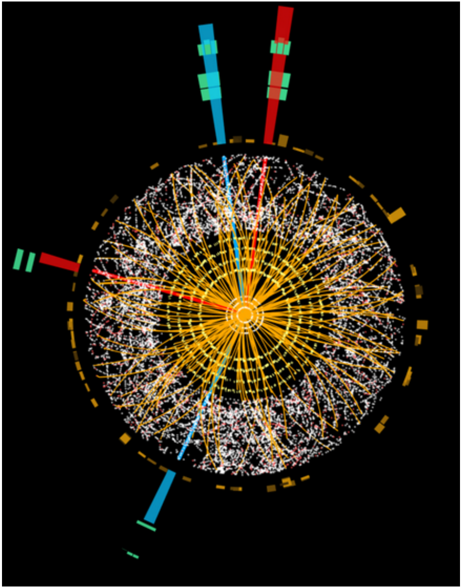

Higgs: SM Issues – Experiment –

Les Houches Workshop Series
“Physics at TeV Colliders” 2015

June 2, 2015

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for Higgs: SM Issues Session: Josh Bendavid, Massimiliano Grazzini, Ciaran Williams, KT

Thanks to Michael Duehrssen, Dag Gillberg and Florian Bernlochner for discussions

Experimental status.

Run1

- Since Higgs boson discovery in summer 2012: property measurements at 7 TeV ($\sim$4.5 fb^{-1}) and 8 TeV ($\sim$20 fb^{-1})
  - ⋆ Precise mass measurement (ATLAS+CMS combined)
  - ⋆ Coupling to SM particles (from different decay modes and separation of production channels)
  - ⋆ Spin and parity tests
  - ⋆ Off-shell measurements
  - ⋆ Fiducial and differential cross sections
  - ⋆ ...
- Run1 measurements close to complete, a few papers are still to come (in particular ATLAS+CMS coupling combination)

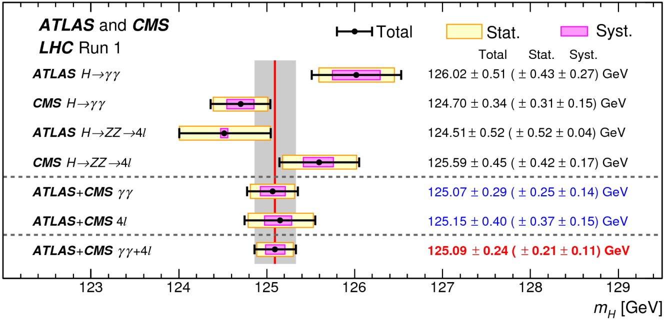
2015

- Stable beams operation at 13 TeV starting this week!
- Expect $\sim$10 fb^{-1} in 2015
- 2015 measurements will not surpass precision of Run1 measurements, but it is enough data to be interesting

Run1 results

Mass measurements.

- Measured in high resolution channels $H \to \gamma\gamma$ and $H \to 4\ell$



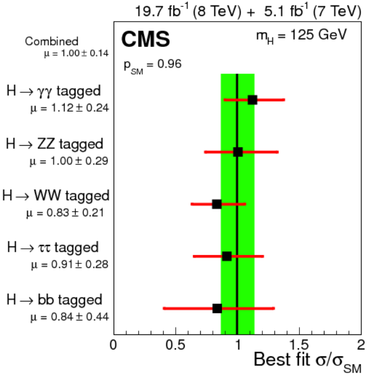
0.2% precision

(dominated by statistical uncertainty)

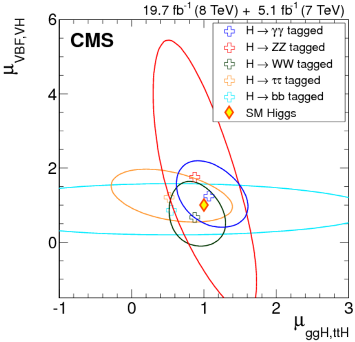
- Builds on careful calibration of electromagnetic calorimeters and muon momentum scale
- Getting back to this precision in Run2 will take a while
- In the long run, a precise mass measurement is an important input to couplings measurements
  - ⋆ E.g. $\Delta m_H = 0.2$ GeV shifts prediction for BR($H \to ZZ$) by 2.5%

Measurements of production and decays.

