# Higgs Hunting at the Tevatron and the LHC

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# Outline

– What is the Higgs boson ?

– Higgs at hadron colliders

– High mass Higgs boson search

– Low mass Higgs boson search

– Conclusion / Outlook

# The Standard Model

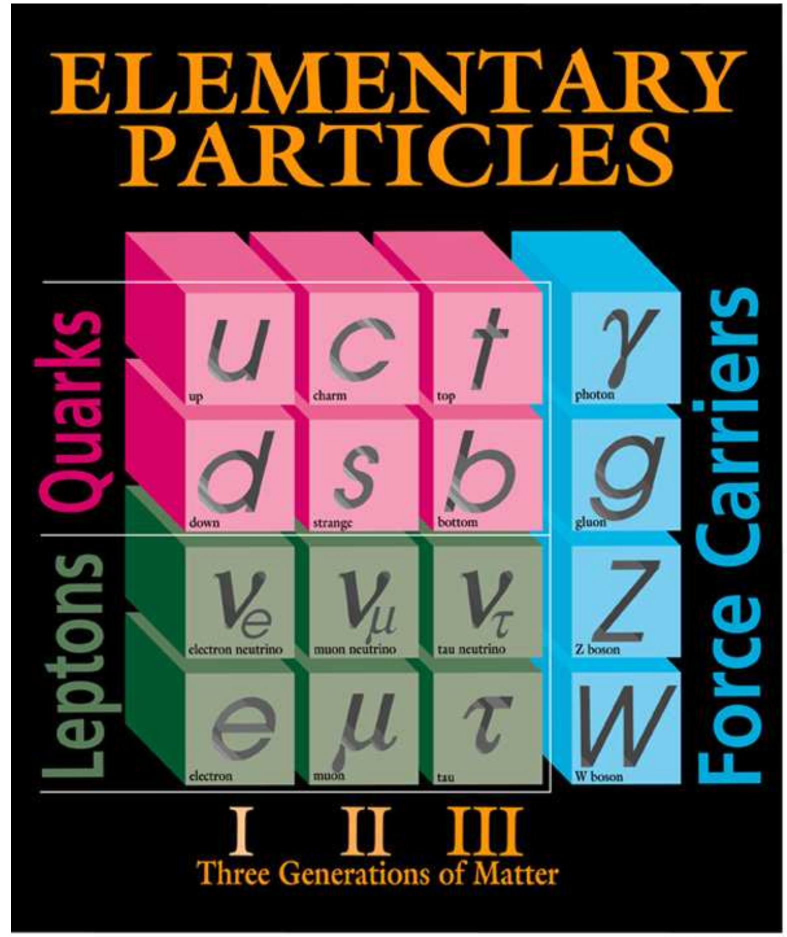
– Elementary particles: quarks, leptons

– Basic forces: weak, strong, electromagnetic

– Standard model describes all

  ∗ Based on (local) gauge symmetries

 ⇒ "Force" particles: $W^{\pm}$, Z, photon, gluon




Fermilab 95-759

⇒ Massless particles

# Mass

- Mass of nucleus $\neq \sum$ mass of protons & neutrons

- Proton/neutron mass: confinement energy, QCD

  * Masses of light hadrons calculable by (lattice) QCD

  $\Rightarrow$ Visible mass of the universe explained by QCD

- But: without massive quarks and W, no stable proton

QCD = Quantum Chromodynamics = theory of strong force

# The Electroweak Theory

– Dirac: $\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi + m\bar{\psi}\psi$

– EW based on local $SU(2)_L \otimes U(1)_Y$ gauge symmetry:

$$\begin{aligned}\mathcal{L}_{\mathsf{EW}} = {} & i\bar{\mathsf{R}}\gamma^\mu(\partial_\mu + \frac{ig'}{2}YB_\mu)\mathsf{R} \\ & + i\bar{\mathsf{L}}\gamma^\mu(\partial_\mu + \frac{ig'}{2}YB_\mu + \frac{ig}{2}\vec{\tau}\cdot\vec{W}_\mu)\mathsf{L} \\ & - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\vec{W}_{\mu\nu}\cdot\vec{W}^{\mu\nu} + \ldots\end{aligned}$$

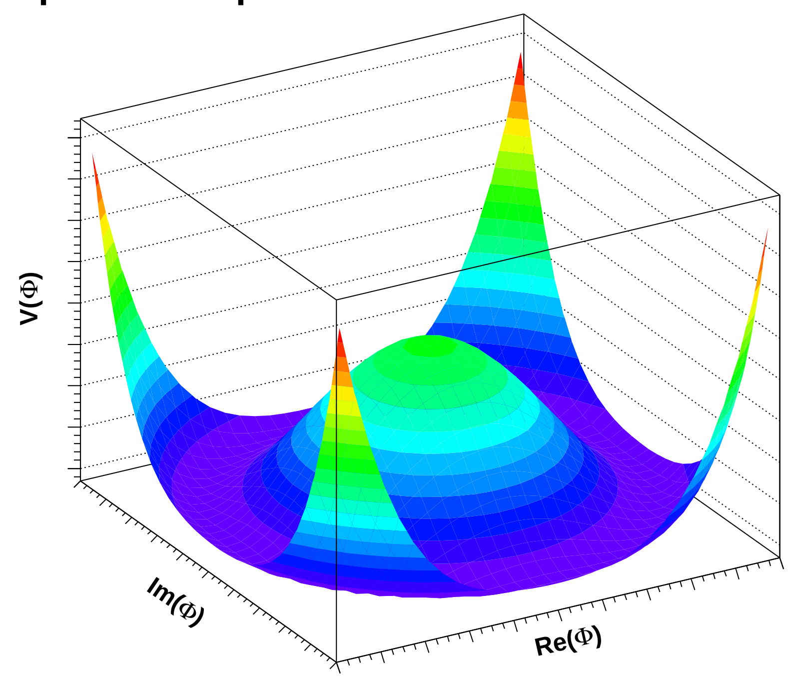
$\Rightarrow$ Gauge-fields $B_\mu$, $\vec{W}_\mu$ : linear combinations of $A_\mu, Z_\mu, W^\pm_\mu$

$\Rightarrow$ Mass terms for fermions or gauge fields forbidden

# Spontaneous Symmetry Breaking

– Introduce another field, with a specific potential

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$




⇒ Lowest energy state (vacuum) not invariant

- Massive W and Z bosons, massless photon
- Massive quarks and leptons
- New massive particle: Higgs boson

# Spontaneous Symmetry Breaking

Complex weak-isospin doublet $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ with $Y = 1$

$$\mathcal{L}_{\mathsf{H}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) + \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$$D_\mu = \partial_\mu + \frac{ig'}{2} Y B_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu$$

Ground state breaks $SU(2)_L \otimes U(1)_Y$ symmetry:

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \mu/\sqrt{\lambda} \end{pmatrix}$$

# Higgs Mechanism

Expand $\Phi(x)$ around the ground state $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$:

$$D_\mu \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \partial_\mu H \end{pmatrix} + \frac{ig' \, B_\mu}{2\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} + \frac{ig \, \vec{\tau} \cdot \vec{W}_\mu}{2\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

$$= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \partial_\mu H \end{pmatrix} + \frac{i}{2\sqrt{2}} \begin{pmatrix} g(W_\mu^1 - iW_\mu^2) \\ g' B_\mu - g W_\mu^3 \end{pmatrix} (v + H)$$

$$= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \partial_\mu H \end{pmatrix} + \frac{i}{2\sqrt{2}} \begin{pmatrix} g\sqrt{2} W_\mu^+ \\ -g Z_\mu / \cos\theta_w \end{pmatrix} (v + H)$$

# Higgs Mechanism

$$(D_\mu\Phi)^\dagger(D^\mu\Phi) = \frac{1}{2}(\partial^\mu H)(\partial_\mu H) +$$

$$\frac{g^2}{8}\left(\frac{Z_\mu Z^\mu}{\cos^2\theta_w} + 2W^+_\mu W^{-\mu}\right)(v^2 + 2vH + H^2)$$

$$\Rightarrow \quad m_W = \frac{gv}{2}, \quad m_Z = \frac{gv}{2\cos\theta_w}, \quad m_A = 0$$

$\Rightarrow$ Couplings $WWH,\ ZZH,\ WWHH,\ ZZHH$

# Higgs Mechanism

$$V(|\Phi|) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$
$$= -\frac{\mu^2}{2}(v+H)^2 + \frac{\mu^2}{4v^2}(v+H)^4$$
$$= \mu^2(H^2 + \frac{H^4}{4v^2} + \frac{H^3}{v} - \frac{v^2}{4})$$

