Higgs boson analyses

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Contents

Standard Model Higgs boson analyses

- pre-LHC searches
- LHC discovery analyses
- determination of Higgs boson properties

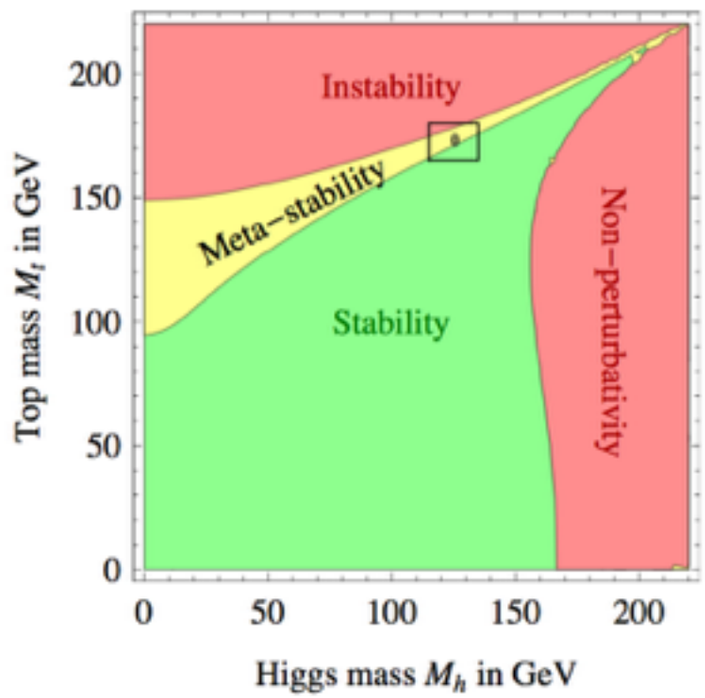
BSM analyses

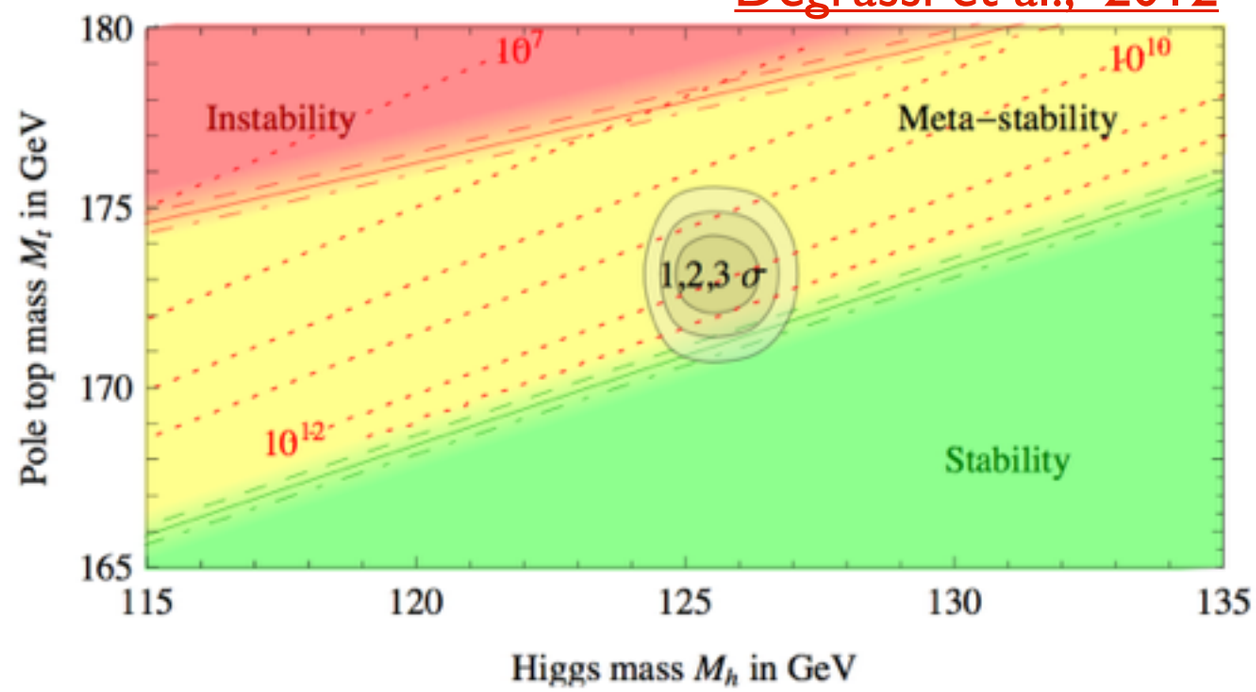
The Standard Model Higgs boson: pre-LHC searches

Pre-history

Forget about the following arguments!

Degrassi et al., 2012





- before the top quark discovery
- two-loop effective Higgs potential calculations not available

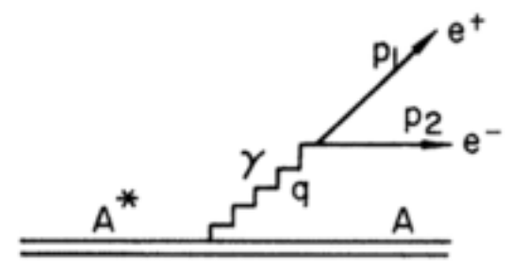
No constraints on m_H at this point

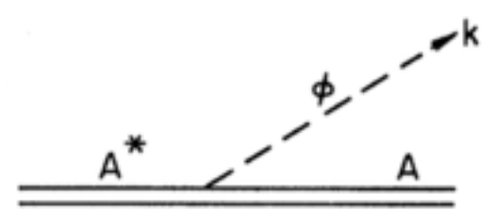
- but see later

Pre-history

A priori any (nonzero) mass is possible! Earliest investigations focused on (very) light Higgs boson. See e.g. early review by Ellis et al., 1976

- no apparent change in measurements of *G* between cm and km length scales: $m_H > 100\ \mu eV$
- no effect on neutron charge form factor and angular distributions in e^-n scattering: $m_H > 13$ MeV
- no $0^+ \rightarrow 0^+$ transitions observed from excited (20 MeV) ^4He: excludes 2 MeV $< m_H <$ 18 MeV





Late 80's:

- no contributions to $B \rightarrow K\ell^+\ell^-$ (and $K \rightarrow \pi\ell^+\ell^-$): $m_H > 2\ m_\tau$ (if $m_t > 40$ GeV!)
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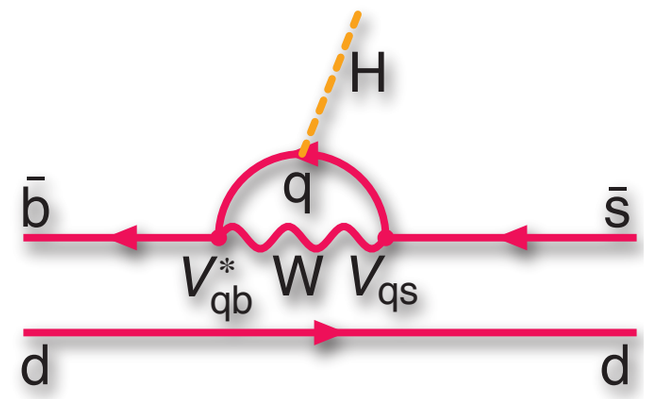

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$$\frac{\Gamma(B \to H^0 X)}{\Gamma(B \to e\nu X)} = \frac{|V_{tb}V_{ts}^*|^2}{|V_{cb}|^2}\frac{27\sqrt{2}}{64\pi^2}G_F m_b^2\left[\frac{m_t}{m_b}\right]^4 \times \left[1-\frac{M_H^2}{m_b^2}\right]^2 \frac{1}{r(m_c/m_b)},$$

Haber, Schwartz, Snyder, 1987; Chivukula, Manohar, 1988

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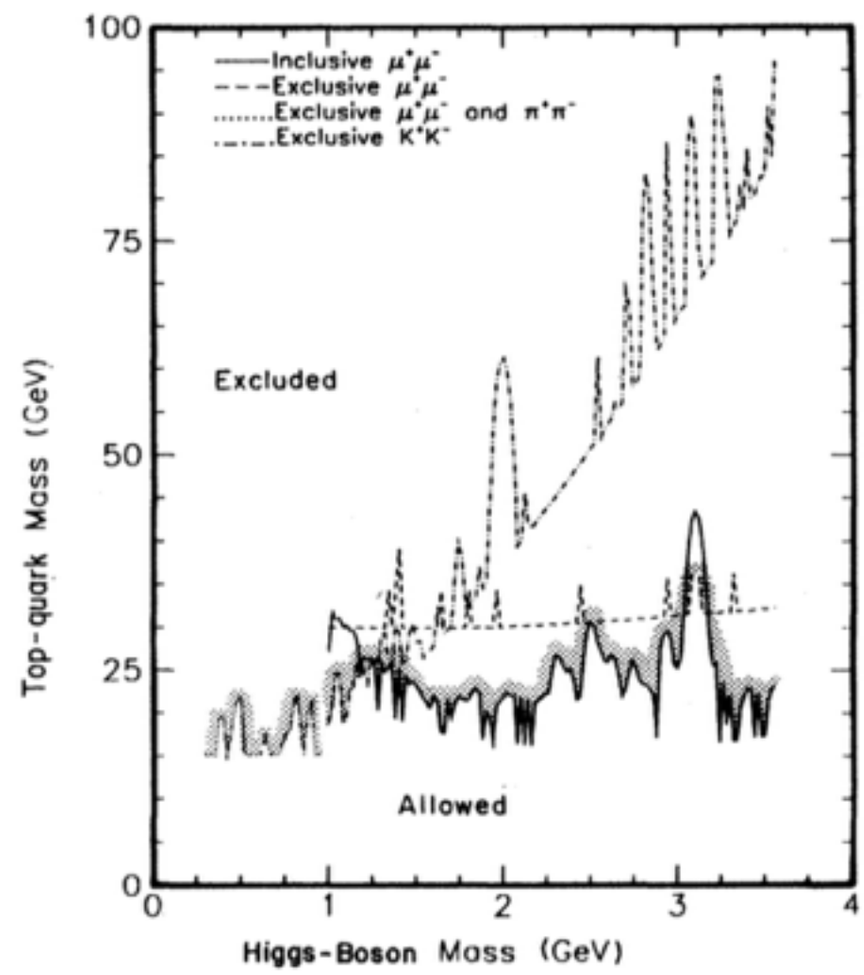
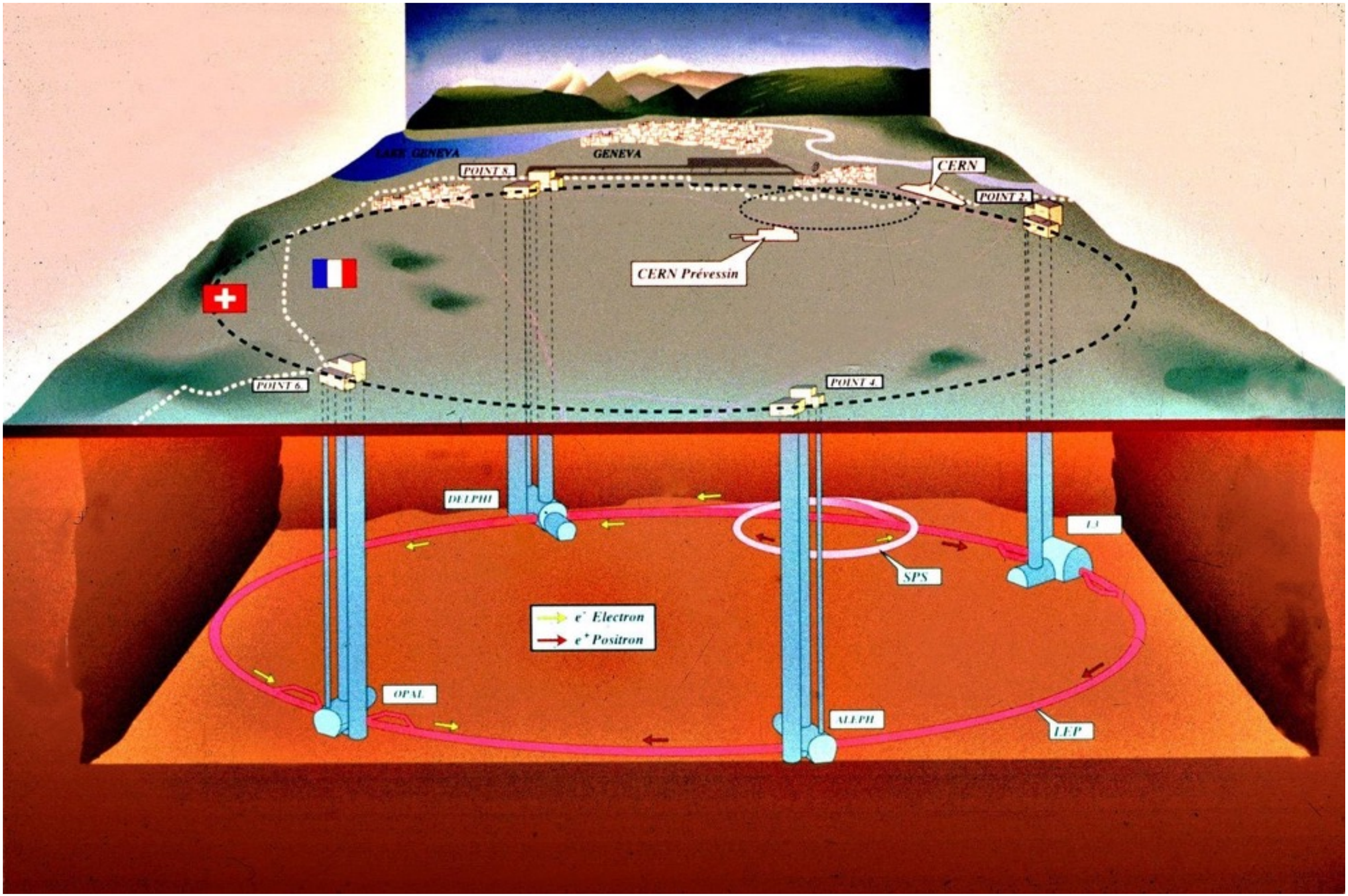


LEP


LAKE GENEVA
GENEVA
POINT 8
CERN
POINT 2
CERN Prévessin
POINT 6
POINT 4
DELPHI
L3
SPS
e⁻ Electron
e⁺ Positron
OPAL
ALEPH
LEP

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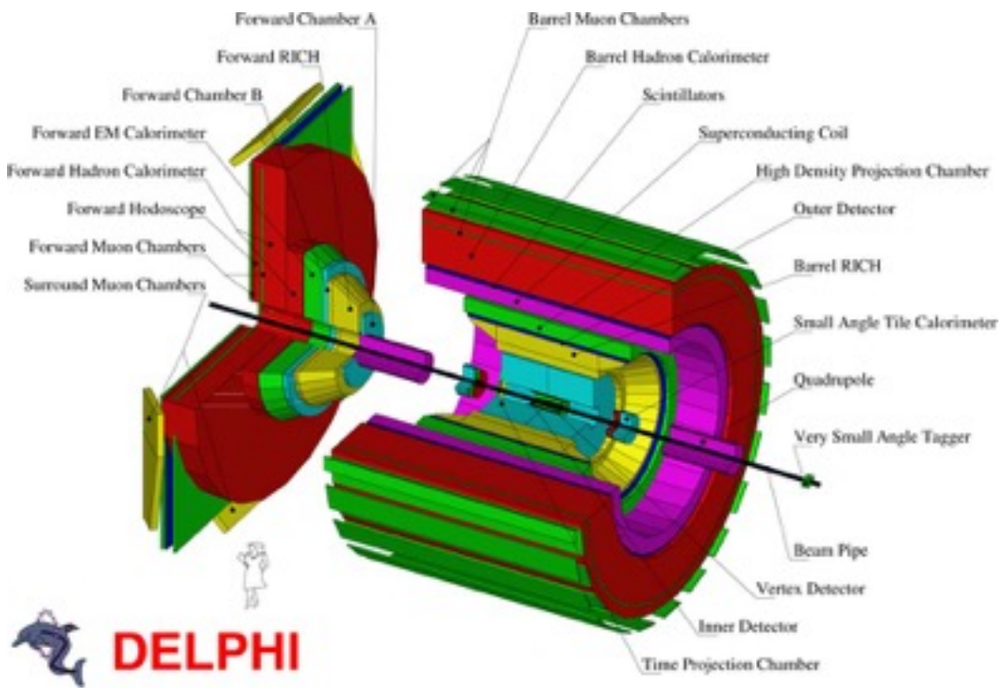
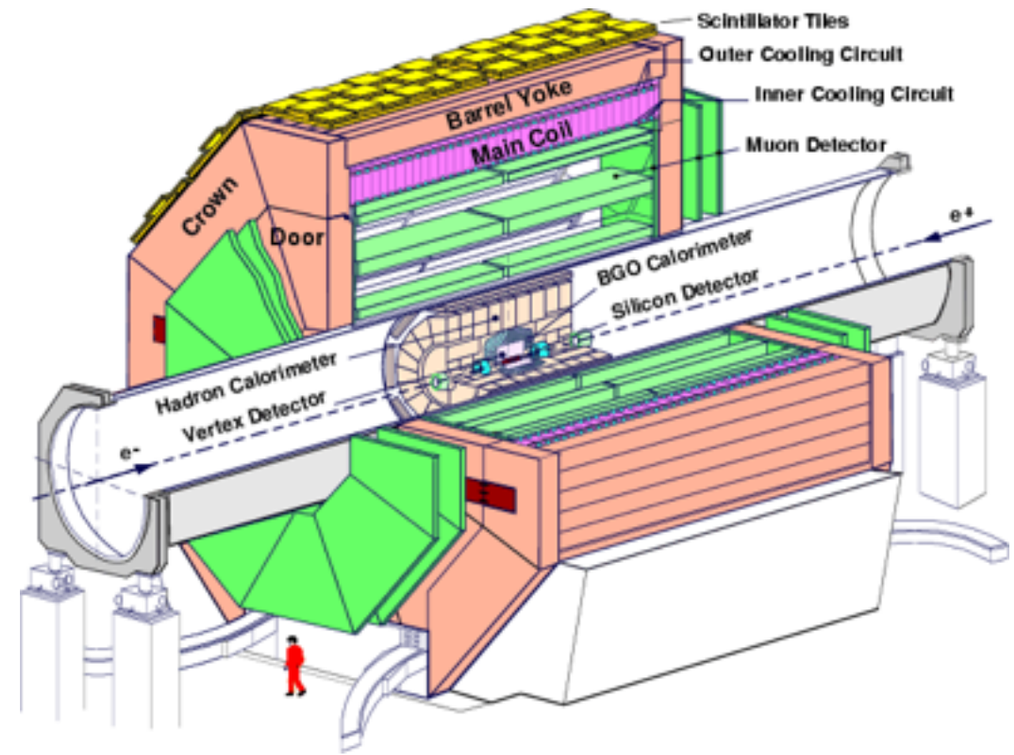
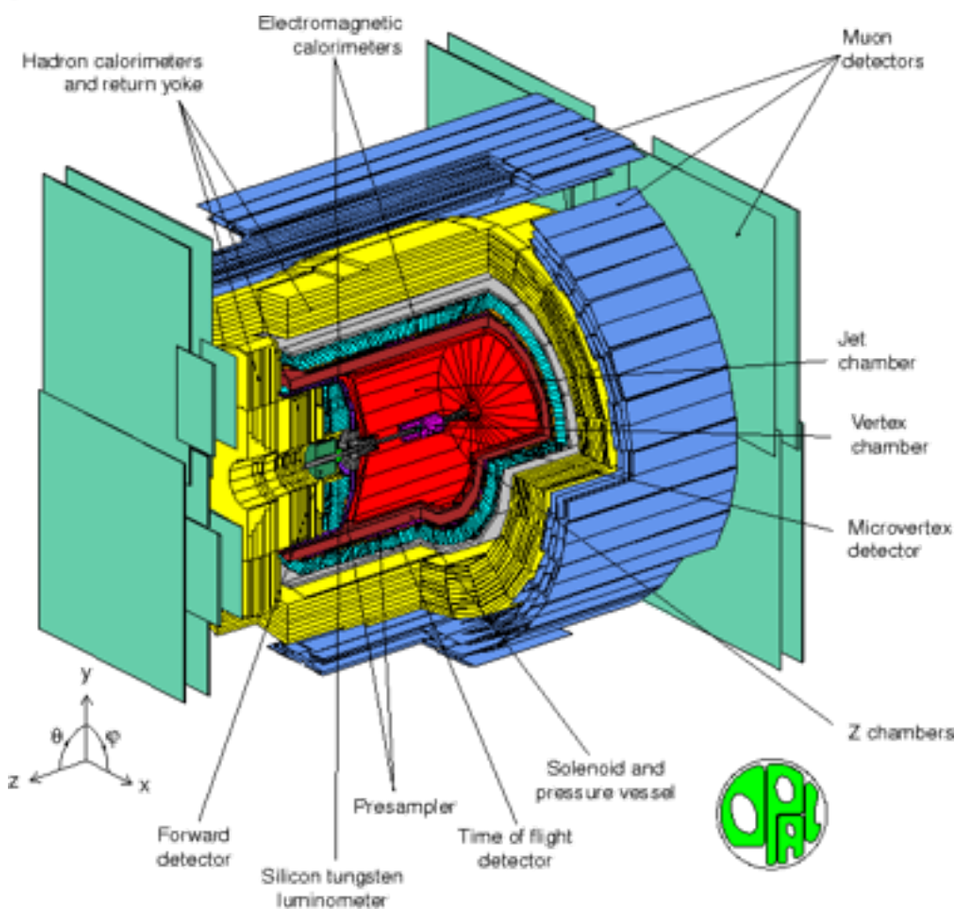






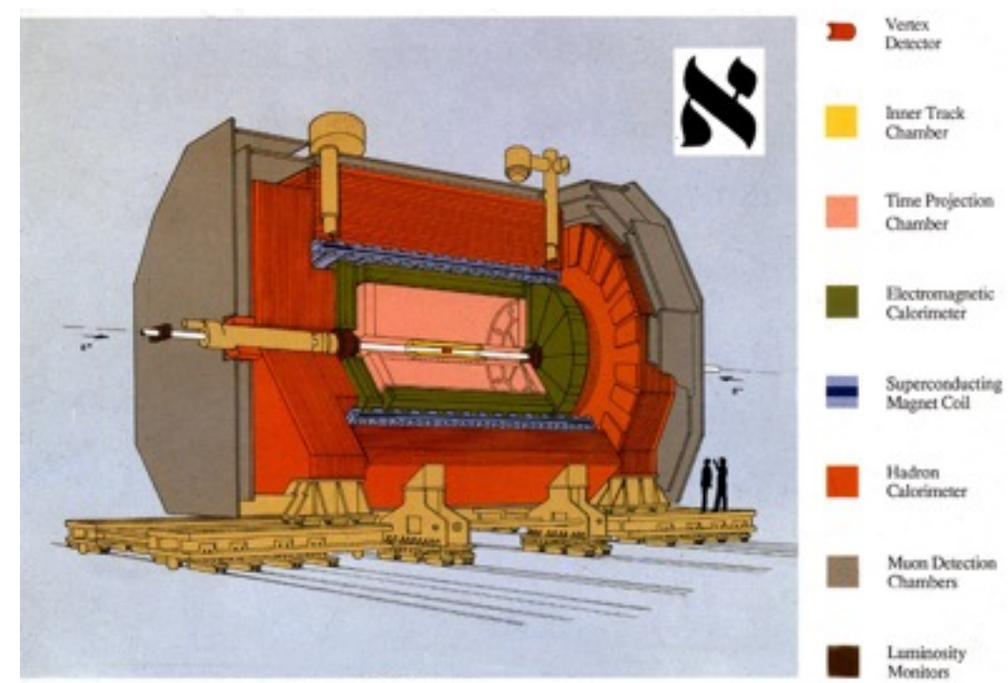
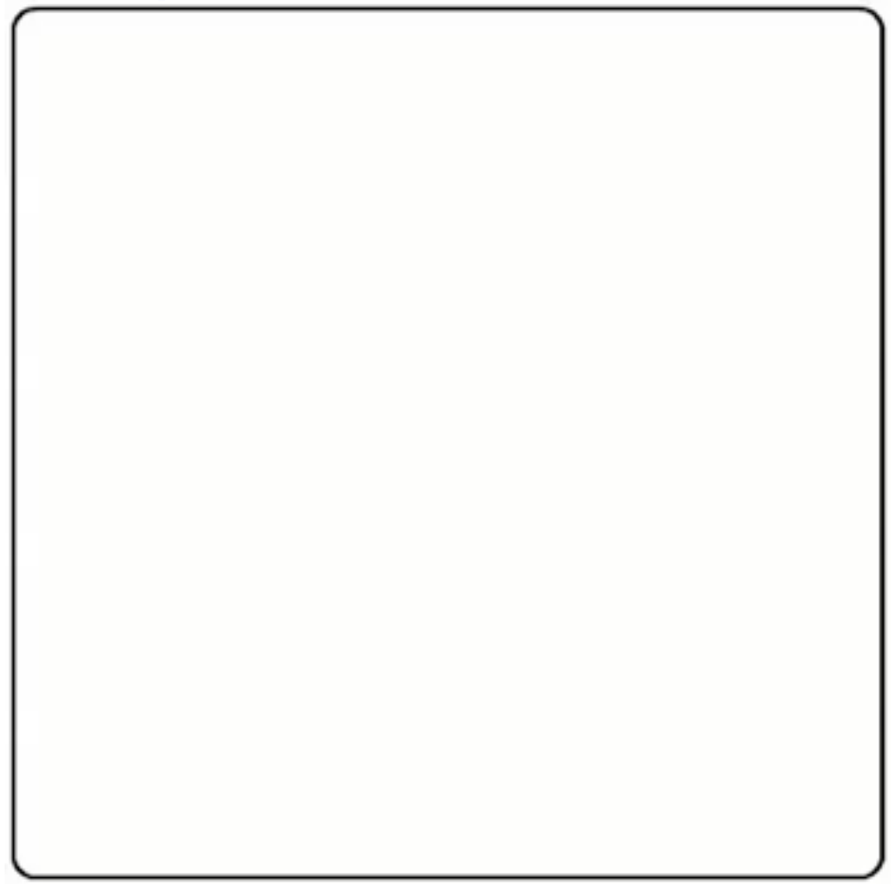


Fig. 1 - The ALEPH Detector

Detection techniques

Always start from "stable" particles!

ATLAS animation,
but techniques are
general for high-energy
collider experiments



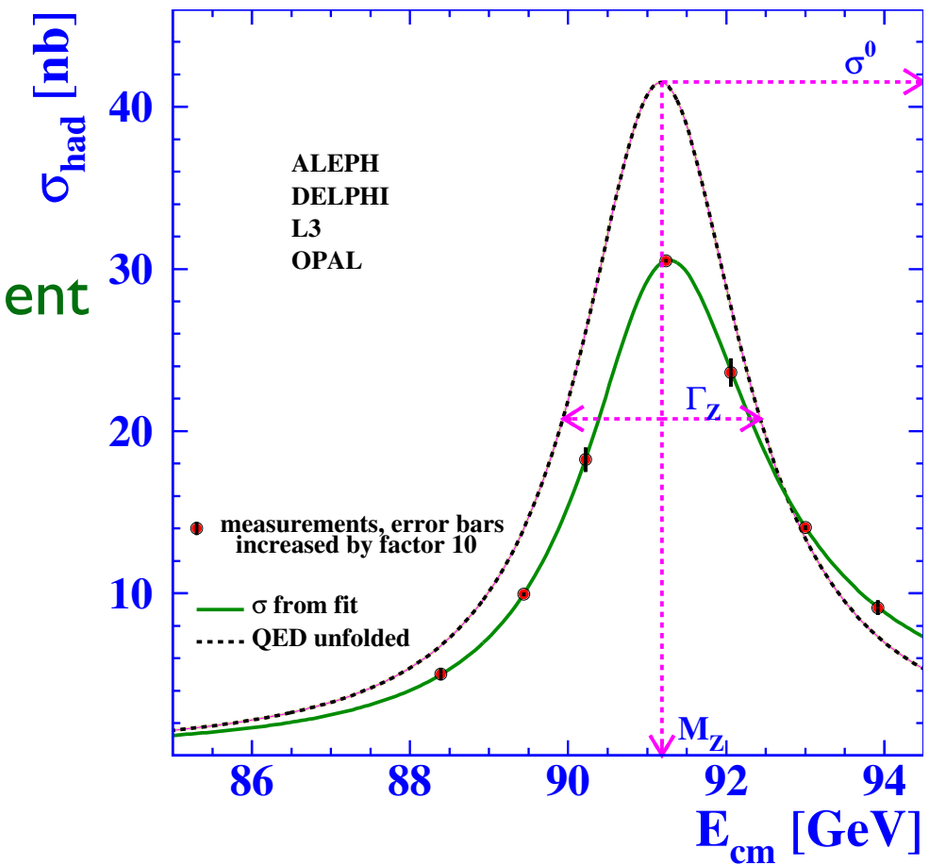
Beyond this:

- jets: collimated streams of hadrons, representative of high-energy q / g
  - LHC: anti-k_t algorithm (ATLAS: R=0.4)
- b-quark jets: identified from τ(b hadrons) ~ 1.5 ps; decays reconstructed using tracking information (ATLAS: for ε_b=70%: ε_c=20%, ε_l=0.2%)
- τ leptons: τ_τ ~ 300 fs; hadronic decays → narrow jets
- neutrinos: seen as apparent lack of momentum balance

LEP

LEP 1 (1989—1994): Z-boson "factory"

- ~ 160 pb-1, collected mostly at $\sqrt{s}$ = mZ
  - σ(e+e- → Z) ~ 30 nb: 5M Z decays / experiment

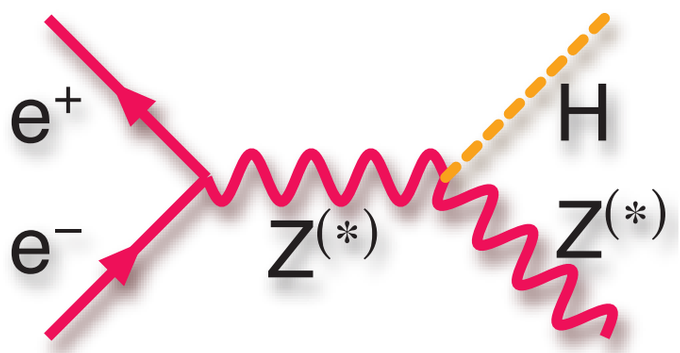


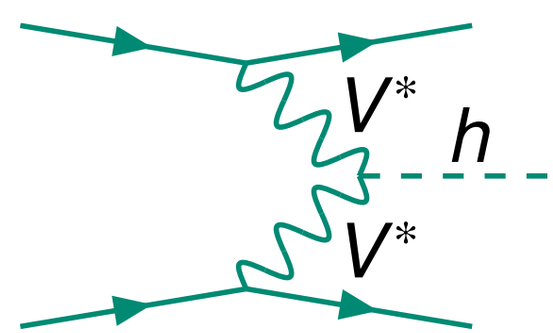
LEP 2 (1995—2000): higher ECM

- $\sqrt{s}$ up to 209 GeV, ~ 0.6 fb-1
- W^+W^-, ZZ production but also searches for new heavy particles

Higgs boson production mainly through Higgs-strahlung process

- exploited both at LEP 1 (decays to off-shell Z) and LEP 2 (decays to on-shell Z)
- vector boson fusion always involves off-shell W/Z bosons





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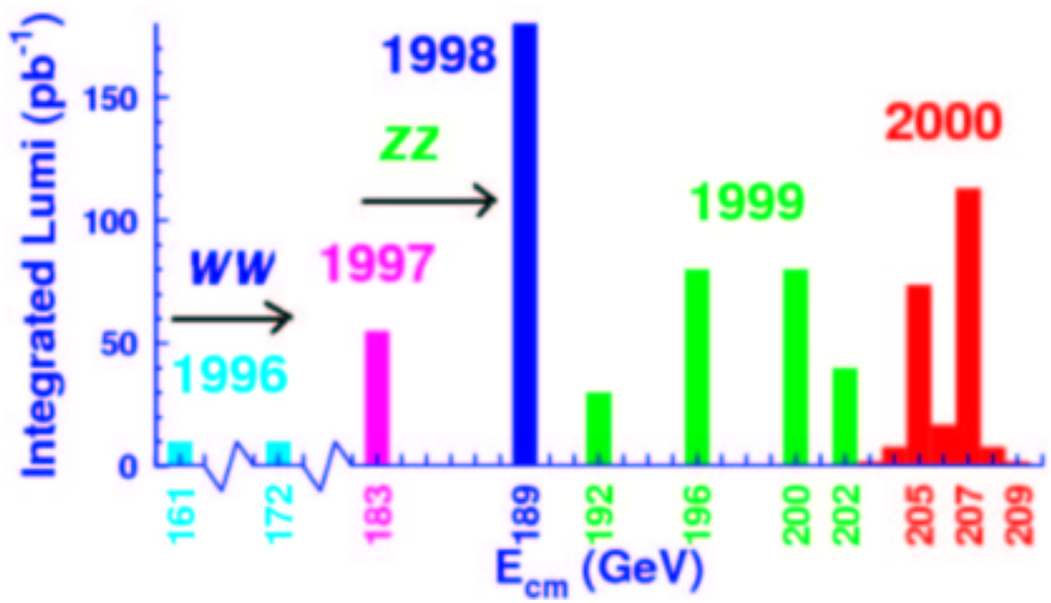

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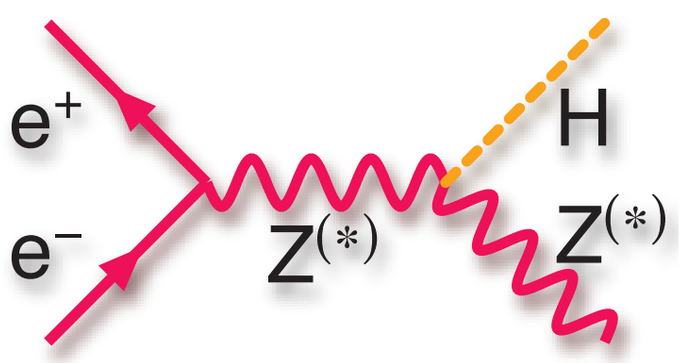
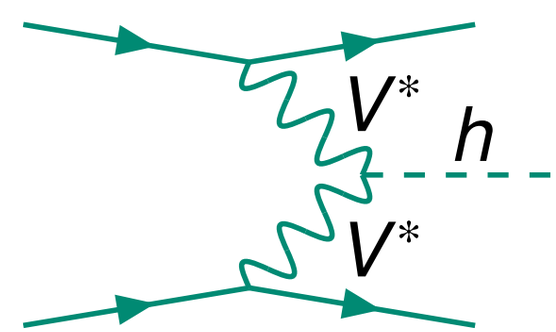
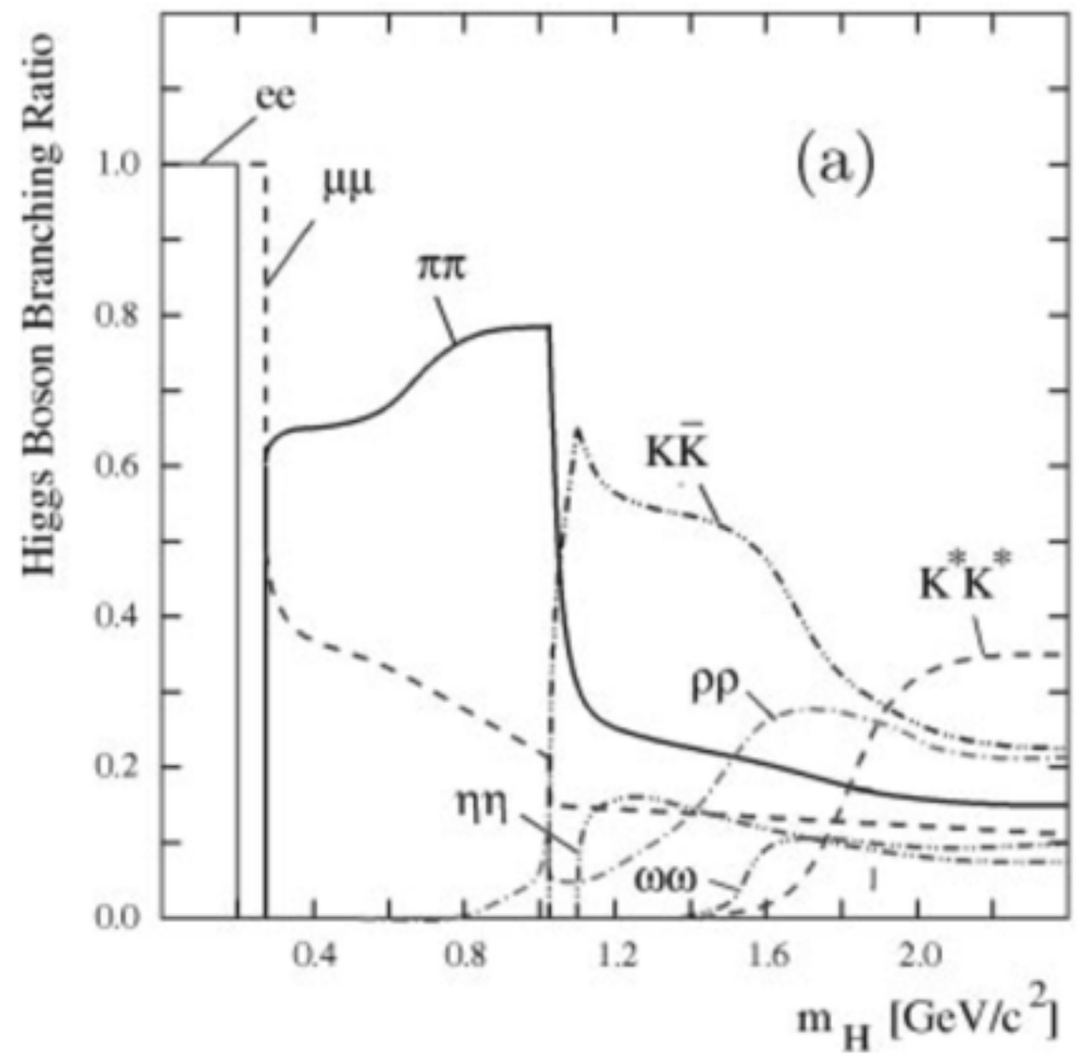


