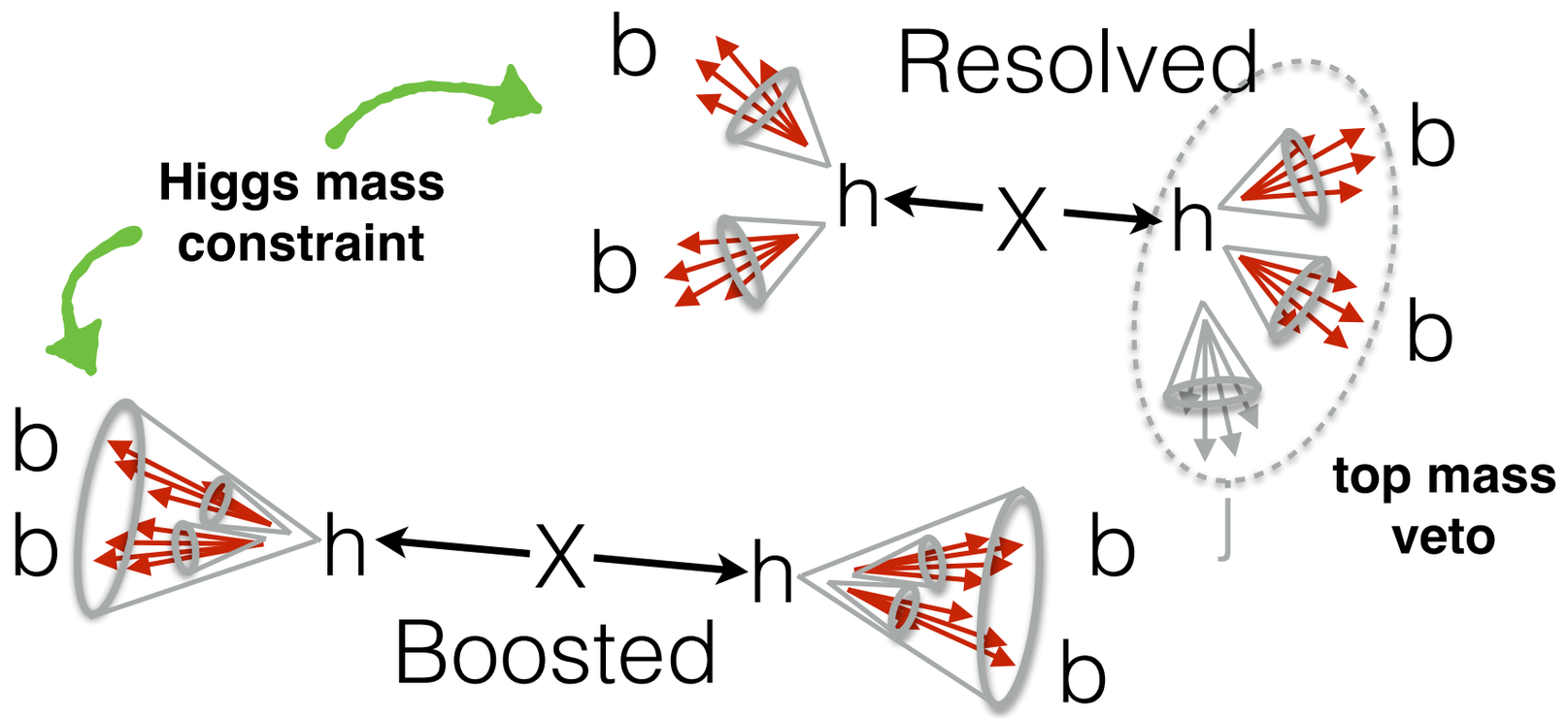
X→hh→4b

Resolved

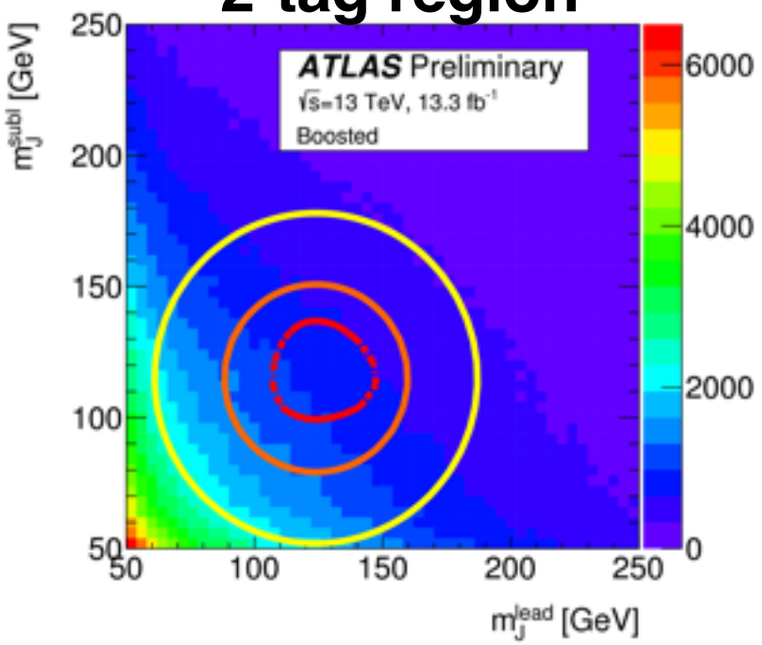


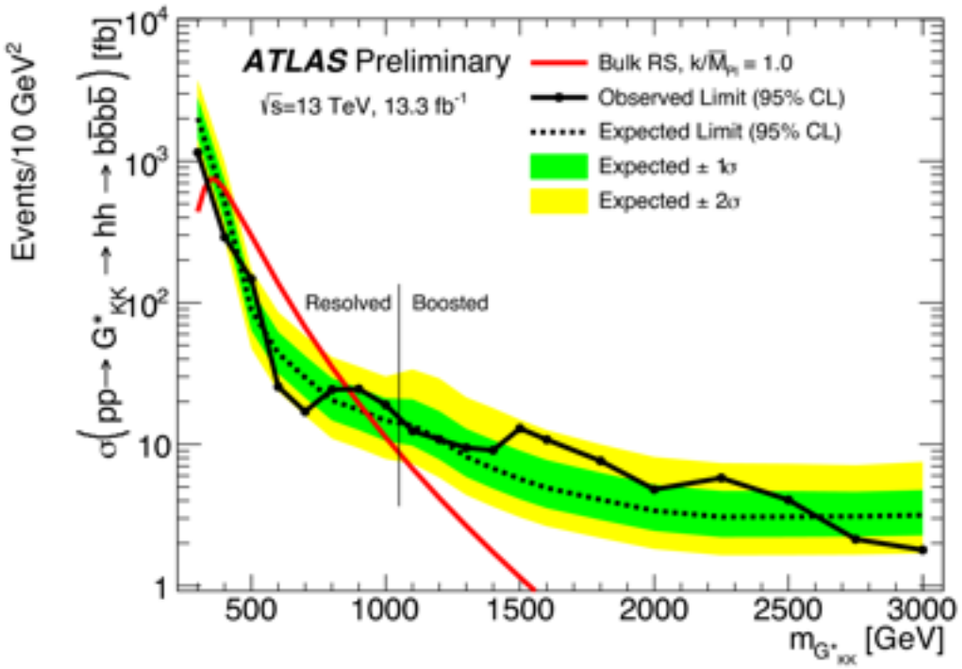
Boosted





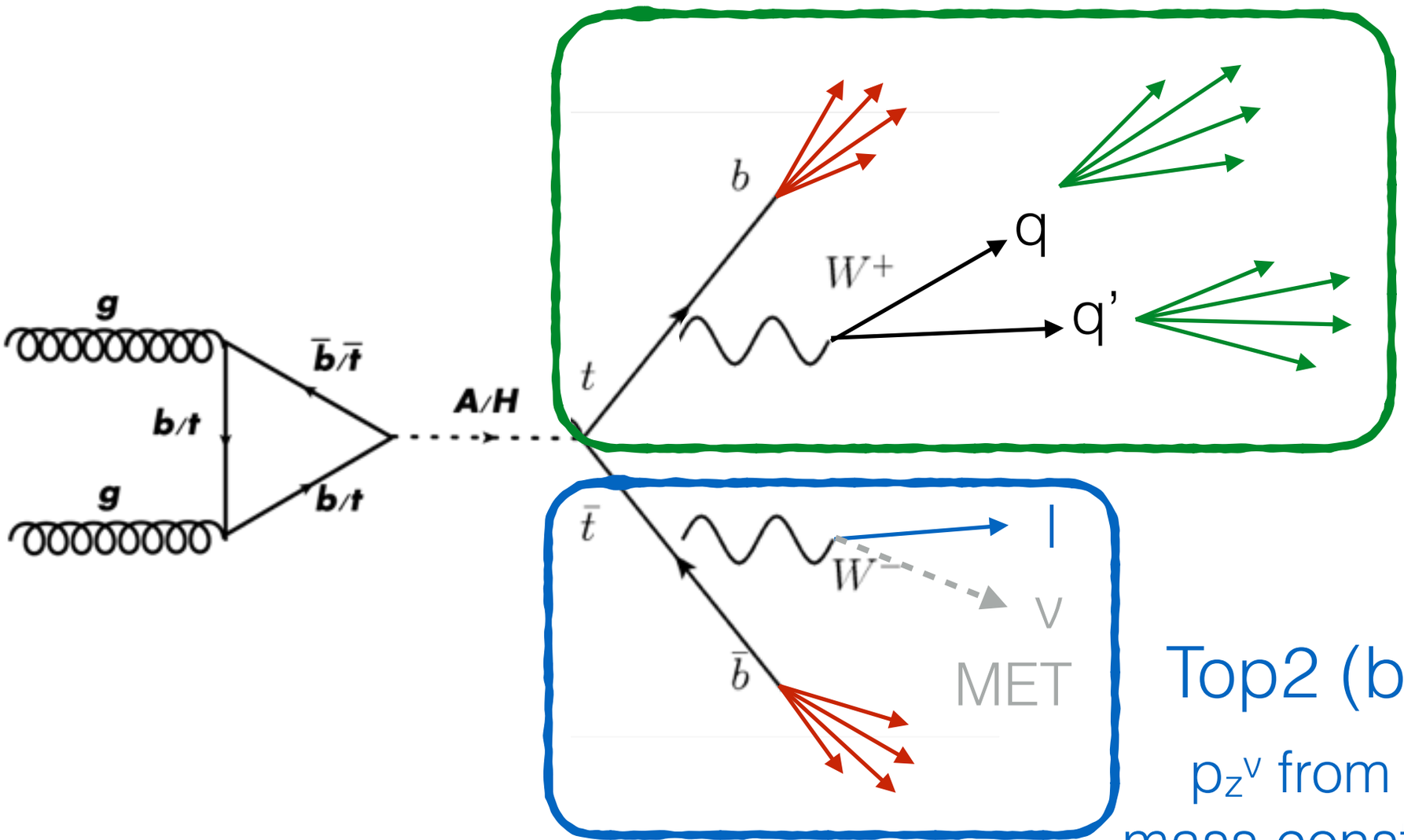
2-tag region





Run 1 excess in 2b2γ (see backup)

H→tt



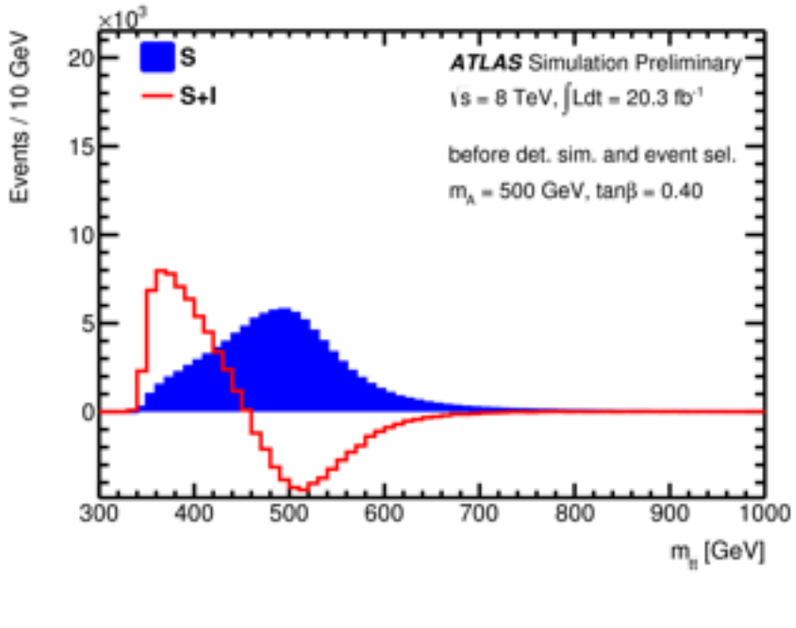
Top1 (bjj)

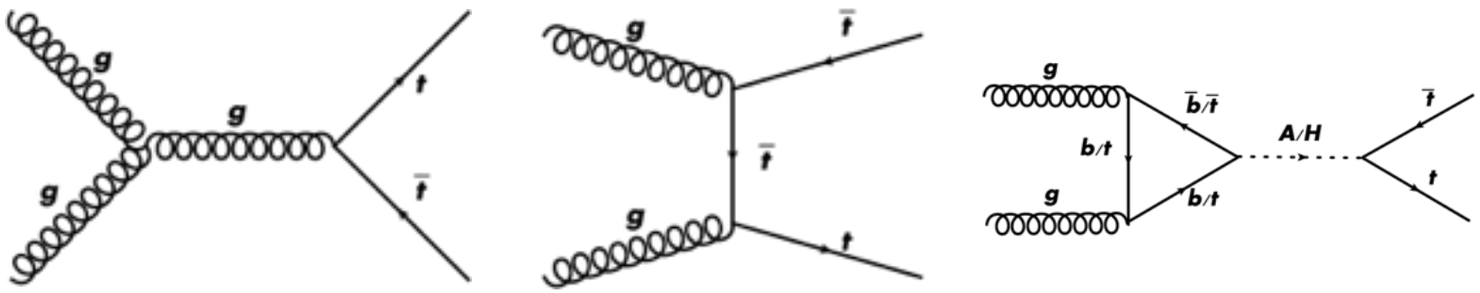
Top2 (blν)

p_z^{ν} from W mass constraint

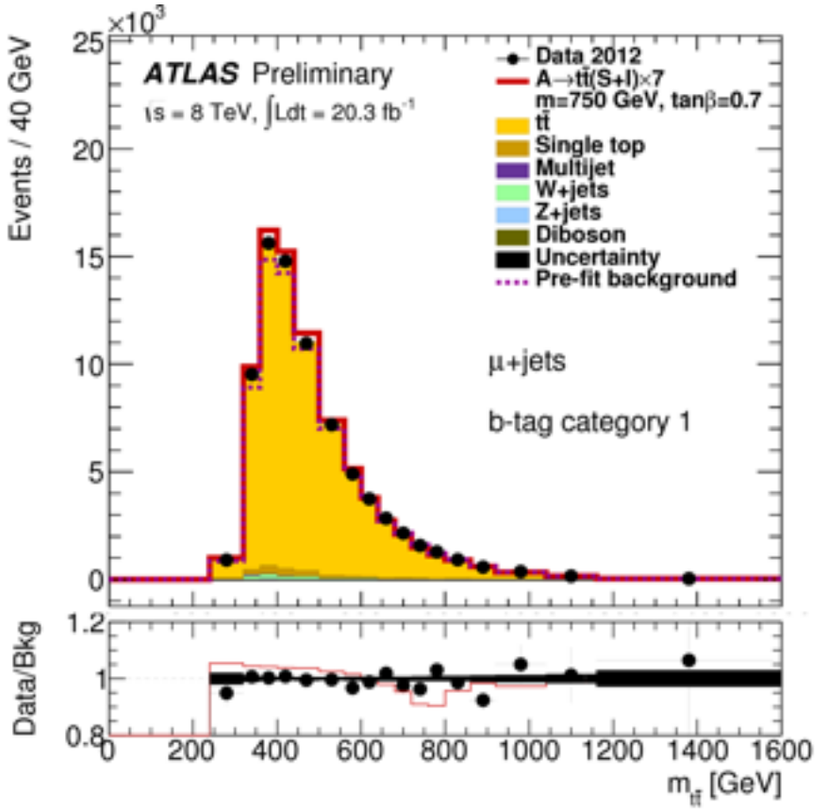
Kinematic fit: assign jets, reject non tt topologies, improve Higgs mass resolution

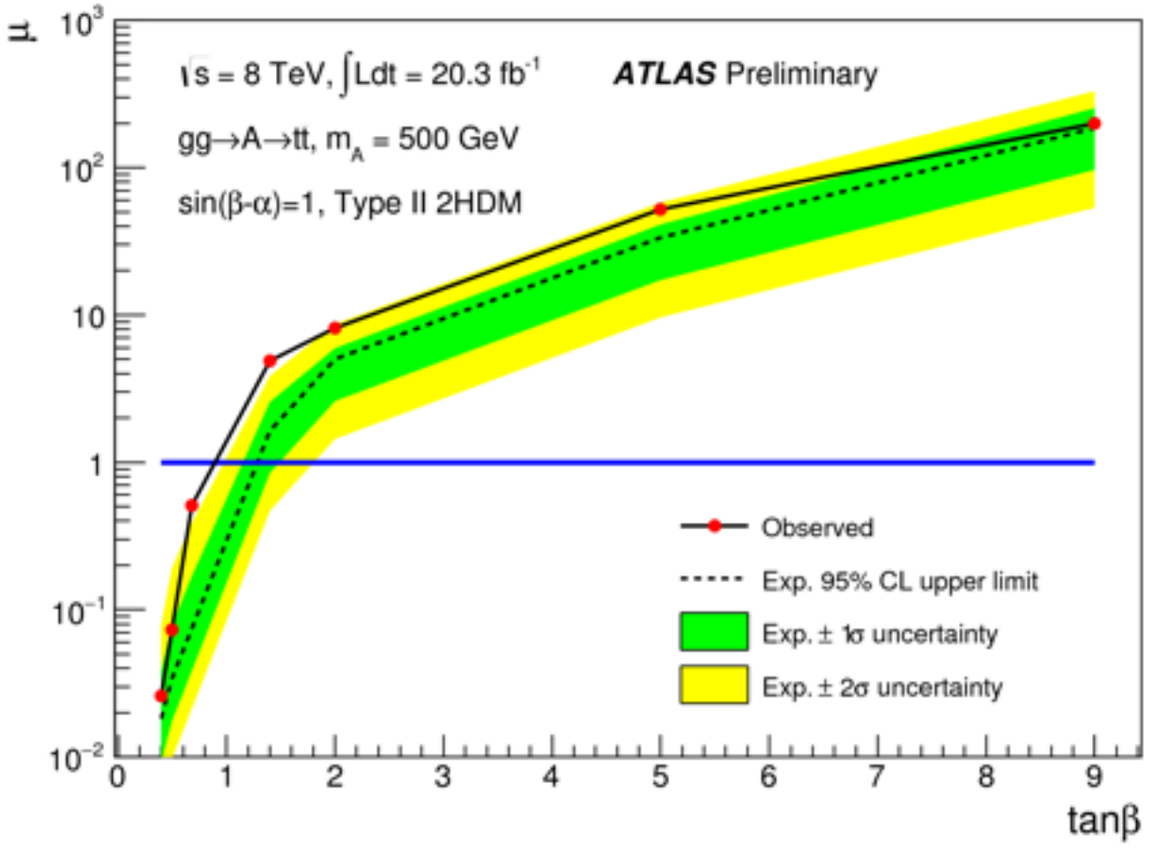
H → tt





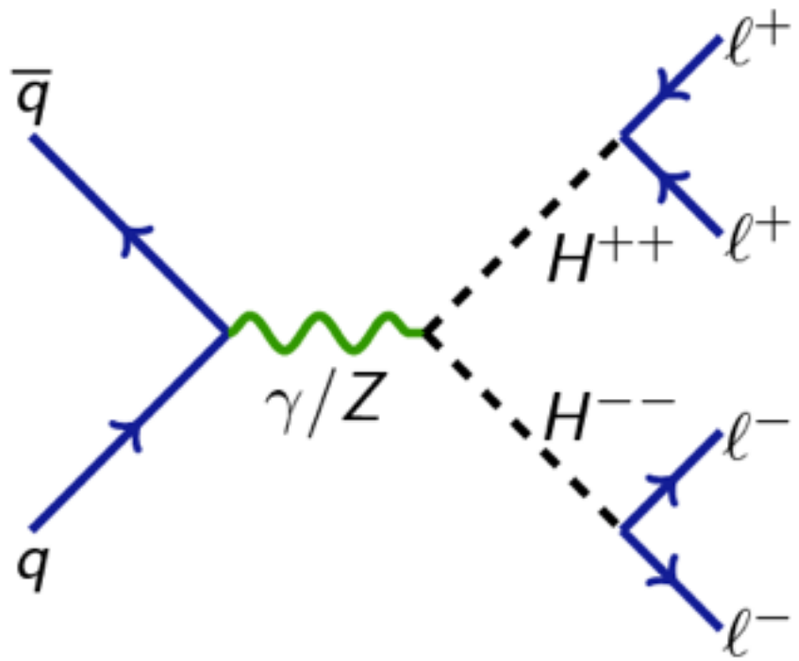
$$\mu \cdot S + \sqrt{\mu} \cdot I + B = \sqrt{\mu} \cdot (S + I) + (\mu - \sqrt{\mu}) \cdot S + B,$$

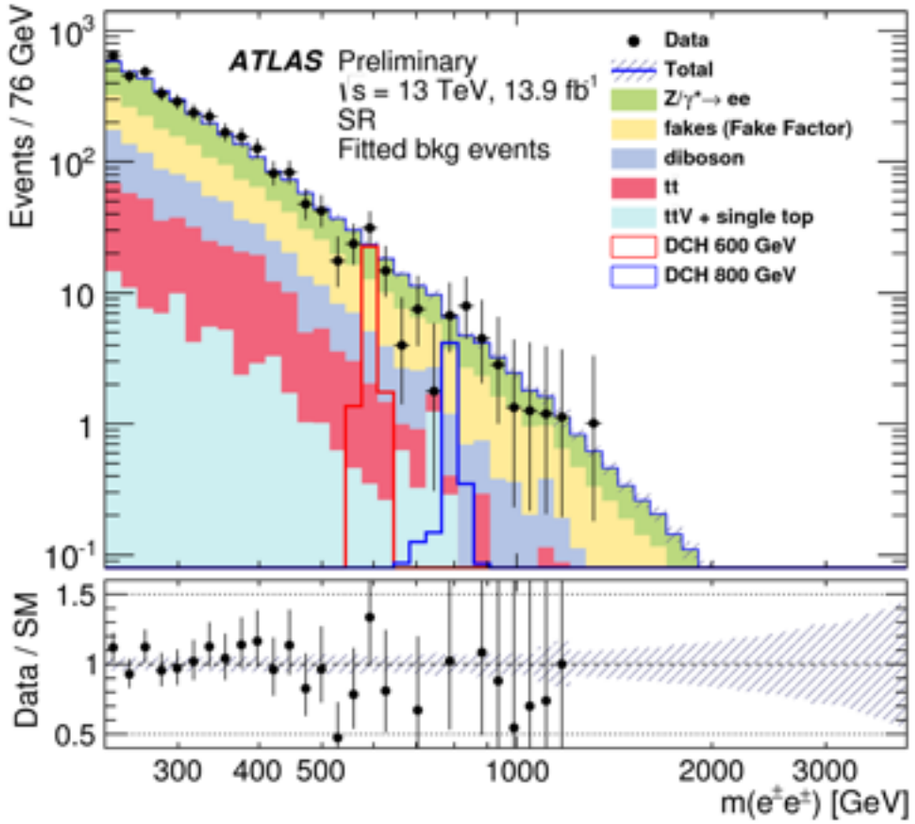


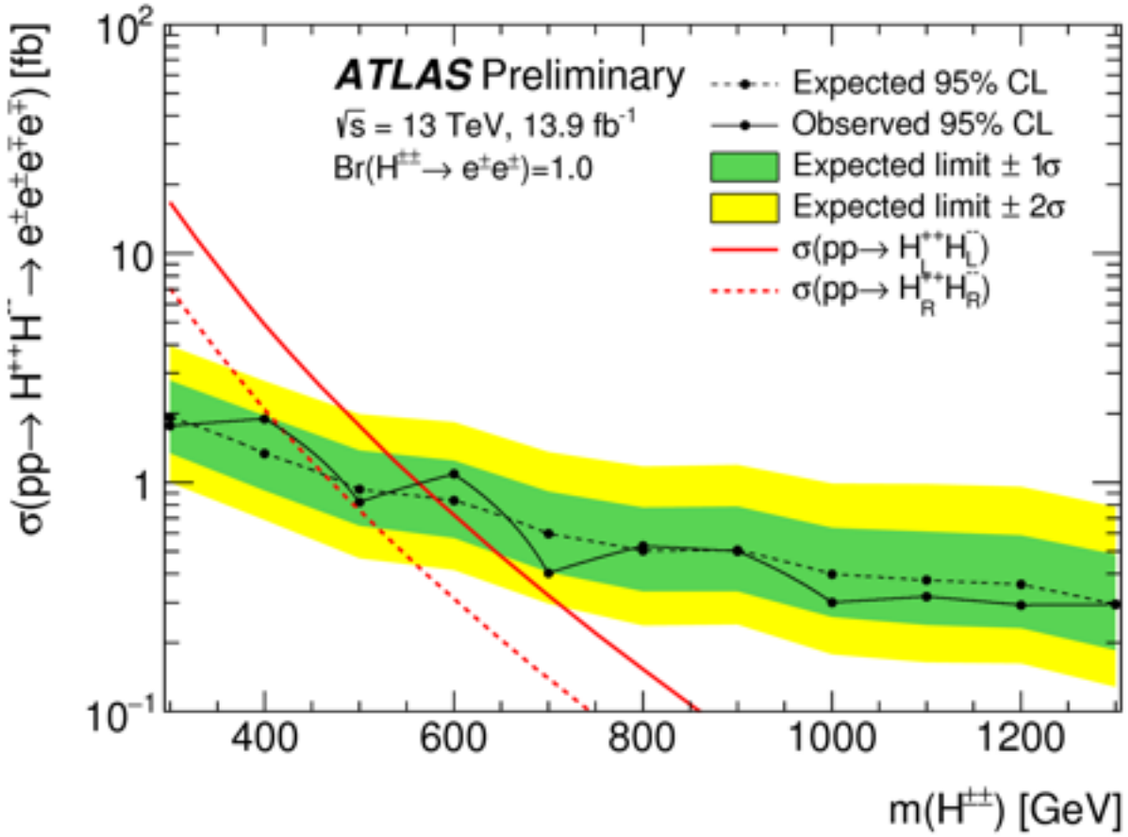


$H^{\pm\pm}$

- LR, Higgs triplet, See-saw, …
- $H^{\pm\pm} \rightarrow l^{\pm} l^{\pm}$ dominant for low triplet vev (else $W^{\pm} W^{\pm}$)
- Search for same-sign dielectrons
- Charge misidentification measured from data







