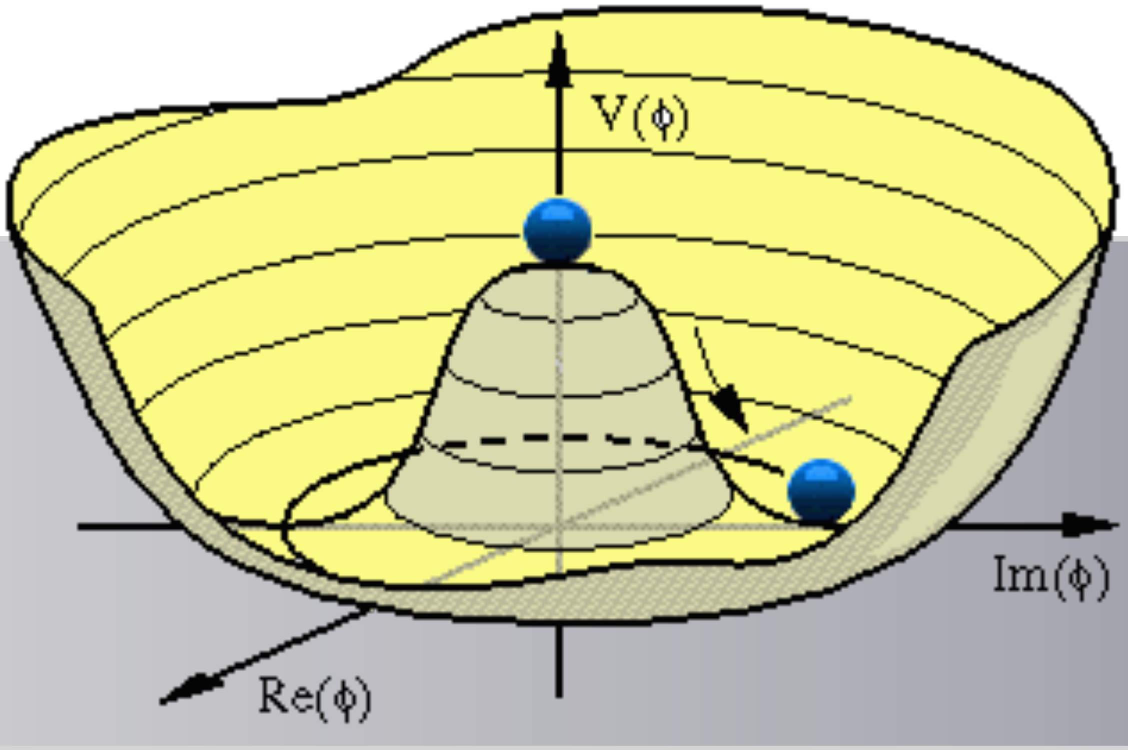
The Higgs

Missing Piece in the Standard Model



Higgs Searches before the discovery

Status before the LHC startup:
no evidence for Higgs production ➛ limits on Higgs mass

Indirect: theoretical upper & lower bounds,
electroweak precision measurements (W and top mass, …)

Direct: searches for Higgs production (e.g. LEP, Tevatron)

Direct searches at the LHC:

Common opinion: if SM Higgs mechanism is realized in nature, LHC will discover the Higgs

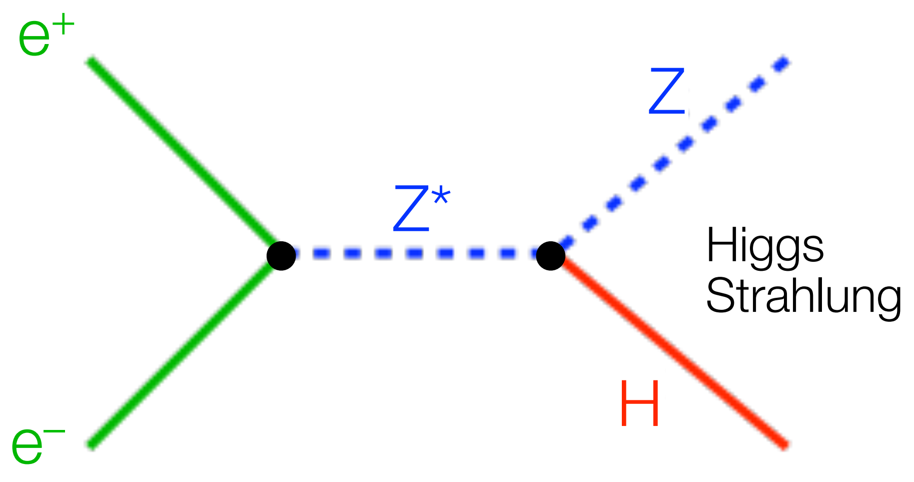
Time scale for results depends on Higgs mass:
low mass Higgs more difficult to observe

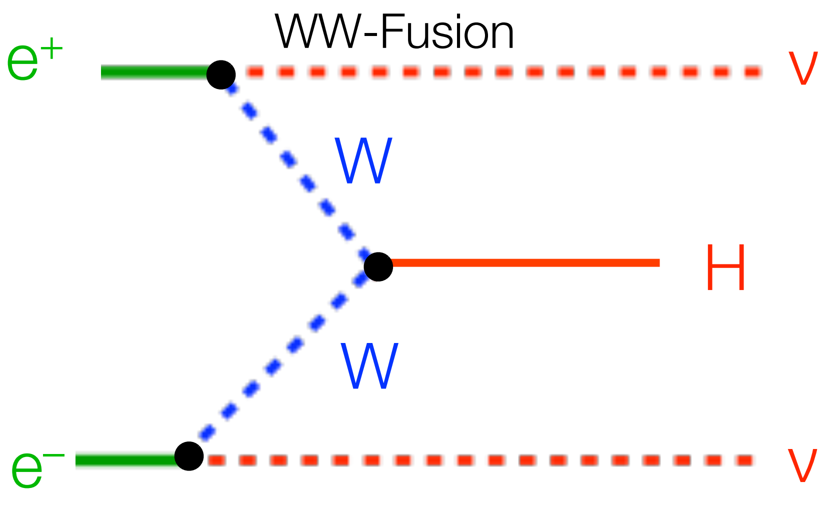
Higgs(-like) particles in many models beyond the SM
[Discovery potential depends on model parameters]

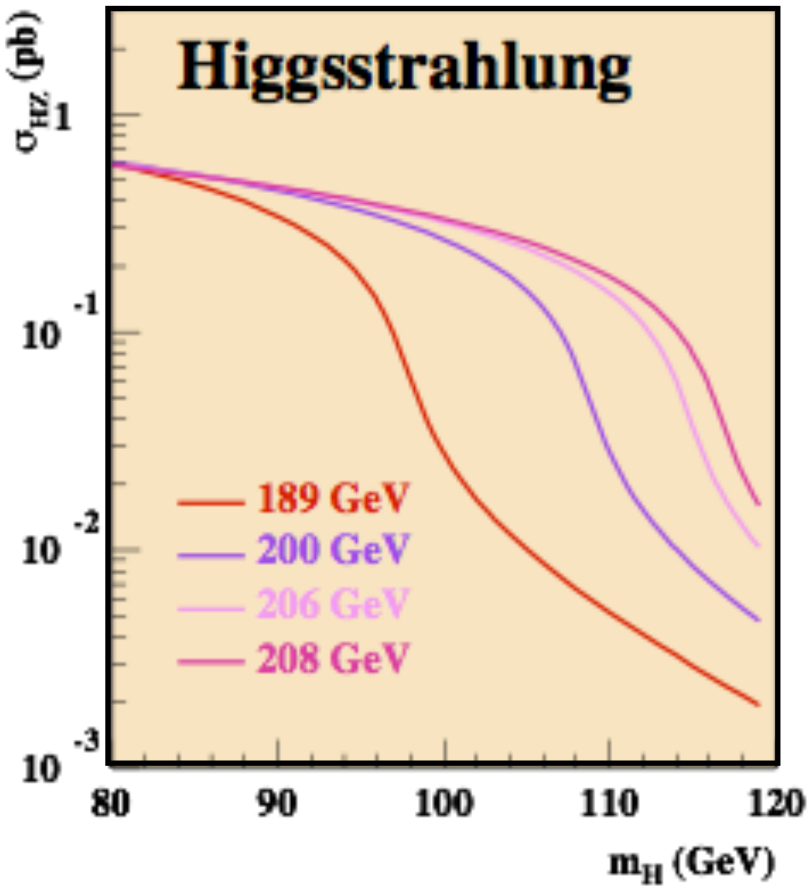
Higgs Search

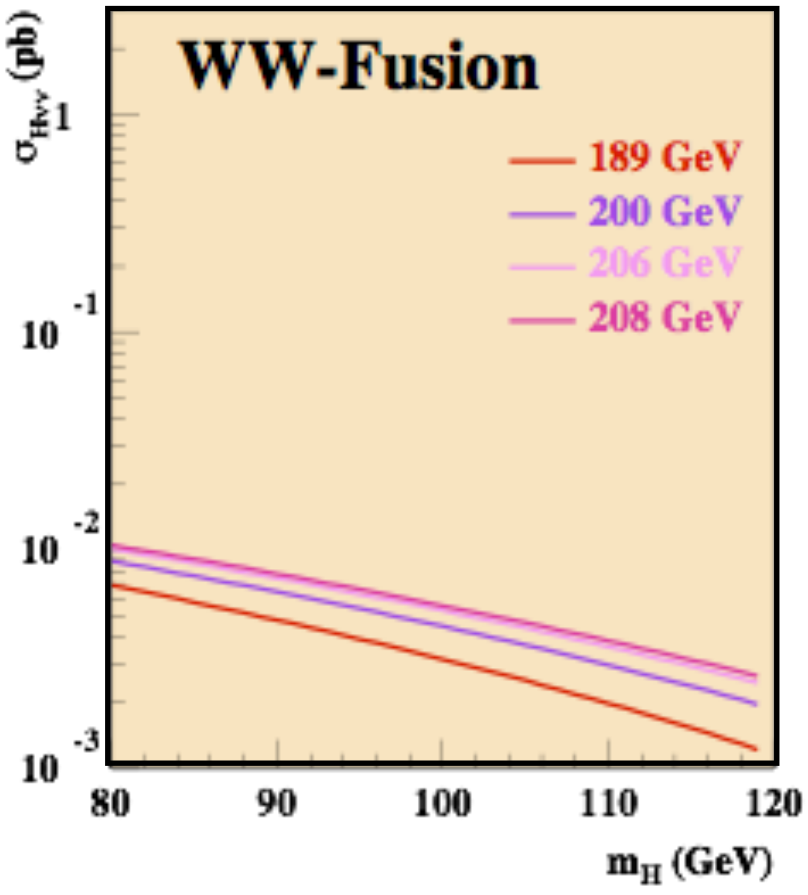
at LEP

SM Higgs Production at LEP

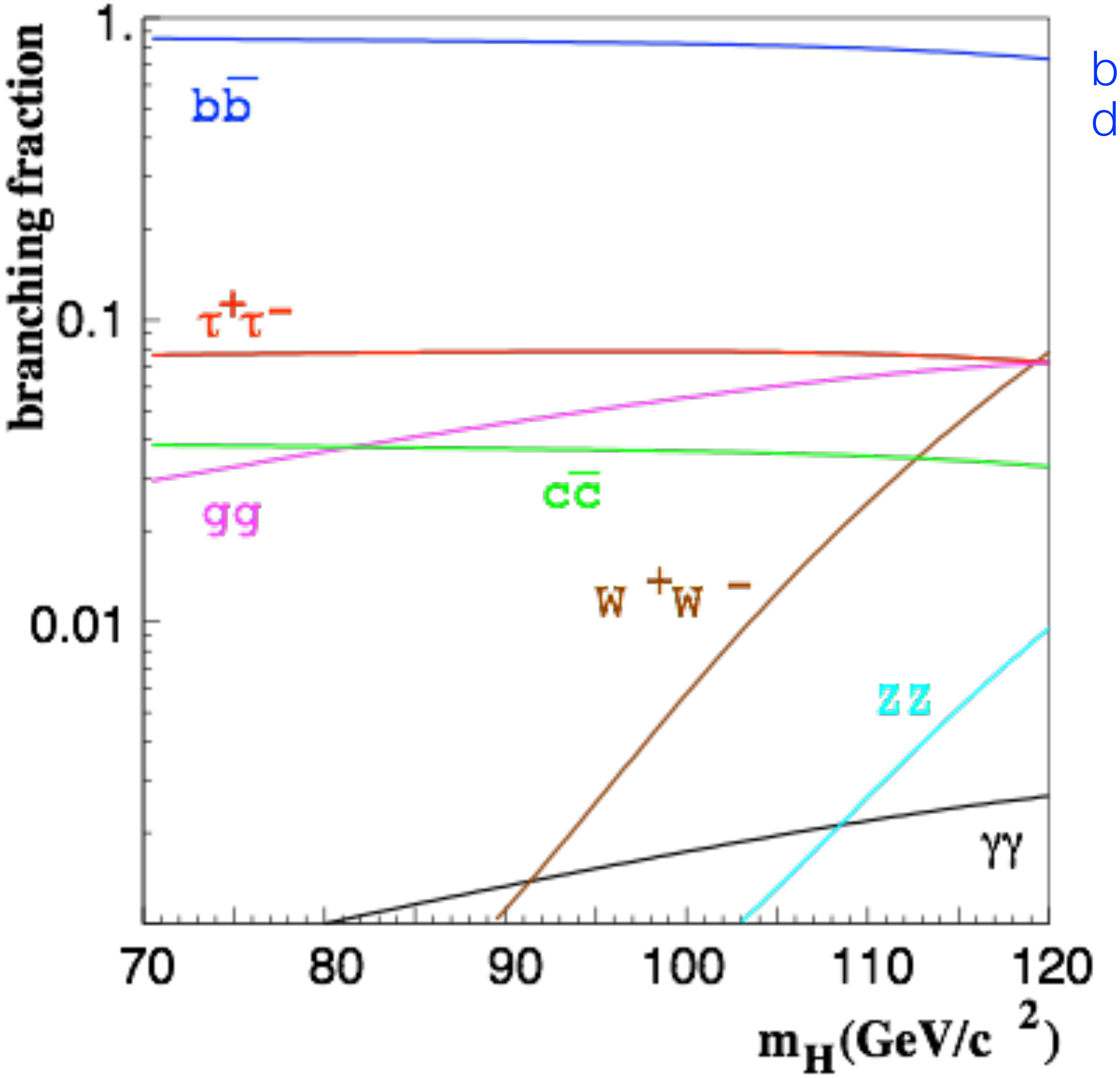






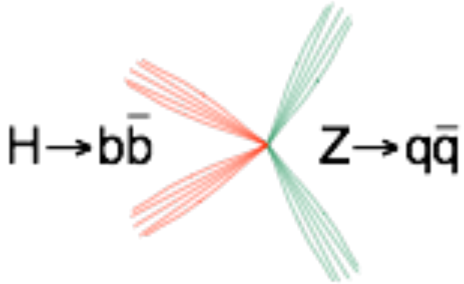
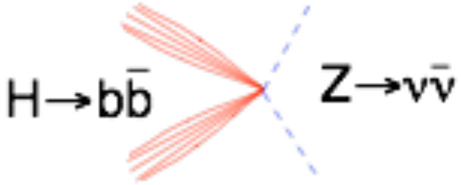
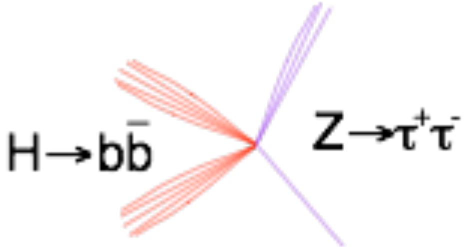
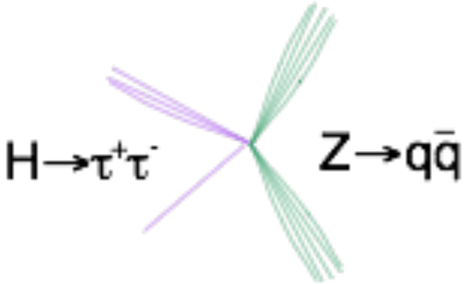


Higgs Decay at LEP Energies

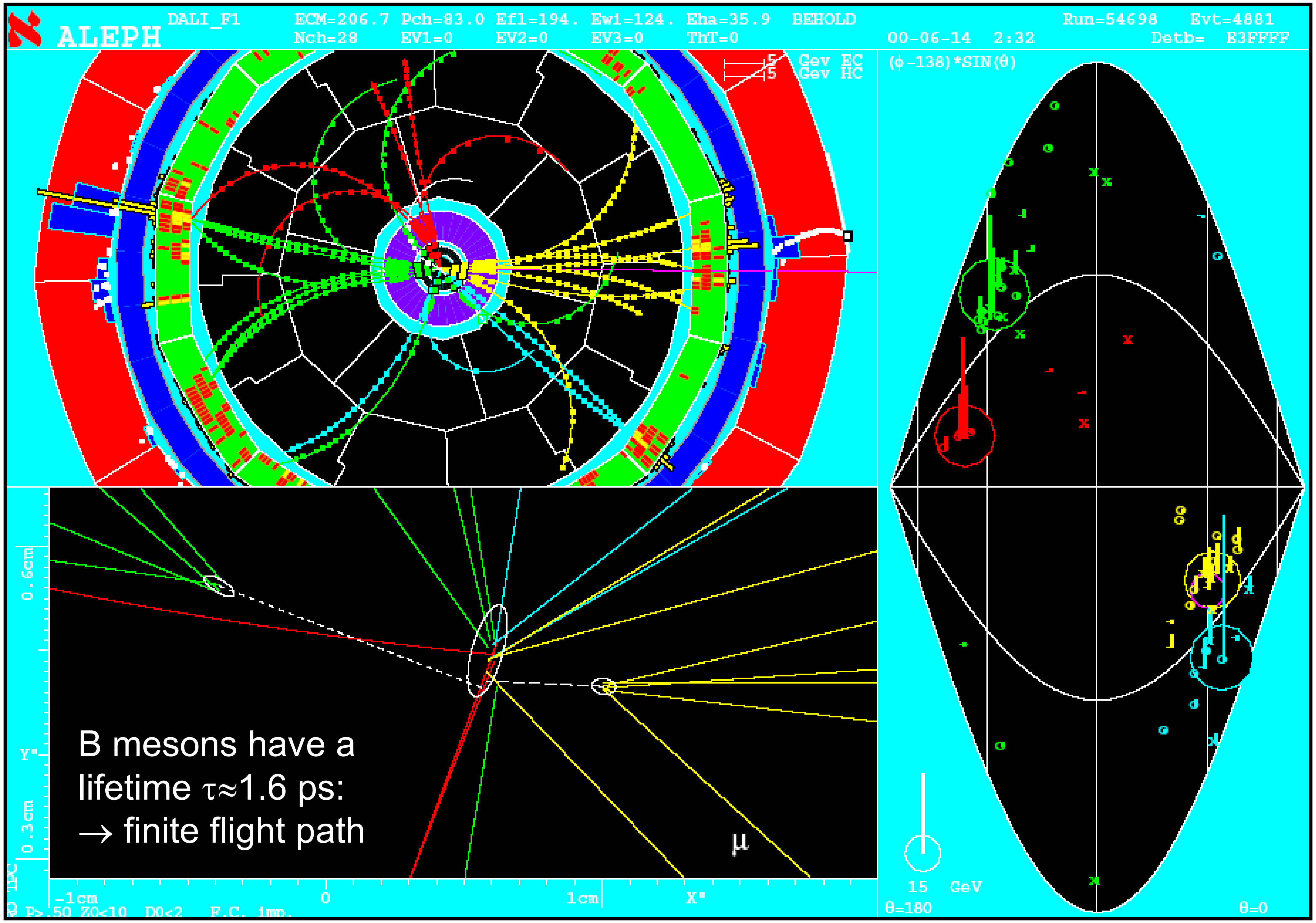


bb-decay
dominant !!

LEP Higgs Signatures

			Backgrounds
	4-jets	51%	WW ➛ qqqq ZZ ➛ qqqq QCD 4-jets
	missing energy	15%	WW ➛ qqlν ZZ ➛ bbνν
	τ-channel	2.4%	WW ➛ qqτν ZZ ➛ bbττ ZZ ➛ qqττ QCD low mult. jets
	τ-channel	5.1%	
	lepton channel	4.9%	ZZ ➛ bbee ZZ ➛ bbμμ

Higgs Candidate [M_H=114 GeV]



B mesons have a
lifetime τ≈1.6 ps:
→ finite flight path

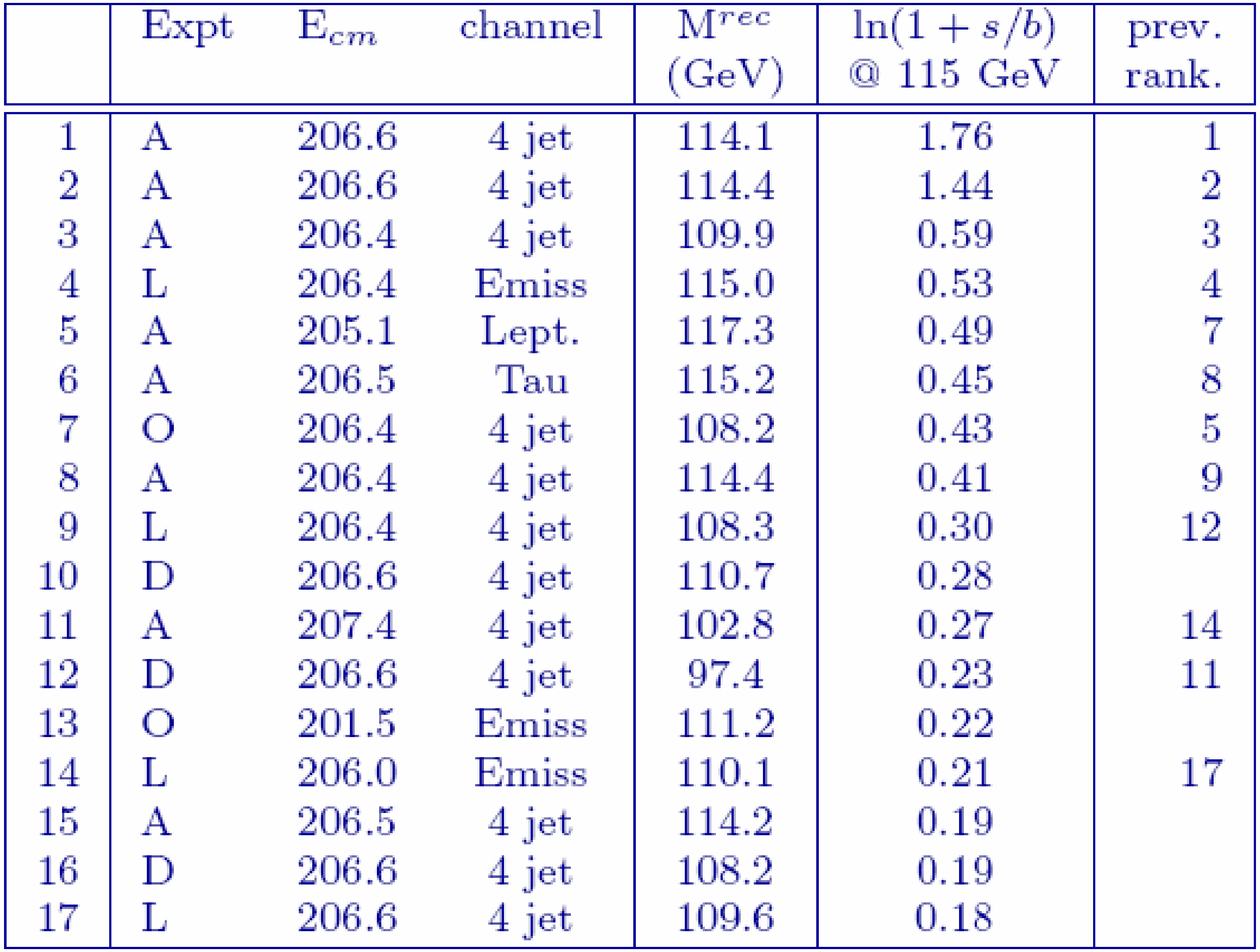
LEP Higgs Candidates

LEP
final result

Observation:
17 candidate
events

Expectation:
15.8 background
events

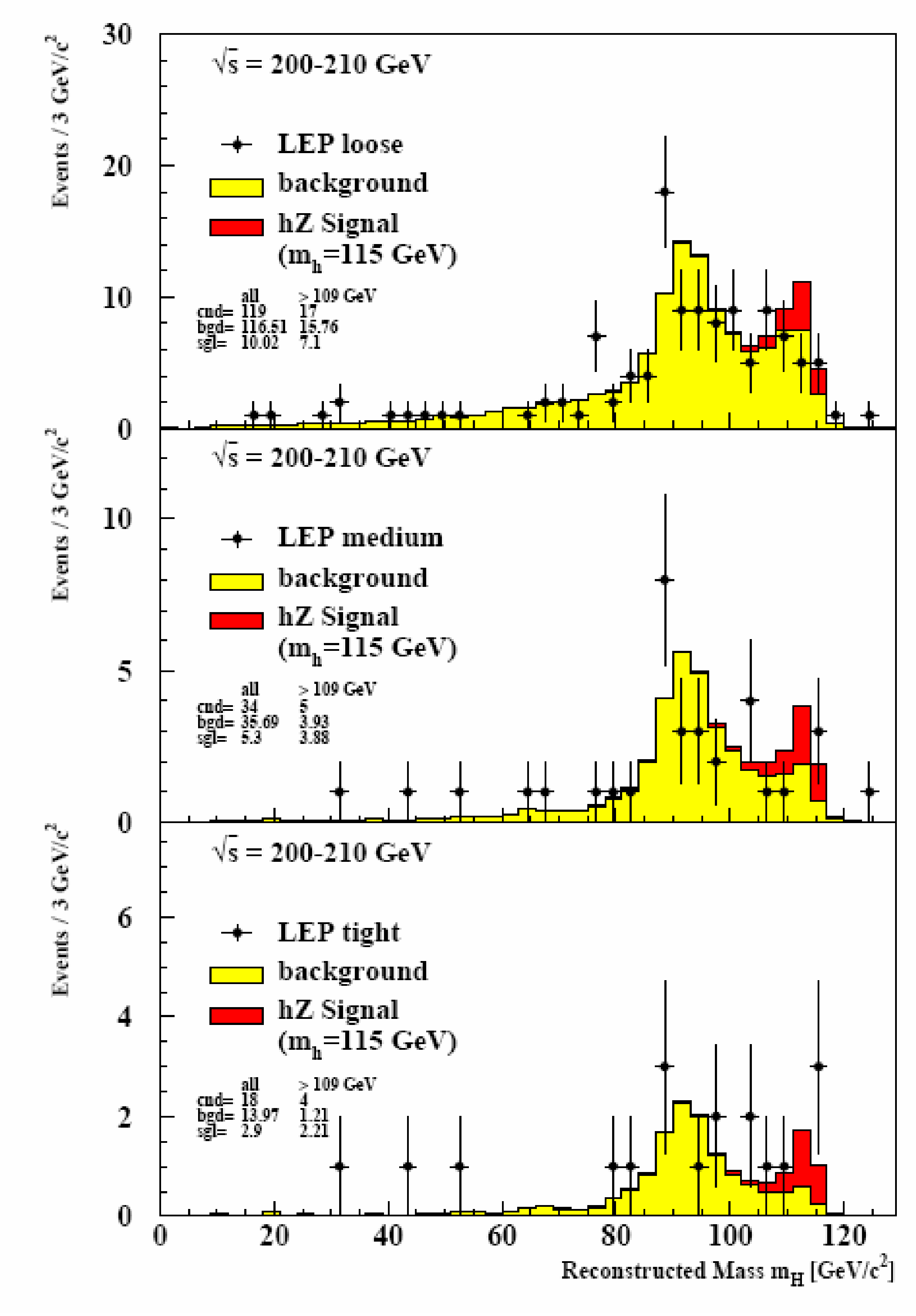
8.4 signal events
for M_H =115 GeV



	Expt	E_{cm}	channel	M^{rec} (GeV)	$\ln(1+s/b)$ @ 115 GeV	prev. rank.
1	A	206.6	4 jet	114.1	1.76	1
2	A	206.6	4 jet	114.4	1.44	2
3	A	206.4	4 jet	109.9	0.59	3
4	L	206.4	Emiss	115.0	0.53	4
5	A	205.1	Lept.	117.3	0.49	7
6	A	206.5	Tau	115.2	0.45	8
7	O	206.4	4 jet	108.2	0.43	5
8	A	206.4	4 jet	114.4	0.41	9
9	L	206.4	4 jet	108.3	0.30	12
10	D	206.6	4 jet	110.7	0.28	
11	A	207.4	4 jet	102.8	0.27	14
12	D	206.6	4 jet	97.4	0.23	11
13	O	201.5	Emiss	111.2	0.22	
14	L	206.0	Emiss	110.1	0.21	17
15	A	206.5	4 jet	114.2	0.19	
16	D	206.6	4 jet	108.2	0.19	
17	L	206.6	4 jet	109.6	0.18	

Observation consistent with background !

Final LEP Result



Reconstructed Mass m_H [GeV]

Invariant mass of Higgs candidates

LEP Summary:

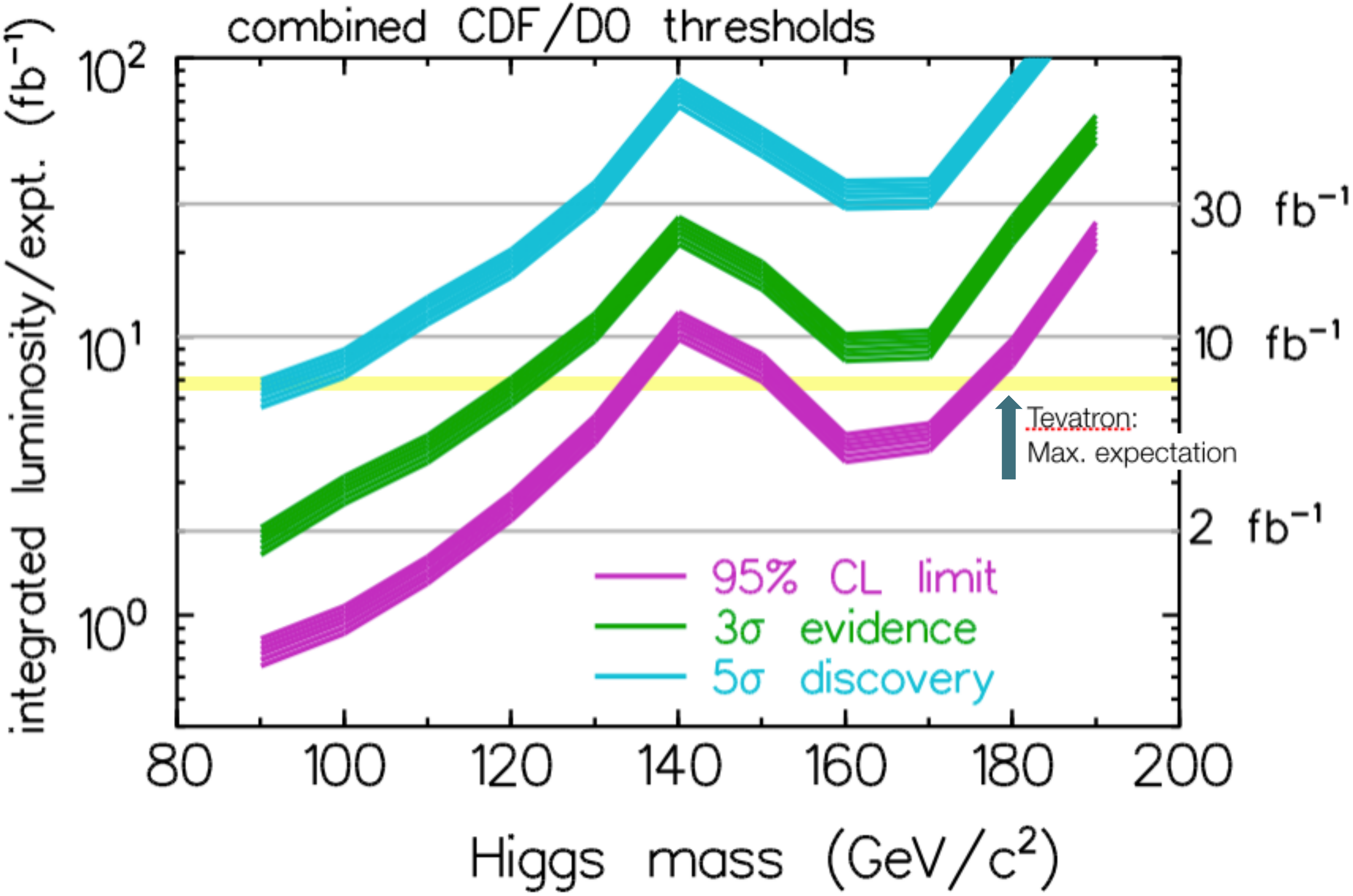
No signal above background

$M_H > 114.4$ GeV @ 95% CL

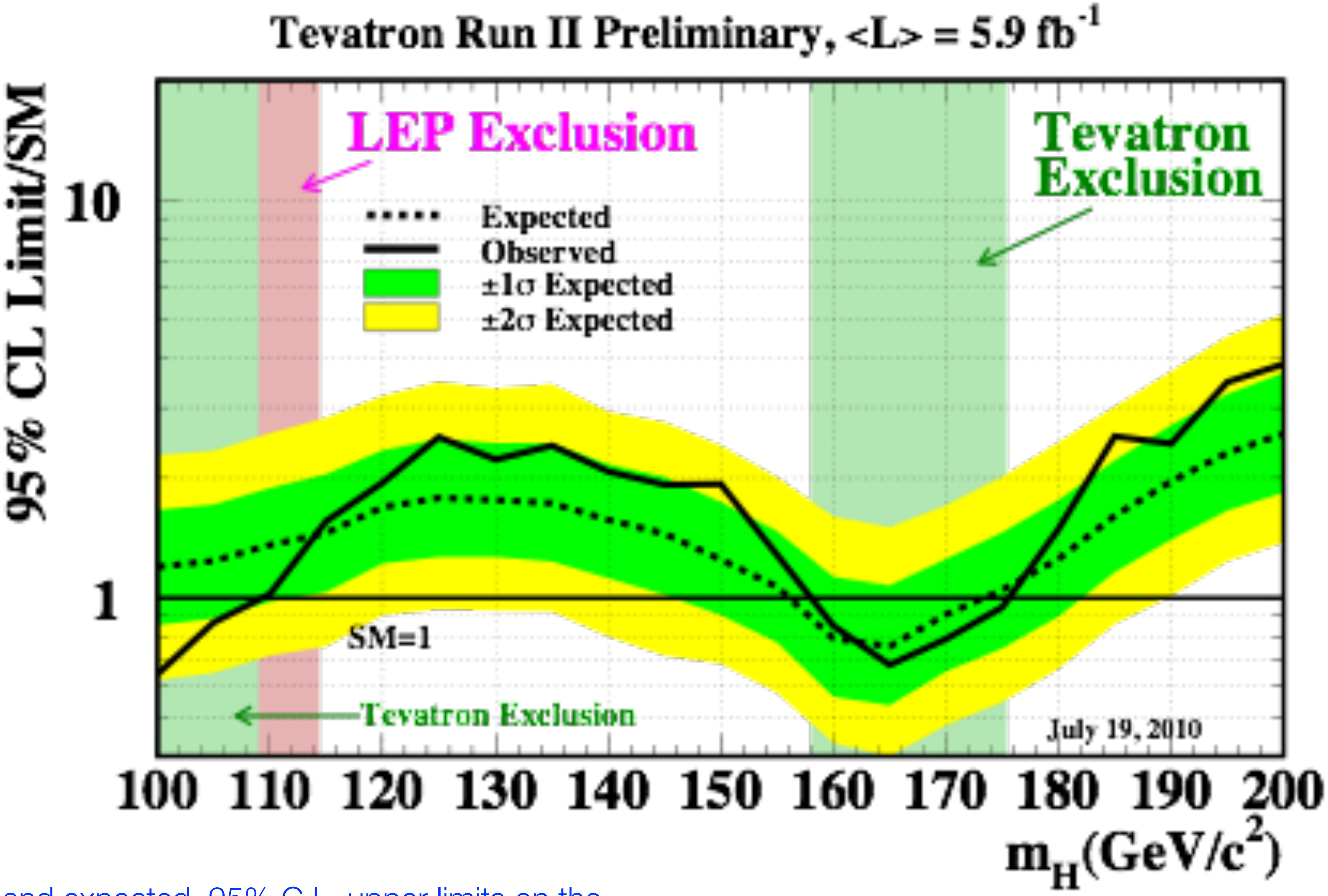
Higgs Search

at Tevatron

Tevatron: Higgs Discovery Potential



Tevatron: Recent Results (@2010!)



