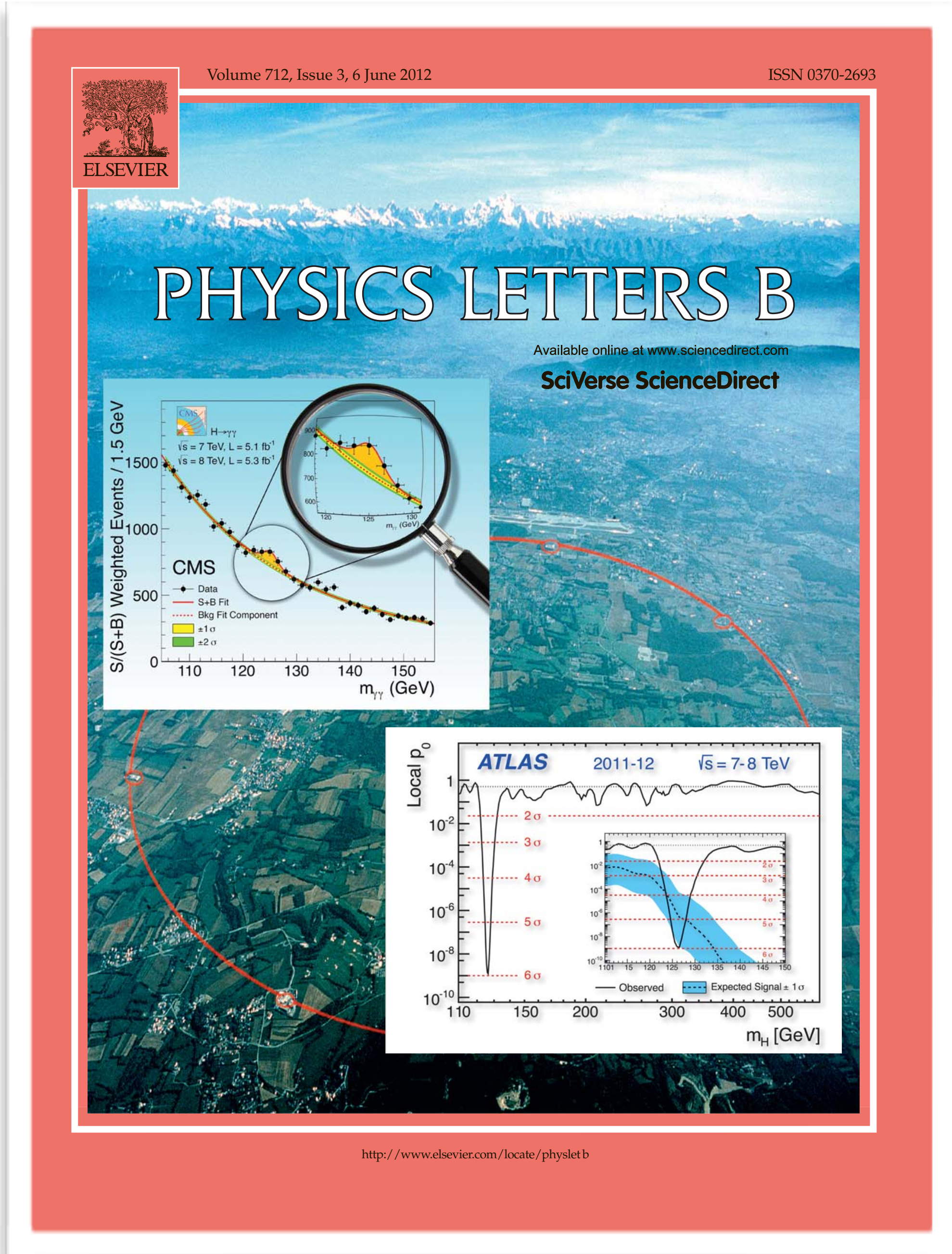
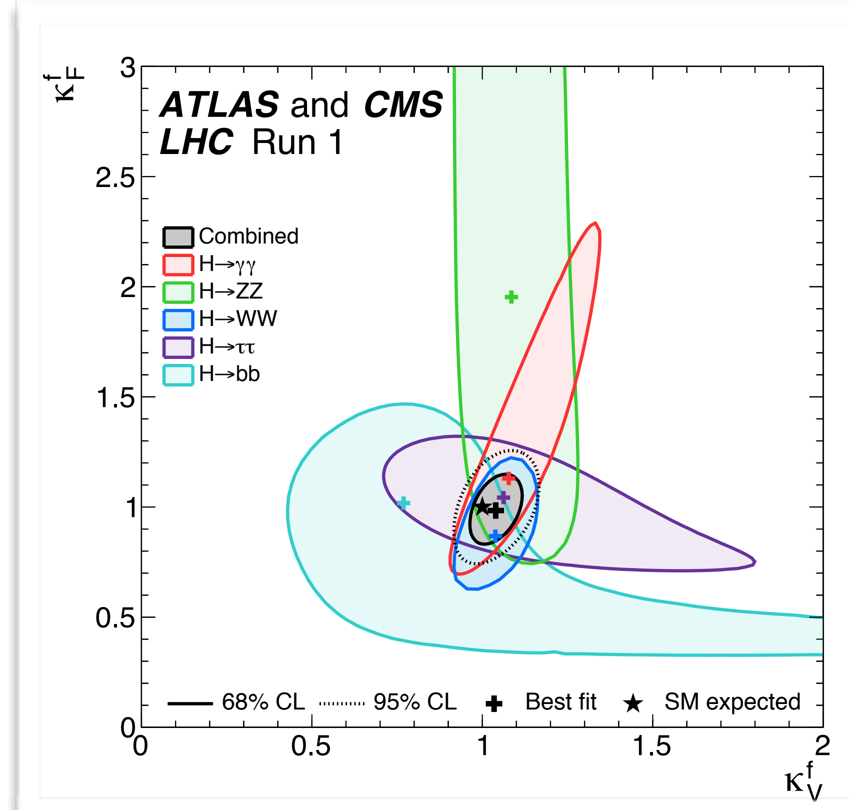
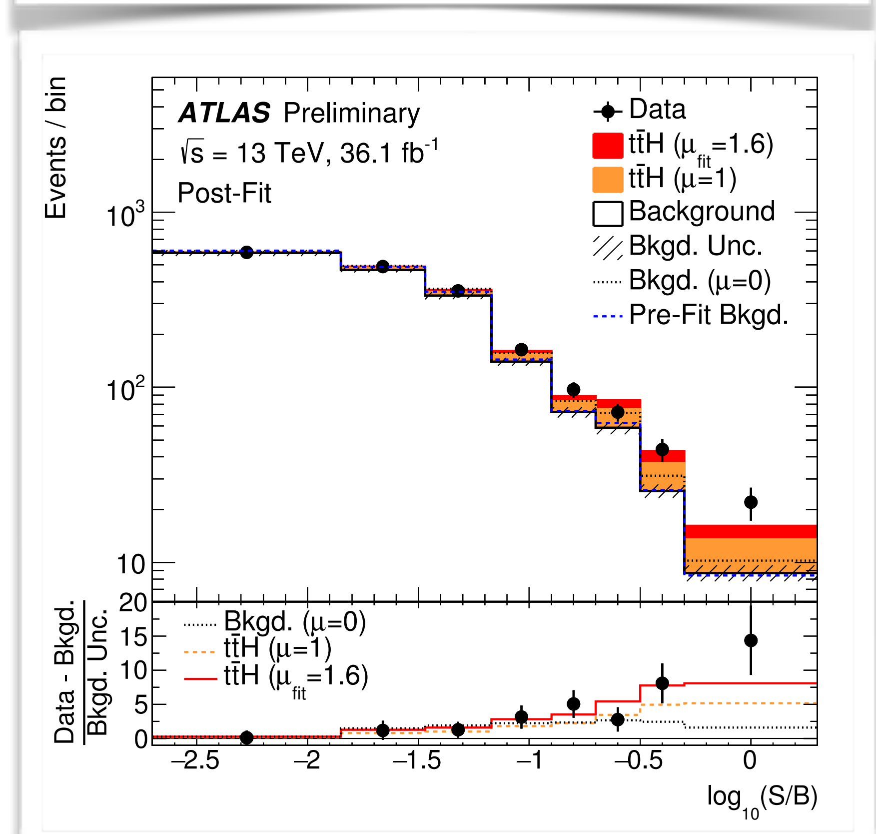
LHC Higgs
From Discovery to Measurement





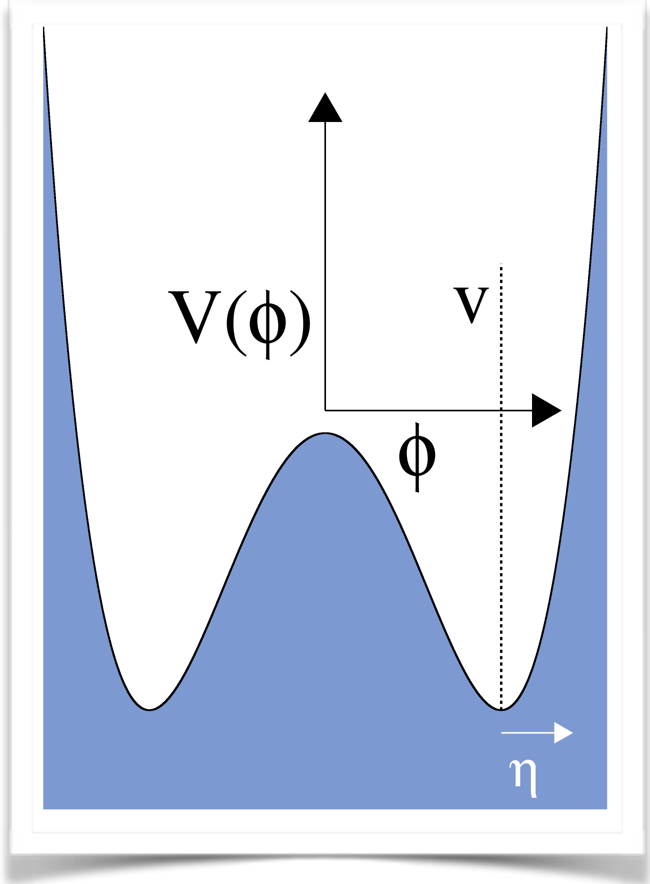


Heather M. Gray,
Lawrence Berkeley National Laboratory,
on behalf of the ATLAS and CMS Collaborations

ICFA Seminar, Ottawa, Canada

The Higgs boson in the Standard Model

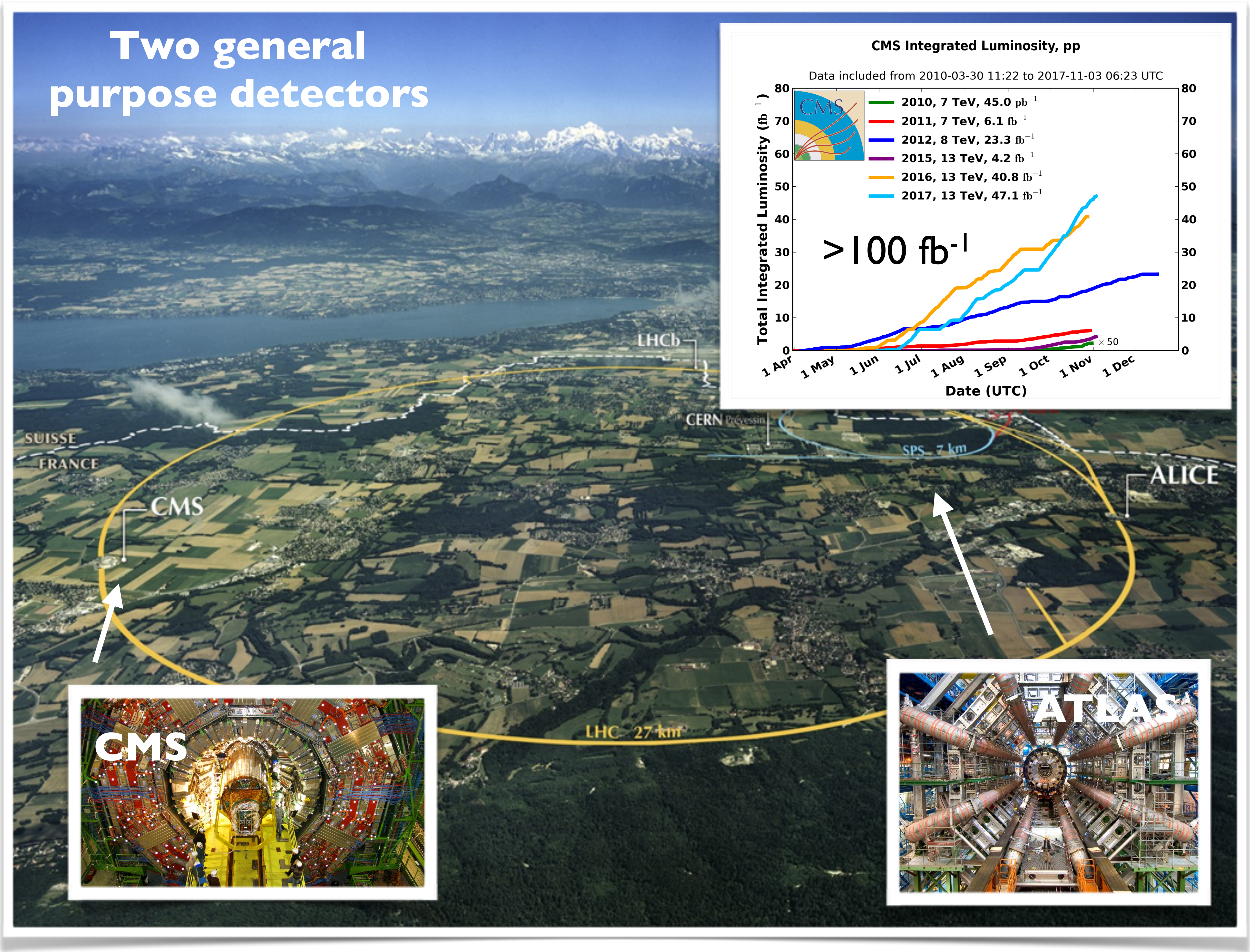
- SM describes all known elementary **particles** and their **interactions**
- **Local gauge invariance** forbids explicit mass terms in the Lagrangian – but experimentally both gauge bosons and fermions have mass
- Introduce a new field with a very specific potential that keeps the full Lagrangian invariant but makes the vacuum not invariant
- **Higgs mechanism** predicts existence of at least one new, neutral boson: the **Higgs boson**
    - SM parameters: mass (**μ** or $\mathbf{m_H}$) and vacuum expectation value, **v**
    - Discovered at CERN by the ATLAS and CMS collaborations in 2012 after 40+ years of searching



$$\mu^2 < 0$$

$$\mathcal{L} = |D^\mu \phi|^2 - y_i q_L^i q_R^i \phi - \mu^2 \phi^2 - \lambda \phi^4 + \ldots$$

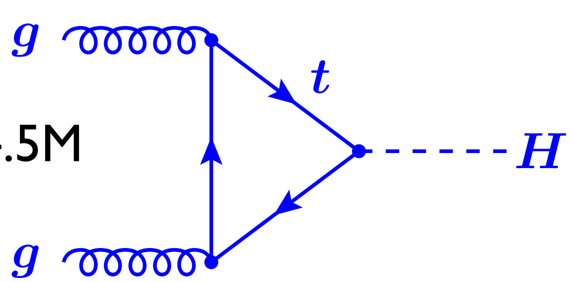
The Large Hadron Collider (LHC)



