Physics Prospects for HL-LHC

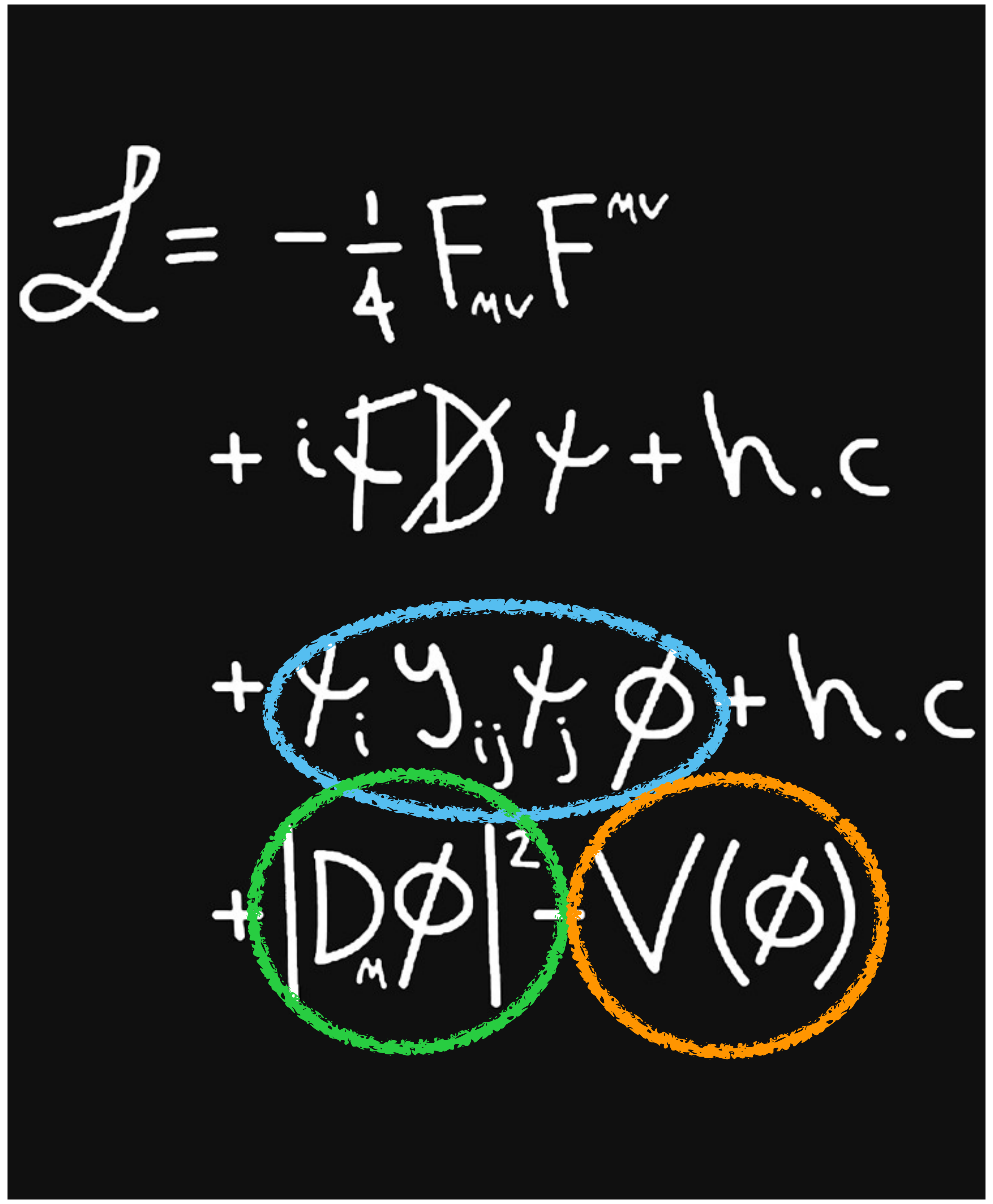
Huilin Qu (CERN)

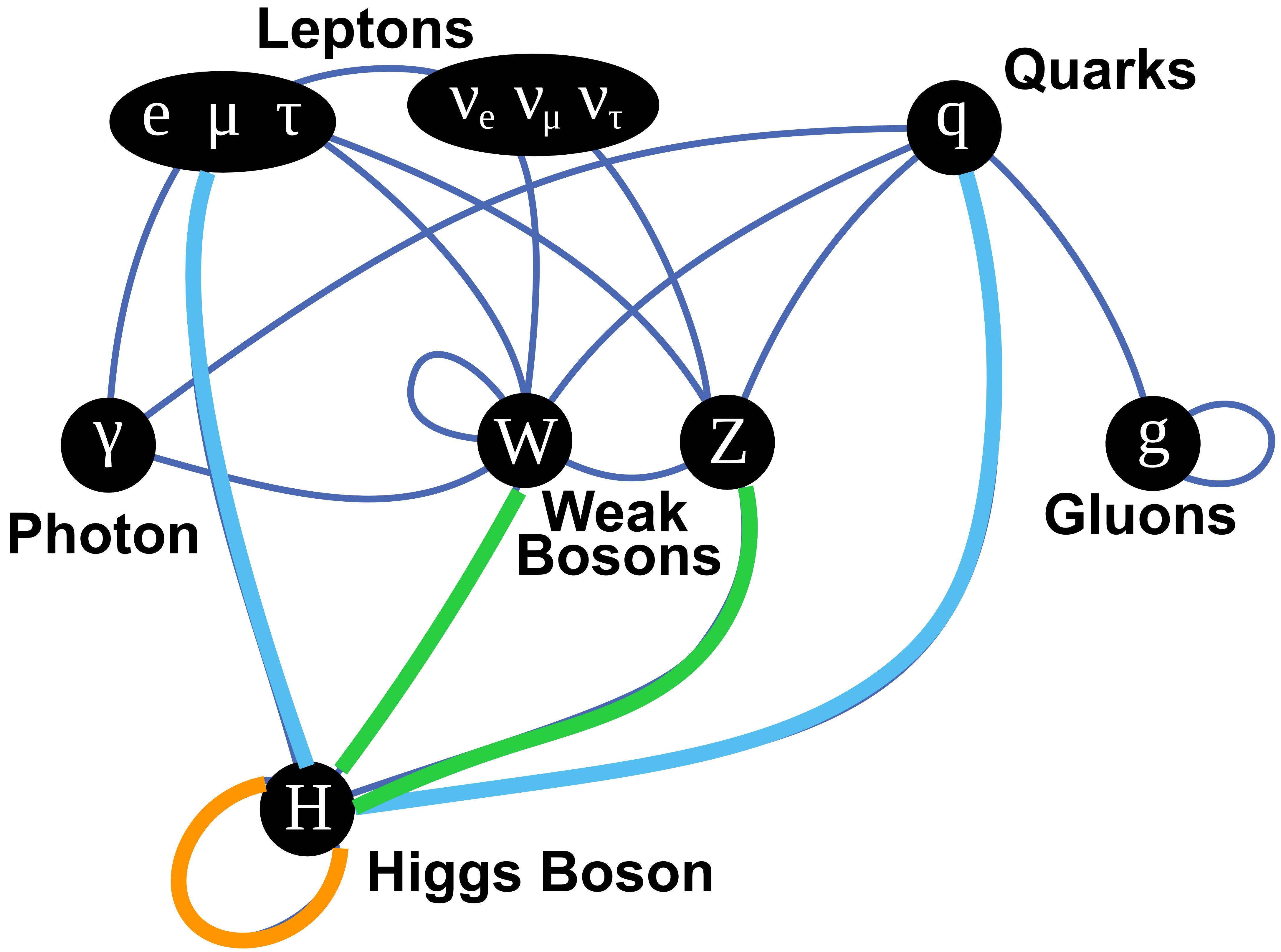
on behalf of ATLAS and CMS Collaborations

Higgs 2023

December 1, 2023

Higgs: Keystone of the SM



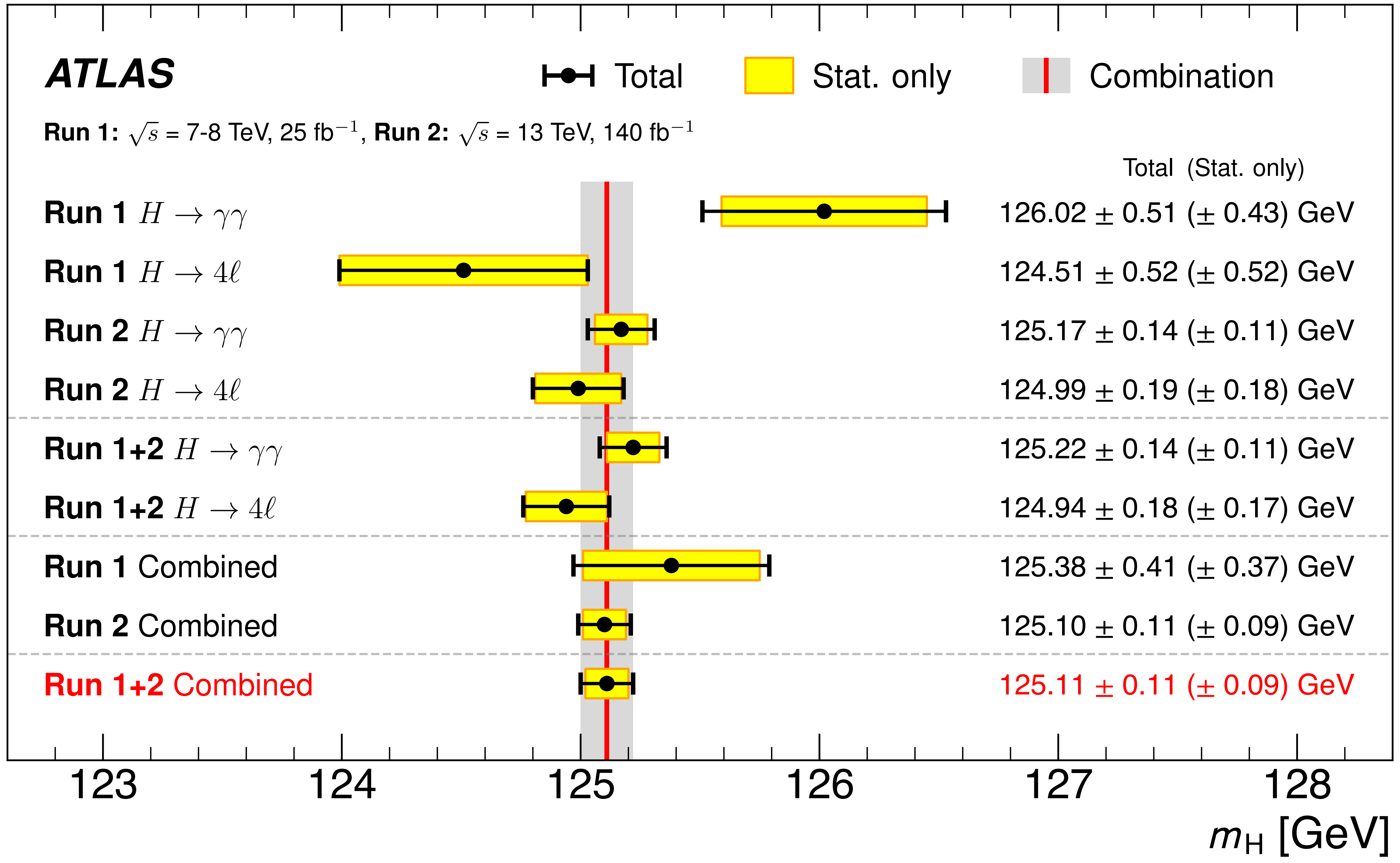


Crucial to probe all these interactions to highest possible precision
— any deviation from the SM prediction would be a clear sign of new physics!

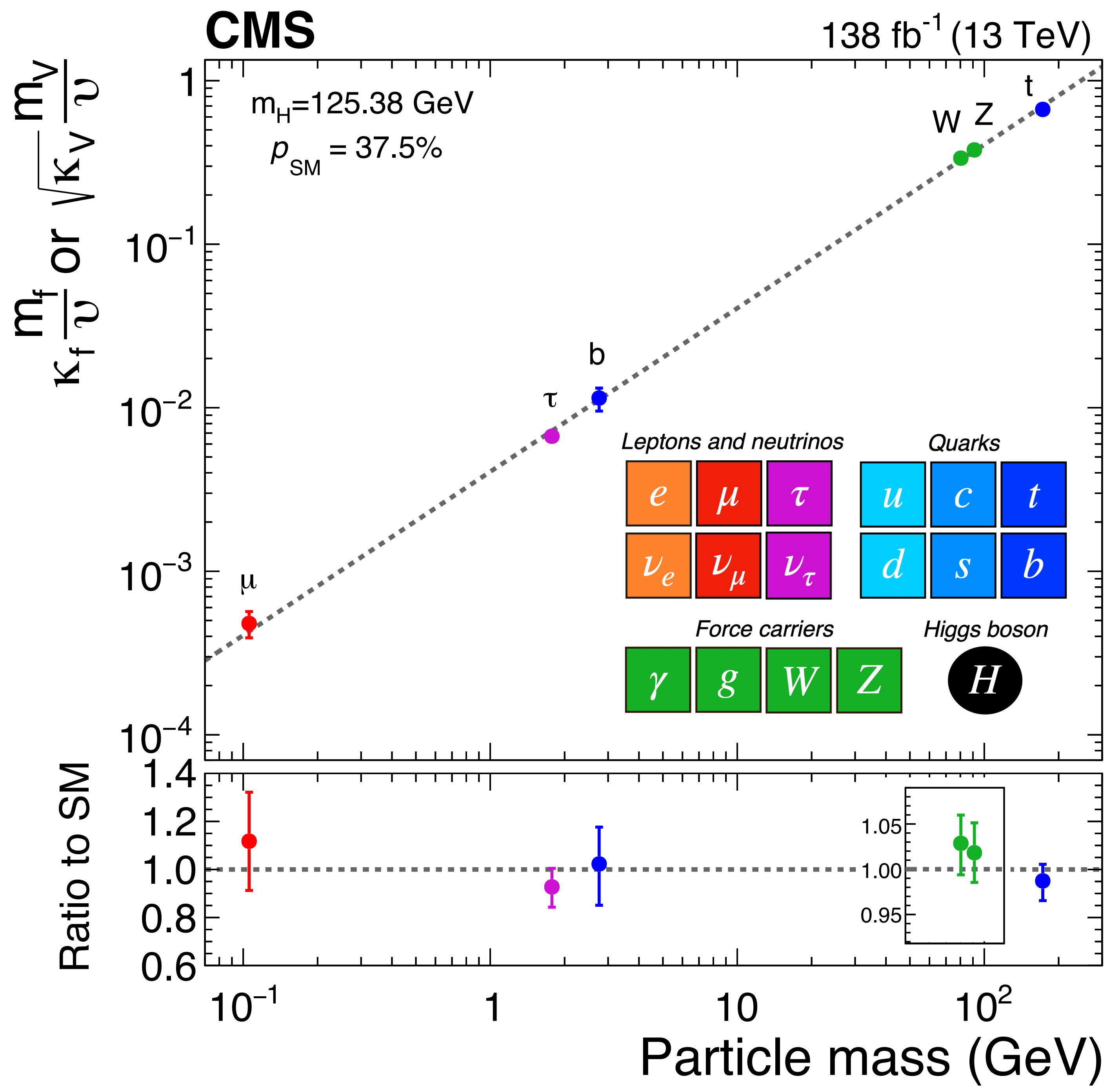
Higgs@LHC: A Decade-Long Effort

- Tremendous progress in our understanding of the Higgs boson in the past decade
  - precision on the mass: < 0.1%
  - precision on the couplings: ~5% (vector bosons), ~10% (3rd generation fermions)
  - rapid progress in second generation couplings, Higgs boson pair production, …
  - **+ many more shown at this conference!**