Observed and expected 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and D0 analyses ...

Tevatron: Explored Channels

CDF

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ (ST,DT,2,3 jet)	5.3	100-150	[14]
$VH \to \tau^+\tau^- b\bar{b}/q\bar{q}\tau^+\tau^-$	4.9	105-145	[15, 16]
$ZH \to \nu\bar{\nu}b\bar{b}$ (ST,TLDT)	5.2-6.4	100-150	[17, 18]
$ZH \to \ell^+\ell^- b\bar{b}$ (ST,DT,ee,$\mu\mu$,ee_{ICR},$\mu\mu_{trk}$)	4.2-6.2	100-150	[19]
$VH \to \ell^\pm\ell^\pm + X$	5.3	115-200	[20]
$H \to W^+W^- \to e^\pm\nu e^\mp\nu, \mu^\pm\nu\mu^\mp\nu$	5.4	115-200	[21]
$H \to W^+W^- \to e^\pm\nu\mu^\mp\nu$ (0,1,2+ jet)	6.7	115-200	[22]
$H \to W^+W^- \to \ell\bar{\nu}jj$	5.4	130-200	[23]
$H \to \gamma\gamma$	4.2	100-150	[24]
$t\bar{t}H \to t\bar{t}b\bar{b}$ (ST,DT,TT,4,5+ jets)	2.1	105-155	[25]

D0

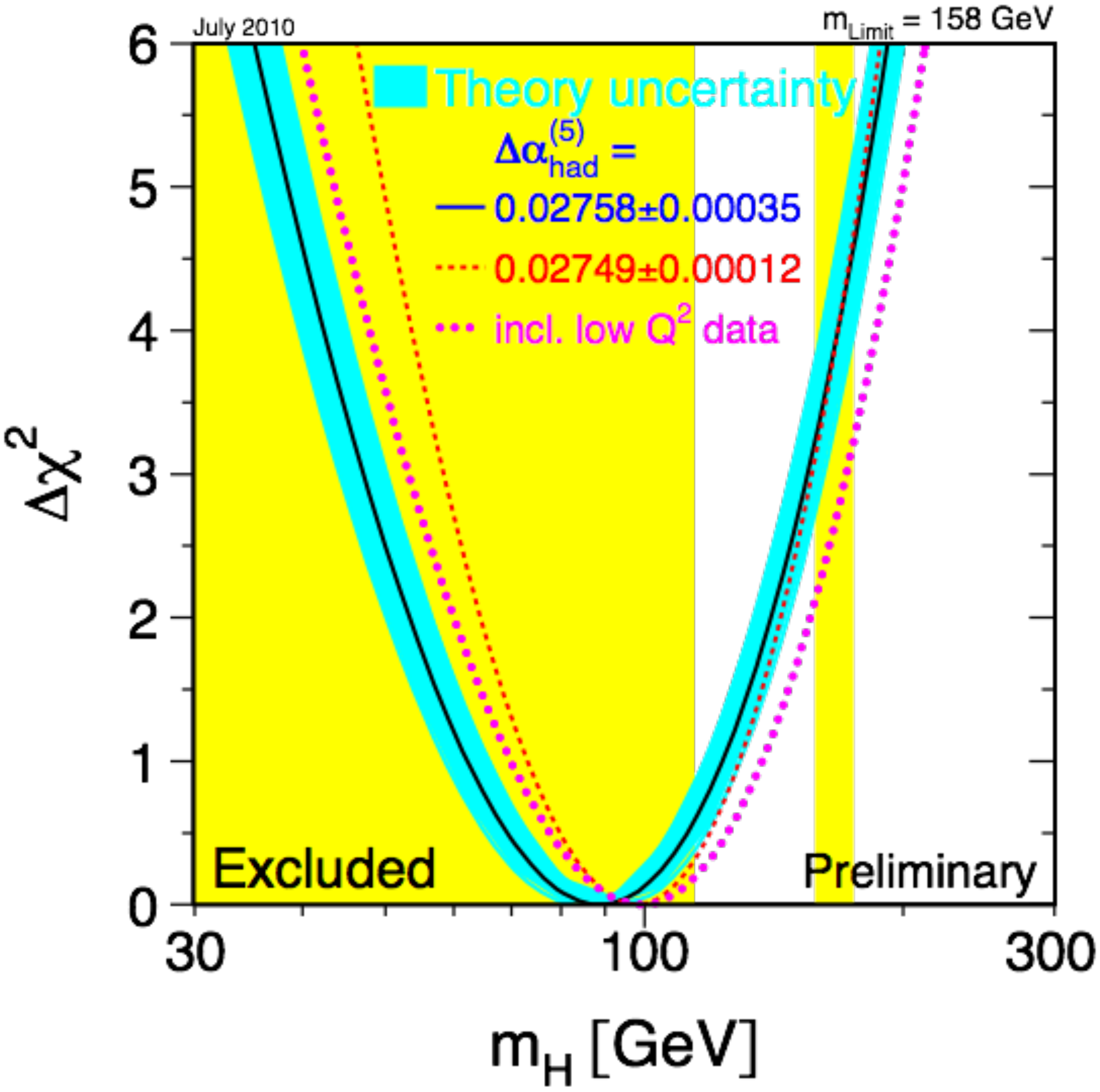
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ 2-jet channels 4×(TDT,LDT,ST,LDTX)	5.7	100-150	[5]
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(TDT,LDT,ST)	5.6	100-150	[6]
$ZH \to \nu\bar{\nu}b\bar{b}$ (TDT,LDT,ST)	5.7	100-150	[7]
$ZH \to \ell^+\ell^- b\bar{b}$ 4×(TDT,LDT,ST)	5.7	100-150	[8, 9]
$H \to W^+W^-$ 2×(0,1 jets)+(2+ jets)+(low-$m_{\ell\ell}$)+(e-τ_{had})+(μ-τ_{had})	5.9	110-200	[10]
$WH \to WW^+W^-$ (same-sign leptons 1+ jets)+(tri-leptons)	5.9	110-200	[10]
$ZH \to ZW^+W^-$ (tri-leptons 1 jet)+(tri-leptons 2+ jets)	5.9	110-200	[10]
$H + X \to \tau^+\tau^-$ (1 jet)+(2 jets)	2.3	100-150	[11]
$WH + ZH \to jjb\bar{b}$ 2×(TDT,LDT)	4.0	100-150	[12]
$H \to \gamma\gamma$	5.4	100-150	[13]

Production via: qq ➛ W/Z H (associate production), gg ➛ H (gluon fusion)
and qq ➛qqH (vector boson fusion)

Blue Band Plot

[Knowledge on SM Higgs]

Our Knowledge about the Higgs … archeology!



EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

From direct
search at LEP:

$M_H > 114$ GeV

@ 95% CL

From direct
search at Tevatron:

$158 < M_H < 175$ GeV

@ 95% CL

[Updated: Summer 2010]

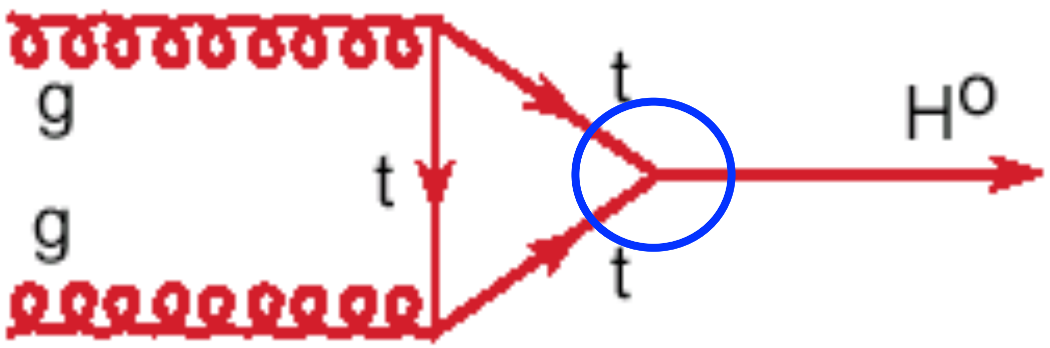
Higgs Search

at the LHC

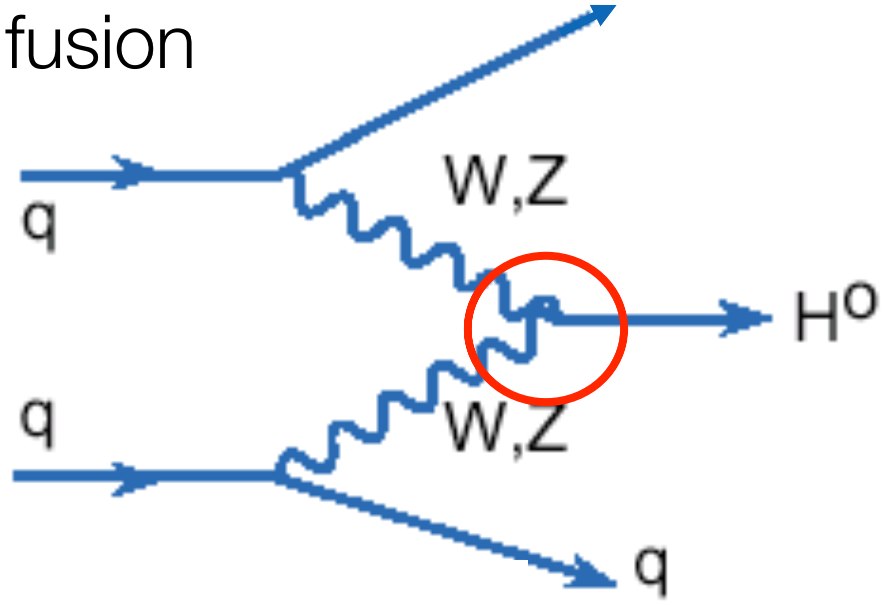
Higgs Production Mechanisms

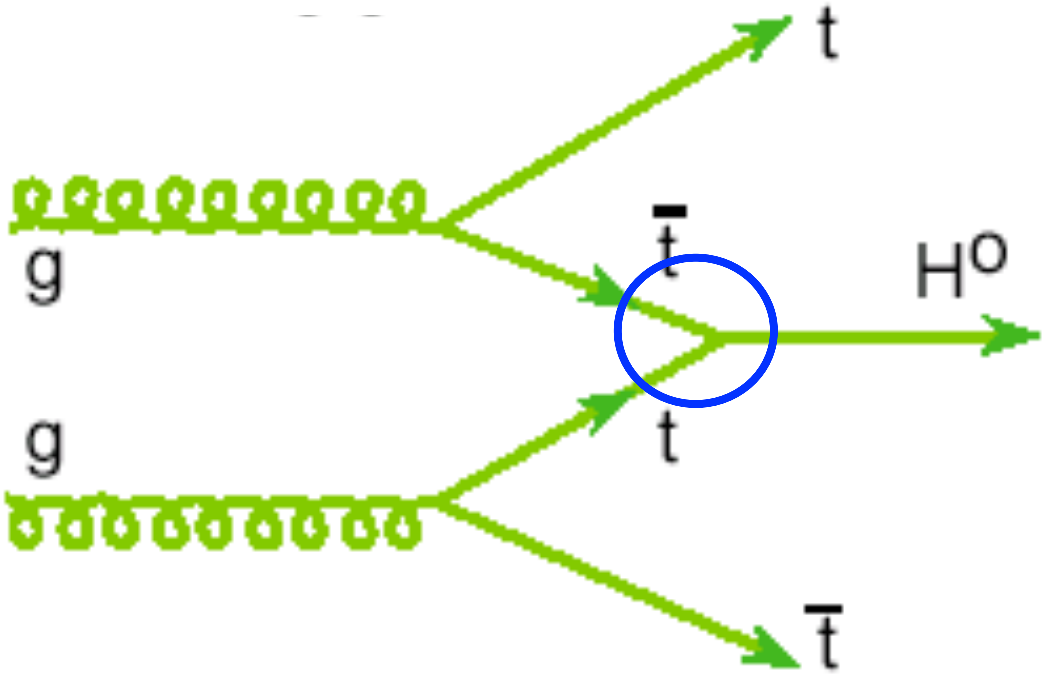
Gluon fusion

Other quarks contribution suppressed by m_q^2



Vector boson fusion



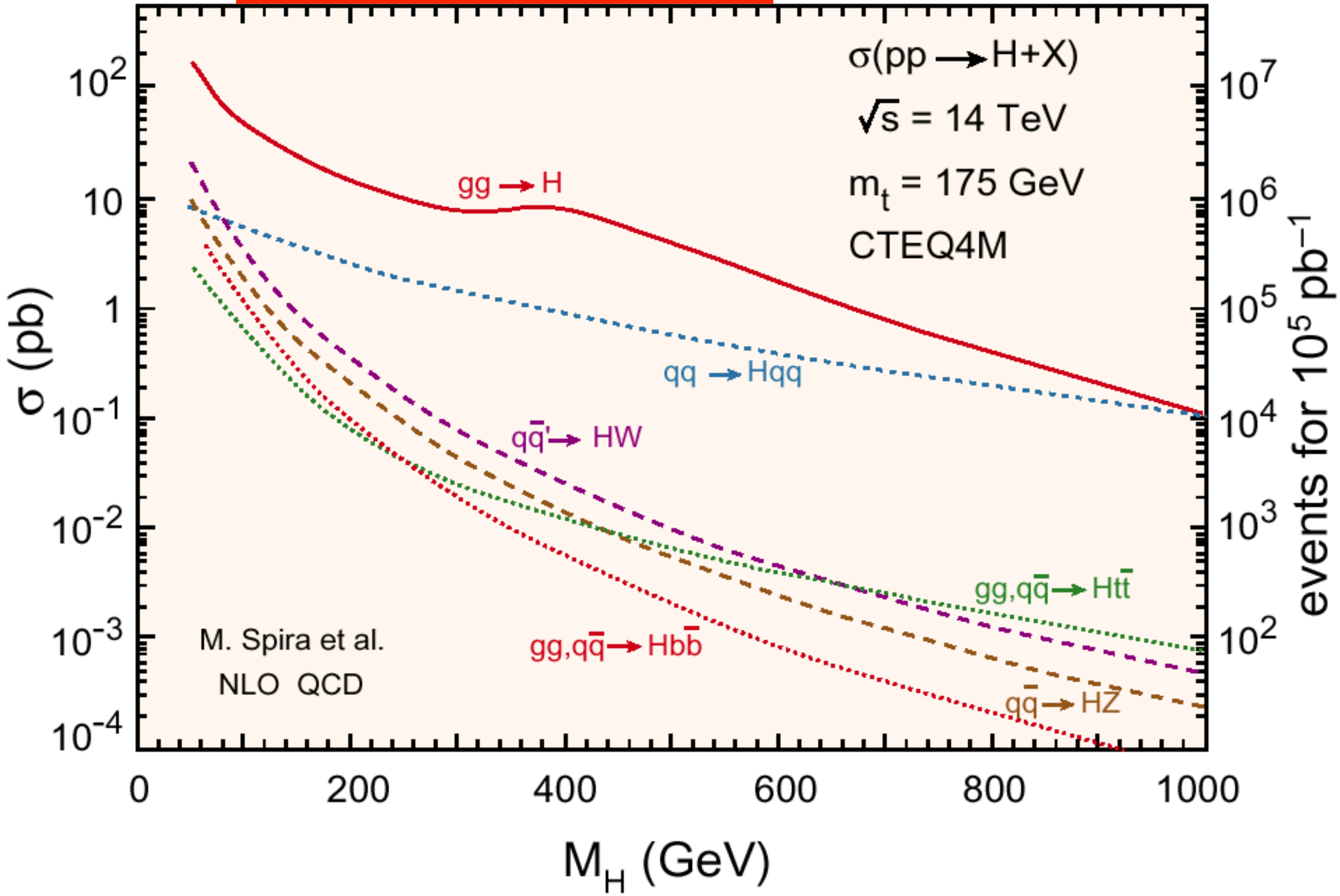


$t\bar{t}$-fusion

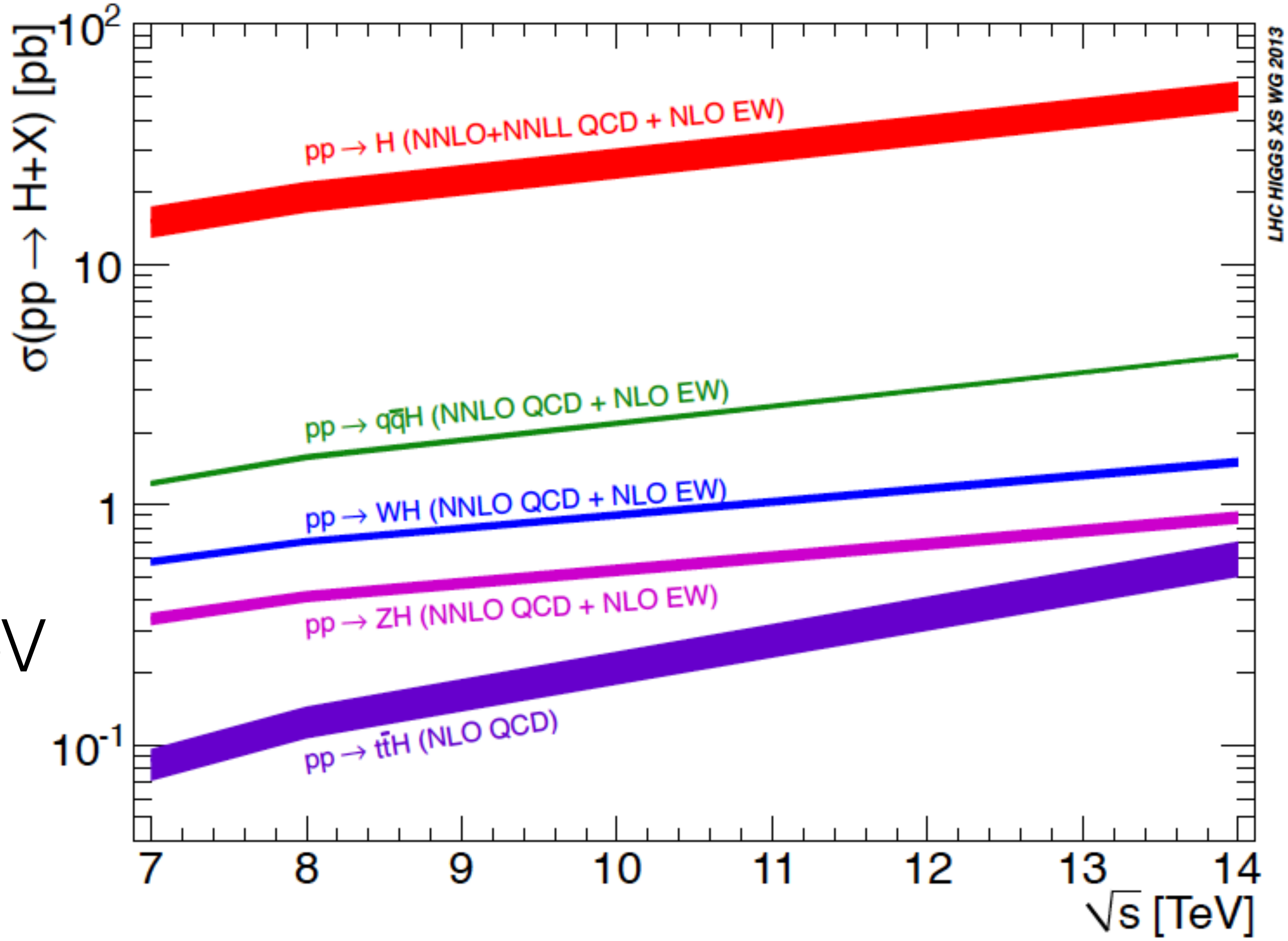
Associated production

Higgs Production Cross Sections

LHC cms 14 TeV



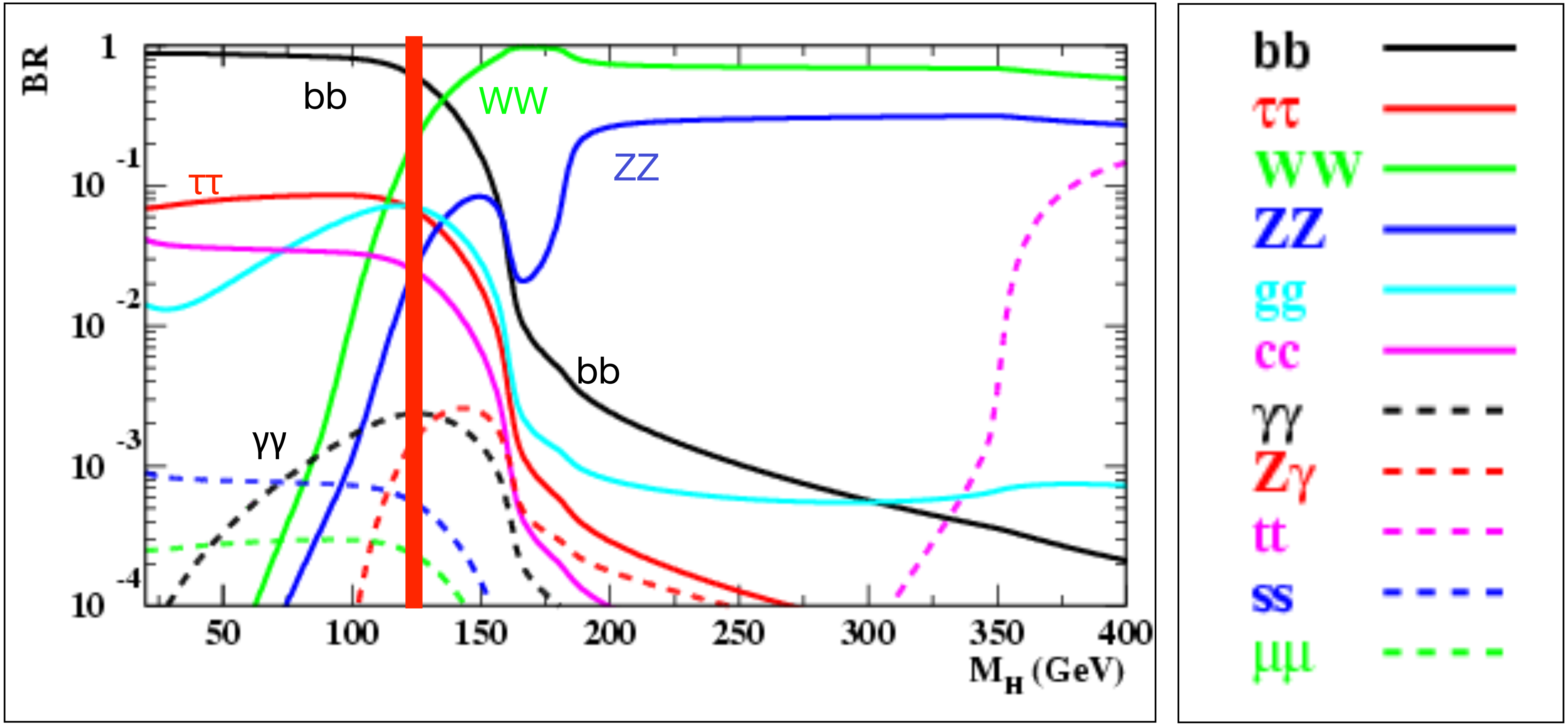
Higgs Production



Higgs mass = 125 GeV

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$15.1^{+15\%}_{-15\%}$	$1.22^{+3\%}_{-2\%}$	$0.58^{+4\%}_{-4\%}$	$0.33^{+6\%}_{-6\%}$	$0.09^{+12\%}_{-18\%}$	17.4
8	$19.3^{+15\%}_{-15\%}$	$1.58^{+3\%}_{-2\%}$	$0.70^{+4\%}_{-5\%}$	$0.41^{+6\%}_{-6\%}$	$0.13^{+12\%}_{-18\%}$	22.1
14	$49.8^{+20\%}_{-15\%}$	$4.18^{+3\%}_{-3\%}$	$1.50^{+4\%}_{-4\%}$	$0.88^{+6\%}_{-5\%}$	$0.61^{+15\%}_{-28\%}$	57.0

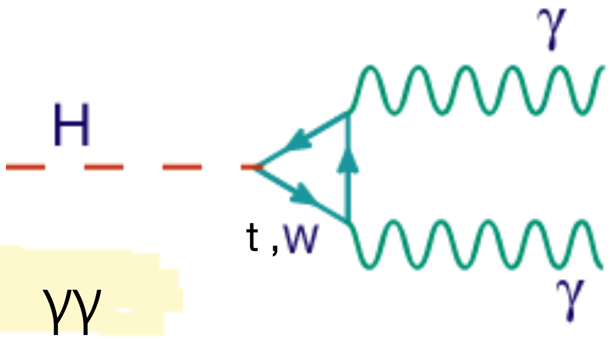
Higgs Boson Decays



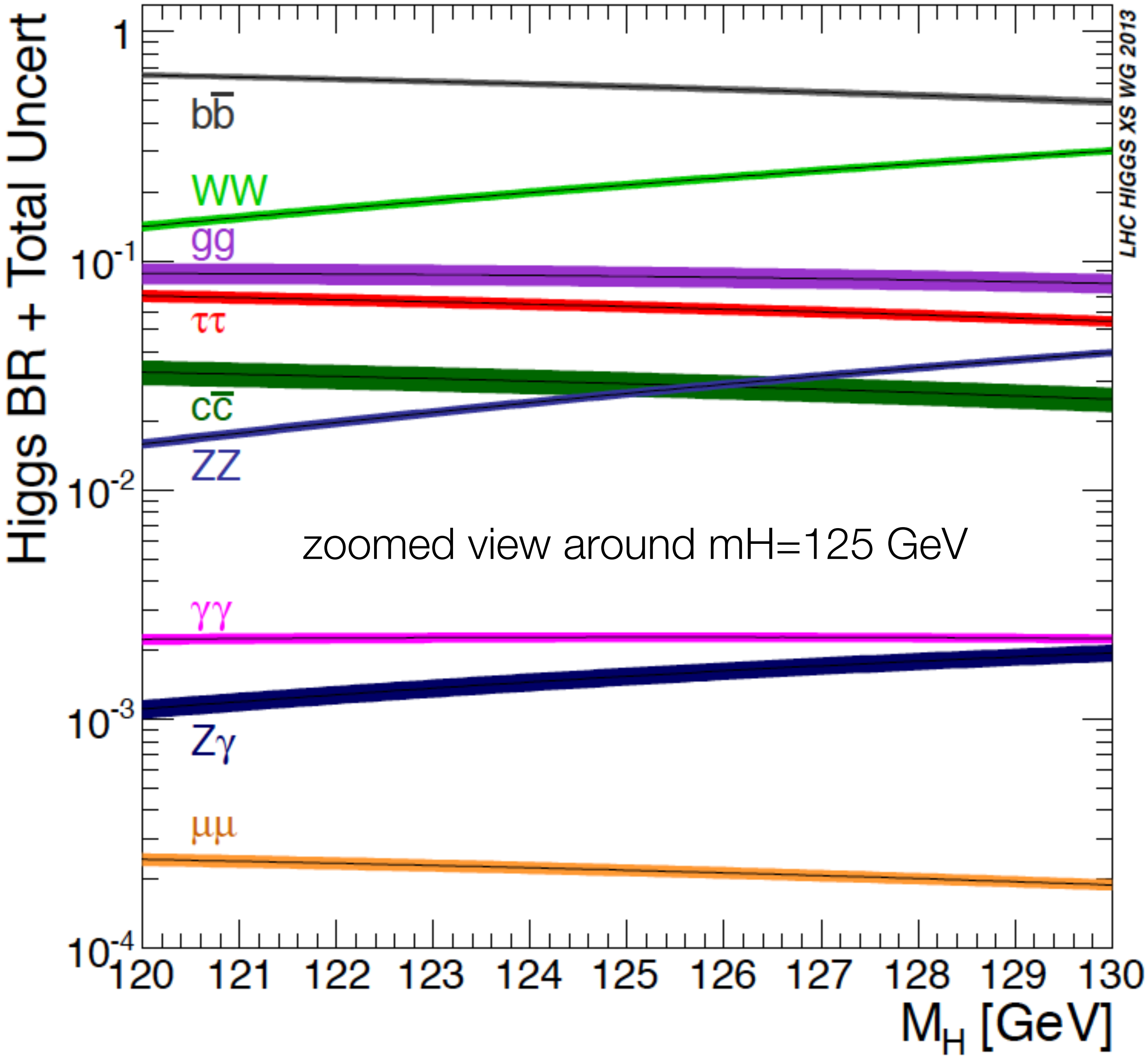
For M < 135 GeV: H ➛ bb, ττ dominant

For M > 135 GeV: H ➛ WW, ZZ dominant

Tiny but also important: H ➛ γγ



Higgs Boson Decays



Since decays to gg, diphotons, Zγ are loop induced they are Sensitive to WW, ZZ, ttbar couplings in different combinations

Pre LHC Higgs diary

- Indirect bounds on m_H from global EW fits : two decades at LEP, SLC, Tevatron suggest

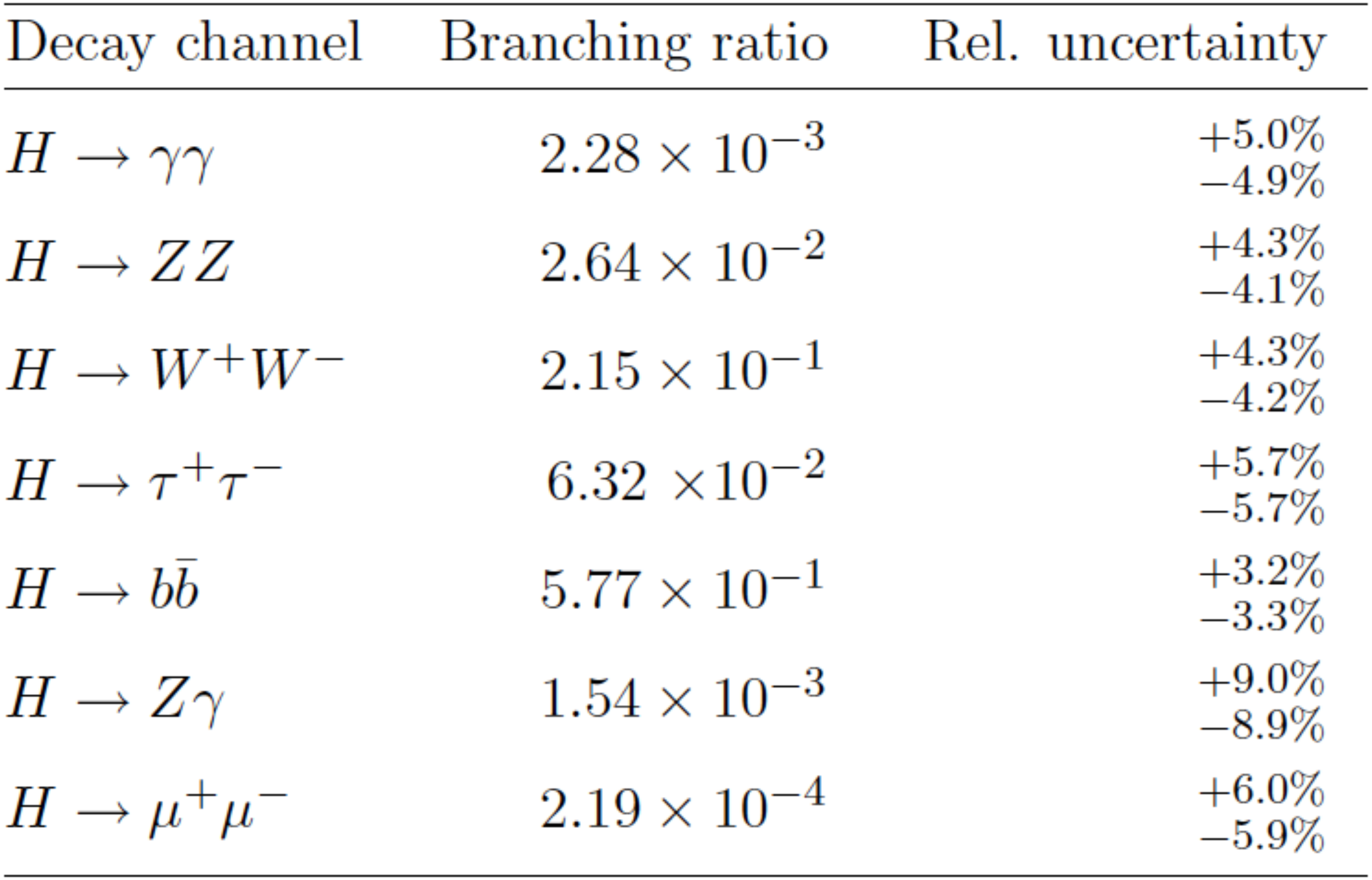
$$m_H = 89^{+22}_{-18} GeV \qquad m_H < 127 GeV @ 90\% CL$$

- Direct and model-independent search at LEP up 20 209 GeV cms yelded a 95% CL lower bound on mH of 114.4GeV

- Direct search after LEP shutdown in 2000 at Tevatron ppbar collider using 10fb-1 gave
  a] excluded intervals 90-109 GeV and 149-182 GeV
  b] broad excess at the level of 3 std in the interval 115<mH<140 GeV with a maximum at 125 GeV

- LHC run in 2011 (7 TeV, 5 fb^{-1}), 2012 (8 TeV, 20 fb^{-1}) evidence for a new particle decaying to $\gamma\gamma$ and ZZ with rates as predicted by SM. Evidence for decays to W^+W^- but no evidence for bbar and $\tau^+\tau^-$

Higgs Boson Decays



Decay channel	Branching ratio	Rel. uncertainty
$H \rightarrow \gamma\gamma$	2.28×10^{-3}	+5.0% −4.9%
$H \rightarrow ZZ$	2.64×10^{-2}	+4.3% −4.1%
$H \rightarrow W^+W^-$	2.15×10^{-1}	+4.3% −4.2%
$H \rightarrow \tau^+\tau^-$	6.32×10^{-2}	+5.7% −5.7%
$H \rightarrow b\bar{b}$	5.77×10^{-1}	+3.2% −3.3%
$H \rightarrow Z\gamma$	1.54×10^{-3}	+9.0% −8.9%
$H \rightarrow \mu^+\mu^-$	2.19×10^{-4}	+6.0% −5.9%