Exotic Higgs/decays

NMSSM: light pseudo scalar

CP odd

a_1 a_2

Can be very light

CP even

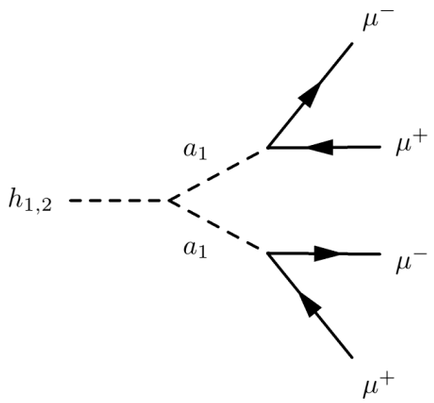
h_1 h_2 h_3

One of these SM-like

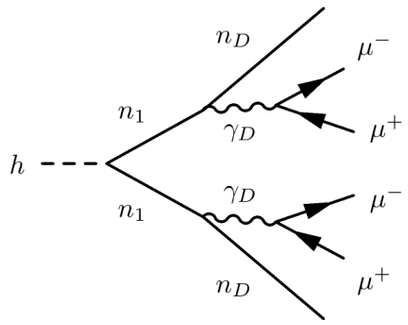
Charged

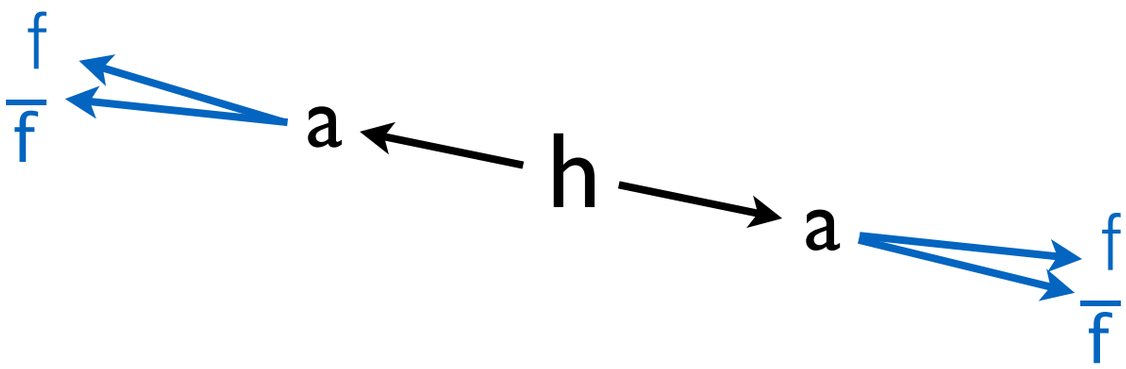
H^+ H^-

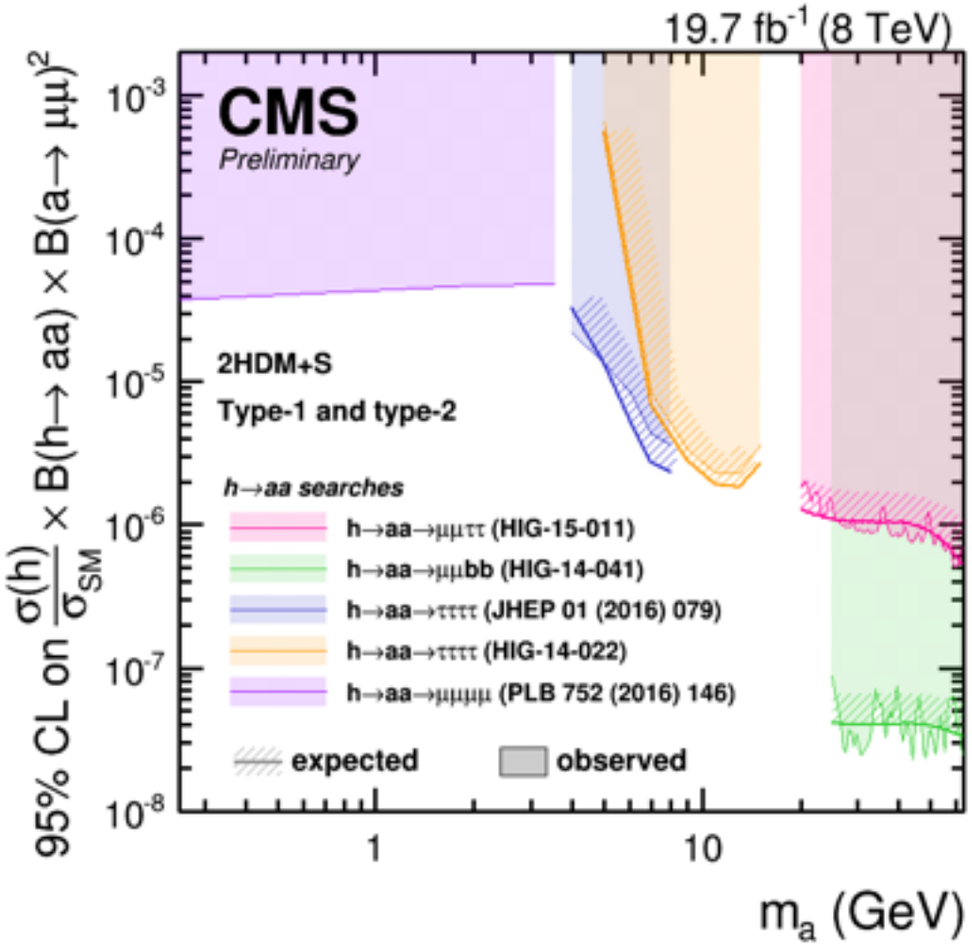
NMSSM



Dark SUSY







NMSSM: light pseudo scalar

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a_1 a_2

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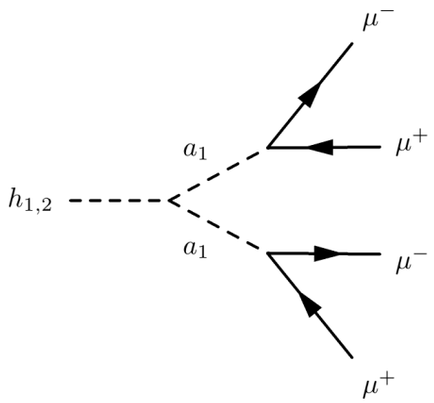
h_1 h_2 h_3

One of these SM-like

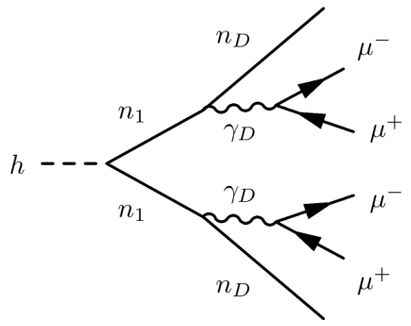
Charged

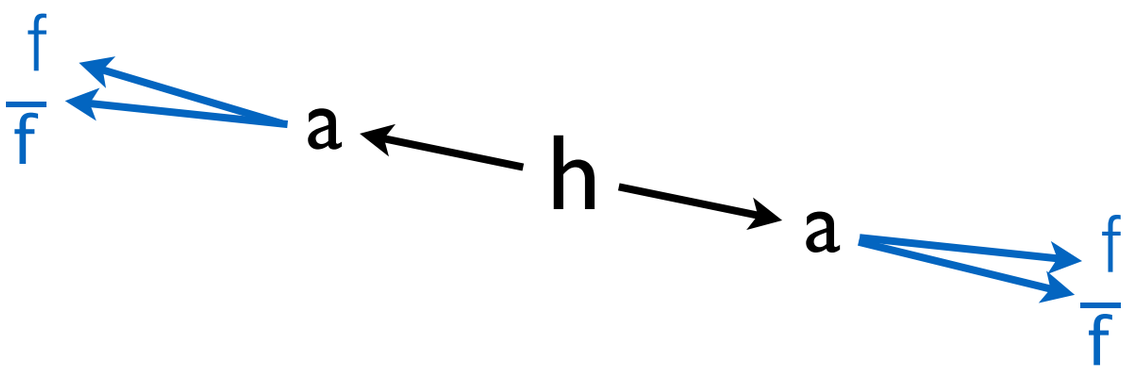
H^+ H^-

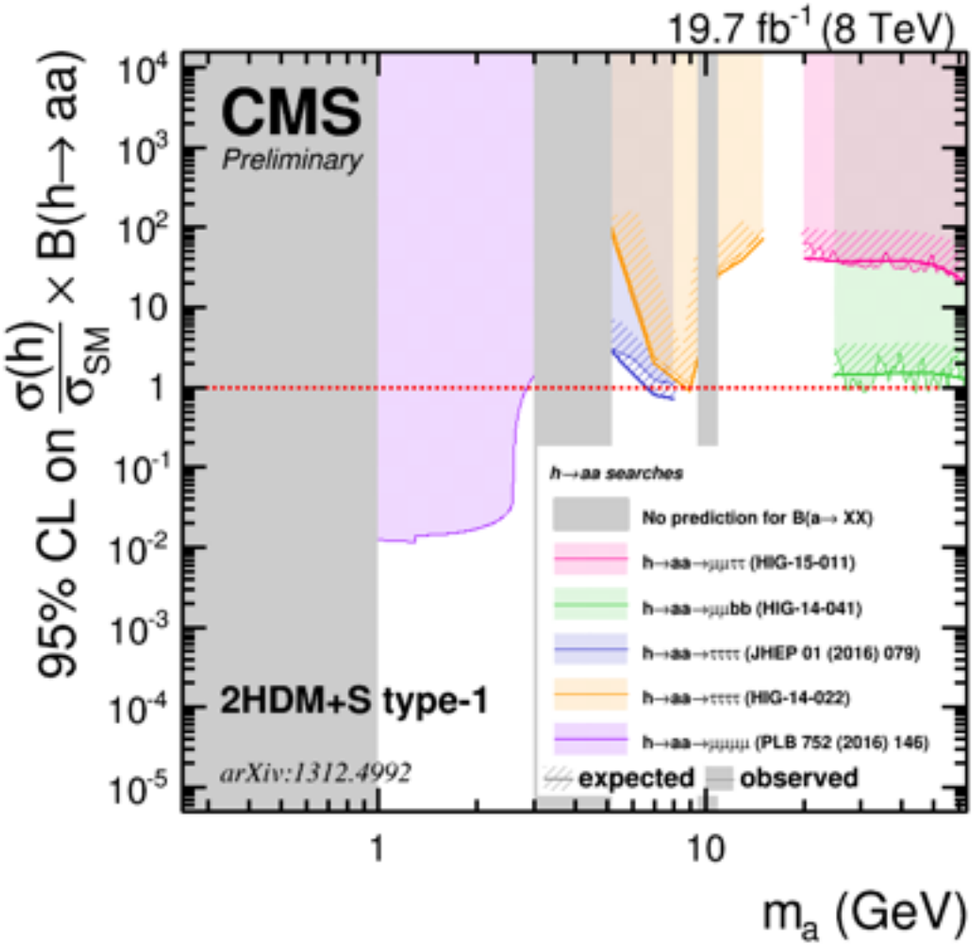
NMSSM



Dark SUSY

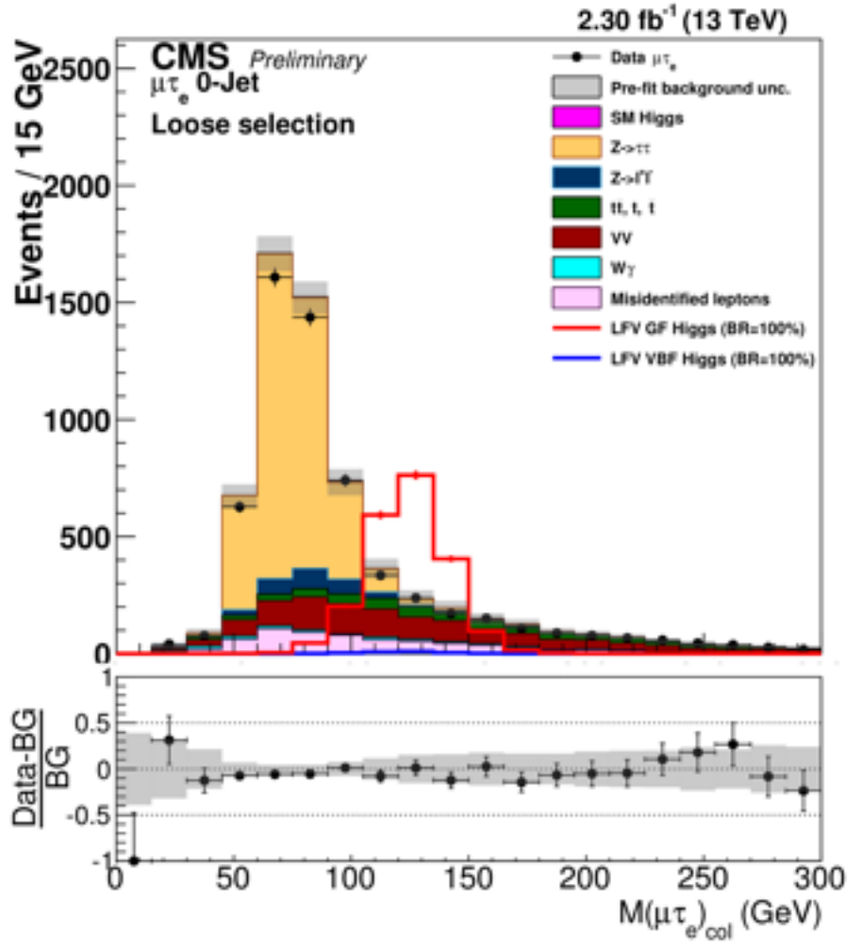


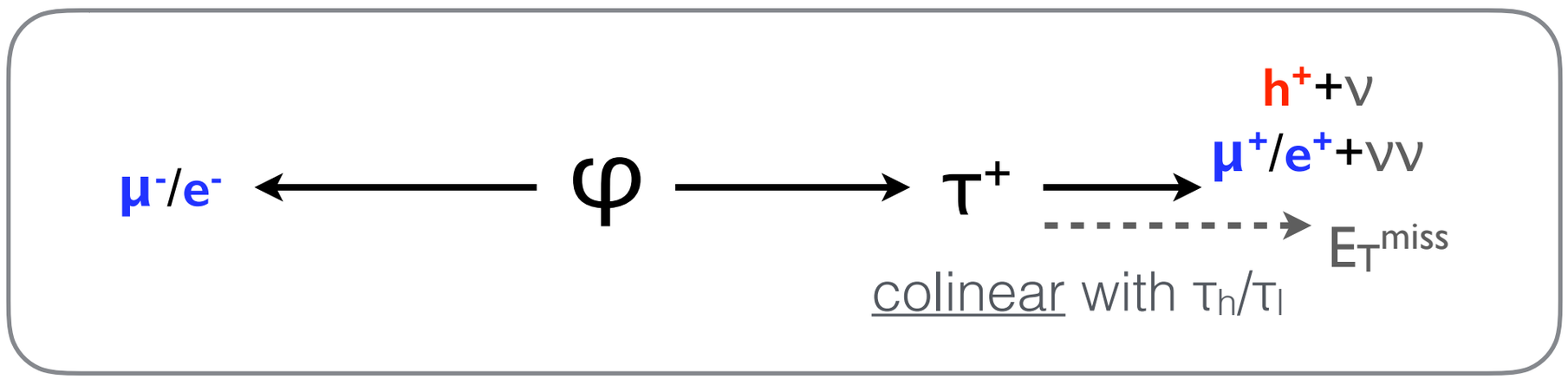




Lepton Flavour Violation

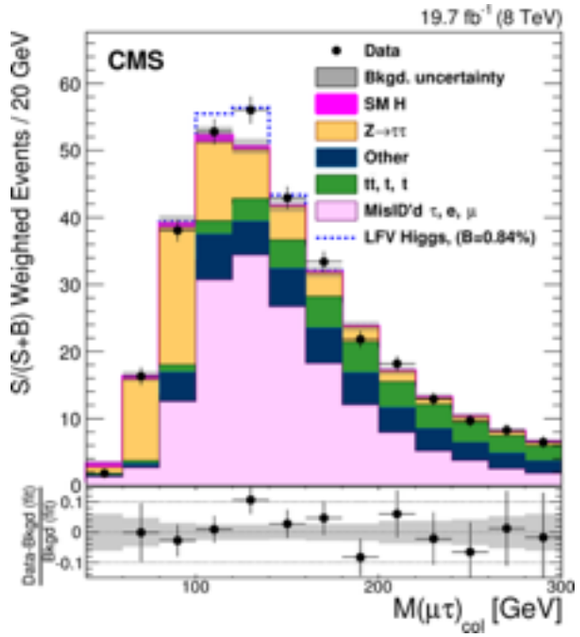
- BR(h→eμ) < O(10^{-8}) from μ→eγ
- Limits on h→eτ/μτ much weaker O(1%)
- Simplified H→ττ analysis with good mass resolution

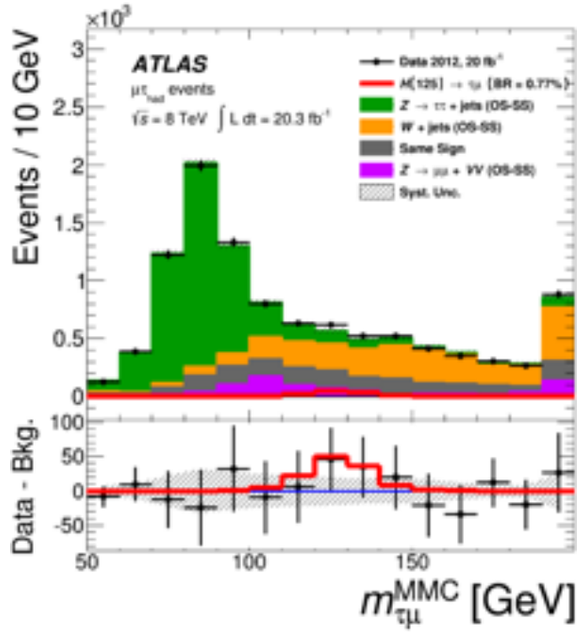




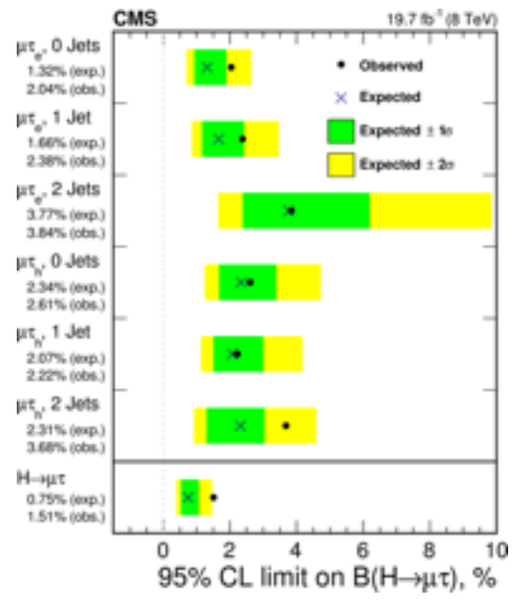
LFV: μτ excess

Run 1

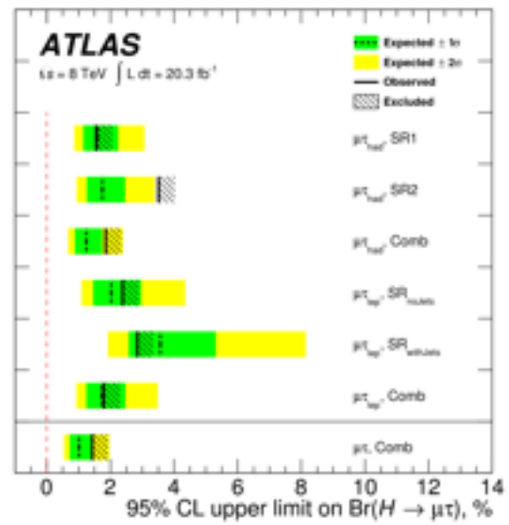




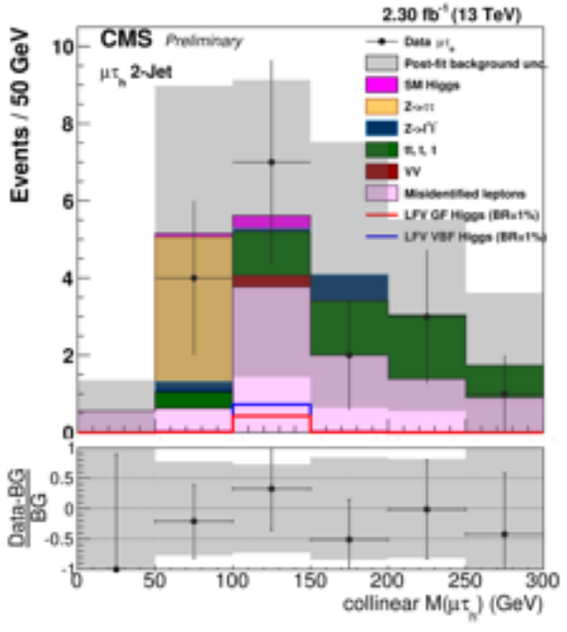
2.4σ



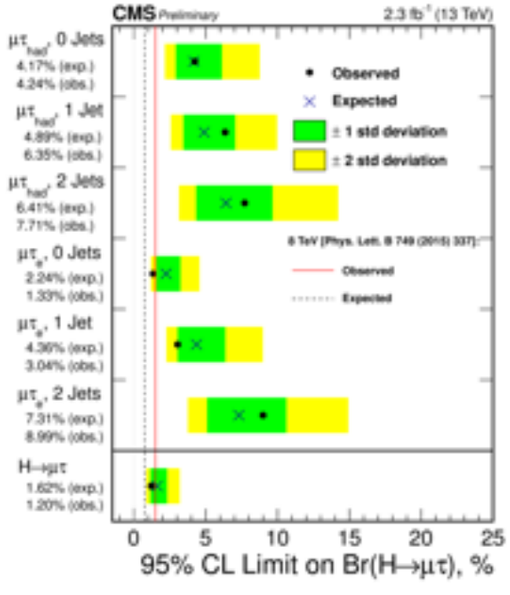
1.3σ



Run 2



Awaiting Results



Awaiting Results

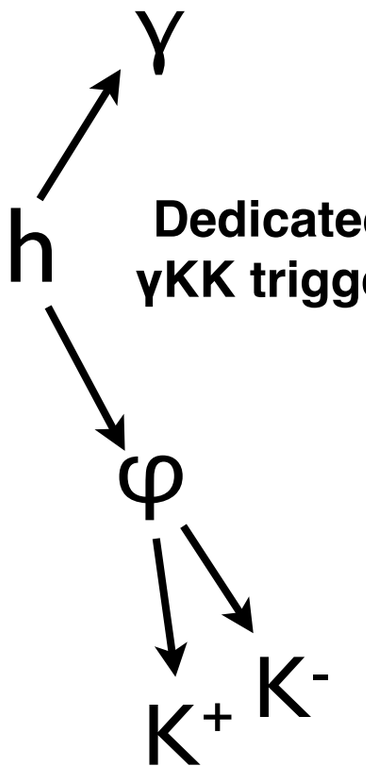
No excess in eτ, eμ channels!

$h \rightarrow \phi\gamma$

- B($h \rightarrow \phi\gamma$) = O(10^{-6}) in SM:
  find BSM physics, probe Yukawa coupling to u, d, s

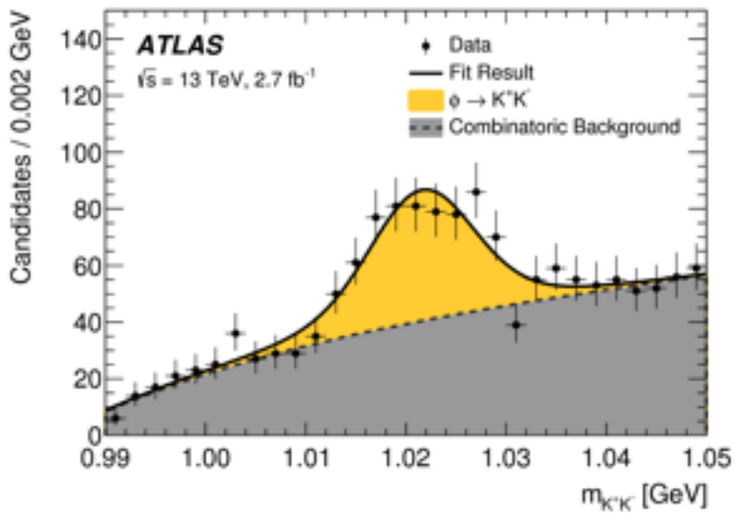
- Similar search for $h \rightarrow J/\psi/\Upsilon+\gamma$ (cf c-quark)

Isolated photon

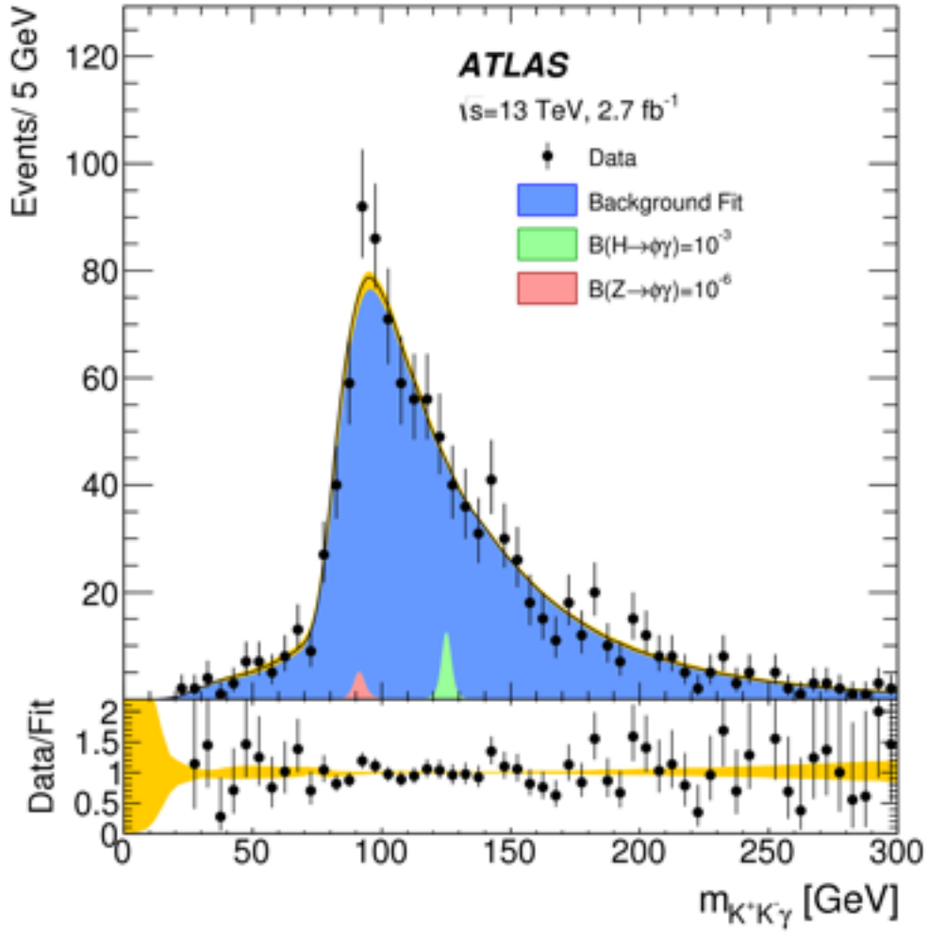


Dedicated γKK trigger

Isolated OS track pair $m_\phi \pm 20$MeV



$B(h \rightarrow \phi\gamma) < 1.4 \times 10^{-3}$



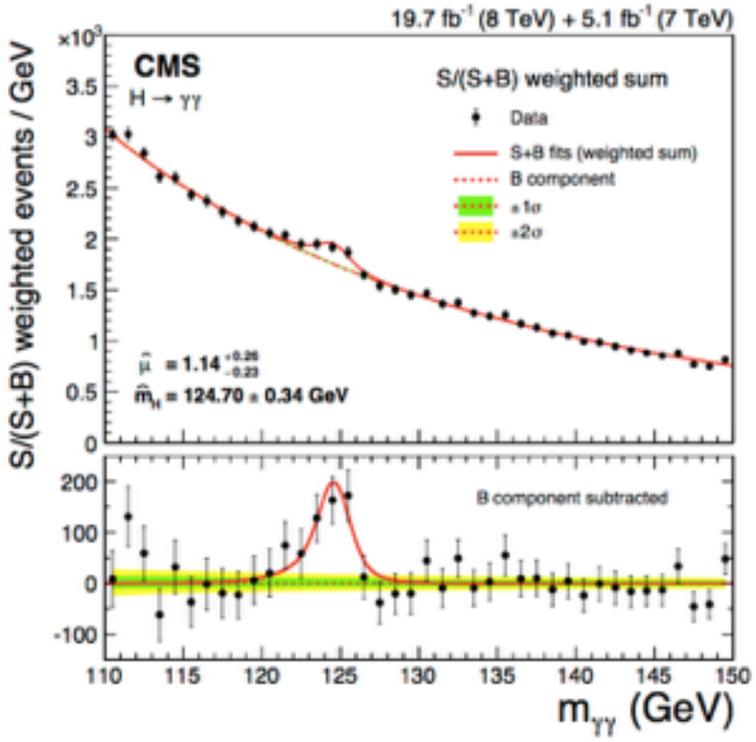
Summary

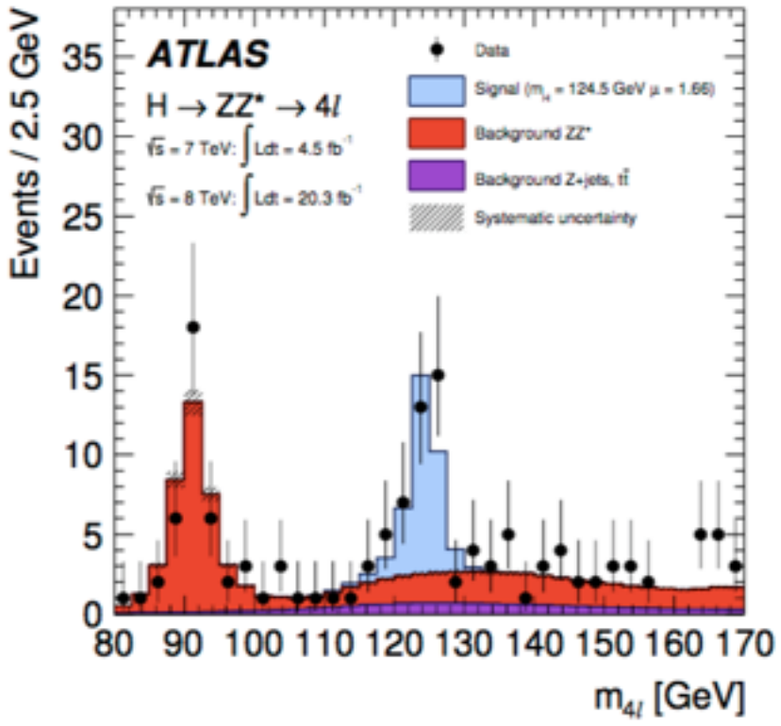
- We've learnt lots about the Higgs with current LHC data
- A few interesting excesses to keep an eye on
- Many plans for further measurements and searches for Run 2 and beyond!
- Much more to learn with more data: Run 2, Run 3, HL-LHC
- Check out links in attached pdf for more details