The Higgs Boson at the LHC

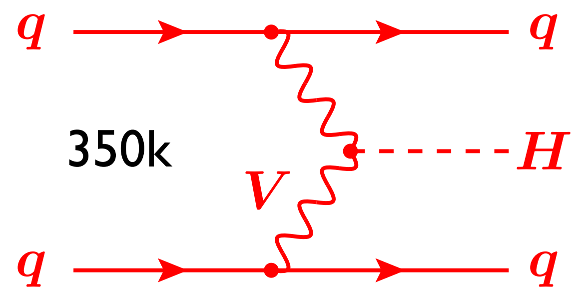
Production

#Higgs produced at 13 TeV until today



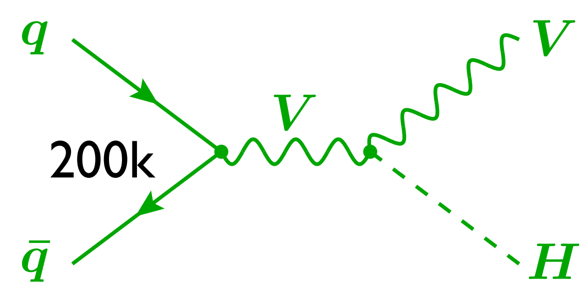
4.5M

Main production channel



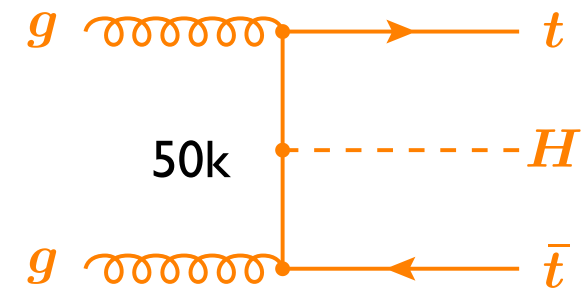
350k

2 forward jets, little central hadronic activity



200k

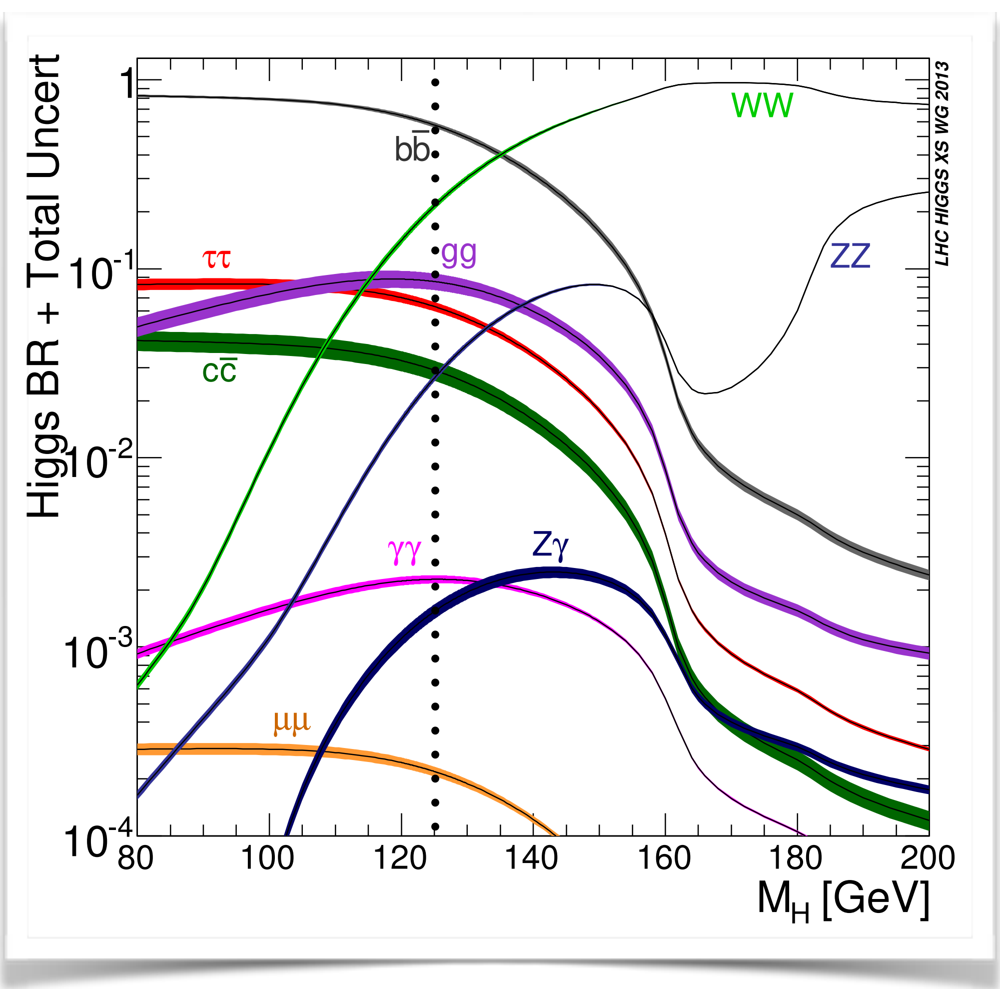
Tag W and Z decays



50k

Tag 2 top quarks

Decays



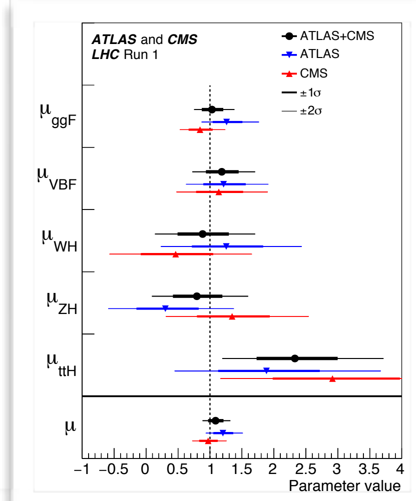
5 main channels at the LHC

Decay branching fractions for m_H = 125 GeV

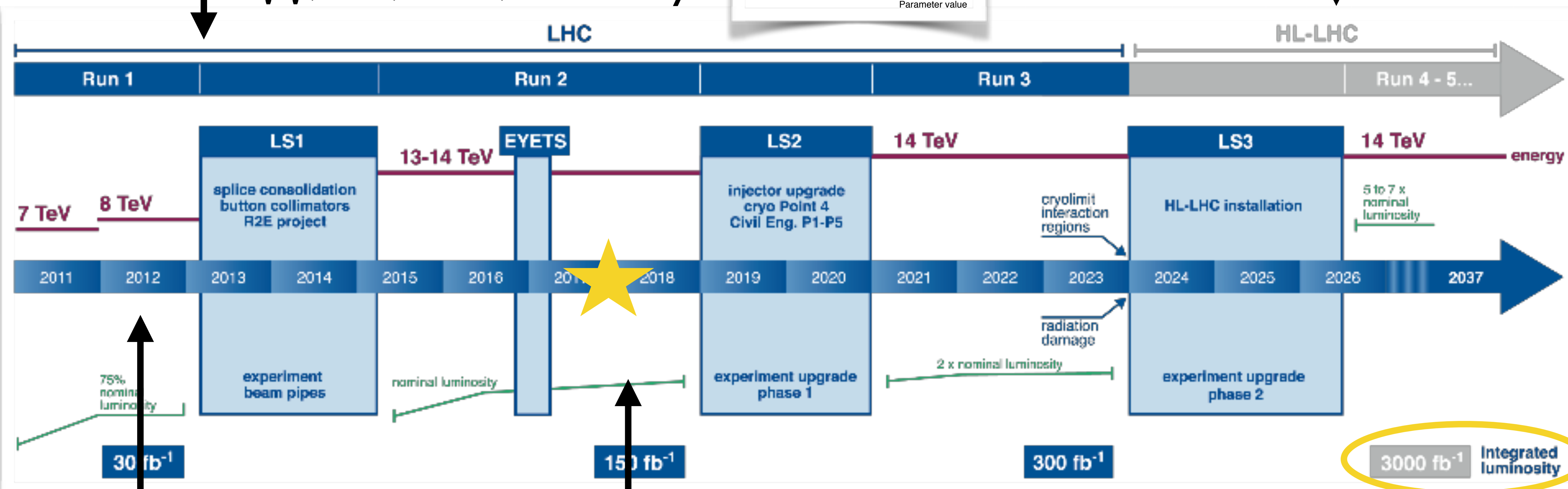
- H→bb: 58 %
- H→WW*: 21%
- H→$\tau^+\tau^-$: 6.3%
- H→ZZ*: 2.6%
- H→γγ: 0.2%

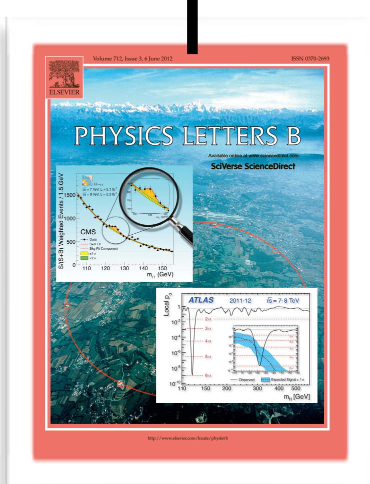
Overview of the LHC Higgs Program

- ggF, VBF production
- mass
- spin/parity,
- γγ, ZZ, WW, ττ decays



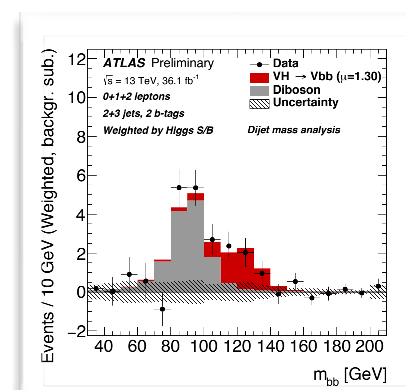
- HH & self-coupling
- ?





Higgs
discovery

- VH, ttH production
- bb decay
- rare decays



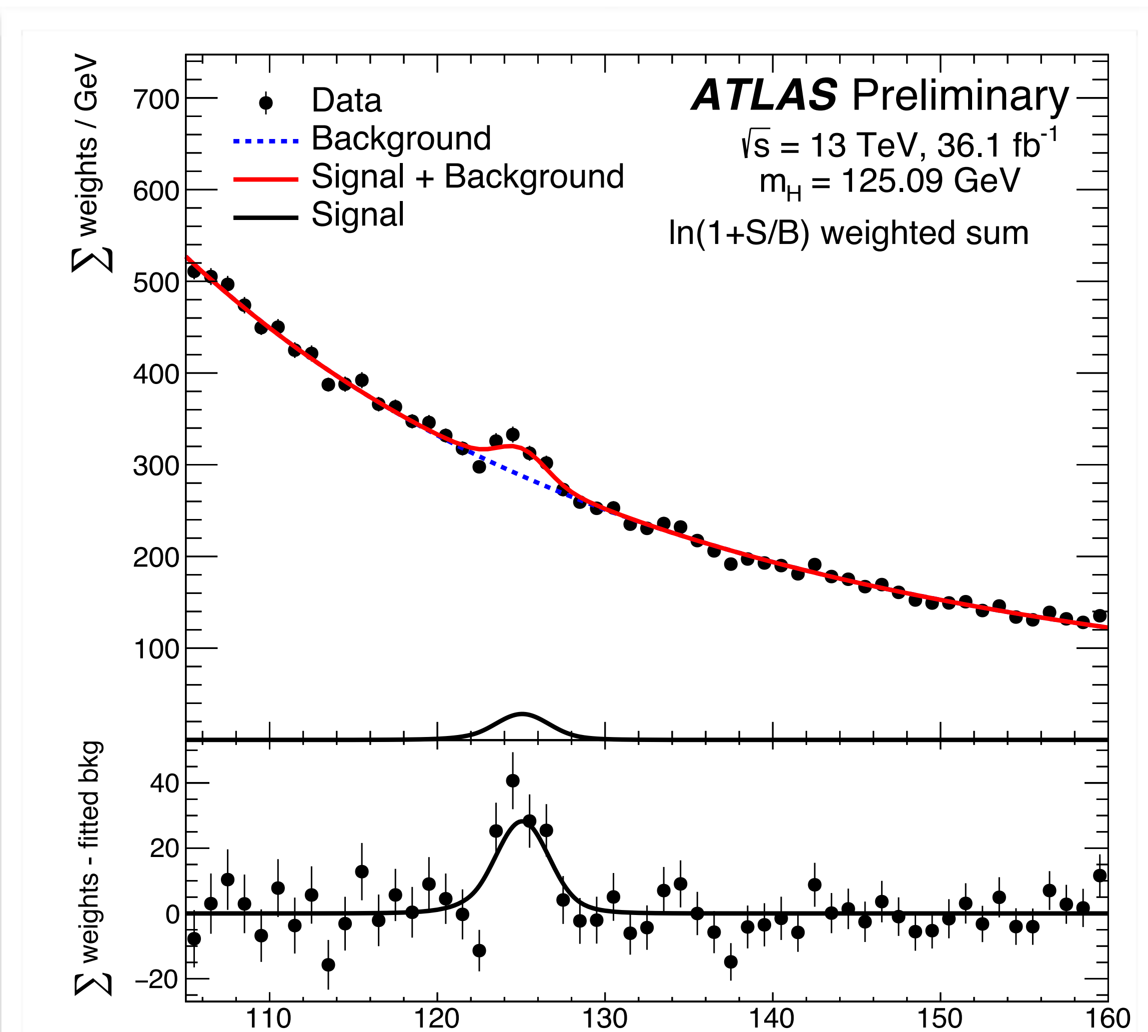
BSM: additional Higgs bosons, non-SM decays

Discovery Channels: H→γγ and H→ZZ→4l

- Similar signal strength precision between channels
- Factor of two improvement in precision wrt Run-1
- 4l is starting to approach theory uncertainty

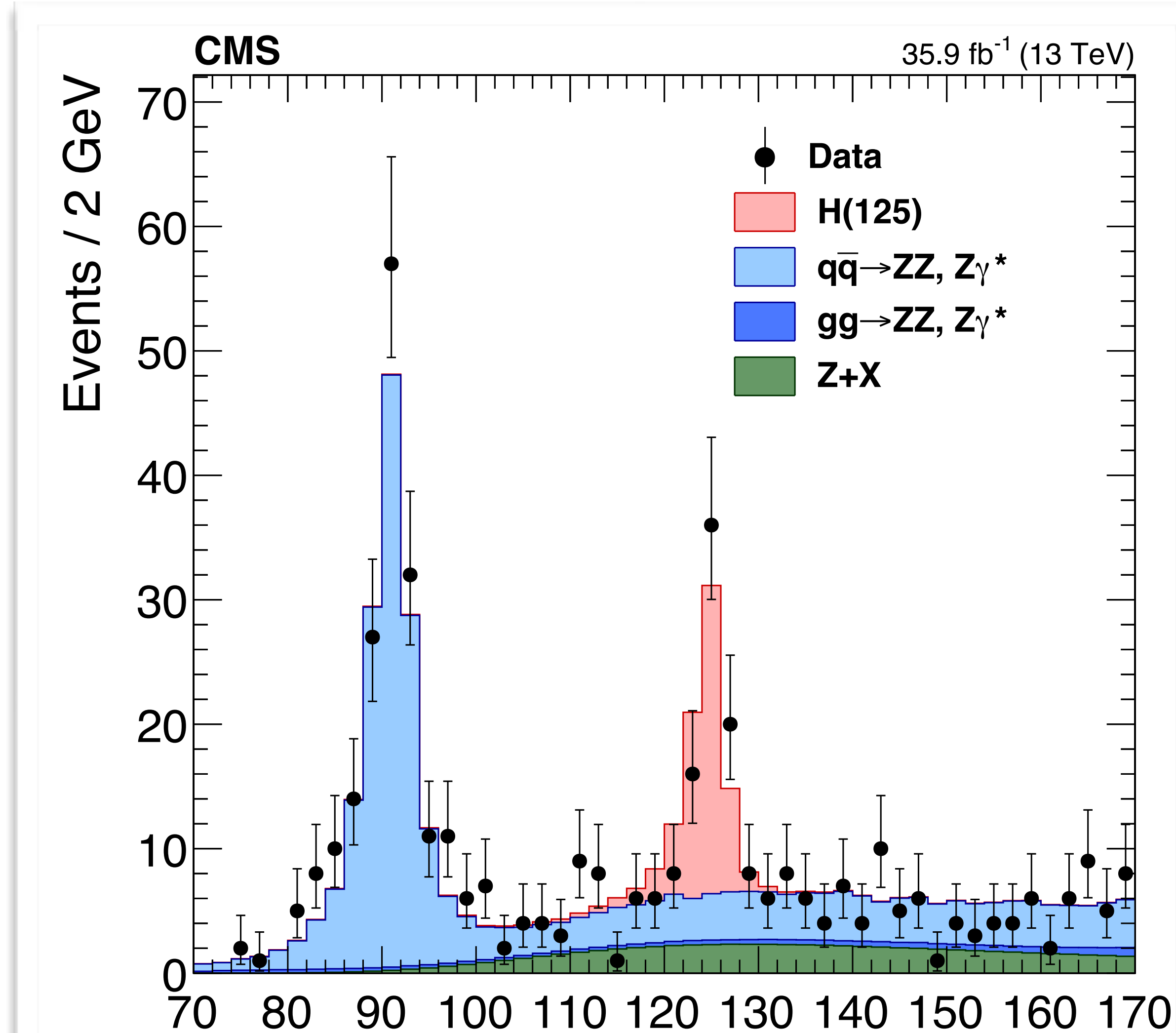
$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\rm SM}}$$

$$\mu = 0.99\,^{+0.14}_{-0.14} = 0.99\,^{+0.12}_{-0.11}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{exp.})\,^{+0.06}_{-0.05}\,(\text{theory})$$