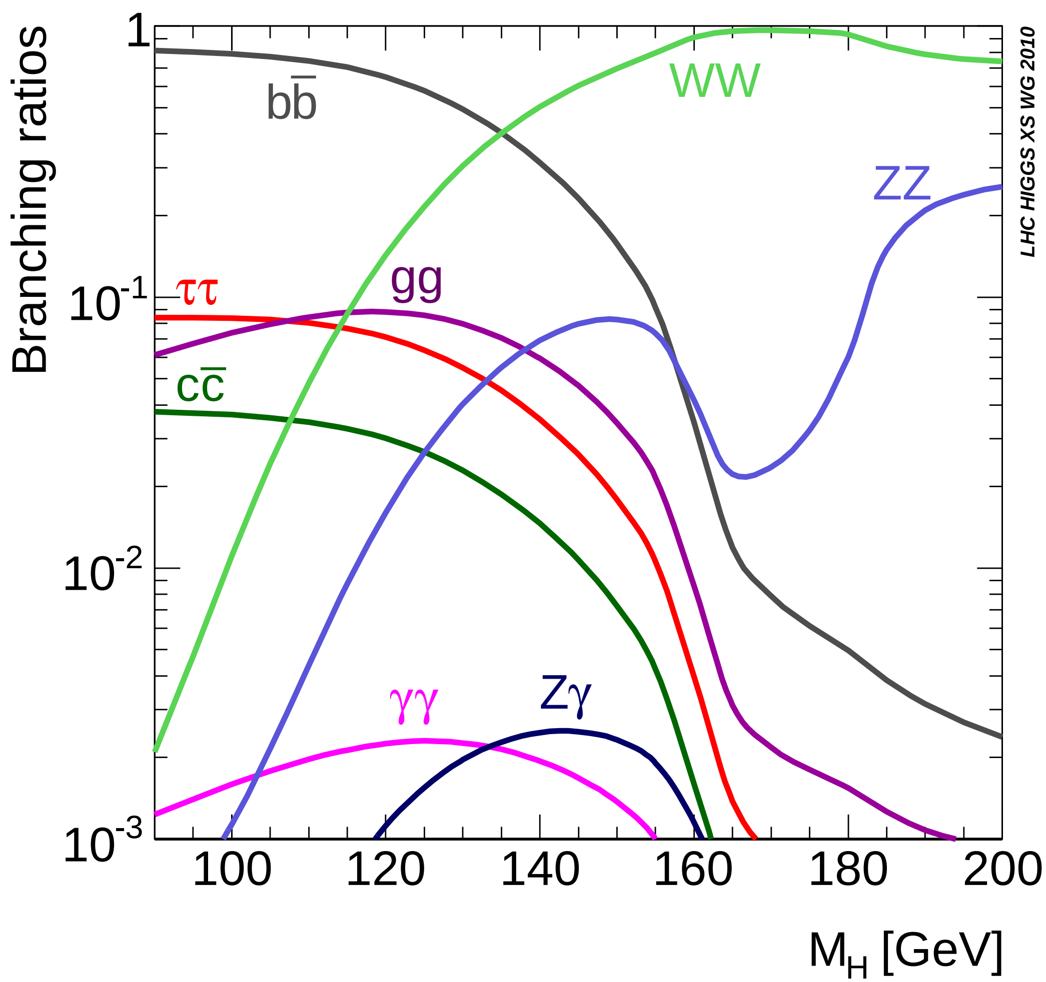
$$\Rightarrow \quad m_H = \sqrt{2}\mu = \sqrt{2\lambda}v$$

$\Rightarrow$ Couplings $HHH,\ HHHH$

Fermion masses: direct coupling of $\Phi$ to fermion fields

# What Do We Know?

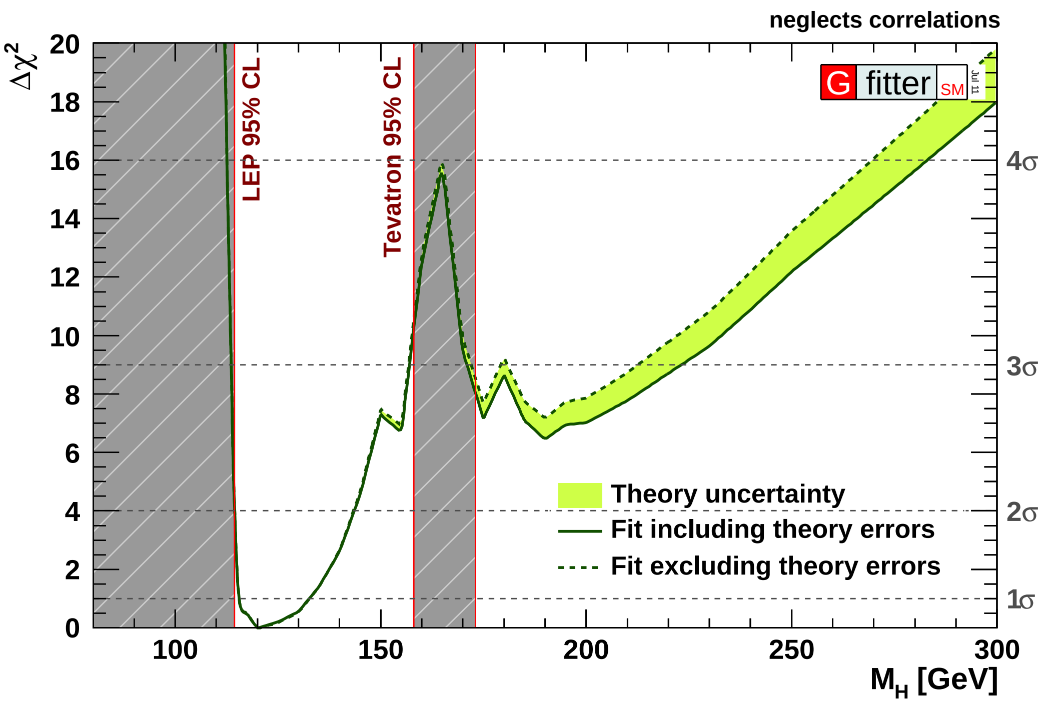
$v = 246$ GeV $\qquad m_{\mathrm{H}} = \sqrt{2}\mu = \sqrt{2\lambda}v = ?$