arXiv:2308.04775

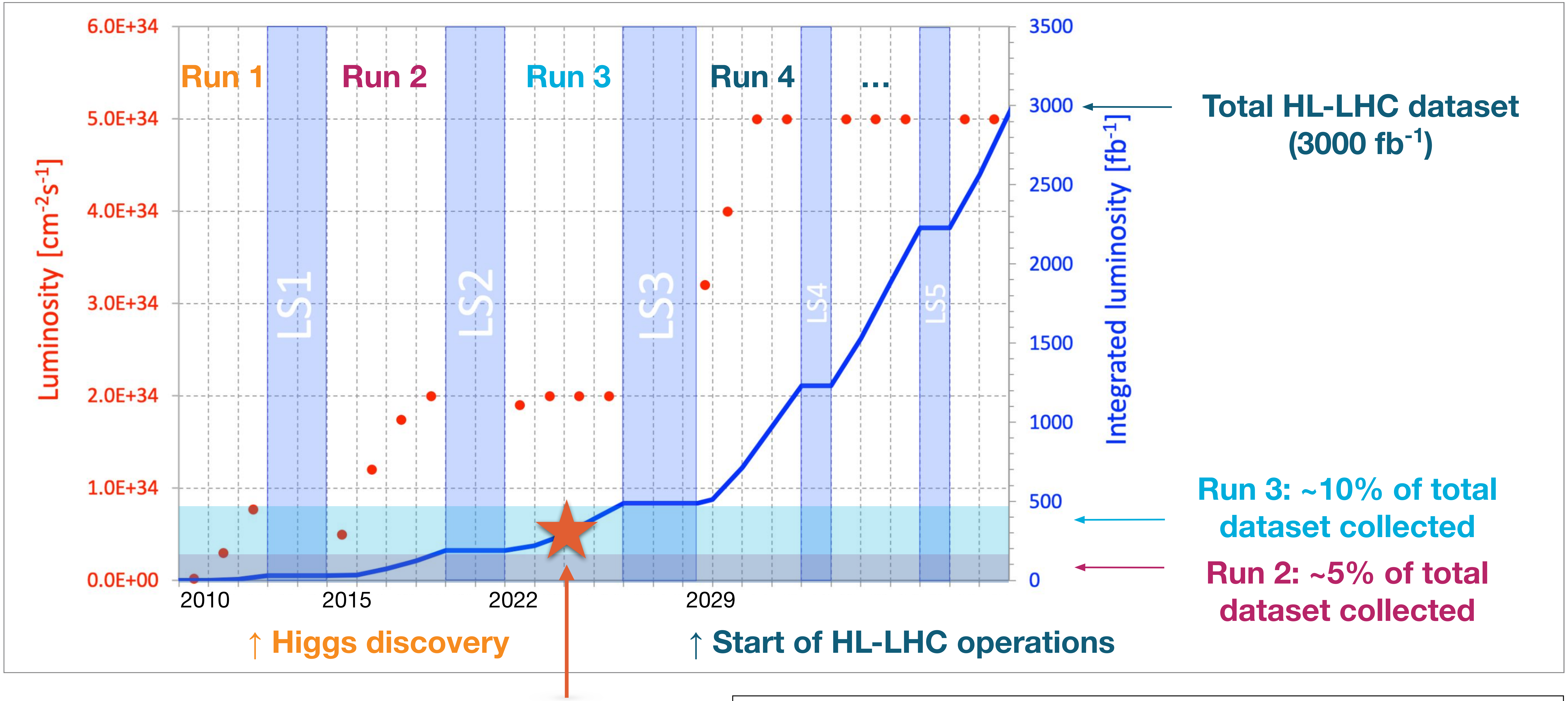


Nature 607 (2022) 60-68



Long Journey Ahead

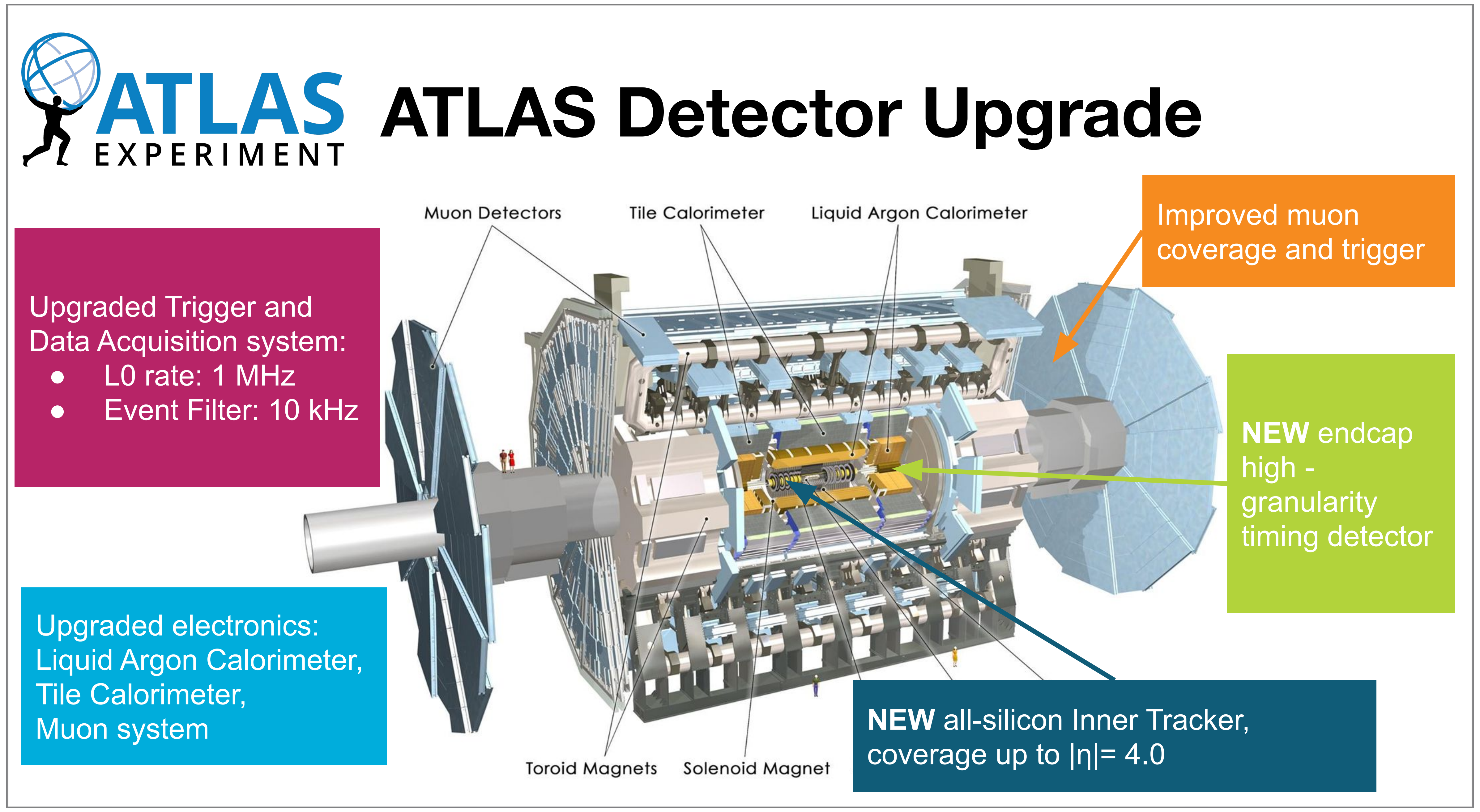
Courtesy Elizabeth Brost

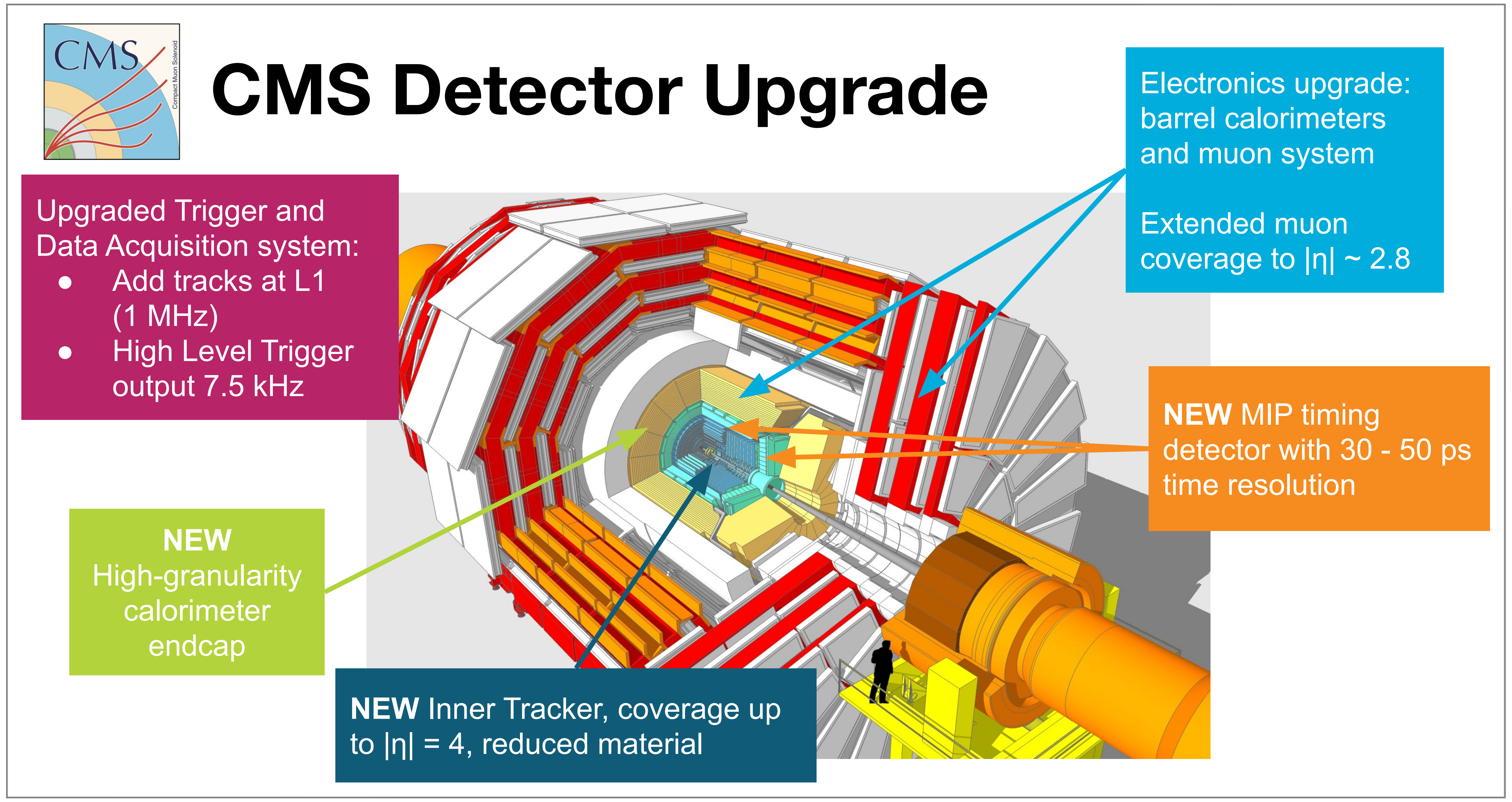


~20x more data to be explored at the (HL-)LHC!

DETECTOR UPGRADES

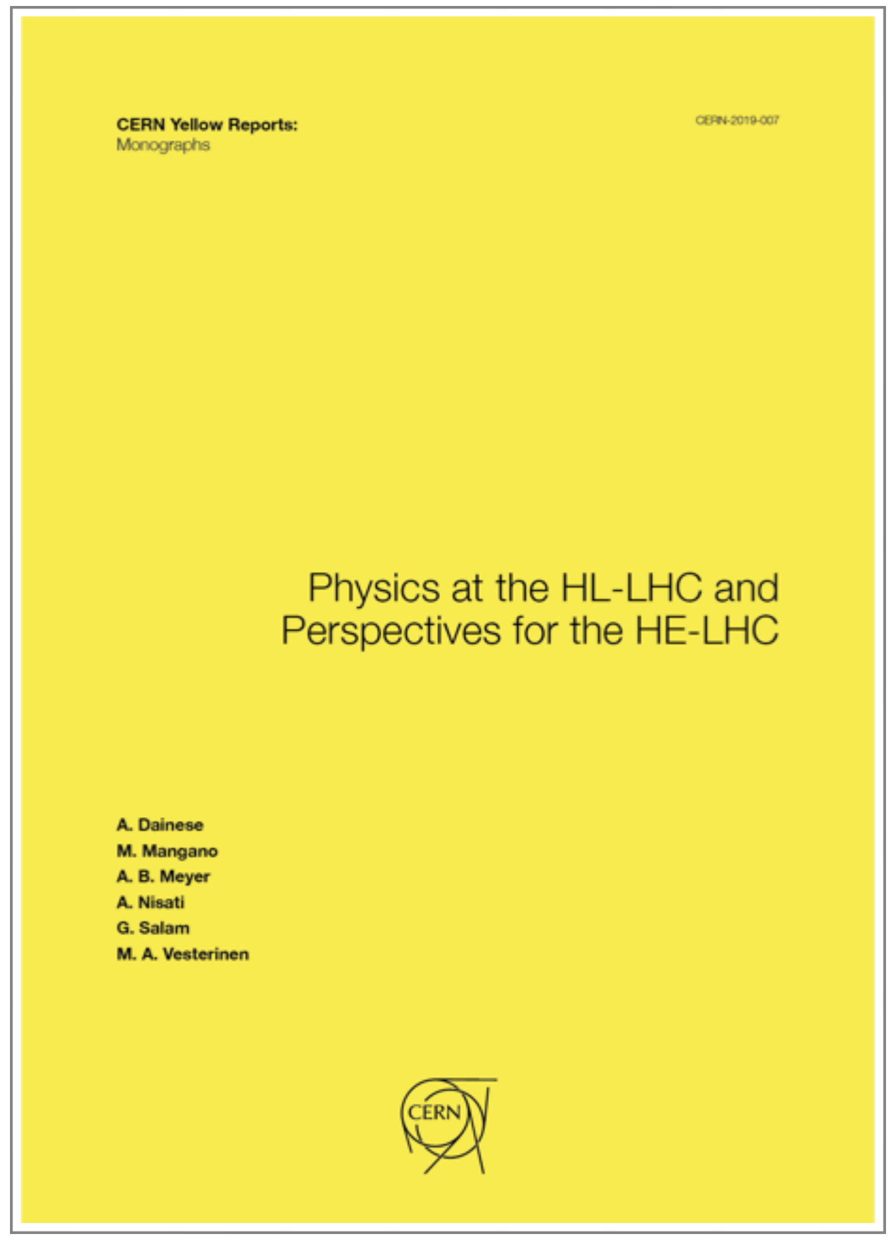
- Comprehensive upgrades of the ATLAS and CMS detectors to meet HL-LHC challenges
  - new:
    - tracker (up to |η| = 4), timing detector (for pileup mitigation), high-granularity calorimeter endcap (CMS)
  - upgraded:
    - trigger and DAQ systems (output@~10kHz), electronics for calorimeters and muon systems, …
  - **crucial for harsh running conditions (PU 140–200), but also lots of potential for performance improvements**





PROJECTION TO HL-LHC

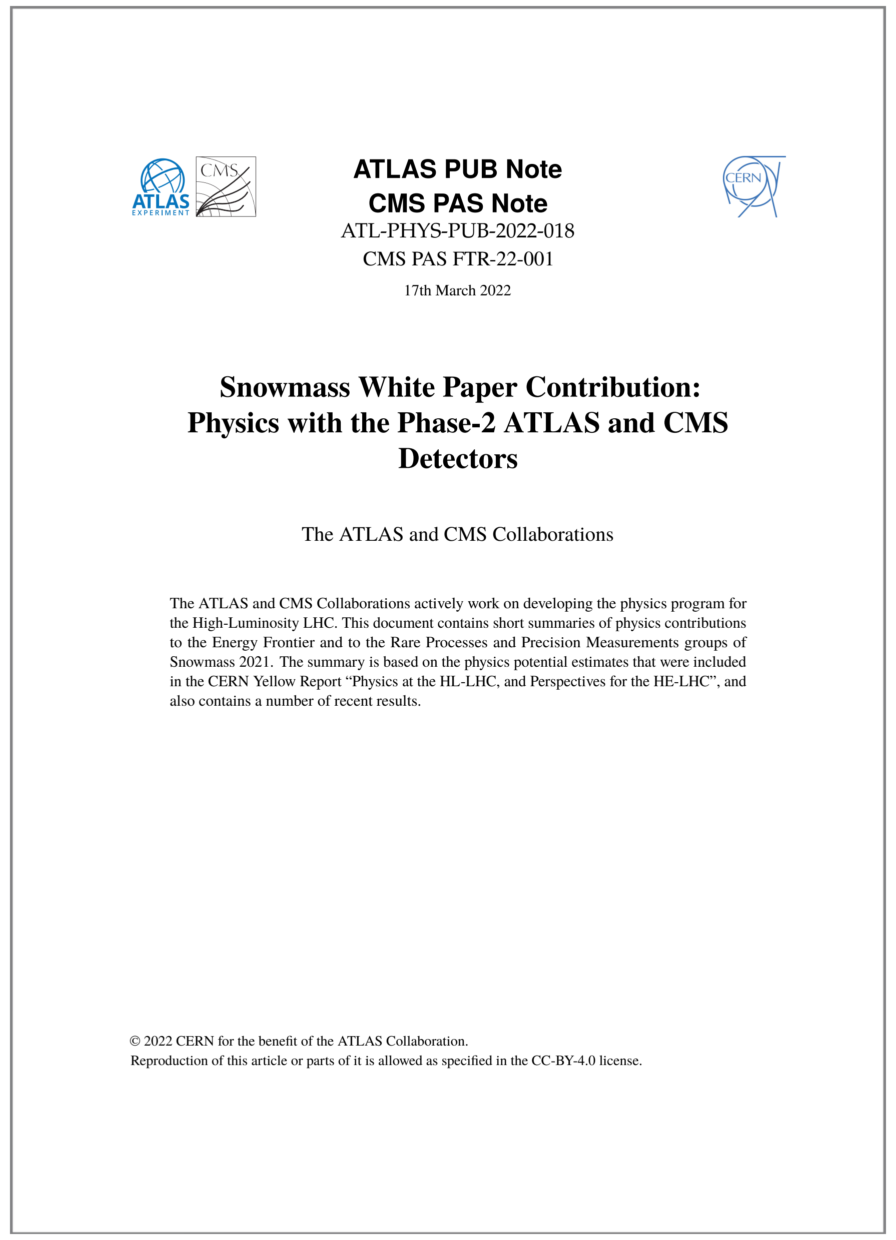
- HL-LHC projection results mainly based on:
  - 2018 Yellow Report [CERN-2019-007]
  - substantial update in the Snowmass2021 report [cds:2805993]
- Strategies for the projection:
  - **extrapolations** of (partial/full) Run-2 results to HL-LHC luminosity
  - **parametric simulations** based on upgraded detectors
- Uncertainty schemes:
  - **YR18 systematics uncertainties (baseline):**
    - theoretical uncertainties: reduced by half
    - most experimental uncertainties: scaled down with 1/sqrt(L)
    - luminosity uncertainty: aiming at 1%
    - uncertainties due to the limited number of simulated events are typically neglected
  - alternatively, to understand the impacts of systematics
    - Run-2 systematic uncertainties
    - statistical-only uncertainties


CERN Yellow Reports:
Monographs

CERN-2019-007

Physics at the HL-LHC and
Perspectives for the HE-LHC

A. Dainese
M. Mangano
A. B. Meyer
A. Nisati
G. Salam
M. A. Vesterinen


ATLAS PUB Note
CMS PAS Note
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001
17th March 2022

Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors

The ATLAS and CMS Collaborations

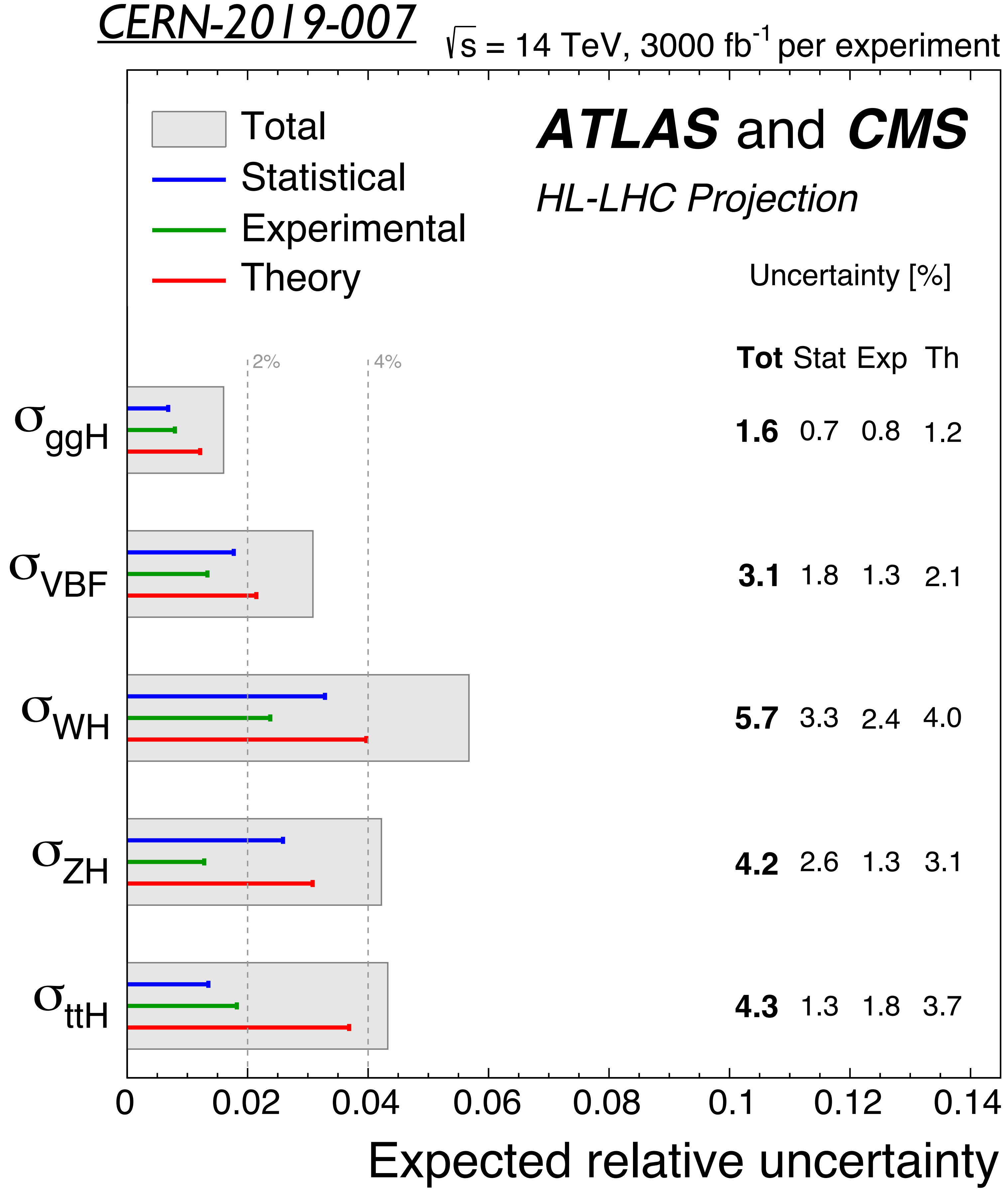
The ATLAS and CMS Collaborations actively work on developing the physics program for the High-Luminosity LHC. This document contains short summaries of physics contributions to the Energy Frontier and to the Rare Processes and Precision Measurements groups of Snowmass 2021. The summary is based on the physics potential estimates that were included in the CERN Yellow Report "Physics at the HL-LHC, and Perspectives for the HE-LHC", and also contains a number of recent results.