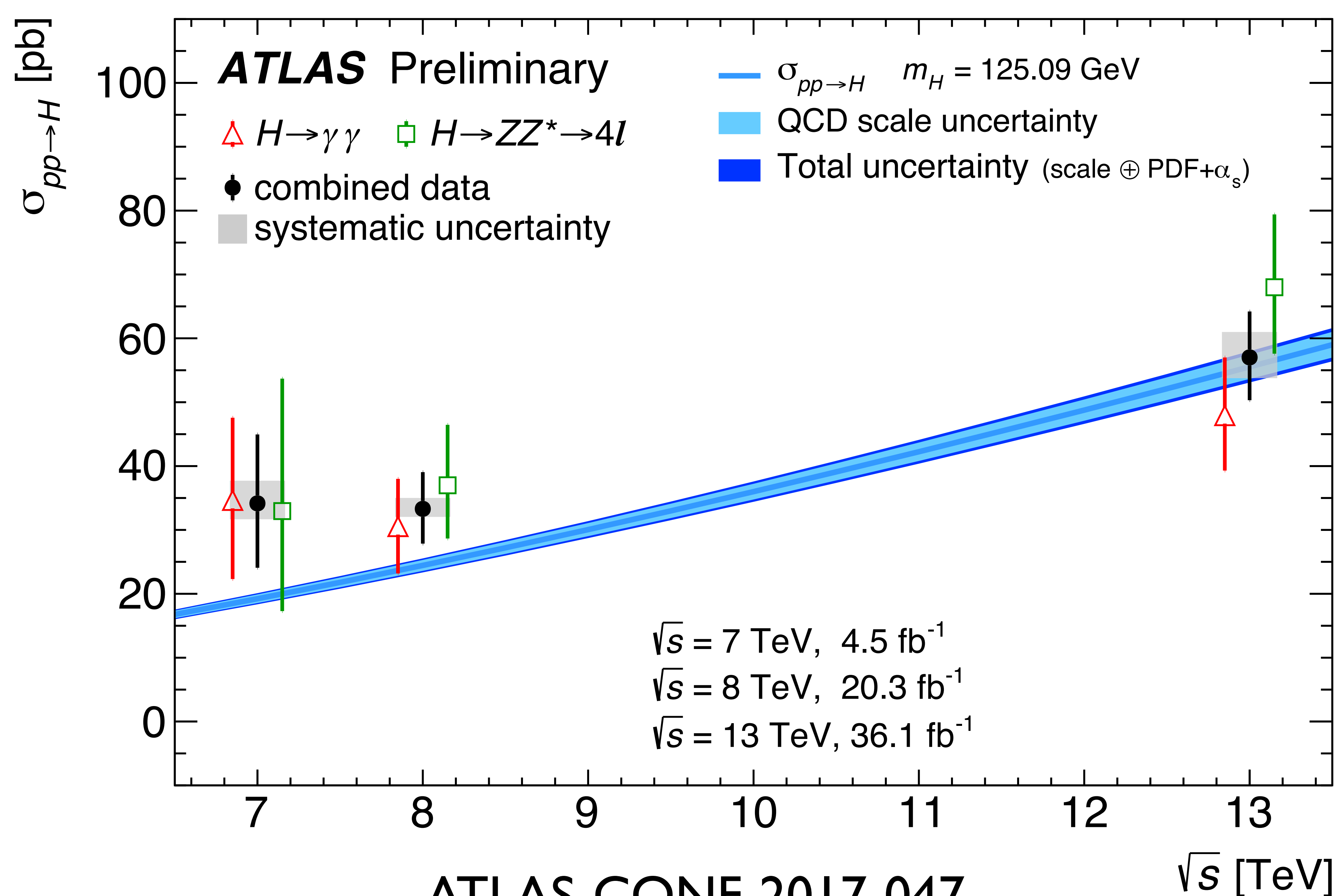
ATLAS-CONF-2017-045

$$\mu = 1.05^{+0.15}_{-0.14}(\text{stat})^{+0.11}_{-0.09}(\text{syst})$$



accepted by JHEP

Inclusive cross-section



ATLAS-CONF-2017-047

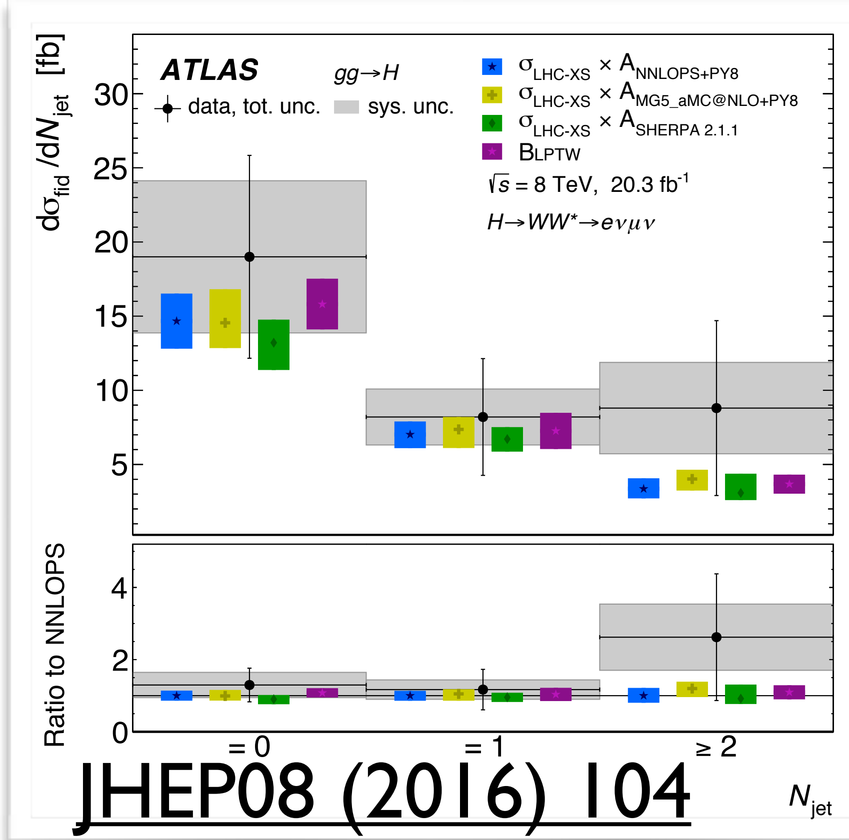
Good agreement with SM prediction

Theory precision (N^3LO) improved x2 between Run-1 and Run-2

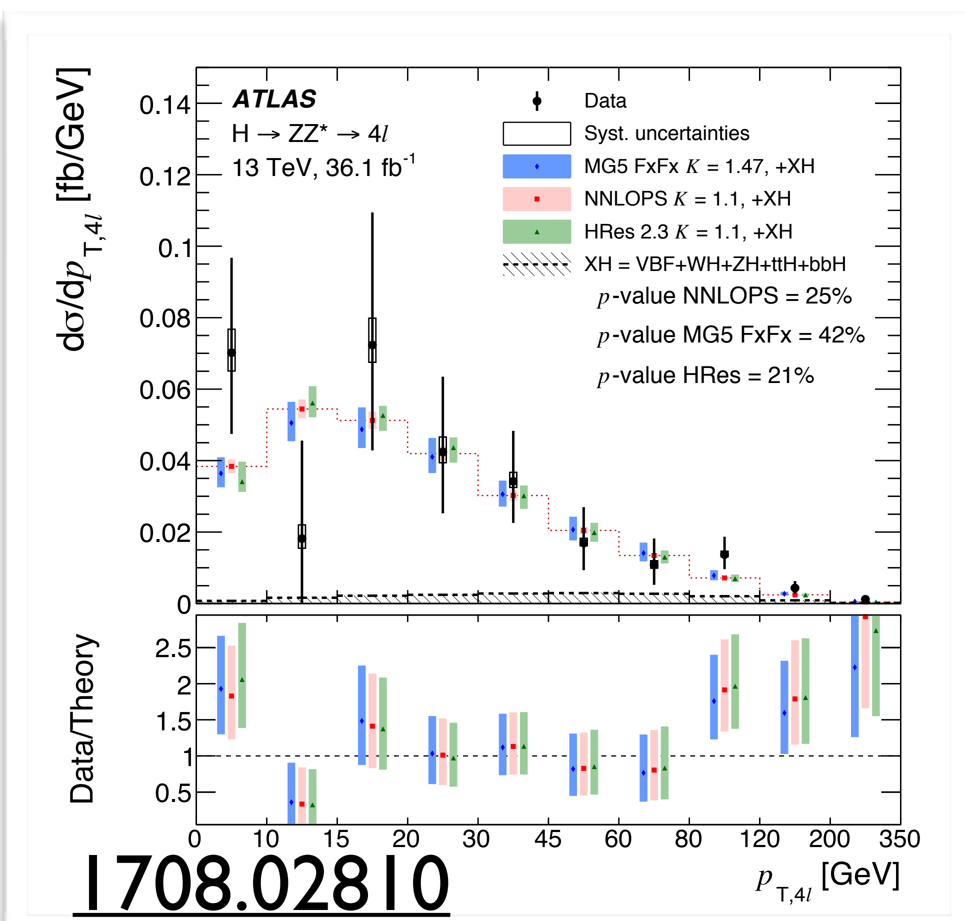
e.g. 1602.00695

Differential distributions

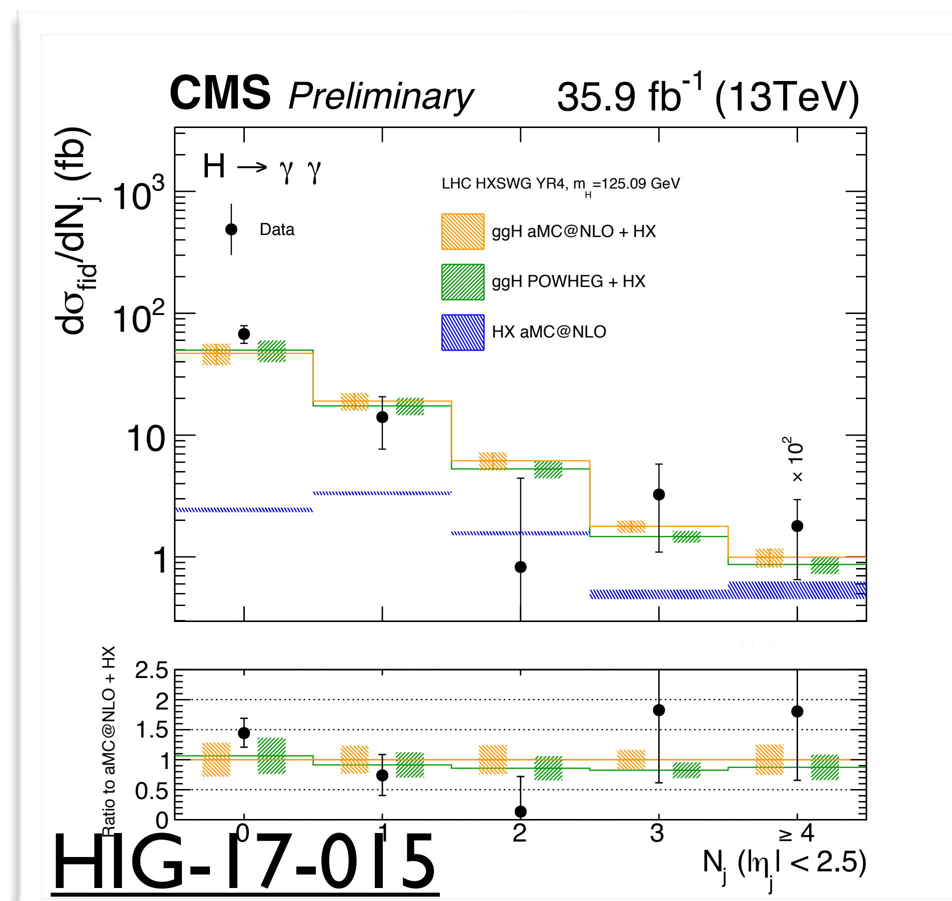
- Model-independent measurements of production and decay kinematics
- Use high precision ZZ, WW and γγ channels
- Allow comparisons to be made to precise calculations
- Also probes new physics: couplings in loops, CP mixing, etc.