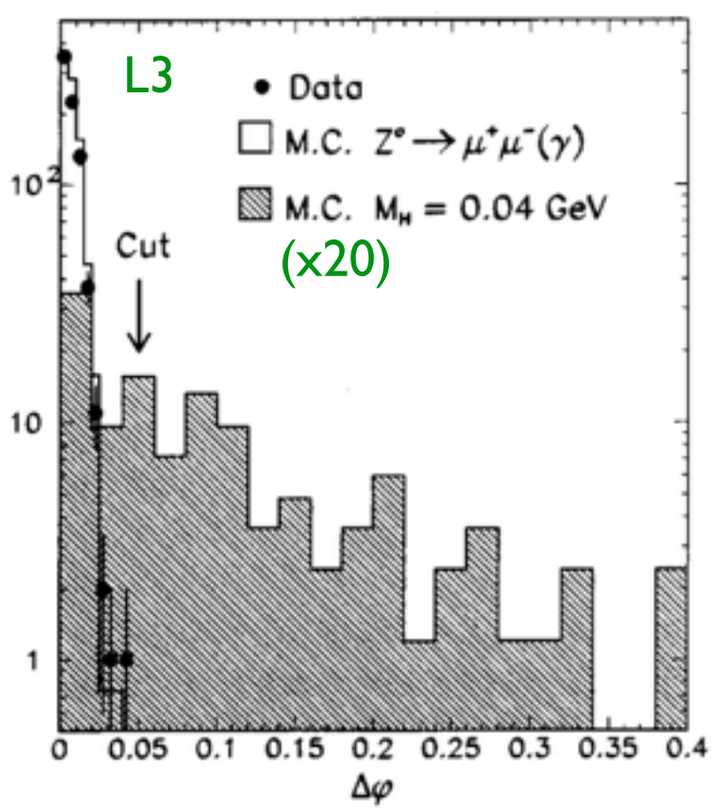


LEP I (I)

Searches covering the low / intermediate m_H range. Search topologies strongly dependent on m_H

- $m_H < 2\ m_\mu$: decays to e^+e^- only
  - search explicitly for a displaced e^+e^- pair: limited to $m_H > 20$ MeV (tracker acceptance)
  - search for acoplanar leptons ($\Delta\varphi<\pi$) from $Z^* \rightarrow \ell^+\ell^-$ in otherwise empty events (decays behind calorimeter)





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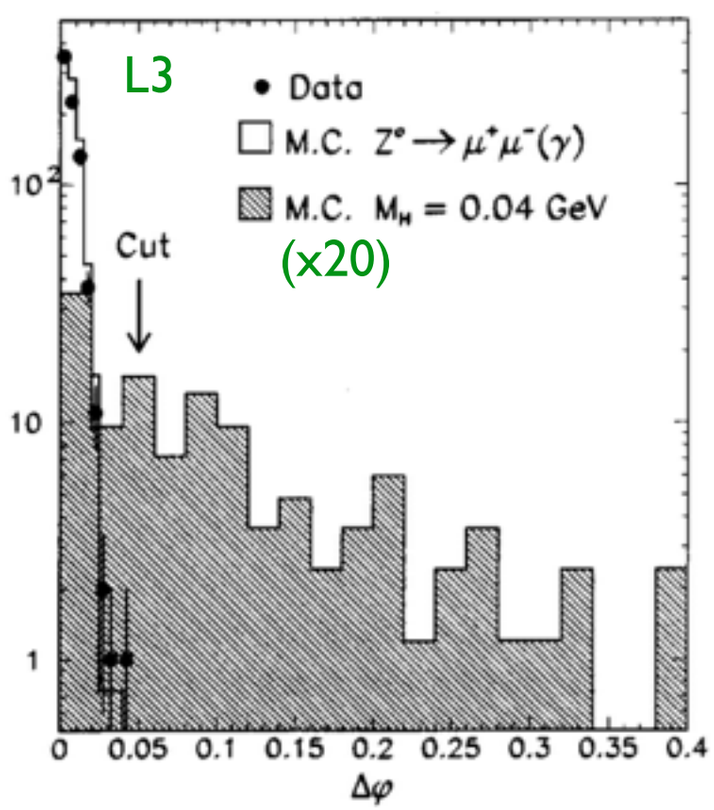
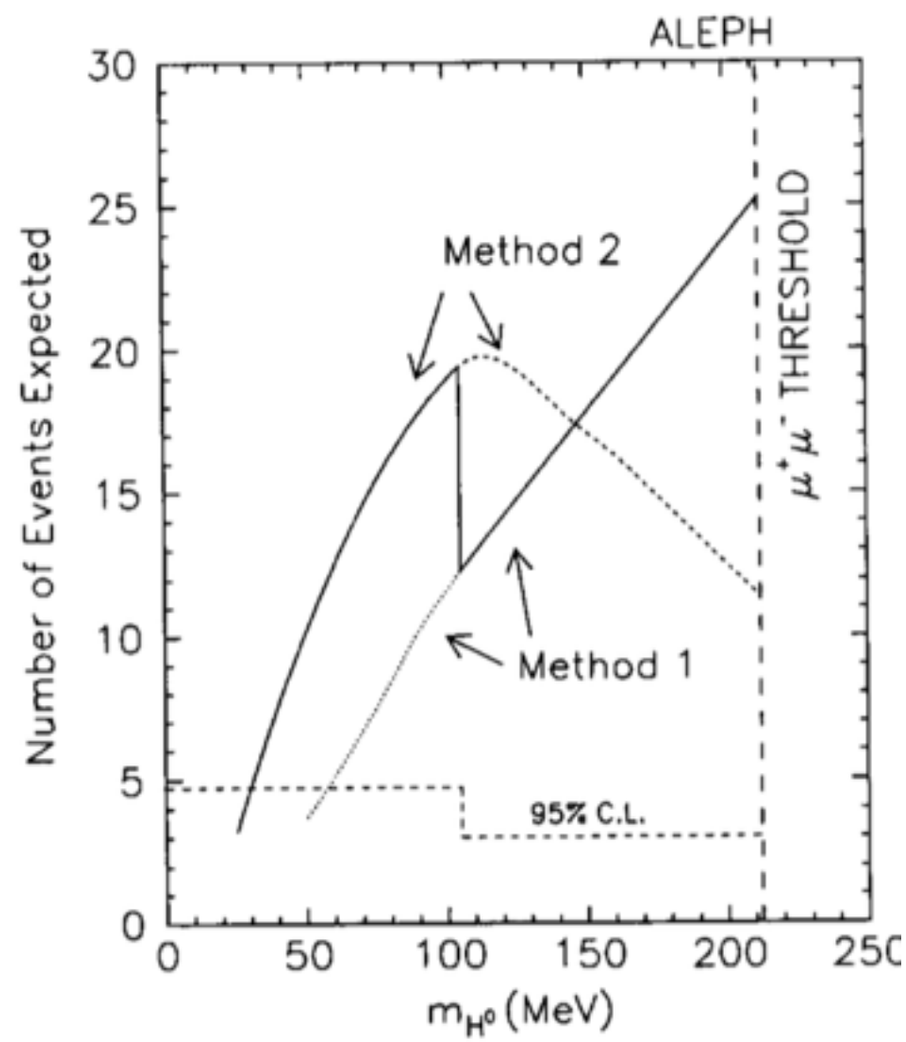




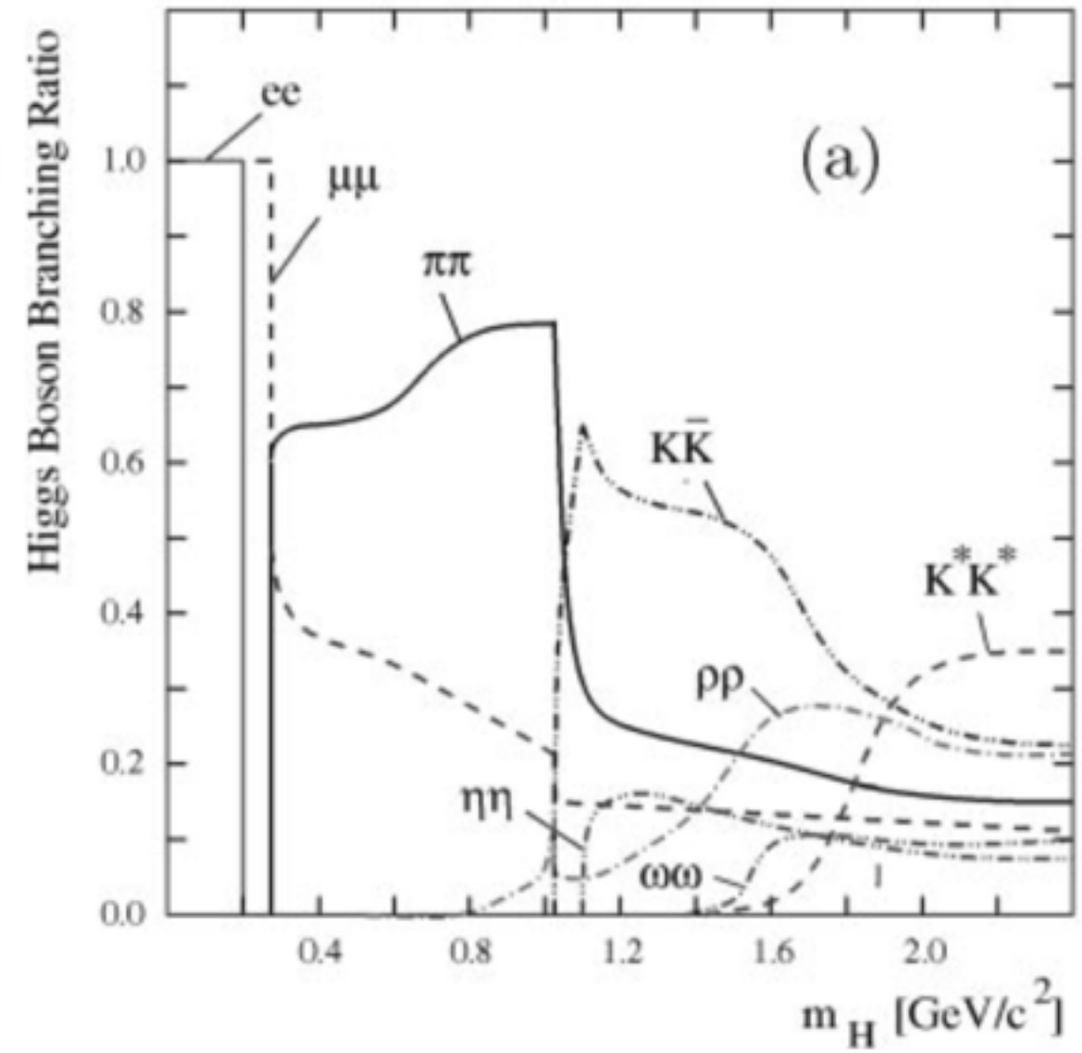
Nearly background-free search results

LEP I (2)

Search strategy for $2m_\mu < m_H < 30$ GeV:

- $H \to \mu^+\mu^-$ ($m_H < 2$ GeV); also for $Z^* \to \bar{q}q$
- mono- or dijet topology: Higgs recoiling against acoplanar lepton pair or missing momentum
  - $Z^* \to \ell^+\ell^-$ and $Z^* \to \bar{\nu}\nu$, respectively
  - inclusive selection intended to reduce sensitivity to QCD uncertainties
  - some bg from radiative events (isolated γ, low m_H) and other SM processes (higher m_H)

$m_H < 30$ GeV excluded by end 1990



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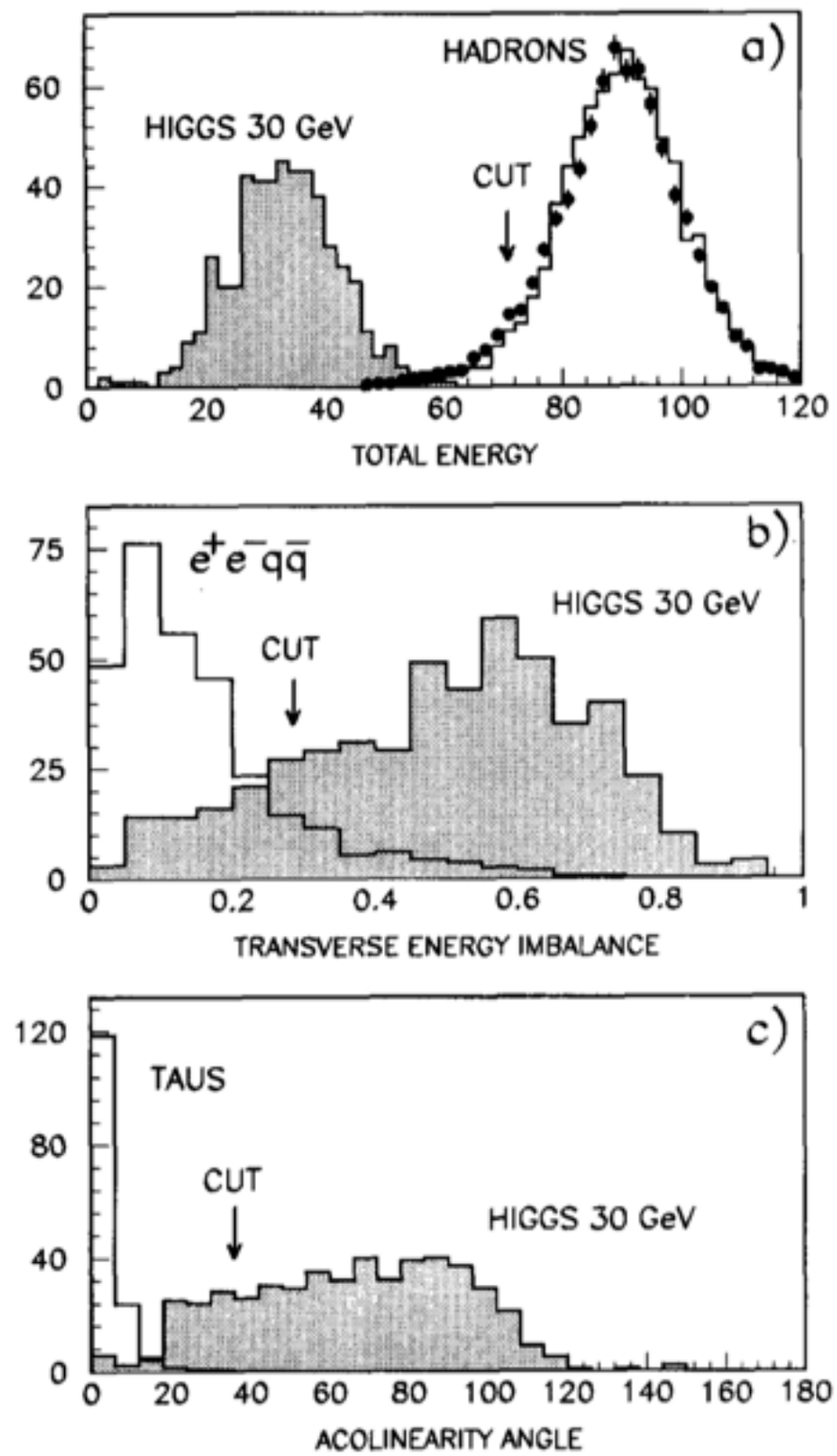
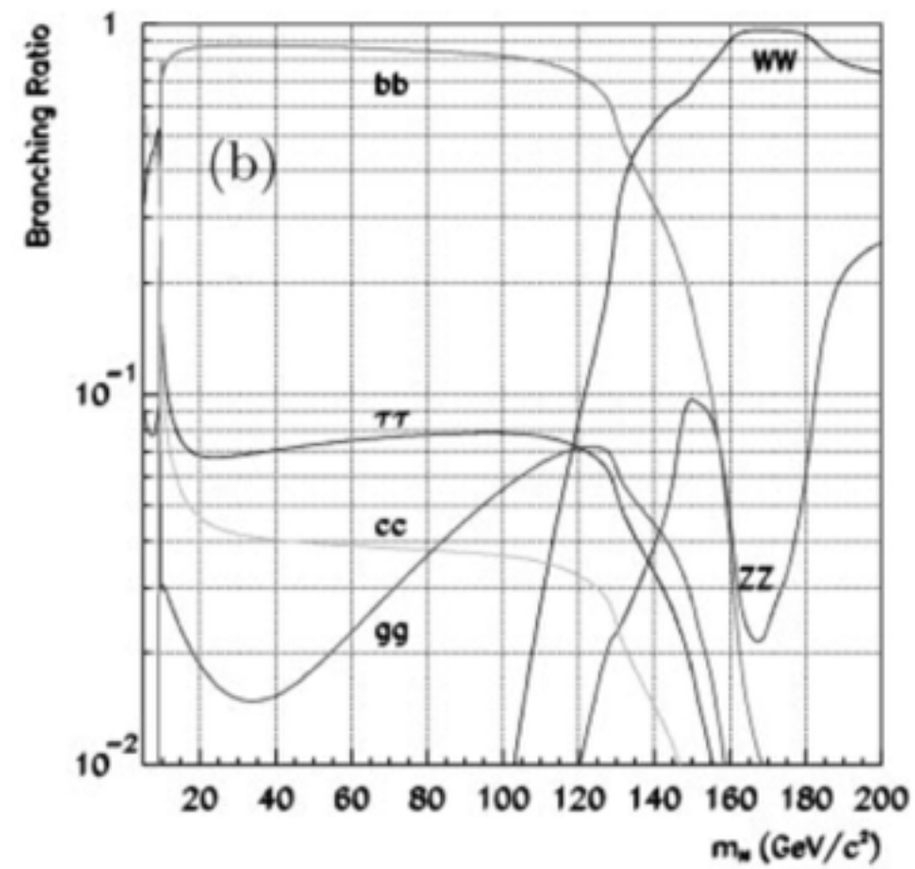
L3, $\bar{\nu}\nu H$ search



LEP I (3)

Situation for m_H > 30 GeV more complicated due to falling cross section

- $H \to \bar{b}b$ dominant for m_H > 15 GeV
- again restrict to $Z \to e^+e^-, \mu^+\mu^-, \bar{\nu}\nu$
  - for m_H = 65 GeV, expect 10 events combined for four experiments
- extensive cuts (and some use of multivariate analysis) to reject especially $e^+e^- \to \ell^+\ell^- \bar{q}q$
  - event shape variables, lepton isolation, signal versus background kinematics
  - NB: even $m(\bar{\nu}\nu)$ can be estimated
- very effective: still managed to find efficient selection criteria but no selected events in data!



m_H (GeV/c^2)	Channel							
	$H\nu\bar{\nu}$		He^+e^-		$H\mu^+\mu^-$		other	total
	eff. (%)	N_{exp}	eff. (%)	N_{exp}	eff. (%)	N_{exp}	N_{exp}	N_{exp}
50	55	7.68	59	1 39	69	1.63	0.41	11.11
55	51	3.74	55	0 69	66	0.84	0.19	5.46
60	43	1.54	49	0.30	61	0.37	0.07	2.28
65	34	0.53	44	0.12	56	0.15	0.02	0.82

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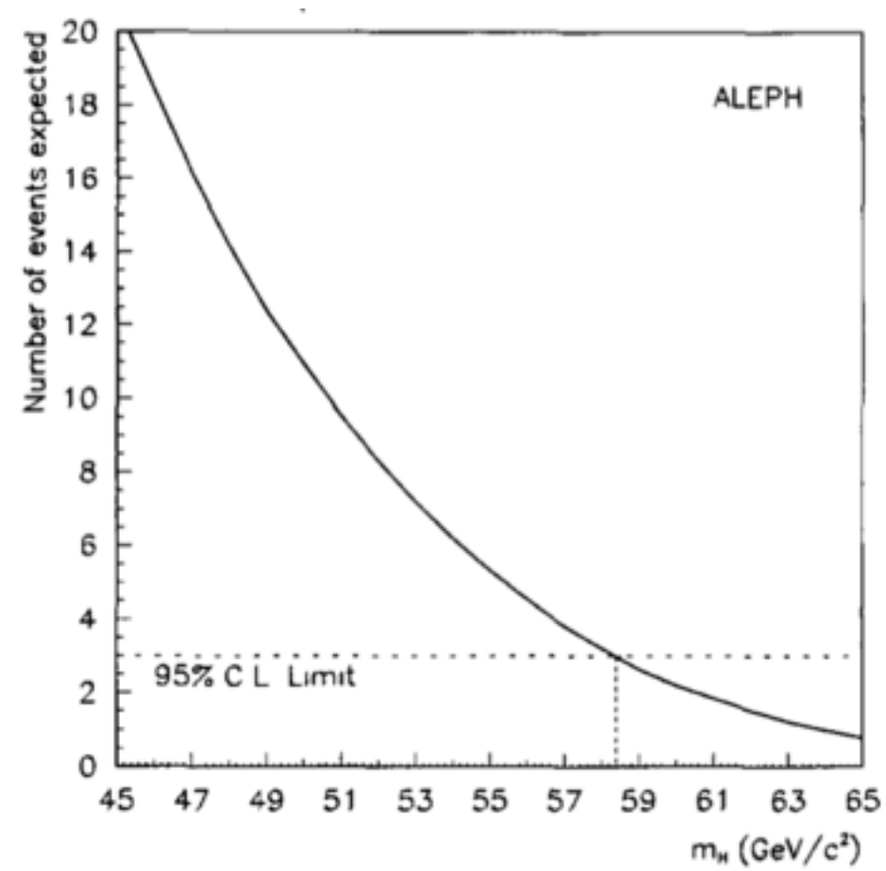
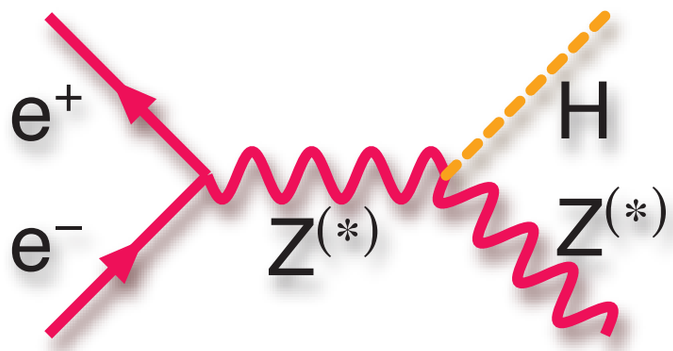


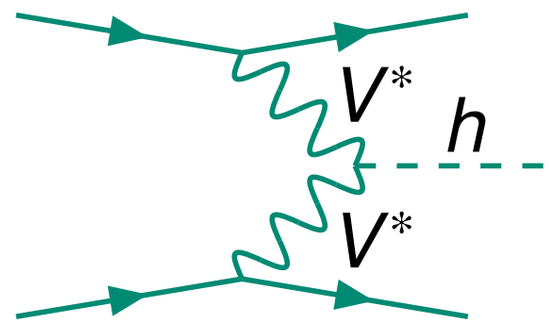
Combination of four experiments' data:
m_H > 65.6 GeV

LEP 2 (I)

Exploit $Z^* \rightarrow ZH$ decay

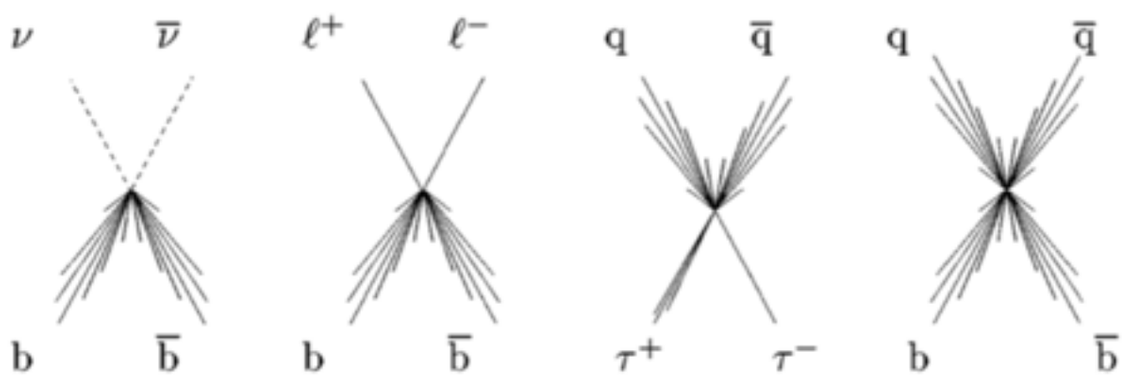
- account for interference with VBF in Hee and $H\bar{\nu}\nu$ final states (appreciable effect only at the Higgs-strahlung kinematic limit)

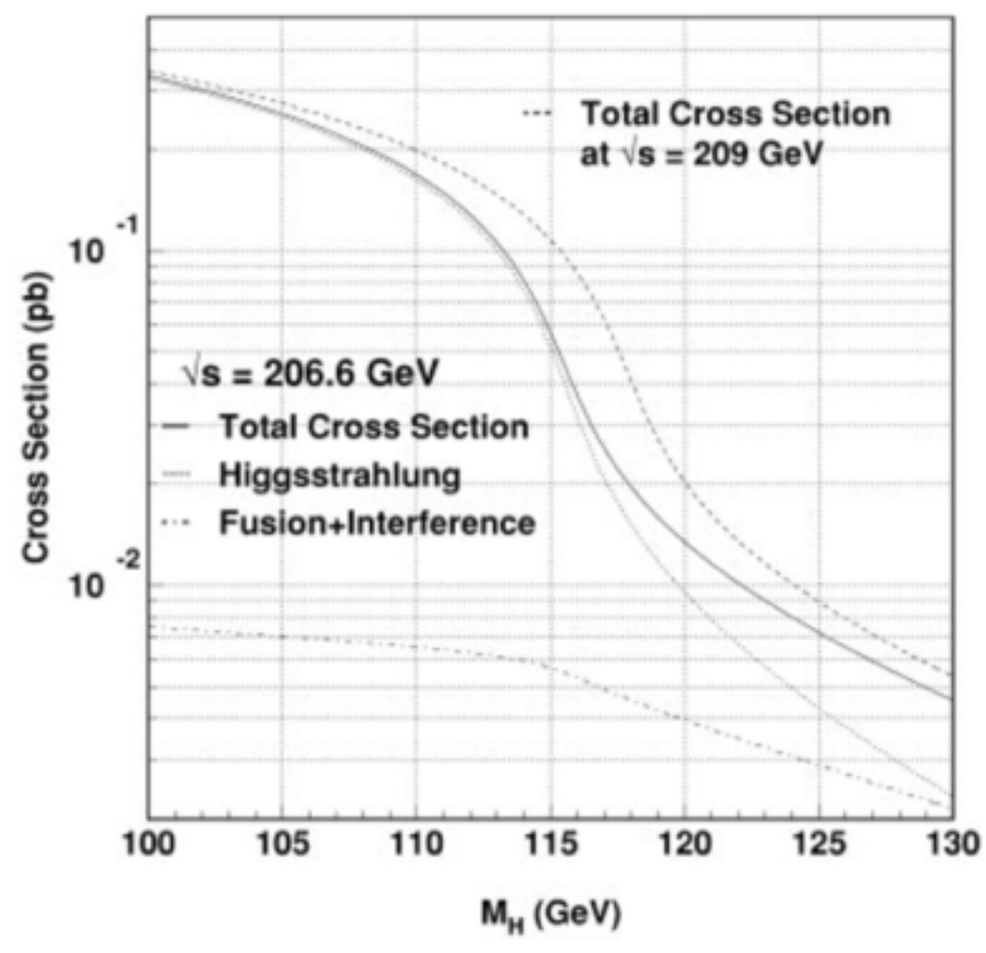




Higgs and Z decay modes as for LEP I, but exploit wider range of decay modes

- $HZ \rightarrow \bar{b}b\bar{\nu}\nu, \bar{b}b\ell^+\ell^-, \tau^+\tau^-\bar{q}q, \bar{b}b\bar{q}q$





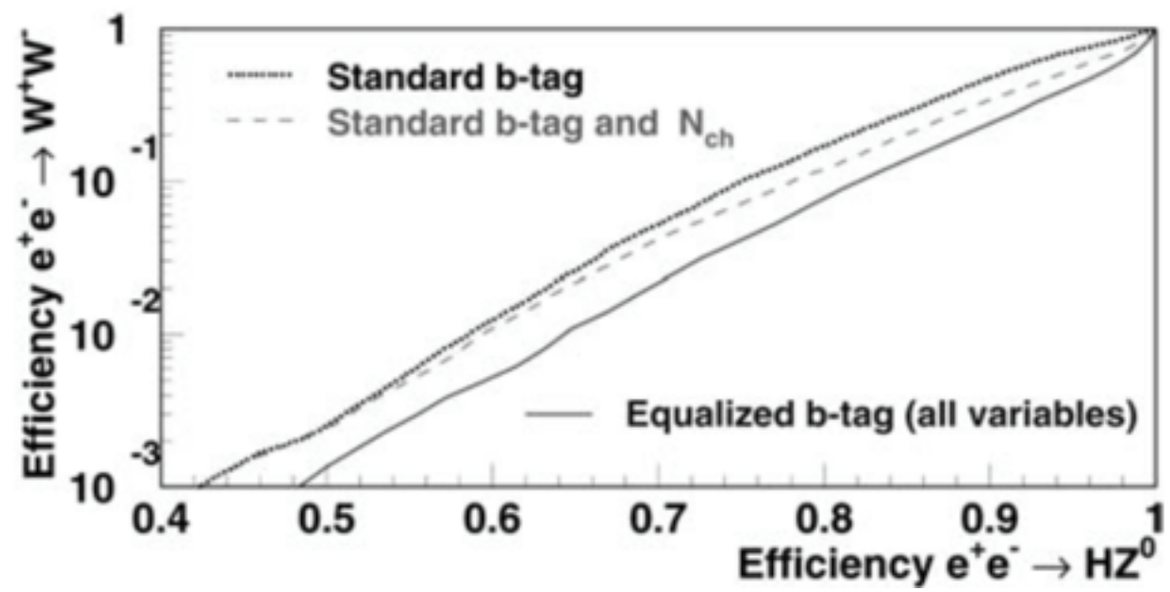
LEP 2 (2)

Exploit dominant $H \to \bar{b}b$ decay using b-tagging

- wider use of silicon tracking detectors; pixel detectors

DELPHI silicon tracker (detail)

resulting performance in simulated signal events

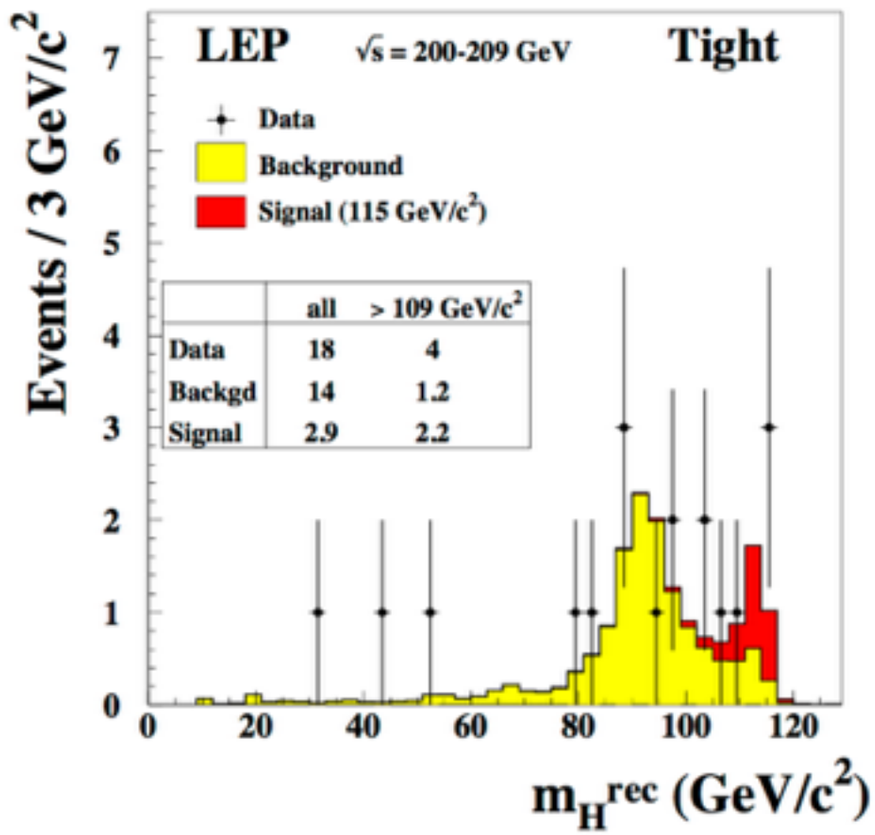


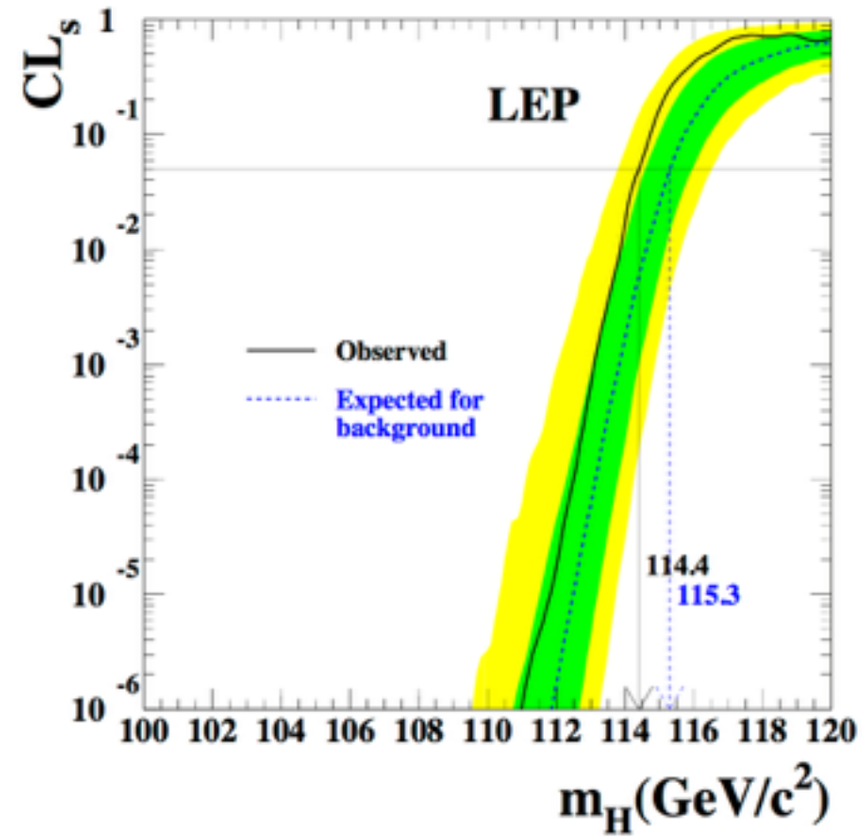
Searches no longer background-free

- more sophisticated statistical tools required to combine results from channels / experiments / CM energies:
  - likelihood ratio $\lambda \equiv \frac{L(\{n\}|s+b)}{L(\{n\},b)} = \prod_i \frac{P(n_i|s_i+b_i)}{P(n_i|b_i)}$
  - CL_s: modify standard exclusion limit accounting for possibility that no signal sensitivity is expected

LEP 2 (3)

Final LEP results obtained by combining results from four experiments





LEP ended (in 2000) with a slight excess at highest candidate mass

- result: mass range m_H < 114.4 GeV excluded

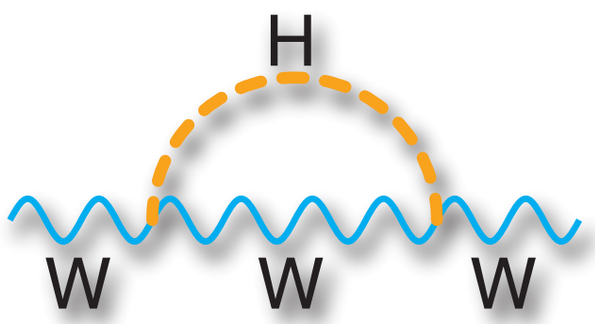
Indirect (electroweak) information

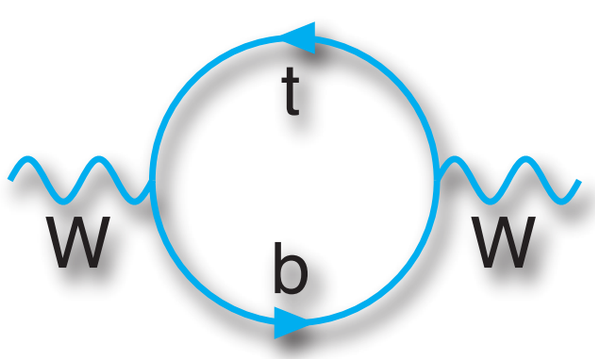
Many precision tests of EW structure carried out (LEP, SLD, Tevatron)

