Karlsruher Institut für Technologie

Teilchenphysik 2 — W/Z/Higgs an Collidern

Sommersemester 2019

Matthias Schröder und Roger Wolf | Vorlesung 11

INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK (ETP)

4. Physics of the W and Z Bosons

4.1 Determination of SM parameters

- Z factories
- Precision measurements at the Z pole
- W production at colliders
- Global electroweak fits

4.2 W/Z physics at the LHC

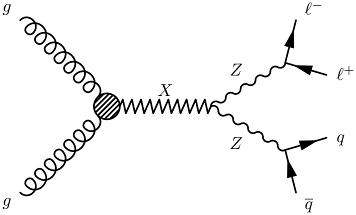
- Single W/Z boson production
- $\mathrm{W}/\mathrm{Z} + $ jets production
- Vector boson pair-production
- Vector boson scattering
- Anomalous couplings
- Exotic resonances

4.2 W/Z physics at the LHC

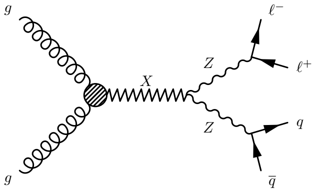
4.2.6. Exotic resonances

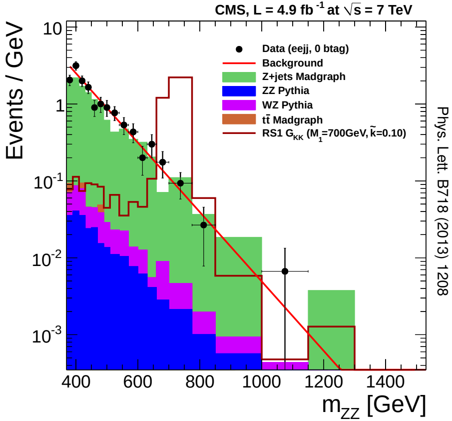
Resonant Diboson Searches

- Typical model: **Graviton** with extra spatial dimensions
- Explains relative weakness of gravity
  - EWK+QCD confined to 3 dimensions
  - Gravitation propagates additionally in extra dimensions
- Compactified extra dimensions: prevent macroscopic effects



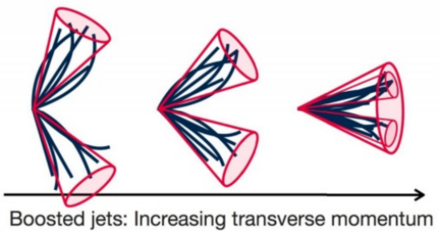
Example: Graviton Search





- Search for G $\rightarrow$ ZZ
  - Reconstruct Z bosons and search for **peak in invariant m_{ZZ} distribution**
- Typically: semi-leptonic decay of ZZ system
  - Good compromise between signal yield and purity (signal-to-bkg. ratio)

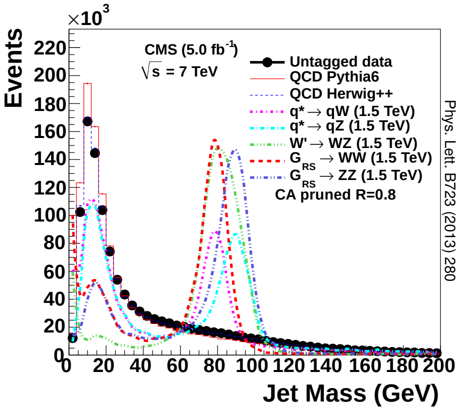
Boosted Topologies



- **Heavy resonances**
  - V bosons strongly boosted (high p_T)
  - (Hadronic) **decay products** collimated $\rightarrow$ **merged into one jet**
    (more precisely: not reconstructed as two resolved jets)
- V tag: find "**fat jet**" compatible with V decays
  - Sensitivity from jet mass and jet substructure

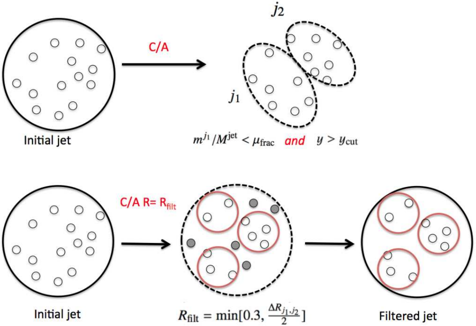
Example: Jet Mass

- Jet mass = **sum of jet-constituents' 4-momenta**
- Steeply falling spectrum for quark/gluon jets
- Peak at $\approx 80/90\,\mathrm{GeV}$ for W/Z
  - W/Z not easy to distinguish (resolution not good enough)



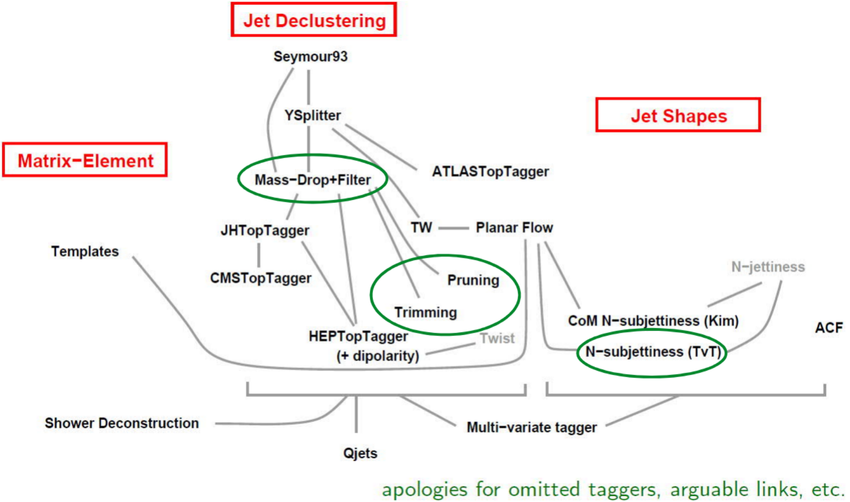
Example: Massdrop + Filter

- Start: fat jet (Cambridge–Aachen algorithm $d_{ij} = \frac{\Delta R_{ij}}{R}$)
- Uncluster jet into pair of subjets
  - Stop in case of mass drop
  - Repeat on more massive subjet otherwise
- New clustering with smaller radius
  - Keep only particles from N hardest subjets ("filtering")
- **Improves mass resolution**



ATLAS-CONF-2012-065

Jet-Substructure Landscape



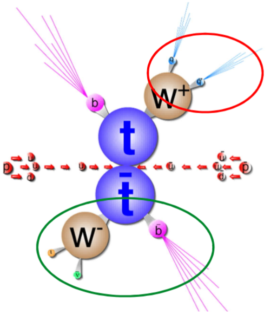
[G. Salam, BOOST 2012]

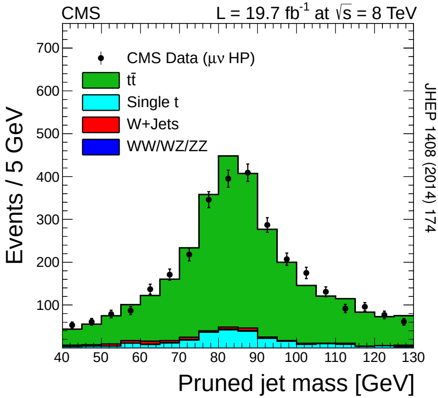
Does This Really Work?

- How to find hadronically decaying V bosons for validation?

