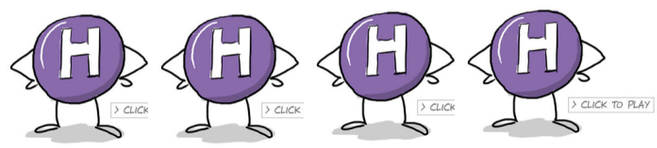
Some thoughts on properly

constraining multi-Higgs models

Sabine Kraml

3rd RISE collaboration meeting on `non-minimal Higgs'

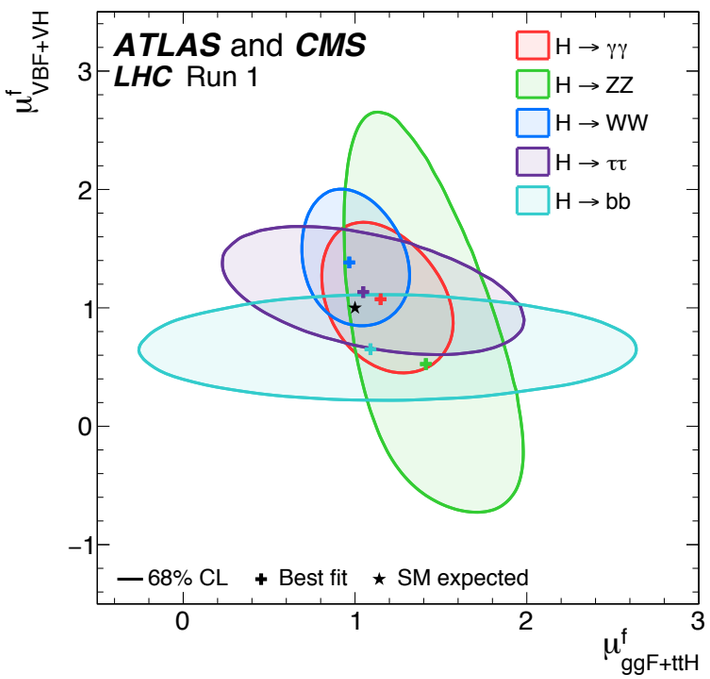
6-7 March 2017 . Toyama . Japan



Current practise

Two types of constraints are typically applied:

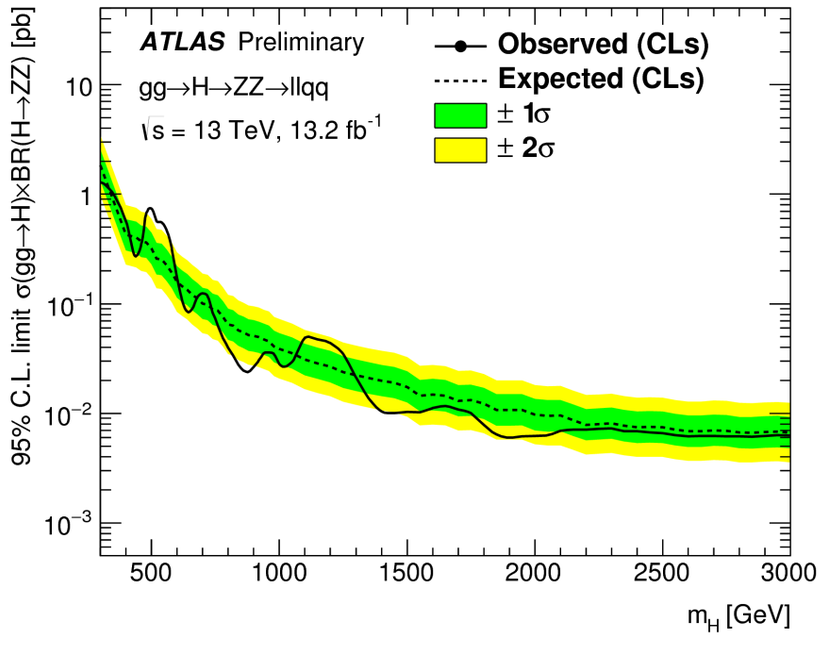
- Signal strengths of the observed Higgs at 125 GeV; two public codes:
  - HiggsSignals [Bechtle et al, 1305.1933]
  - Lilith [Bernon, Dumont, 1502. 04138]



- Cross section x branching ratio limits from searches for additional Higgs-like states;

  public code: HiggsBounds [Bechtle et al, 1311.0055]

- BR(H→inv, new)<~20% from global fit



signal strengths -I-

decay mode ($\gamma\gamma$, WW, ZZ, bb, $\tau\tau$, ...)

$$\mu(X,Y) \equiv \frac{\sigma(X)\,\mathrm{BR}(H\to Y)}{\sigma(X_{\mathrm{SM}})\,\mathrm{BR}(H_{\mathrm{SM}}\to Y)}$$

fundamental production mode such as gg fusion (ggF), VBF, etc.

(note that μ(Y) is not sufficient because BSM contributions may affect different production modes differently!)

- In experimental practice, the data related to a single decay mode H→Y are divided into different categories (or "sub-channels") ***I***, in order to improve sensitivity or discrimination among the production mechanisms X.

  Example: for $\gamma\gamma$, these include "untagged", 2-jet tagged, and lepton tagged categories, designed to be most sensitive to ggF, VBF, and VH, respectively.

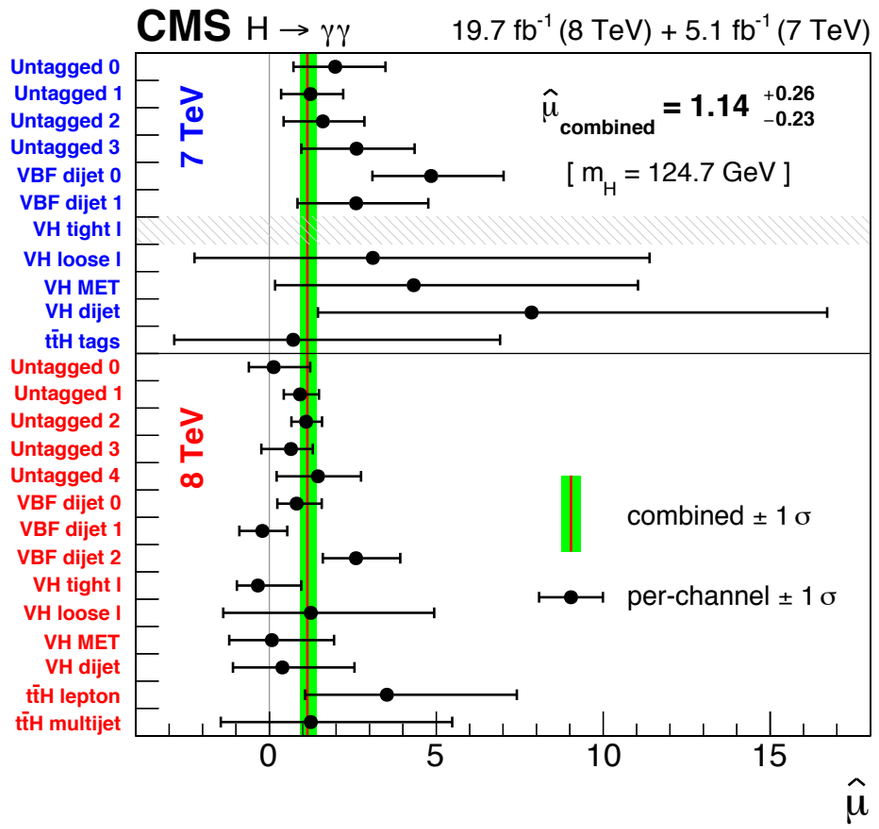
using sub-channel information

- The likelihood in terms of μ(X,Y) can be approximately recomputed combining the χ^2 of all categories I using an efficiency-weighted sum:

$$\mu_I(Y) = \sum_X \mu(X,Y)\, T(I,X)\, \sigma(X_{\mathrm{SM}})\, \mathrm{BR}(H_{\mathrm{SM}} \to Y)$$

selection efficiencies for each production mode, normalized to one.

