Physics at the HL-LHC in ATLAS and CMS

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on behalf of the US-ATLAS and US-CMS Collaborations
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

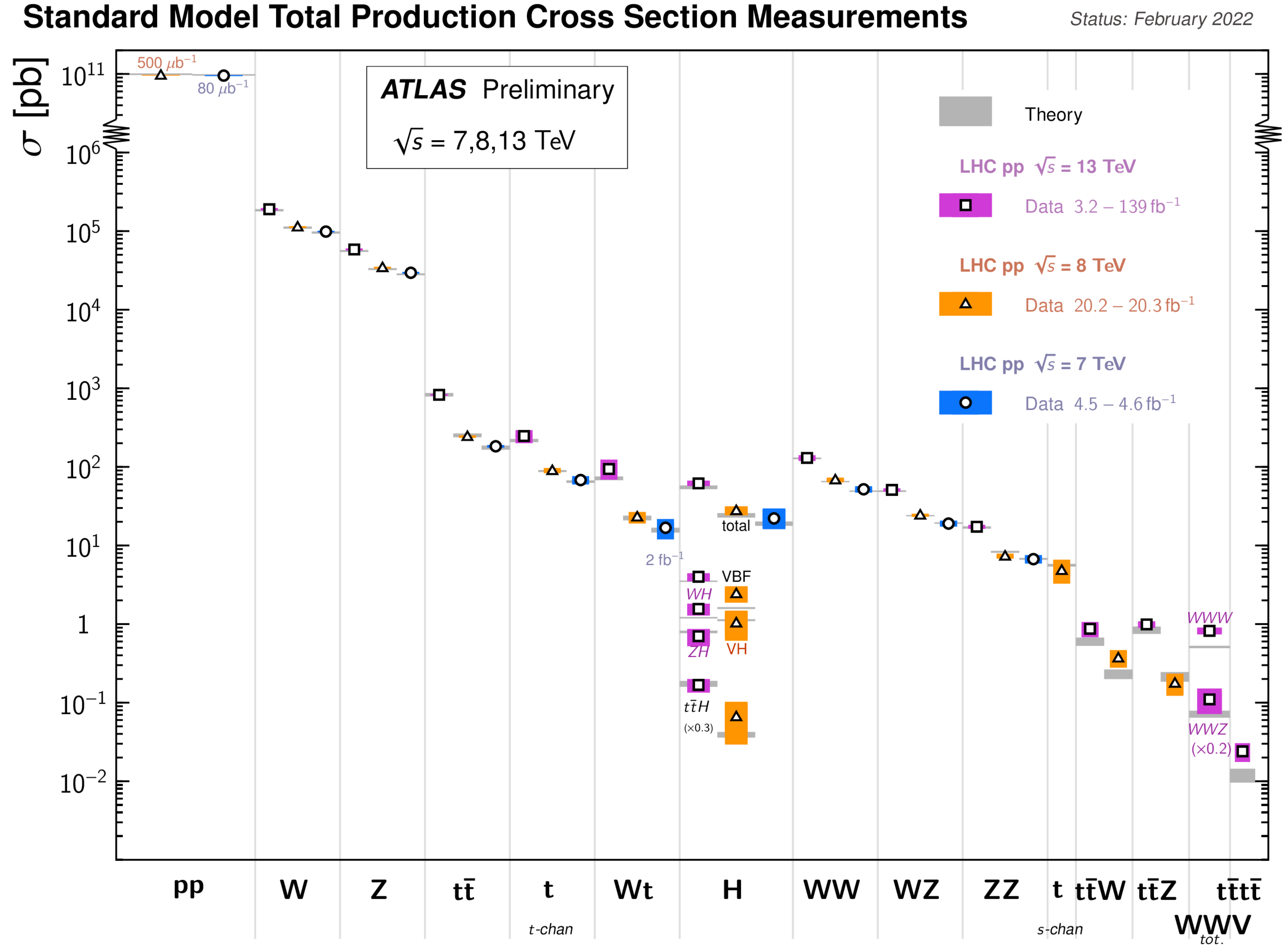
P5 Town Hall
Brookhaven National Laboratory, April 12, 2023

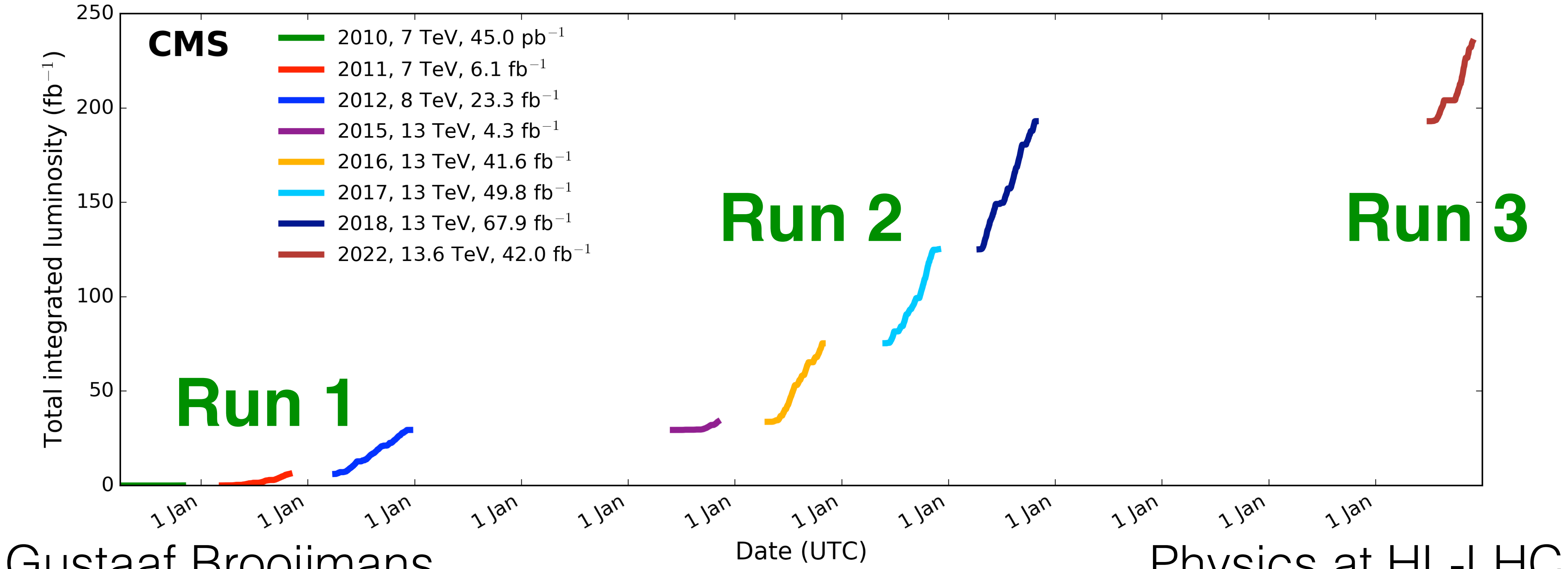
Outline

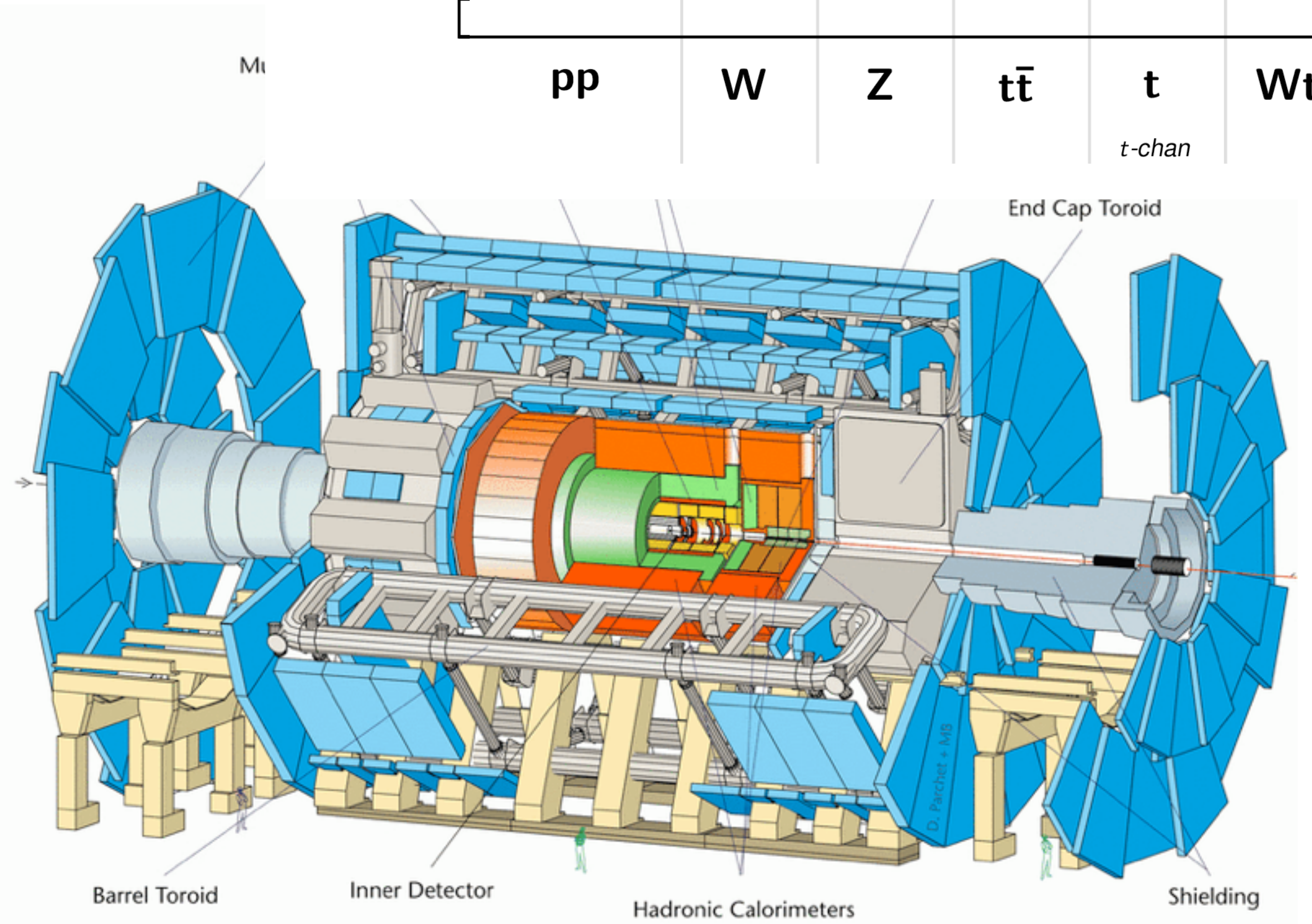
- The High Luminosity LHC
- Higgs Physics
  - Higgs precision physics
  - Di-higgs and the Higgs potential
- Beyond the Standard Model
  - A reason to believe in (some) answers at the TeV scale
  - What 20x more luminosity buys you
  - But also new tools, more complex analyses
- Standard Model Measurements
- Closing
- ATLAS+CMS Snowmass White Paper: ATL-PHYS-PUB-2022-018

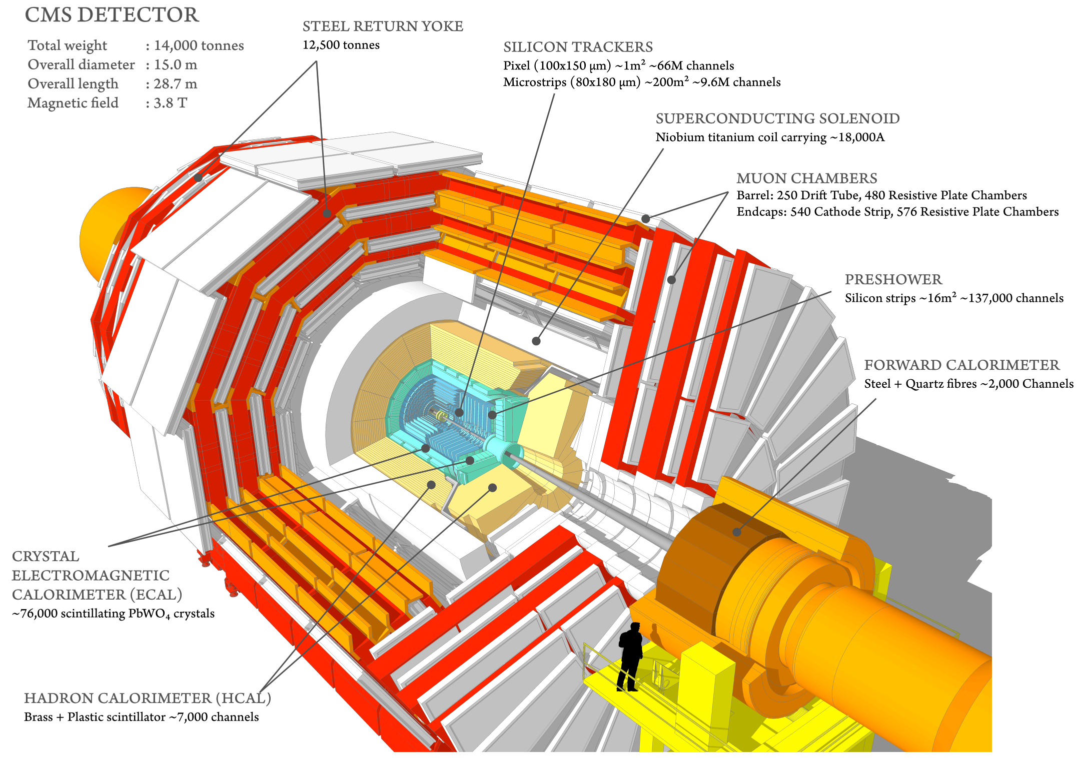
High Luminosity-LHC

- LHC so far
  - Run 1 (2010-2012, 7-8 TeV, ~30 fb^{-1})
    - Higgs discovery
  - Run 2 (2015-2018, 13 TeV, ~150 fb^{-1})
    - Observed Higgs is within ~20% of the SM Higgs, tribosons, 4 tops, … no new physics yet
  - Run 3 (2022-2025, 13.6 TeV, ~40 fb^{-1} so far)
    - Get to ~500 fb^{-1} total
    - Reaching the edge of current detector capabilities (pile-up at ~60 interactions/bunch crossing)
- HL-LHC: 14 TeV, 3000+ fb^{-1}
  - **20x** more data than analyzed so far!