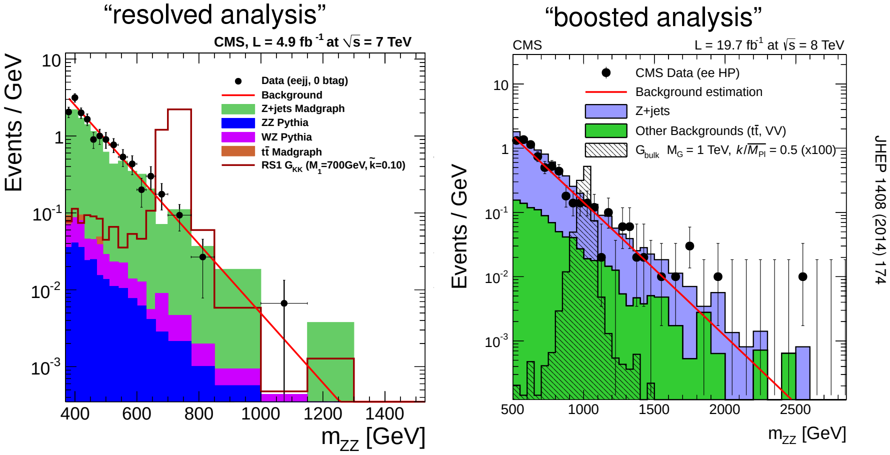
→ look at semi-leptonic $t\bar{t}$ events

  - Select events with lepton + b-jet (= t quark)
    → a second t quark is likely in the event
  - Remaining jets: non b-tagged jets likely from W boson decay





Graviton Search with Boosted W/Z

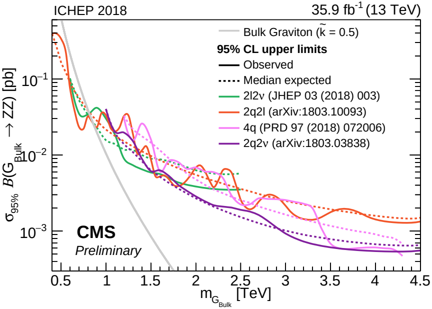


Boosted topologies: higher reach in diboson mass

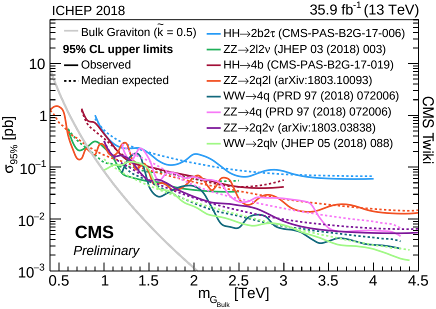
But as of now, still no graviton found . . .

A More Complete Picture

G → ZZ

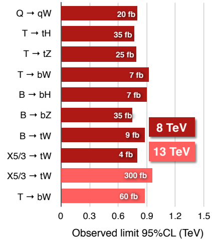


G → diboson

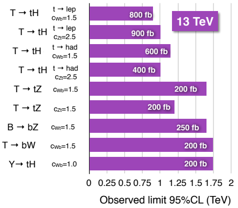


Many More Searches

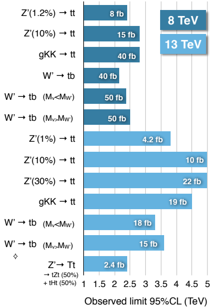
Vector-like quark pair production



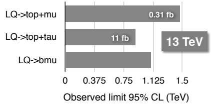
Vector-like quark single production



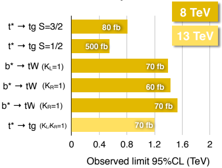
Resonances to heavy quarks



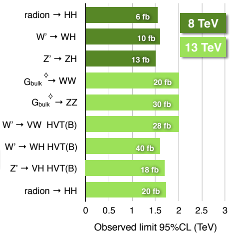
Leptoquarks



Excited quarks



Resonances to dibosons



◊model-independent

B2G
new physics searches with heavy SM particles

CMS TWiki

Models with W' and Z'

- Many new-physics models include **new heavy gauge bosons**
  - Often called W'/Z', but properties can vary wildly depending on model
- W': additional SU(2) gauge group
  - Examples: left-right symmetric models, GUTs, Superstring theories
  - Common assumption: same left-handed couplings as W (but also purely right-handed and mixed states)
- W' phenomenology
  - For W' masses $\gtrsim 180\,\mathrm{GeV}$: decay $\mathrm{W}' \rightarrow \mathrm{tb}$ kinematically allowed
  - If only right-handed couplings and right-handed neutrinos more massive than W': decay to leptons suppressed

Models with W’ and Z’

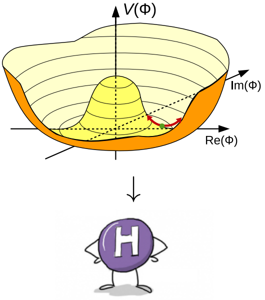
- Hundreds of models with Z’ bosons
  - New broken U(1) gauge symmetries, E_6 gauge group
  - Additional strong force
  - Extradimensions (Kaluza–Klein models)
- Z’ phenomenology
  - (Within conservation laws) arbitrary fermion couplings depending on model: leptophobic, leptophilic, ...
  - Many possible decays: l^+l^-, $t\bar{t}$, W^+W^-, ZH, ...
  - Decay width: narrow (1 % of mass) or wide ($>$ 10 % of mass) $\rightarrow$ different search strategies
  - Some models: mixing between SM Z boson and Z’ boson $\rightarrow$ distortion in mass spectrum or decay products

5. Physics of the Higgs Boson

5.1 Properties of the Standard Model Higgs-Boson

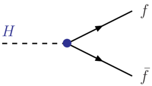
The Higgs Boson

- **Consequence of the Higgs mechanism**: massive scalar particle
- Prediction: coupling to gauge bosons and fermions (and self-interaction) with **very specific coupling structure**



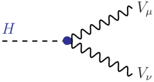
Higgs-Boson Couplings

to fermions:

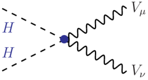


$$g_{Hff} = \frac{m_f}{v} = \frac{\lambda_f}{\sqrt{2}} \quad (\times i)$$

to massive gauge bosons $V = W^{\pm}, Z$:

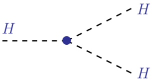


$$g_{HVV} = 2\frac{m_V^2}{v} \quad (\times - ig^{\mu\nu})$$

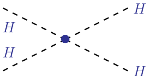


$$g_{HHVV} = 2\frac{m_V^2}{v^2} \quad (\times - ig^{\mu\nu})$$

self coupling:



$$g_{HHH} = 3\frac{m_H^2}{v} \quad (\times i)$$

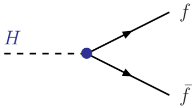


$$g_{HHHH} = 3\frac{m_H^2}{v^2} \quad (\times i)$$

- Coupling terms can be read-off from Lagrangian
  - H is indistinguishable particle: additional combinatorial factor to all amplitudes with more than 1 H field at vertex
  - At vertex, additional factors i or $-ig^{\mu\nu}$

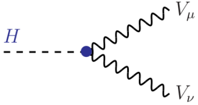
Higgs-Boson Partial Decay Widths

- Decay to fermions and massive gauge bosons (LO)



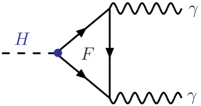
$$\Gamma(H \to f\bar{f}) = \frac{1}{8\pi v^2} N_c m_\mathrm{H} m_f^2 \beta_f^3$$

$$\Gamma(H \to \mathrm{VV}) = \frac{1}{8\pi v^2} \frac{m_V^4}{m_\mathrm{H}} \delta_V \left(\frac{1}{4x^2} - \frac{1}{x} + 3 \right) \beta_V$$



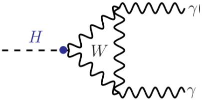
more complicated for virtual V^*
(3-body decay $H \to \mathrm{VV}^* \to V f\bar{f}$)

with $\delta_W = 2$, $\delta_Z = 1$, $x_{f,V} = \frac{m_V^2}{m_\mathrm{H}^2}$, $\beta_{f,V} = \sqrt{1 - 4x}$



- Decay to photons ($m_\mathrm{H} \ll 2m_\mathrm{t}, 2m_\mathrm{W}$)

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha_\mathrm{em}^2}{256\pi^2 v^2} m_\mathrm{H}^3 \Big[\underbrace{\tfrac{4}{3} N_c q_t^2}_{t\text{-quark}} \underbrace{-7}_{W} \Big]^2$$



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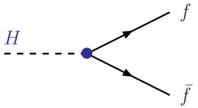
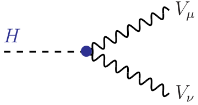


$$\Gamma(H \to f\bar{f}) = \frac{1}{8\pi v^2} N_c m_{\mathrm{H}} m_f^2 \beta_f^3$$

$$\Gamma(H \to \mathrm{VV}) = \frac{1}{32\pi v^2} m_{\mathrm{H}}^3 \delta_V \left(1 - 4x + 12x^2\right) \beta_V$$



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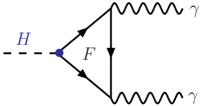
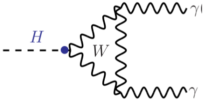
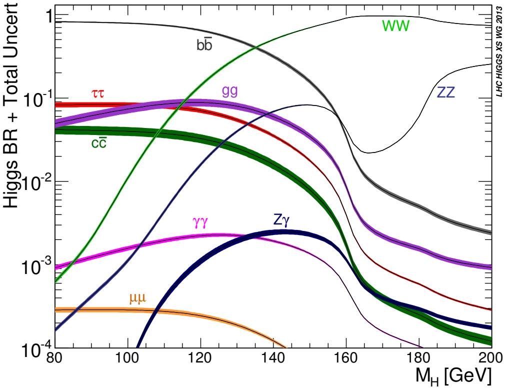