- Approach adopted by HiggsSignals.
- It is crucial that for each of the categories I the selection efficiencies (and uncertainties thereon) be provided for all production modes !
- NB difficult to take into account correlations from, e.g., systematic uncertainties that lead to migration of events between categories; these uncertainties can dominate over the statistical ones.



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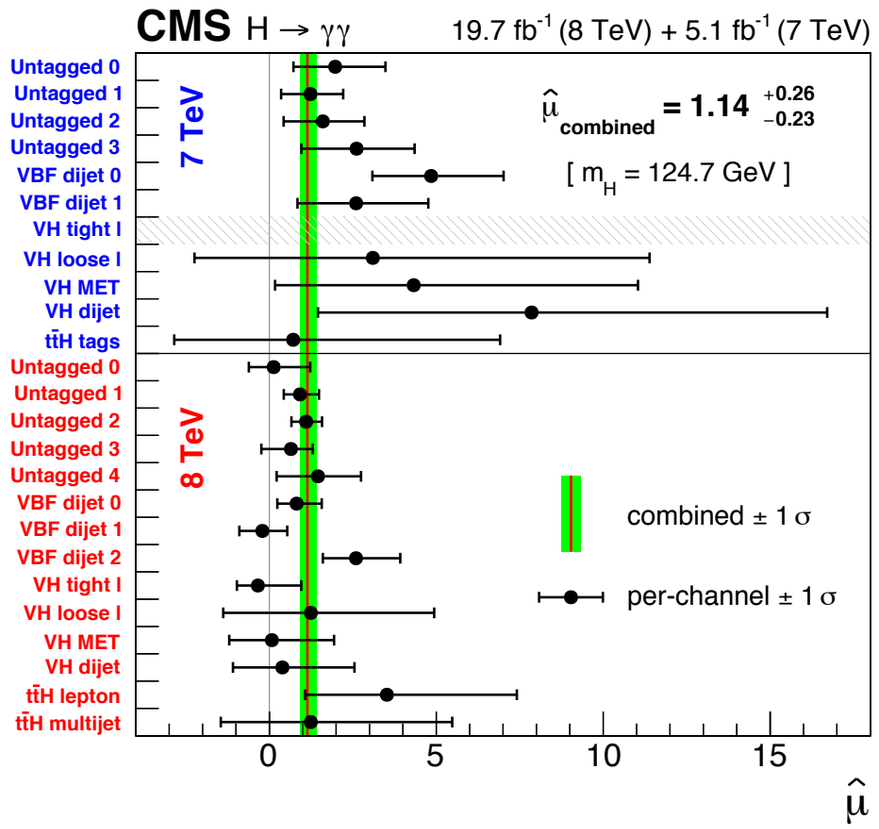
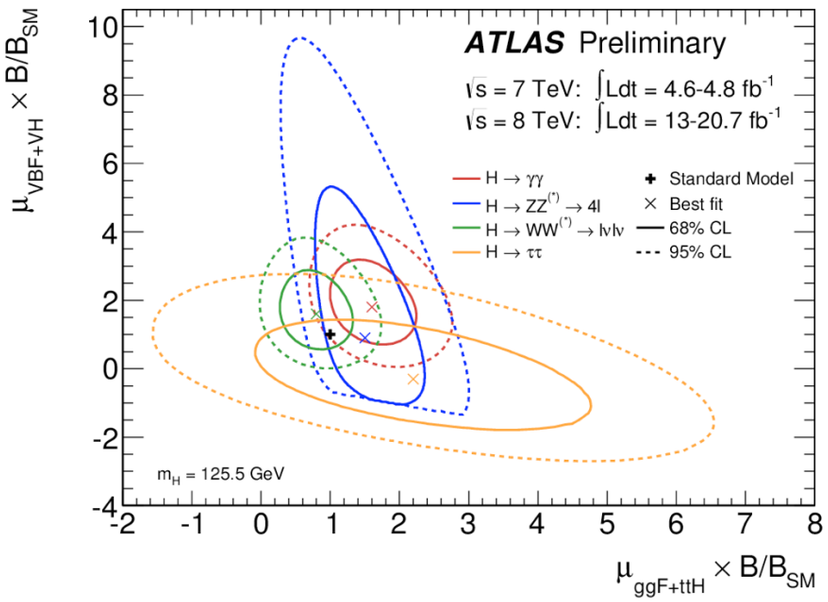
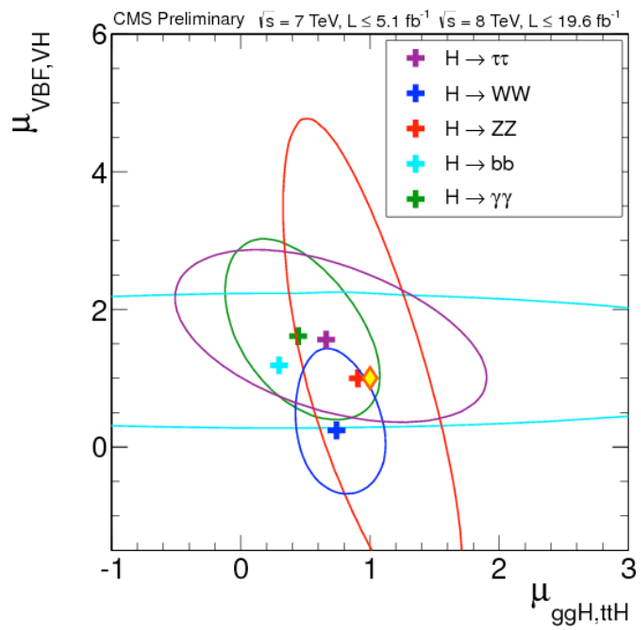


2D likelihoods for μ

- It has basically become standard that for each decay mode the experiments present 68% and 95% CL contours in the μ(ggF+ttH) versus μ(VBF+VH) plane:

VH=WH+ZH





- Also other μ(X,Y) vs μ(X',Y) combinations, e.g. WH vs. ZH for H→bb
- Fundamental production modes are already "unfolded" from the experimental categories; correlations resolved by the experiments.
- Approach followed by Lilith.

signal strengths -2-

$$\mu(X,Y) \equiv \frac{\sigma(X)\,\mathrm{BR}(H \to Y)}{\sigma(X_{\mathrm{SM}})\,\mathrm{BR}(H_{\mathrm{SM}} \to Y)}$$

Caveat 1

- It is crucial that the nominator and denominator in μ be evaluated at the same order in perturbation theory. Easy when working with reduced couplings (2HDM, …) but delicate when there are new particles contributing to gg→H production (MSSM, …).