Direct Higgs Channels

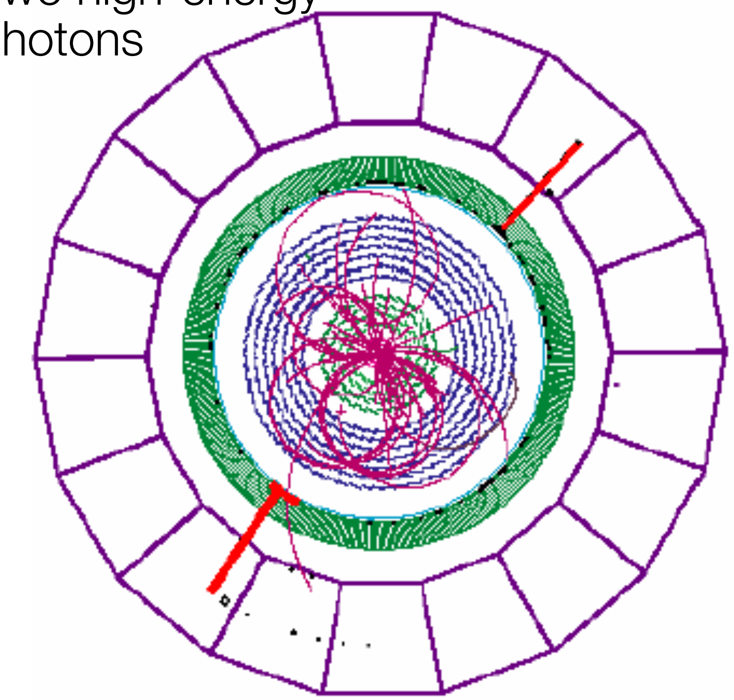
Channel	LHC Potential
gg ➛ H ➛ bb	Huge QCD background (gg ➛ bb); extremely difficult
gg ➛ H ➛ ττ	Higgs with low p_T, hard to discriminate from background; problematic
gg ➛ H ➛ γγ	Small rate, large combinatorial background, but excellent determination of m_H (CMS: crystal calorimeter)
gg ➛ H ➛ WW	Large rate, but 2 neutrinos in leptonic decay, Higgs spin accessible via lepton angular correlations
gg ➛ H ➛ ZZ	ZZ ➛ 4μ: "gold-plated" channel for high-mass Higgs (ATLAS: muon spectrometer)

Vector Boson Fusion

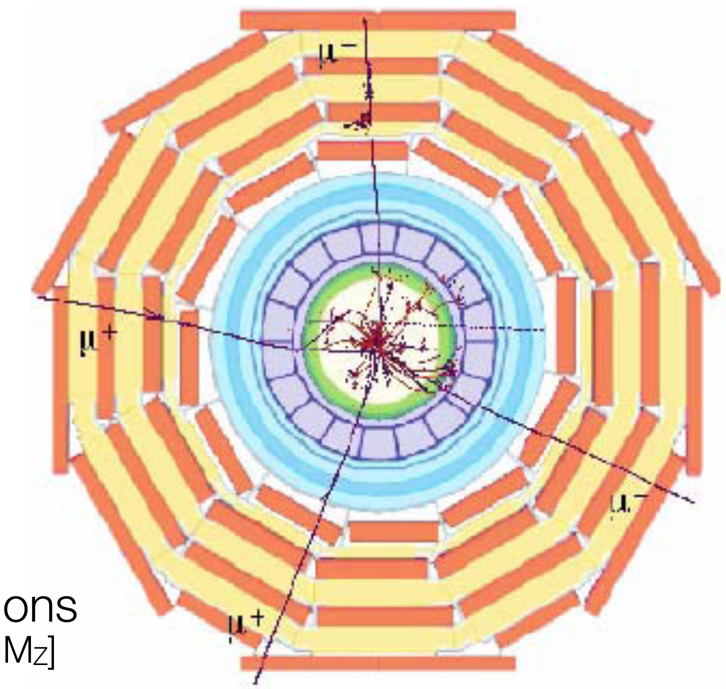
Channel	LHC Potential
qq ➛ qq H [with H ➛ bb]	Very large QCD background (gg/qq ➛ bbqq); still very difficult
qq ➛ qq H [with H ➛ ττ]	Higher p_T than direct channel; interesting discovery channel for $m_H < 135$ GeV
qq ➛ qq H [with H ➛ γγ]	Most likely combined with gg ➛ H ➛ γγ to inclusive diphoton signal
qq ➛ qq H [with H ➛ WW]	Additional background suppression w.r.t. direct channel; interesting discovery channel for $m_H > 135$ GeV
gg ➛ ttH [with H ➛ bb]	Top-associated production; Seemed very promising, but overwhelmed by SM ttbb production

Higgs Searches @ LHC: Examples

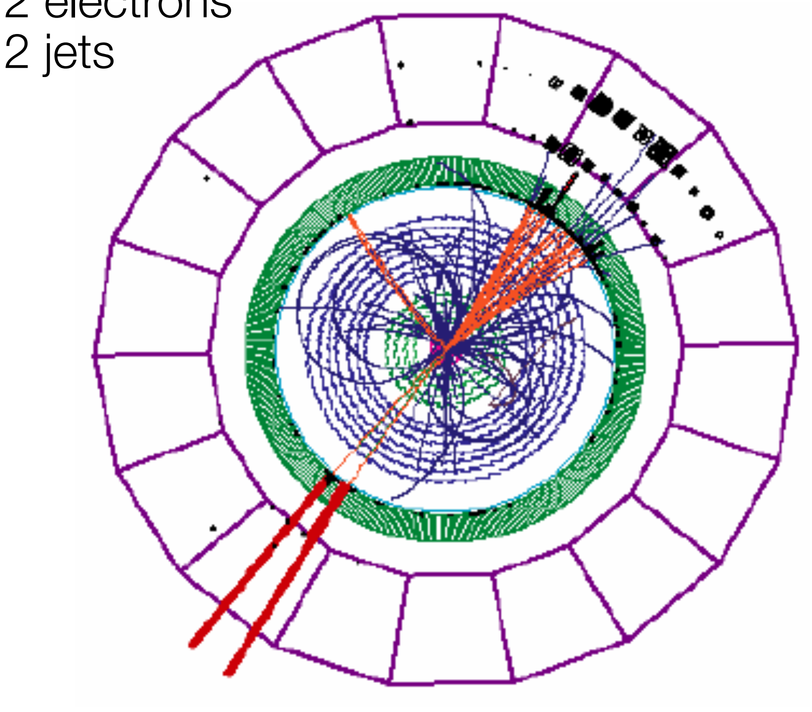
Two high-energy
photons

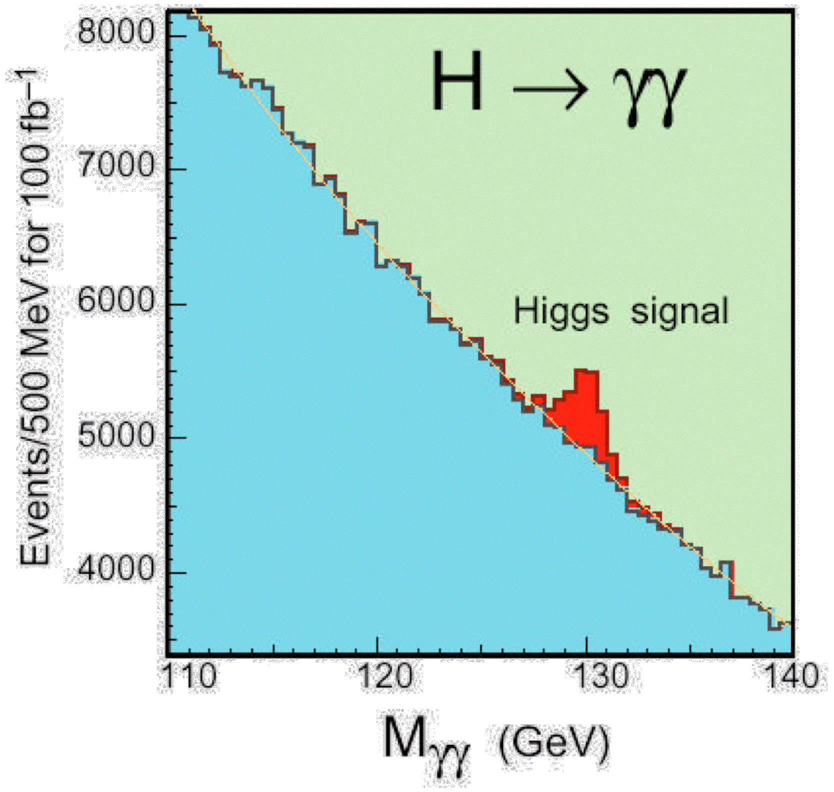


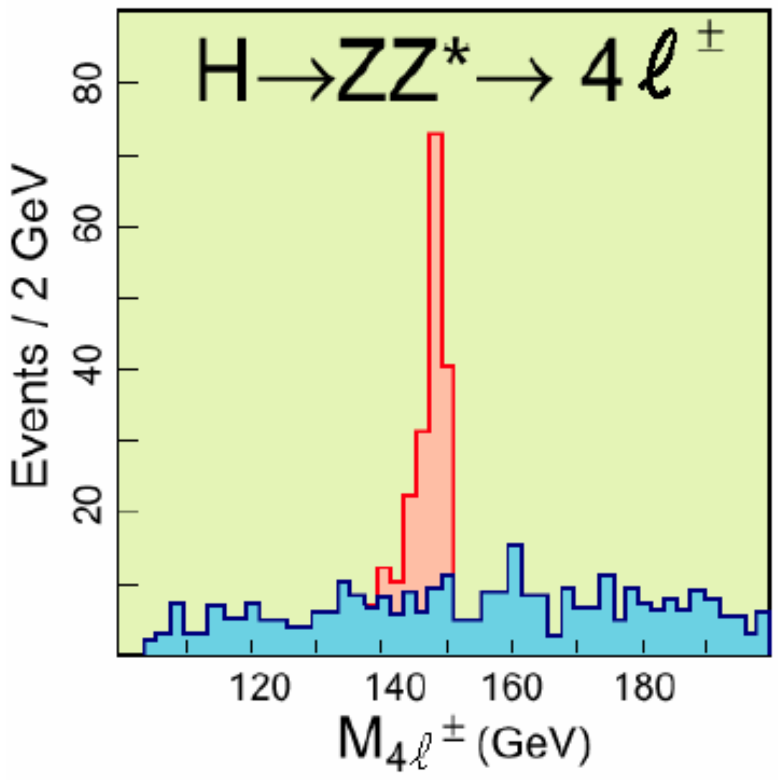
4 muons
[$M_{\mu\mu} = M_Z$]

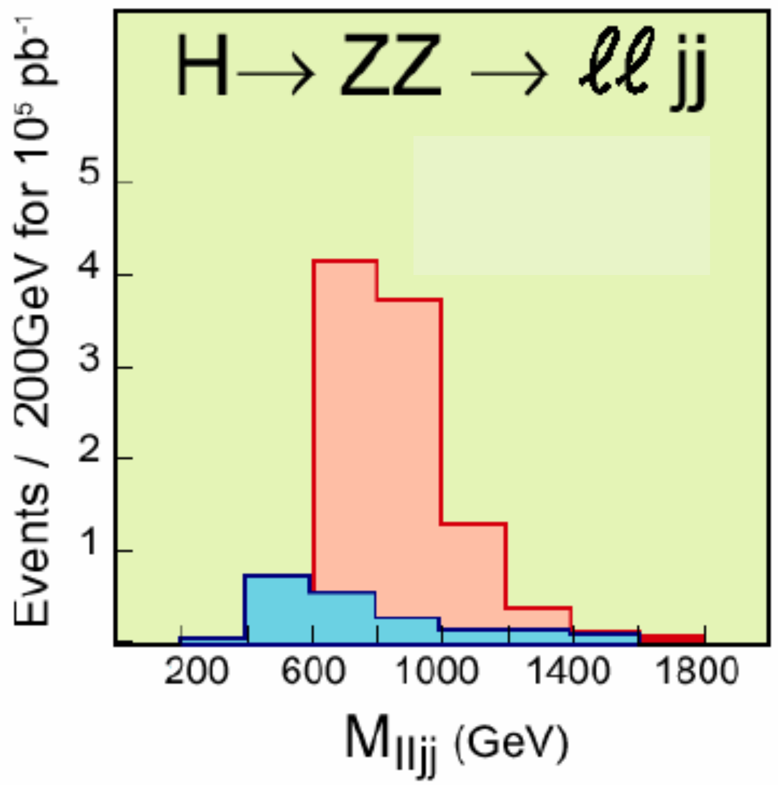


2 electrons
2 jets

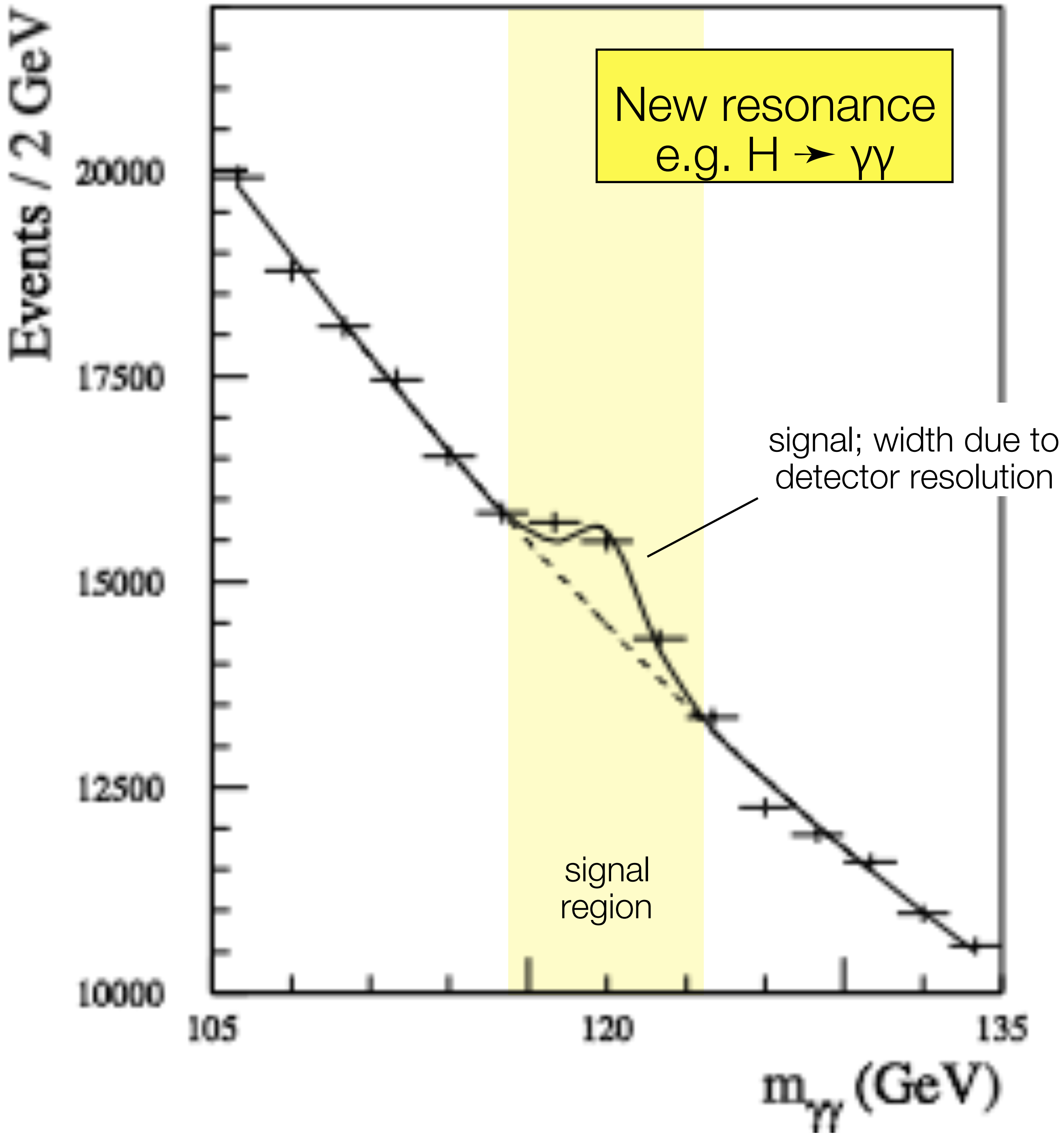








How to Make a Discovery



New resonance
e.g. H ➛ γγ

signal; width due to detector resolution

signal region

+ categorize events in classes

Signal significance:

$$S = \frac{N_S}{\sqrt{N_B + N_S}}$$

N_S: # signal events
N_B: # background events

... in peak region

S > 5:

Signal $N_S = N_{tot} - N_B$ is 5 times larger than statistical uncertainty on $N_B + N_S$ ...

Gaussian probability that upward fluctuation by more than 5σ is observed ...

$P_{5\sigma} = 10^{-7}$.

Discovery!

Maximizing the Significance S

1. Choose channels with low SM background

not possible: H → bb ... without associated production ...

possible: H → γγ ... despite of small branching ratio ...

H → ZZ ... with at least one Z decaying leptonically ...

tt H → ttbb ... via additional top selection ...

2. Optimize detector resolution

Example: mass resolution σ_m increases by a factor of 2;

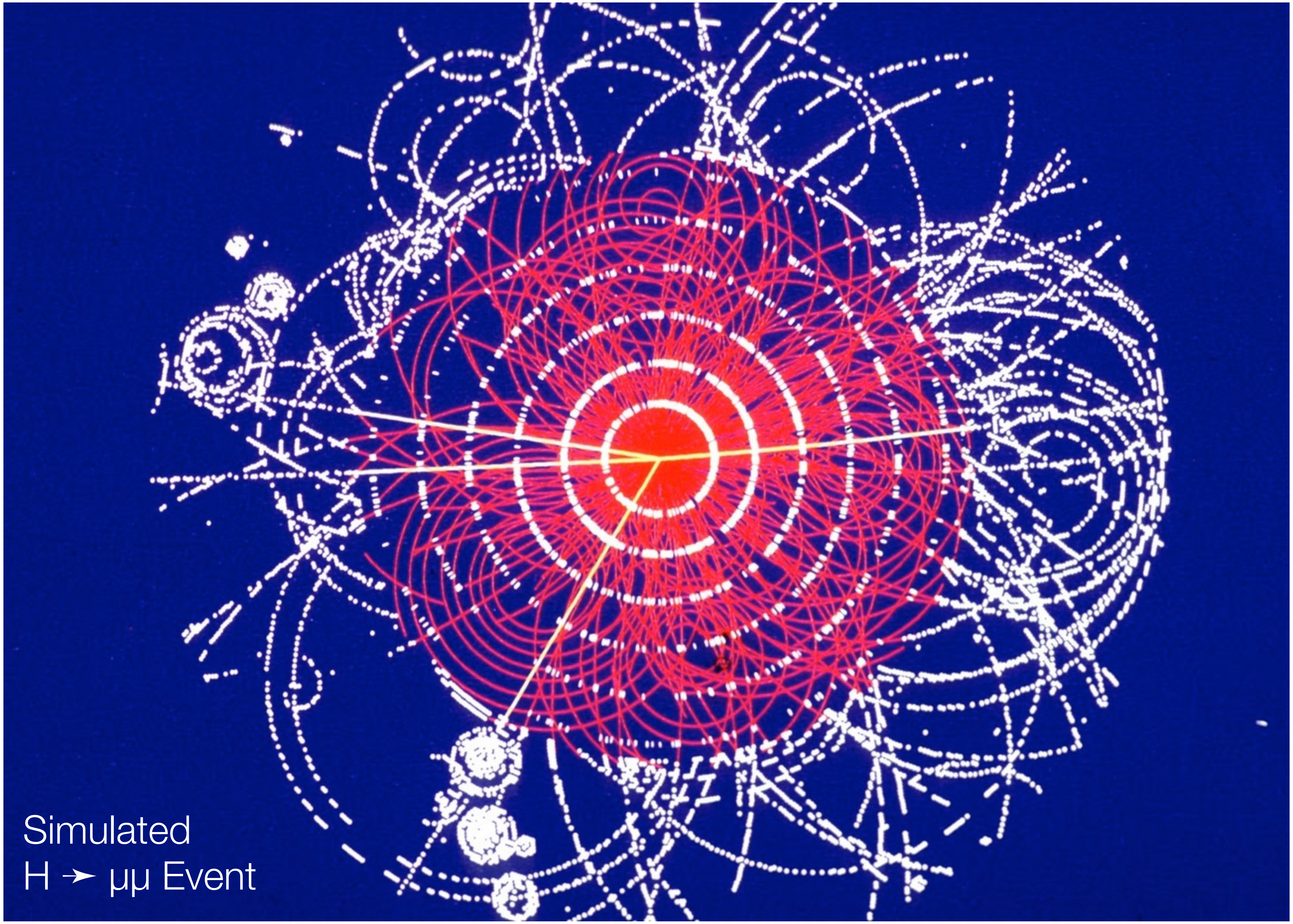
thus: peak region has to be increased by a factor 2 and number N_B of background events increases by factor of 2

$S = N_S/\sqrt{N_B}$ decreases by $\sqrt{2}$ $\longrightarrow$ $\boxed{S \sim \frac{1}{\sqrt{\sigma_m}}}$

3. Maximize luminosity L

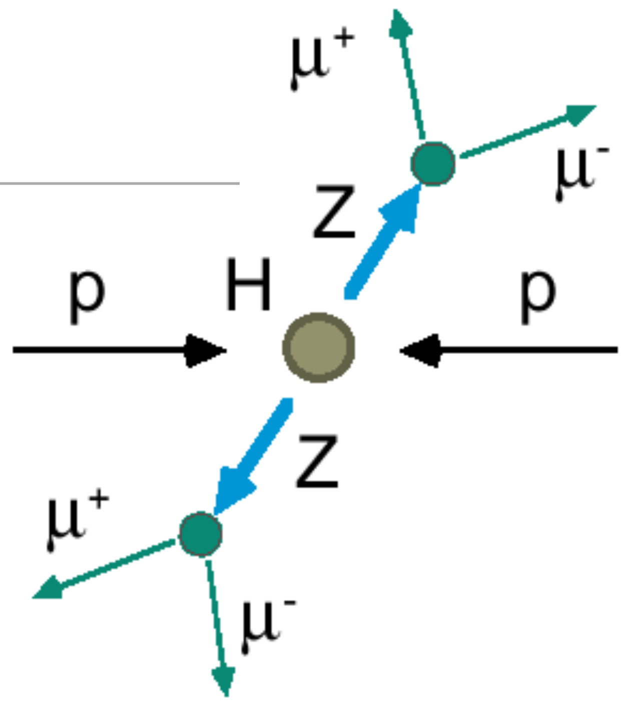
$$\left.\begin{array}{ll}\text{Signal:} & N_S \sim L \\ \text{Background:} & N_B \sim L\end{array}\right\} \longrightarrow \boxed{S \sim \sqrt{L}}$$

The Golden Channel: H ➛ 4ℓ



Simulated
H ➛ μμ Event

The Golden Channel: H ➛ 4ℓ



Signal: $\sigma \cdot BR = 5.7$ fb [$m_H = 100$ GeV]

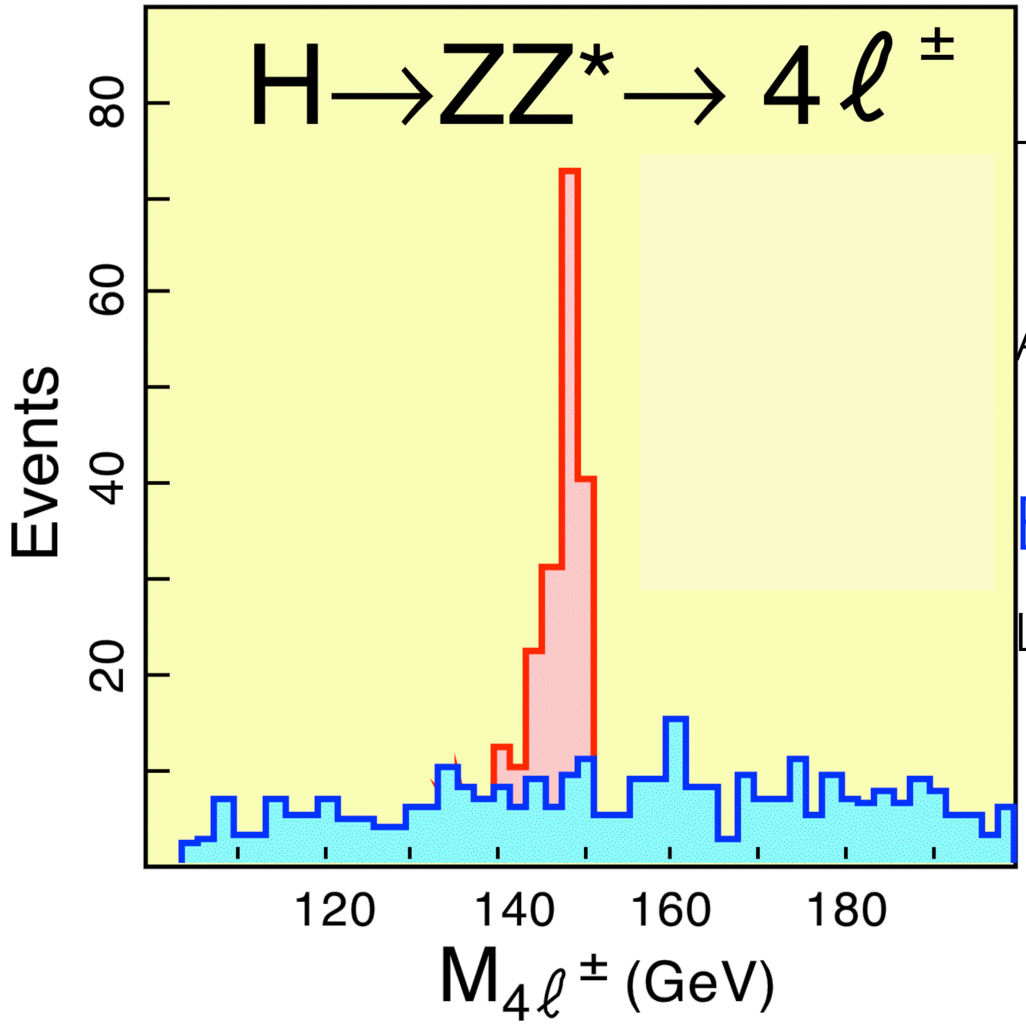
Selection cuts:

isolated leptons within $|\eta| < 2.5$,

$P_{T\,(1,2)} > 20$ GeV and $P_{T\,(3,4)} > 7$ GeV

one lepton pair around Z mass

Discovery potential:
130 – 600 GeV



Main backgrounds:

Top production:

$t\bar{t} \xrightarrow{[\sigma \cdot BR = 1300\ \text{fb}]} Wb\,Wb \rightarrow \ell\nu\,c\ell\nu\ \ell\nu\,c\ell\nu$

Associated Z-production:

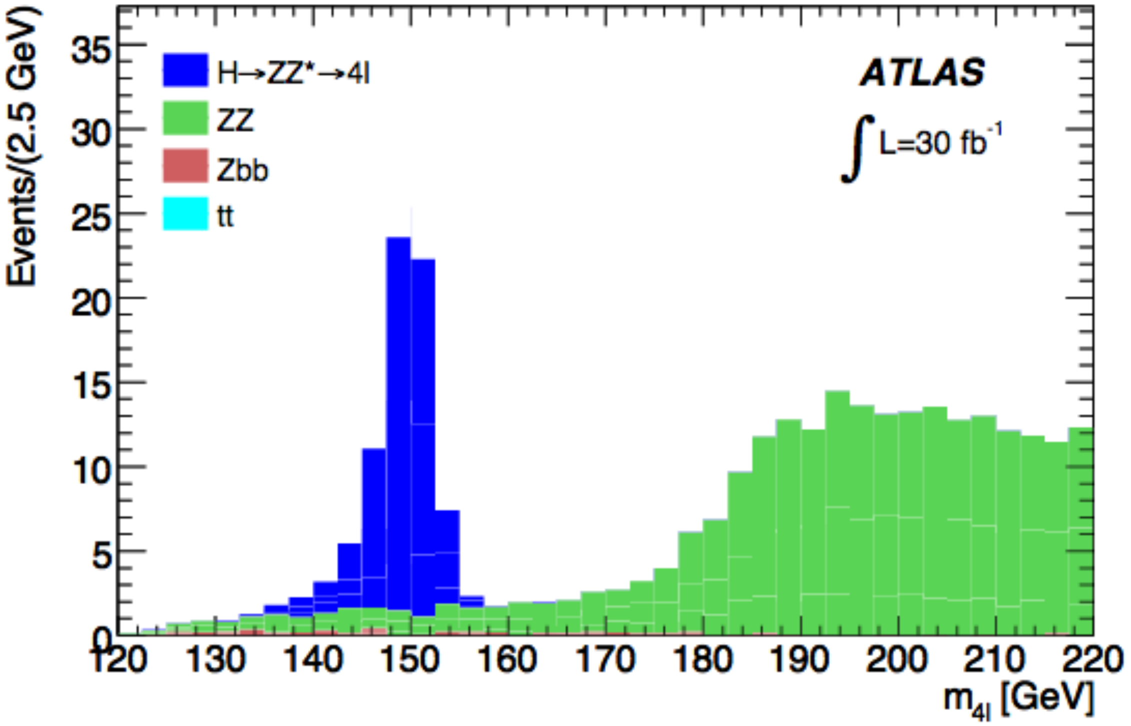
$Z\,bb \rightarrow \ell\ell\,c\ell\nu\ c\ell\nu$

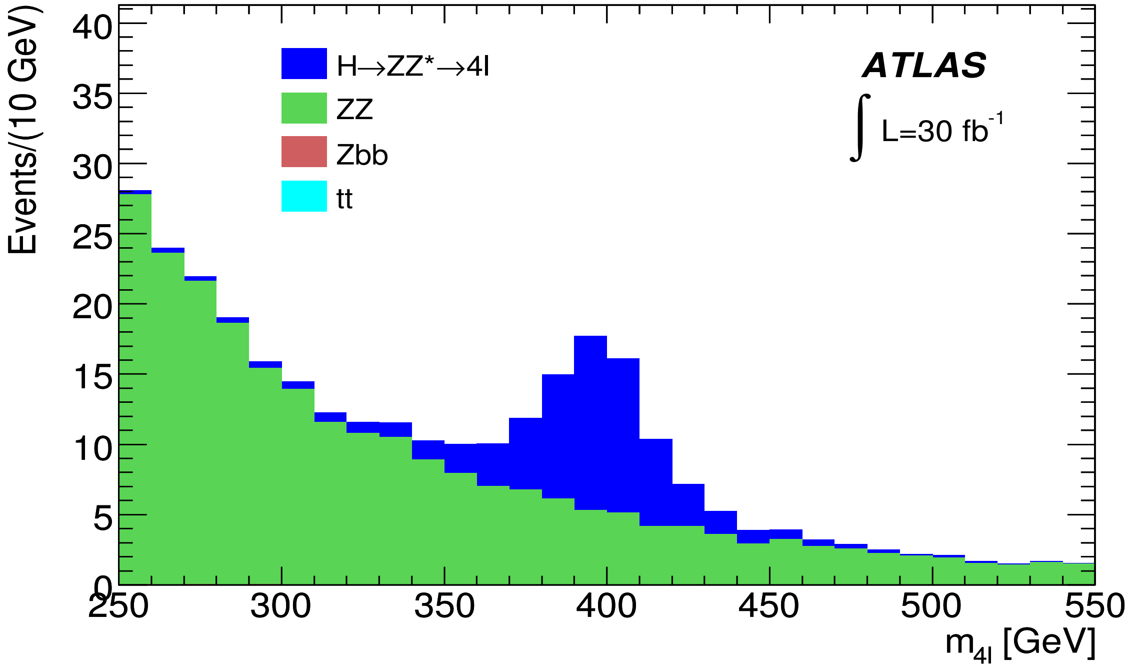
Background rejection:

Leptons: non-isolated (inside jet)
not from primary vertex

very clean; remaining: ZZ continuum

The Golden Channel: H ➛ 4ℓ





ATLAS: discovery with 30 fb^{-1}
in wide mass range ...