- Decay to photons ($m_{\mathrm{H}} \ll 2m_{\mathrm{t}}, 2m_{\mathrm{W}}$)

$$\Gamma(H \to \gamma\gamma) = \frac{\alpha_{\mathrm{em}}^2}{256\pi^2 v^2} m_{\mathrm{H}}^3 \Big[\underbrace{\tfrac{4}{3} N_c q_t^2}_{t\text{-quark}} \underbrace{-7}_{W} \Big]^2$$

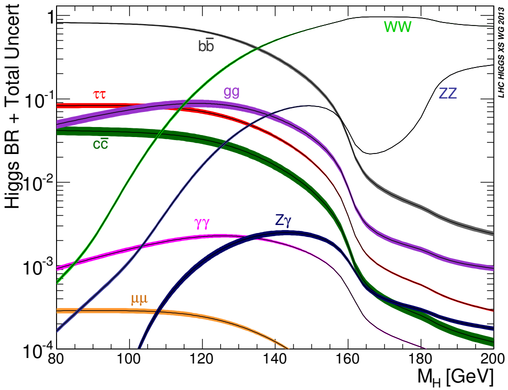


Higgs-Boson Branching Ratios



- **Higgs boson couples to mass of particles**
- ≈ dominant decay channels: to heaviest particles (that are kinematically allowed)
  - In case of *WW*, *ZZ*: one (or both) can be virtual
  - Also different factors than for fermions

Higgs-Boson Branching Ratios



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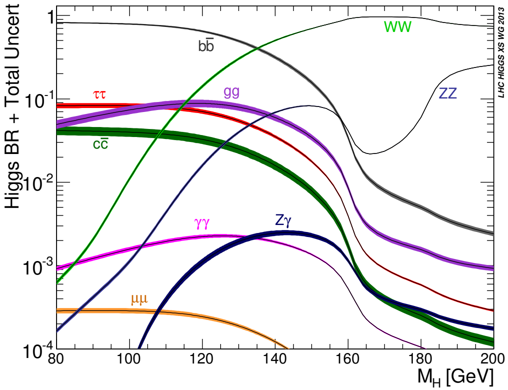
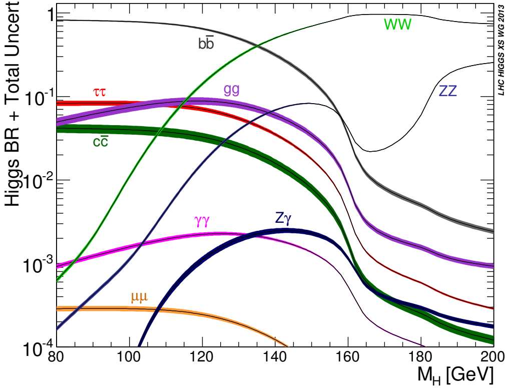


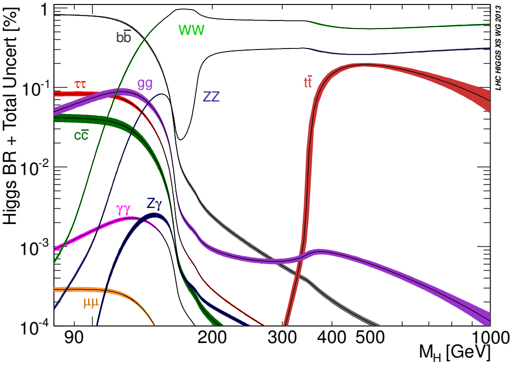
- $m_{\mathrm{H}} \lesssim 130\,\mathrm{GeV}$: dominated by $b\bar{b}$

Higgs-Boson Branching Ratios



- $m_H \lesssim 130\,\text{GeV}$: dominated by $b\bar{b}$
- $130\,\text{GeV} \lesssim m_H \lesssim 2m_Z$: $H \to \text{VV}(^*)$ starts to dominate
  - $\Gamma(H \to f\bar{f})$ approximately $\propto m_H m_f^2$
  - $\Gamma(H \to \text{VV})$ approximately $\propto m_H^3$
  - WW entirely dominates between $2m_W < m_H \lesssim 2m_Z$

Higgs-Boson Branching Ratios



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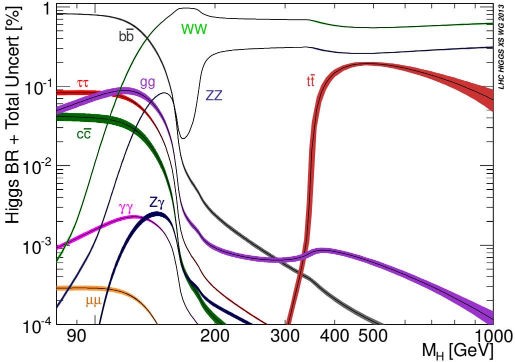
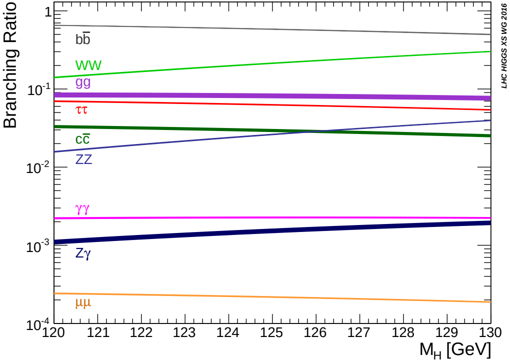


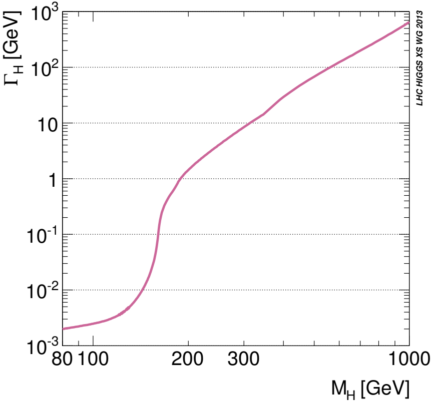
- $m_H \lesssim 130\,\text{GeV}$: dominated by $b\bar{b}$
- $130\,\text{GeV} \lesssim m_H \lesssim 2m_Z$: $H \to \text{VV}(^*)$ starts to dominate
- $m_H \gtrsim 2m_Z$: H decays to $\approx \frac{2}{3}$ to WW and $\approx \frac{1}{3}$ to ZZ ($\propto m_H^3$)
  - Opening of $t\bar{t}$ channel changes little, contribution decreases for larger m_H

Higgs-Boson Branching Ratios



- **At 125 GeV: many open channels — experimentally interesting!**
  - But not all experimentally accessible. . .

Higgs-Boson Total Decay Width



- **Very narrow in low m_H regime**
  - At 125 GeV: 4 MeV
  - Experimentally: entirely dominated by detector and reconstruction effects
- Steep increase with m_H, in particular where $H \to$ VV opens

Summary

- **Consequence of the Higgs mechanism**: massive scalar particle
- Very specific **coupling** to gauge bosons and fermions (and self-interaction), **depending on particle masses**
  - Dominant coupling to heaviest particles
  - Coupling to massless particles ($\gamma\gamma$, gg) via loops
  - $m_{\mathrm{H}} = 125\,\mathrm{GeV}$: many open decay channels (VV with one virtual V^*)
- Only free parameter: m_{H}

Summary

- **Consequence of the Higgs mechanism**: massive scalar particle
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  - $m_{\text{H}} = 125\,\text{GeV}$: many open decay channels (VV with one virtual V^*)
- Only free parameter: m_{H}
- **As soon as Higgs-boson mass known: all Higgs-boson interactions determined!**

5.2 Discovery and first measurements of the Higgs boson

5.2.1. Search for the Higgs boson and discovery

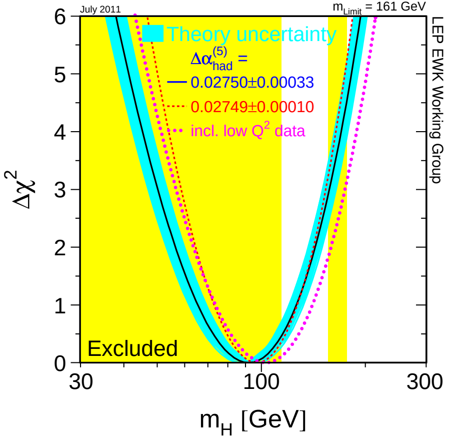
Overview

- Higgs boson **mass range limited** by theoretical arguments (perturbativity, triviality, vacuum stability)
  $\rightarrow$ roughly **100 GeV to 1 TeV**
- **Strategies** to search for the Higgs boson (or any new particle):
  - **Direct search** for Higgs production and decay at colliders
    $\rightarrow$ limited by centre-of-mass energy and luminosity
  - Search for **indirect effects** in higher-order corrections ("loops")
    $\rightarrow$ sensitive to much higher Higgs masses but possibly model-dependent
- Brief **history** of Higgs boson searches
  - **LEP** (1989–2000), **SLC** (1989–1998): **direct** and **indirect** searches
  - **Tevatron** (1992–1996, 2001–2011): **direct** searches
  - **LHC** (Run I 2010–2012): **direct** searches $\rightarrow$ **discovery**