Caveat 2 (most important issue for this talk)

- The likelihood in terms of μ(X,Y) allows for reinterpretation of the results in models where the efficiency and acceptance for each (X,Y) is the same as in the SM !

  → SM tensor structure

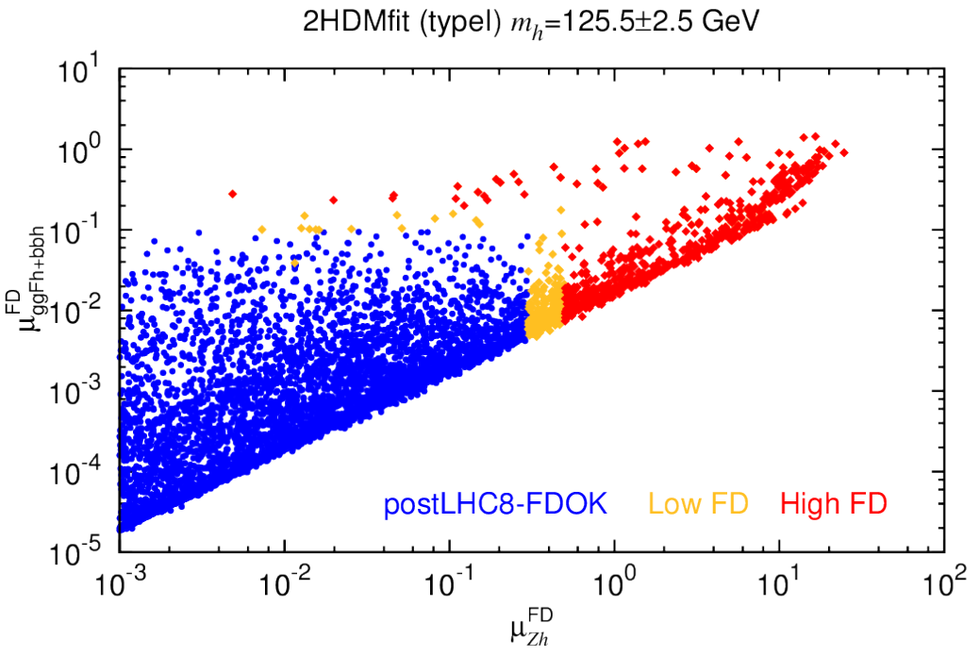
  → no new production modes

new production modes

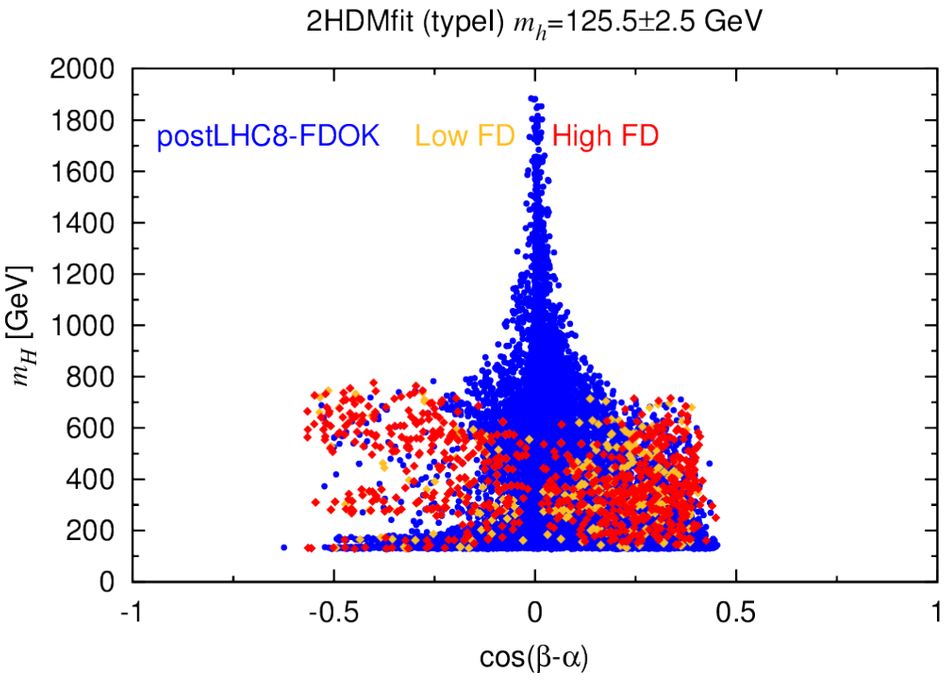
- Multi-Higgs models often feature additional production modes for the 125 GeV Higgs trough, e.g., Higgs-to-Higgs decays ($H \to hh, A \to Zh, H^+ \to W^+h$, etc.)
- First addressed by A. Arhrib, P. Ferreira and R. Santos in "Are There Hidden Scalars in LHC Higgs Results?" [arXiv:1311.1520].
- We refined this in 1405.3584*, limiting the amount of "feed down" (FD) to the 125 GeV Higgs signal in our signal strength fits.

* B. Dumont, J.F. Gunion, Y. Jiang, SK

h+X prod.



Zh prod.



crude, but all we could do at the time

fiducial cross sections

- In situations in which the kinematic distribution of the 125 GeV Higgs signal depends on model parameters, simple scaling of production cross sections and decay branching ratios (relative to the SM) is not sufficient → one must account for the change in the signal selection efficiency.

- In order to address such cases, in arXiv:1307.5865 we advocated the use of fiducial cross sections, i.e. cross sections (total or differential) for specific final states within the phase space defined by the experimental selection and acceptance cuts.

$$\sigma_i^{\rm fid} = \sum_j \underbrace{A_{ij}^{\rm th}}_{\text{fiducial volume acceptance}} \times \sigma_j^{\rm tot}$$

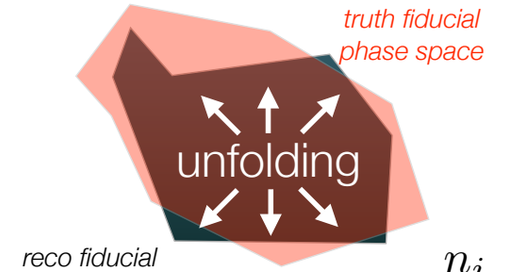
- Fiducial cross sections can be interpreted in the context of whatever model, if a) the model and b) the selection criteria defining defining the "fiducial volume" can be implemented in a MC generator.

- Also has advantage of largely separating experimental and theoretical errors.

