PROSPECTS FOR PHYSICS AT THE LHC

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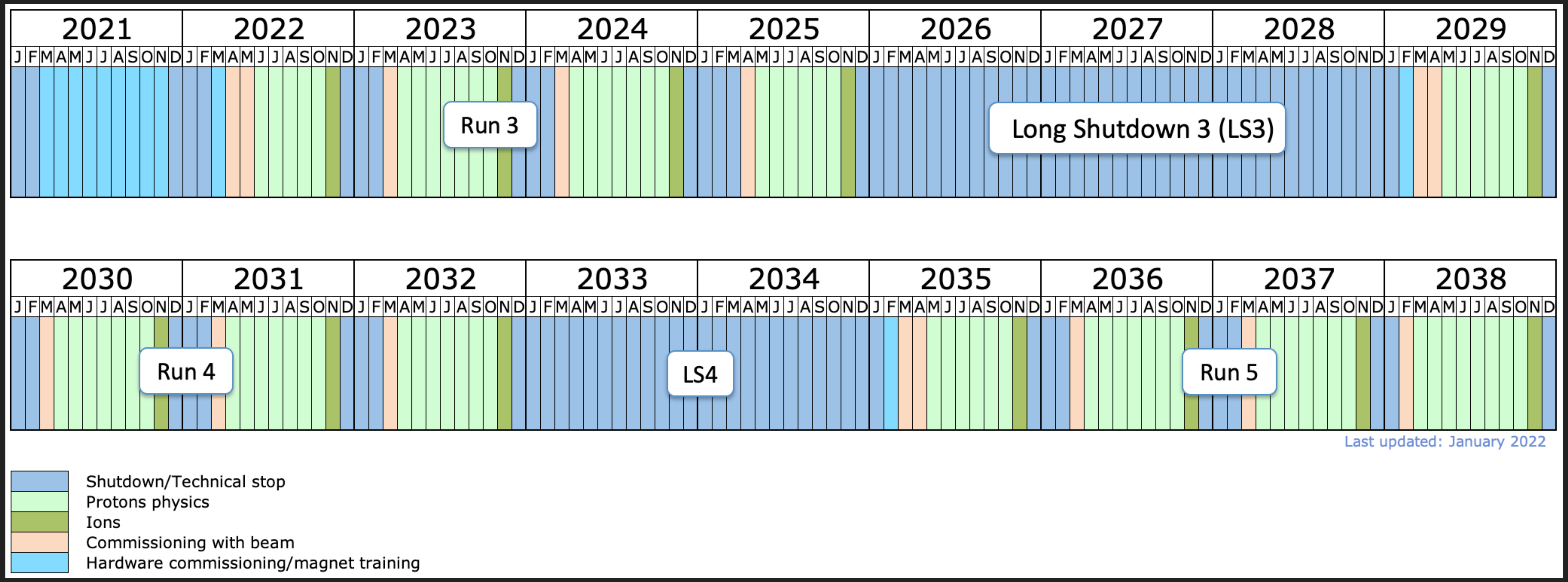
ON BEHALF OF THE ATLAS, CMS AND LHCB COLLABORATIONS