Reminder: Constraints on Higgs-Boson Mass

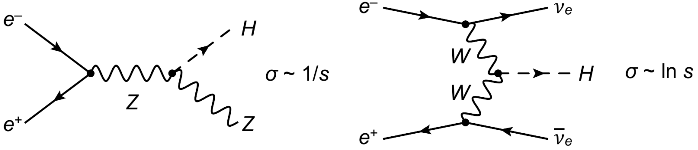
- **Global fit**
  - LEP Electroweak Working Group (Summer 2011): last result before Higgs discovery
  - 18-parameter χ^2 fit: Z pole + W boson + top quark
- Results
  - Best-fit Higgs mass: $\boldsymbol{m_{\mathrm{H}} = 94^{+29}_{-25}}$ **GeV**
  - **Light** Higgs preferred
  - **Logarithmic** dependence: m_{H} only weakly constrained

"Blue Band Plot": Higgs mass limits (before LHC)



Production Processes at LEP

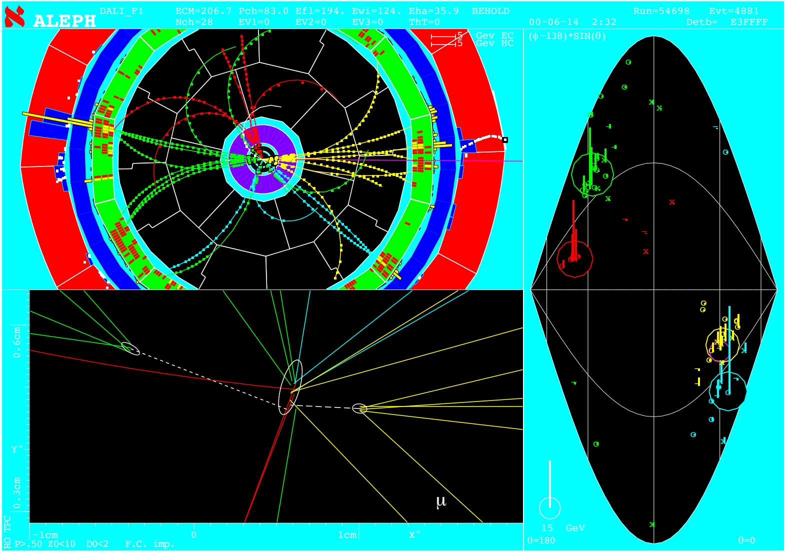
- **LEP 1**: centre-of-mass energy $\approx 91\,\text{GeV}$ (Z pole)
  - Only lower limits from non-observation of Z decays including Higgs bosons
  - Exclusion of **light scalar particles**
- **LEP 2**: nominal centre-of-mass energy increased from 161 GeV (WW production threshold, 1996) and 209 GeV (limit of LEP cavities, 2000)
  - Production channels: **Higgs-strahlung** (most sensitive), $\nu\nu$H (WW fusion)



  - Access up to $\boxed{m_\text{H} \approx \sqrt{s} - m_\text{Z} \approx 118\,\text{GeV}}$
  - Preferred decay channels: $\text{H} \to \text{b}\bar{\text{b}}/\tau\tau$, $\text{Z} \to ll/\text{q}\bar{\text{q}}/\nu\nu$

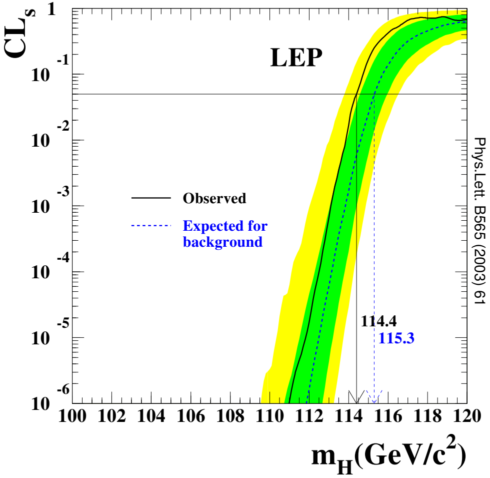
Higgs-Boson Candidate at ALEPH

Process: $e^+e^- \to ZH \to q\bar{q}b\bar{b}$



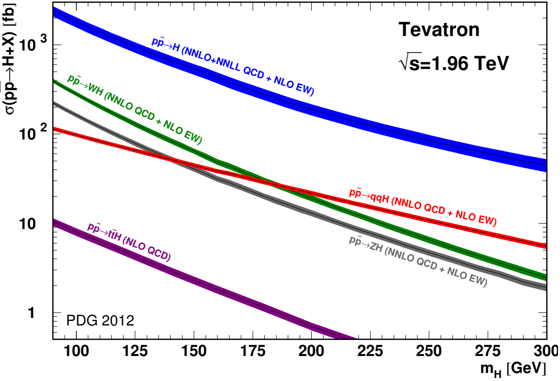
Mod. Phys. Lett. A 29 1430004 (2014)

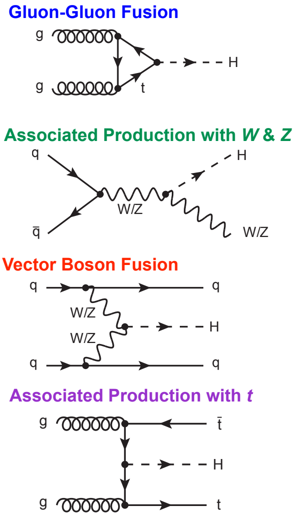
The Final Word from LEP



- Observed (expected) 95 % C.L. limit: $m_H > \mathbf{114.4\,GeV}$ $(\mathbf{115.3\,GeV})$

Higgs Production at the Tevatron



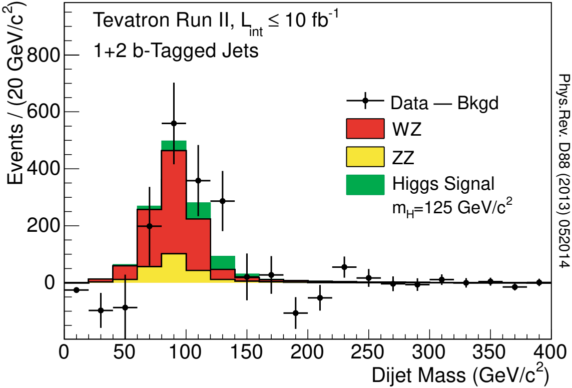


- Cross section **steeply falling** with m_H
  $\rightarrow$ only accessible for **light** Higgs boson
- gluon-gluon fusion: large QCD background
  $\rightarrow$ preferred: associated **WH production**

Decay Channels at the Tevatron

- Relevant Higgs-boson **decay channels** at the Tevatron:
  - $H \to b\bar{b}$: identification via b-tagging, but large QCD background
  - $H \to \tau\tau$: large background from QCD (and $Z \to \tau\tau$)
  - $H \to WW$: sensitivity for $m_H = 2m_W \approx$ 160 GeV, works with gg fusion
  - $H \to \gamma\gamma$: very clean but small branching fraction, works with gg fusion
- Most sensitive channels: **VH($b\bar{b}$)**
  - $p\bar{p} \to WH \to l\nu b\bar{b}$
  - $p\bar{p} \to ZH \to ll b\bar{b}$

dijet mass in VH($b\bar{b}$) after background subtraction

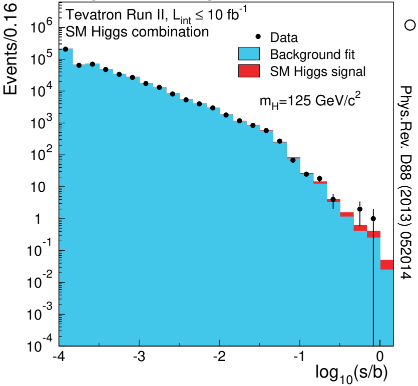


Phys.Rev. D88 (2013) 052014

Combination & Statistical Analysis

Karlsruher Institut für Technologie

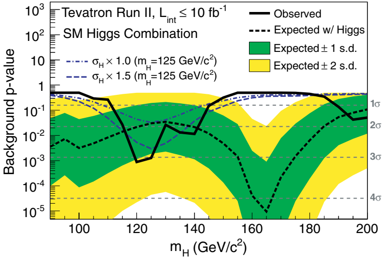
All analysis bins sorted by signal-to-background ratio