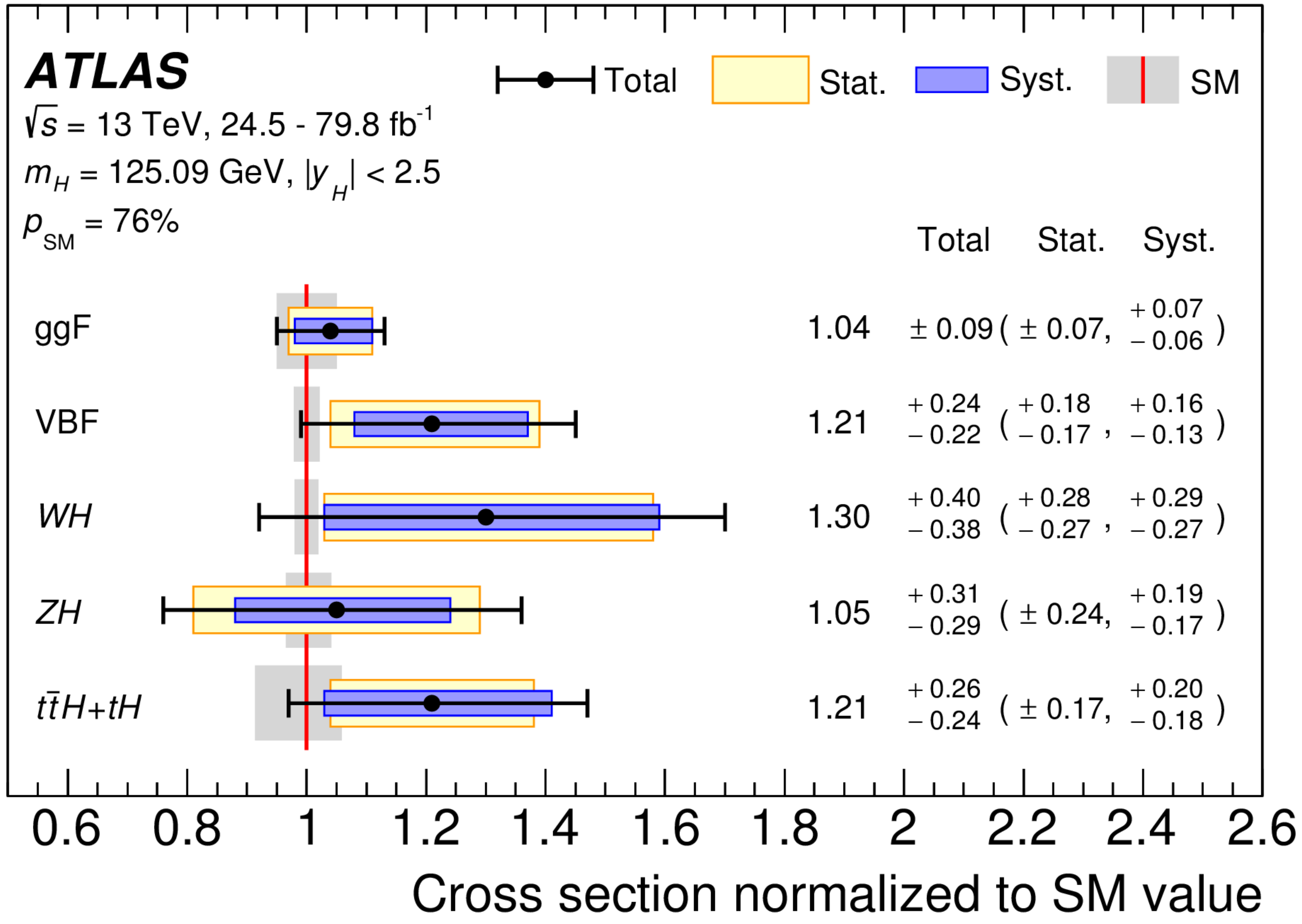


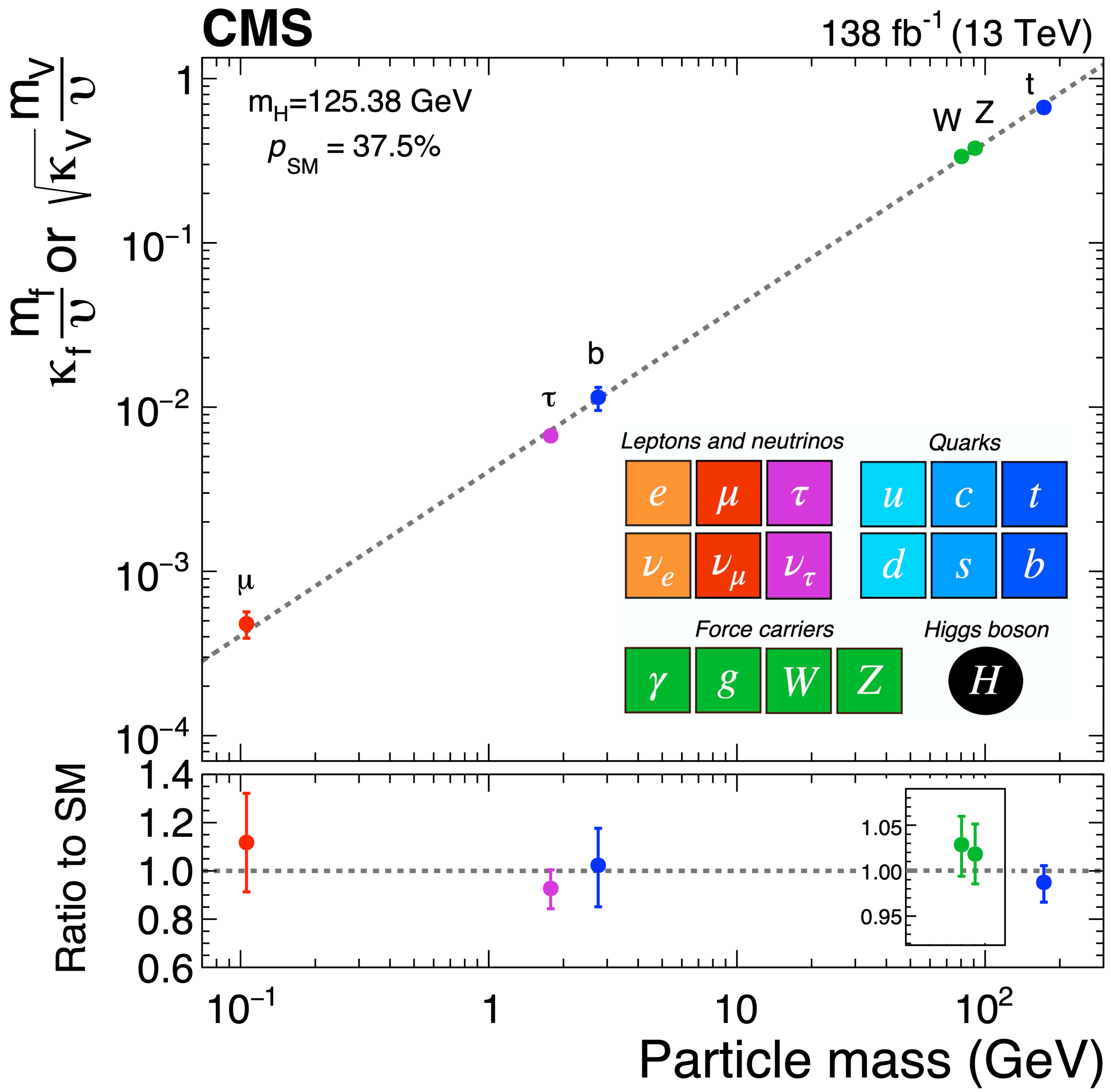




Higgs Observation at the LHC

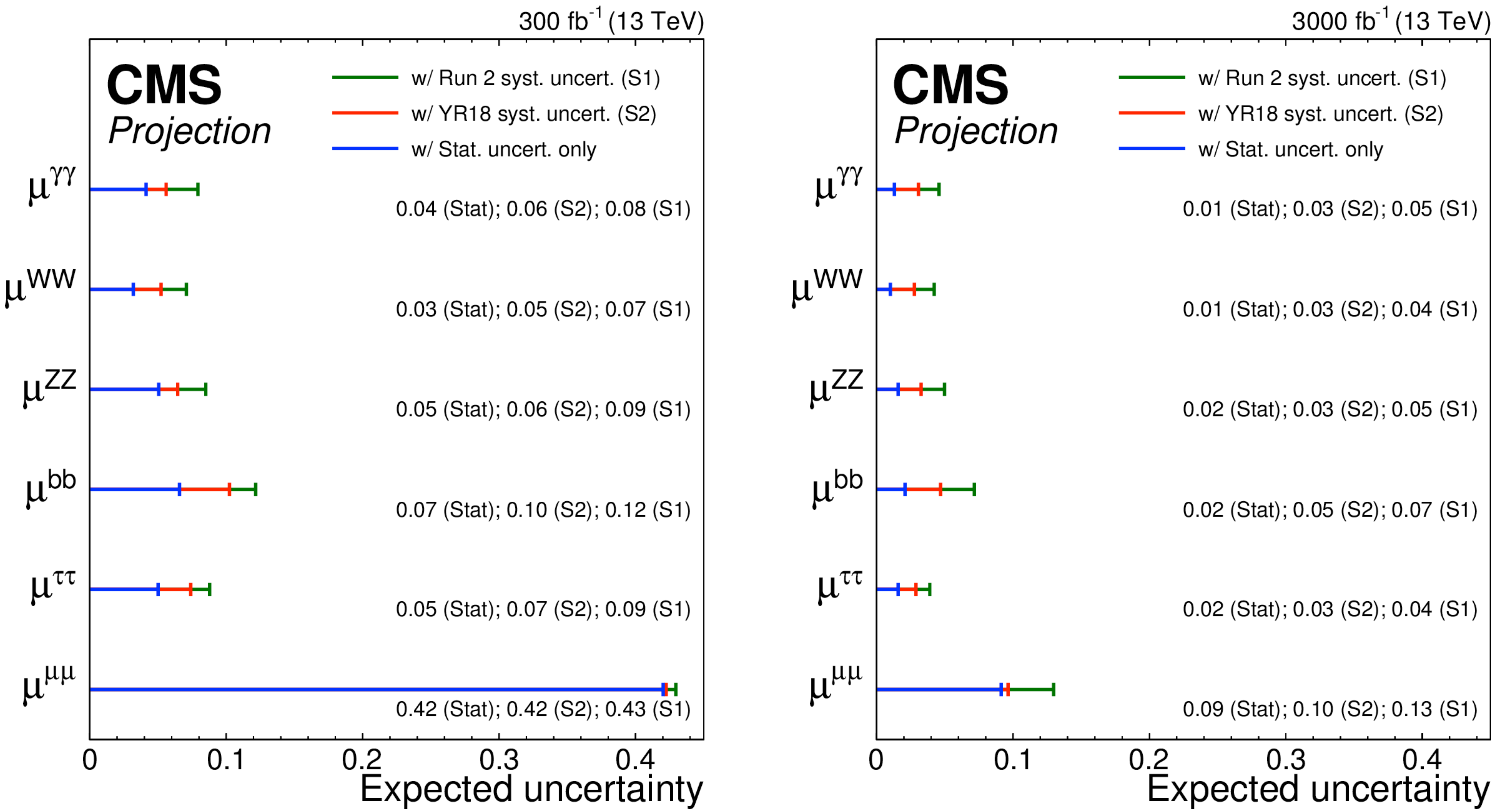
- The existence of *a* Higgs boson is firmly established
  - Couplings match SM prediction fairly well, but 20-100% level deviations allowed





HL-LHC: Measure, Measure

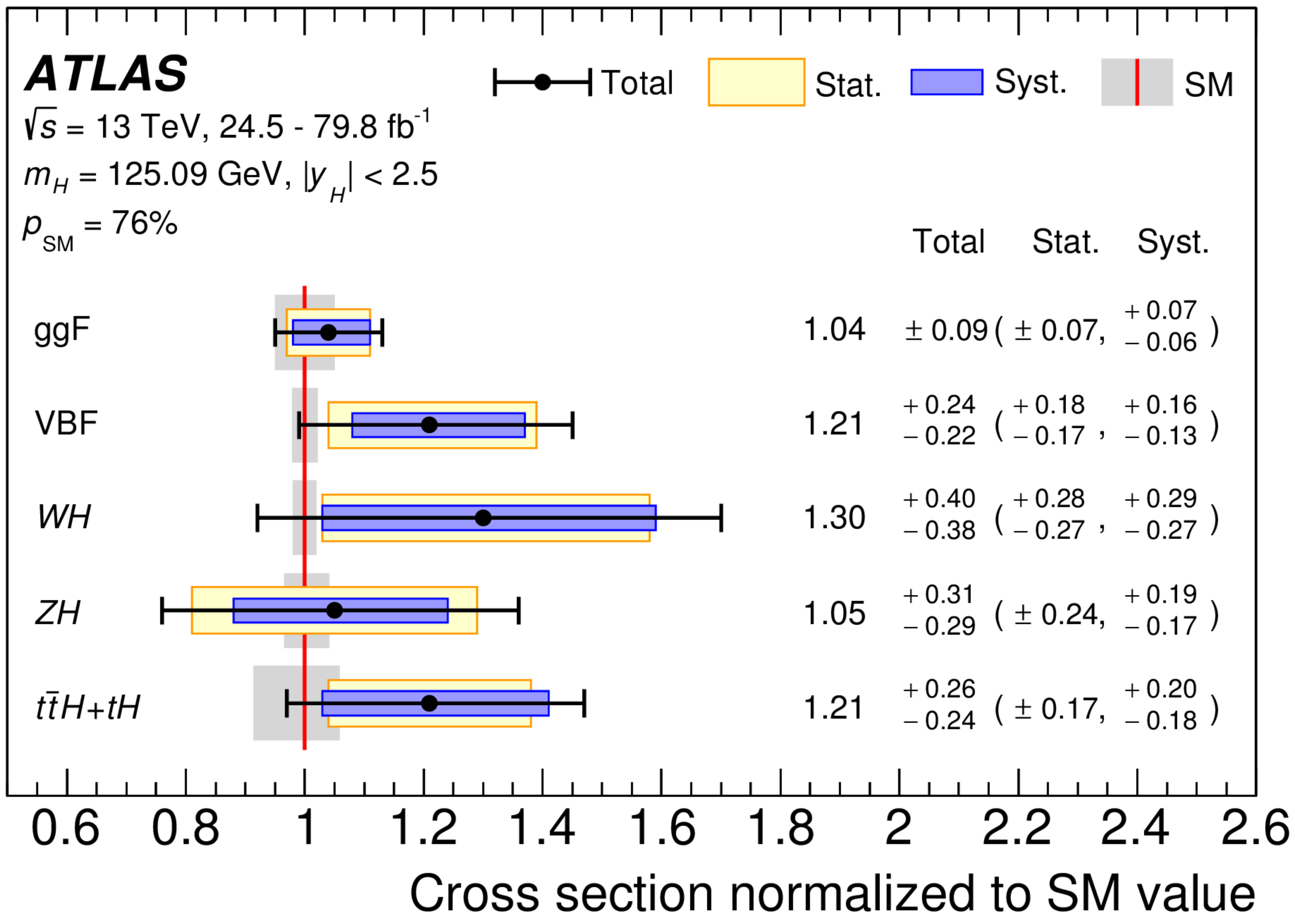
- Is it really the Standard Model Higgs?
  - What does 20x more data buy you?
  - Measure accessible decays at the 5% level (10% for μμ)