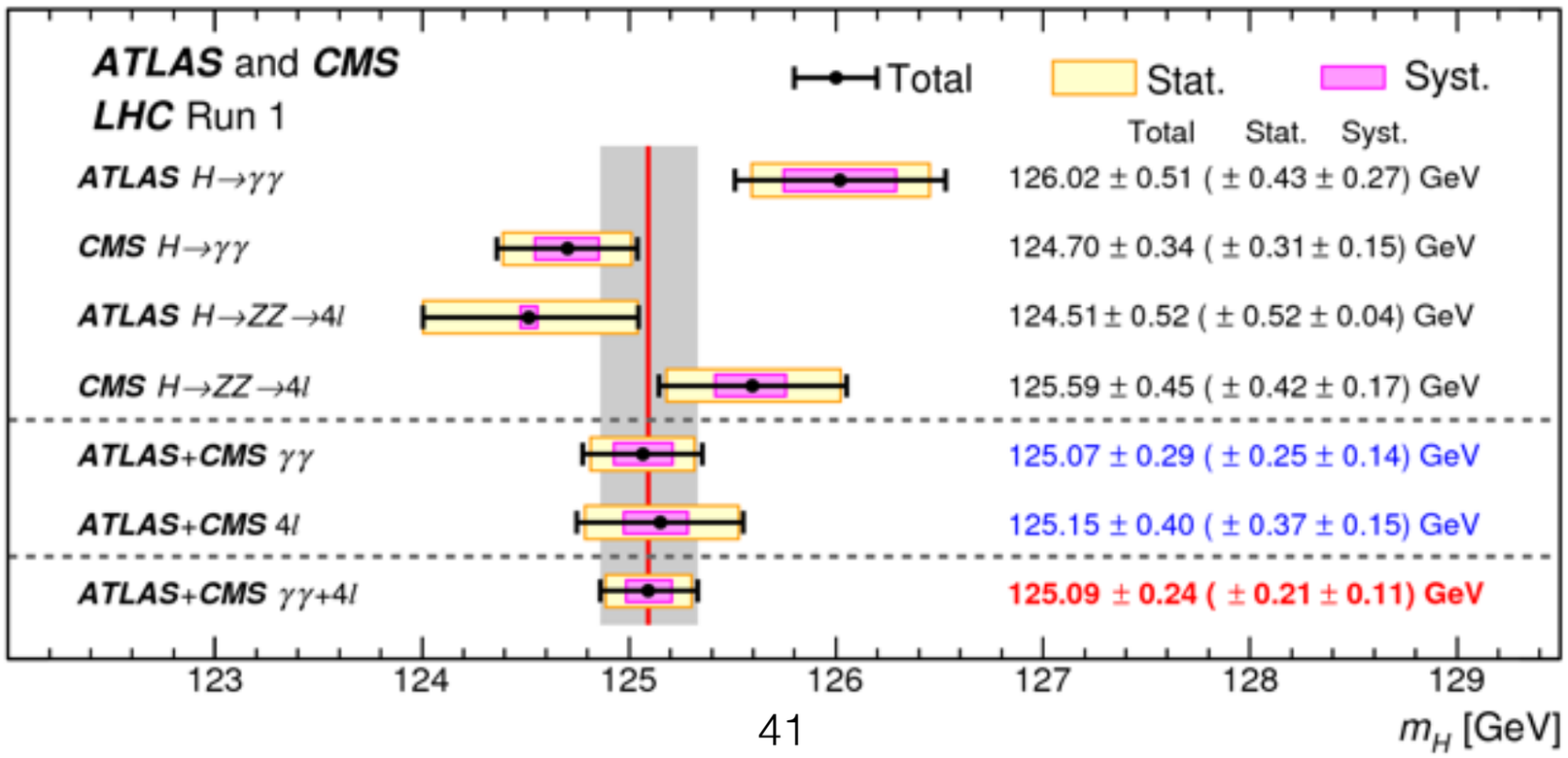
Thanks for your attention

Backup

h(125) mass

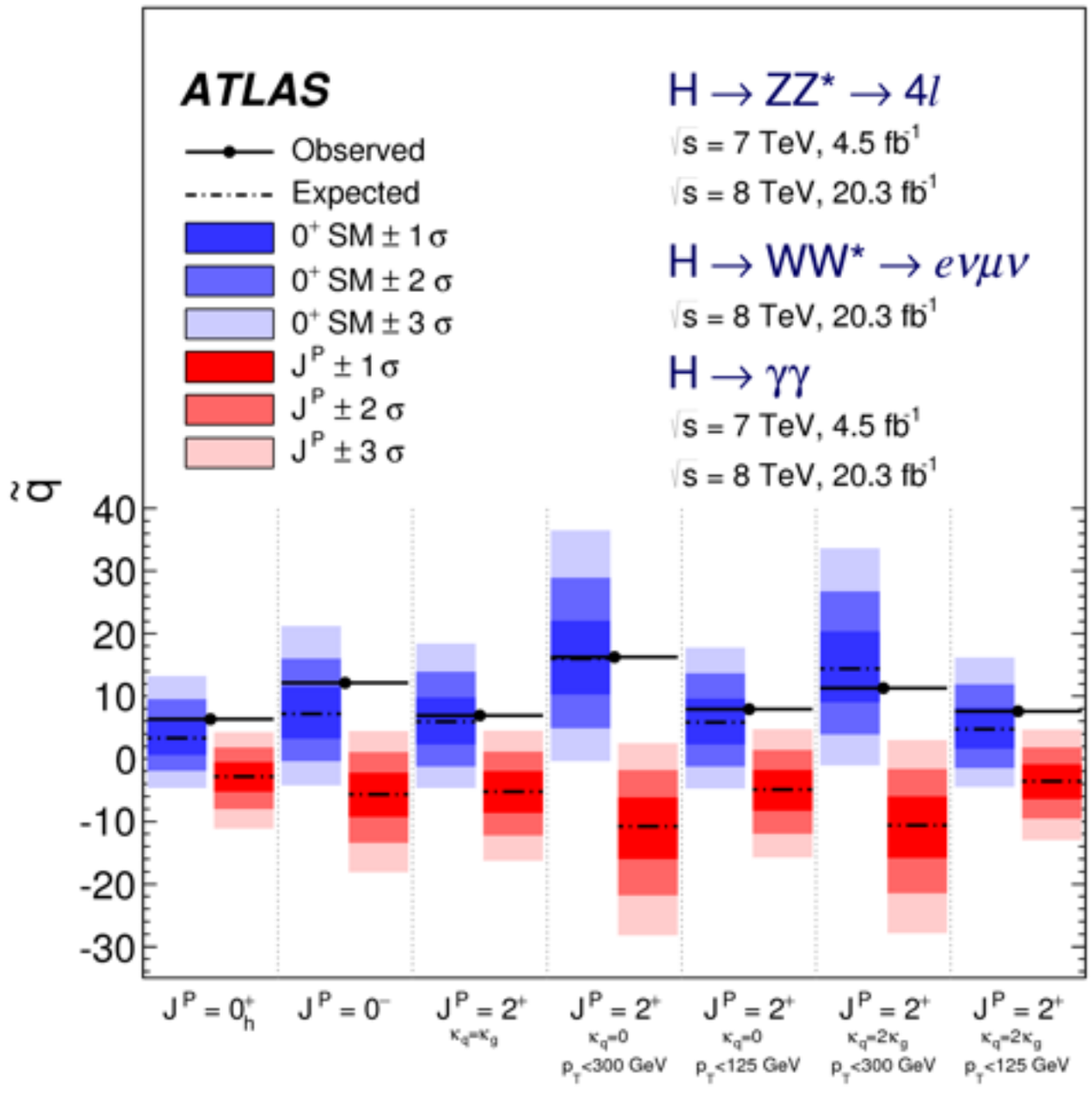

19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
$\hat{\mu}$ = 1.14 $^{+0.26}_{-0.23}$
$\hat{m}_H$ = 124.70 ± 0.34 GeV
S/(S+B) weighted events / GeV
B component subtracted
$m_{\gamma\gamma}$ (GeV)

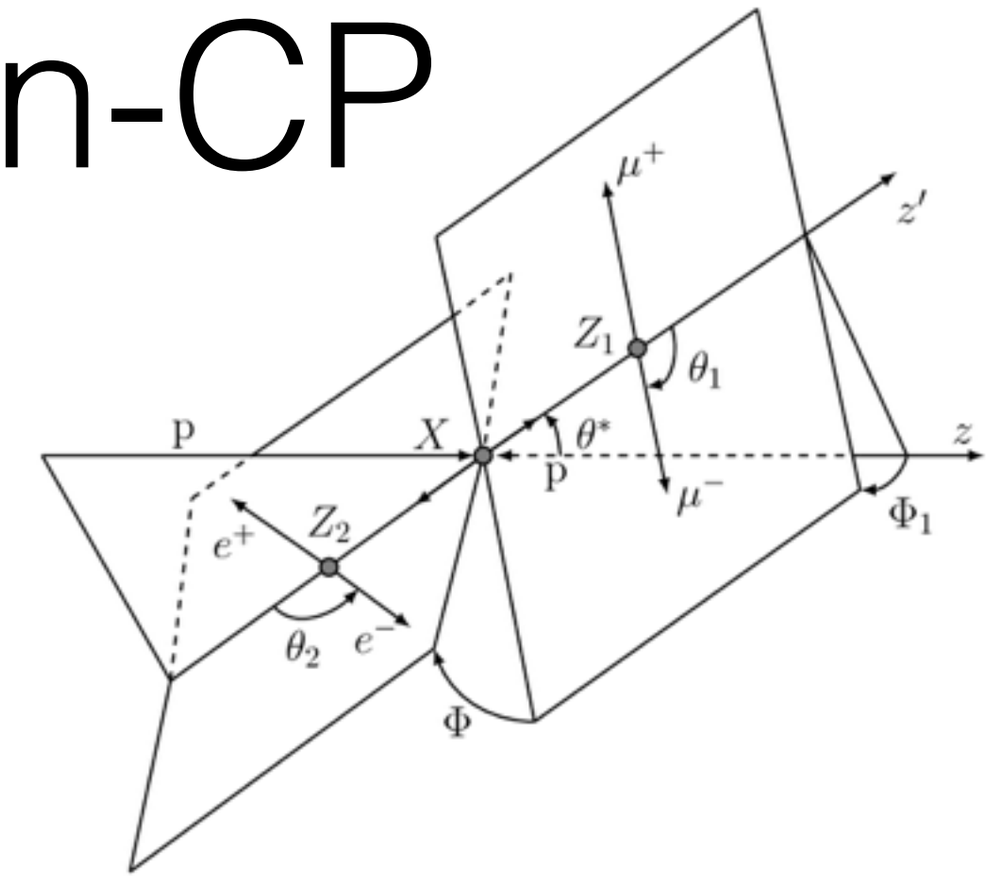

ATLAS
H → ZZ* → 4l
√s = 7 TeV: ∫Ldt = 4.5 fb^{-1}
√s = 8 TeV: ∫Ldt = 20.3 fb^{-1}
Data
Signal (m_H = 124.5 GeV μ = 1.66)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
Events / 2.5 GeV
m_{4l} [GeV]

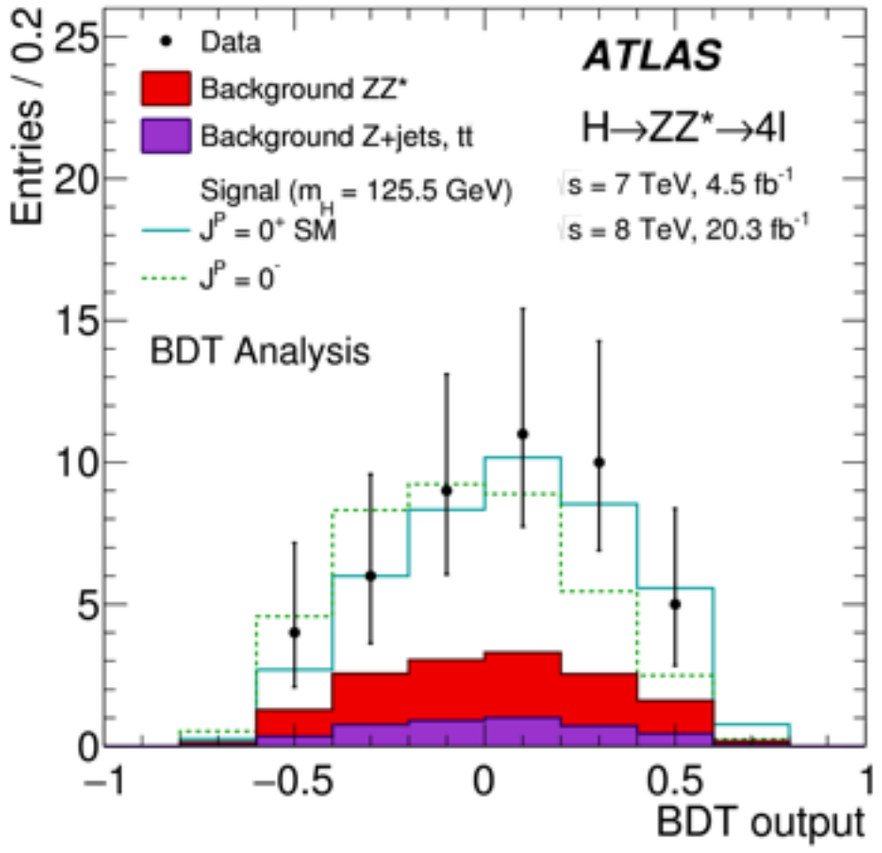

ATLAS and CMS
LHC Run 1
Total
Stat.
Syst.
Total Stat. Syst.
ATLAS H→γγ 126.02 ± 0.51 (± 0.43 ± 0.27) GeV
CMS H→γγ 124.70 ± 0.34 (± 0.31 ± 0.15) GeV
ATLAS H→ZZ→4l 124.51 ± 0.52 (± 0.52 ± 0.04) GeV
CMS H→ZZ→4l 125.59 ± 0.45 (± 0.42 ± 0.17) GeV
ATLAS+CMS γγ 125.07 ± 0.29 (± 0.25 ± 0.14) GeV
ATLAS+CMS 4l 125.15 ± 0.40 (± 0.37 ± 0.15) GeV
ATLAS+CMS γγ+4l 125.09 ± 0.24 (± 0.21 ± 0.11) GeV
m_H [GeV]

h(125) spin-CP

$J^P = 0^+$ strongly favoured



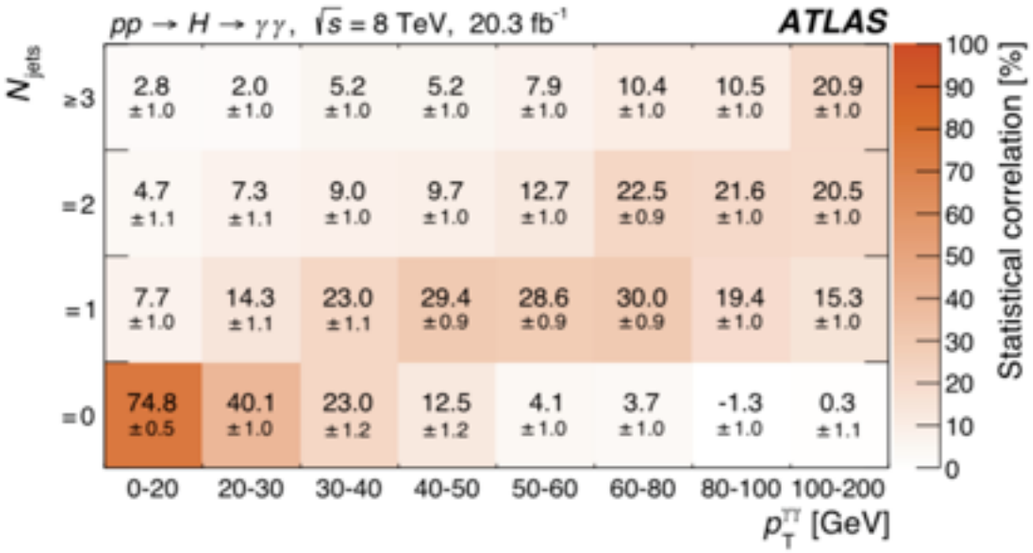


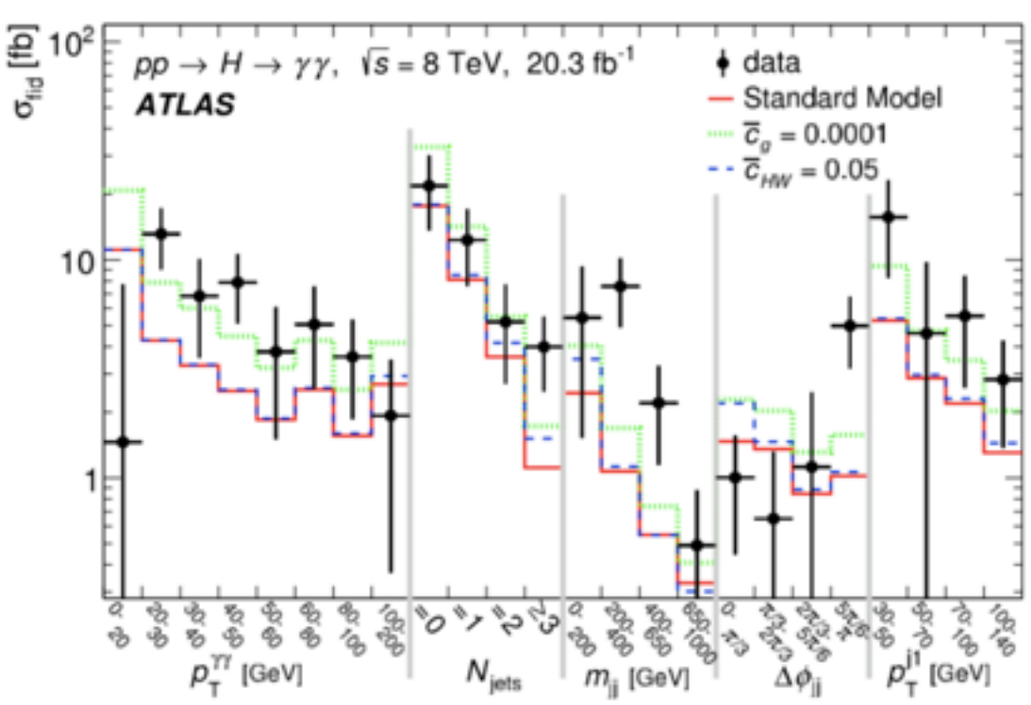


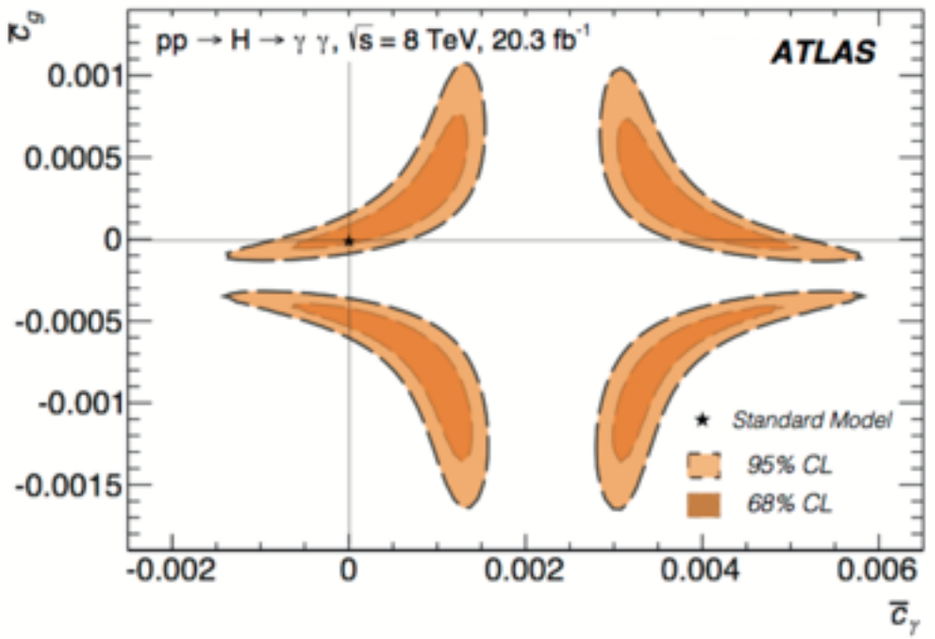
EFT approach

- Alternate to kappa approach accounting for impact on differential distributions, demonstrated using H→γγ

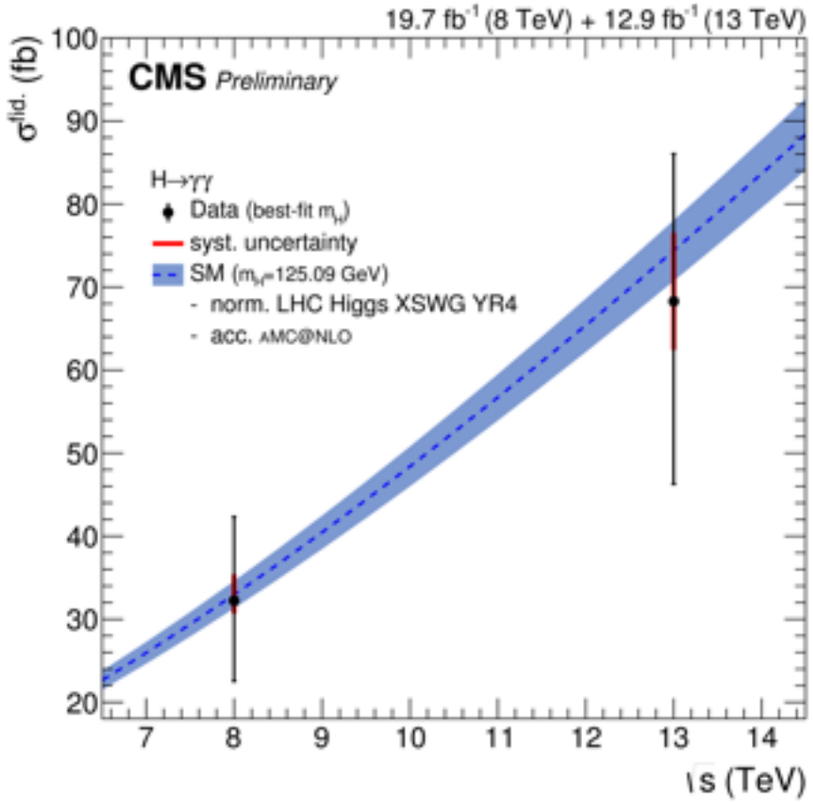
$$\mathcal{L}_{\text{eff}} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

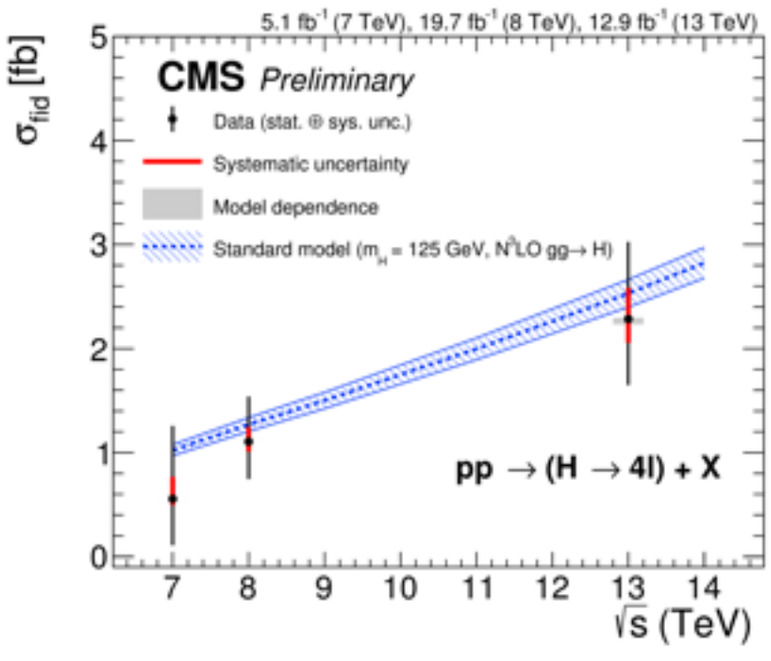


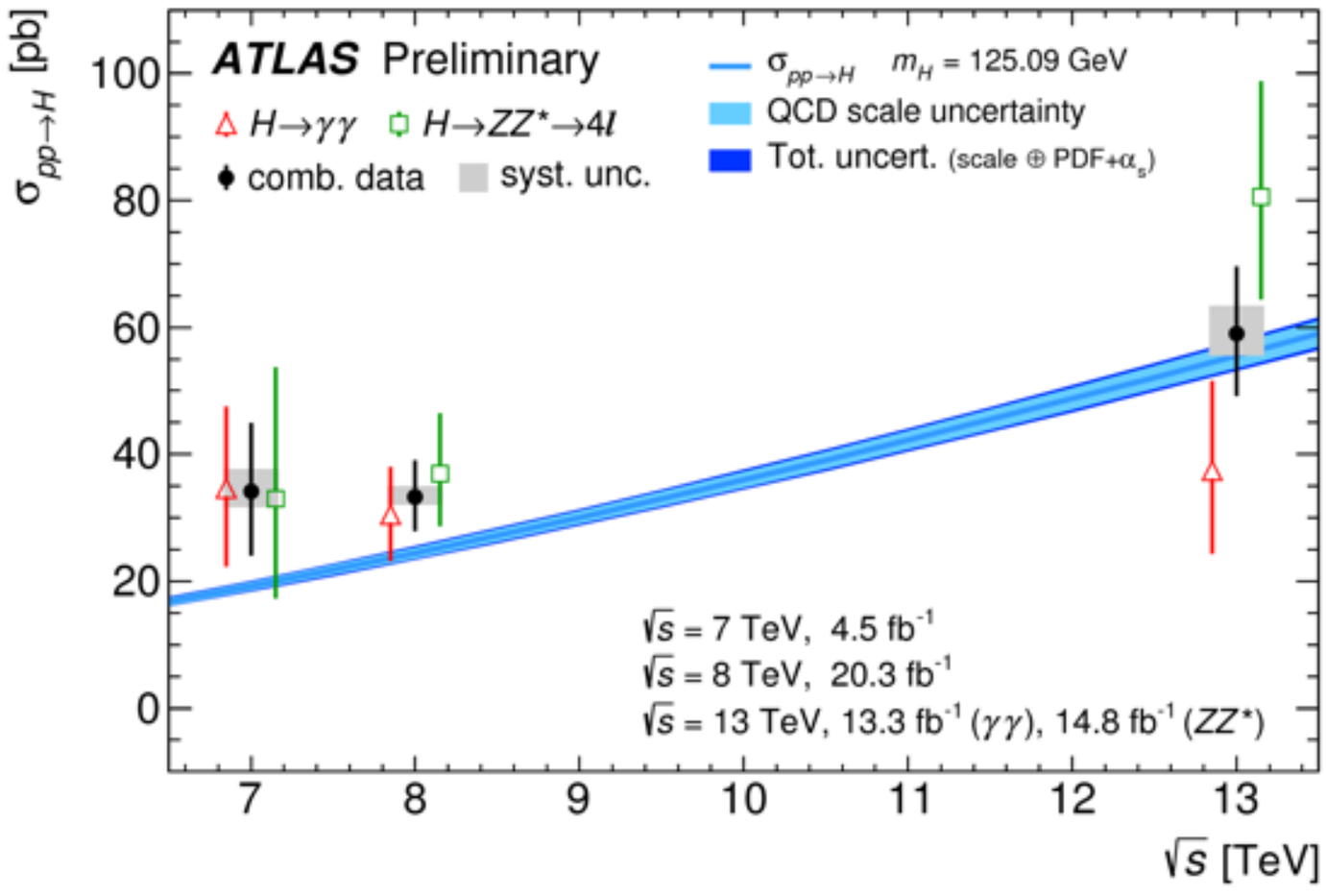




√s dependence





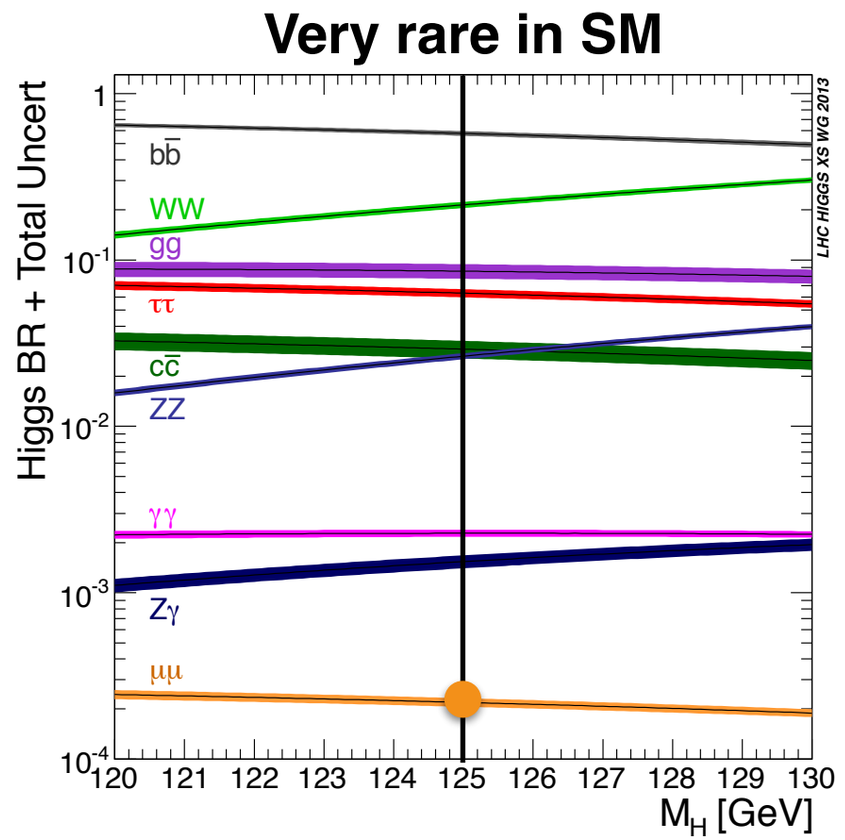


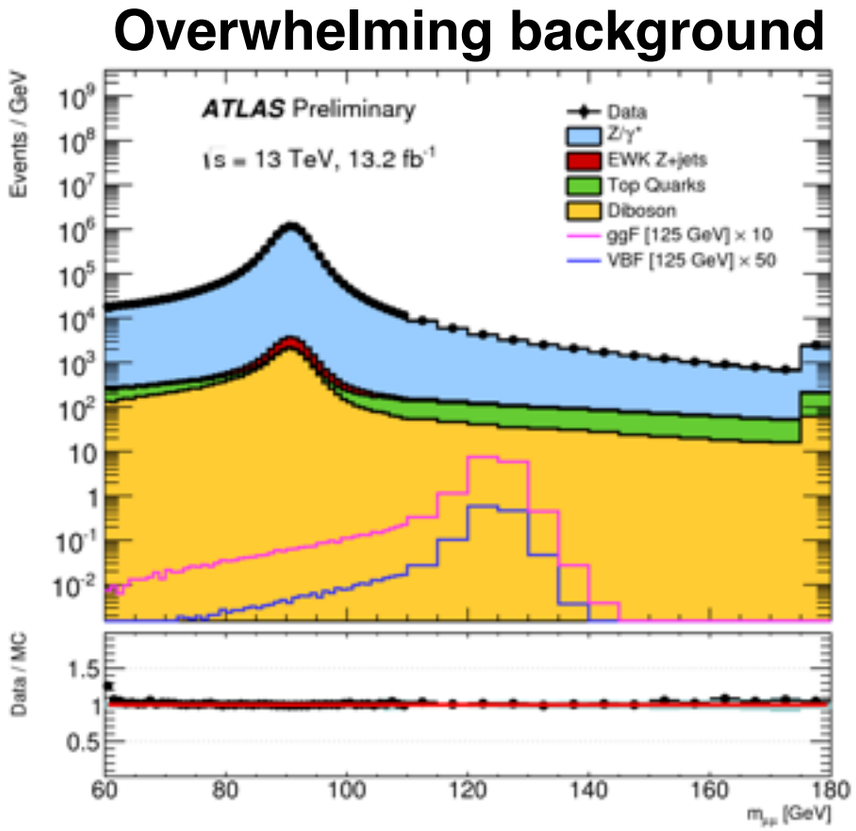
H→μμ

- **Goal:** probe Yukawa mass dependence, 2nd gen. coupling, lepton coupling

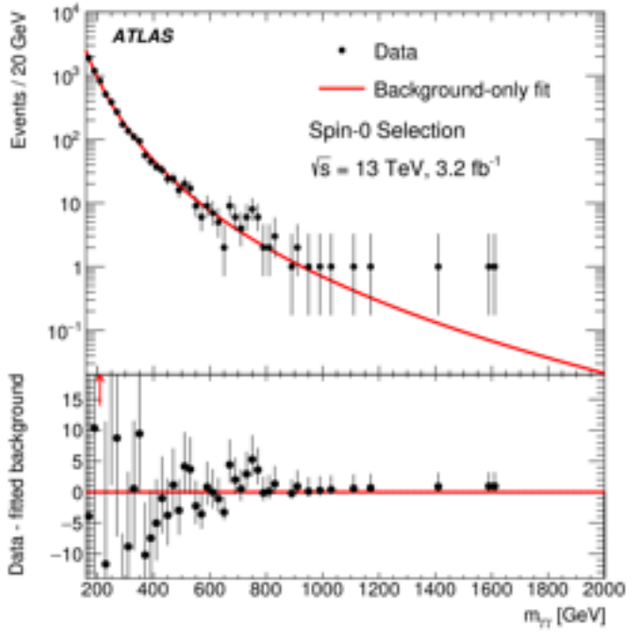
- **Signature:** very clean dimuon final state but overwhelming irreducible Z/γ*→μμ