— dedicated fiducial cross sections `task force' in LHCHXSWG (YR4)
— effort is required also from the theory community to develop the necessary tools

fiducial cross sections

- Fiducial cross sections -total and differential- already available from ATLAS and CMS for $\gamma\gamma$ and ZZ→4l final states

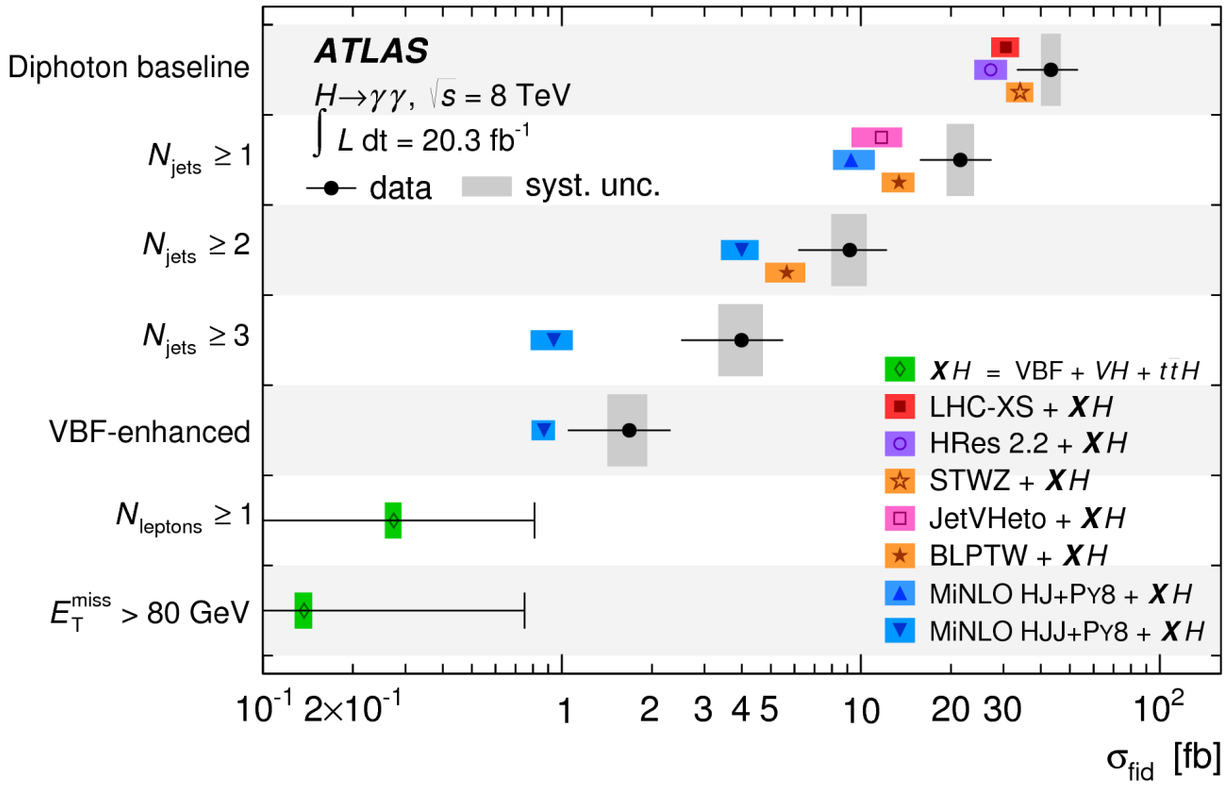


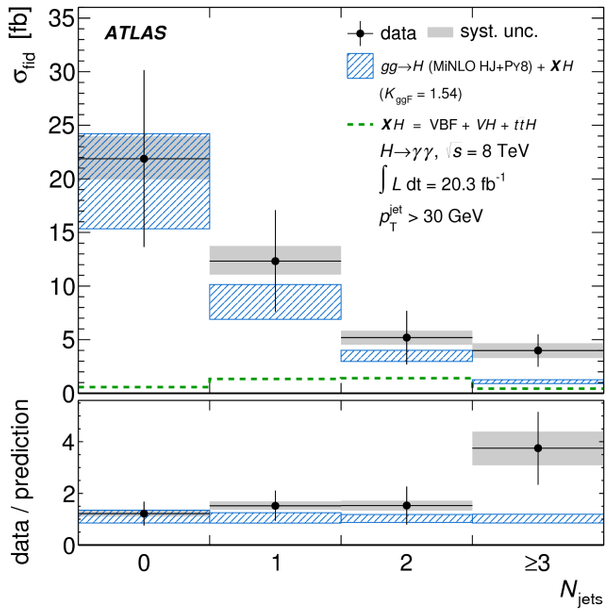
$$\sigma_i = \frac{n_i}{\mathcal{L}\, c_i}$$

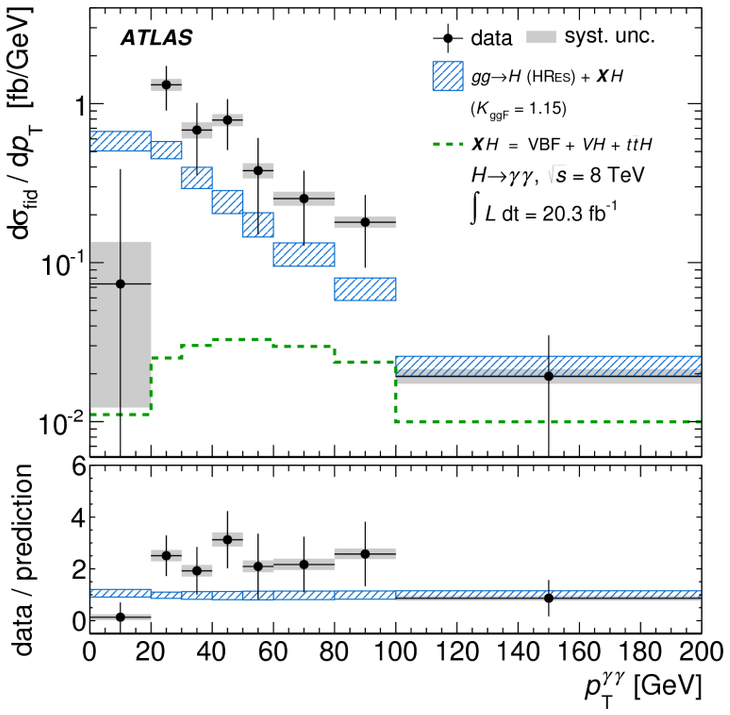
- NB these are detector-unfolded quantities !
- Experimental results report for each final state
  - <u>total fiducial cross section</u> (sometimes in)
  - <u>Higgs boson kinematics</u>: transverse momentum and rapidity distributions
  - <u>jet activity</u>: N_{jets}, pT_{j1}, pT_{j2}, rapidity, HT, ….
  - <u>angular observables</u>, e.g., angle between the Higgs decay products and the beam axis or the azimuthal angle between the two leading jets in events containing two or more jets
  - sometimes additional information on #leptons, missing energy, …

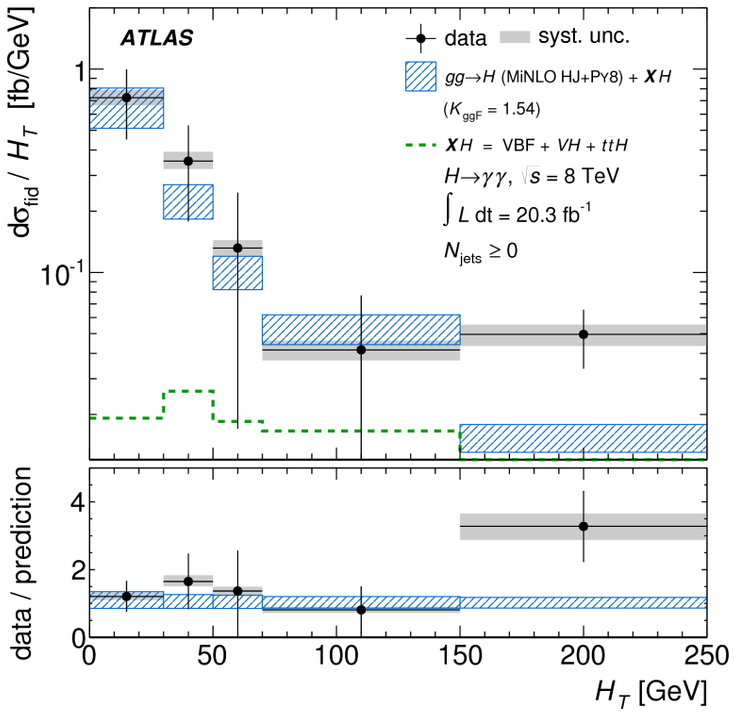
re kinematic distributions, see also talk by Kentarou on Higgs characterisation