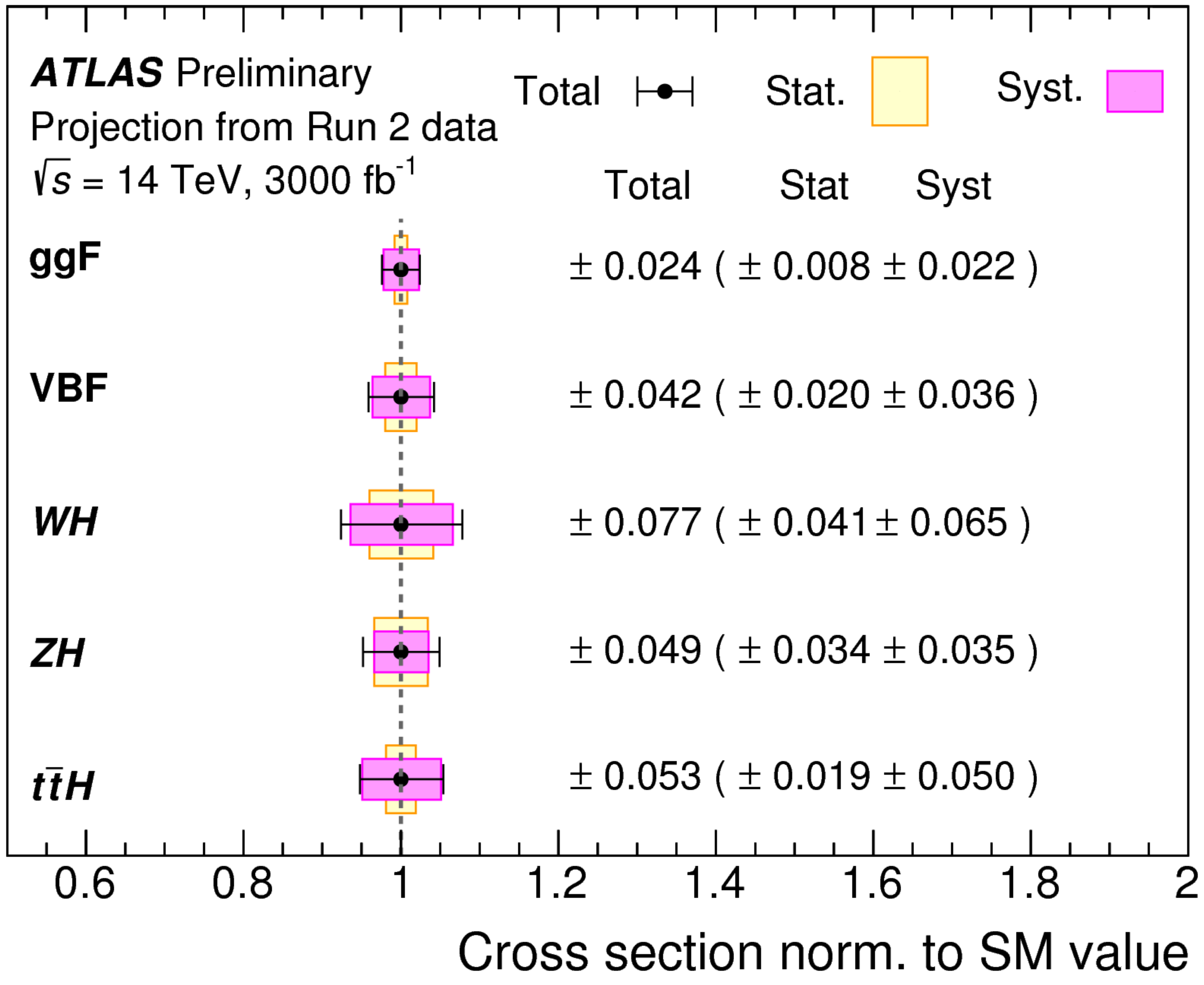


CMS-PAS-FTR-18-011

HL-LHC: Measure, Measure

- Is it really the Standard Model Higgs?
  - What does 20x more data buy you?
  - In production modes, reduce wiggle room to ~10% (and could eg see evidence for 15% deviation in Vector Boson Fusion cross-section); differential measurements



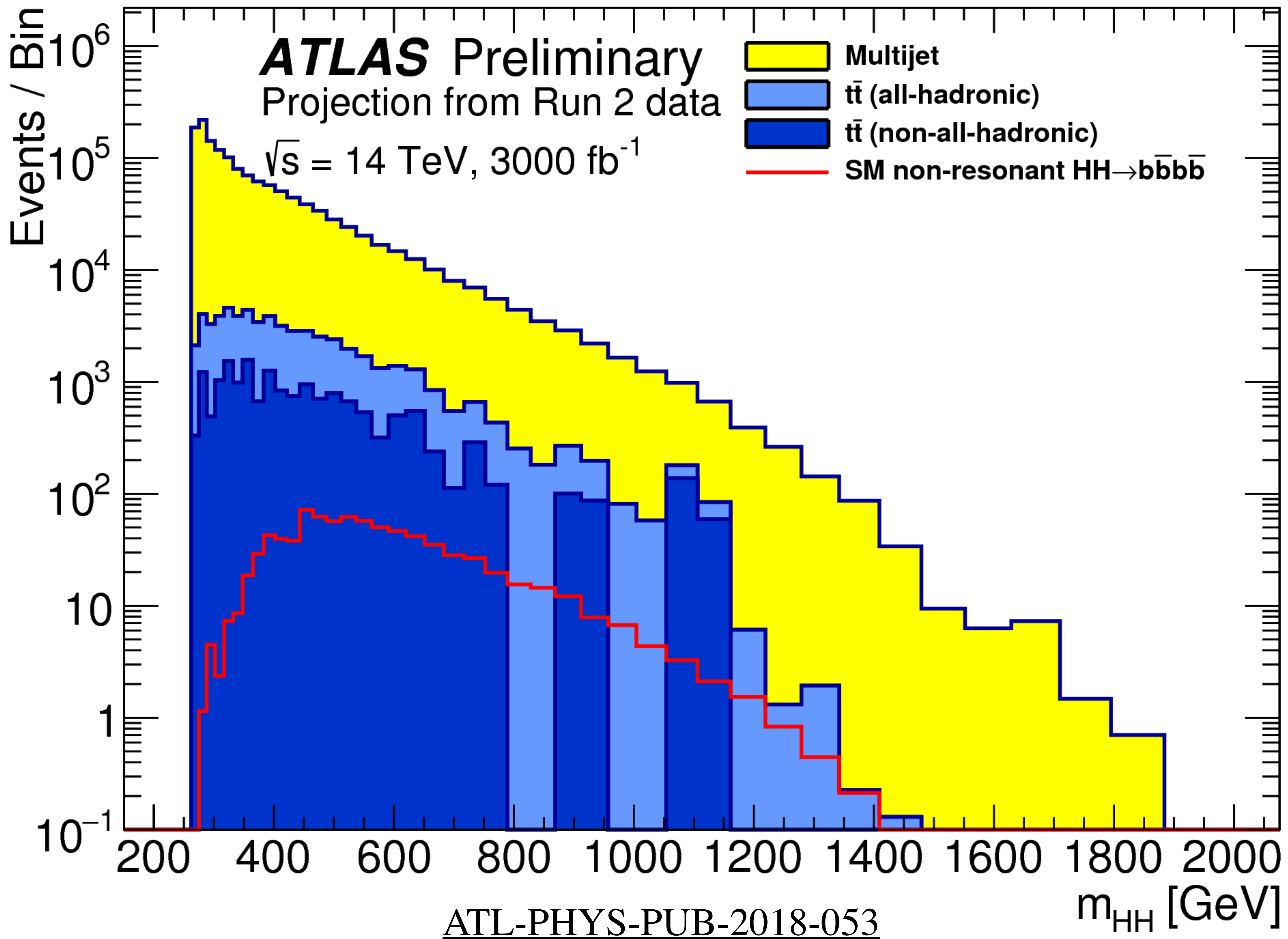


Measuring the Higgs Potential

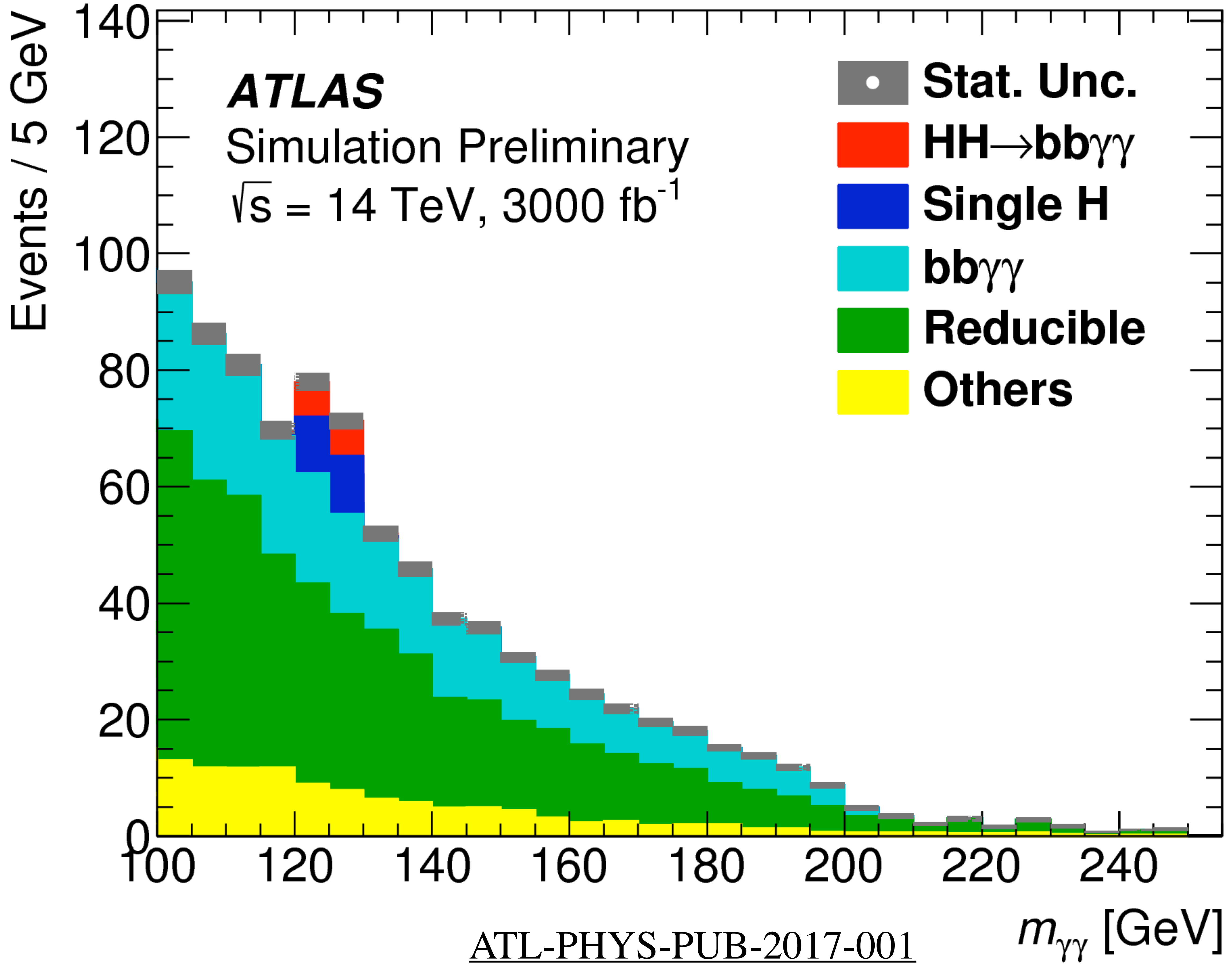
- The Standard Model predictions for Higgs production and decay are robust, as the couplings to bosons and fermions are set by their masses
  - But this is not so true for the Higgs potential, which could be more complex
    - Around minimum, expand $V = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \supset \lambda v^2 H^2 + \lambda v H^3 + (\lambda/4)H^4$
    - First term is just Higgs mass, next are trilinear and quartic couplings
    - So Higgs mass sets λ, then probe if indeed get the same λ for the others
      - Requires measuring multi-Higgs production
- Multi-Higgs production cross-sections are small
  - In particular in the Standard Model, where there is large destructive interference
    - It's (mostly) easier to see new physics than the Standard Model!
- Quartic term will need higher energy (VBF di-Higgs production…)

The Challenge

- The Higgs mass is only 125 GeV, and ~60% BR to *b* quarks
  - So we get 4 *b*-jets of ~60 GeV… and few events if look for one Higgs decaying to γγ