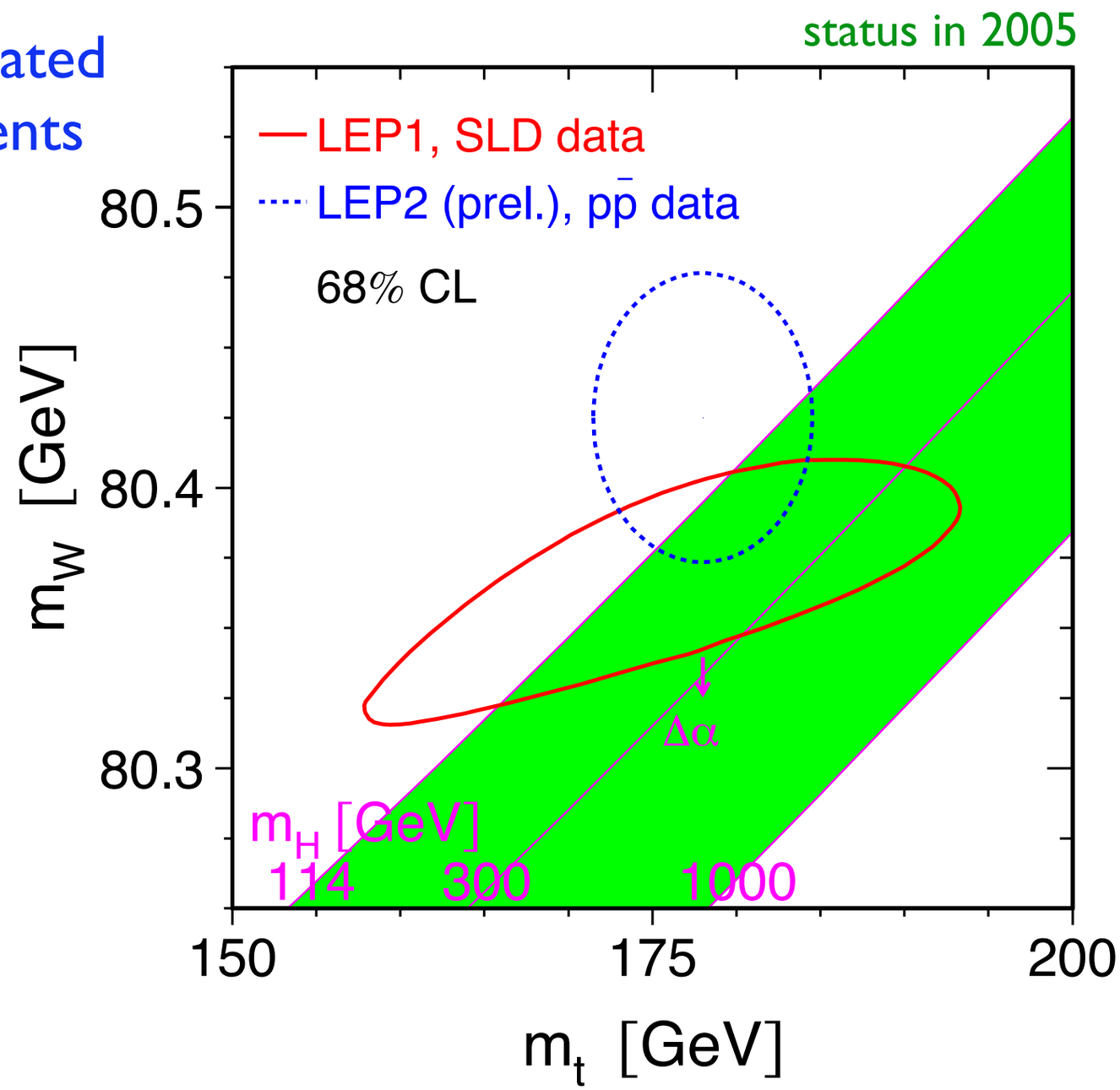
- good internal consistency fitting to pseudo-observables (m_Z, m_H, $\Delta\alpha^{(5,had)}(m_Z^2)$, $\alpha_s(m_Z^2)$, m_t, m_b, m_c)

Constraints on M_H dominated by m_Z, m_W, m_t measurements

➠ prefer low m_H



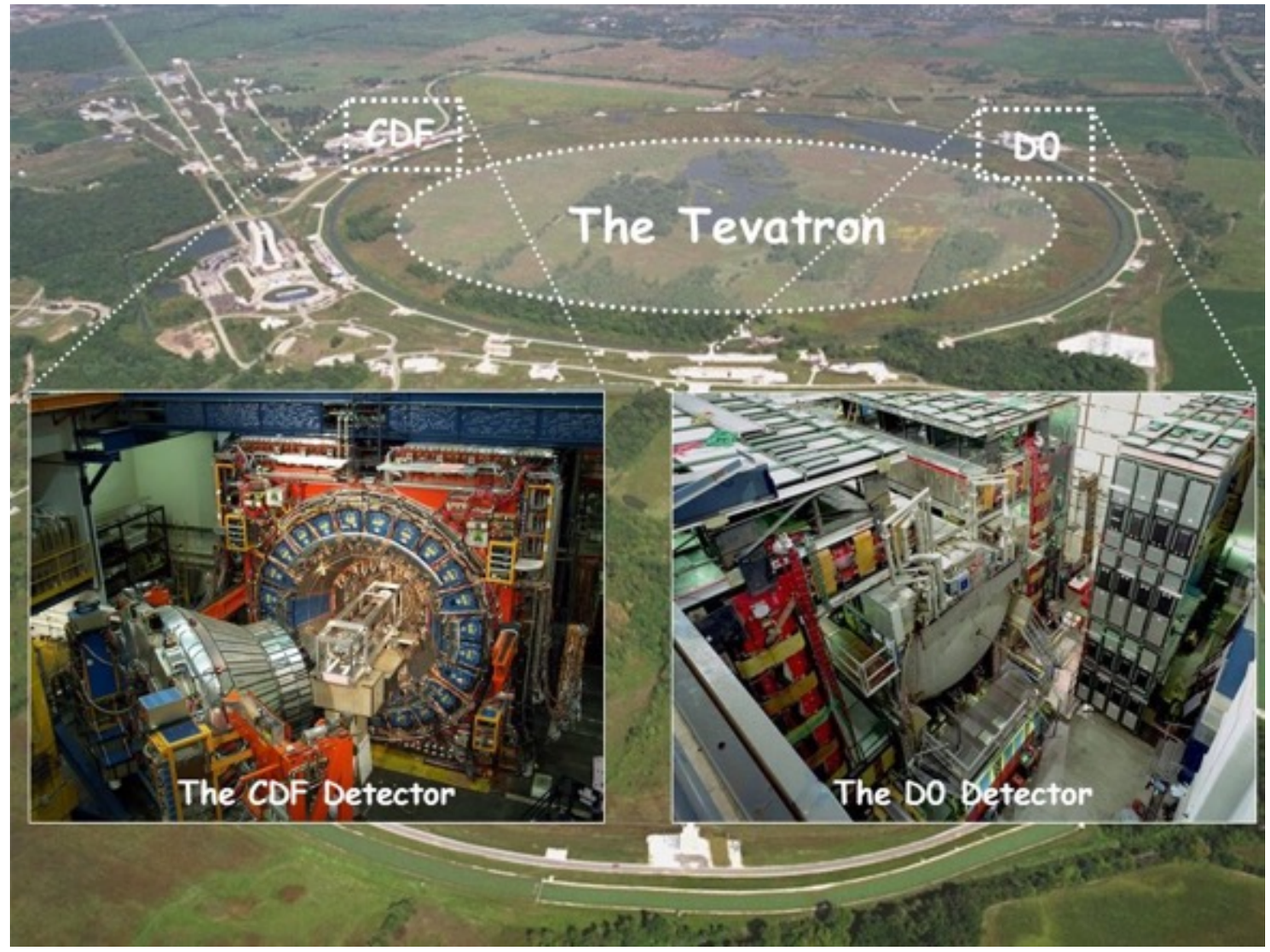




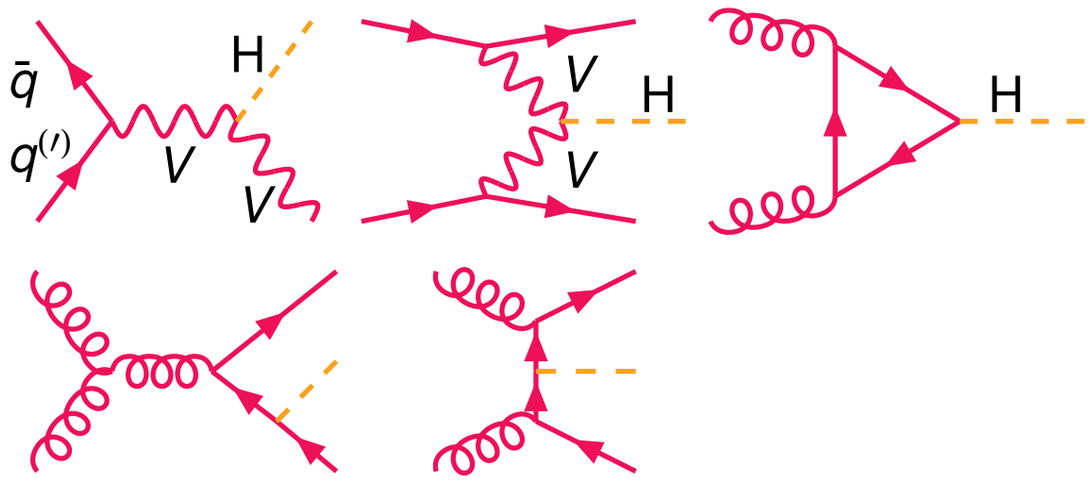
Tevatron (1)

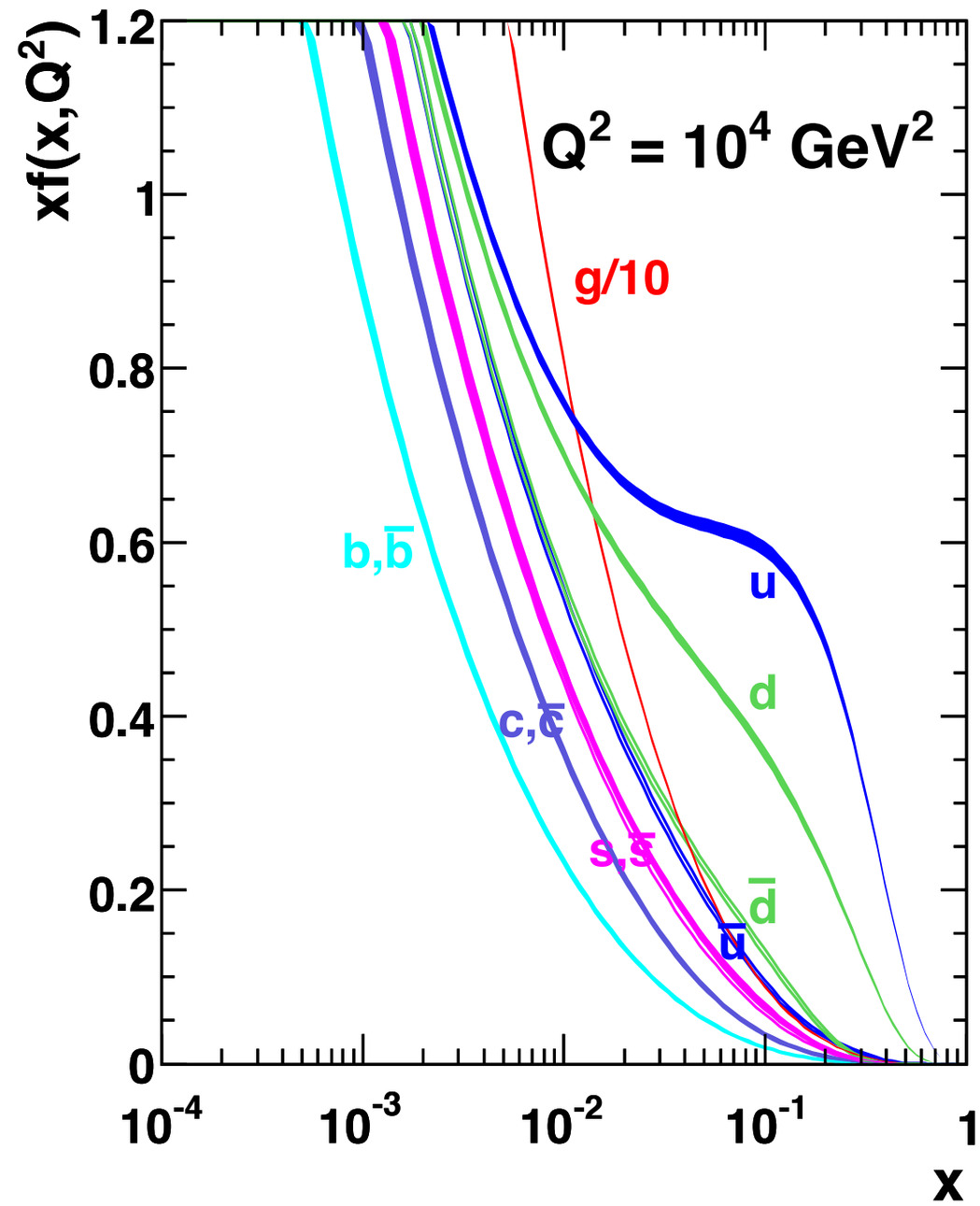
$p\bar{p}$ collisions, $\sqrt{s}$ = 1.96 TeV

- upgraded after 1995 (Run 1)
  - top quark discovery
- Run 2: 2001— 2010
  - 10 fb^{-1} delivered
  - instantaneous luminosity limited by antiproton production (one $\bar{p}$ for every 10^5 proton-target collisions)



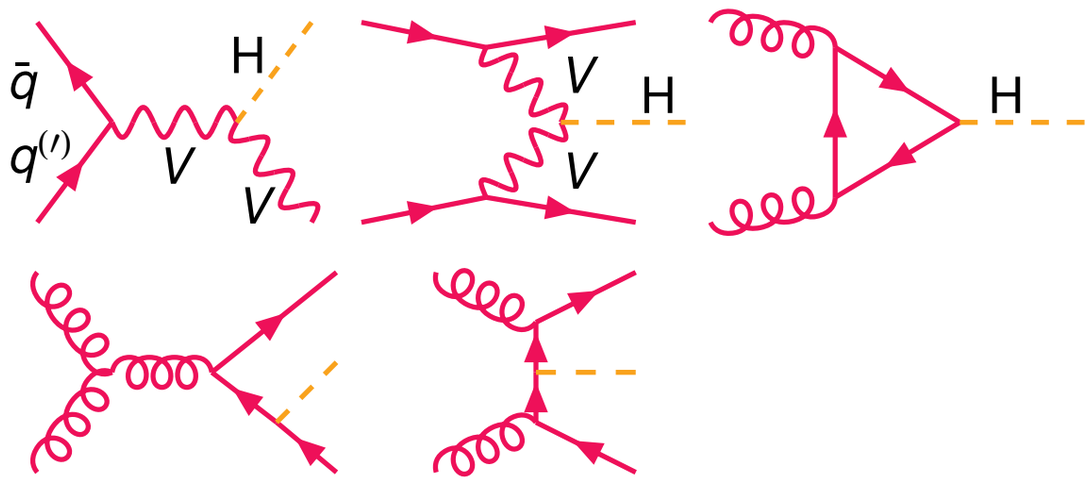
Tevatron (2)

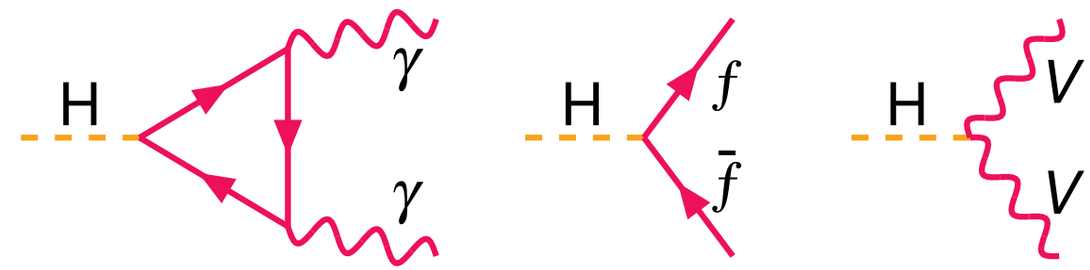


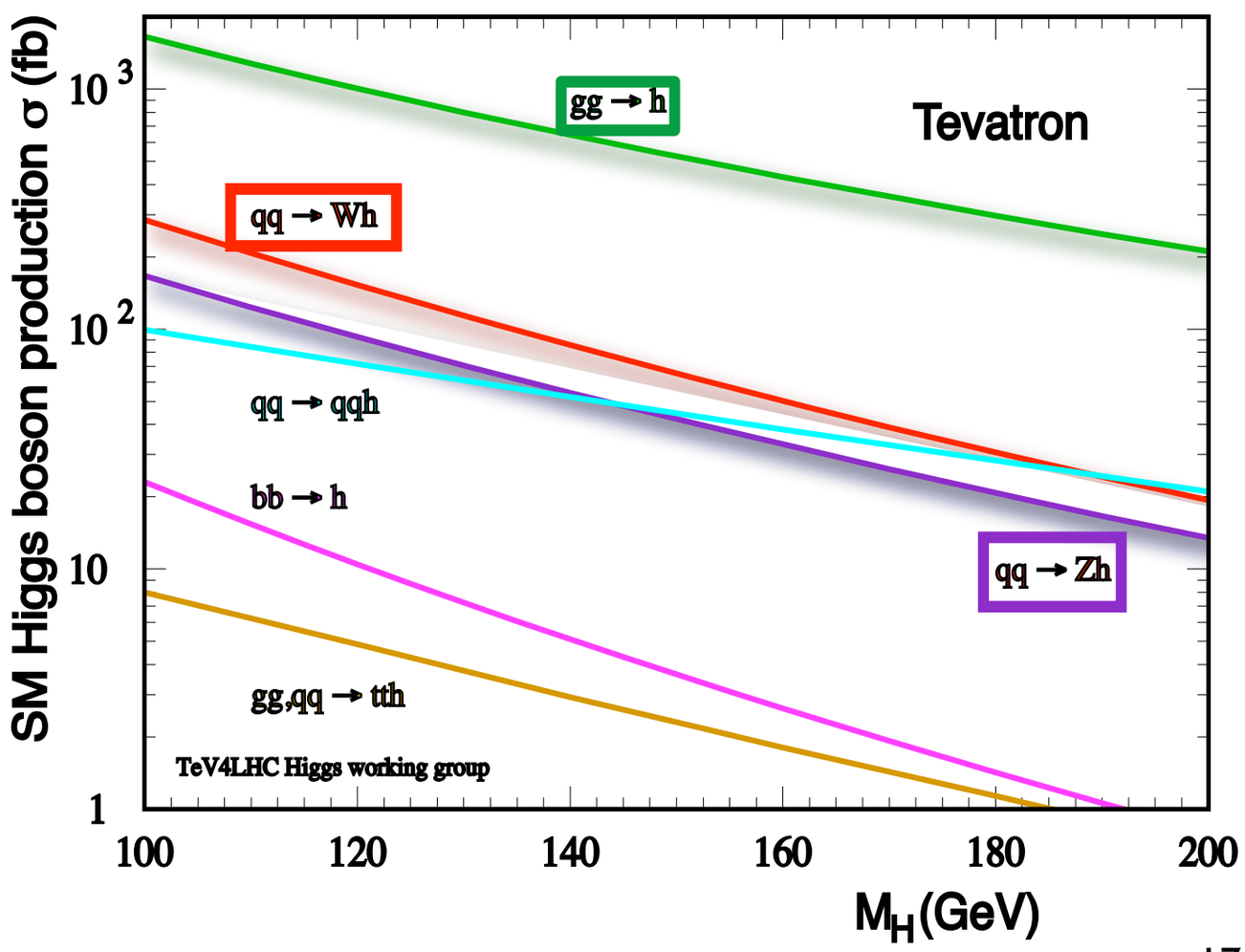


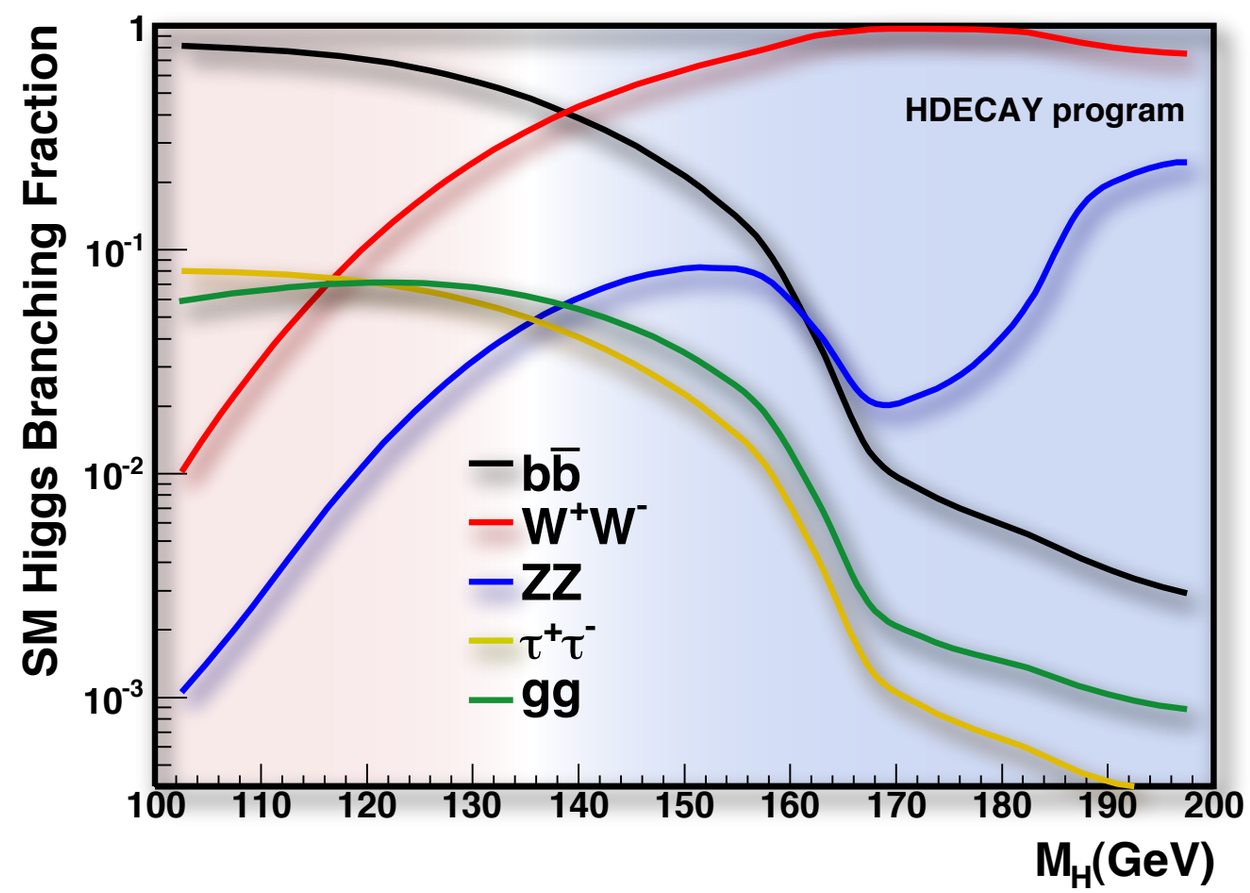
- large-x regime ($\hat{s} = x_1 x_2 s$)
- $\bar{q}q$ initial states (VH associated production) benefit greatly from valence quarks extracted from both p, $\bar{p}$

Tevatron (2)


$\bar{q}$
$q^{(\prime)}$
V
H
V
V
V
H
H


H
γ
γ
H
f
$\bar{f}$
H
V
V

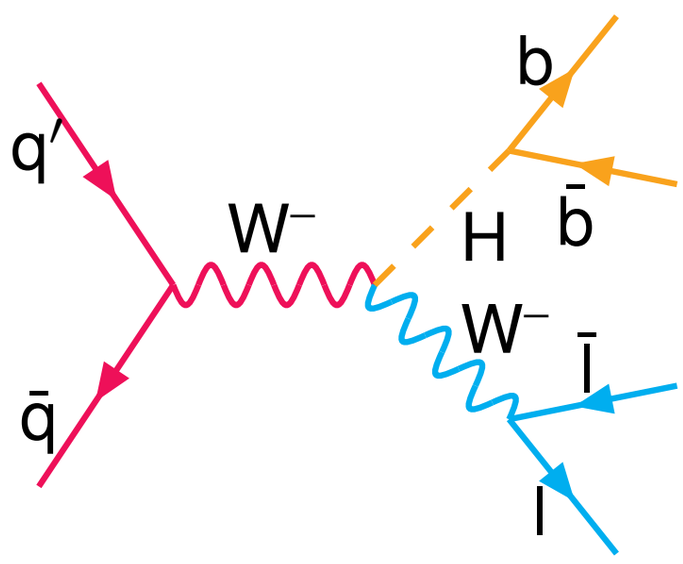

SM Higgs boson production σ (fb)
10^3
10^2
10
1
gg → h
Tevatron
qq → Wh
qq → qqh
bb → h
qq → Zh
gg,qq → tth
TeV4LHC Higgs working group
100
120
140
160
180
200
M_H(GeV)

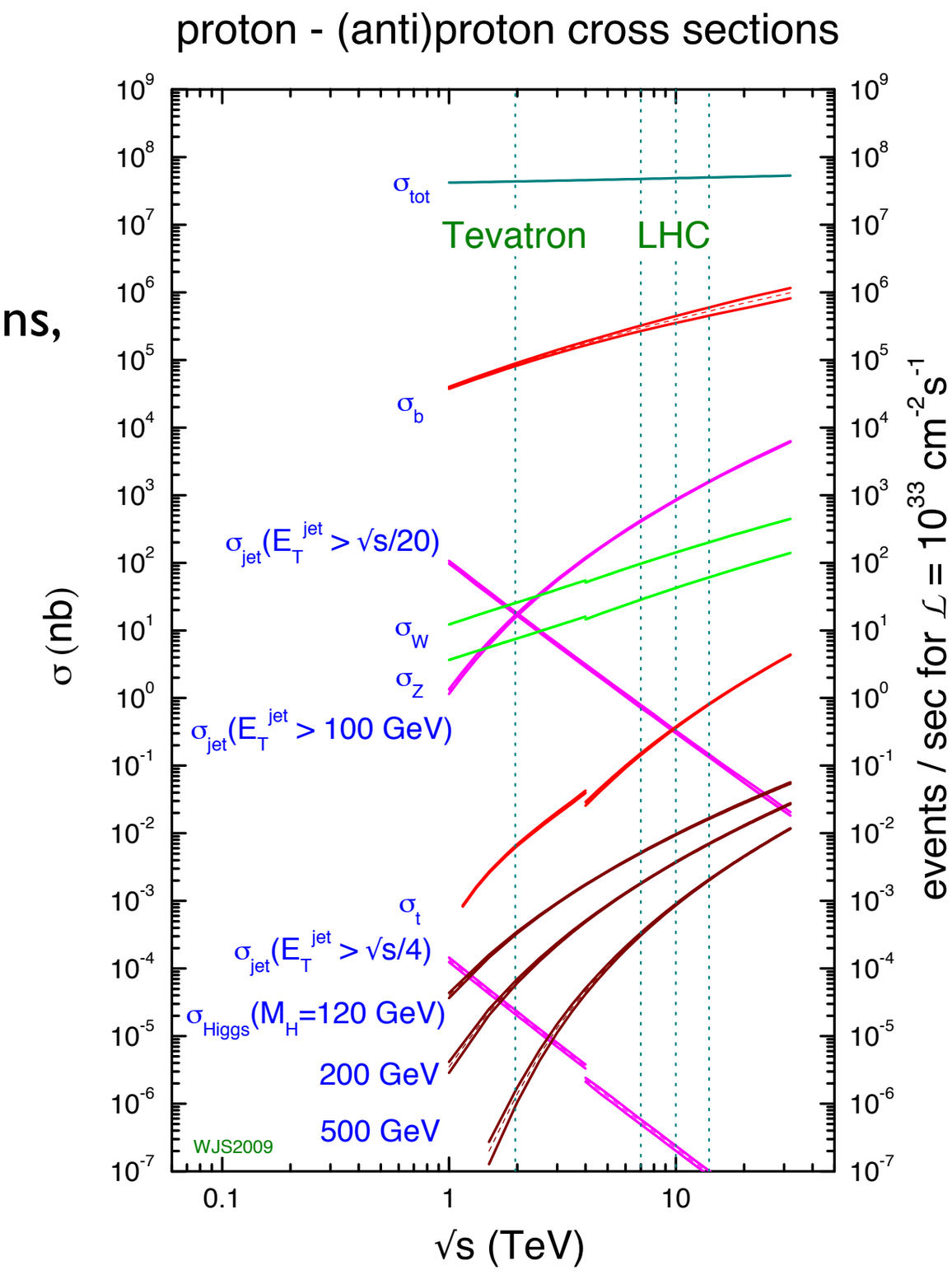

SM Higgs Branching Fraction
1
10^{-1}
10^{-2}
10^{-3}
HDECAY program
$b\bar{b}$
W^+W^-
ZZ
$\tau^+\tau^-$
gg
100
110
120
130
140
150
160
170
180
190
200
M_H(GeV)

Tevatron (3)

Higgs production cross section is tiny compared to total inelastic scattering cross section

- focus on channels with sufficiently distinctive signatures (leptons, missing transverse momentum)
  - m_H < 135 GeV: associated production with leptonic W/Z decays
  - m_H > 135 GeV: $H \rightarrow W^+W^-$ with leptonic W decays

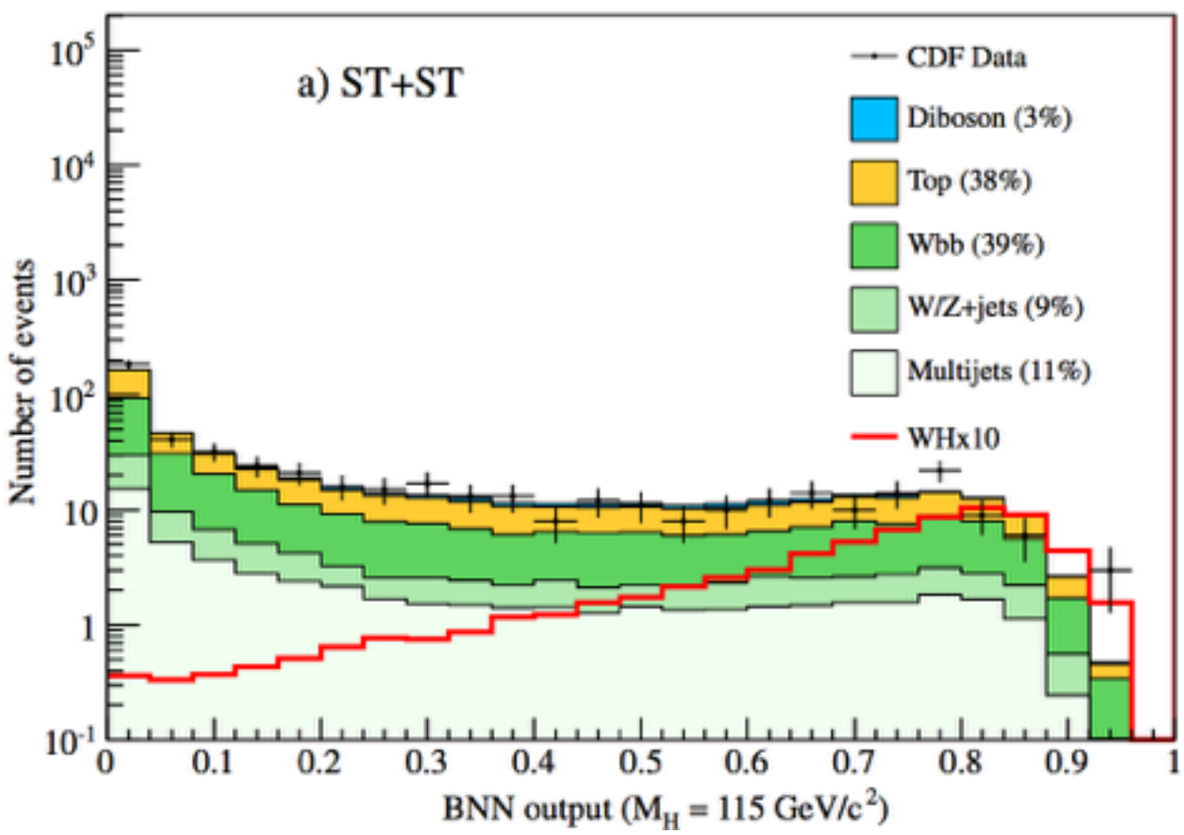


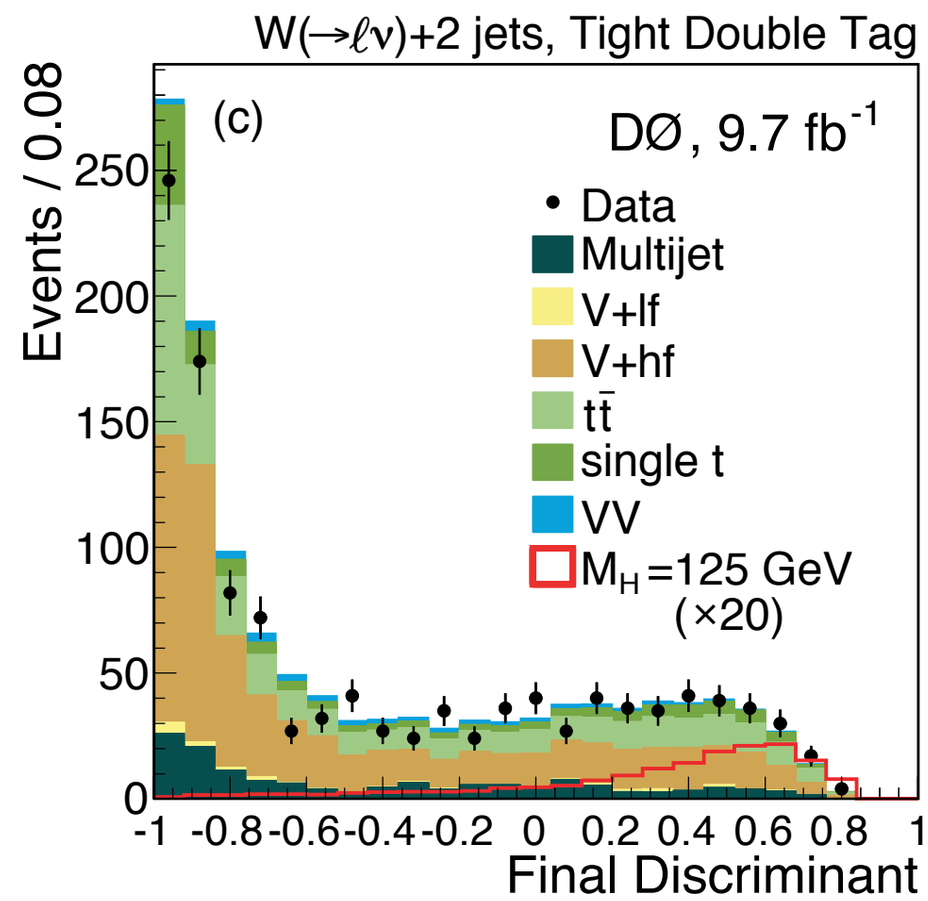


Tevatron (4)

Results:

- excluded ranges at both low m_H (associated production) and high m_H (WW)
- slight excesses observed in intermediate m_H range (associated production)
  - excess of 2.8 standard deviations at m_H = 125 GeV





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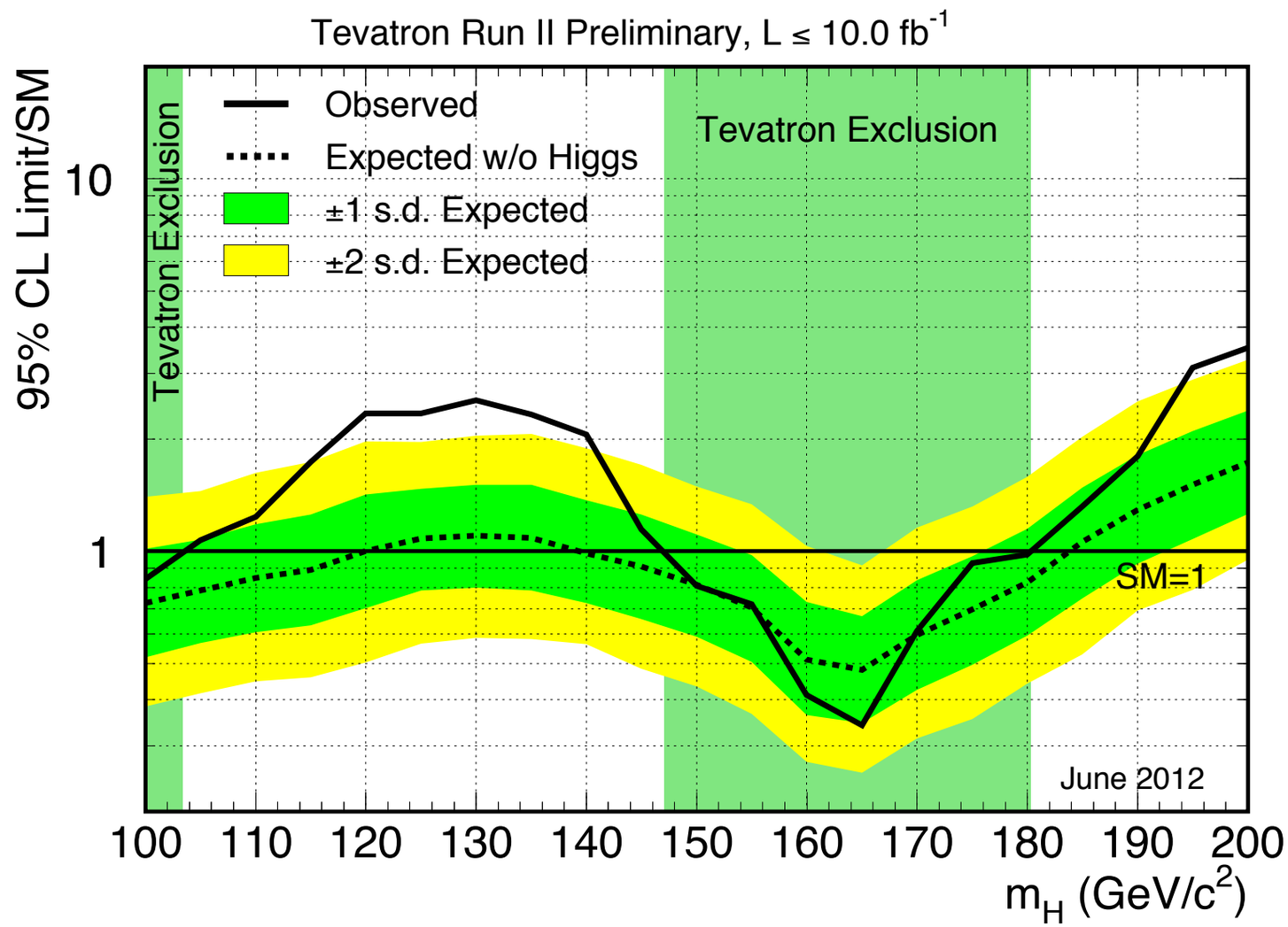
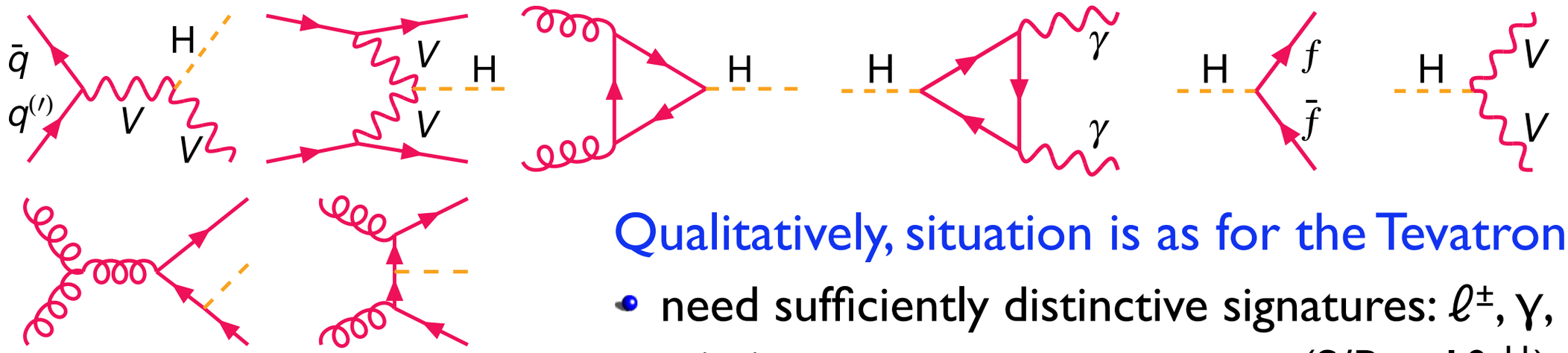