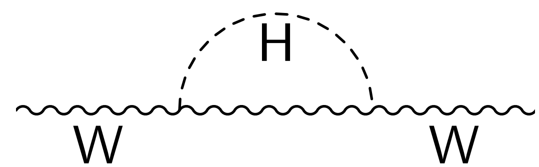


# What Do We Know?

– Precision EW measurements at Tevatron, LEP and SLD

– Direct Higgs search results from LEP, Tevatron, LHC

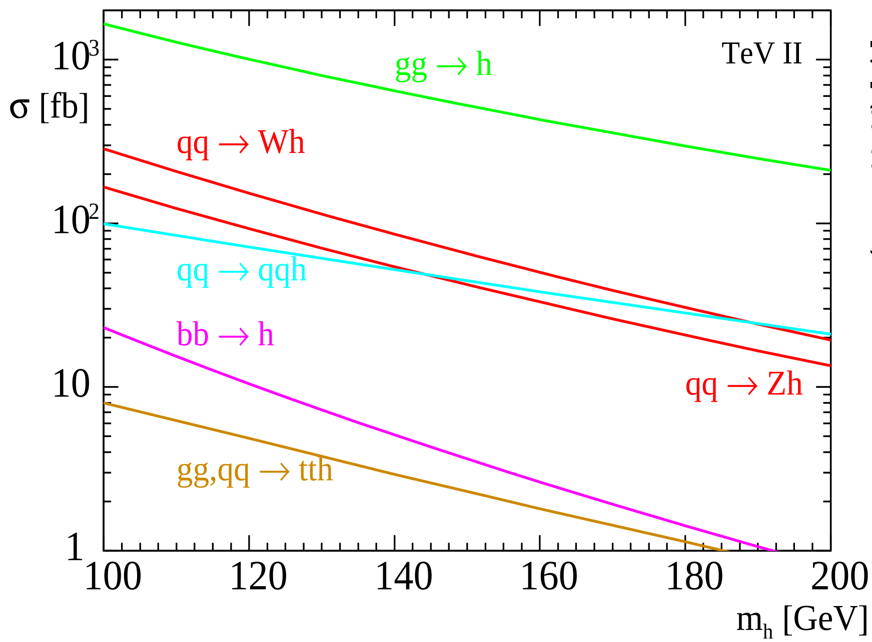


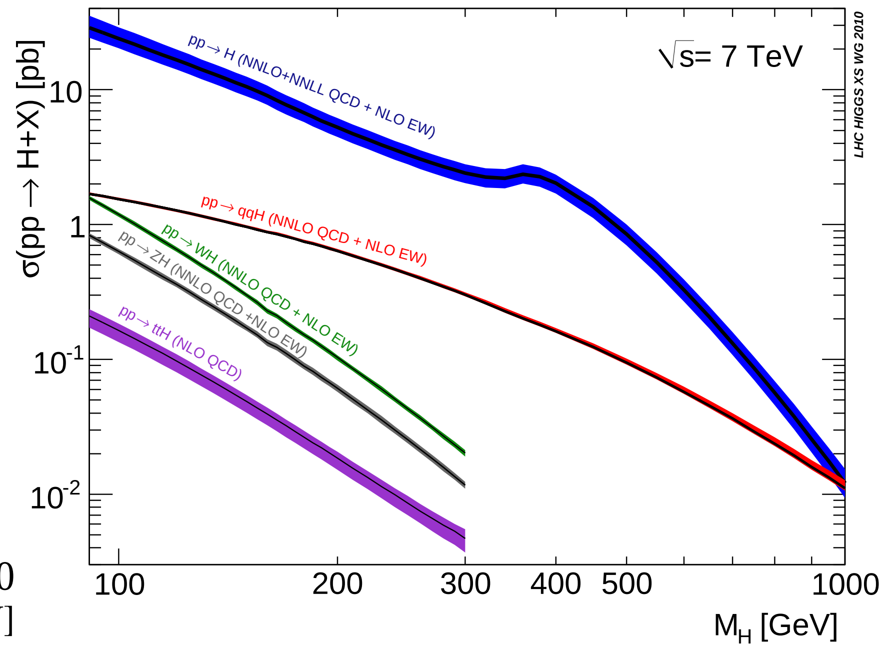

$$m_H = 120^{+12}_{-5}\ \text{GeV}$$

# Higgs Production @ Hadron Colliders

$p\bar{p}$ @ $\sqrt{s} = 1.96$ TeV

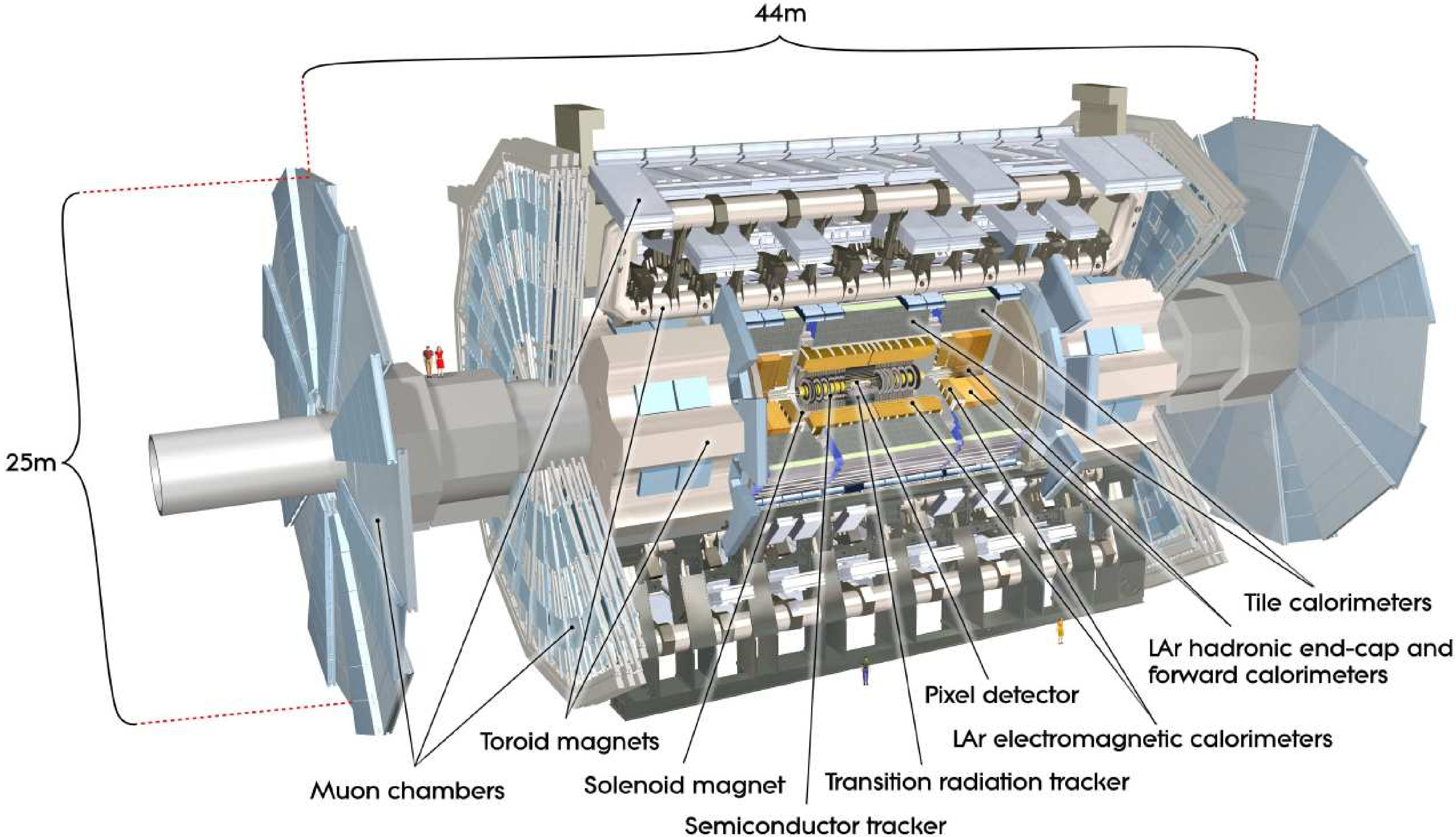



pp @ $\sqrt{s} = 7$ TeV




- Gluon fusion through a heavy-quark loop
- Weak boson fusion
- VH associated production

# Typical Particle Detector: ATLAS



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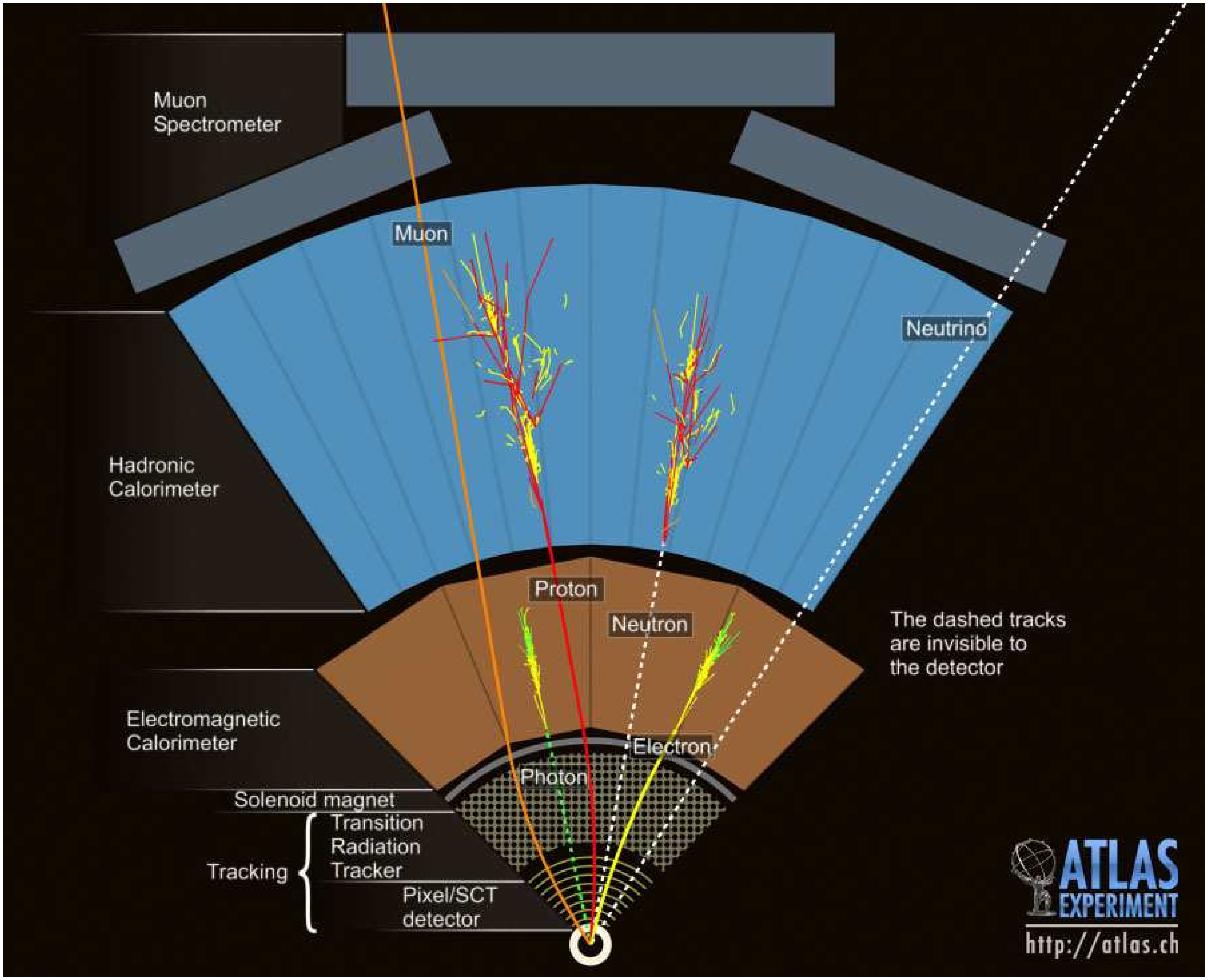
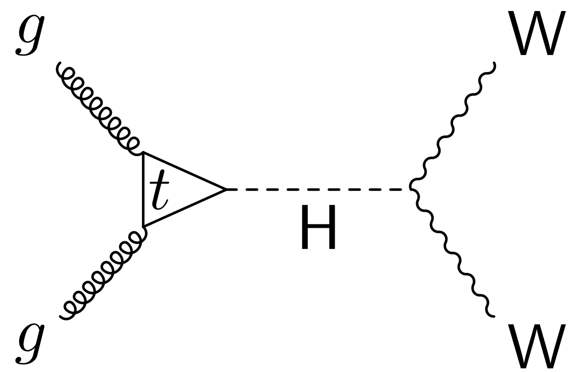
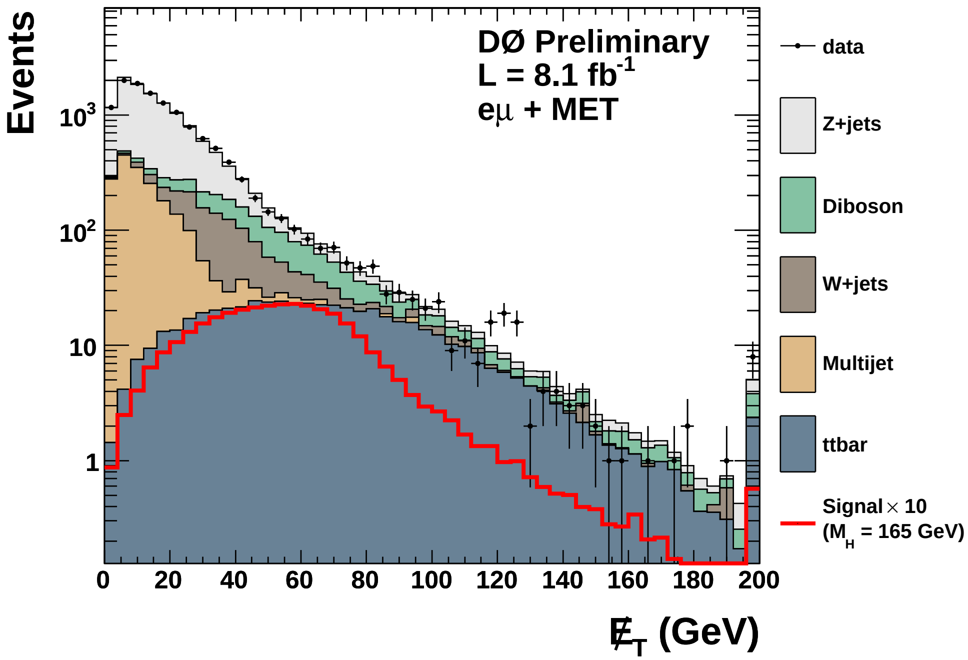