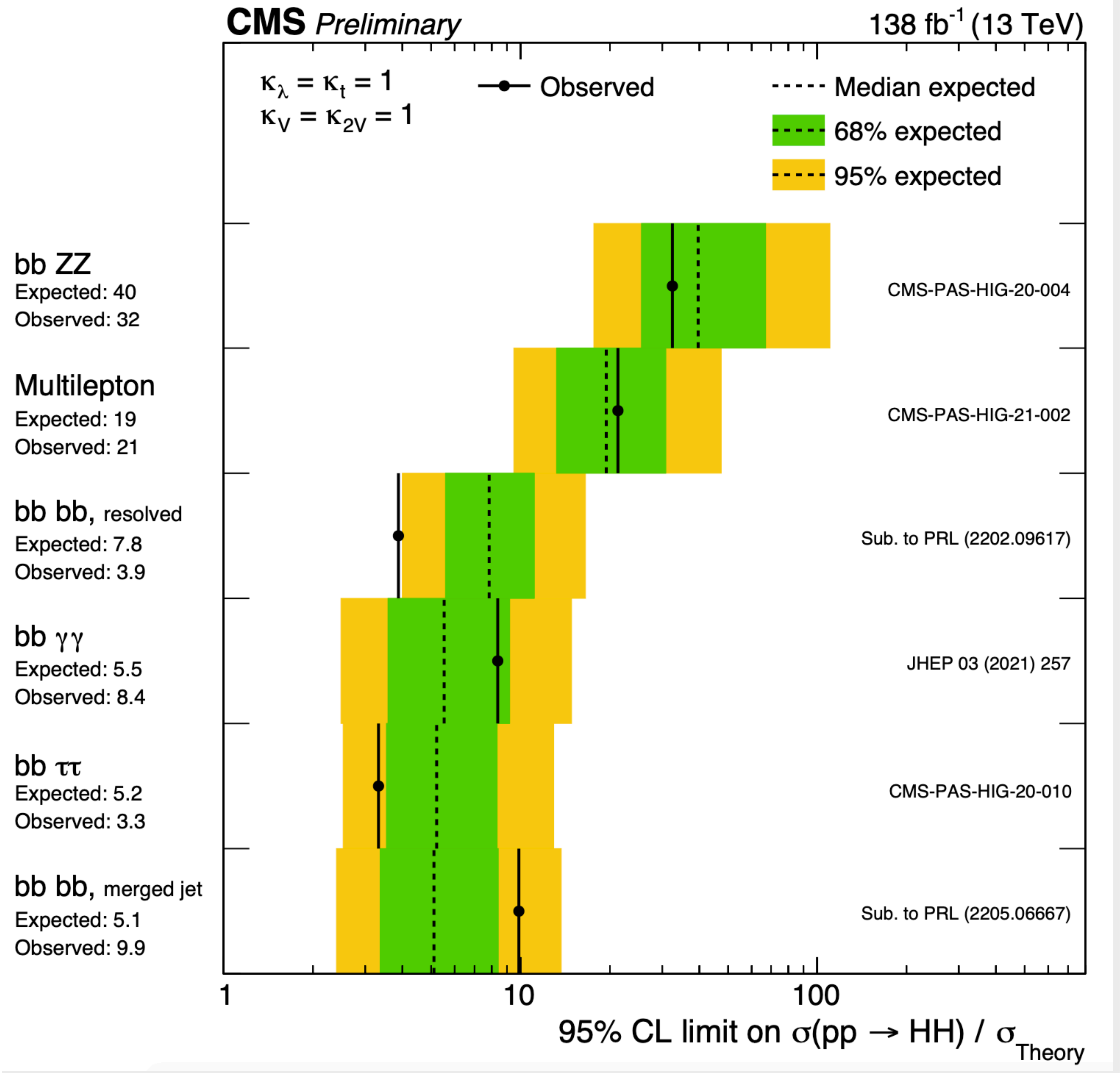
ATL-PHYS-PUB-2018-053

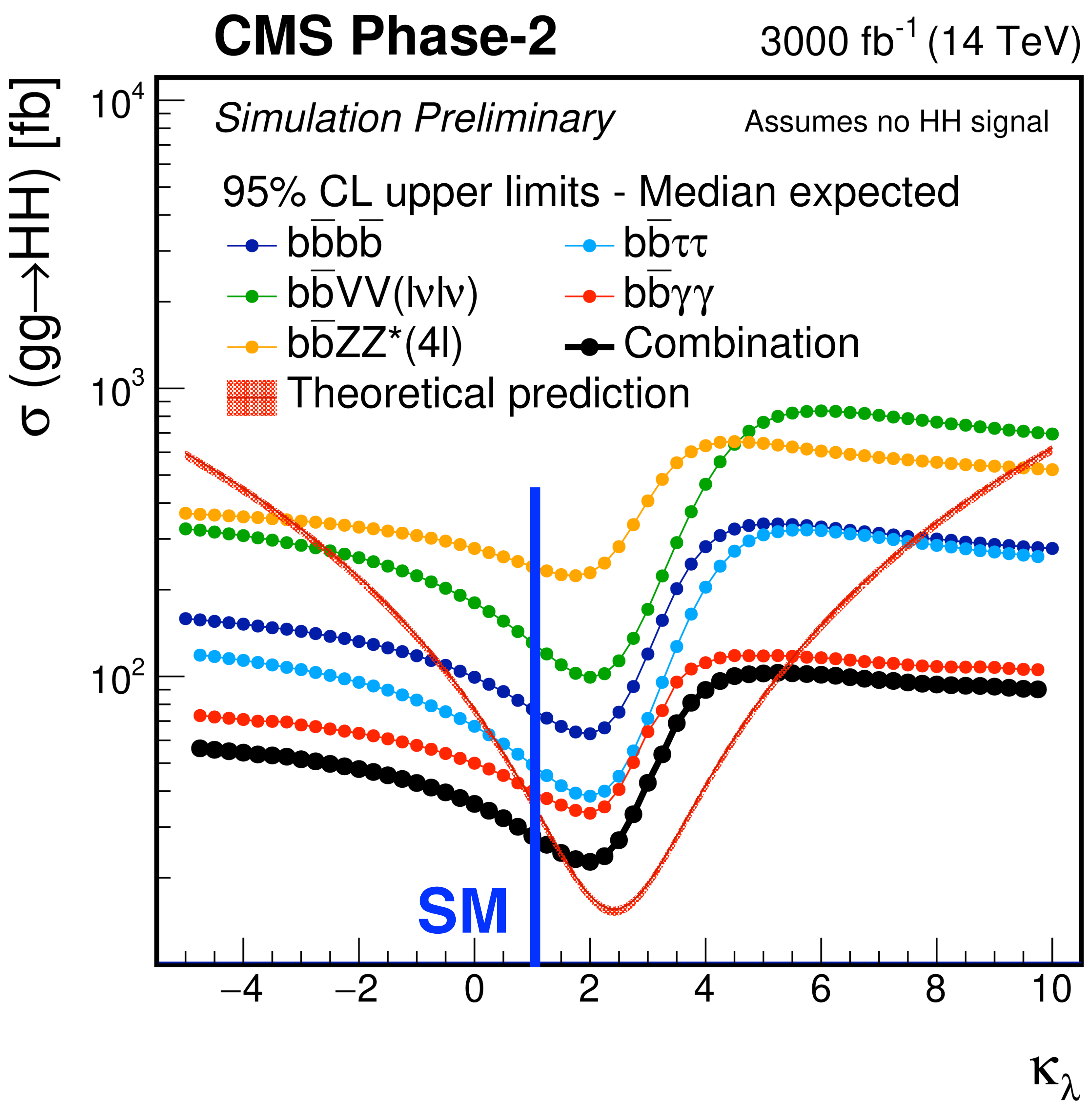


ATL-PHYS-PUB-2017-001

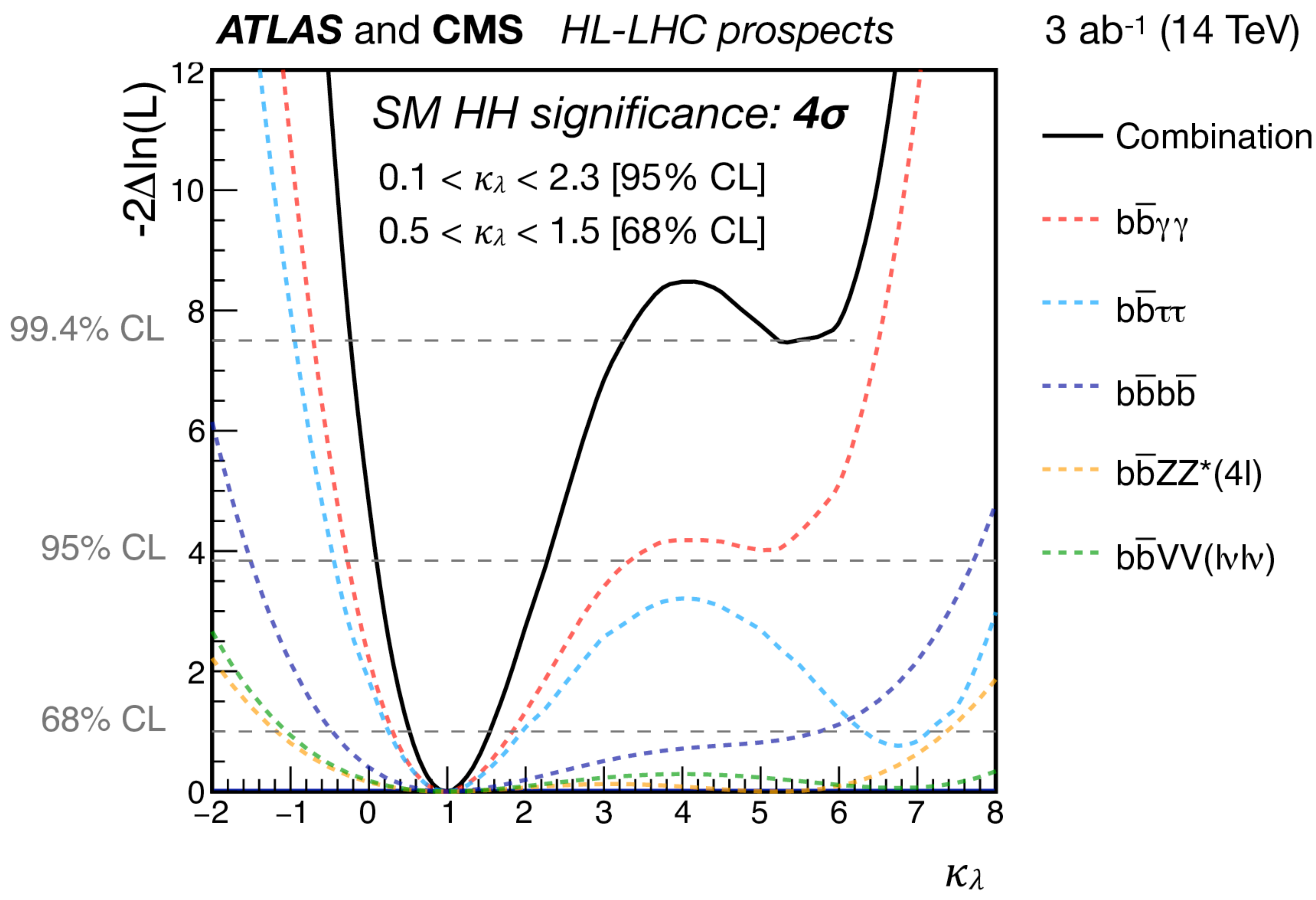
Di-Higgs Sensitivity

- Current sensitivity (5% of HL-LHC dataset): 95% CL expected limits at ~5x SM
- With 3000 fb^{-1}, could exclude SM… or, at SM signal strength, see evidence





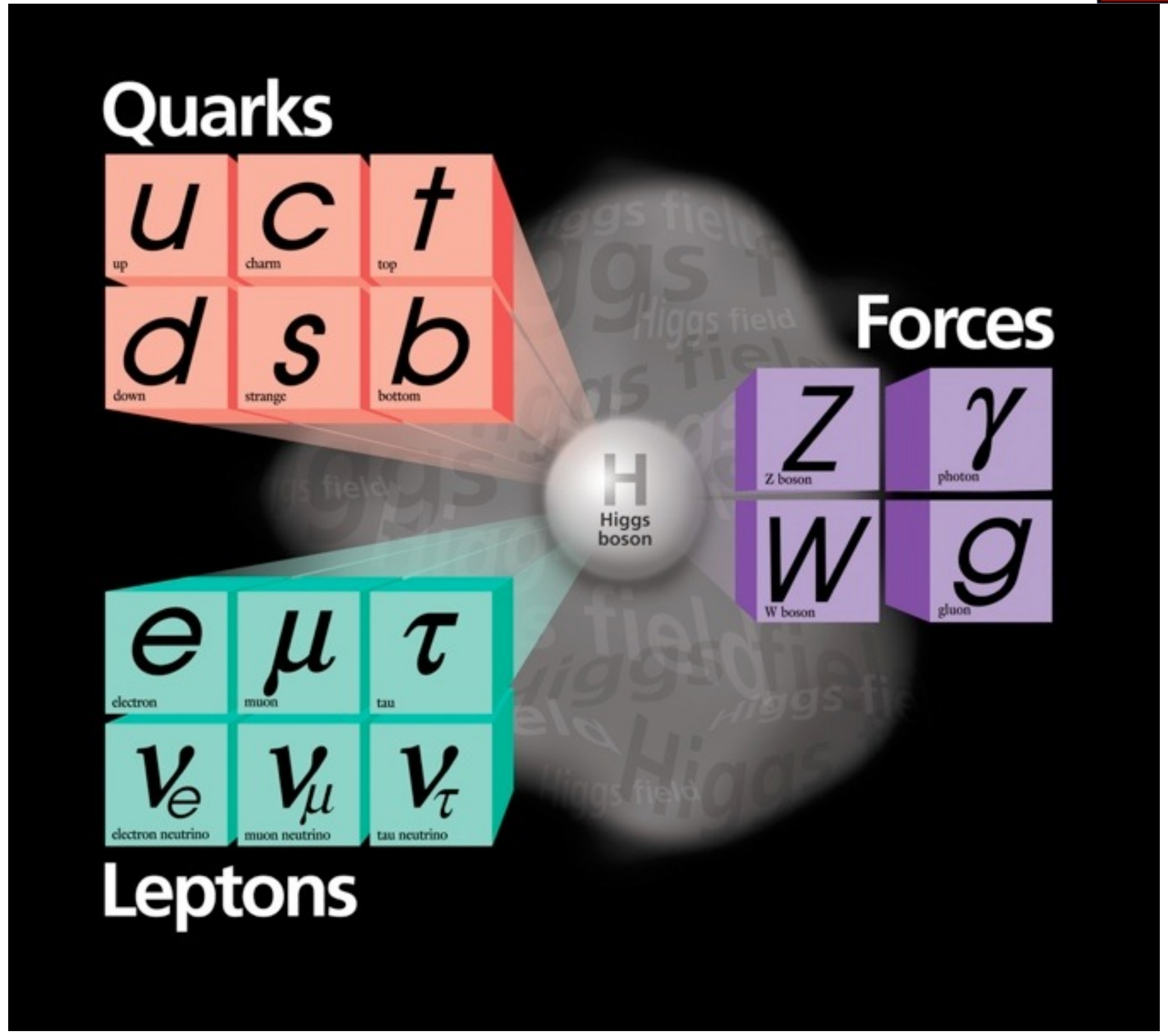
CMS-PAS-FTR-18-019



ATL-PHYS-PUB-2022-018

Lacking in the Standard Model

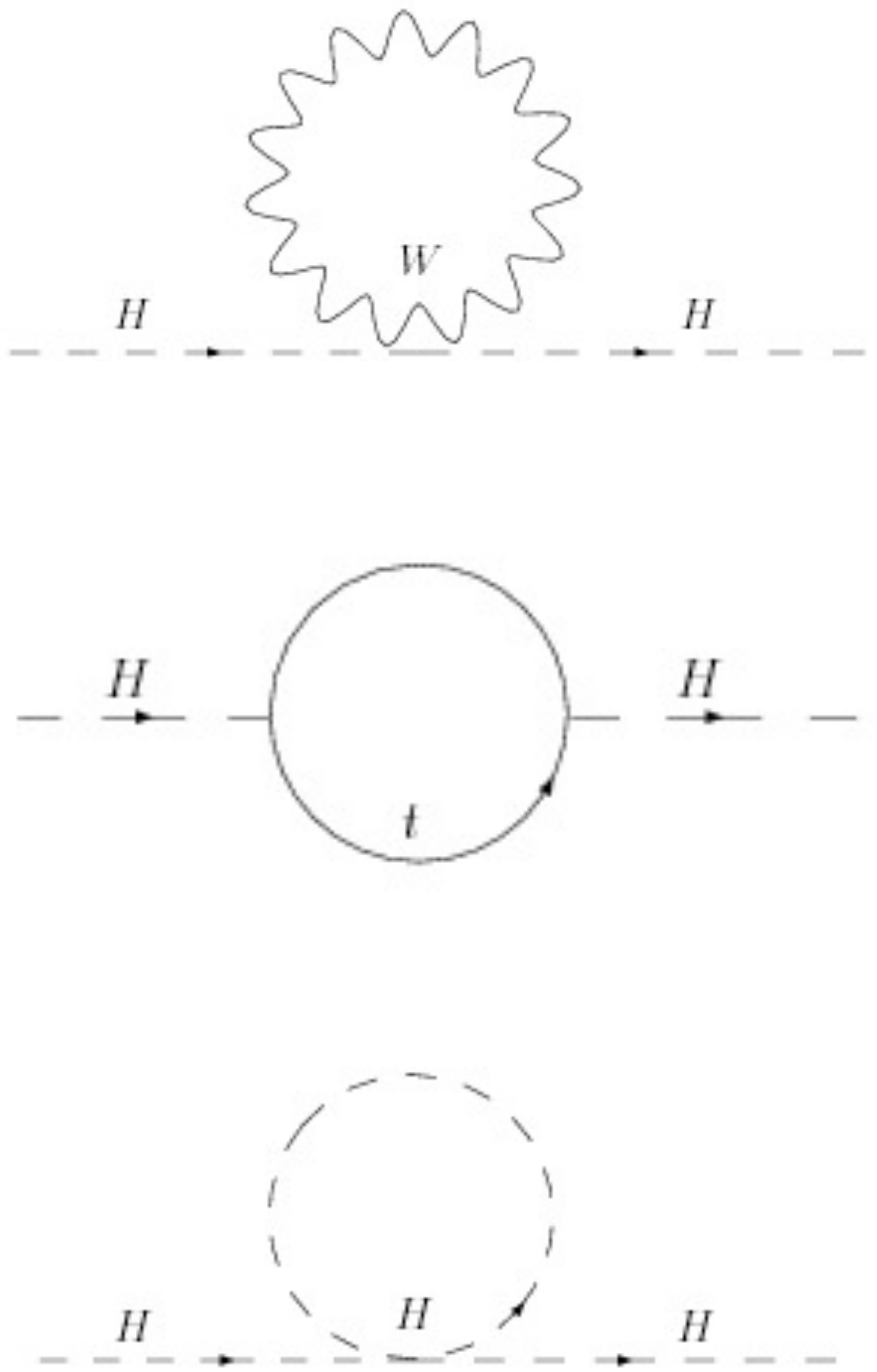
- Clear structure in fermionic sector unexplained
  - No understanding of the "charges"
  - Evidence of selective principle(s)
    - E.g. no neutral colored fermions
  - And links between quarks and leptons
    - q(down) = q(e)/N_c
  - ➡ Interpreted as evidence for (grand) unification
    - Grand or less grand? (One or more scales?)
- Many cosmological issues
  - Dark matter and dark energy
  - Not enough CP violation in the quark sector for baryogenesis
  - Strong CP symmetry?
  - Baryon number violation
- 42?



