LHC Physics – Higgs

DESY Summer Student Lectures, 16.08-17.08.2022

Claudia Seitz

This lecture

Measure

Standard Model

parameters with high precision

Search for the

Higgs boson

and measure it's properties

Search for

New Physics

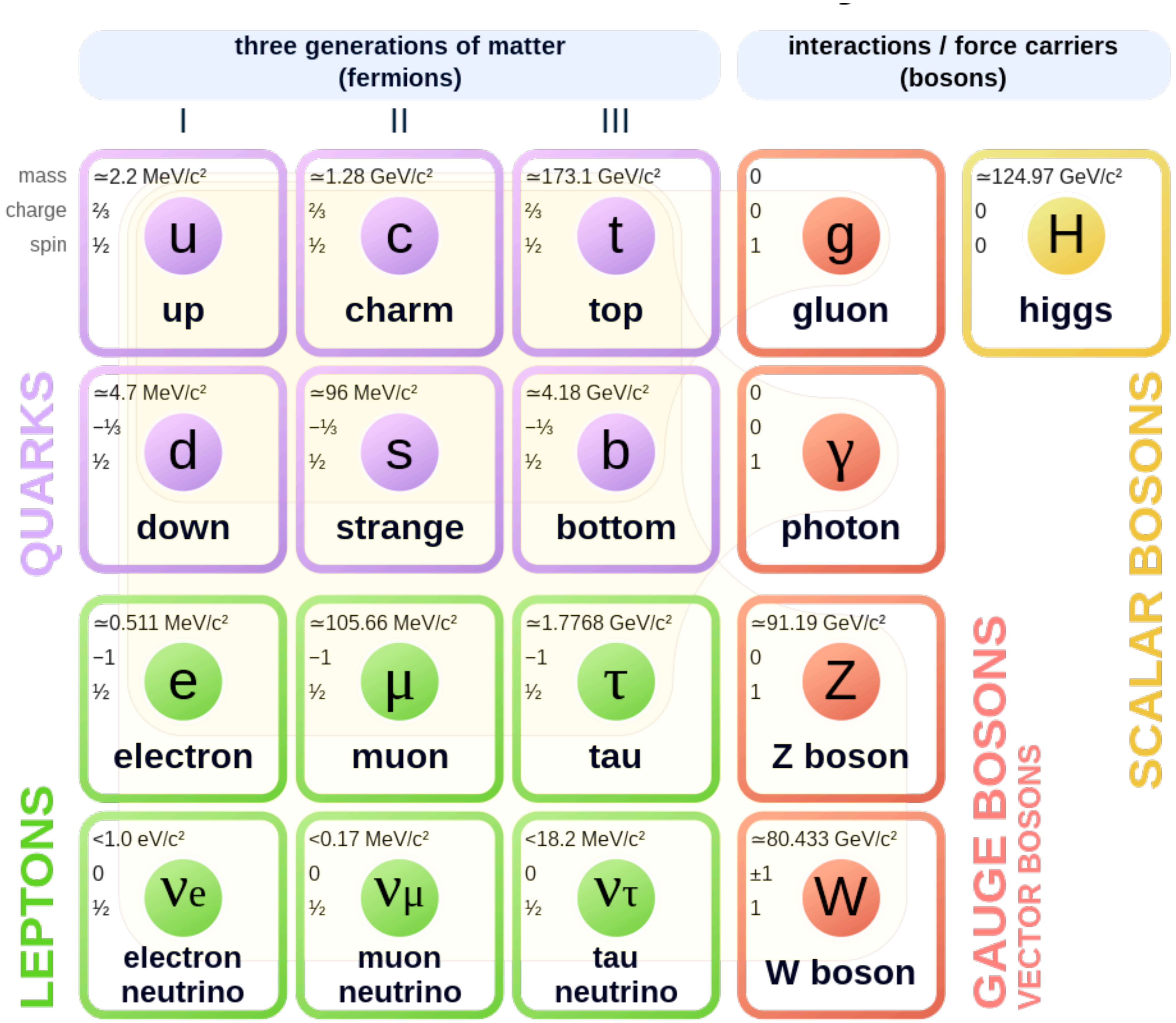
Beyond the Standard Model

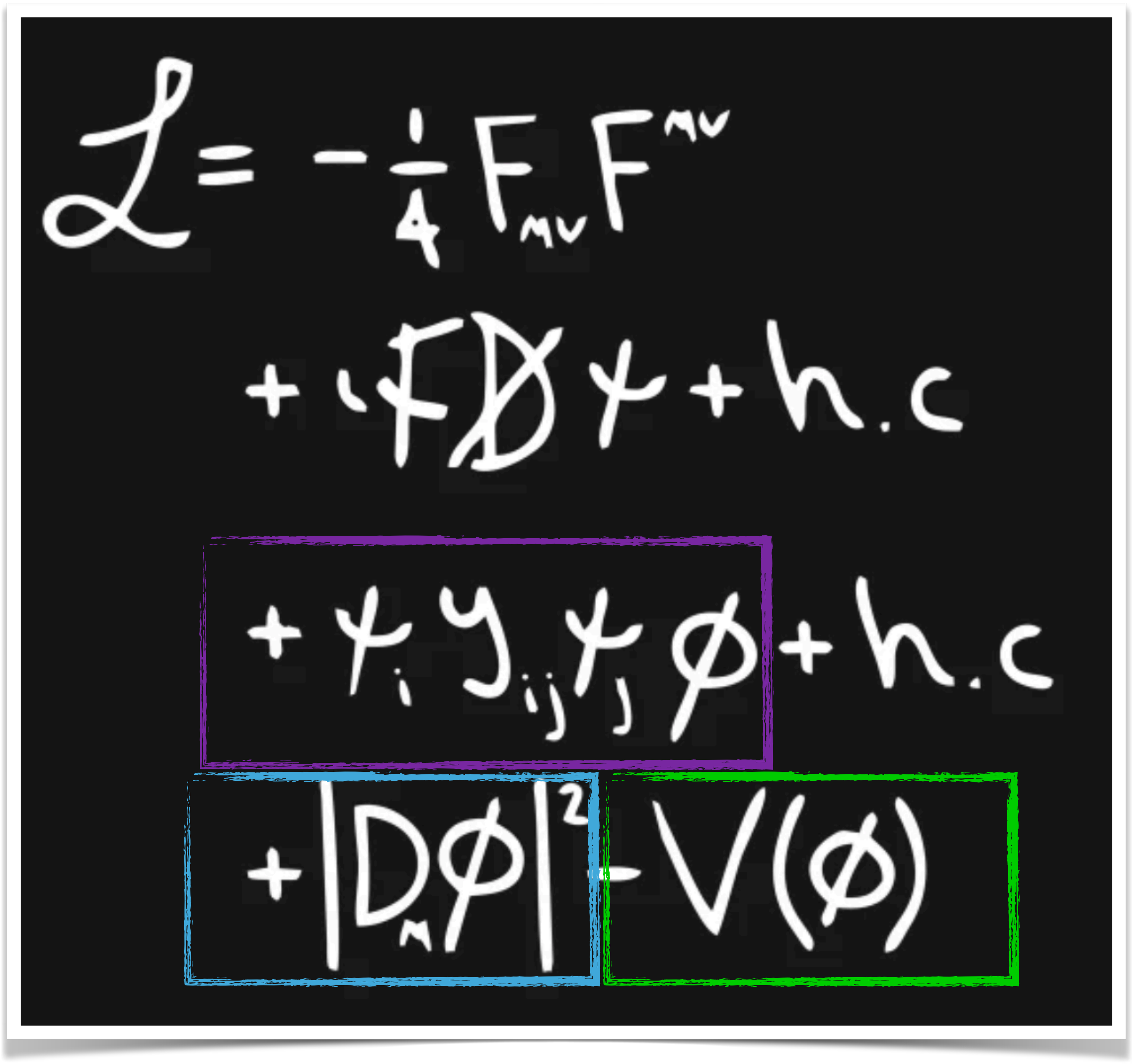
Study

Quark-Gluon Plasma

Large Hadron Collider

The Brout-Englert-Higgs mechanism in the SM





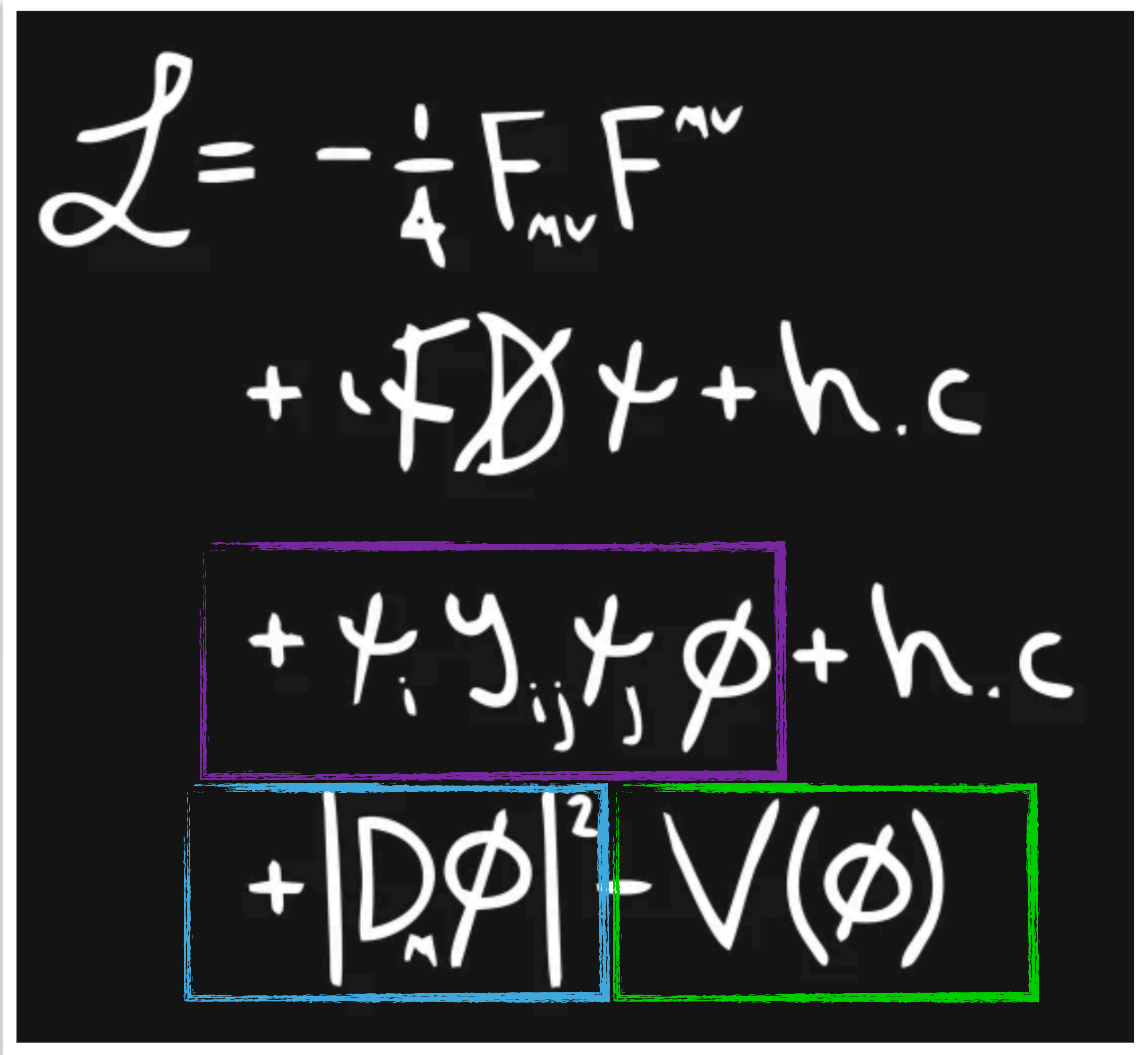
Higgs-fermion interactions

Higgs-self interactions/ potential

Higgs-gauge boson (W,Z) interactions

The Brout-Englert-Higgs mechanism in the SM

- Introduction of the presence of a scalar field into the SM leads to
  - Particles acquire mass
    - Bosons: 3 out of 4 through electroweak symmetry breaking
    - Fermions: described by Yukawa y_{ij} couplings
  - Prediction of the existence of a particle → Higgs boson
    - Higgs boson interacts with itself



Higgs-fermion interactions

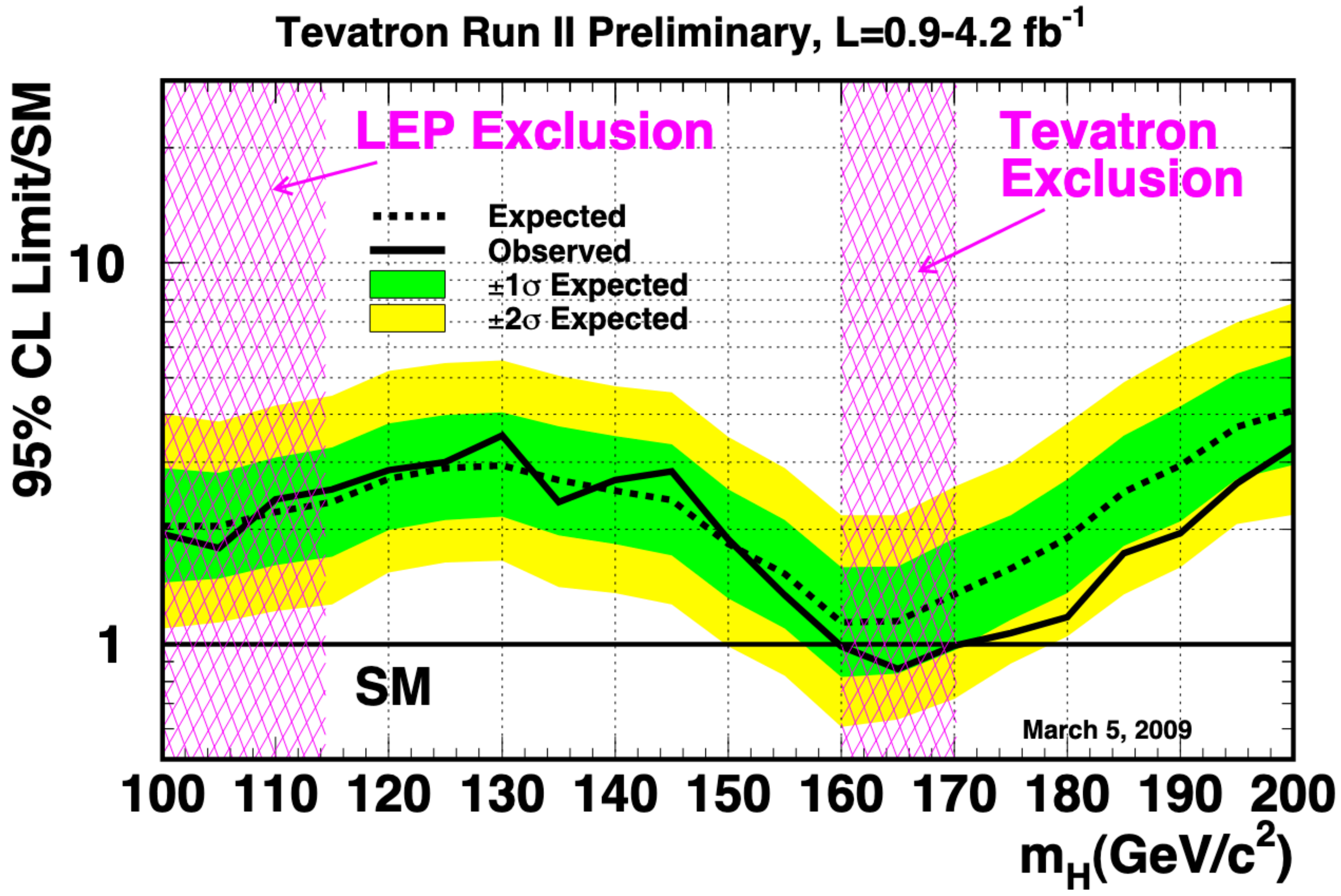
Higgs-gauge boson interactions

Higgs-self interactions/ potential

The situation before the LHC

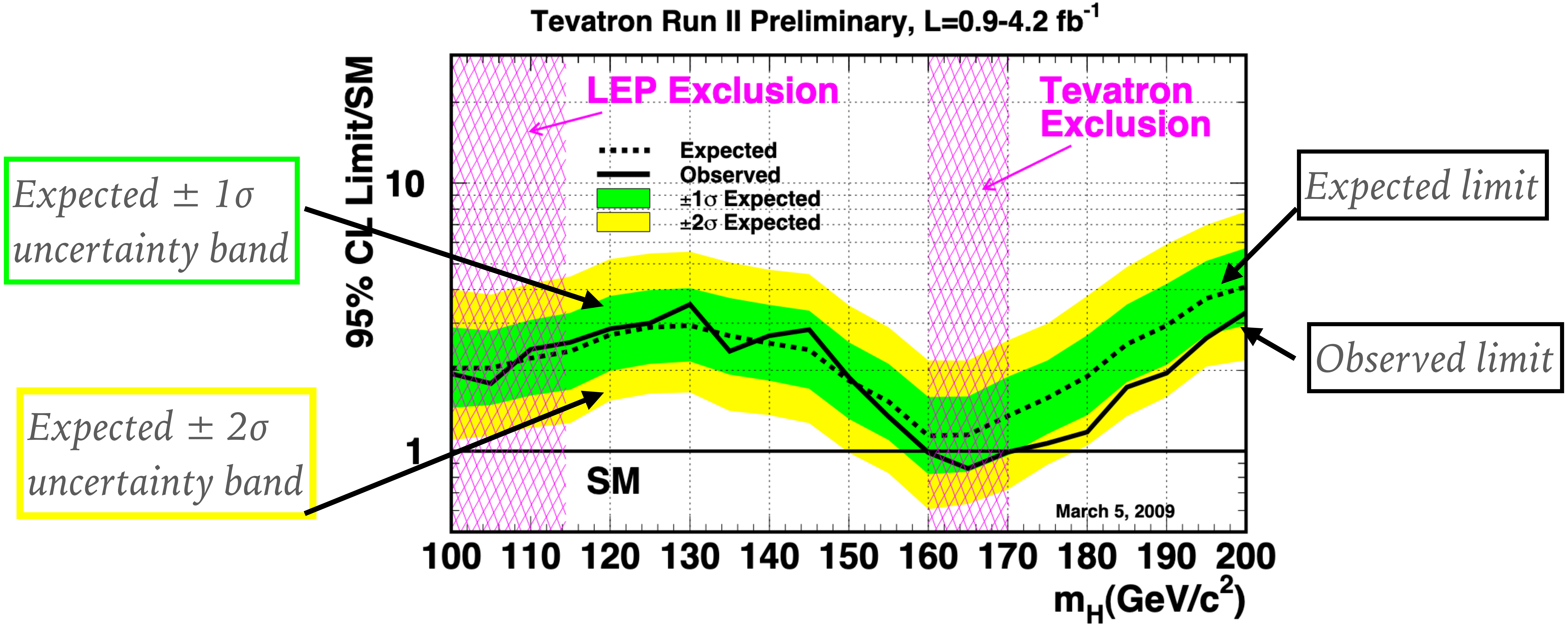
➤ Prediction from EW fits 2012: SM Higgs mass 95 $^{+30}_{-23}$ GeV

➤ Status 2009: SM Higgs mass above 114 GeV, and NOT in the range 160-170 GeV



Interlude: Limits, how to read them and how to make them

- Status 2009: SM Higgs mass above 114 GeV, and NOT in the range 160-170 GeV

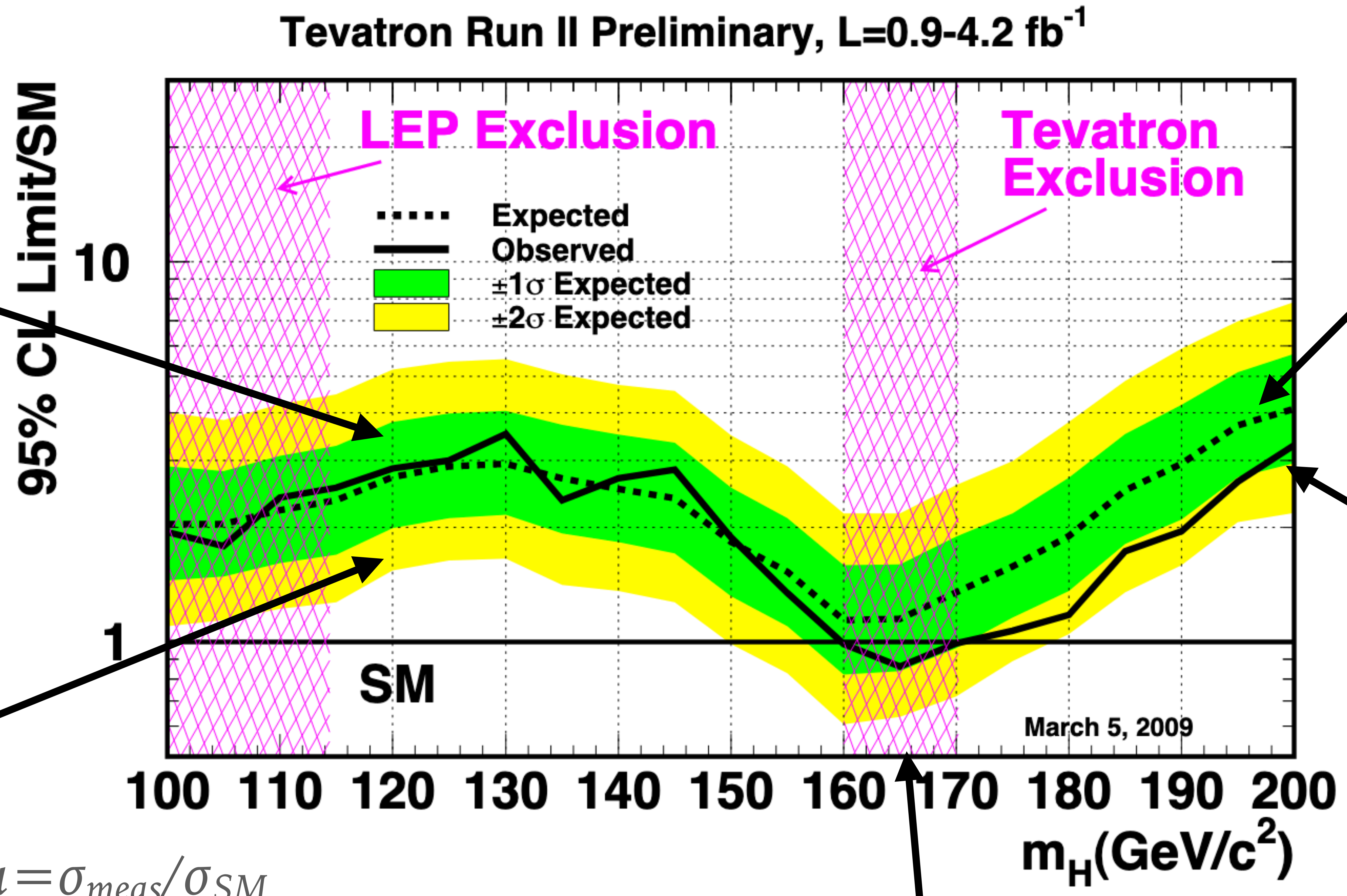


Interlude: Limits, how to read them and how to make them

➤ Status 2009: SM Higgs mass above 114 GeV, and NOT in the range 160-170 GeV

Expected ± 1σ uncertainty band

Expected ± 2σ uncertainty band



Expected limit

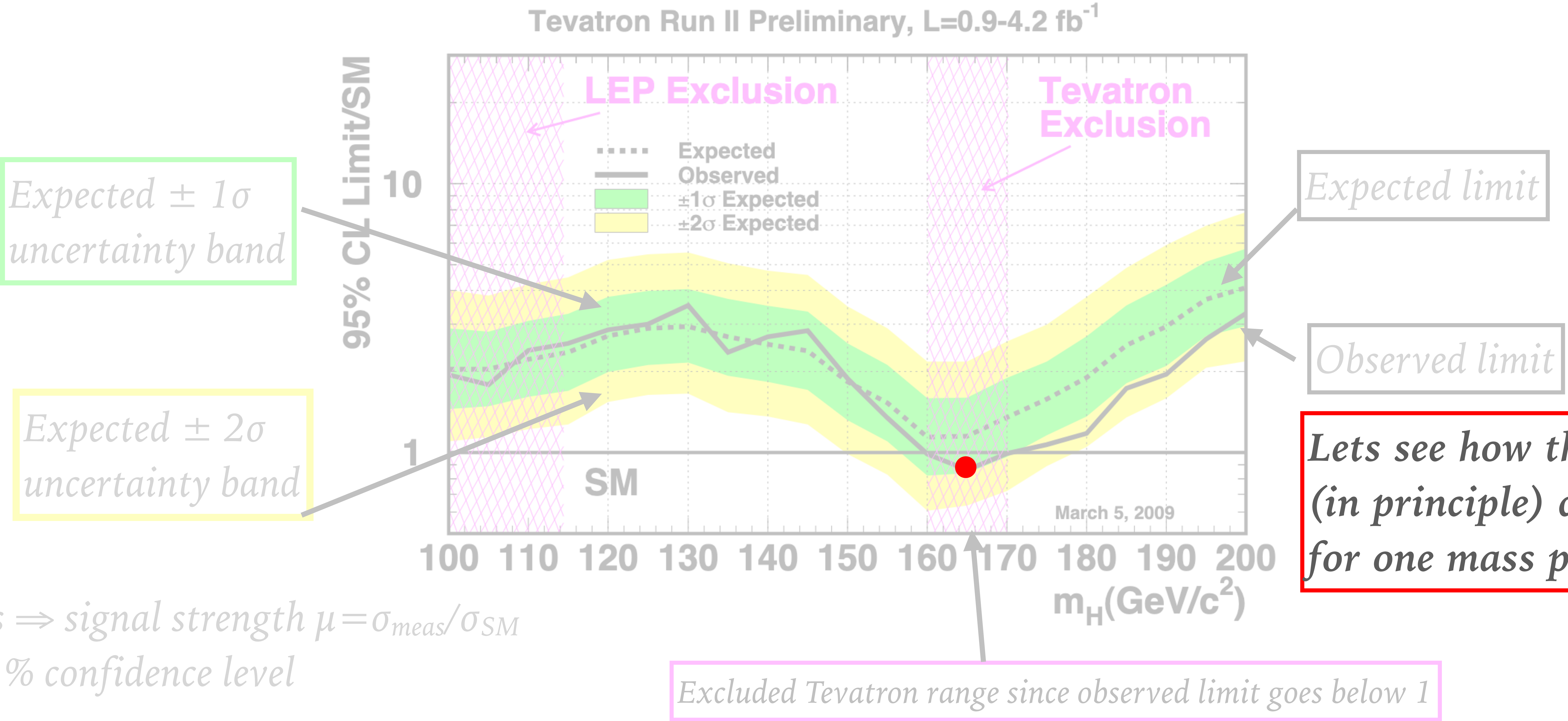
Observed limit

y-axis ⇒ signal strength $\mu = \sigma_{meas}/\sigma_{SM}$ *at 95 % confidence level*

Excluded Tevatron range since observed limit goes below 1

Interlude: Limits, how to read them and how to make them

➤ Status 2009: SM Higgs mass above 114 GeV, and NOT in the range 160-170 GeV



y-axis ⇒ signal strength $\mu = \sigma_{meas}/\sigma_{SM}$ at 95 % confidence level

Lets see how this is (in principle) calculated for one mass point

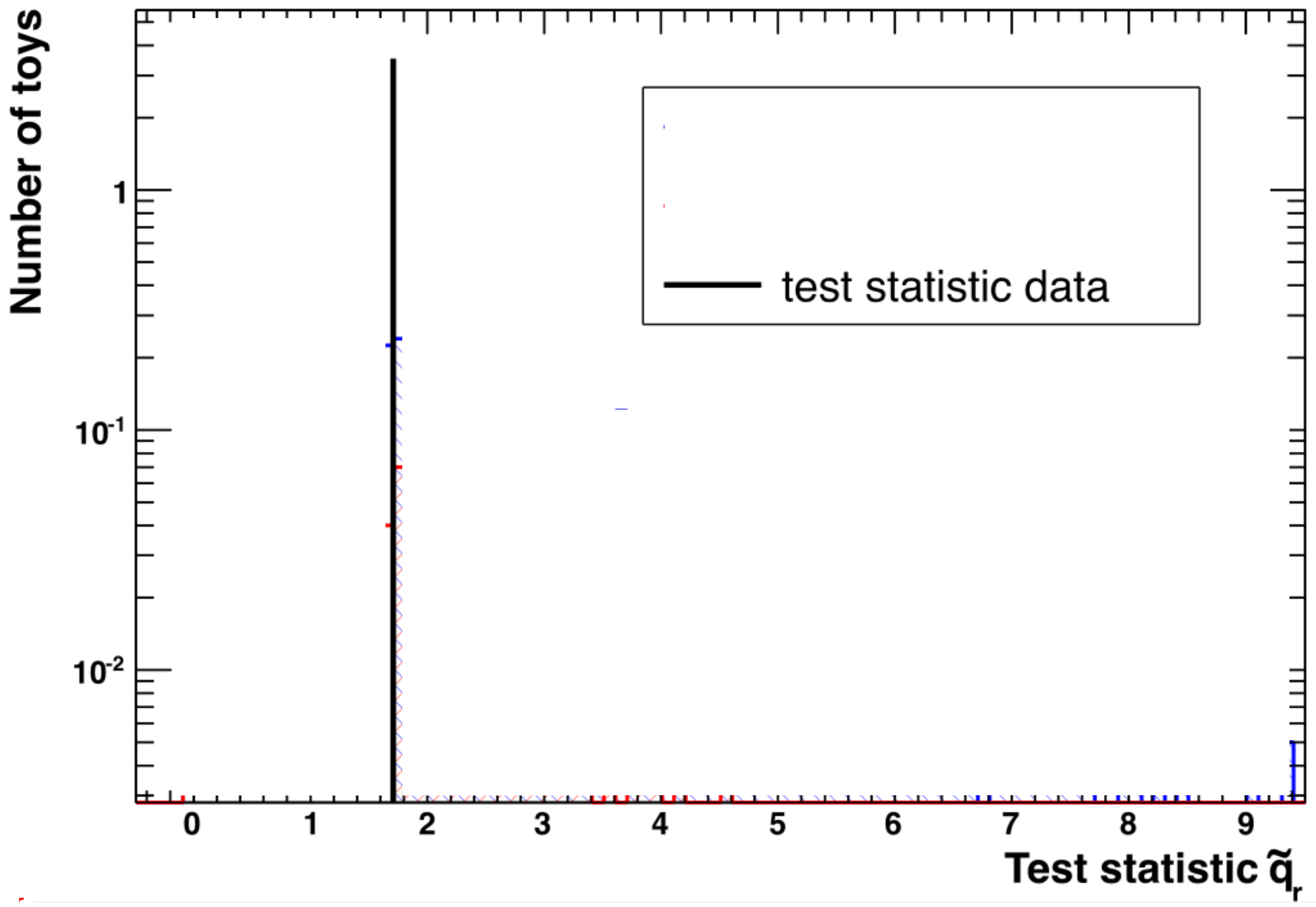
Interlude: Calculate observed limit

s = *number of signal events*
b = *number of background events*
θ = *nuisance parameters*