JHEP08 (2016) 104



1708.02810

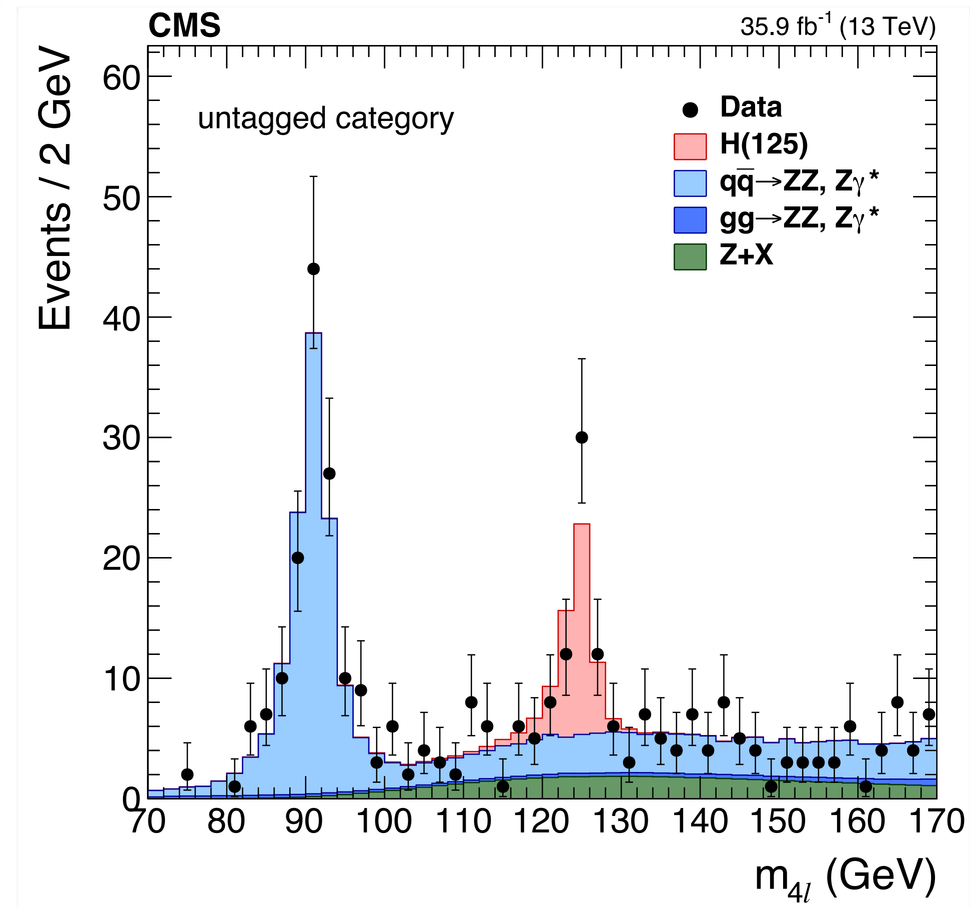


HIG-17-015

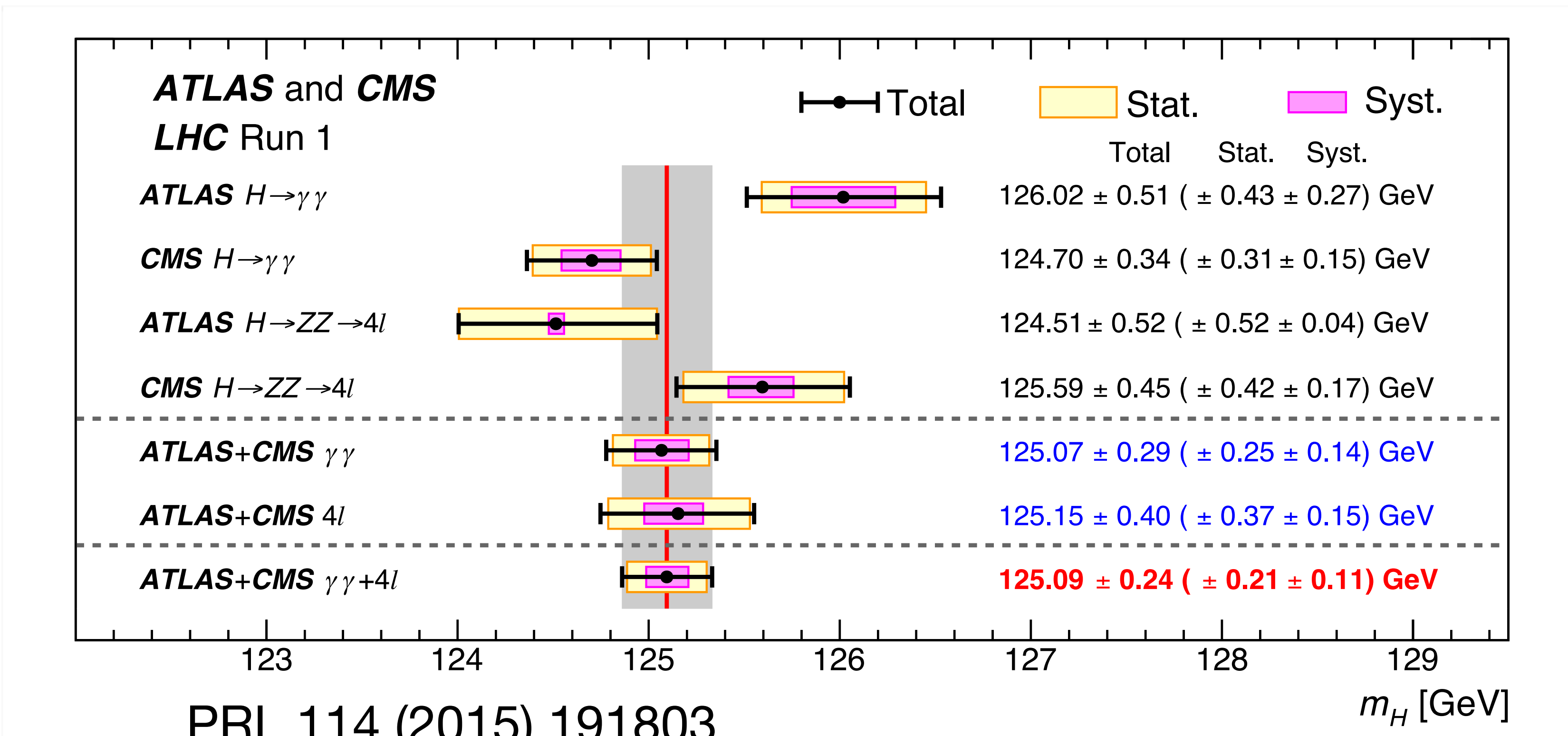
Higgs Properties

Mass measurement

- Higgs mass is a SM parameter that needs to be determined from experiment
- Measure in the high resolution channels: H→γγ and H→ZZ(4l)
- Precision depends on muon momentum scale and electromagnetic calorimeter calibration



arXiv:1706.0993, accepted by JHEP

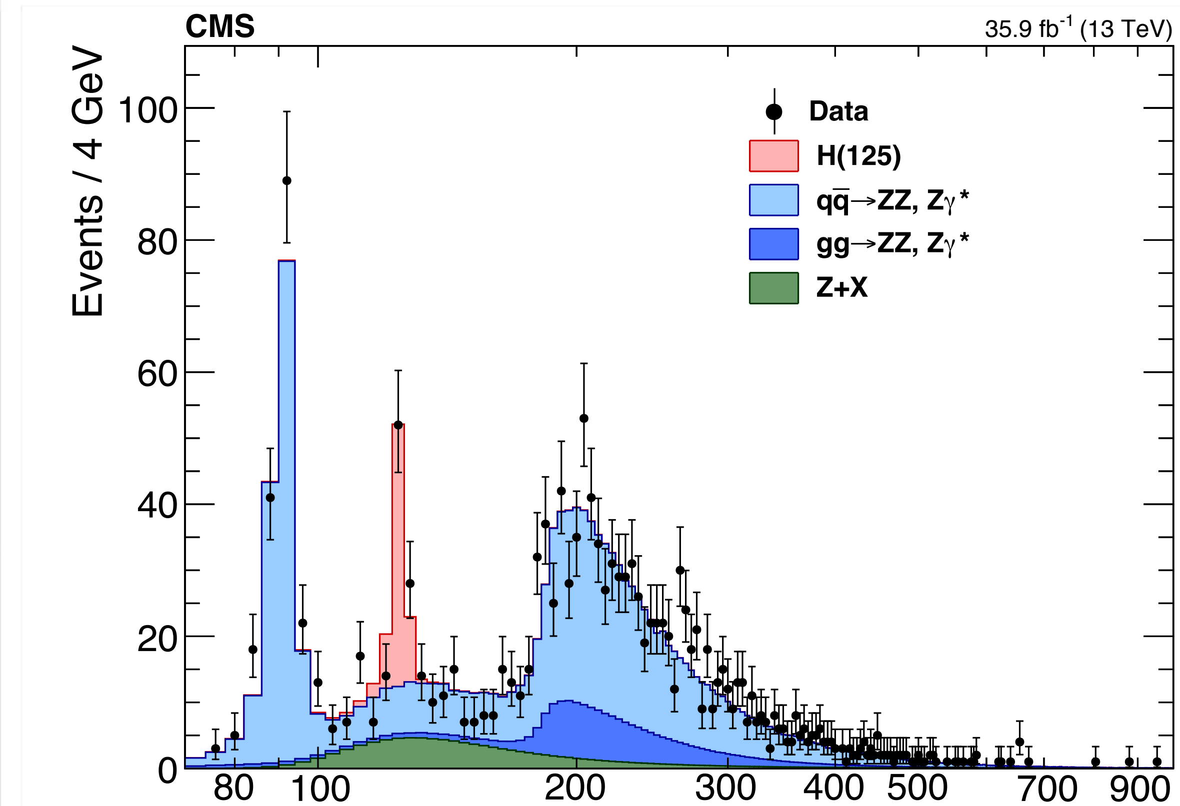


PRL 114 (2015) 191803

Run-2
CMS: 125.26 ± 0.21 GeV
ATLAS: 124.98 ± 0.28 GeV

Total width

- Lower bound on total width from decay measurements
- Direct experimental measurements probe 3 orders of magnitude larger than SM width (Γ=4 MeV)
- Indirect constraint* on the width via measurement of ratio of off-peak to on-peak cross-section
  - CMS: Γ < 13 MeV
  - ATLAS: Γ < 22 MeV



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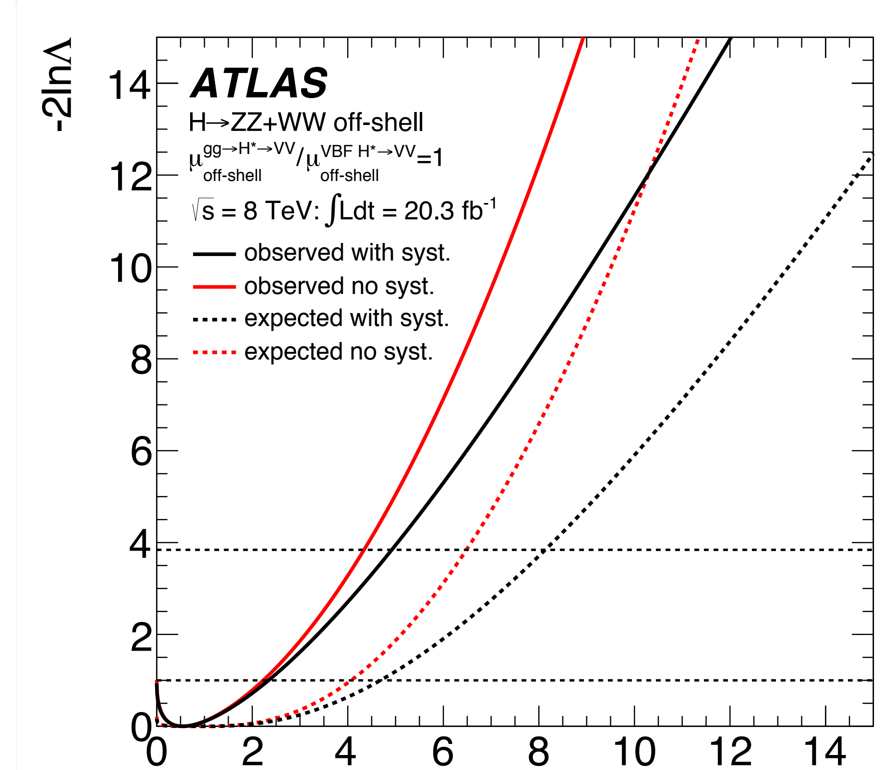
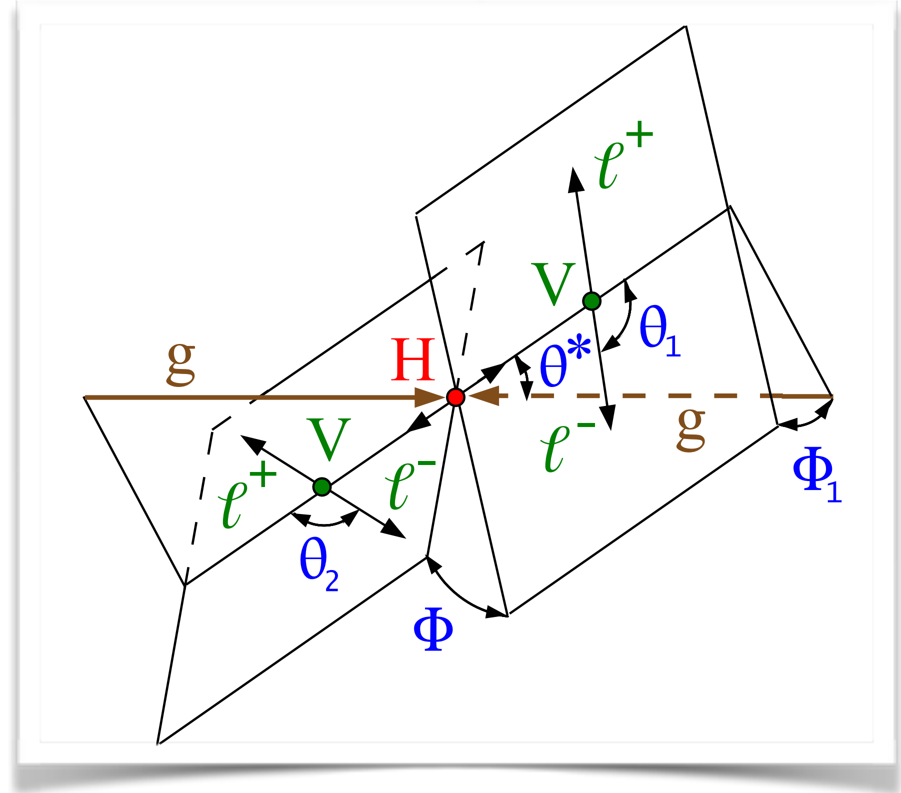


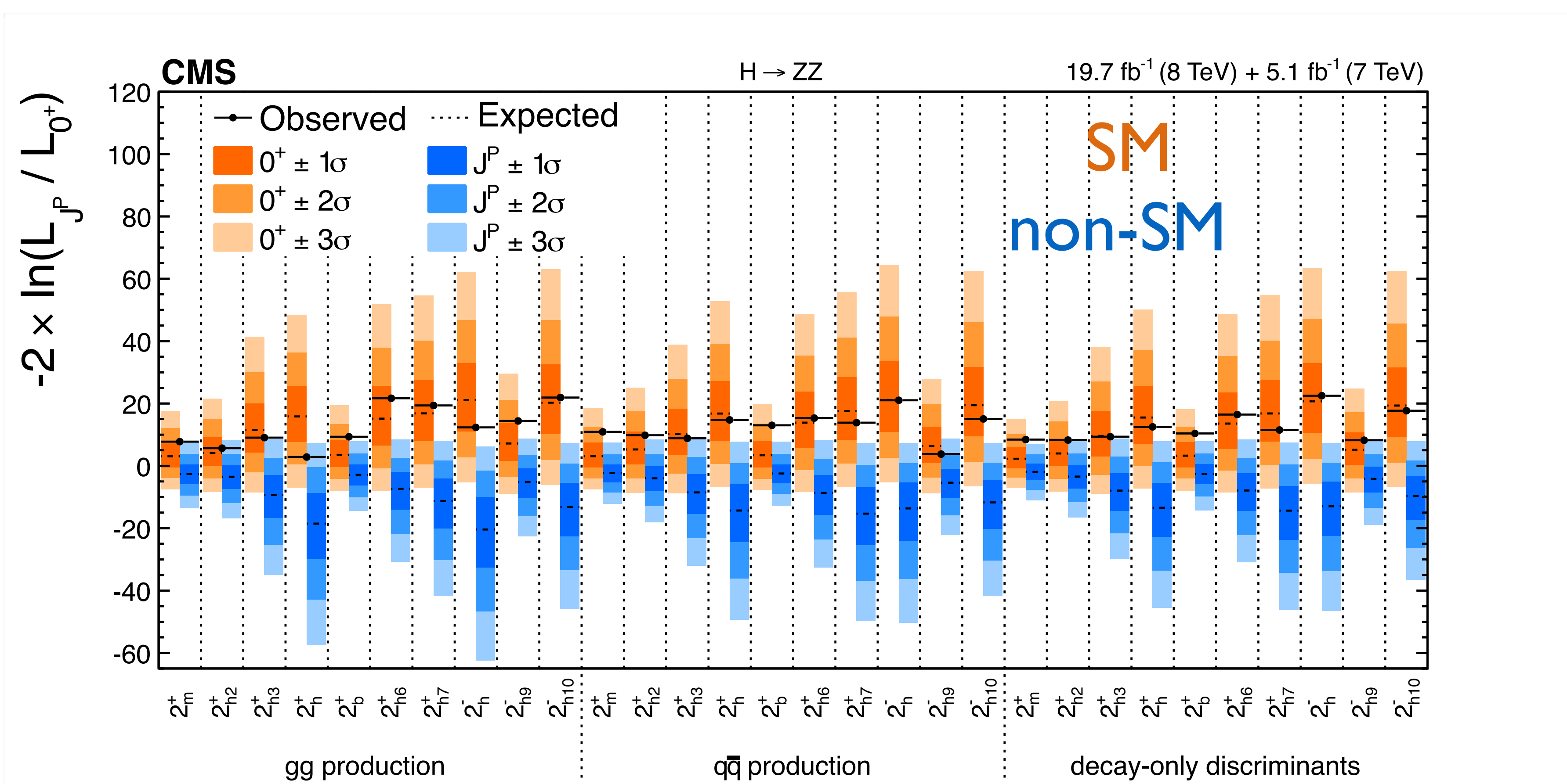
EPJC (2015) 75:335

*N. Kauer and G. Passarino, JHEP (2012) 2012: 116
*F. Caola and K. Melnikov,PRD88 (2013) 054024