"Light" Higgs!?

- The low Higgs mass (compared to e.g. the unification scale) is a puzzle
  - Should be at the limit of validity of the theory
  - Either the Higgs mass is unnatural …
  - … or there is new physics "nearby"
- Of course hierarchies are common in nature
  - But so far gaps no larger than 1-2 orders of magnitude in mass/energy, not 10…

➡ Expect new physics at the 1-10 TeV scale



$\rightarrow \frac{1}{16\pi^2} g^2 E^2$

$\rightarrow \frac{3}{16\pi^2} y_t^2 E^2$

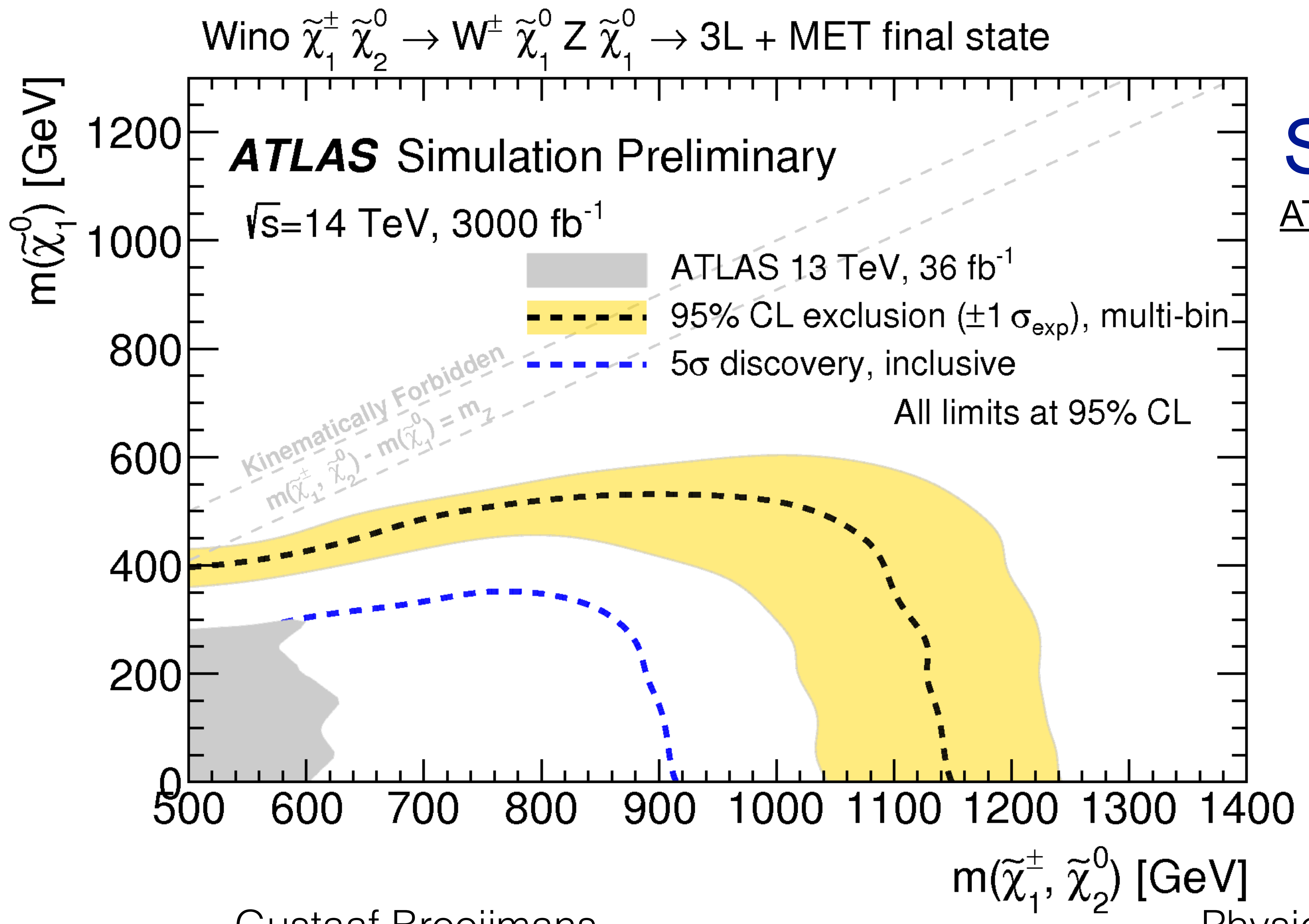
$\rightarrow \frac{1}{16\pi^2} \lambda E^2$

New Physics Models

- Models can largely be organized in a few categories
  - "Electroweak-inspired": add new elementary particles that compensate for the divergent Higgs mass loops
    - Just like the introduction of W, Z, c, H addressed problems in the electroweak sector
  - "QCD-inspired": the Higgs is really (partially?) composite so at higher energy scale the loops are cut off
    - Just like in QCD dimensional transmutation generates a fixed scale
  - "String-inspired": the Planck scale is really much lower than it appears, so there is no hierarchy
    - Turns out this may be another way of looking at QCD-inspired (AdS/CFT)
- Manifestations are different, but in models that address the hierarchy problem, *something* happens at the TeV scale

New Physics at the HL-LHC

- HL-LHC will run at same energy as LHC (same dipole magnets)
  - But 20x more luminosity (or more)
    - For background-free searches, sensitivity is linear (in signal cross-section) with data increase
    - For searches with background, sensitivity goes with square root

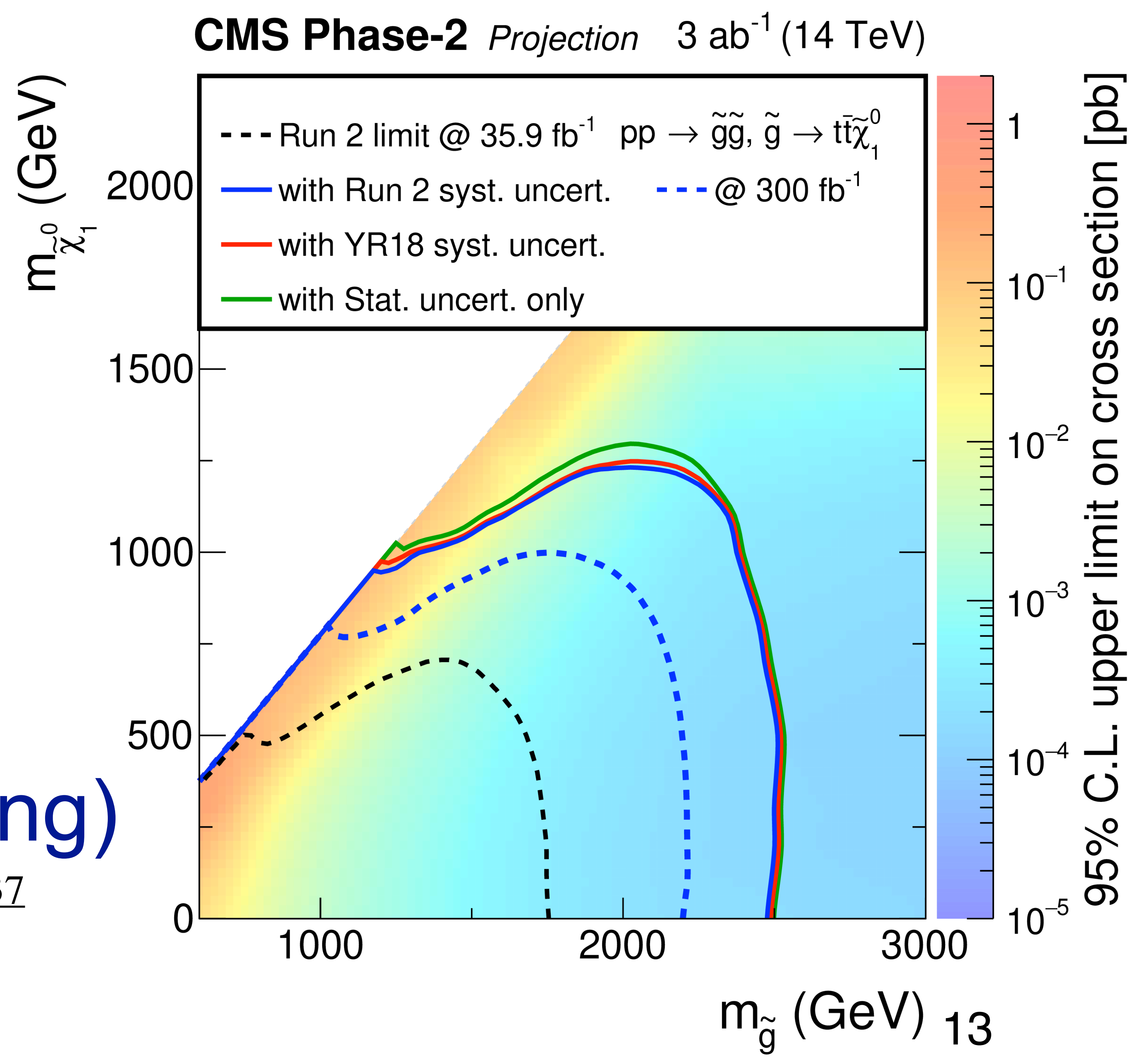


SUSY (Weak)

ATLAS-PHYS-PUB-2018-048

SUSY (Strong)

CMS-PAS-FTR-18-037

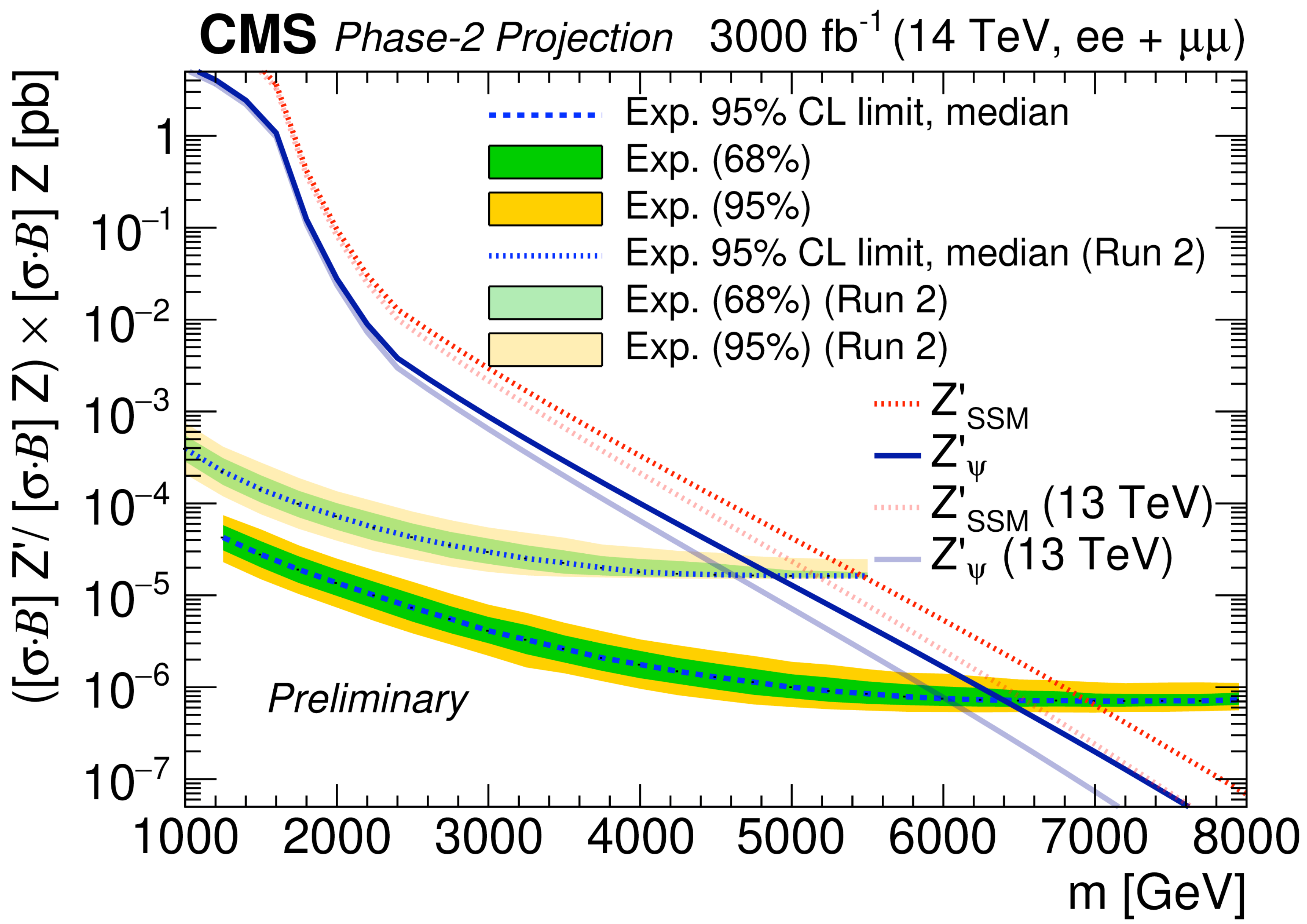


New Physics at the HL-LHC

- HL-LHC will run at same energy as LHC (same dipole magnets)
  - But 20x more luminosity (or more)
  - And new tools, more complex analyses, etc.
    - Machine learning increasingly part of our arsenal

Dilepton Resonances

CMS-PAS-FTR-21-005



New Tools

ATLAS-CONF-2022-045

Anomaly detection search for new resonances decaying into a Higgs boson and a generic new particle X in hadronic final states using $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