Precision Measurements

CROSS SECTIONS AND COUPLINGS

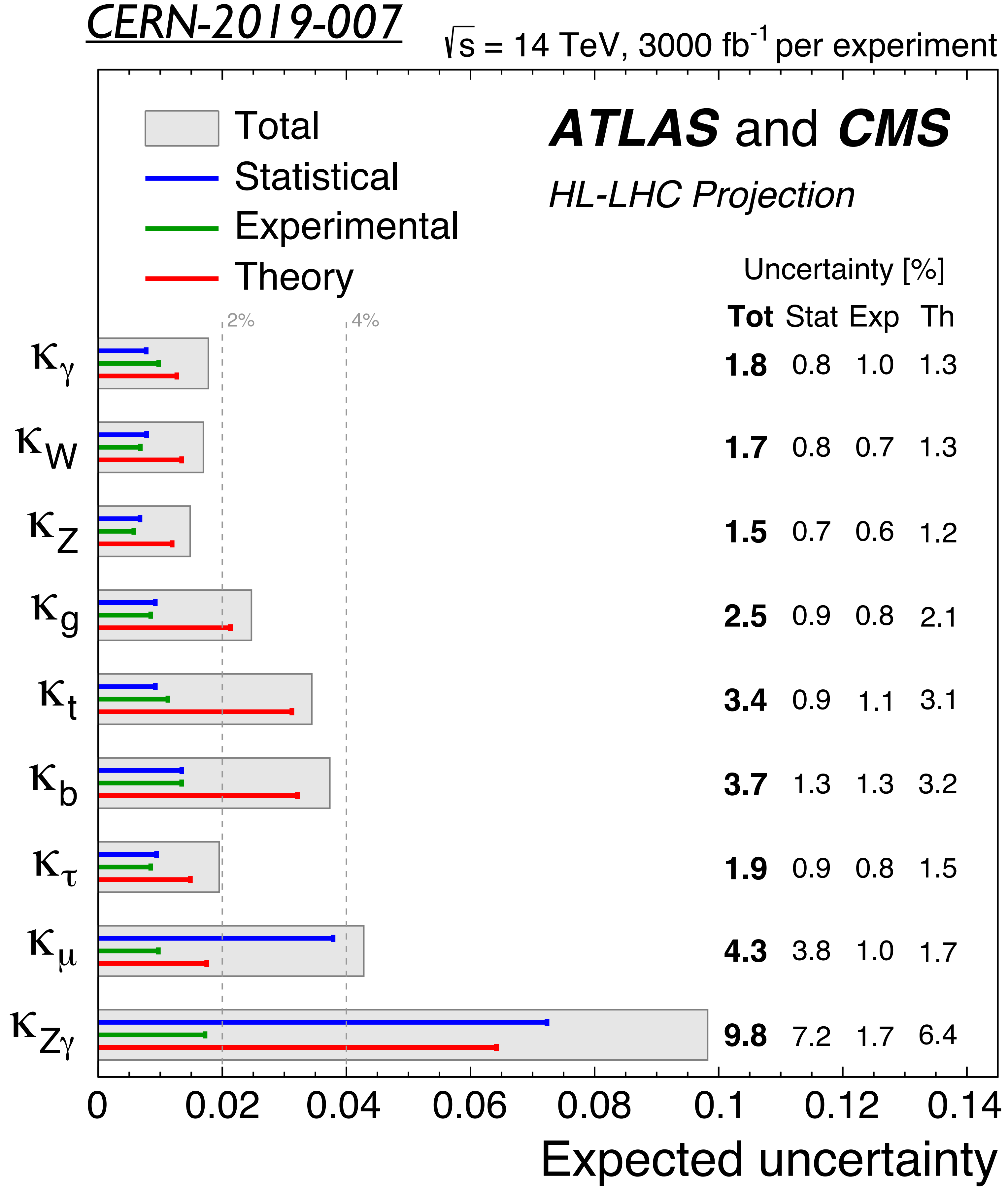
Production cross sections

CERN-2019-007



Coupling modifiers

CERN-2019-007

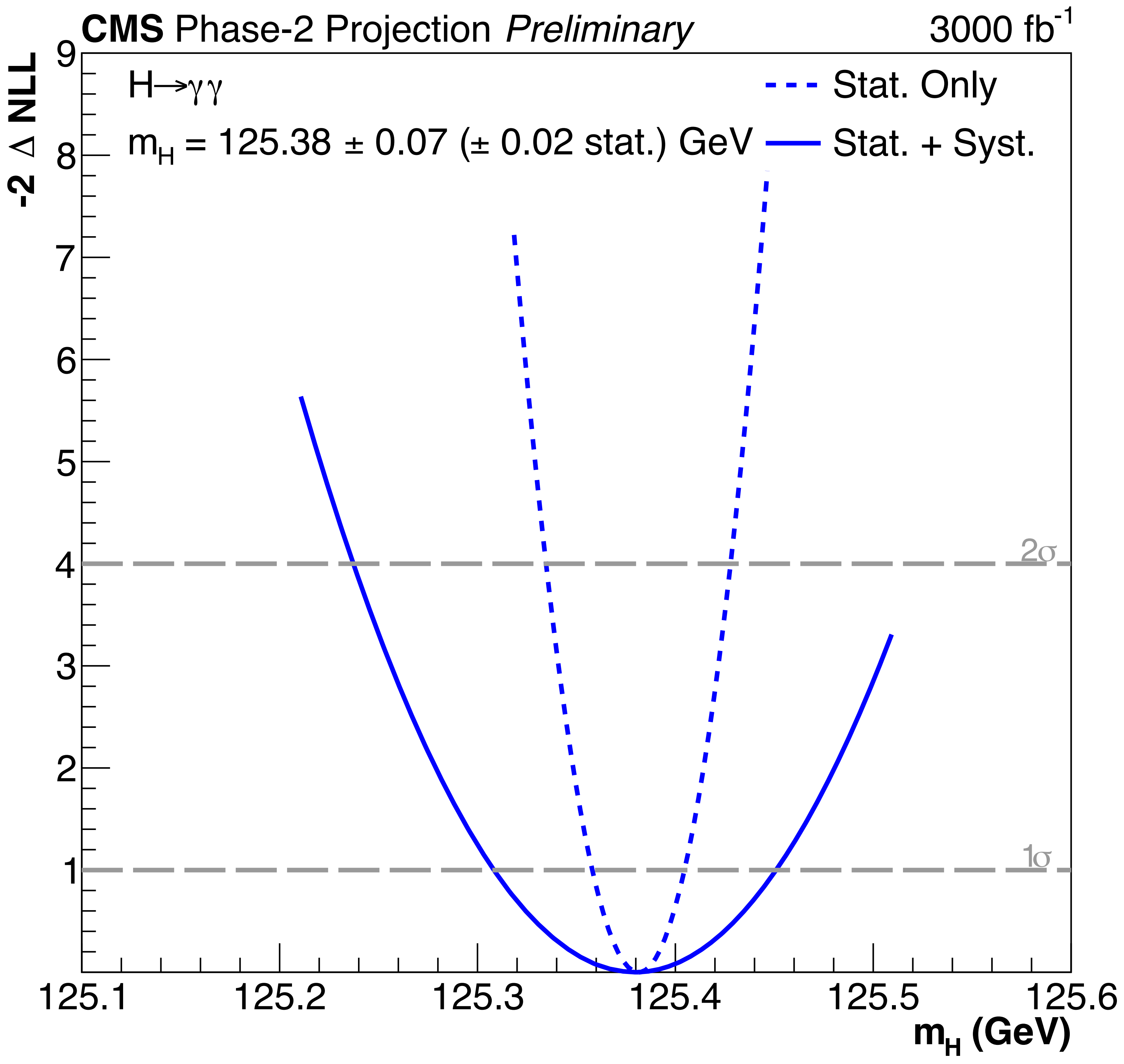


- Expected precision reaching 2 - 5% at the end of HL-LHC (CMS+ATLAS)
- Large impact of theory uncertainty in many cases (despite the /2)

HIGGS BOSON MASS AND WIDTH

Mass in H→γγ

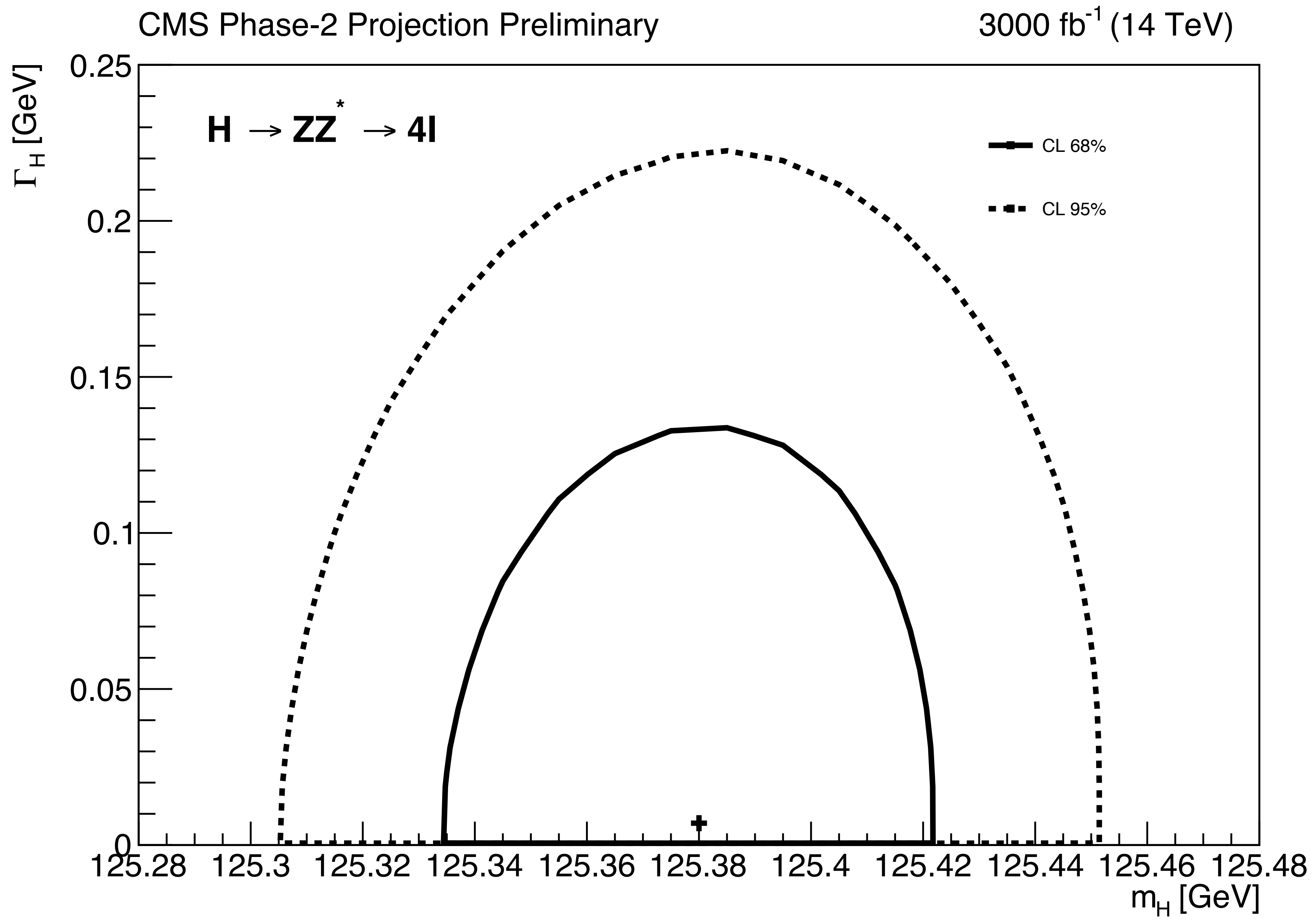
CMS-PAS-FTR-21-008



- Total uncertainty on m_H: **70 MeV**
- Limited by photon energy scale (~0.05%)

Mass vs width in H→ZZ→4ℓ

CMS-PAS-FTR-21-007

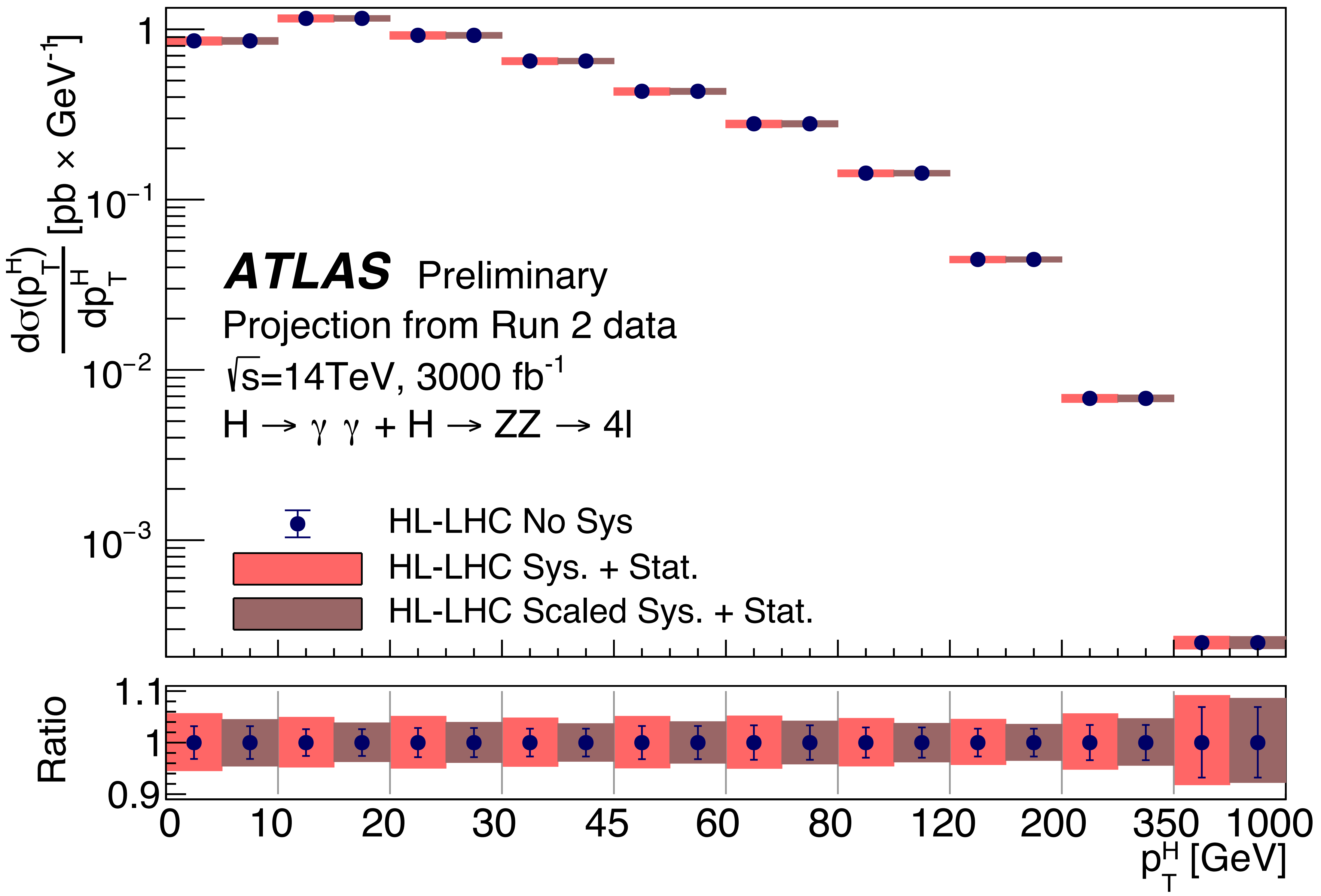


- Total uncertainty on m_H: **25–30 MeV**
  - comparable stat. and syst. unc.
- Direct constraint on width: **Γ_H < 177 MeV**
  - cf. indirect constraint (on-shell vs off-shell H→ZZ):
    - $\Gamma_H = 4.1^{+0.7}_{-0.8}$ MeV (CMS+ATLAS combined)