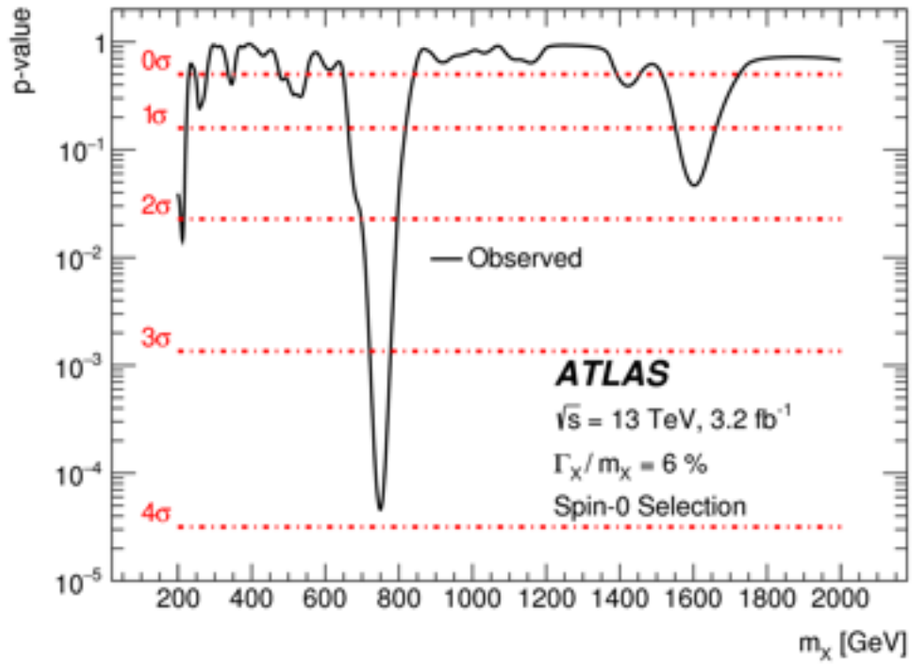
- **Strategy:** cf H→γγ

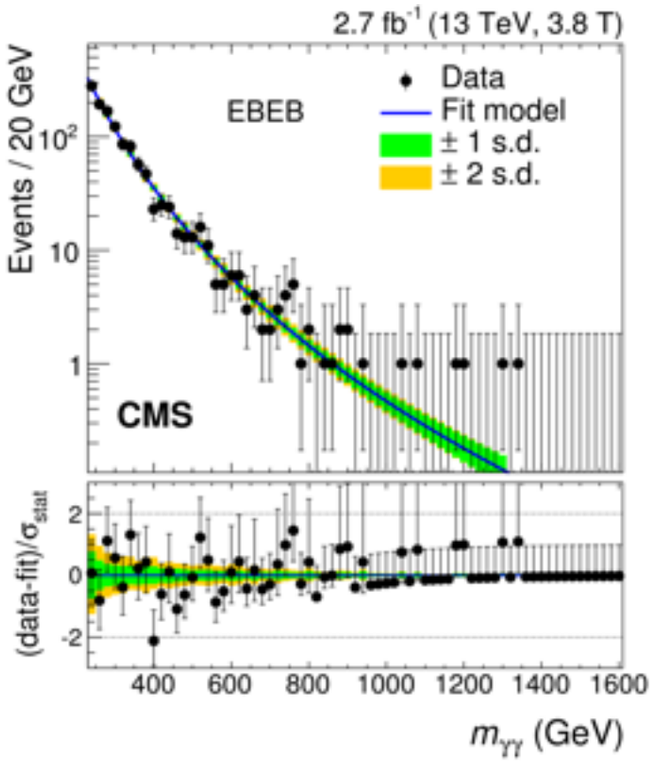


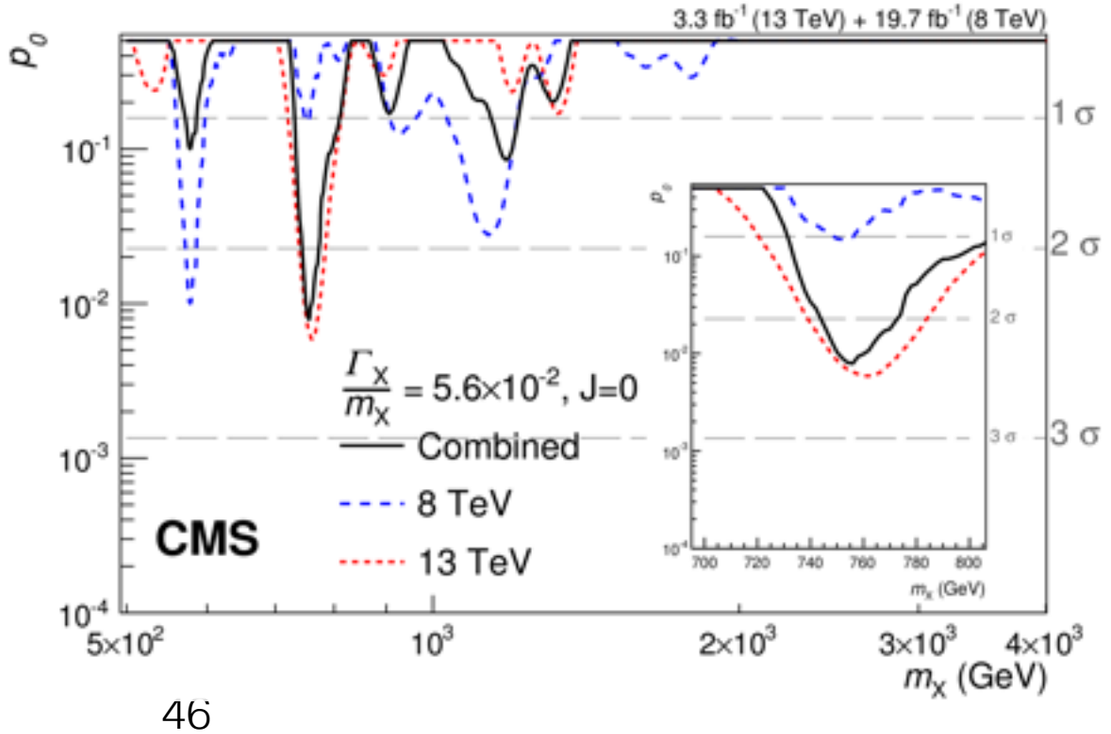


“X(750)” appears

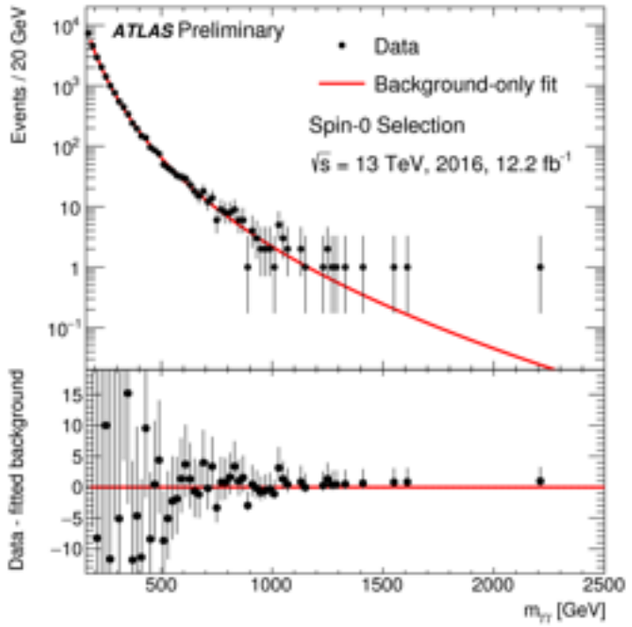


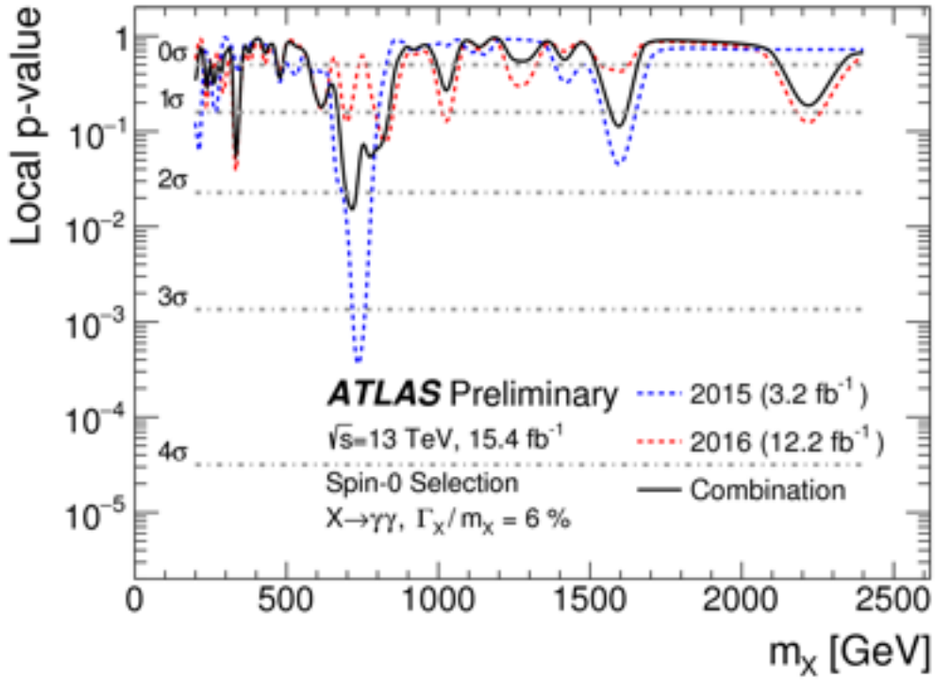


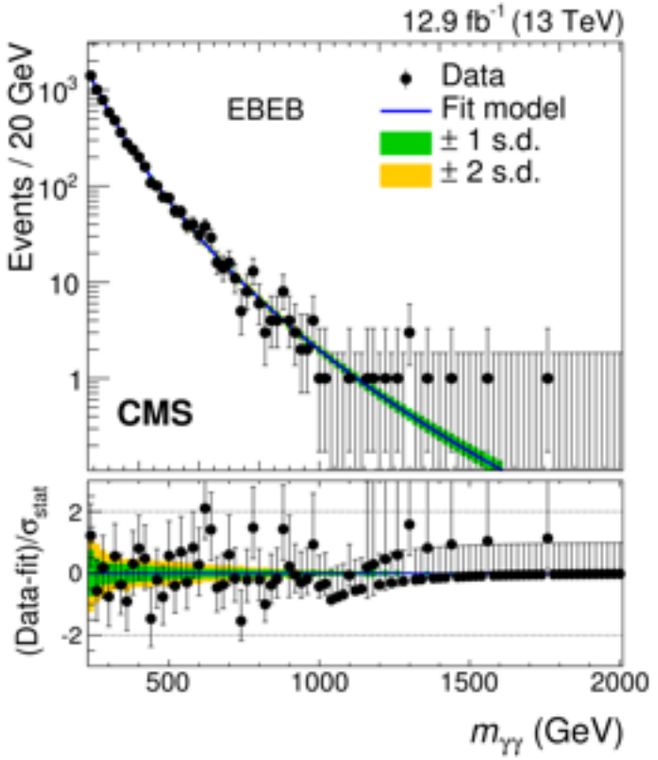


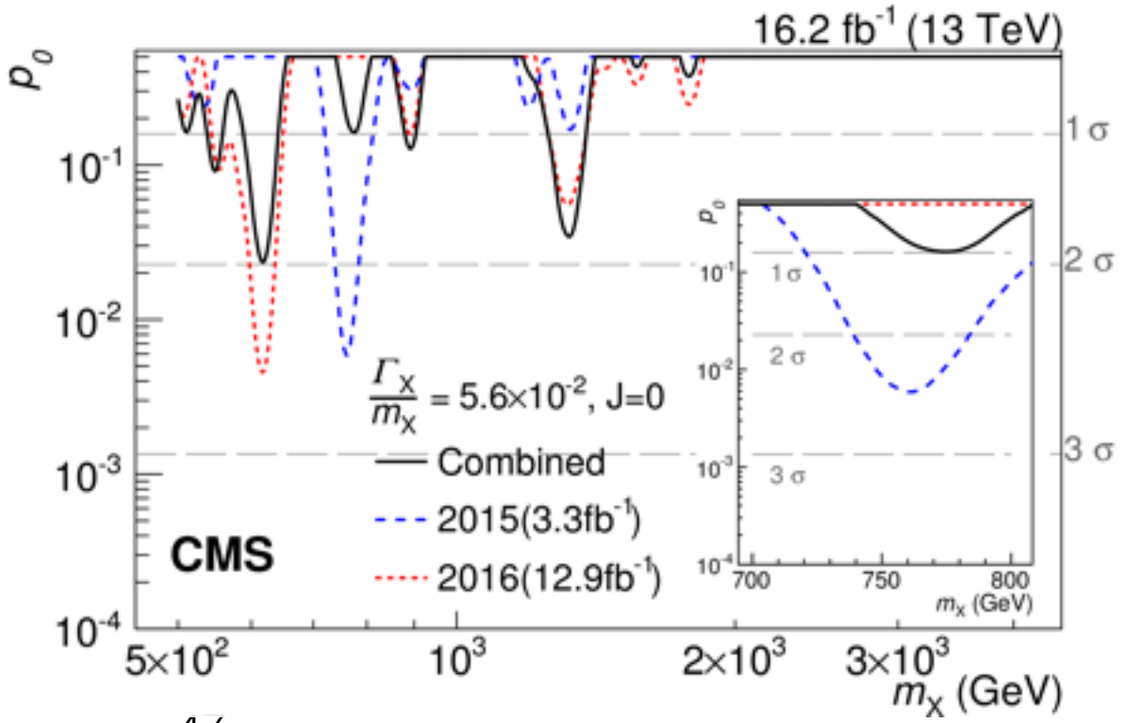


“X(750)” disappears





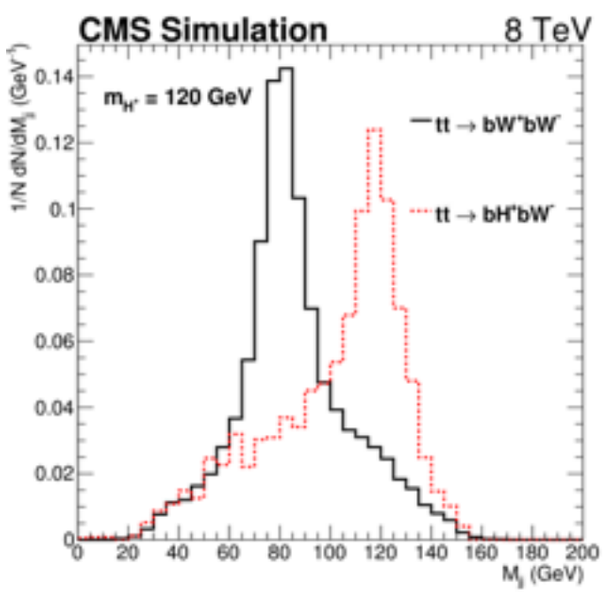


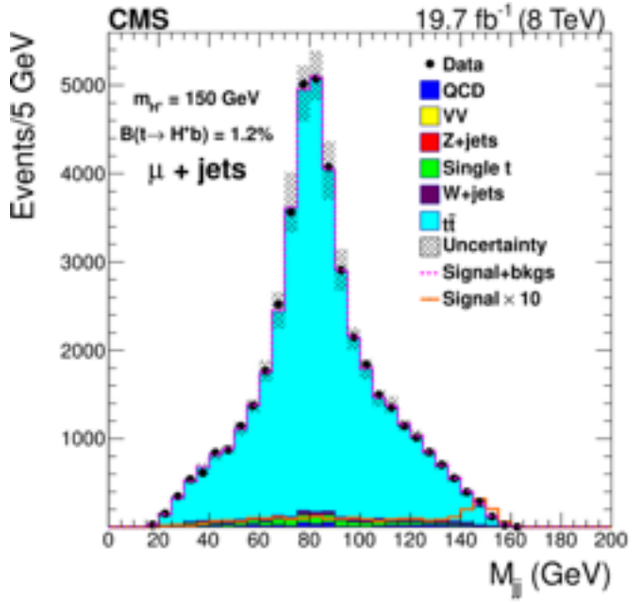


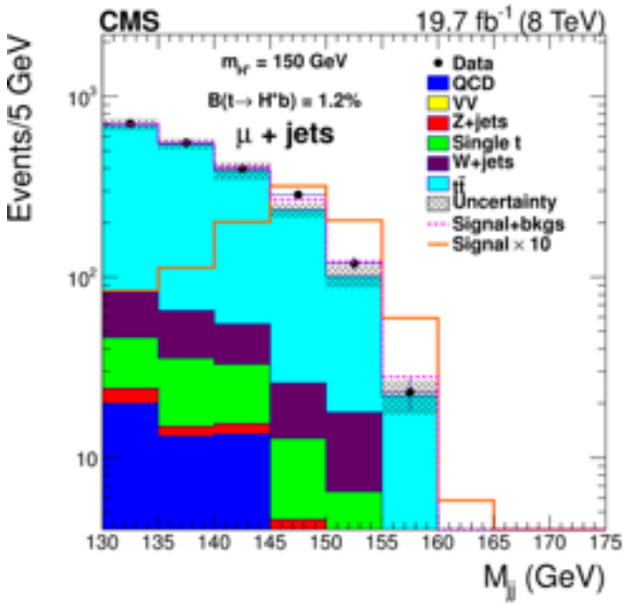
$H^{\pm} \rightarrow cs$

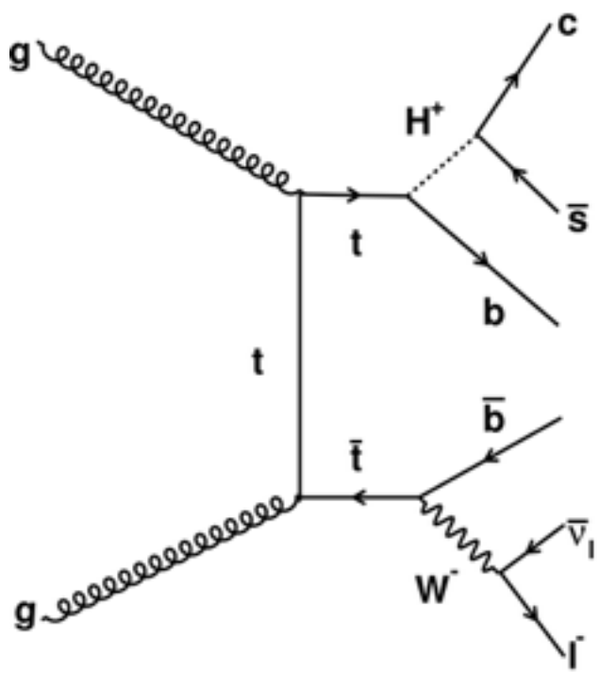
Dominant for low mass higgs with tanb < 1 in MSSM
(and some 2HDM parameter space)

Select: 1 isolated lepton, ≥4 jets (≥2 b-tagged)

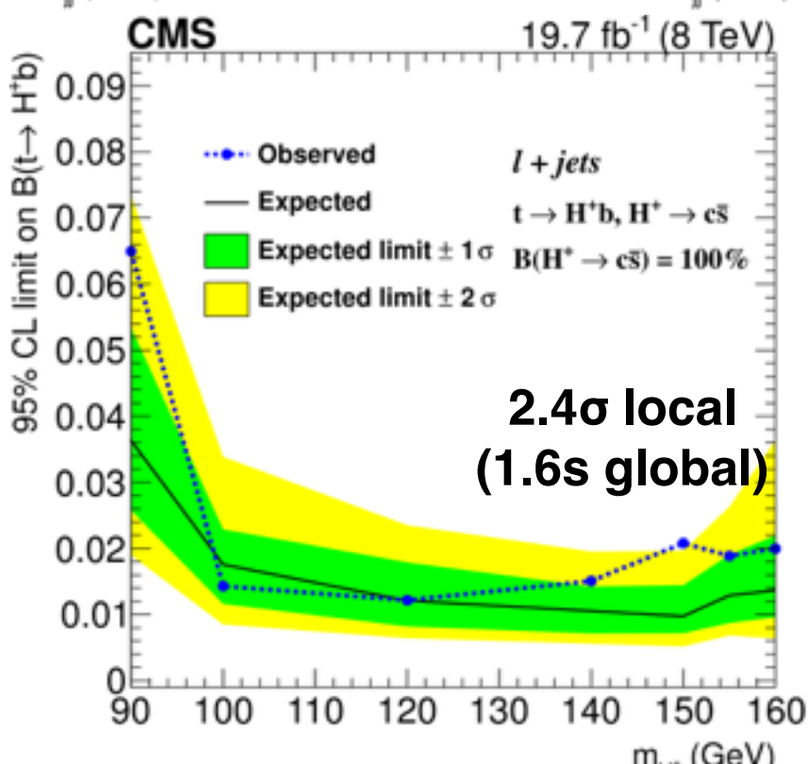




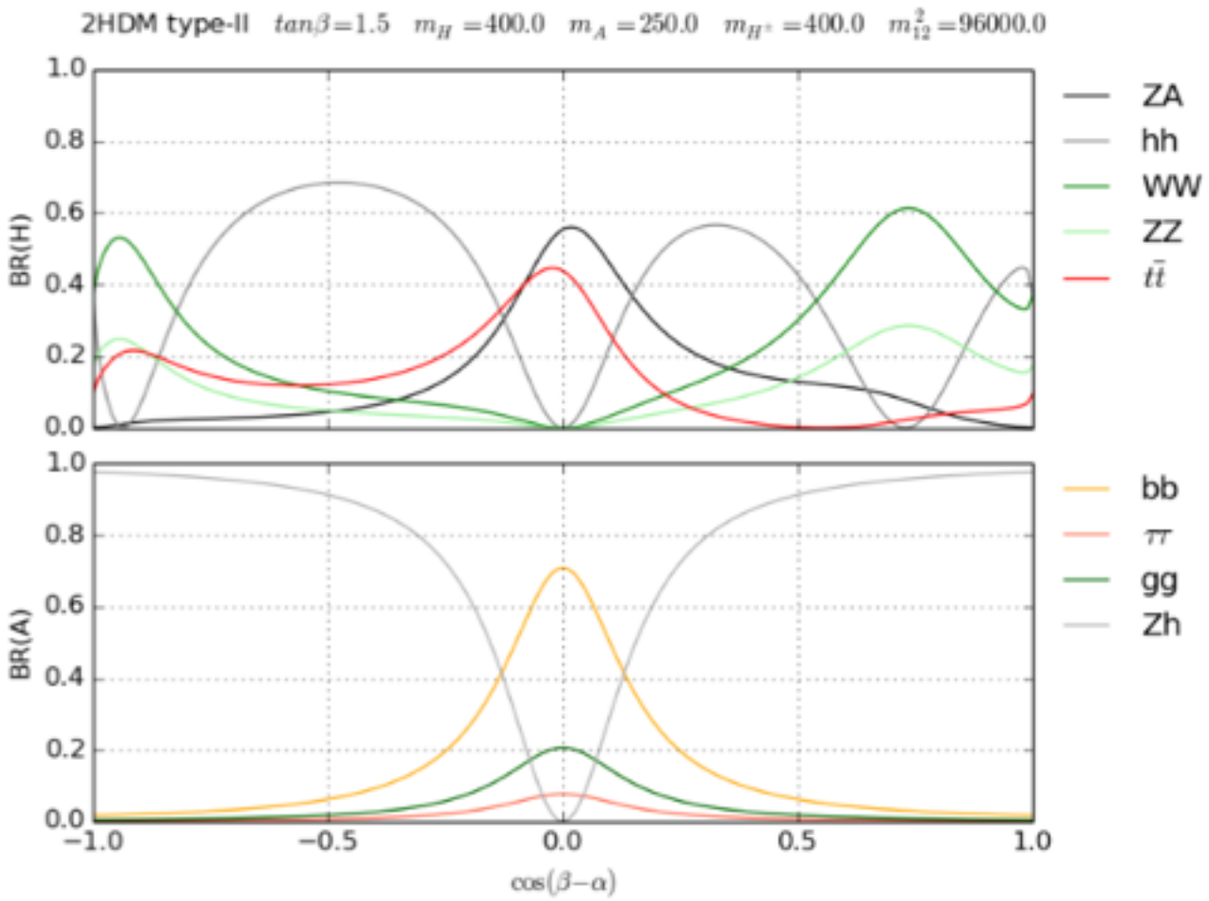


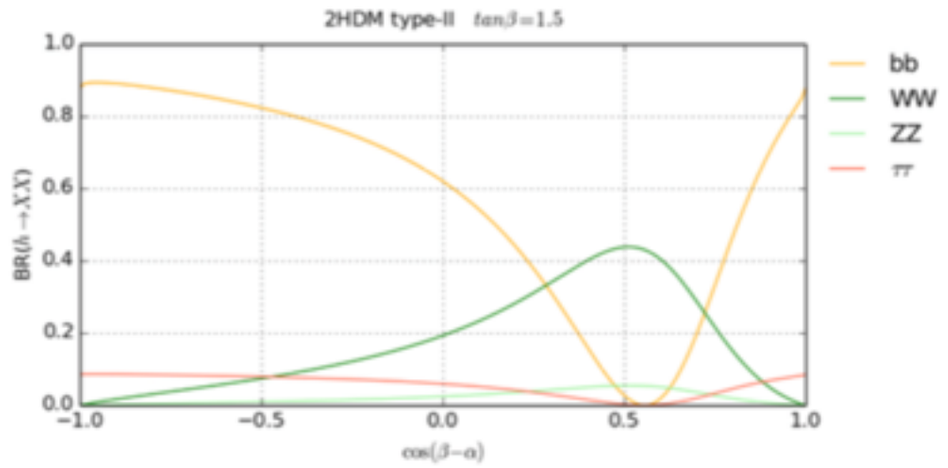


Kinematic fit: b-jet assignment, W/H masses



2HDM BRs

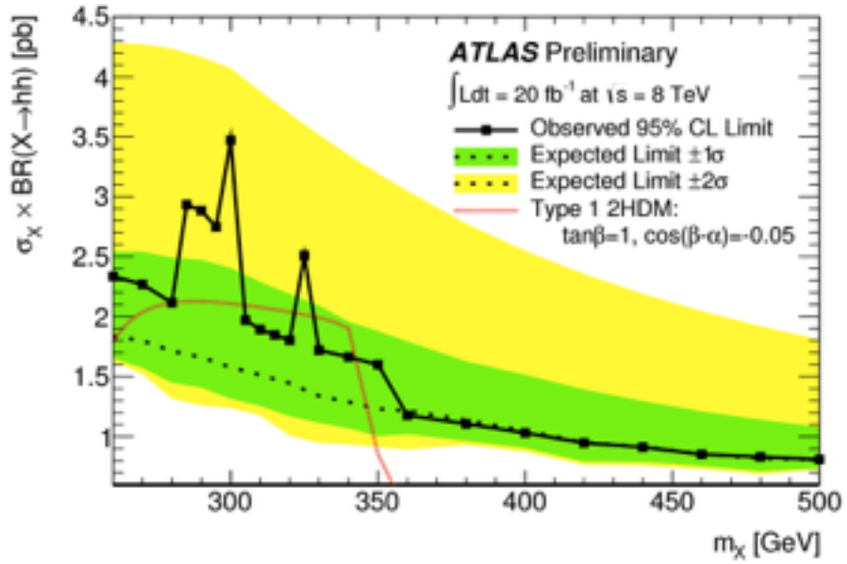

2HDM type-II $tan\beta=1.5$ $m_H=400.0$ $m_A=250.0$ $m_{H^\pm}=400.0$ $m^2_{12}=96000.0$
BR(H)
ZA
hh
WW
ZZ
$t\bar{t}$
BR(A)
bb
$\tau\tau$
gg
Zh
$\cos(\beta-\alpha)$