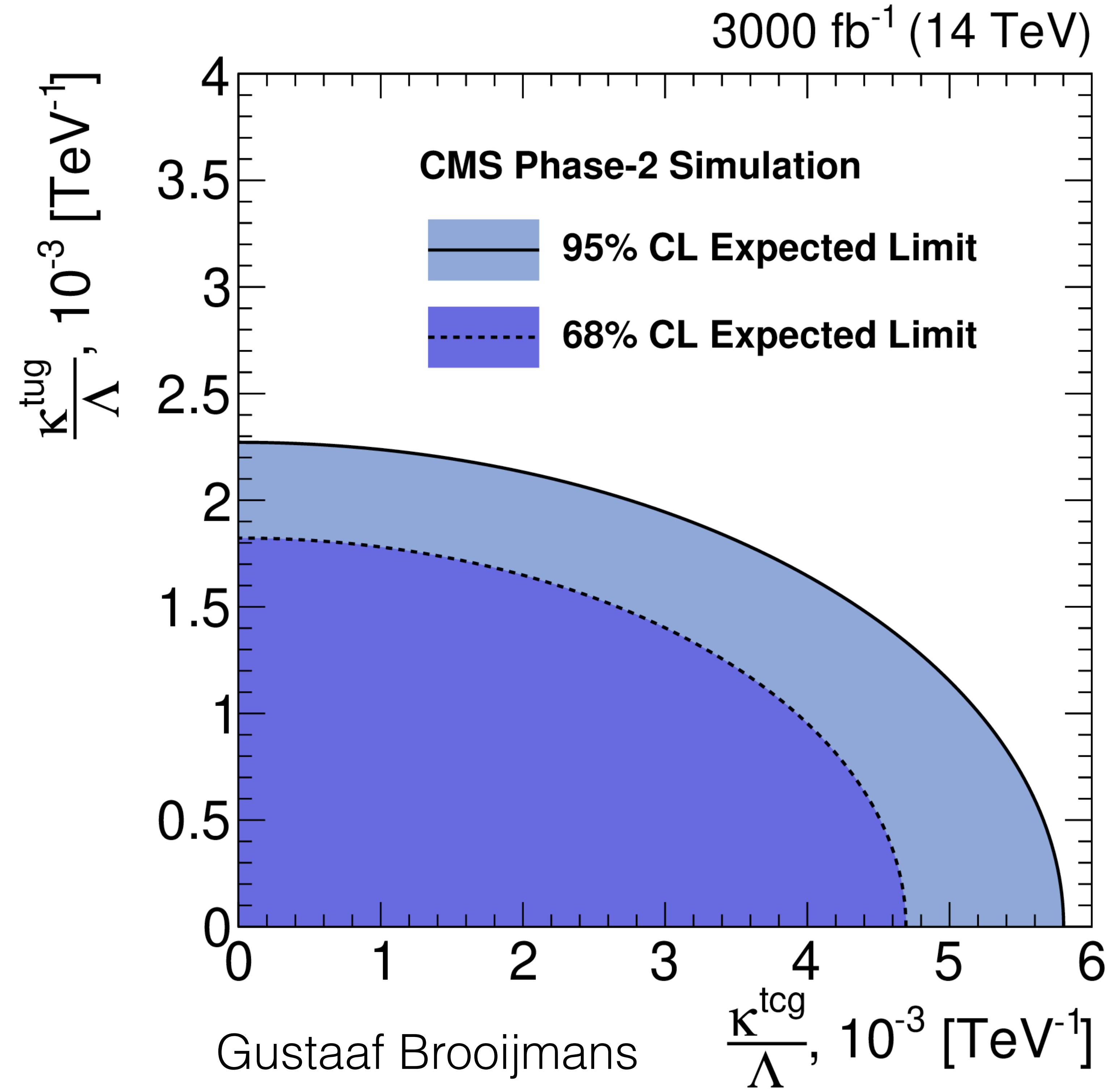
Y mass regime, where the H and X have a significant Lorentz boost. A novel anomaly detection signal region is implemented based on a jet-level score for signal model-independent tagging of the boosted X, representing the first application of fully unsupervised machine learning to an ATLAS analysis. Two additional signal regions are implemented to target a

(Indirect) New Physics at HL-LHC

- Precision measurements to probe higher energy scales
  - Probe PeV scale in up-type quark sector
  - Pin down CP violation in B_s system (π/K separation from timing detectors?)
  - Observe $B_d \to \mu\mu$, measure $B_s \to \mu\mu$ at better than 10% level

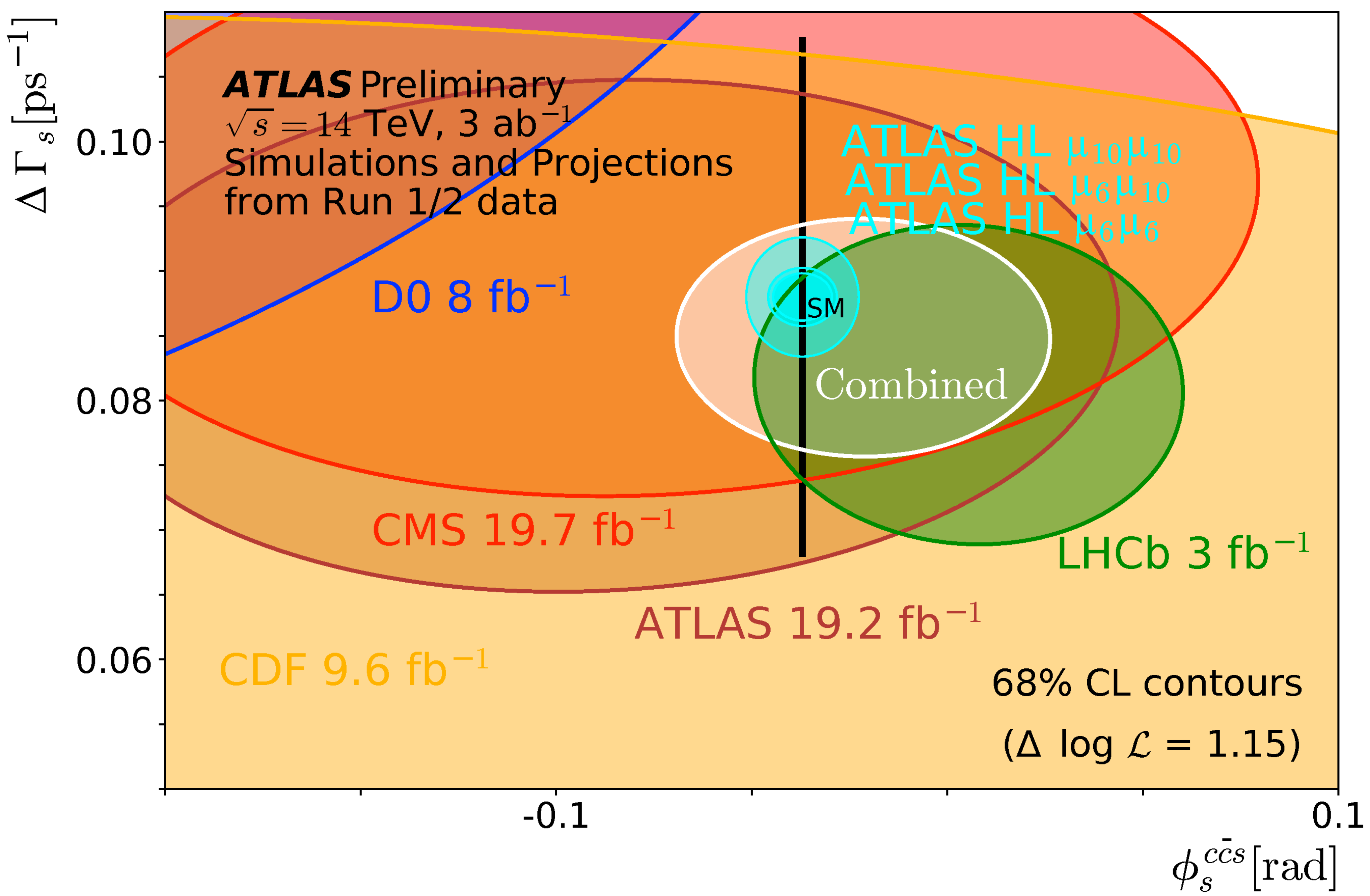
Top FCNC

CMS-PAS-FTR-2018-004



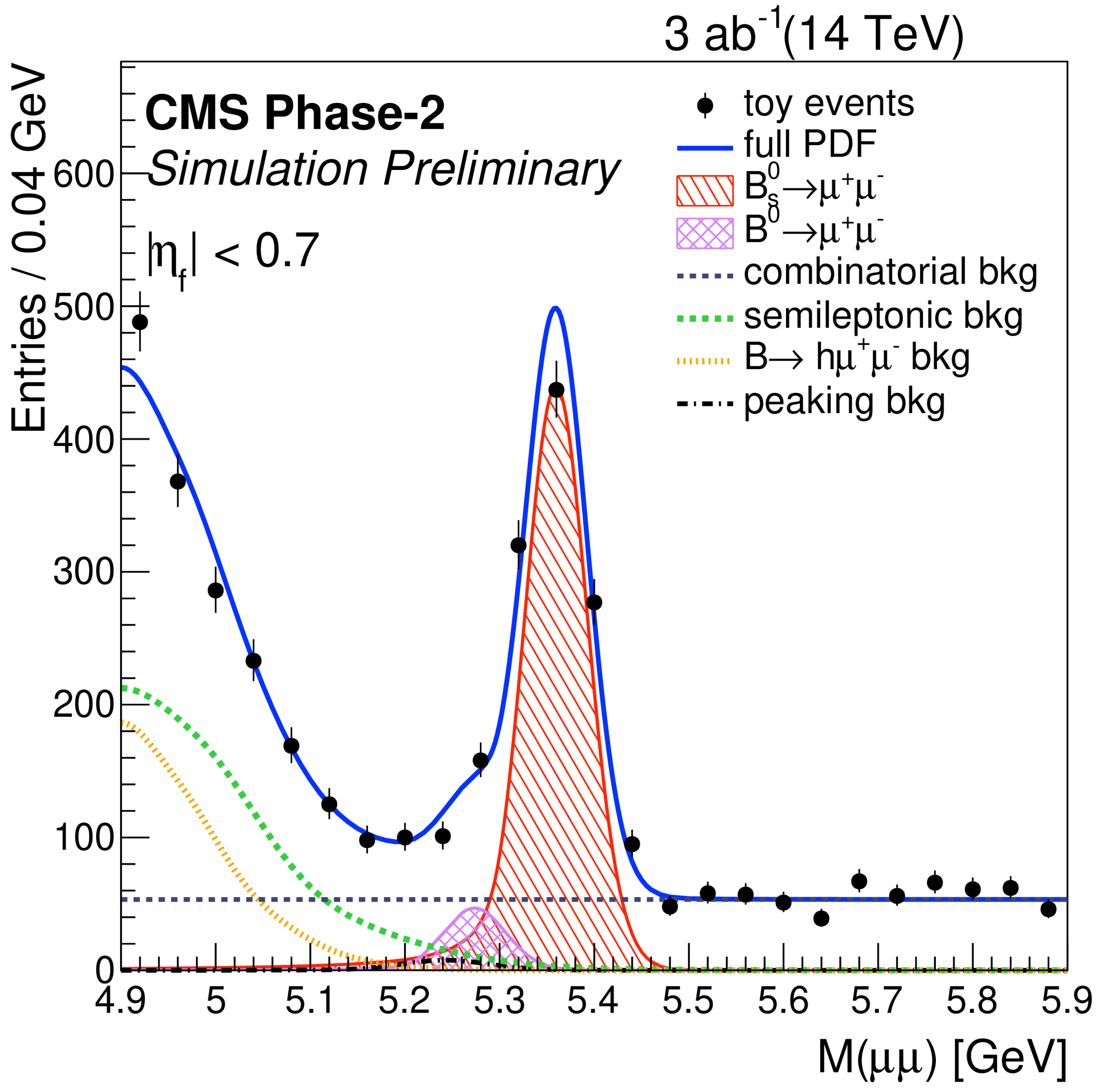
CPV in B_s

ATLAS-PHYS-PUB-2018-041



$B_{d/s} \to \mu\mu$

CMS-PAS-FTR-2018-013

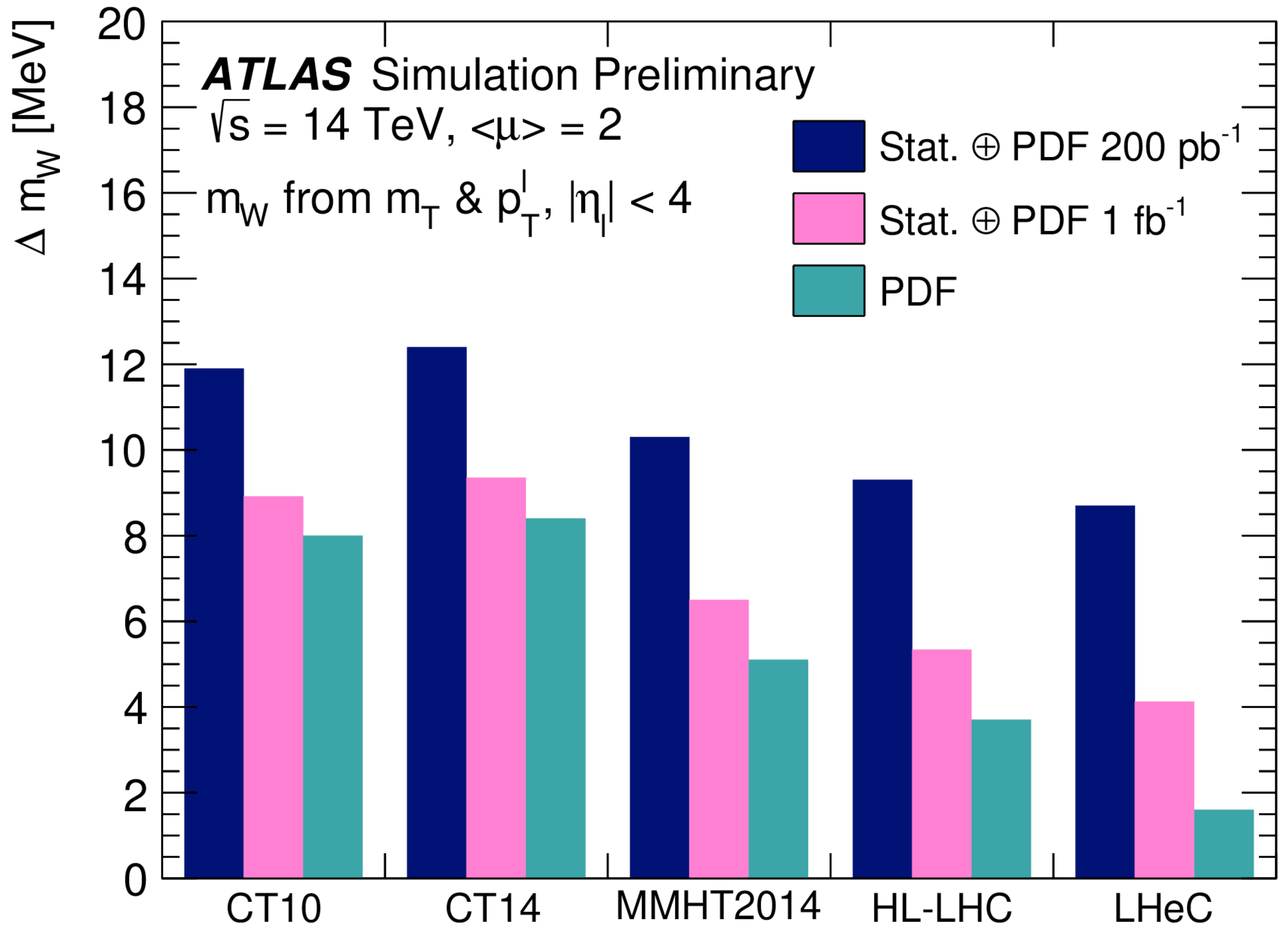


Precision SM Measurements

- (HL-)LHC is a top, Z, W factory; only place to study vector boson scattering, …
- Will also want to include special runs
  - “Low" luminosity for W mass measurement
  - Heavy ions: quark-gluon plasma studies, light-by-light scattering, …