Higgs Boson Quantum Numbers

- SM predicts $J^{PC} = 0^{++}$
- Angular distributions sensitive to JP
- Wide range of alternative quantum numbers excluded at >99% CL
- All observations consistent with expectations for the SM Higgs boson



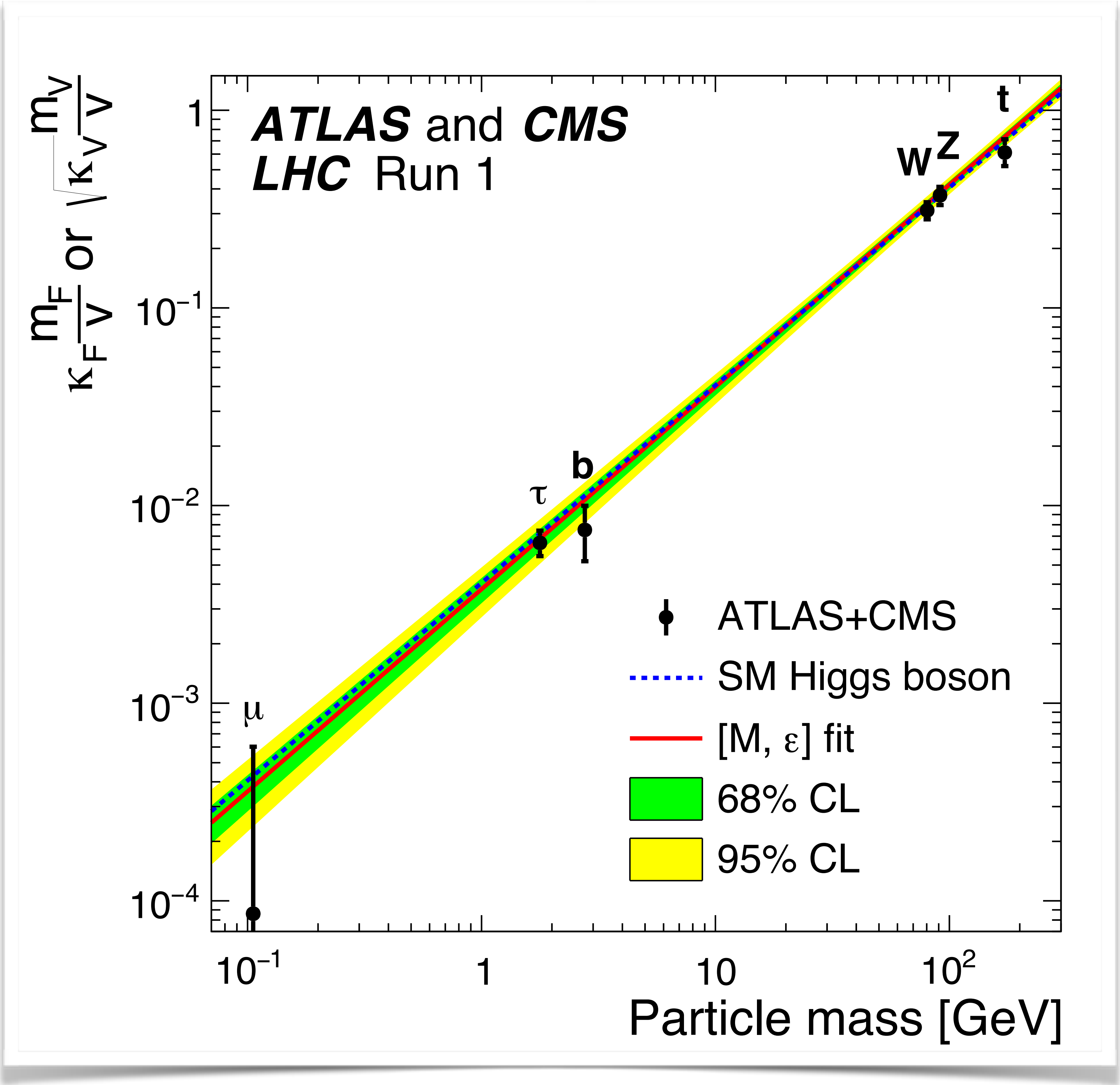


PRD 92 (2015) 012004

Tests of alternative J^P hypotheses in ZZ

Coupling to Fermions

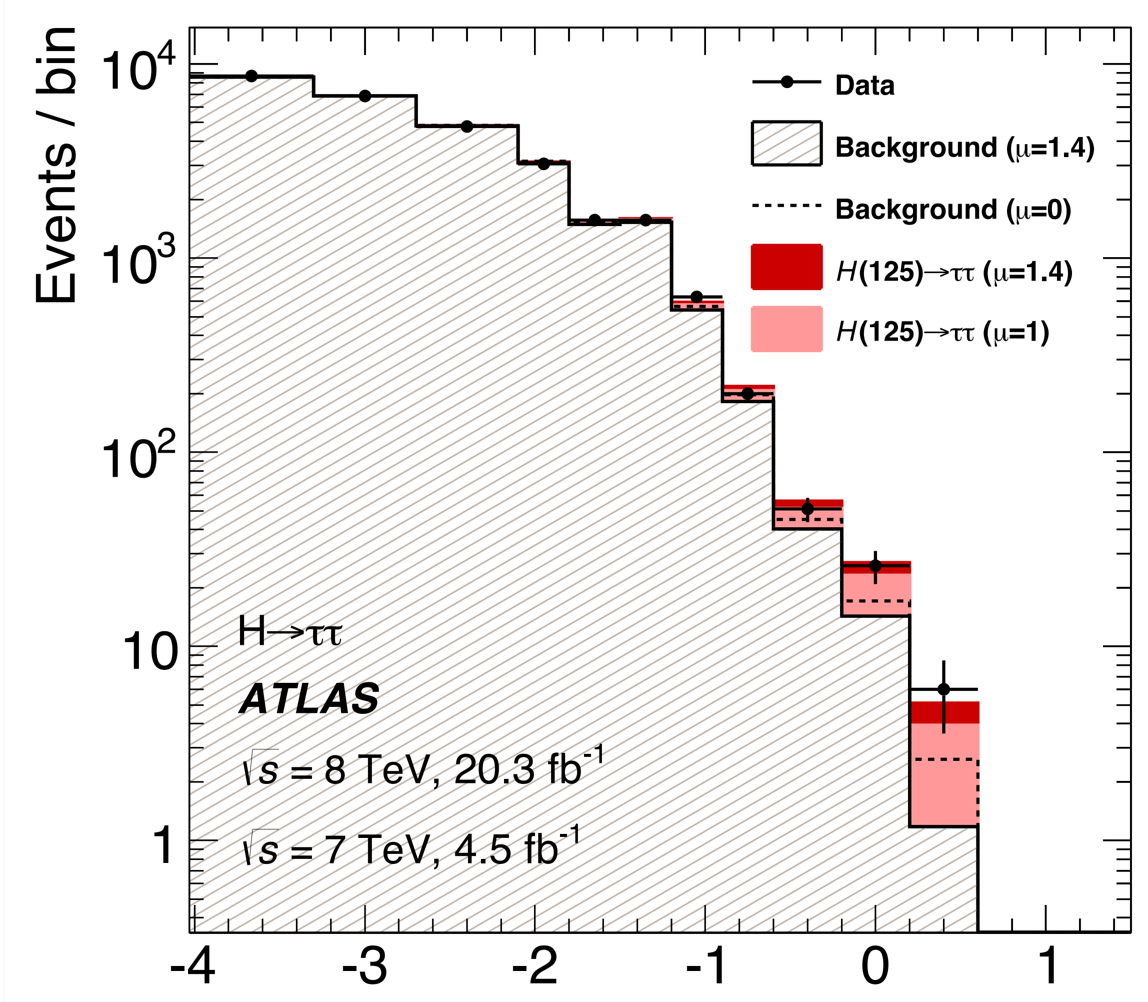
Coupling vs Mass



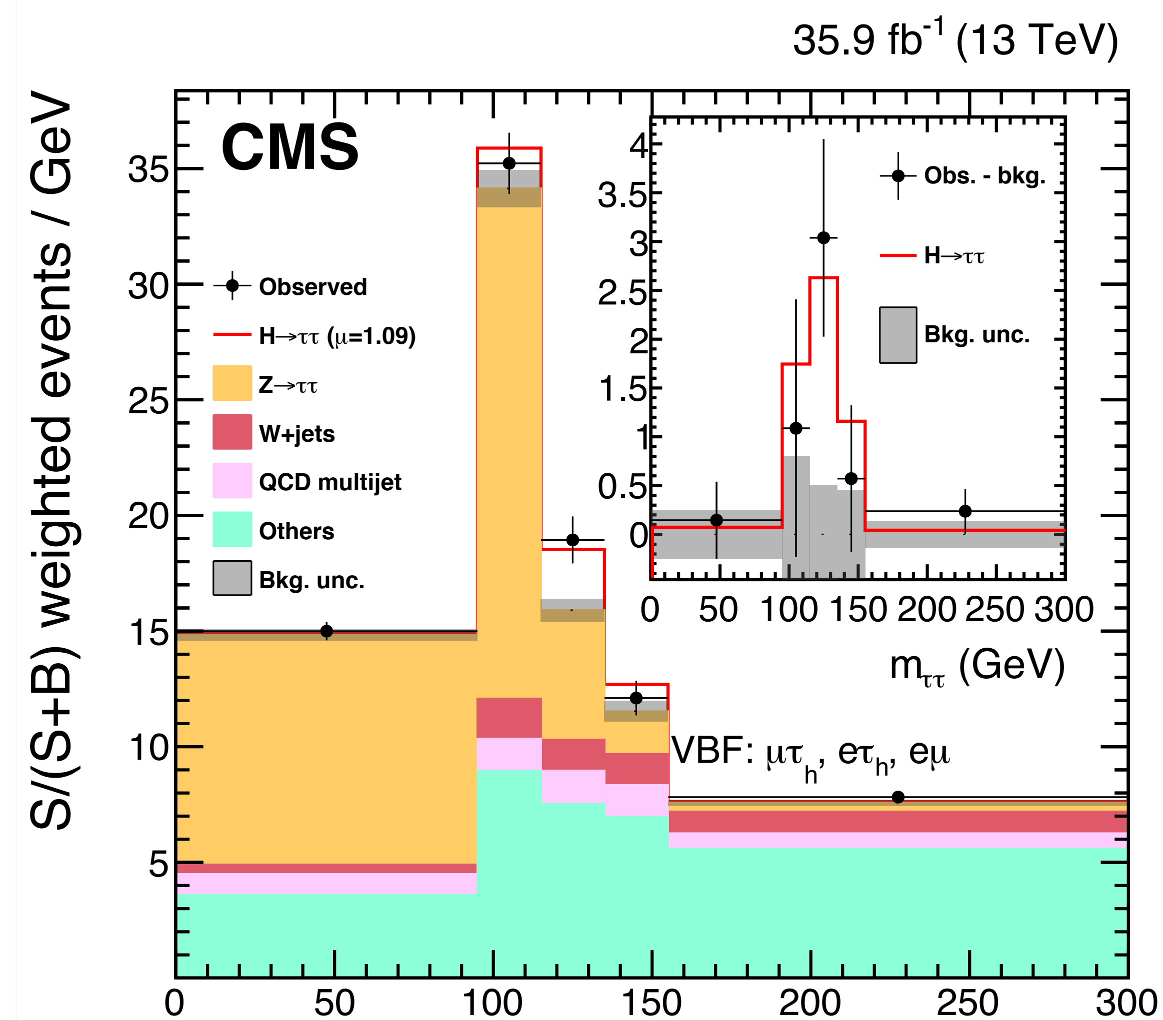
JHEP08 (2016) 045

Observation of coupling to τ-leptons

- 5.5σ observation of H→ττ from combination of ATLAS and CMS Run-1 results
- 5.9σ observation from CMS from combination of 7, 8 and 13 TeV results
- Most sensitive decay channel for VBF production