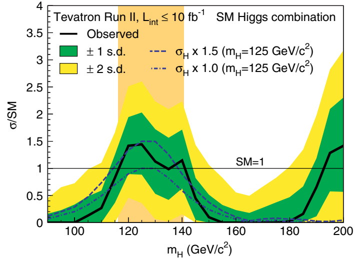
- Strategy for final combination
  - **Very small** signal cross section
    $\rightarrow$ **combine** as many production/decay channels as possible ($>$ 50 per experiment, all add to final sensitivity)
  - **Uncertainty** of background **much larger** than signal
    $\rightarrow$ event selection & b-tagging rely heavily on **multivariate** analysis methods

The Final Word from Tevatron

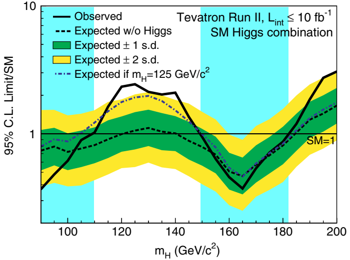
Background-Only *p* Value



Best-Fit Signal Cross Section



Bayesian 95% CL Upper Limit



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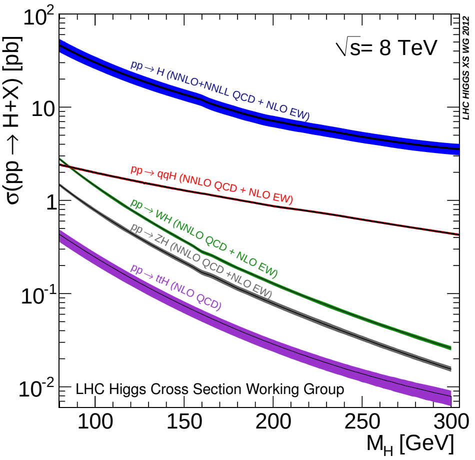
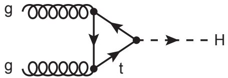
- **Excess** observed in Tevatron data:
  - Up to 3σ for **115 GeV < m_H < 140 GeV**
  - Compatible with approx. **1.5 × σ_{SM}**
- 95%-CL **exclusion** from Tevatron data:
  - 90 GeV < m_H < 109 GeV
  - 149 GeV < m_H < 182 GeV

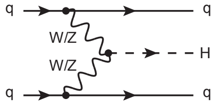
Higgs Production at the LHC



Gluon-Gluon Fusion

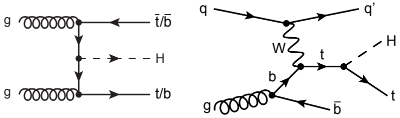


Vector Boson Fusion

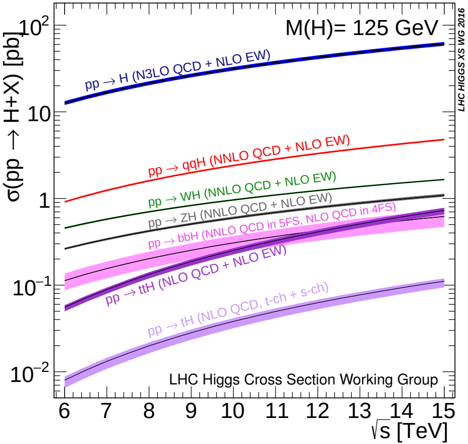


Associated Production with *W* and *Z*

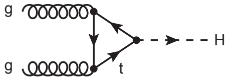
Associated Production with *t* and *b*



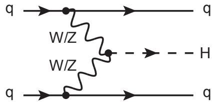
Higgs Production at the LHC



Gluon-Gluon Fusion



Vector Boson Fusion



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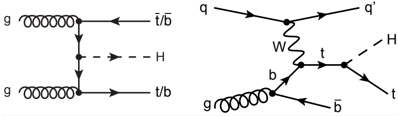
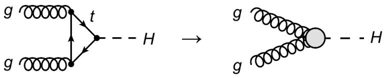
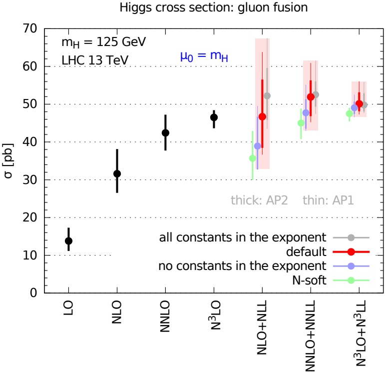


Example: gg $\to$ H

- State-of-the-art for gg $\to$ H inclusive cross section: NNNLO QCD and NLO electroweak (EWK) corrections[1]
  - **NNNLO** in effective field theory (EFT) with $m_t \to \infty$, rescaled to exact LO result ($\sigma^{\mathrm{LO}}_{\mathrm{ex}} / \sigma^{\mathrm{LO}}_{\mathrm{EFT}}$)



  - Corrections: massive quarks, EWK $\mathcal{O}(\alpha^3)$, mixed QCD-EWK $\mathcal{O}(\alpha\alpha_s^3)$
  - Result for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ at $13\,\mathrm{TeV}$



Handbook of LHC Higgs Cross Sections, Vol. 4

$$\sigma(\mathrm{gg} \to \mathrm{H}) = 48.58\,^{+2.22}_{-3.27}\ (\text{theory}) \pm 1.56\ (\text{PDF} + \alpha_s)\ \text{pb} \ \to\ \text{about } \mathbf{6\,\%\ uncertainty}$$

[1] Details: (C. Anastasiou et al., JHEP 1605 (2016) 058) and Handbook of LHC Higgs Cross Sections, Vol. 4

Most Important Analysis Channels

Rationale: favourable combination of cross section times branching ratio, selection efficiency, signal-to-background ratio, resolution, . . .

Production	Decay	Remark
$gg \to H$	$H \to ZZ(^*) \to 4\ell$	excellent mass resolution
$gg \to H$ $qq \to qqH$	$H \to \gamma\gamma$	small branching fraction but excellent mass resolution
$gg \to H$ $qq \to qqH$	$H \to WW(^*) \to \ell\nu\,\ell\nu$	large production cross section but poor mass resolution (two neutrinos)
$gg \to H$ $qq \to qqH$	$H \to \tau\tau$	decay into fermions with large branching fraction but large QCD background
$\mathrm{q\bar{q}} \to VH$	$H \to \mathrm{b\bar{b}}$	large QCD background → additional tag through (leptonic) vector-boson decay
$gg \to \mathrm{t\bar{t}H}$ $gg \to \mathrm{tHq/tHW}$	$H \to \mathrm{b\bar{b}}$, $\gamma\gamma$, multi-leptons	access to top-quark Yukawa coupling

Higgs Discovery Timeline

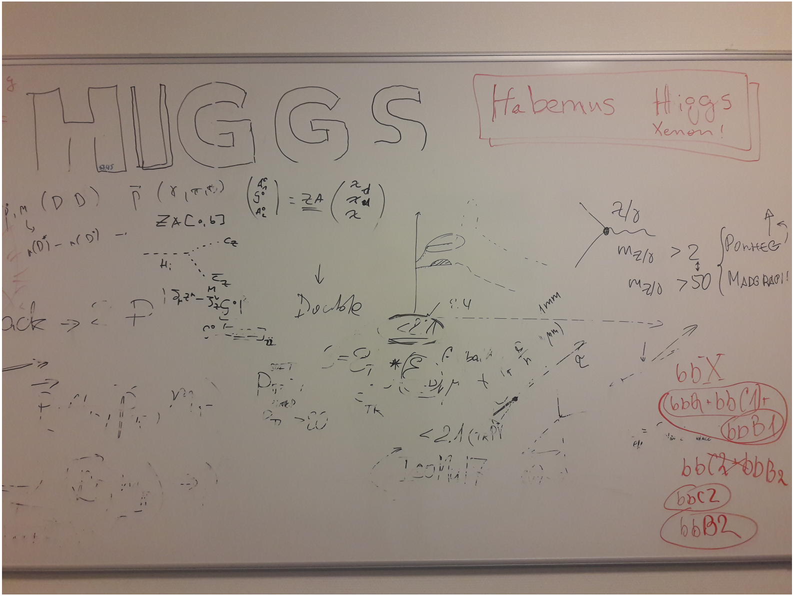
- First serious Higgs searches at the LHC: **2011 dataset** (5 fb^{-1} @ 7 TeV)
- CERN public seminar (December 13, 2011)
  - **Excess** at $m_\text{H} \approx 125\,\text{GeV}$, **both** in ATLAS and CMS
  - $\approx 3\,\sigma$ ($\approx 2\,\sigma$) local (global) significance
- Update[2] with 2011 data + first part of 2012 data (July 4, 2012):
  - Significance: $\mathbf{5.0\,\sigma/4.9\,\sigma}$ in ATLAS/CMS on $5 + 5\text{fb}^{-1}$ per experiment
- CERN DG R. Heuer: "As a layman I would say: 'I think we have it!'"