W Mass

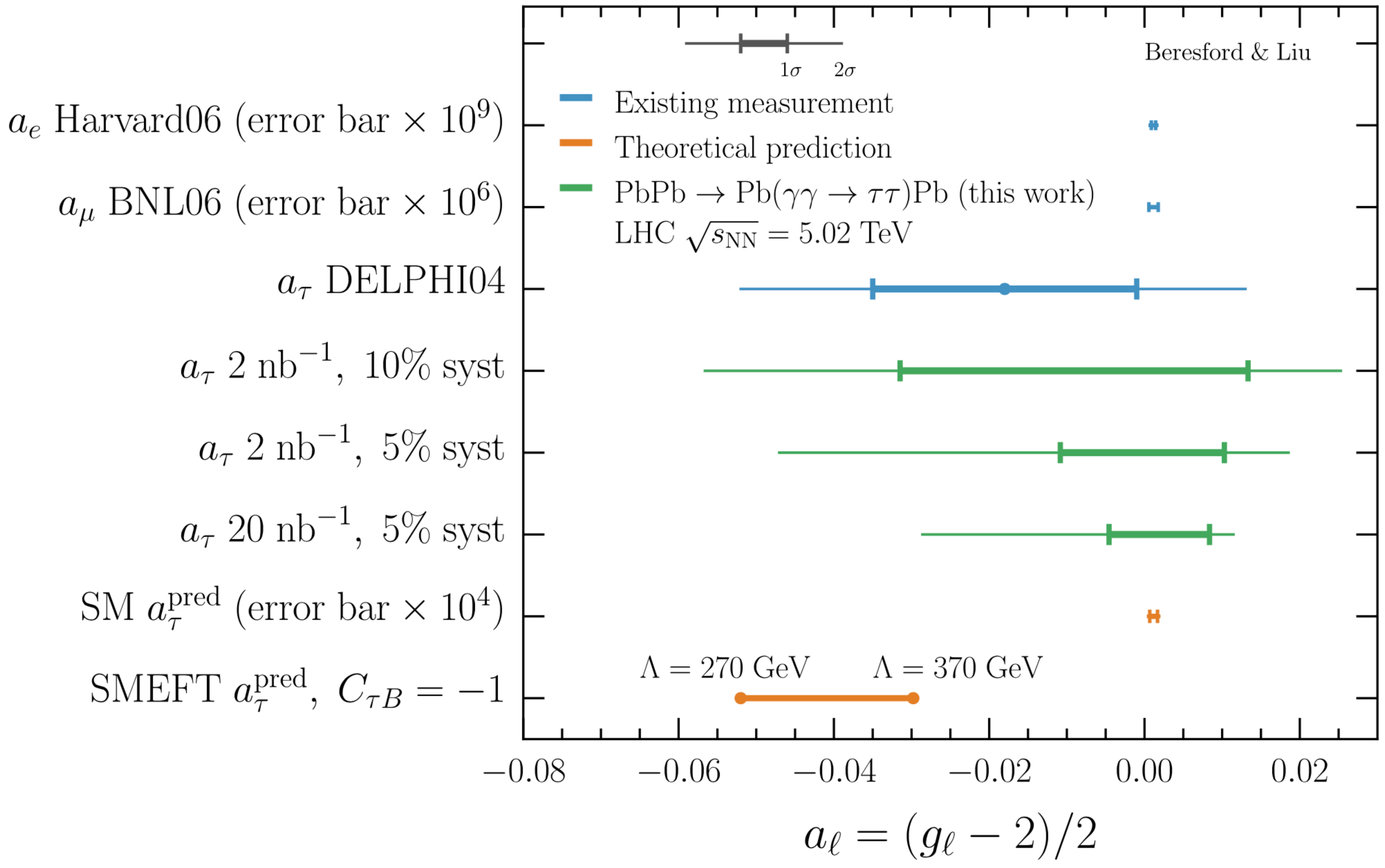
ATLAS-PHYS-PUB-2018-026



Current uncertainty is 16 MeV, from 7 TeV run, ATLAS-CONF-2023-004

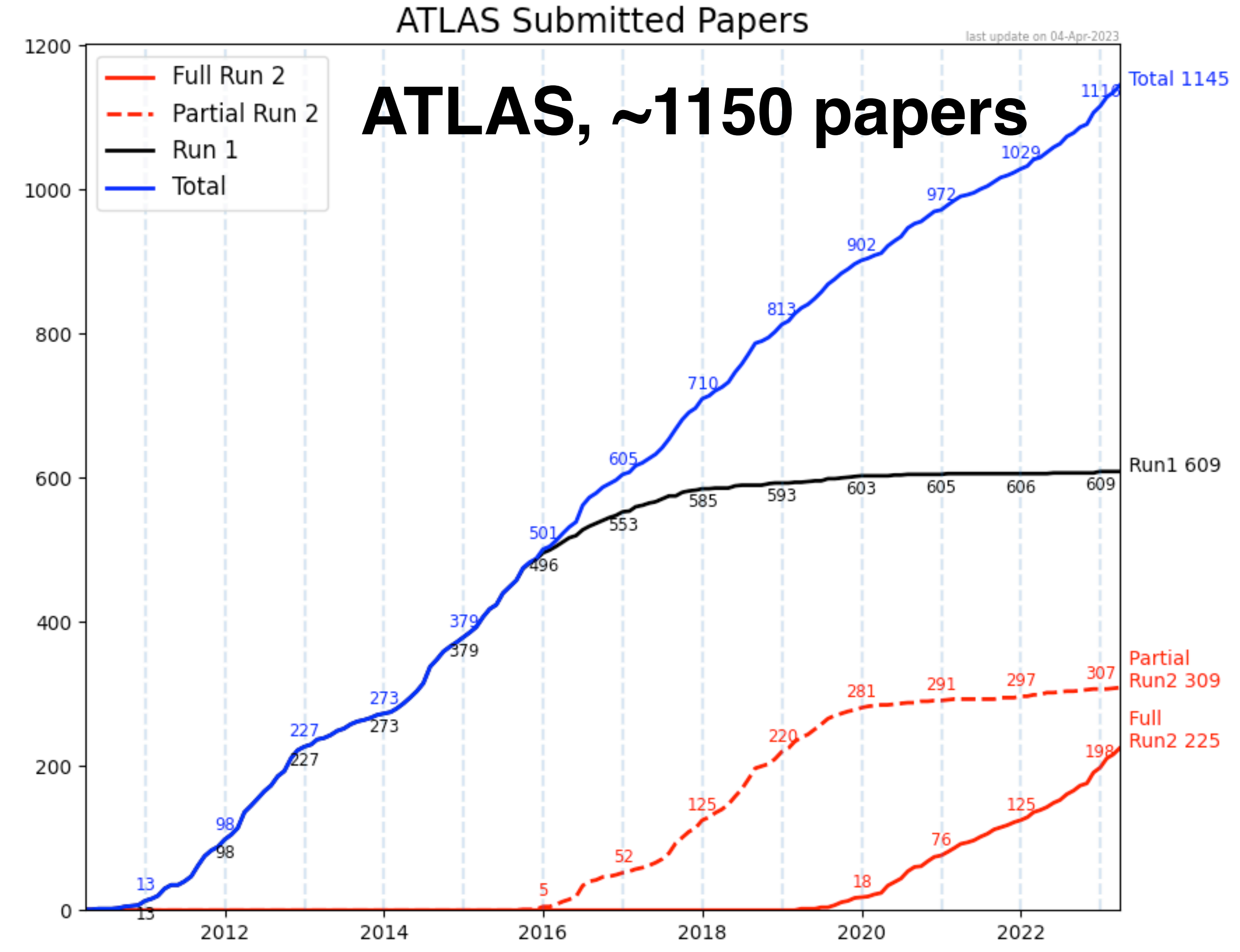
Tau g-2

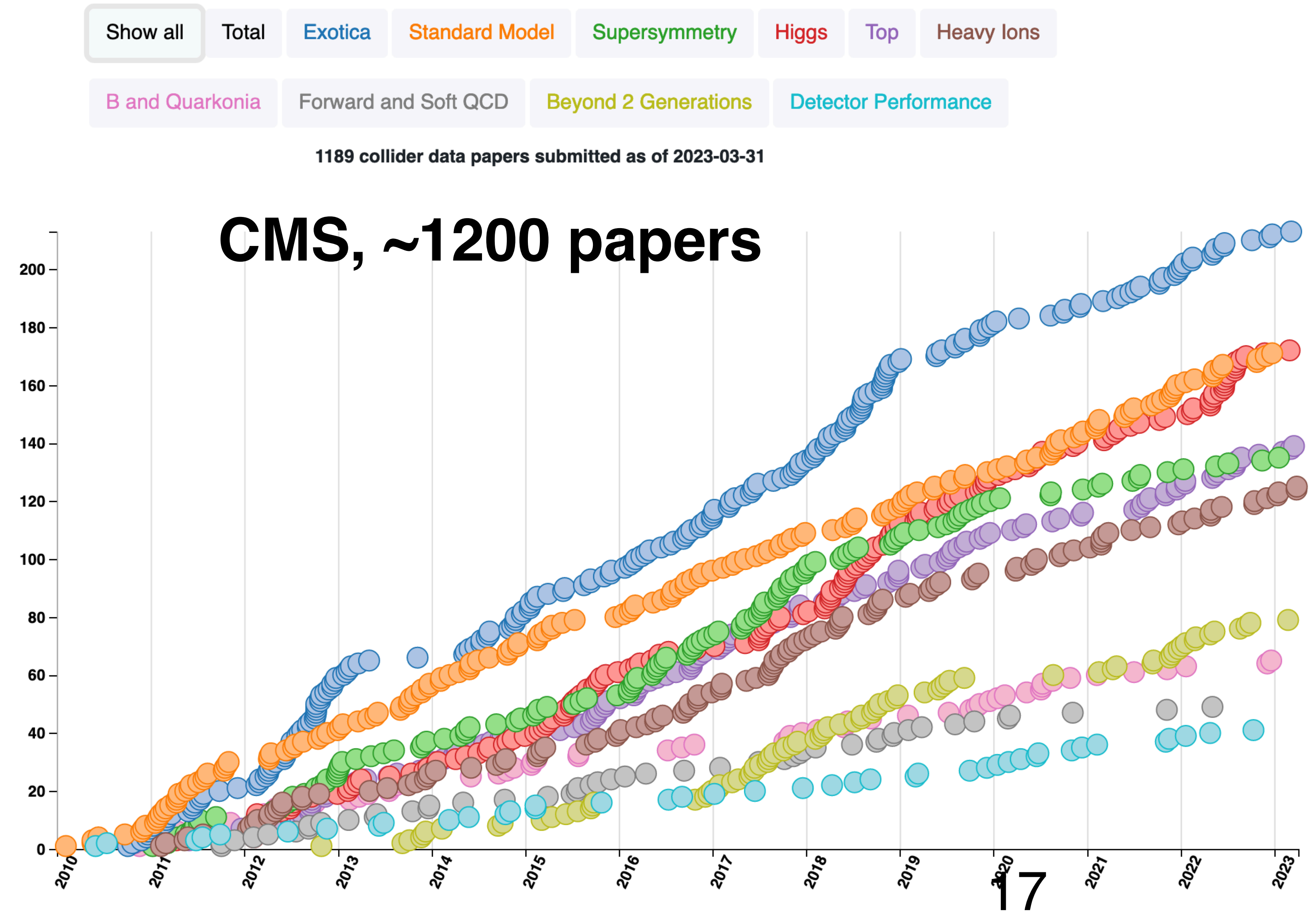
Beresford & Liu, PRD 106 039902



Closing

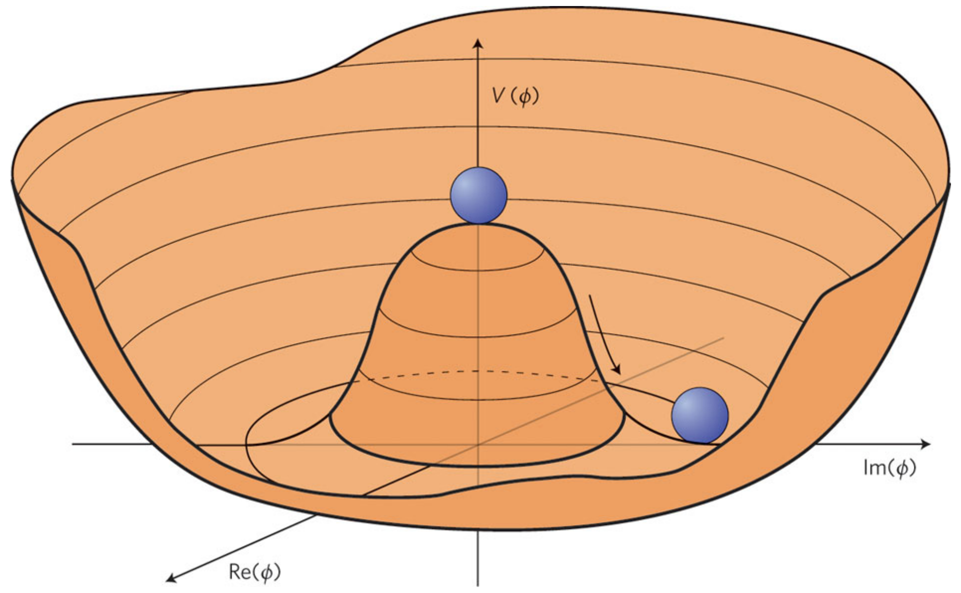
- The Standard Model is "complete"
  - An amazing achievement 40+ years in the making
  - And more crucial measurements to make
    - In particular the Higgs potential, a huge challenge
- High Luminosity LHC construction is underway
  - Much deeper probe of the TeV scale and beyond
  - ATLAS and CMS are very versatile experiments, **publishing ~2 papers/week (since 2010!)**
  - Good reason to believe something new will appear
    - Lots of phase space to explore!
- This may require a new paradigm
  - After all, nobody (could have?) predicted QCD