- Construct a likelihood $\mathcal{L}(\text{data} \mid \mu, \theta) = \text{Poisson}\left(\text{data} \mid \mu \cdot s(\theta) + b(\theta)\right) \cdot p(\tilde{\theta}|\theta)$
- Compare the measured data with two hypothesis
  - H_0 (**b** only, μ=0)
  - H_1 (μ×**s** +**b**)
- Define test statistic (based on the profile likelihood ratio)

$$\tilde{q}_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}$$

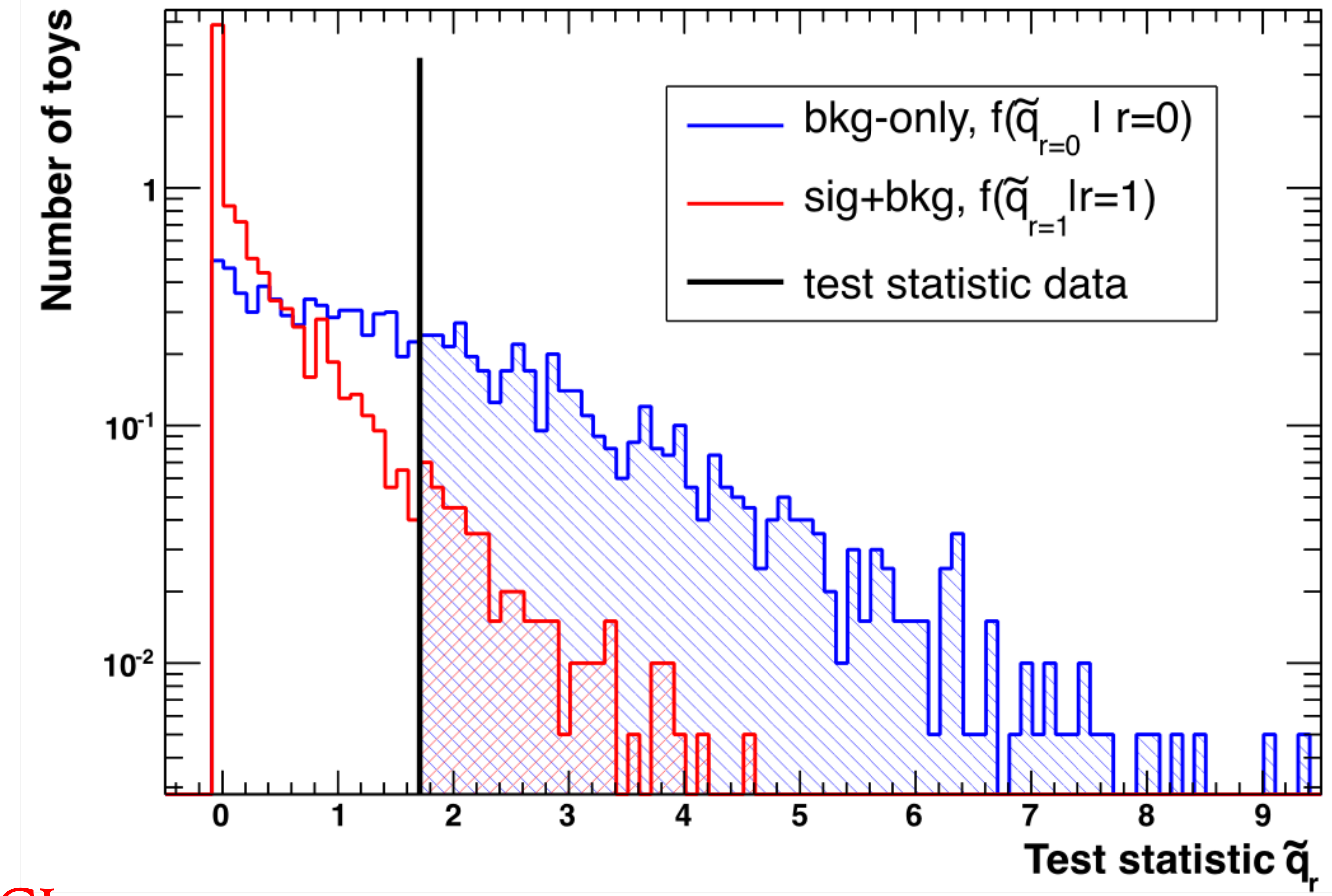
- **Calculate $\tilde{q}_\mu^{obs}$ for a specific μ under test**



Interlude: Calculate observed limit

s = *number of signal events*
b = *number of background events*
θ = *nuisance parameters*

- Construct a likelihood $\mathcal{L}(\text{data}\,|\,\mu,\theta) = \text{Poisson}\,(\,\text{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,)\cdot p(\tilde{\theta}|\theta)$
- Compare the measured data with two hypothesis
  - H_0 (**b** only, μ=0)
  - H_1 (μ×**s** +**b**)
  - Define test statistic (based on the profile likelihood ratio) $$\tilde{q}_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}$$
    - **Calculate $\tilde{q}_\mu^{obs}$ for a specific μ under test**
  - Generate pdfs for the test statistic for H_0 and H_1 for specific μ
    - Asymptotic approximation (i.e. a formula) or throwing toys (i.e. using computer generated random numbers)
    - Integrate pdfs of H_0 and H_1 from $\tilde{q}_\mu^{obs} \to \infty$ to obtain CL_B and CL_{S+B}
  - Exclude a μ-value if $CL_S < \alpha$ (i.e. $\mu^{95\%}$ or μ at 95% confidence level)
  - Repeat for next μ under test

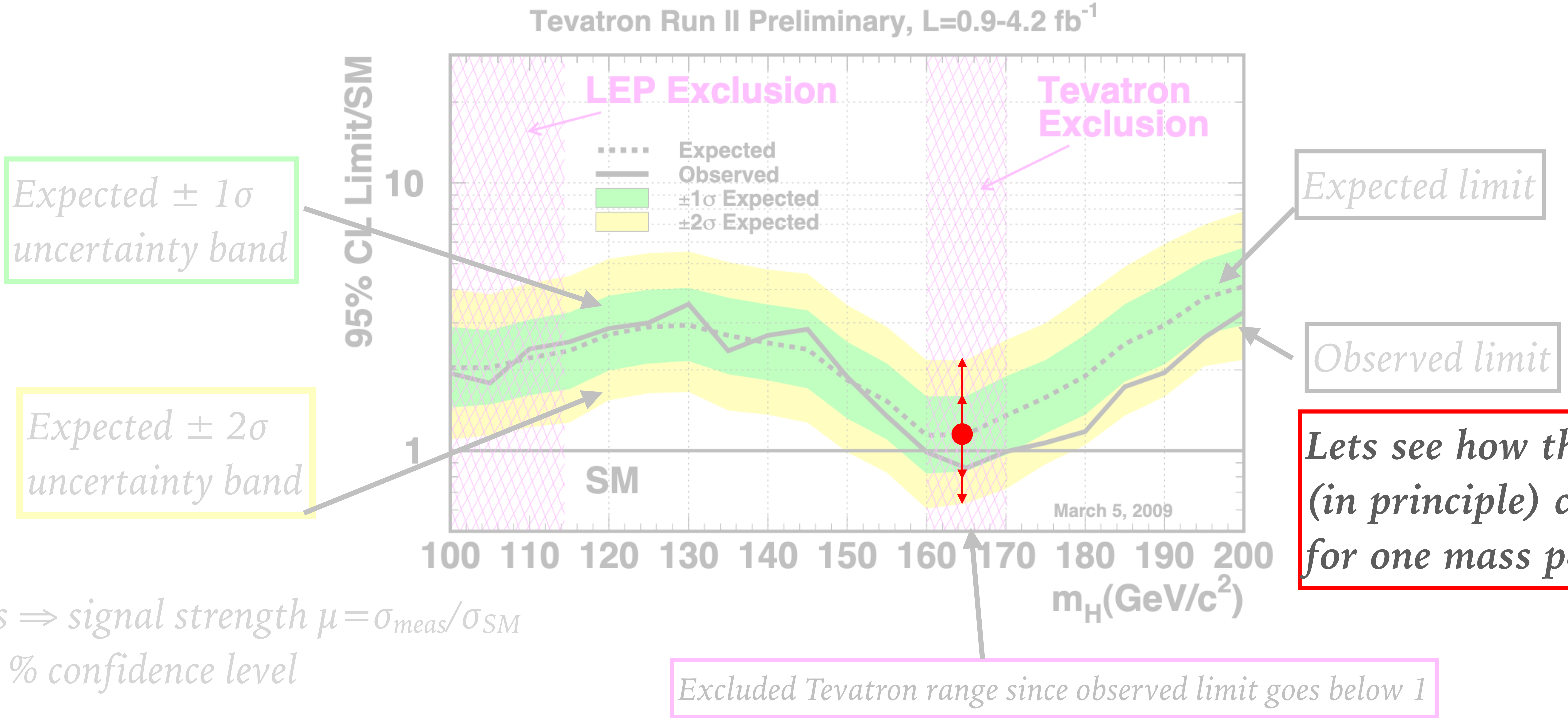


$$CL_S = CL_{S+B}/CL_B < \alpha$$

α conventionally chosen to be 0.05
➔ 95% confidence level (C.L.) limits

Interlude: Limits, how to read them and how to make them

➤ Status 2009: SM Higgs mass above 114 GeV, and NOT in the range 160-170 GeV



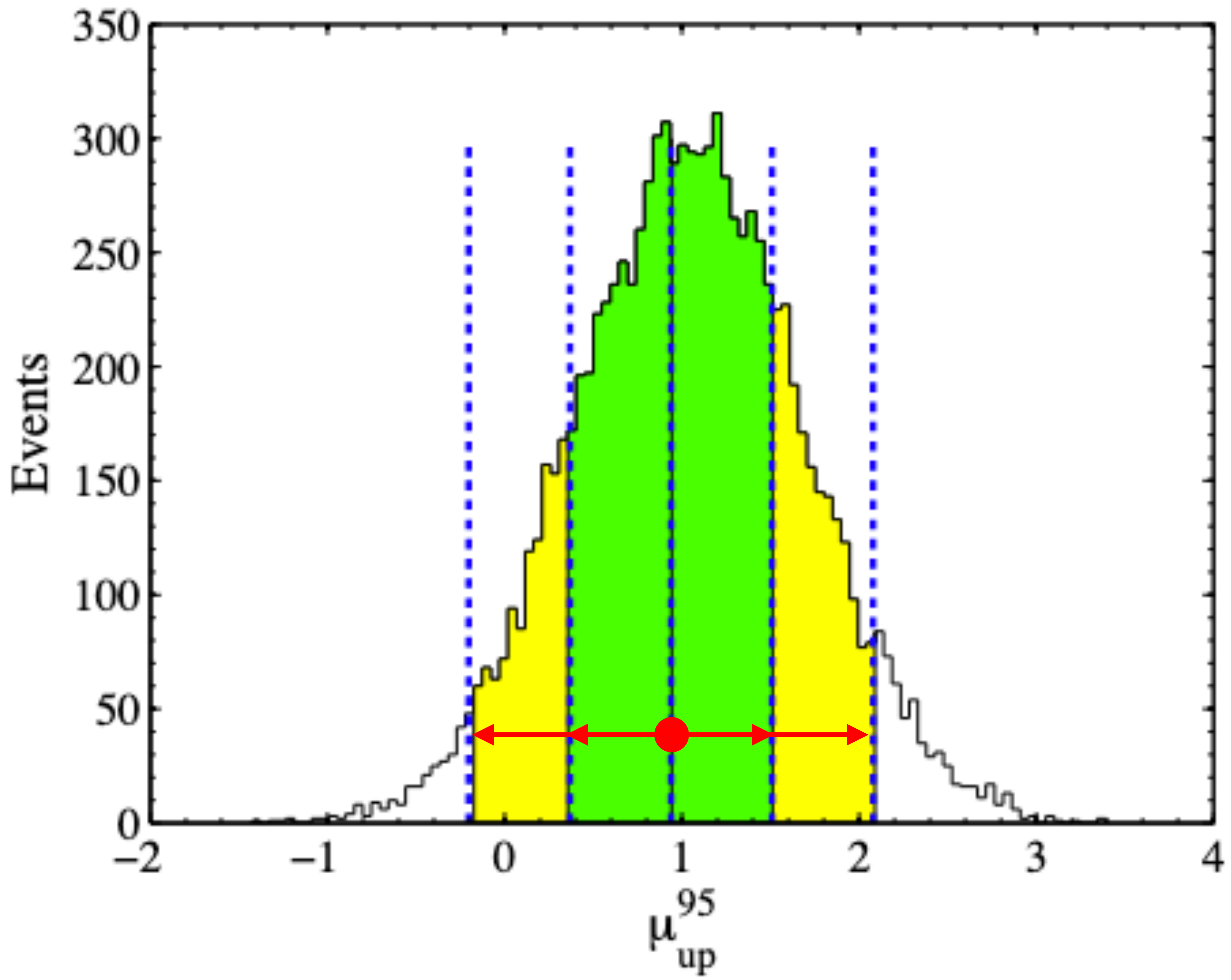
Lets see how this is (in principle) calculated for one mass point

y-axis ⇒ signal strength $\mu = \sigma_{meas}/\sigma_{SM}$ at 95 % confidence level

[Lectures K. Cramer]

Interlude: Calculate expected limits

- Repeat the same previous procedure **but** assuming now that the background only hypothesis H_0 (**b** only, $\mu=0$) represents the real data
  - generate large set of toys (or pseudo data)
  - calculate $\mu^{95\%}$ for each one of them
  - find mean 50%, 68% (1 sigma), 95% (2 sigma) ranges

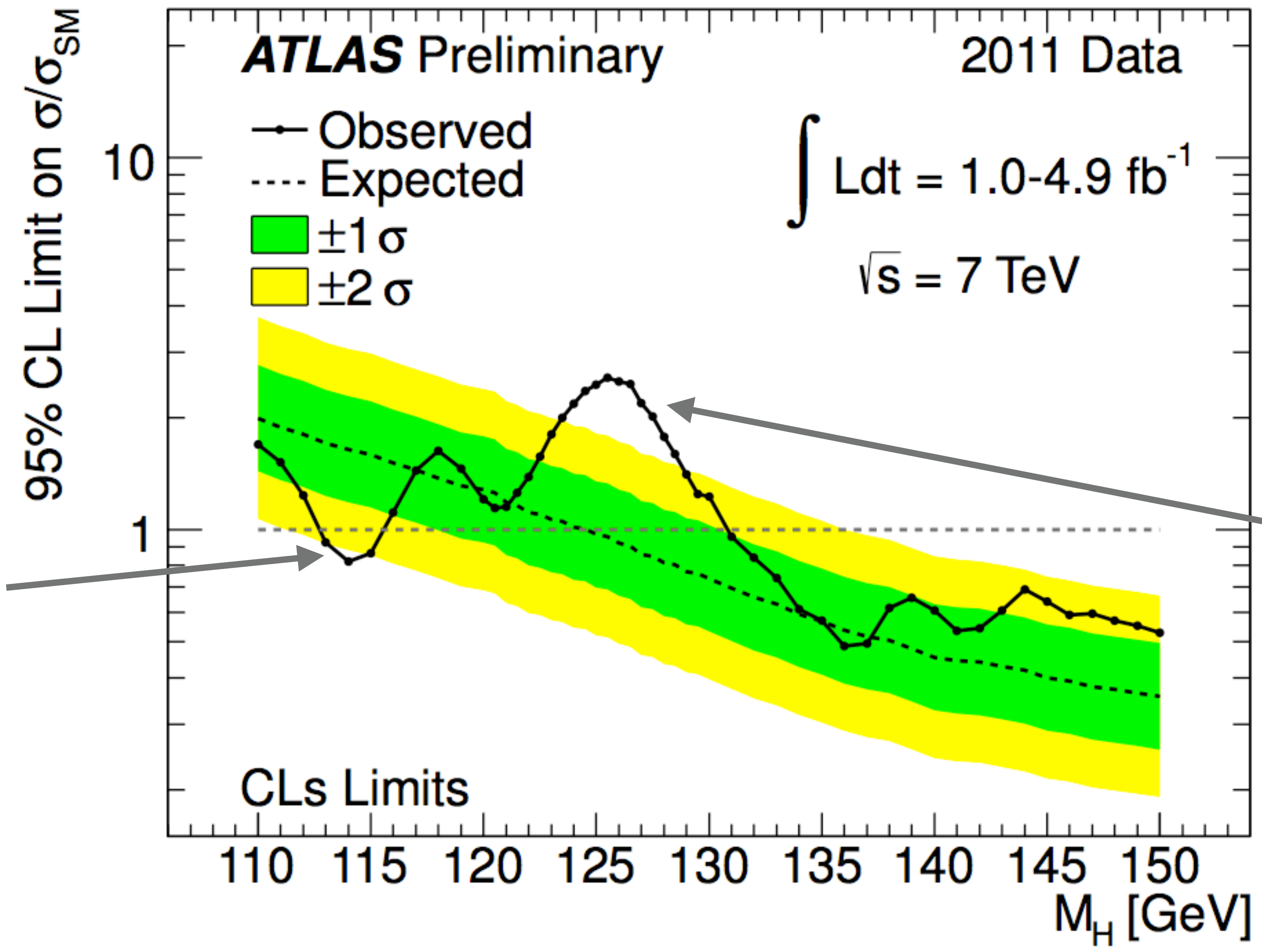


- In absence of signal, observed and expected limit should be very similar
- pseudo-data are very time-intensive, preferable to do this analytically where poss

Fun fact: it gets worse before it gets better

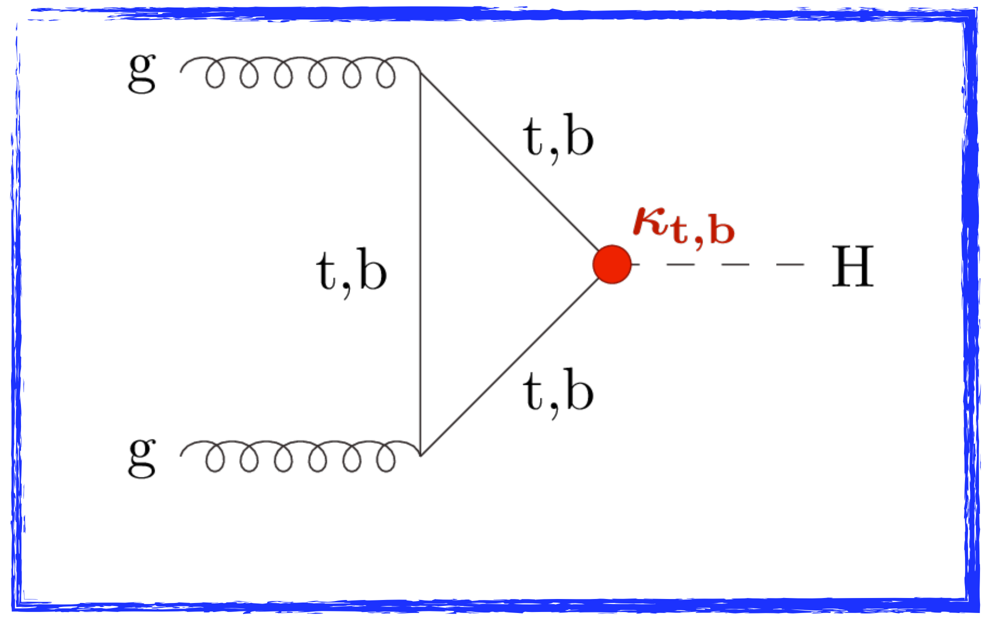
- The limit for a given model will improve by adding more data
  - However if a signal is there the observed limit does not improve anymore

- If the expected limit is worse than the observed
$\Rightarrow$ you have a deficit



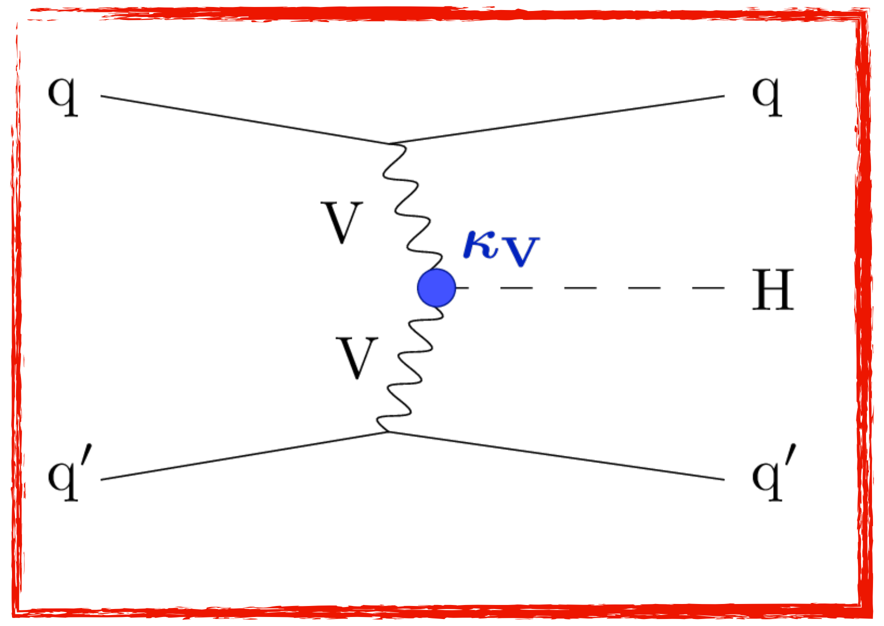
- If the expected limit is better than the observed
$\Rightarrow$ you have an excess