Measurements for the main decay channels



Separate production modes by their specific signatures



Signal strength $\mu = \sigma_{\text{meas}}/\sigma_{\text{SM}}$

Consistent with SM predictions within current uncertainties

- Evidence for $t\bar{t}H$ production: 3.5 σ (1.2 σ exp.) (CMS)

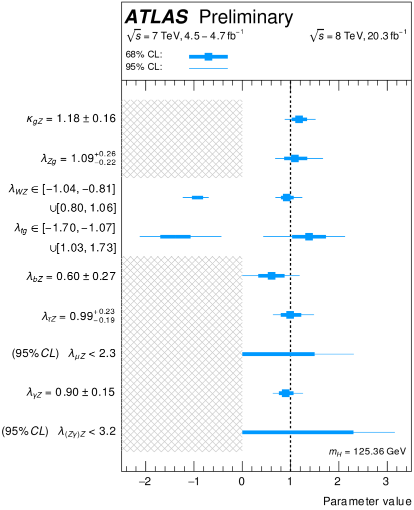
Couplings to (SM) particles.

Introduce coupling modifiers κ_i

- Assumes no other differences to SM (single state, narrow, 0^+, only modification of couplings)
- Without further assumptions, LHC can measure ratios: $\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ij} = \kappa_i\kappa_j/\kappa_H$
  - ⋆ κ_H width scale factor

Most generic fit from LHC

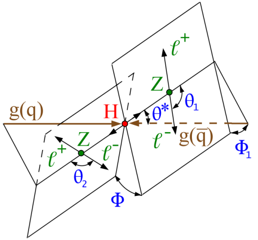
- Free couplings to SM particles
- Allow for BSM contributions in loops ($gg \to H$, $H \to \gamma\gamma$)
- Allow for invisible and undetected final states



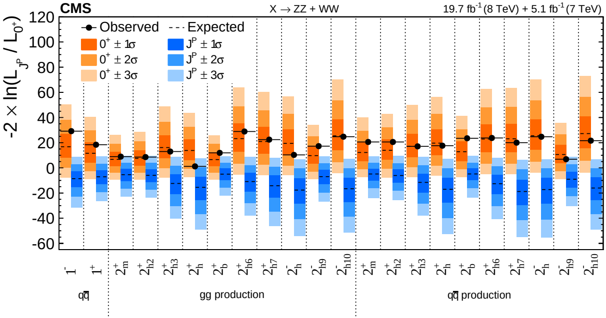
Consistent with SM predictions within current uncertainties

Probing Higgs boson quantum numbers.

Angular distributions sensitive to J^P



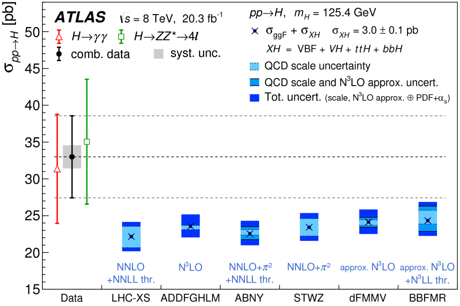
Test of alternative J^P hypotheses in WW and ZZ

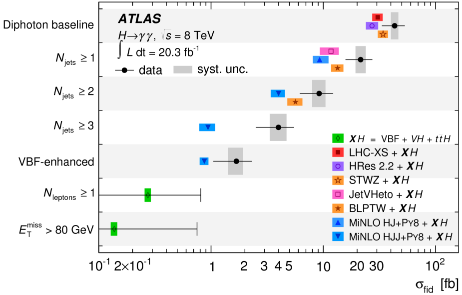


- Different classes of models tested by CMS and ATLAS
  - ⋆ CMS: JHU (LO ME)
  - ⋆ EFT approach (allowing for emission of additional partons)
- All tested alternative models excluded at $>$99.9% CL
- Does not exclude admixture of CP-odd state to SM-like 0^+

Total and fiducial cross sections.