PLANCK 2022

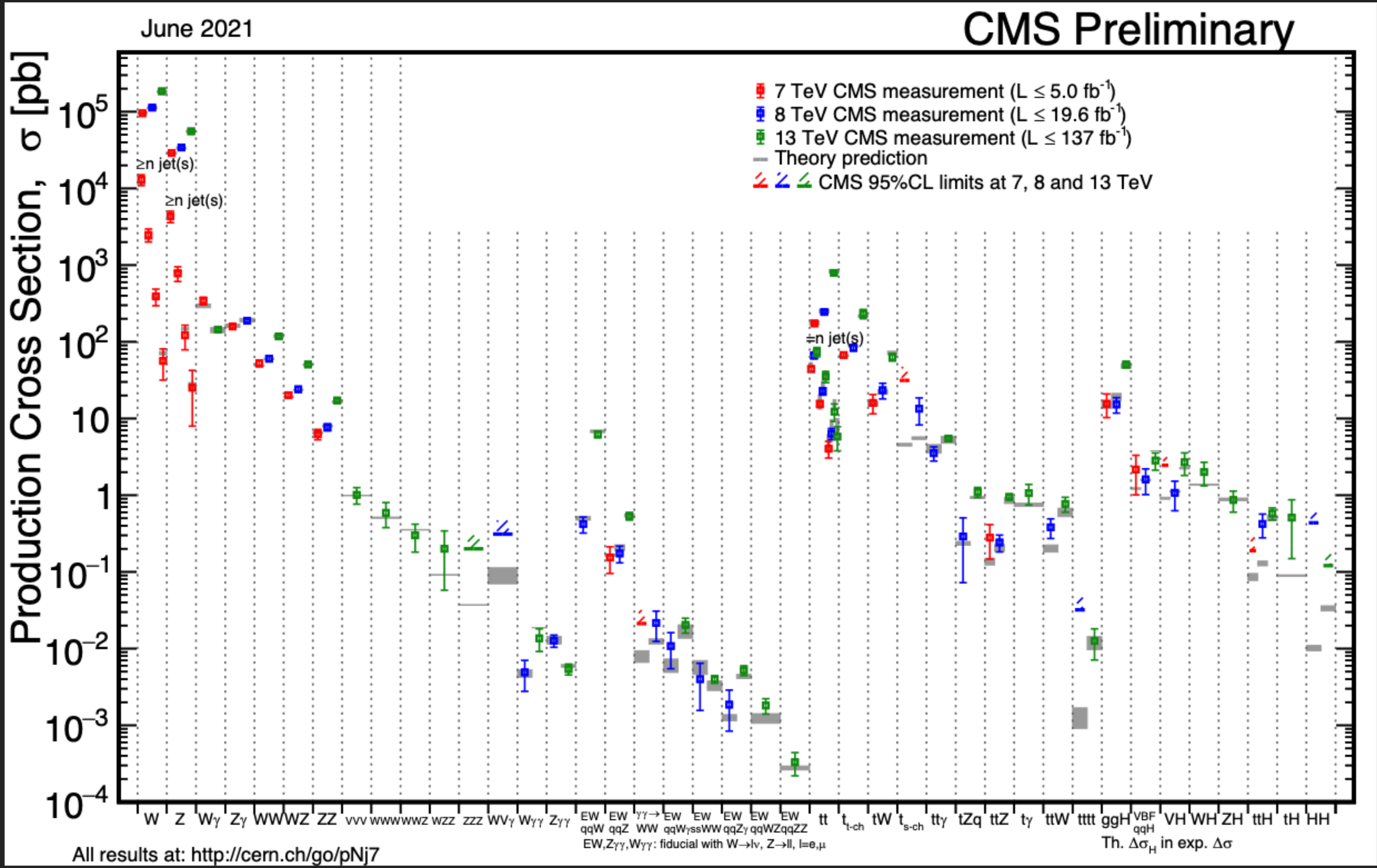
THE FUTURE OF LHC

- Run-3 is about to start @ 13.6 TeV, with about 300 fb^{-1} to be collected by each ATLAS and CMS
- HL-LHC will follow, with 3-4 ab^{-1} of data for ATLAS & CMS each (and at least 300 fb^{-1} for LHCb)
- In this talk, I will cover prospects comprising the entire HL-LHC program