[2] July 4, 2012: "Latest update in the search for the Higgs boson"

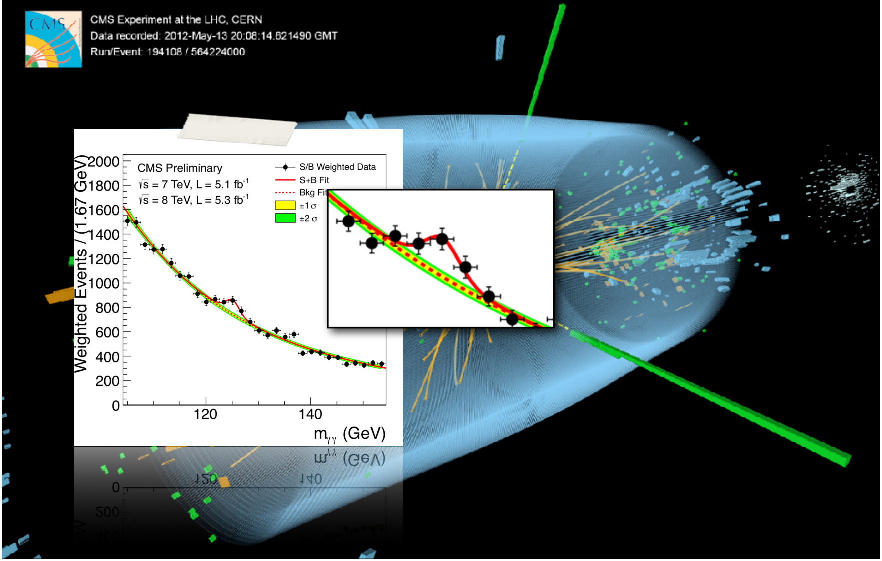
July 4th, 2012

July 4th, 2012

July 4th, 2012

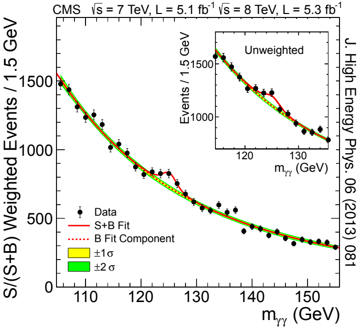

HIGGS
Habemus Higgs
Xenon!
Double
bbX
bbC2
bbB2

$H \to \gamma\gamma$ Candidate



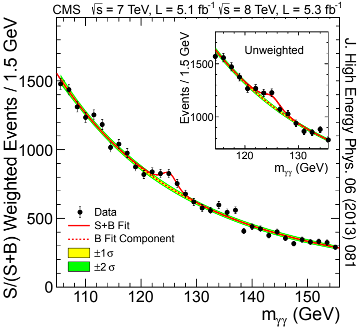
H $\rightarrow \gamma\gamma$ Analysis

- Signature: **small narrow peak** on huge **combinatorial** background



H $\rightarrow \gamma\gamma$ Analysis

- Signature: **small narrow peak** on huge **combinatorial** background
- Detect **photons** (ECAL) and e^+e^- pairs from **photon conversion** before ECAL



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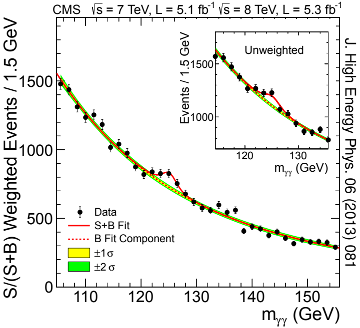

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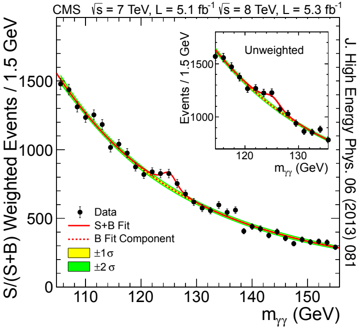
- Background: QCD **diphoton** production + **jets misidentified as photons**
- Background **estimated from data**: fit empirical function outside signal region



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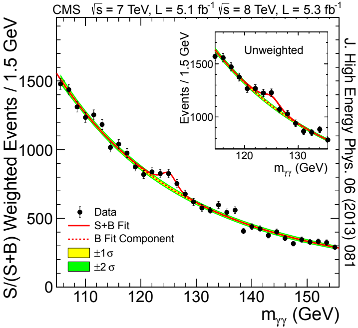

- Signal and background separation: **cut-based** or **boosted decision trees** (ECAL cluster shape, object kinematics, consistency with primary vertex)

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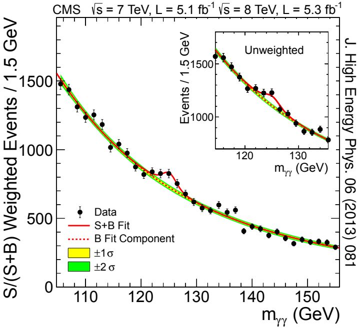
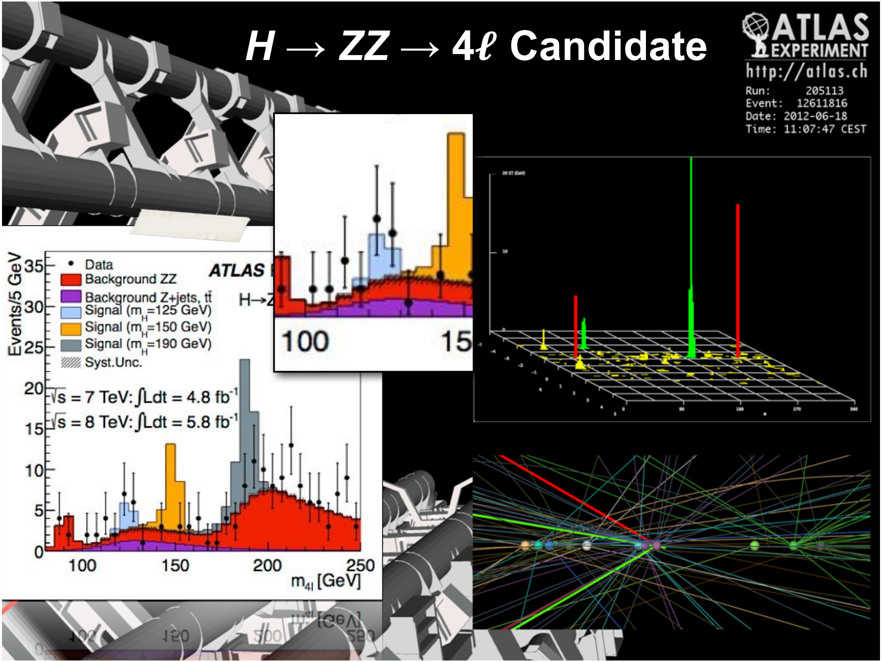


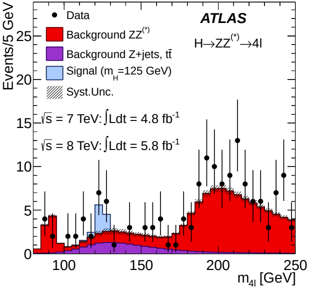
- Signal and background separation: **cut-based** or **boosted decision trees** (ECAL cluster shape, object kinematics, consistency with primary vertex)
- Experimental challenge: excellent calibration of **photon energy scale**

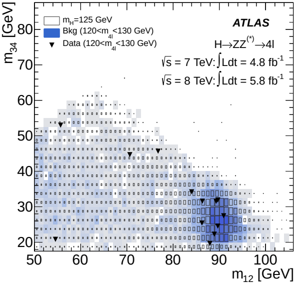
$H \to ZZ \to 4\ell$ Candidate



$H \to ZZ \to 4l$ Analysis

- Signature: **4 isolated high-p_T leptons** (e, μ), invariant mass of one pair compatible with Z boson