2HDM type-II $tan\beta=1.5$
bb
WW
ZZ
$\tau\tau$
$\cos(\beta-\alpha)$

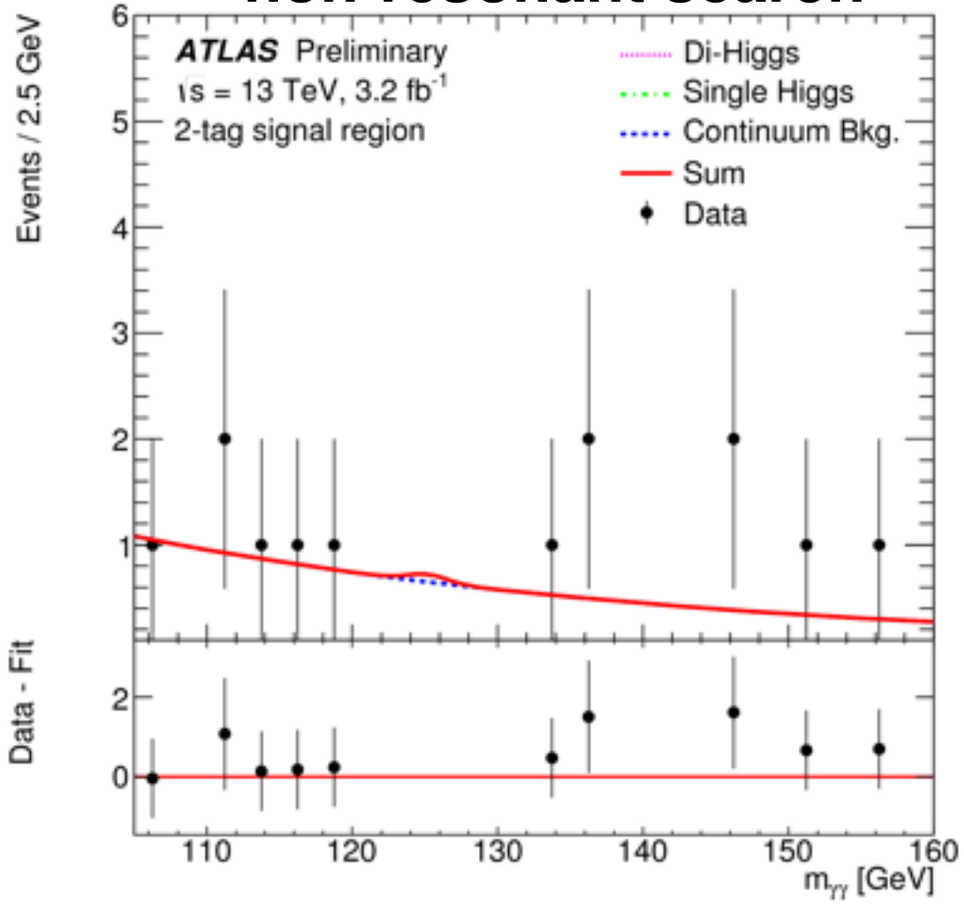
X→hh→bbγγ

"Similar strategy to 4b with some tricks from SM h→γγ analysis"

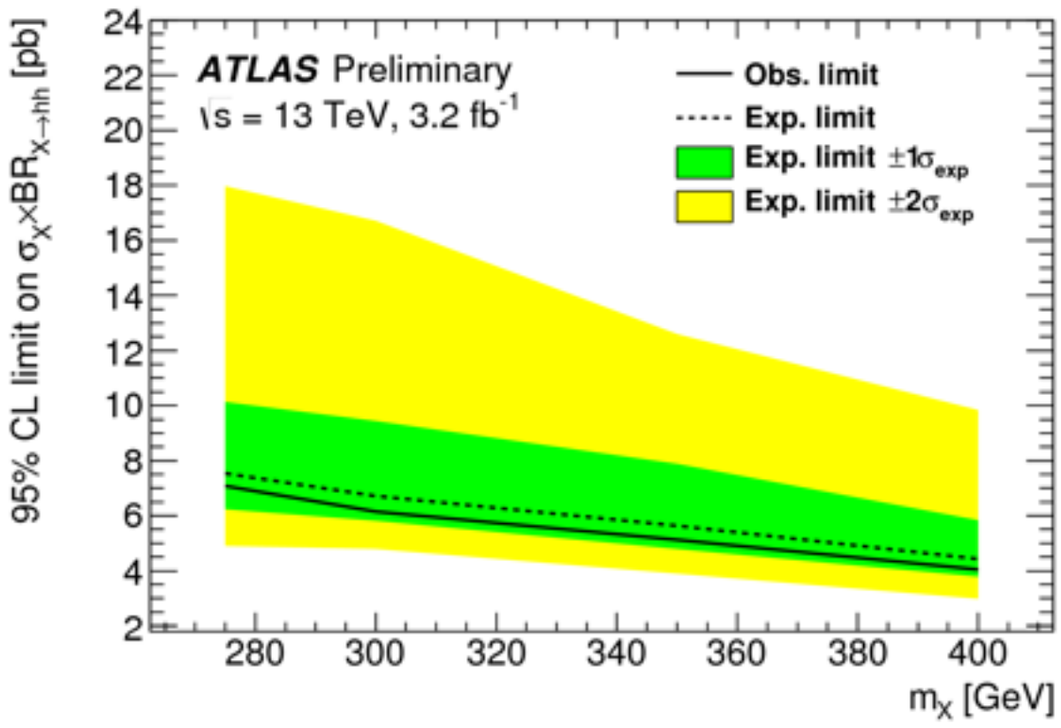
Run 1 "excess"



non-resonant search

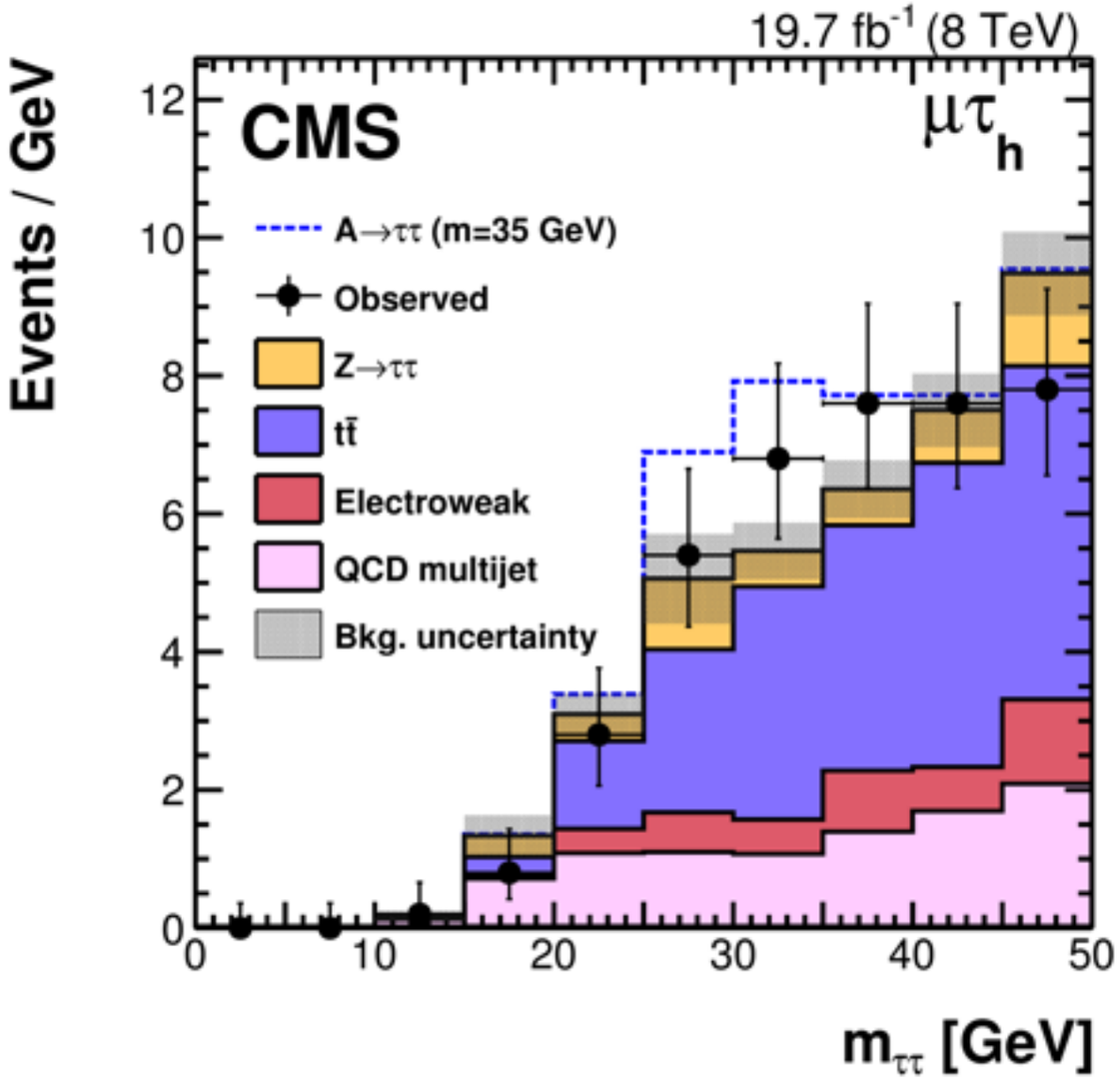


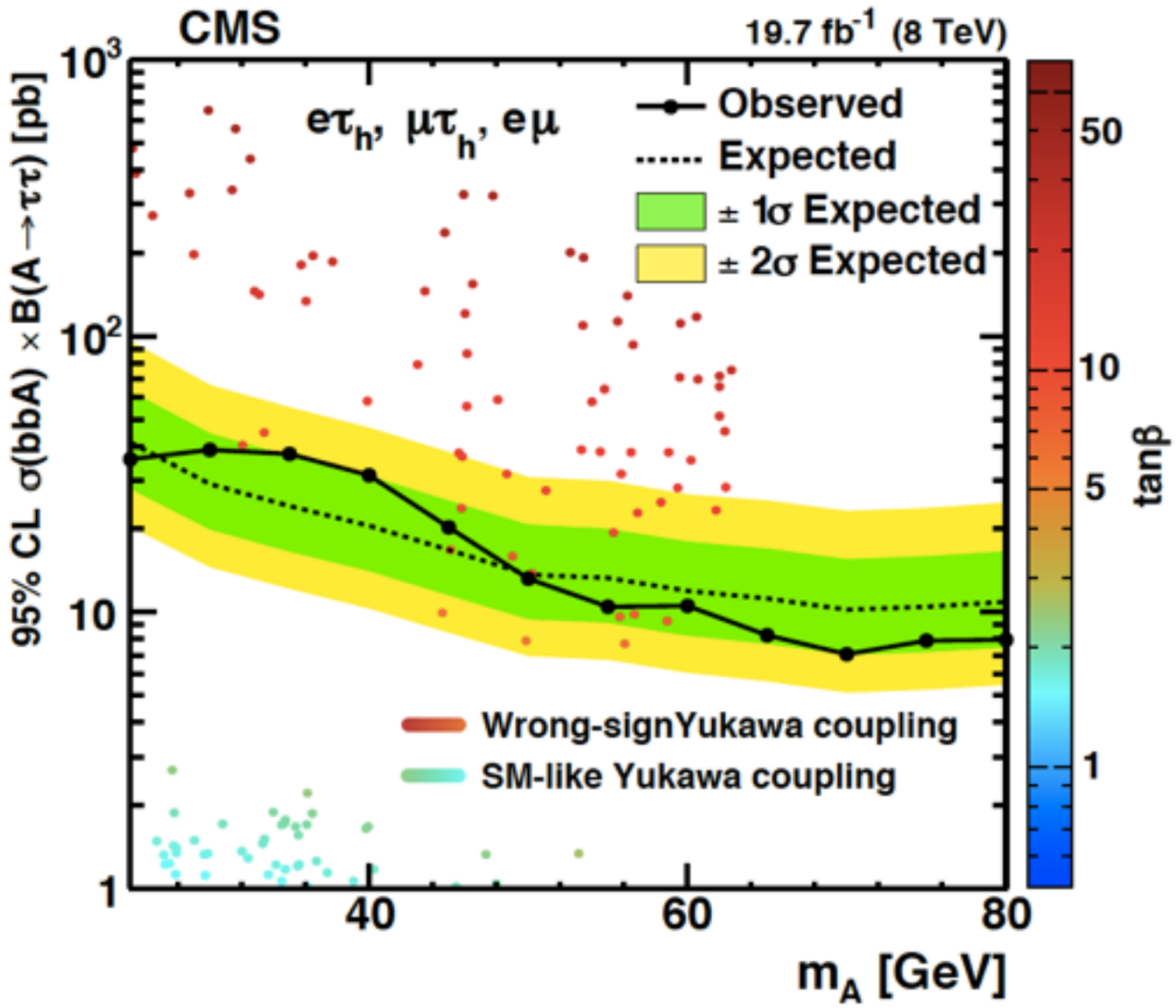
resonant search



Low mass pseudo scalar ditau

- Exclusion of 2HDM type II, wrong-sign Yukawa coupling, high tan β

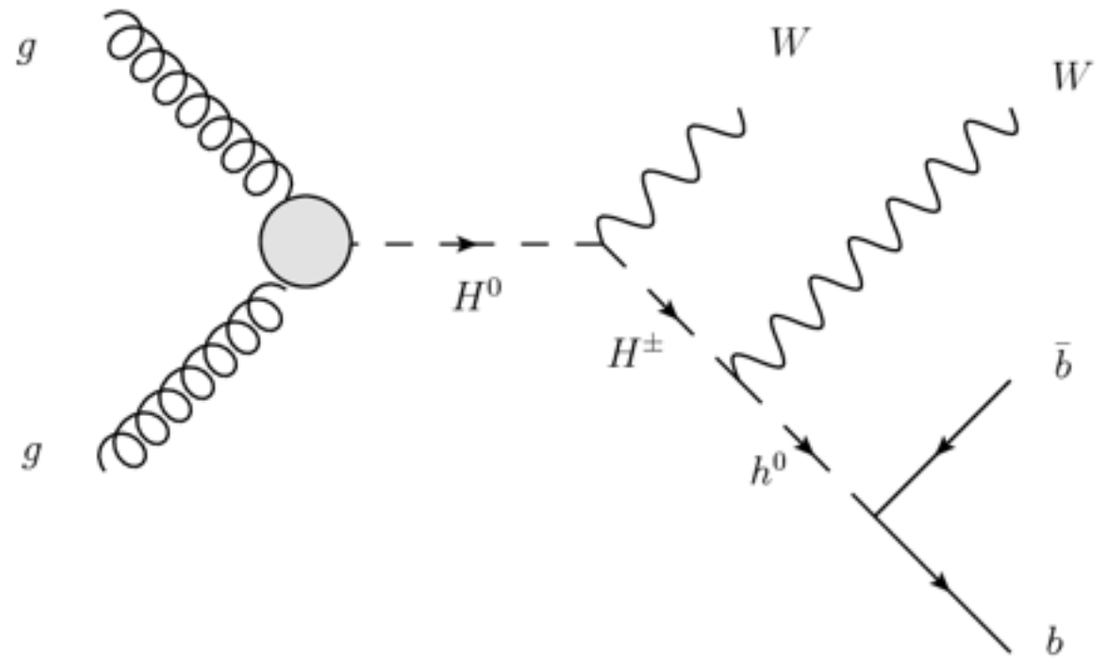




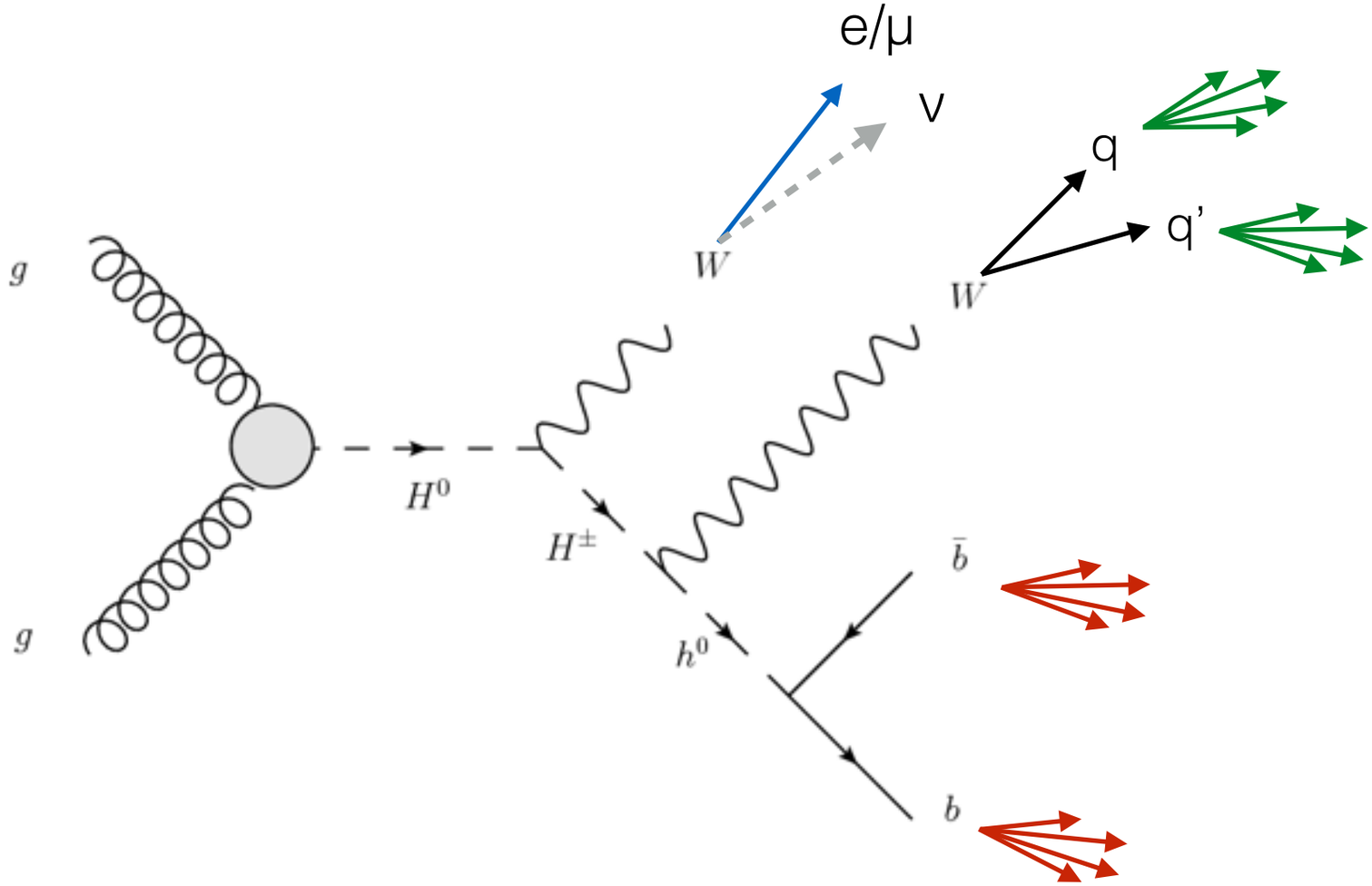
Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	—	—		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	—	—		κ_W^2
$\sigma(qq/qg \to ZH)$	—	—		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	—	—		κ_t^2
$\sigma(gb \to tHW)$	—	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	—	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	—	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

ATLAS: Higgs Cascade

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



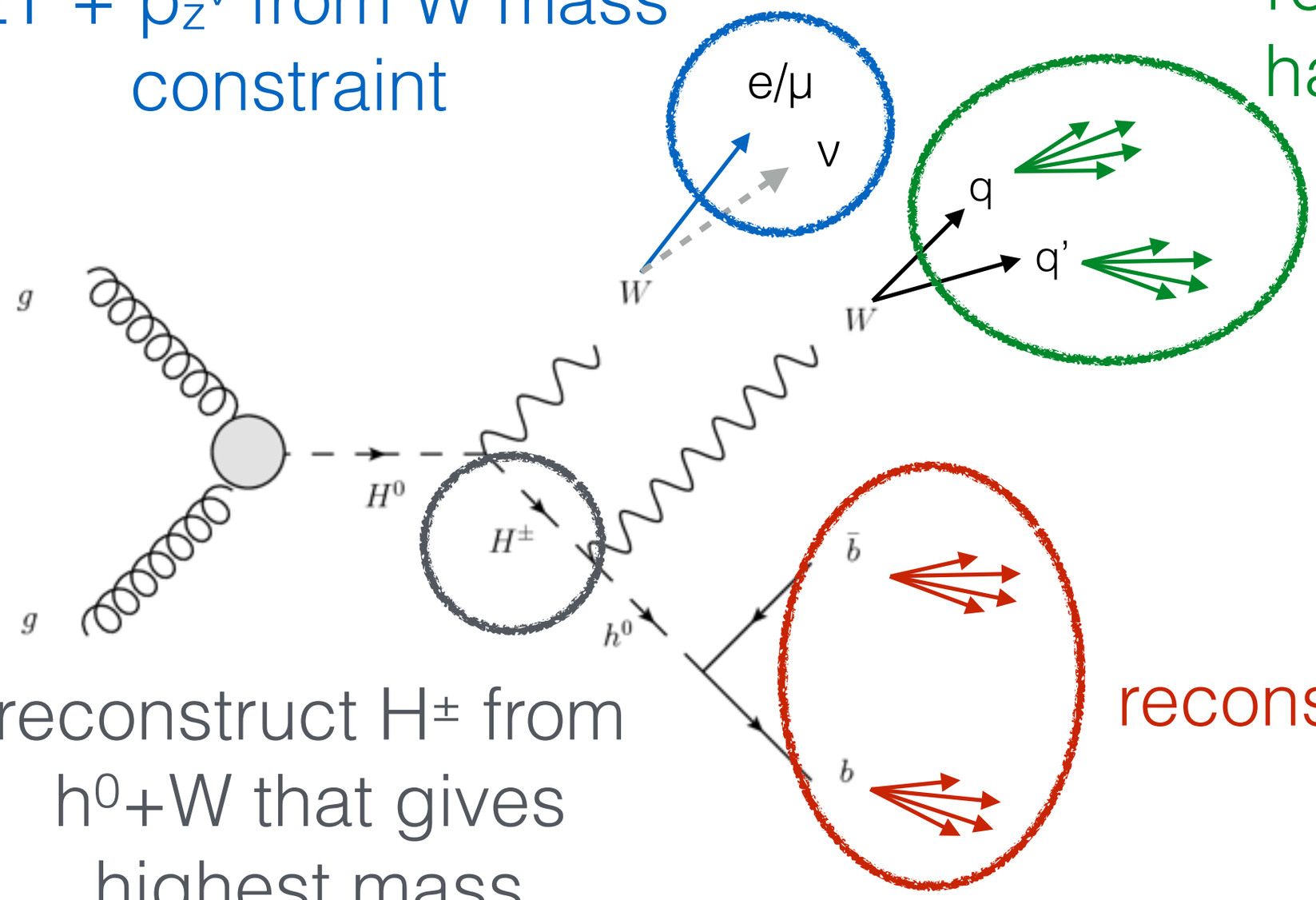
ATLAS: Higgs Cascade



ATLAS: Higgs Cascade

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

reconstruct
hadronic W

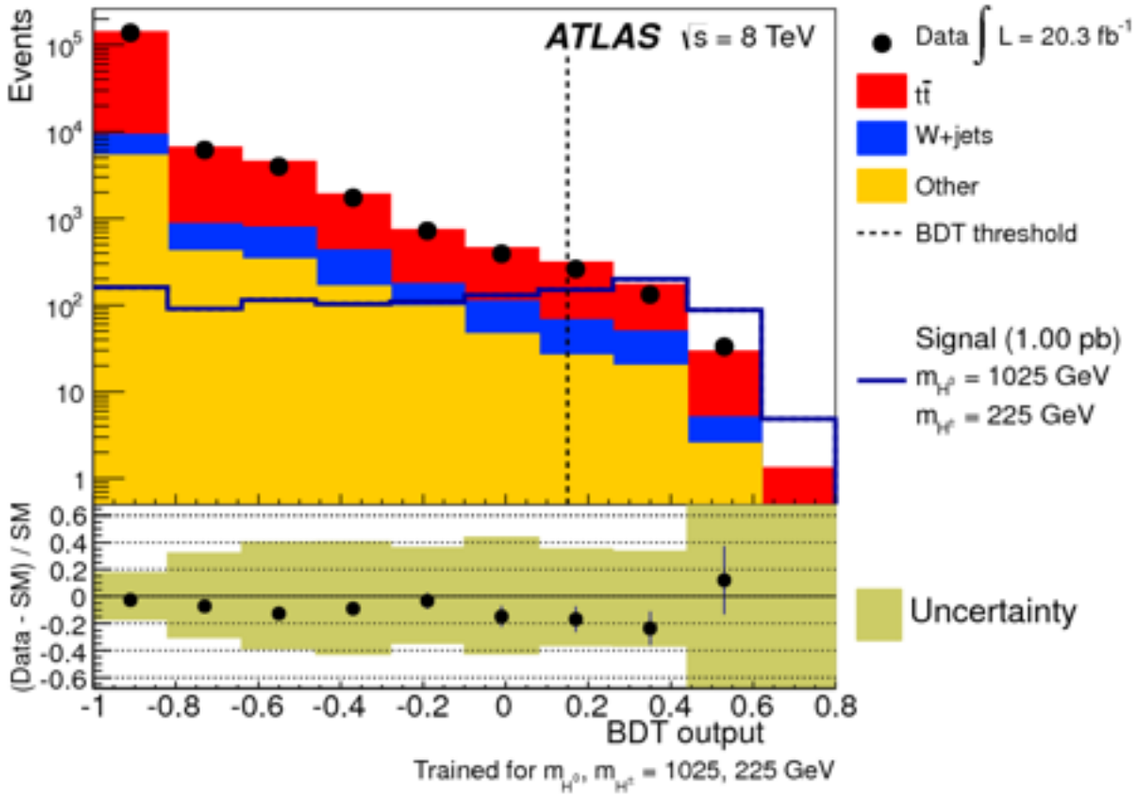


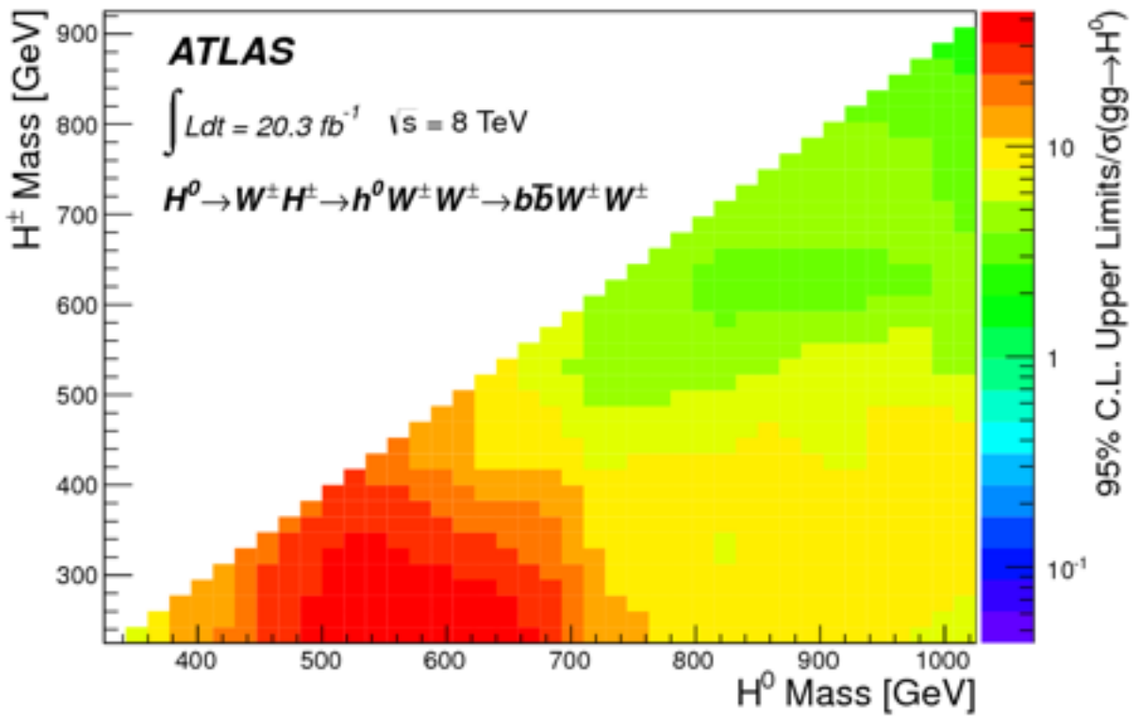
reconstruct $H^\pm$ from
h^0+W that gives
highest mass

reconstruct h^0

ATLAS: Higgs Cascade

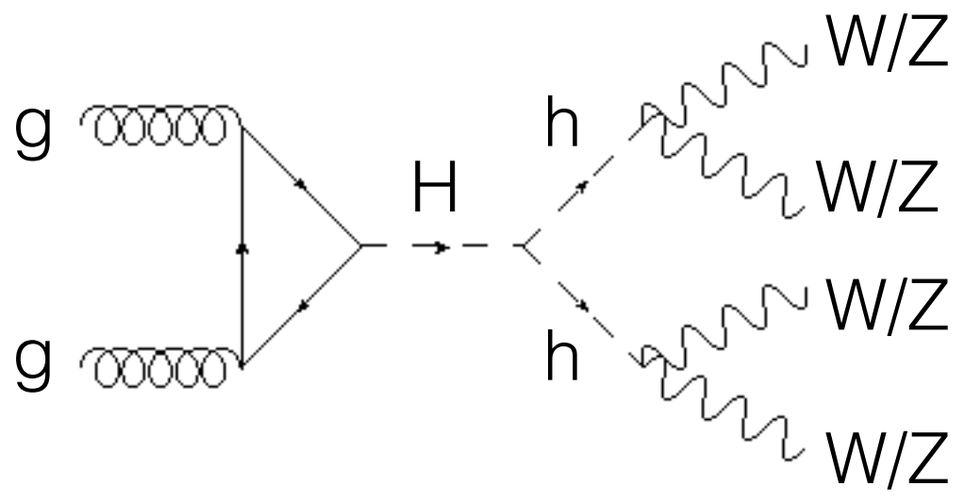
- BDT to discriminate against ttbar using event kinematics
- Dominant Systematics: b-tag eff., jet energy, ttbar norm.
- Almost sensitive to SM-strength production