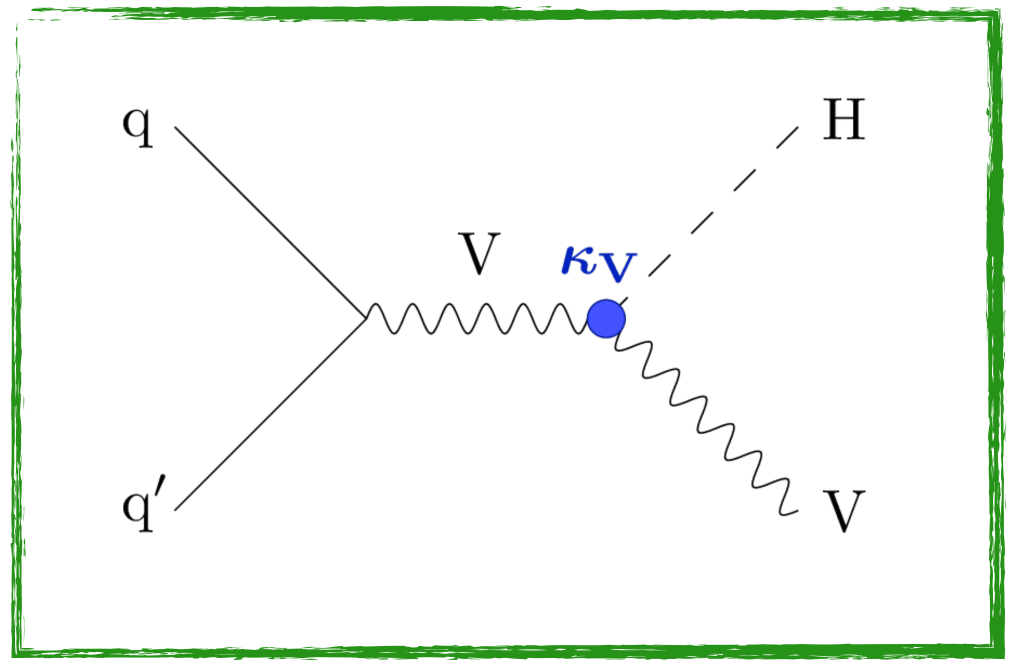
Higgs production modes at the LHC



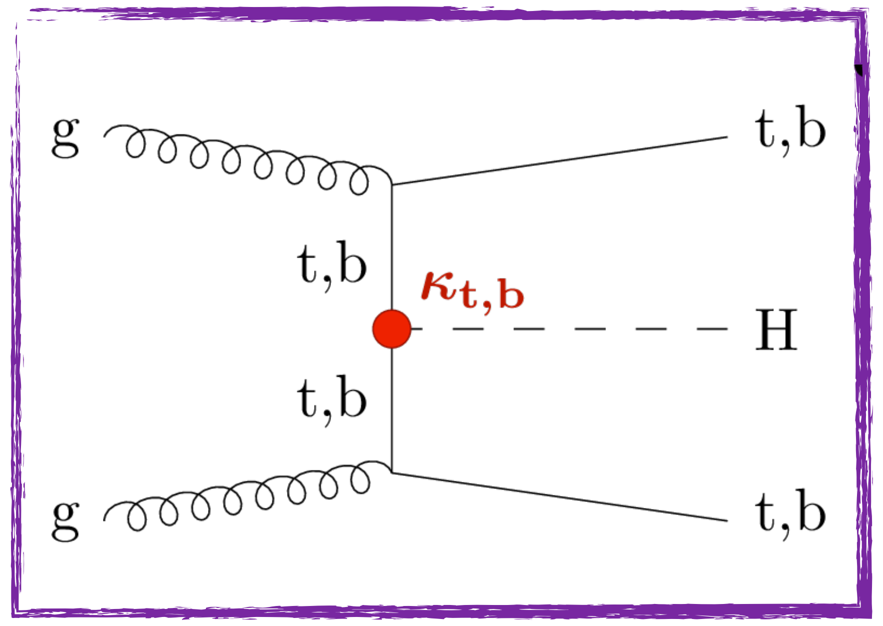
ggF

VBF

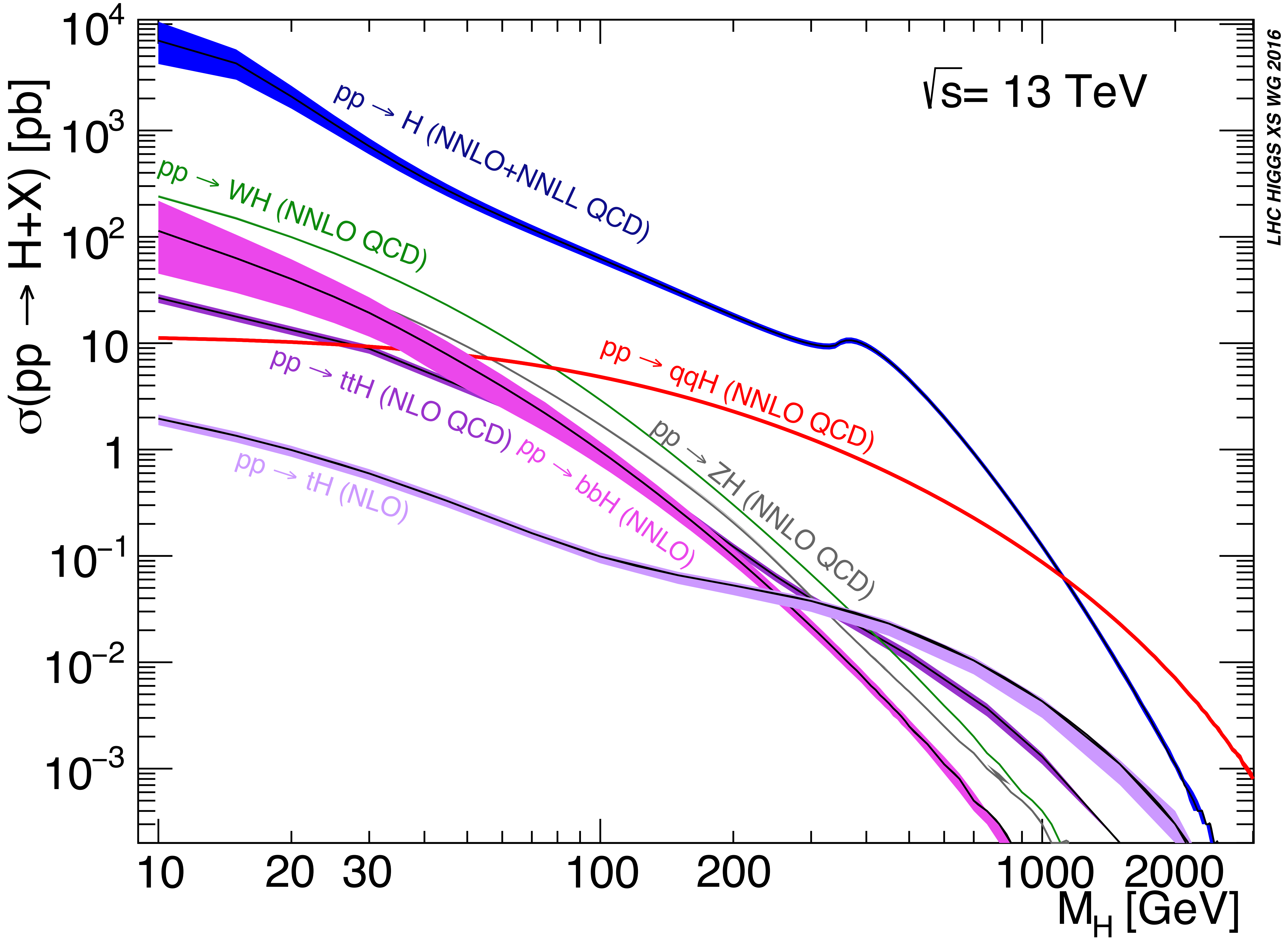




Higgs strahlung



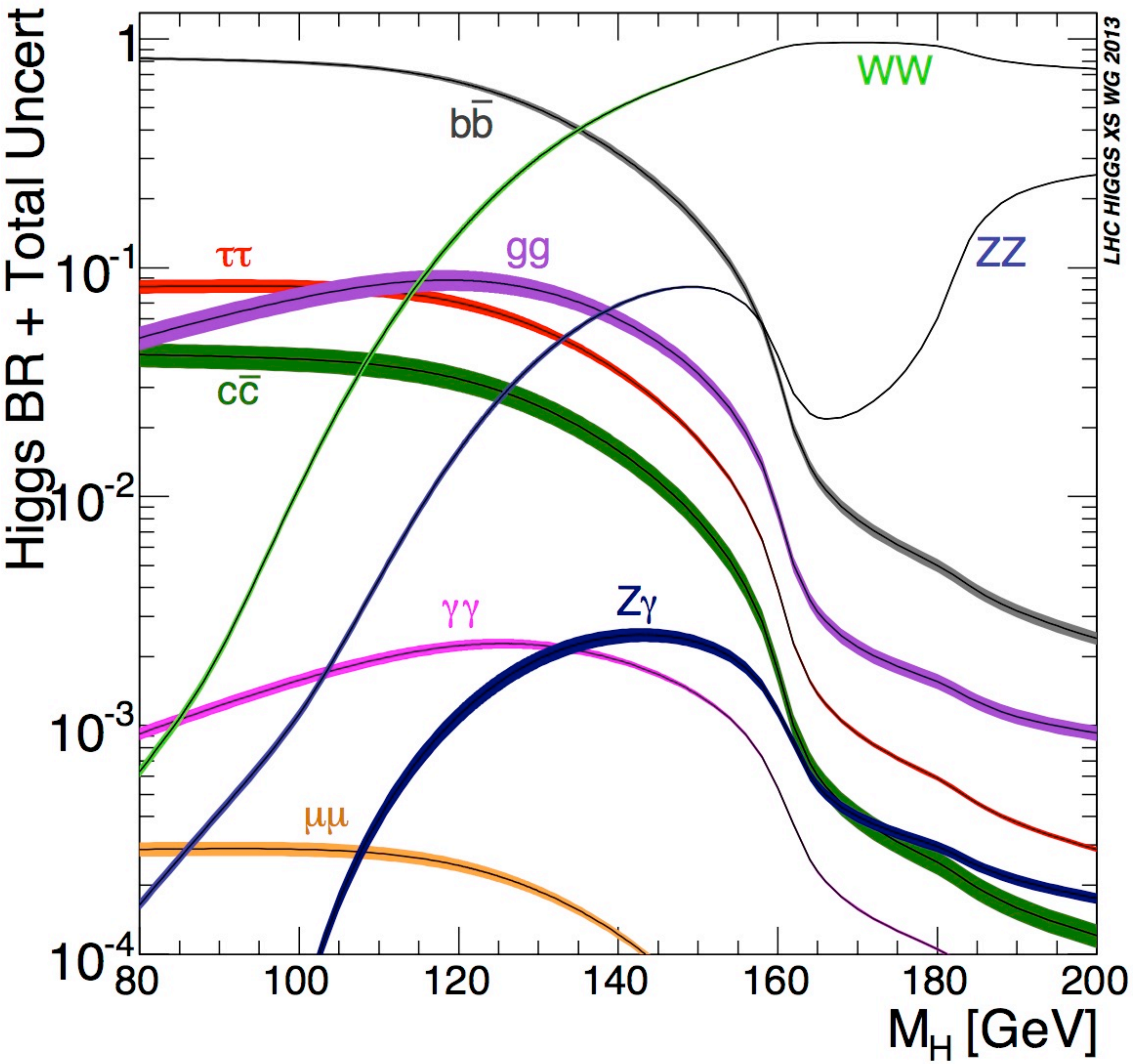
ttH



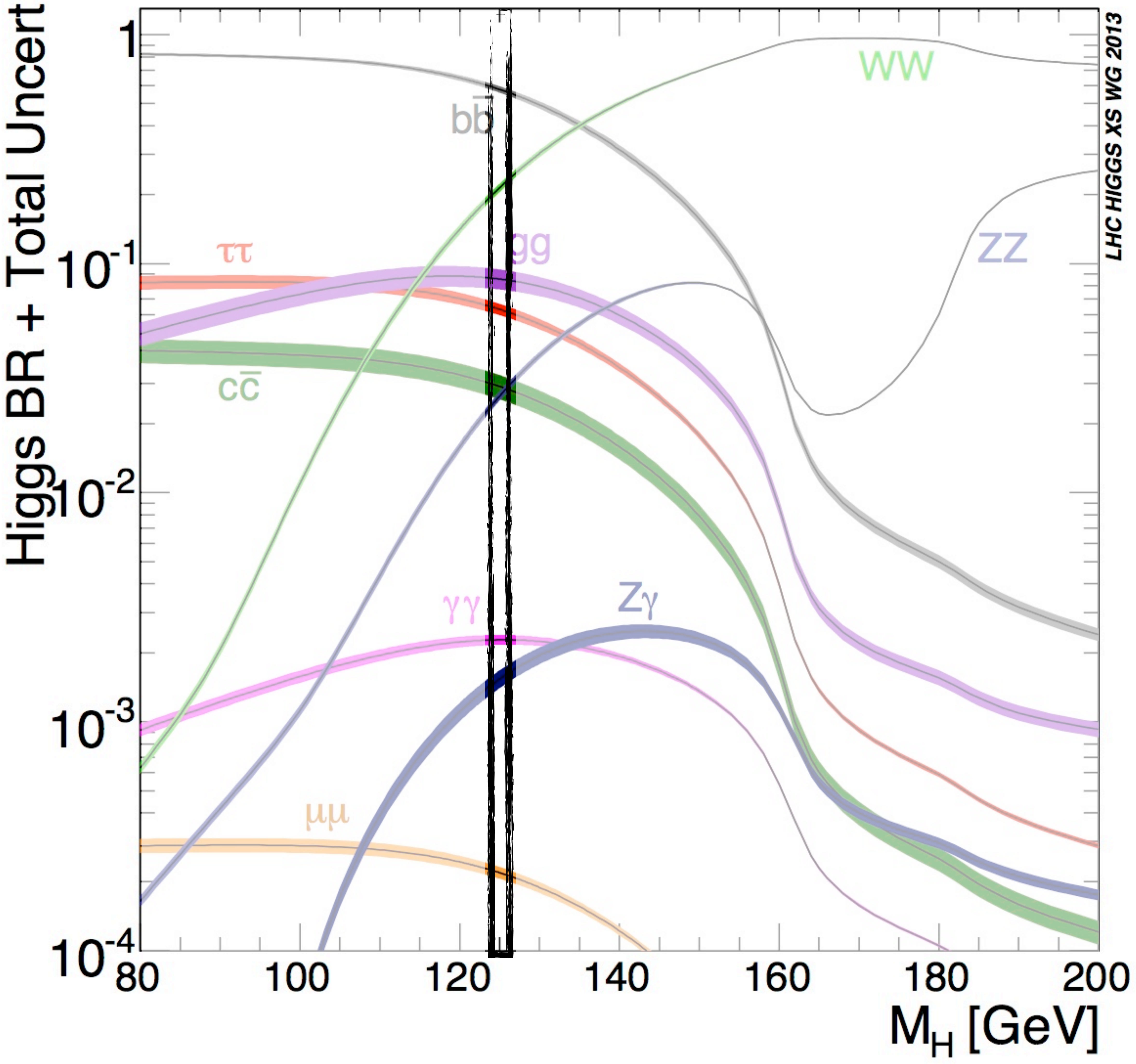
➤ Higgs production cross section as a function of m_H

[Nature 607 (2022) 60-68]

Higgs decay modes: a little bit of everything



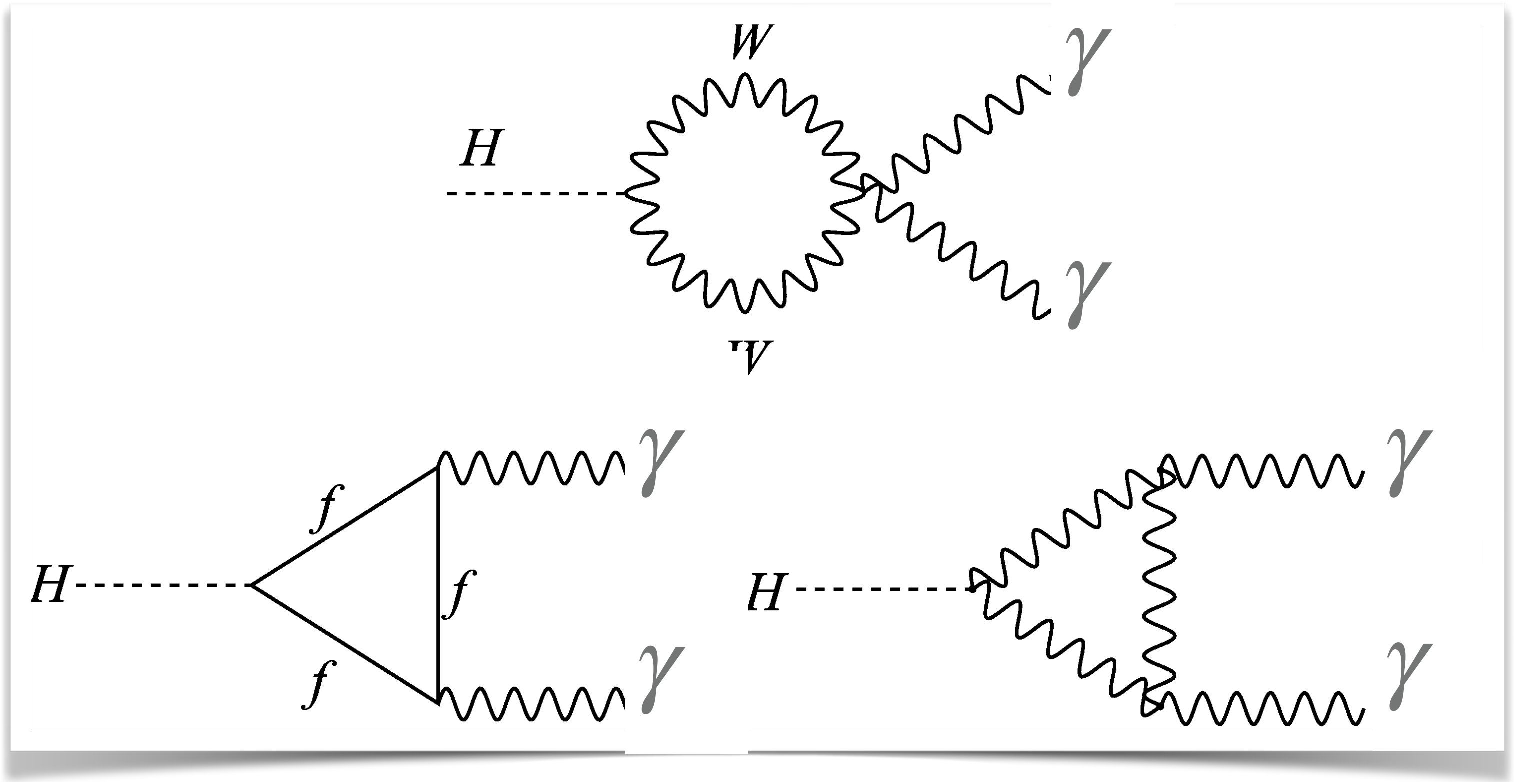
Higgs decay modes: a little bit of everything



Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

- At m_H = 125 GeV
  - $H \to b\bar{b}$: dominant decay, however large backgrounds
  - $H \to \gamma\gamma$ and $H \to ZZ$, $H \to WW$ are the "discovery channels"

Higgs to $\gamma\gamma$

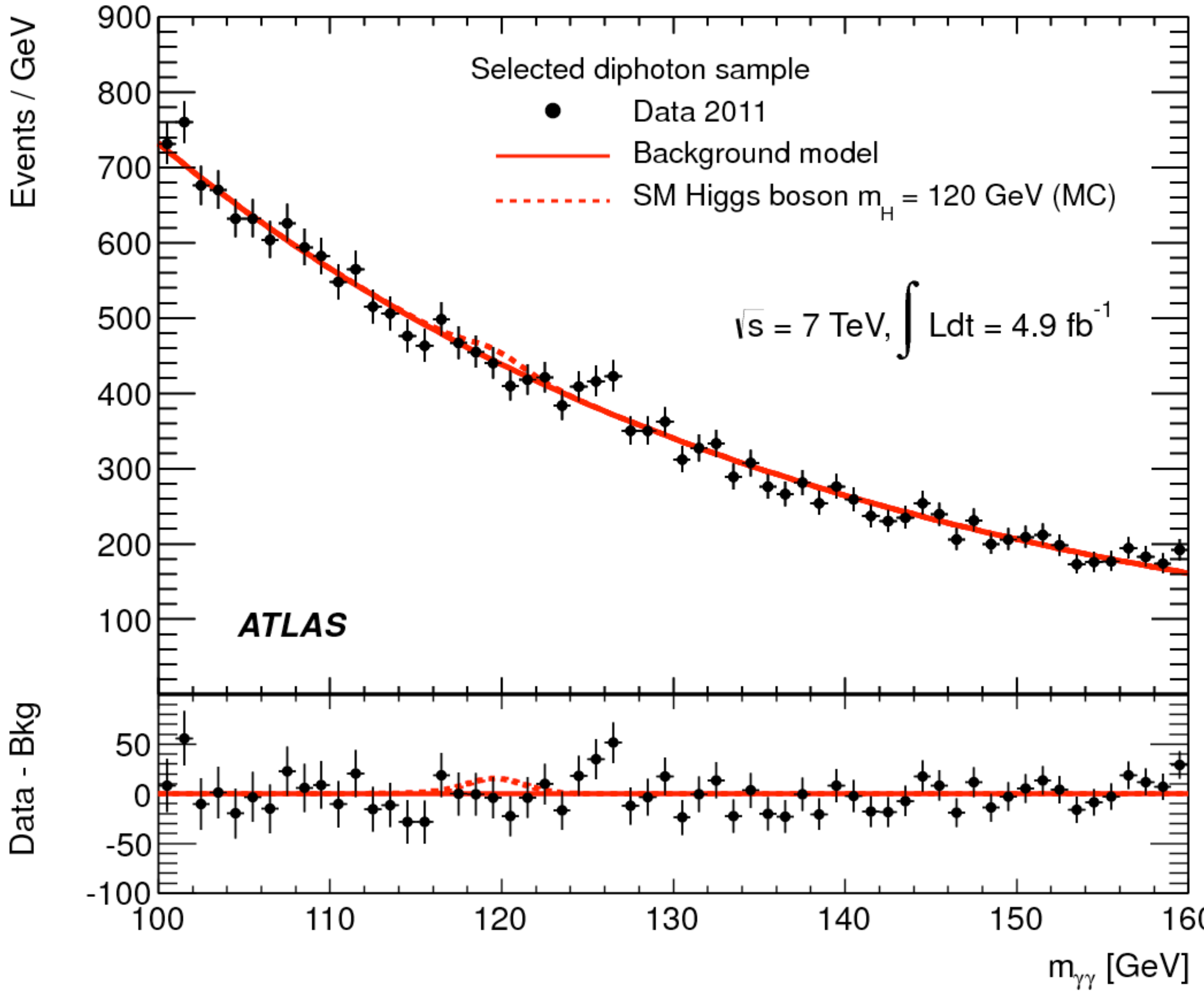


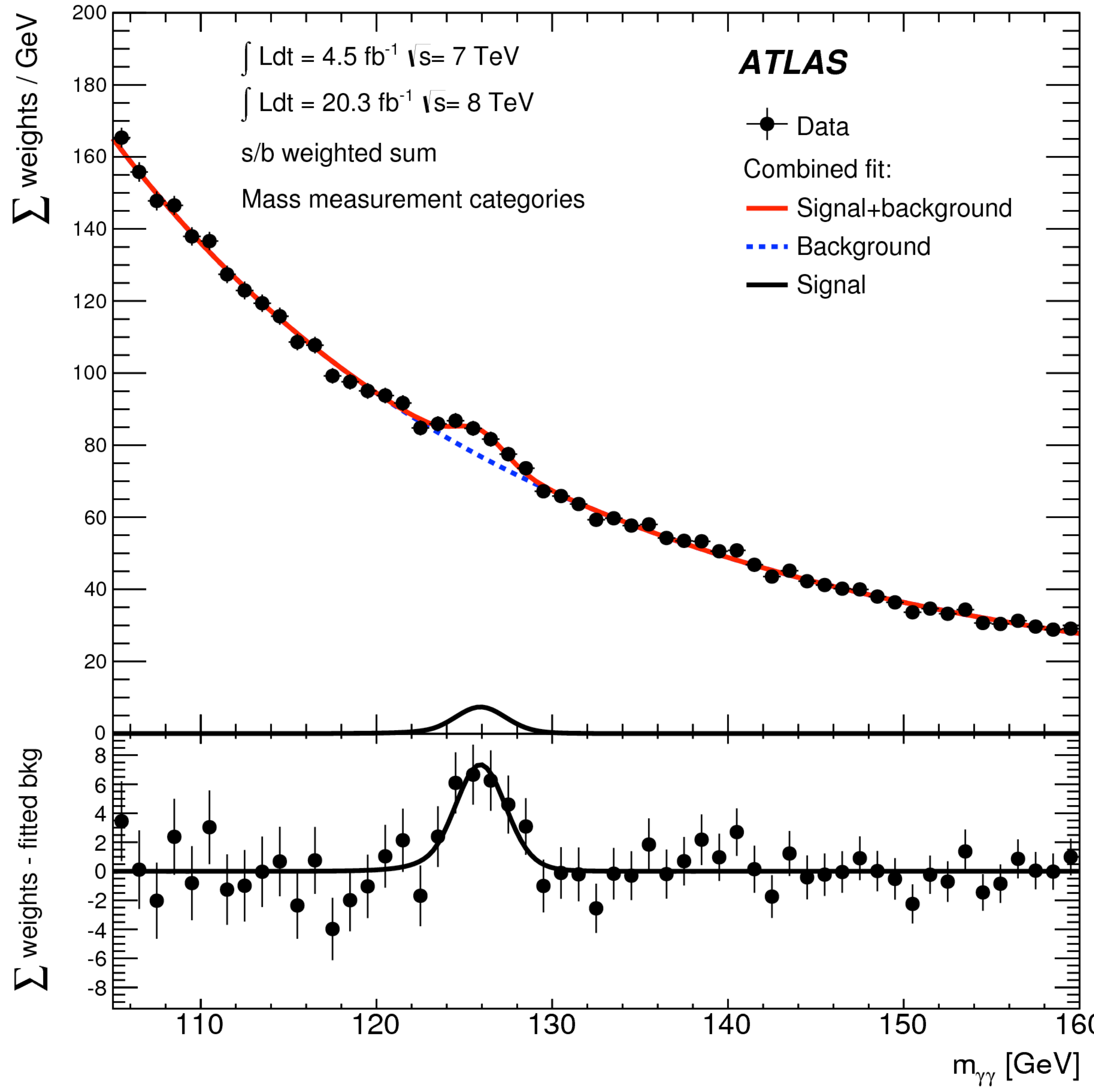
- Fairly clean signature: 2 photons + reconstruct their invariant mass
  - Lots of work goes into dedicated photon reconstruction and calibration
  - Very good mass resolution ⇒ excellent channel for mass measurement
- Large but smoothly falling di-photon background

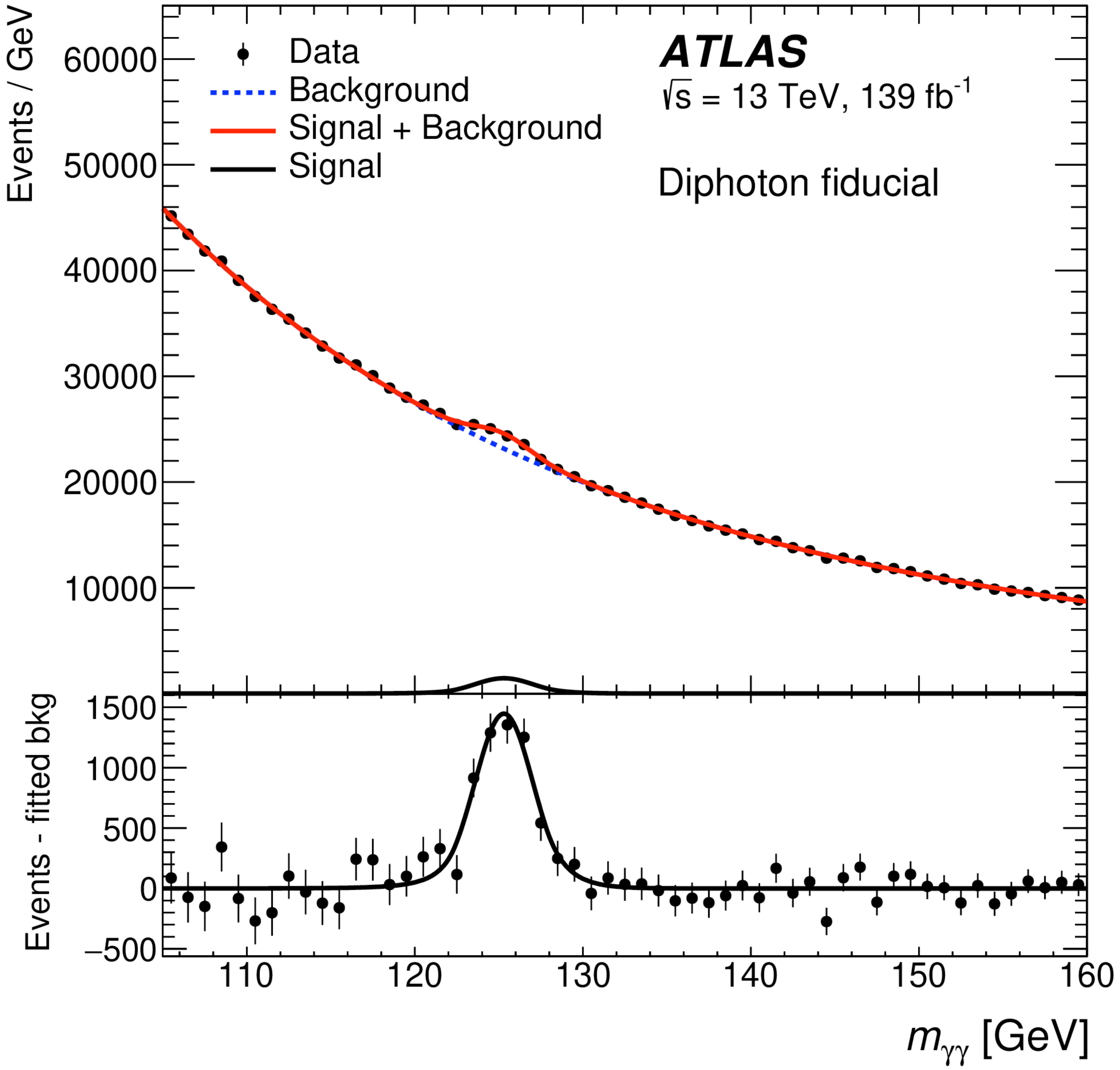
Full Run2 @ 13 TeV

Full Run1 @ 7, 8 TeV

5fb-1 @ 7 TeV

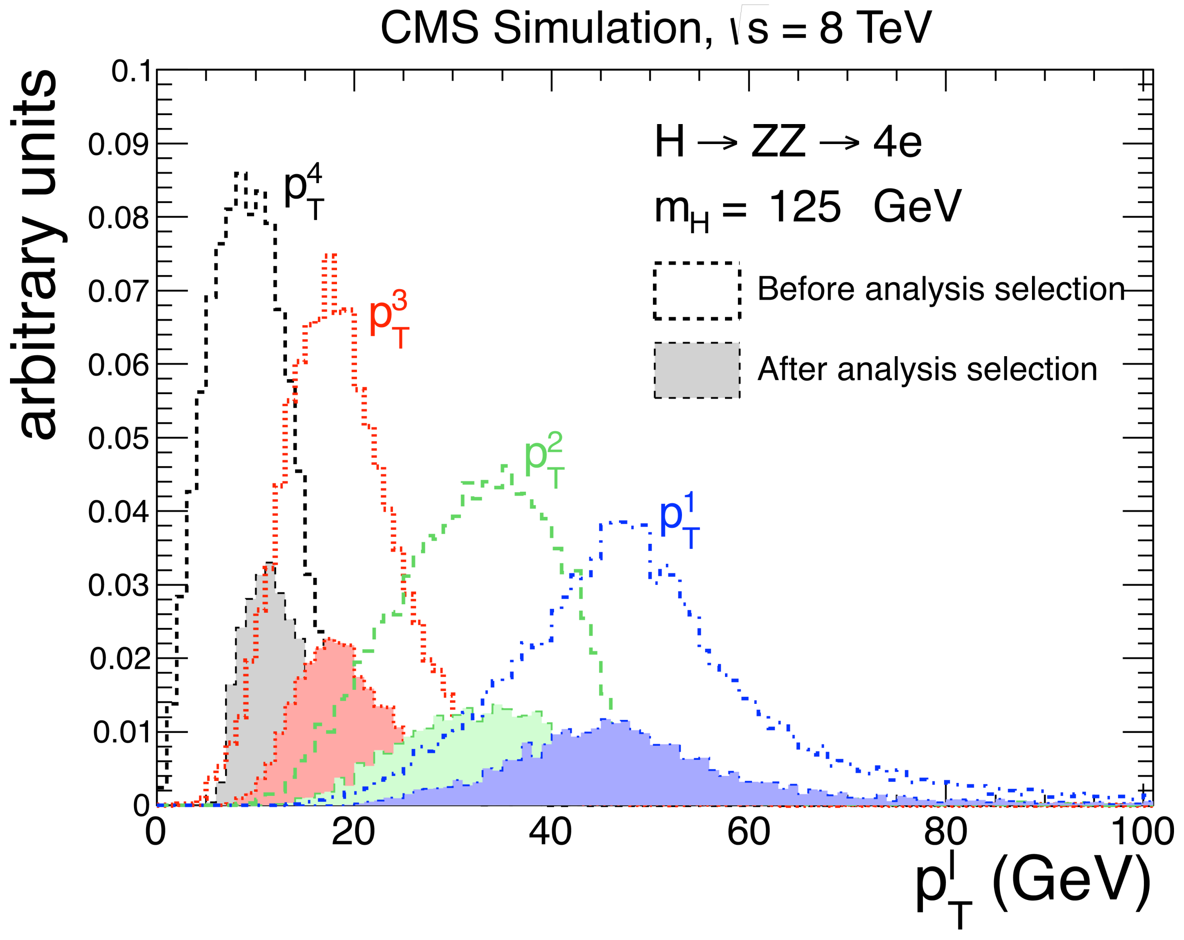




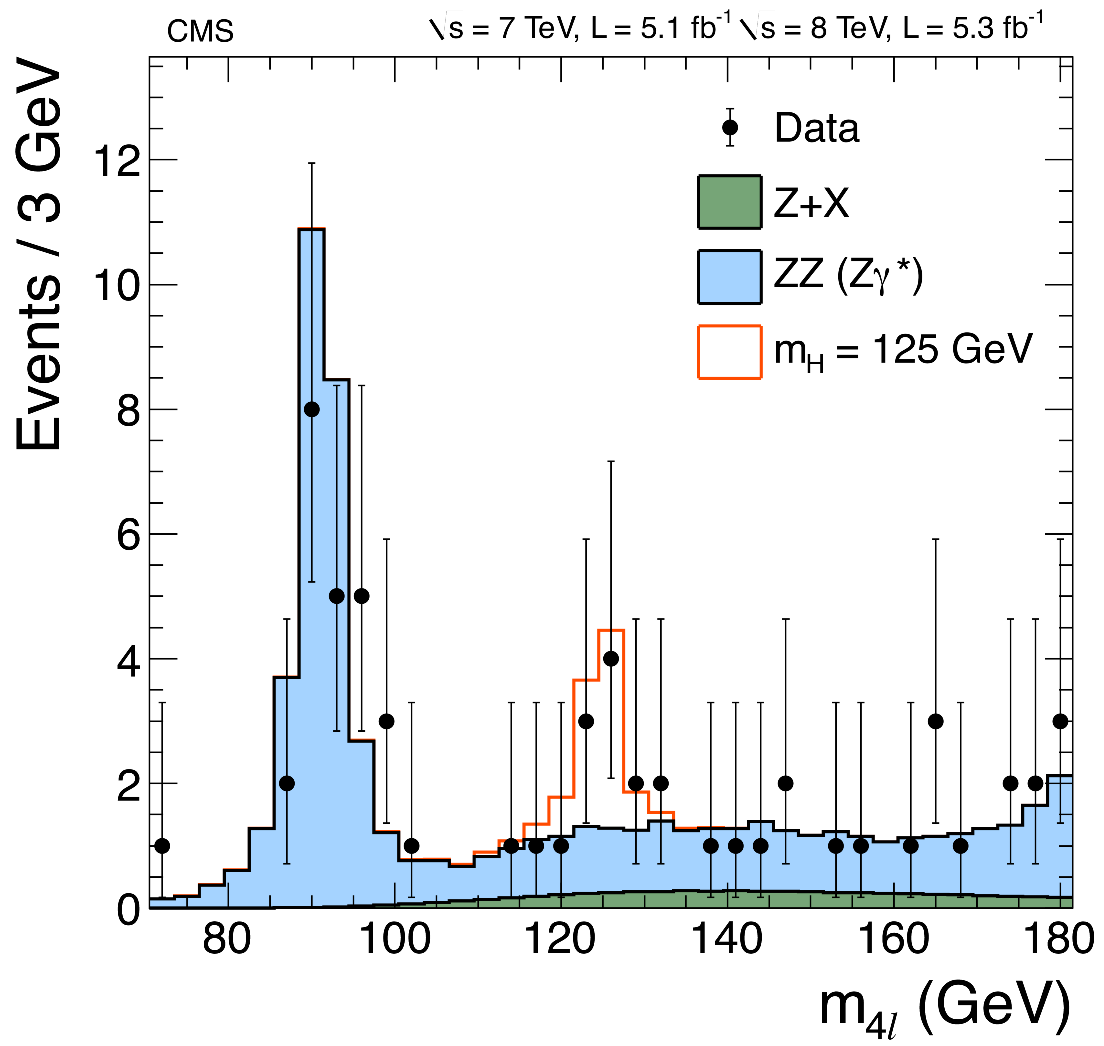


Higgs to ZZ

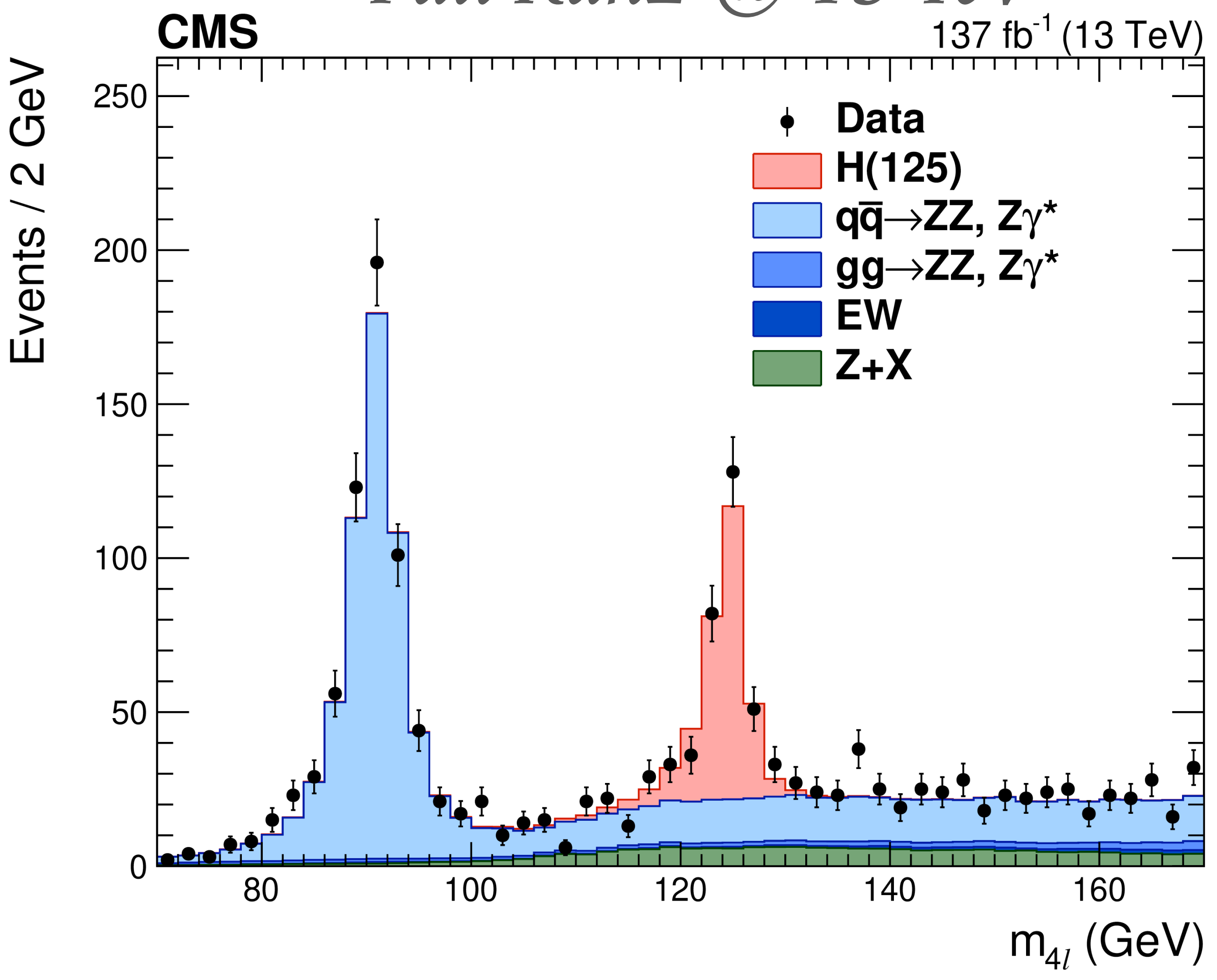
- Very clean signature: 4 leptons (electrons and muons, 2 same flavor opposite sign pairs)
- Channel with high S/B ratio
- Other important features:
  - Very low rate due to branchings of ZZ and Z to leptons
  - The trailing lepton is at low pT
  - The polarisation of the two Z can be reconstructed
  - Typically one Z is on-mass shell