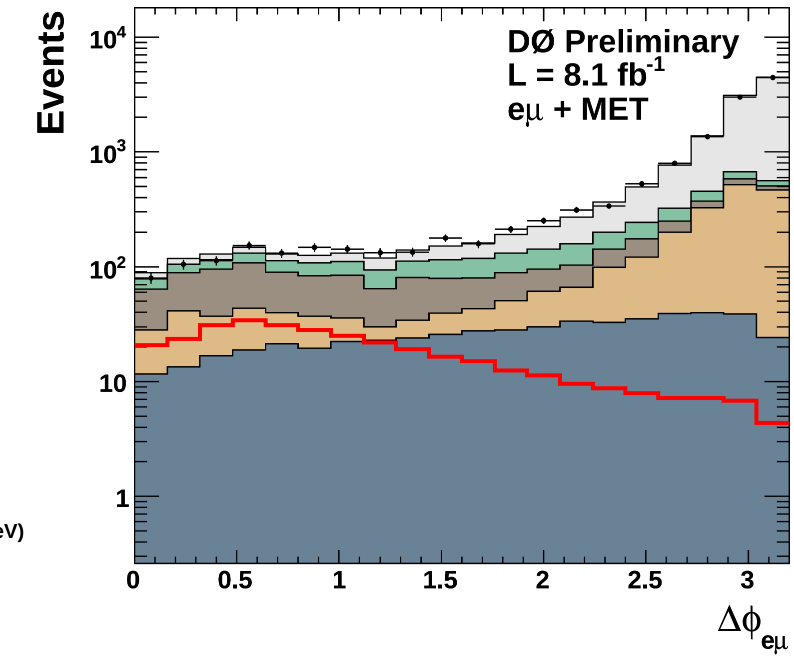
# Higgs at High Mass: H $\rightarrow$ WW




- H $\rightarrow$ WW $\rightarrow \ell\nu\ell\nu$
- Gluon fusion and WBF
- Final states with $e^+e^-$, $\mu^+\mu^-$ or $e^\pm\mu^\mp$ and large $\not{E}_T$
- Background sources:
  * Di-boson (WW, WZ, ZZ)
  * $t\bar{t}$, DY di-lepton production
  * W + mis-identified jet/$\gamma$

# Higgs at High Mass: H → WW (DØ)




– Cannot reconstruct $m_{\mathrm{H}}$, but . . .

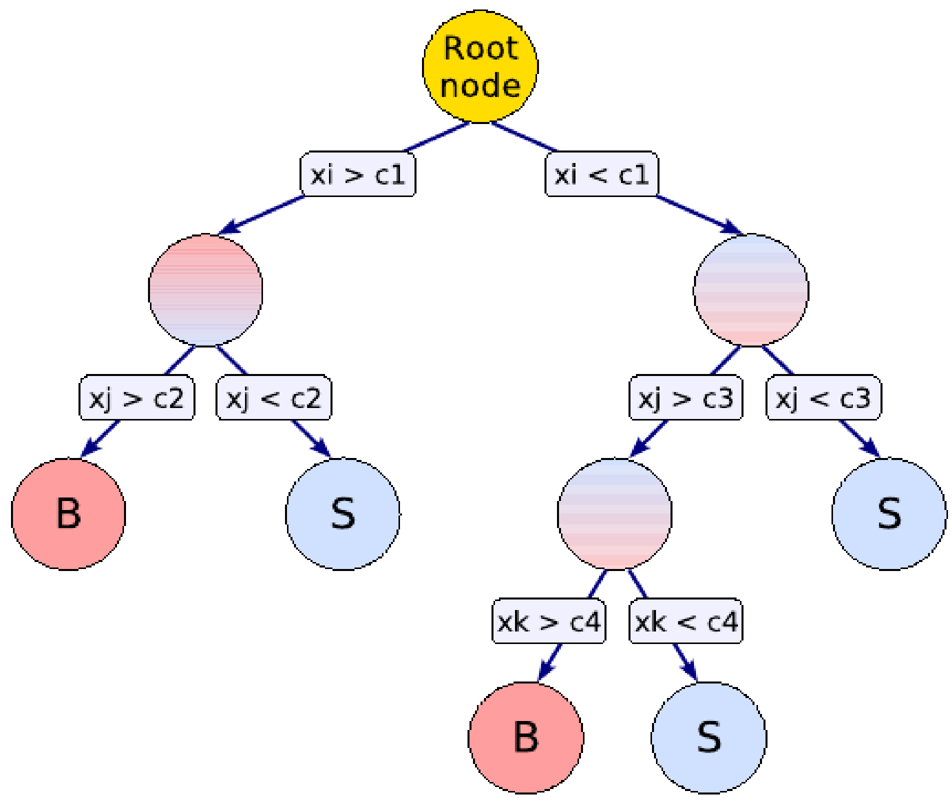
– Spin correlations: $\Delta\phi(\ell\ell)$ small for H → WW → $\ell\nu\ell\nu$

– Use "random forests"

# Advanced Technique: Random Forest

- Decision tree: recursively cut on kinematic variables

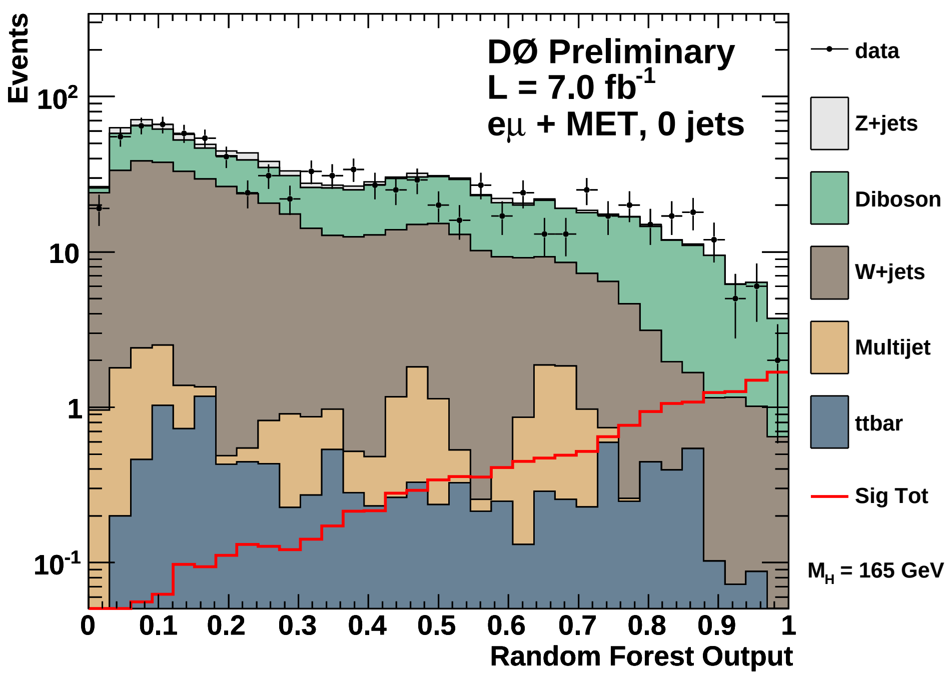
- Random forest: trees with random subsets of variables