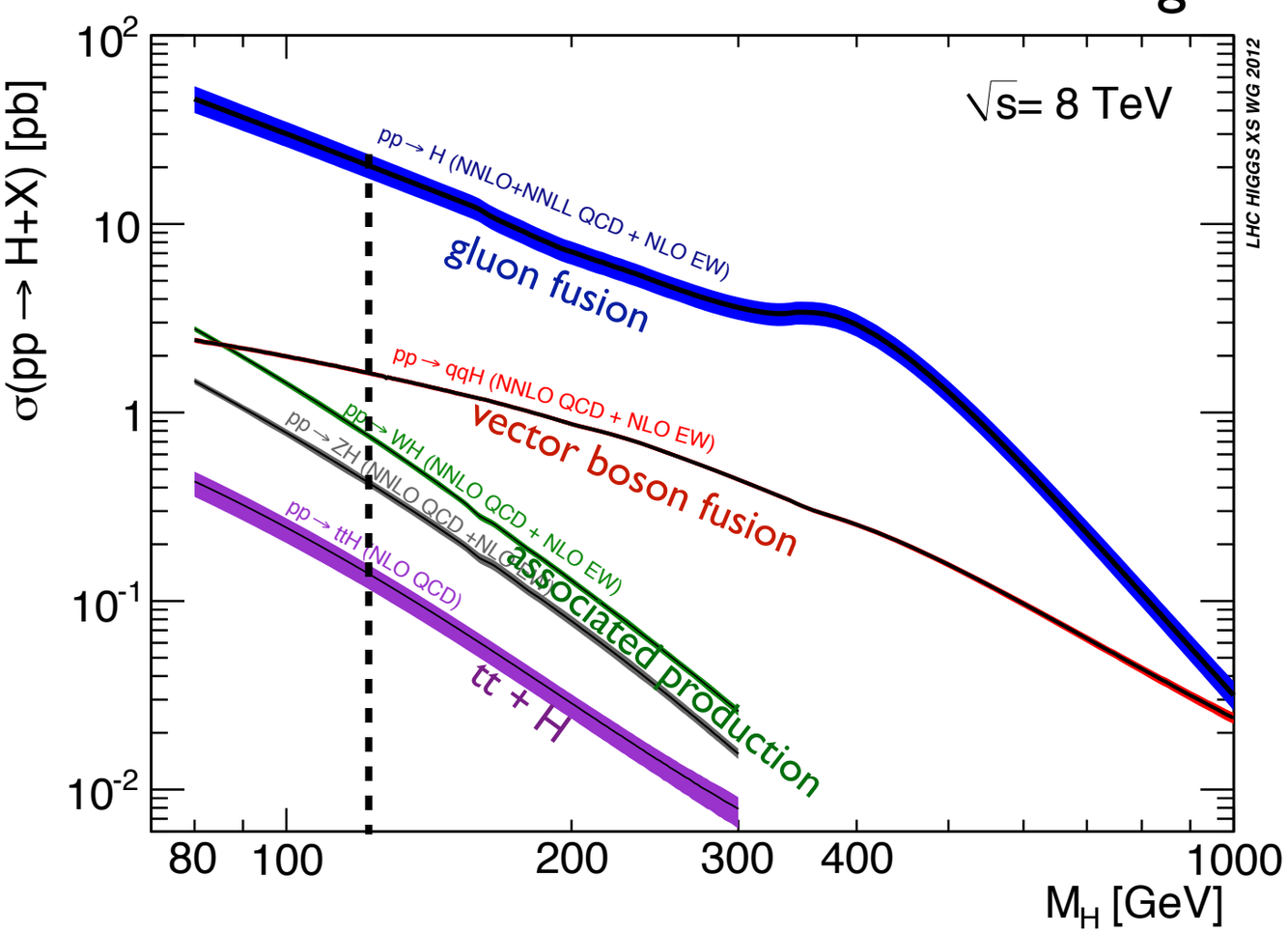
LHC discovery analyses

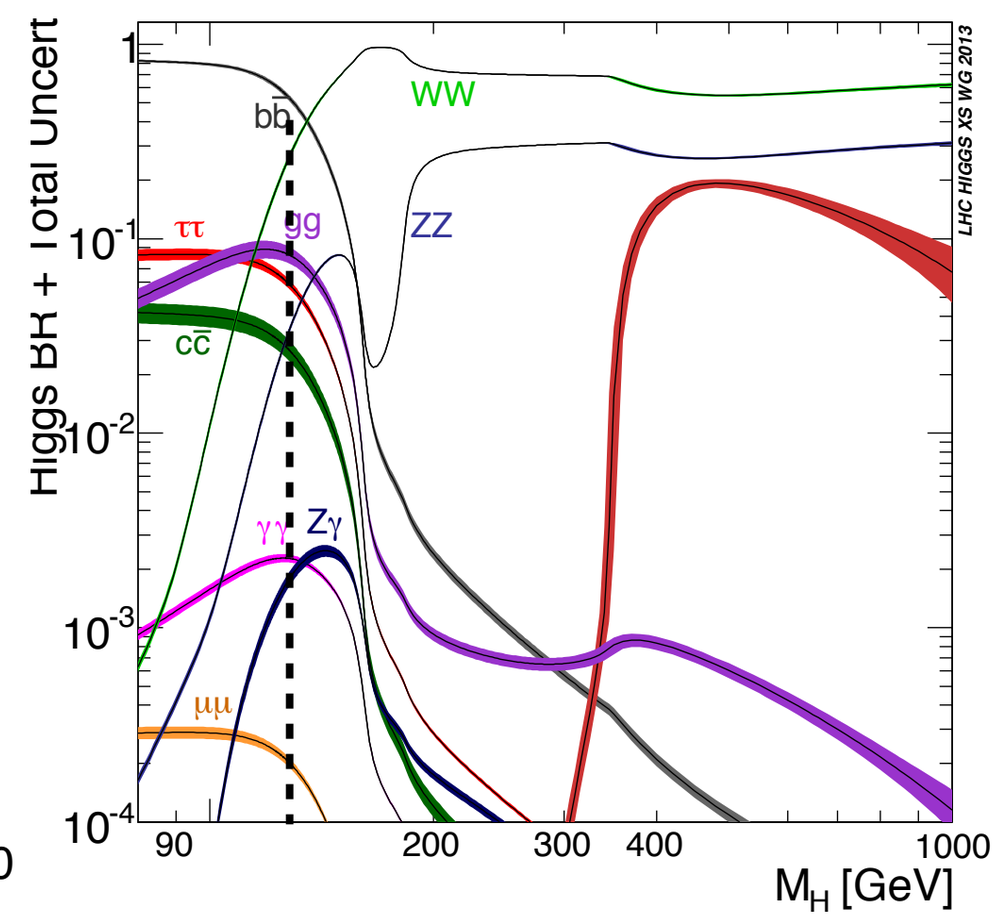
Higgs boson production & decay



Qualitatively, situation is as for the Tevatron

- need sufficiently distinctive signatures: $\ell^{\pm}$, γ, missing transverse momentum (S/B ~ 10^{-11})



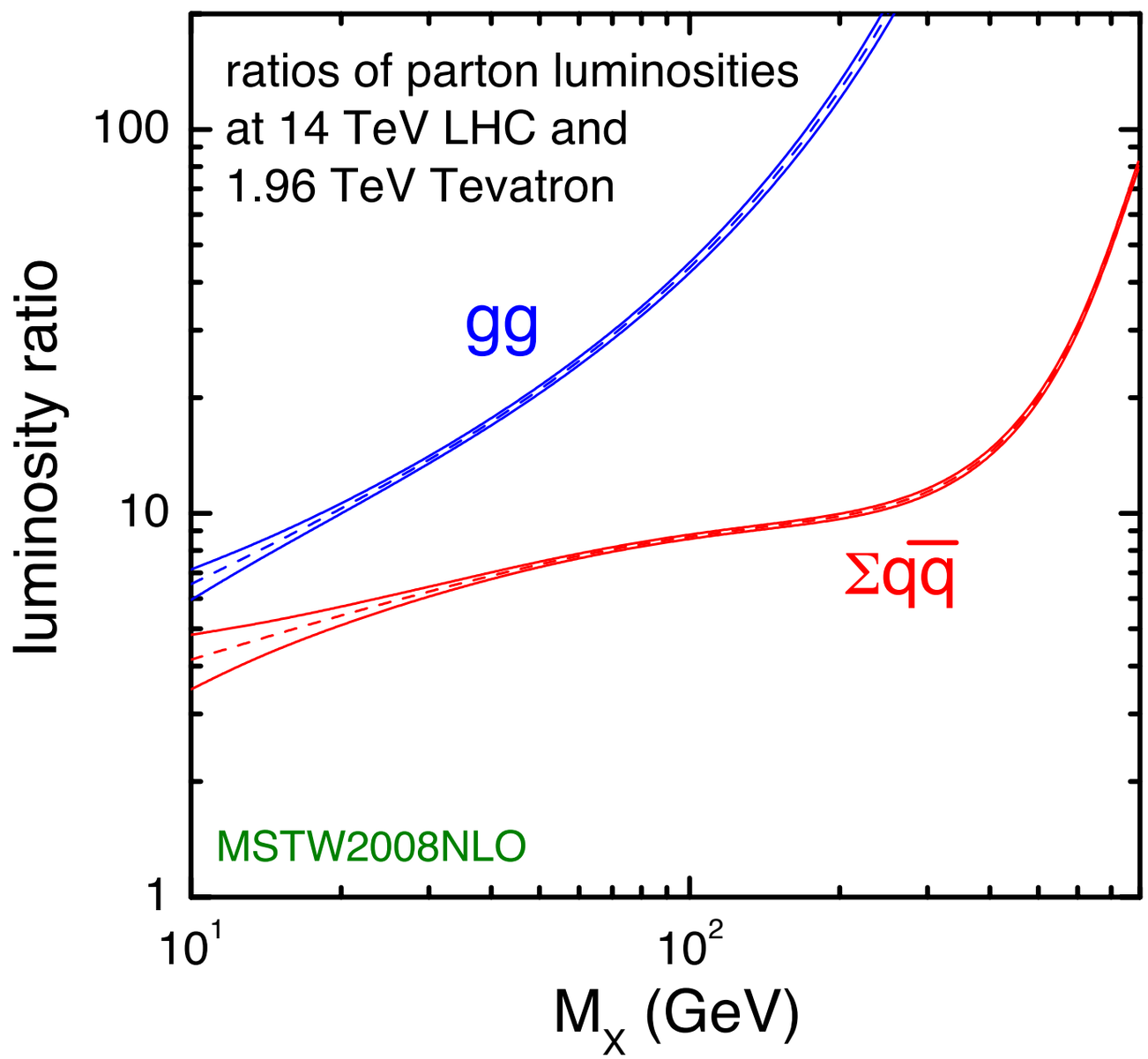


figures from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Comparison to Tevatron

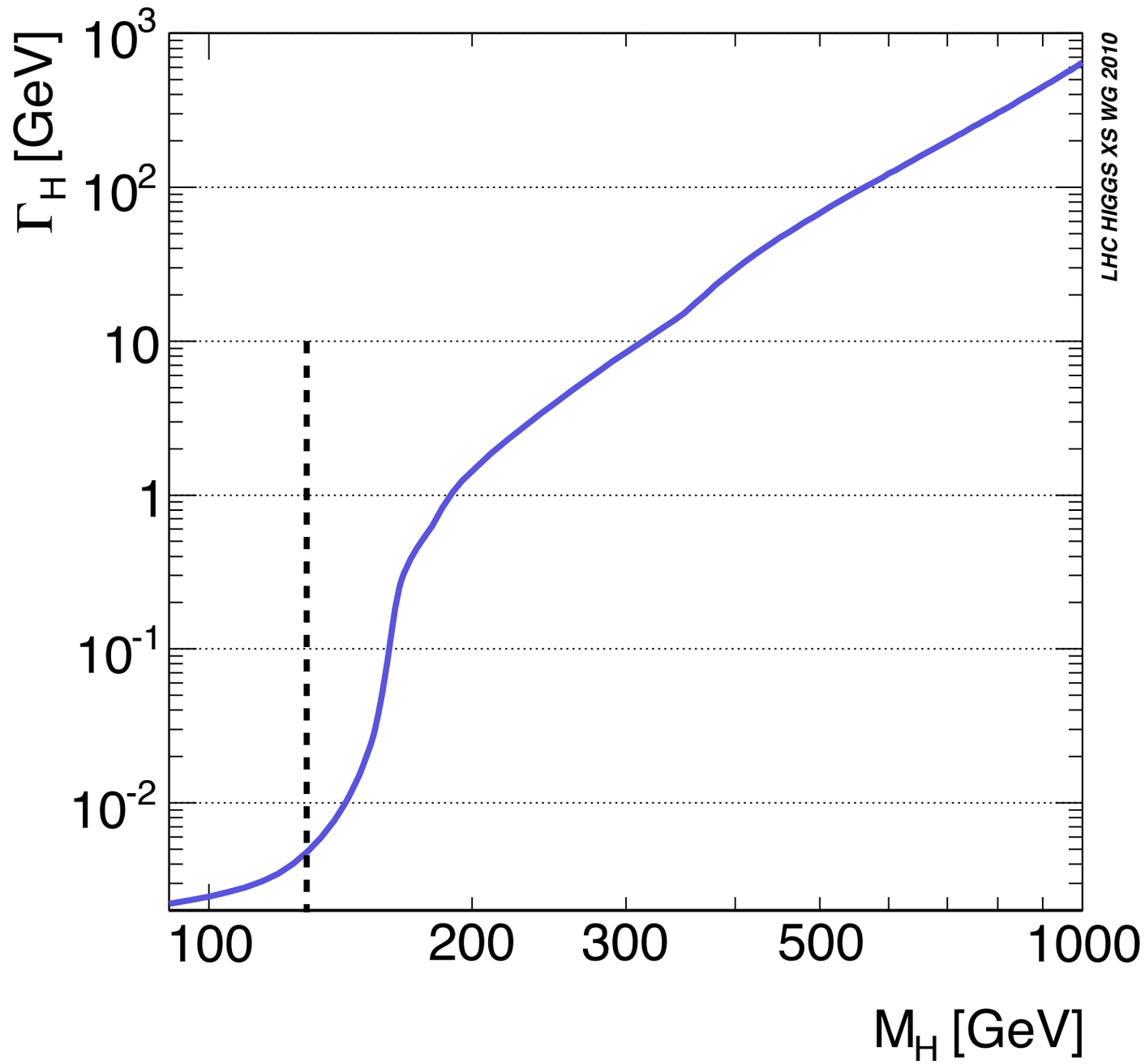
Essentially all analyses benefit from higher CM energy. But note:

- this plot compares 14 TeV (not 8 TeV) to 2 TeV
- also cross sections for background processes increase



A narrow resonance

"Low" m_H searches benefit from a precise mass reconstruction



Hadron collider kinematics (I)

Hard interactions collisions are between partons, not protons.
Consequences:

- partonic system typically boosted along beam axis
  - long detectors!
  - useful to describe system in terms of quantities transforming "conveniently" under boosts along z: p_T, φ, y (or η, for massless particles)
    - (pseudo)rapidity differences invariant under boosts

$$y \equiv \frac{1}{2} \ln \left(\frac{E - p_z}{E + p_z} \right) \qquad \eta \equiv -\ln \tan(\theta/2)$$

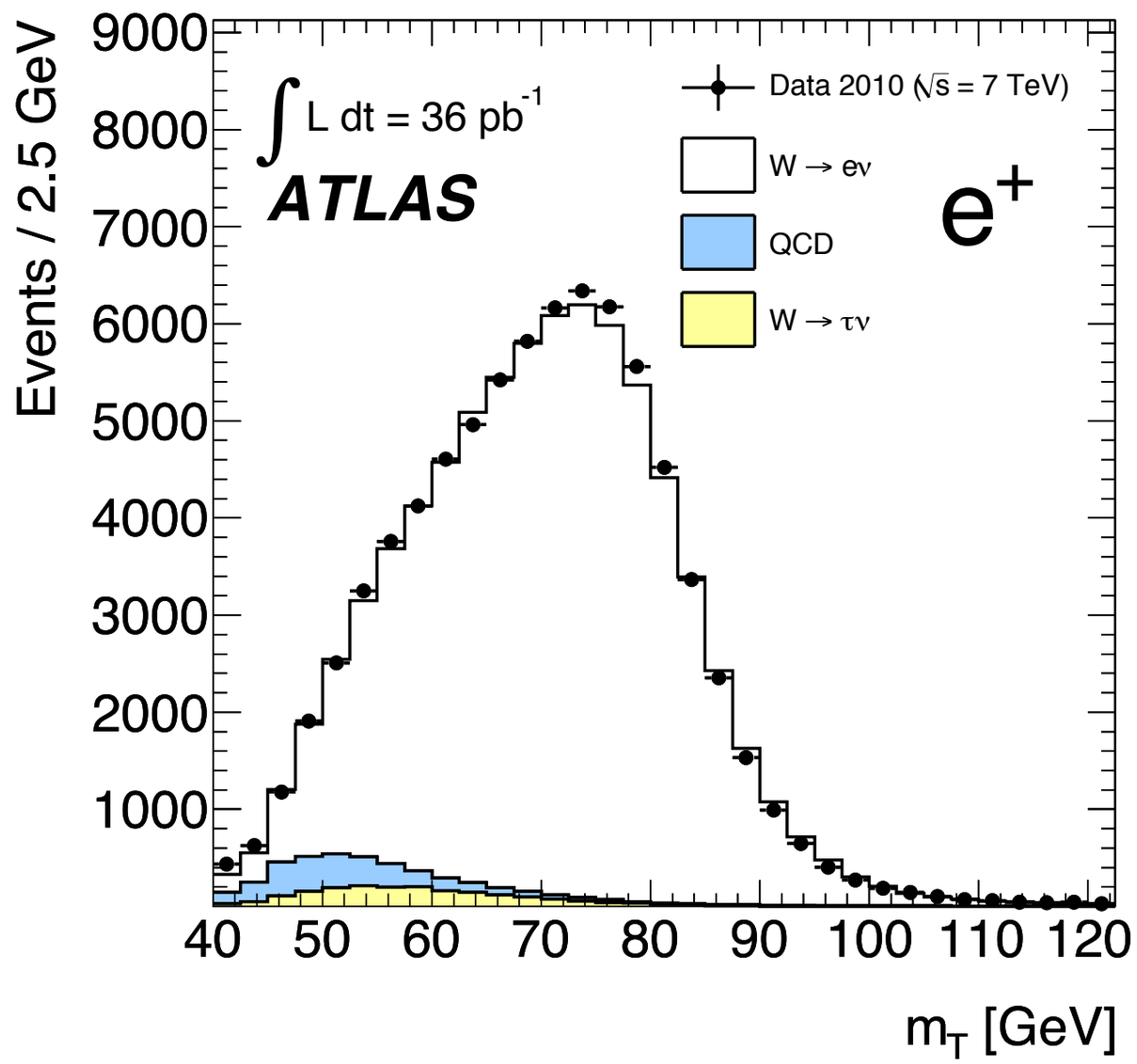
- partons not participating in the hard interaction typically escape along the beam pipe (but some colour flow remains ➠ "underlying event")
  - overall p_z of the hard interaction is a priori unknown ➠ only ν transverse momenta can be estimated (in absence of final-state specific constraints)

Hadron collider kinematics (2)

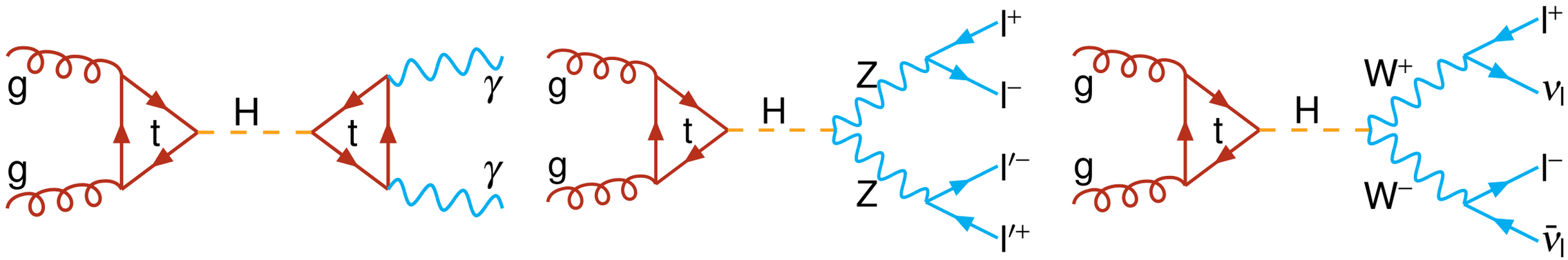
Example: transverse mass m_T for W-boson production: $m_T < m_W$

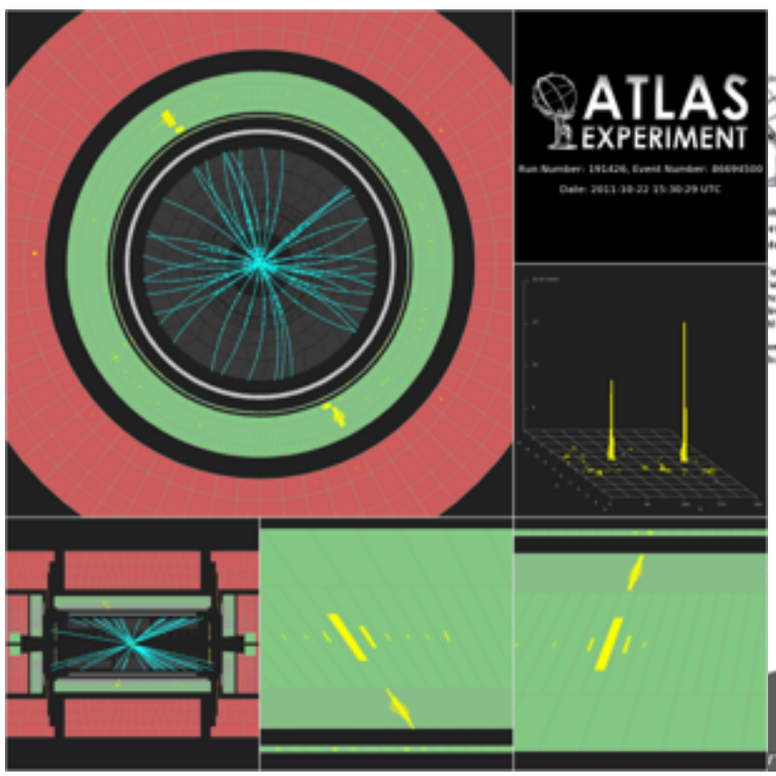
- in absence of Γ_W effects and experimental resolution

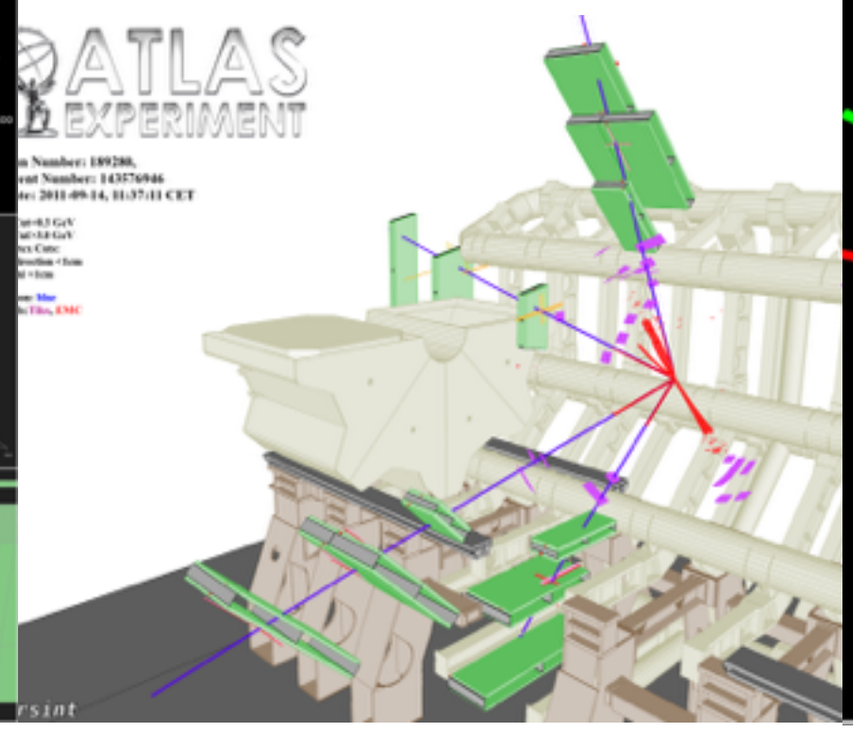
$$m_T^2(\ell,\nu) \equiv (|\vec{p}_{T,\ell}| + |\vec{p}_{T,\nu}|)^2 - (\vec{p}_{T,\ell} + \vec{p}_{T,\nu})^2$$

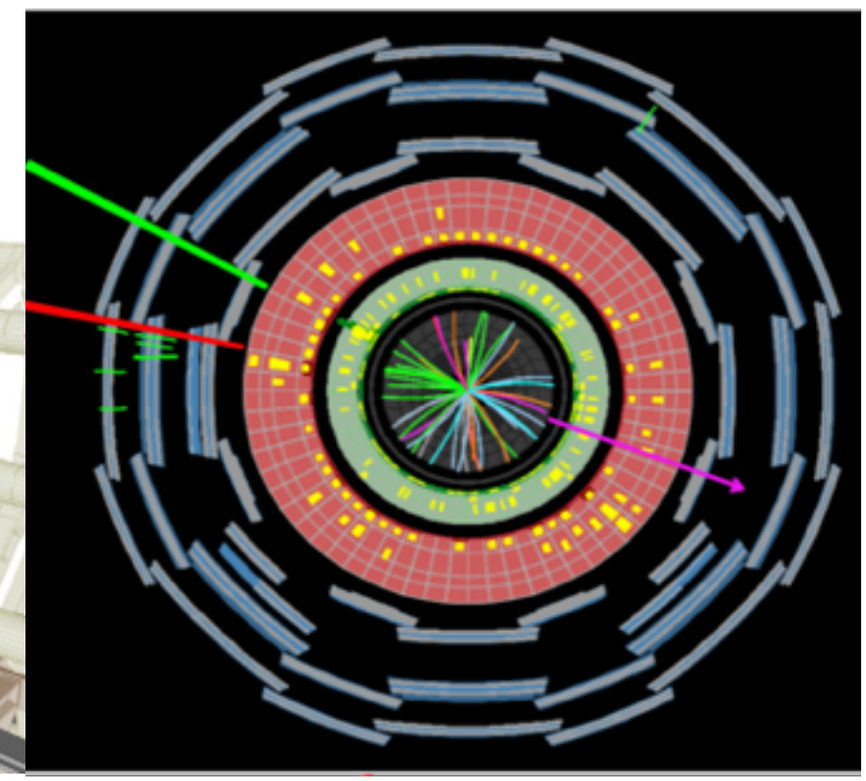


Discovery channels





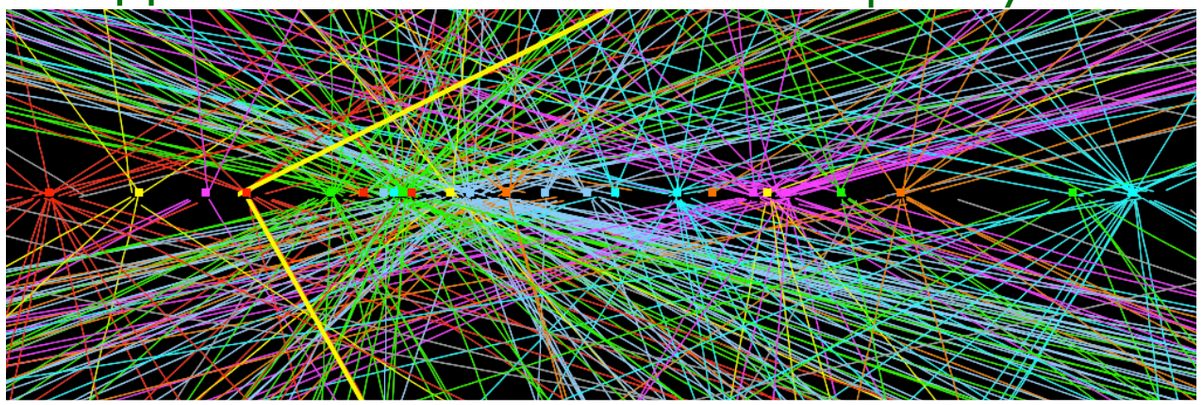




H → γγ (I)

A "simple" search, provided photons can be identified and reconstructed properly. Two main challenges:

Z → μμ candidate with 25 reconstructed primary vertices



- m(γγ) reconstruction: needs photon vertex
  - difficult especially in presence of pile-up (multiple interactions per bunch crossing) and for "soft" events
  - MVA vertex selection; multiple event categories with different efficiencies
    - use converted γ (good direction from tracks, but worse m(γγ) resolution)
- background from jets fragmenting to single π^0
  - stringent cuts on calorimeter shower shapes
  - split event categories with different mass resolutions

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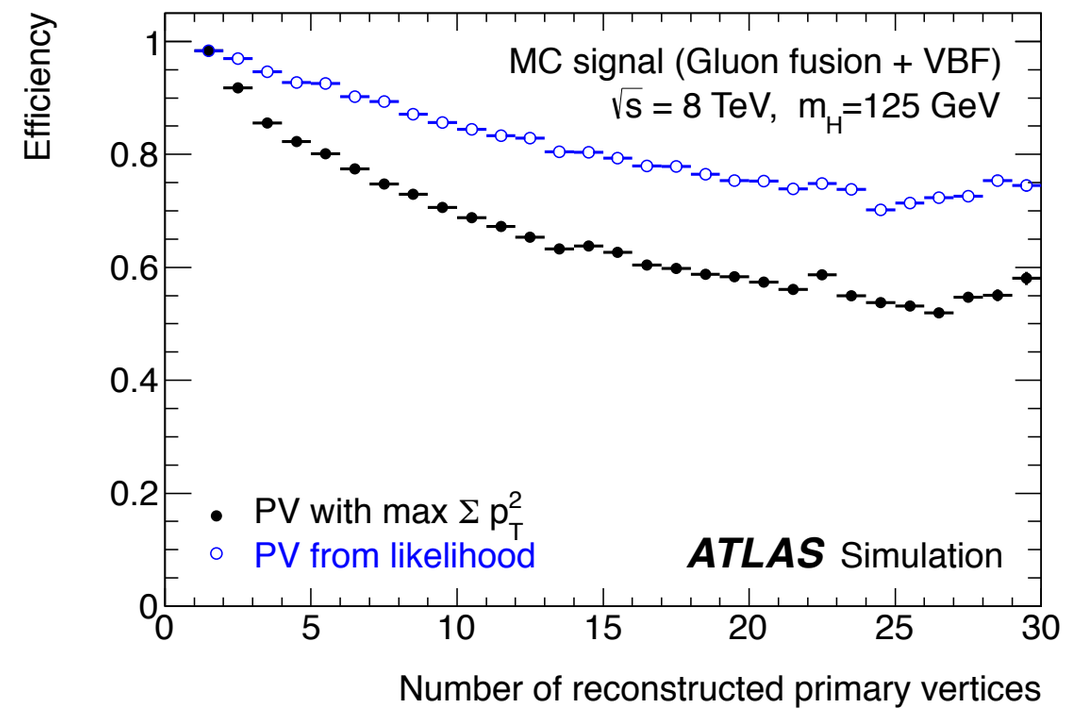
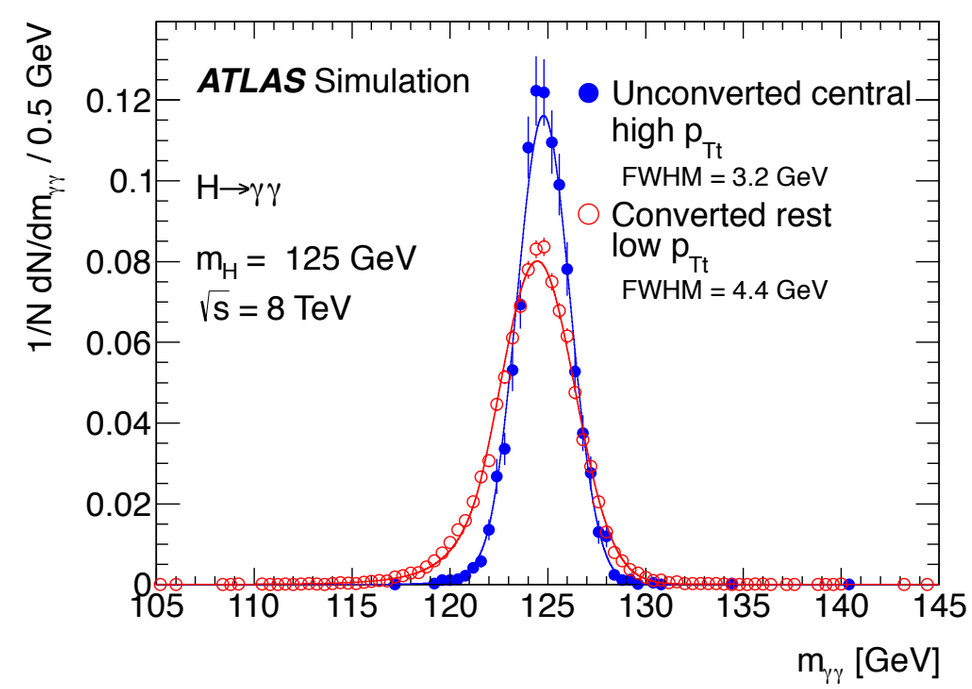
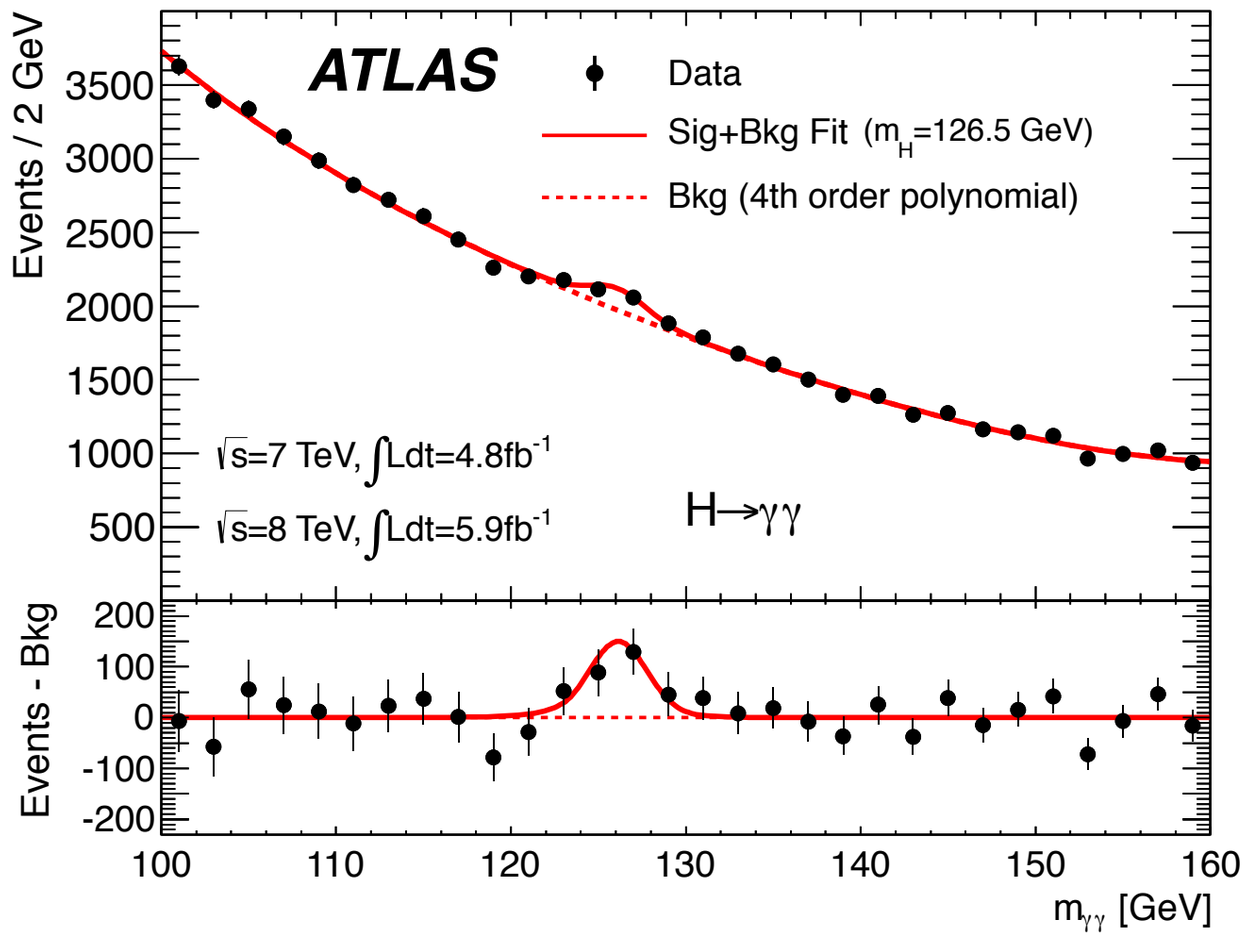




H → γγ (2)

Are these photons??