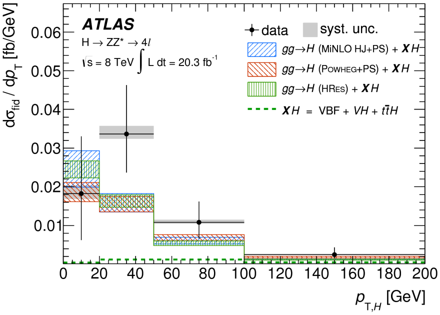
- Almost model-independent measurements in $H \to \gamma\gamma$ and $H \to 4\ell$
- Combined total cross section
  - ⋆ Assumes SM branching ratios to $\gamma\gamma$ and 4ℓ
  - ⋆ Compare to several $gg \to H$ predictions
- Fiducial cross sections (and limits) for several event topologies
  - ⋆ Fiducial volume defined to minimize MC-based acceptance corrections

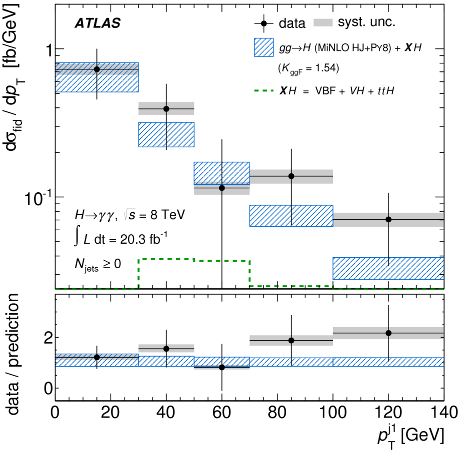




Differential cross sections.

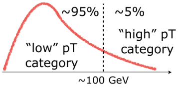
- Measured in $H \to \gamma\gamma$ and $H \to 4\ell$ in fiducial volumes, and combined (after acceptance correction)
- Distributions sensitive to production kinematics, jet activity, ...





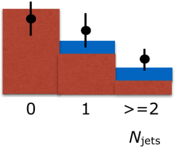
A few specific items

Higgs boson p_T and jet binning: usage in analyses.

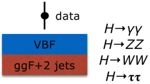


ggF Higgs pT (or pTt)

$H \to WW$



VBF region (category)



(Mostly) used in event categorization

- p_T used to select/separate high-p_T events ($\gamma\gamma$, $\tau\tau$) or even the shape (4ℓ)
- $H \to WW$: different background composition depending on $N_{\mathbf{jet}}$
- VBF-enriched event categories require at least 2 jets (still significant $gg \to H$ contamination)

Use of p_T and $N_{\mathbf{jet}}$ in CMS

	p_T	n(jet)		p_T	n(jet)
$H \to \gamma\gamma$	yes	VBF, VH, ttH	$H \to bb$(*)	no	VBF
$H \to WW$	no	0, 1, VBF, VH	$H \to \mu\mu$	yes	0-1, VBF
$H \to ZZ$	yes	0-1, 2	$H \to Z\gamma$	no	0-1, VBF
$H \to \tau\tau$	yes	0, 1, VBF	$H \to inv$(*)	yes	VBF

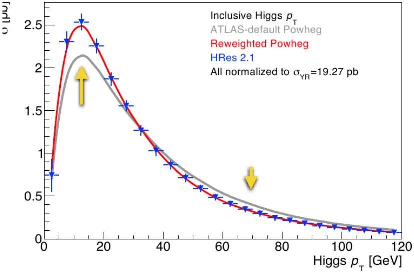
(*) for the VBF analyses, not VH ones

Higgs boson p_T: treatment in ATLAS.

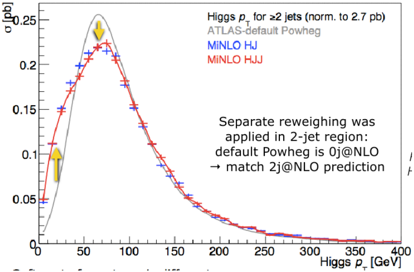
Use ATLAS as an example, details are different in CMS

- $gg \to H$ simulation uses Powheg+Pythia8 with k-factor for inclusive cross section (19.15 pb at 125.4 GeV)
- Reweighting to match inclusive spectrum from HRes 2.1 with dynamical scale ($\mu = m_H \oplus p_T$)
- Special reweighting for events with ≥ 2 jets to match p_T spectrum from MINLO HJJ

inclusive

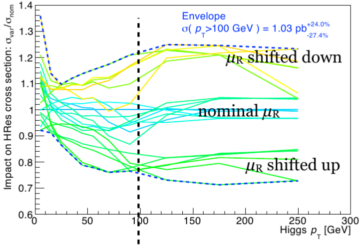


≥ 2 jets



Higgs boson p_T and N_{jet}: uncertainties in ATLAS.