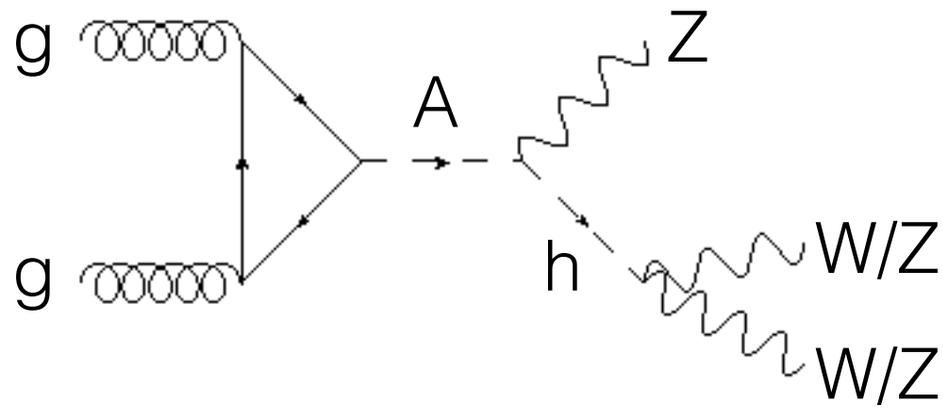




CMS: H→hh / A→Zh

- 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

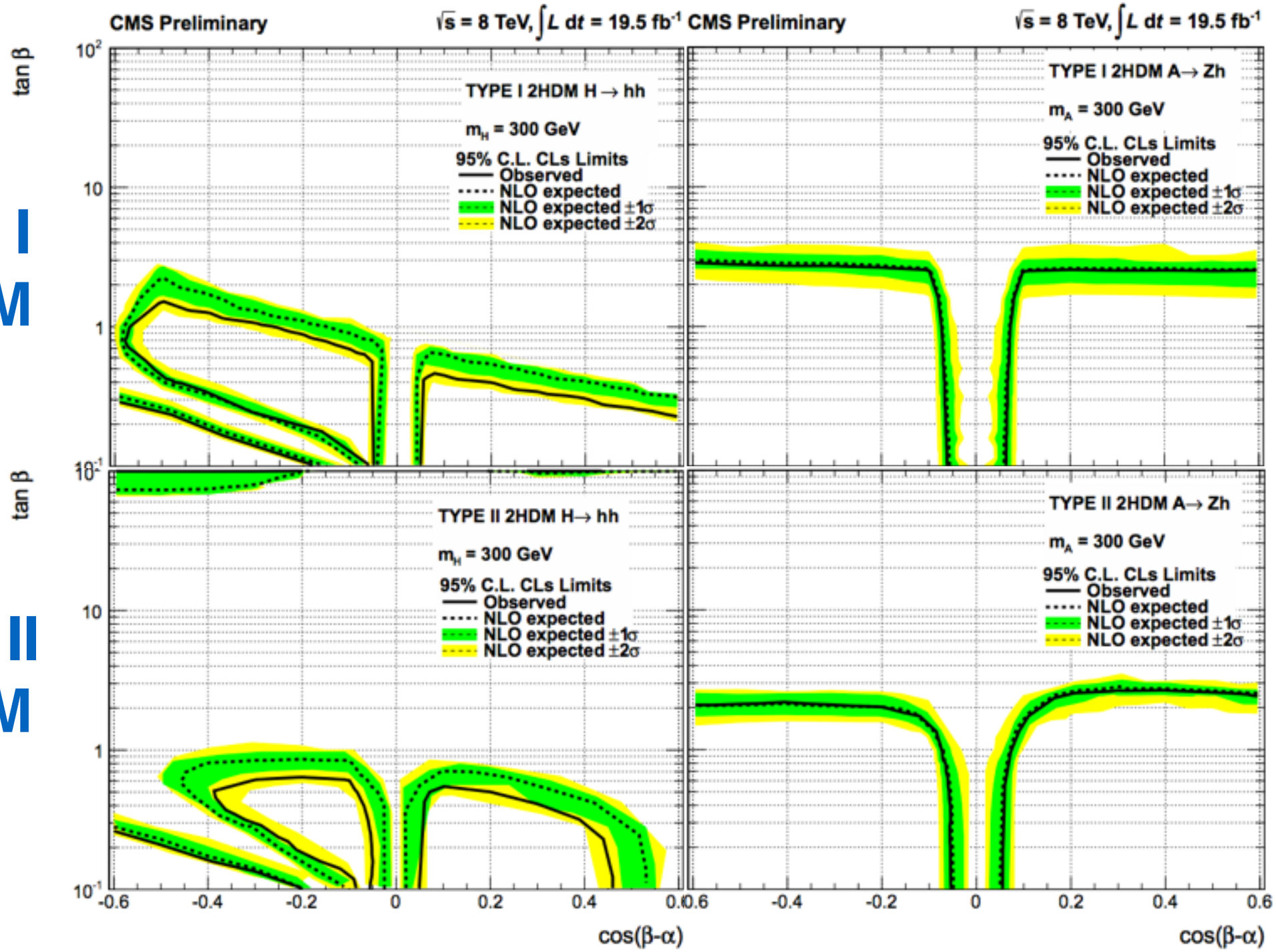
CMS: Results

H→hh

A→Zh

Type I 2HDM

Type II 2HDM



α is H-h mixing angle…

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

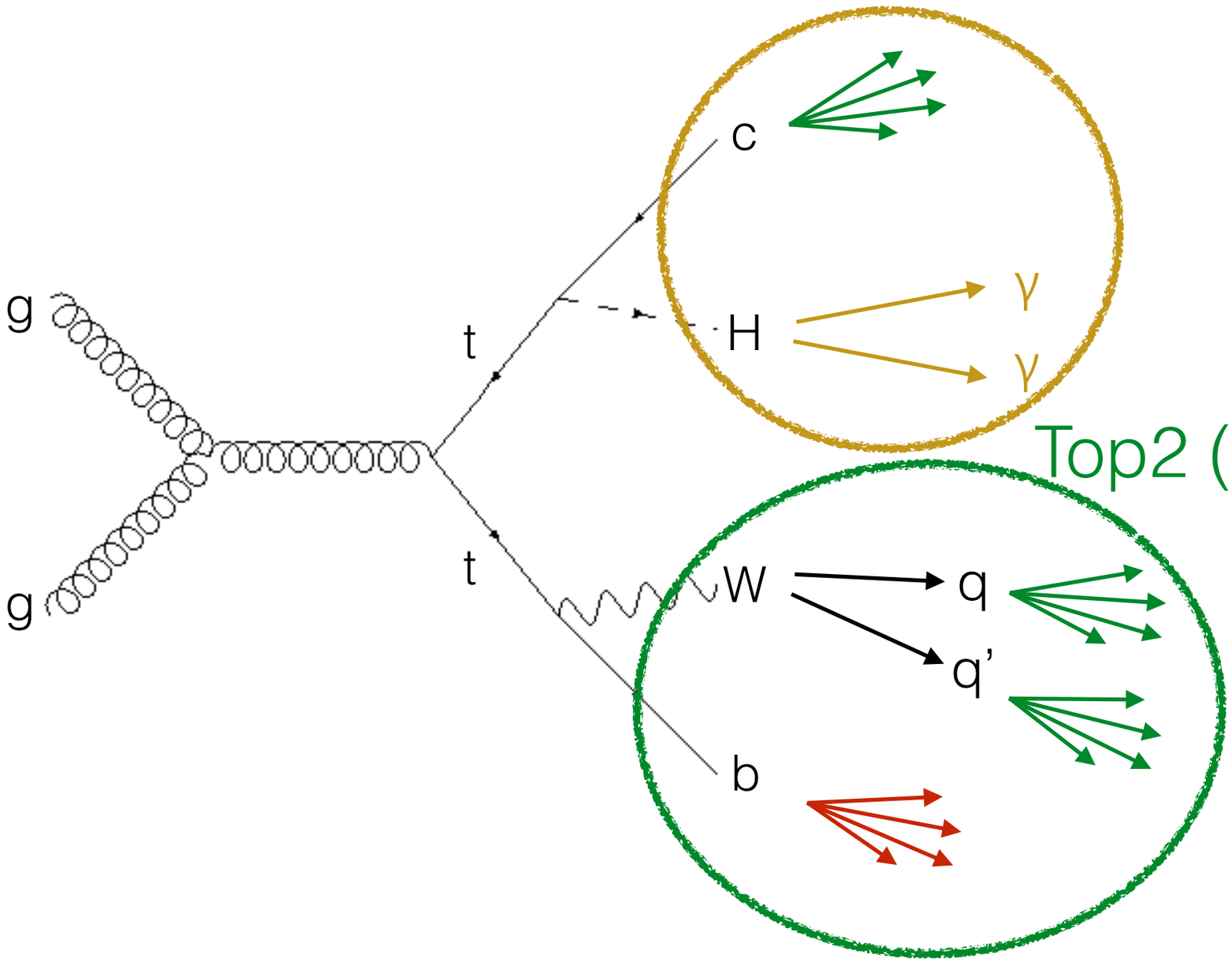
Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$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

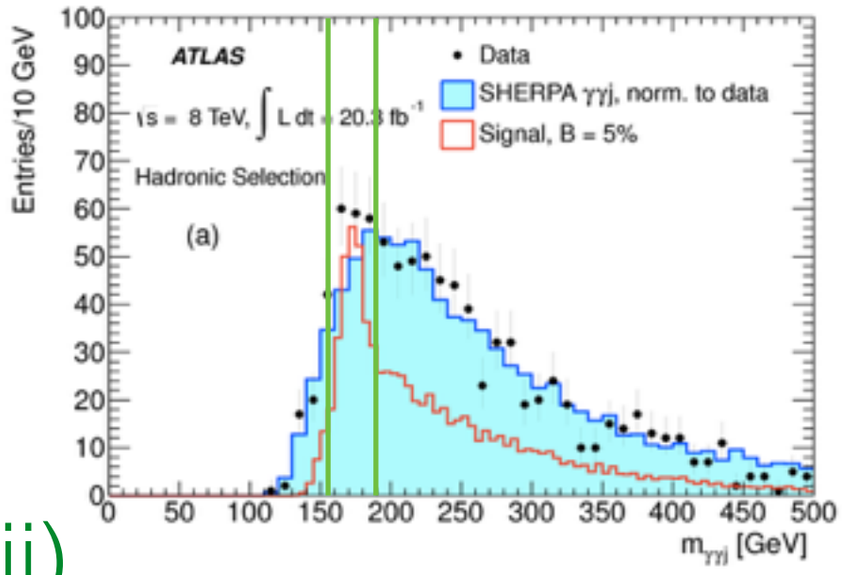
Coll.	Dataset	Cite
ATLAS	**25fb-1(7+8TeV)**	**arXiv:1403.6293 [hep-ex]**
CMS	20fb-1(8TeV)	CMS-PAS-HIG-13-034

ATLAS: tHc search

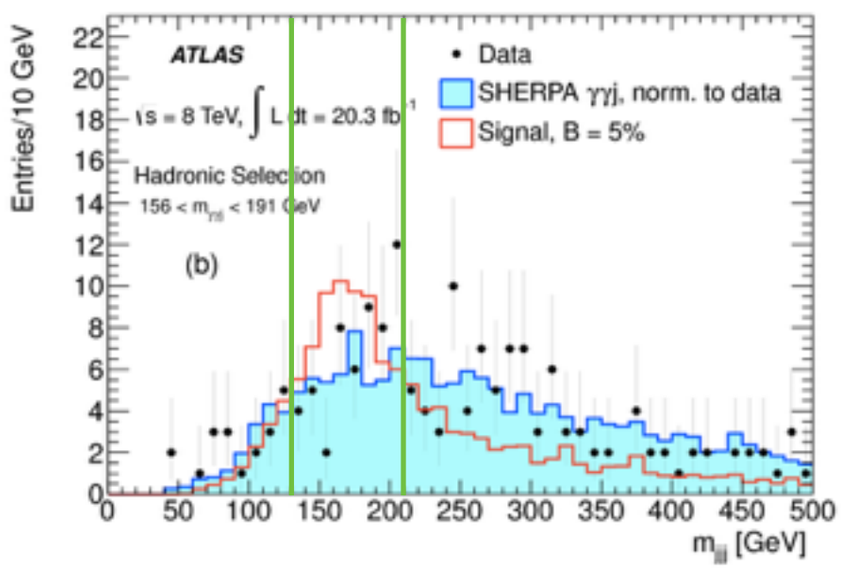
Hadronic Channel

Top1 (γγj)



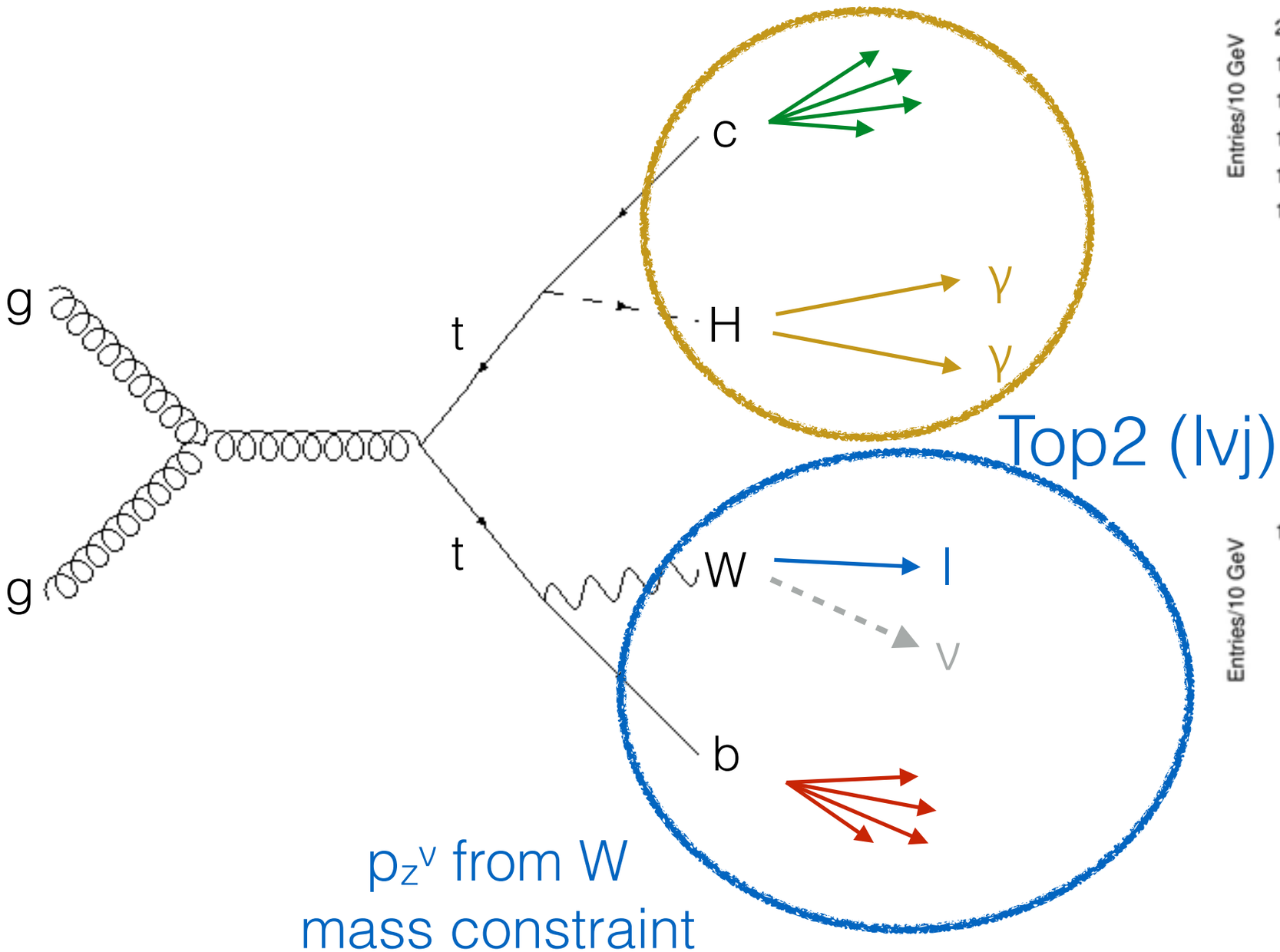


Top2 (jjj)

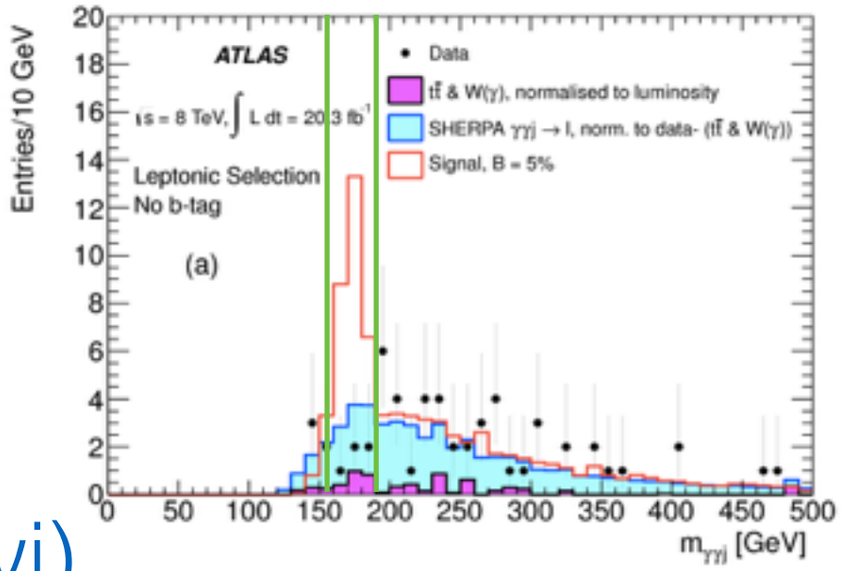


ATLAS: tHc search

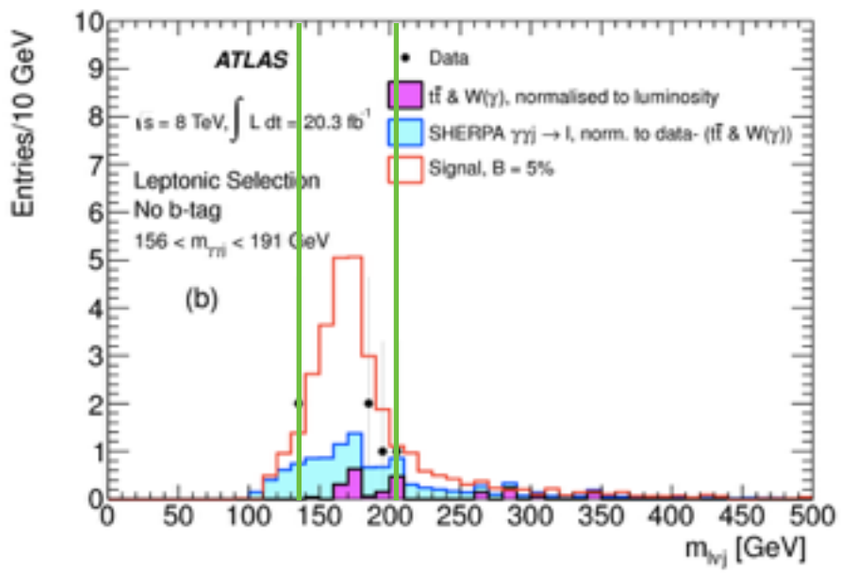
Leptonic Channel



Top1 (γγj)



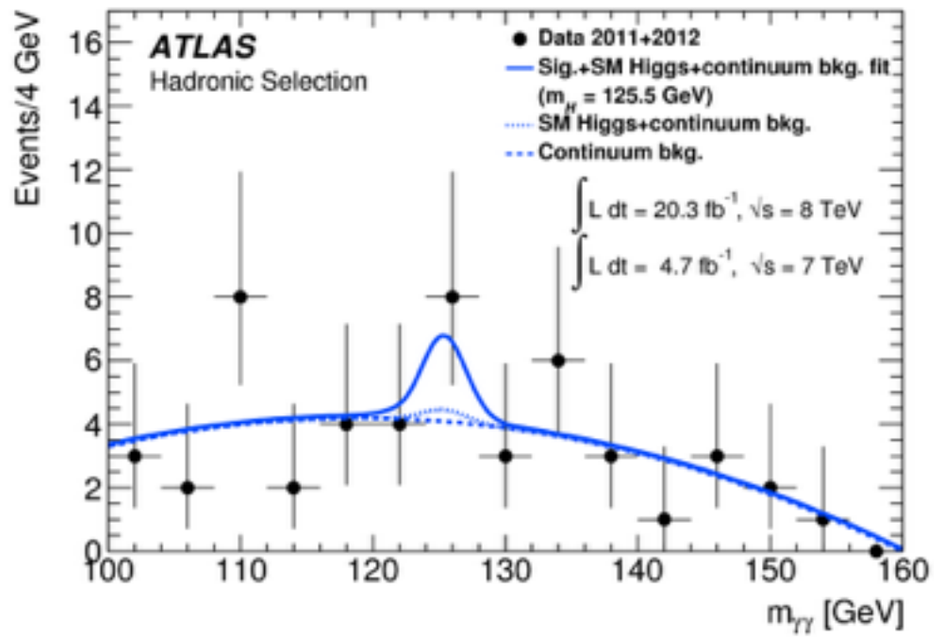
Top2 (lνj)



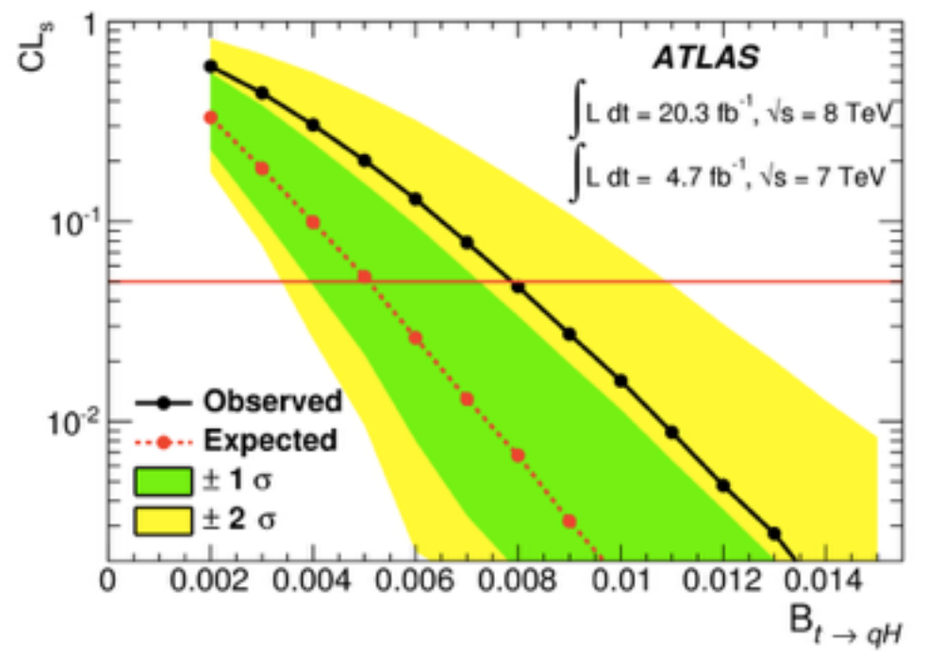
p_z^{ν} from W mass constraint

ATLAS/CMS: Results

- Search for excess in diphoton mass spectrum:
  - **B(t→Hc)< 0.83%** (0.53%)
  - $\lambda_{tHc/u} < 0.17$ (0.14)

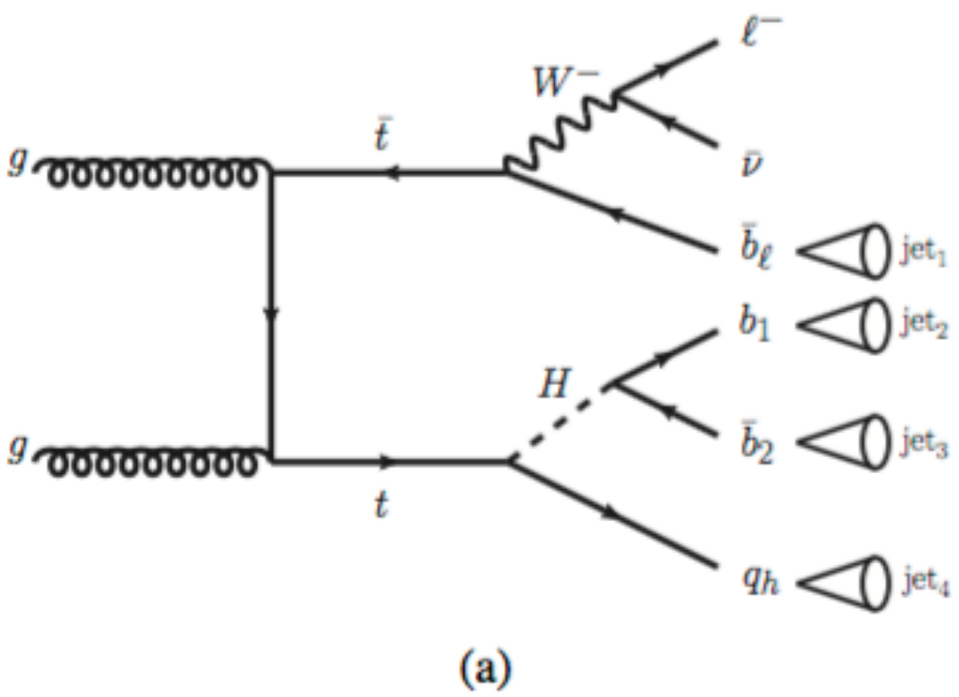


- CMS reinterpretation of diphoton+multileptons searches:
  - **B(t→Hc)<0.56%** (0.65%)
  - $\lambda_{tHc/u} < 0.14$