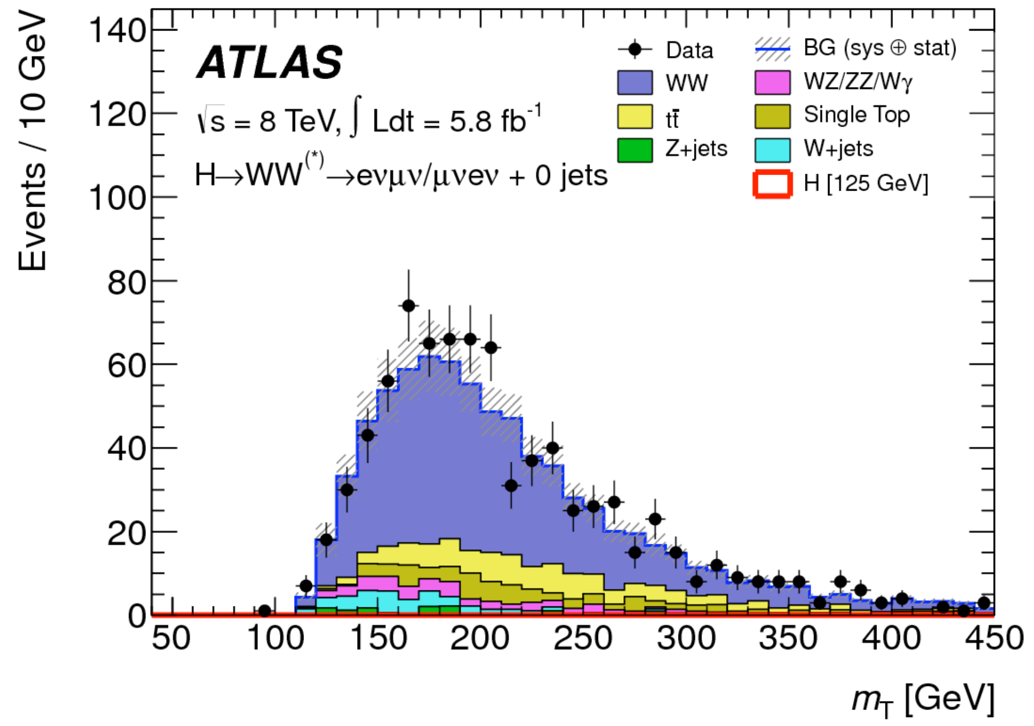
$10fb^{-1}$ @ 7, 8 TeV



Full Run2 @ 13 TeV



Higgs to WW

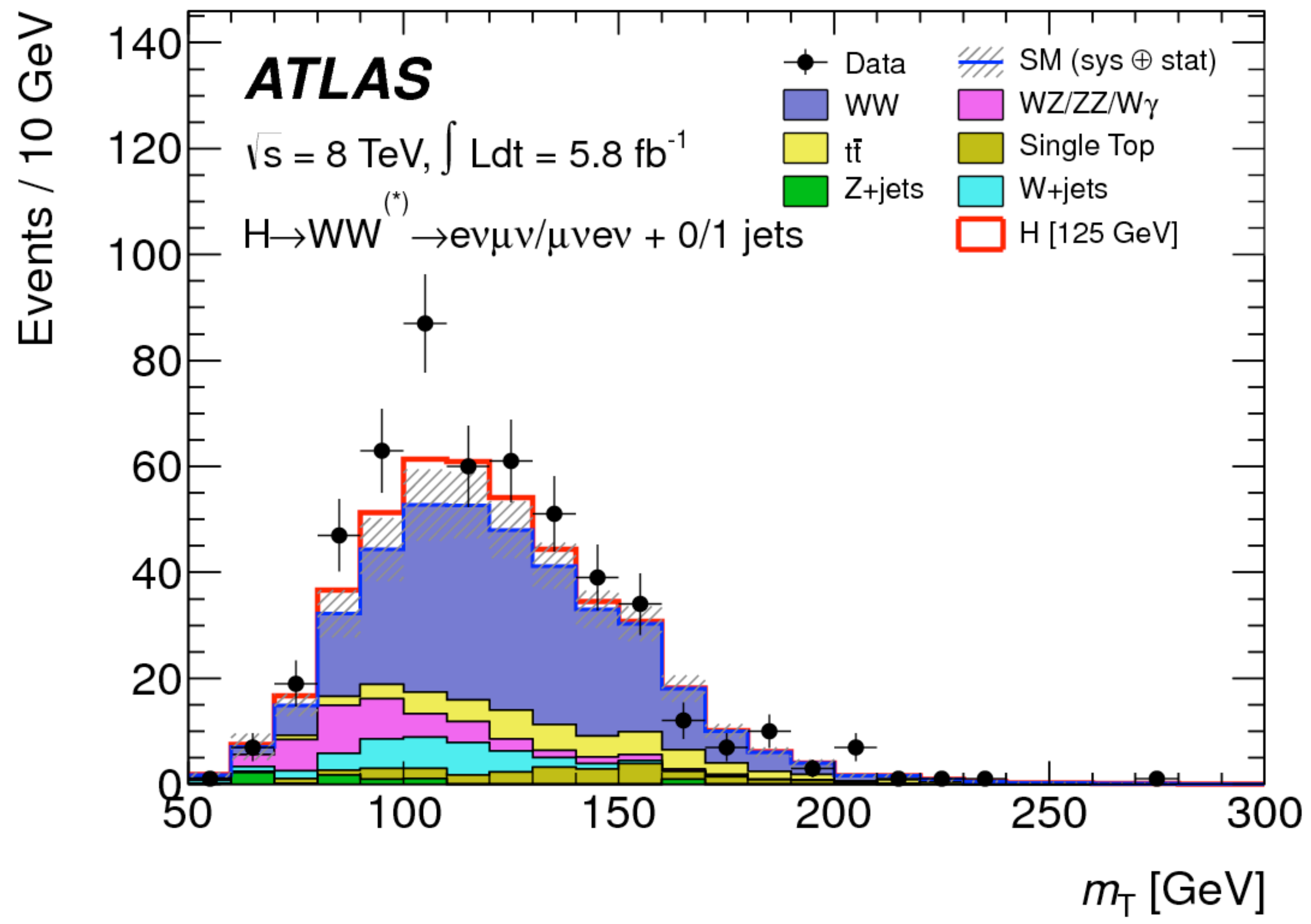


WW control region

- no signal expected

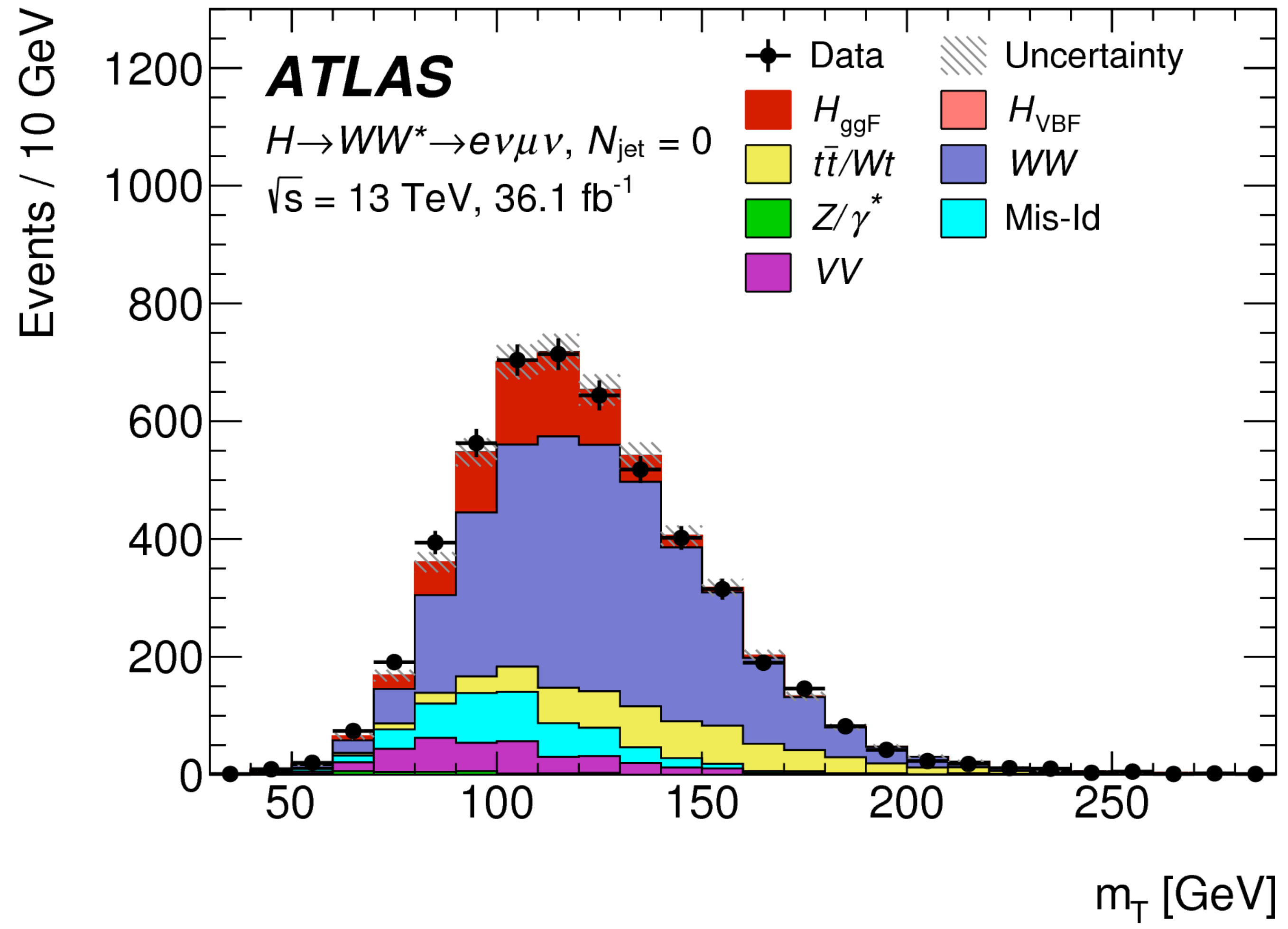
- orthogonal to the SR

- ➤ Final states including two leptons and two neutrinos
  - ➤ Higgs mass diluted by the presence of neutrinos ⇒ mT variable is used
- ➤ Large event rate, but also large backgrounds from SM WW and top production
  - ➤ Control regions in data needed to estimate these backgrounds



$5fb^{-1}$ @ 8 TeV

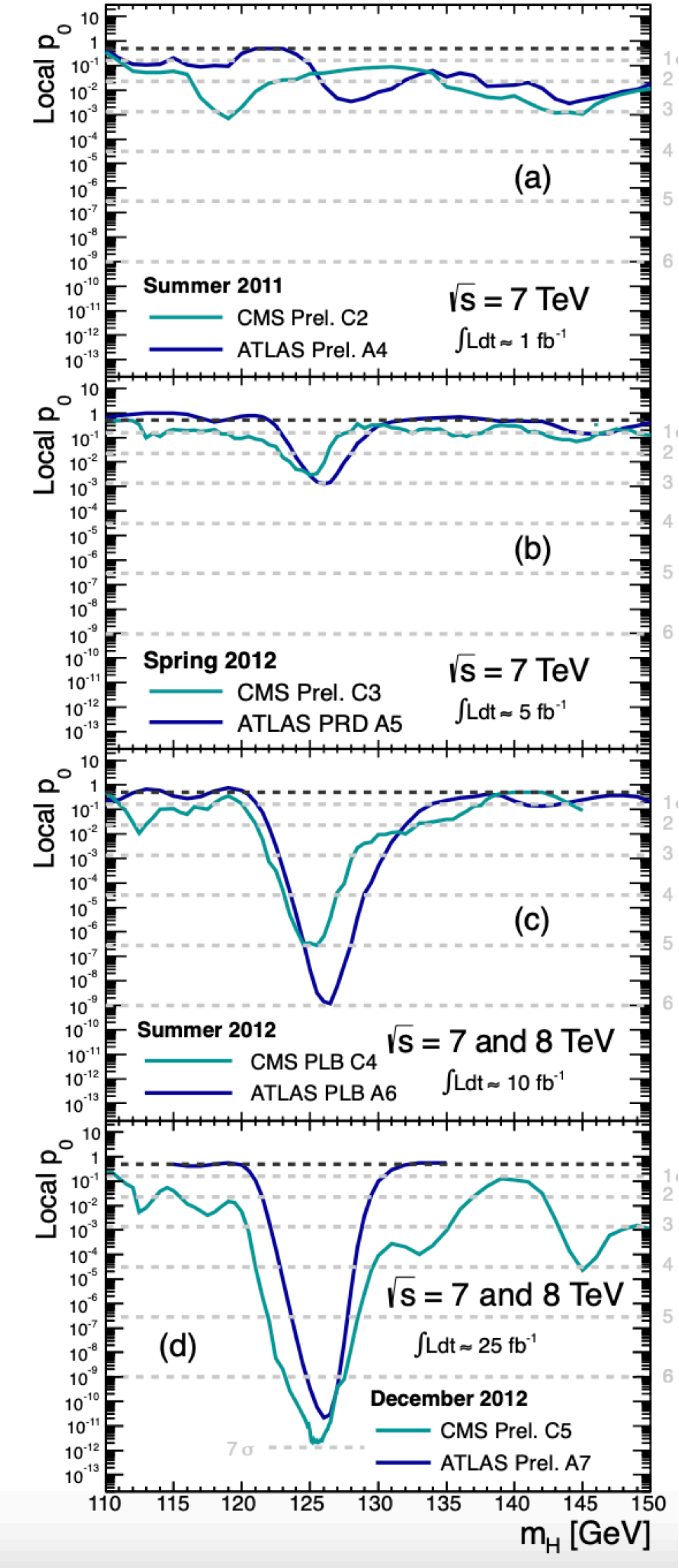
$36fb^{-1}$ @ 13 TeV



A textbook discovery

- Summer 2011 EPS and Lepton-Photon
  ⇒ **Still focused on limits**
- December 2011 CERN Council:
  ⇒ **First hints**
- Summer 2012 CERN Council and ICHEP
  ⇒ **Discovery!**
- December 2012 CERN Council
  ⇒ **Beginning of a new era!**

[PDG 2013]



- Strongly Motivated
- Significance increased with luminosity to reach unambiguous levels
- Two experiments
- Several channels

The Higgs turned 10!

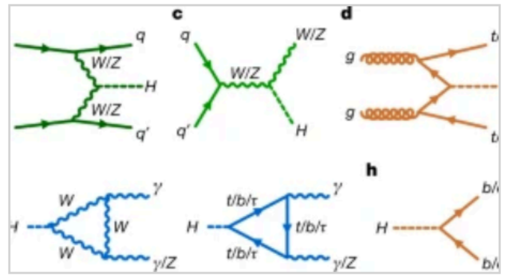
Research Articles

Article
Open Access
4 Jul 2022
Nature

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

Ten years after the discovery of the Higgs boson, the ATLAS experiment at CERN probes its kinematic properties with a significantly larger dataset from 2015–2018 and provides further insights on its interaction with other known particles.

The ATLAS Collaboration

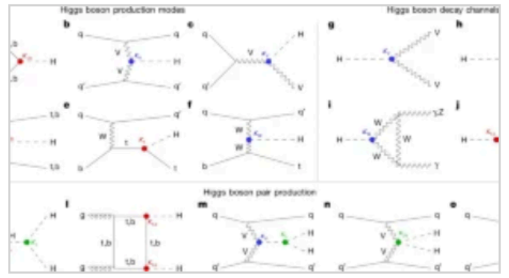


Article
Open Access
4 Jul 2022
Nature

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

The most up-to-date combination of results on the properties of the Higgs boson is reported, which indicate that its properties are consistent with the standard model predictions, within the precision achieved to date.

The CMS Collaboration



Adding more and more pieces of the puzzle

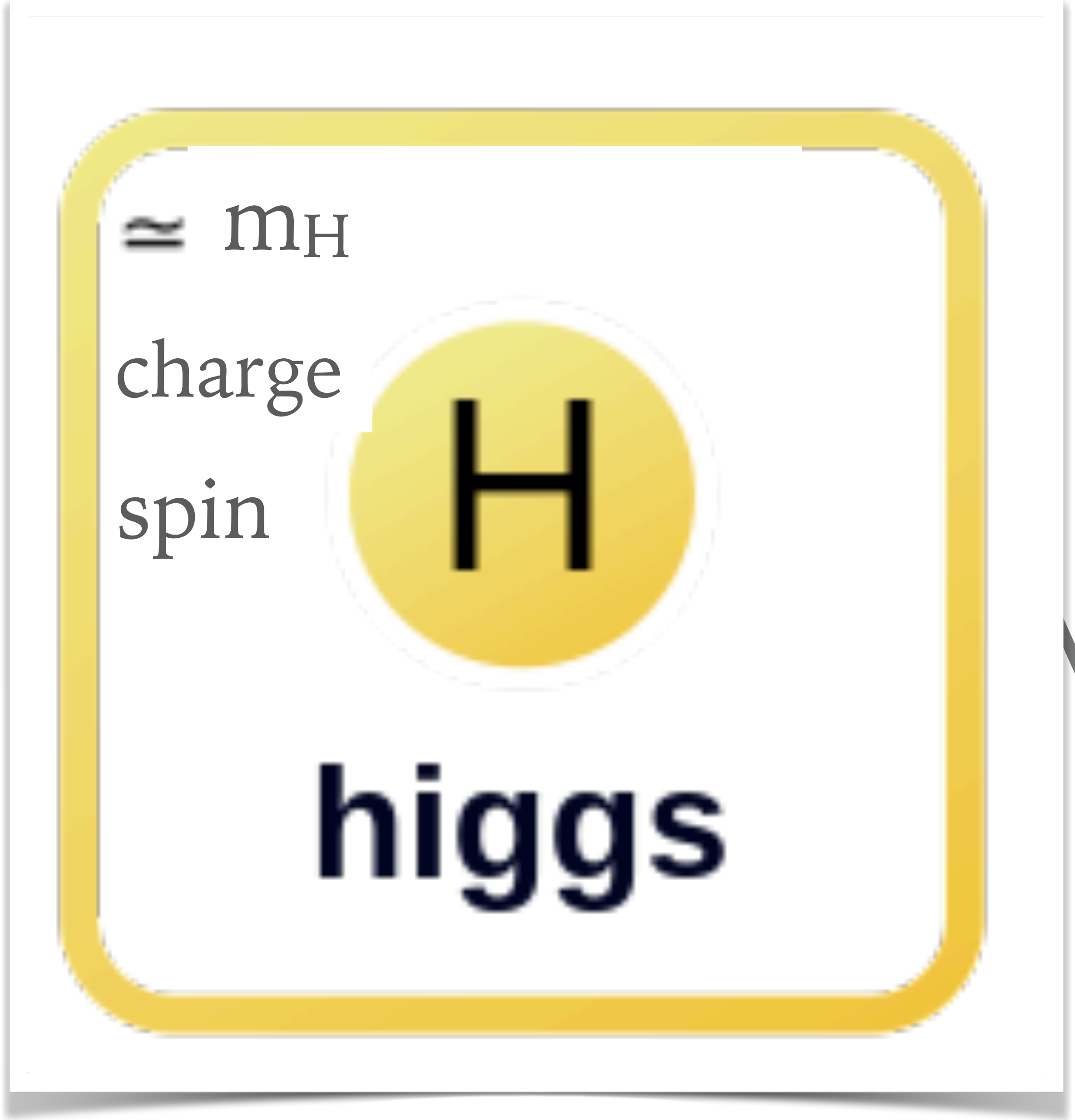
- What das the SM predict for the Higgs?

Spin and CP

scalar: spin 0, CP even

Width

Depends on the mass



Couplings

Higgs-Fermion couplings ~ fermion mass
Higgs-Boson couplings ~ boson mass^2

⇒ SM Higgs sector is overall very predictive:
Knowing the fermion masses, only free parameter is m_H

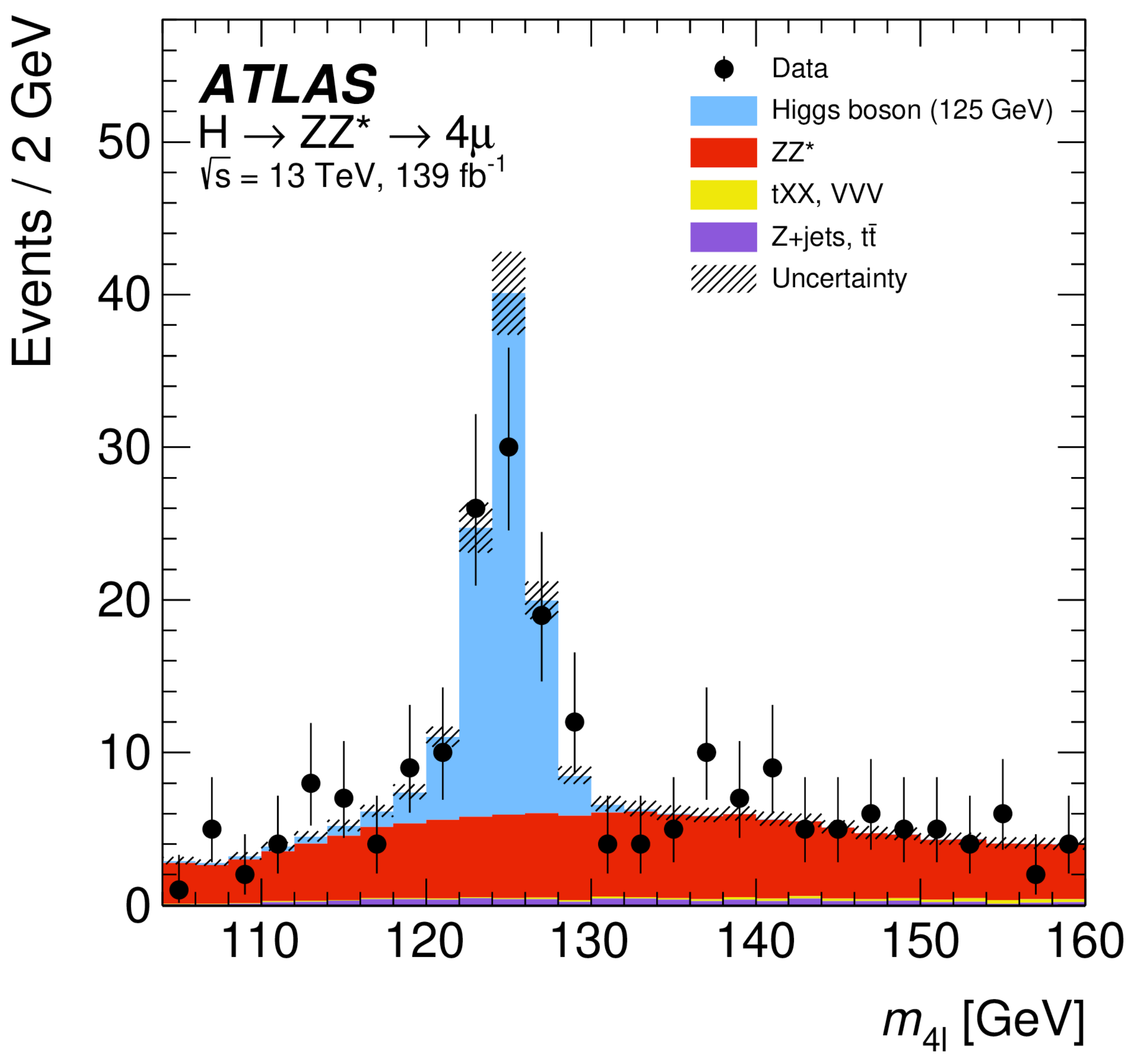
Let's test these predictions

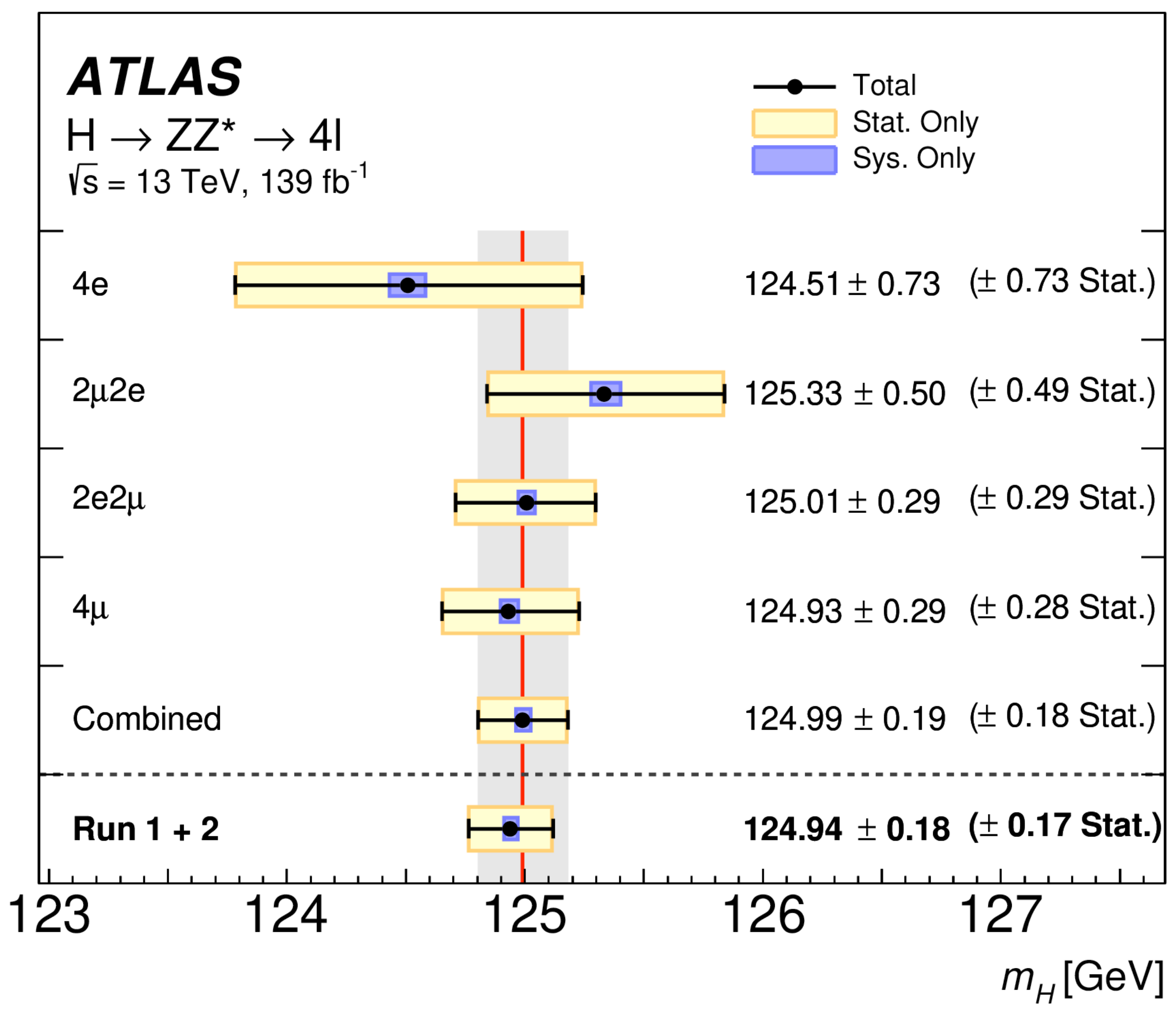
- Measure all properties:
  - Mass, spin, CP, couplings
- Deviations could point to physics beyond the SM
- Higgs can also play an important role in searches for New Physics