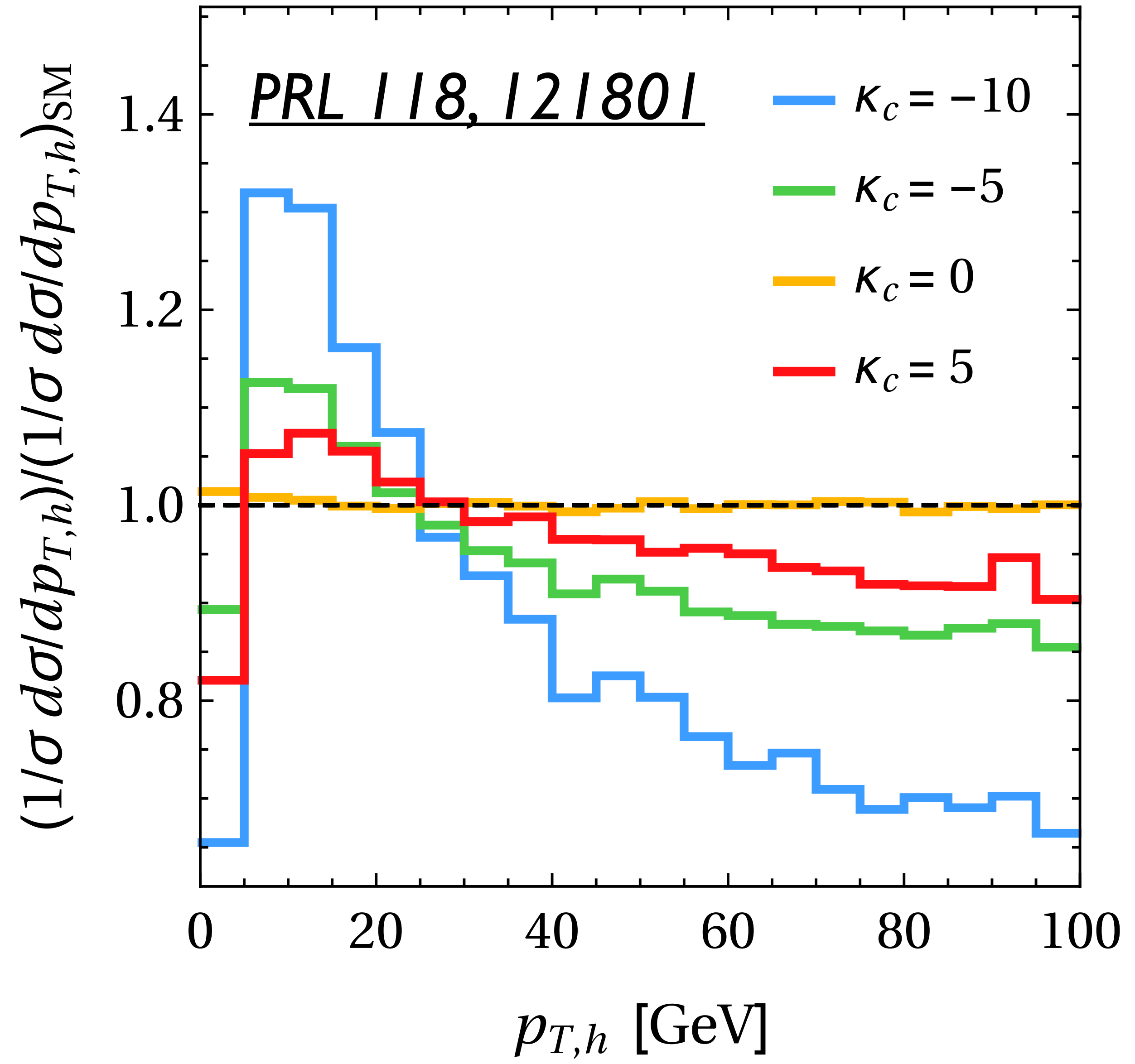
Differential Measurements

$H \to \gamma\gamma + ZZ$

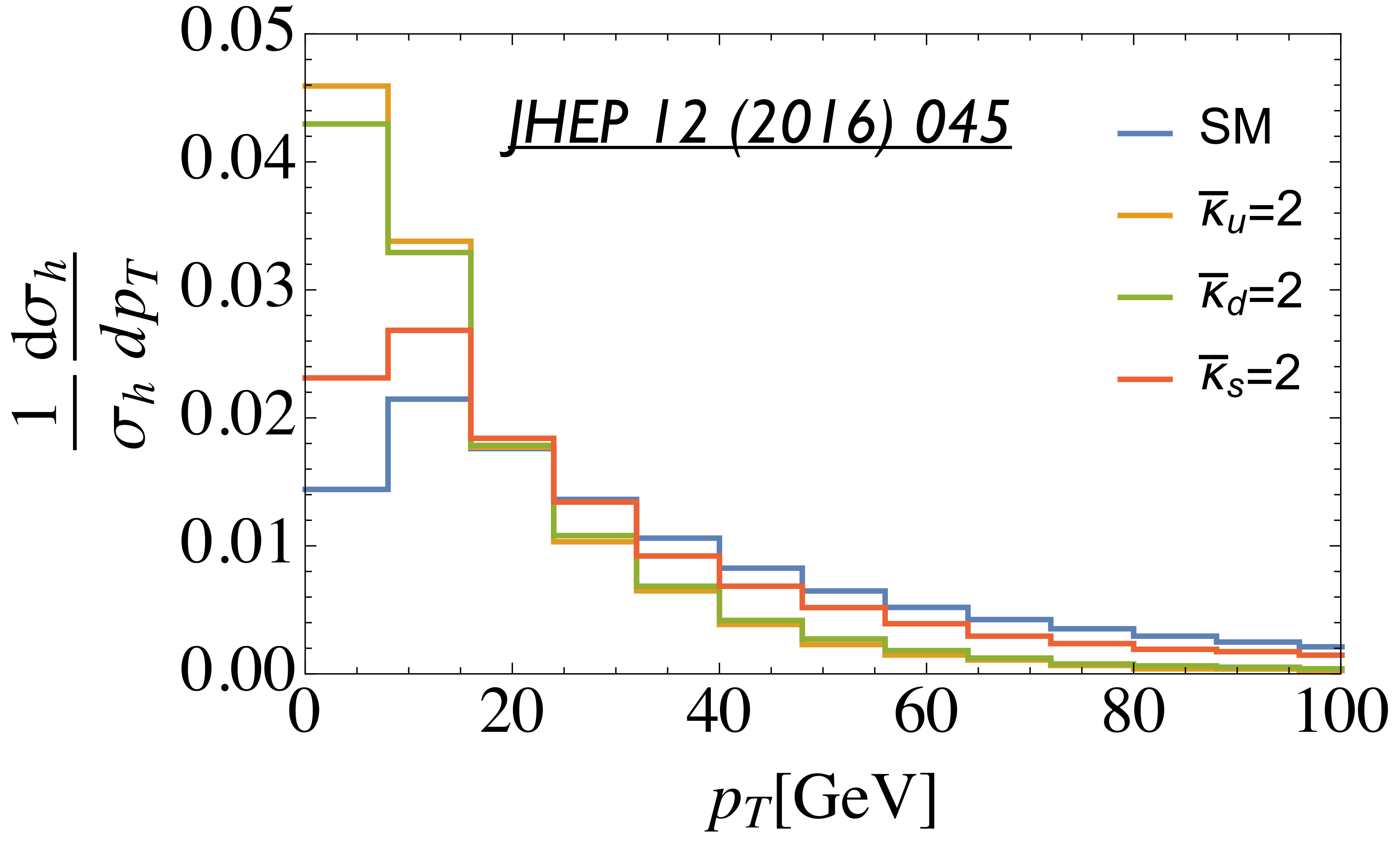
CERN-2019-007



- Expected to reach ~5% except the highest bin (> 350 GeV)
- Powerful to constraint light quark Yukawa couplings



Variation of $p_T(H)$ shape as a function $\kappa_c = y_c/y_c^{SM}$

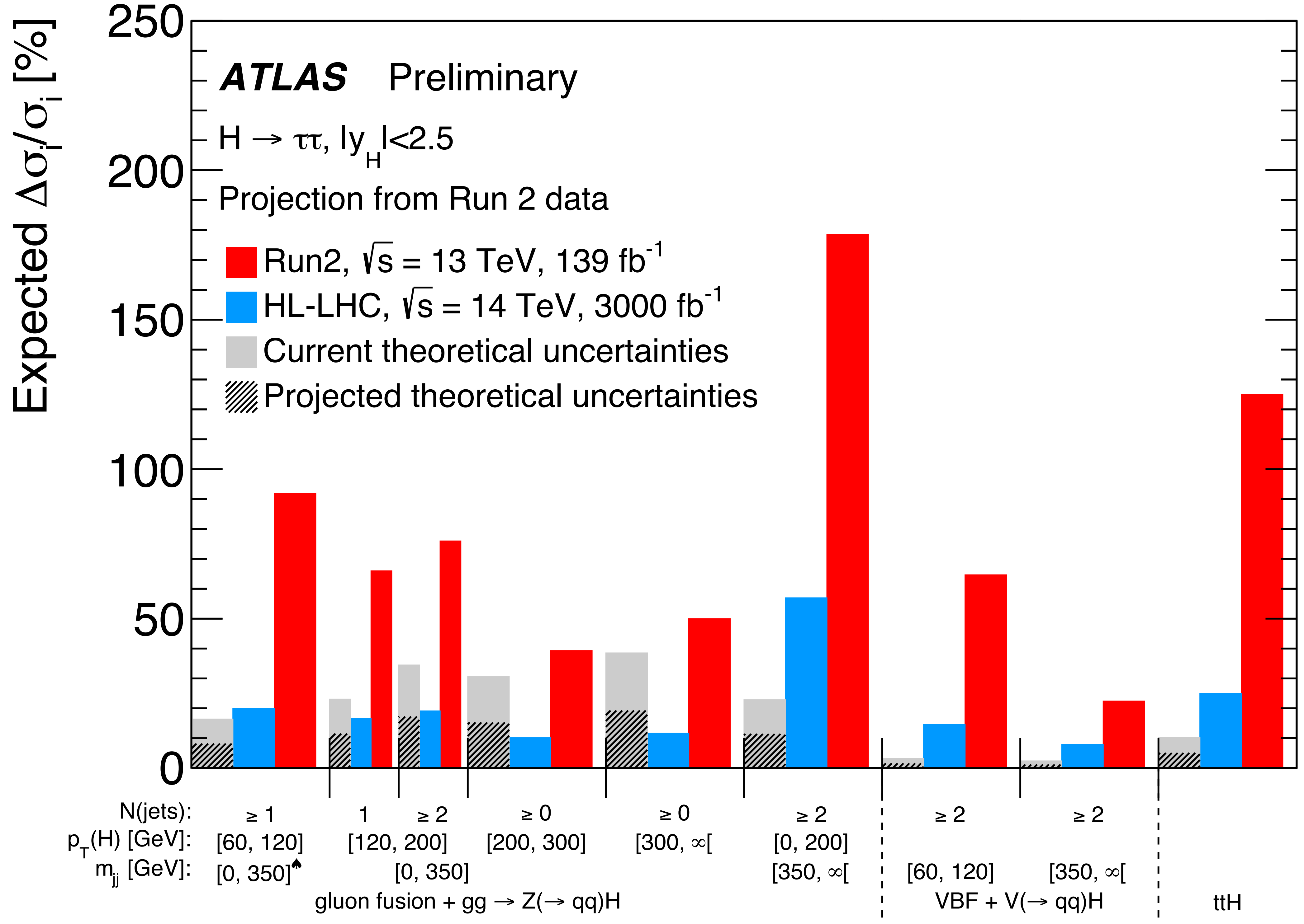


$p_T(H)$ vs light quark couplings (u, d, s)

DIFFERENTIAL MEASUREMENTS (II)

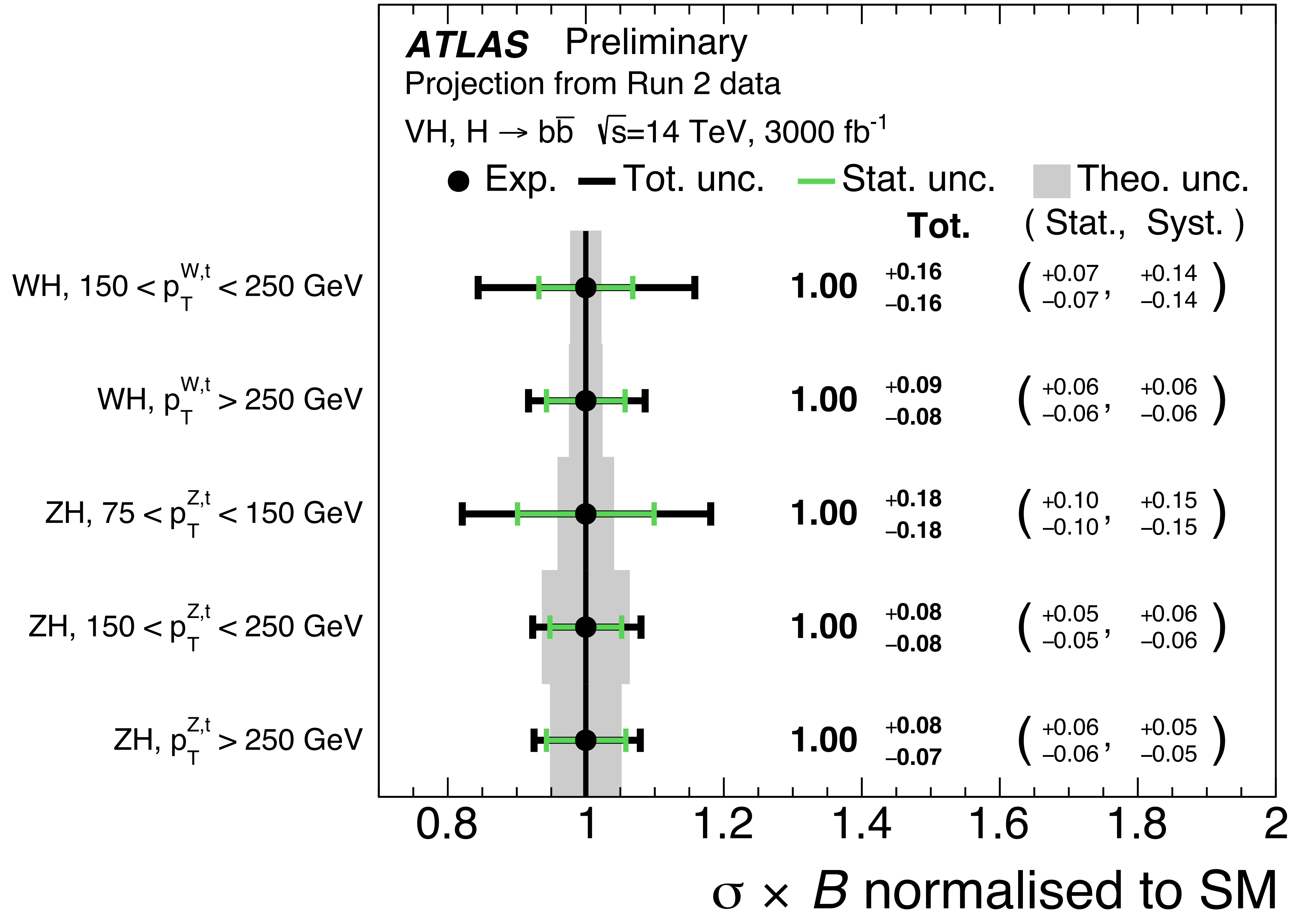
$H \to \tau\tau$

ATL-PHYS-PUB-2022-003



$VH(H \to bb)$

ATL-PHYS-PUB-2021-039



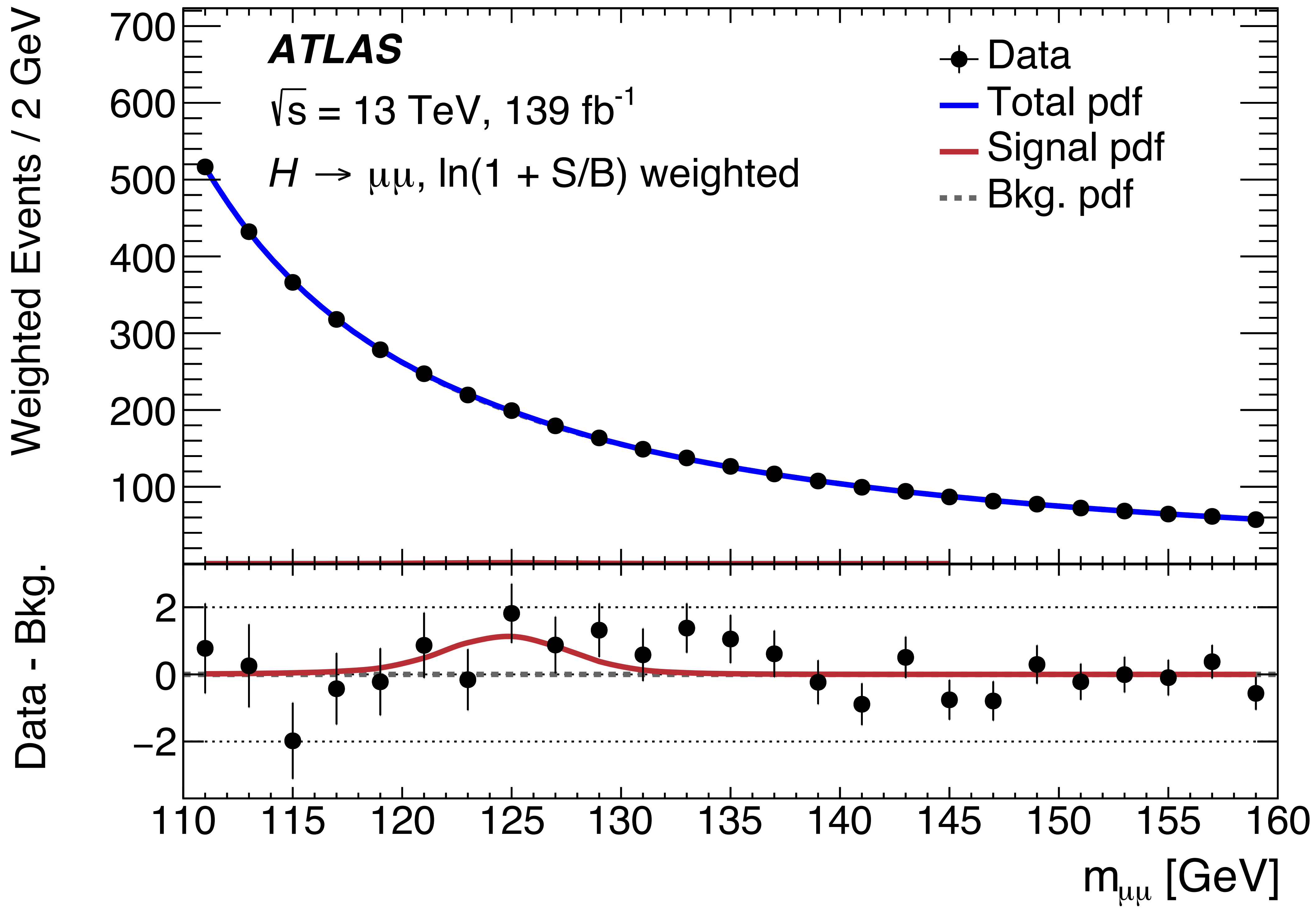
- Updated for Snowmass:
  - Expected precision reaching 5 - 20% in most STXS bins
  - Both measurements limited by systematic uncertainties (th. / bkg. modeling) at low to intermediate p_T^H

Couplings to Second Generation Fermions

Evidence for $H\to\mu\mu$ in Run 2

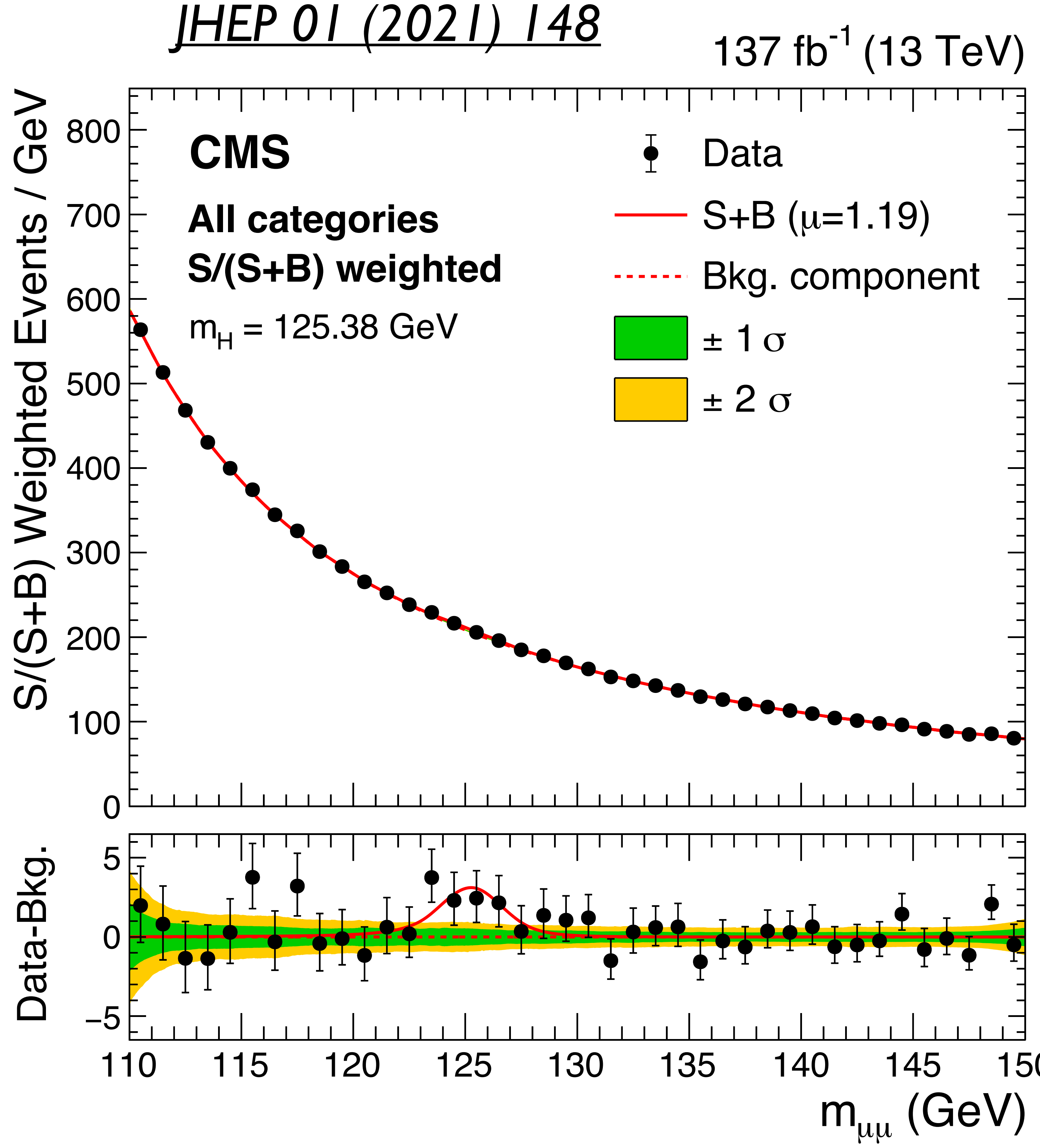
- Very challenging analysis
  - $Br(H\to\mu\mu) = 2.2 \times 10^{-4}$ in SM – extremely small S/B
  - dimuon invariant mass resolution is the key

PLB 812 (2021) 135980



2.0σ obs.
(1.7σ exp.)

JHEP 01 (2021) 148



3.0σ obs.
(2.5σ exp.)