- need a <u>statistical</u> background subtraction



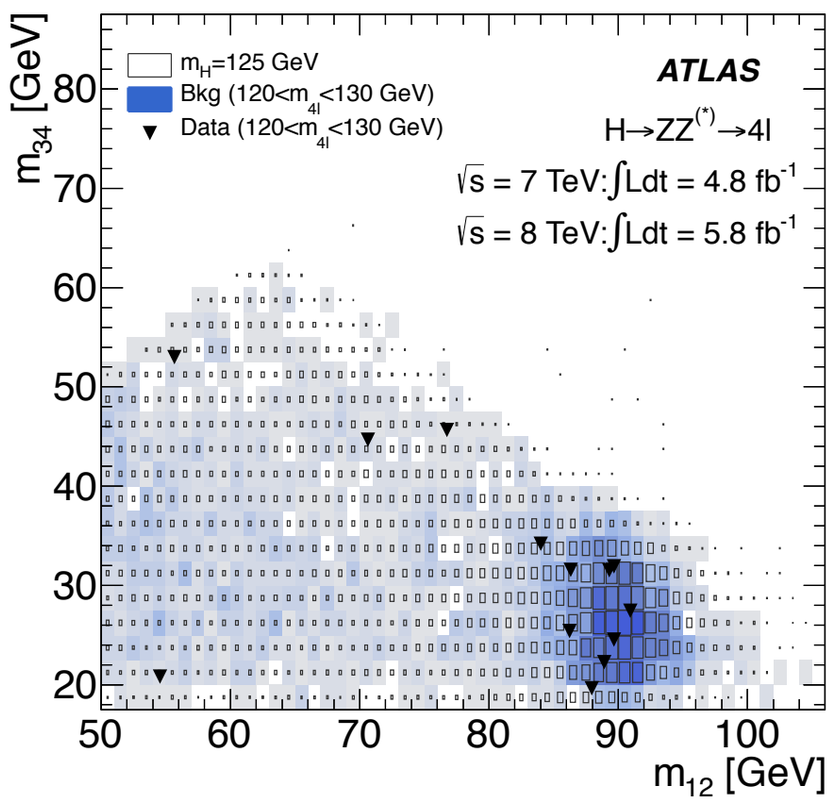
Note: observation in this channel precludes spin-1 hypothesis

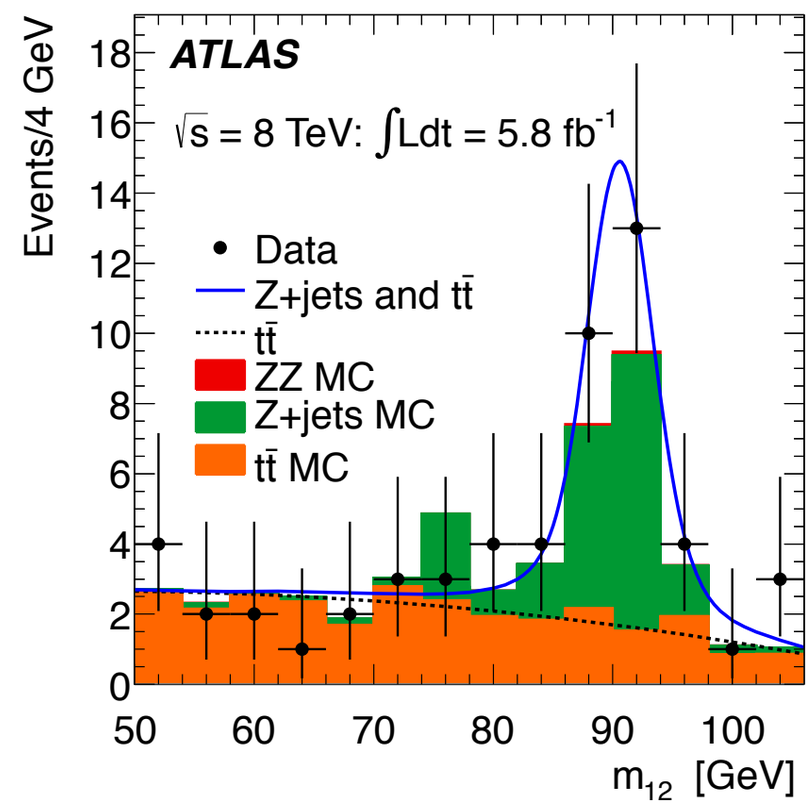
- Landau-Yang theorem

H → ZZ → 4 leptons

"Easy": select four isolated electrons / muons

- drawback: low Z → $\ell^+\ell^-$ branching fractions (3.4%)
- also: one off-shell Z boson ➠ one pair of very soft leptons ($p_T(\ell)$ > 6 GeV)
  - control regions to constrain background normalisations (here: $\bar{t}t$, Z+jets bg from sample with isolation requirements removed from sub-leading lepton pair and at least one lepton failing impact parameter requirement)





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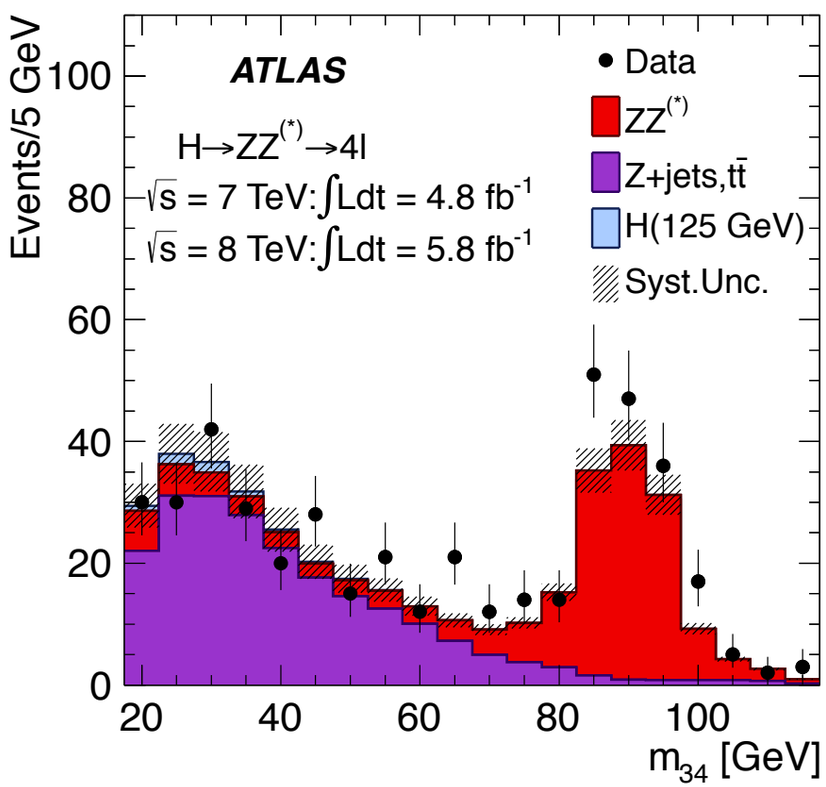
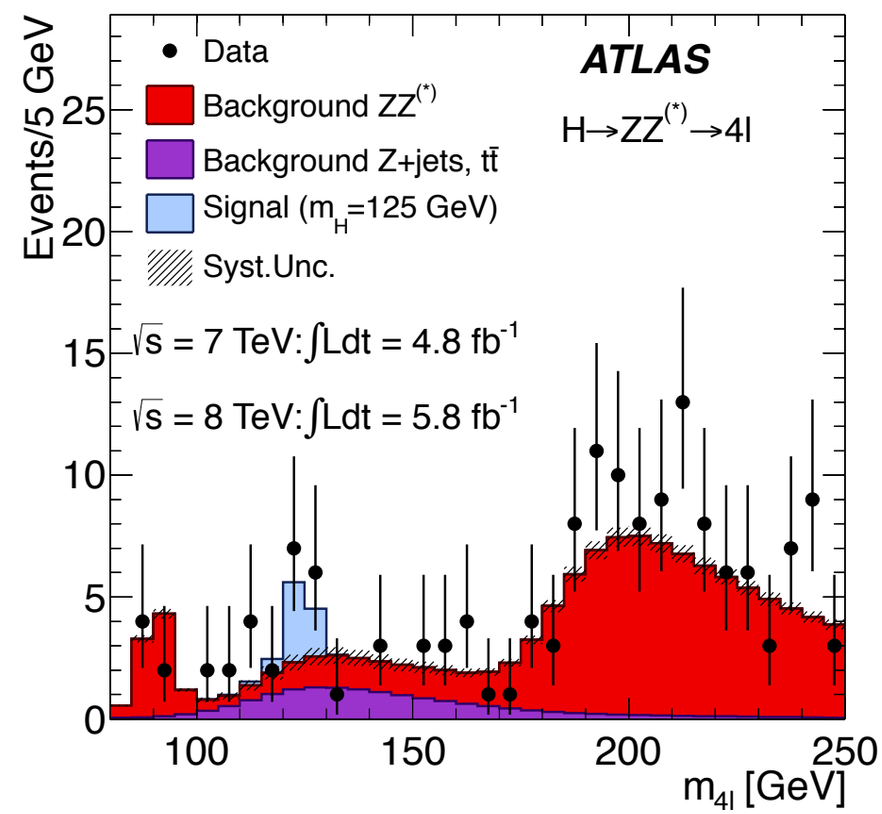
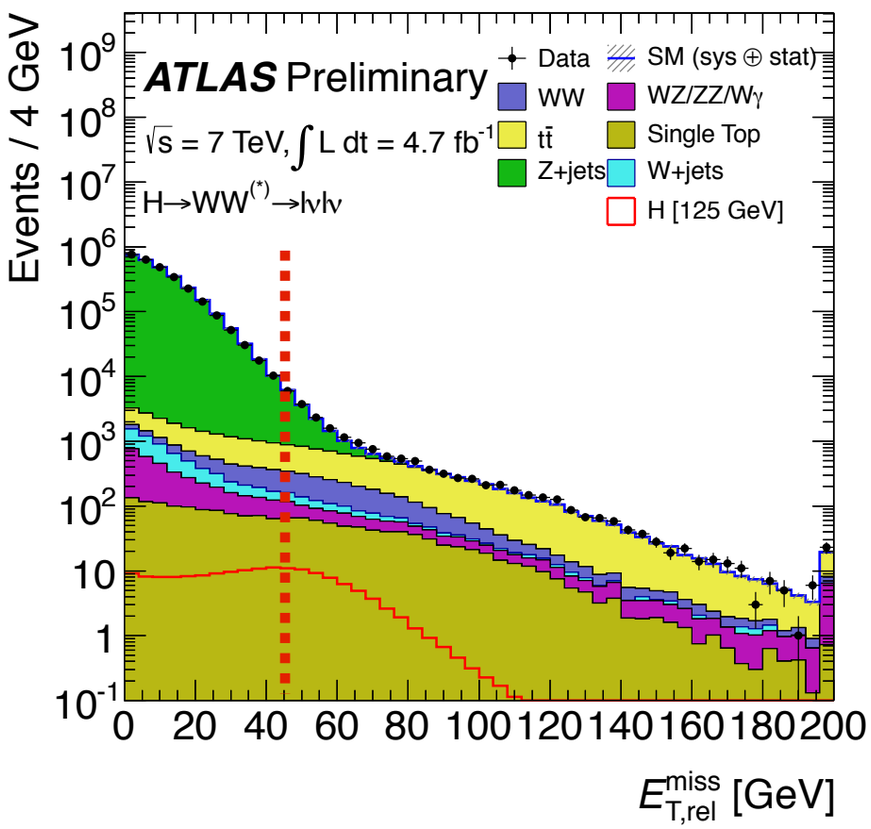


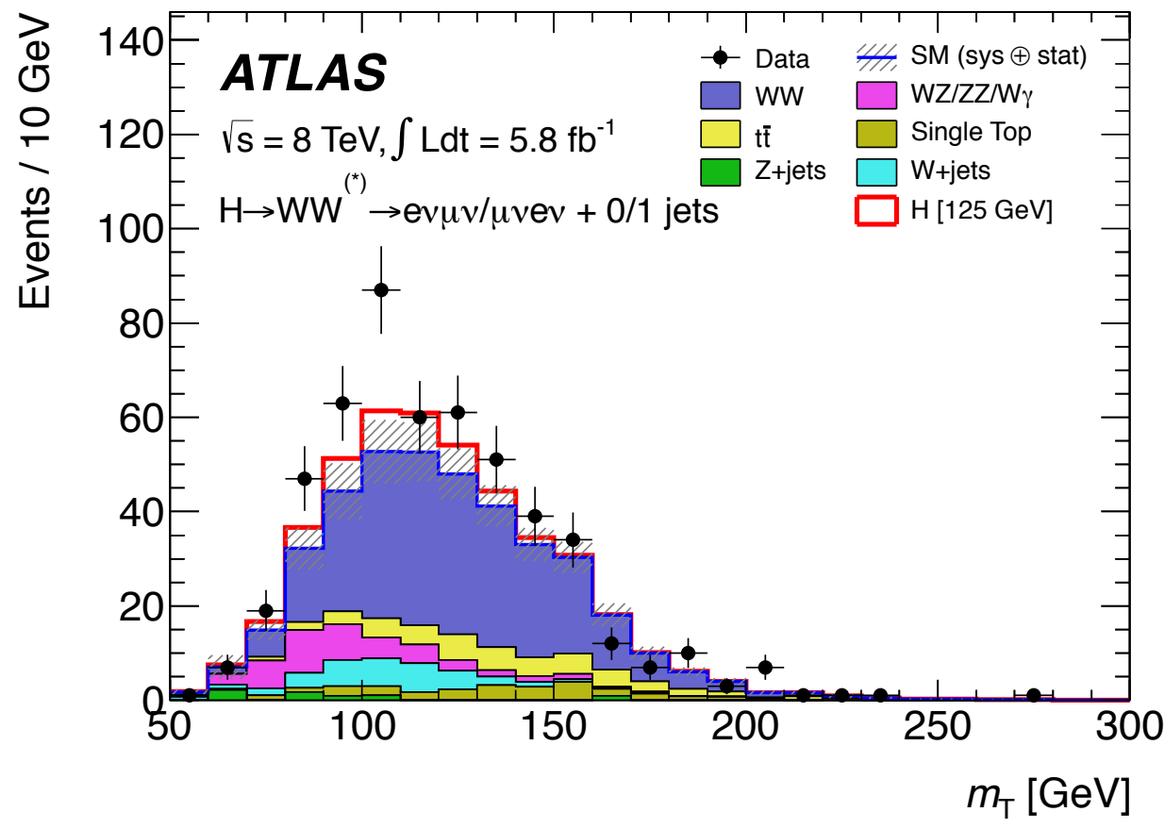


$H \to W^+W^- \to \ell^+\nu\, \ell'^-\bar{\nu}$ (I)

With two escaping ν, mass reconstruction not possible

- but some sensitivity retained: $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss}|^2}$, $E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$
- did not use ee and μμ channels (background from Z + fake missing p_T)

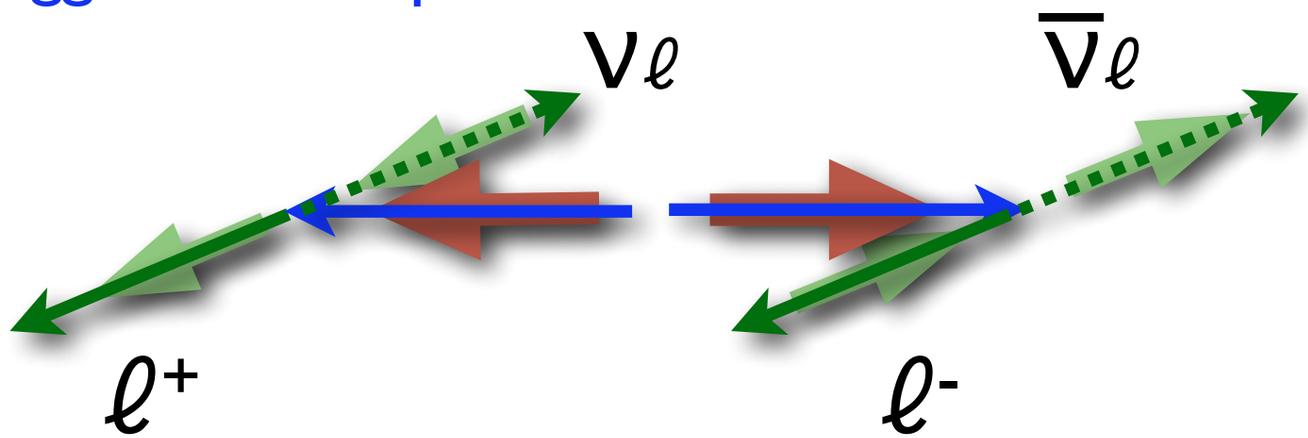




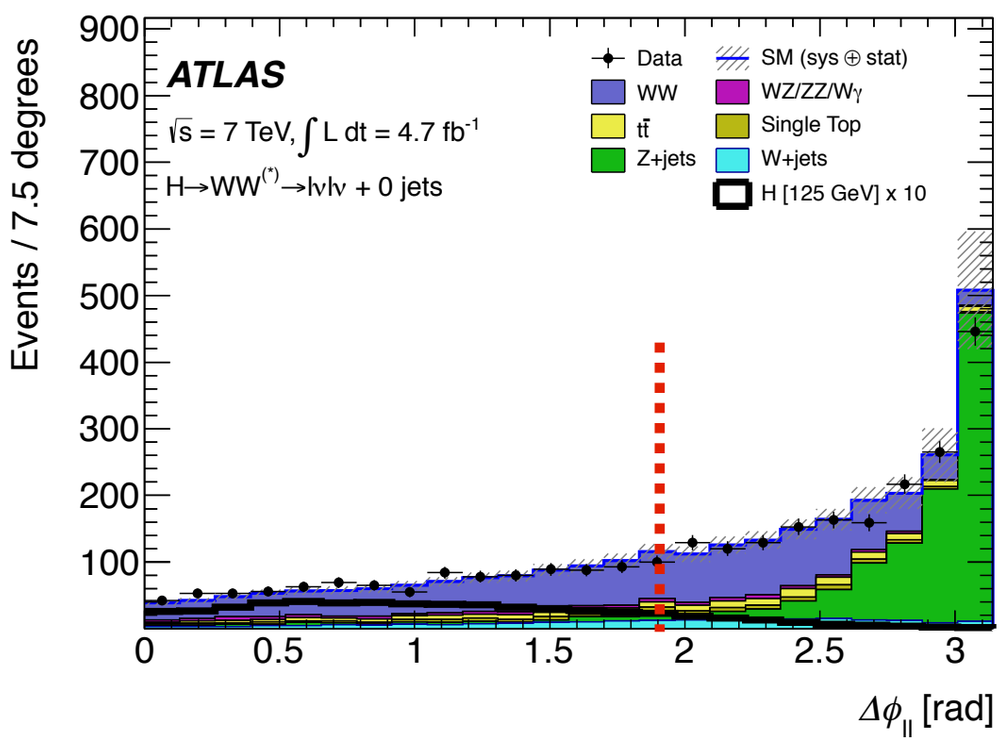
$$E_{T,rel}^{miss} = \begin{cases} E_T \sin\Delta\phi & \Delta\phi < \pi/2 \\ E_T & \Delta\phi > \pi/2 \end{cases}$$

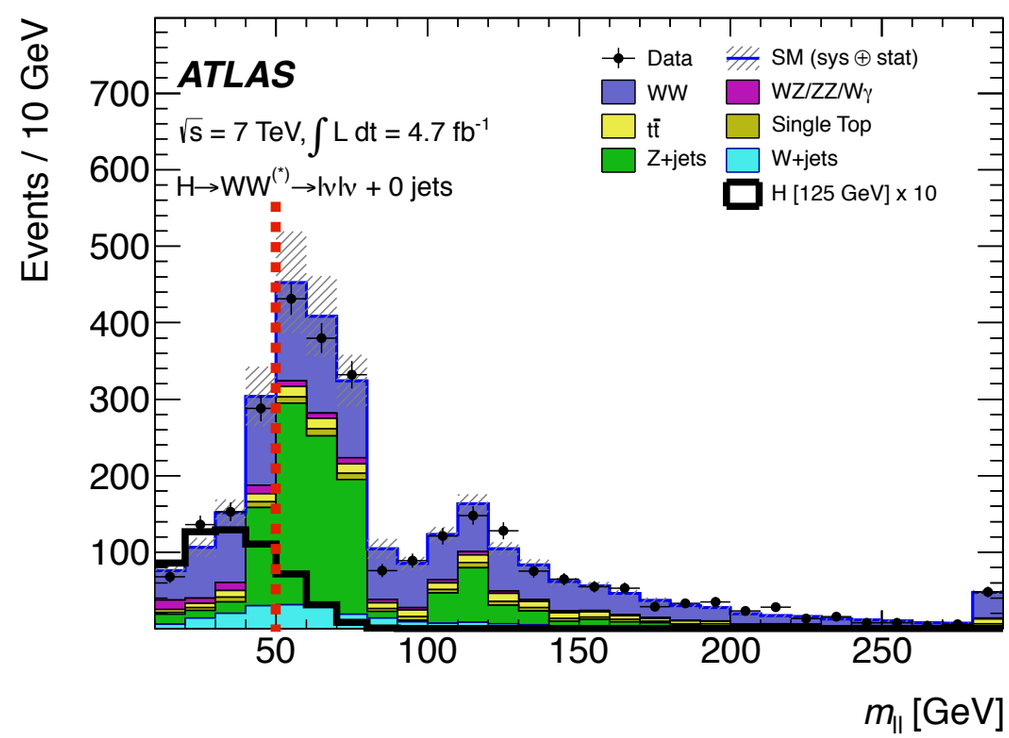
$H \rightarrow W^+W^- \rightarrow \ell^+\nu\, \ell'^-\bar{\nu}$ (2)

Exploit the Higgs boson's spin-0 nature



- exploit by removing events (especially irreducible bg) with large $\Delta\varphi(\ell\ell)$ or large $m(\ell\ell)$

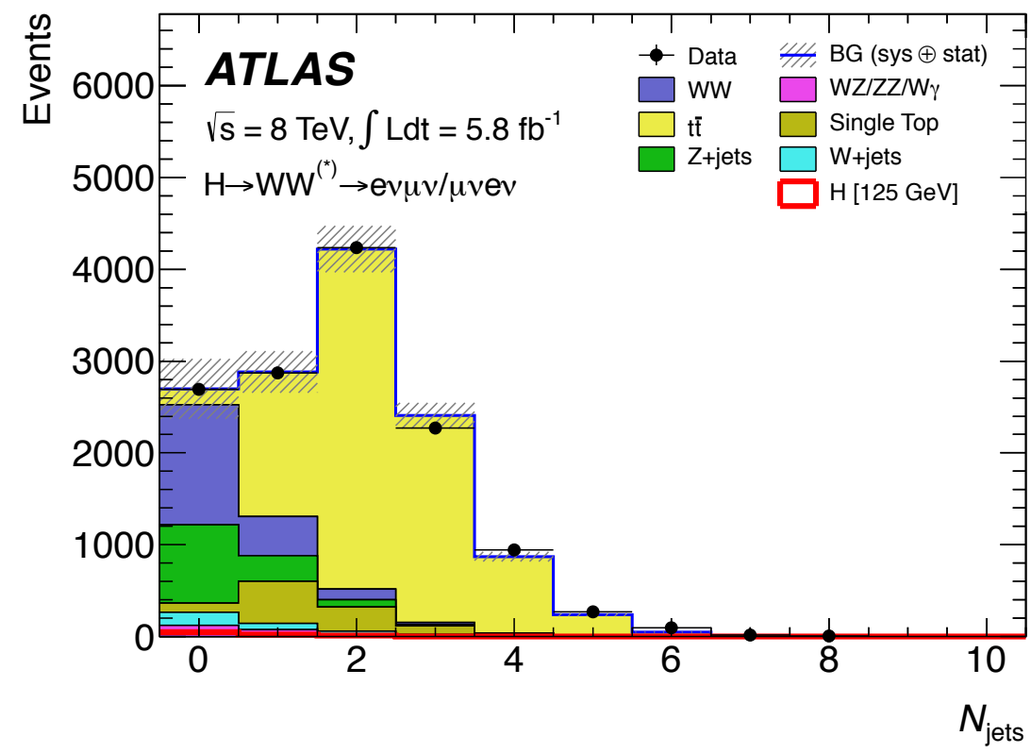




$H \to W^+W^- \to \ell^+\nu\, \ell'^-\bar{\nu}$ (3)

No scattering without radiation…

- in principle, aim is to be inclusive; but overwhelming $\bar{t}t$ background makes this impossible (even after vetoing events with b-tagged jets)
  ➠ bin in jet multiplicity
  - NB: b-tagged samples provide excellent control regions
- problem: theoretical uncertainties are typically given for inclusive N_{jet} observables
  - account for migration between N_{jet} bins by anti-correlating uncertainties: Stewart-Tackmann approach (leads to larger uncertainties)

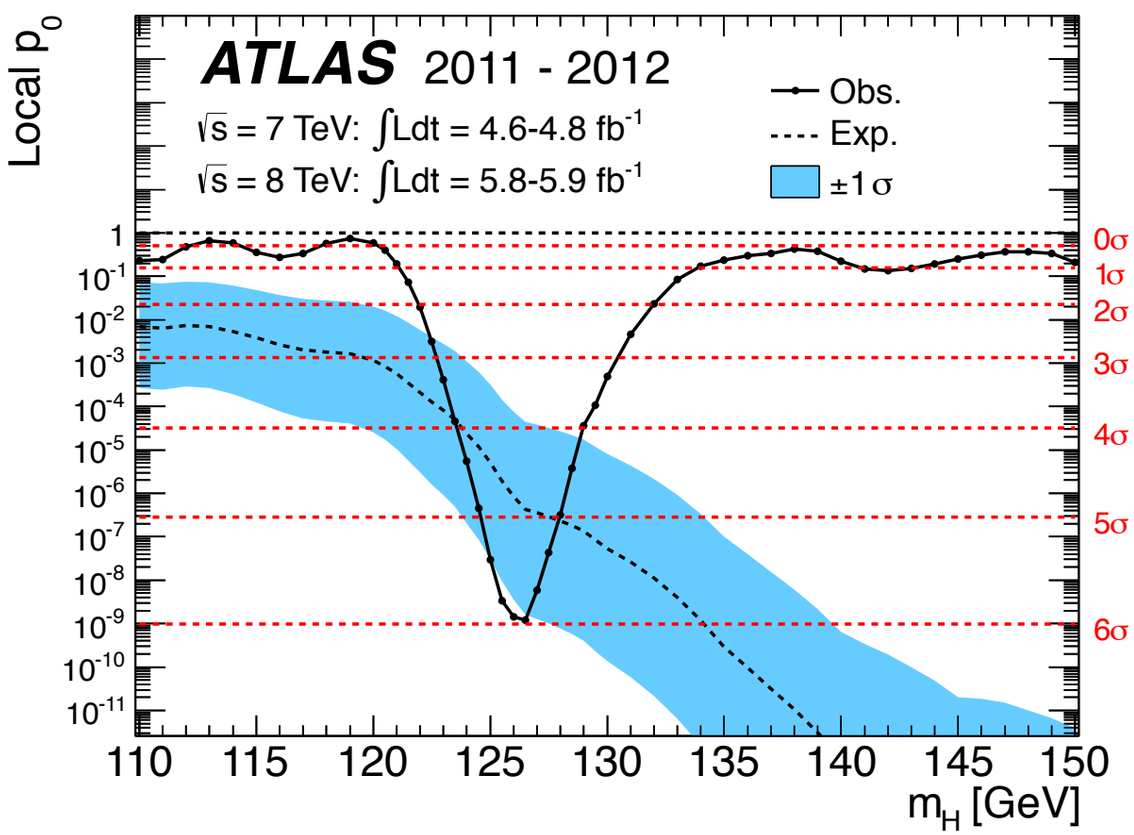


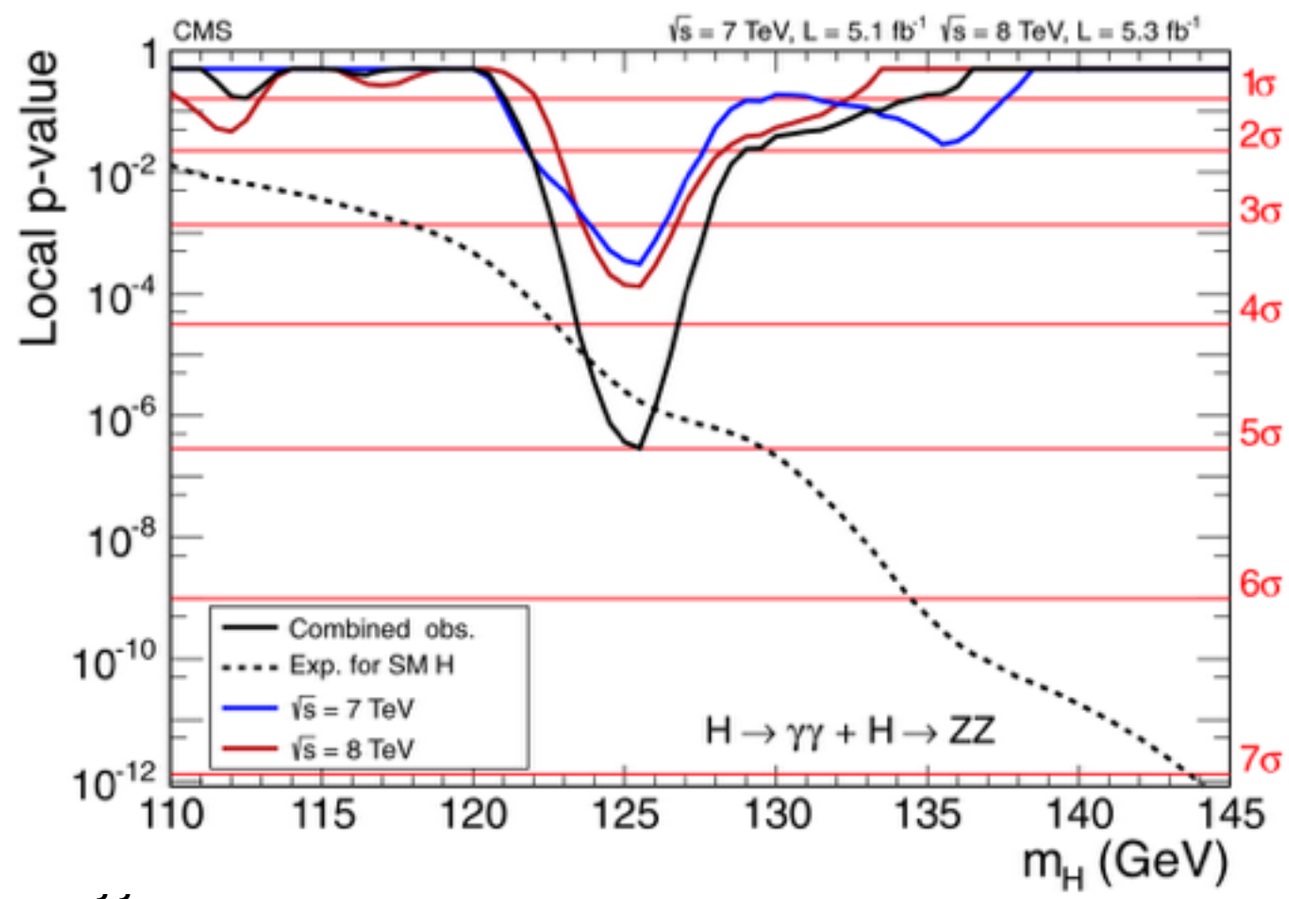
Statistical analysis

Basic approach: use (binned or unbinned) likelihood ratio

$$\lambda(\mu) = L\left(\mu, \hat{\hat{\vec{\theta}}}(\mu)\right) / L\left(\hat{\mu}, \hat{\vec{\theta}}\right)$$

- μ: assumed signal strength
- θ: nuisance parameters parametrising effect of systematic uncertainties on predictions
- per channel or combined





Determination of Higgs boson properties

Spin/parity determination (1)

Relax and test assumptions about Higgs spin and parity properties.
Sensitivity especially in decay angular distributions

- spin 0: $A(X \to VV) = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right)$ 0^+, 0^-
- spin 2:

$$A(X \to VV) = \Lambda^{-1}\Big[2g_1^{(2)} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2^{(2)} t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}$$
$$+ g_3^{(2)}\frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4^{(2)}\frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2\left(2g_5^{(2)} t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2g_6^{(2)}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}\left(\epsilon_1^{*\nu}\epsilon_2^{*\alpha} - \epsilon_1^{*\alpha}\epsilon_2^{*\nu}\right) + g_7^{(2)}\frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu}\epsilon_1^* \epsilon_2^*\right)$$
$$+ g_8^{(2)}\frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha}\tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right)\Big]$$

graviton-like tensor: $g_1^{(2)} = g_5^{(2)}$

- only polarisation states ±1 ($\bar{q}q$), ±2 (gg) possible ➠ predictions depend on fraction of events produced from each initial state
- (spin 1 also considered)

Not an exhaustive list of options!