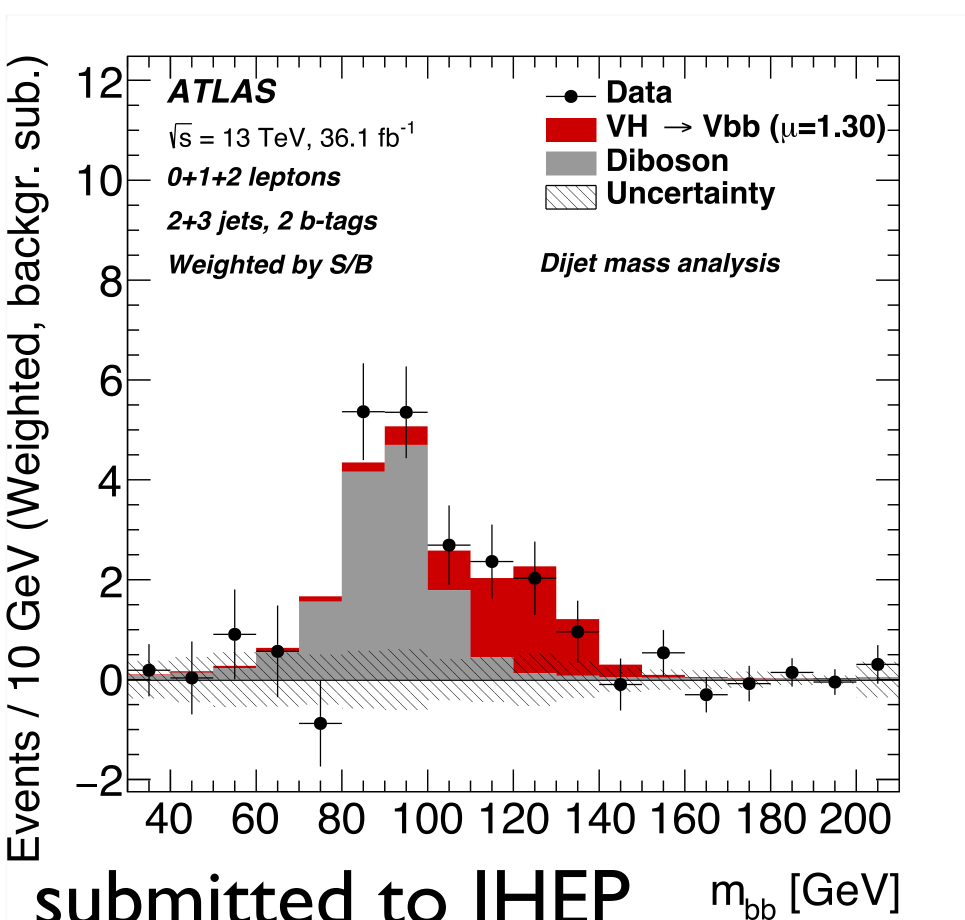
JHEP 04 (2015) 117



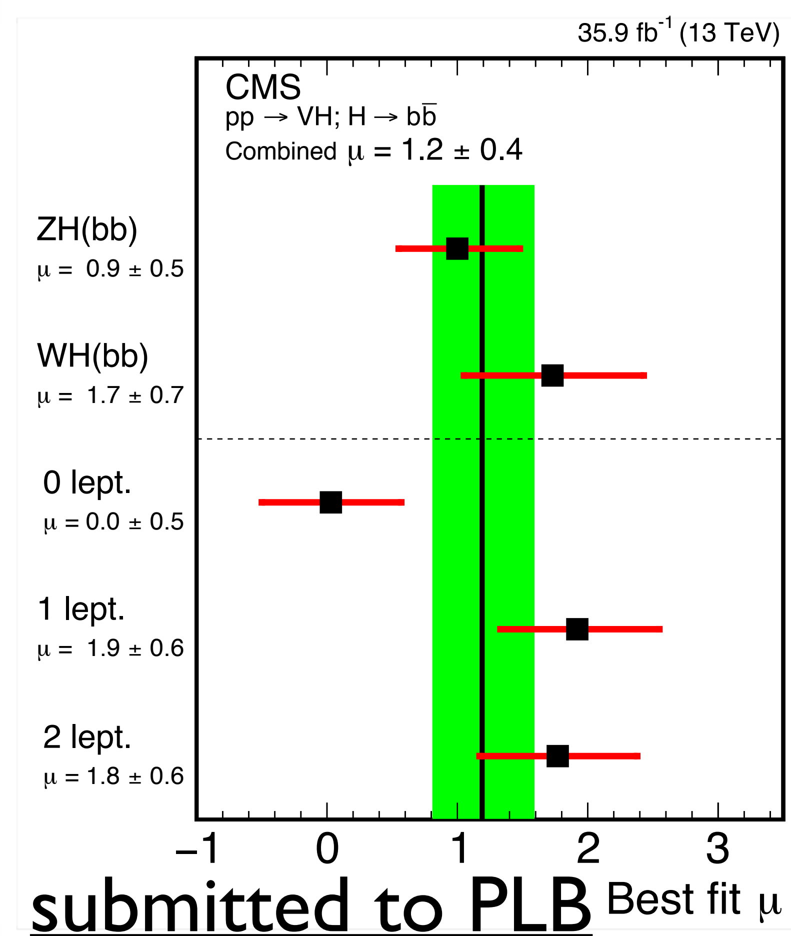
Submitted to PLB

Evidence for coupling to b-quarks

- Difficult channels despite the large branching ratio (58%) due to large backgrounds
- Direct evidence recently obtained by ATLAS (3.5σ) and CMS (3.3σ) using most sensitive production mode: VH production
  - Further searches using ggF, VBF and ttH production
- Analysis cross-checked via observation of VZ(bb) production
- Most sensitive channel for VH production



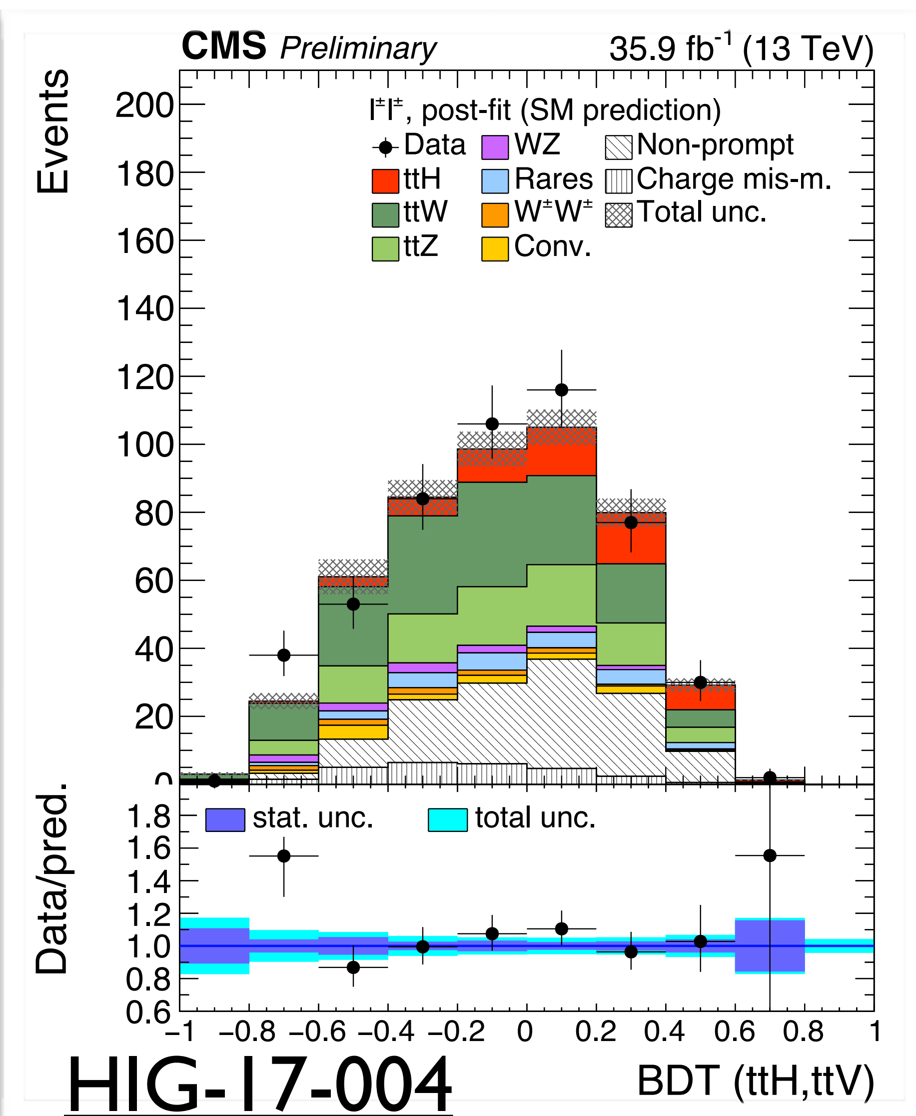
submitted to JHEP

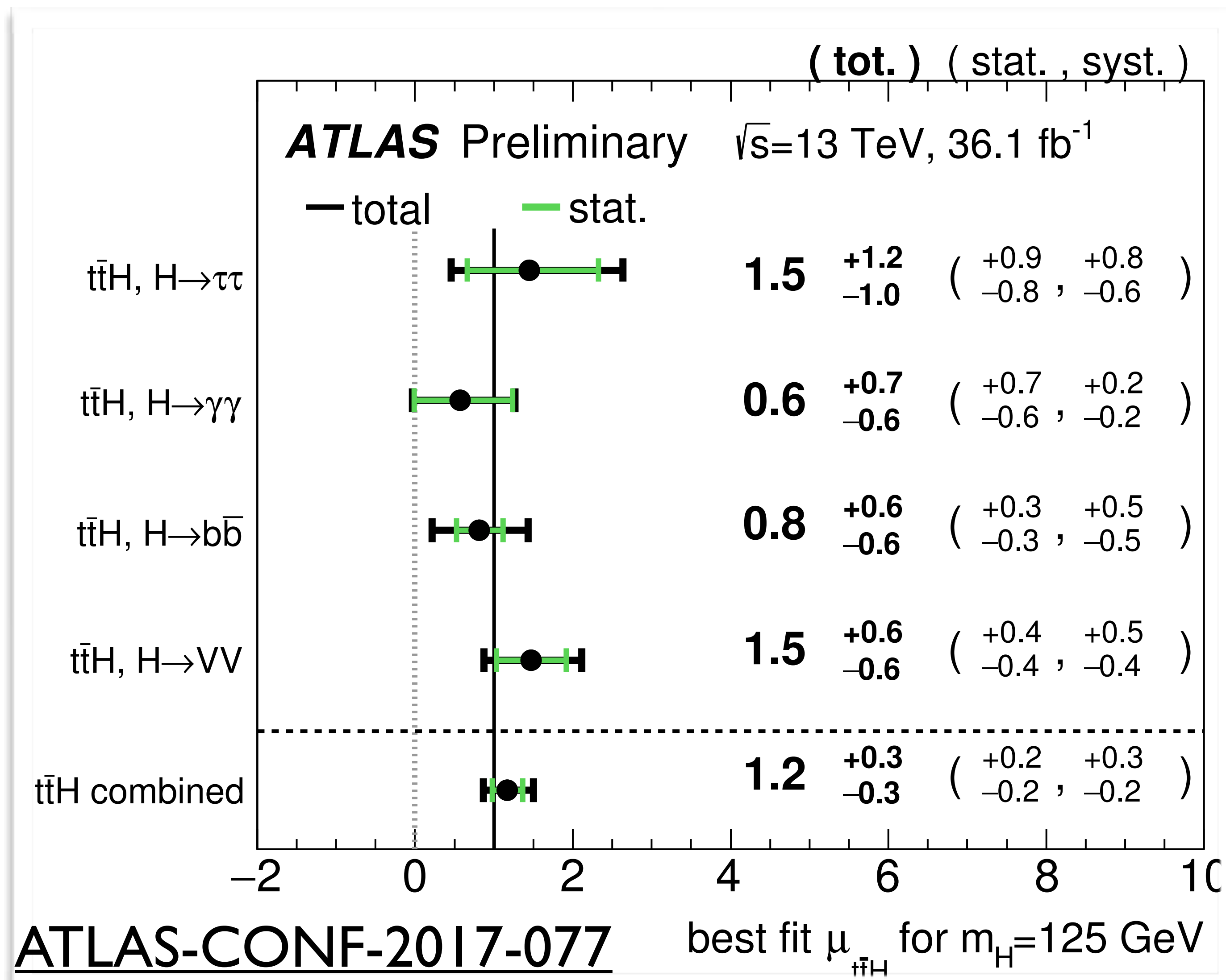


submitted to PLB

Direct evidence for coupling to top quarks

- ttH production provides a probe of the direct coupling of the Higgs boson to top quarks
- 3.3σ evidence for ttH production from CMS using leptonic final states
- 4.2σ evidence from ATLAS from combination of five major decay modes

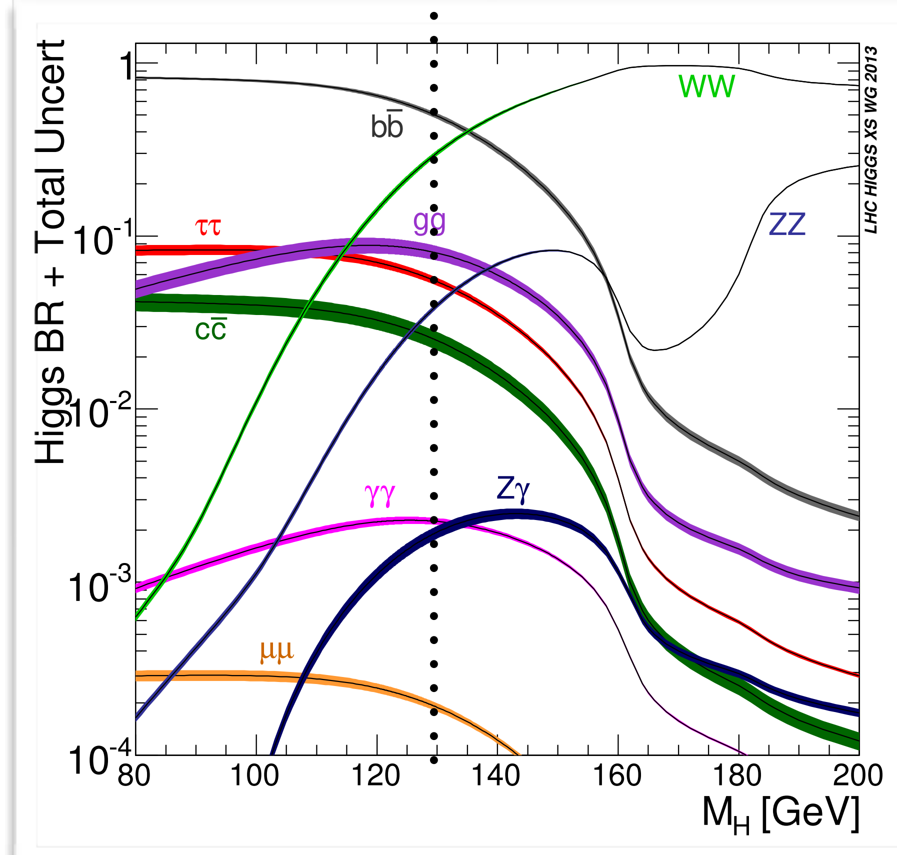


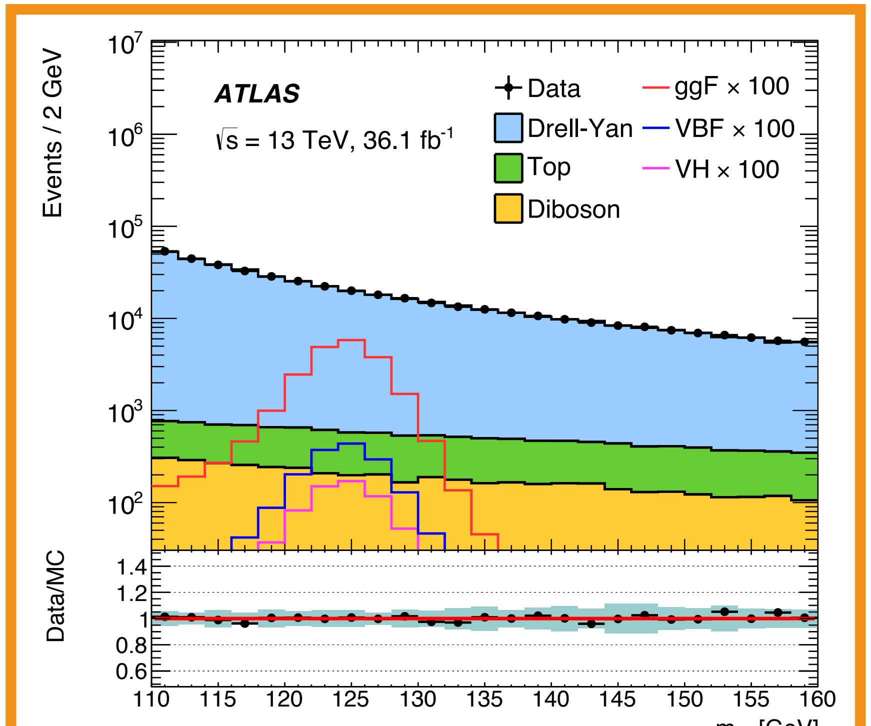


Other decays

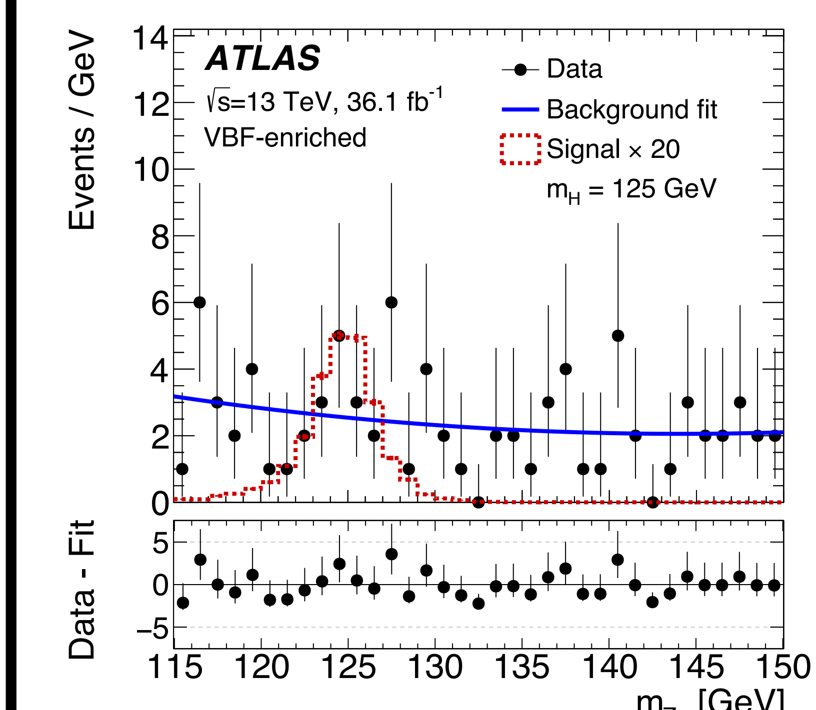
Probing rare Higgs decays

- Exploit growing LHC dataset to explore further decay channels
  - H→μμ: 2.8 x SM
  - H→Zγ: 6.6 x SM
  - H→cc:
    - 110 x SM (ZH(cc))
    - 200 x SM (J/ψγ)
  - H→φγ: 200 x SM
  - H→ργ: 50 x SM