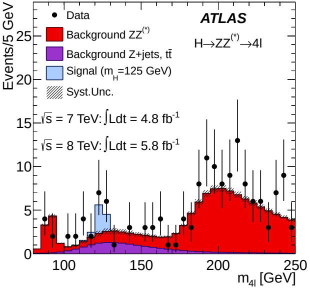


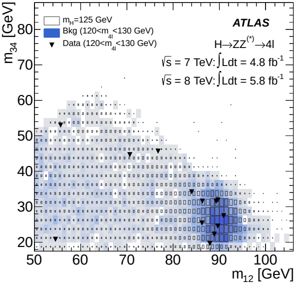


Phys.Lett. B716 (2012) 1

H $\rightarrow$ ZZ $\rightarrow$ 4l Analysis

- Signature: **4 isolated high-p_T leptons** (e, μ), invariant mass of one pair compatible with Z boson
- Sensitive over **wide Higgs-boson mass range** (100–600 GeV)
- Excellent Higgs mass resolution **1–2 %**





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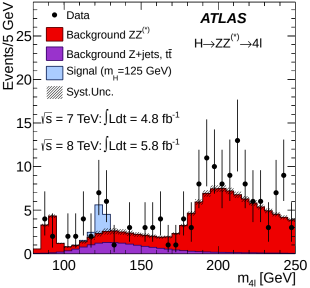
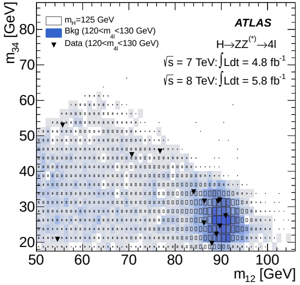
- Background:
  - **ZZ^* continuum**: estimated from MC
  - $Z+$jets, $t\bar{t}$: estimated from control regions in data





Phys.Lett. B716 (2012) 1

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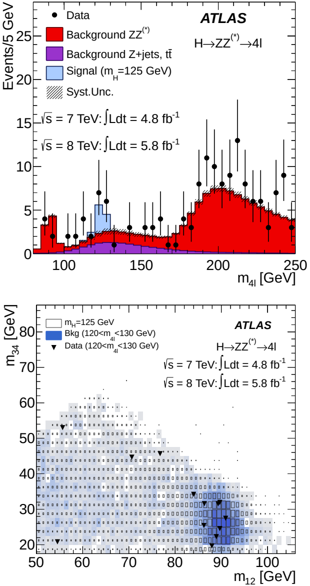
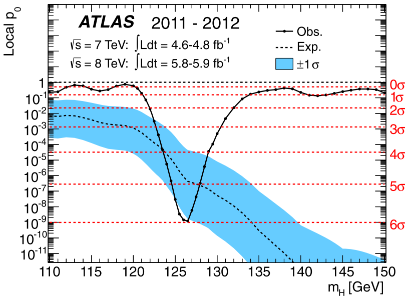
- Excellent Higgs mass resolution **1–2 %**
- Background:
  - **ZZ* continuum**: estimated from MC
  - Z + jets, t$\bar{t}$: estimated from control regions in data
- Selection: kinematics of 4-lepton system (5 angles, 2 pair masses)



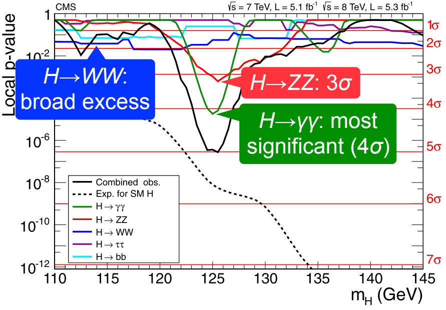
Phys.Lett. B716 (2012) 1

Combination

- Best sensitivity: **combination** of all decay channels **H** $\rightarrow \gamma\gamma$, **H** $\rightarrow$ **ZZ**$(^{*}) \rightarrow$ **4*l***, H $\rightarrow$ WW$(^{*}) \rightarrow l\nu l\nu$, H $\rightarrow \tau\tau$, H $\rightarrow$ b$\bar{\text{b}}$
- Local p values for combination: $\geq$ **5** $\boldsymbol{\sigma}$ **excess** around $m_{\text{H}} = 125\,\text{GeV}$

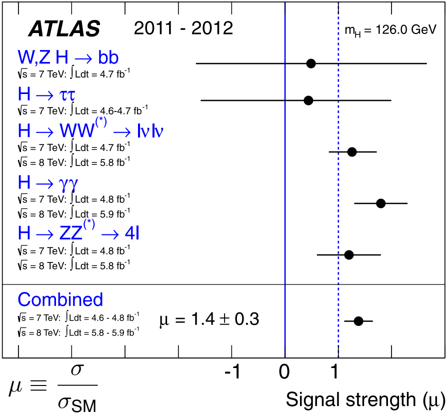


Phys. Rev. B716 (2012) 1



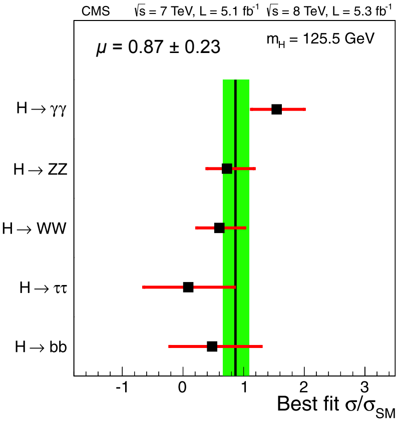
Phys. Rev. B716 (2012) 30

Best-Fit Signal Cross Section



$$\mu \equiv \frac{\sigma}{\sigma_{SM}}$$

Phys. Rev. B716 (2012) 1



Phys. Rev. B716 (2012) 30

- All decay channels **compatible with SM** ($\mu = 1$)
- First measurement of $\boldsymbol{m_H}$:
  - 126.0 ± 0.6 GeV (ATLAS)
  - 125.3 ± 0.6 GeV (CMS)

The Nobel Prize in Physics 2013

François Englert, Peter Higgs

The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Summary

- Higgs searches at the **Tevatron**
  - Challenging: low cross sections, large backgrounds
  - Combination of all analysis channels in CDF and D0: **up to 3 σ excess** compatible with Higgs boson production in **115 GeV $<$ m_H $<$ 140 GeV**
- Large **theory effort**: accurate predictions of Higgs signals and important backgrounds (up to NNNLO)
- July 4, 2012: **discovery** of a "Higgs-like particle" at the LHC
  - Main discovery channels: **$H \to \gamma\gamma$, $H \to ZZ^{(*)} \to 4l$** (mass peaks)
  - Other channels contributing: $H \to WW^{(*)} \to l\nu l\nu$, $H \to \tau\tau$, $H \to b\bar{b}$
  - Combination of all analysis channels: $\geq$ **5 σ** independently in ATLAS and CMS

5.2.2. Property Measurements

Higgs-Boson Mass

- Reminder: importance of the Higgs-boson mass
  - m_H **only free parameter of SM Higgs sector**: consistency check of SM (relation to m_t and m_W through quantum corrections)
  - Improved knowledge on m_H $\rightarrow$ more precise predictions of other Higgs properties
  - Decay channels with **best mass resolution**: $H \rightarrow \gamma\gamma$ (low signal purity), $H \rightarrow ZZ \rightarrow 4l$ (small signal rate)

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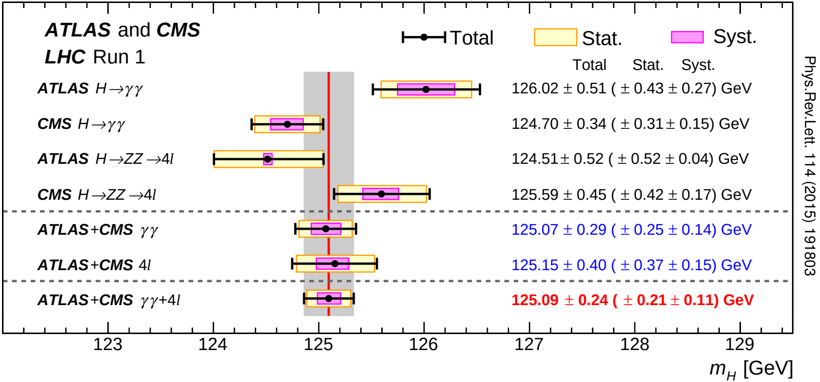
  - Decay channels with **best mass resolution**: $H \rightarrow \gamma\gamma$ (low signal purity), $H \rightarrow ZZ \rightarrow 4l$ (small signal rate)
- Experimental challenge: control of **calibration uncertainties**
  - $\gamma\gamma$: **ECAL response** and **material** in front of ECAL
  - $4l$: **energy/momentum scale** and resolution for e^- / μ

Higgs-Boson Mass: Run 1 Combination



- Measurement precision: $2 \cdot 10^{-3}$ → one of **most precisely known** SM parameters, still **statistics limited**