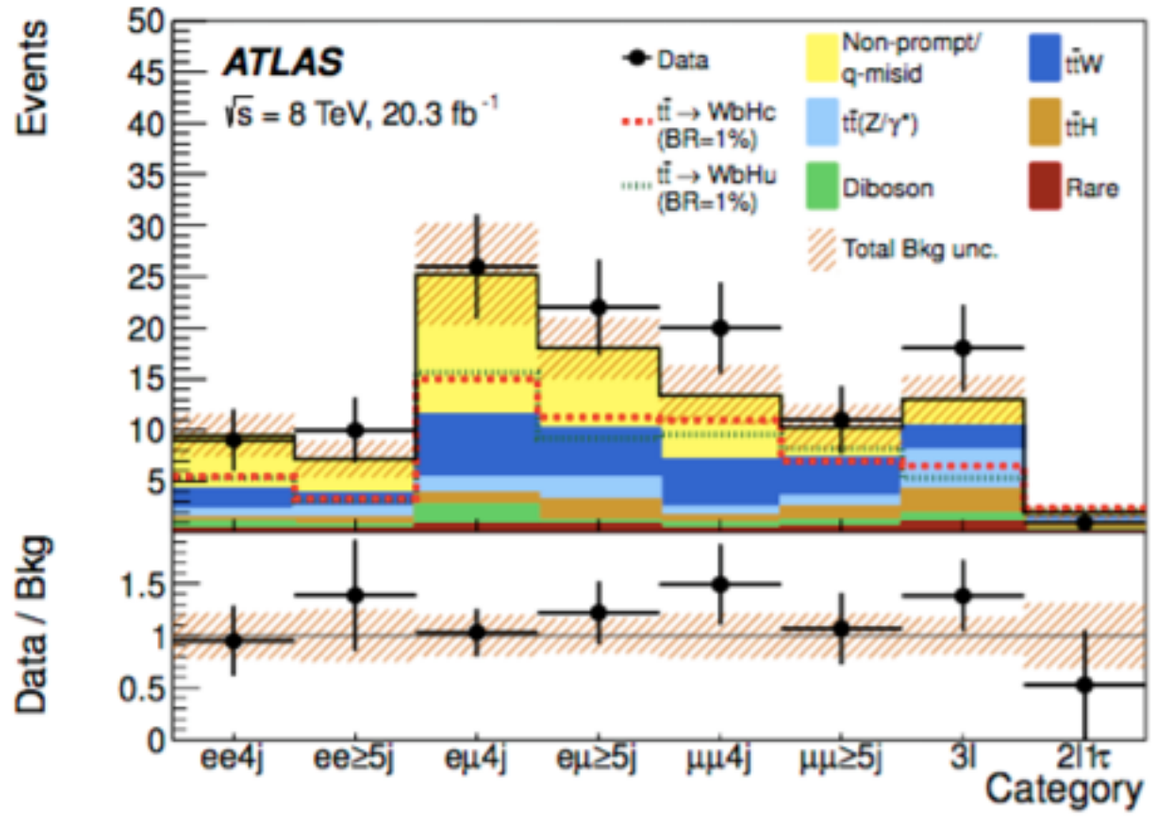


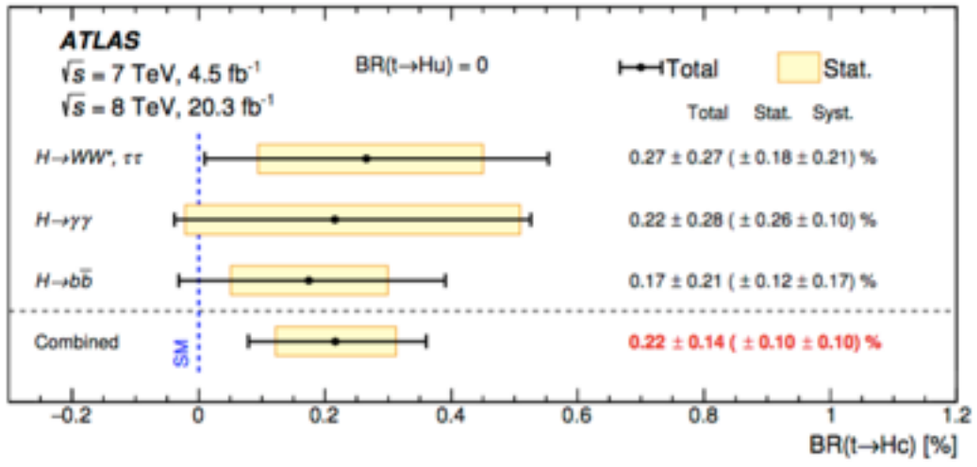
Run 2 update: **ATLAS-CONF-2016-104**

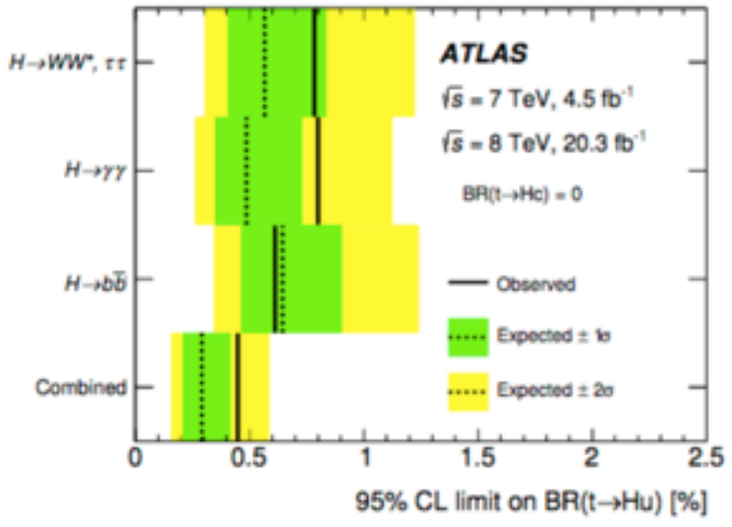
Run 1 tHc excess

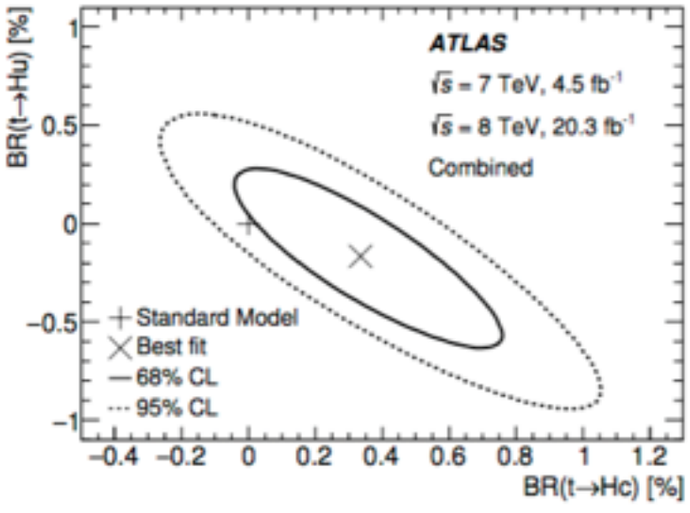


(a)





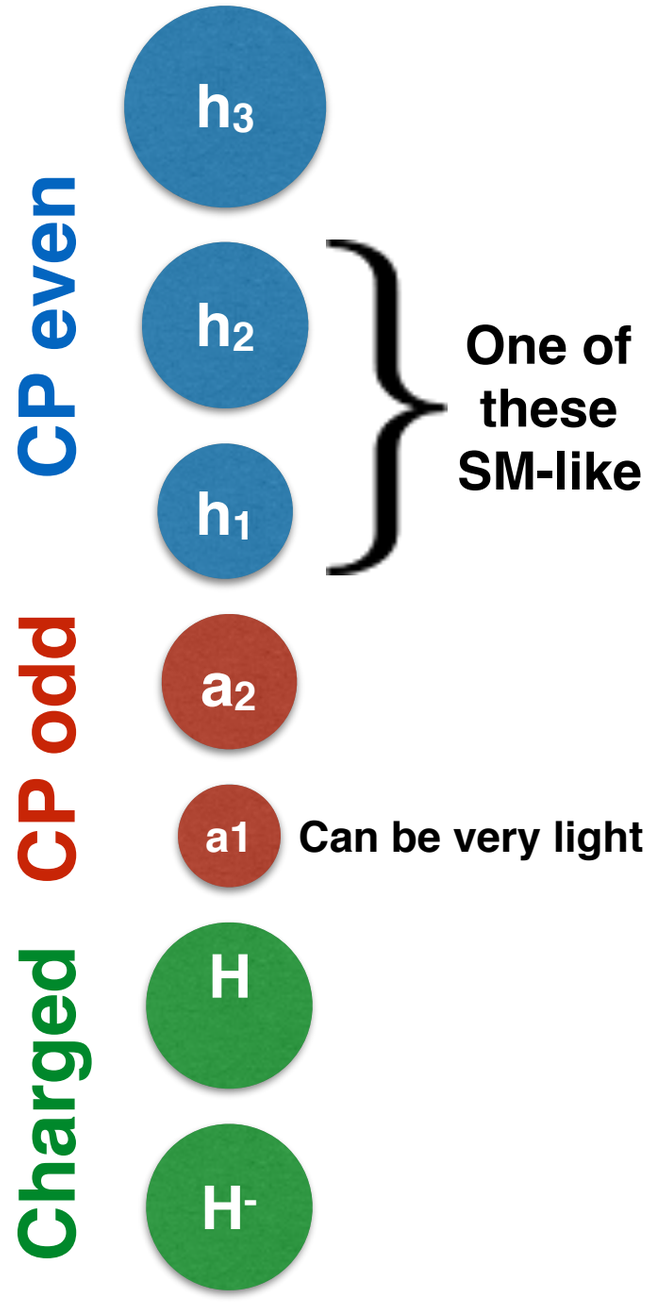


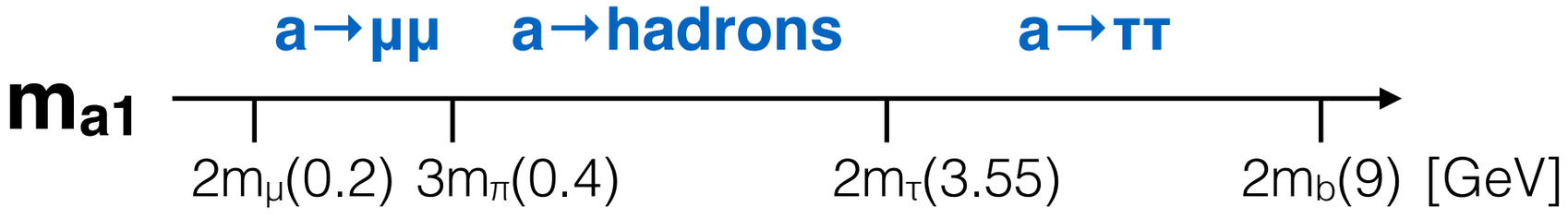


NMSSM

- 2 Doublets (H_u,H_d) **+ 1 Singlet (S)**
  - alleviates μ-problem of MSSM

- $h \rightarrow a_1 a_1$ dominant ($h \rightarrow bb$ greatly reduced)



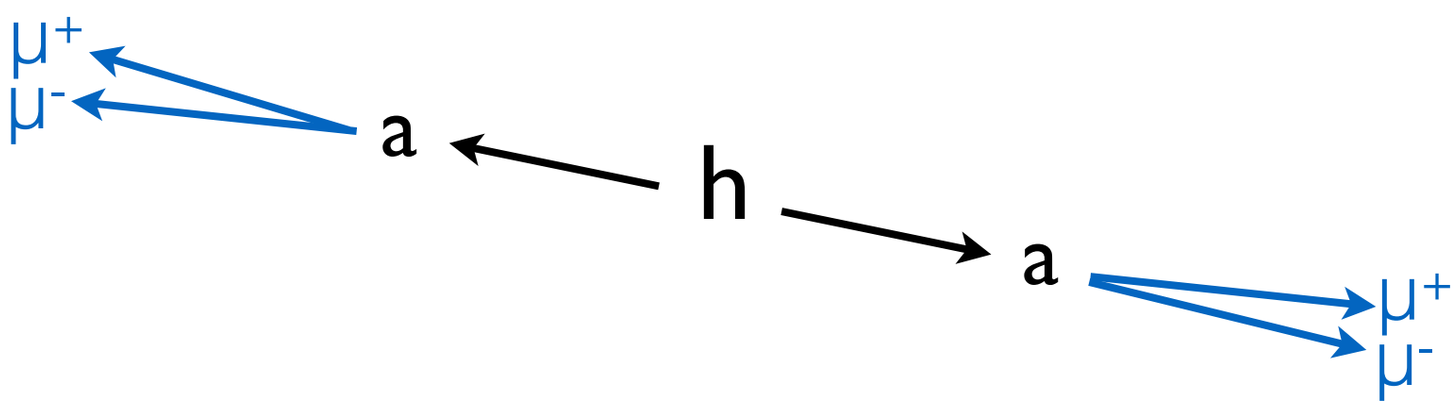


Coll.	Channel	m_a range [GeV]	Dataset	Cite
CMS	**h→2a→4μ**	**0.25 - 3.55**	**21fb-1(8TeV)**	**CMS-PAS-HIG-13-010**
D0	h→2a→4μ/2μ2τ	0.2 - 20	4fb-1(2TeV)	PRL 103, 061801 (2009)
ATLAS	h→2a→4γ	0.1 - 0.4	5fb-1(7TeV)	ATLAS-CONF-2012-079
CMS	a→2μ	5.5 -14	1fb-1(7TeV)	PRL 109, 121801 (2012)
CDF	t→H+b→Wa(→ττ)b	4 - 9	3fb-1(2TeV)	CDF Note 10104

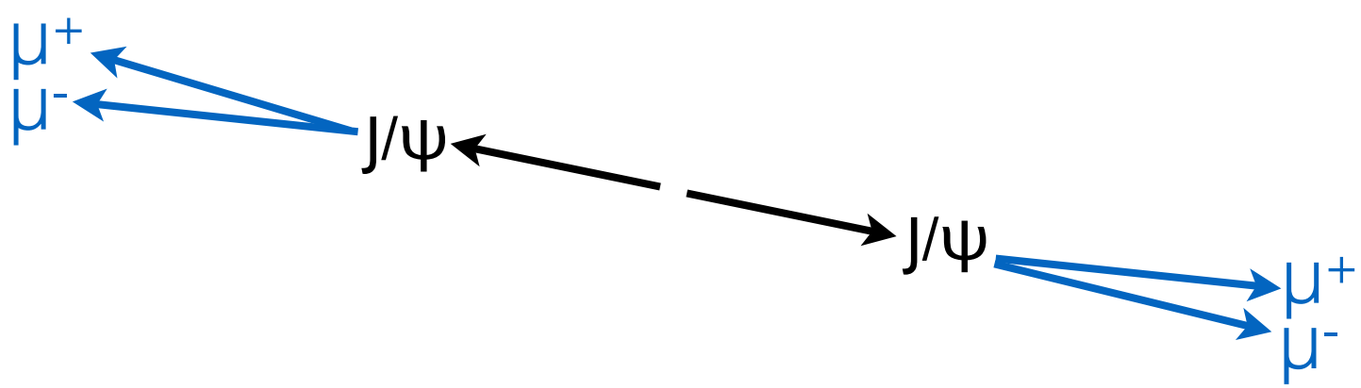
CMS: h→2a→4μ

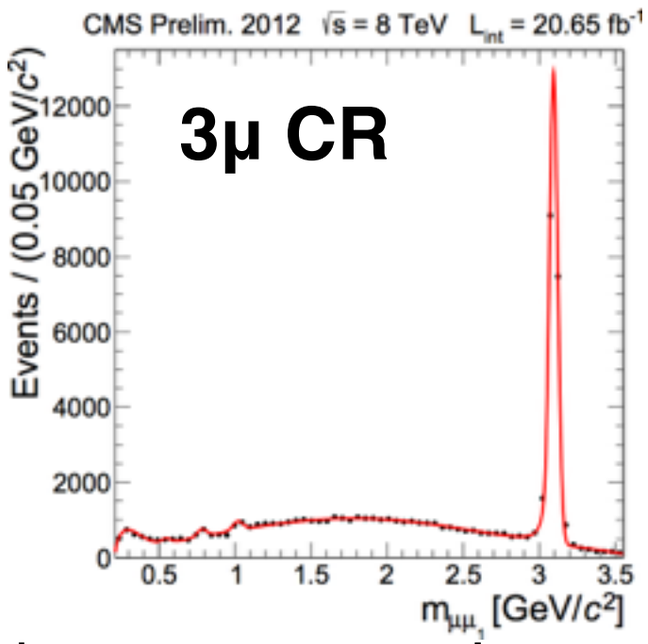
- 2 Isolated OS muon pairs with compatible masses

Signal



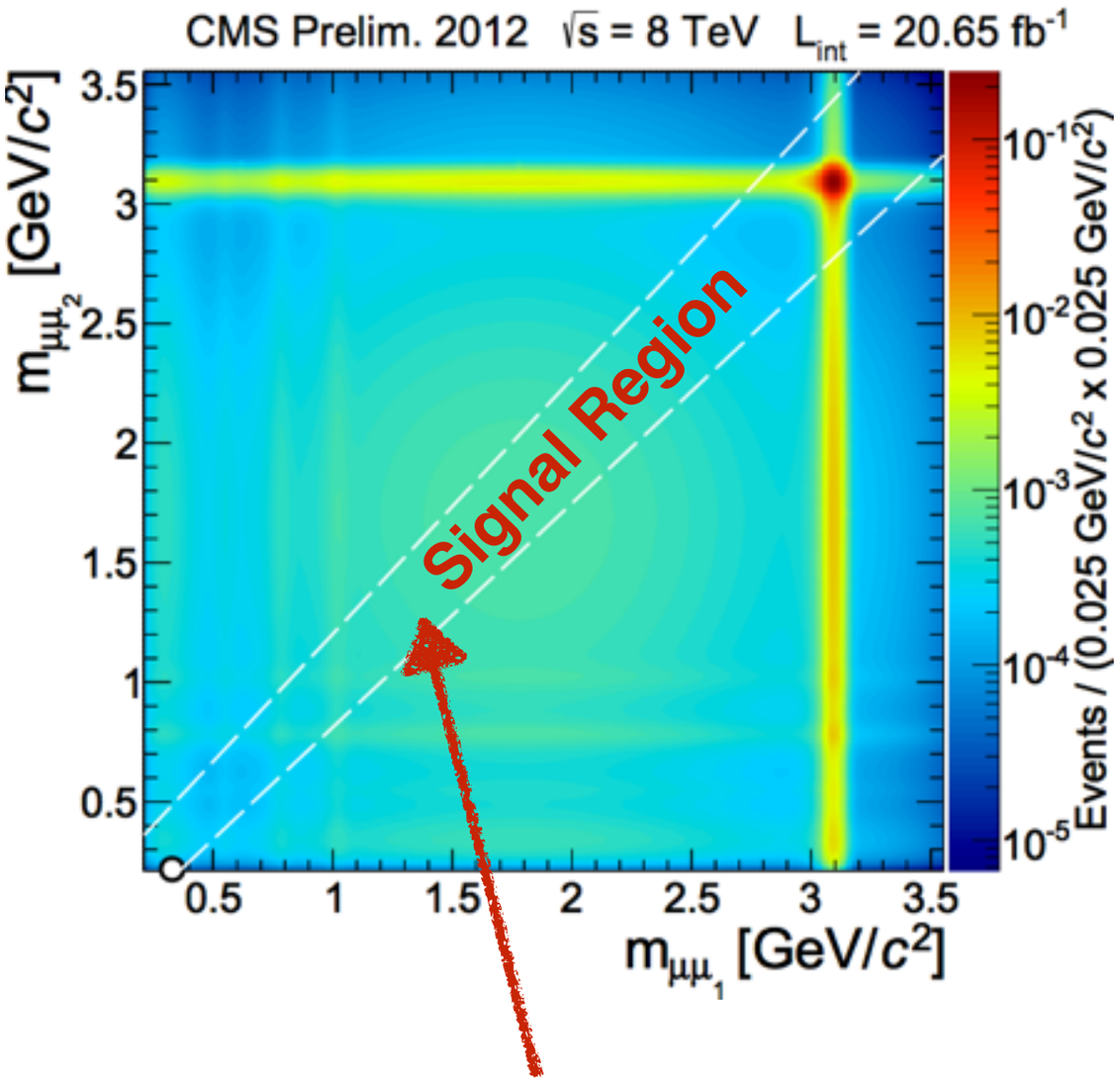
Background: B and J/ψ pair production



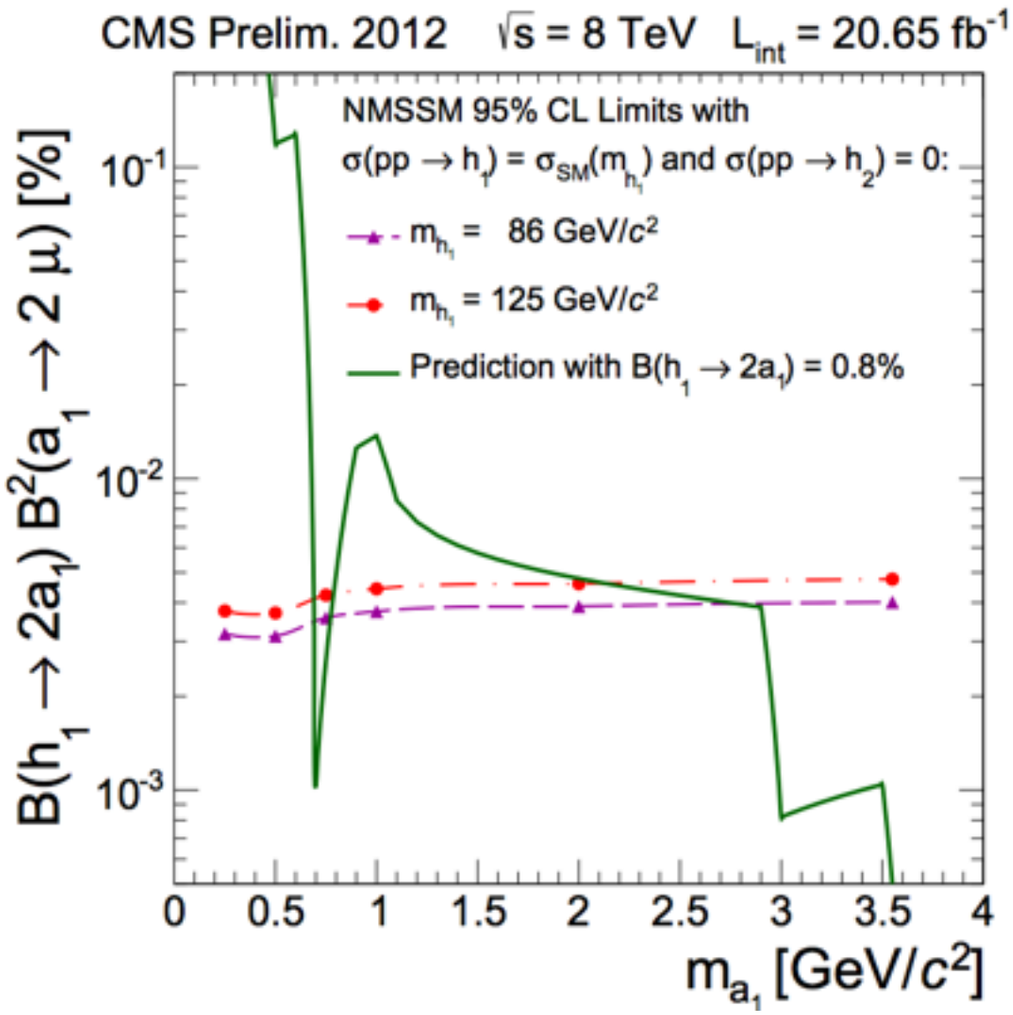


Estimation: BB from 3μ CR, J/ψ from MC+data correction

CMS: Results



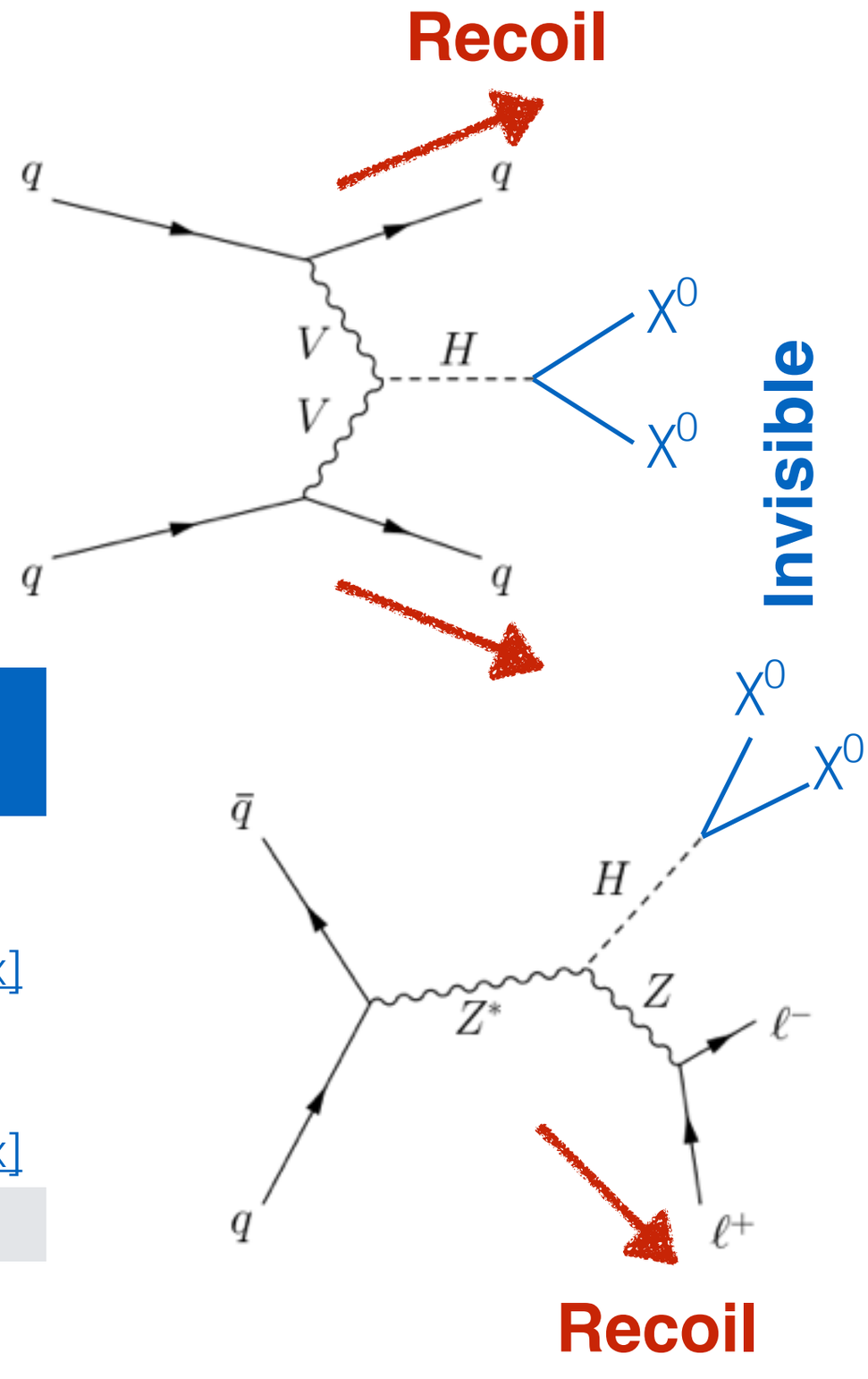
Expected: 3.8±2.1
Observed: 1



Also sensitive to Dark SUSY…

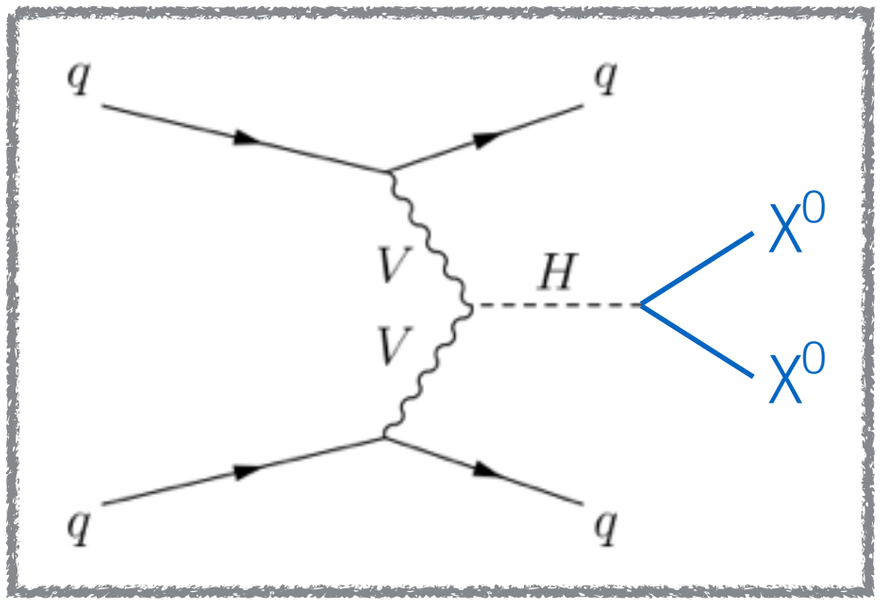
Invisible Higgs

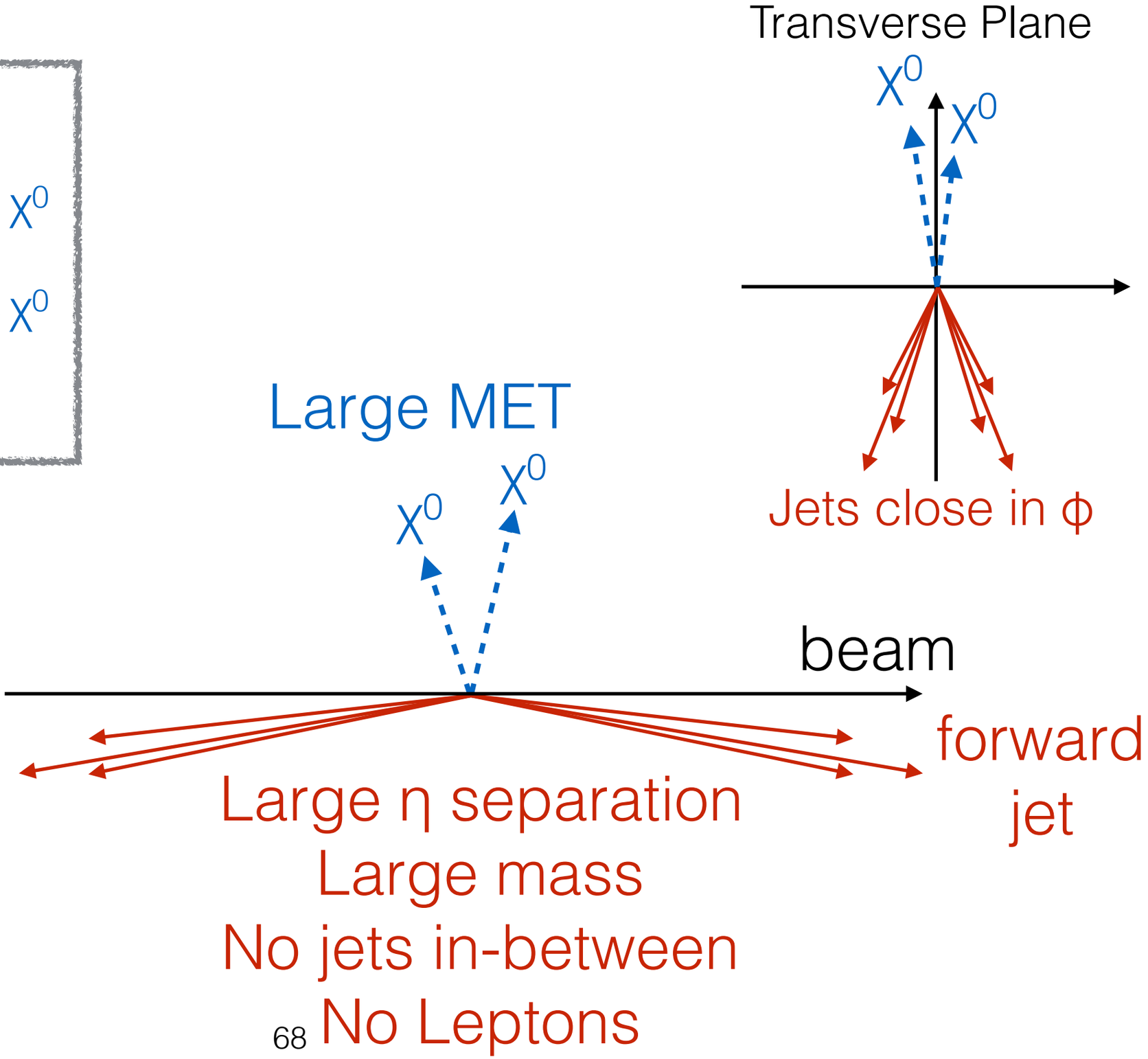
- Search for Higgs decaying into **new weakly interacting particles**
- SM B(H→inv.)~1.2E-3 (H→ZZ→4v)
- **Indirect Limits**: from vis. decay modes **ATLAS 60%, CMS 64%**