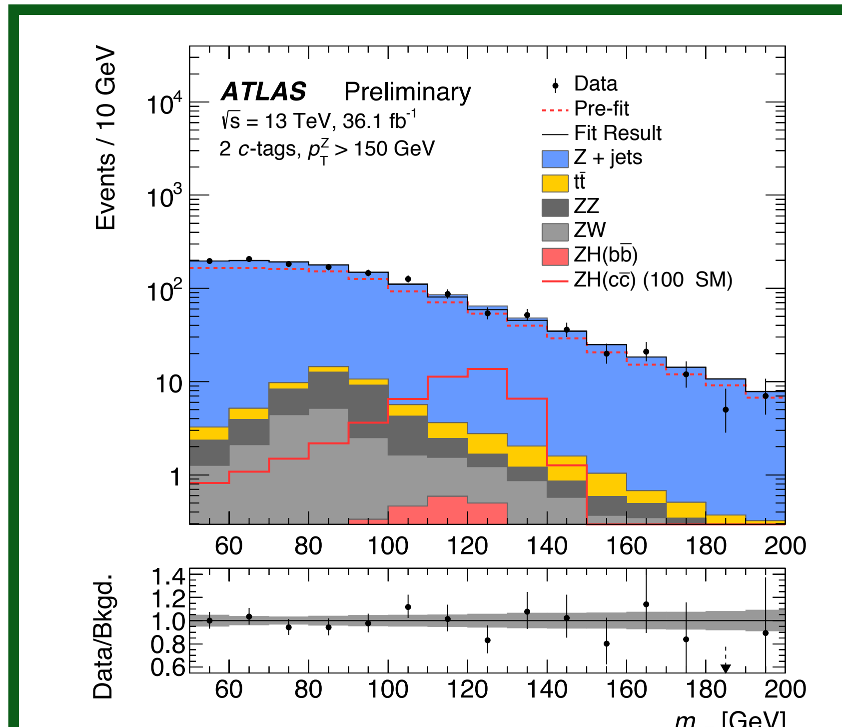




PRL 119 (2017) 05182



JHEP 10 (2017) 112

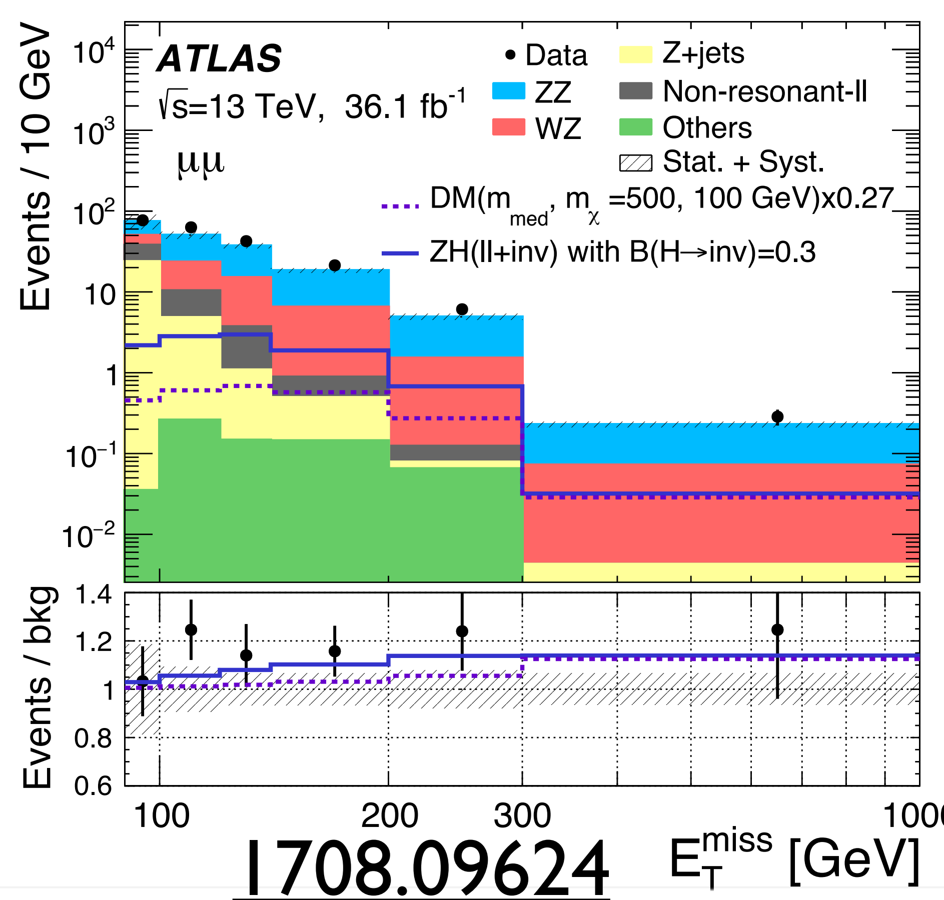


ATLAS-CONF-2017-078

Invisible Higgs Decays

- The Higgs could decay to invisible or undetected BSM particles
- For invisible, the most sensitive channel is VBF
- Upper limit of ~30% at the 95% CL on branching fraction from combined ATLAS and CMS Run-1 results
  - Assumes unitarity-inspired constraint of $\kappa_V < 1$
- Recent ATLAS search using associated ZH production sets a limit of 67% at the 95% CL

Direct



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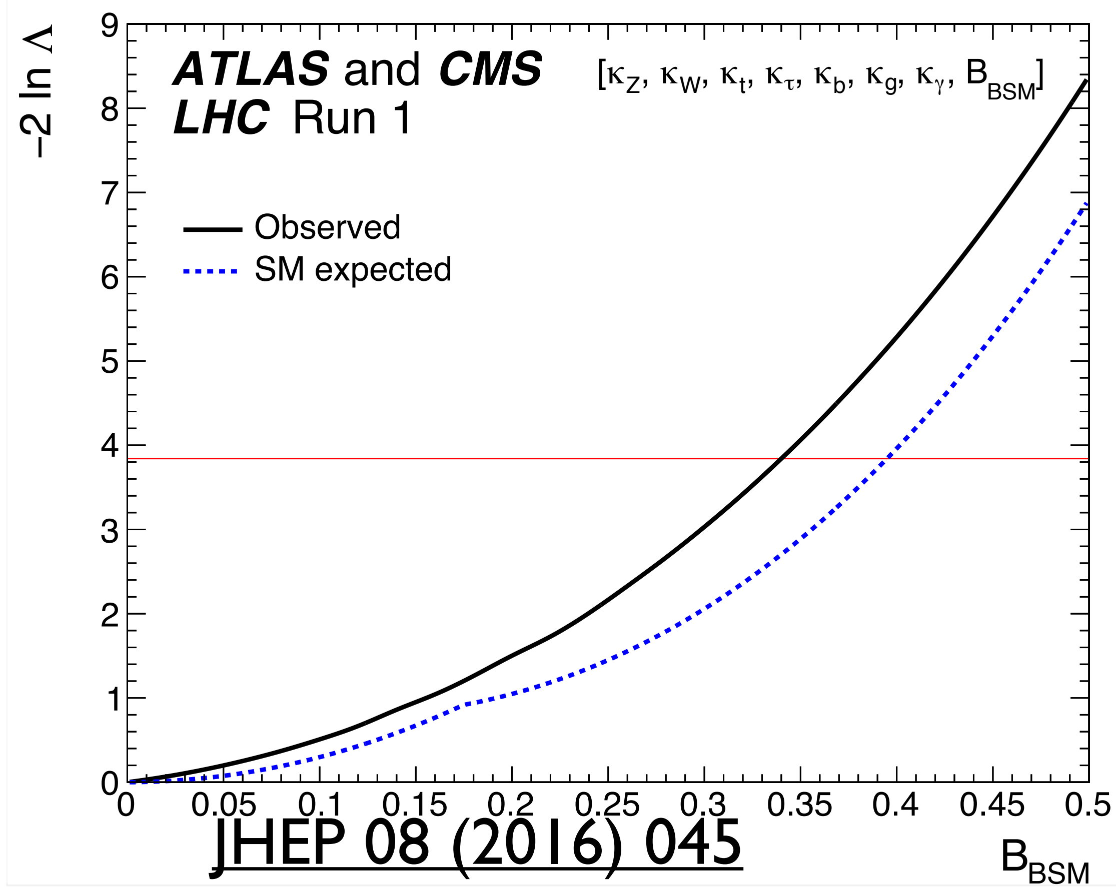
Indirect

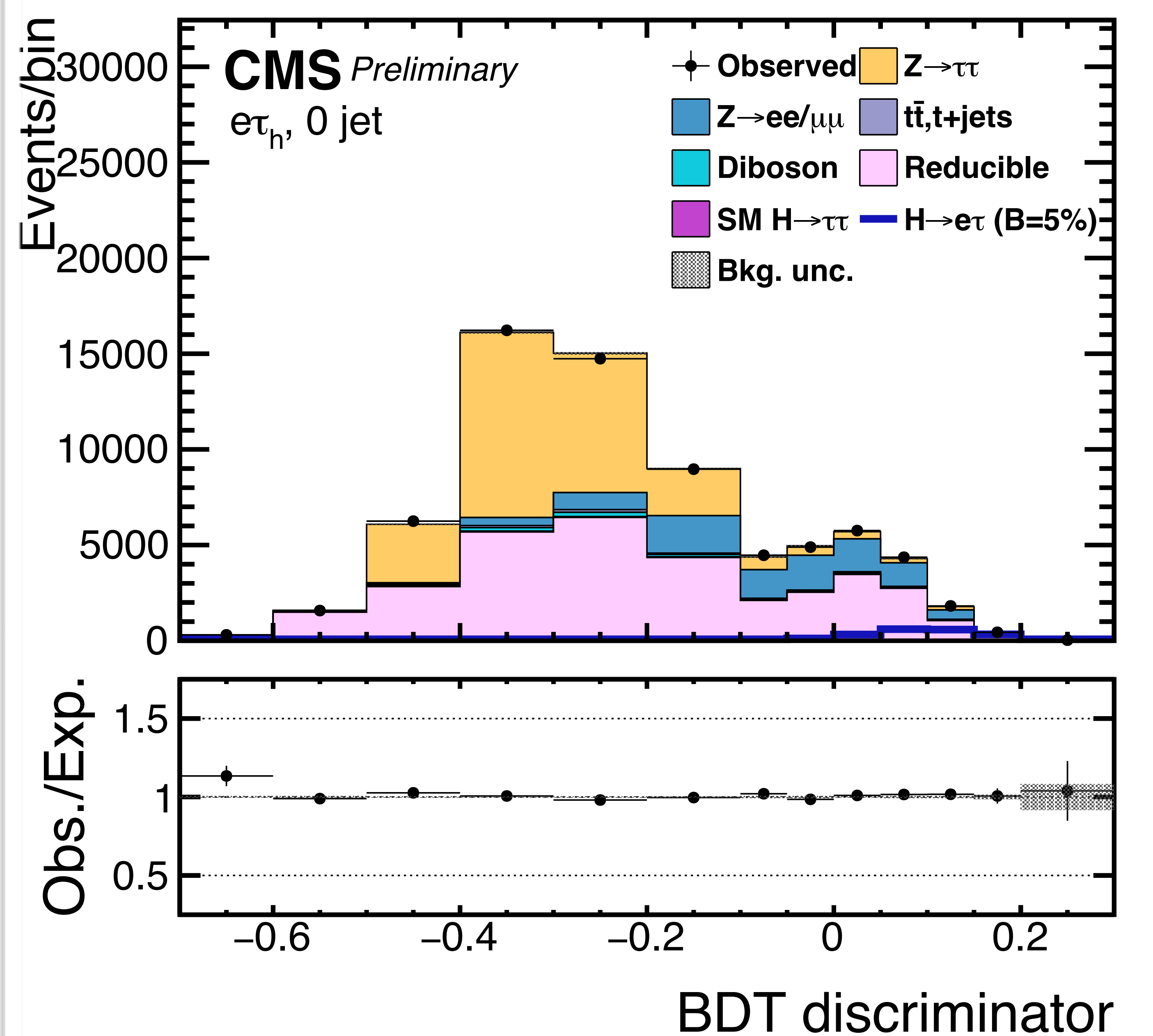


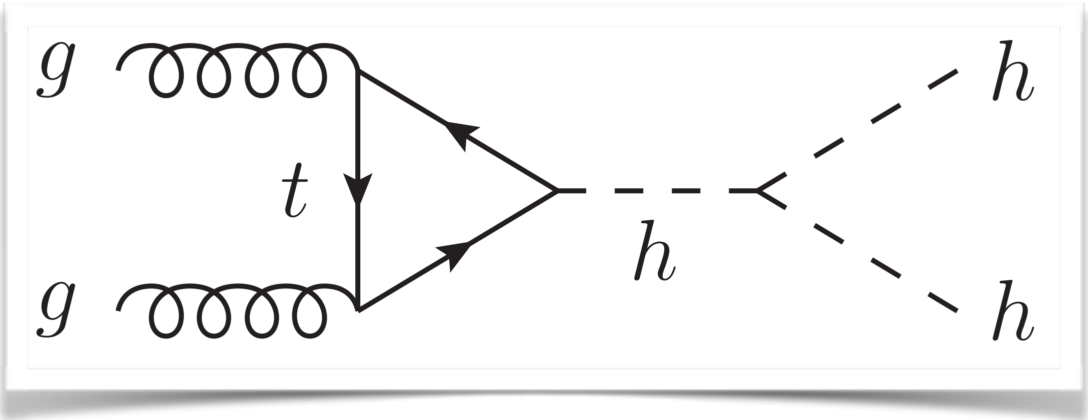
JHEP 08 (2016) 045

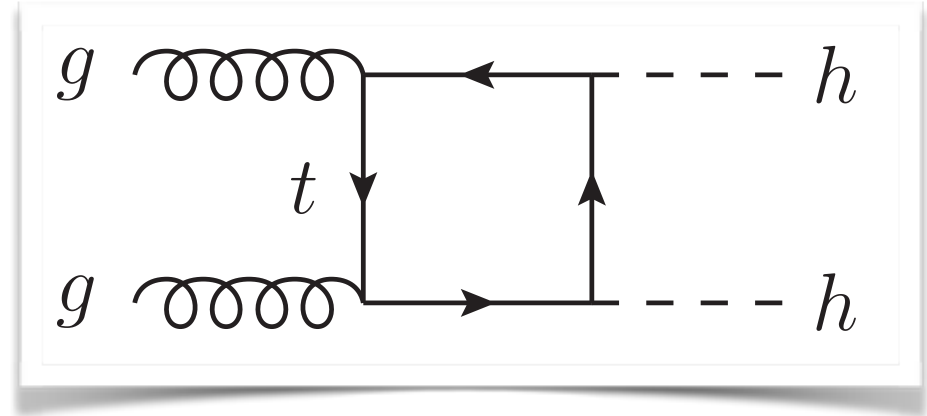
Lepton-flavour violating Higgs decays

- No lepton flavour violating Higgs decays in the Standard Model
- Search for lepton flavour violation via H→eτ and H→μτ
- Slight tension with SM in Run-1 with a mild excess
- Obtain limits of ~10^{-3} on the off-diagonal couplings