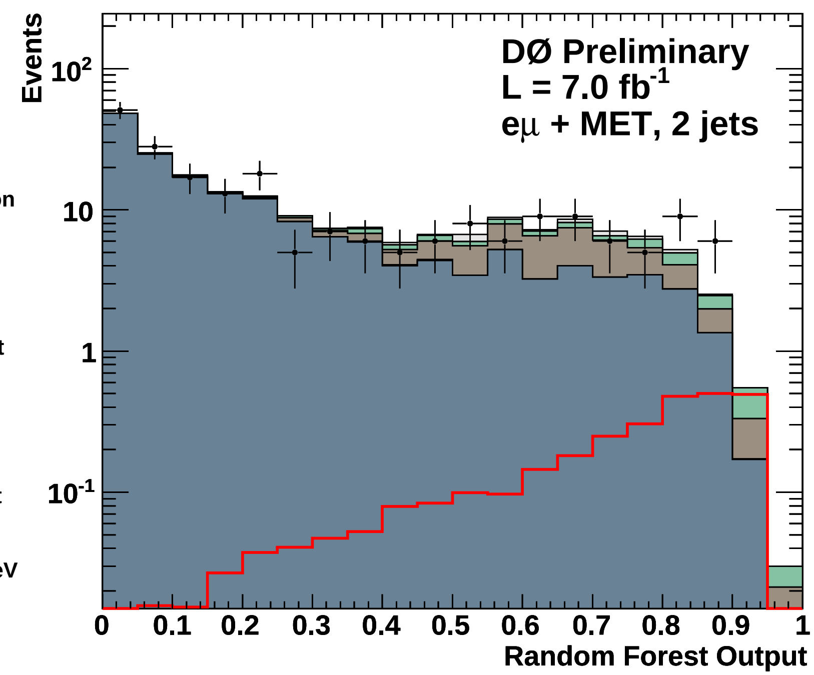


# Higgs at High Mass: $H \rightarrow WW$ (DØ)

– Background and signal vary with number of jets

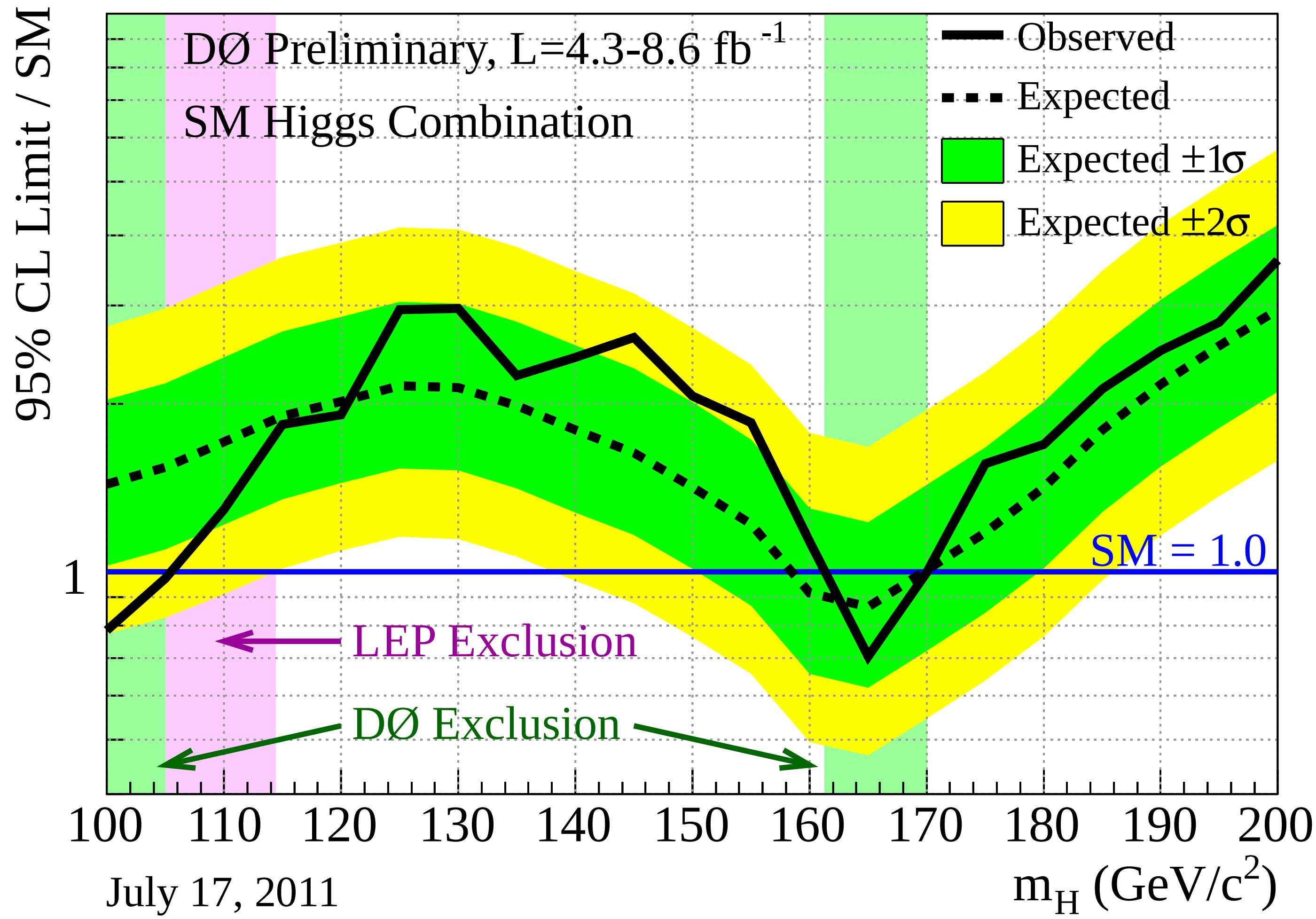
⇒ Analyze in jet-multiplicity bins



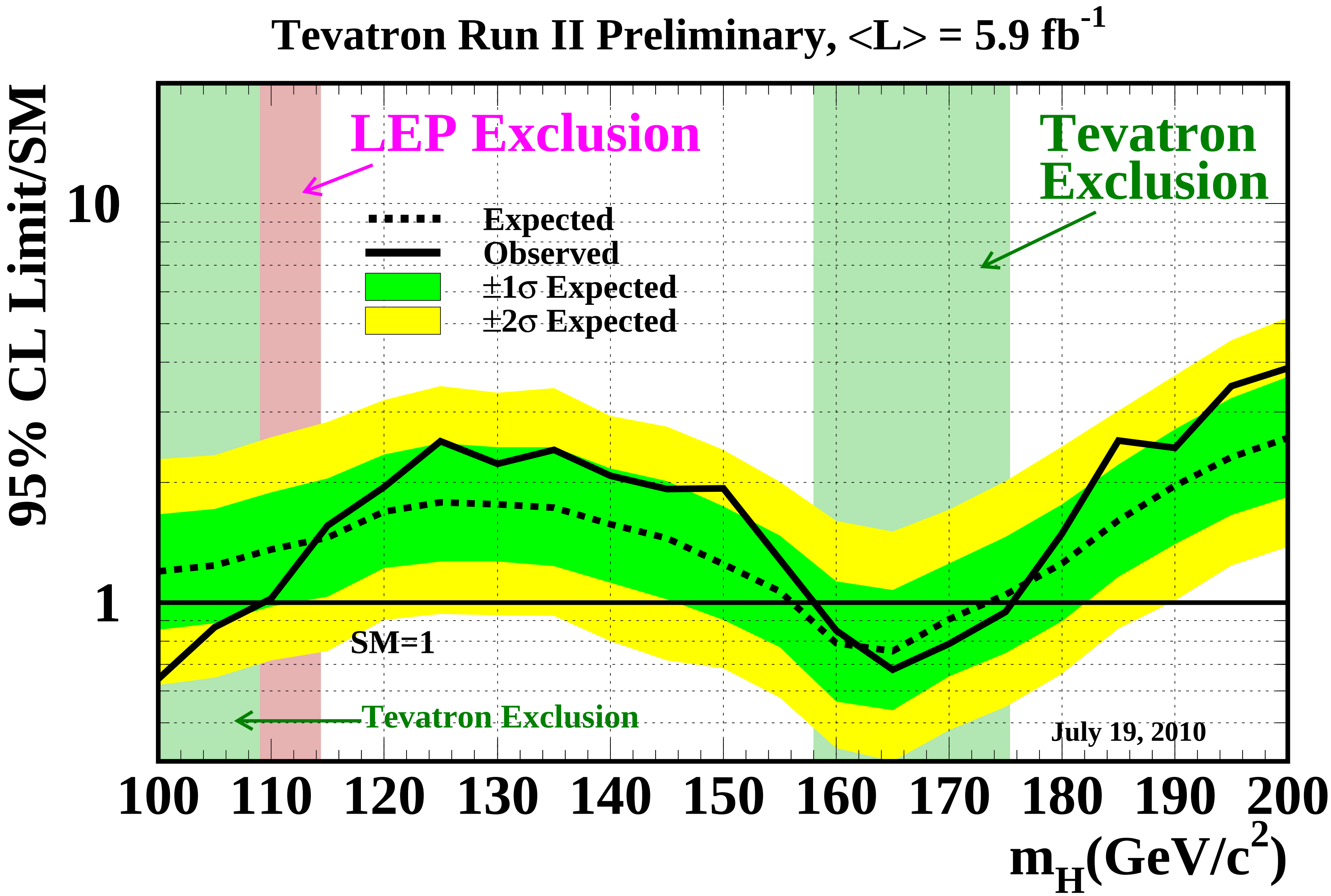
# Combined DØ Higgs Limit

High- and low-mass ($WH \to \ell\nu b\bar{b}$, $ZH \to \ell\ell b\bar{b}$, $ZH \to \nu\bar{\nu} b\bar{b}$)