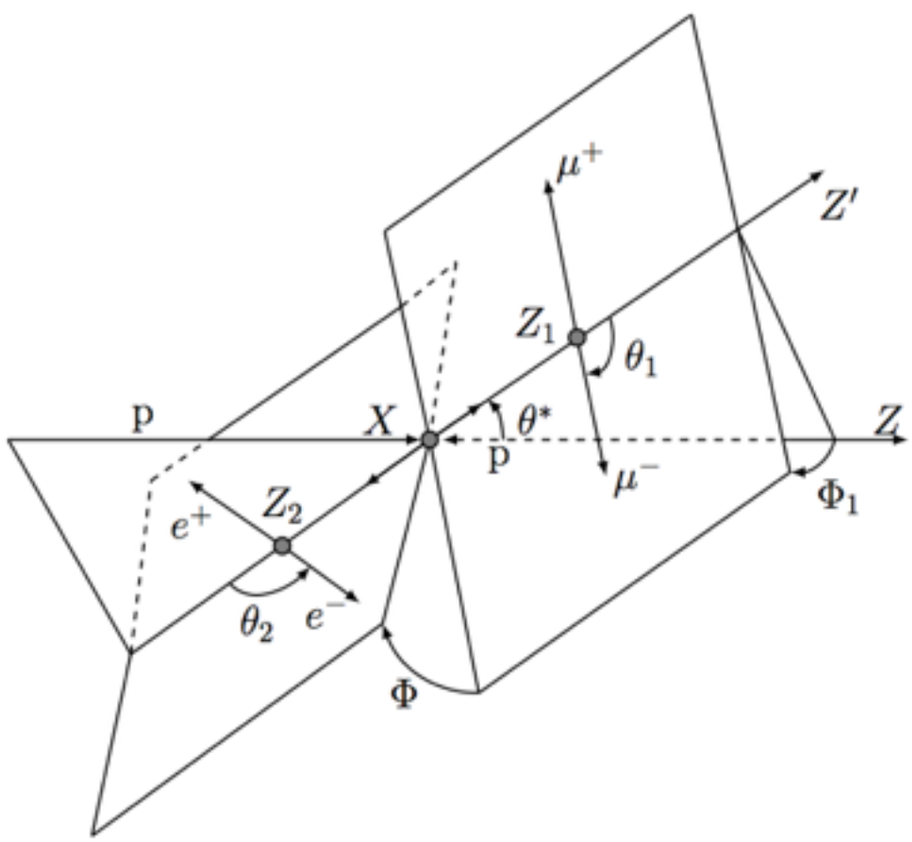
- CP admixtures in principle possible (property of the coupling, not the particle)

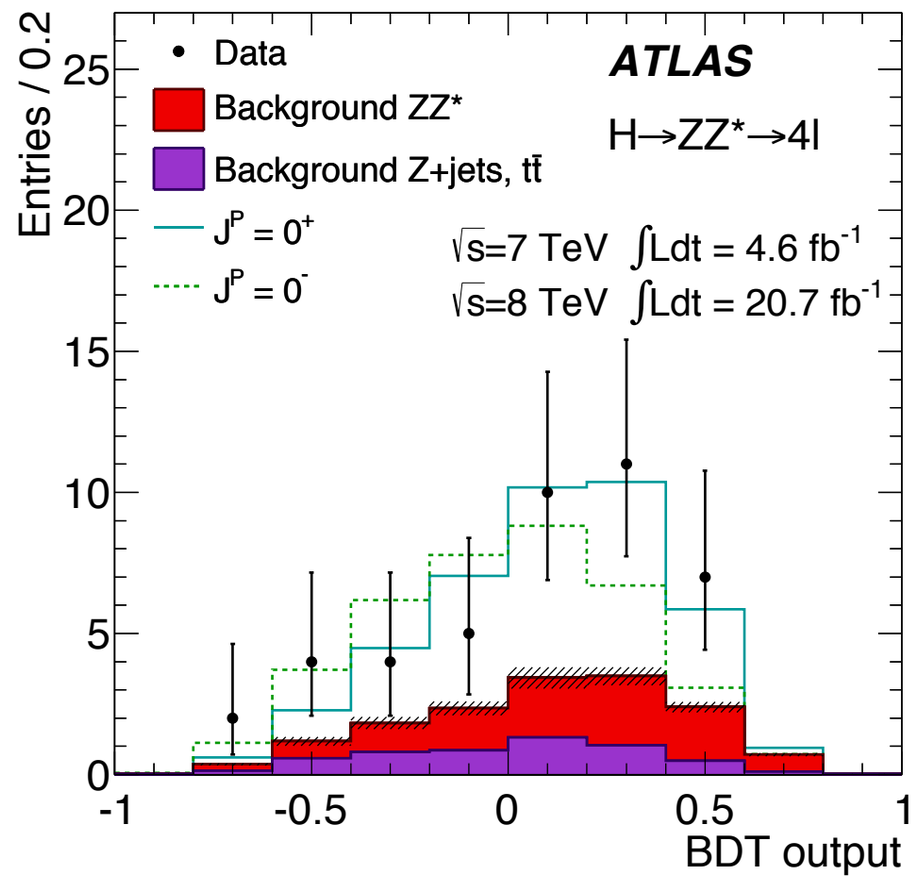
Spin/parity determination (2)

Maximum information can be obtained from H→WW, ZZ analyses (leptons carry information about W, Z spins)

H→ZZ: 5 angles in addition to m_{12}, m_{34}

- build BDTs using all information, trained to distinguish each spin/parity hypothesis from the 0^+ one
  - alternative: likelihood ratio computed from matrix element calculations





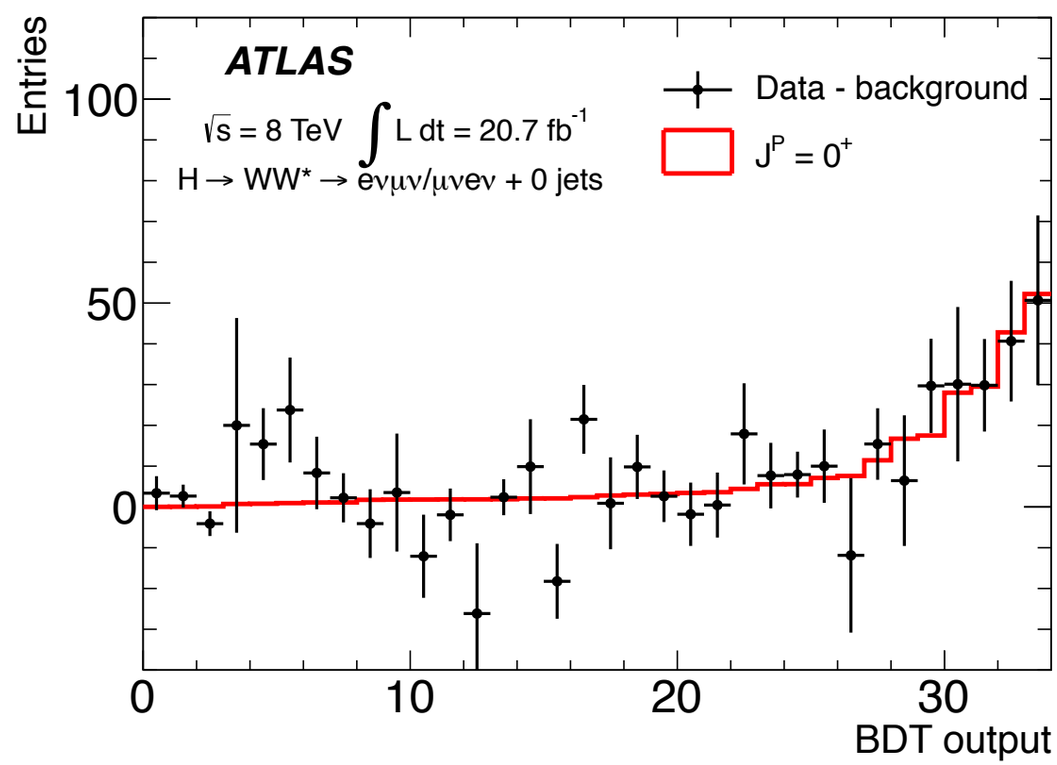
Spin/parity determination (3)

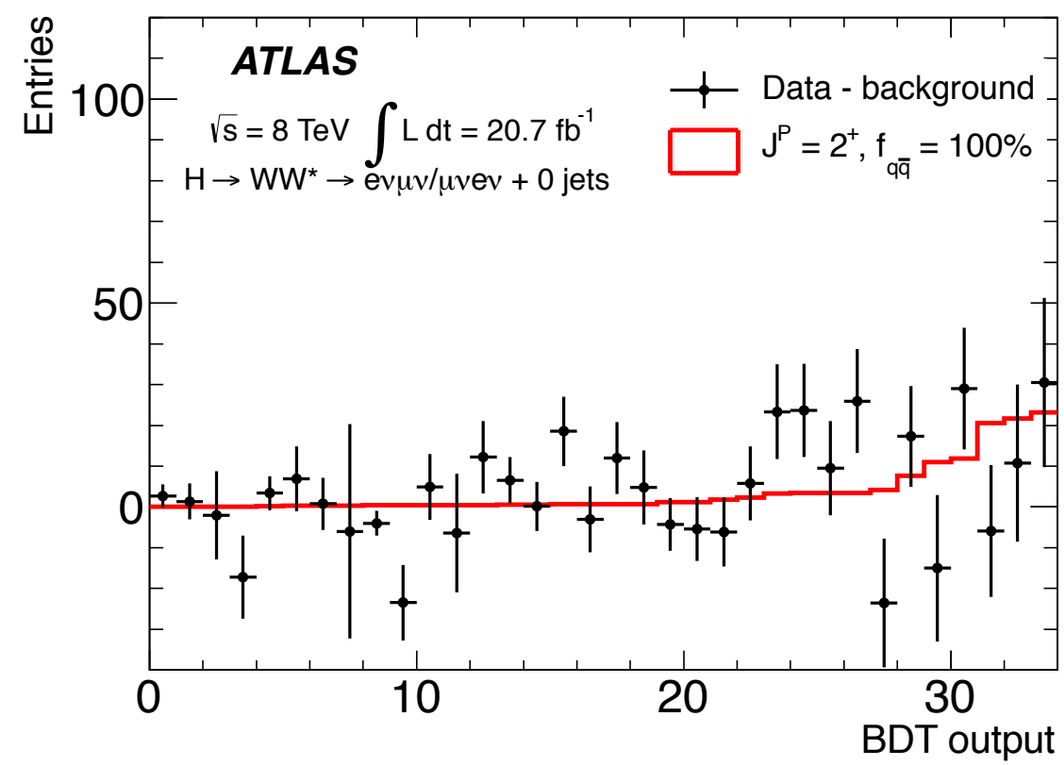
H→WW: relax m(ℓℓ) and Δφ(ℓℓ) cuts. Subsequently, use two BDTs:

- $J^P=0^+$ signal trained against bg
- $J^P=0^+$ signal trained against alternative J^P hypothesis

2D BDT output mapped onto 1D, with bins ordered in increasing number of <u>expected signal</u> events for the assumed hypothesis

- relies sensitively on good modelling of BDT discriminant distributions; verified in validation regions

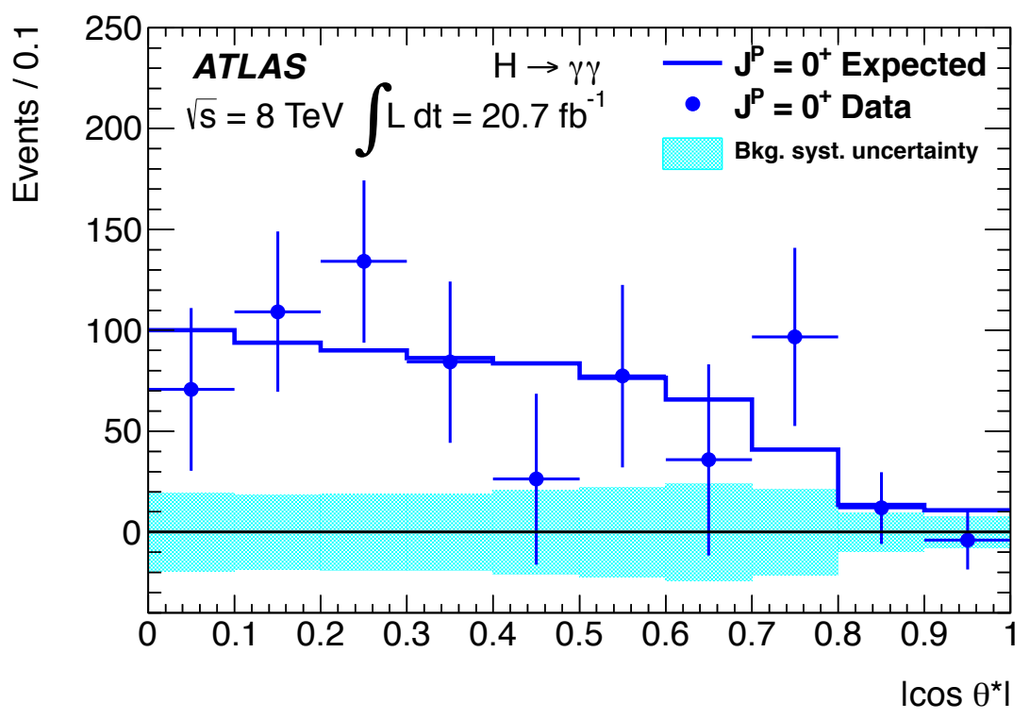


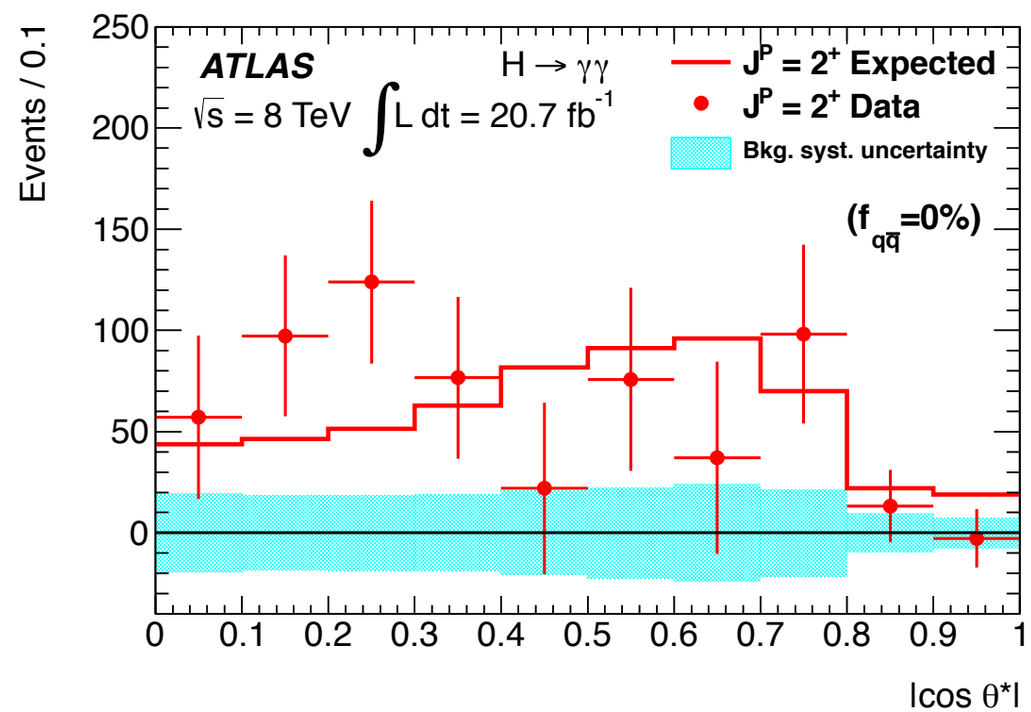


Spin/parity determination (4)

Some information can be obtained from H→γγ: scattering angle in Collins-Soper frame

$$|\cos\theta^*| = \frac{\sinh \Delta\eta_{\gamma\gamma}}{\sqrt{1+(p_{T,\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_{T,\gamma_1}p_{T,\gamma_2}}{m^2_{\gamma\gamma}}$$





- background subtraction depends slightly on nuisance parameters
  - different for different J^P hypotheses

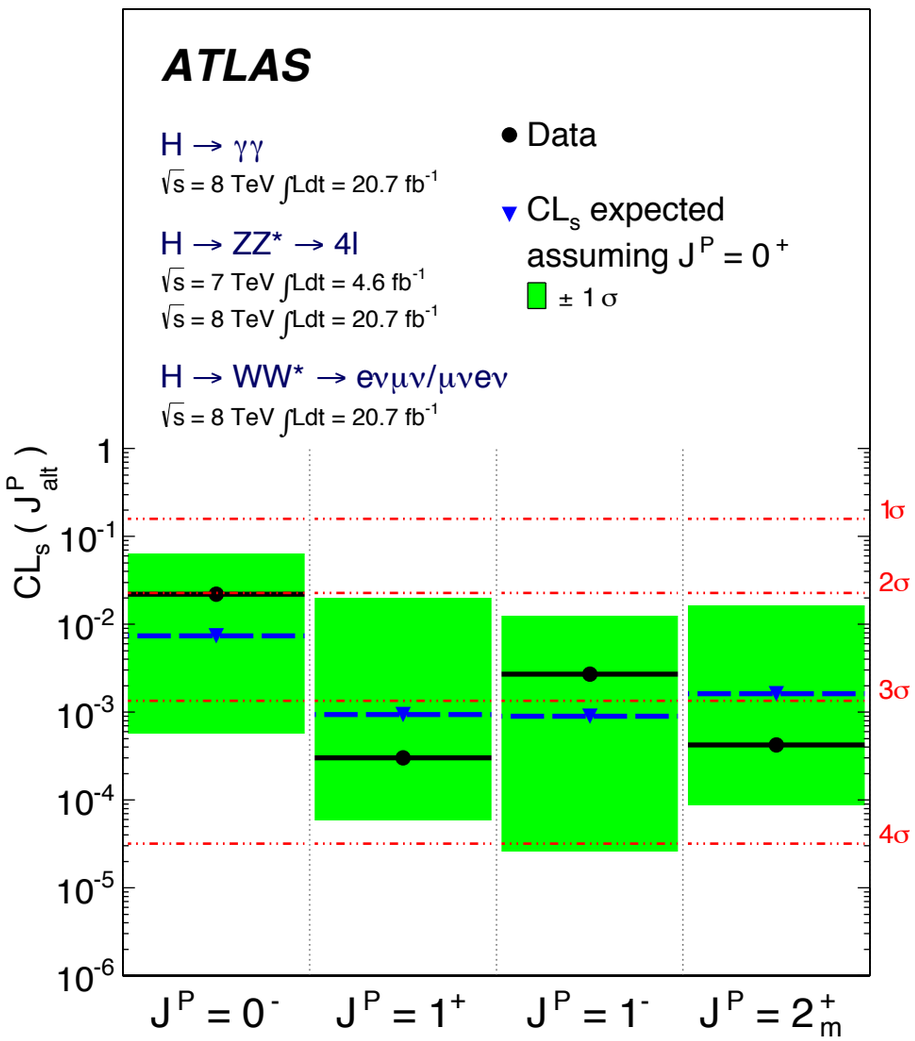
Spin/parity determination (5)

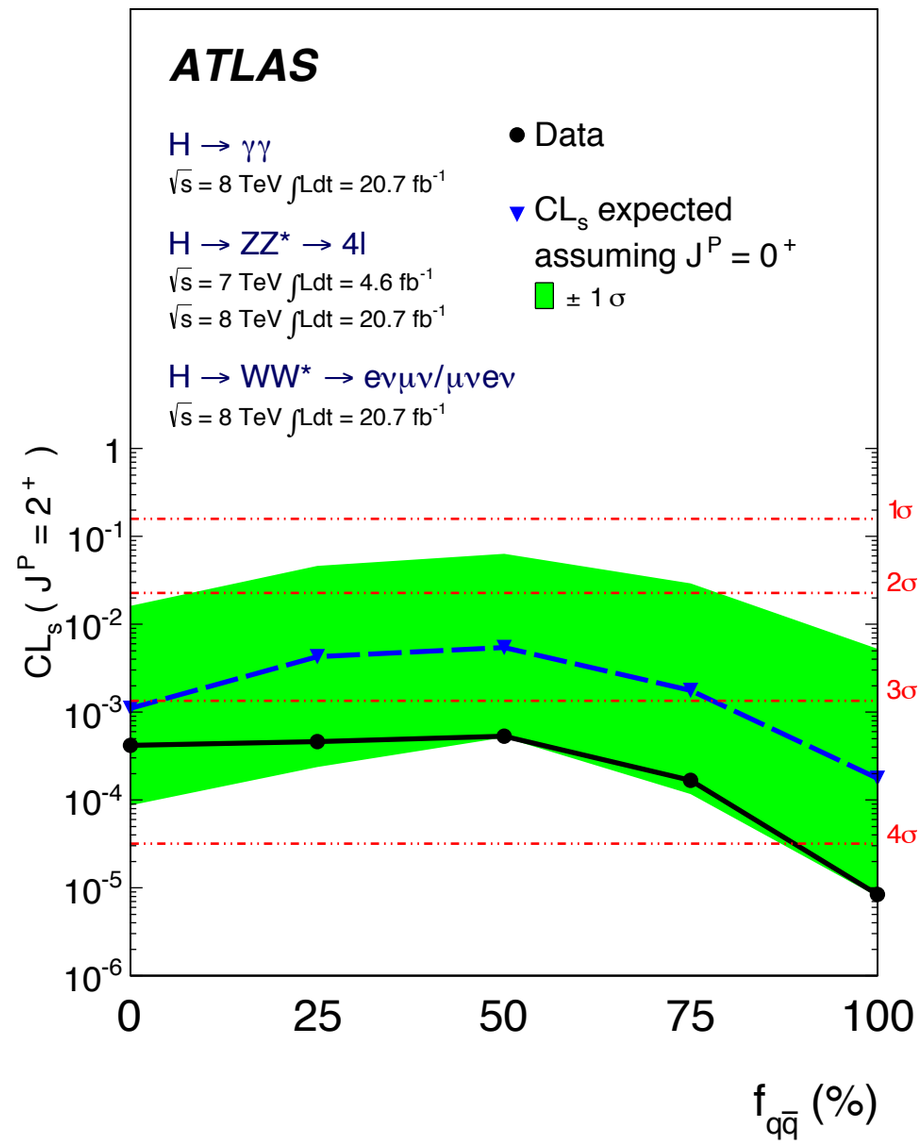
Statistical procedure again using likelihood ratio

$$q = L\left(\hat{\mu}(J^P), \hat{\vec{\theta}}(J^P)\right) / L\left(\hat{\mu}(0^+), \hat{\vec{\theta}}(0^+)\right)$$

All alternative hypotheses rejected at 95% CL

- but CP admixtures are still possible! Analyses are ongoing





Other processes (1)

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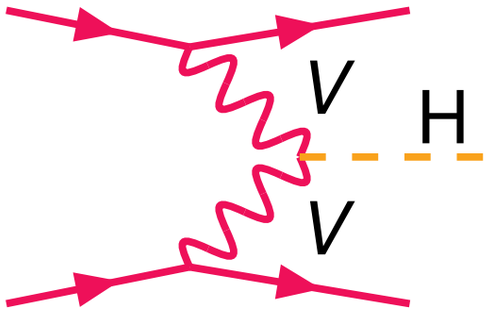
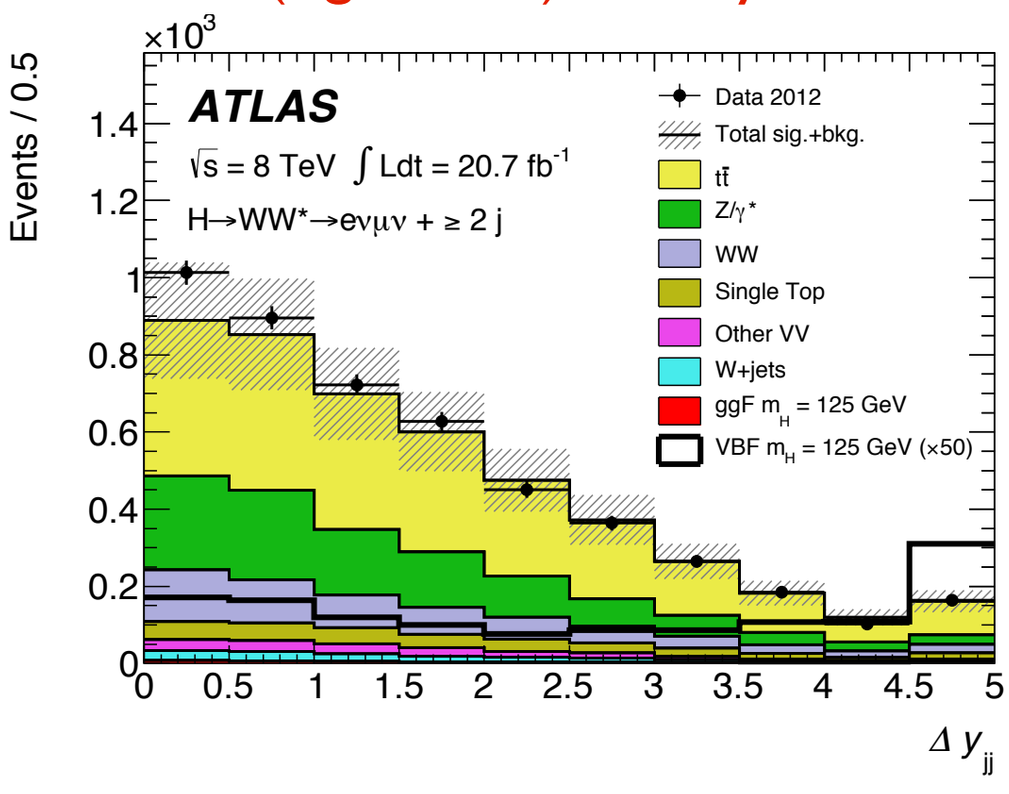
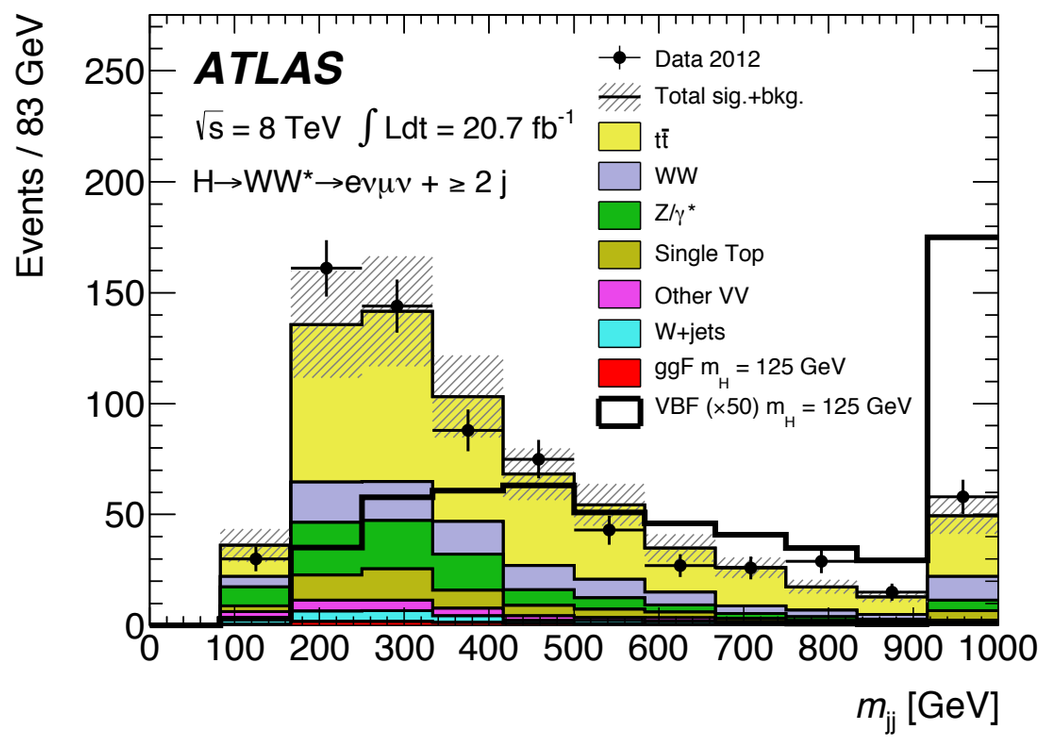


- VBF production: two ($q/\bar{q}$) jets with large $\Delta\eta$
  - H is a colour singlet ➠ no colour flow in central region
  - example: $H \rightarrow WW$: events with two (non-b-tagged) jets
    - veto on (significant) activity in central region





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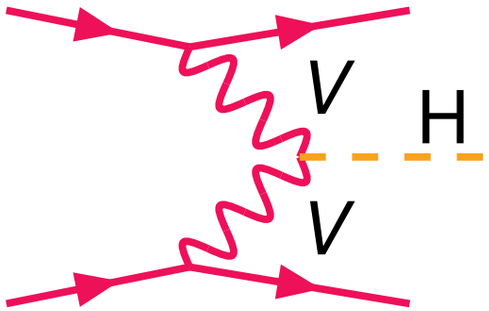

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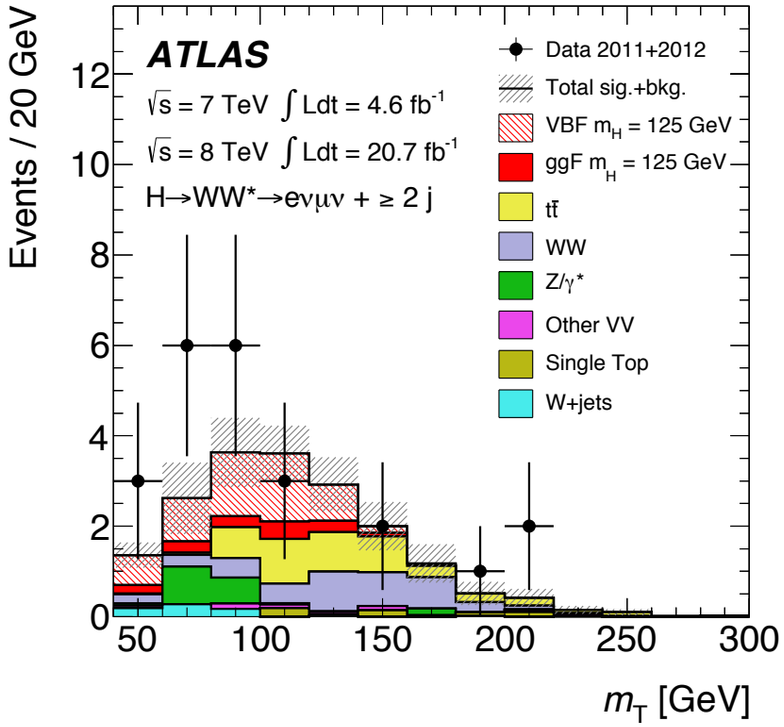
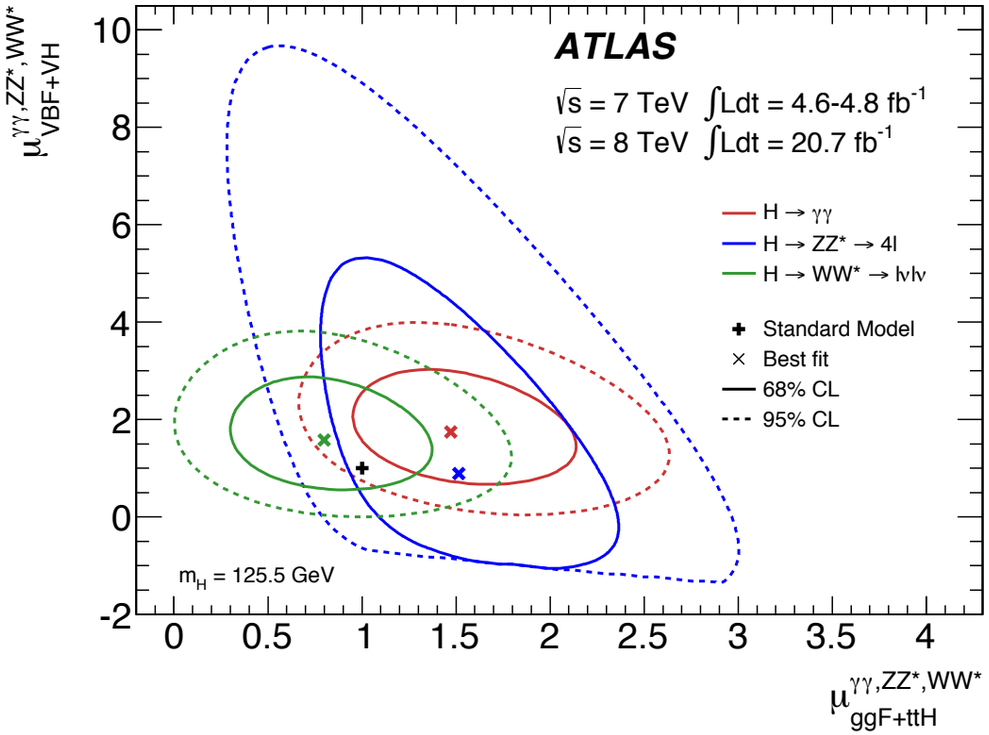
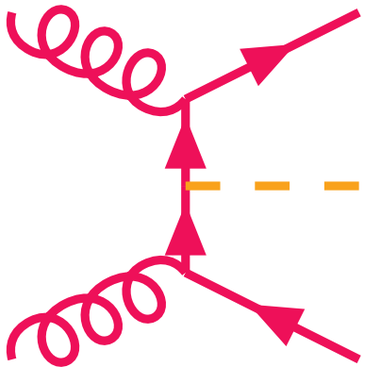




Other processes (2)



Production in association with a $\bar{t}t$ pair:

- basic $\bar{t}t$ event selection + more H decay specific criteria
  - $\bar{b}b$, $\gamma\gamma$, "multilepton" ($\tau\tau$, WW)
- $\bar{b}b$: busy final state with 6/4 jets (and 4 b jets) ➠ nontrivial reconstruction (not done explicitly for Run-1 analyses)
  - MVA carried out in different N_{jet}/N_b bins
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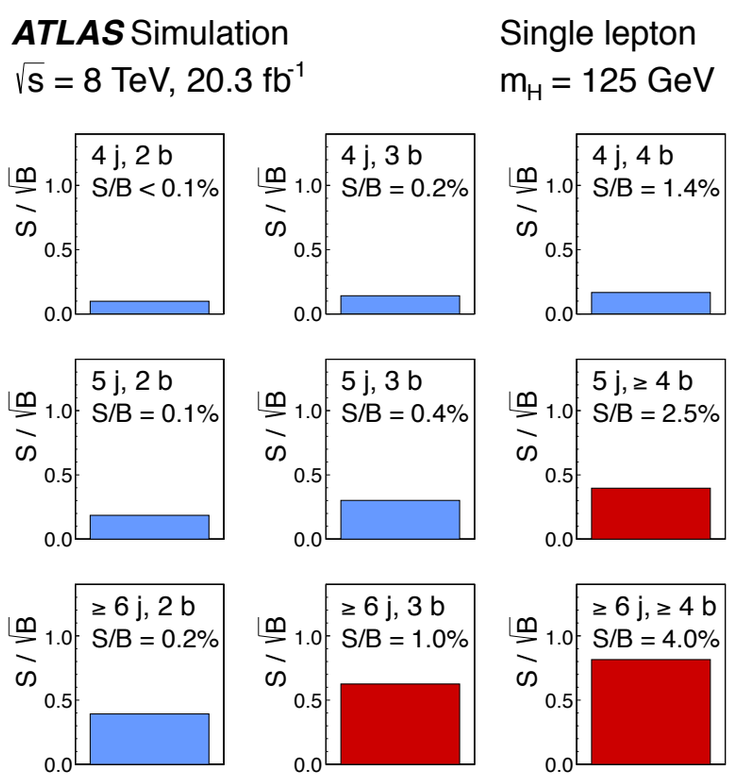

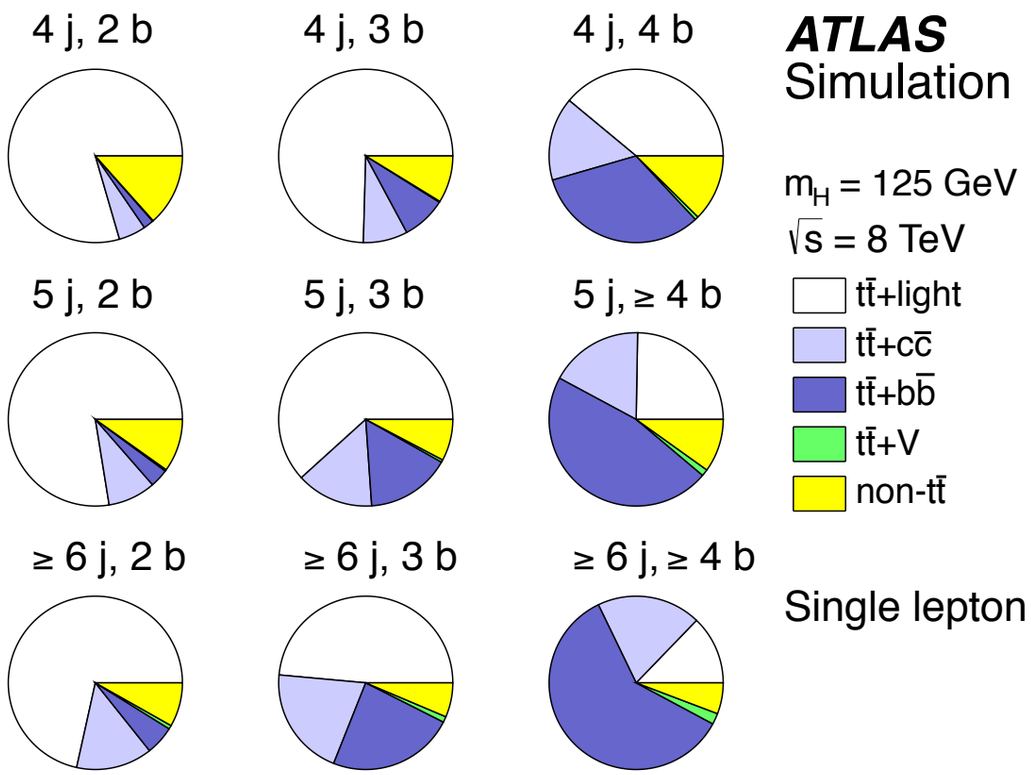

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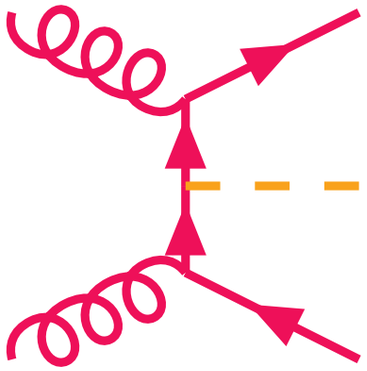

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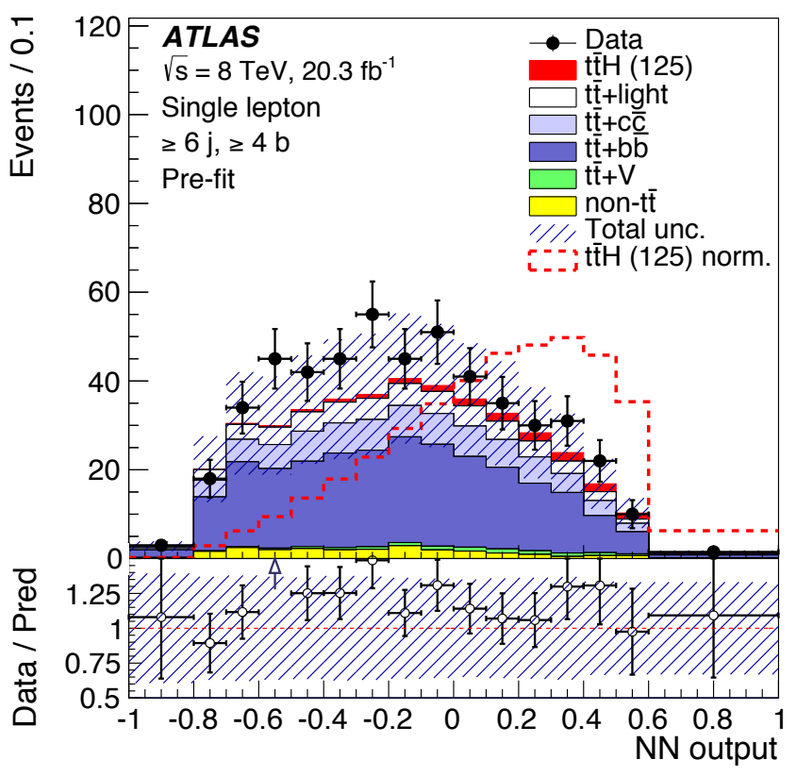

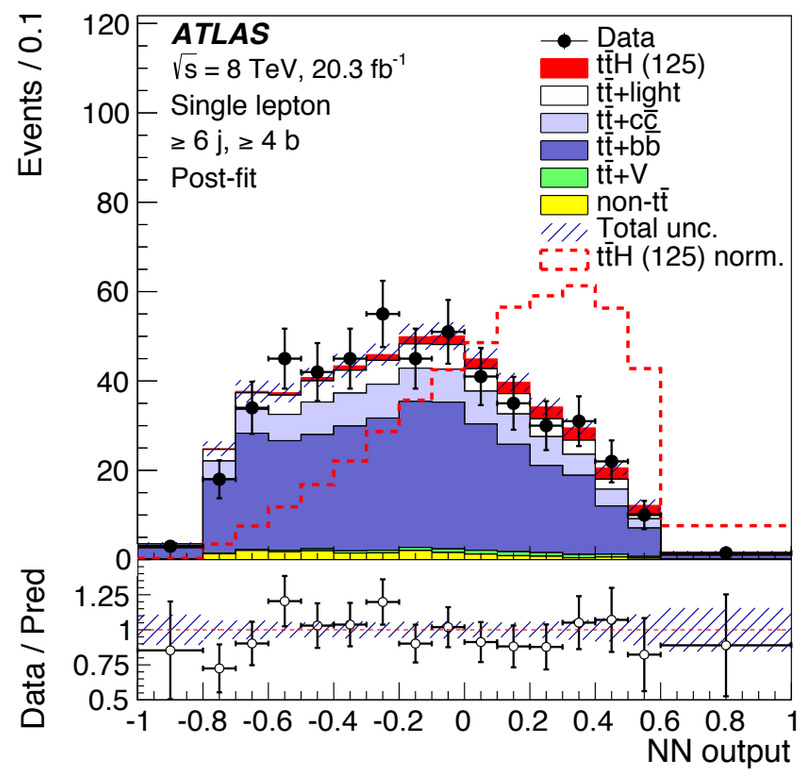

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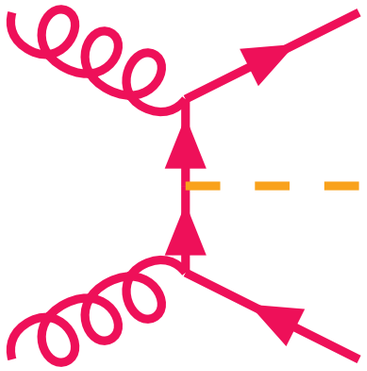