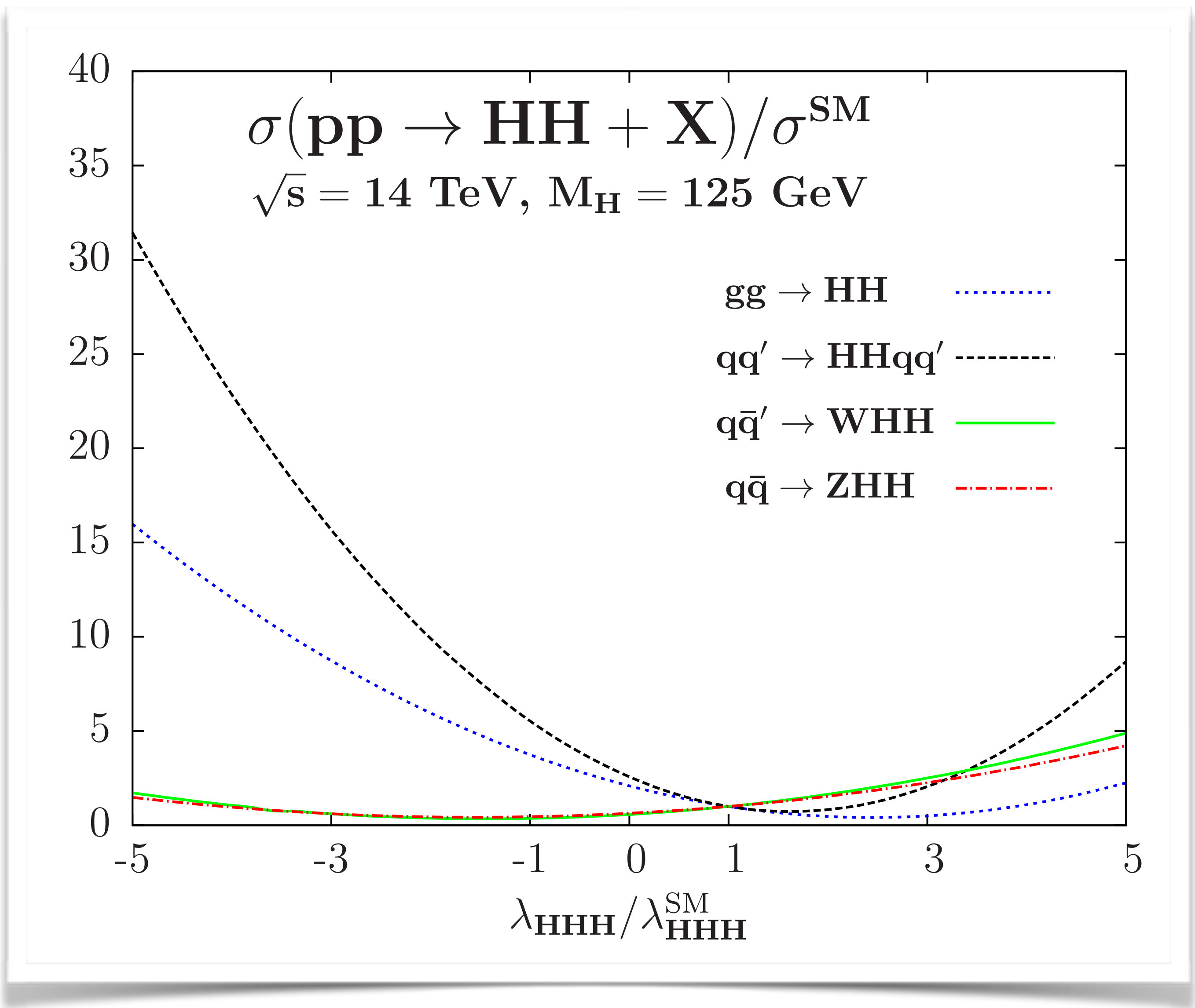
HIG-17-001







DiHiggs Production



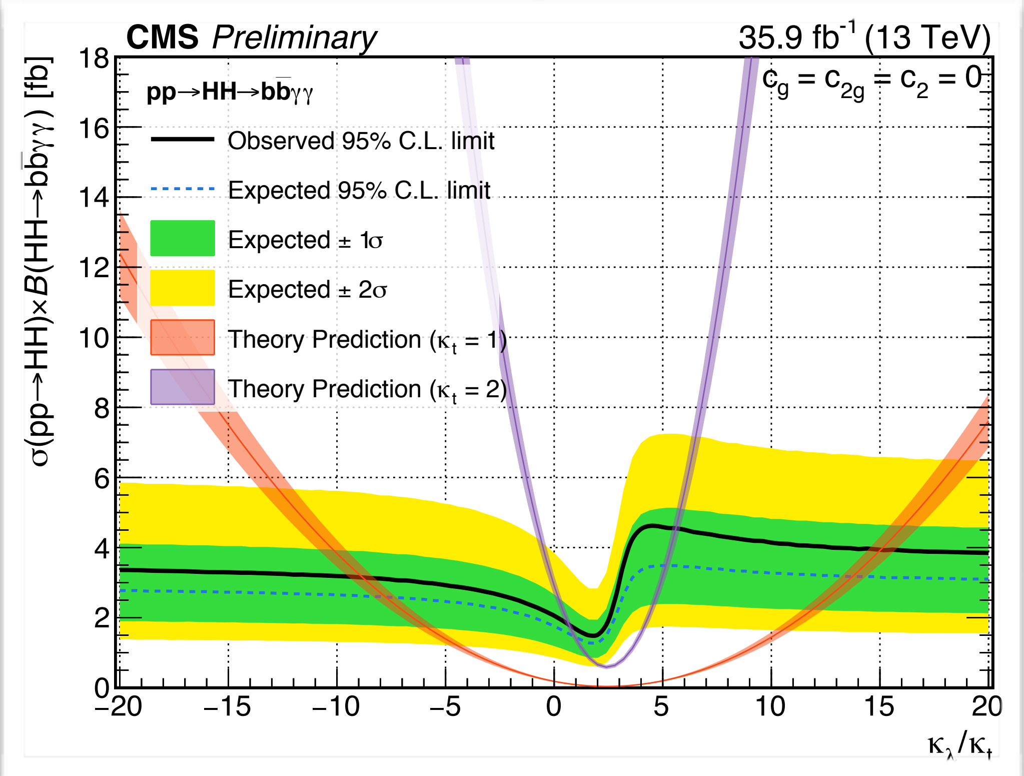
1212.5581

Double Higgs production

- Non-resonant HH production main probe for the Higgs self-coupling
- Tiny cross-section, σ = 33 fb, due to destructive interference
- Many possible channels: product of individual Higgs decay channels
- Sensitivity currently O(10) x SM
- Require full HL-LHC statistics to approach SM sensitivity

μ < @95%	ATLAS	CMS
bbbb	< 29	< 342
bbWW		< 79
bbττ		< 30
bbγγ	< 117	< 19
WWγγ	< 747	

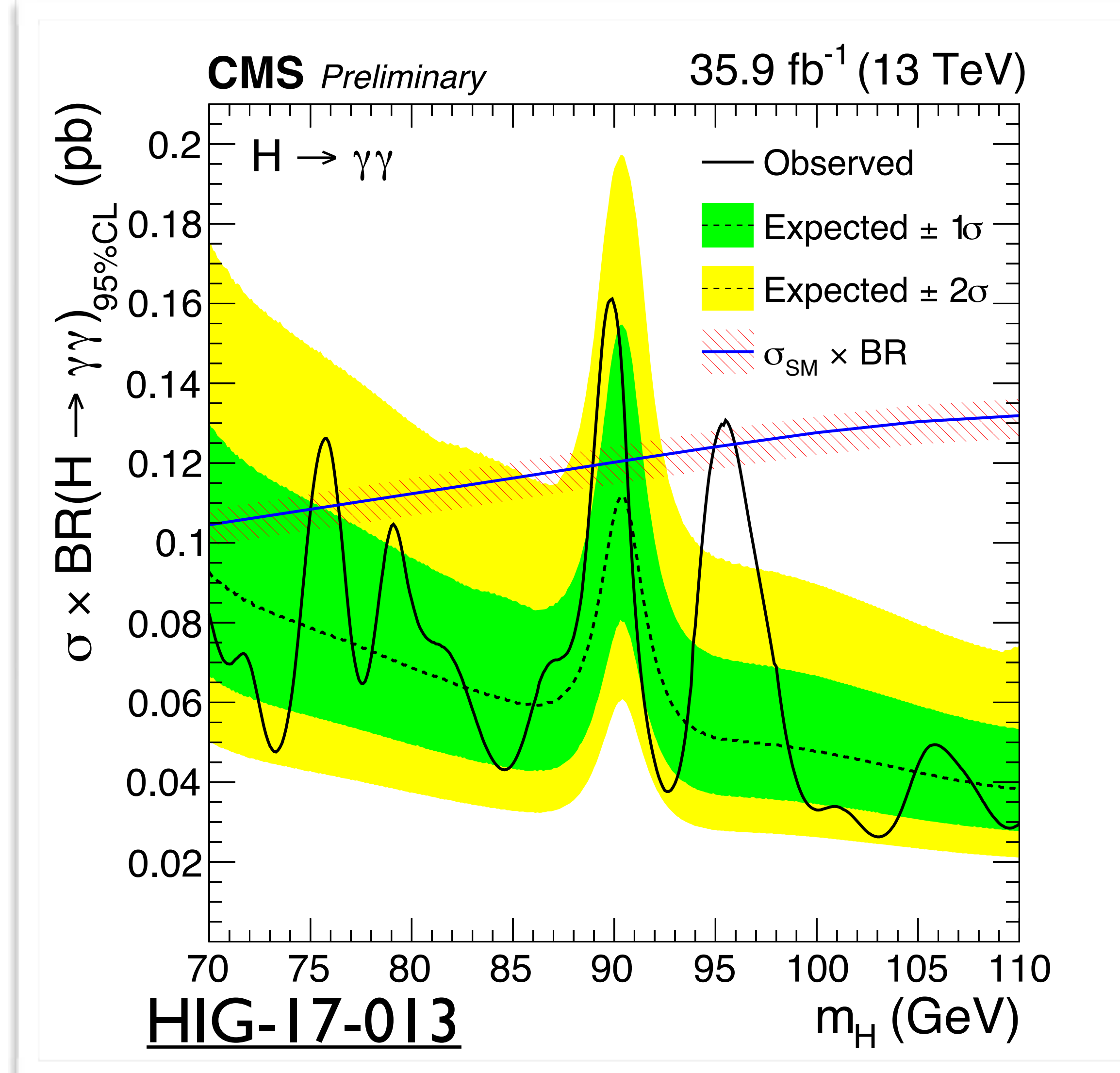
Run-2	3 fb^{-1}	13 fb^{-1}	36 fb^{-1}



HIG-17-008

Additional Higgs Bosons

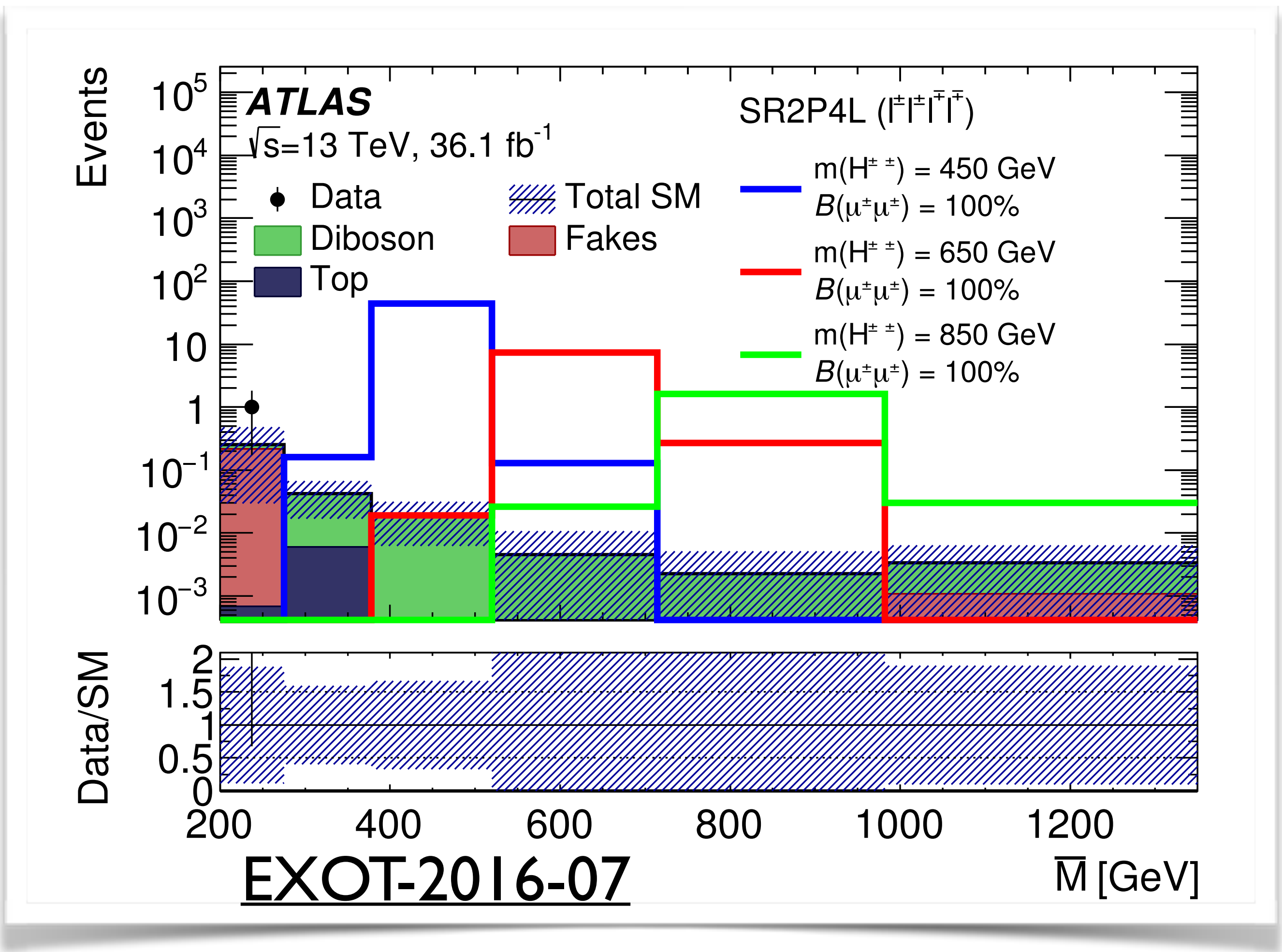
Searches for Additional Higgs Bosons



Many BSM models predict additional neutral or charged Higgs bosons

Additional neutral SM-like Higgs bosons with different mass

Example: cross-section limit from a low mass $H\to\gamma\gamma$ search



Charged Higgs bosons

Example: Search for a doubly-charged Higgs boson decaying to two or three leptons

Conclusion

- Rapid progress in the Higgs measurement program at the LHC
- Observation or evidence for all main production and decay modes
    - Recent exploration of the fermionic sector
    - Searches for additional decay modes are being developed
- Mass measured to 0.2% precision
- Constraints on width from off-shell measurements
- Charge and parity consistent with SM predictions
- Searches have begun for diHiggs production
- No evidence for non-SM Higgs decays
- No evidence for additional Higgs bosons

Overall, excellent consistency with SM predictions

Backup