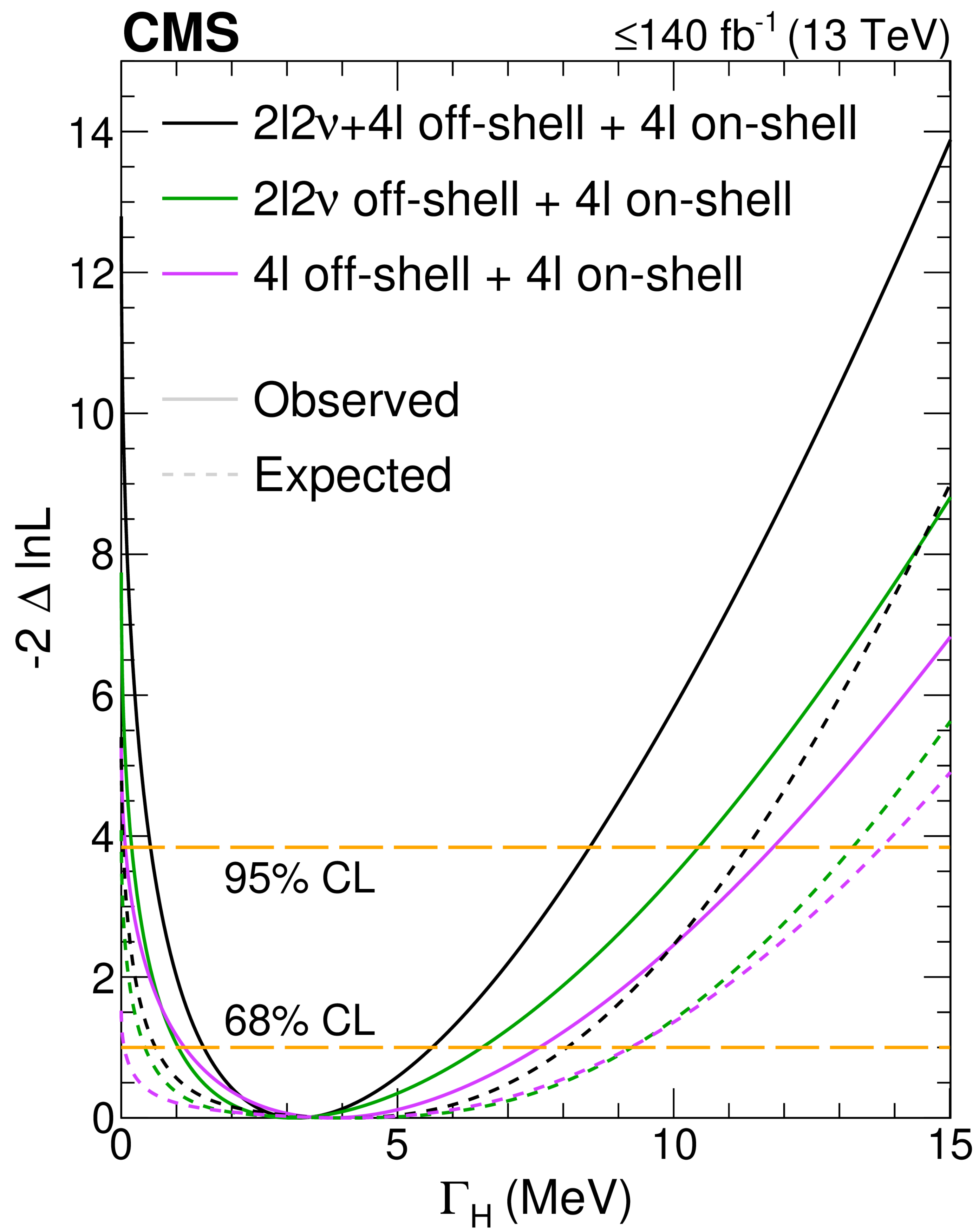
The Higgs Sector

- Left-handed nature of weak interactions forbids "direct" fermion masses
  - Mechanism by which fermions acquire mass has to "connect" to parity violation
  - Mass terms $y_f(\overline{\psi}_L\phi\psi_R)$ rather than $m(\overline{\psi}_L\psi_R)$, with ϕ a weak $SU(2)_L$ (at least) doublet
- Of ϕ's 4 degrees of freedom
  - 3 are the longitudinal W and Z polarizations (which thus acquire mass)
  - 1 physical Higgs boson state
- For everything to work, $V(\phi)$ is (lightly) constrained:
  - Higgs vacuum expectation value cannot be 0 (or $-\infty$)
    - In polynomial form, at least order 4
    - SM ***assumes*** minimal form: $V = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$ with $\mu^2 < 0$ and $\lambda > 0$

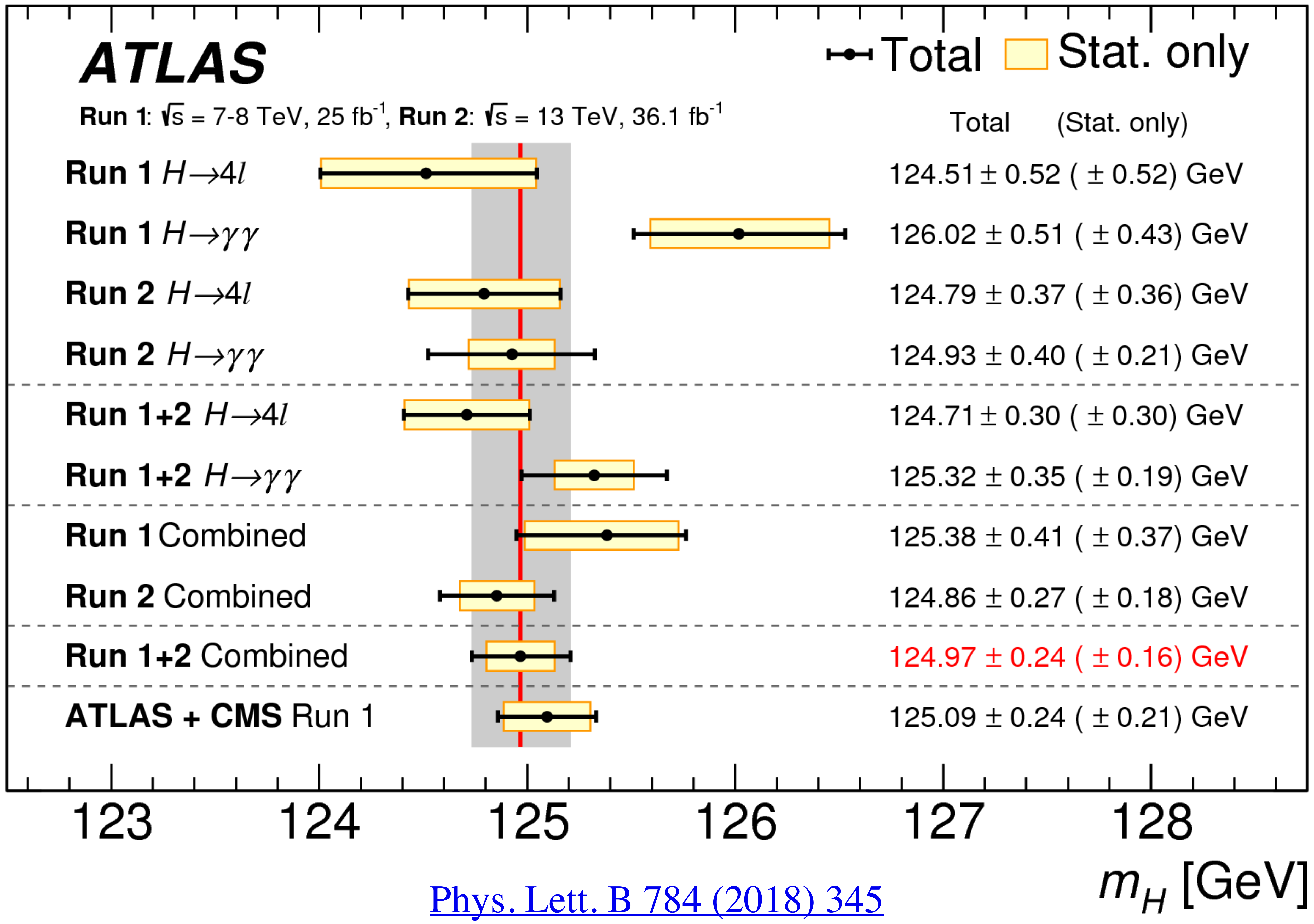


Higgs Observation

- The existence of *a* Higgs boson is firmly established.. at 125 GeV
  - Width compatible with SM prediction (4.1 MeV)… if no NP "interference"



Nat. Phys. 18 (2022) 1329



Phys. Lett. B 784 (2018) 345

Lacking in the Standard Model

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  - No understanding of the “charges”
  - Evidence of selective principle(s)
    - E.g. no neutral colored fermions
  - And links between quarks and leptons
    - $q(\text{down}) = q(e)/N_c$
  - Interpreted as evidence for (grand) unification
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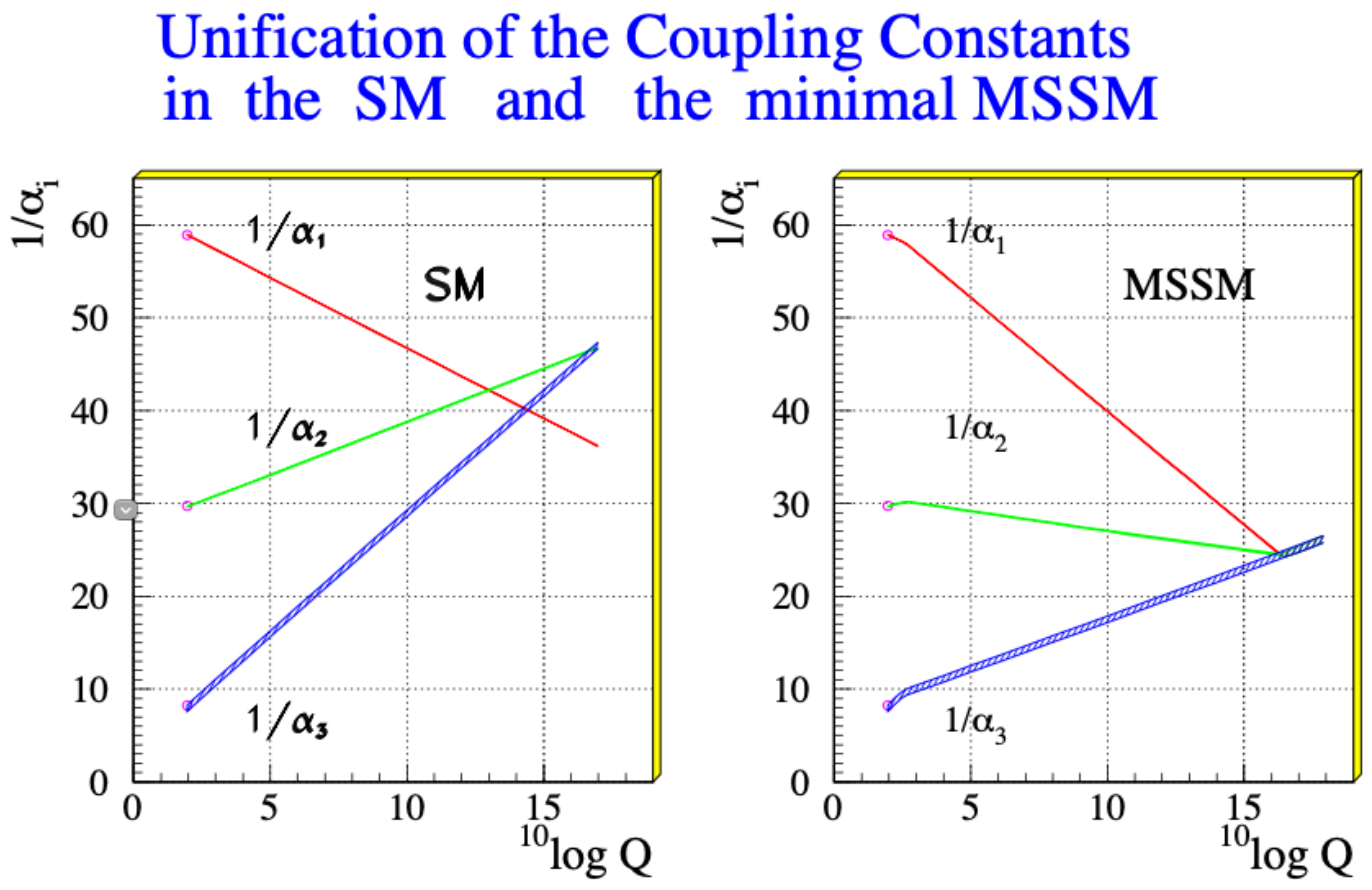


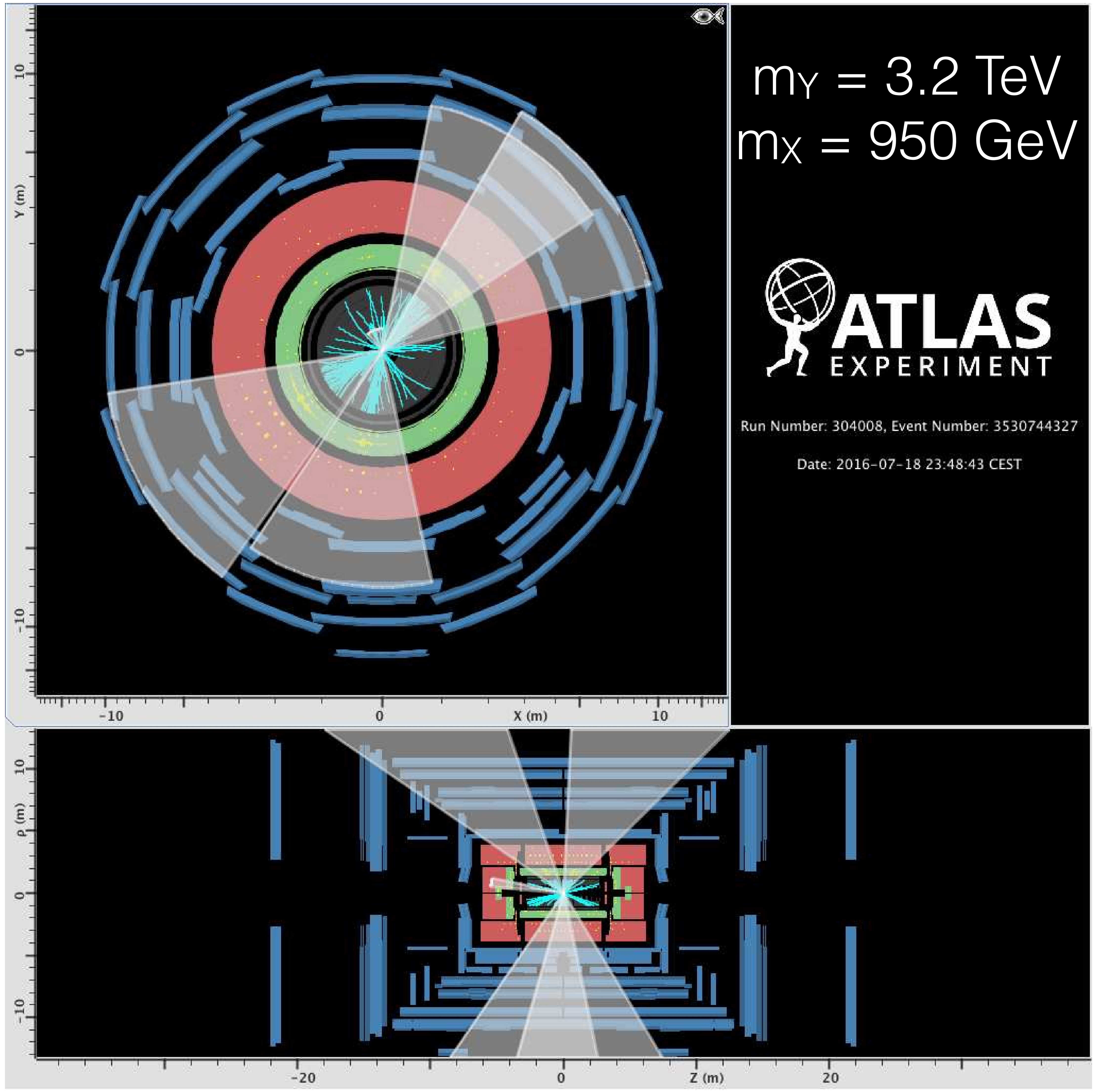
arXiv:hep-ph/0012288

Lacking in the Standard Model

- Many cosmological issues
  - Dark matter and dark energy
  - Not enough CP violation in the quark sector for baryogenesis
  - Baryon number violation
- 42?

New Physics at HL-LHC

- But also want to become “smarter”, and expand the scope of analyses
  - Example: we perform many searches for new resonances, Z’, W’, Heavy Higgs…
    - In many cases, these primarily couple to W, Z, H, top quark (because they help address the hierarchy problem)
    - So we look for “di-boson” resonances, i.e. Y ⇒ WW, ZZ, HH, ZH, …
  - However, if Y exists, there are likely to be other new particles
    - Need to broaden searches!
  - Same for VLQs etc.



Standard Model Today

- Higgs discovery completes the Standard Model
  - Fully consistent, complete, precise description of strong, electromagnetic and weak ***interactions***
- Even generate fermion masses
  - But that is the ***only*** property of fermions we "understand"