$\Rightarrow$ Exclude $161 < m_H < 170$ GeV, $1.8 \times$ SM at $m_H = 115$ GeV

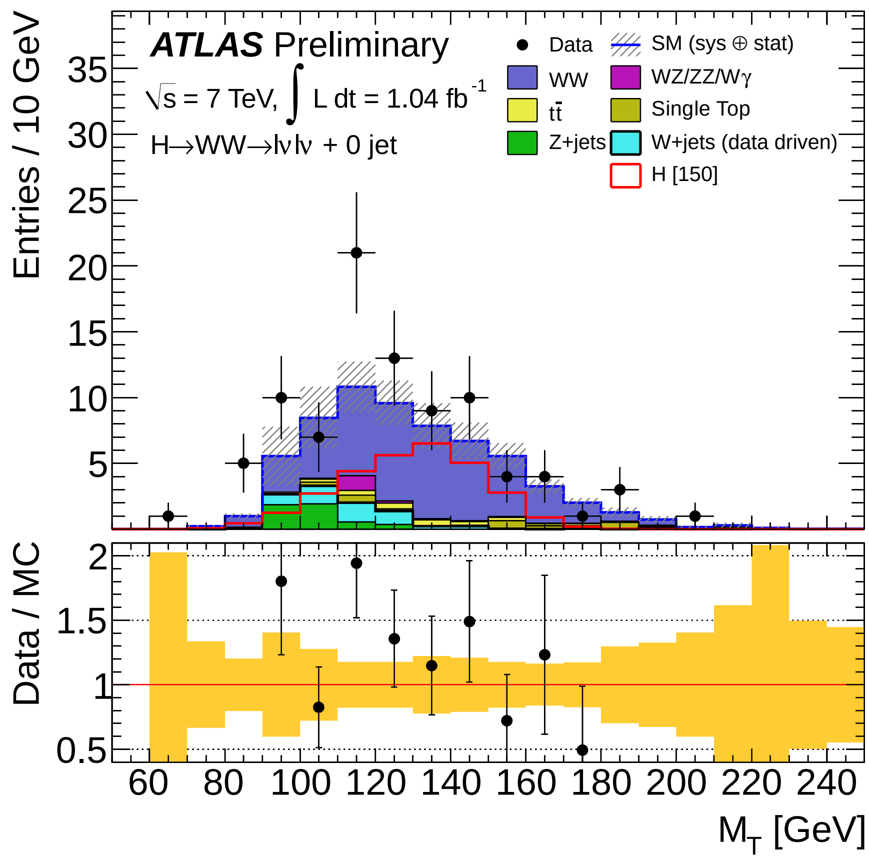
# (Old) Combined Tevatron Limit

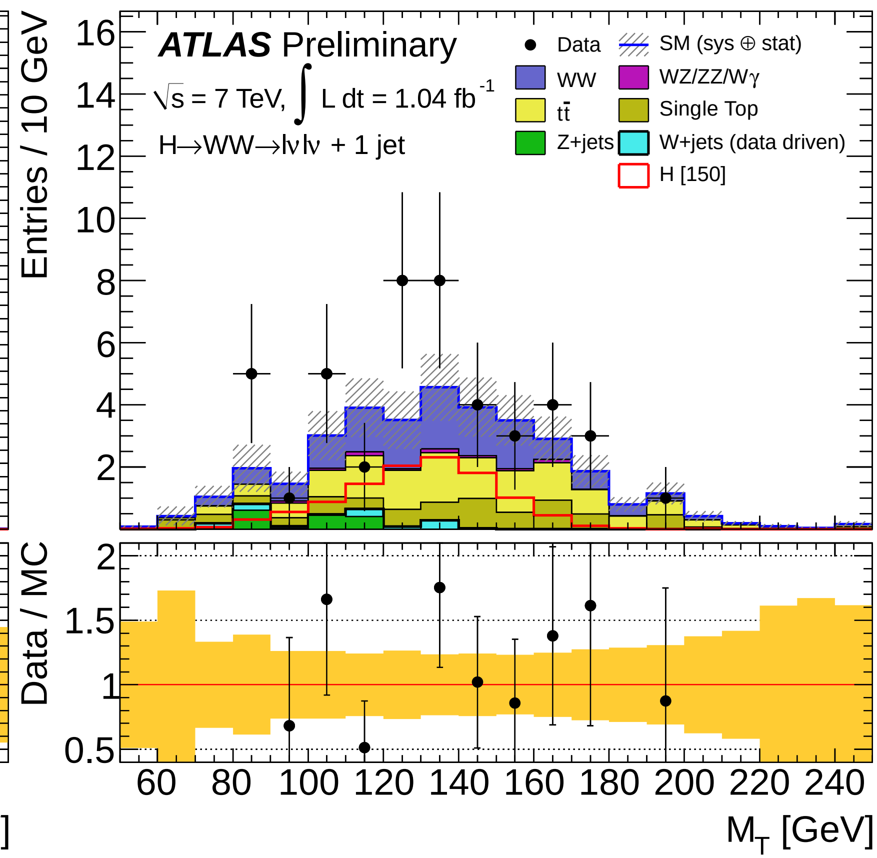



$\Rightarrow$ Exclude $158 < m_\mathrm{H} < 175$ GeV, $1.6 \times$ SM at $m_\mathrm{H} = 115$ GeV

# Higgs at High Mass: $H \rightarrow WW$ (ATLAS)

$$m_T = \sqrt{(E_T^{\ell\ell} + \not{E}_T)^2 - (\vec{p}_T^{\,\ell\ell} + \vec{\not{E}}_T)^2},\ 0.75 \times m_H < m_T < m_H$$



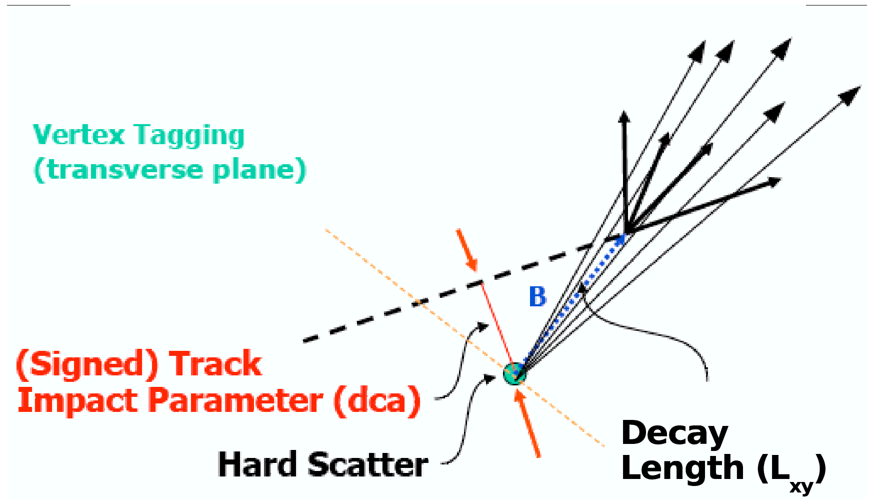

21 H, 33 non-H events

7.2 H, 15 non-H events

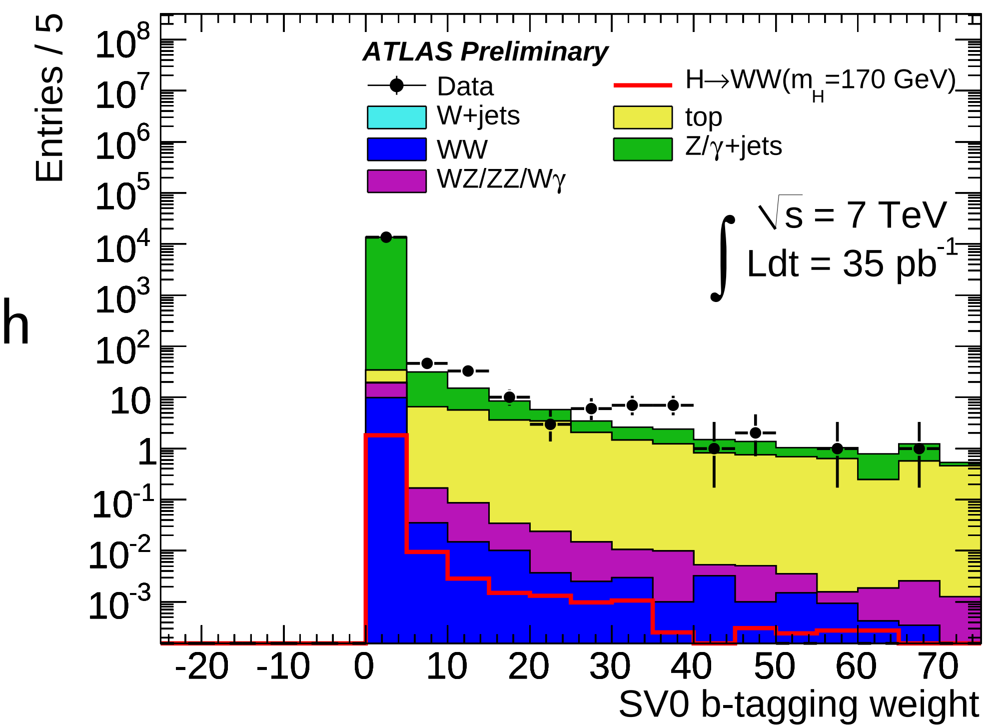
$\Rightarrow$ Significant sensitivity with little data !

# Higgs at High Mass: $H \to WW$ (ATLAS)

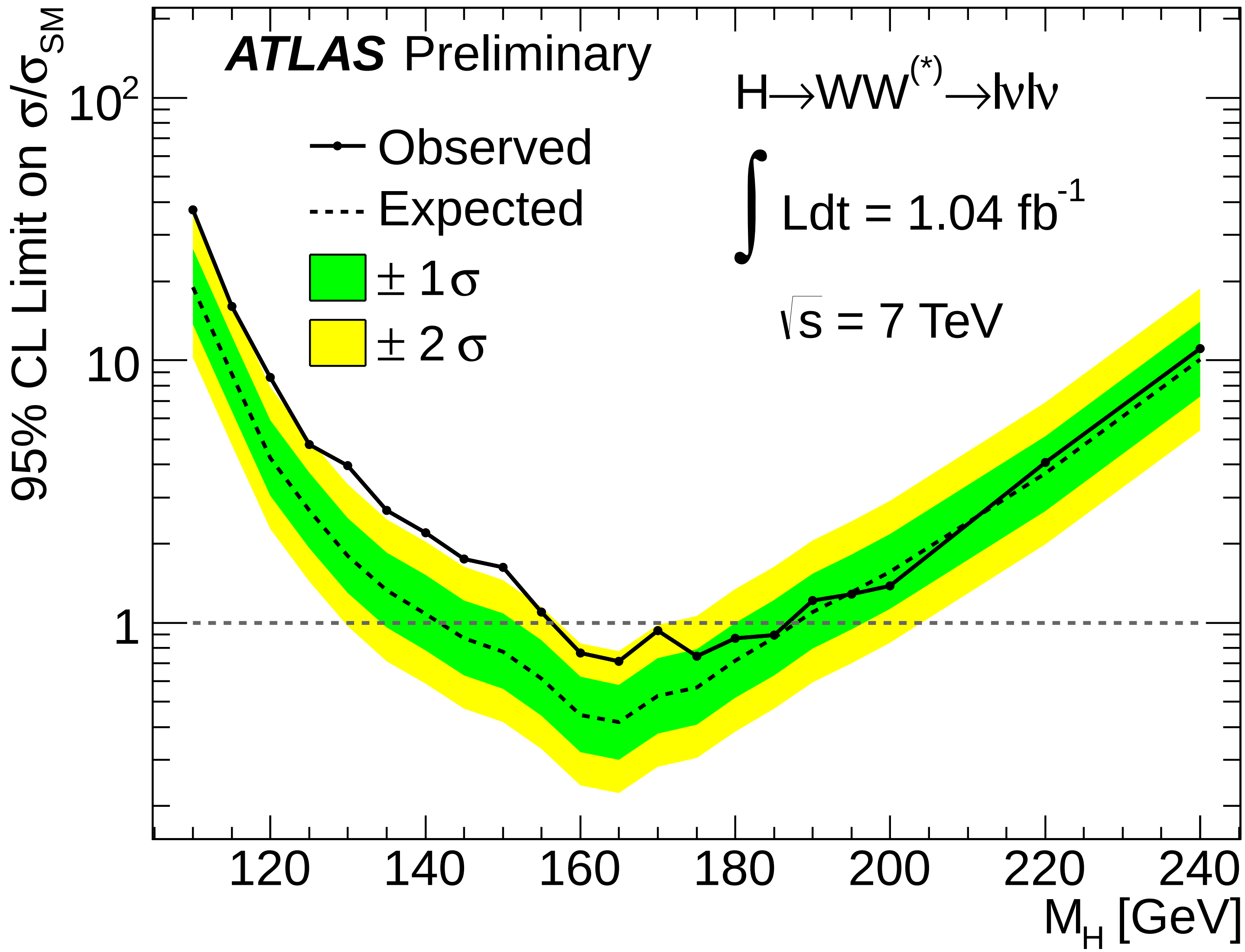
B-hadron decay:




Reduce $t\bar{t}$ background with anti-b-tagging

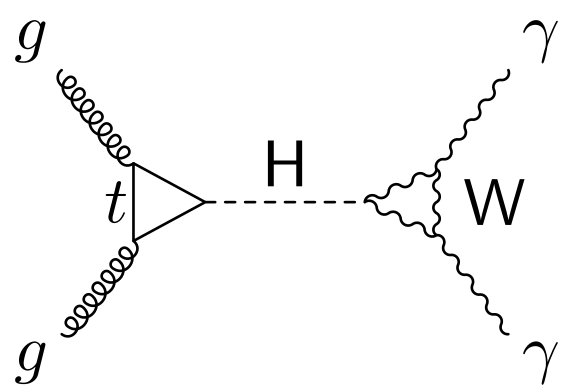


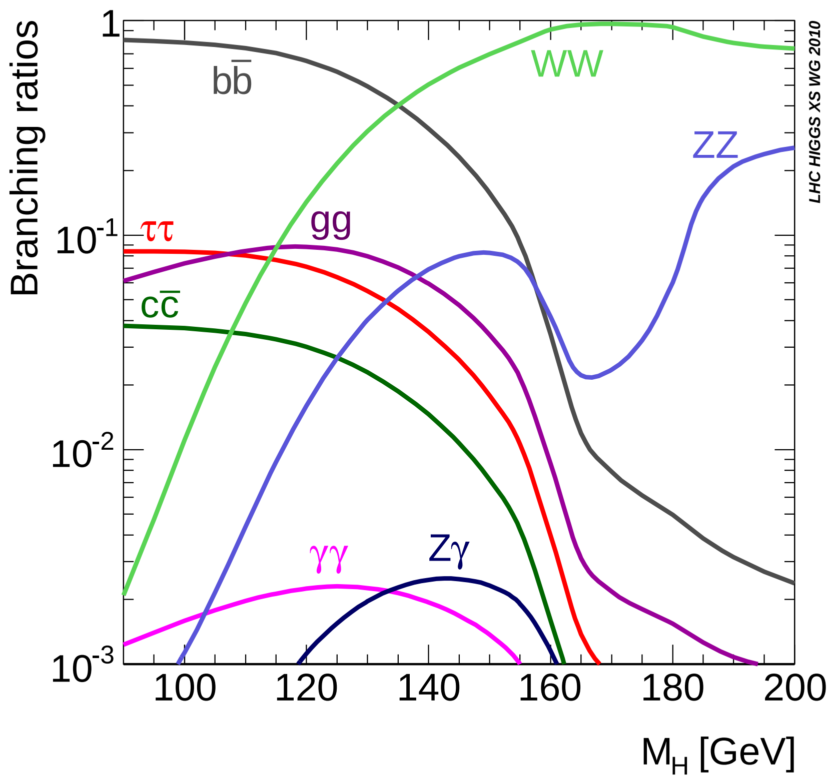
# H → WW Results (ATLAS)




⇒ Exclude $158 < m_{\mathrm{H}} < 186$ GeV

# Higgs at Low Mass: $H \to \gamma\gamma$



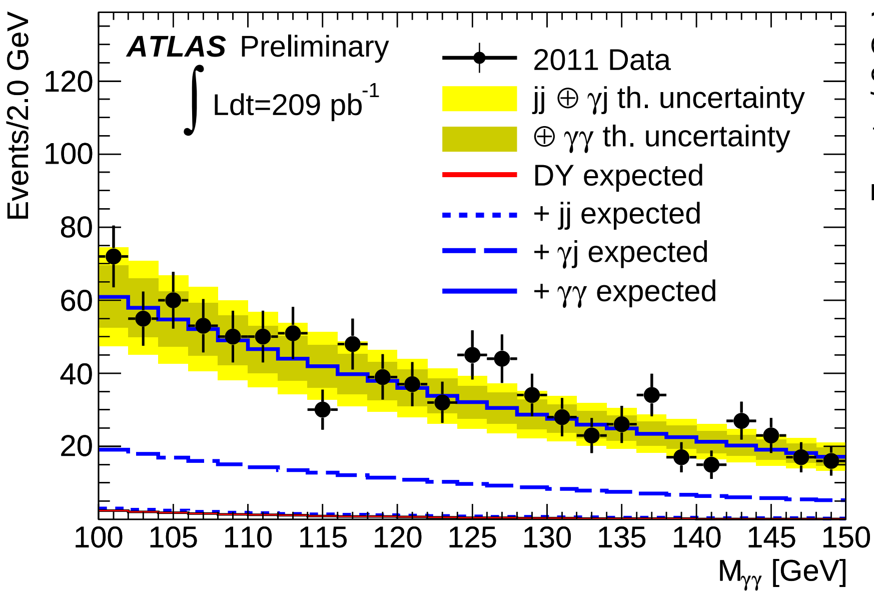

- Very small branching ratio
- Excellent mass resolution
  * At $m_{\mathrm{H}} = 120$ GeV: $\sim 1.5$ GeV (ATLAS)
- Backgrounds:
  * $Z/\gamma^*$, $\gamma\gamma$
  * $\gamma$+jet, di-jet
  * Jets: $\pi^0, \eta$

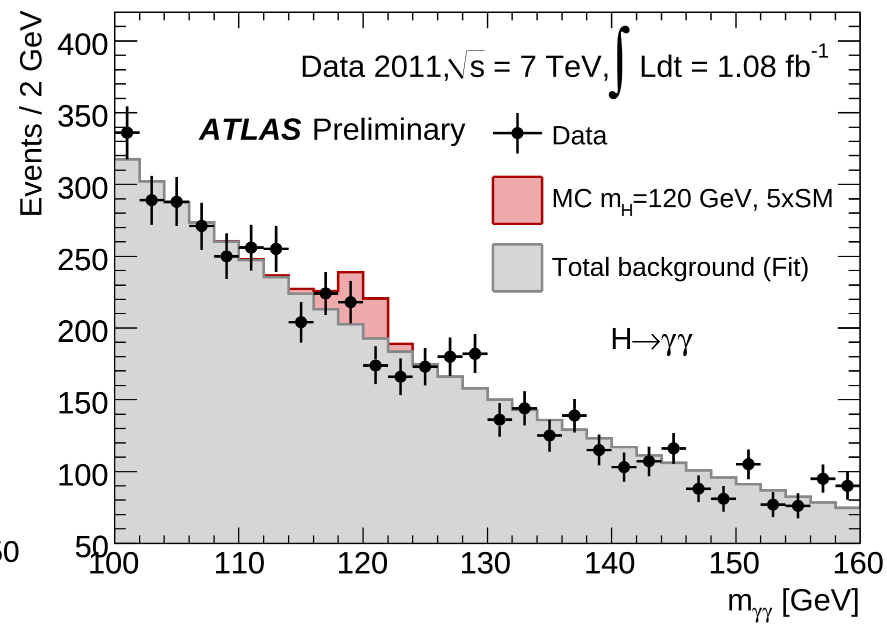
# $H \to \gamma\gamma$ (ATLAS)

– High pile-up environment $\to$ use calorimeter pointing

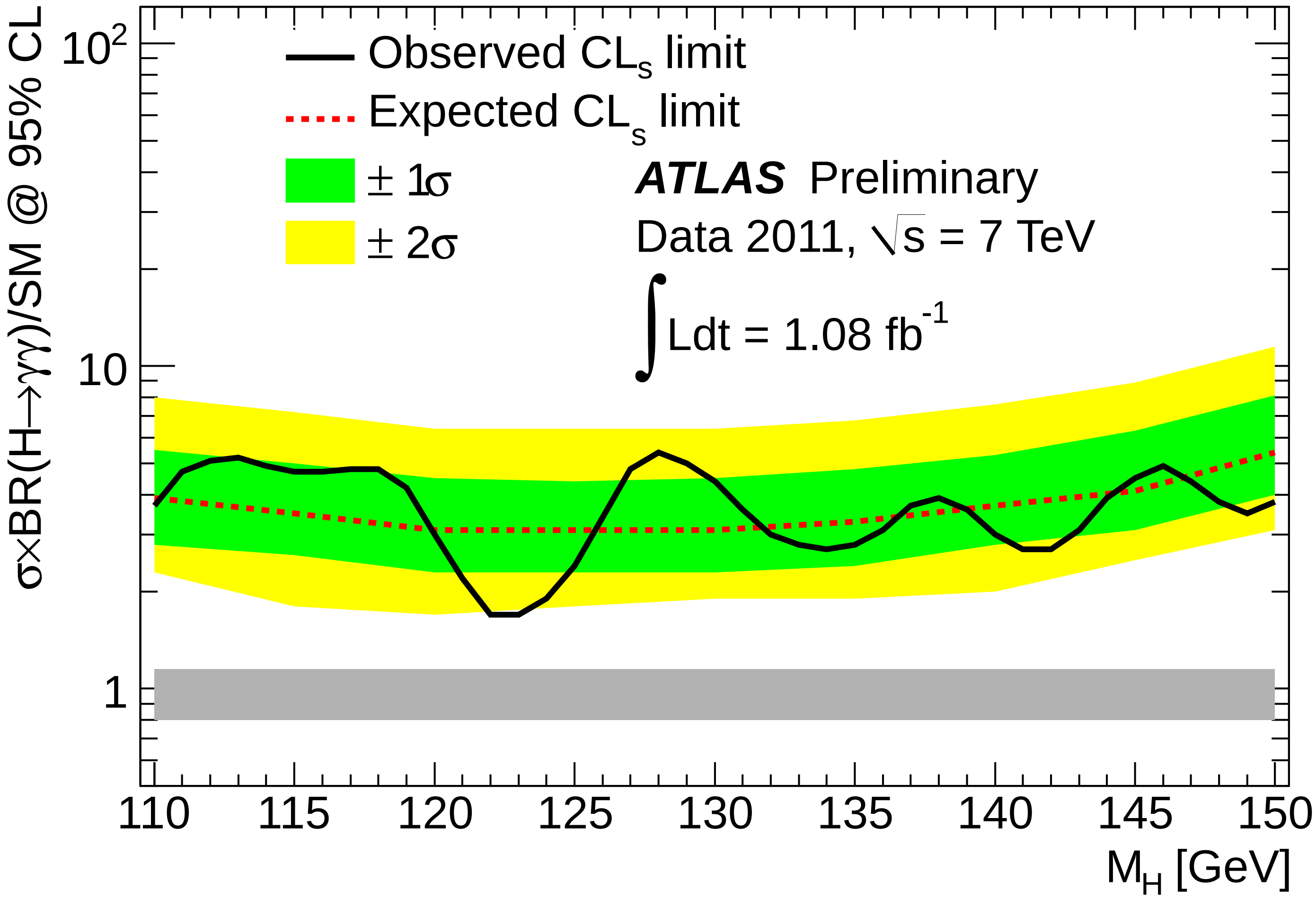
– Split in categories: detector region, conversion