120 GeV – 600 GeV

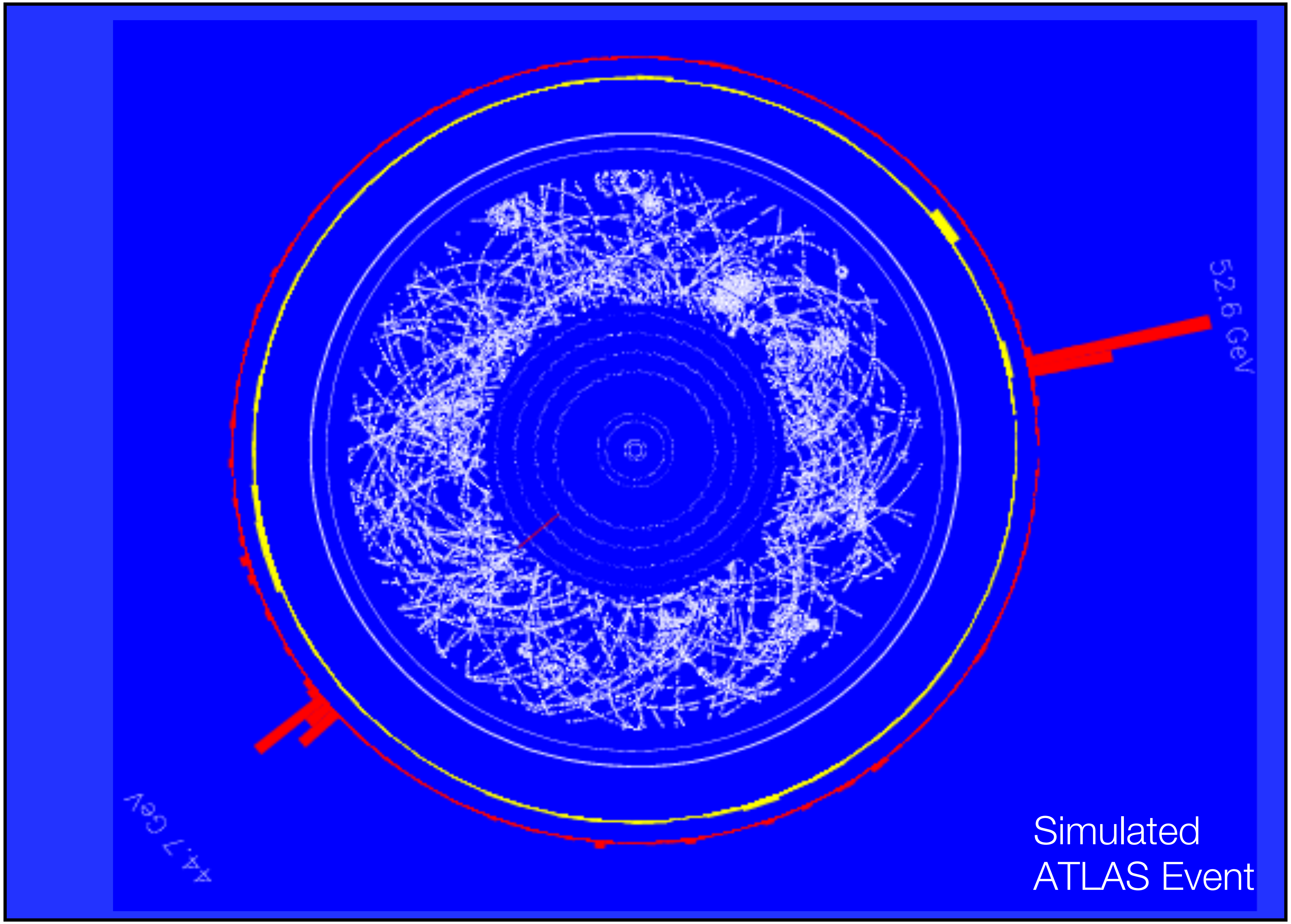
[note: Higgs width increases, too]

Difficult regions:

- very low Higgs mass [115 GeV]
- ZZ threshold [180 GeV]

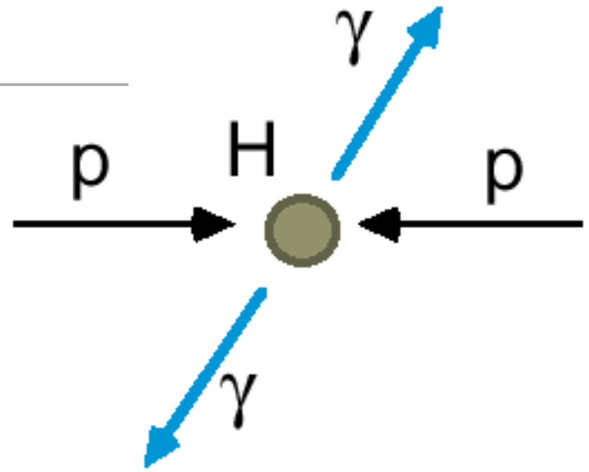
[CERN-OPEN-2008-020]

The Hard One: H ➛ γγ



Simulated
ATLAS Event

The Hard One: $H \to \gamma\gamma$



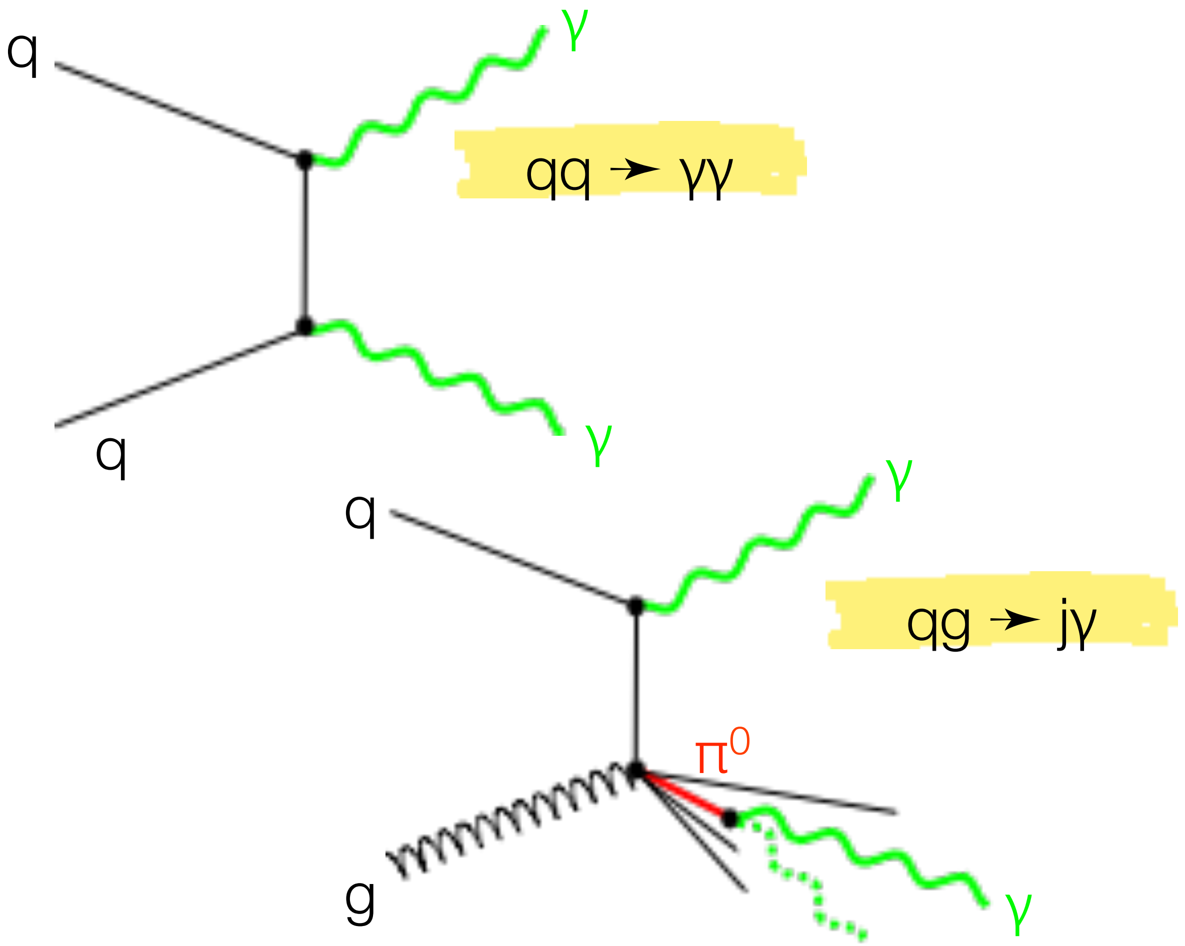
Signal: $\sigma \cdot BR = 50$ fb [$m_H = 100$ GeV]

very demanding channel due to huge irreducible background ...

very harsh requirements on calorimeter performance (acceptance, E and θ-resolution, separation of γ from jets and π^0

Discovery potential:
< 150 GeV

Two main background sources:



$qq \to \gamma\gamma$

$qg \to j\gamma$

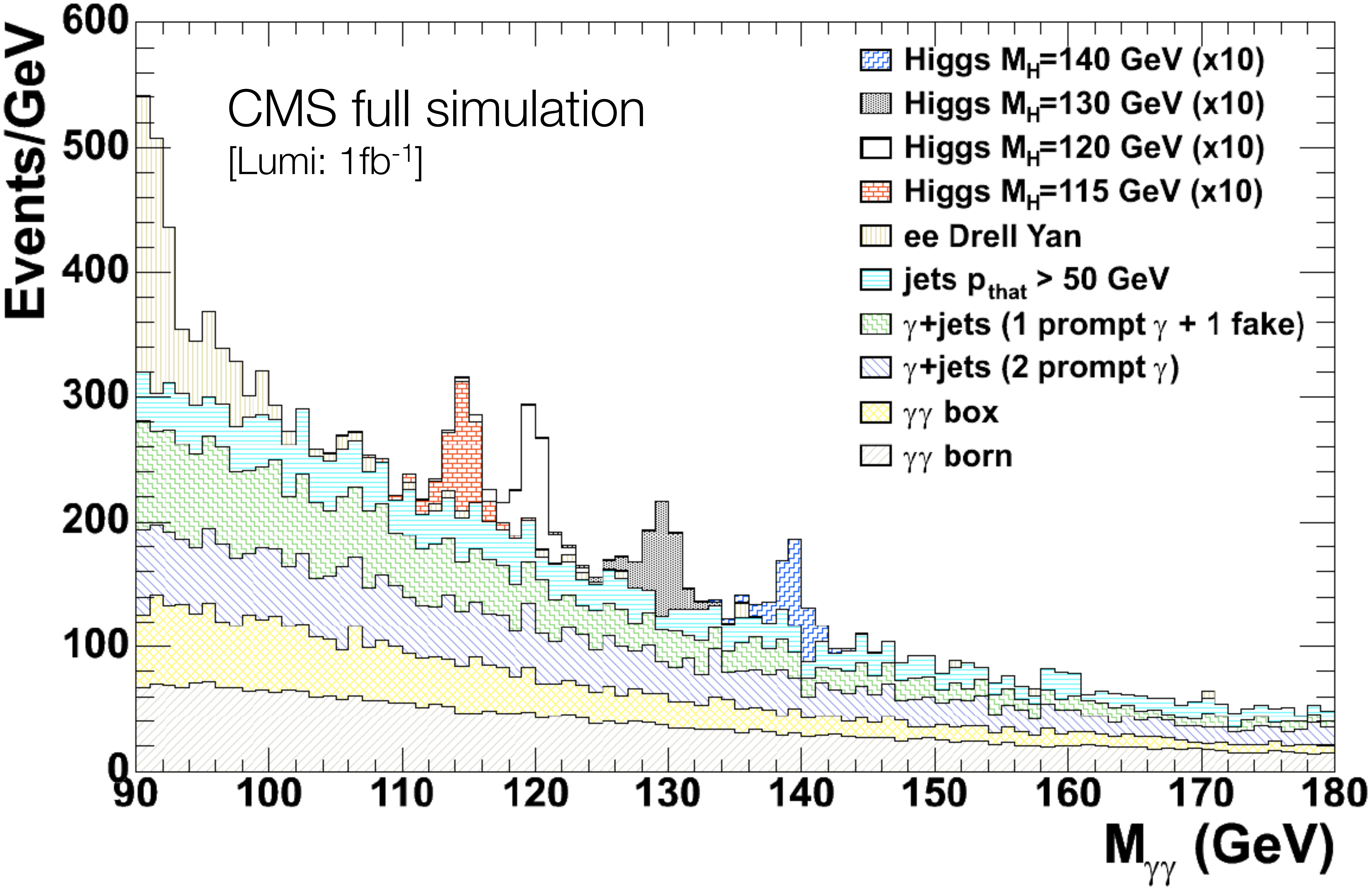
2γ-production: irreducible background

$\sigma_{\gamma\gamma}$ ~ 2 pb/GeV and Γ_H ~ MeV
implies $\sigma(m_{\gamma\gamma})/m_{\gamma\gamma} \sim 1\%$

γ-jet and dijet production: reducible background

$\sigma_{\gamma j+jj} \sim 10^6\, \sigma_{\gamma\gamma}$; jet rejection of $> 10^3$ needed

The Hard One: H ➛ γγ



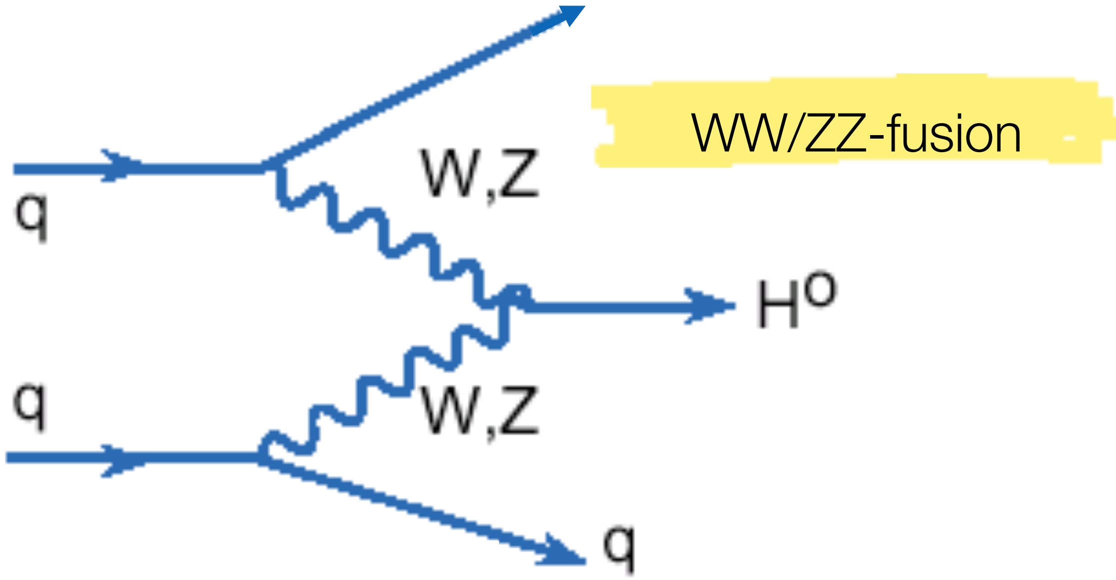
The Vector Boson Fusion Channel

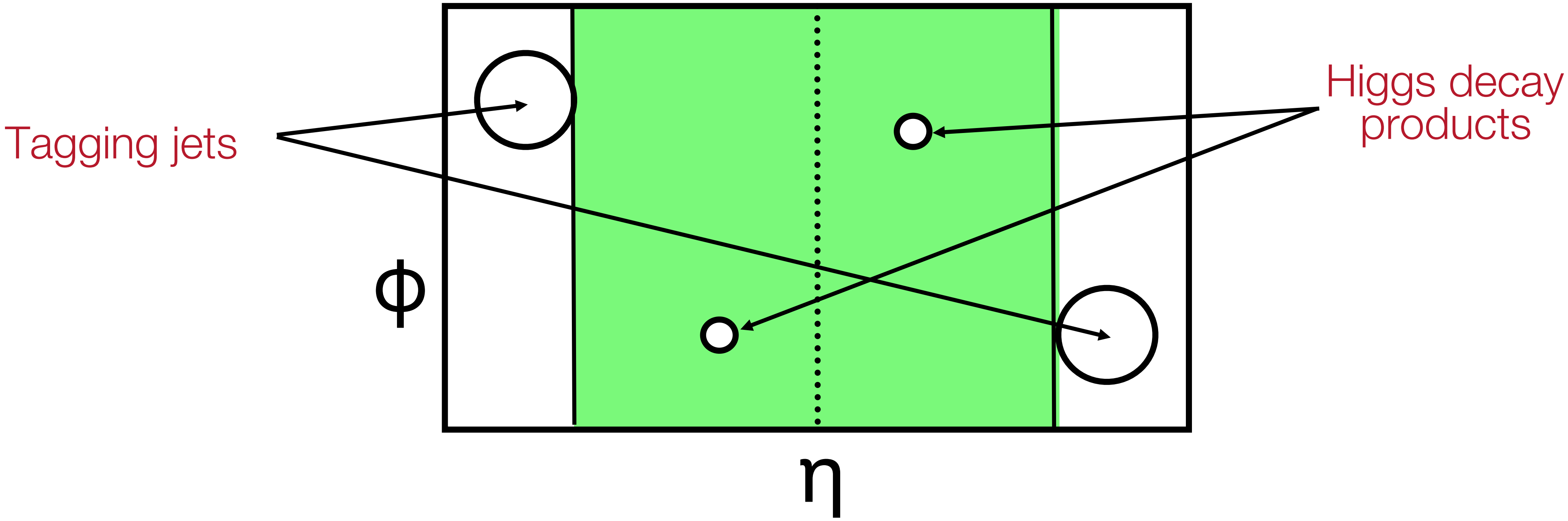
Motivation: Improve low mass discovery potential
Improve measurement of Higgs boson parameters

[Coupling to bosons, fermions]

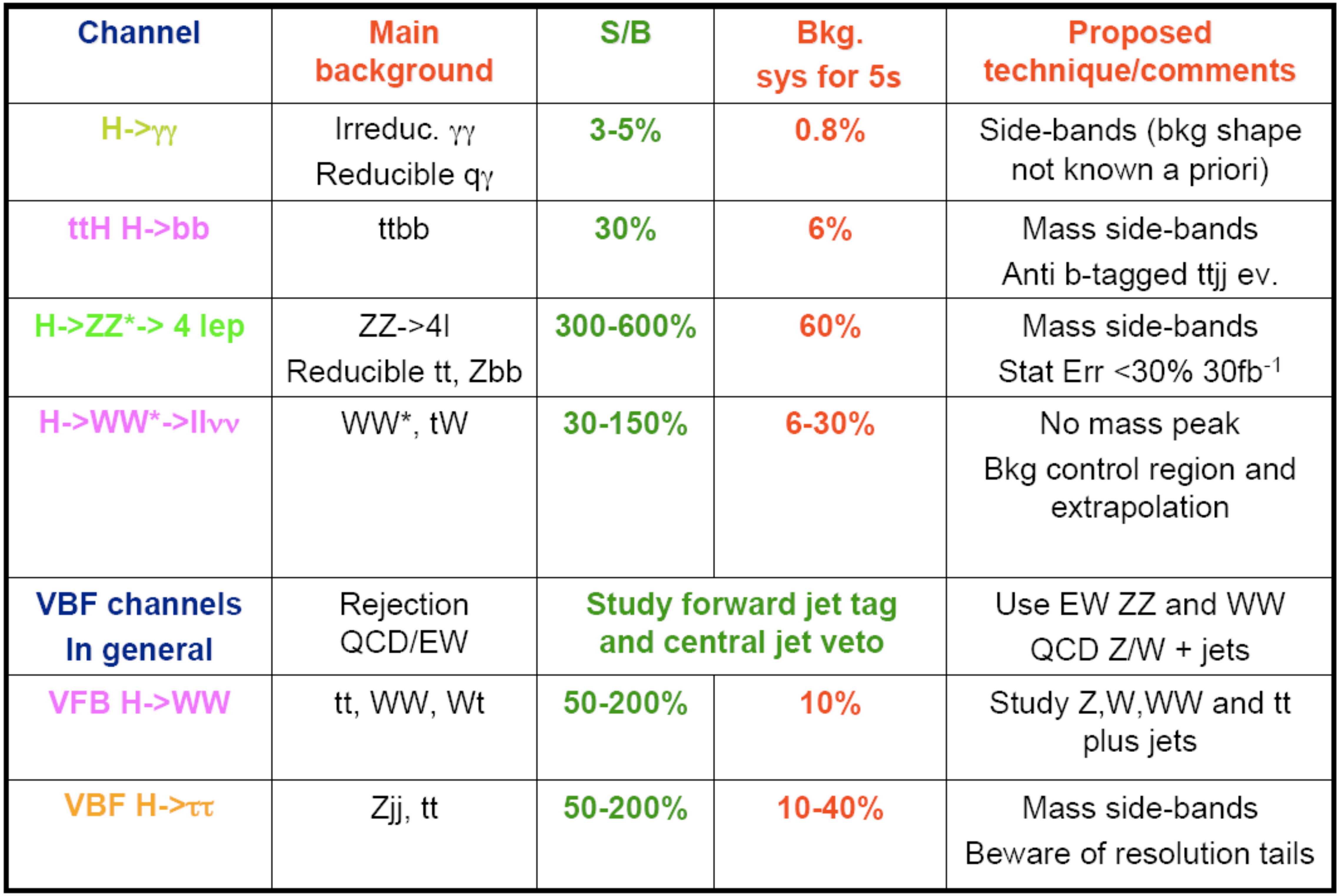
Distinctive signature:

- two forward jets (tagging jets)
- little (jet) activity in central region (central jet veto)





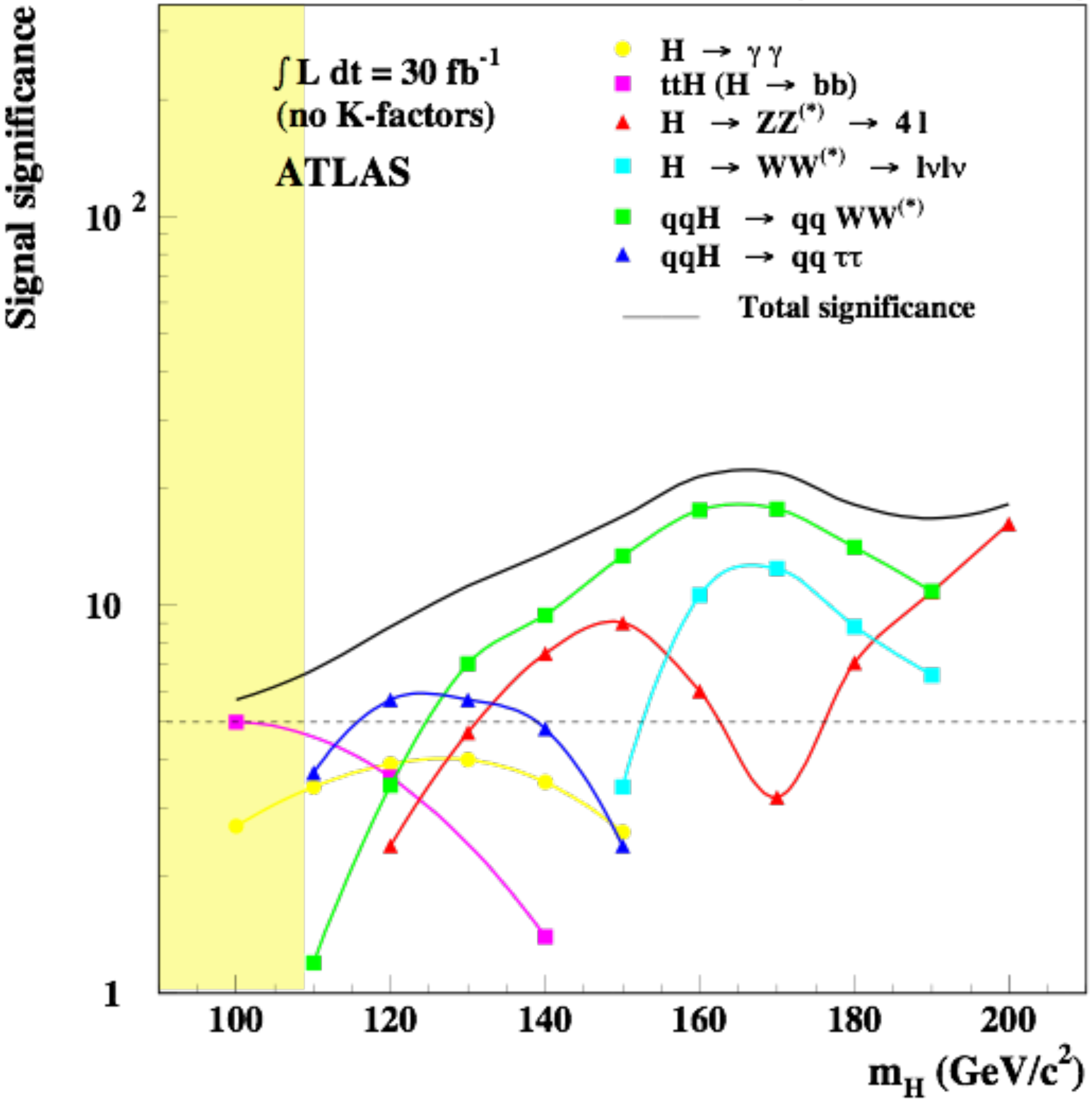
Higgs: Background Systematics



Channel	**Main background**	**S/B**	**Bkg. sys for 5s**	**Proposed technique/comments**
H->γγ	Irreduc. γγ Reducible qγ	**3-5%**	**0.8%**	Side-bands (bkg shape not known a priori)
ttH H->bb	ttbb	**30%**	**6%**	Mass side-bands Anti b-tagged ttjj ev.
H->ZZ*-> 4 lep	ZZ->4l Reducible tt, Zbb	**300-600%**	**60%**	Mass side-bands Stat Err <30% $30fb^{-1}$
H->WW*->llνν	WW*, tW	**30-150%**	**6-30%**	No mass peak Bkg control region and extrapolation
VBF channels In general	Rejection QCD/EW	**Study forward jet tag and central jet veto**		Use EW ZZ and WW QCD Z/W + jets
VFB H->WW	tt, WW, Wt	**50-200%**	**10%**	Study Z,W,WW and tt plus jets
VBF H->ττ	Zjj, tt	**50-200%**	**10-40%**	Mass side-bands Beware of resolution tails

LHC: Higgs Discovery Potential

[ATL-PHYS-2003-005]



Full mass range can already be covered after a few years at low luminosity

Several channels available over a large range of masses

Low mass discovery requires combination of three of the most demanding channels

Comparable situation for the CMS experiment

The Particle Data Group (PDG)
(real recent stuff)
http://pdg.lbl.gov/2014/reviews/rpp2014-rev-higgs-boson.pdf

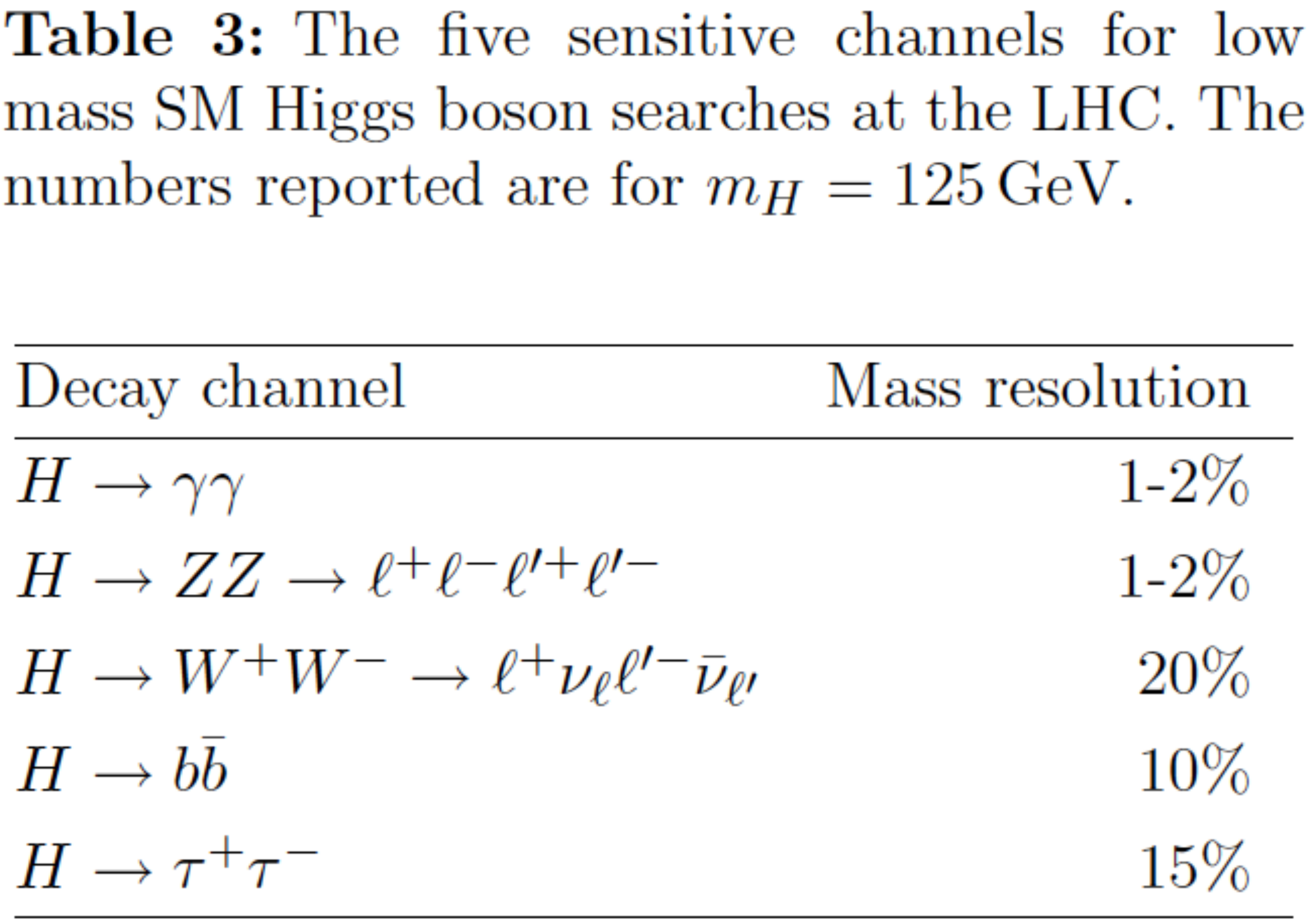
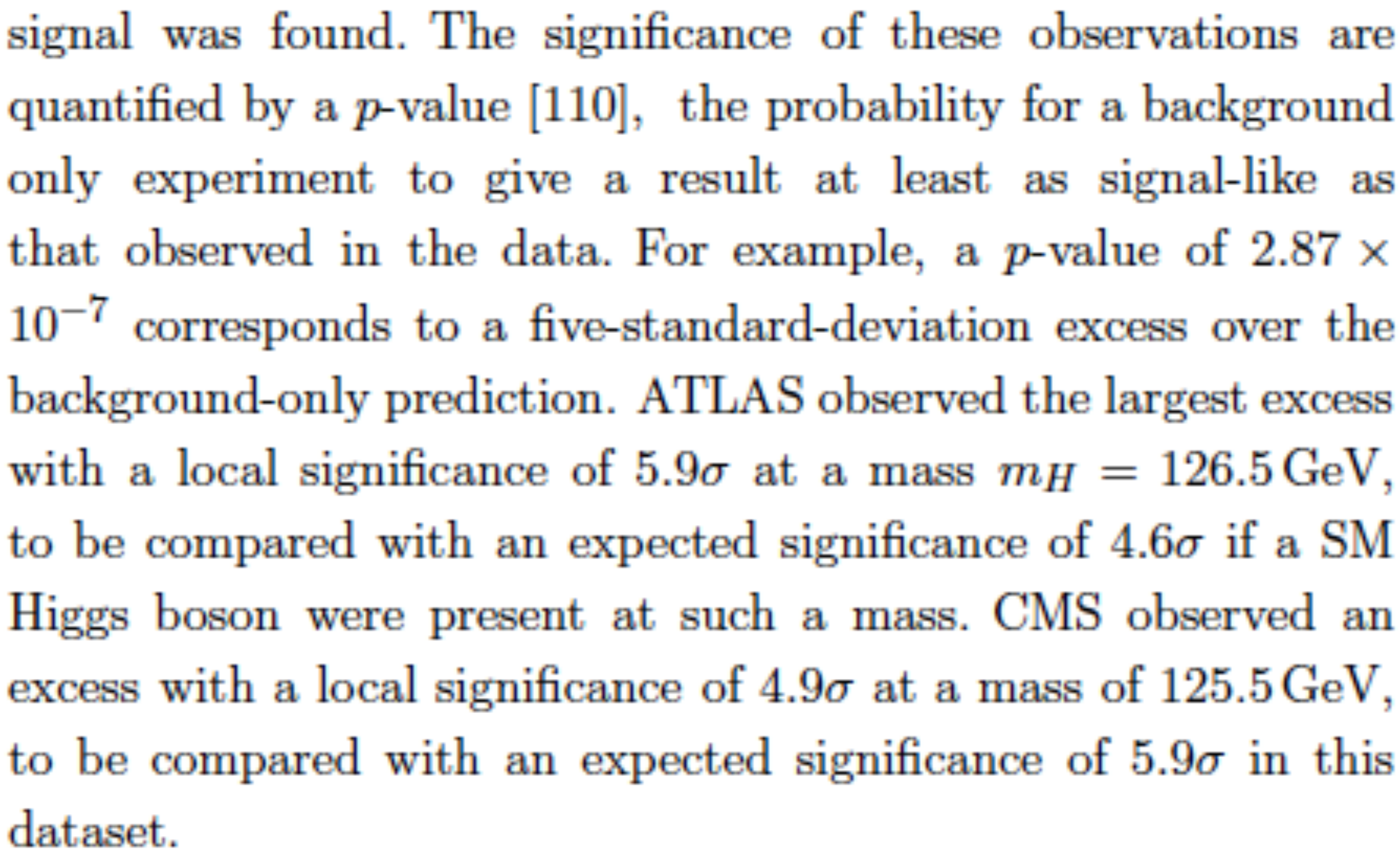


Table 3: The five sensitive channels for low mass SM Higgs boson searches at the LHC. The numbers reported are for $m_H = 125\,\mathrm{GeV}$.

Decay channel	Mass resolution
$H \to \gamma\gamma$	1-2%
$H \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	1-2%
$H \to W^+W^- \to \ell^+\nu_\ell\ell'^-\bar{\nu}_{\ell'}$	20%
$H \to b\bar{b}$	10%
$H \to \tau^+\tau^-$	15%

The evolution of the p-value



signal was found. The significance of these observations are quantified by a p-value [110], the probability for a background only experiment to give a result at least as signal-like as that observed in the data. For example, a p-value of 2.87×10^{-7} corresponds to a five-standard-deviation excess over the background-only prediction. ATLAS observed the largest excess with a local significance of 5.9σ at a mass $m_H = 126.5\,\mathrm{GeV}$, to be compared with an expected significance of 4.6σ if a SM Higgs boson were present at such a mass. CMS observed an excess with a local significance of 4.9σ at a mass of $125.5\,\mathrm{GeV}$, to be compared with an expected significance of 5.9σ in this dataset.

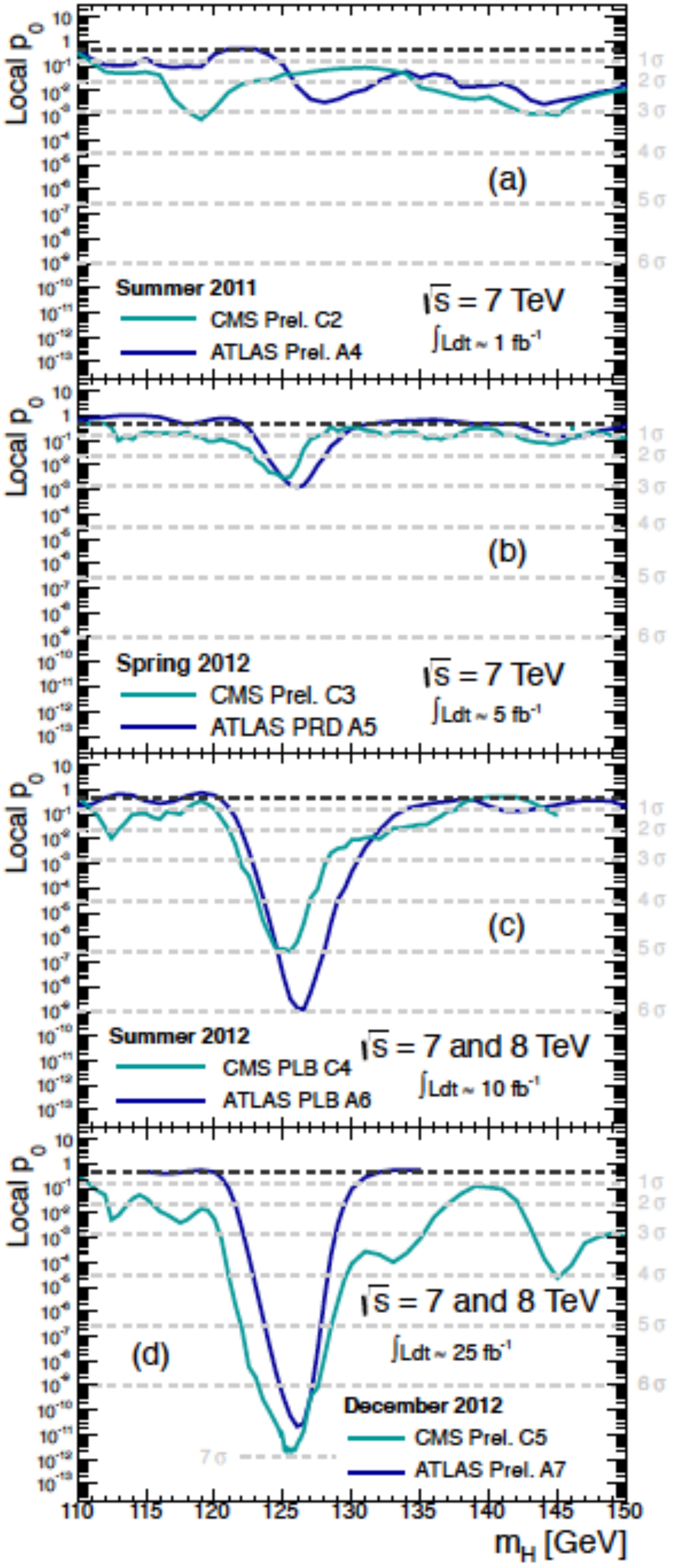
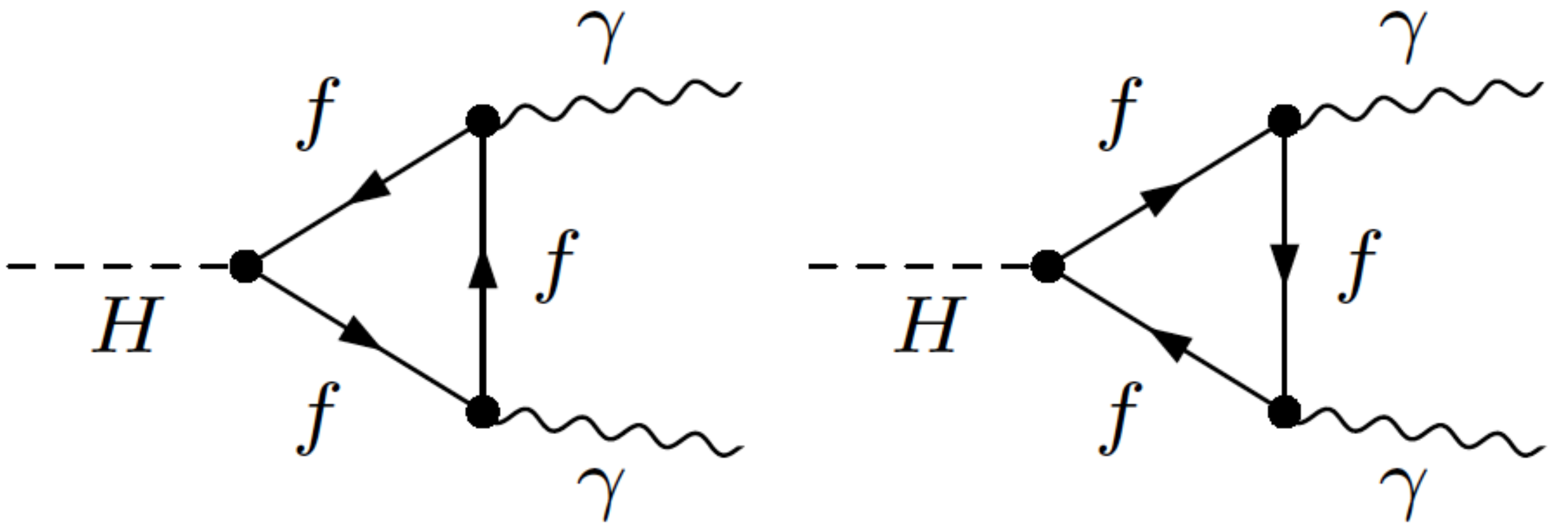
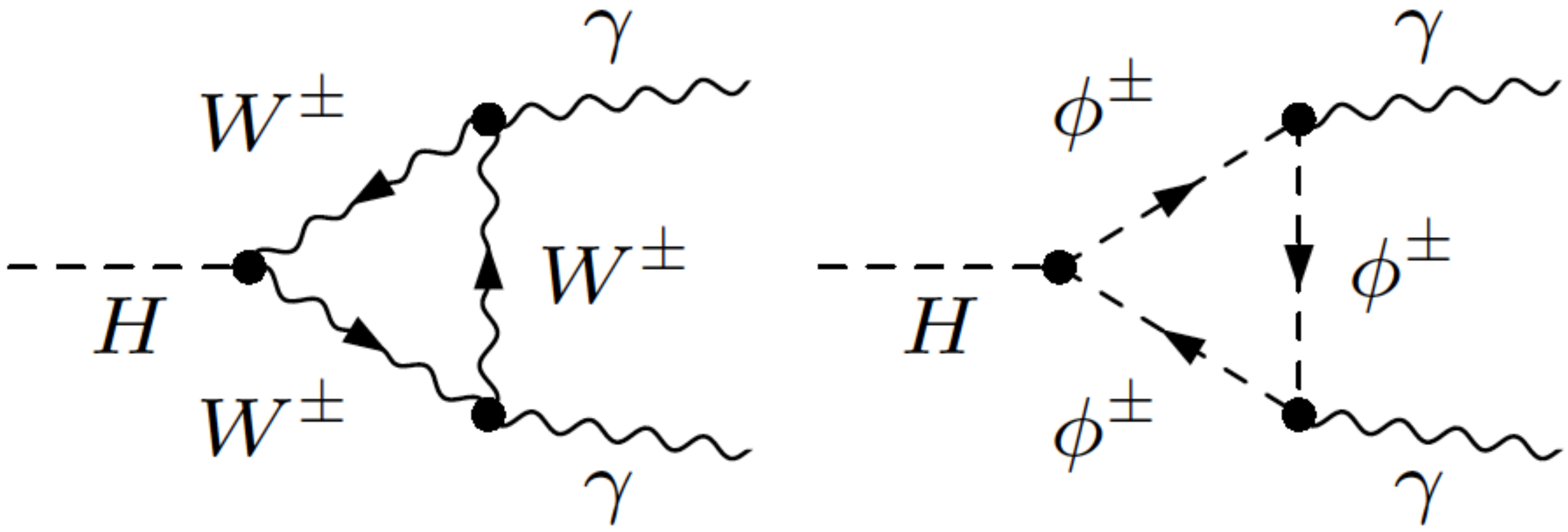


Figure 5: Evolution of the p-value and the signal significance observed by the ATLAS and CMS experiments with increasingly larger datasets: (a) Summer 2011 ($\approx 1\,\mathrm{fb}^{-1}$/expt) for ATLAS A4 [112] and CMS C4 [113], (b) Spring 2012 ($\approx 5\,\mathrm{fb}^{-1}$/expt) for ATLAS A5 [114] and CMS C3 [115], (c) Summer 2012 ($\approx 10\,\mathrm{fb}^{-1}$/expt) for ATLAS A6 [1] and CMS C4 [2], and (d) December 2012 ($\approx 25\,\mathrm{fb}^{-1}$/expt) for ATLAS A7 [116] and CMS C4 [117].