Significant improvement over early Run 2 expectation.

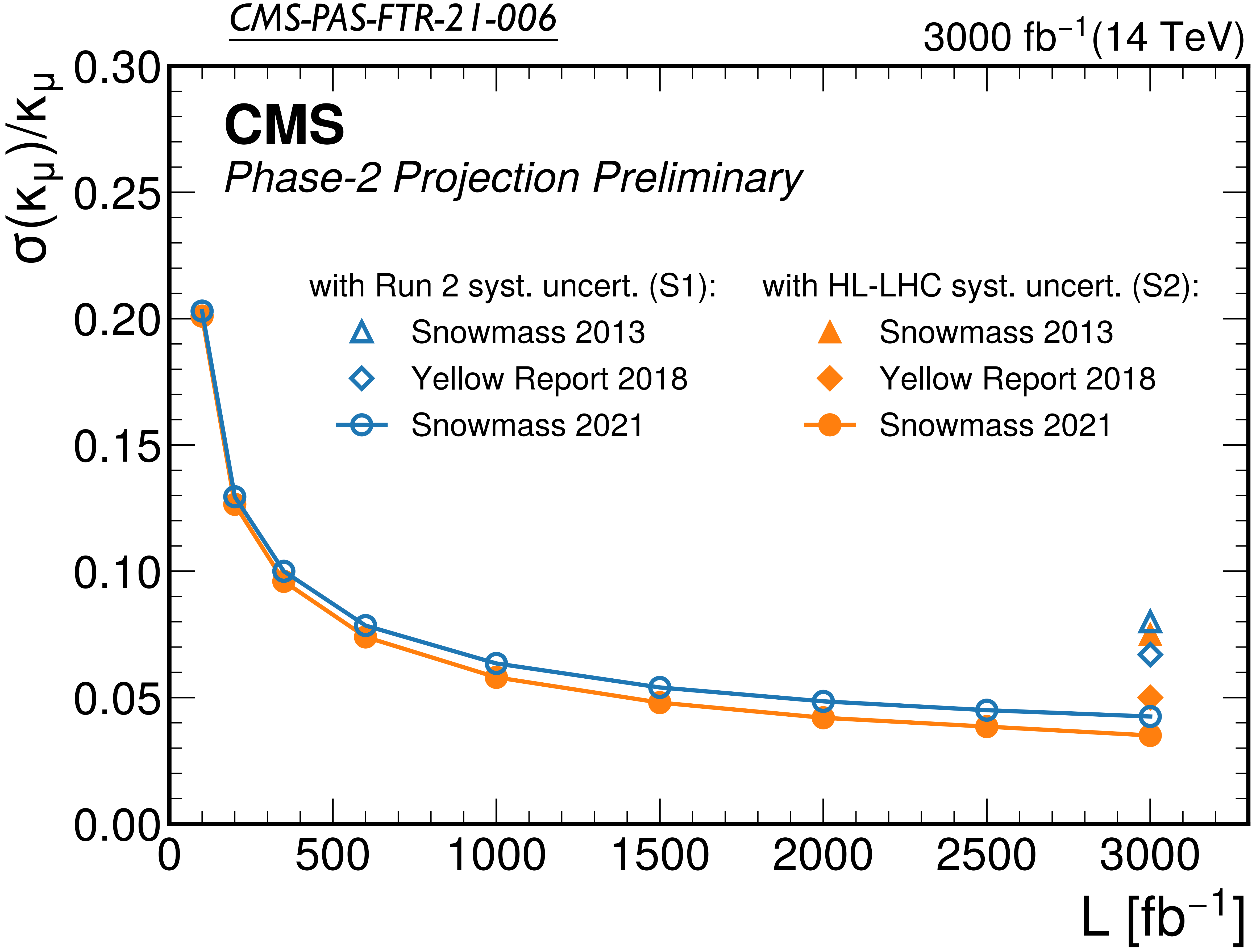
Prospects for H→μμ

- New projection based on the CMS full Run 2 analysis
- In addition: improvements from Phase-2 upgrades
  - new tracker:
    - ~30% in dimuon mass resolution
  - extended coverage (|η| < 2.8) of muon system:
    - ~10% increase in signal acceptance
- **3—4% uncertainty on κ_μ at HL-LHC**
  - ~30% improvement compared to YR18
    - largely due to improved analysis strategy

Uncertainty on the coupling modifier κ_μ

		Statistical	Experimental	Theoretical	Total
S1	Snowmass 2013	-	-	-	8.0%
	YR 2018	4.7%	2.7%	3.9%	6.7%
	Snowmass 2021	3.2%	1.9%	2.2%	4.3%
S2	Snowmass 2013	-	-	-	7.5%
	YR 2018	4.7%	1.5%	1.1%	5.0%
	Snowmass 2021	3.2%	1.1%	0.8%	3.5%

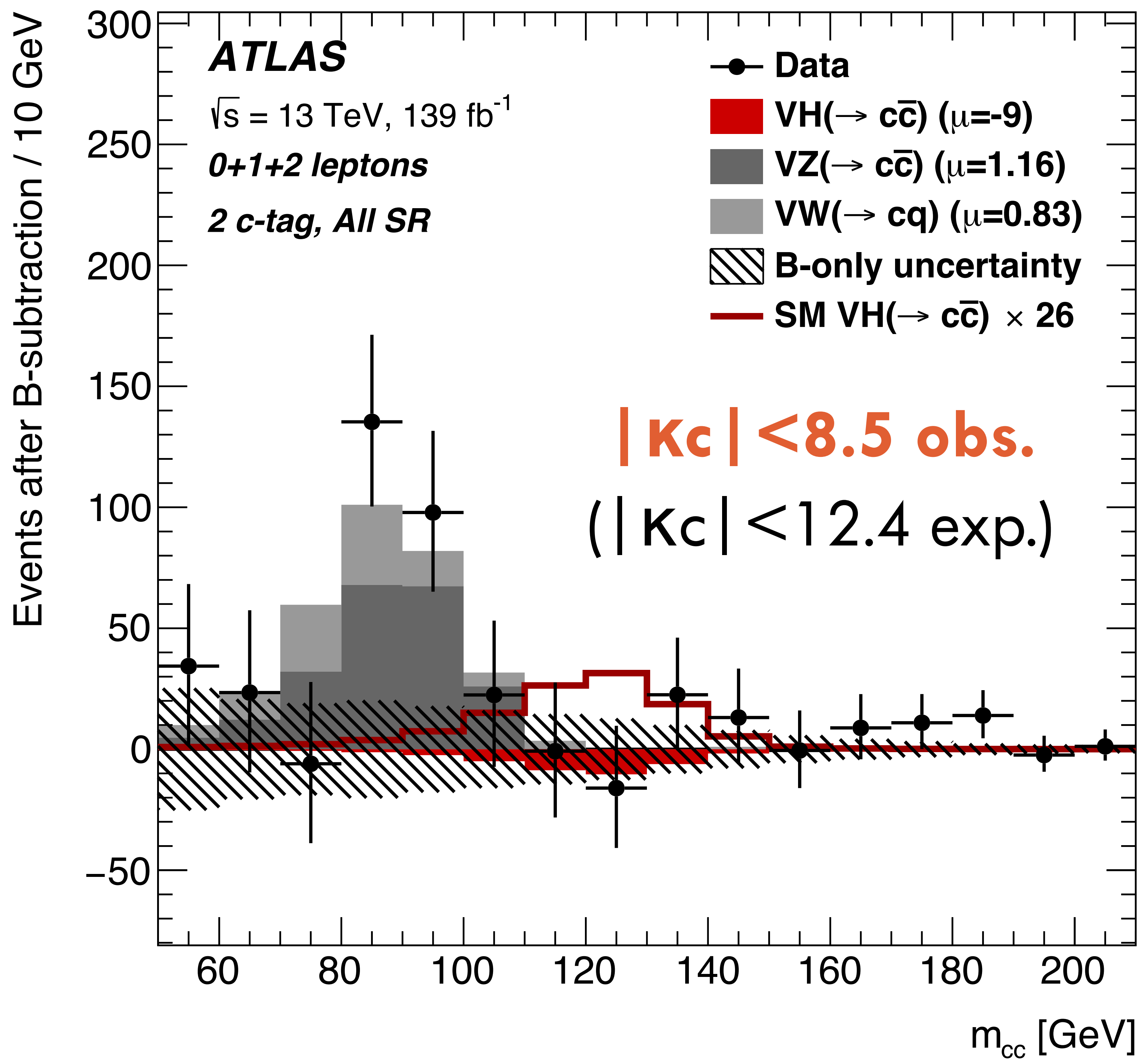
CMS-PAS-FTR-21-006



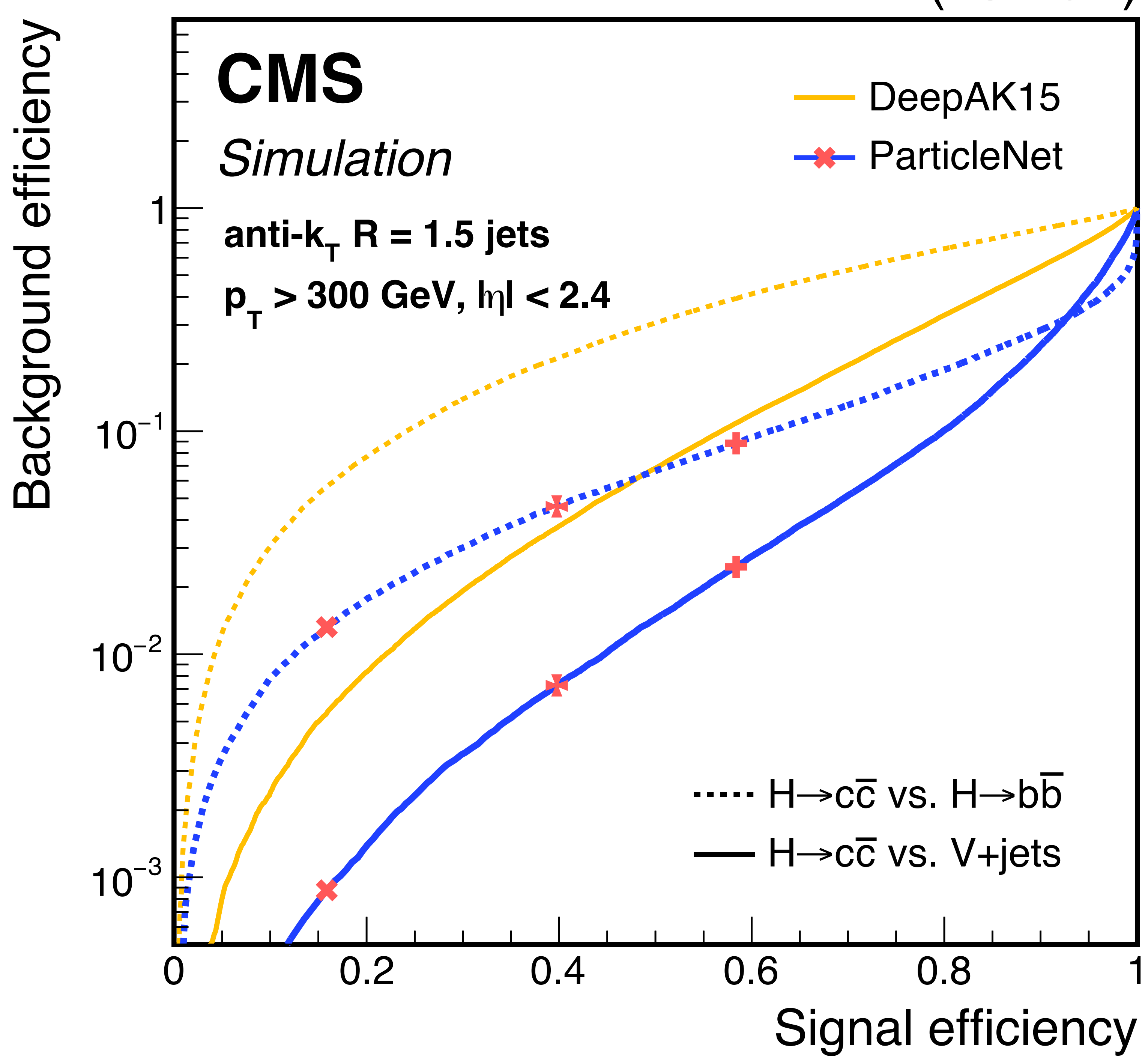
Higgs-Charm Coupling in Run 2

- Extremely challenging search at the LHC
  - small branching fraction (~3%) vs enormous hadronic backgrounds — charm tagging is the key
- Substantial progress in Run 2 — far beyond previous expectations
  - advanced machine learning techniques + merged-jet topology play a key role