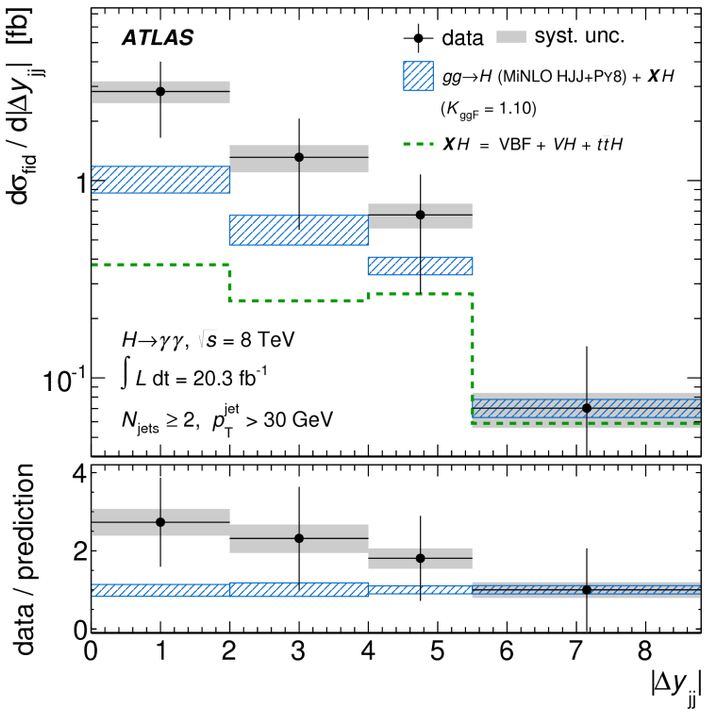
ATLAS, 1407.4222



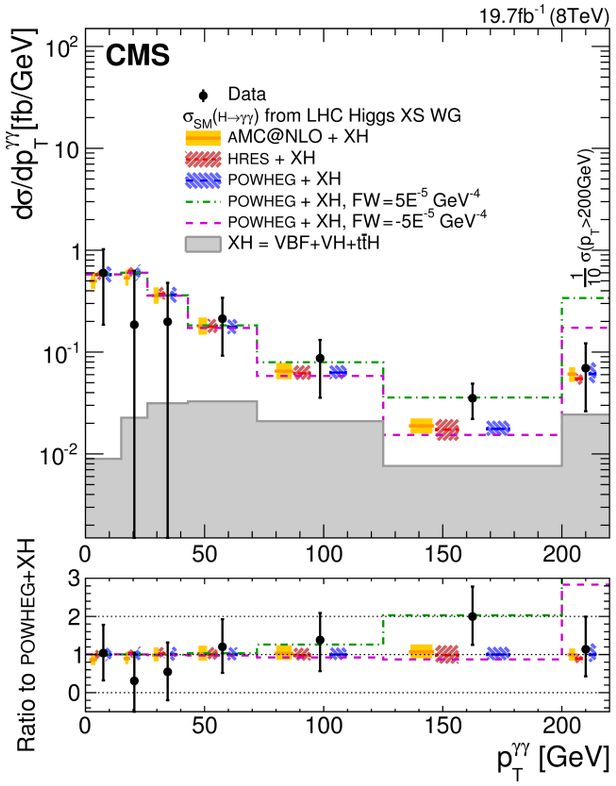


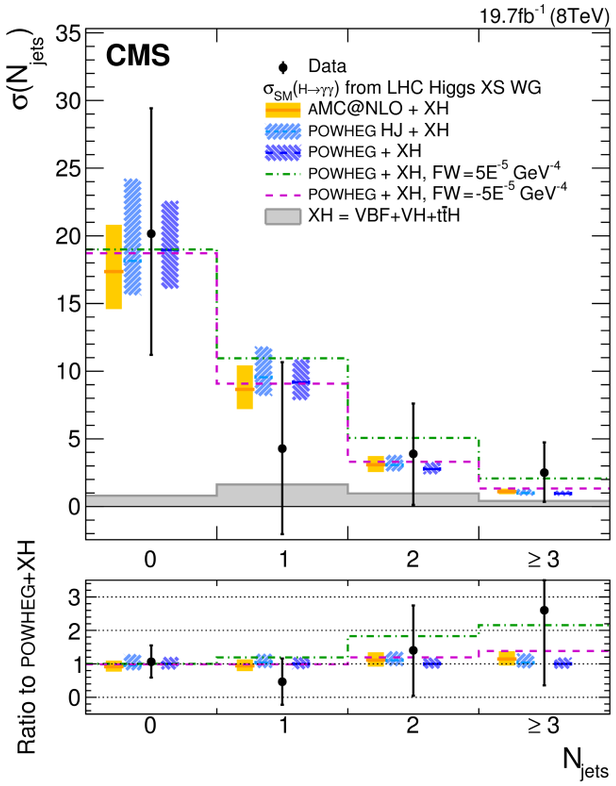


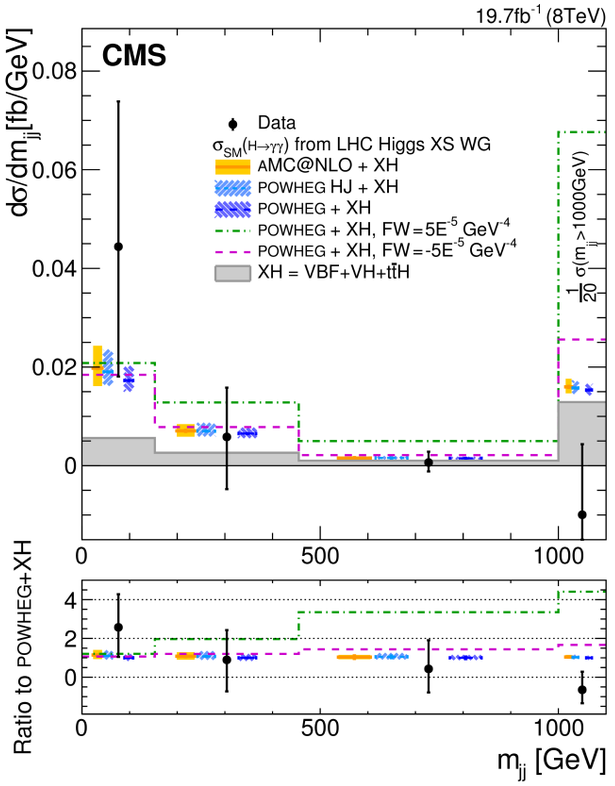




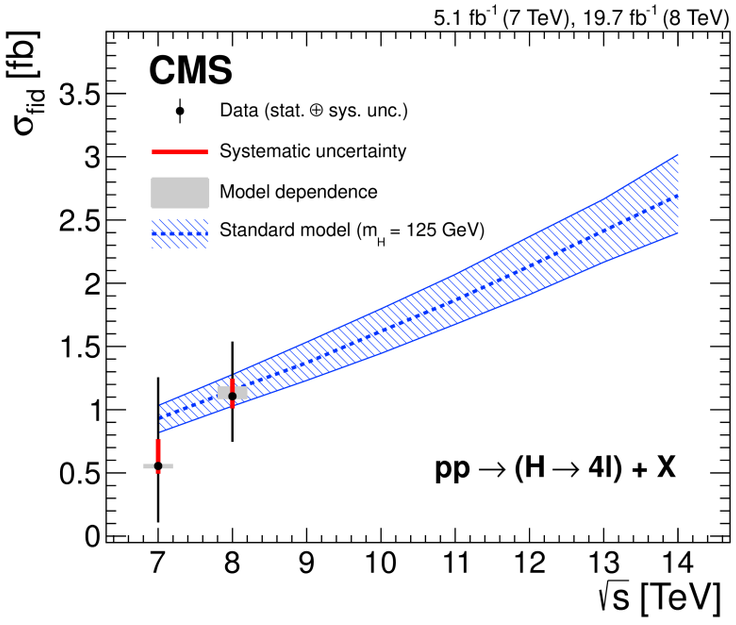
CMS 1508.07819

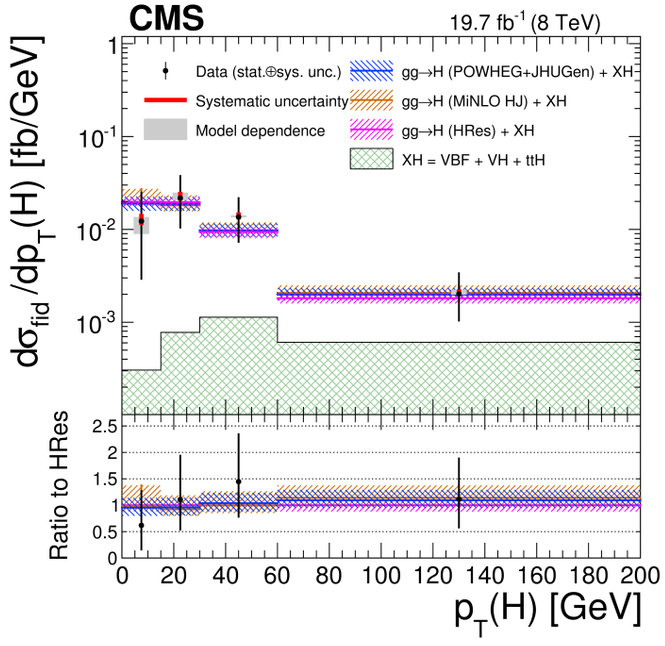


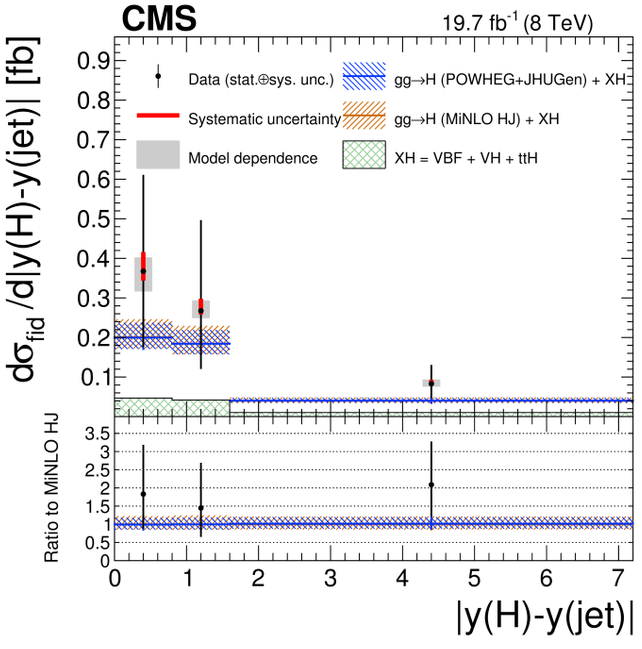




CMS 1512.08377

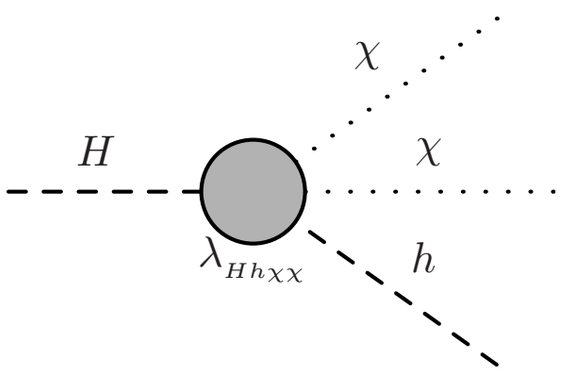


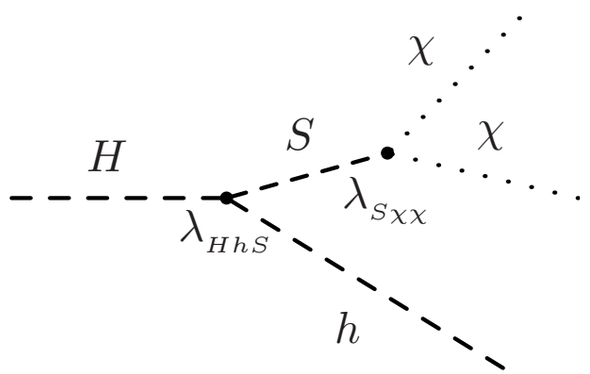