Higgs decay to 2 photons



Only top quarks contribute, contributions from light fermions negligible



W-bosons, Goldstone-bosons and ghosts occur in the loops

The H to γγ channel

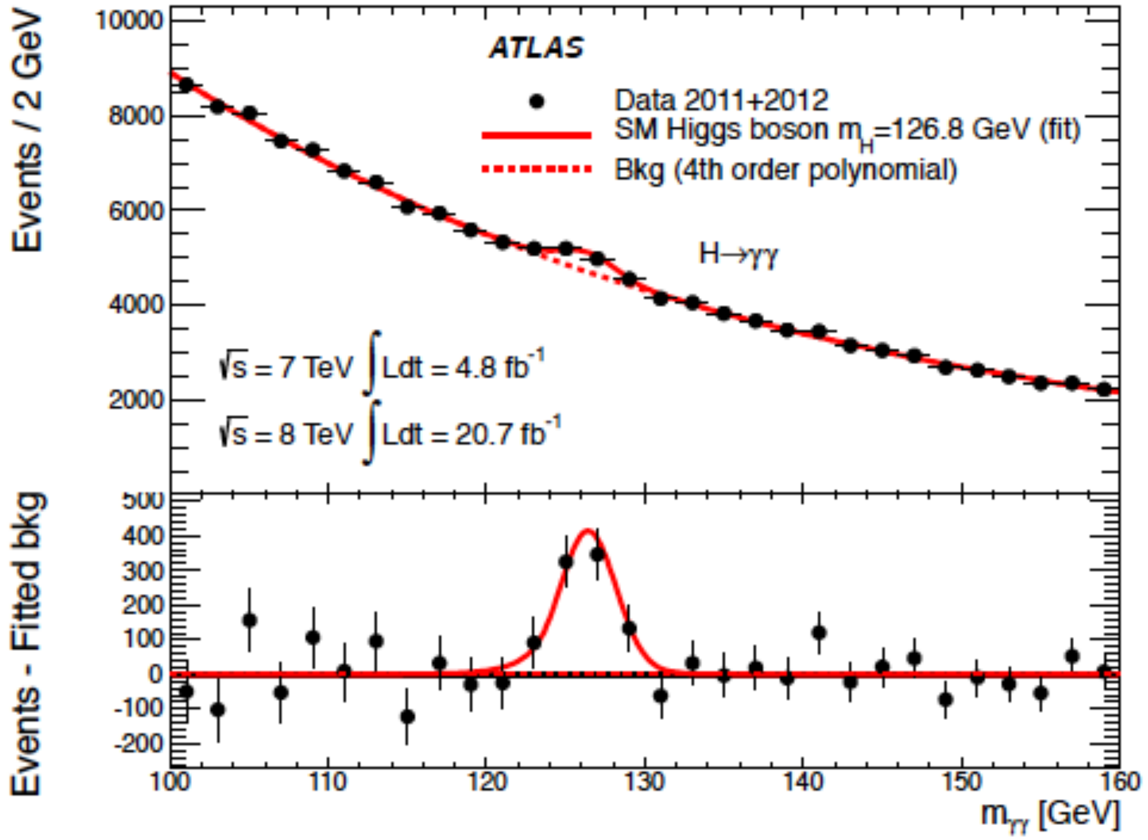


Figure 6: The combined invariant mass distribution of diphoton candidates observed by ATLAS [119]. The residuals of the data with respect to the fitted background are displayed in the lower panel.

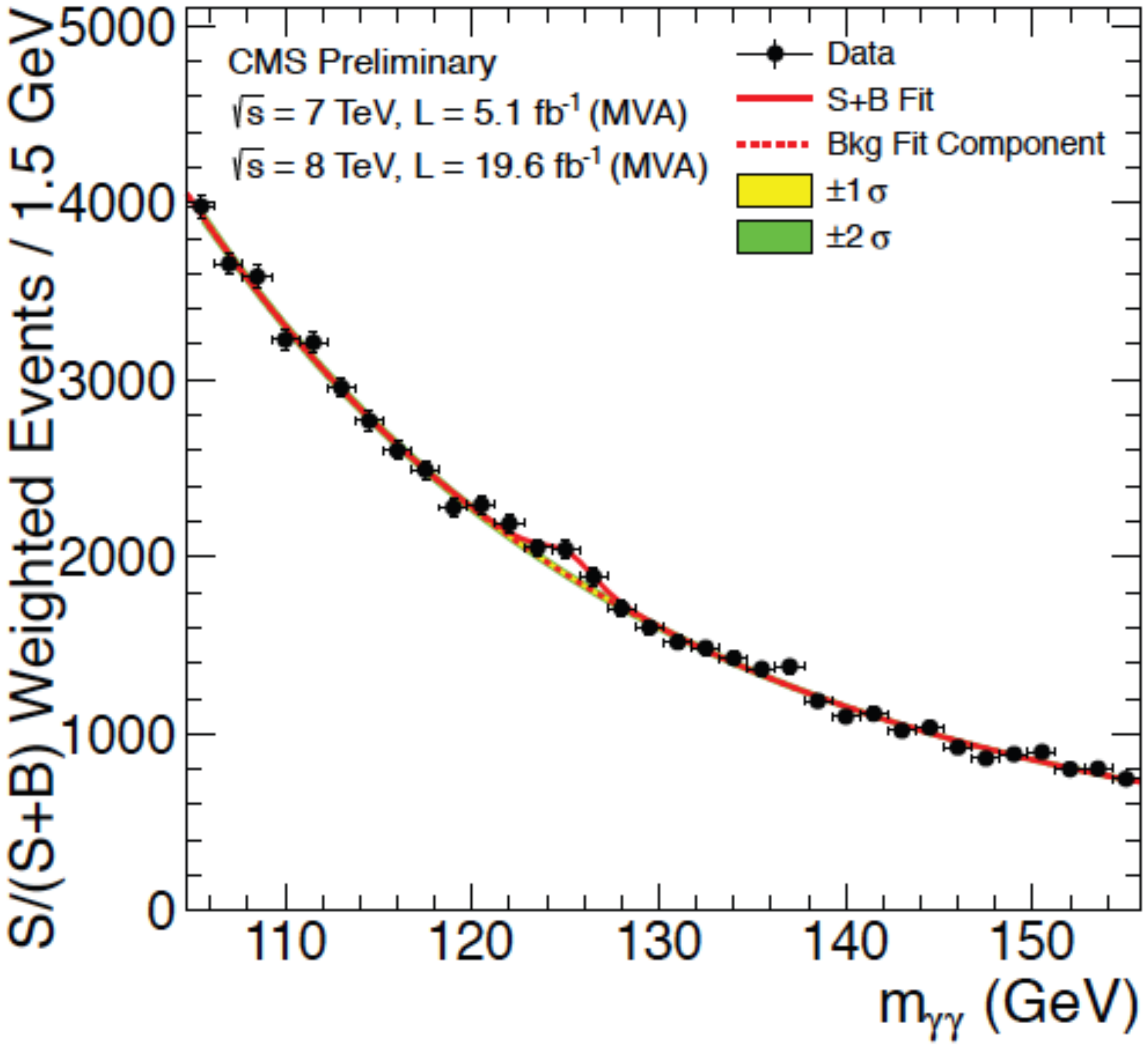


Figure 7: The combined CMS $M_{\gamma\gamma}$ distribution with each event weighted by the ratio of signal-to-background in each event category [120].

Higgs to 4 leptons

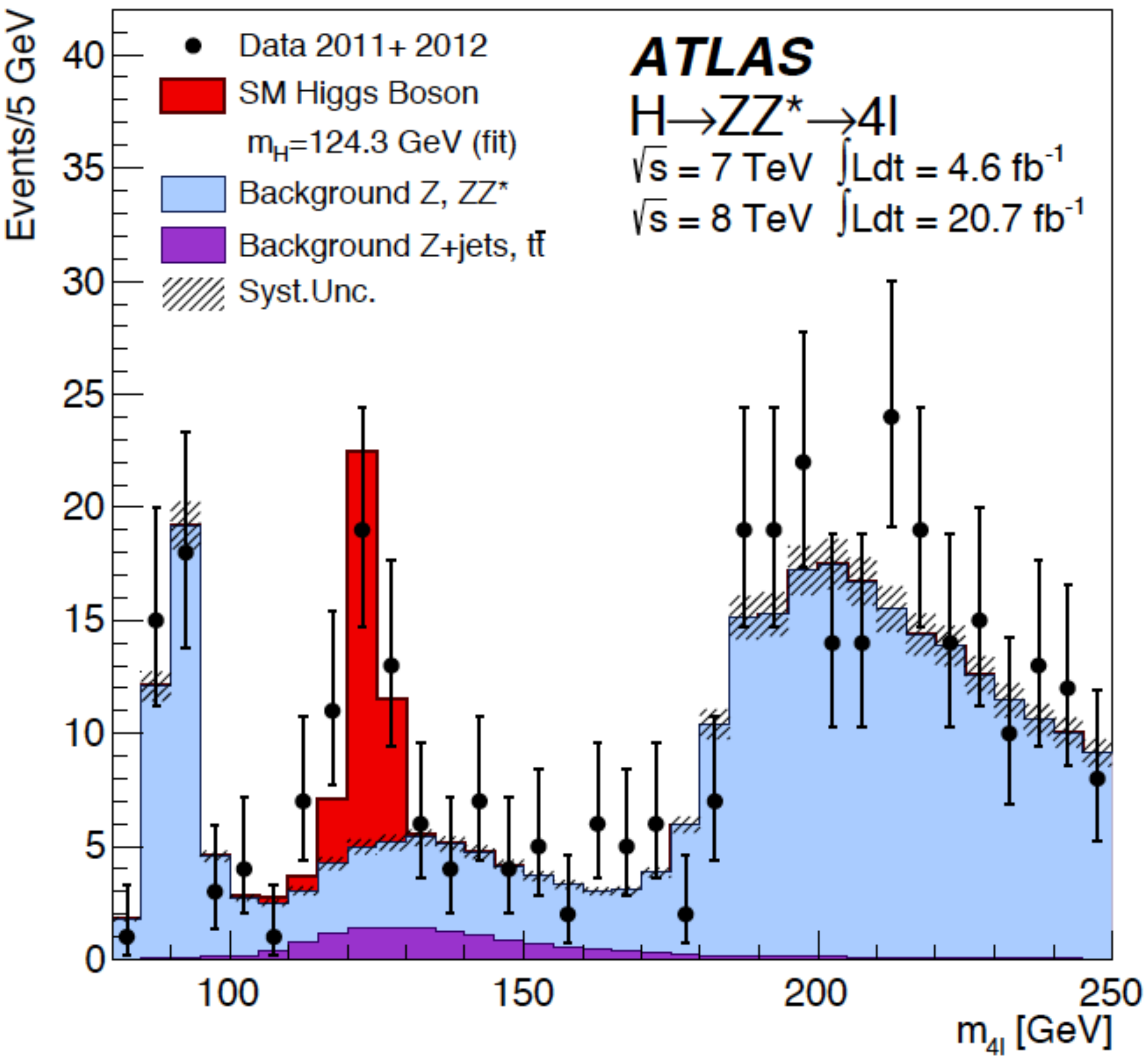


Figure 8: The combined $m_{4\ell}$ distribution fron ATLAS [119].

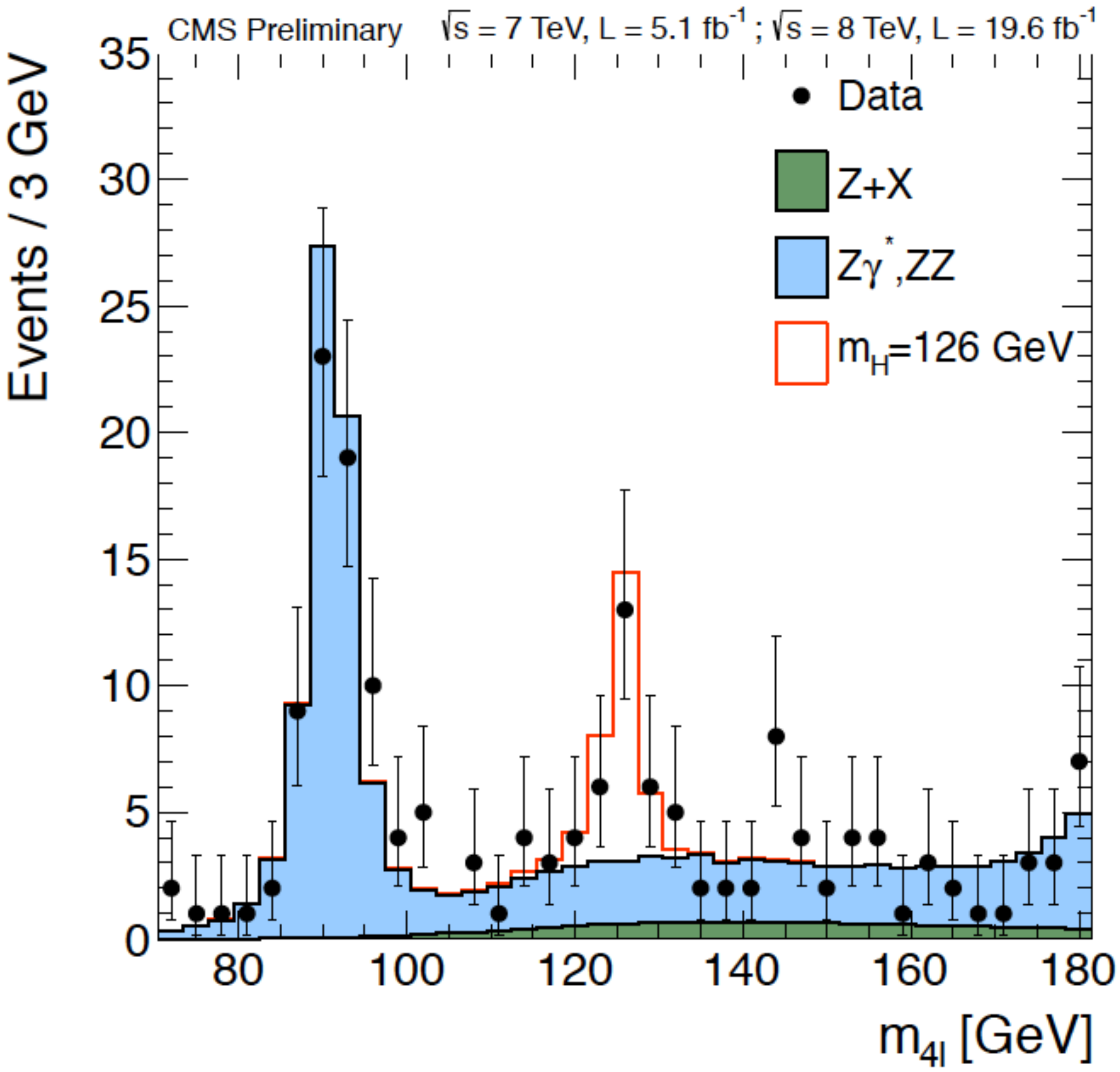
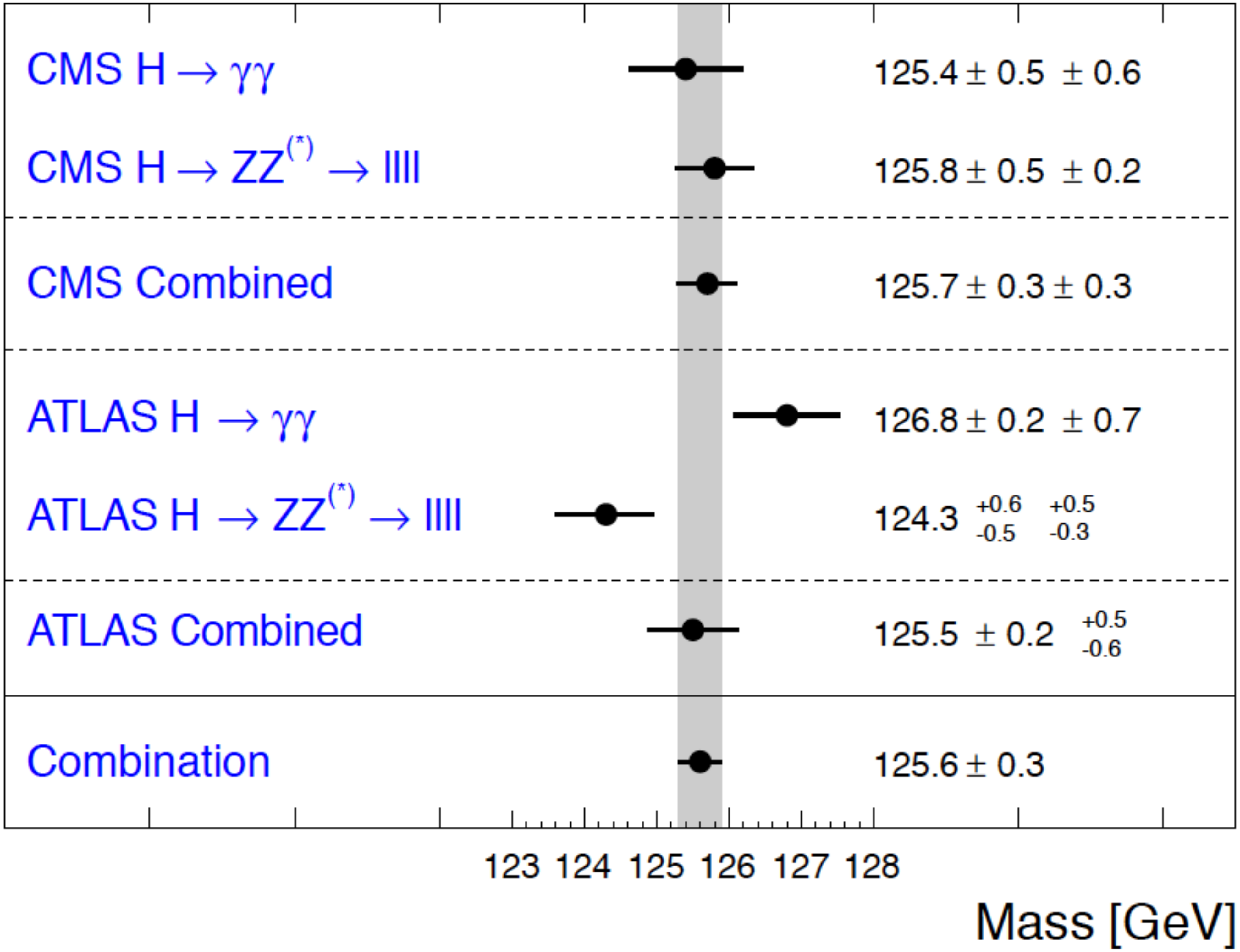
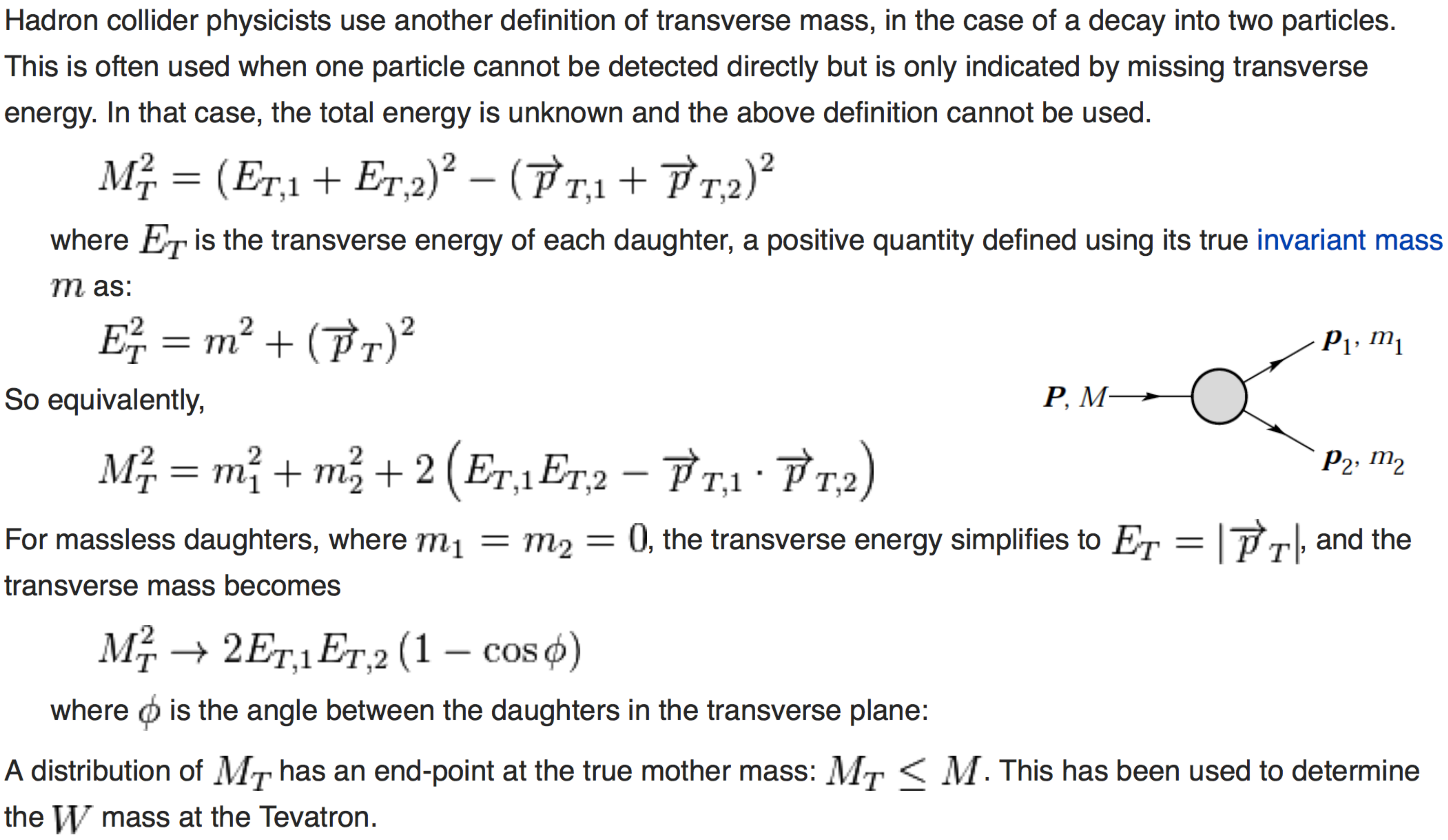


Figure 9: The combined $m_{4\ell}$ distribution from CMS [121].

The mass of the Higgs Boson



Transverse Mass (Wikipedia) in $H \to W^+W^- \to l^+\upsilon l^-\bar{\upsilon}$



Hadron collider physicists use another definition of transverse mass, in the case of a decay into two particles. This is often used when one particle cannot be detected directly but is only indicated by missing transverse energy. In that case, the total energy is unknown and the above definition cannot be used.

$$M_T^2 = (E_{T,1} + E_{T,2})^2 - (\overrightarrow{p}_{T,1} + \overrightarrow{p}_{T,2})^2$$

where E_T is the transverse energy of each daughter, a positive quantity defined using its true invariant mass m as:

$$E_T^2 = m^2 + (\overrightarrow{p}_T)^2$$

So equivalently,

$$M_T^2 = m_1^2 + m_2^2 + 2\left(E_{T,1}E_{T,2} - \overrightarrow{p}_{T,1} \cdot \overrightarrow{p}_{T,2}\right)$$

For massless daughters, where $m_1 = m_2 = 0$, the transverse energy simplifies to $E_T = |\overrightarrow{p}_T|$, and the transverse mass becomes

$$M_T^2 \to 2E_{T,1}E_{T,2}\,(1 - \cos\phi)$$

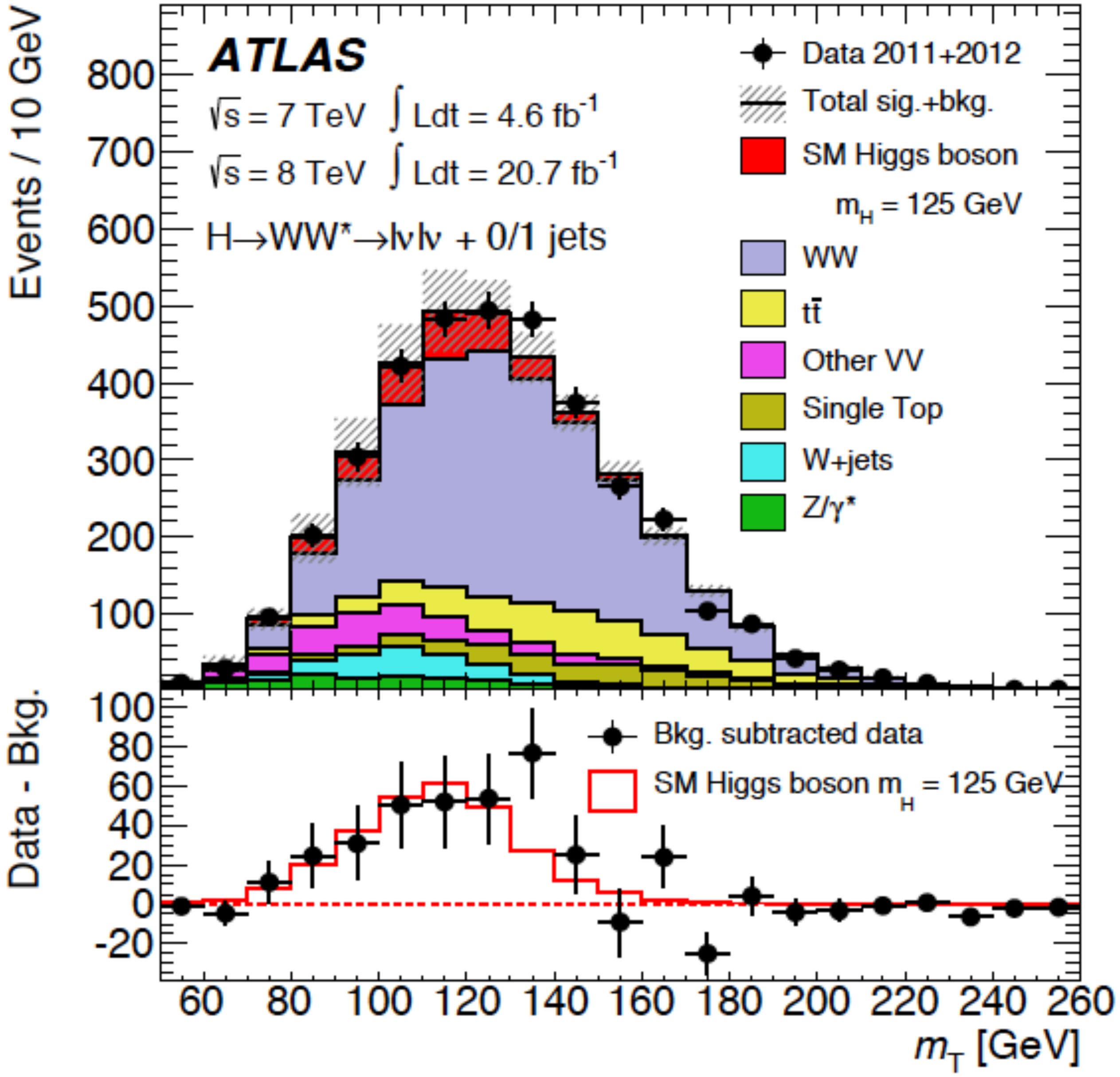
where ϕ is the angle between the daughters in the transverse plane:

A distribution of M_T has an end-point at the true mother mass: $M_T \leq M$. This has been used to determine the W mass at the Tevatron.