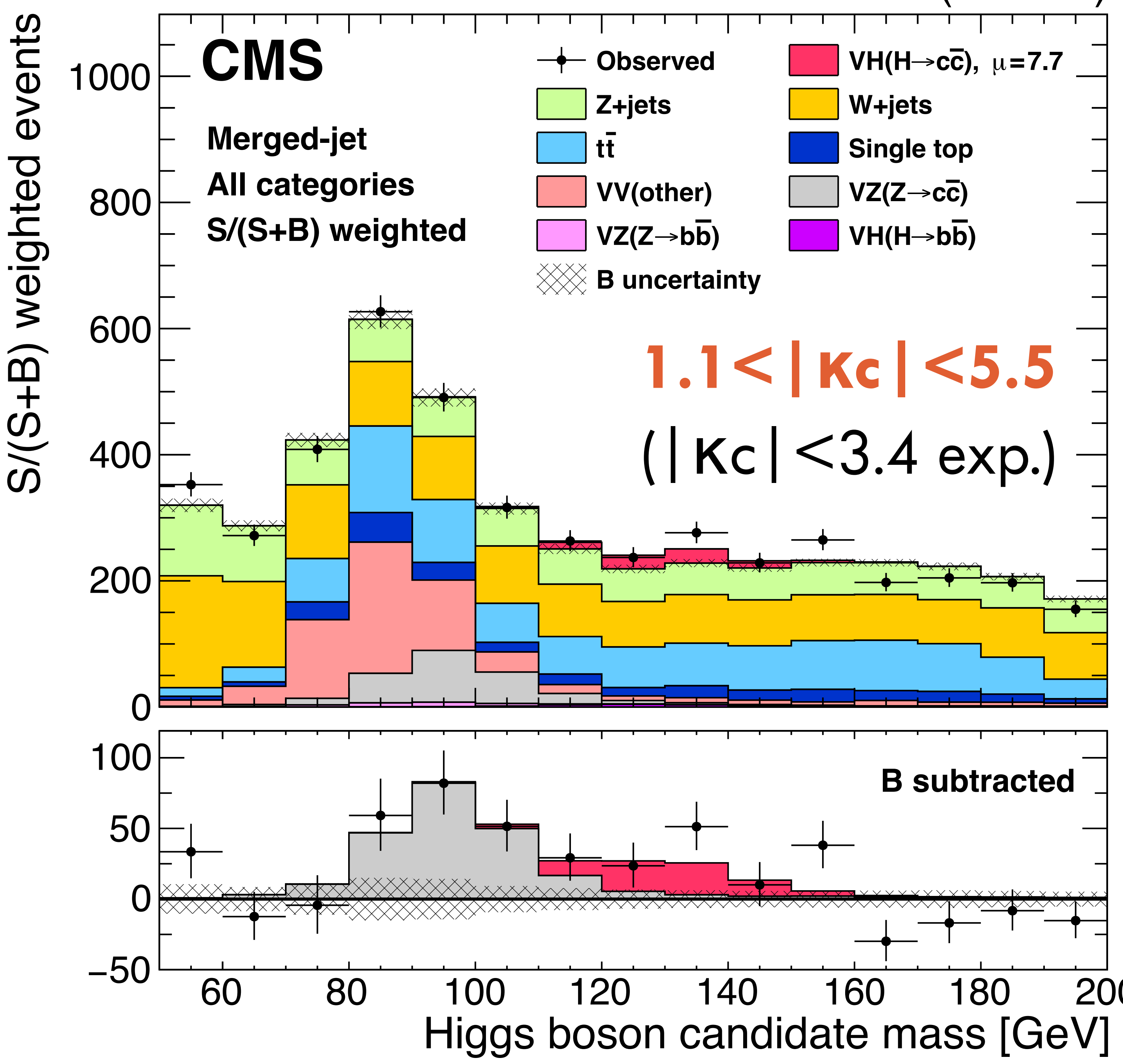
EPJC 82 (2022) 717



H → cc tagging with large-R jets

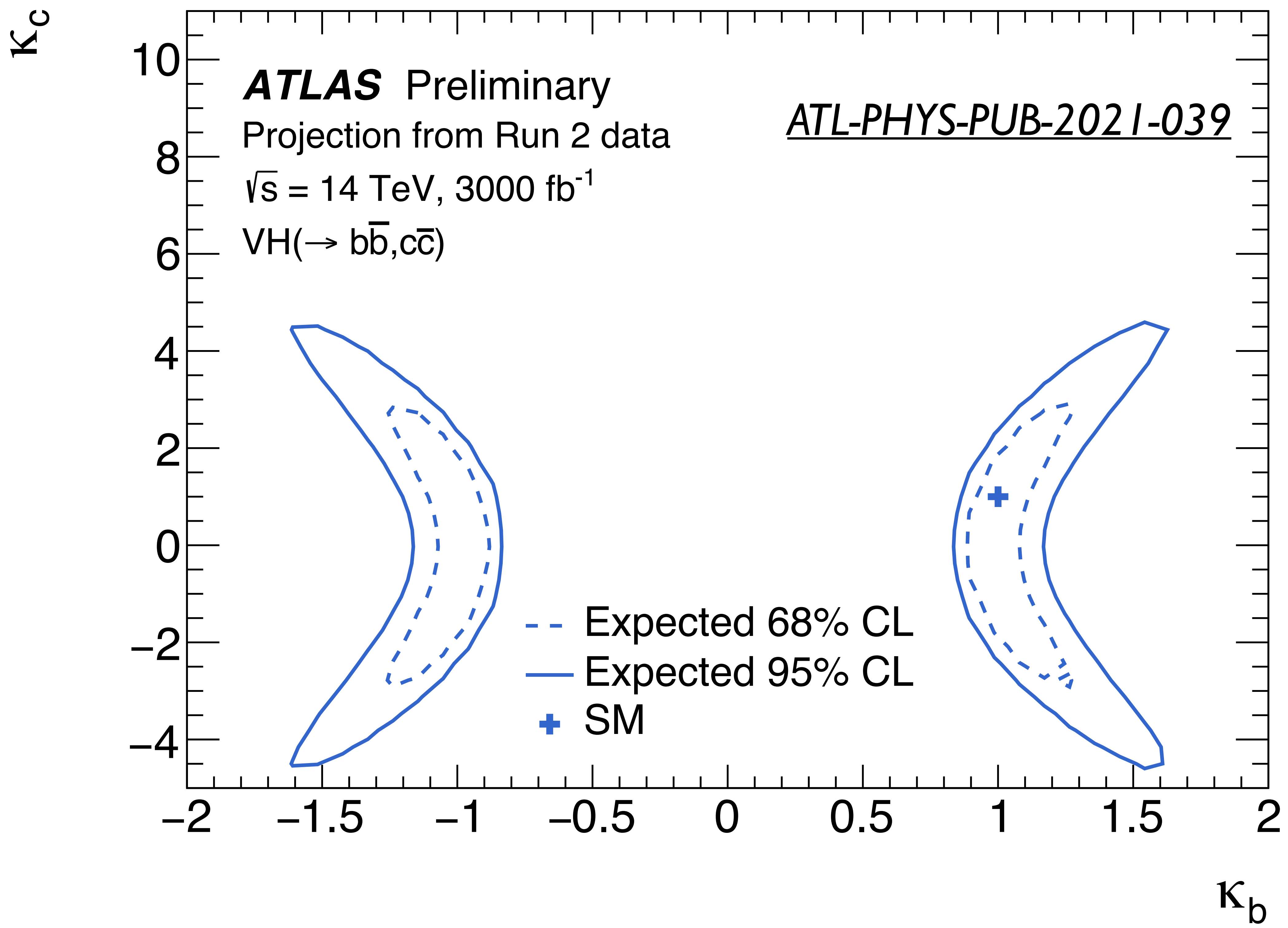


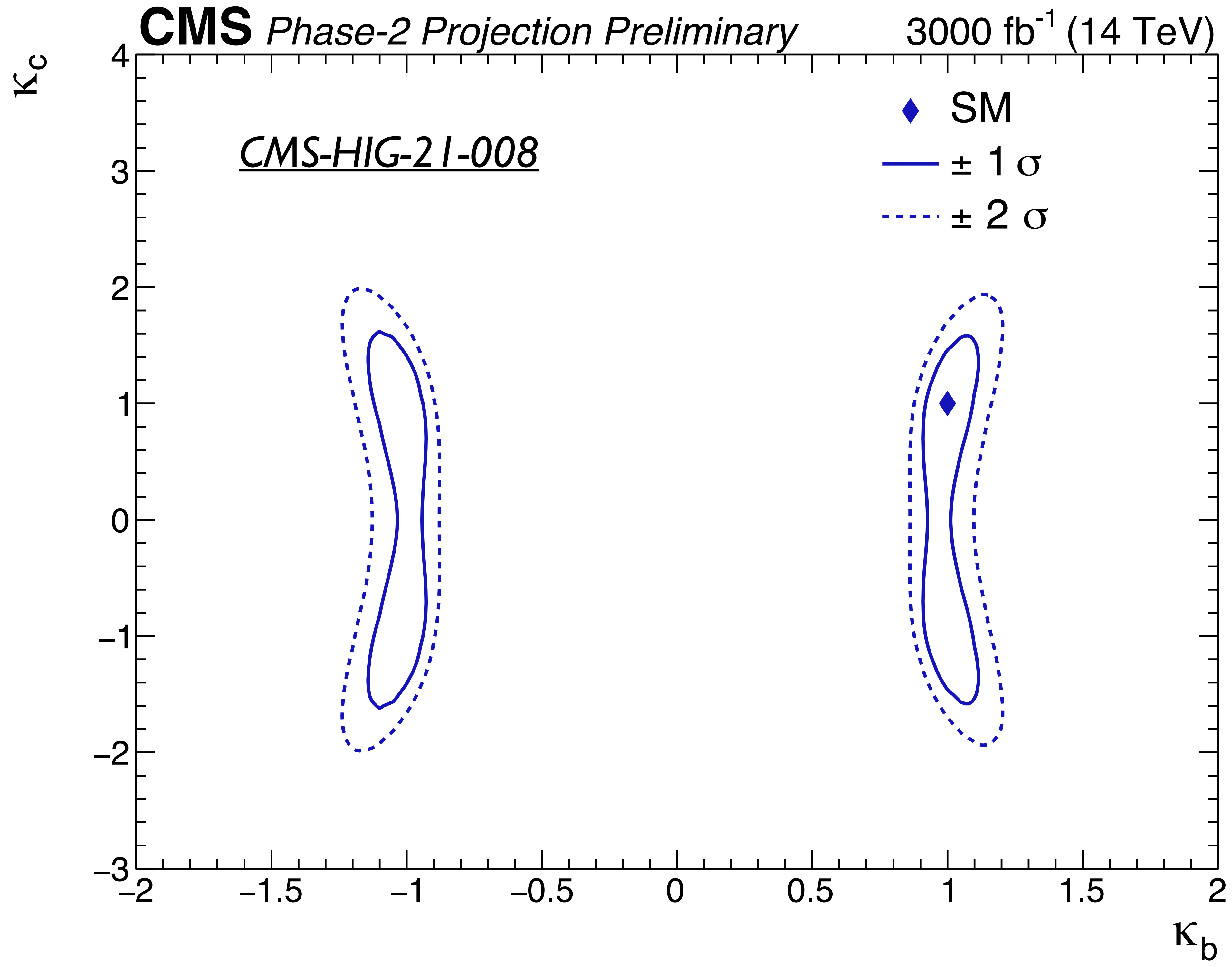
PRL 131 (2023) 061801



Prospects for H→cc

- Projection of the Run 2 analysis to HL-LHC
  - CMS: merged-jet topology only, w/ large-R jet p_T threshold lowered from 300 GeV to 200 GeV
- Simultaneous constraint of H → bb and H → cc

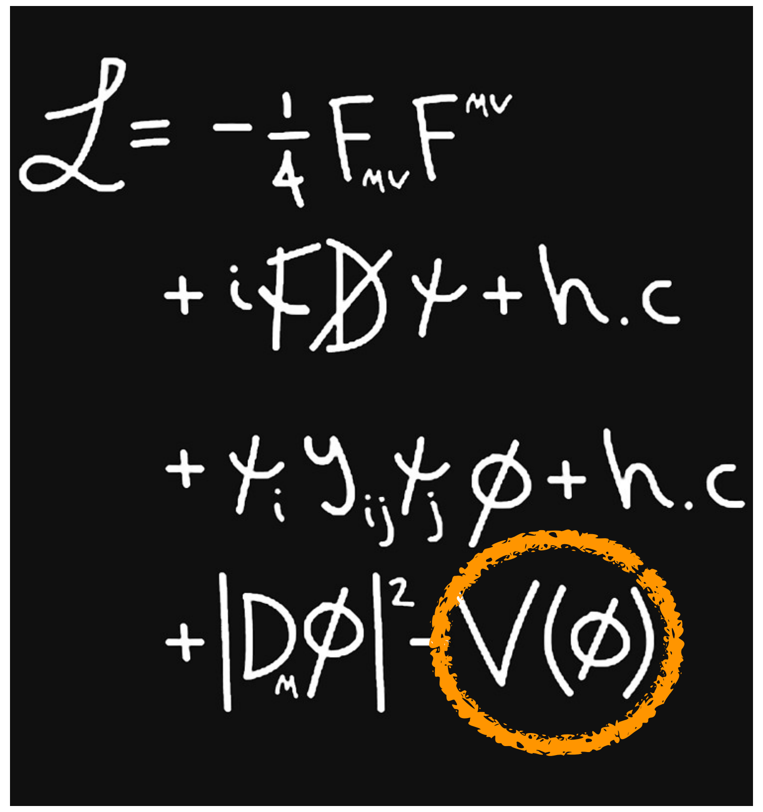




Expected sensitivity approaches the SM value for the Higgs-charm coupling.

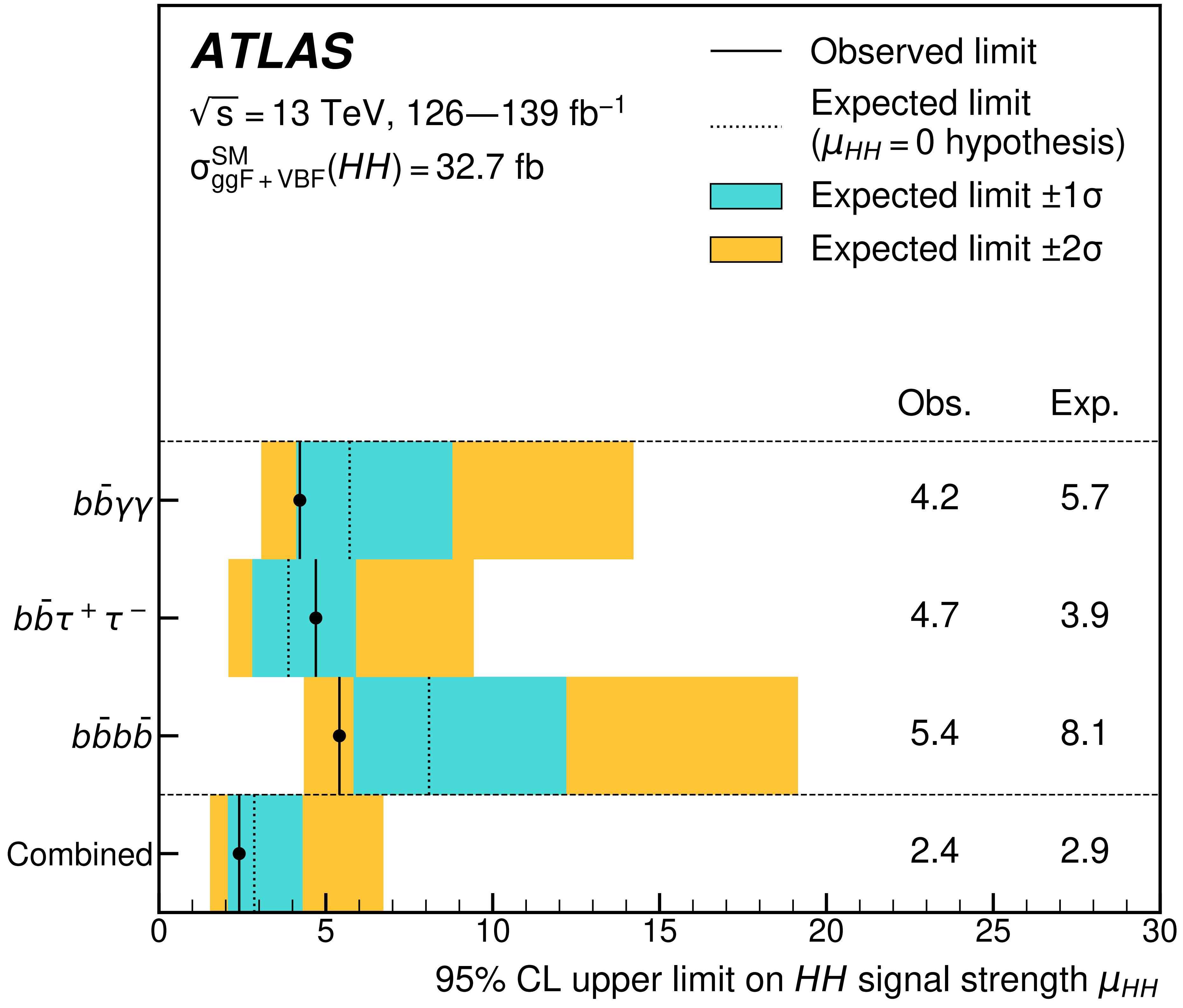
TOWARDS DI-HIGGS OBSERVATION

Higgs Boson Pair Production

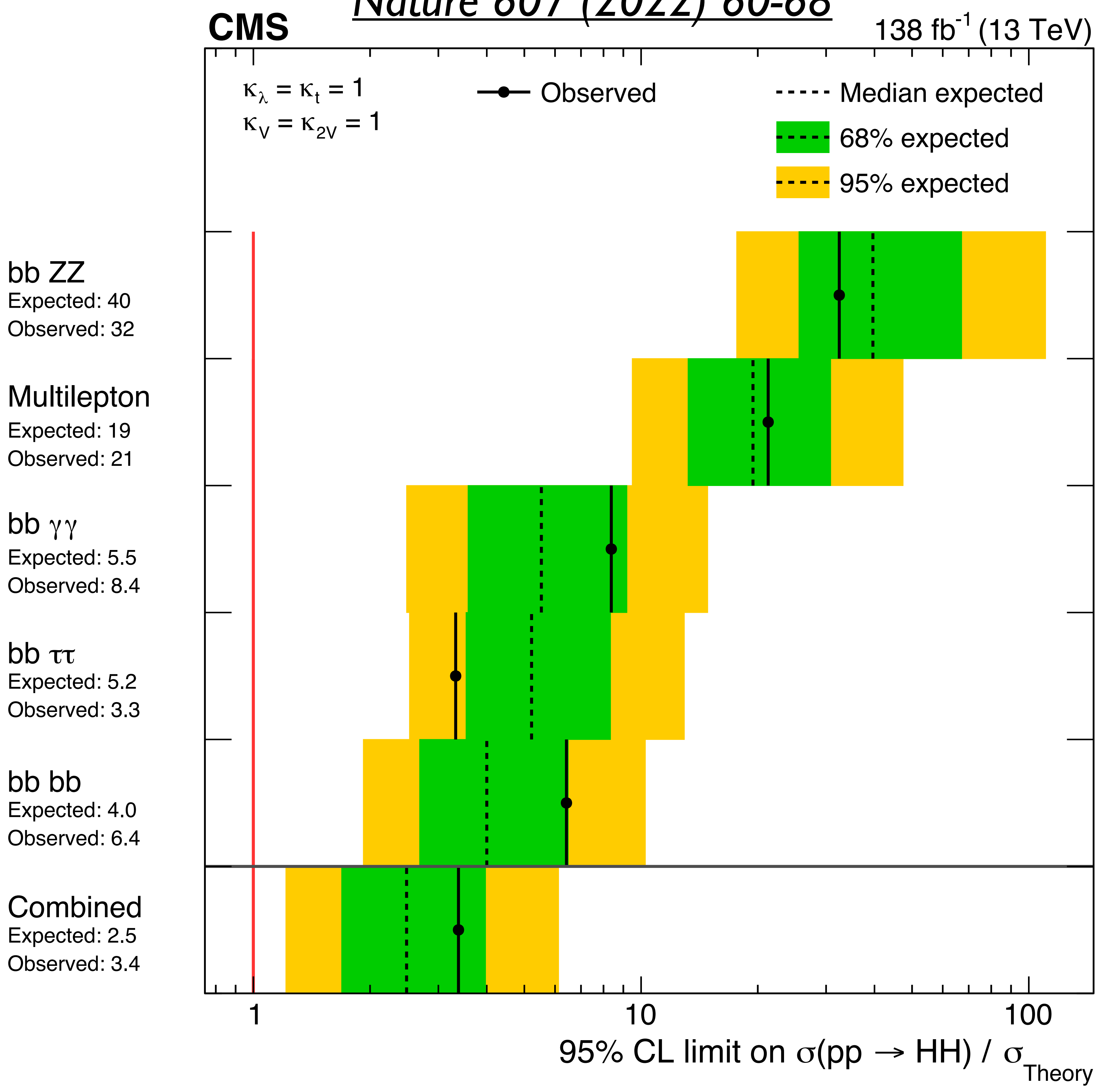


- Higgs boson pair (HH) production: one of the top priorities at the HL-LHC
  - crucial to probe the Higgs potential in SM
- Substantial progress in Run 2: upper limit < 3