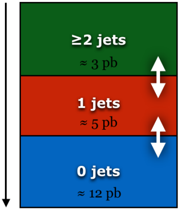
Procedures and numbers are a bit simplified, for illustration



- Uncertainties on cross section in low/high p_T region assigned using HRes scale variations
- Uncertainty for $\sigma(p_T > 100\,\text{GeV}) \sim 25\%$
- Uncertainty for σ(low p_T) assigned using ST method:

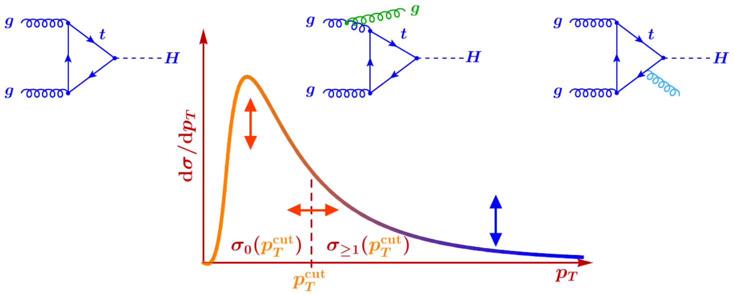
$$\Delta\sigma_0 = \Delta\sigma_{\geq 0} \oplus \Delta\sigma_{\geq 1}$$
$$\Delta\sigma_{\text{low-pT}} = \Delta\sigma_{\text{total}} \oplus \Delta\sigma_{\text{high-pT}}$$
$$\Delta\sigma_{\text{low-pT}} = 19.15 * 0.08 \oplus 1.03 * 0.25 \text{ pb}$$

>=0 and >=1 treated as separate sources
>=1 source affect migration between regions
(i.e. enter with opposite sign)



- Sizable uncertainties from jet binning, especially from cuts on variables that restrict the additional radiation (explicit or implicit jet vetos)
- Uncertainty on ggH contribution to jet bins evaluated with ST ($\gamma\gamma$, 4ℓ) and JVE (WW) methods

Higgs boson p_T and $N_{\rm jet}$: correlations in ATLAS.



- Phase space correlation between low-p_T/0 jet and high-p_T/1 jet
- $p_T > 100$ GeV (typically used for p_T categories) and $p_T^j > 30$ GeV (typically used for jet binning) do not really correspond to each other, but correlation found to be 80%

$\rightarrow$ Treated as correlated in the analysis

Higgs boson p_T and jet binning: how to do better?

...in the analyses in the medium-term and/or long-term

- How can we use the best available predictions? Is reweighting the best we can do?
  - ⋆ If so, can we improve how the reweighting is done?

- What is a sound treatment of shape uncertainties and their correlation accross the spectrum and with the total cross section uncertainty?

- How about correlations between p_T shape and jet binning?
  - ⋆ Phase space regions in p_T categories and jet binning not exactly the same
  - ⋆ Correlation due to “physics”, technically p_T shape and jet binning uncertainties derived from predictions at different order (HRes for p_T shape, JetVHeto/MCFM for jet binning)

Fiducial and differential cross sections.

- In Run1, fiducial and differential measurements were complementary to the main signal strength measurements and coupling analyses
  - ⋆ Designed to be (almost) model-independent

→ How can we best make use of these measurements, especially in Run2?
  - ⋆ How/where can they best help to test predictions?

→ How can we make them more useful (both fiducial and differential)?
  - ⋆ Choice of binning (consistently between different decay channels) could be important (e.g. to correctly correlate theoretical uncertainties)?
  - ⋆ Are we missing important distributions or regions of phase space?

- Where can measurements of SM processes yield complementary or additional information?
  - ⋆ Drell-Yan, SM diphoton production, ...
  - ⋆ Which measurements would be useful, in which regions of phase space?

Fiducial + differential cross sections: object definitions.