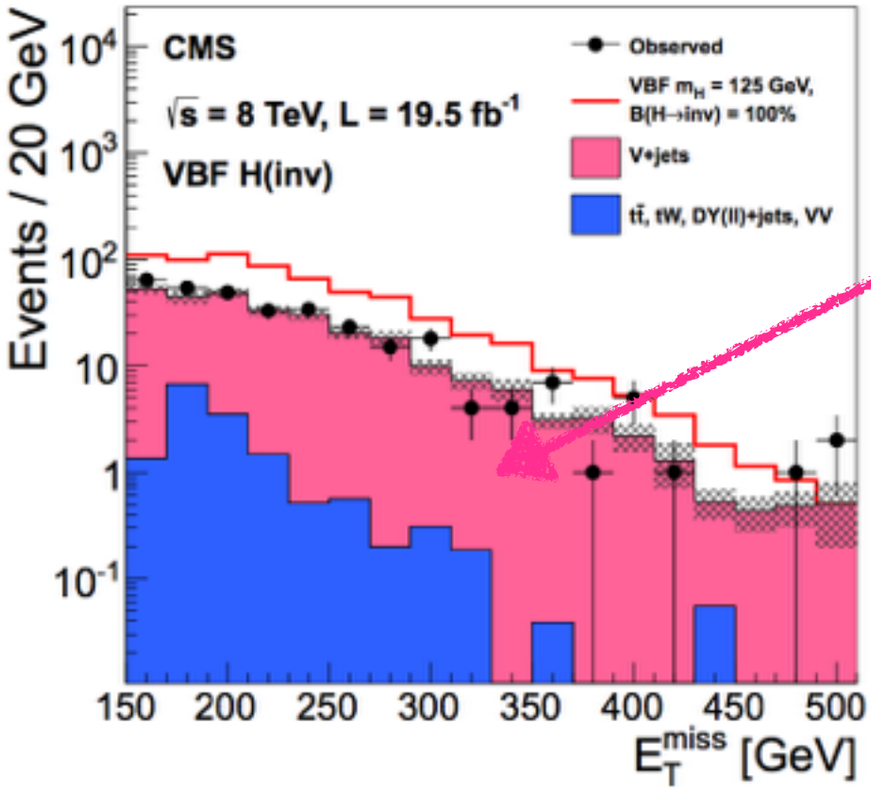
Direct Searches			
Coll.	**Channel**	**Dataset**	**Cite**
CMS	**VBF**	**20fb-1(8TeV)**	
CMS	Z(→ll)H	25fb-1(7+8TeV)	arXiv:1404.1344 [hep-ex]
CMS	Z(→bb)H	19fb-1(8TeV)	
CMS	Comb.	19-25fb-1	
ATLAS	Z(→ll)H	25fb-1(7+8TeV)	arXiv:1402.3244 [hep-ex]
CDF	Z(→ll)H	10fb-1(2TeV)	CDF Note 11068

CMS: VBF Invisible



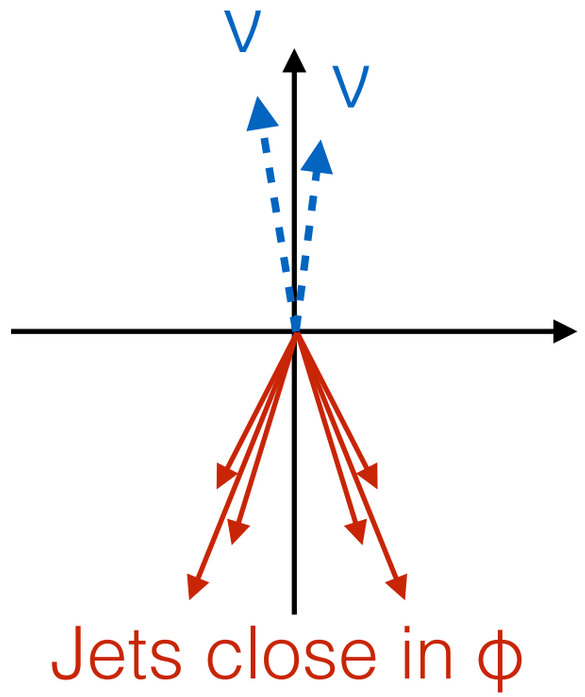


CMS: Z(→νν)+2 jet background



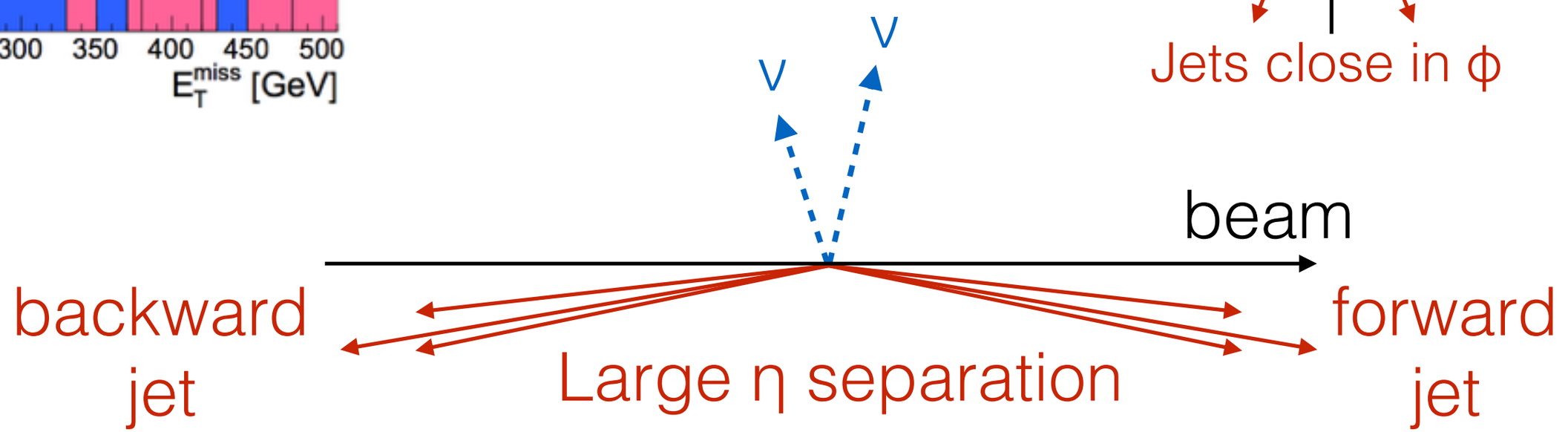
Dominant background

Transverse Plane



Jets close in ϕ

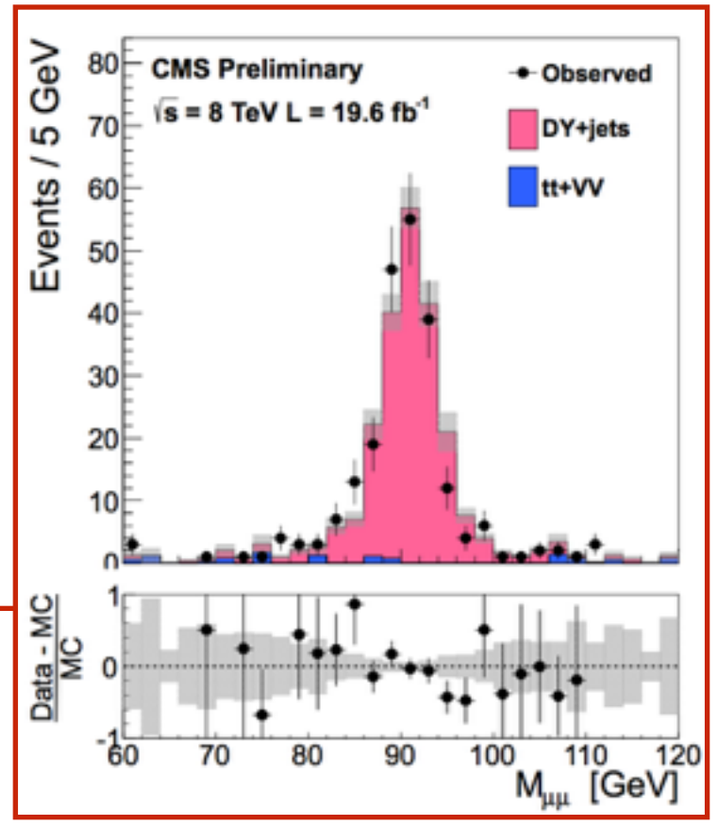
Large MET



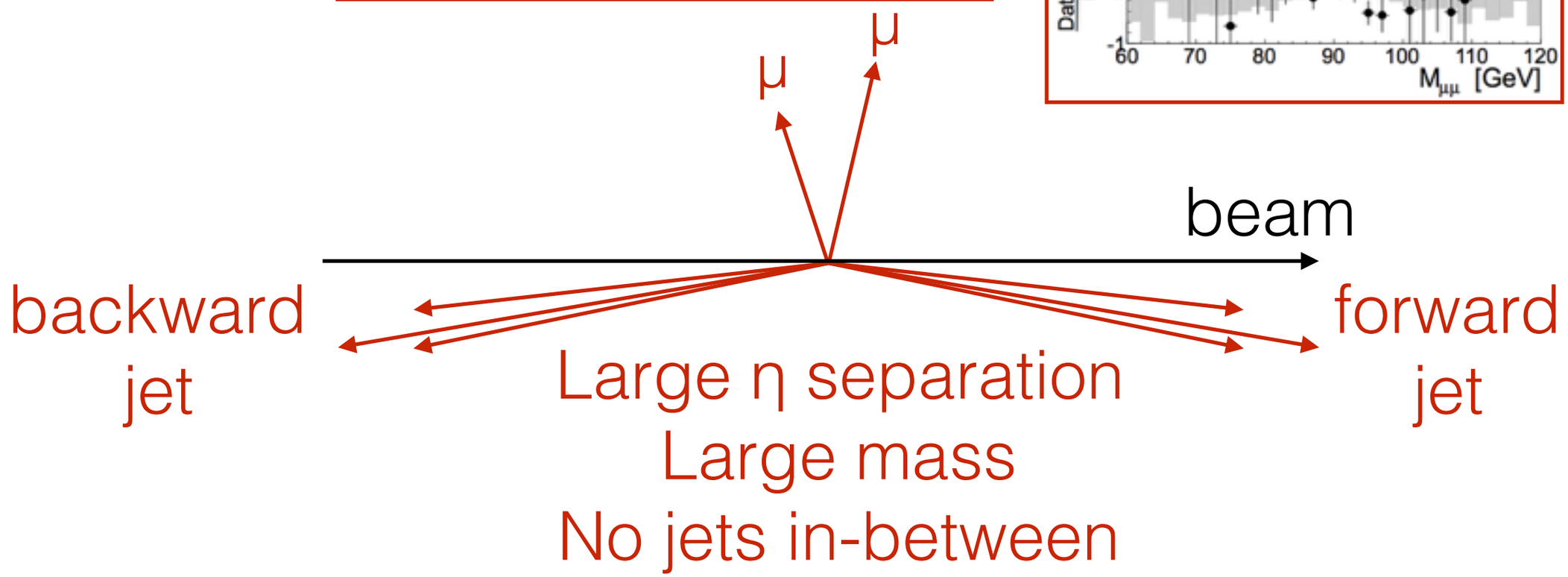
Large η separation
Large mass
No jets in-between
No Leptons

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)



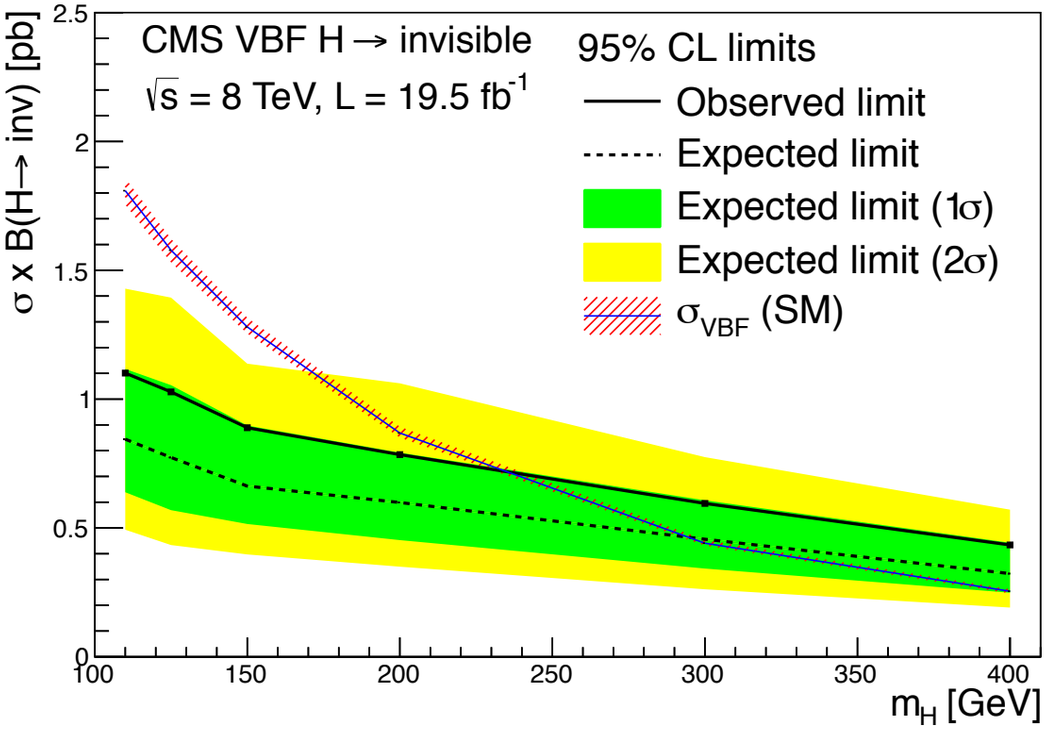
2μ in Z mass window



CMS: Results

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

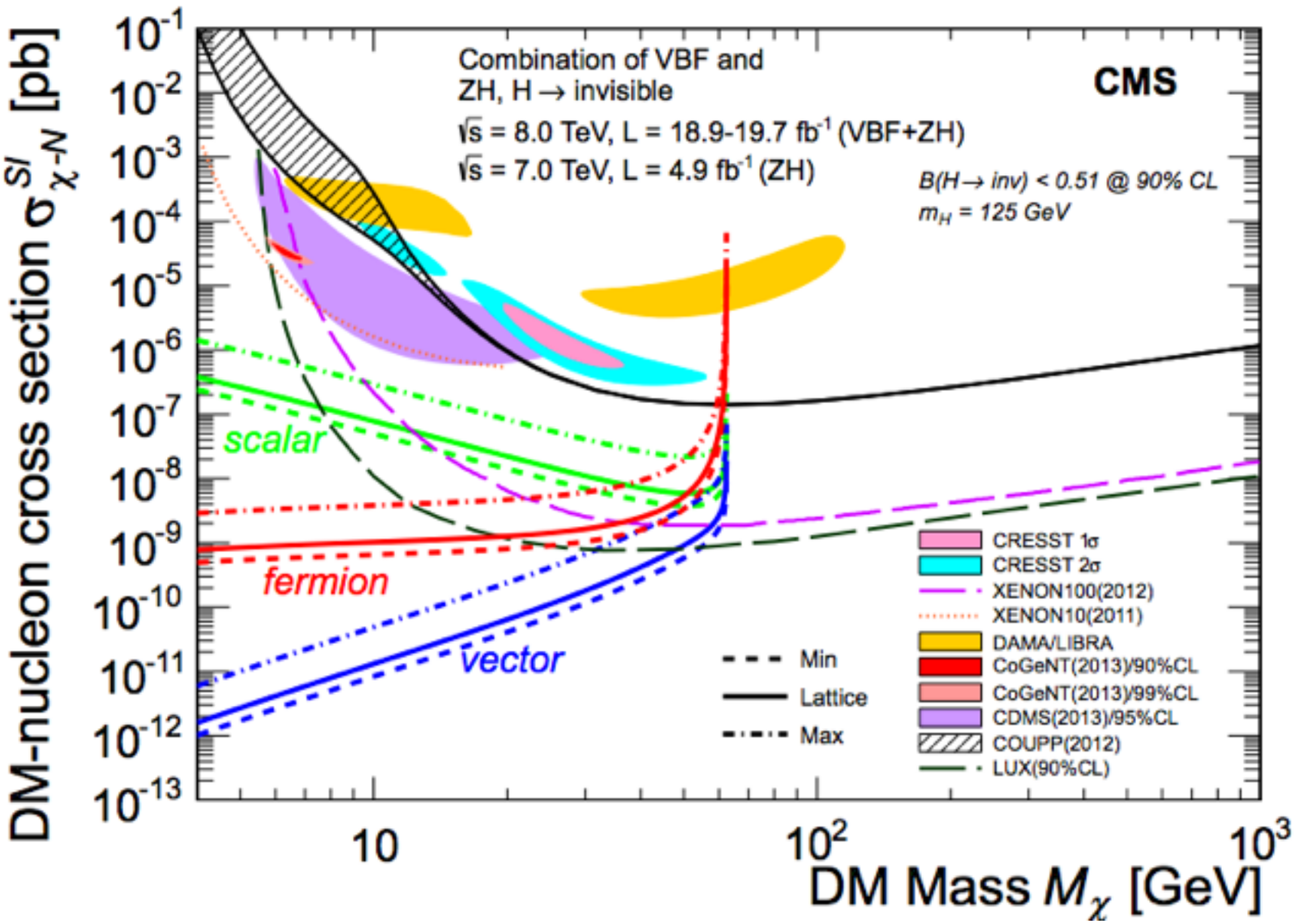
Dominant Systematic	
Zμμ emb. stat.	± 30 events



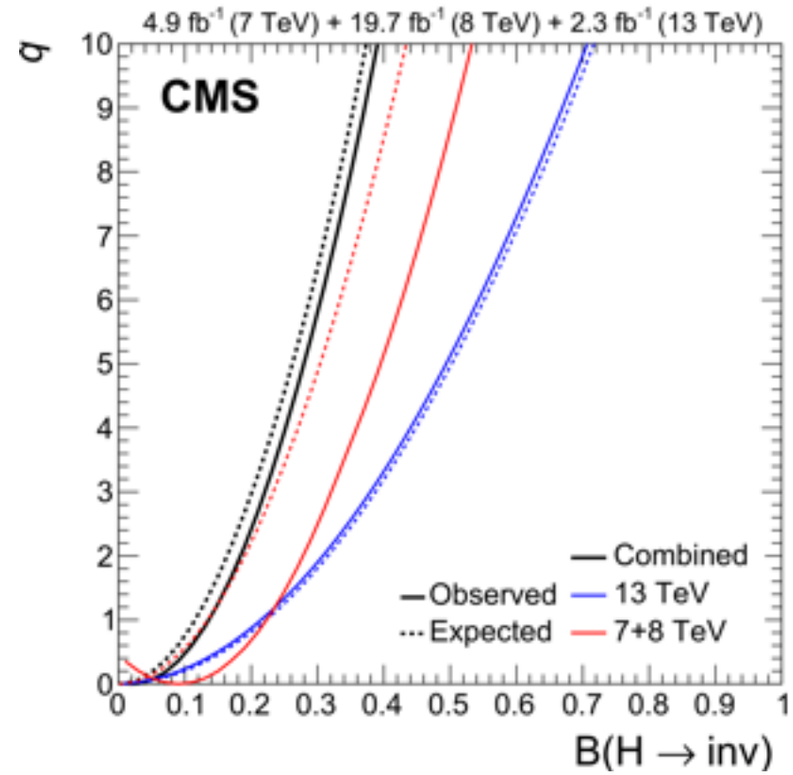
Summary of Direct Searches		
Coll.	**Channel**	**Limit B(H→inv.)**
CMS	**VBF**	**69% (53%)**
CMS	Z(→ll)H	75% (91%)
CMS	Z(→bb)H	(1.8 x σSM)
CMS	**Comb.**	**58% (44%)**
ATLAS	Z(→ll)	65% (62%)

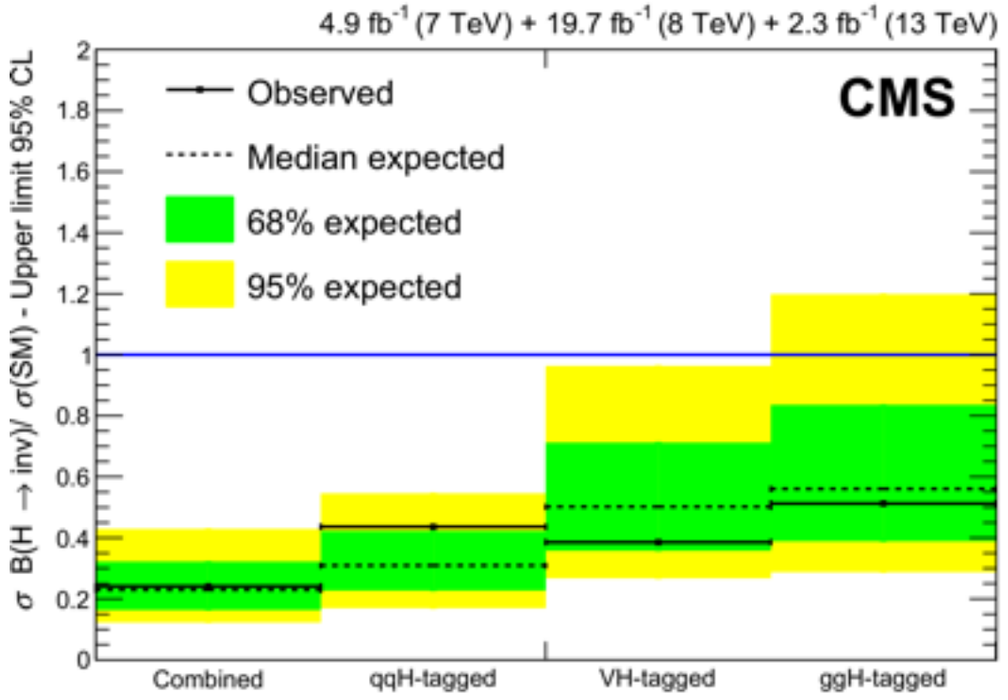
Comparison to direct dark-matter detection

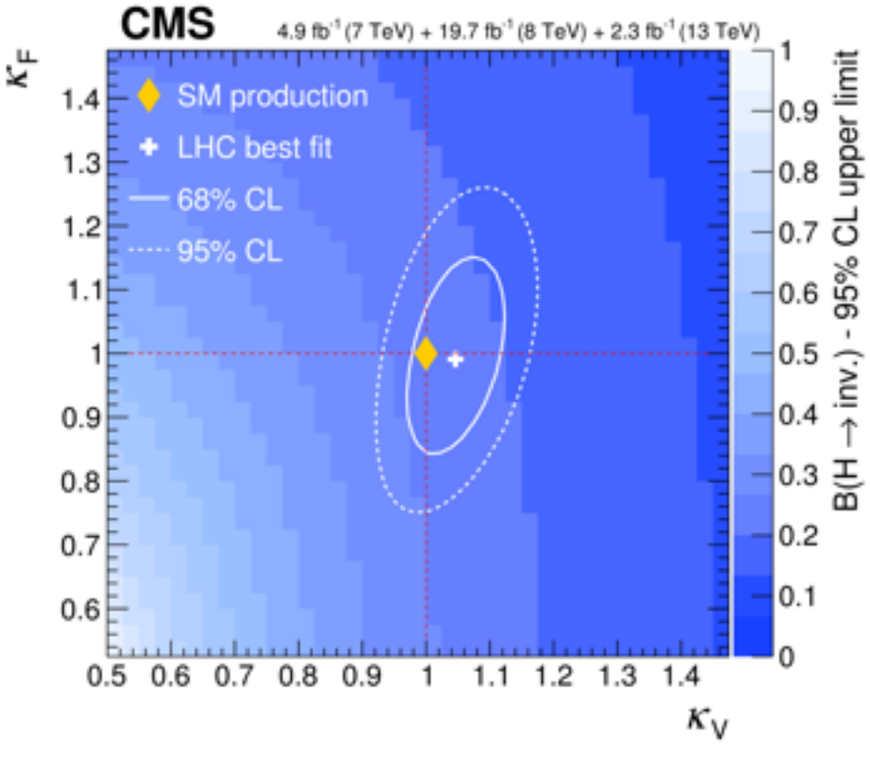
- B(H→inv.) limits constrain DM-nucleon scattering in Higgs portal models.

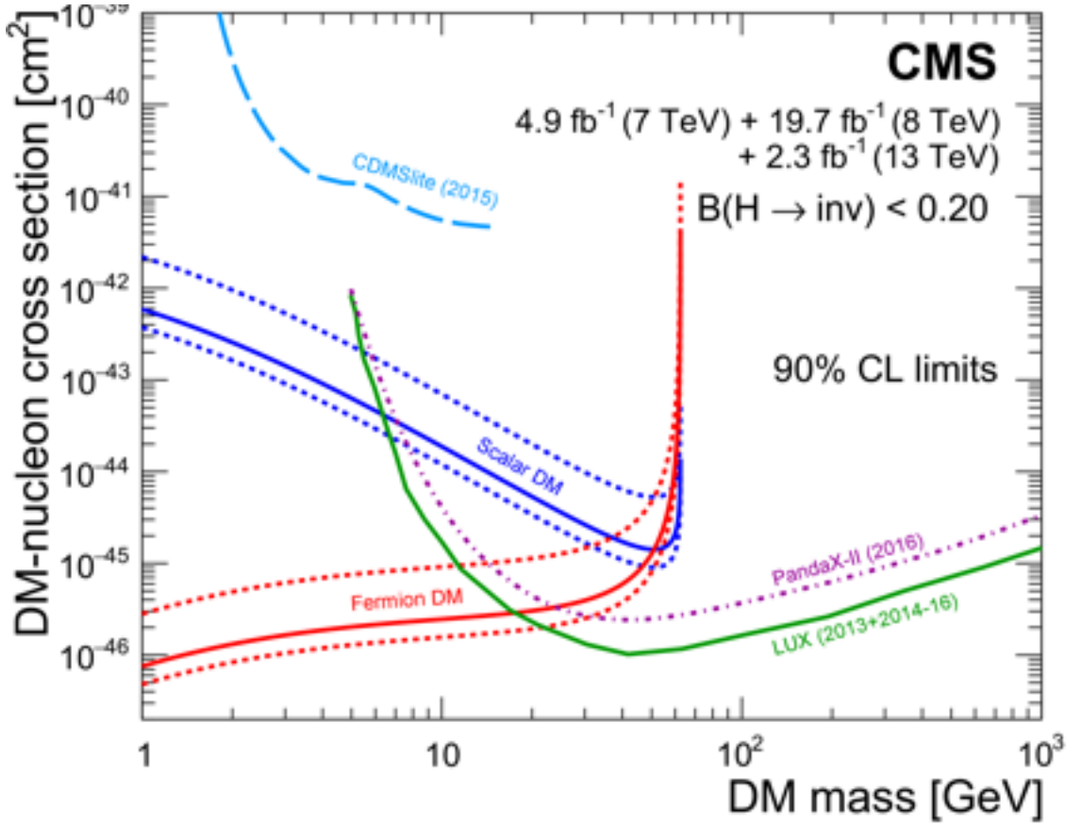


CMS Run 1+2


4.9 fb-1 (7 TeV) + 19.7 fb-1 (8 TeV) + 2.3 fb-1 (13 TeV)
CMS
q
Observed
Expected
Combined
13 TeV
7+8 TeV
B(H → inv)


4.9 fb-1 (7 TeV) + 19.7 fb-1 (8 TeV) + 2.3 fb-1 (13 TeV)
CMS
Observed
Median expected
68% expected
95% expected
σ B(H → inv)/ σ(SM) - Upper limit 95% CL
Combined
qqH-tagged
VH-tagged
ggH-tagged


CMS
4.9 fb-1 (7 TeV) + 19.7 fb-1 (8 TeV) + 2.3 fb-1 (13 TeV)
SM production
LHC best fit
68% CL
95% CL
κF
κV
B(H → inv.) - 95% CL upper limit


CMS
4.9 fb-1 (7 TeV) + 19.7 fb-1 (8 TeV)
+ 2.3 fb-1 (13 TeV)
B(H → inv) < 0.20
90% CL limits
CDMSlite (2015)
Scalar DM
Fermion DM
PandaX-II (2016)
LUX (2013+2014-16)
DM-nucleon cross section [cm2]
DM mass [GeV]