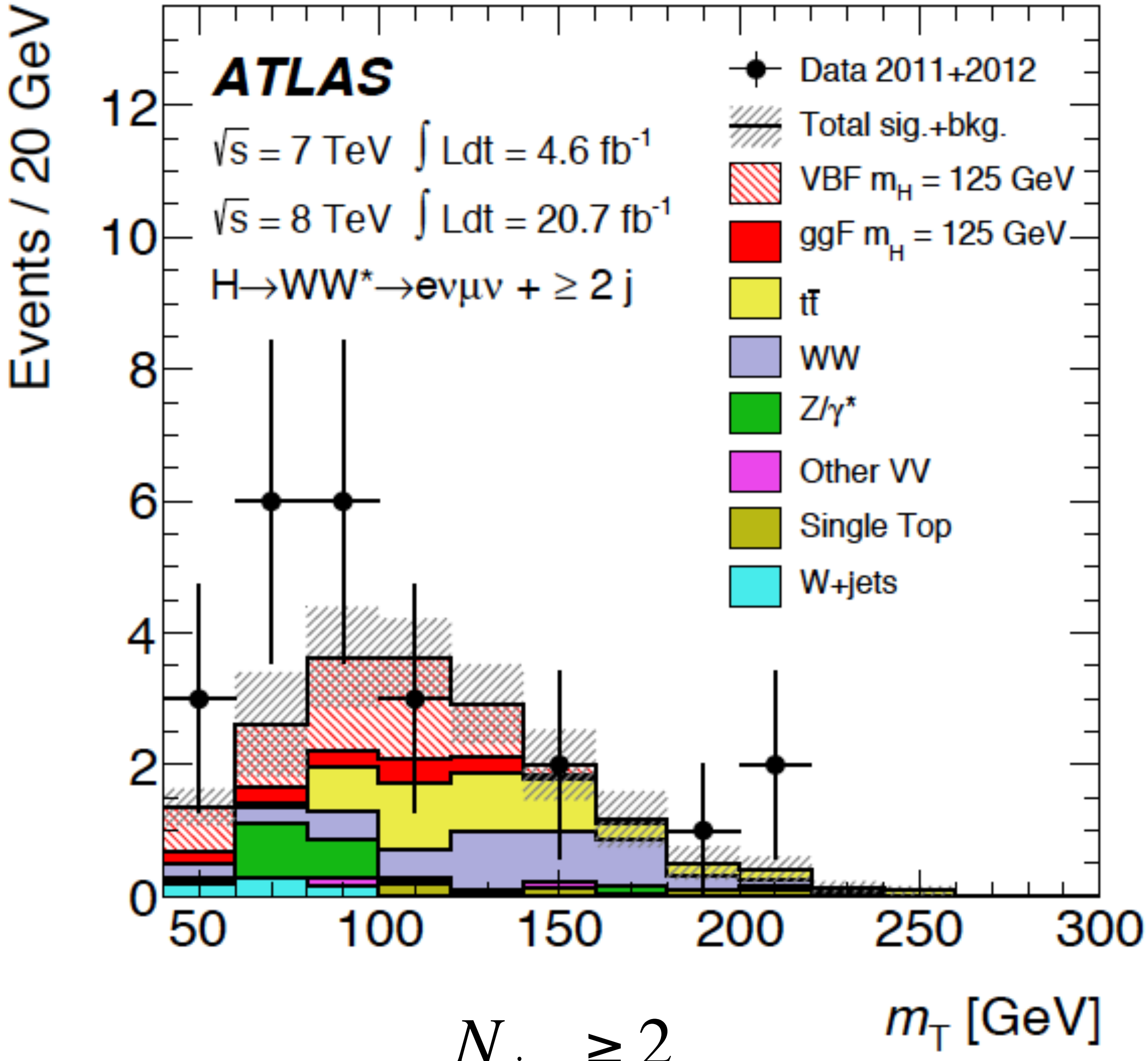
ATLAS: $H \rightarrow W^{+}W^{-} \rightarrow l^{+}\upsilon l^{-}\overline{\upsilon}$

$$m_T = \sqrt{2p_T^{\ell\ell}E_T^{\rm miss}(1-\cos\Delta\phi_{E_T^{\rm miss}\ell\ell})}$$

Undetected υ's ➡ M_T

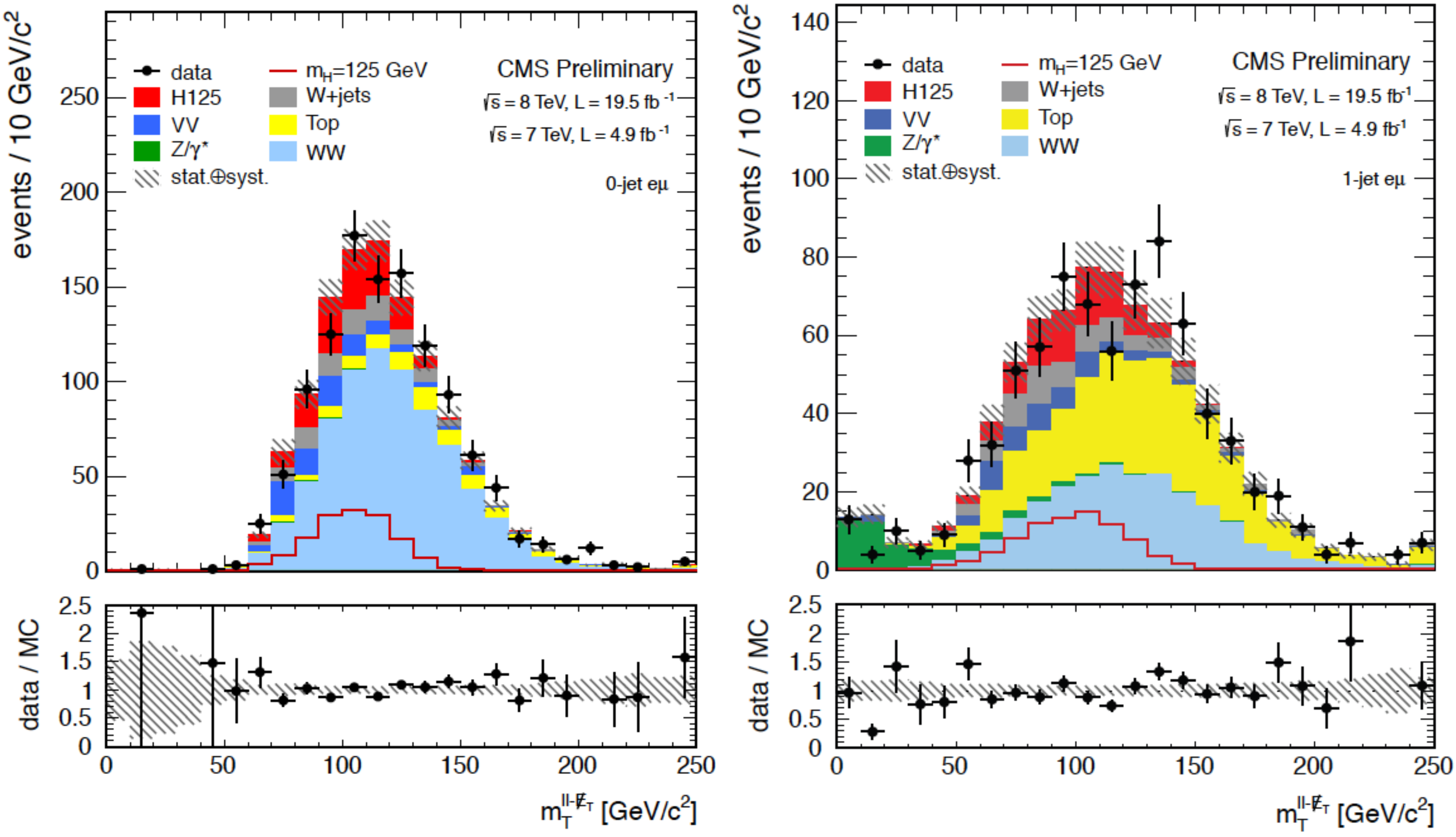


$N_{jets} \leq 1$

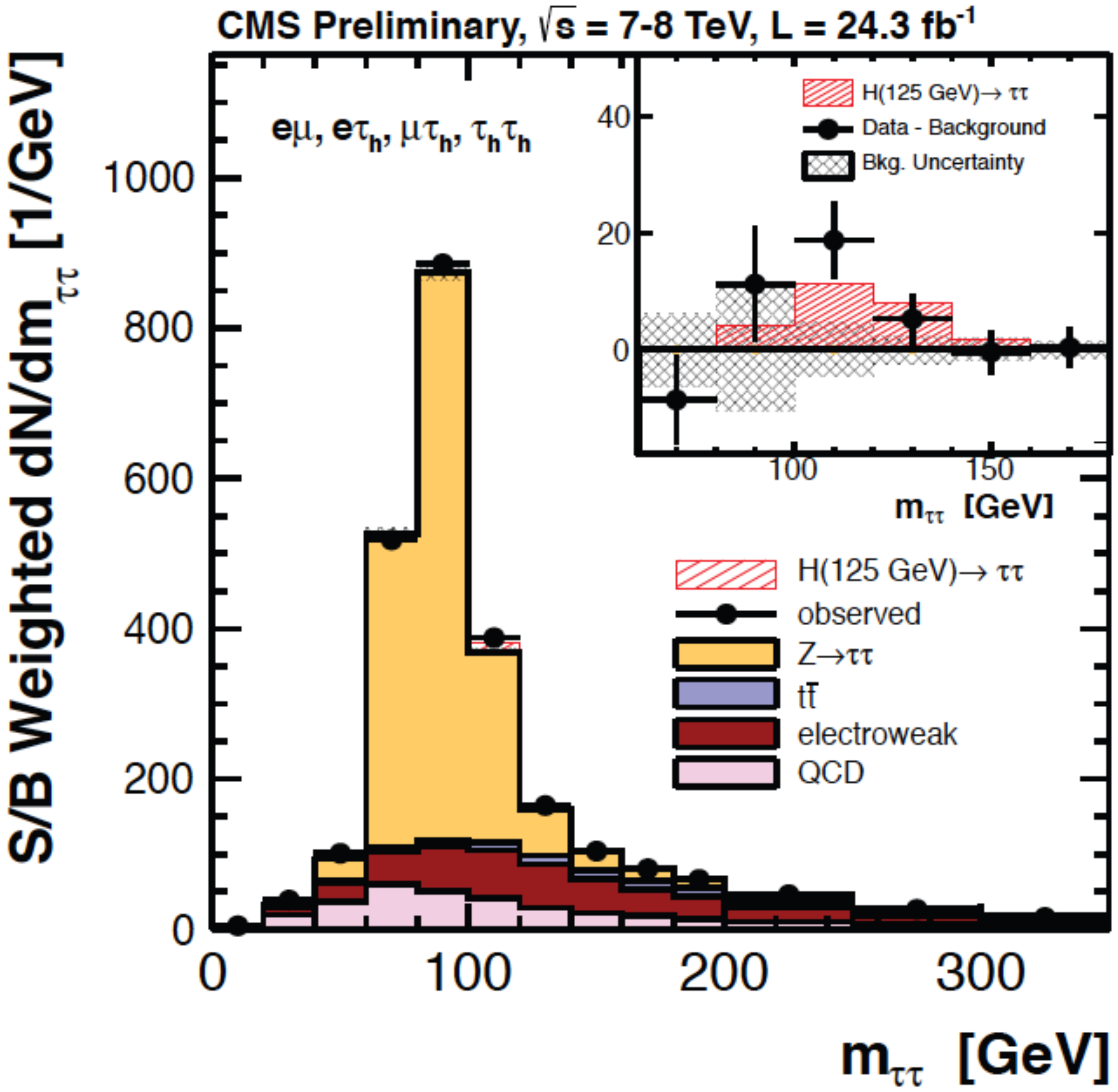


$N_{jets} \geq 2$

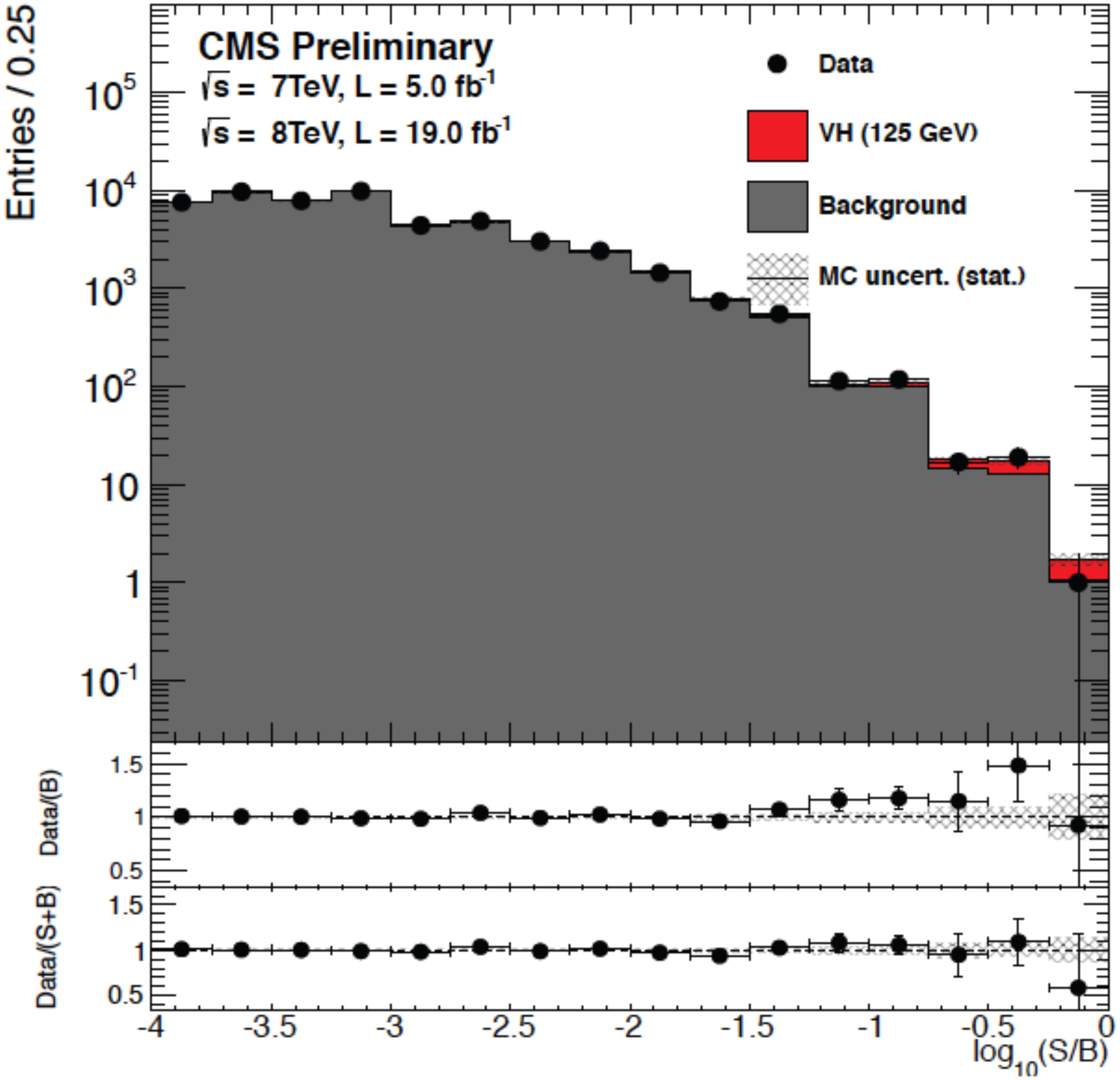
CMS : $H \rightarrow W^{+}W^{-} \rightarrow l^{+}\upsilon l^{-}\overline{\upsilon}$

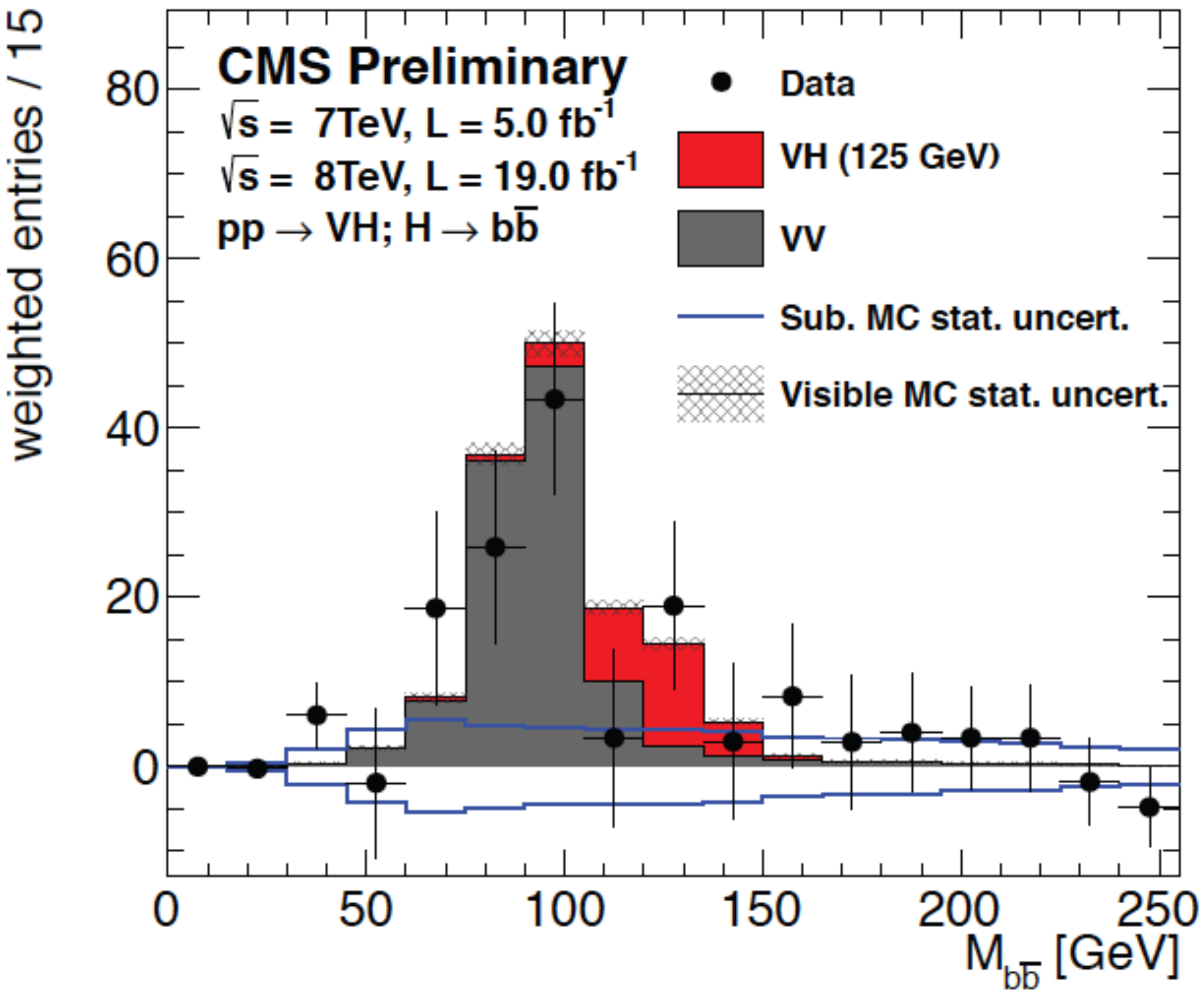


Higgs decays to fermions: $\tau\tau$



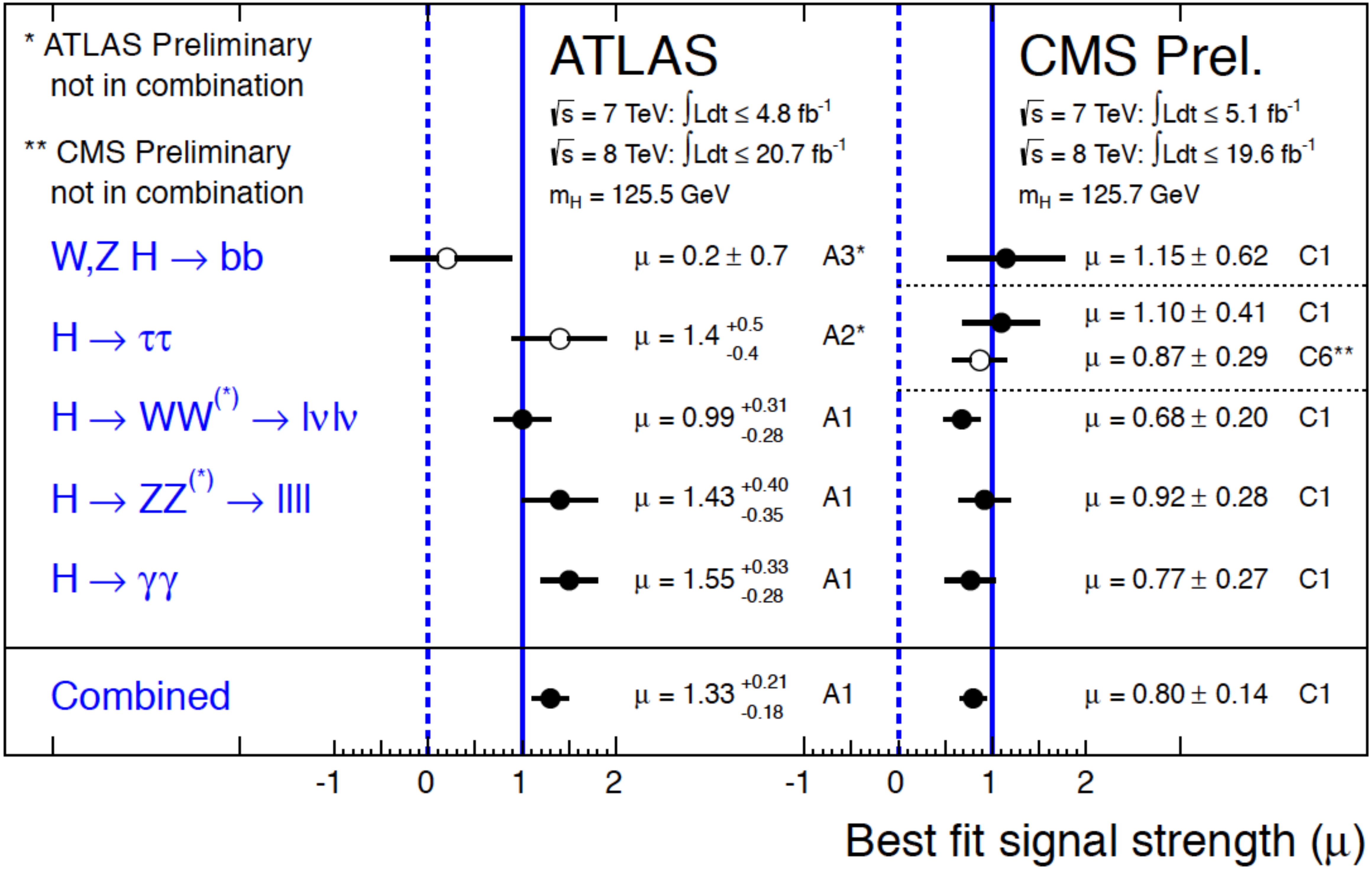
Higgs decays to fermions : bb





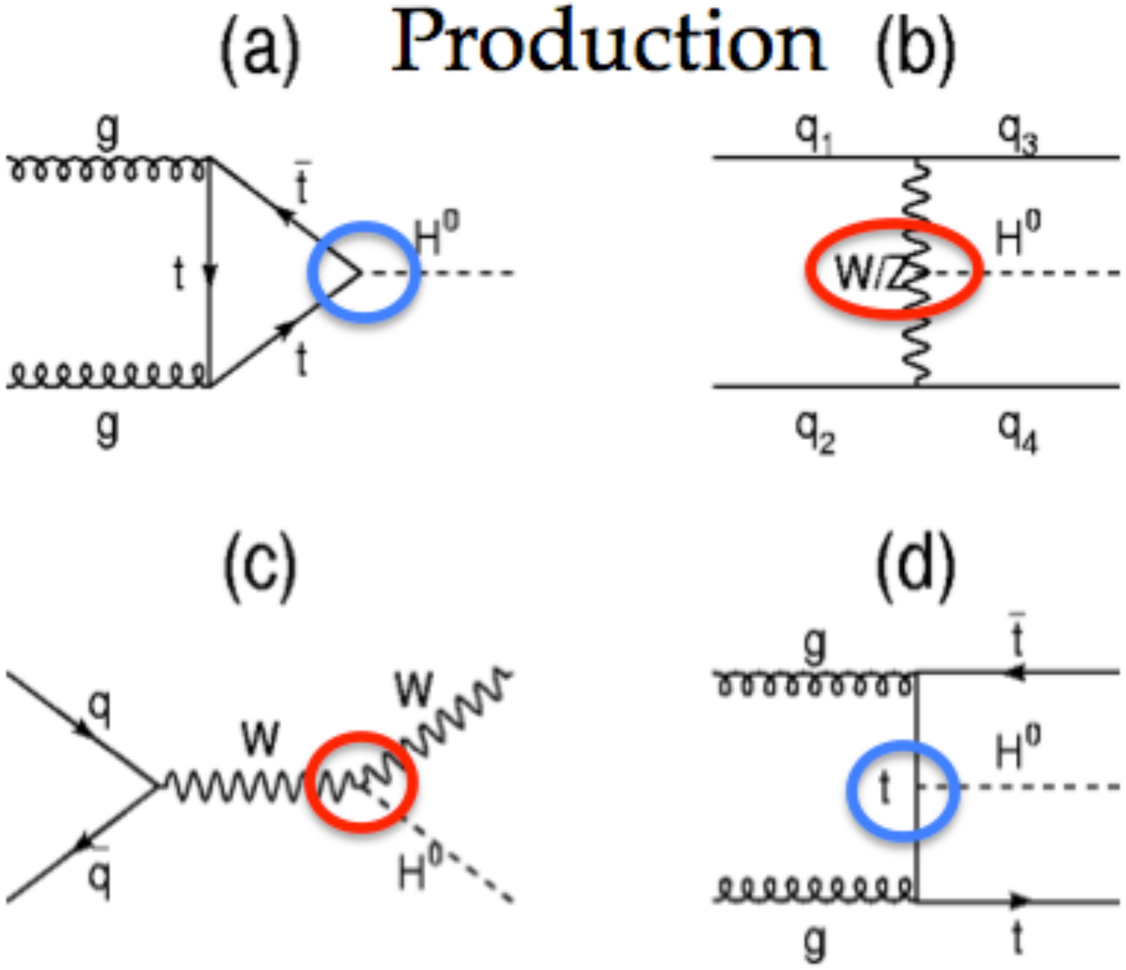
Signal strength (μ)

The signal strength $\mu = (\sigma \cdot \mathcal{B})_{\text{obs}} / (\sigma \cdot \mathcal{B})_{\text{SM}}$



Effective Couplings: diagrams

Production



(a) gluon fusion (19 pb @8 TeV)

(b) VBF (WW or ZZ fusion)

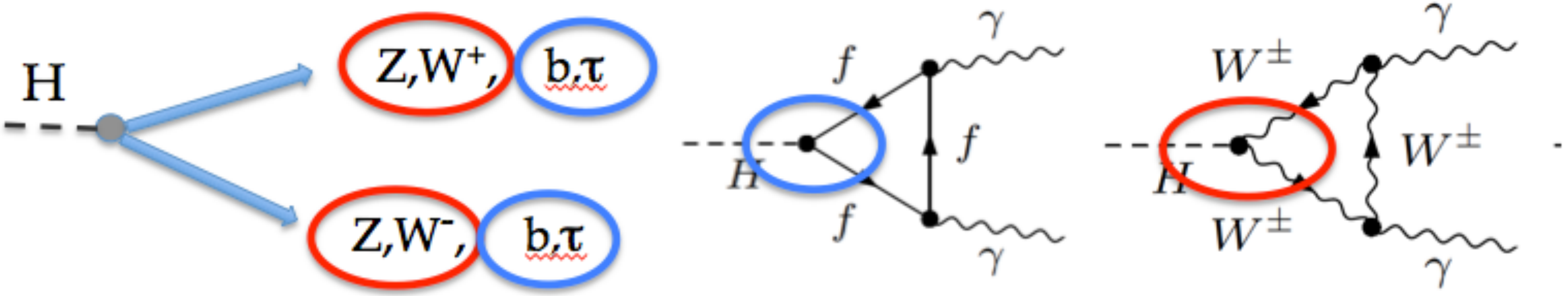
(c) Associated production (VH)

(d) ttH production

Fermions

Bosons

Decay



Estimators of Effective Couplings

Best value

Nuisance parameters

$$q_0 = -2\ln\frac{\mathcal{L}(\text{obs}\,|\,b,\,\hat{\theta}_0)}{\mathcal{L}(\text{obs}\,|\,\hat{\mu}\cdot s + b,\,\hat{\theta})},$$

b,s background, signal; $\hat{\Theta}$ "nuisance parameters"; $\hat{\mu}$ signal strength modifier

$$q(a) = -2\ln\frac{\mathcal{L}(\text{obs}\,|\,s(a) + b,\,\hat{\theta}_a)}{\mathcal{L}(\text{obs}\,|\,s(\hat{a}) + b,\,\hat{\theta})}.$$

'a' is quantity of interest, profile it. $q_0(a)$ is best fit of q(a) with fit nuisance parameters

Value at "a"

$$\hat{\mu} = \hat{\sigma} / \sigma_{SM}$$

Signal strength. The best fit value for the common signal strength modifier provides the first compatibility test. μ is 0 in absence of H, 1 in case of SM H.

- Test $\mu_{\gamma\gamma}$, μ_{ZZ} … $\mu_{ggF+ttH}$ and μ_{VBF+VH}

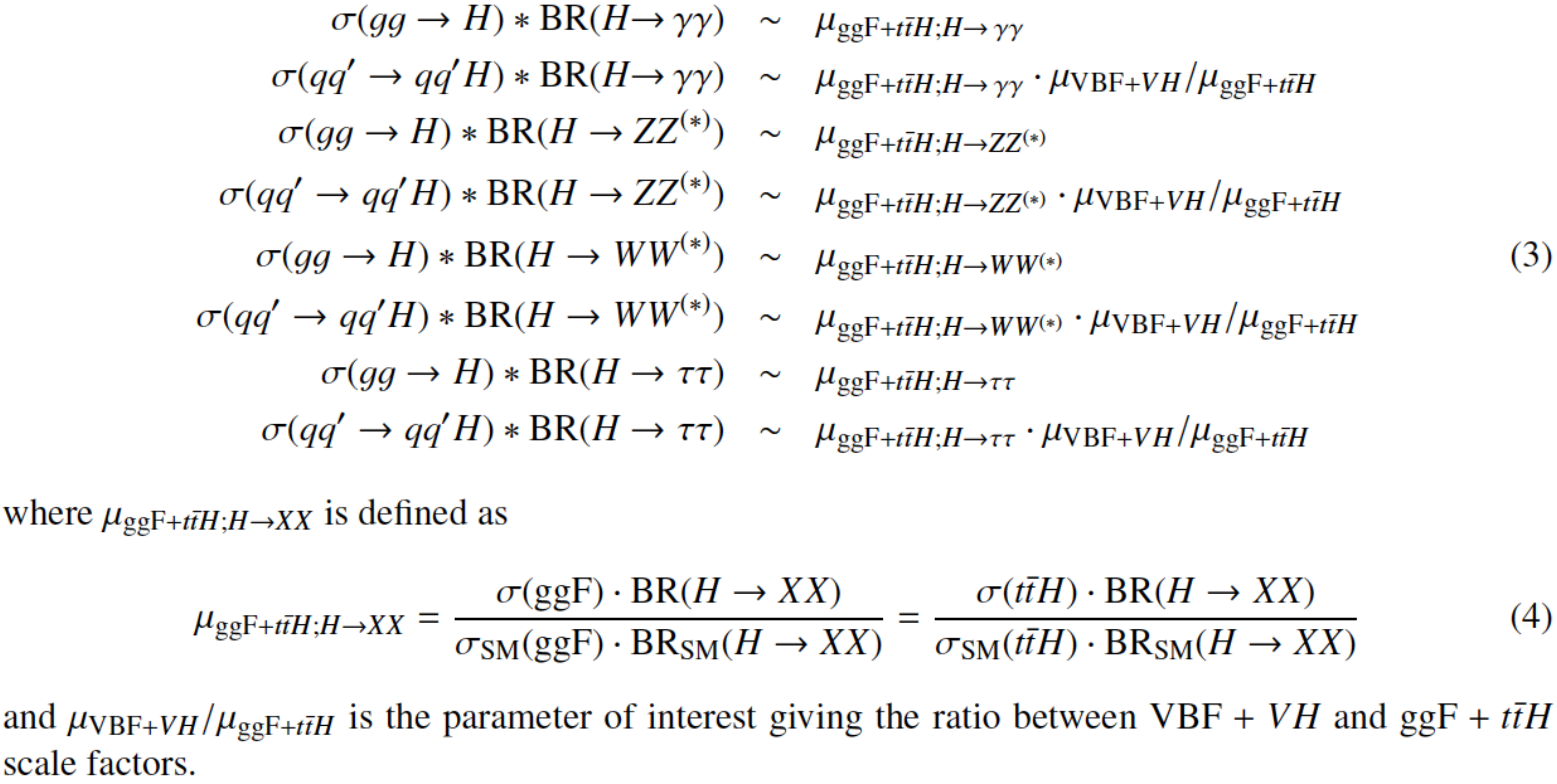
$$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

ii and *ff* couplings modified by k_i^2 and k_f^2 Example:

$$\sigma \cdot \mathrm{BR}\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- Test $\lambda_{WZ}=k_W/k_Z$ ("costudial symmetry", ==1 in SM)
- Test $\lambda_{du}=k_d/k_u$ $\lambda_{WZ}=k_W/k_Z$

A bit of gimnastic …



$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to \tau\tau) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}
\end{aligned} \tag{3}$$

where $\mu_{\mathrm{ggF}+t\bar{t}H;H\to XX}$ is defined as

$$\mu_{\mathrm{ggF}+t\bar{t}H;H\to XX} = \frac{\sigma(\mathrm{ggF}) \cdot \mathrm{BR}(H \to XX)}{\sigma_{\mathrm{SM}}(\mathrm{ggF}) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to XX)} = \frac{\sigma(t\bar{t}H) \cdot \mathrm{BR}(H \to XX)}{\sigma_{\mathrm{SM}}(t\bar{t}H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to XX)} \tag{4}$$

and $\mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$ is the parameter of interest giving the ratio between VBF + VH and ggF + $t\bar{t}H$ scale factors.

Signal strength (μ)

The luminosity collected by ATLAS & CMS gives

Production mechanism	ggf	VBF	VH/ZH	ttH
# events produced LHC	500K	40K	20K	3K
# selected events	O(100)	O(100)	O(10)	
# events produced Tevatron	10K		2K	

For each decay channel “c” we define categories to maximize the sensitivity of the analysis to one particular production mode. However a mixture of different mechanisms in one category is inevitable. This implies the cross section of one category is not the cross section of one production mechanism.

$$n^c_{signal} = \mu_c\left(\sum_i \sigma_{i,SM} \times A^c_{if} \times \varepsilon^c_{if}\right) \times B_{f,SM} \times \mathcal{L}$$

Where μ_c is ration between measured & expected events in that category and

i=ggf,VBF,VH,tth and f=$\gamma\gamma$,WW,ZZ,bb,$\tau\tau$

Measurement of μ_c gives an indication of how well SM describes data

More of signal strengths in categories

$$n^c_{signal} = (\sum_i \mu_i \sigma_{i,SM} \times A^c_{if} \times \varepsilon^c_{if}) \times \mu_f \times B_{f,SM} \times \mathcal{L}\,, \quad (19)$$

Where μ_i is the production mode modifier and μ_f is the decay mode modifier of the SM. Of course, if we study one category only the only measurable observable is the product

$$\mu_i \; \mu_f$$

But if we compare two categories with the same decay channel then a fit with “f” fixed is possible. Assume ggf and ttH are assumed to scale in the same way, similarly VBF and VH scale with the same strength.