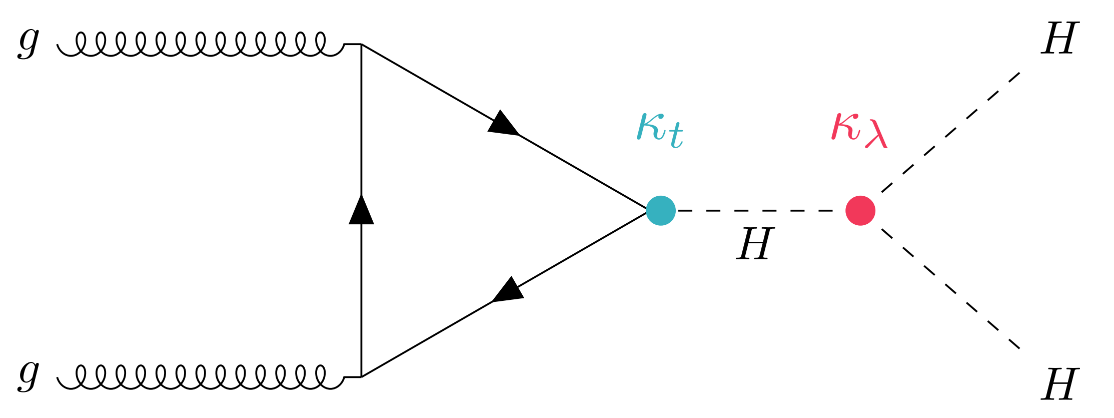
PLB 843 (2023) 137745



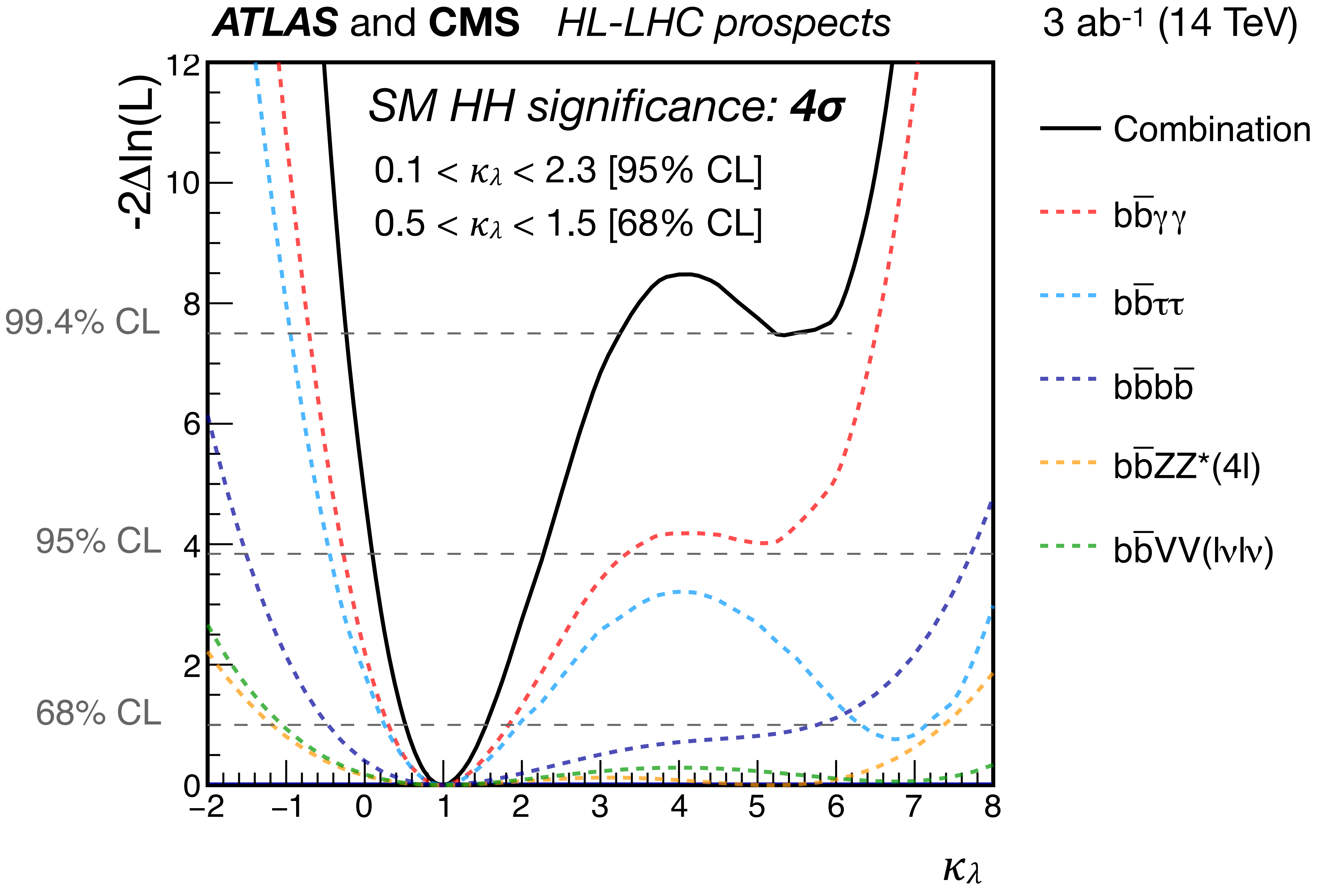
Nature 607 (2022) 60-68



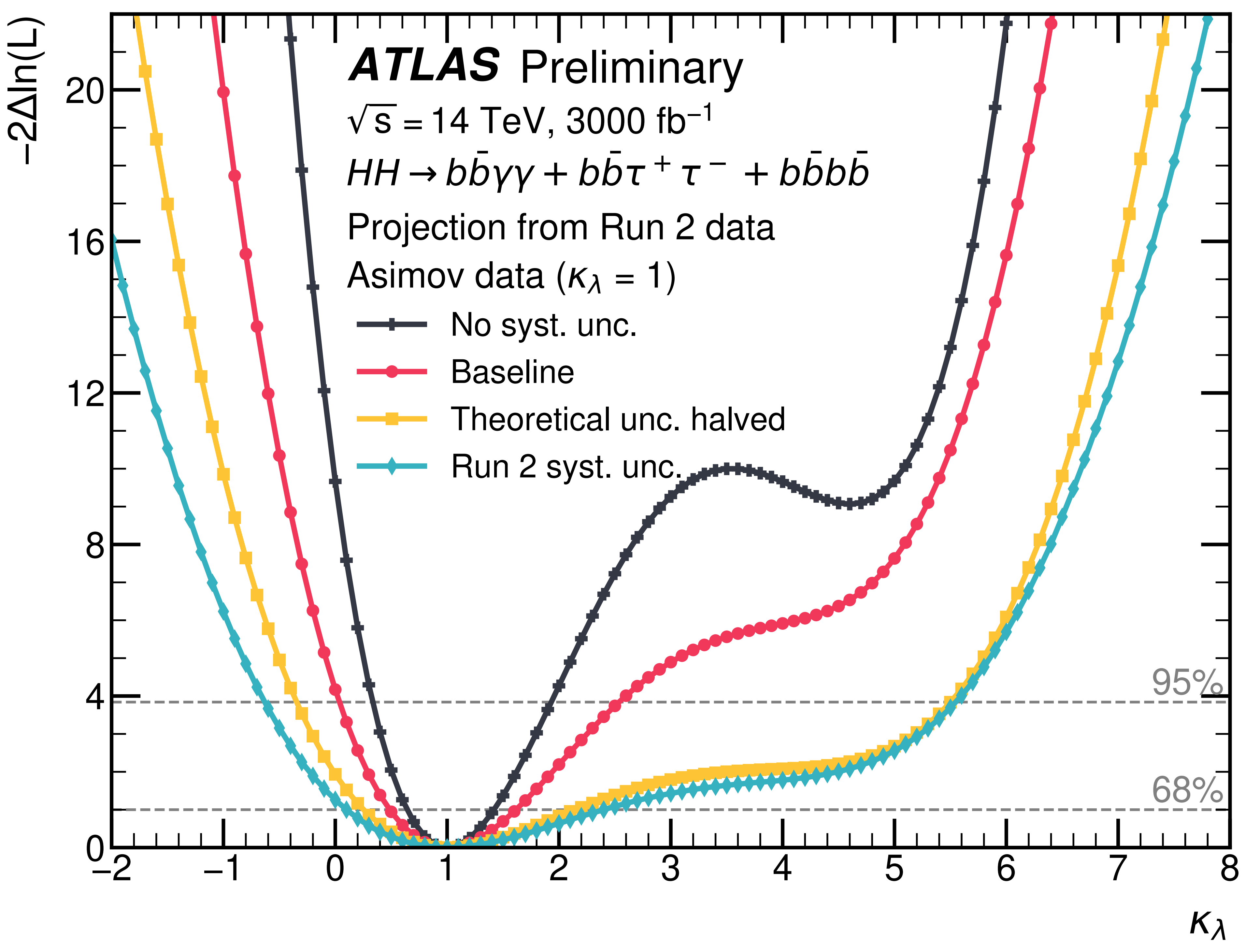
Prospects for HH



CERN-2019-007



ATL-PHYS-PUB-2022-053



- YR18 (CMS+ATLAS)
  - 4.0σ with baseline systematics (4.5σ w/o syst.)
  - $0.5 < \kappa_\lambda < 1.5$ [68% CL]

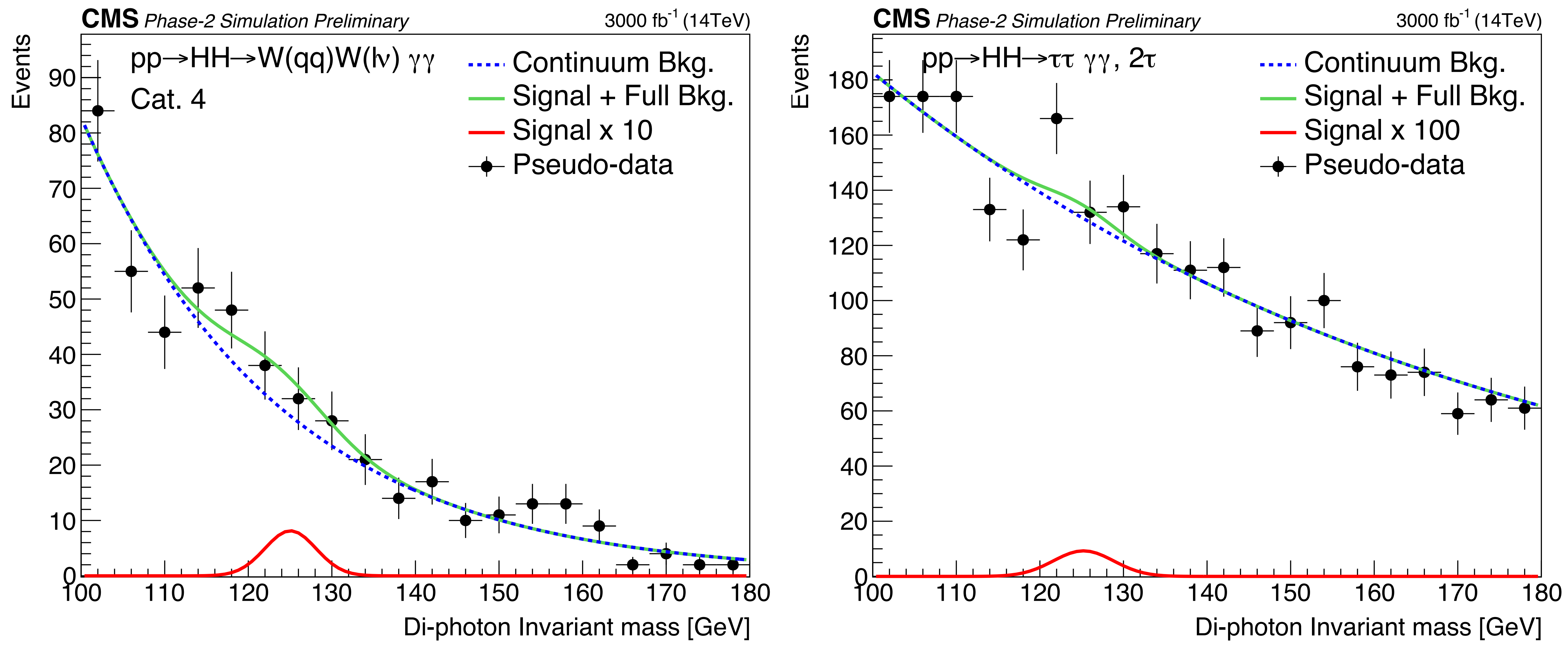
~20% (50%) improvement

- 2022 update (ATLAS)
  - 3.4σ with baseline systematics (4.9σ w/o syst.)
  - $0.5 < \kappa_\lambda < 1.6$ [68% CL]
- CMS updated bbγγ result shows similar improvement

HH: More Channels

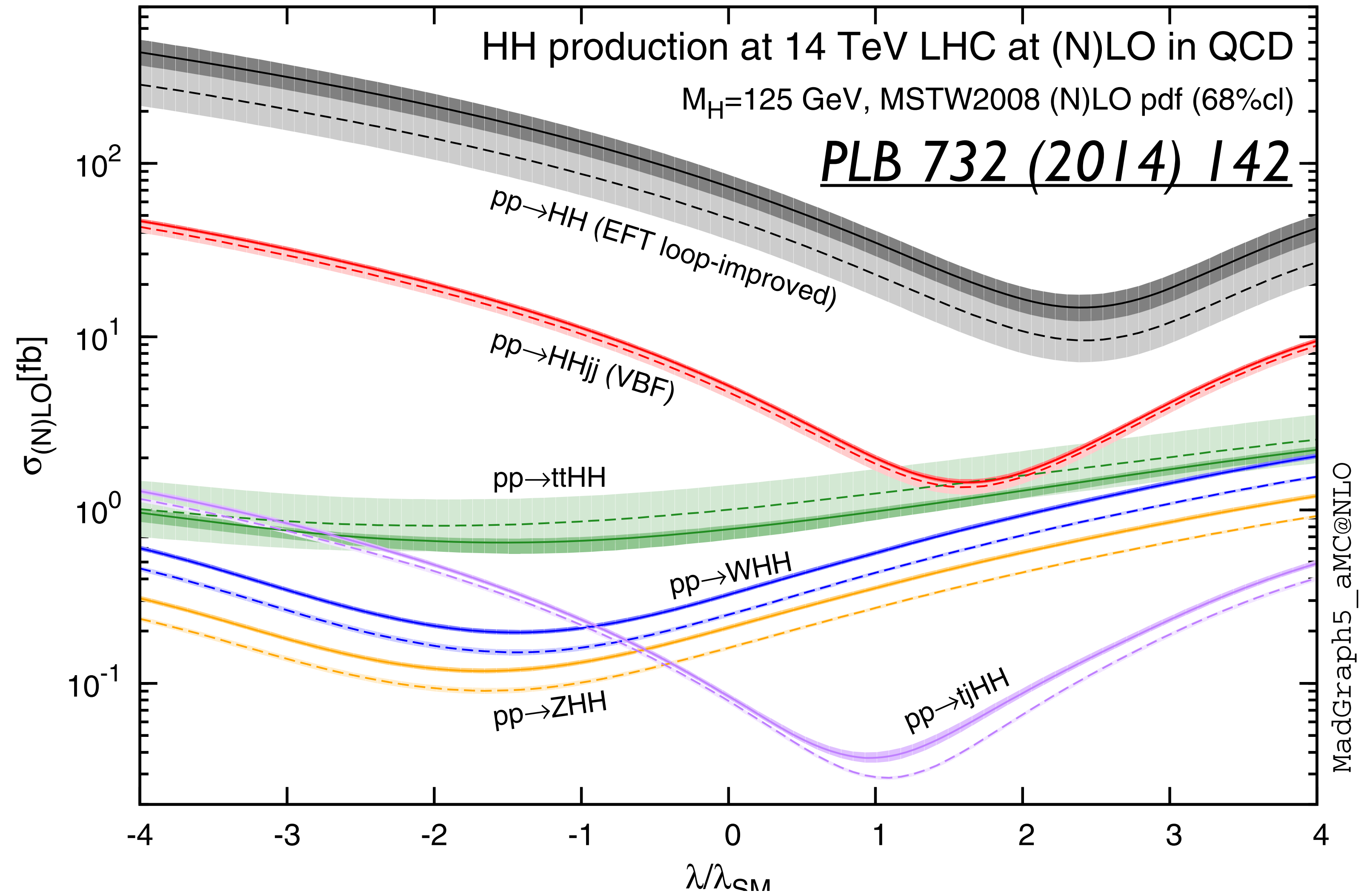
$HH \to WW\gamma\gamma + \tau\tau\gamma\gamma$

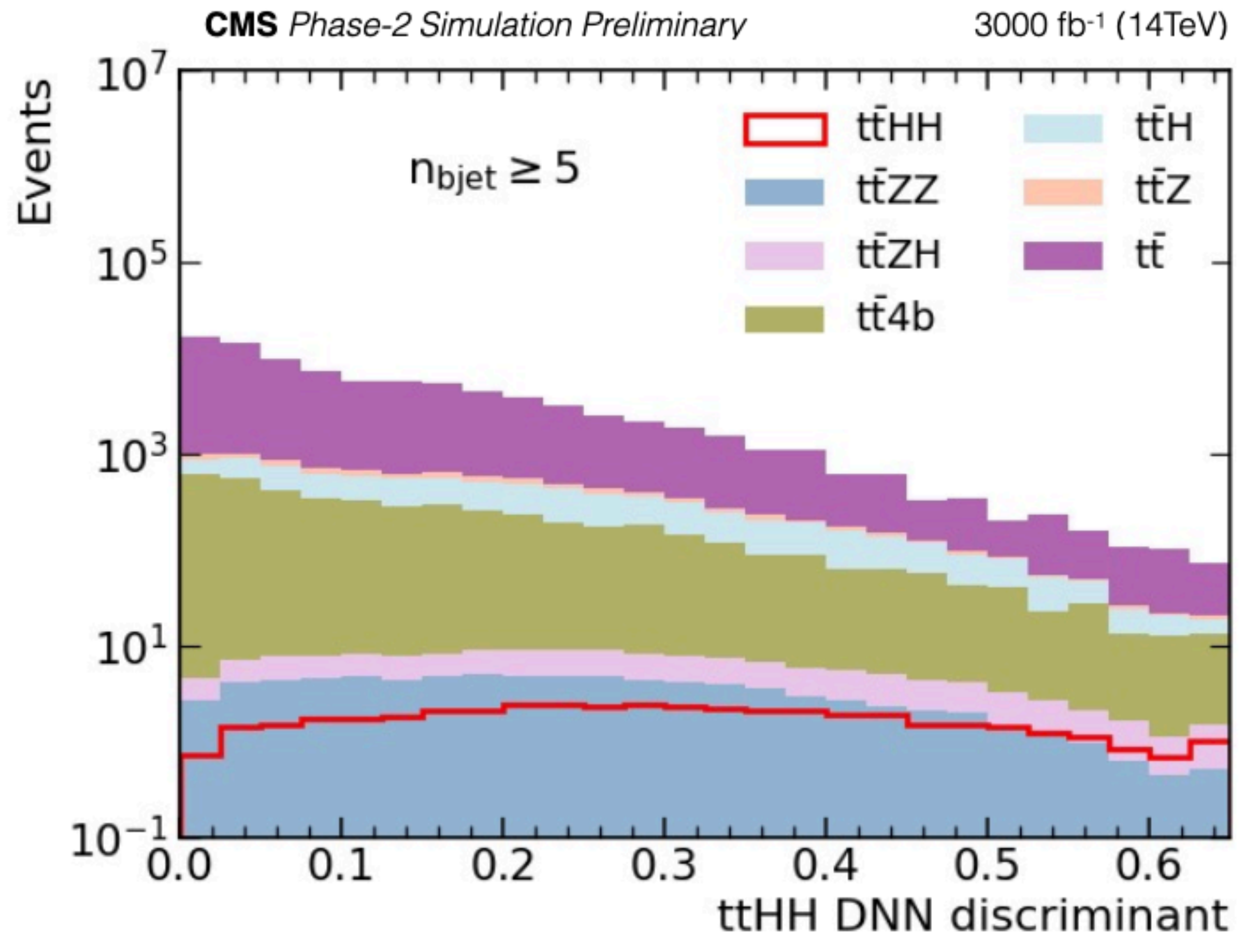
CMS-PAS-FTR-21-003



Final State	Significance (stat+exp+theory)
$WW\gamma\gamma$	0.21
$\tau\tau\gamma\gamma$	0.08
Combination	0.22

ttHH





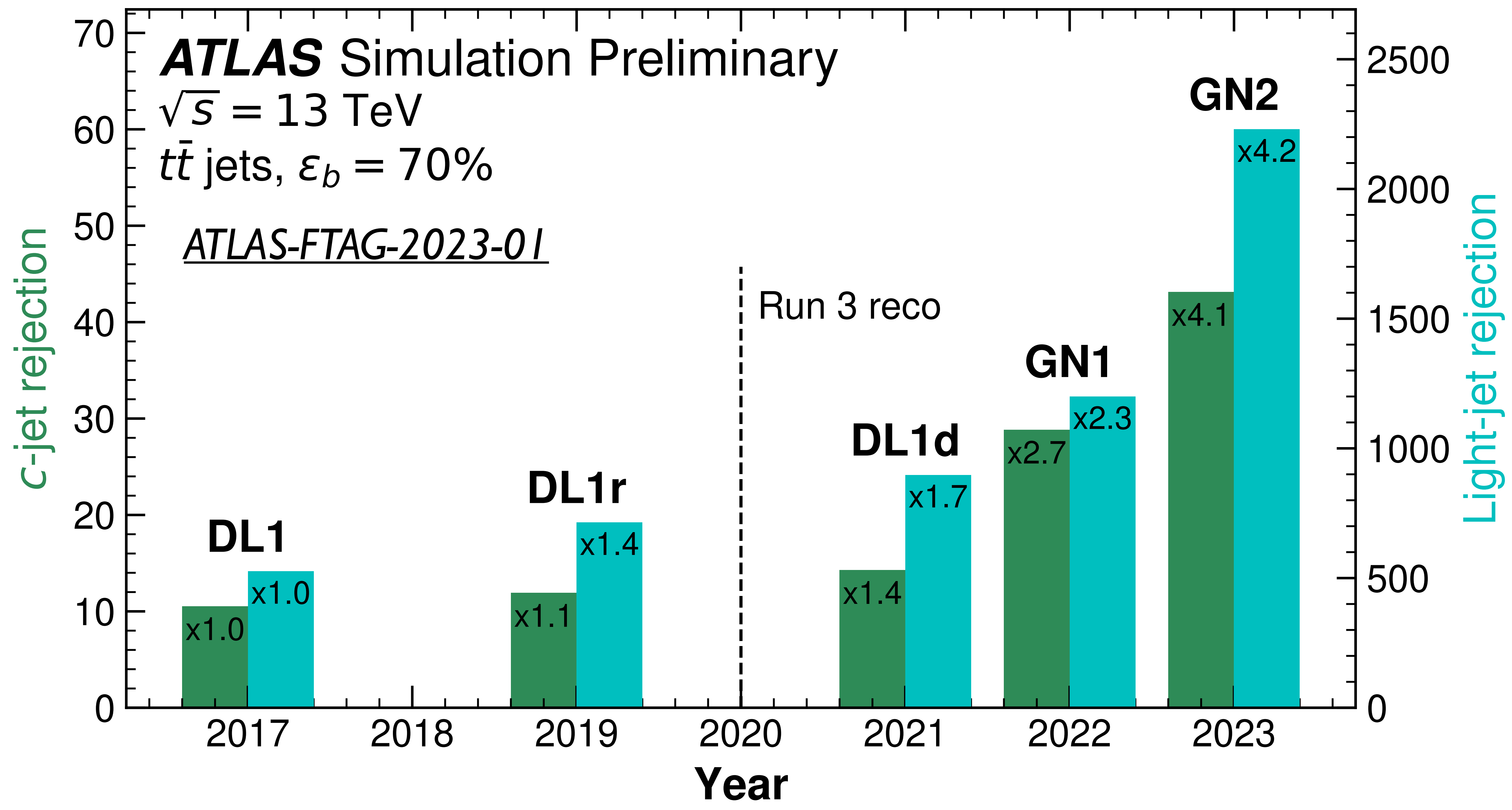
CMS-PAS-FTR-21-010

- tt(l+jets)+HH(4b):
  - $\mu_{ttHH} < 3.14$
- More potential w/ extra channels
  - cf. PRD 101 (2020) 055043