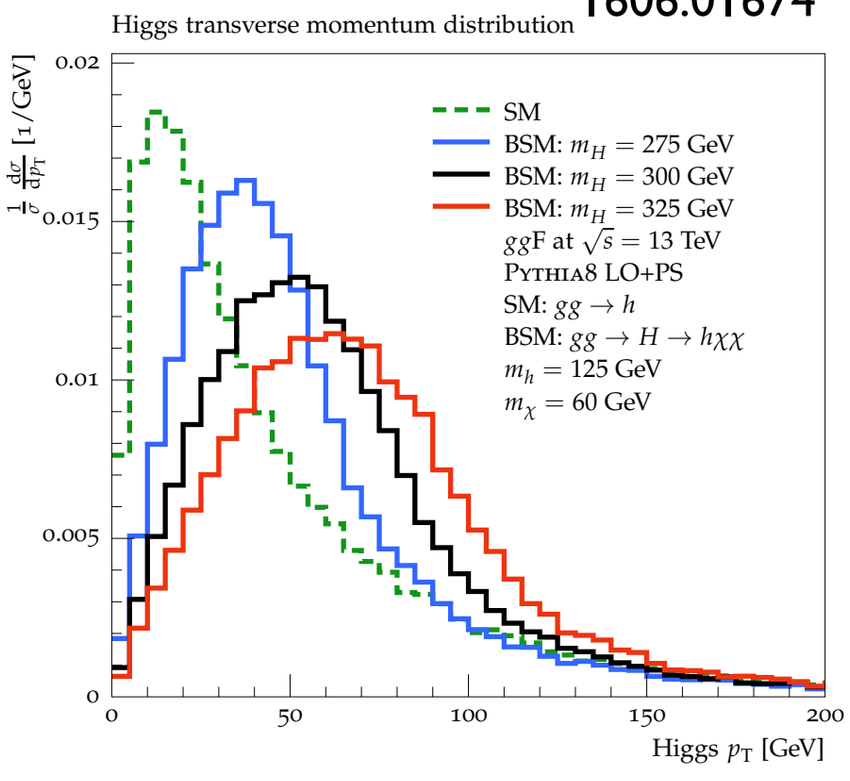
concrete use example

S. von Buddenbrock et al.





1606.01674



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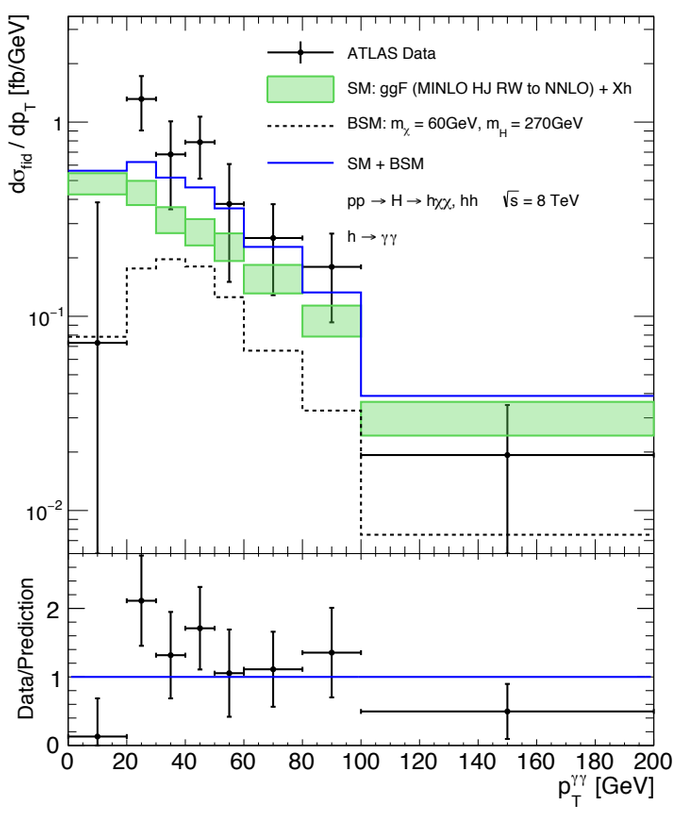


to take home

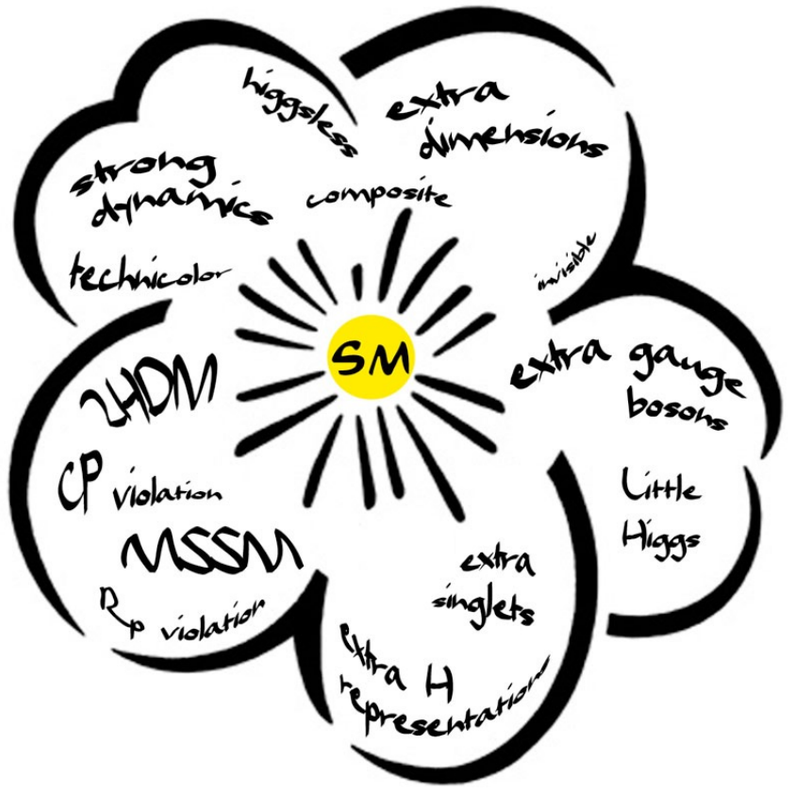
- We have to distinguish between two classes of models by whether or not the selection efficiencies and detector acceptances for the various channels are independent of the model parameters.