Signal strengths in individual categories

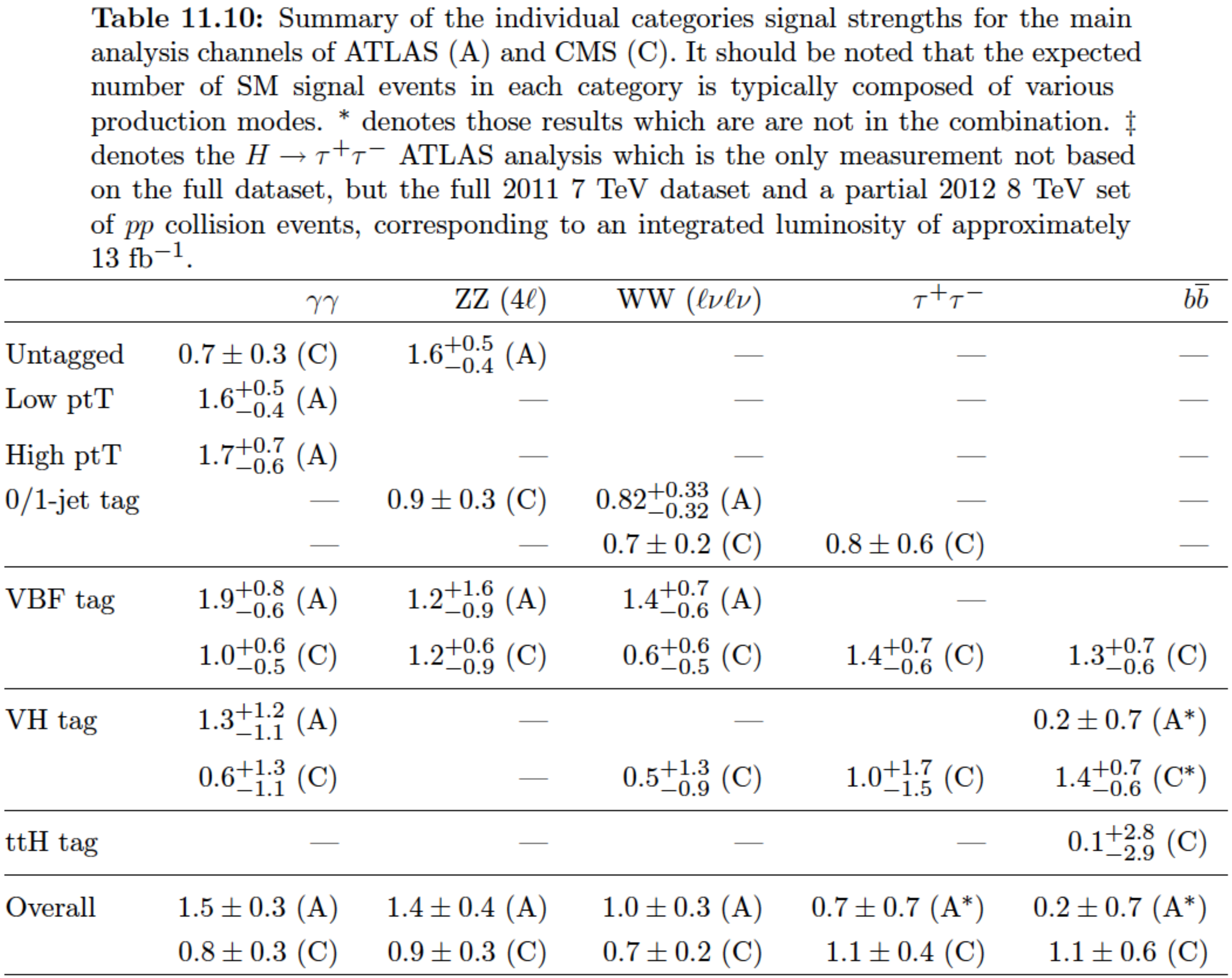
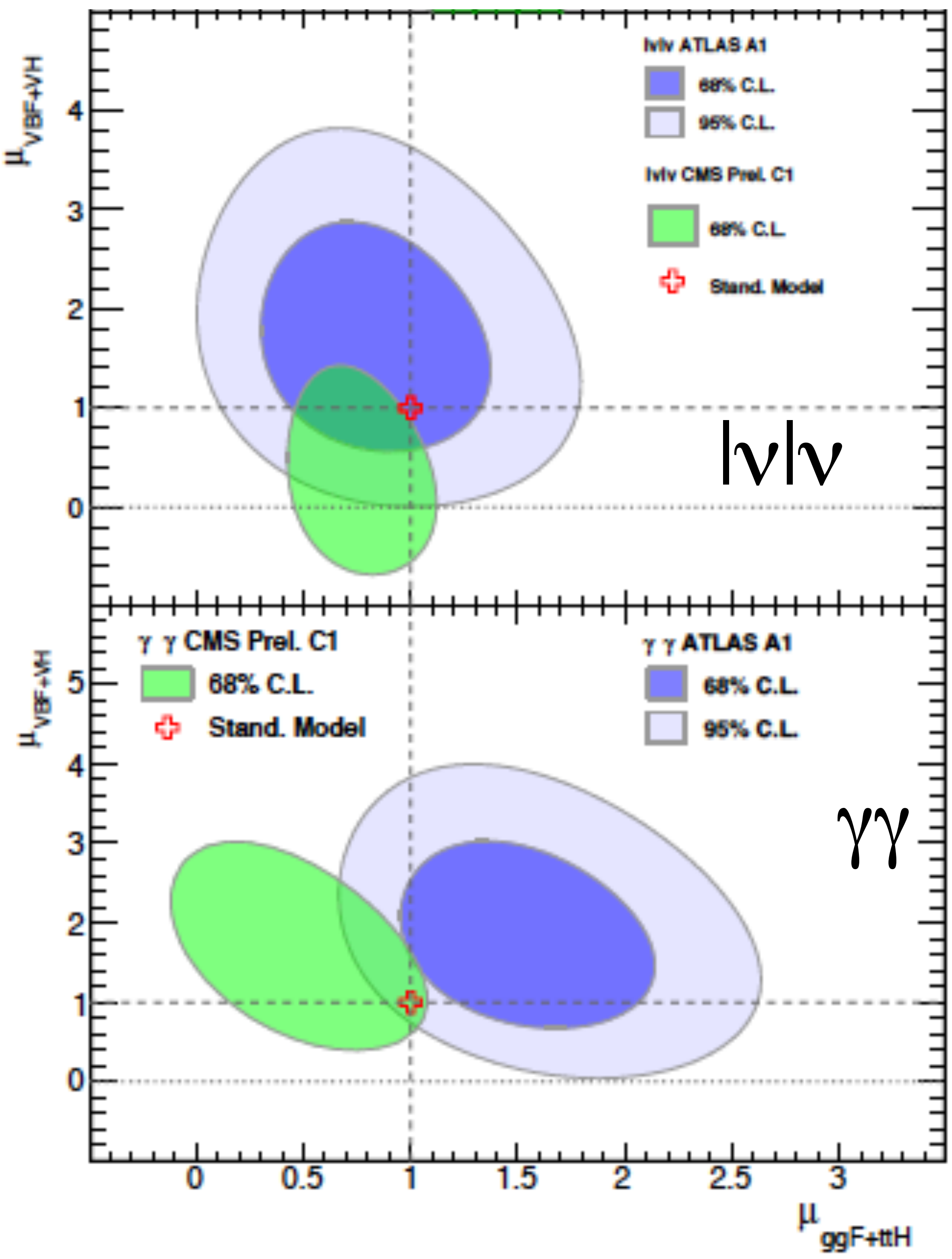
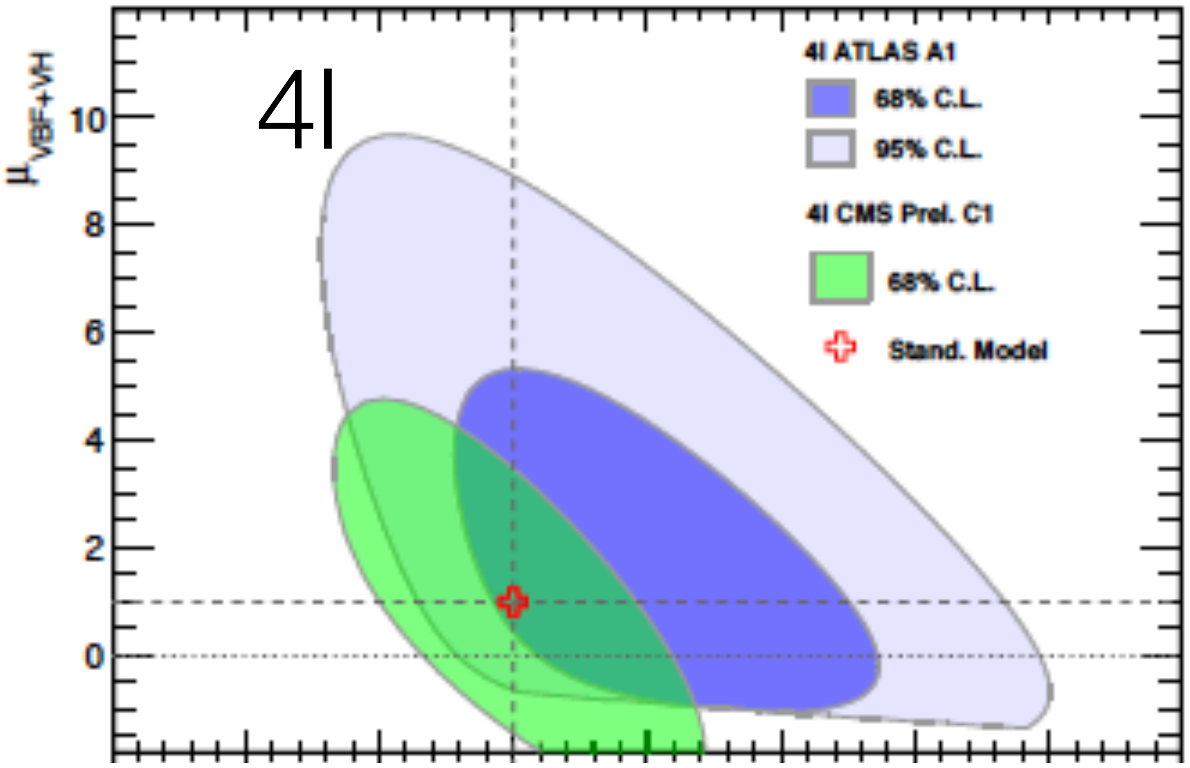


Table 11.10: Summary of the individual categories signal strengths for the main analysis channels of ATLAS (A) and CMS (C). It should be noted that the expected number of SM signal events in each category is typically composed of various production modes. * denotes those results which are are not in the combination. ‡ denotes the $H \to \tau^+\tau^-$ ATLAS analysis which is the only measurement not based on the full dataset, but the full 2011 7 TeV dataset and a partial 2012 8 TeV set of *pp* collision events, corresponding to an integrated luminosity of approximately 13 fb^{-1}.

	$\gamma\gamma$	ZZ (4ℓ)	WW ($\ell\nu\ell\nu$)	$\tau^+\tau^-$	$b\bar{b}$
Untagged	0.7 ± 0.3 (C)	$1.6^{+0.5}_{-0.4}$ (A)	—	—	—
Low ptT	$1.6^{+0.5}_{-0.4}$ (A)	—	—	—	—
High ptT	$1.7^{+0.7}_{-0.6}$ (A)	—	—	—	—
0/1-jet tag	—	0.9 ± 0.3 (C)	$0.82^{+0.33}_{-0.32}$ (A)	—	—
	—	—	0.7 ± 0.2 (C)	0.8 ± 0.6 (C)	—
VBF tag	$1.9^{+0.8}_{-0.6}$ (A)	$1.2^{+1.6}_{-0.9}$ (A)	$1.4^{+0.7}_{-0.6}$ (A)	—	
	$1.0^{+0.6}_{-0.5}$ (C)	$1.2^{+0.6}_{-0.9}$ (C)	$0.6^{+0.6}_{-0.5}$ (C)	$1.4^{+0.7}_{-0.6}$ (C)	$1.3^{+0.7}_{-0.6}$ (C)
VH tag	$1.3^{+1.2}_{-1.1}$ (A)	—	—		0.2 ± 0.7 (A*)
	$0.6^{+1.3}_{-1.1}$ (C)	—	$0.5^{+1.3}_{-0.9}$ (C)	$1.0^{+1.7}_{-1.5}$ (C)	$1.4^{+0.7}_{-0.6}$ (C*)
ttH tag	—	—	—	—	$0.1^{+2.8}_{-2.9}$ (C)
Overall	1.5 ± 0.3 (A)	1.4 ± 0.4 (A)	1.0 ± 0.3 (A)	0.7 ± 0.7 (A*)	0.2 ± 0.7 (A*)
	0.8 ± 0.3 (C)	0.9 ± 0.3 (C)	0.7 ± 0.2 (C)	1.1 ± 0.4 (C)	1.1 ± 0.6 (C)

Signal strengths in categories for a fixed f





Evidence for VBF production

In the expression of μ_{VBF+VH} we put together VBF and VH, assuming they scale equally. If we want to have more information on the signal strength of VBF only we can use the expression with same "f"

$$\rho_{VBF+VH,ggH+ttH} = \frac{\mu_{VBF+VH}\mu_f}{\mu_{ggF+ttH}\mu_f} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

We can combine two categories, one sensitive enough to VH to extract VBF obtaining
The ratio $\rho_{VBF,ggH+ttH}$

$$\rho_{VBF,ggH+ttH} = 1.1^{+0.4}_{-0.3} \quad (A)$$

$$\rho_{VBF+VH,ggH+ttH} = 1.1^{+0.4}_{-0.3} \quad (A)$$

$$\rho_{VBF+VH,ggH+ttH} = 1.7^{+0.7}_{-0.5} \quad (C)$$

ATLAS excludes $\rho_{VBF,ggH+ttH} = 0$ at more than 3σ thus giving evidence for VBF production. Even more significance when CMS included

Coupling properties of the Higgs Boson

Elaborate even more: introduce modifiers k_x of vertices in the Lagrangian. In this way production and decay vertices are treated on the same footing. Remember

- In SM H does not couple to massless particles directly (only via loops).

$$
\begin{aligned}
\mathcal{L} = {} & \boxed{\kappa_3} \frac{m_H^2}{2v} H^3 + \boxed{\kappa_Z} \frac{m_Z^2}{v} Z_\mu Z^\mu H + \boxed{\kappa_W} \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
& + \boxed{\kappa_g} \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \boxed{\kappa_\gamma} \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \boxed{\kappa_{Z\gamma}} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\
& + \boxed{\kappa_{VV}} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W^+_{\mu\nu} W^{-\mu\nu} \right) H \\
& - \left(\boxed{\kappa_t} \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \boxed{\kappa_b} \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \boxed{\kappa_\tau} \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H .
\end{aligned}
$$

Parametrizations in SM

$$(1-\cos^4\theta_W)\kappa_{VV} = \sin 2\theta_W \kappa_{Z\gamma} + \sin^2\theta_W \kappa_{\gamma\gamma}.$$

The κ_g, κ_γ and $\kappa_{Z\gamma}$, can be treated effectively as free parameters in the fit or in terms of the know SM field content and as a function of the SM coupling modifiers, in the following way:

Independent of SM expressions

$$\begin{aligned}\kappa_g^2(\kappa_t,\kappa_b) &= 1.06\cdot\kappa_t^2 - 0.07\cdot\kappa_t\kappa_b + 0.01\cdot\kappa_b^2\\ \kappa_\gamma^2(\kappa_F,\kappa_V) &= 1.59\cdot\kappa_V^2 - 0.66\cdot\kappa_V\kappa_F + 0.07\cdot\kappa_F^2 \qquad (11.24)\\ \kappa_{Z\gamma}^2(\kappa_F,\kappa_V) &= 1.12\cdot\kappa_V^2 - 0.15\cdot\kappa_V\kappa_F + 0.03\cdot\kappa_F^2\end{aligned}$$

These parametrizations are given for a Higgs boson mass hypothesis of 125 GeV.

The global fit is then performed expressing the μ_i and μ_f parameters in terms of a limited number of κ_k parameters or their ratios, under various assumptions. The parametrization for the production modes are: $\boxed{\mu_{ggF} = \kappa_g^2}$ for the gluon fusion; $\boxed{\mu_{VBF,VH} = \kappa_V^2}$ for the VBF and VH processes when the W and Z couplings are assumed to scale equally, and the following expression for the VBF production mode is used:

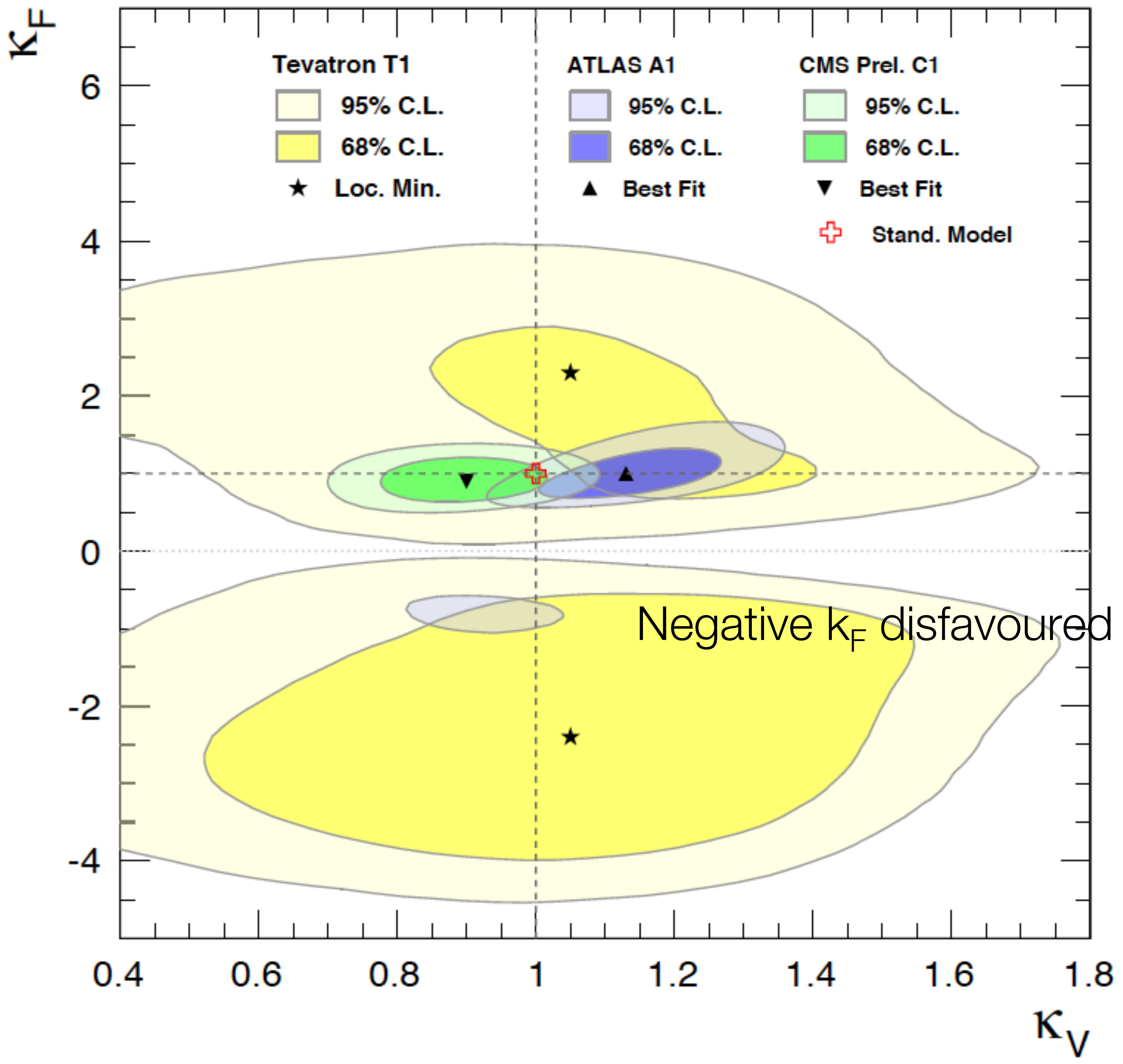
W & Z are assumed to scale differently

$$\boxed{\kappa_{VBF}^2(\kappa_W,\kappa_Z) = \frac{\kappa_W^2\sigma_{WWH} + \kappa_Z^2\sigma_{ZZH}}{\sigma_{WWH}+\sigma_{ZZH}}} \qquad (11.25)$$

Benchmarks considered

- Relative couplings to bosons and fermions. Introduce k_V and k_F
- **Couplings to Z and W**, ratio of couplings is a fundamental test of SM (custodial symmetry). Several production processes and decay modes may be used to test this assumptions. Ratio $\lambda_{WZ}=k_W/k_Z$ can be probed under a large number of conditions. First step is assuming all fermions scale as k_F and introduce K_{ZZ} which affects the total width. Second to be less dependent on loops, only decay channels to WW and ZZ have been considered (indetermination of sign but k_γ may give indication for the interference term between W and top in the loop)
- **Probing new physics**: it is assumed that no field distorts loop contributions of the H to gluons and photons. Possible deviations may indicate existence of new physics (new fields). This is done by assuming k_V and k_F equal to 1 in all expressions and leaving k_g and k_γ as free parameters of the fit

K_F vs K_V, *simplified* view: all fermions “F”, bosons “V”



Negative k_F disfavoured at the level of 2 sigmas

K_g vs K_γ

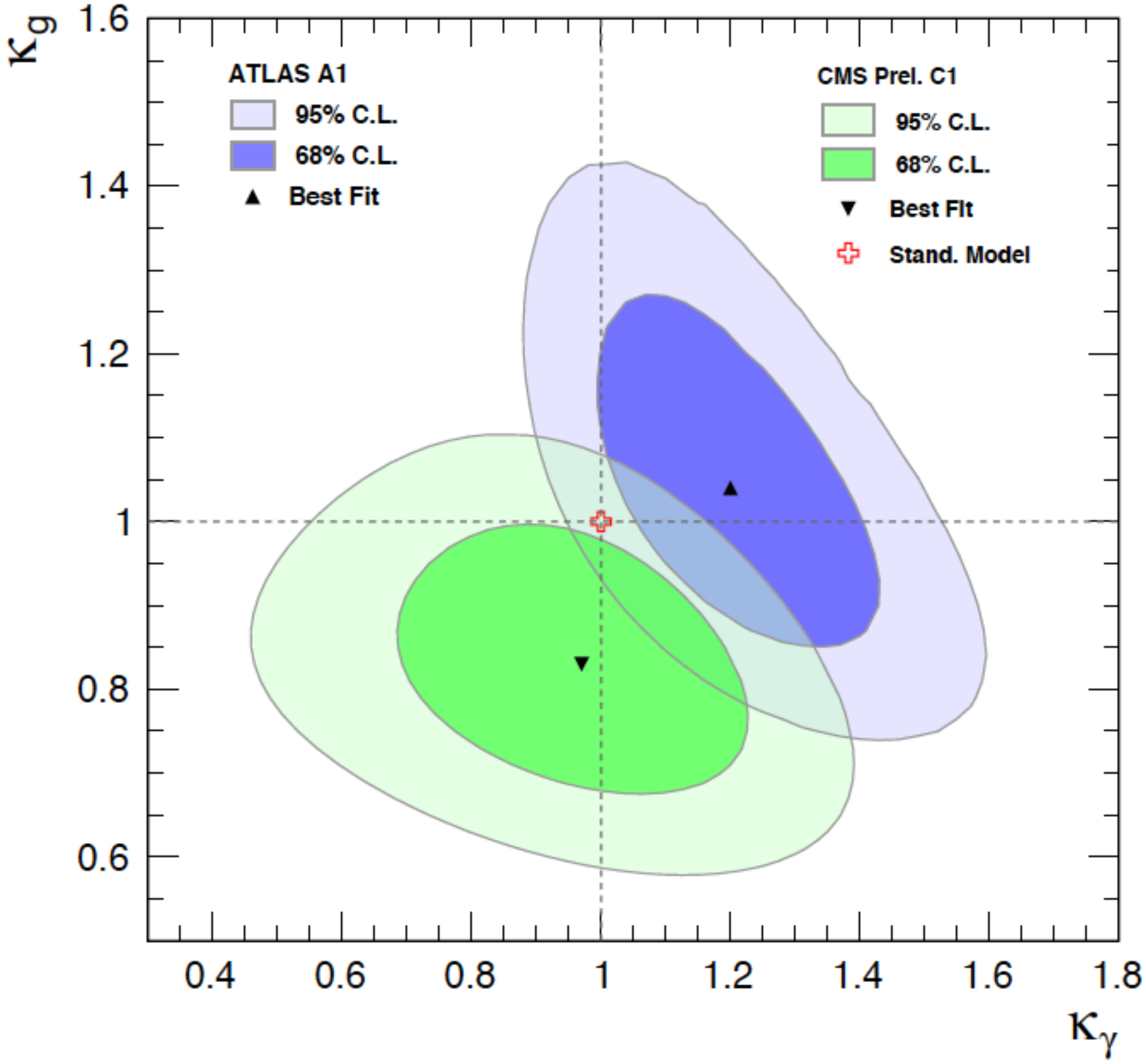


Figure 11.19: Likelihood contours of the global fit in the $(\kappa_g, \kappa_\gamma)$ plane for the ATLAS experiment A1 [119] and the CMS experiment C1 [120] results.

Summary of the Higgs Boson coupling properties

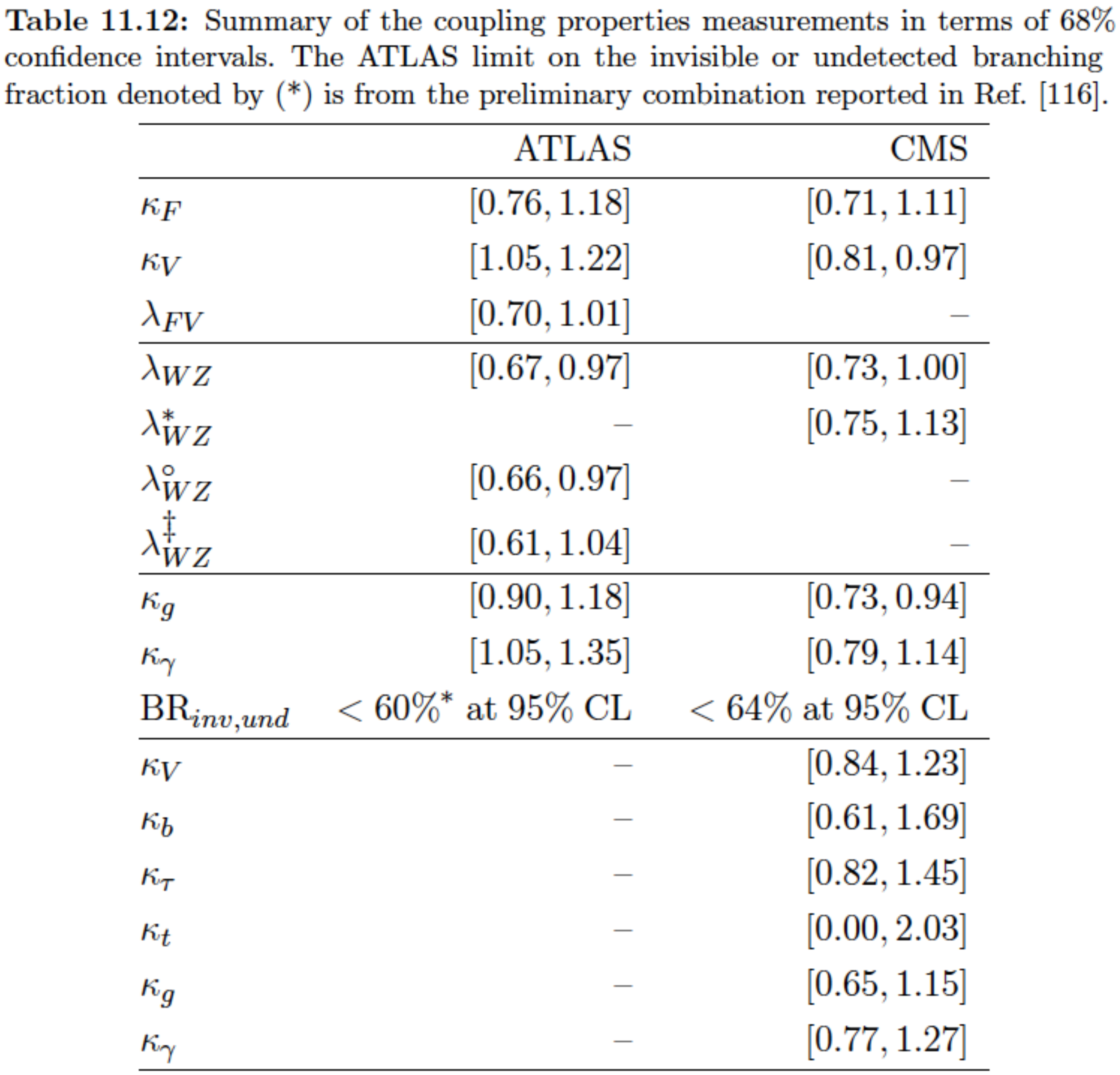


Table 11.12: Summary of the coupling properties measurements in terms of 68% confidence intervals. The ATLAS limit on the invisible or undetected branching fraction denoted by (*) is from the preliminary combination reported in Ref. [116].

	ATLAS	CMS
κ_F	$[0.76, 1.18]$	$[0.71, 1.11]$
κ_V	$[1.05, 1.22]$	$[0.81, 0.97]$
λ_{FV}	$[0.70, 1.01]$	–
λ_{WZ}	$[0.67, 0.97]$	$[0.73, 1.00]$
λ^{*}_{WZ}	–	$[0.75, 1.13]$
λ°_{WZ}	$[0.66, 0.97]$	–
$\lambda^{\ddagger}_{WZ}$	$[0.61, 1.04]$	–
κ_g	$[0.90, 1.18]$	$[0.73, 0.94]$
κ_γ	$[1.05, 1.35]$	$[0.79, 1.14]$
$\mathrm{BR}_{inv,und}$	$< 60\%^{*}$ at 95% CL	$< 64\%$ at 95% CL
κ_V	–	$[0.84, 1.23]$
κ_b	–	$[0.61, 1.69]$
κ_τ	–	$[0.82, 1.45]$
κ_t	–	$[0.00, 2.03]$
κ_g	–	$[0.65, 1.15]$
κ_γ	–	$[0.77, 1.27]$

The ttH production mode

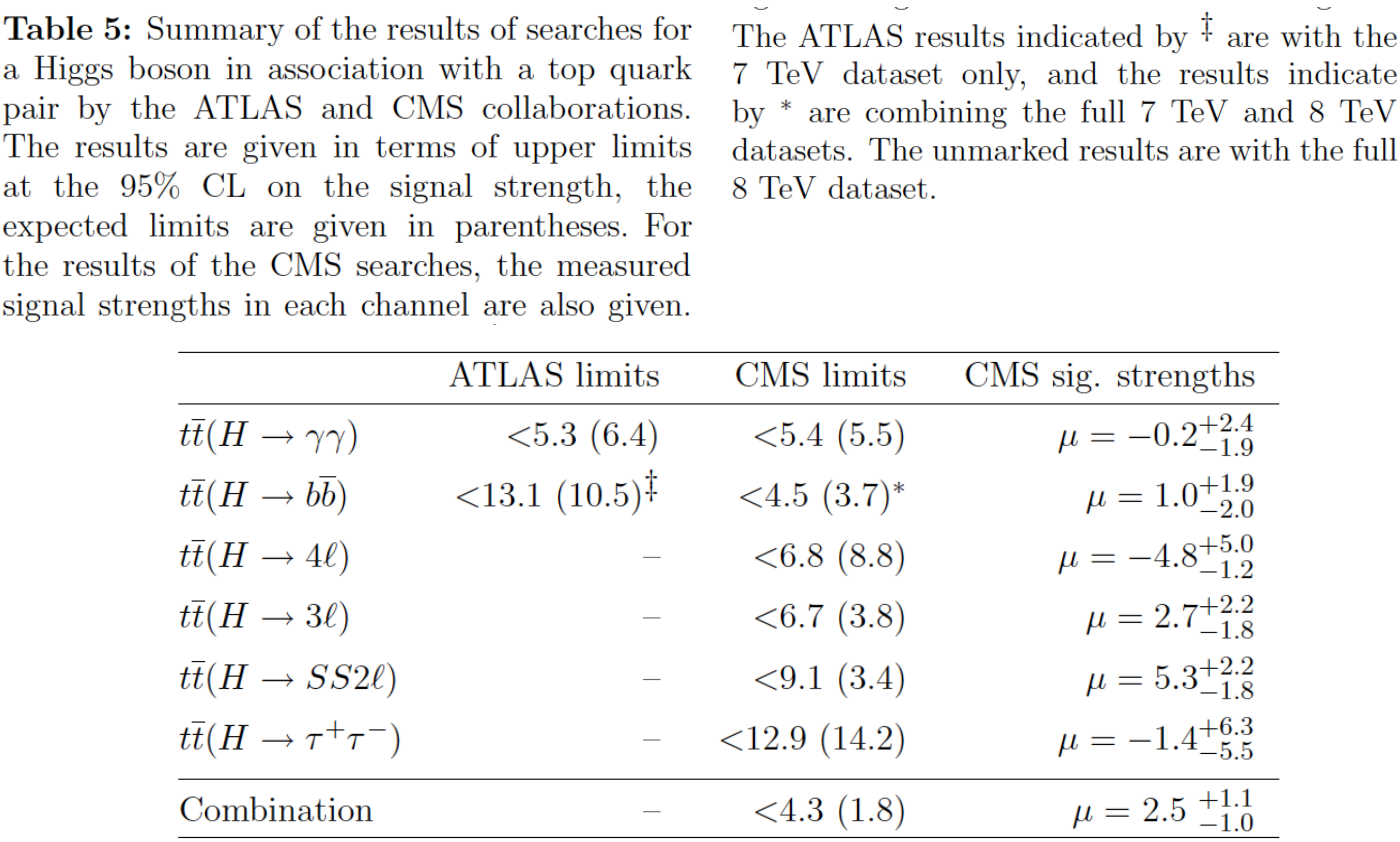


Table 5: Summary of the results of searches for a Higgs boson in association with a top quark pair by the ATLAS and CMS collaborations. The results are given in terms of upper limits at the 95% CL on the signal strength, the expected limits are given in parentheses. For the results of the CMS searches, the measured signal strengths in each channel are also given. The ATLAS results indicated by ‡ are with the 7 TeV dataset only, and the results indicate by * are combining the full 7 TeV and 8 TeV datasets. The unmarked results are with the full 8 TeV dataset.

	ATLAS limits	CMS limits	CMS sig. strengths
$t\bar{t}(H \rightarrow \gamma\gamma)$	<5.3 (6.4)	<5.4 (5.5)	$\mu = -0.2^{+2.4}_{-1.9}$
$t\bar{t}(H \rightarrow b\bar{b})$	<13.1 (10.5)‡	<4.5 (3.7)*	$\mu = 1.0^{+1.9}_{-2.0}$
$t\bar{t}(H \rightarrow 4\ell)$	–	<6.8 (8.8)	$\mu = -4.8^{+5.0}_{-1.2}$
$t\bar{t}(H \rightarrow 3\ell)$	–	<6.7 (3.8)	$\mu = 2.7^{+2.2}_{-1.8}$
$t\bar{t}(H \rightarrow SS2\ell)$	–	<9.1 (3.4)	$\mu = 5.3^{+2.2}_{-1.8}$
$t\bar{t}(H \rightarrow \tau^+\tau^-)$	–	<12.9 (14.2)	$\mu = -1.4^{+6.3}_{-5.5}$
Combination	–	<4.3 (1.8)	$\mu = 2.5\ ^{+1.1}_{-1.0}$

Spin – Parity Determination (SM 0^+)

- Use observables that are sensitive to Spin and Parity of the New Boson independent of the coupling strengths
- Onshell decay of a spin=1 particle into $\gamma\gamma$ is forbidden by Landau-Yang theorem: spin=1 assignment strongly disfavoured
- Several alternative specific models: 0^-, 1^+, 1^-, 2^+ tested against the SM Higgs 0^+ hypothesis
- The spin-2 resonance can be produced either via gluon fusion (gg) or via P-wave quark-antiquark annihilation. Several scenarios corresponding to different admixtures of the production modes are considered.
- The discrimination between the spin hypotheses is enhanced when the spin-2 particle is produced predominantly via gluon fusion.