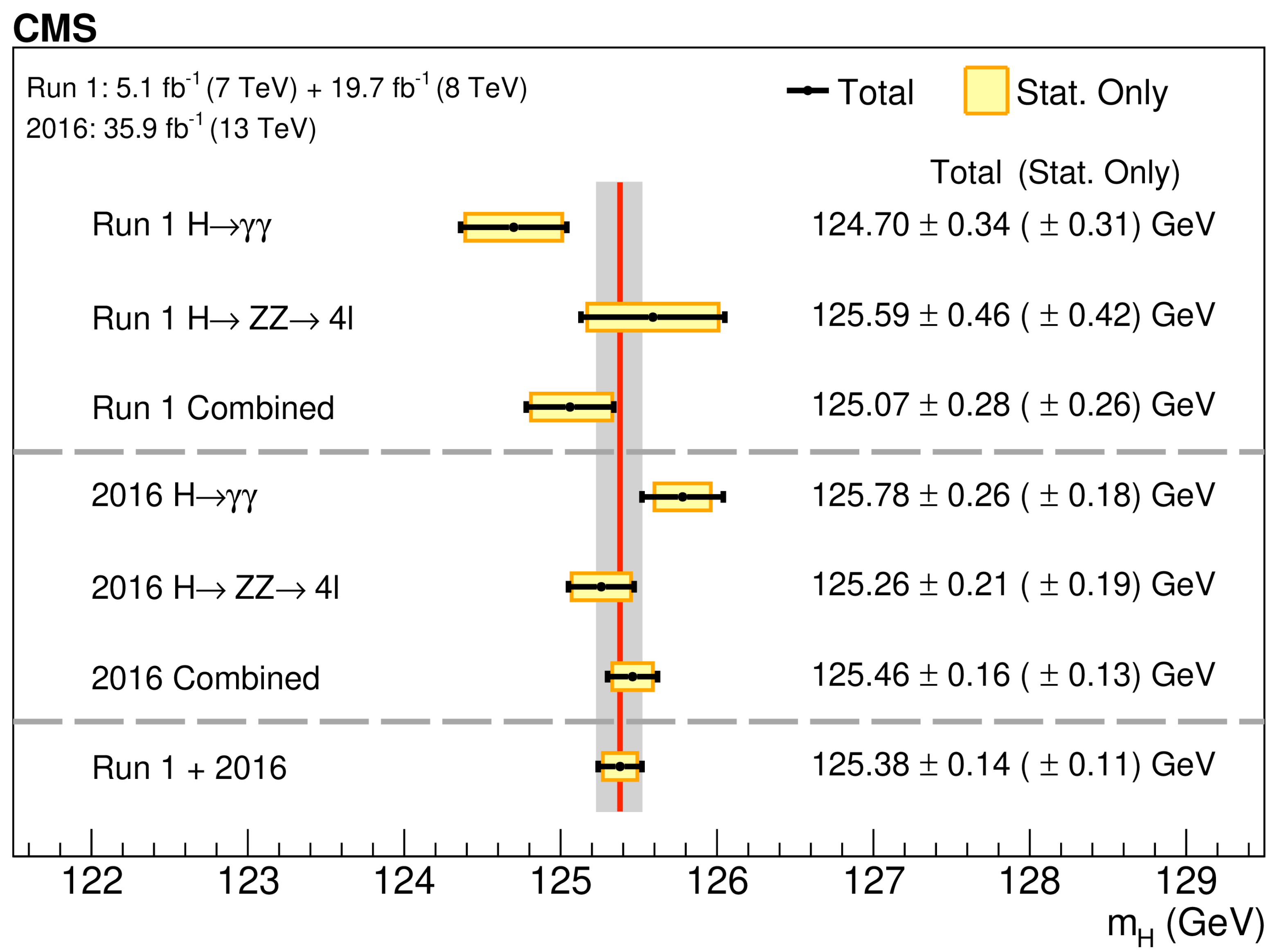
Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$ ✓	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$ ✓	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$ ✓	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

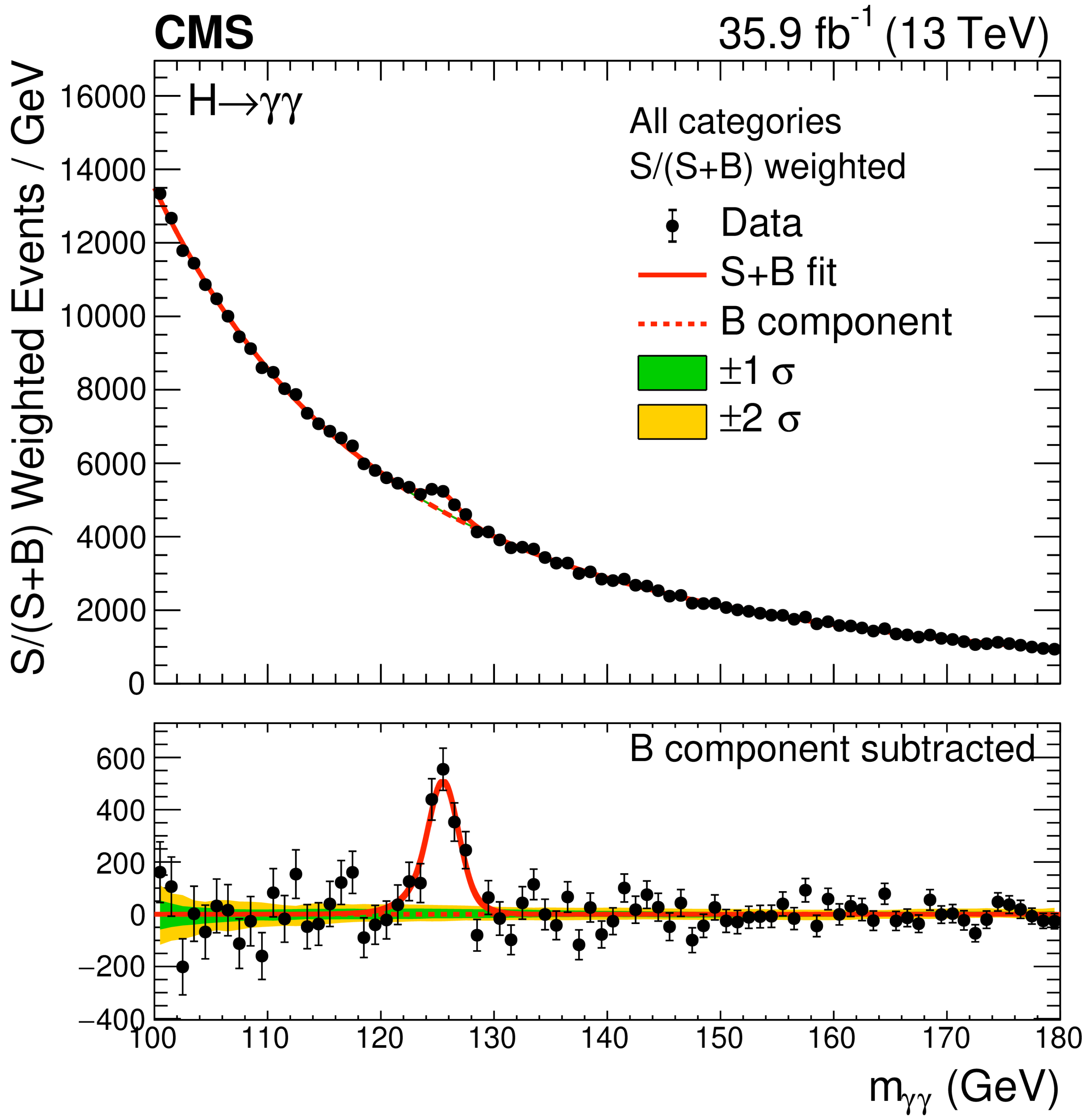
Higgs mass measurements

- Not predicted by the SM
- Mass measurements in the “golden channels” H → γγ and H → ZZ
- Optimized analyses in categories with best mass resolution (photon, electron and muons energy response)
- Reached a 0.2% precision



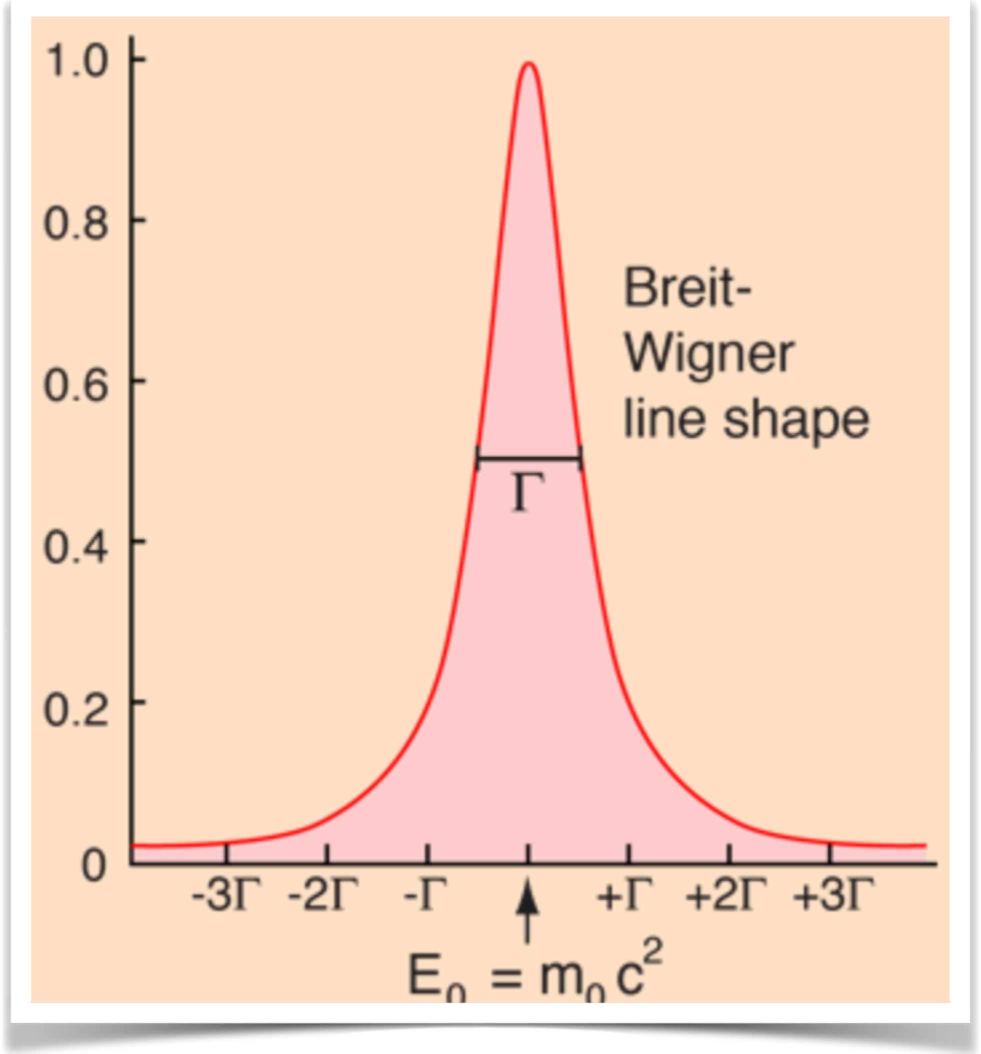






Higgs width

- What is the "width" of a particle?
  - Heisenberg Uncertainty Principle implies that the energy (i.e. also mass) of all unstable particles must have an uncertainty
    $\Rightarrow$ inversely proportional to their lifetime
  - the large the width the smaller the lifetime



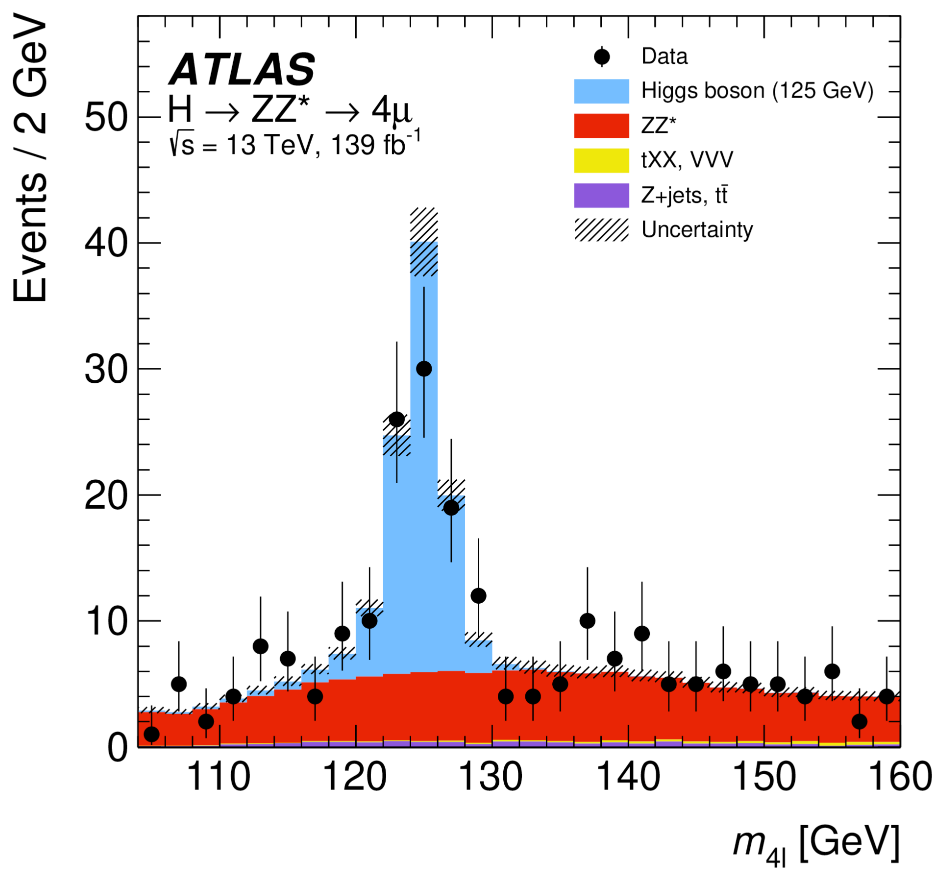
- Higgs width is predicted to be 4 MeV
  - If Higgs width is larger than SM predicts
    $\Rightarrow$ possible new physics decay channels

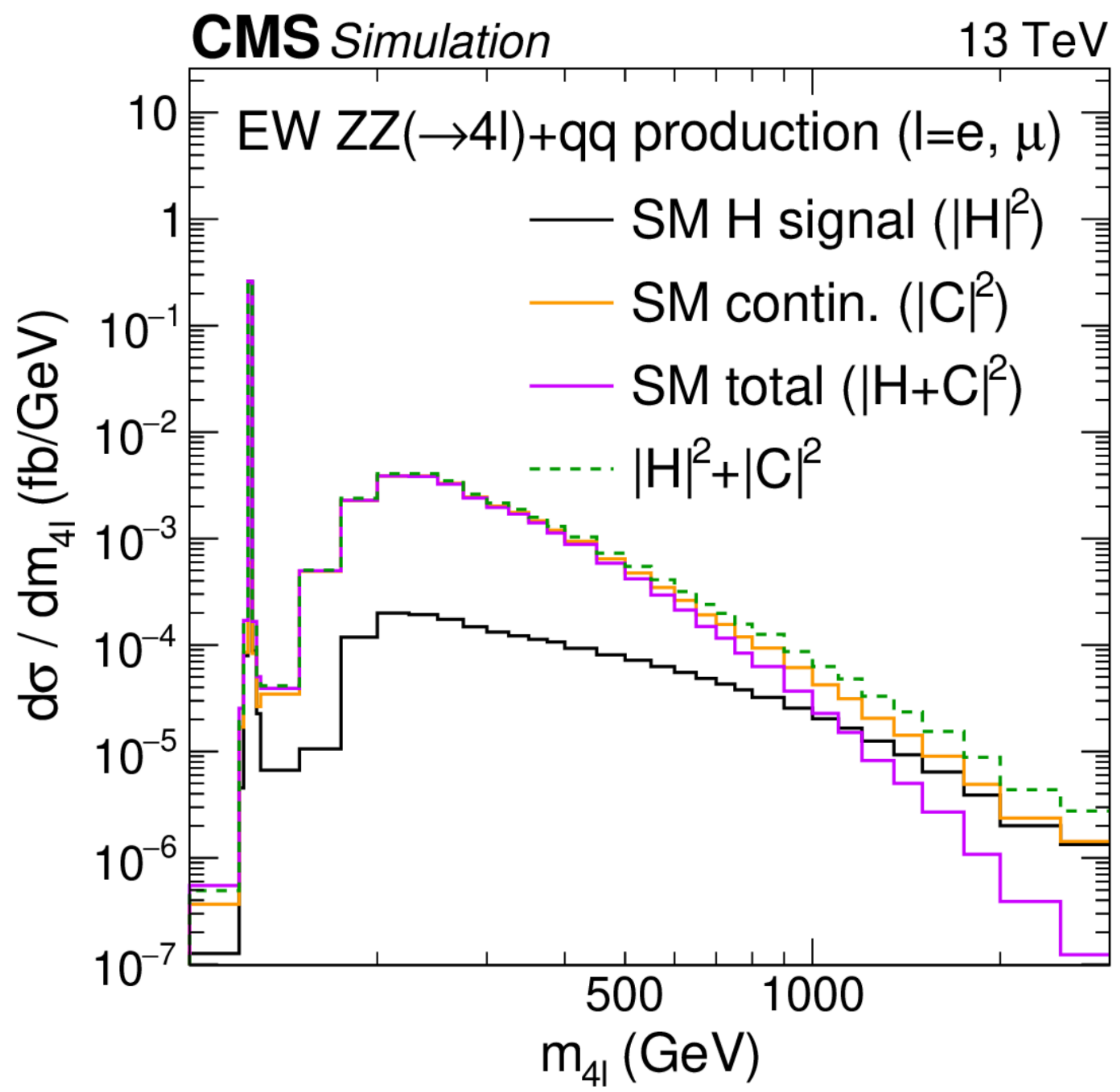
[https://arxiv.org/abs/2202.06923]

Higgs width

- Two ways to access Higgs width
  - Direct mass measurement
    - Limited by experimental resolution to around 1-2 GeV
  - Indirect methods exist, p.ex. using off-shell signal strength offshell: away from the peak
    - on-shell cross section depends on width, off-shell does not ⇒ ratio is sensitive to width!
  - Latest CMS result:

$$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV}$$

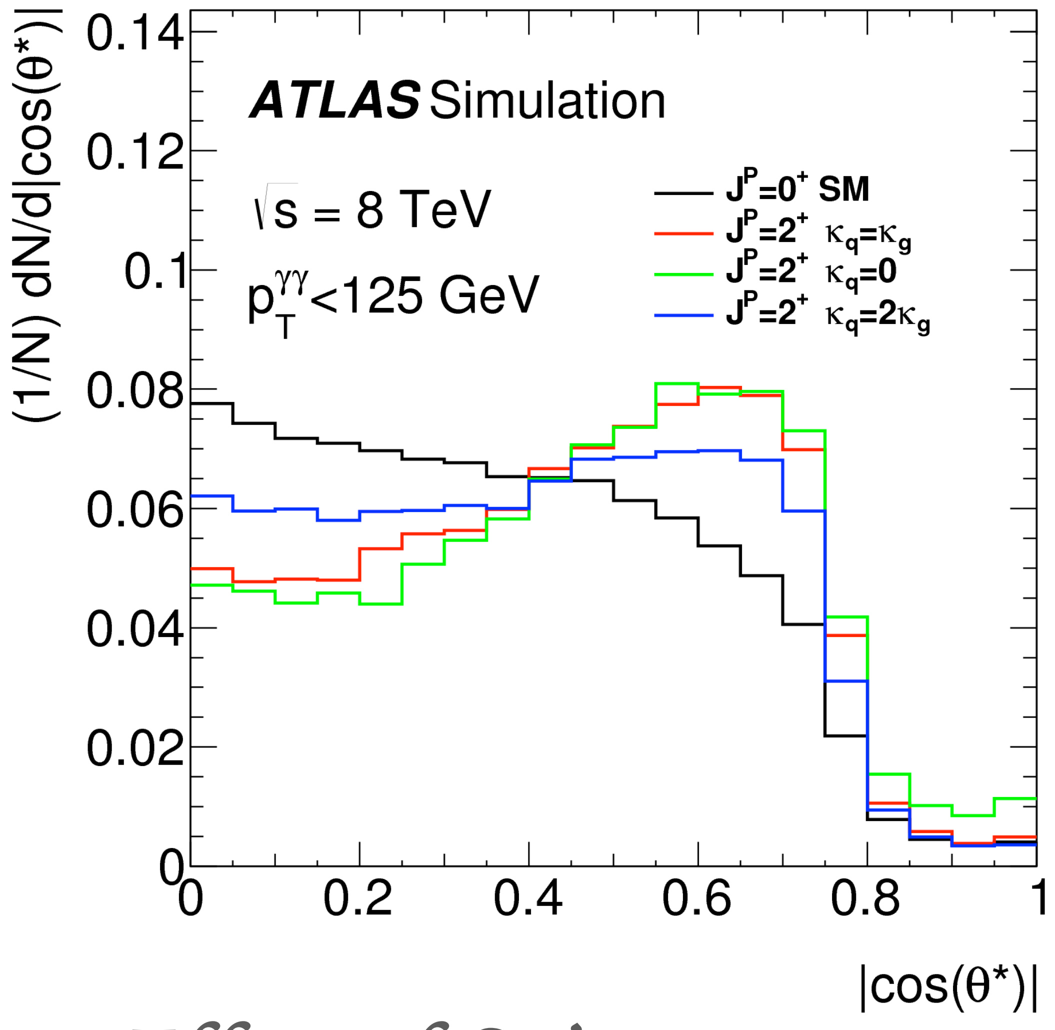




[Eur. Phys. J. C 75 (2015) 476]

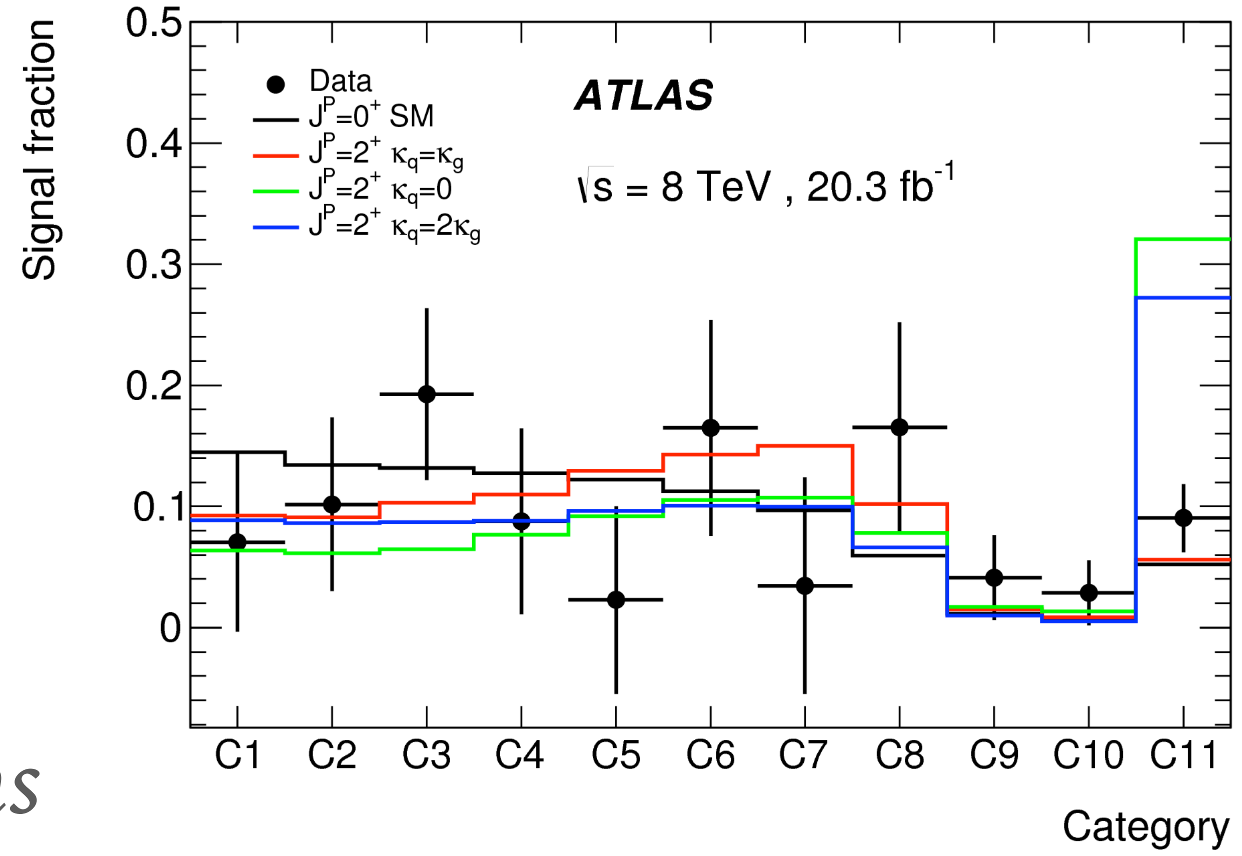
Spin and CP

- **Spin** (SM = 0)
  - Spin 1 excluded using ZZ, WW decays (and by the fact that Higgs decays into photons)
  - Spin 2 excluded for a number of different tensor structures (~ 99.9%)
    => Spin 0 as predicted for the SM Higgs



Effect of Spin on |cosθ| of the two photons*

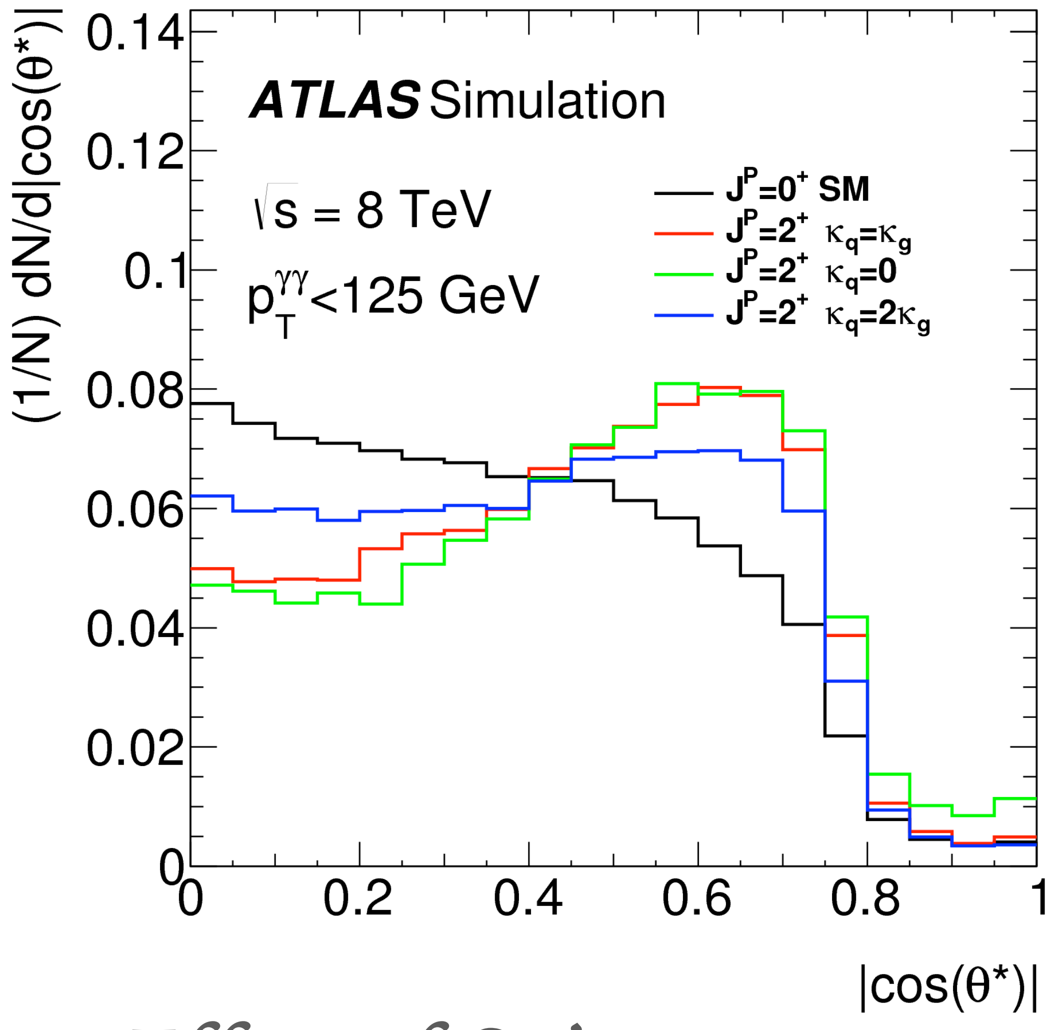
$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



[Eur. Phys. J. C 75 (2015) 476]

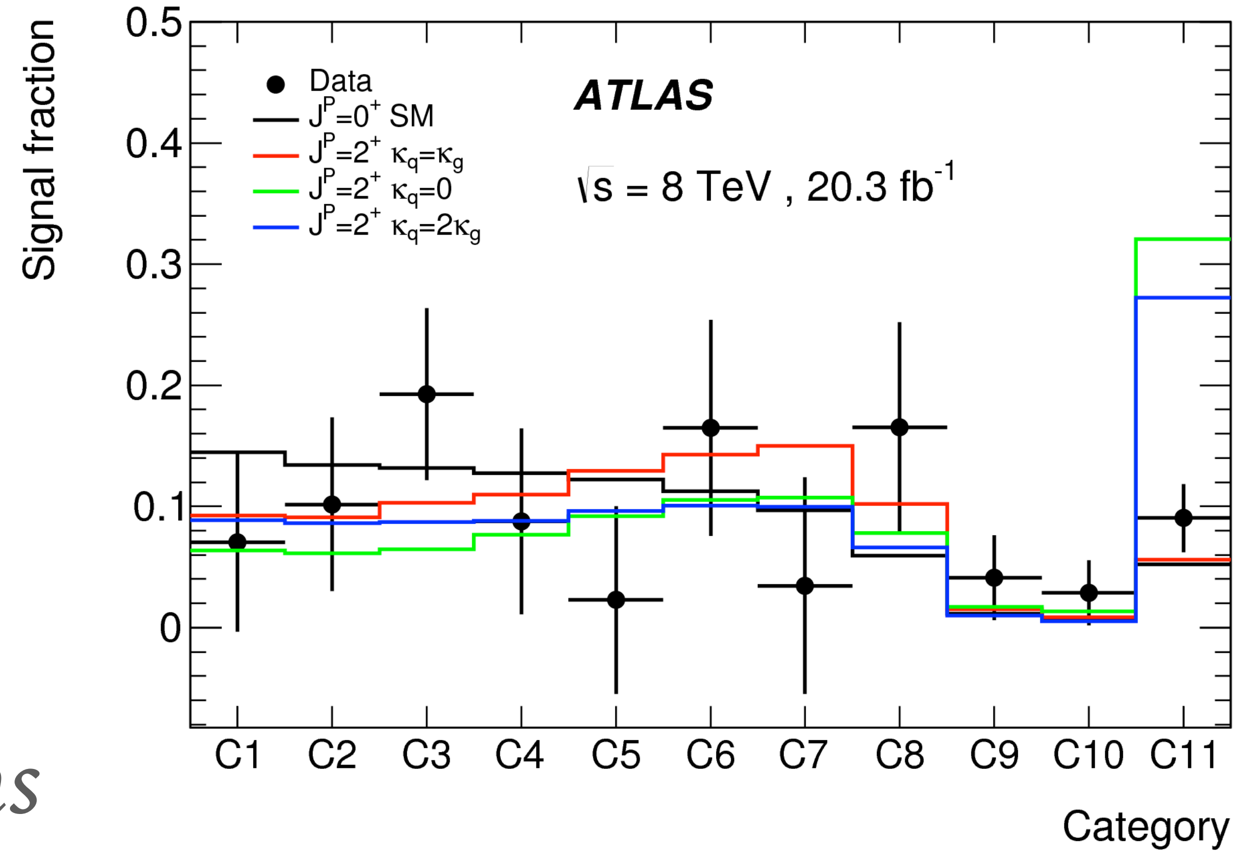
Spin and CP

- **Spin** (SM = 0)
  - Spin 1 excluded using ZZ, WW decays (and by the fact that Higgs decays into photons)
  - Spin 2 excluded for a number of different tensor structures (~ 99.9%)
    => Spin 0 as predicted for the SM Higgs