Photons ($H \to \gamma\gamma$)

- Fiducial region includes isolation requirement
  - ⋆ Summed transverse momentum of all particles in a cone of $\Delta R = 0.4$ (excluding neutrinos and muons) $<$ 14 GeV, matching the experimental calorimetric isolation
  - ⋆ Allows for close to model independent isolation efficiency corrections
    - Isolation efficiency much smaller for $t\bar{t}H$ than for other production modes
- $H \to \gamma e^+e^-$ not included in definition of fiducial region
  - ⋆ Pythia8 generates 5.74% of $H \to \gamma\gamma$ as $H \to \gamma f^+f^-$
  - ⋆ Very small efficiency for $H \to \gamma e^+e^-$ to pass $H \to \gamma\gamma$ selection, treated as (small) background in the analysis and corrected for
    - Assign 100% uncertainty on $H \to \gamma f^+f^-$

Leptons ($H \to 4\ell$)

- Fiducial region defined by Born leptons
  - ⋆ Acceptance differs by $<$0.5% for dressed leptons

Are these definitions fine, or should they be discussed/improved?

Interpretation of measurements.

...this might (also) be a topic for Session 2...

- LHC Run1 coupling measurements have been based on the "κ framework"

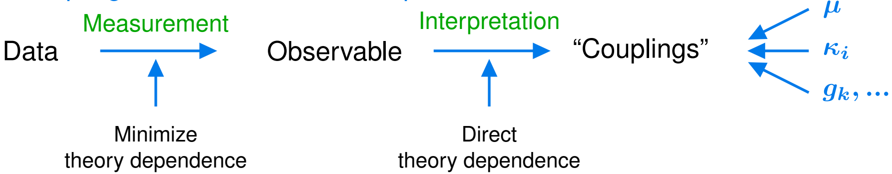
$$\sigma(ii \rightarrow h+X) \times BR(h \rightarrow ff) = \sigma_{ii} \frac{\Gamma_{ff}}{\Gamma_h} = \frac{\kappa_{ii}^2 \kappa_{ff}^2}{\kappa_h^2} \sigma_{SM} \times BR_{SM}$$

  assuming a single Higgs, no light NP, zero width approximation for on-shell production
- Developed for the interpretation of the early Higgs measurements
- Only allows for coupling scale factors, does not take into account potential change of kinematic distributions

- Important ongoing discussion about the direction this should take for Run2 (form factor expansions, direct EFT interpretations, measurement of pseudo observables, ...)

Interpretation of measurements.

Decoupling measurement and interpretation:



- Splitting of “measurement” and “interpretation” to minimize theory dependence in measurements
  - ⋆ Dependence on underlying physics model (e.g. assumption of SM production)
  - ⋆ Minimize theoretical uncertainties on measurements

→ Decouples measurements from discussions about e.g. specific EFT bases and allows for interpretations in multiple models (or bases)

→ Ensures that measurements stay long-term useful

- NB: this does not exclude to also have model-dependent, optimized analyses for specific purposes

→ 3 sessions on June 8 (morning+afternoon) and June 9 (morning) on “presentation of results and fiducial cross sections”

Some uncertainties could use some discussion.

- Uncertainties for specific processes, especially if they should cover BSM scenarios
  - tH contribution to $t\bar{t}H$ selection
  - $gg \to ZH$ contribution to high-p_T $VH(\to b\bar{b})$
- Underlying event and hadronization
  - Different methods used currently, e.g. MPI on/off, Pythia/Herwig

Backup

Higgs boson p_T: treatment and uncertainties in CMS.

- $gg \to H$ uses different p_T predictions for different channels
  - Powheg(hfact=1.2)+Pythia6 (WW, $\gamma\gamma$), Powheg(hfact=1.2, finite $m_{t,b}$+Pythia6 (4ℓ), reweighting to HREs+finite $m_{t,b}$ ($\tau\tau$)
- Uncertainties from reweighting p_T to HRes with varied scales, scale variations in Powheg, and $m_{t,b}$ variation in Powheg
- Predictions for N_{jets} from Powheg+Pythia6 (0-, 1-jet efficiencies) and Minlo HJJ+Pythia6 for 2-jet efficiency and CJV
- Uncertainties based on ST method (including p_T for $\tau\tau$)

κ framework.

- LO-inspired coupling scale factors κ_j:

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

- κ_j defined such that $\kappa_j = 1$ for SM (including higher-order corrections)
- Effective coupling scale factors κ_γ and κ_g treated as function of more fundamental scale factors κ_t, κ_b, κ_W, ... for some tests