Spin - Parity

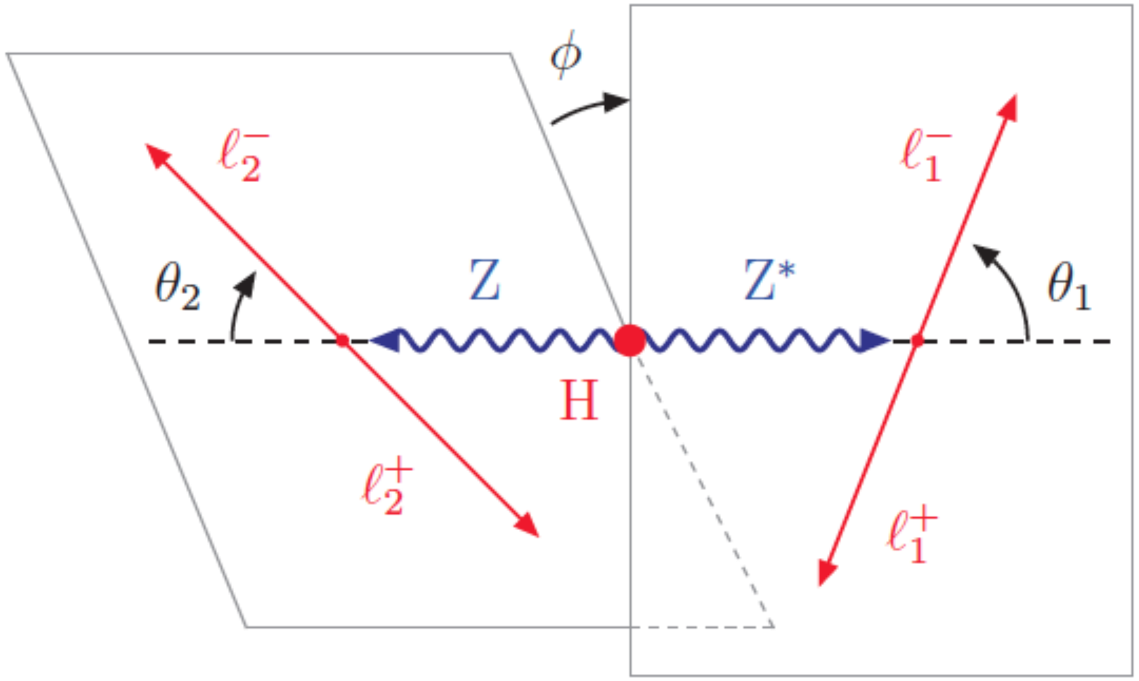
H to$\gamma\gamma$ decay angle cos(θ*) in Collins Soper frame sensitive to J

$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

The definition chosen for the polar angle in the rest frame is the Collins–Soper frame, which is defined as
the bisector axis of the momenta of the incoming protons in the diphoton rest frame

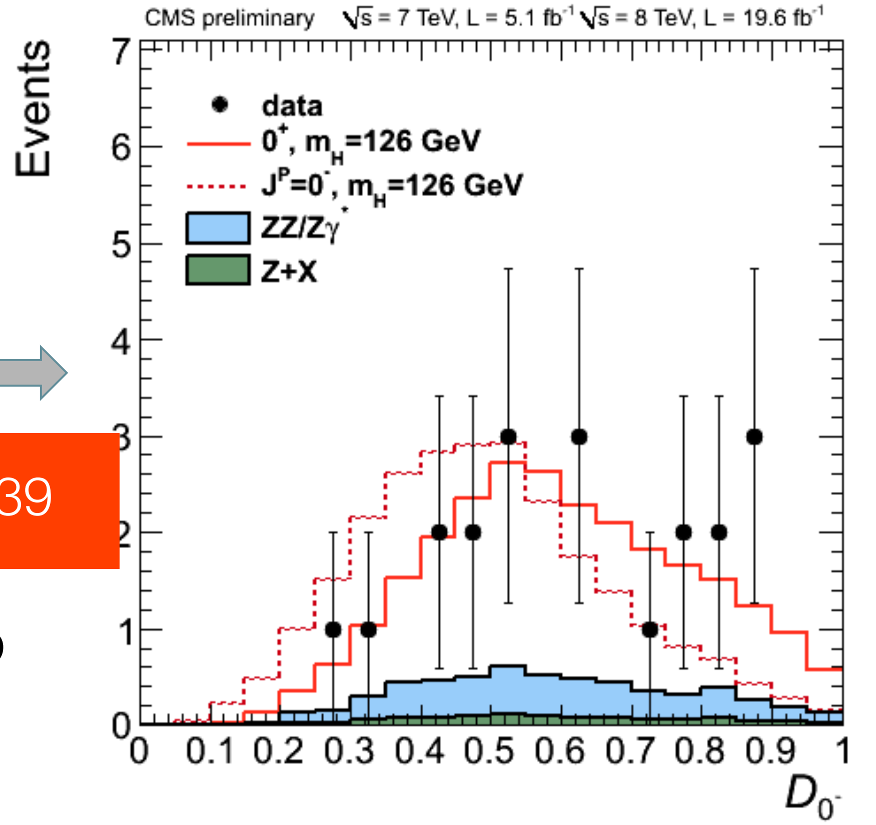
Several observables of H to WW* to $l\nu l\nu$ are sensitive to J^P: $\Delta\phi_{ll}$, M_{ll}, .. Combined with Boosted-Decision-Tree (BDT) technique

H to ZZ* to 4l: full final state reconstruction (2 masses, M_{Z1},M_{Z2}, and 5 angles) is sensitive to J^P. Combined with BDT or Matrix-Element discriminant D_{JP}



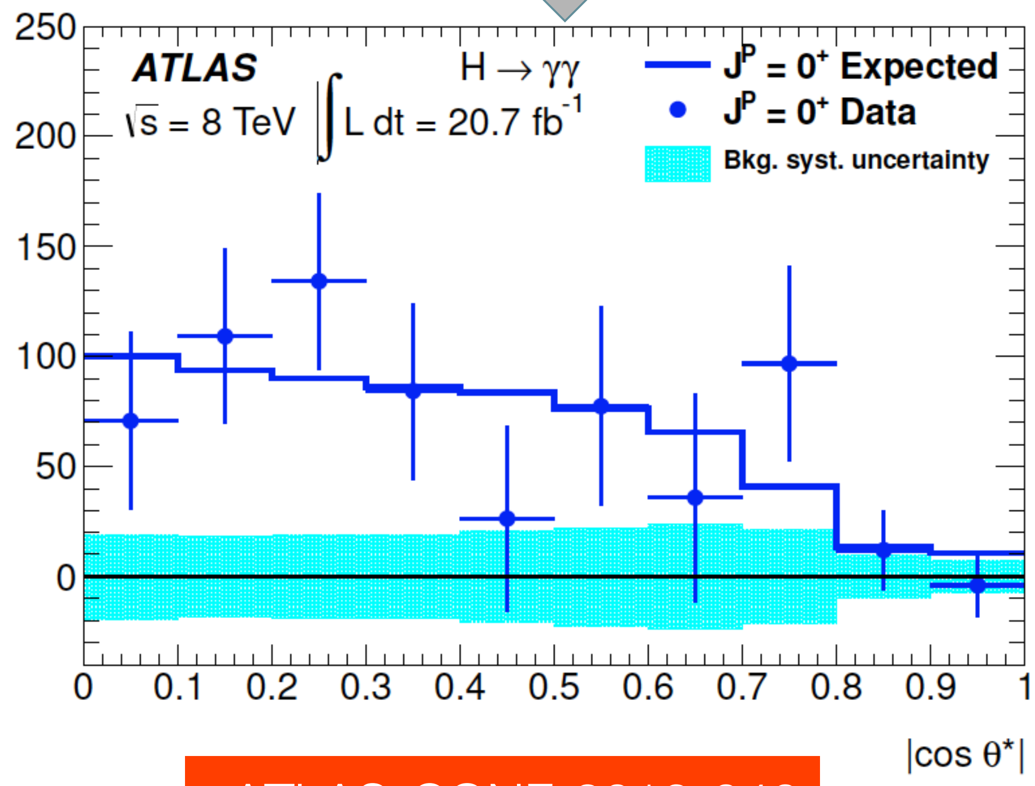
Spin – Parity, 0^+ vs 0^-

CMS 2 masses and 5 angles in H to ZZ* decay combined in a BDT output D_{JP}.



CMS:arXiv:1212.6639

ATLAS: cos(Q*) in H to gg decay compared to 0^+ 2^+ distributions.



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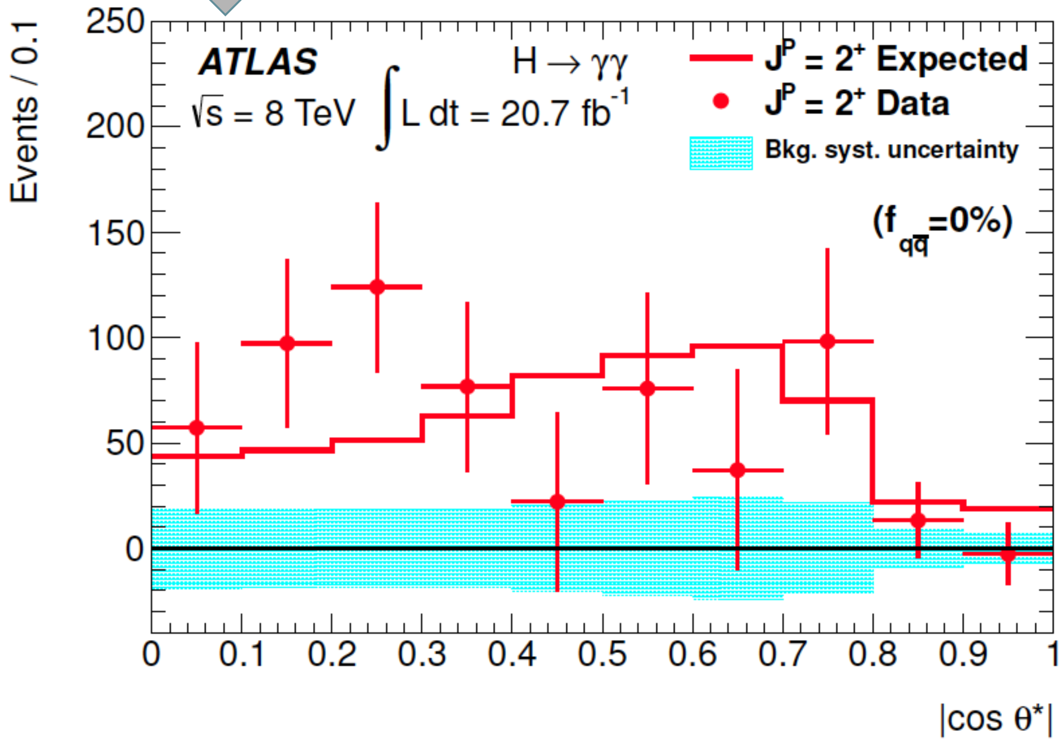
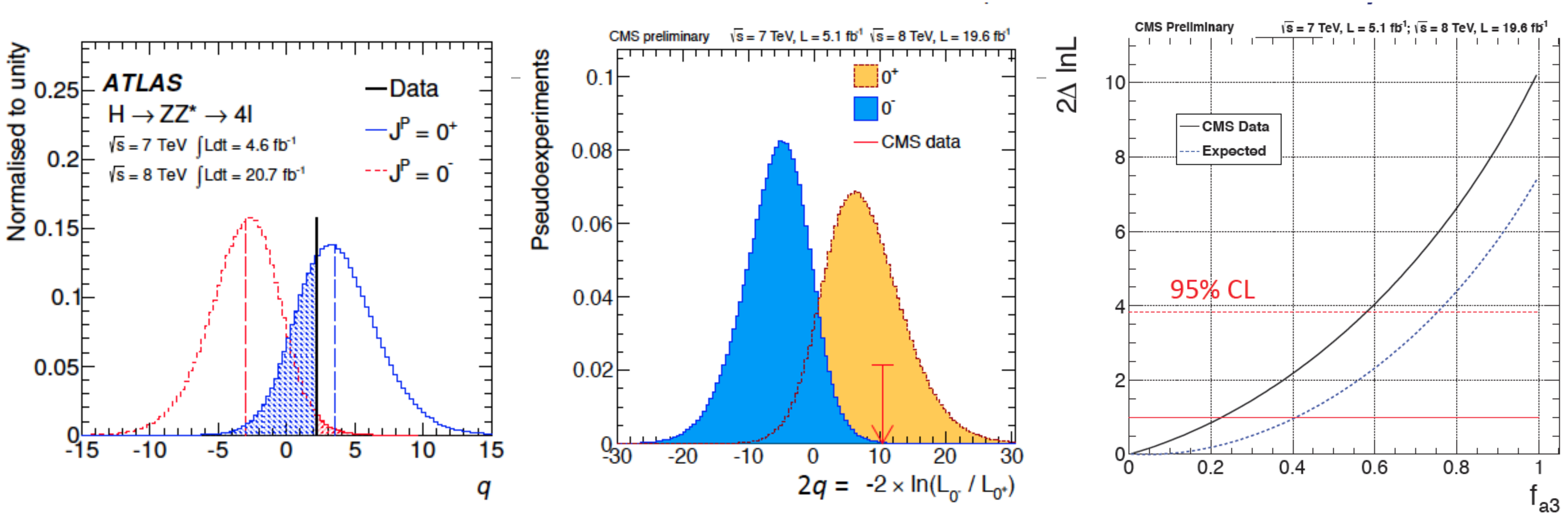


Testing O^+,O^- in H to ZZ*



$$ATLAS : O^- Excluded @ 97.8\% CL(observed), 99.6\% CL(\exp ected)$$

$$CMS : O^- Excluded @ 99.8\% CL(observed), 99.5\% CL(\exp ected)$$

CMS also investigated the possibility of CP amplitudes other than SM: The most general decay amplitude for a spin-zero boson can be defined as: A_1(CP even)=1,A_2(Interference)=A_3(CP odd)=0

$$A = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right) = A_1 + A_2 + A_3$$

$$CMS : a_3 = 0.00^{+0.23}_{-0.00} ; a_3 < 0.58 @ 95\% CL$$

Testing 0+ vs 2+

- A specific spin-2 “*graviton-like*” model with minimal couplings has been compared to the 0^+ predictions of the SM. In this specific model the spin-2 resonance can be produced either via gluon fusion (gg) or via P-wave quark-antiquark annihilation.

- The corresponding angular distributions follow

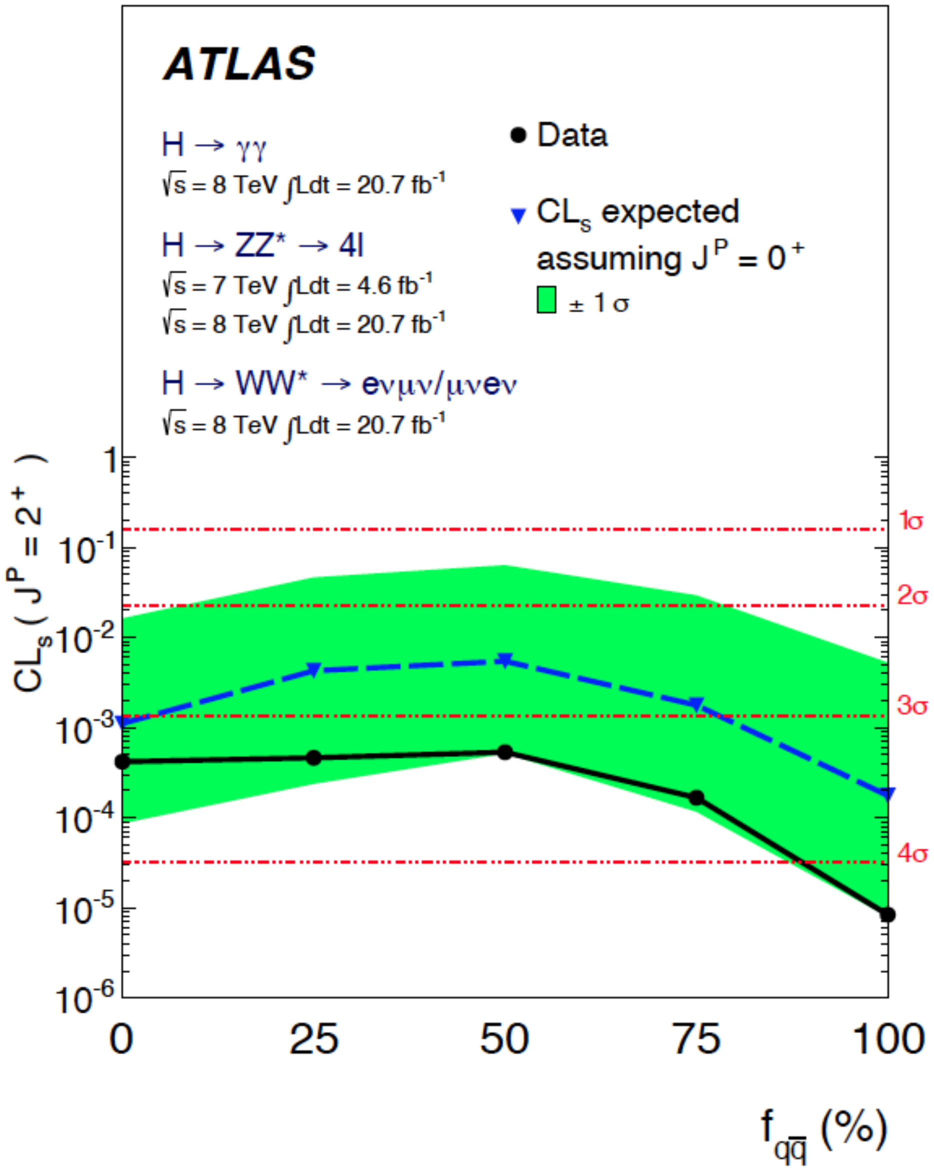
$$dN / d\cos\vartheta^* = 1 - \cos^4\vartheta^* (gluon - gluon - fusion)$$

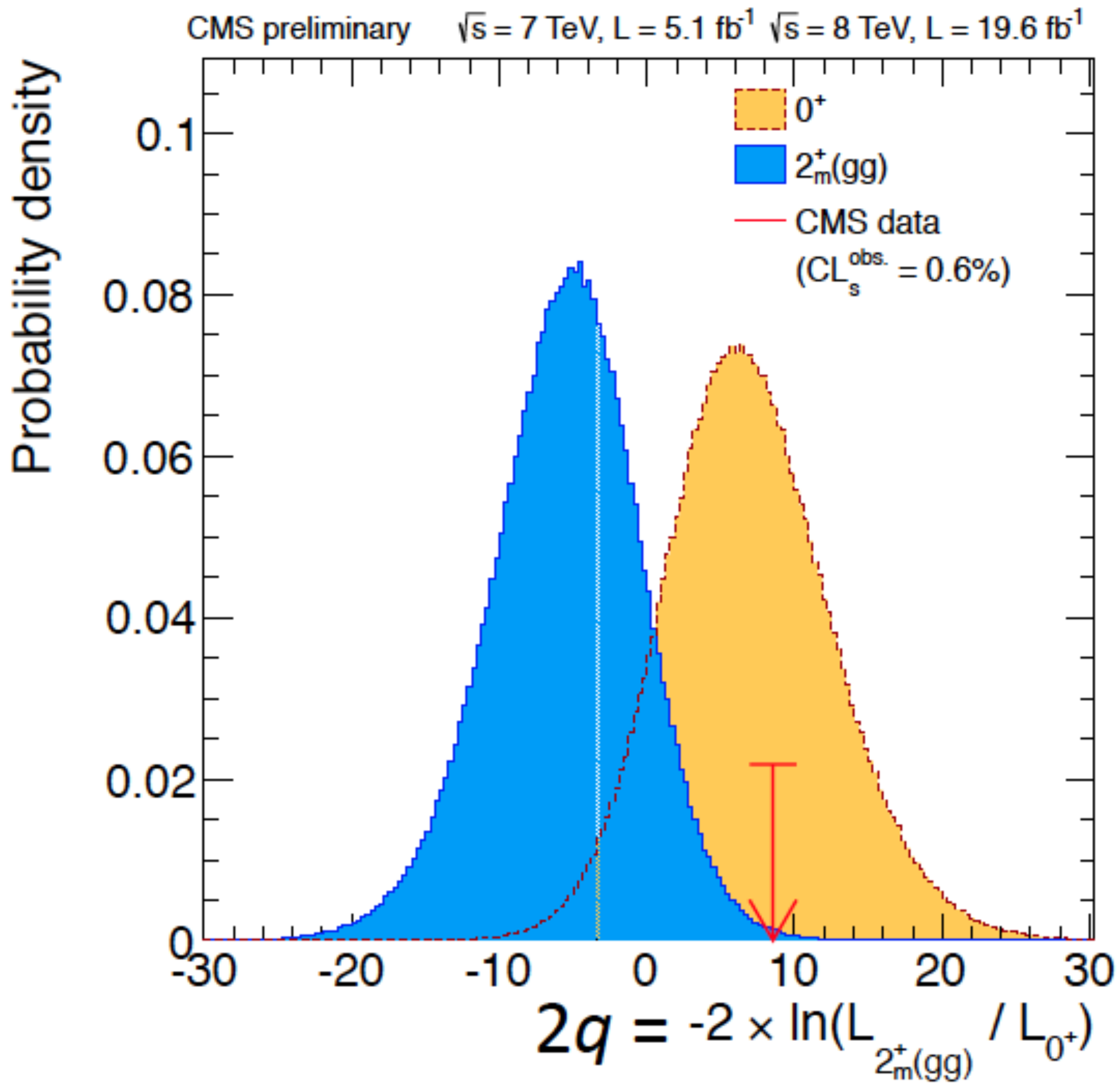
and

$$dN / d\cos\vartheta^* = 1 + 6\cos^2\vartheta^* + \cos^4\vartheta^* (q\bar{q} - production)$$

- Five scenarios corresponding to different admixtures of the production modes are considered. The discrimination between the spin hypotheses is enhanced when the spin-2 particle is produced predominantly via gluon fusion.

0^+ vs 2^+ Results





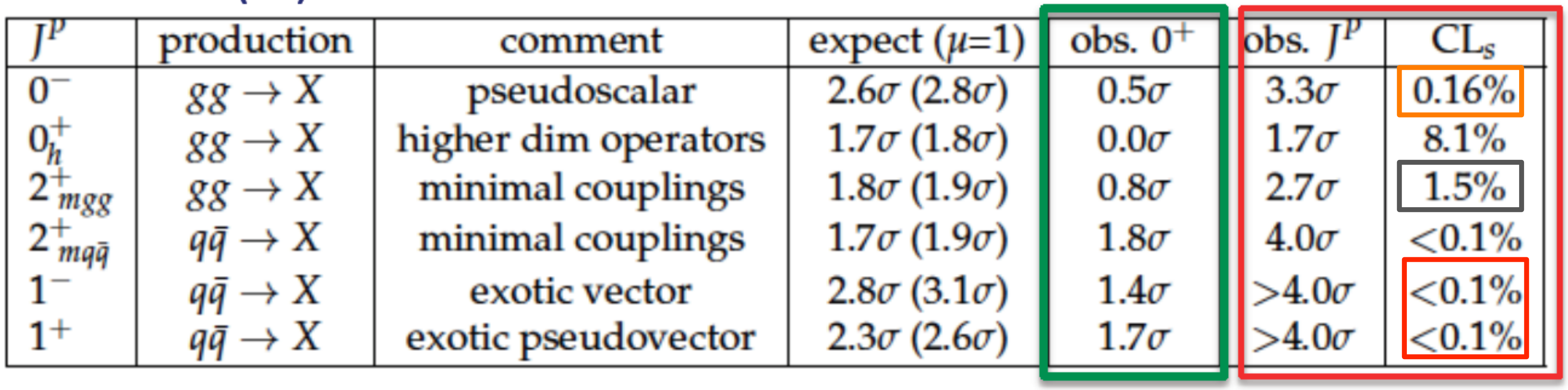
$CMS - Combined Exclusion(ZZ^*, WW^*): 2^+ (100\% gg) 99.4\% CL (expected 98.8\%)$

$ATLAS - Combined Exclusion(\gamma\gamma, ZZ^*, WW^*): 2^+ (100\% gg) 99.9\% CL (expected 99.9\%)$

$ATLAS - Combined Exclusion(\gamma\gamma, ZZ^*, WW^*): 2^+ (100\% q\bar{q}) 99.9\% CL (expected 99.9\%)$

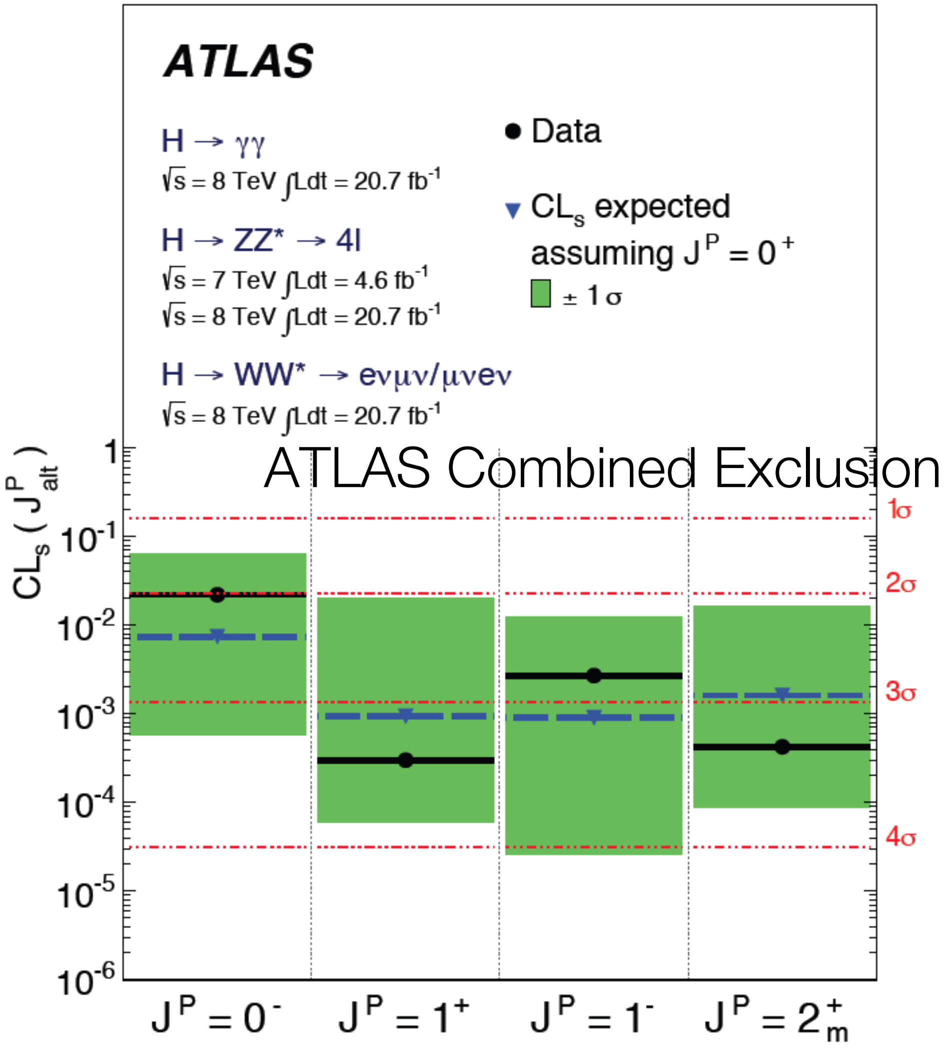
Summary of Spin Parity Results

CMS ZZ*(4ℓ)



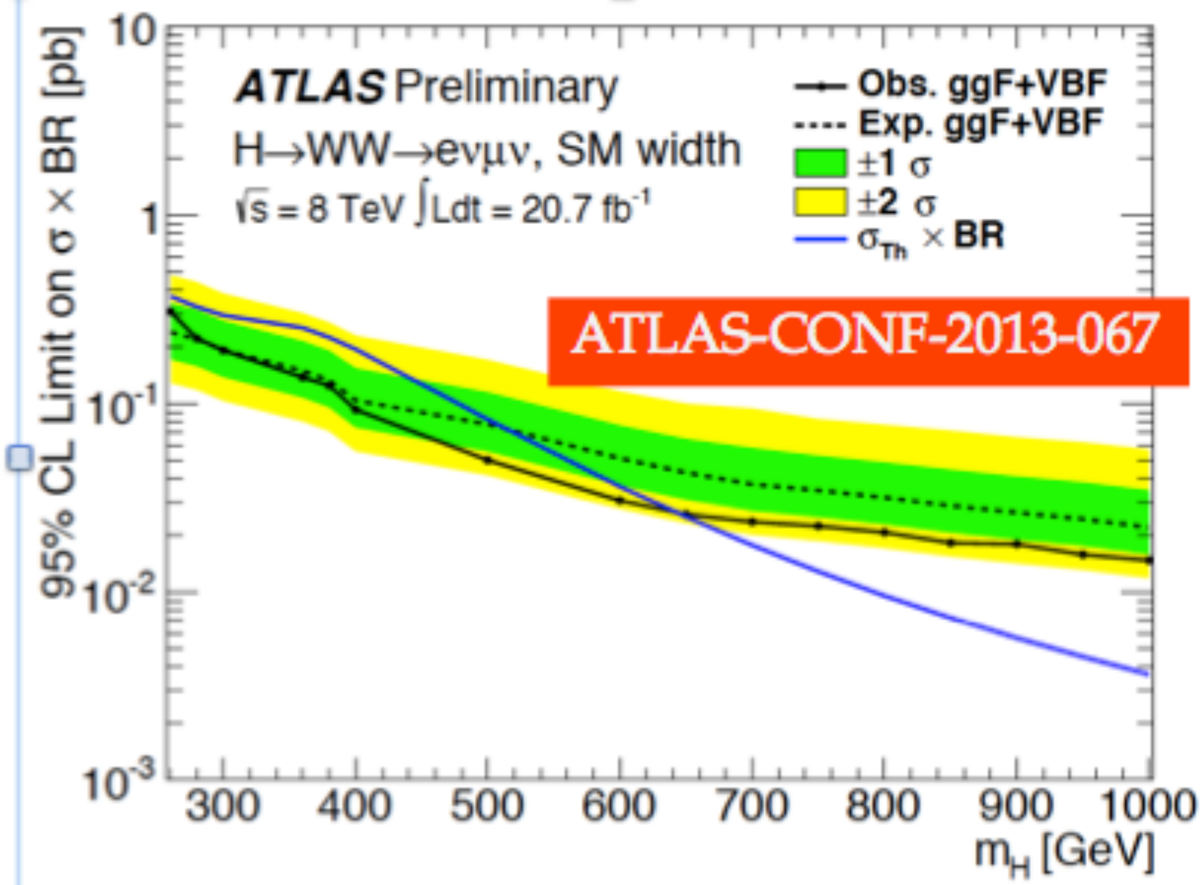
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

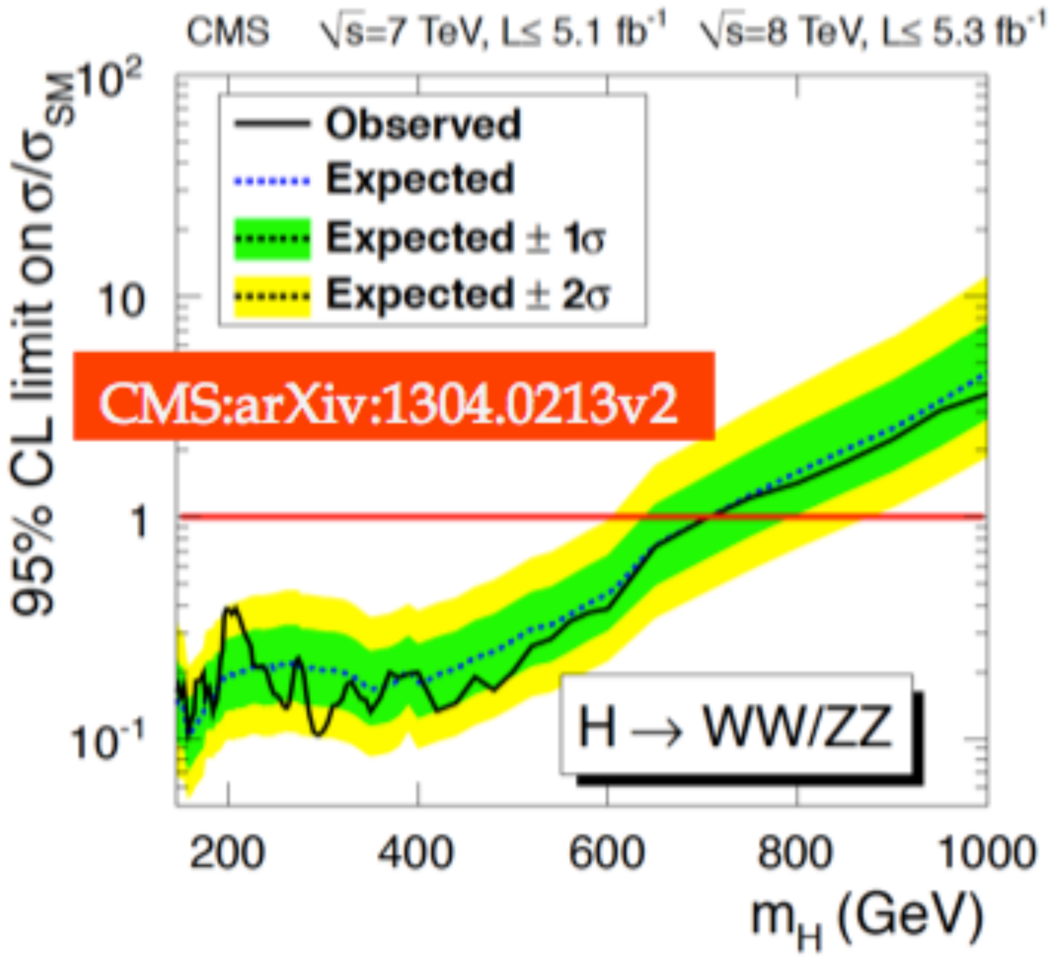
- Only bosonic decays used
- SM J^P quantum numbers strongly preferred wrt other assumptions
- Specific models excluded at more than 95%CL



From SM to BSM. High Mass Higgs

The most popular extension of the SM is SUSY. In this model there are 5 Higgs bosons, the lightest of which has the same behaviour of the unique SM Higgs.



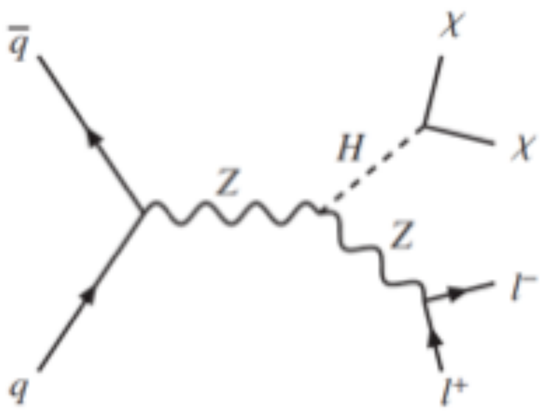


Finding one or more Higgs bosons at high mass would be an indication of something beyond SM. ATLAS and CMS have both, unsuccesfully done so.

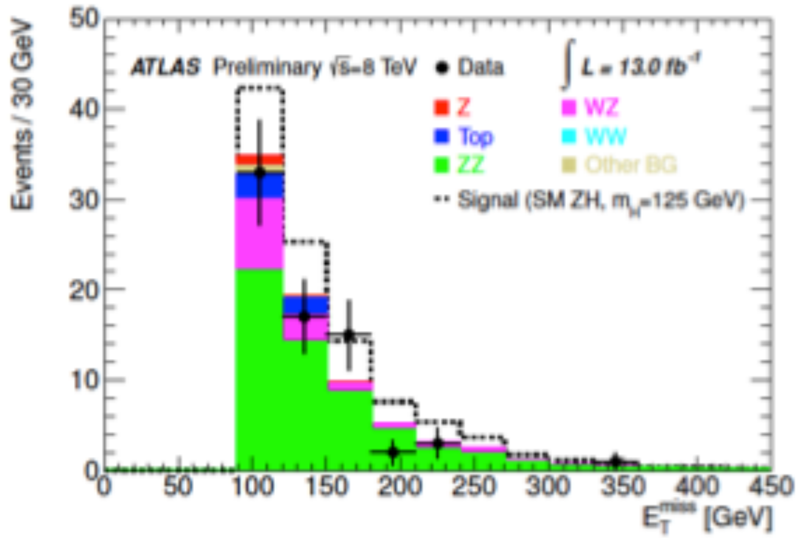
95% CL UL σxBR CMS: $145<M_H<710$, ATLAS $260<M_H<640$

From SM to BSM. Invisible Higgs decays

Another approach to some evidence of New Physics would be looking for invisible decays of the Higgs. There might be a contribution from dark particles as predicted by SUSY. Again search was, so far, unsuccesful.



100% decay to invisible particles



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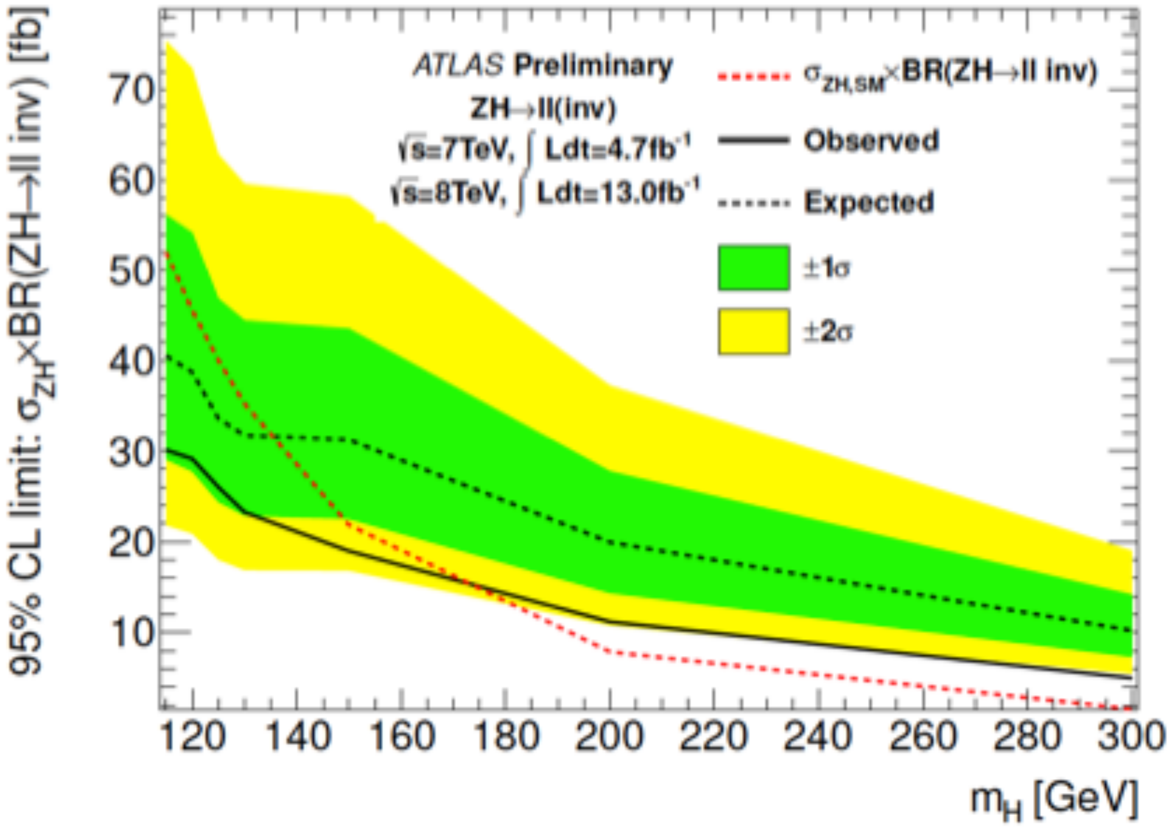

CMS-HIG-12-034