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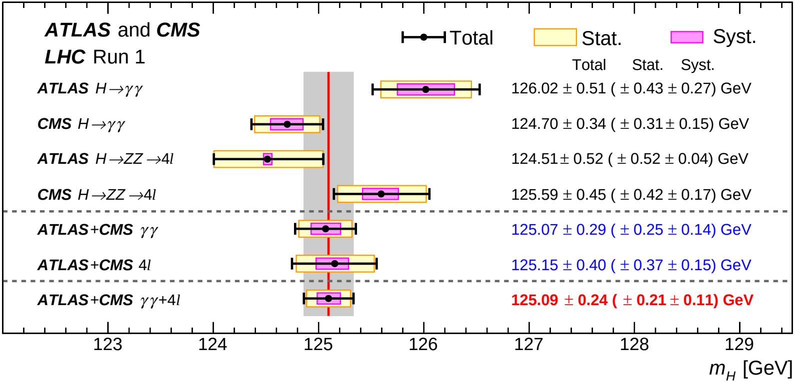
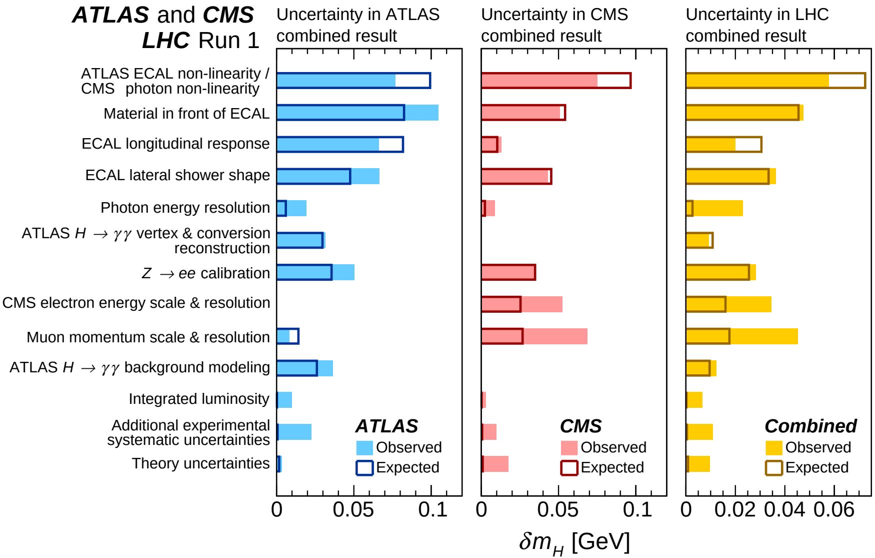


Phys.Rev.Lett. 114 (2015) 191803

- Measurement precision: $2 \cdot 10^{-3}$ → one of **most precisely known** SM parameters, still **statistics limited**
- Breakdown of systematic uncertainties:
  ± 0.11 (scale) $\pm$ 0.02 (others) $\pm$ 0.01 (theory) GeV
  → **energy scale** uncertainties dominant

Higgs-Boson Mass: Uncertainties



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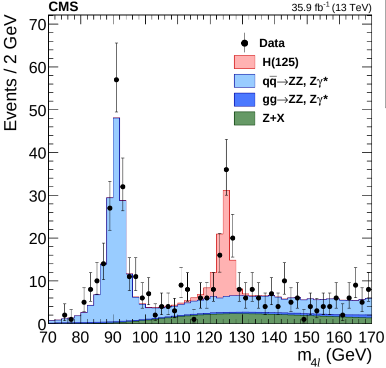
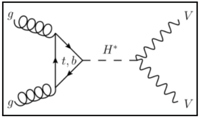
Higgs-Boson Mass: Status (2019)

[JHEP 1711 (2017) 047]





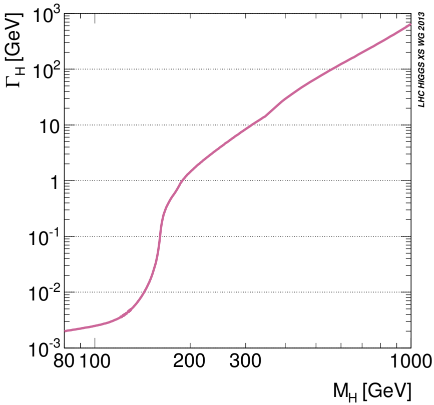
Most precise measurement in H $\to$ ZZ $\to$ 4l channel by CMS

3D fit of mass, event-by-event resolution, S/B discriminant

$m_\mathrm{H} = 125.26 \pm 0.20\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst})\,\mathrm{GeV}$ ($<$ **0.2 % level**)

Higgs-Boson Width

- Reminder: natural **total decay width Γ_H** of Higgs boson in SM **only 4 MeV**
  - Typical mass resolution in H $\rightarrow \gamma\gamma/4l$: **1–2.5 %** (1–3 GeV)
  - Measured Higgs line shape entirely **resolution dominated**



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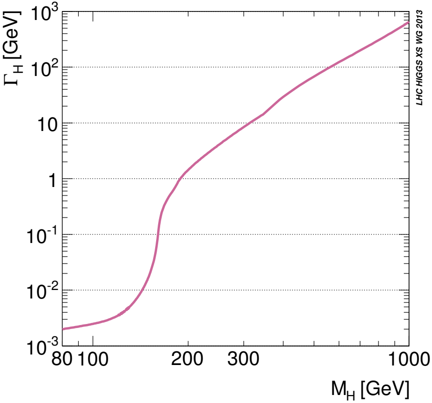
- Ideas for Higgs-boson width **measurement**
  - **Direct** (model-independent): fit of Higgs line shape
  - **Indirect** (model-dependent): **off-shell effects**



Γ_H: Direct Measurement

- Invariant mass distribution of unstable particles with decay width Γ:
  Breit–Wigner distribution

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m^2} \propto \frac{1}{(q^2 - m^2)^2 + m^2\Gamma^2} \quad \xrightarrow{\Gamma \to 0} \quad \frac{\pi}{m\Gamma}\delta(q^2 - m^2)$$

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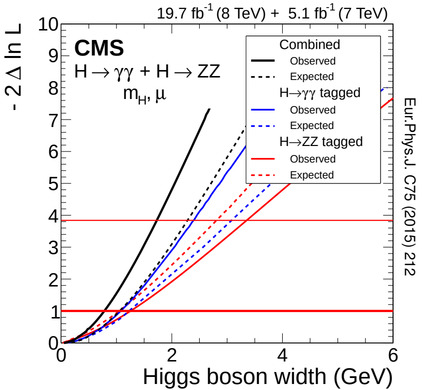
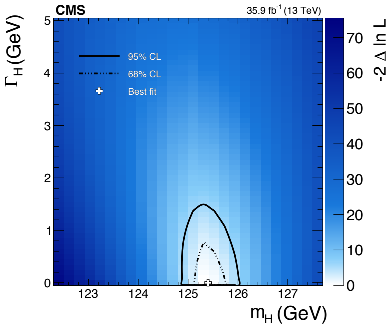
  - $\Gamma \to 0$: **narrow-width approx.** $\to$ production and decay factorise
- Experimentally accessible: **convolution** of decay width and **detector resolution**
  - Decay channels: $H \to \gamma\gamma$, $H \to 4l$
  - Likelihood fit to signal model: consistent with $\Gamma_H = 0$
  - Upper 95 % CL limit (Run 1): $\mathbf{\Gamma_H < 1.7\,GeV}$ (2.3 GeV expected)

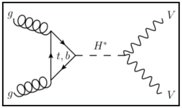


Higgs-Boson Width (Status 2019)

[JHEP 1711 (2017) 047] [Phys. Rev. D99 (2019) 112003]

- Most precise measurements in $H \to ZZ \to 4l$ channel





Direct measurement: $\Gamma_H < 1.10\,\text{GeV}$ (95 % C.L.)

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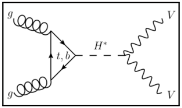
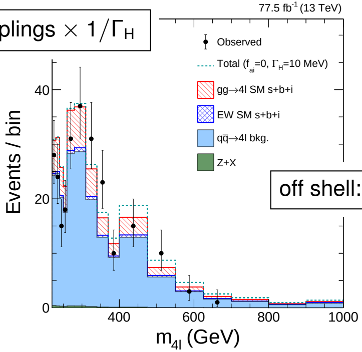


on shell: $\sigma \propto$ couplings $\times 1/\Gamma_H$



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From on-shell/off-shell cross-section ratio: $\Gamma_H < 14.4\,\text{MeV}$ (95 % C.L.)