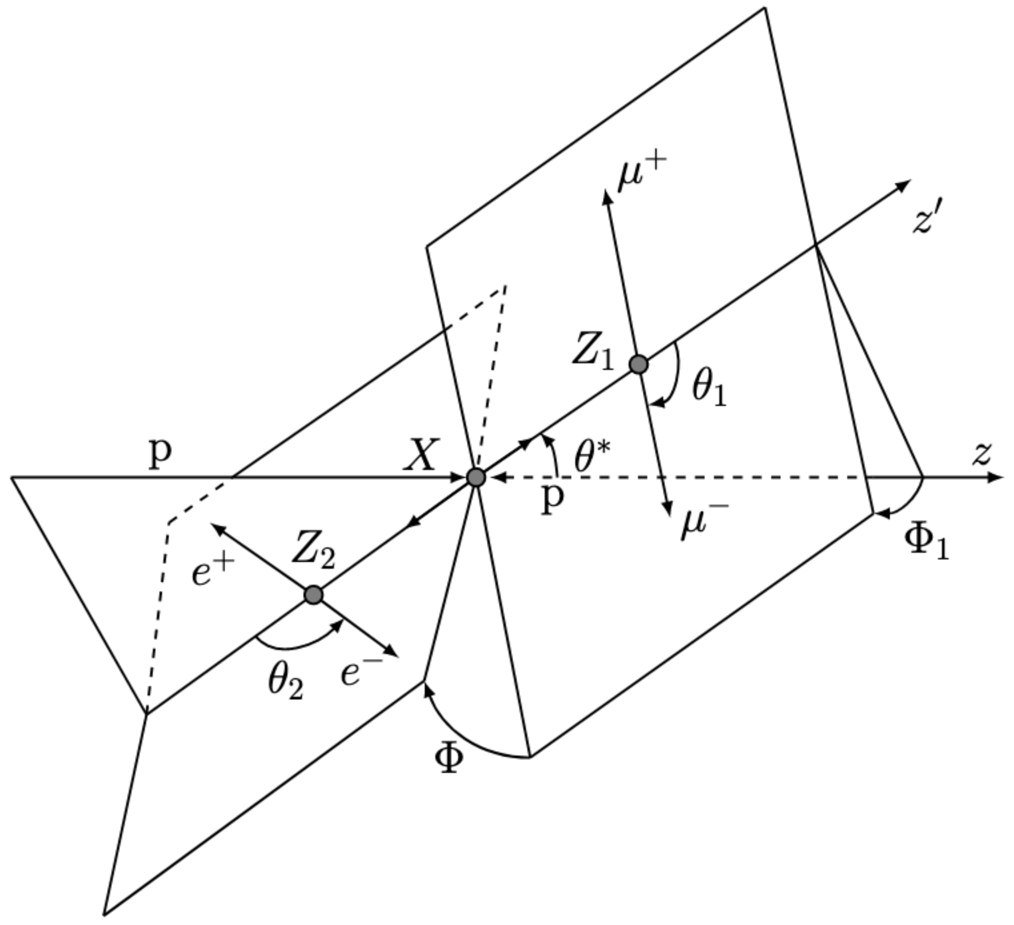


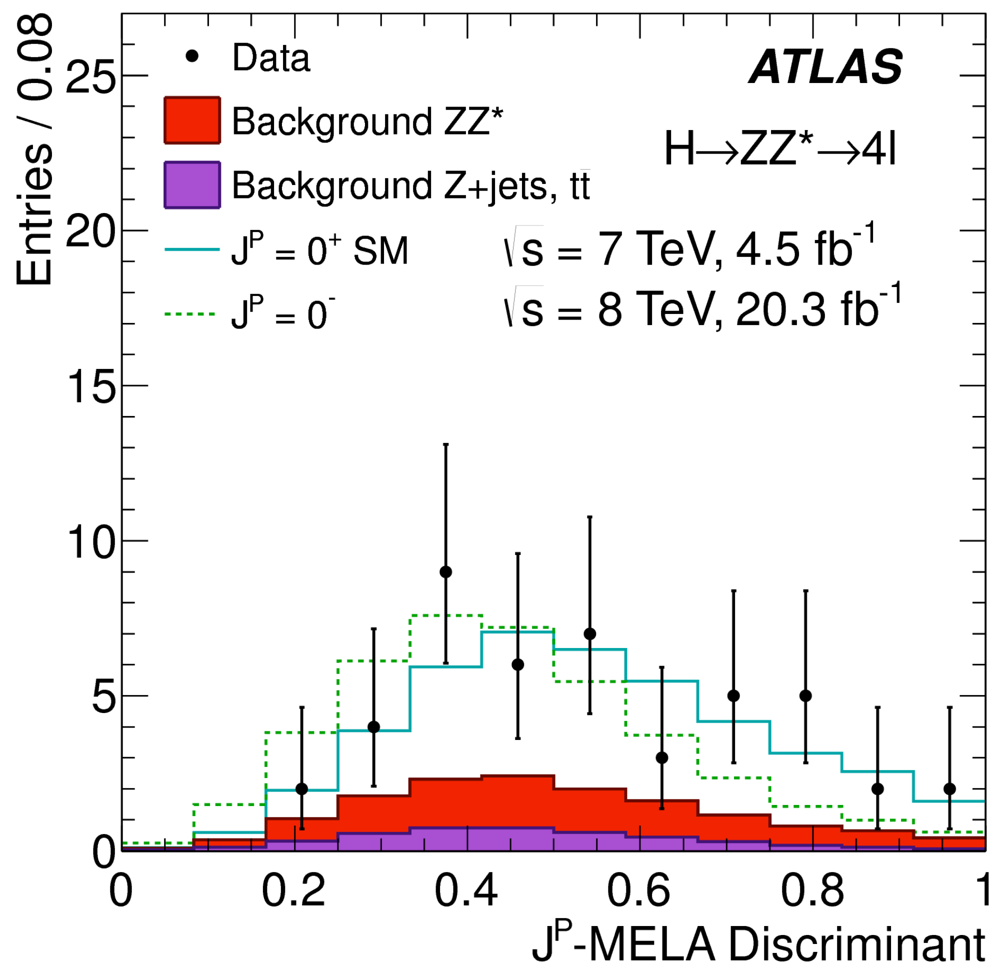
Effect of Spin on |cosθ| of the two photons*

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



- **Parity** (SM: even)
  - Parity odd excluded at > 99.9% (ATLAS, CMS) Admixtures (CP even and CP odd couplings) still possible (fermion channel play important role in these studies!)



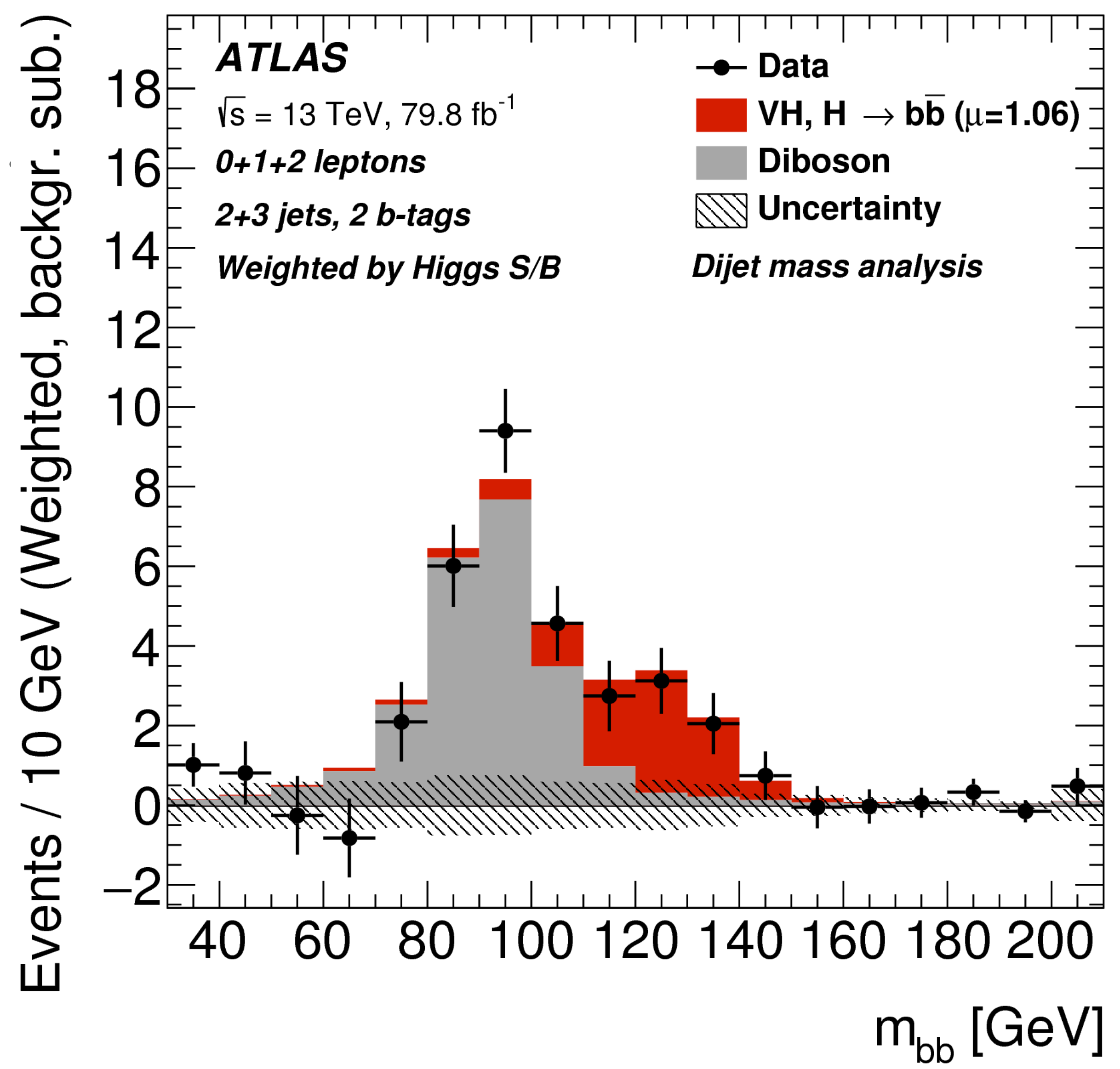


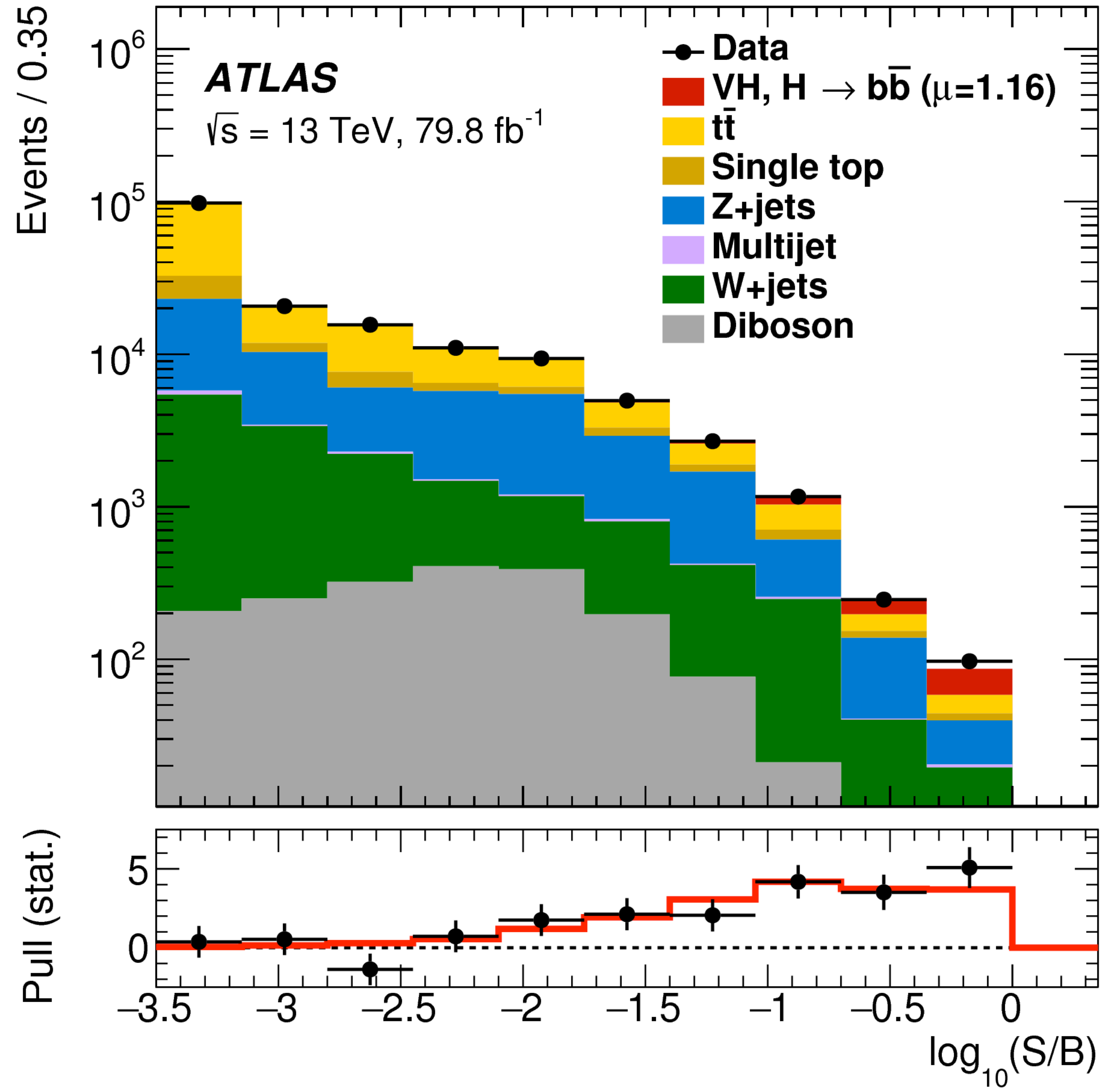
Variables can be defined in the H→ZZ decay that are sensitiv to spin and parity

Higgs to bbar

- Highest branching ratio of Higgs decays to two b-quarks
  - large SM backgrounds
  - statistical combination of various "channels" or "regions"
  - often machine learning techniques used
- Analysis based on three main channels targeting WH and ZH production:
  - 0 leptons ($Z \rightarrow \nu\nu$)
  - 1-lepton ($W \rightarrow \mu\nu$, $e\nu$)
  - 2-leptons ($Z \rightarrow \mu\mu$, ee)

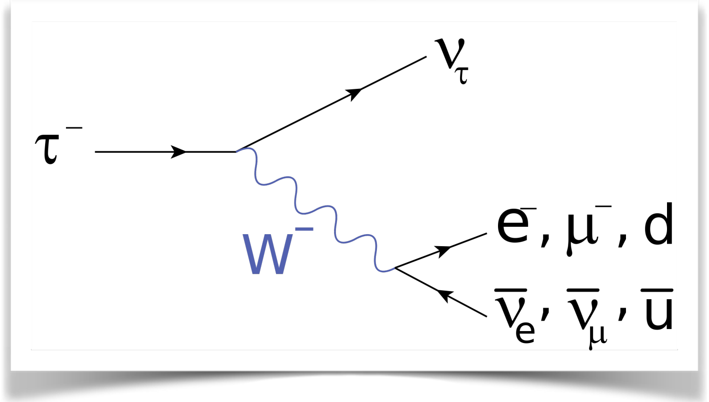
Analysis is sensitive to $Z \rightarrow bb$, can be used to validate the techniques





[arXiv:2201.08269]

Higgs to $\tau\tau$



- τ leptons are complicated to reconstruct
  - Various decay modes all including neutrinos

leptonic

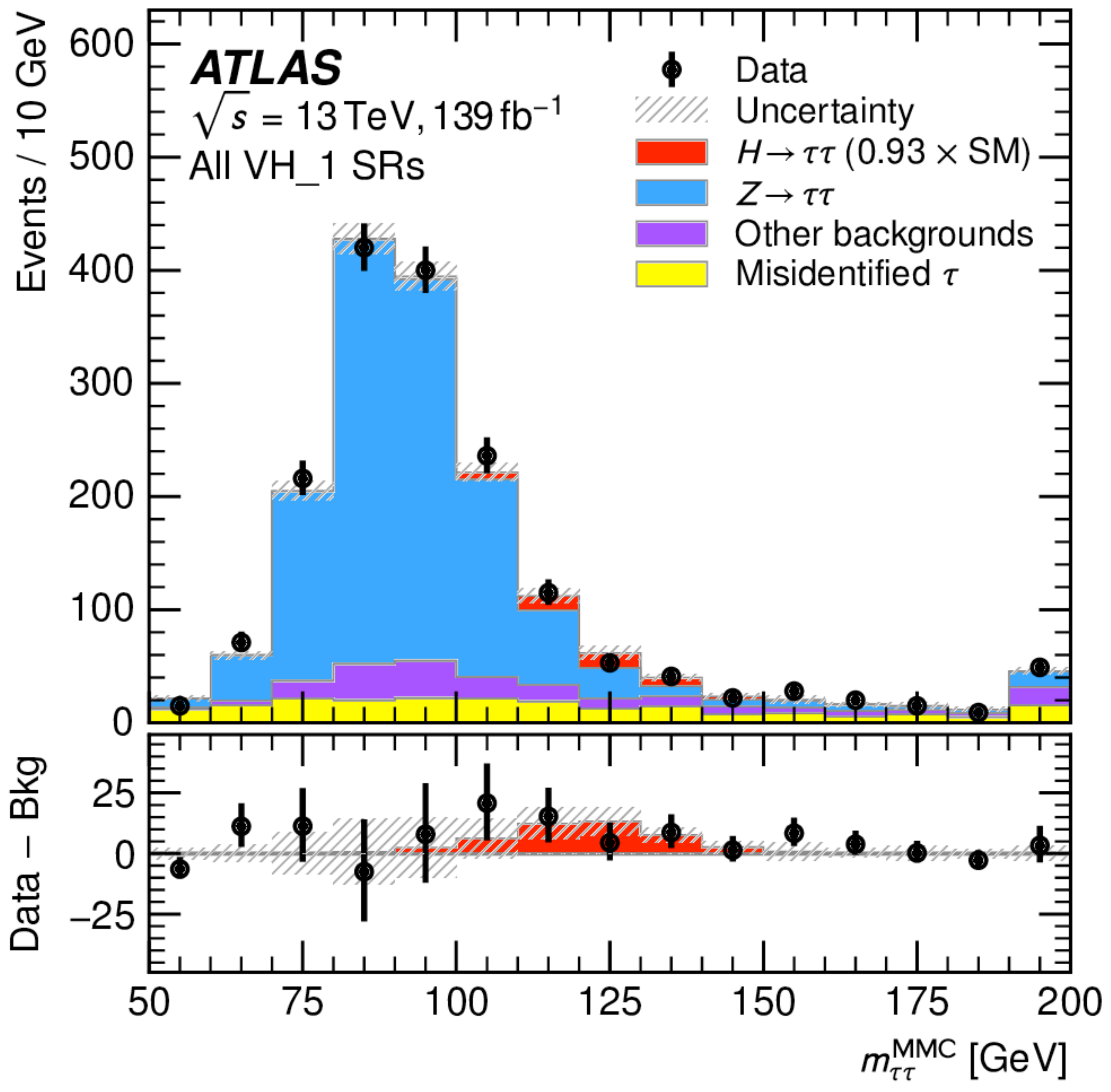
τ^-	$\rightarrow$	$e^- + \bar{\nu}_e + \nu_\tau$	$(17{,}82 \pm 0{,}04)\ \%$
τ^-	$\rightarrow$	$\mu^- + \bar{\nu}_\mu + \nu_\tau$	$(17{,}39 \pm 0{,}04)\ \%$

hadronic

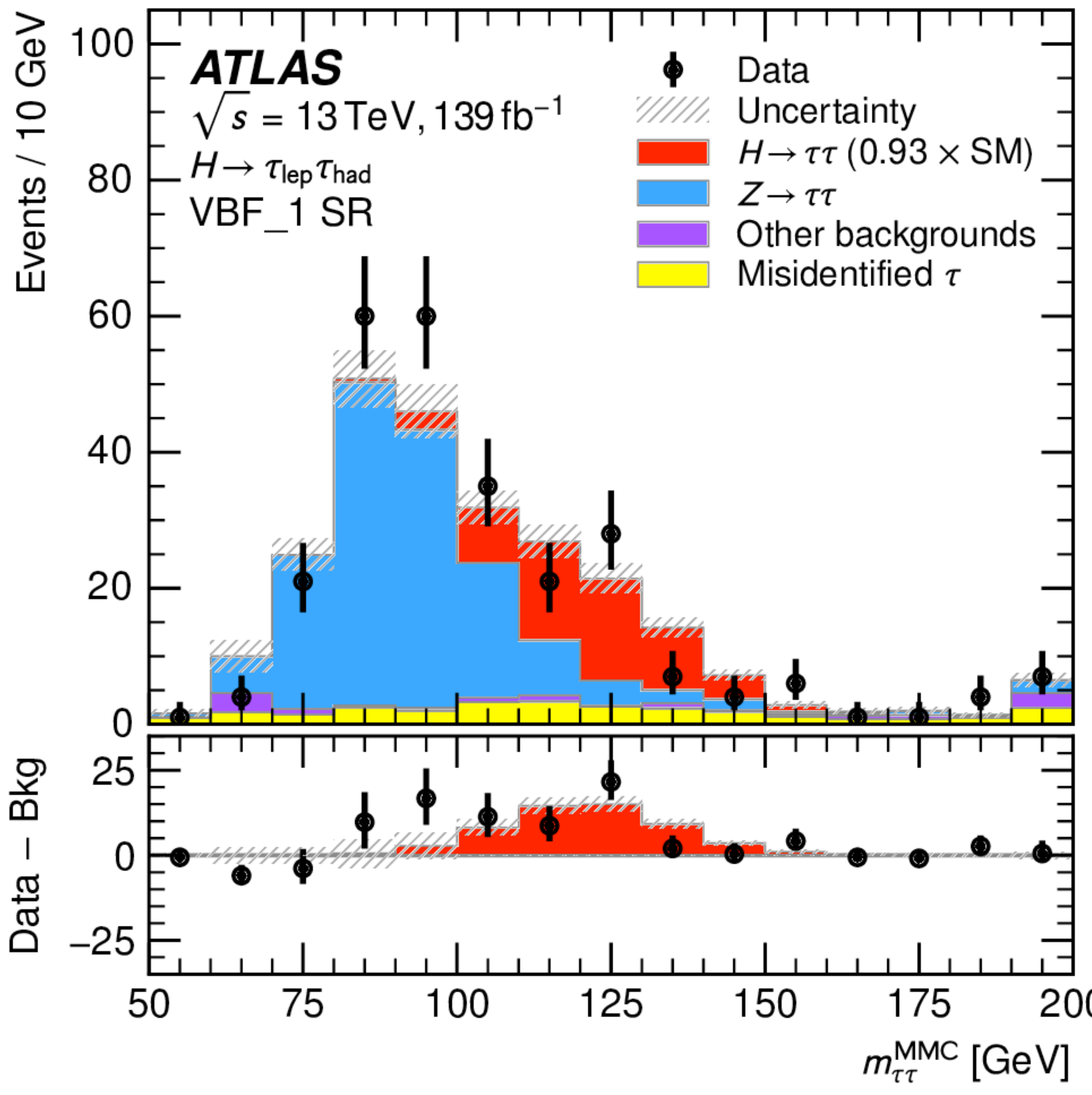
τ^-	$\rightarrow$	$\pi^- + \pi^0 + \nu_\tau$	$(25{,}49 \pm 0{,}09)\ \%$
τ^-	$\rightarrow$	$\pi^- + \nu_\tau$	$(10{,}82 \pm 0{,}05)\ \%$
τ^-	$\rightarrow$	$2\pi^- + \pi^+ + \nu_\tau$	$(9{,}31 \pm 0{,}05)\ \%$
τ^-	$\rightarrow$	$\pi^- + 2\pi^0 + \nu_\tau$	$(9{,}26 \pm 0{,}10)\ \%$

- Analysis through statistical combination of a variety of channels
- Large backgrounds from **Z+jets production with Z $\rightarrow\tau\tau$** need to be understood
  - Embedding techniques employed where muons in data (Z → μ μ) are replaced by simulated taus