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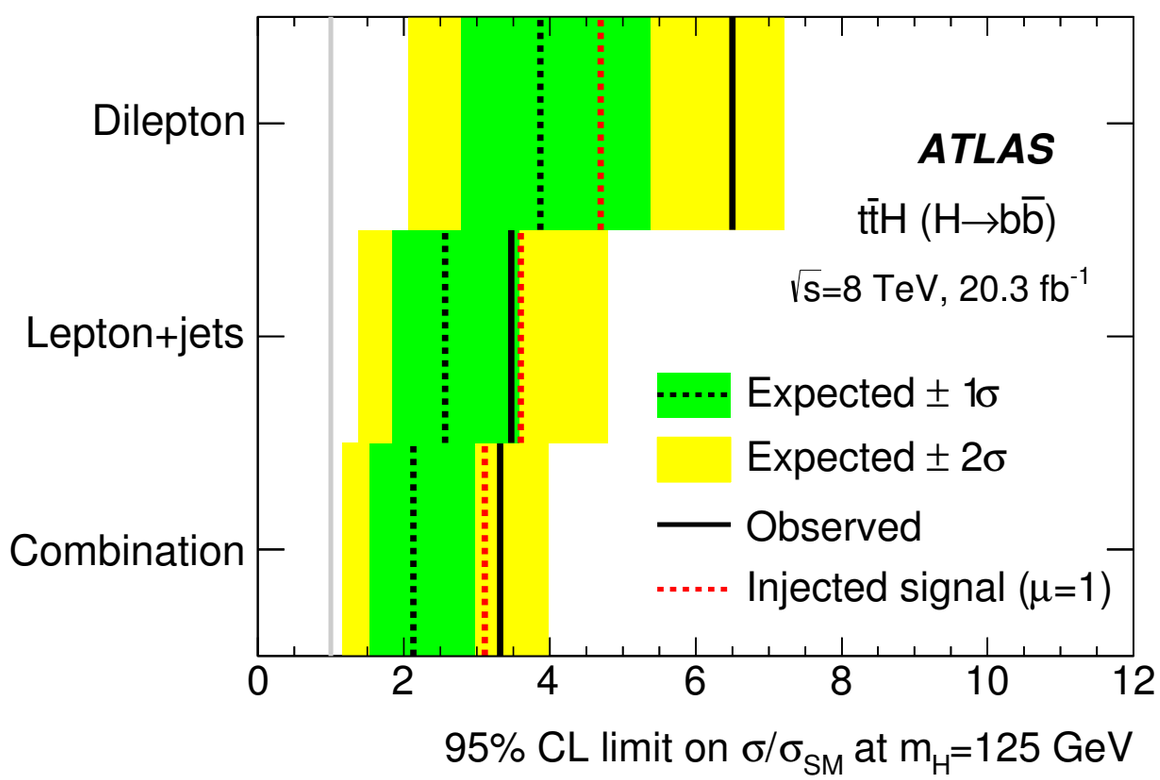

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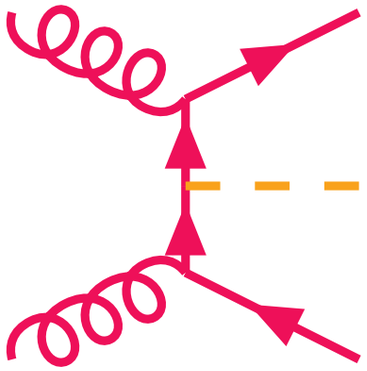

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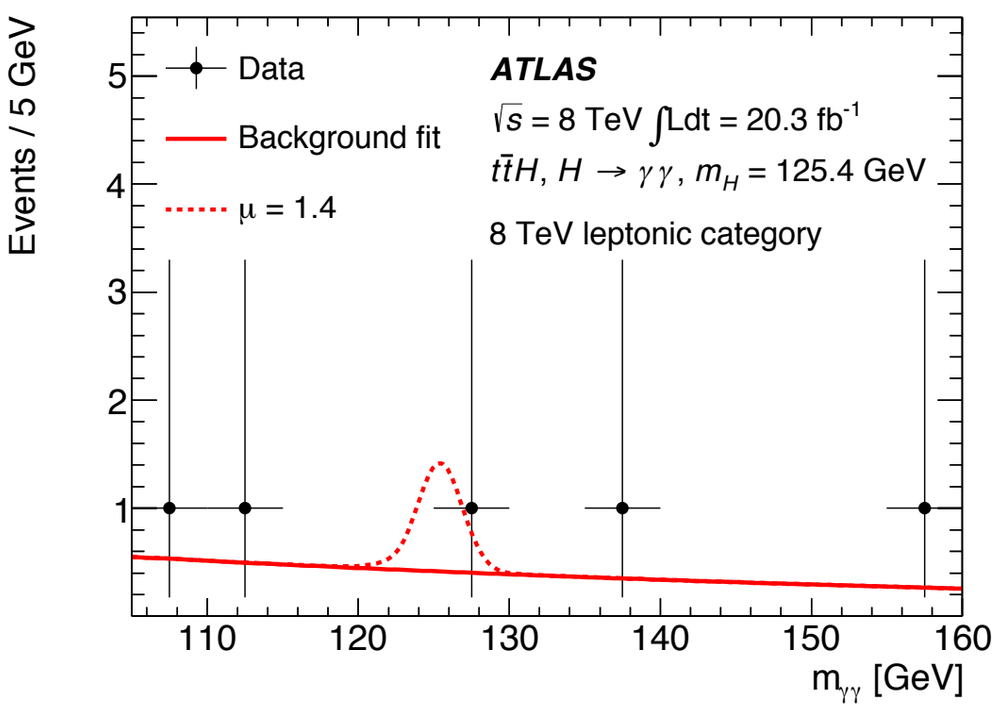

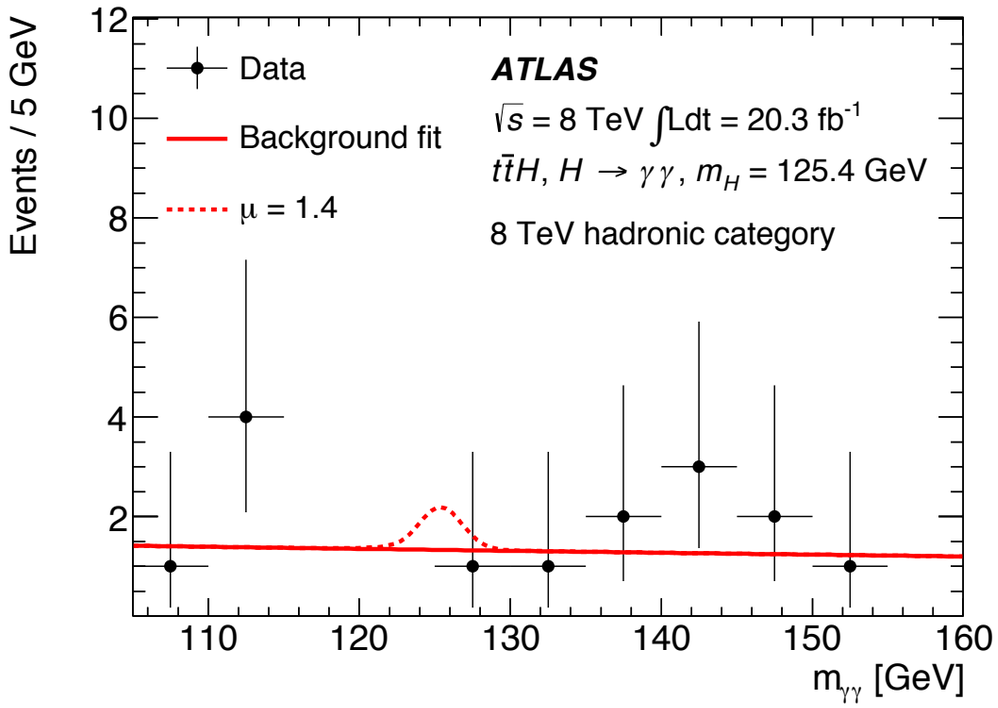

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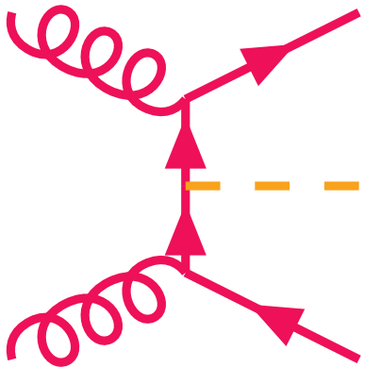

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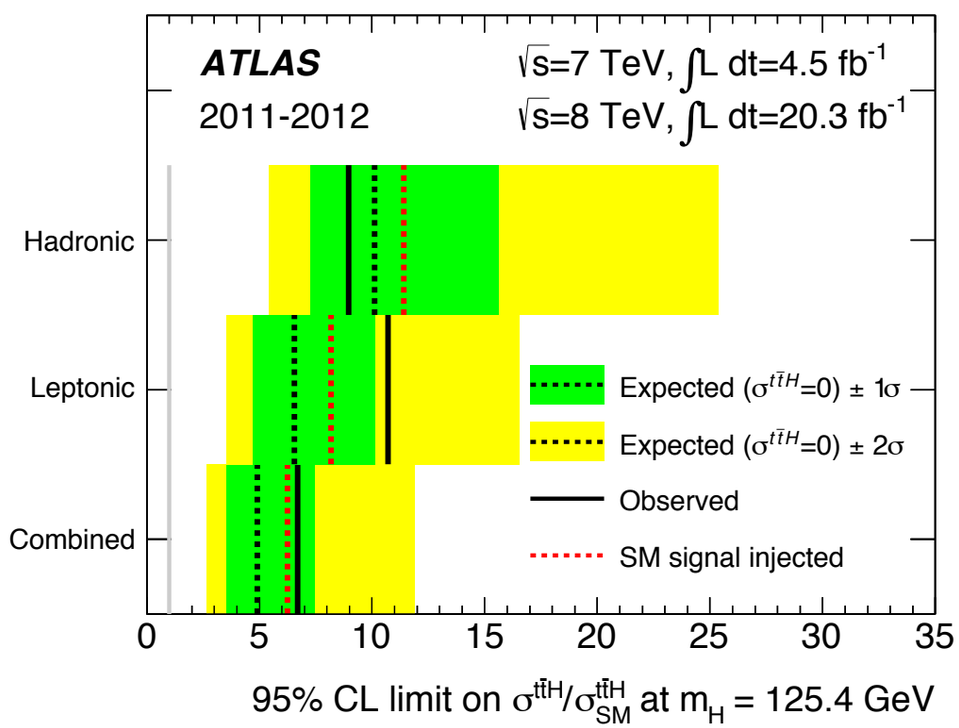

Other processes (3)

Decays to fermions: not covered at discovery time. Important to determine Yukawa couplings

- no evidence (from LHC) for $H \rightarrow \bar{b}b$ yet
  - not discussed: W/Z+ H production
- $H \rightarrow \tau^+\tau^-$: complicated due to multiple decay modes ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$) and missing ν
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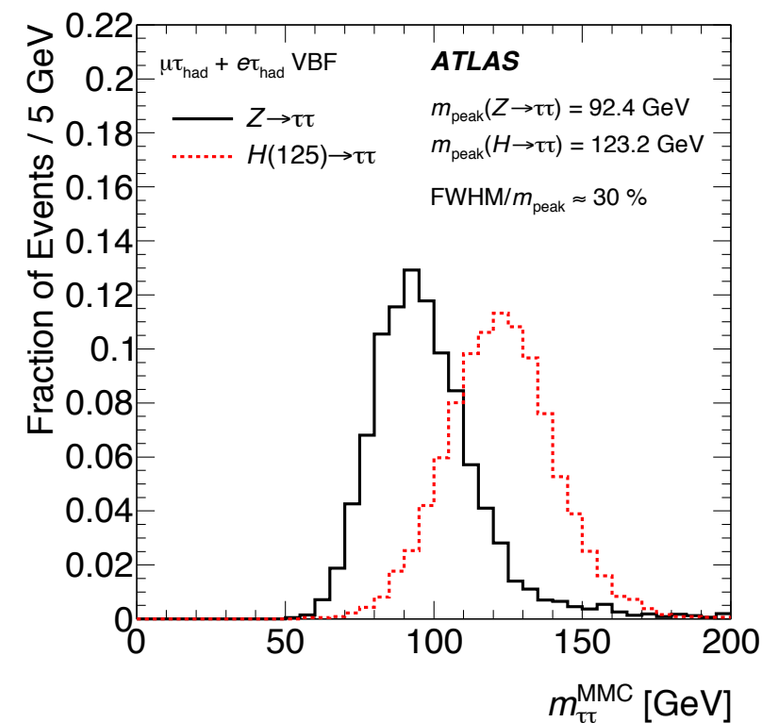

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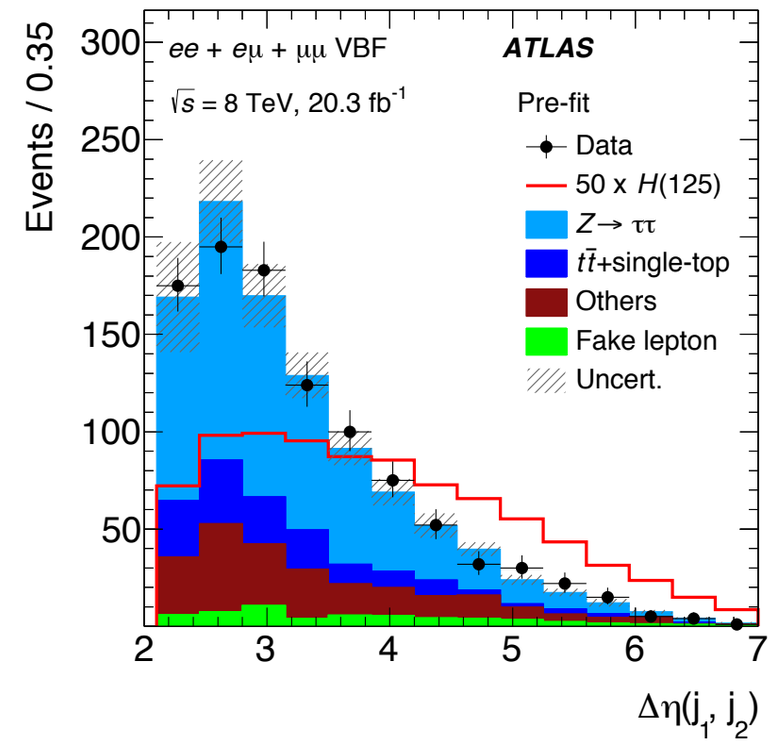

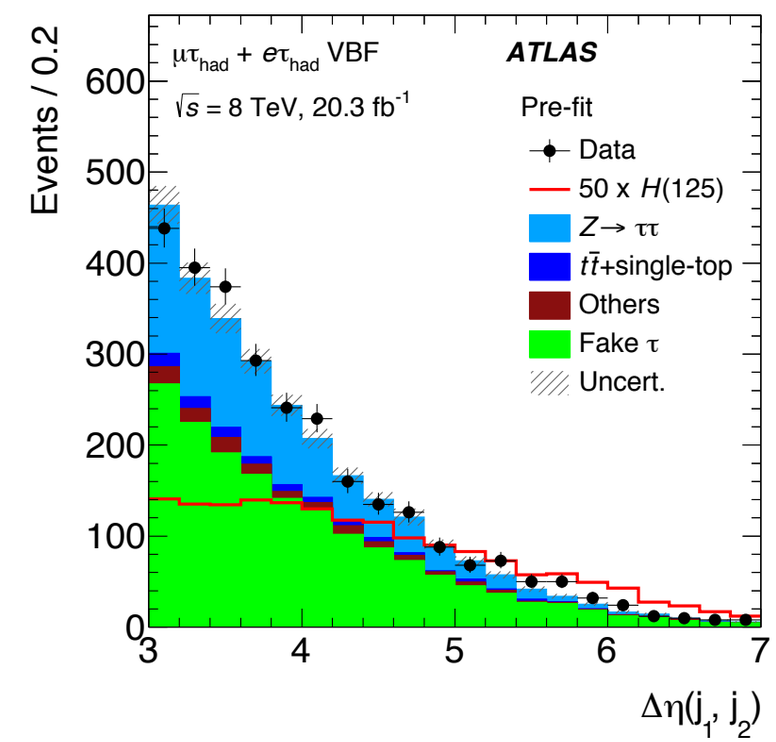

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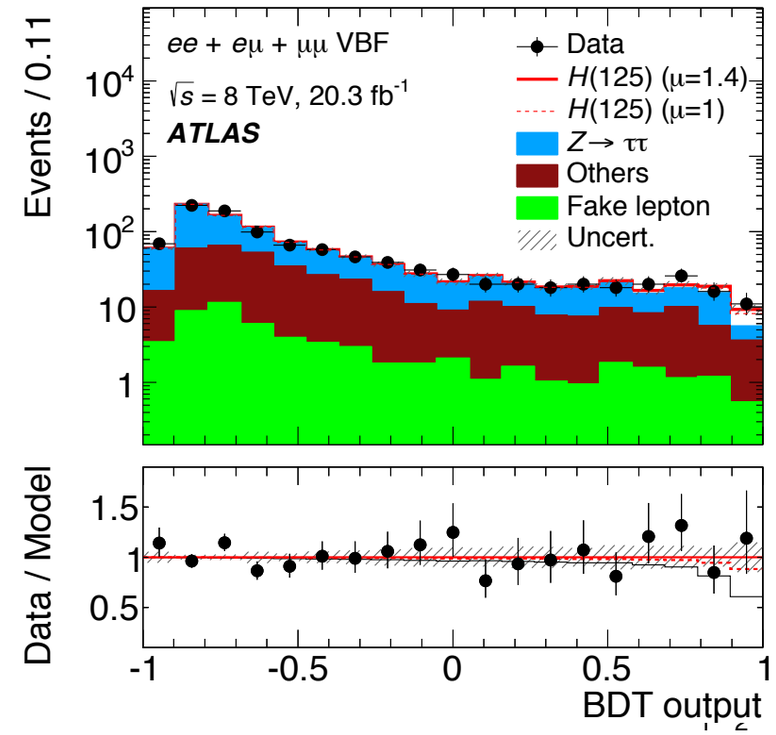

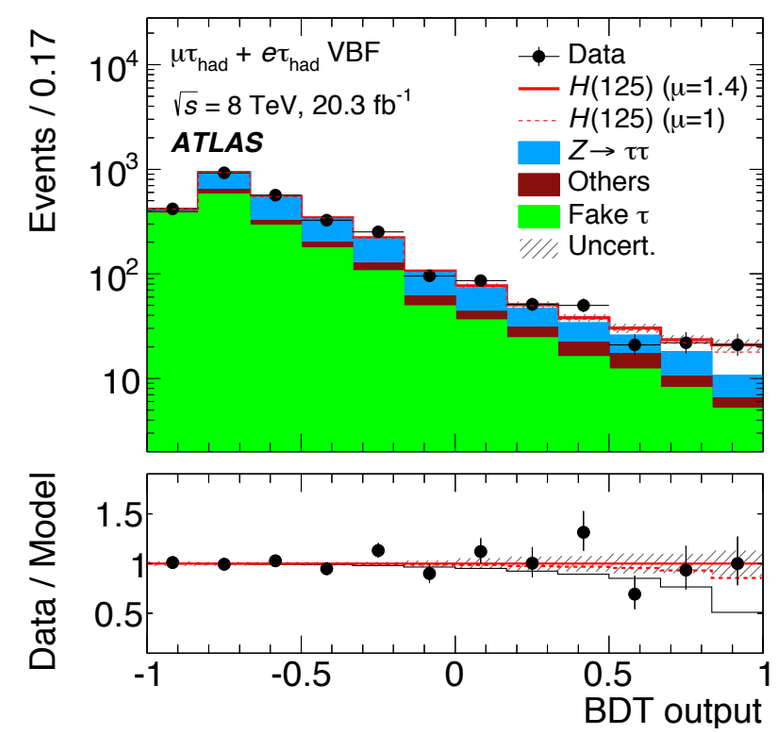

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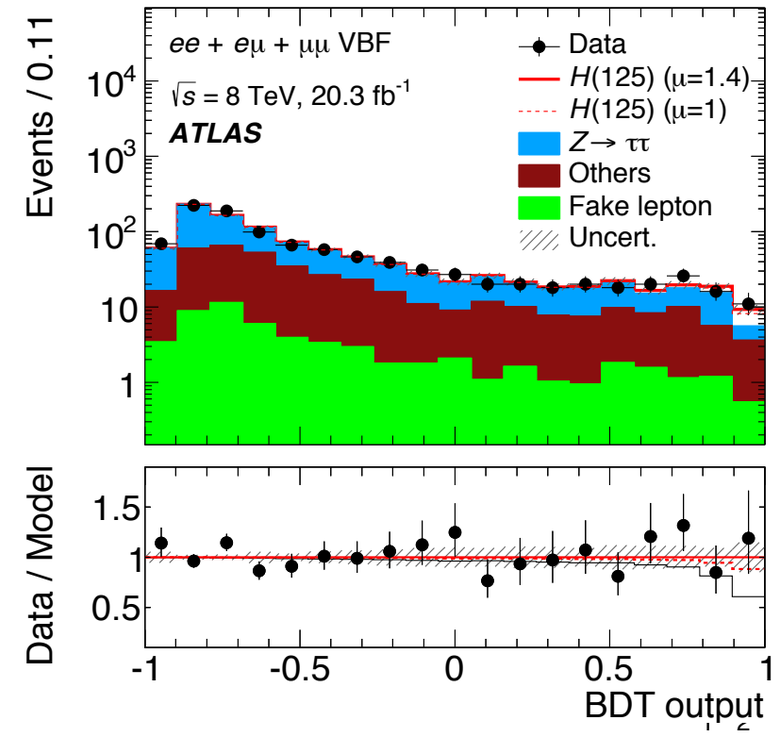
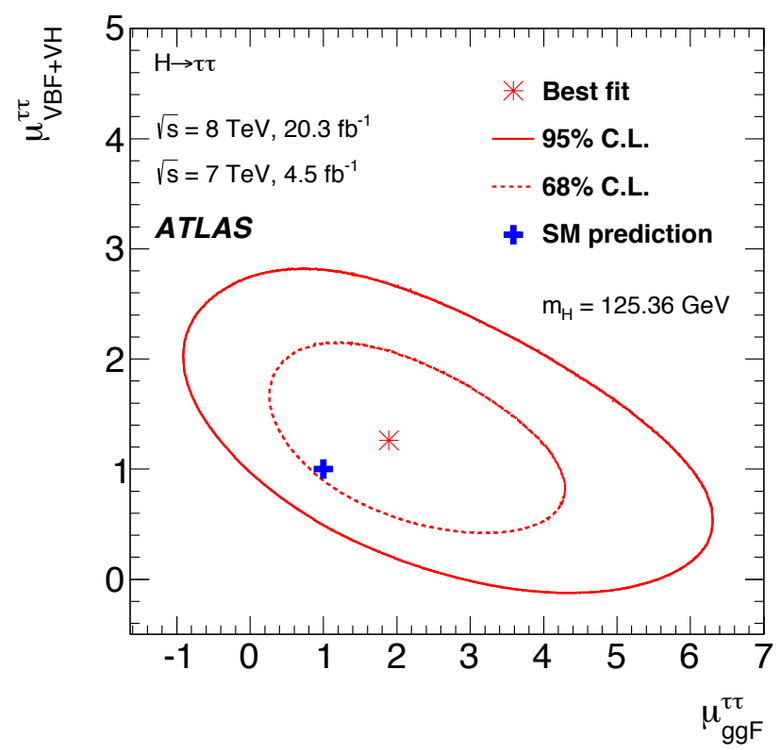
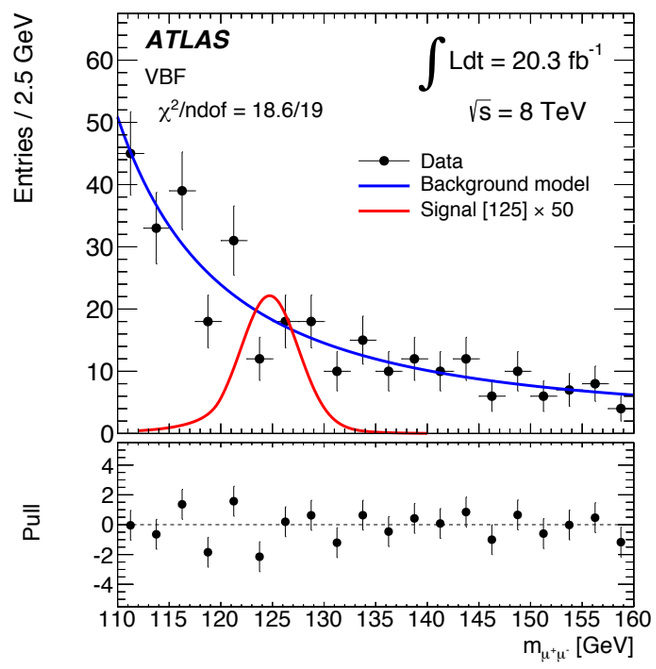


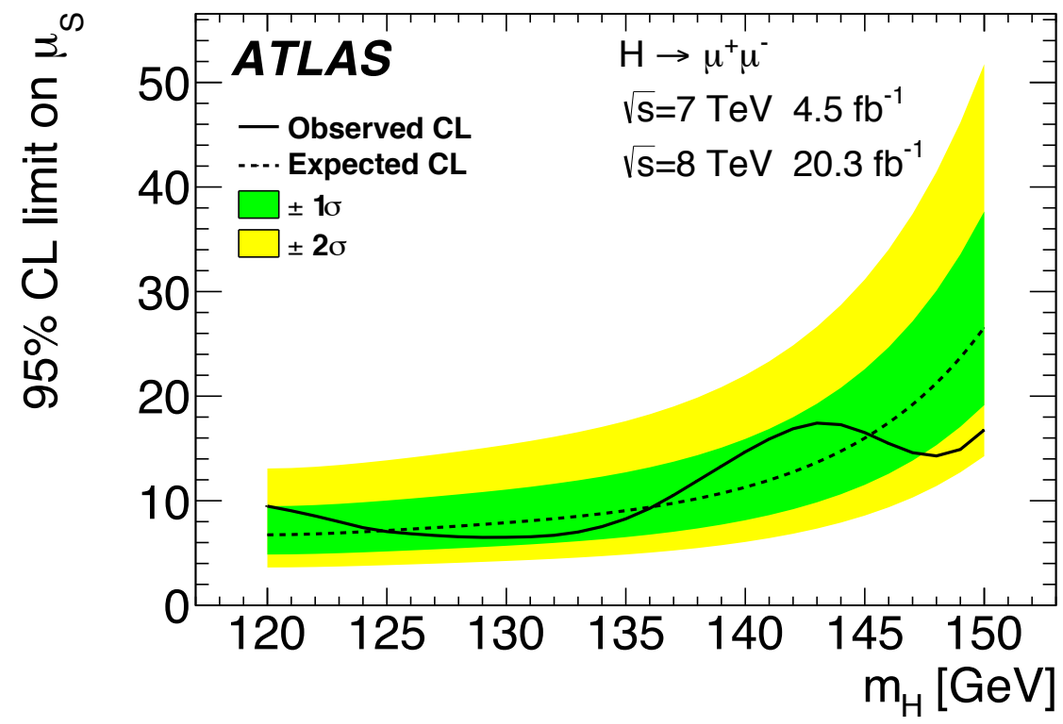


Other processes (4)

Similarly, look for evidence of Higgs coupling to 2nd generation fermions: $H \rightarrow \mu^+\mu^-$

- excellent mass resolution and efficiency… but very low rate
- most sensitive search (reduced $Z \rightarrow \mu^+\mu^-$ bg) again in VBF production mode
- statistics limited; discovery for SM strength will need full Run-2 dataset





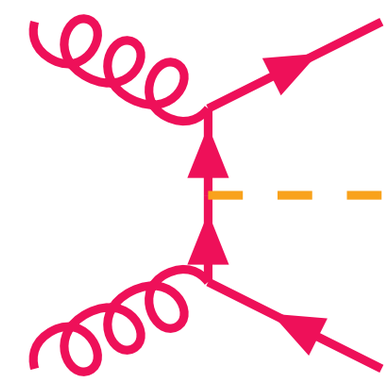
BSM Higgs searches

Neutral MSSM Higgs boson searches

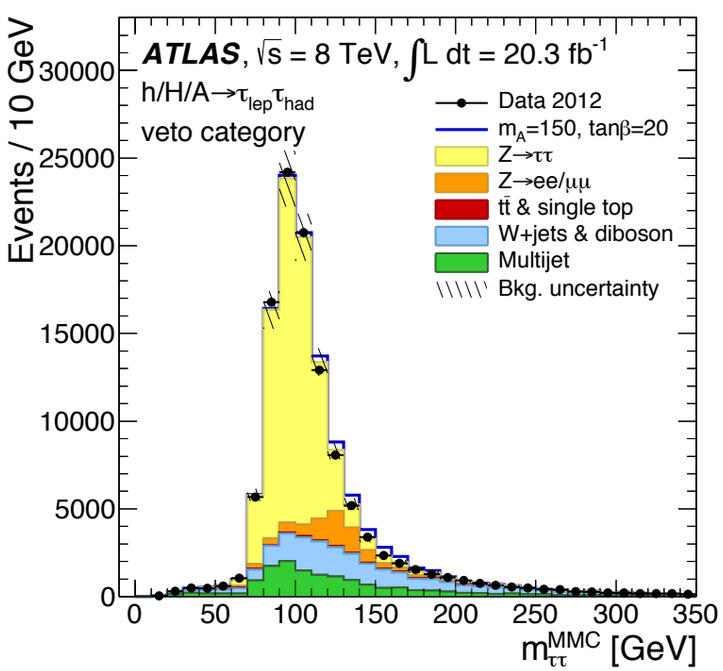
The MSSM knows 5 Higgs bosons: h, H, A, $H^{\pm}$

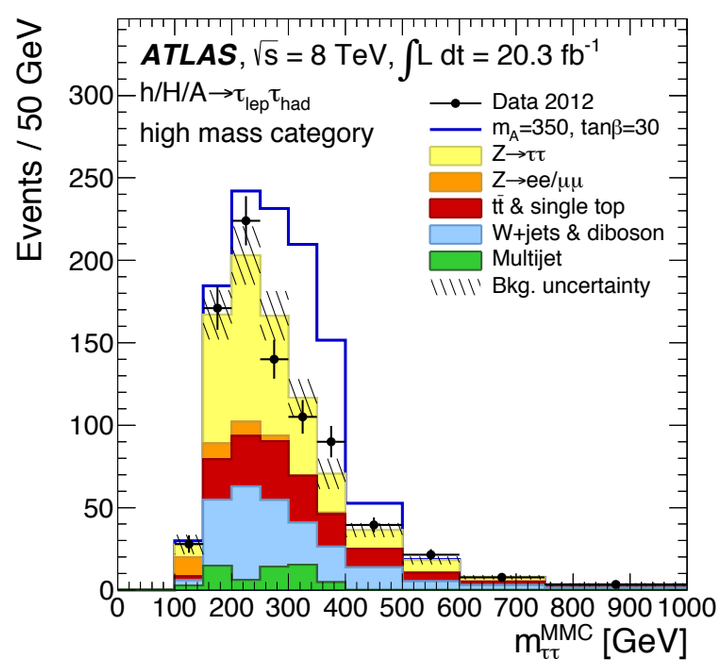
- assume that the 125 GeV boson is h ➠ strong constraints on (m_A, tanβ)
- will not discuss here any (re-)interpretation of existing measurements in terms of MSSM parameters but focus only on <u>additional</u> searches

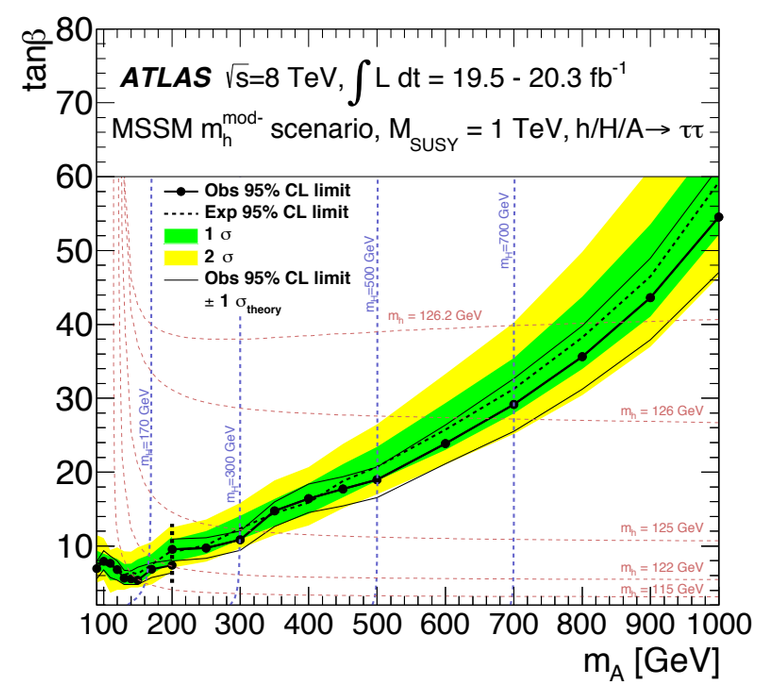
Neutral Higgs bosons:



- high tanβ: H/A → $\tau^+\tau^-$ ($\bar{b}b$ more difficult..)
  - heavy ➠ H/A masses become degenerate
  - VBF production suppressed ➠ gluon fusion or $\bar{b}b$ H/A







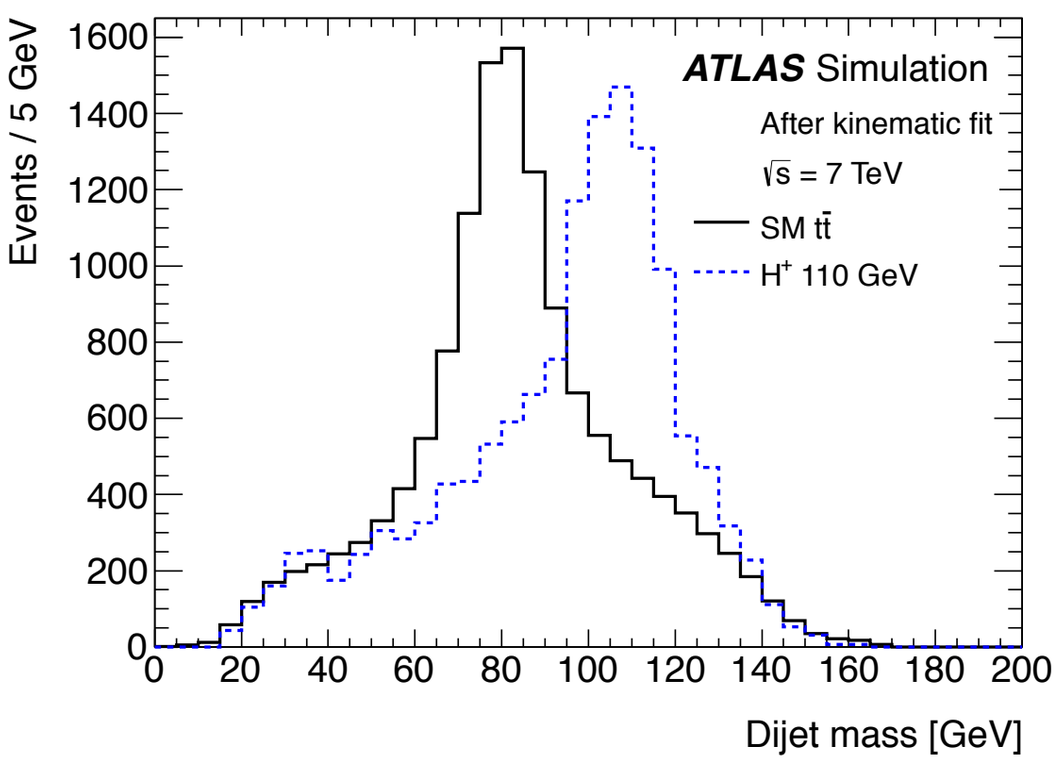
Charged MSSM Higgs boson searches (1)

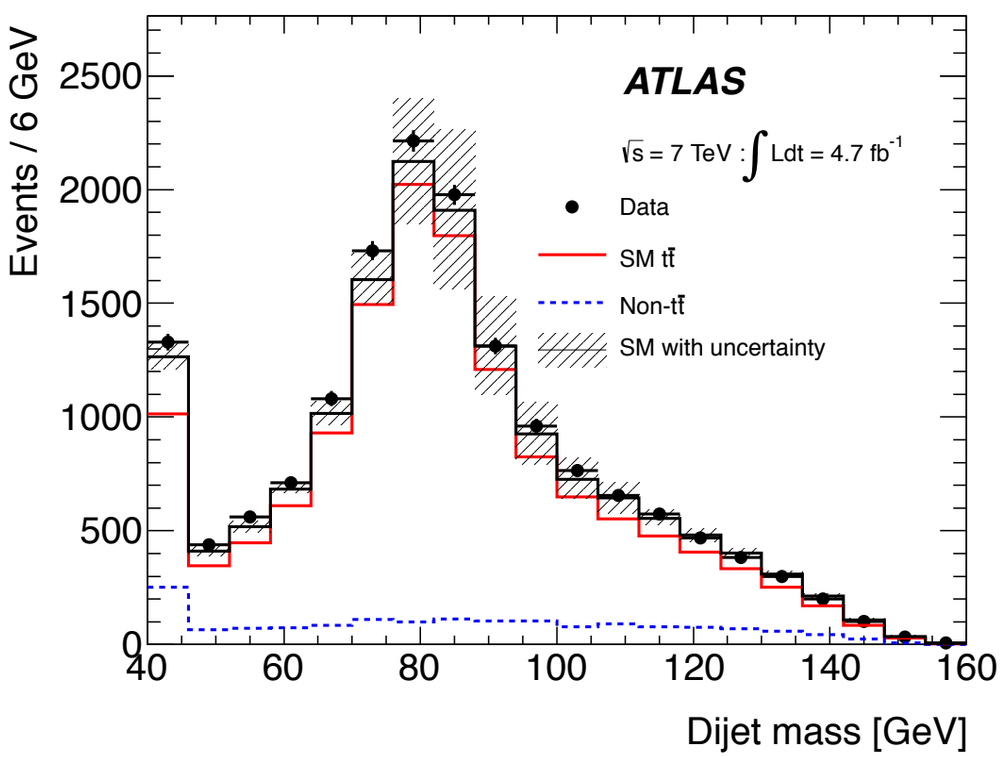
Charged Higgs boson coupling to fermions (e.g. tb):

$$H^{\pm} tb \text{ coupling} \sim V_{tb}\,(m_t \cot\beta(1-\gamma_5) + m_b \tan\beta(1+\gamma_5))$$