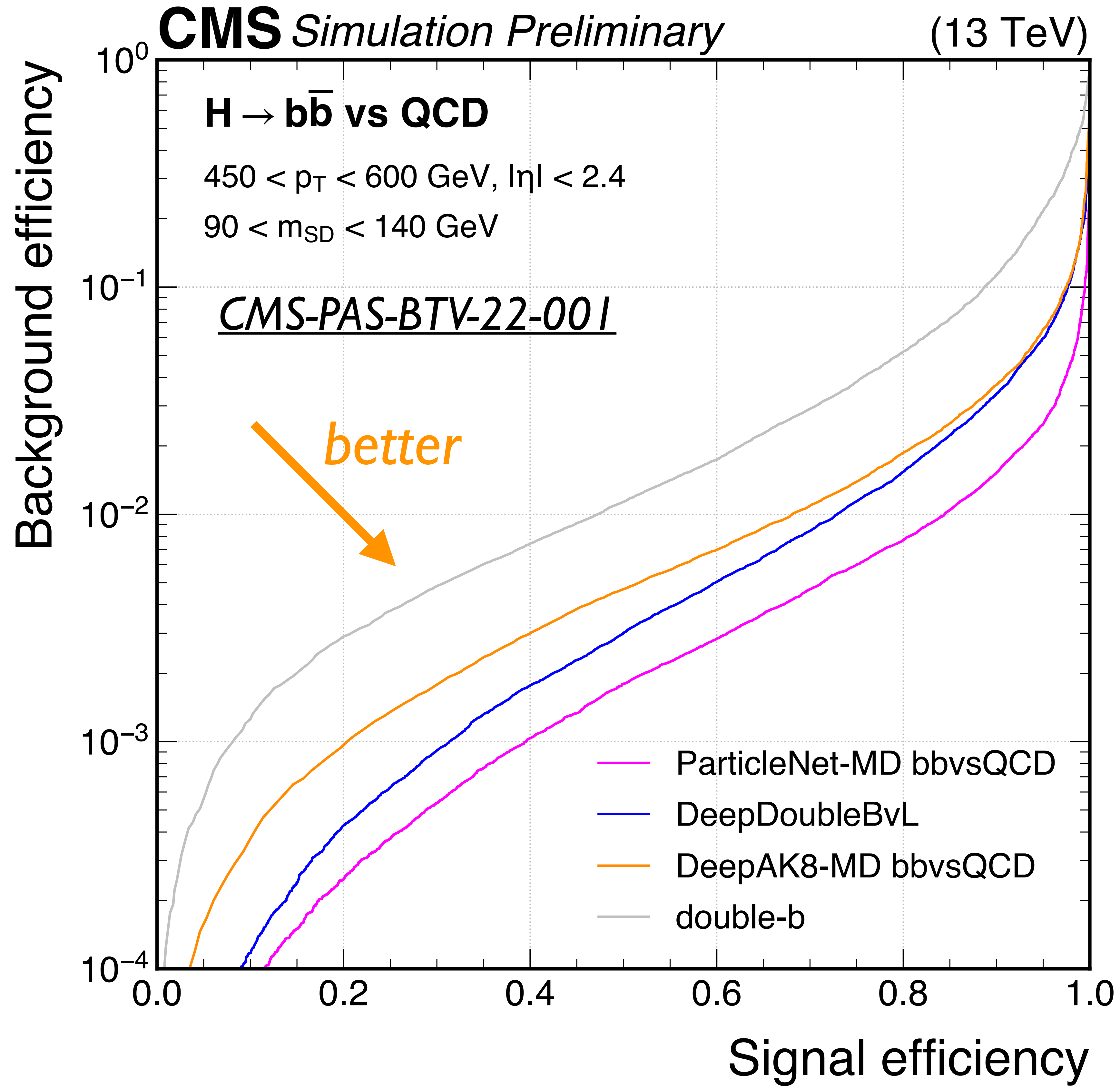
HH: Better Tools

- Advanced machine learning flavor taggers (GNN/Transformers) have become the standard in ATLAS & CMS
  - significant performance improvement in H→bb/cc tagging, mass regression, etc.
  - powerful handles for HH searches involving b-jet final states — further gains in Run 3

Jet flavor tagging with small-R jets



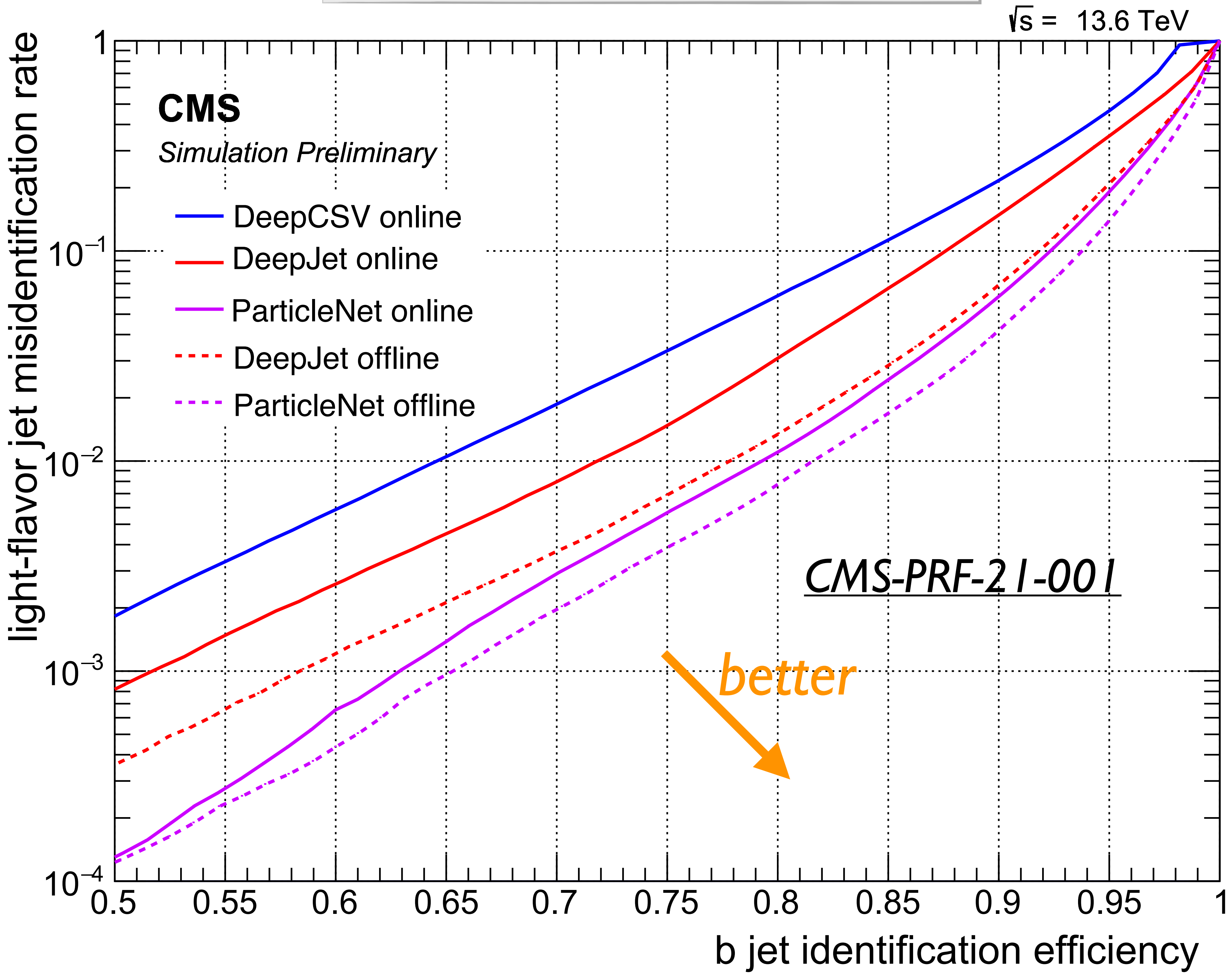
H→bb tagging with large-R jets



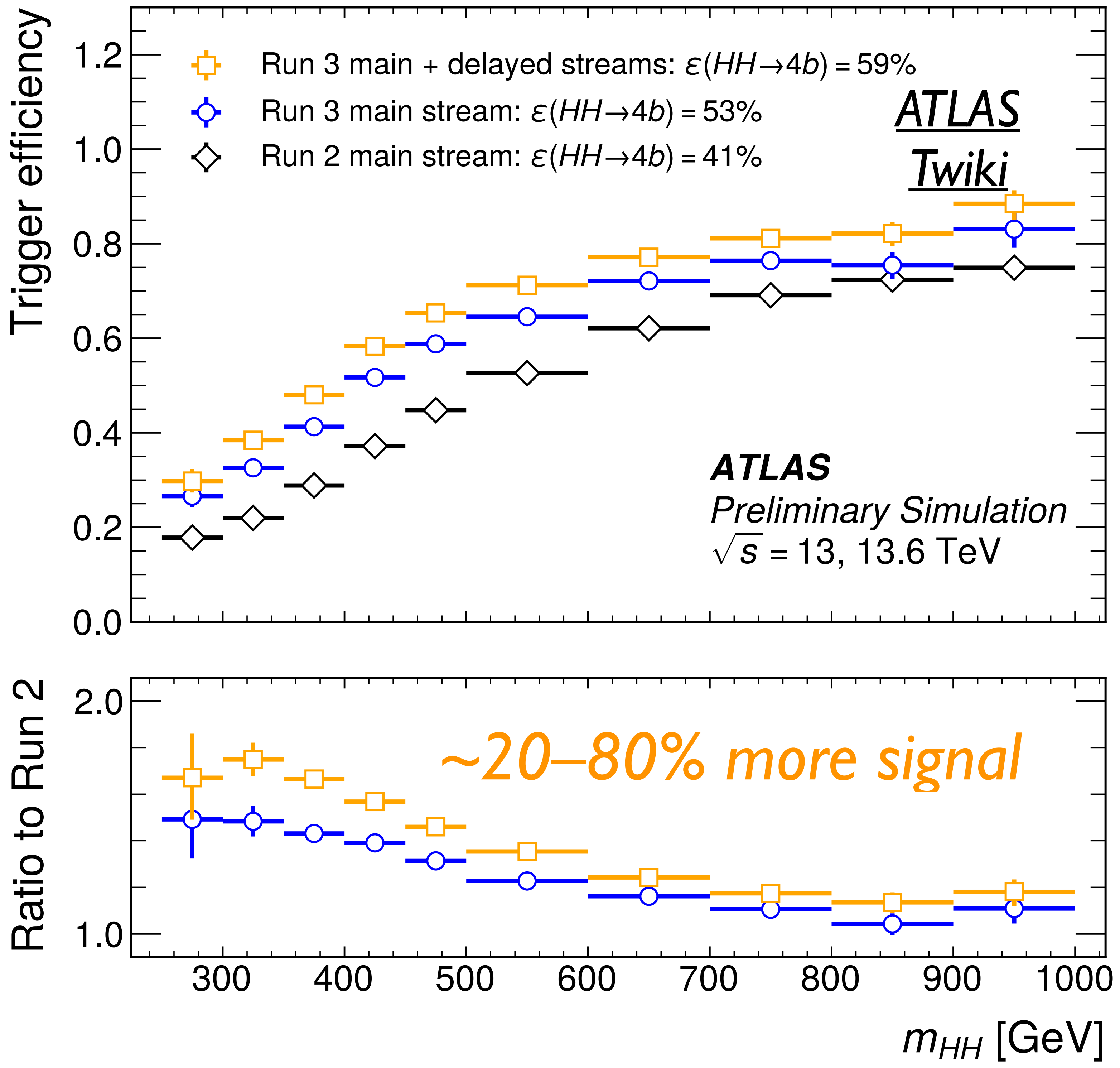
HH: Better Triggers

- Run 3 also sees these state-of-the-art taggers deployed at HLT for online event selection
  - substantial improvement in trigger efficiency for e.g. HH→4b final states

b-tagging performance @ HLT



Trigger efficiency for HH→4b



With all these improvements

— HH observation may arrive (much) sooner than expected!

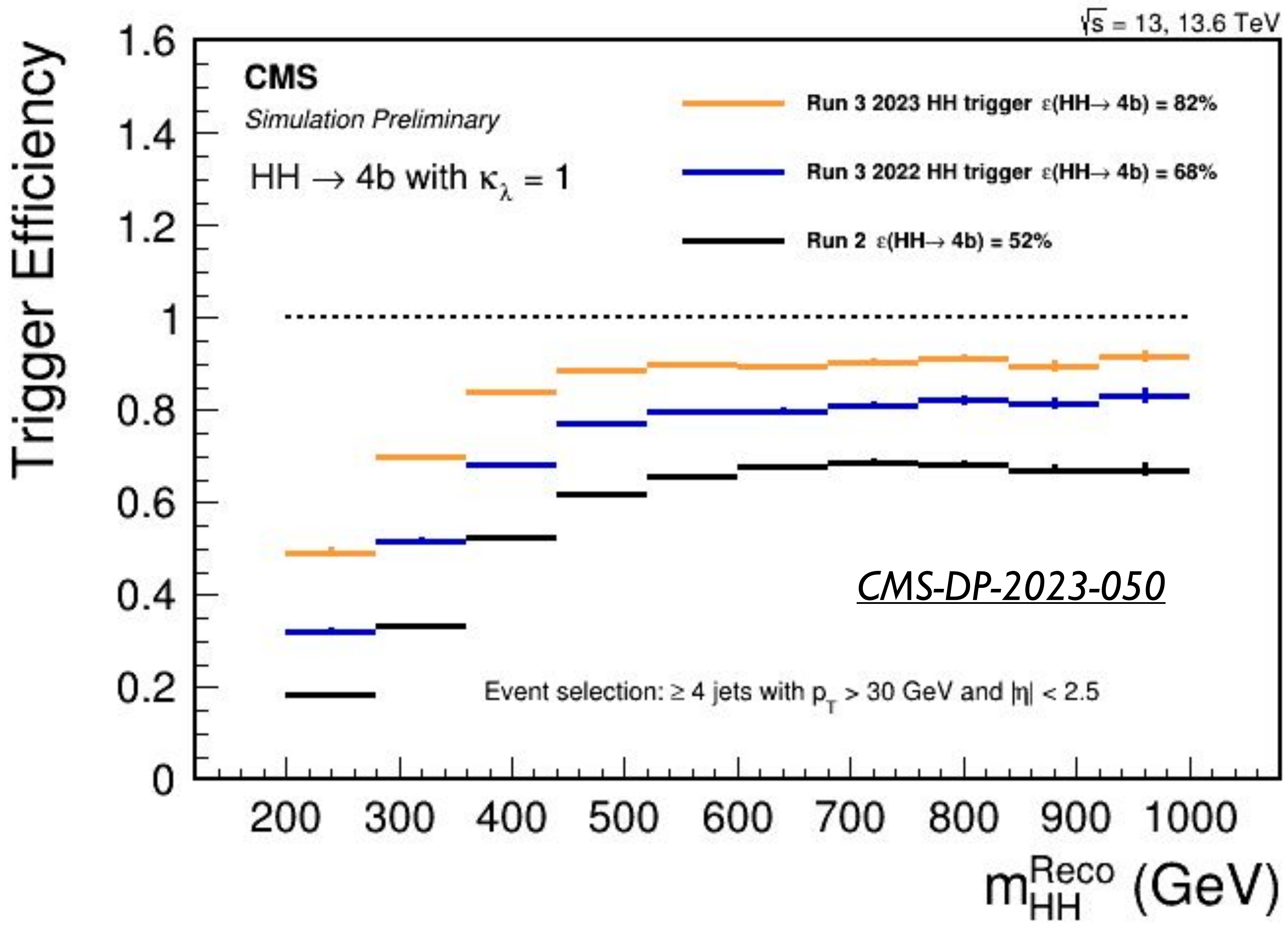
Summary & Outlook

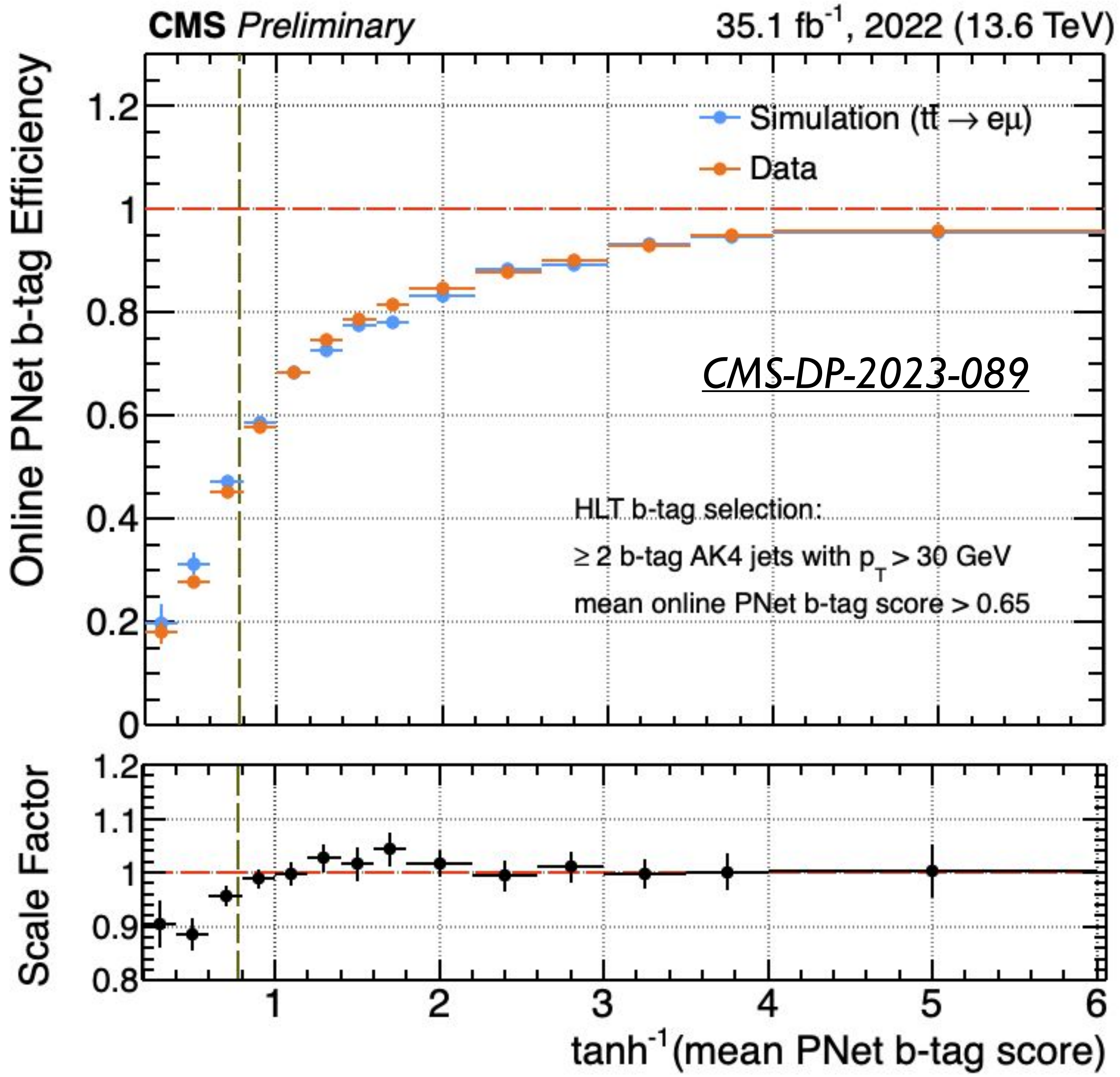
Summary & Outlook

- Tremendous progress in our understanding of the Higgs boson in the past decade
- But still a lot more to be learned:
  - higher precision
  - couplings to second generation
  - structure of Higgs potential
  - …
- HL-LHC: a unique opportunity to explore many of these questions
  - vast amount of data: ~20x more than what we have analyzed
  - comprehensive detector upgrades: new capabilities and better performance
- Moreover: history proves that we can always do better than expected
  - in fact, the biggest missing factor from the projections is the ingenuity of people
  - of course, this will not come for free
    - requires a combined effort from theory, instrumentation, objects & reconstruction, as well as analysis techniques, …
- **A challenging but exciting journey ahead!**

Extras

CMS B-TAG HLTs





Trigger	Requirement	Rates at 2×10^{34} $cm^{-2}s^{-1}$
2023 HH trigger	HT > 280 GeV, 4 jets with pT > 30 GeV, PNet@AK4(mean 2 highest b-tag score) > 0.55	180 Hz
2022 HH trigger	4 jets pT > 70, 50, 40, 35 GeV, PNet@AK4 (mean 2 highest b-tag score) > 0.65	60 Hz
2018 triple b-tag trigger	HT > 340 GeV, 4 jets pT > 75, 60, 45, 40 GeV, 3 b-tags with DeepCSV > 0.24	8 Hz