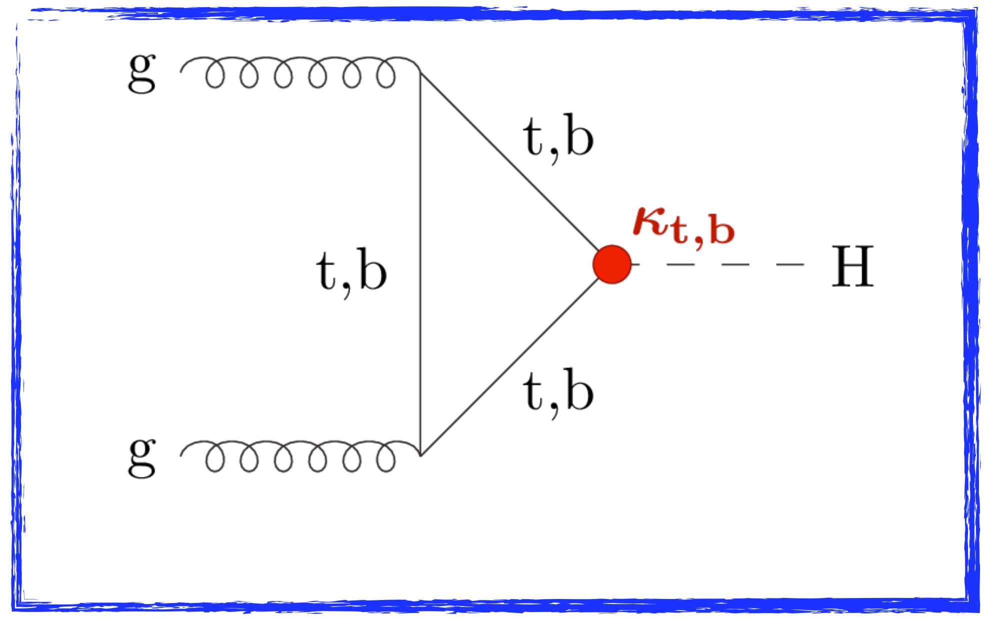
VH all τ



VBF $\tau_{lep}\tau_{had}$

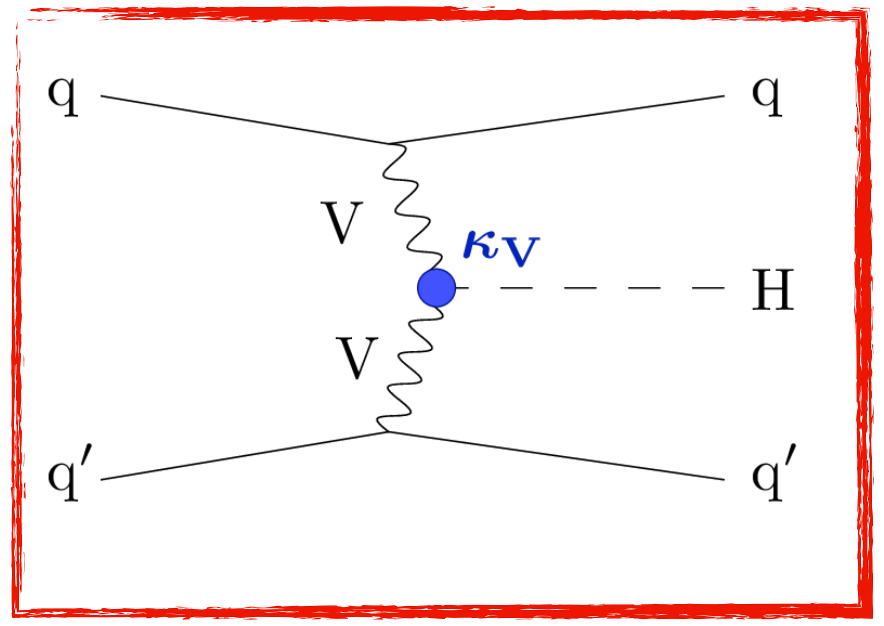


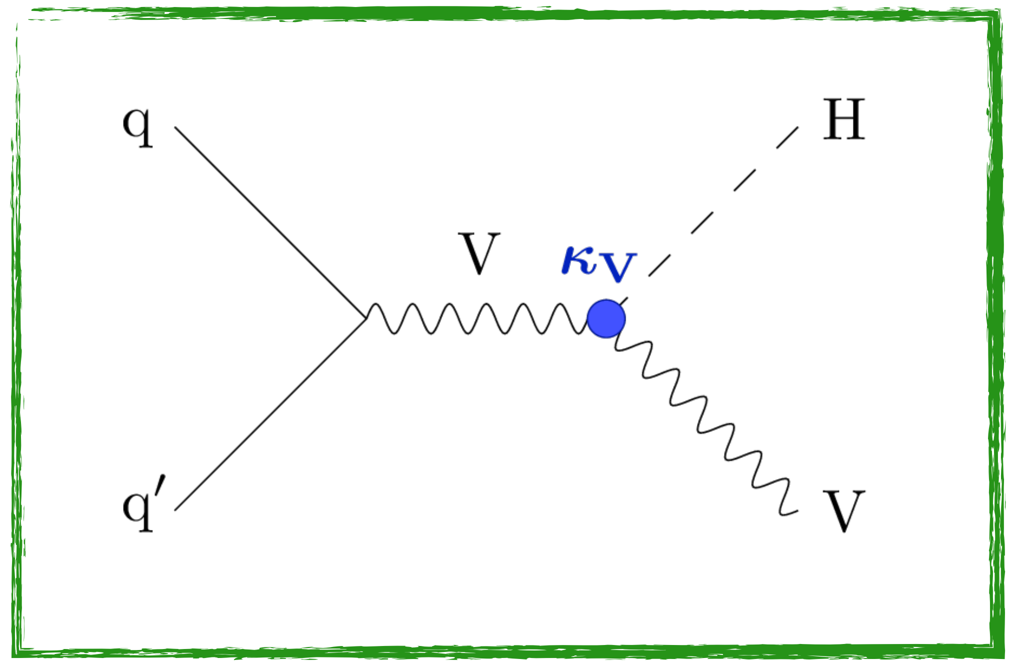
Higgs production modes at the LHC



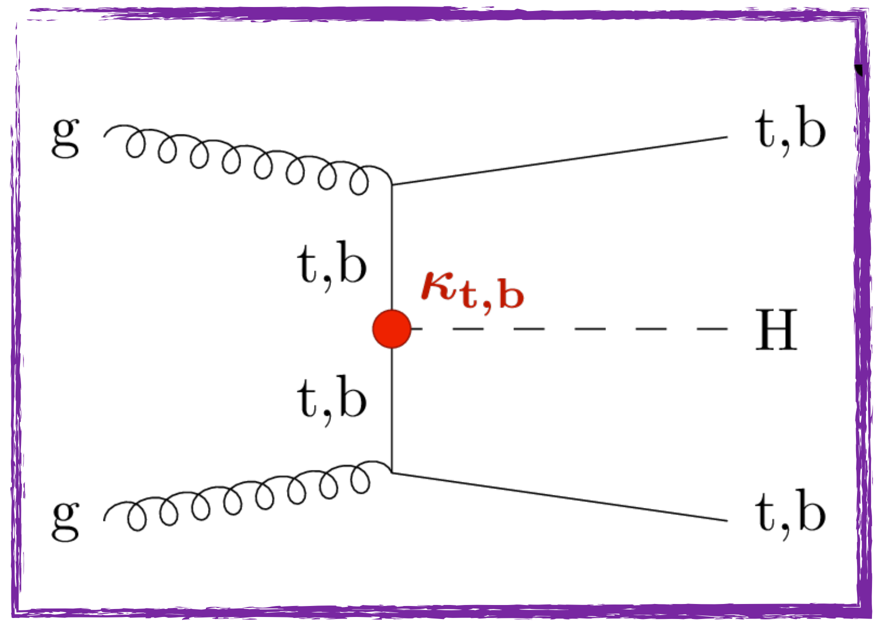
ggF

VBF





Higgs strahlung



ttH

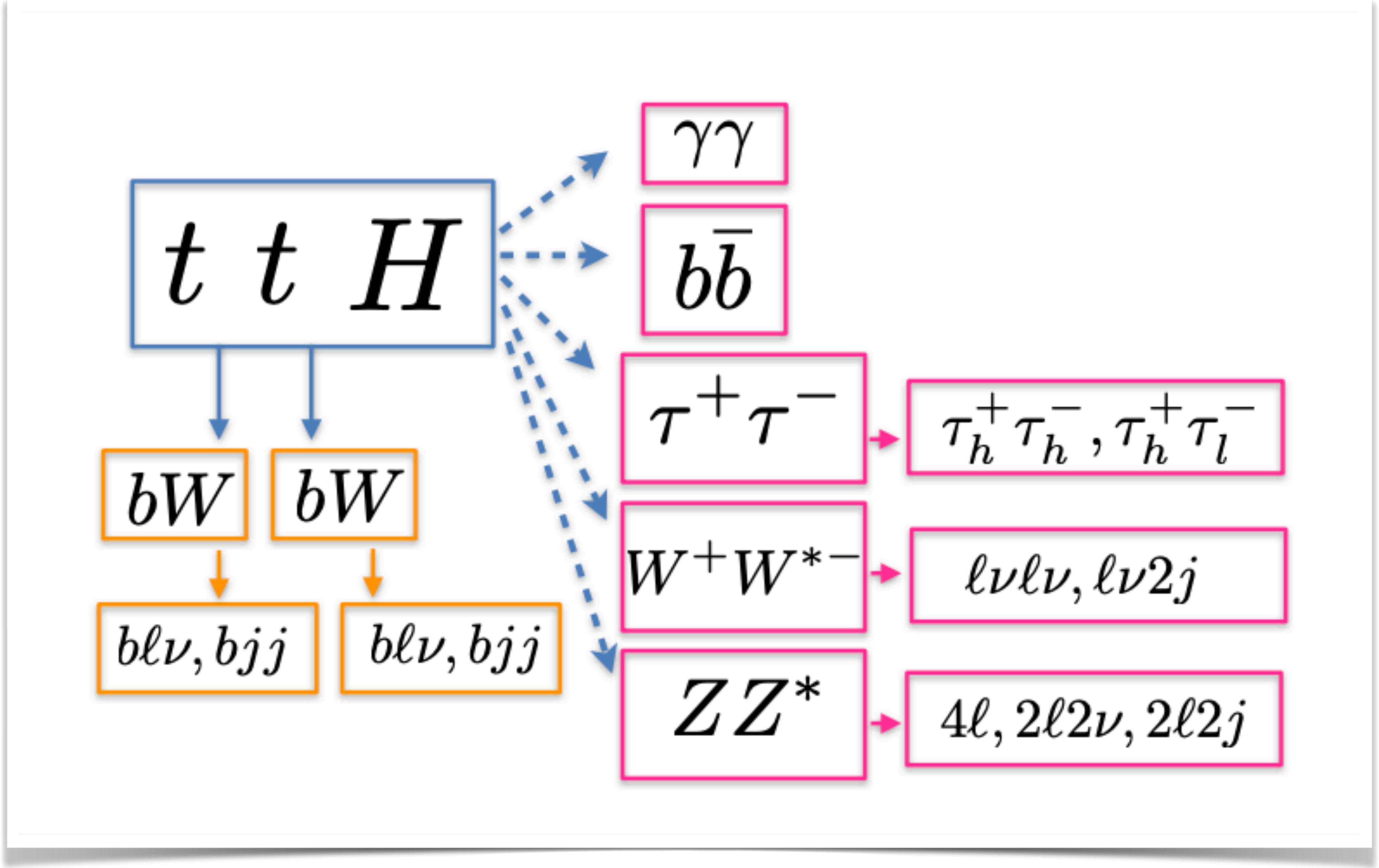
- Most analyses so far were carried out in the **ggF**, **VBF** and **Higgs strahlung (VH)** production modes
- Observation of the **ttH** process would provide direct access to the top Yukawa coupling of the Higgs

ttH: direct probe of the top Yukawa coupling

- Very small production cross section: one of the latest discoveries

- Large number of complex final states: mixture of b-jets, leptons, taus and photons

- Many different channels: many different backgrounds and different systematic uncertainties → excellent way to cross check each other

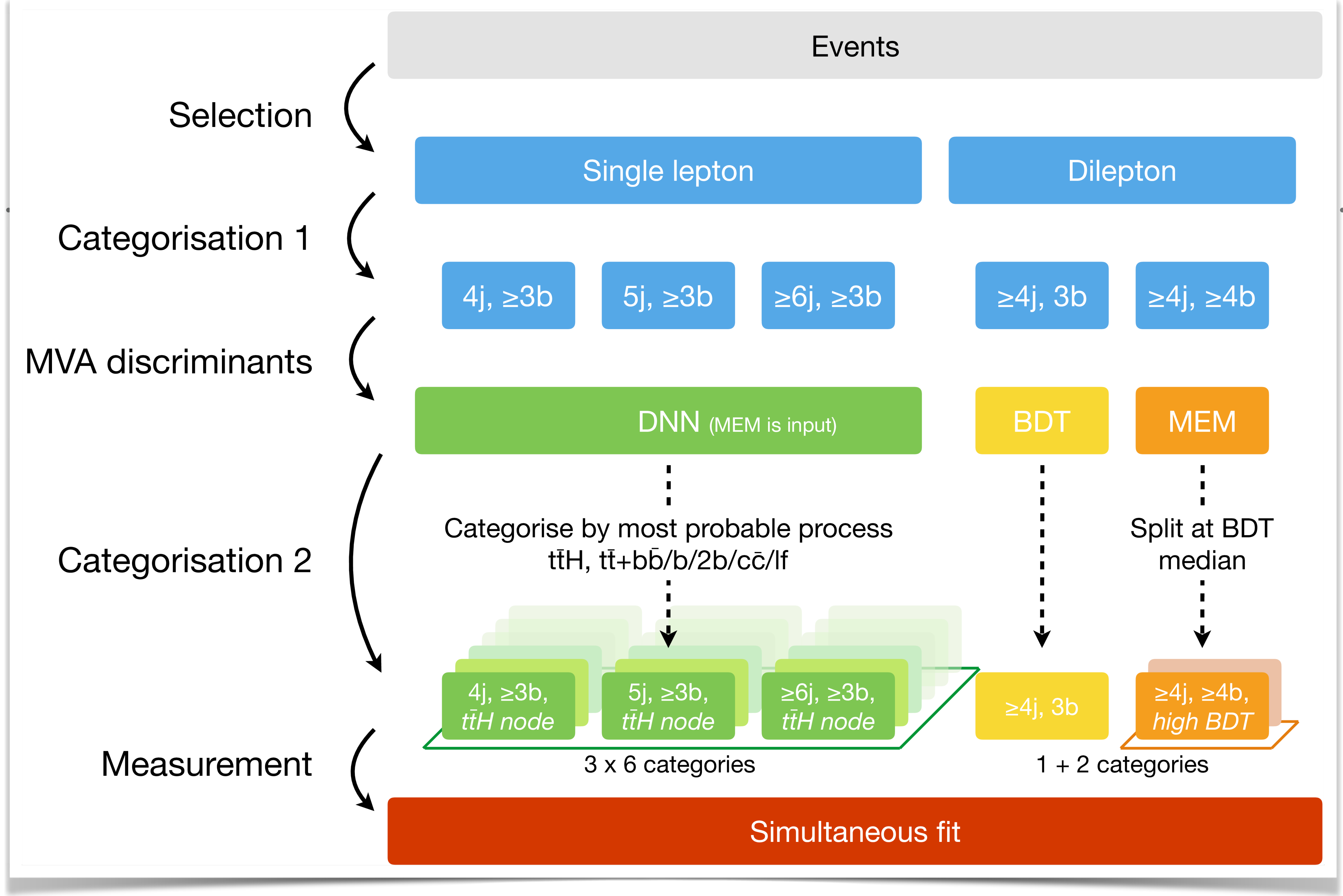


Marumi Kado

[JHEP 03 (2019) 026]

ttH→bb: squeezing the most out of the data

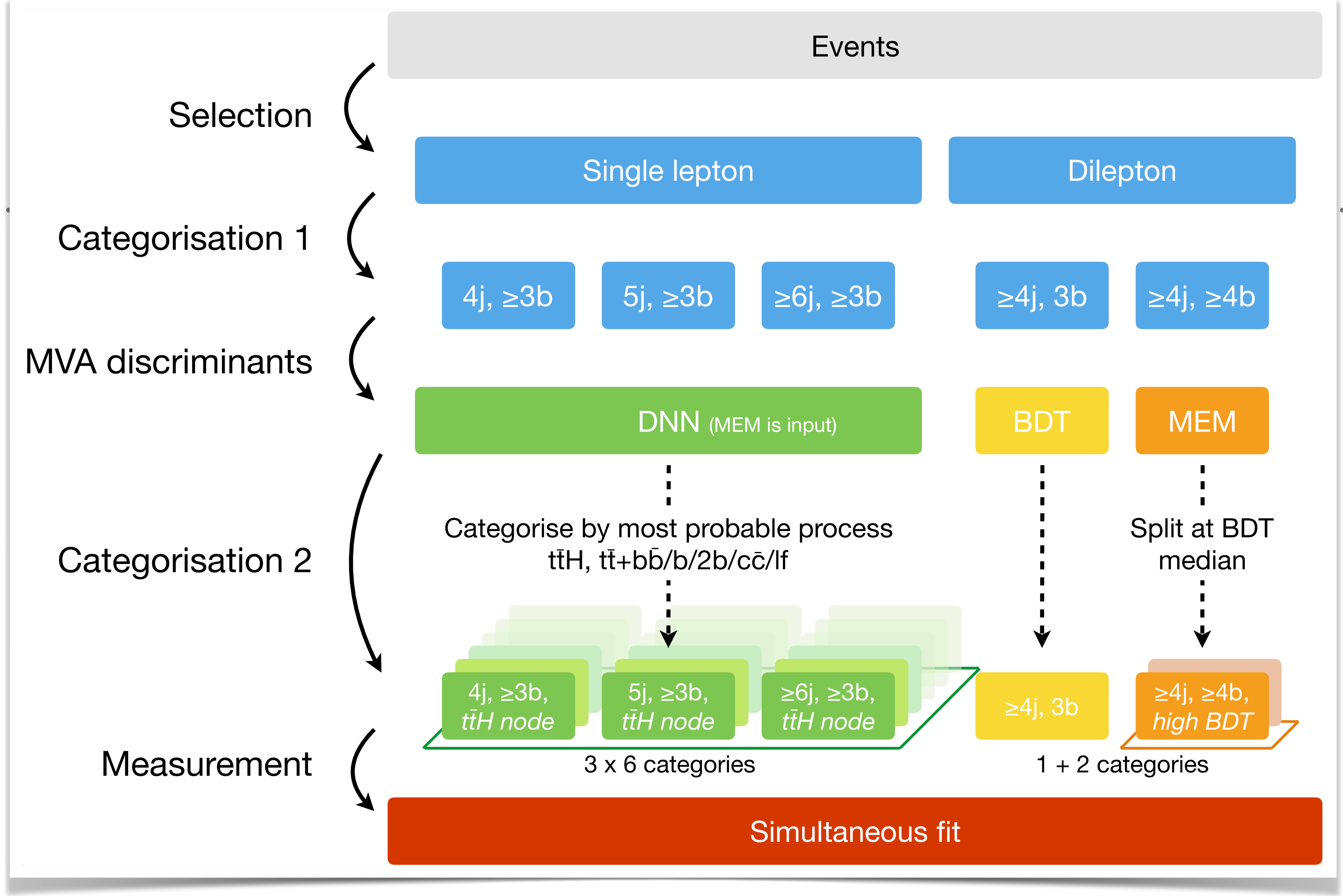
- ➤ Many different event categories
- ➤ Use of sophisticated machine learning techniques
- ➤ Combined fit of various different categories (all statistically independent)
- ➤ SM ttbar + light and heavy flavor are main backgrounds

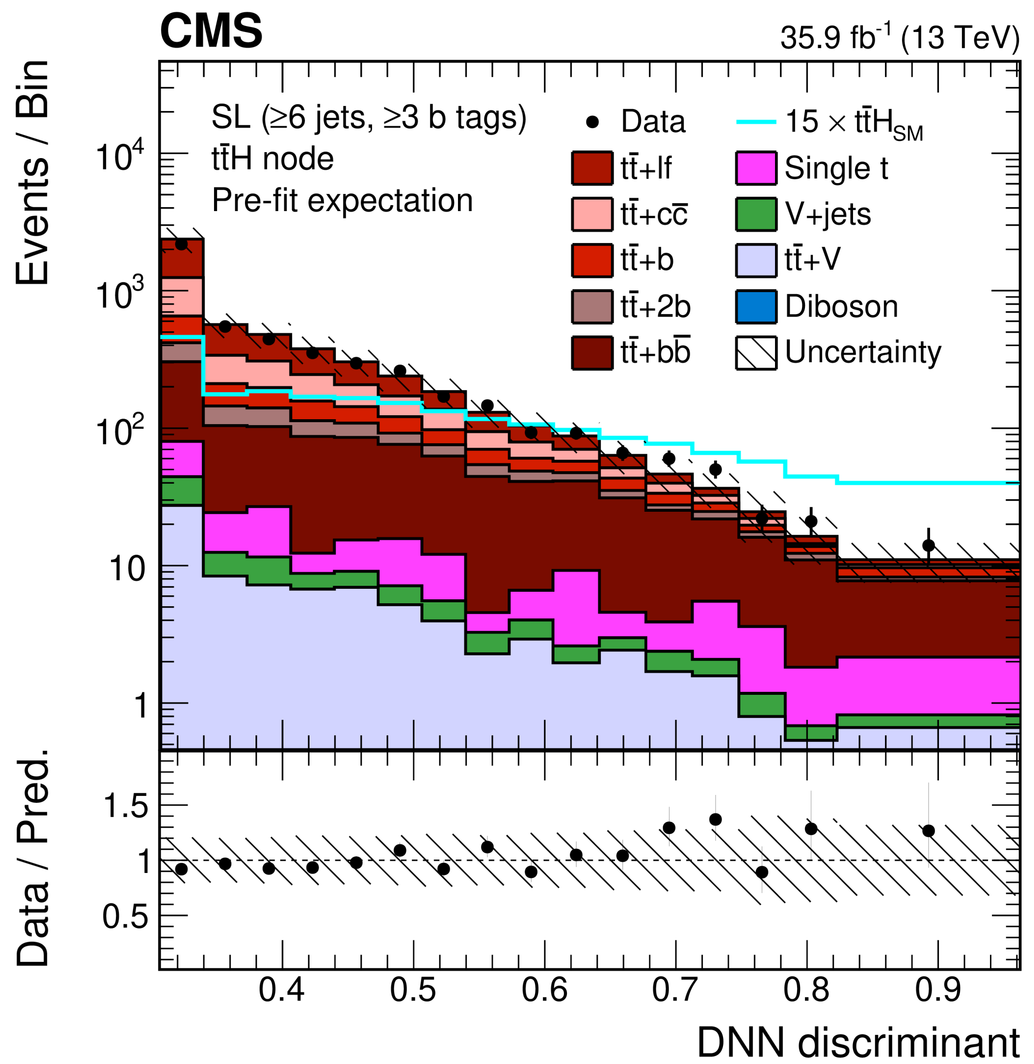


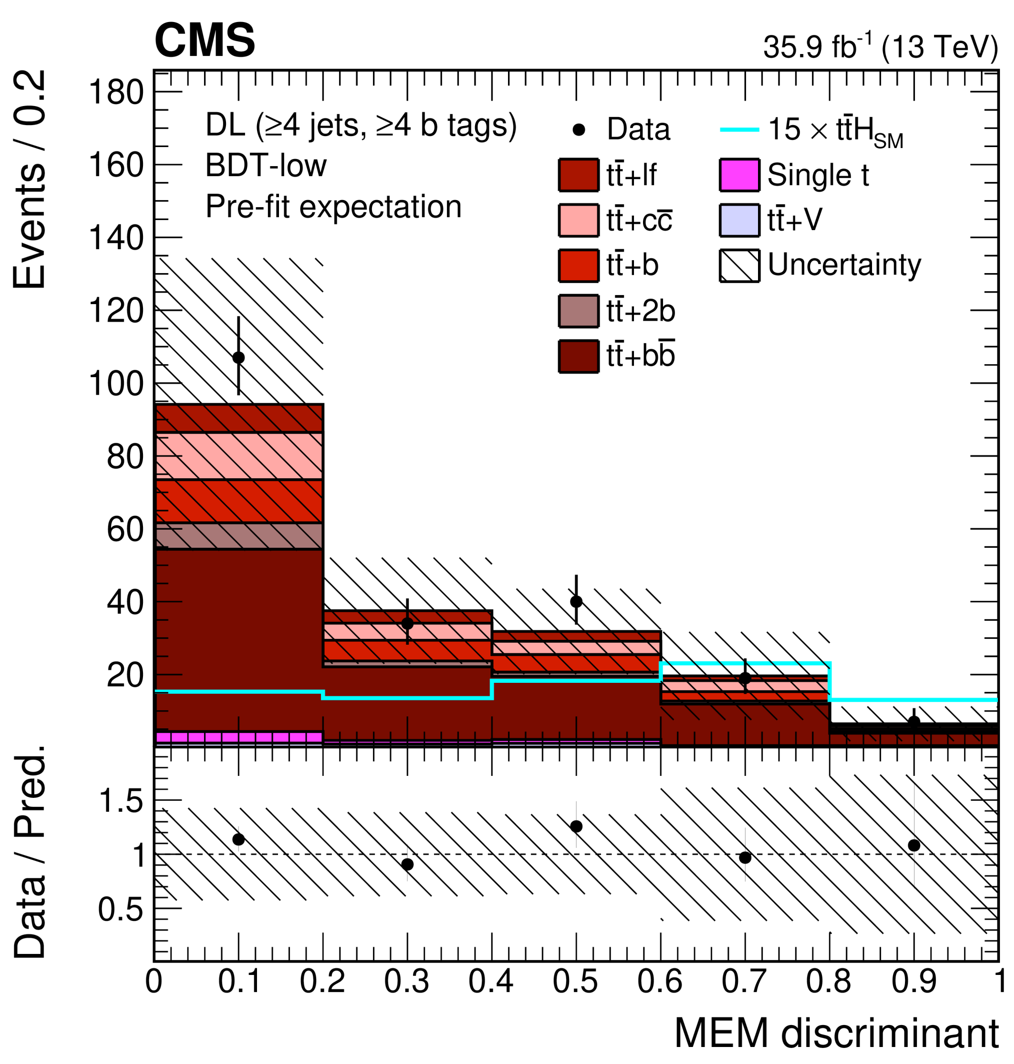
[JHEP 03 (2019) 026]

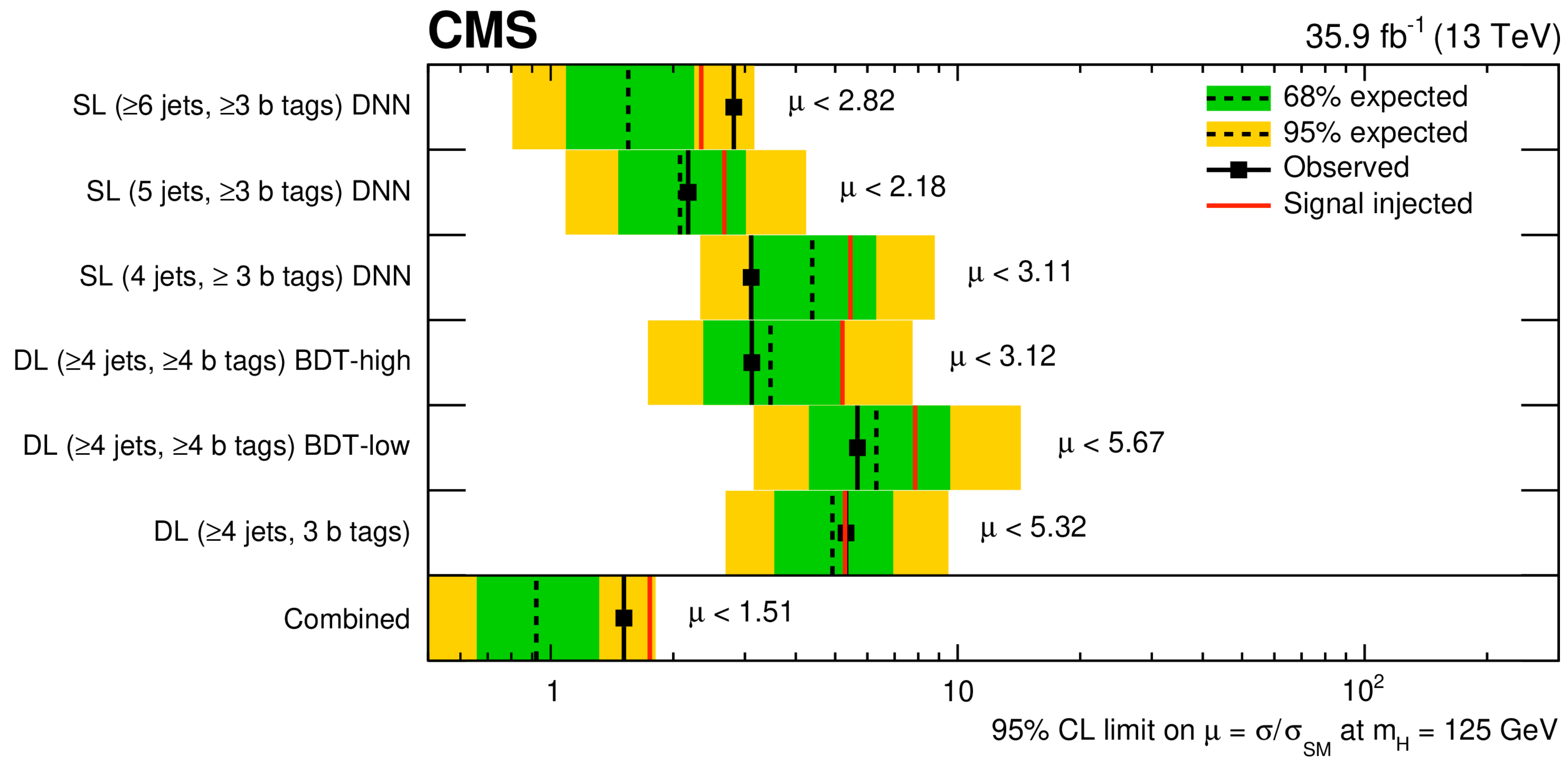
ttH→bb: squeezing the most out of the data

- ➤ Many different event categories
- ➤ Use of sophisticated machine learning techniques
- ➤ Combined fit of various different categories (all statistically independent)
- ➤ SM ttbar + light and heavy flavor are main backgrounds

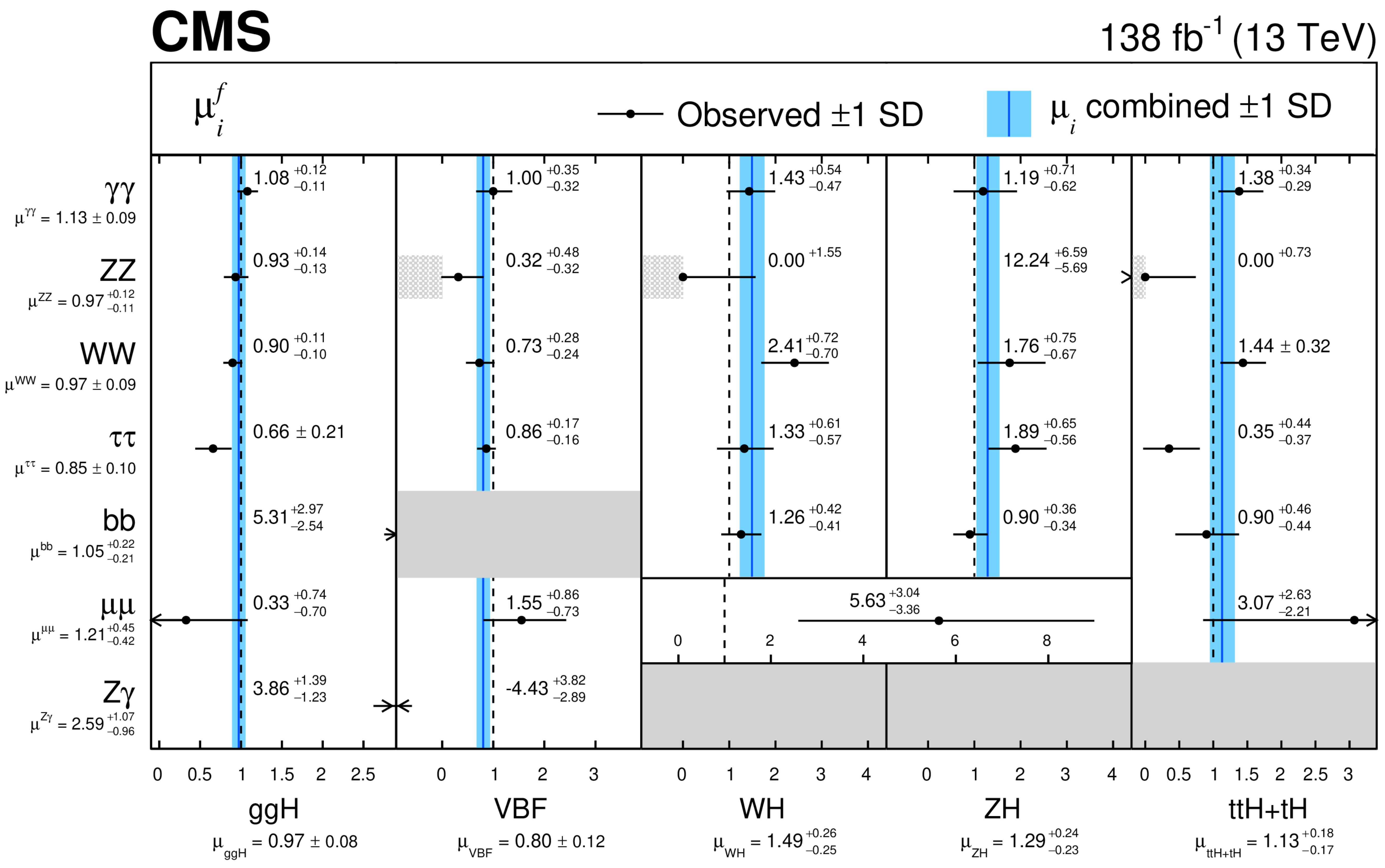


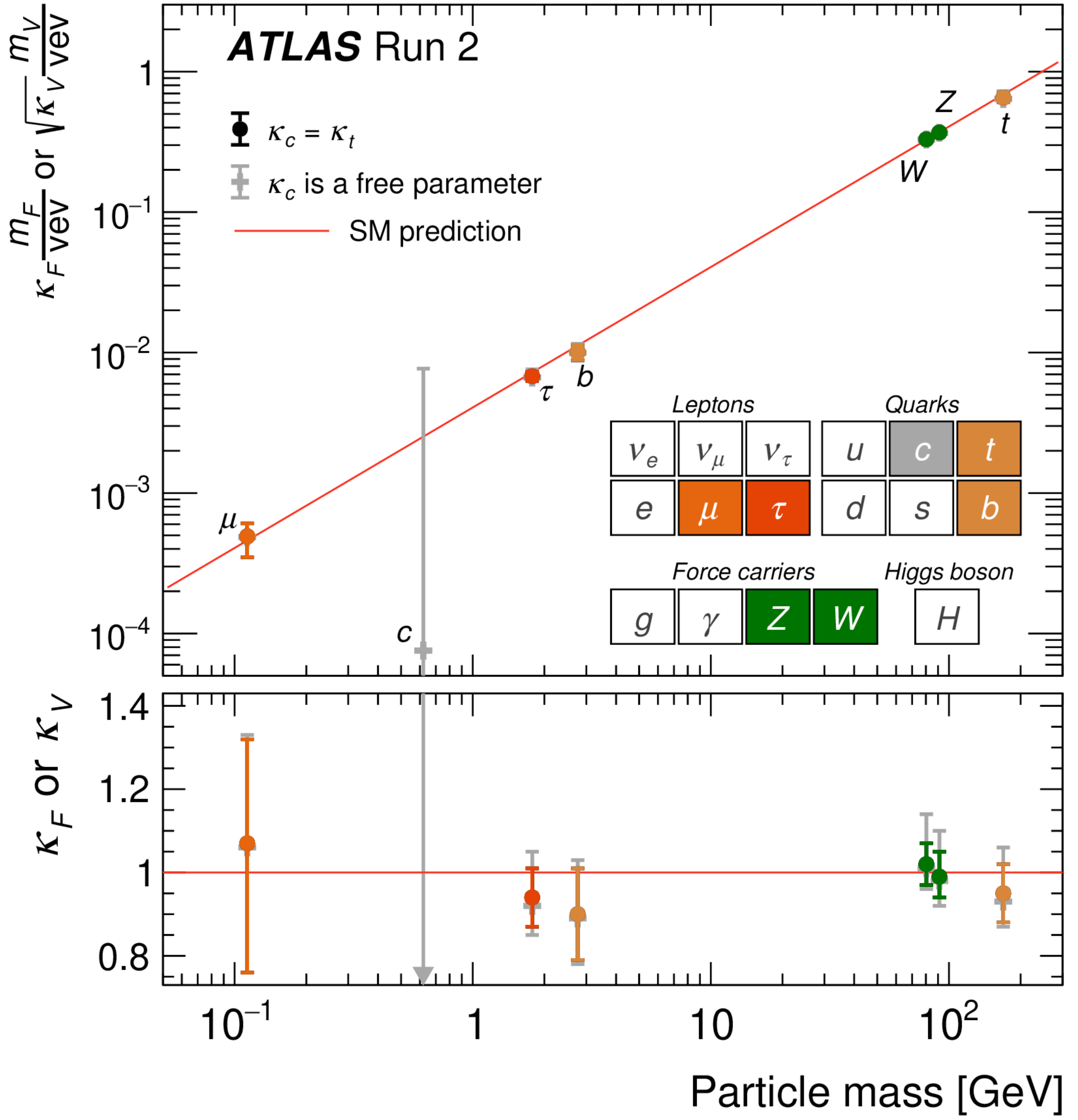






Putting it all together





Almost all production modes established

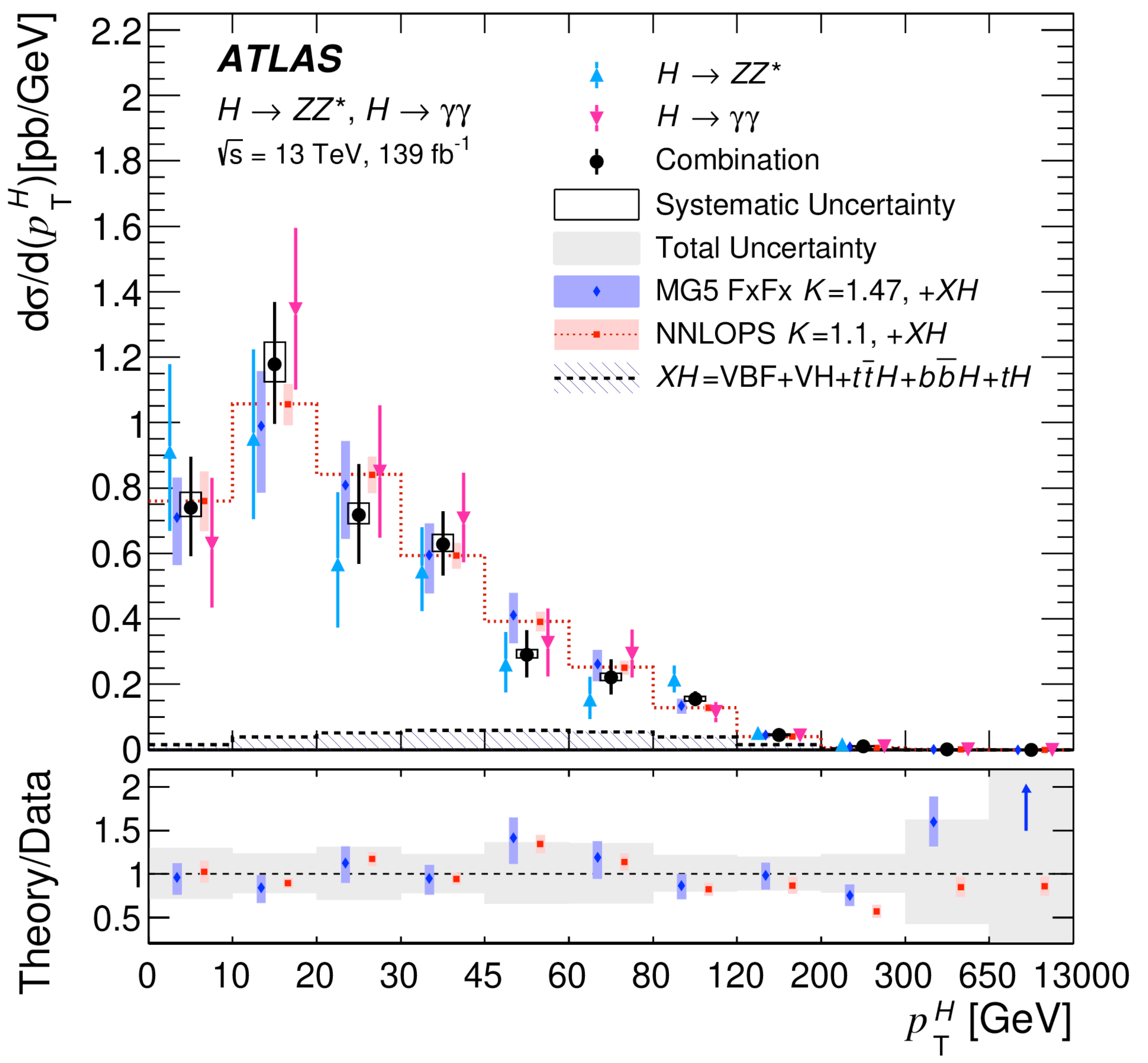
So far all measured couplings consistent with the SM