– Final background estimate: exponential fit



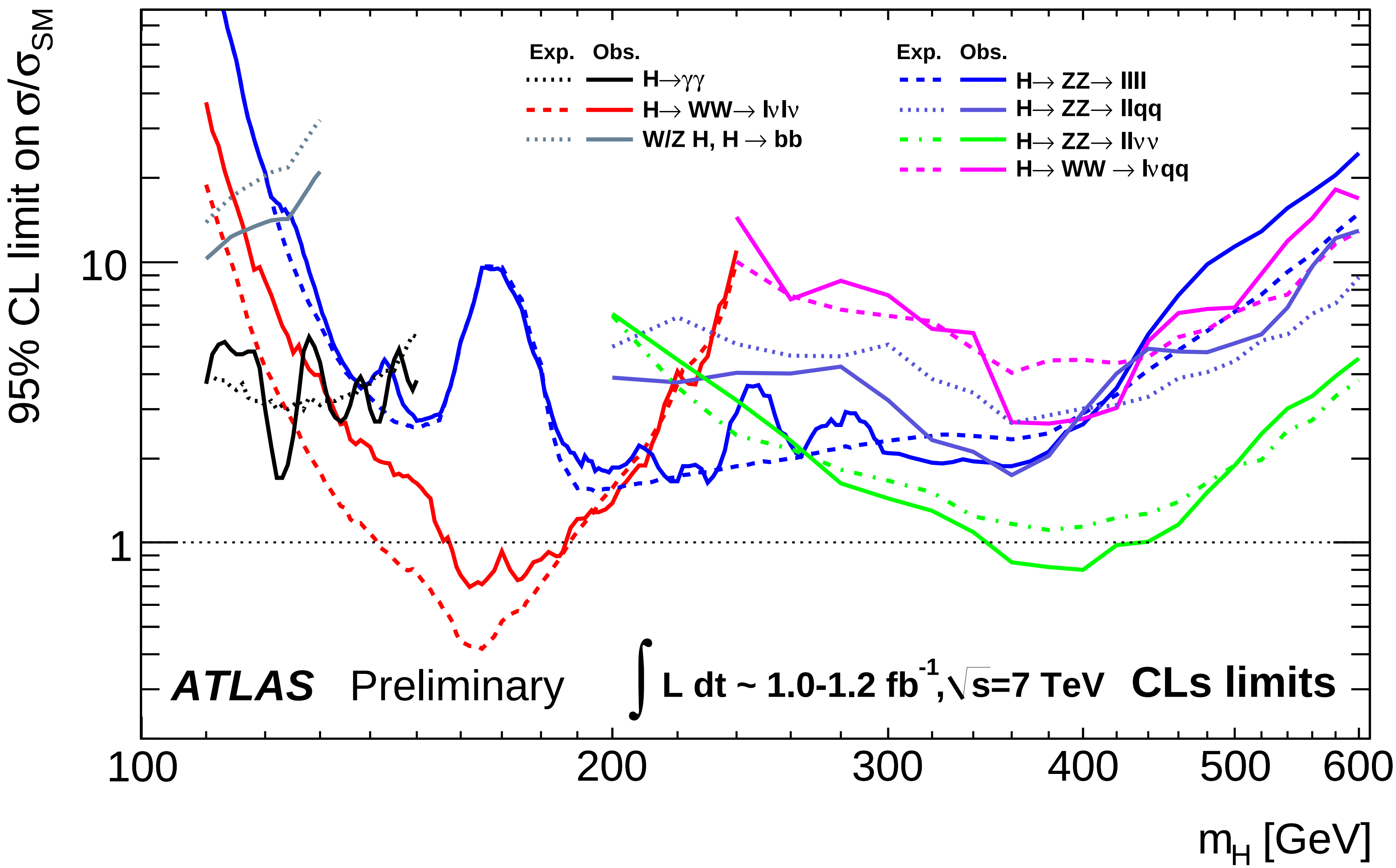



# $H \to \gamma\gamma$ Result (ATLAS)




More sensitive than $H \to WW$ for $m_H \lesssim 125$ GeV

# Combined Atlas Limit



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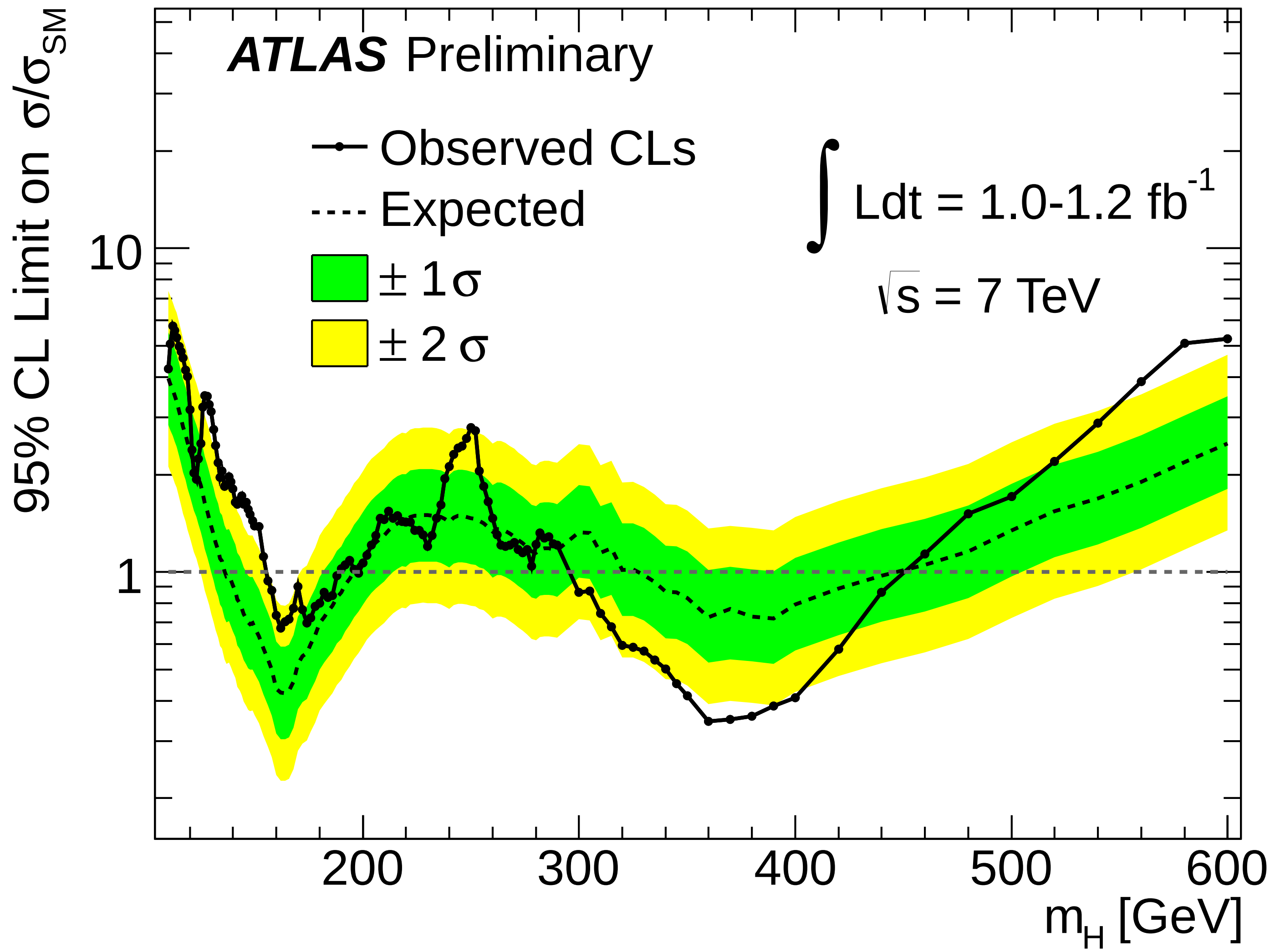


Exclude $155 < m_{\mathrm{H}} < 190$ GeV, $295 < m_{\mathrm{H}} < 450$ GeV

# Conclusion / Outlook

– Need a Higgs boson, or something like it

– Not found yet

– Keep looking. . .

– Discovering something is not the end of the story

– What is mass, really?

– More Higgs on Friday