- Same tensor structure as in the SM,
  no new production modes
  → signal strength modifiers

- BSM with new Higgs production modes:
  MC simulation to compare with exp. data
  → fiducial cross sections

- Lots of experimental results beyond signal strengths already available, more coming.

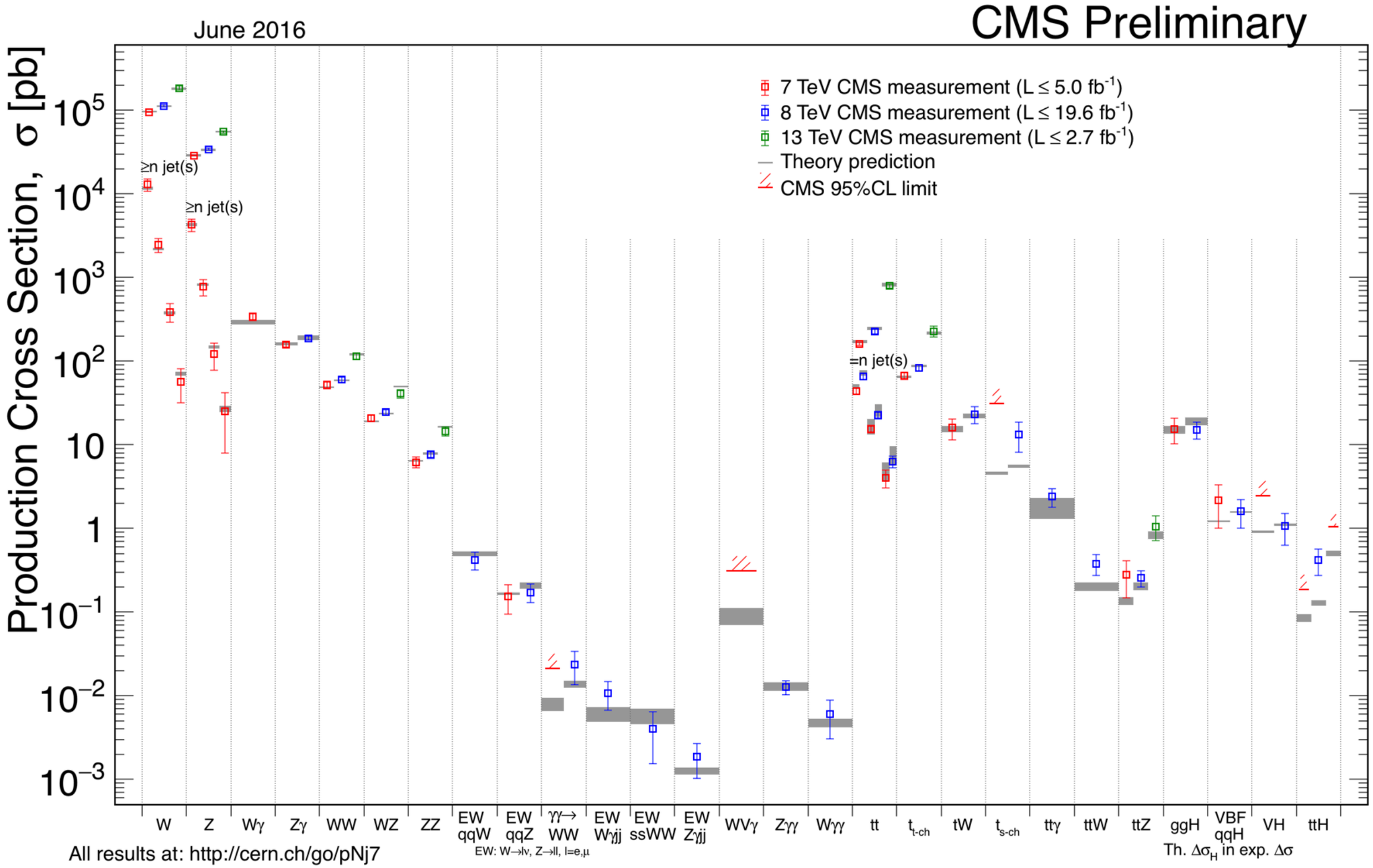
- We need to build more sophisticated tools to properly interpret the upcoming Run2 results.