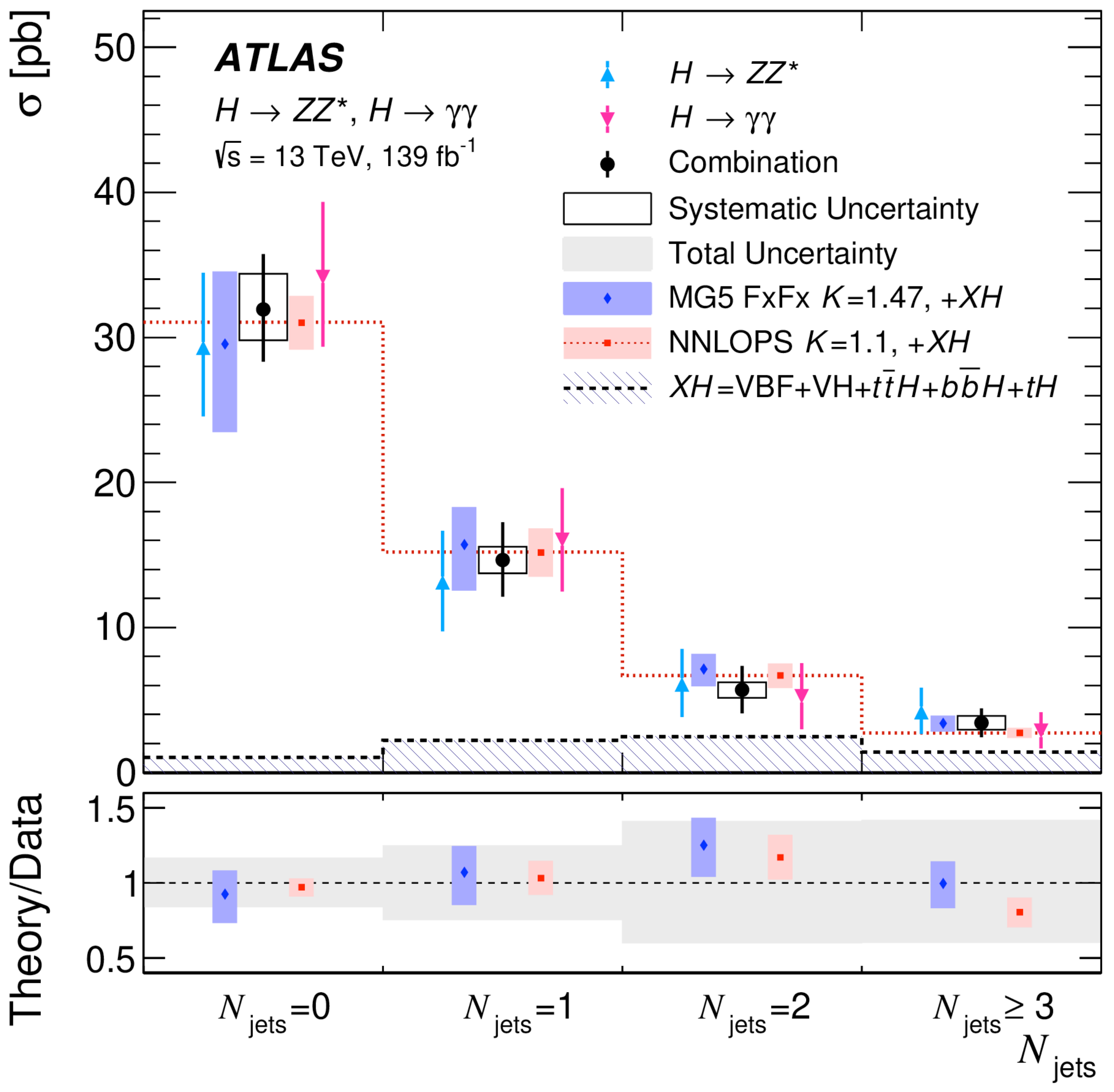
Differential Higgs measurement

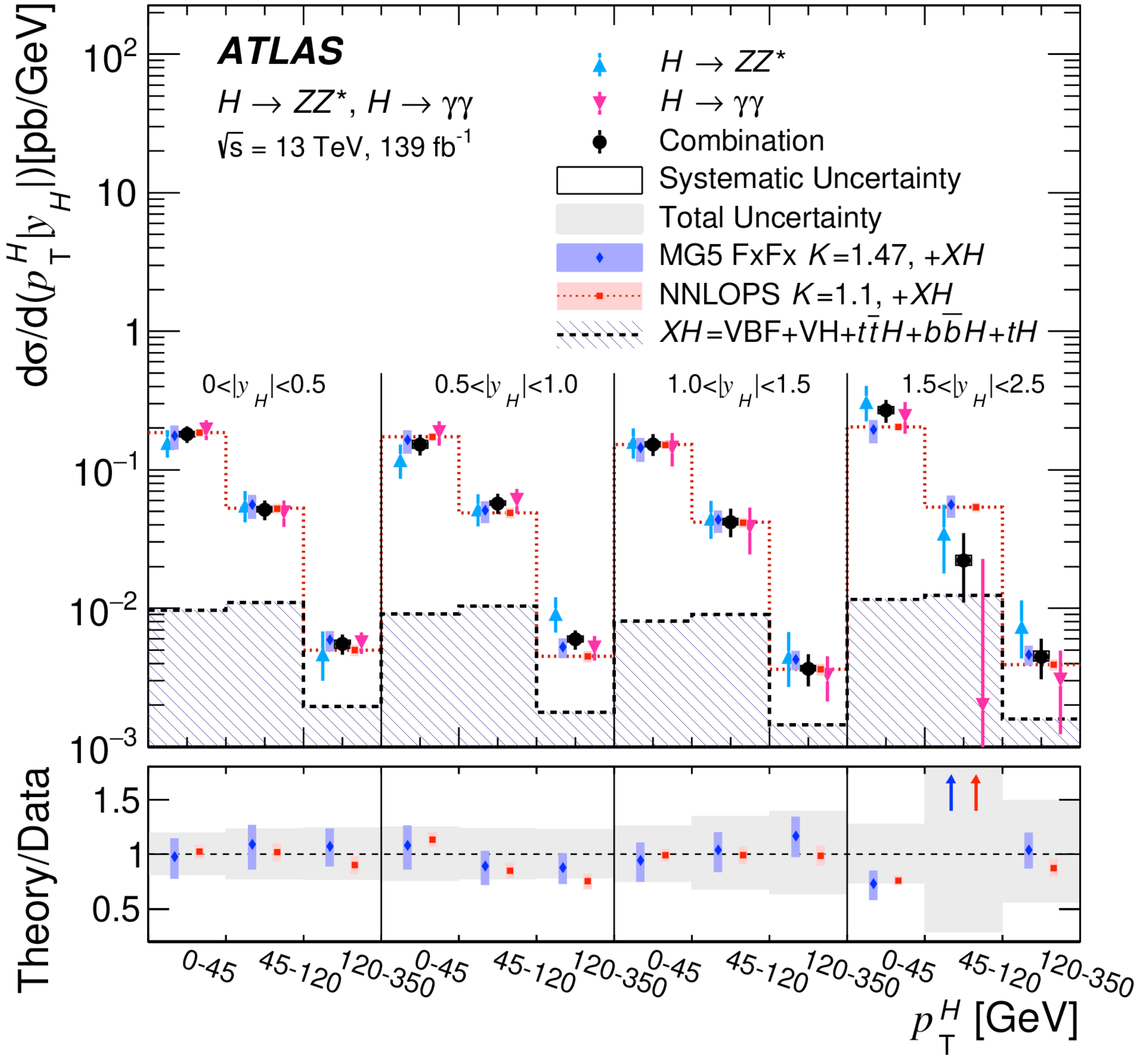
➤ Enough Higgs candidates collected to perform differential measurements for a variety of observables

2-dimensional

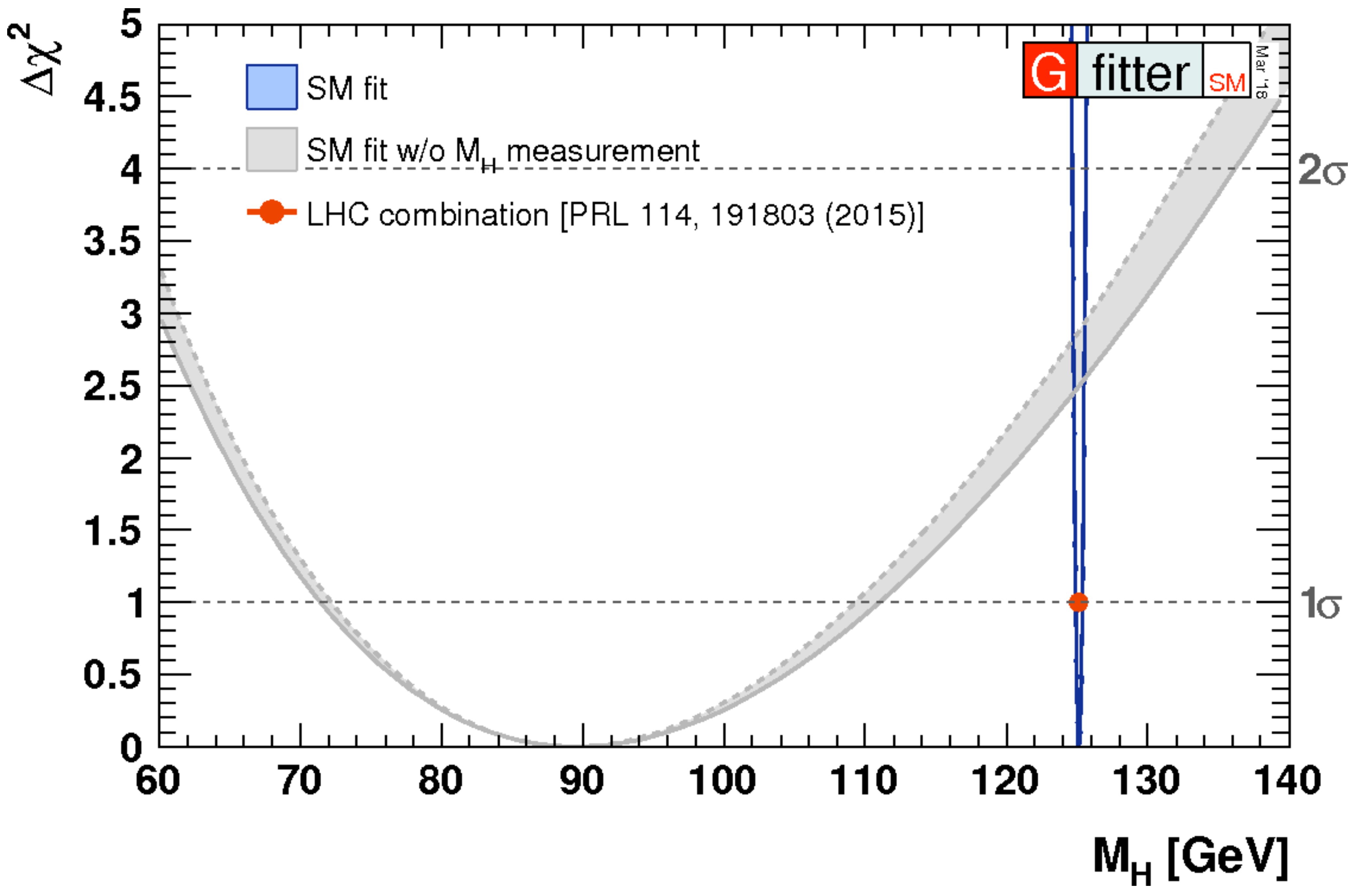
1-dimensional



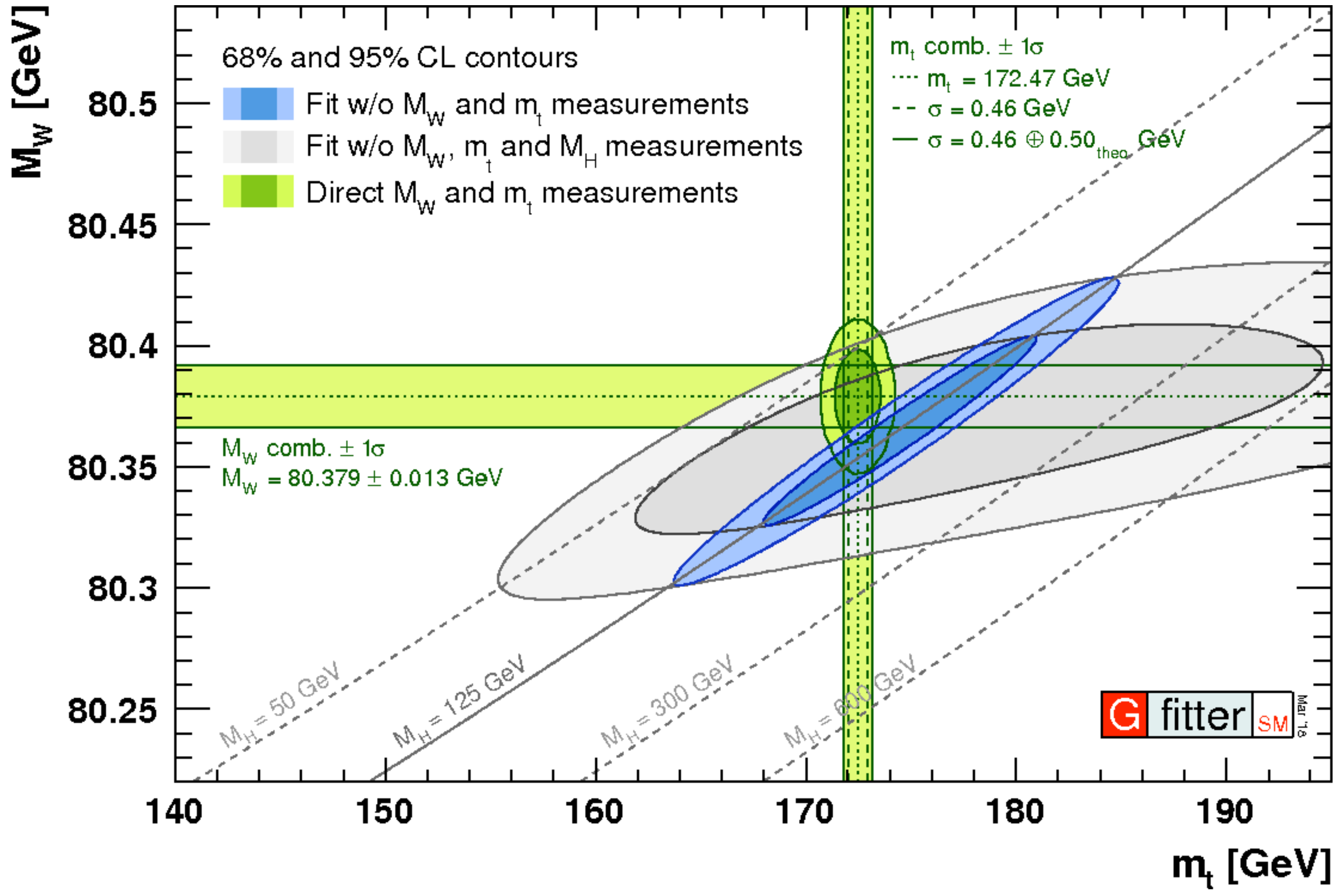




Standard Model fits after the Higgs discovery: 2022



Higgs mass measured with excellent precision

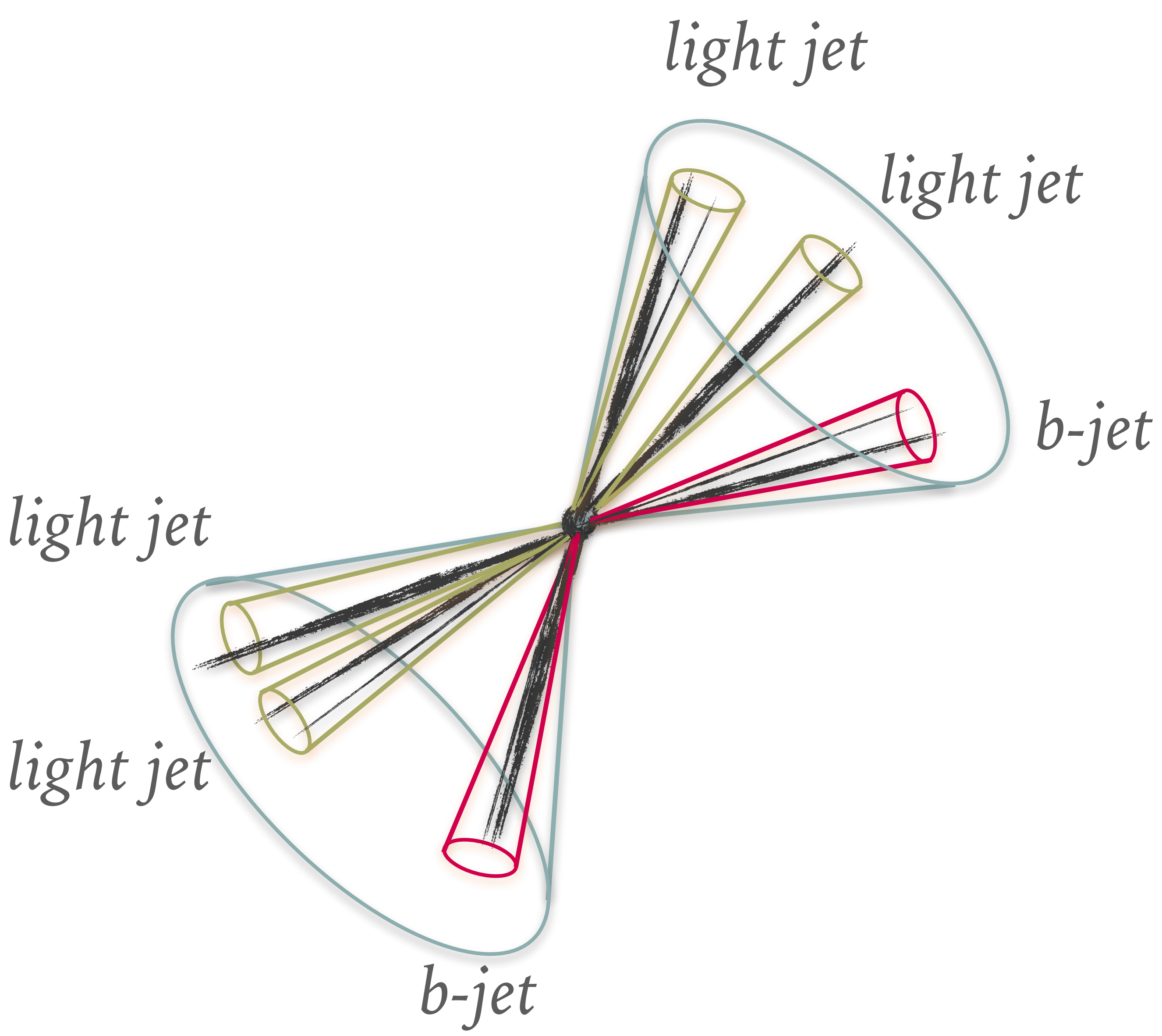


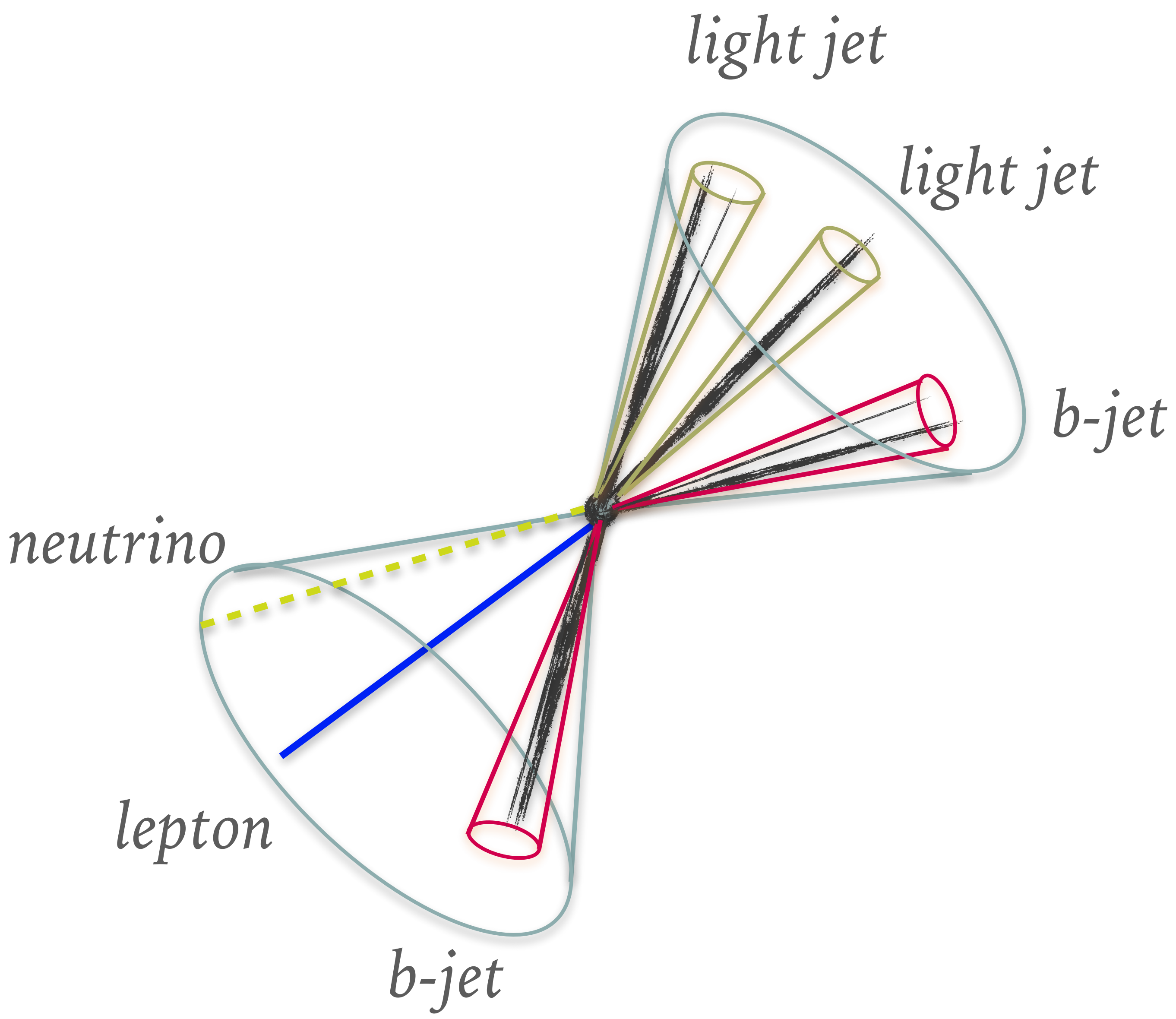
Knowing the Higgs boson mass has a large impact on global fits (compare grey vs blue)

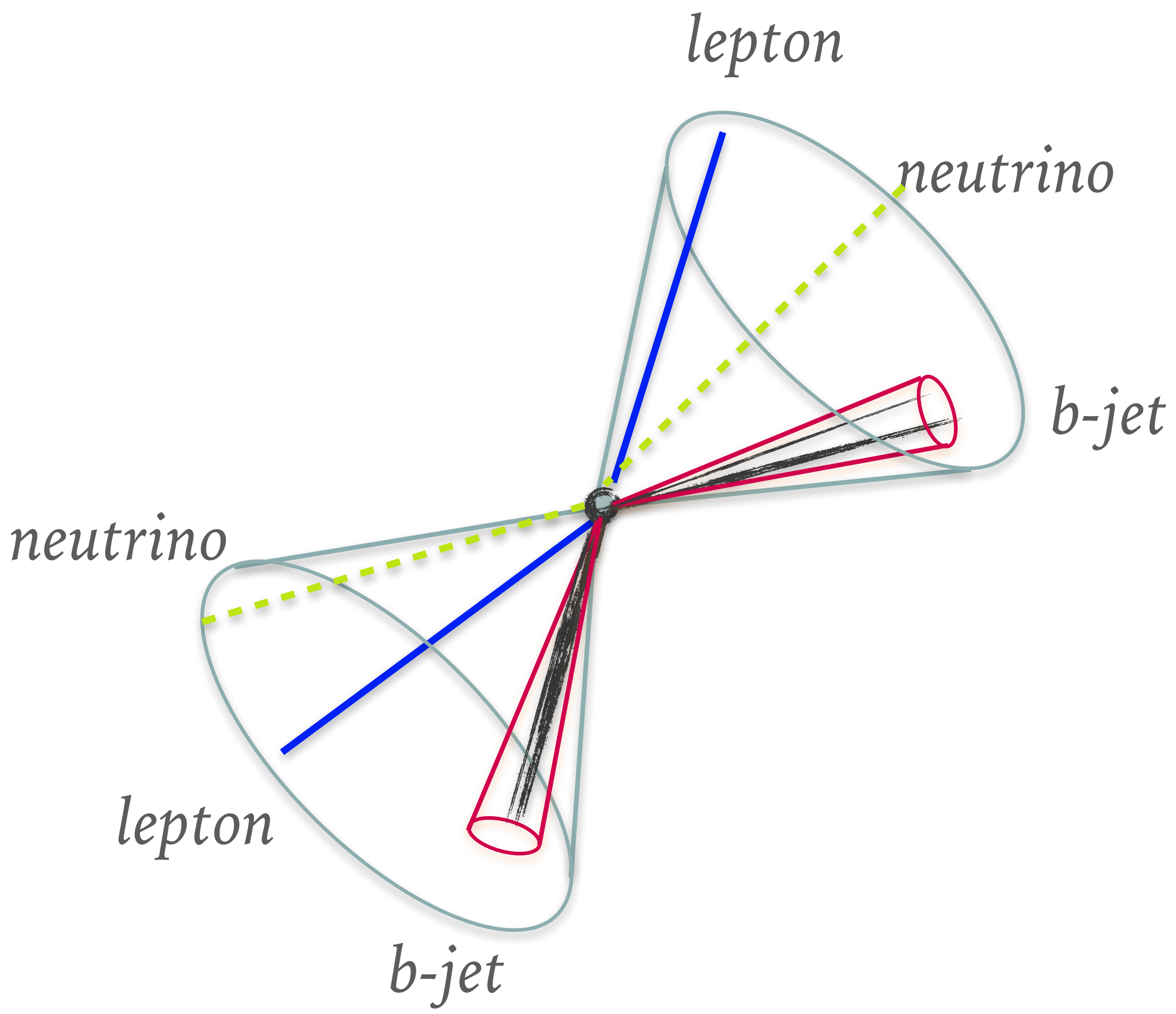
Next Lecture

Measure **Standard Model** *parameters with high precision*	*Search for the* **Higgs boson** *and measure it's properties*	*Search for* **New Physics** *Beyond the Standard Model*	*Study* **Quark-Gluon Plasma**

Large Hadron Collider


light jet
light jet
b-jet
light jet
light jet
b-jet


light jet
light jet
b-jet
neutrino
lepton
b-jet


lepton
neutrino
b-jet
neutrino
lepton
b-jet

- https://upload.wikimedia.org/wikipedia/commons/7/75/Standard_Model_Feynman_Diagram_Vertices.png