$m_{H\pm} < m_t + m_b$: production in top quark decays, decay to cs (low tanβ) or τν (high tanβ)

- decay to cs "straightforward" but relies on precise m_{jj} reconstruction in $t \to bjj$ decays
- decay to $\tau_{had}\nu$: test for deviations from lepton universality + use





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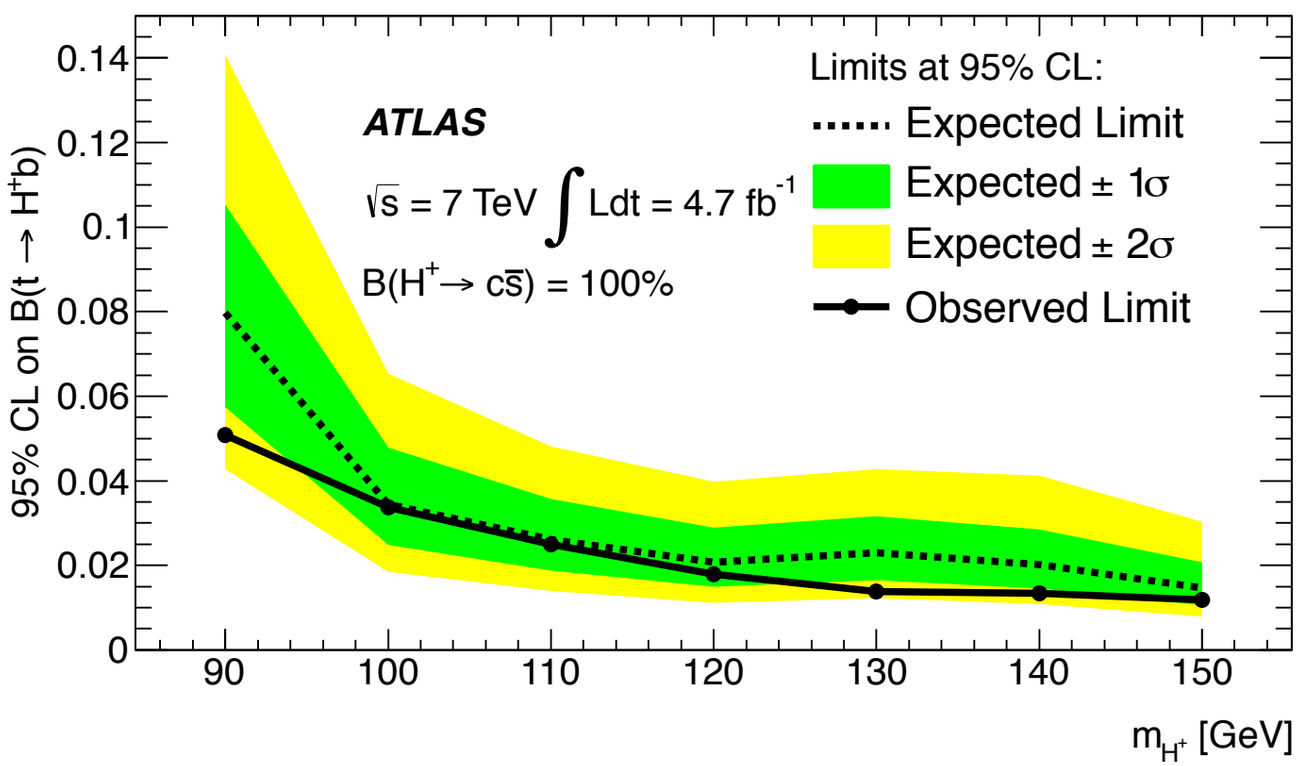


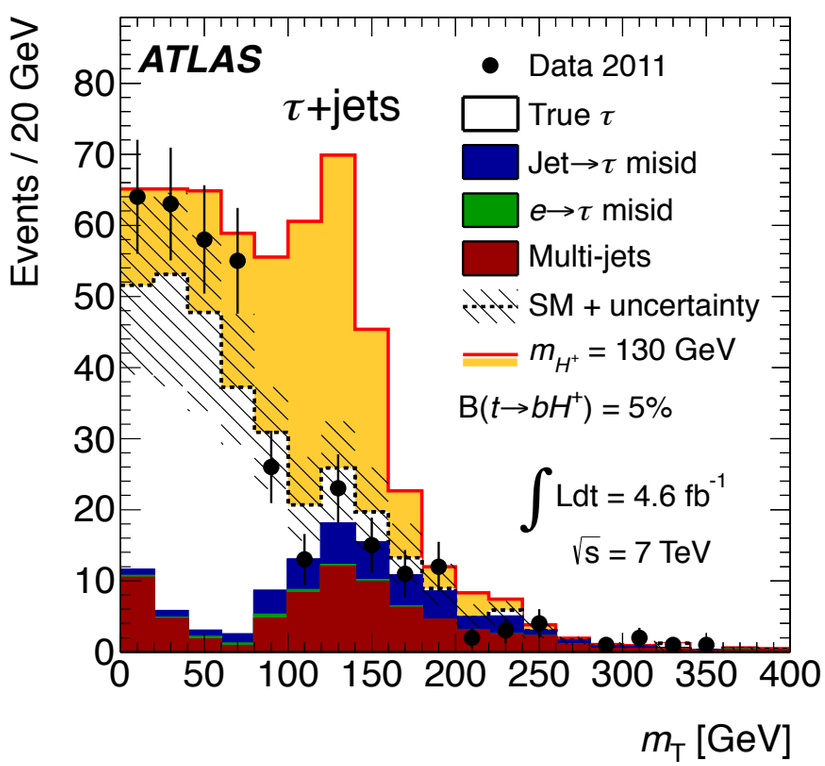
Charged MSSM Higgs boson searches (1)

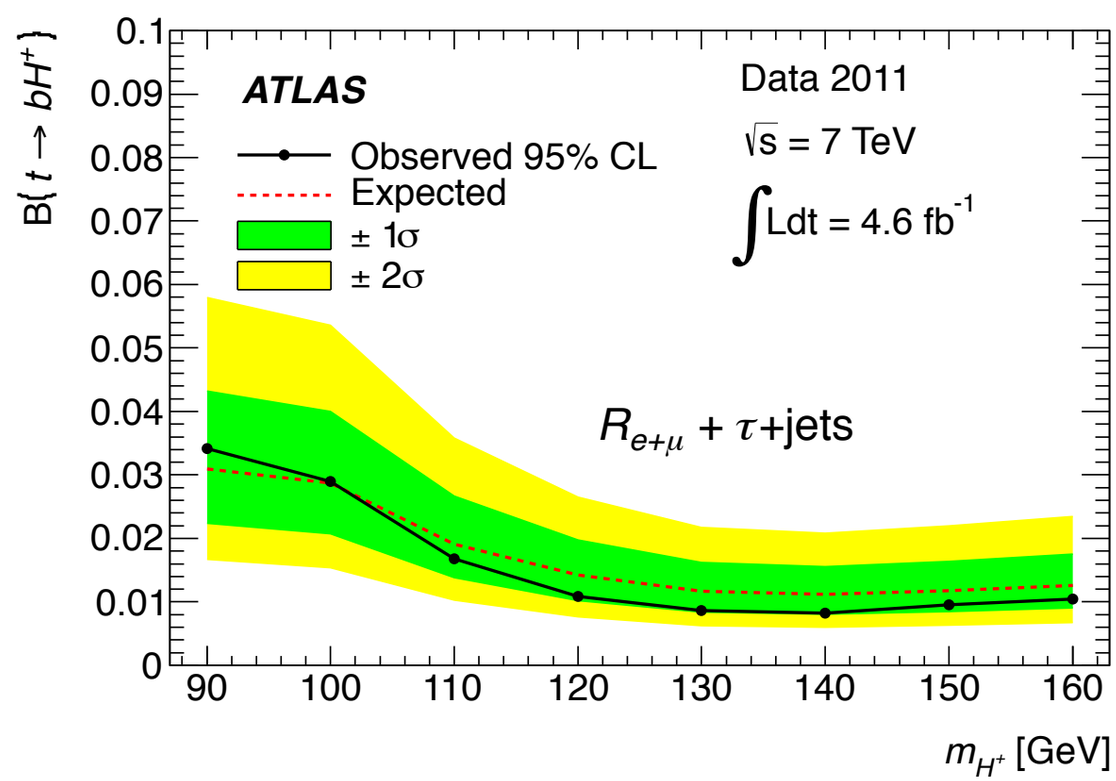
Charged Higgs boson coupling to fermions (e.g. tb):

$$H^{\pm} tb \text{ coupling} \sim V_{tb}\,(m_t \cot\beta(1-\gamma_5) + m_b \tan\beta(1+\gamma_5))$$

$m_{H\pm} < m_t + m_b$: production in top quark decays, decay to cs (low tanβ) or τν (high tanβ)

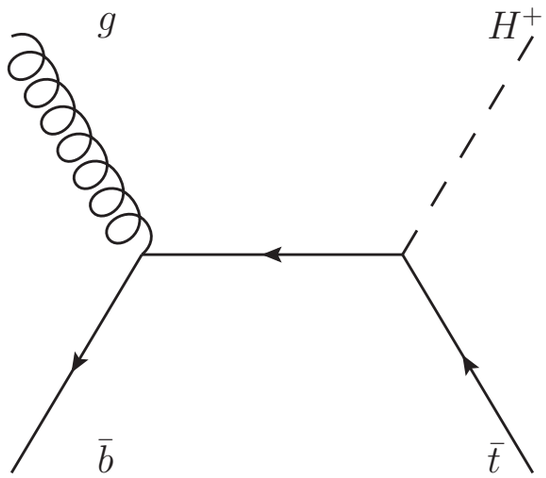
- decay to cs "straightforward" but relies on precise m_{jj} reconstruction in t → bjj decays
- decay to $\tau_{had}\nu$: test for deviations from lepton universality + use



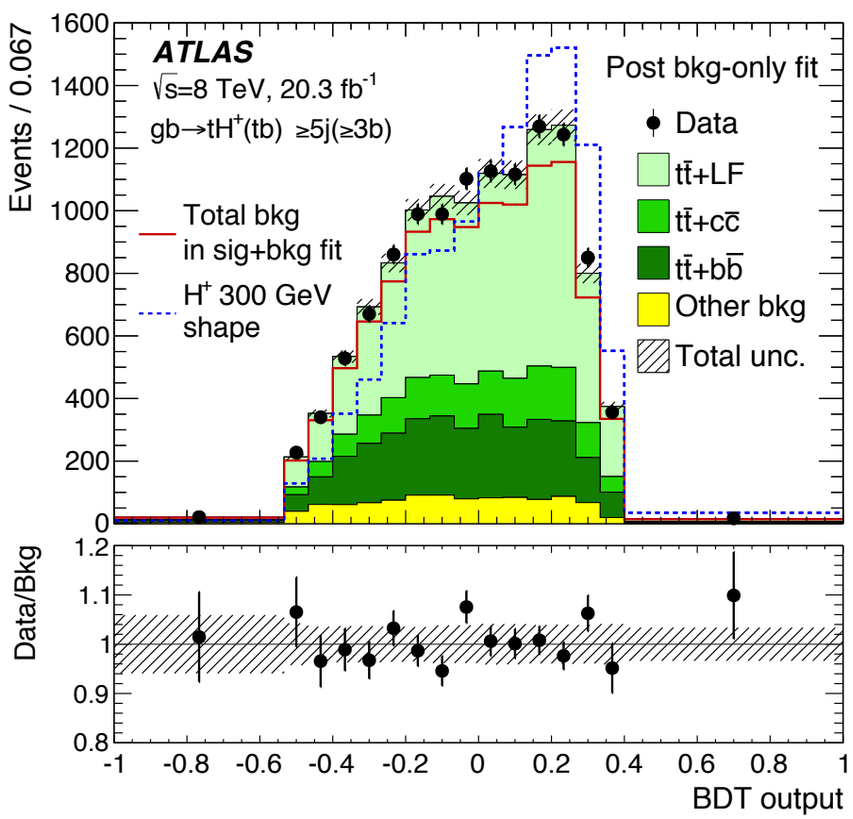


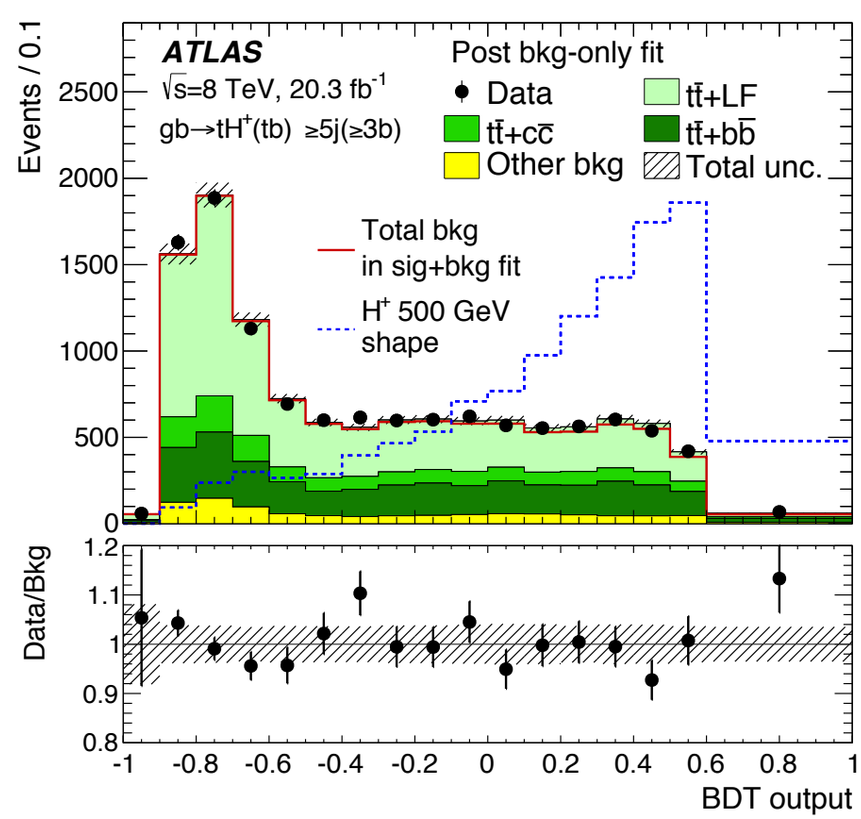
Charged MSSM Higgs boson searches (2)

Heavy $H^{\pm}$: decay to tb, but also main production with t



- final state as for SM $\bar{t}tH(\rightarrow\bar{b}b)$, but with different kinematics
  - borrows most analysis ingredients from SM search
- search becomes "easier" as $m_{H\pm}$ increases..
  but this requires specific techniques optimised for dealing with boosted top quarks: "jet trimming"





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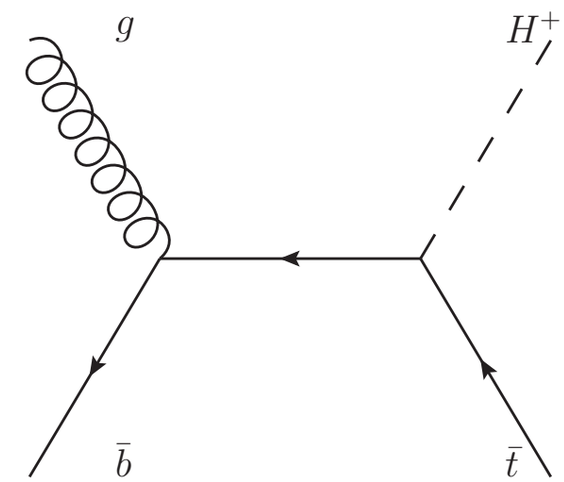

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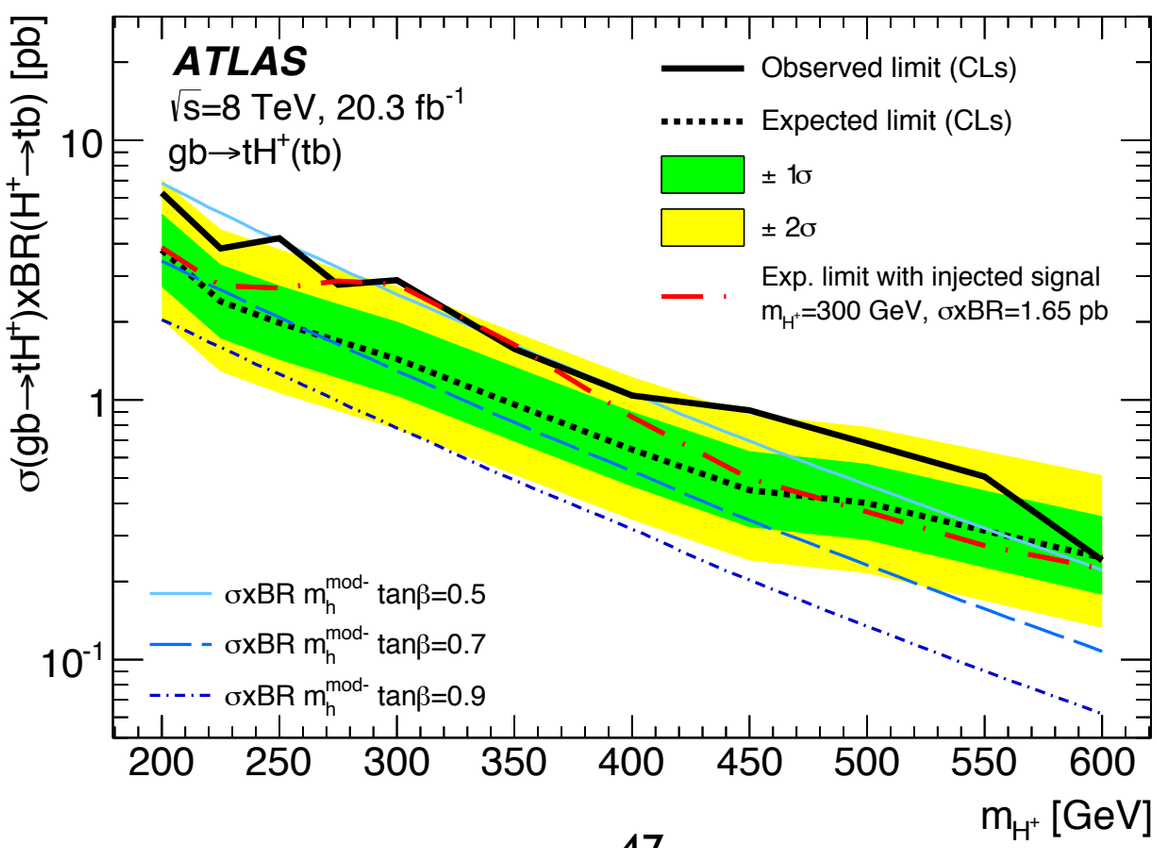

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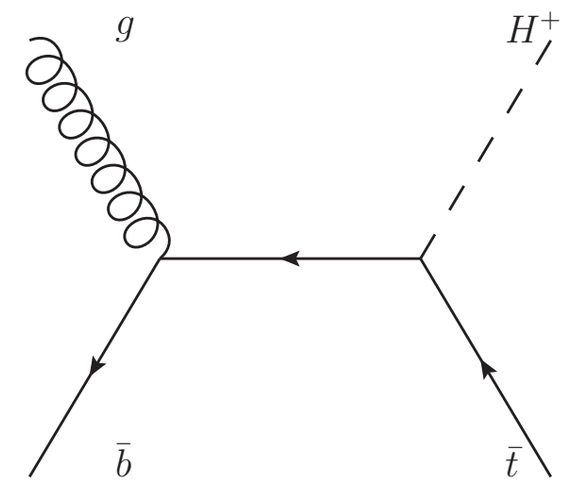

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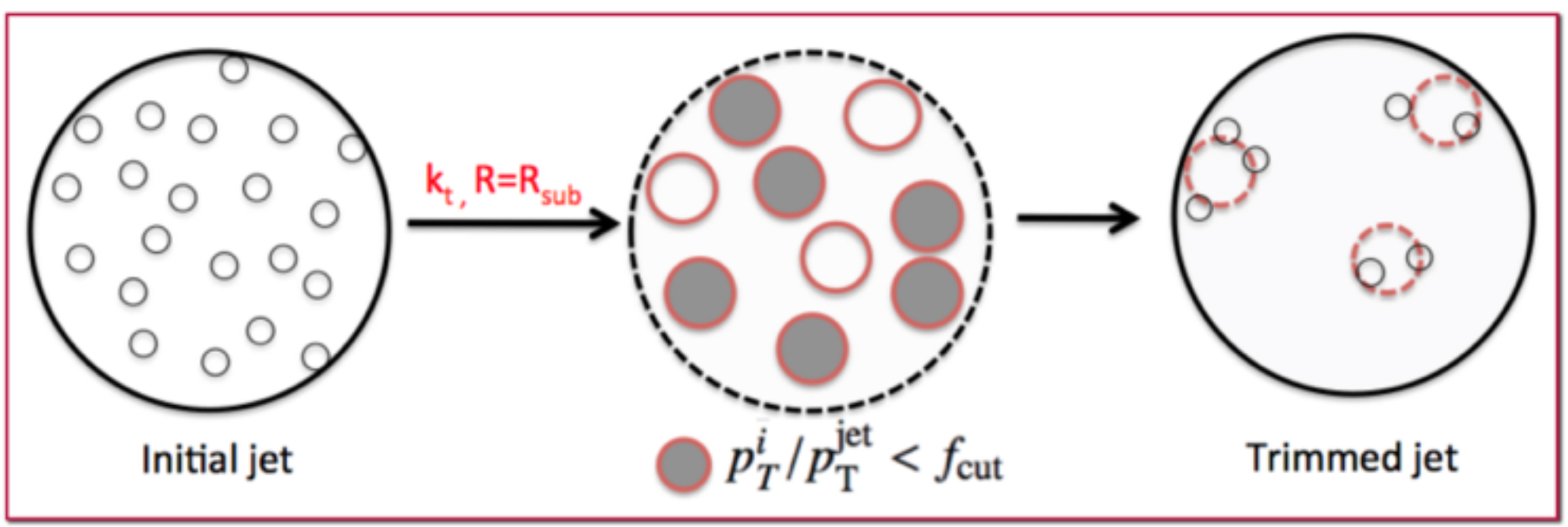

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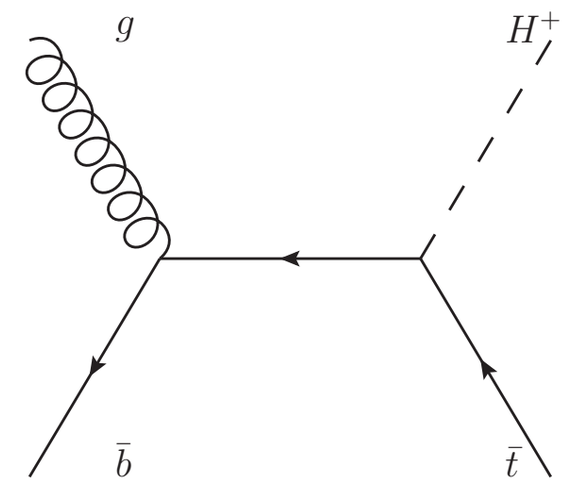

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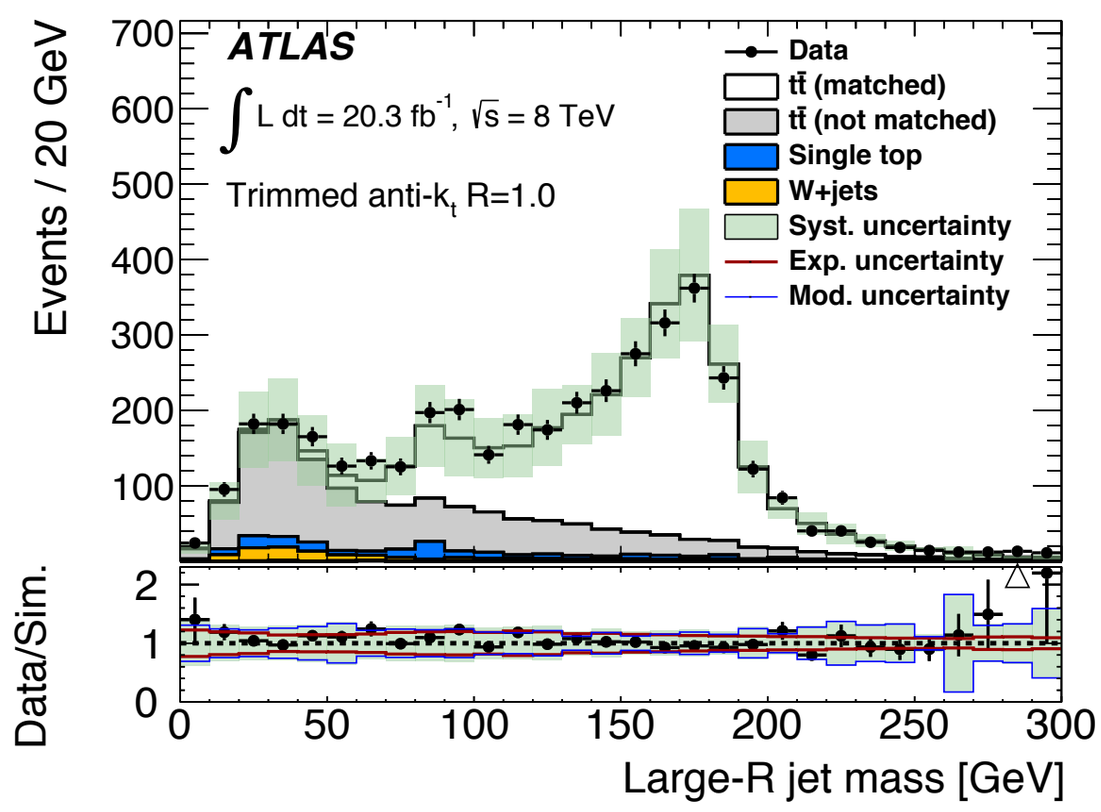
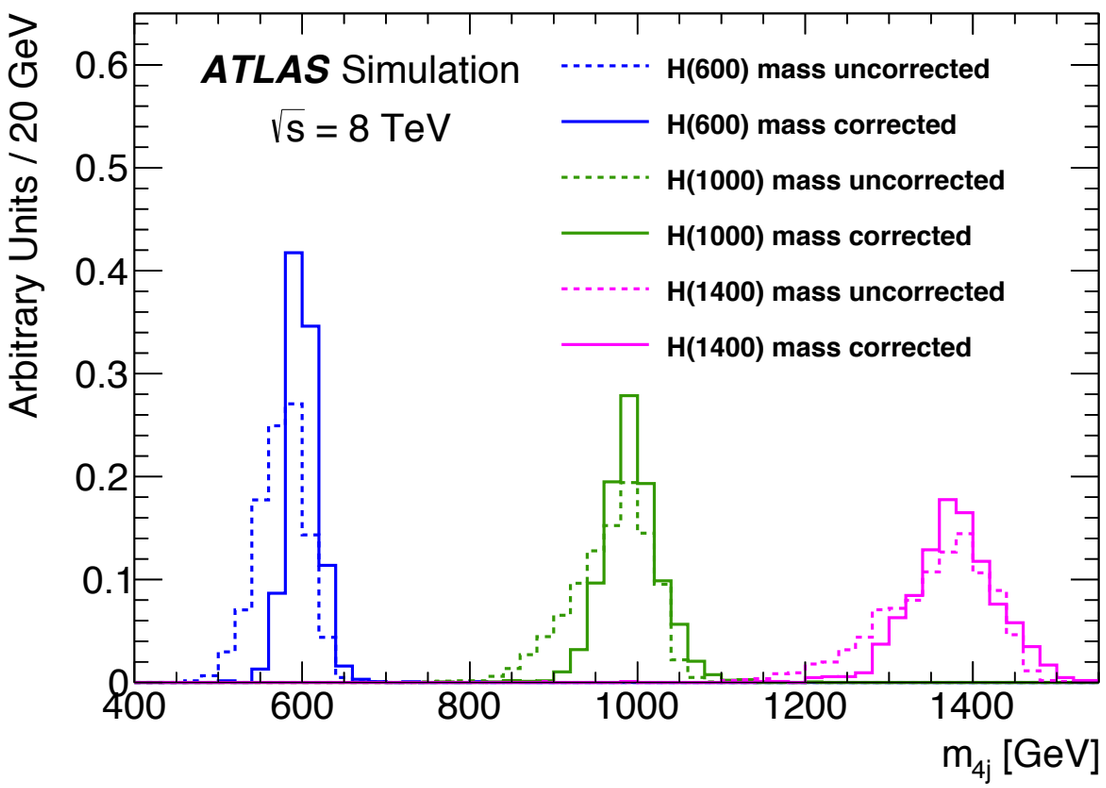
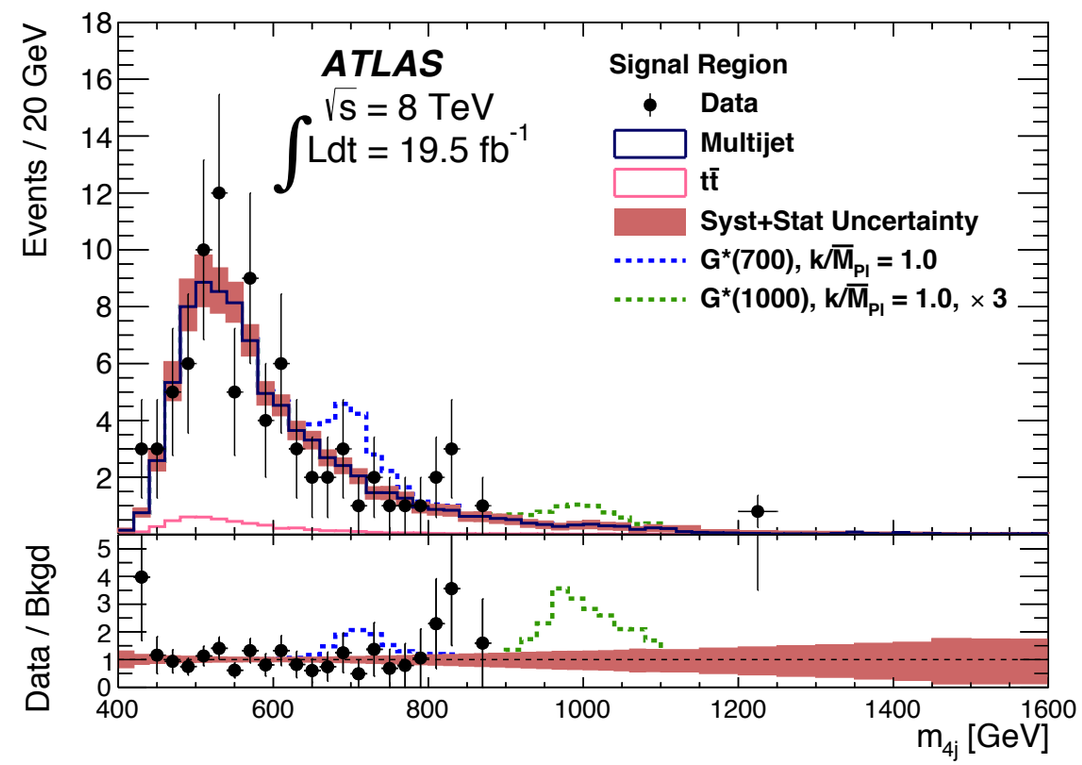


The SM Higgs boson as a tool

Many models exist in which (very) heavy particles decay to high p_T "SM" Higgs bosons. Example: Randall-Sundrum graviton

- needs boosted $H \to \bar{b}b$ reconstruction ➠ use jet substructure techniques as in high-p_T top tagging
  - improved in case of identified semileptonic decays: $P(b \to \mu\nu X)$
- sensitivity helped enormously by b-tagging both b jets from H decay
  - use small-radius (R=0.2), b-tagged track jets associated with calorimeter jets





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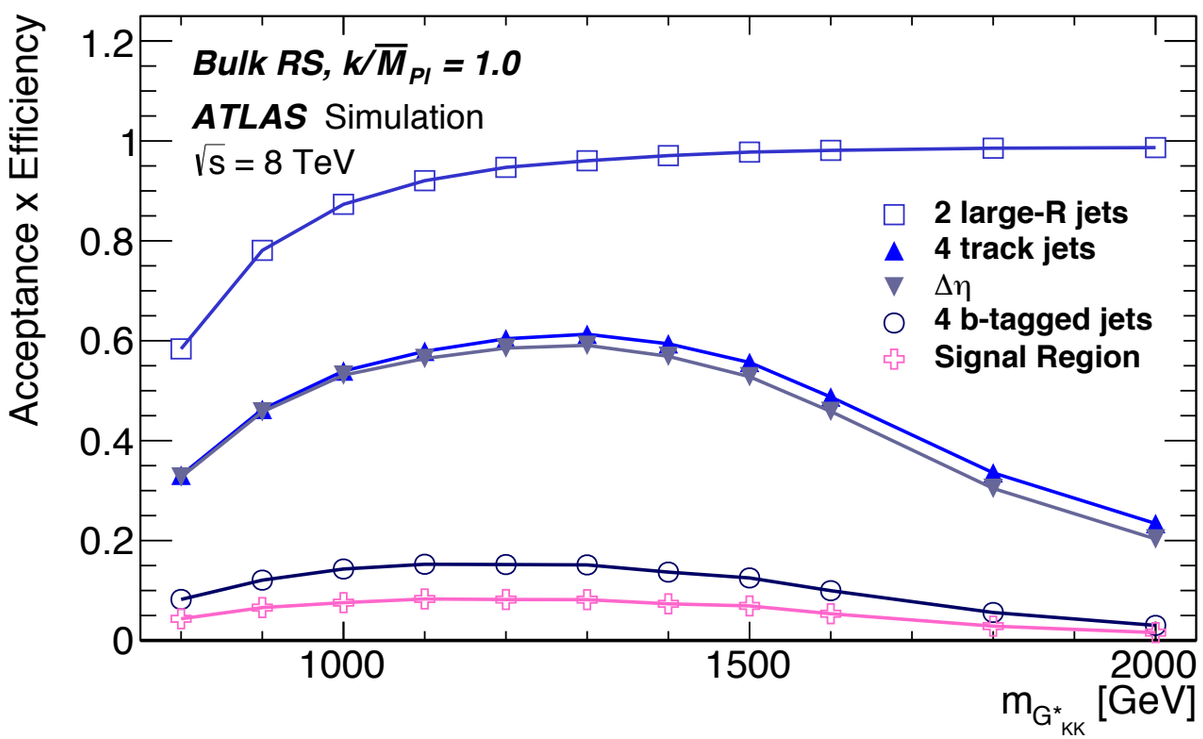

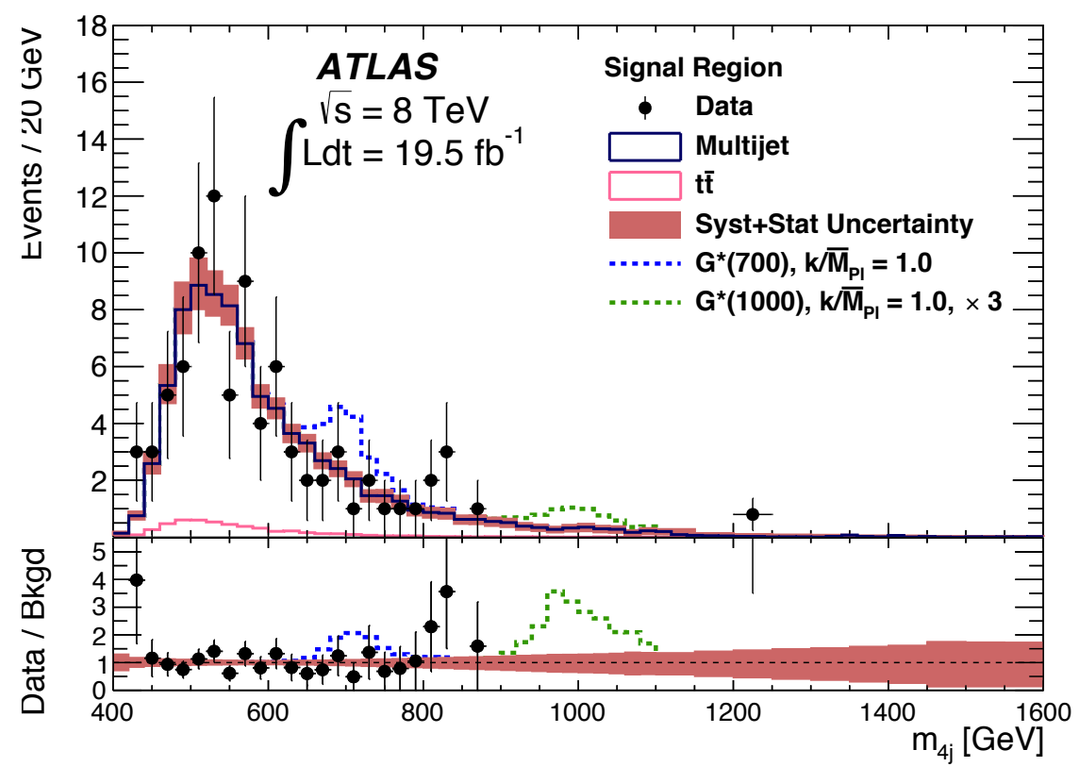

Finally

Many topics (especially BSM Higgs physics) not discussed; e.g.

- decays of heavy Higgs bosons to WW or ZZ
- NMSSM (additional, possibly very light) Higgs bosons
- lepton flavour violating Higgs boson decays
- $A \rightarrow Zh$ searches
- measurement of differential distributions
- searches for SM HH production

LHC luminosity will increase further

- challenges for precision Higgs physics (especially couplings measurements)
- techniques optimised for the heaviest new (Higgs) particles

Future lepton collider will offer a much cleaner environment