See also talk by Darren Price at Dec 2016 Interpretation Forum workshop,
https://indico.cern.ch/event/571190/

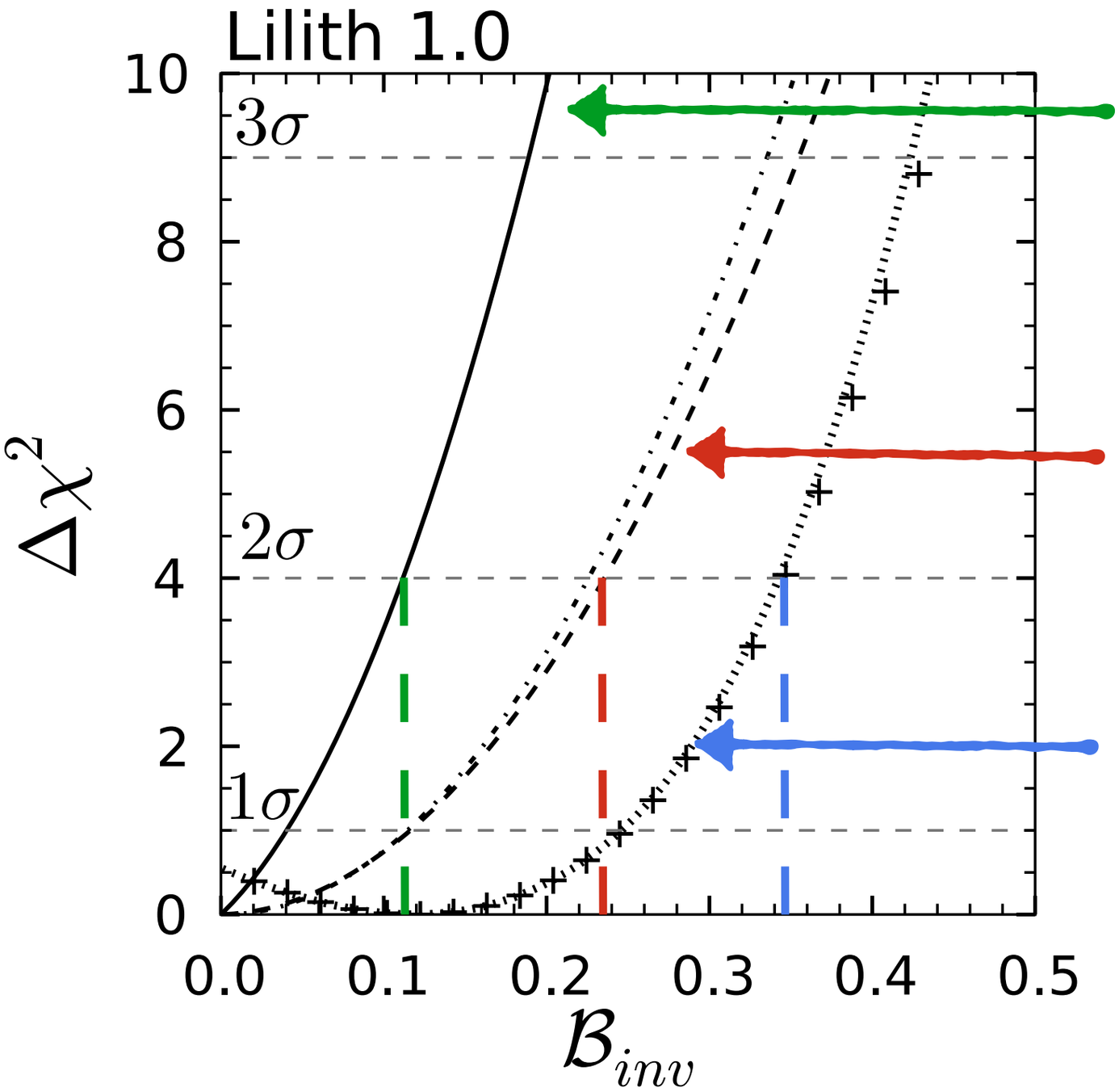
backup

What measurements are available?



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

Invisible branching ratio fits



SM+invisible

$\mathcal{B}_{inv} < 0.11$ at 95.4% C.L.

C_U, C_D, C_V <1

SM+ΔC_γ, ΔC_g +invisible

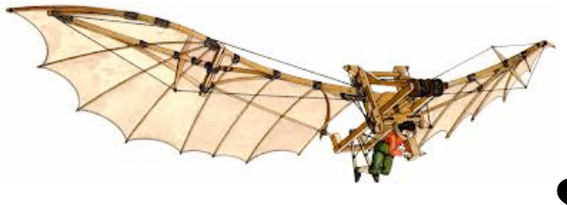
$\mathcal{B}_{inv} \lesssim 0.24$ at 95.4% C.L.

Roughly the same limits for undetected BR

C_U, C_D, C_V +invisible

C_U, C_D, C_V, ΔC_γ, ΔC_g

$\mathcal{B}_{inv} \lesssim 0.34$ at 95.4% C.L.



signal strengths: future directions

- Eventually, we want to test ggF, ttH, VBF, ZH and WH separately, which means that we need a more detailed break down of the channels beyond 2D plots.
- Moreover, the dependence on the Higgs mass is important information
- We would thus like to advocate that for each final state Y the experiments give the signal strength likelihood in the 6D form

$$\mathcal{L}(m_H, \mu_{\mathrm{ggF}}, \mu_{\mathrm{ttH}}, \mu_{\mathrm{VBF}}, \mu_{\mathrm{ZH}}, \mu_{\mathrm{WH}})$$

- This way, a significant step could be taken towards a more precise fit in the context of a given BSM theory.

arXiv:1307.5865

- The likelihood could be communicated either as a standalone computer library or simply as a grid data file → HepData / INSPIRE.
- Open point: final state correlations → covariance matrix ?