THE BIG PICTURE: PRECISION MEASUREMENTS

9 orders of magnitude



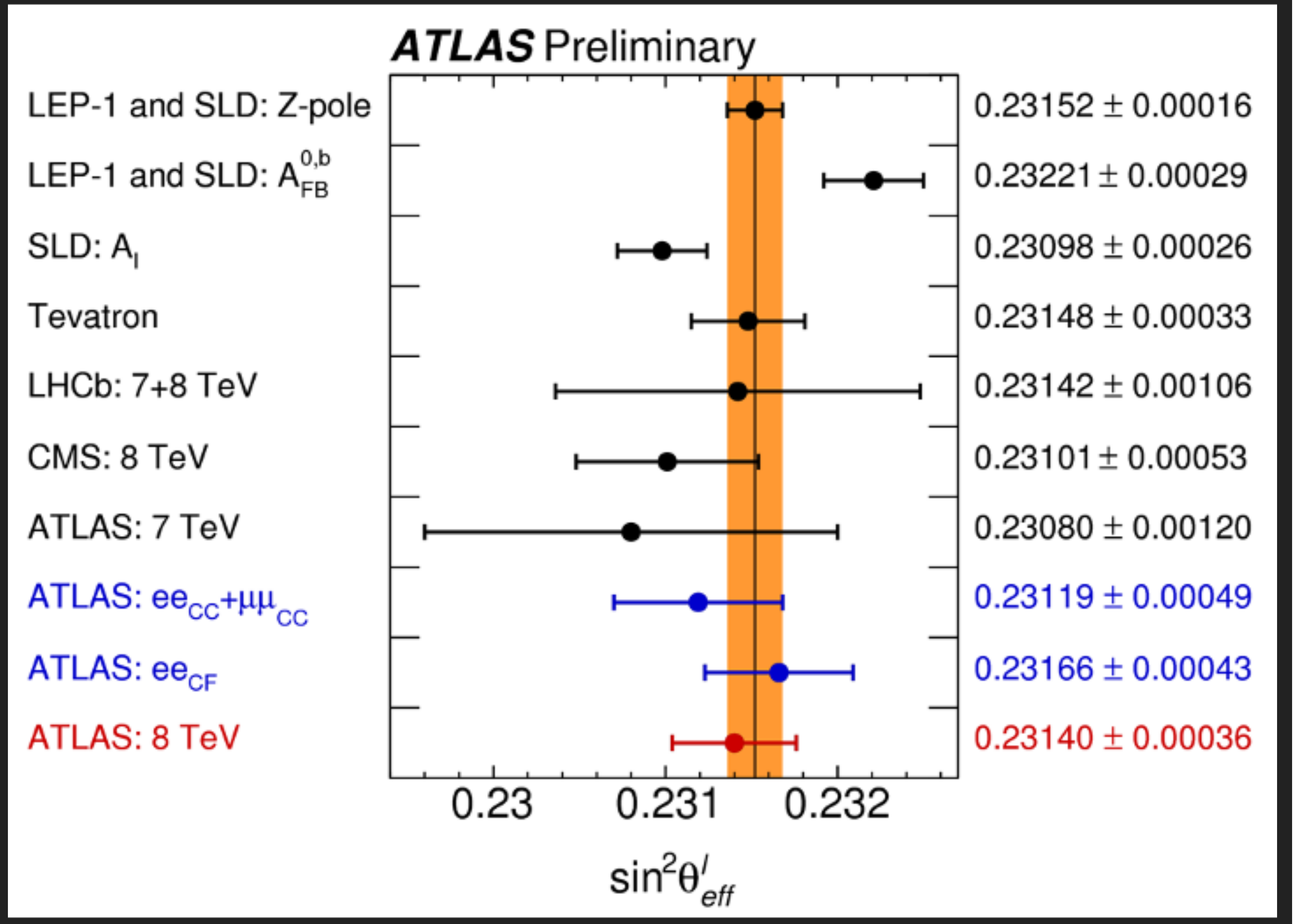
Electroweak

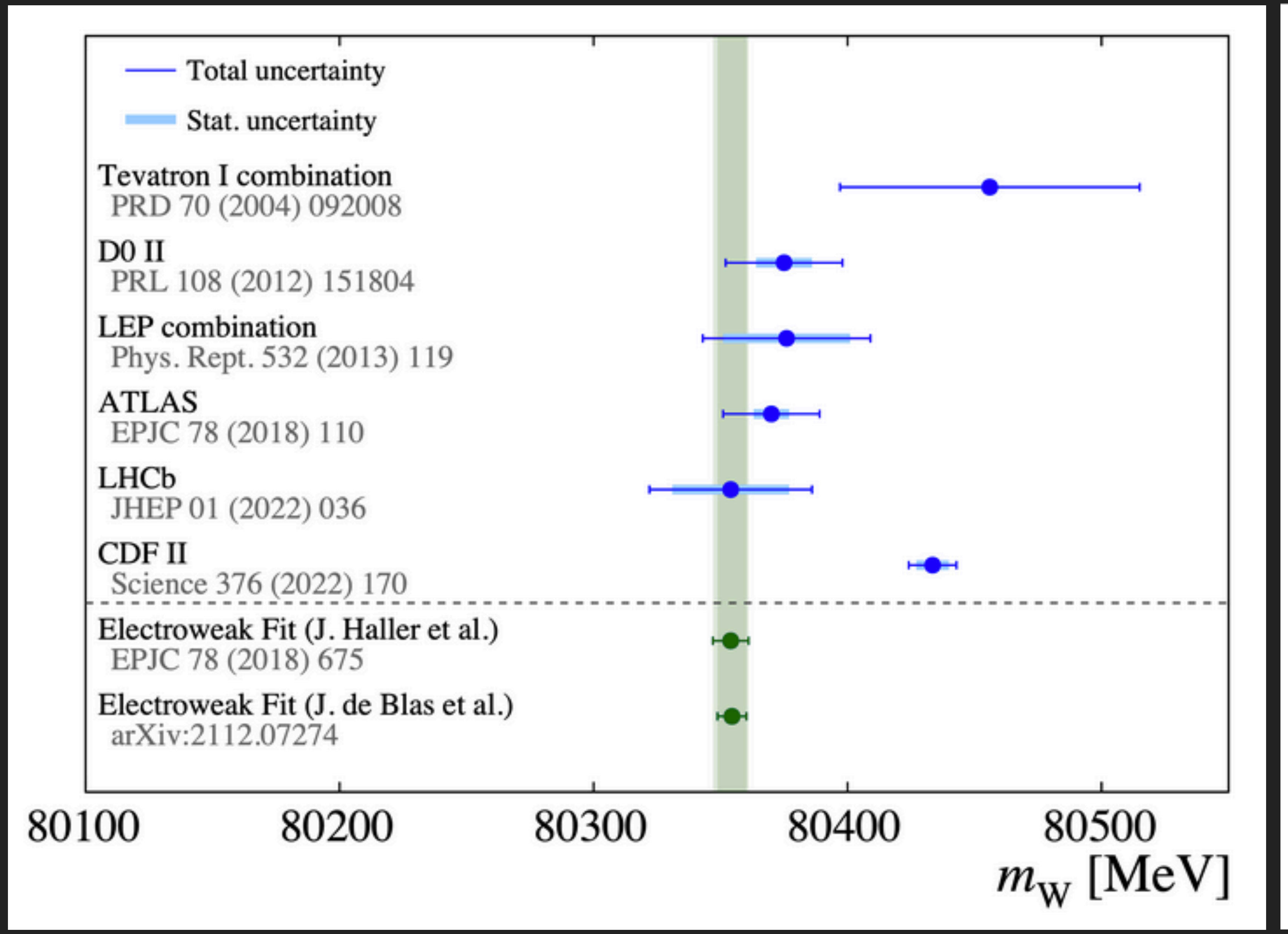
Top

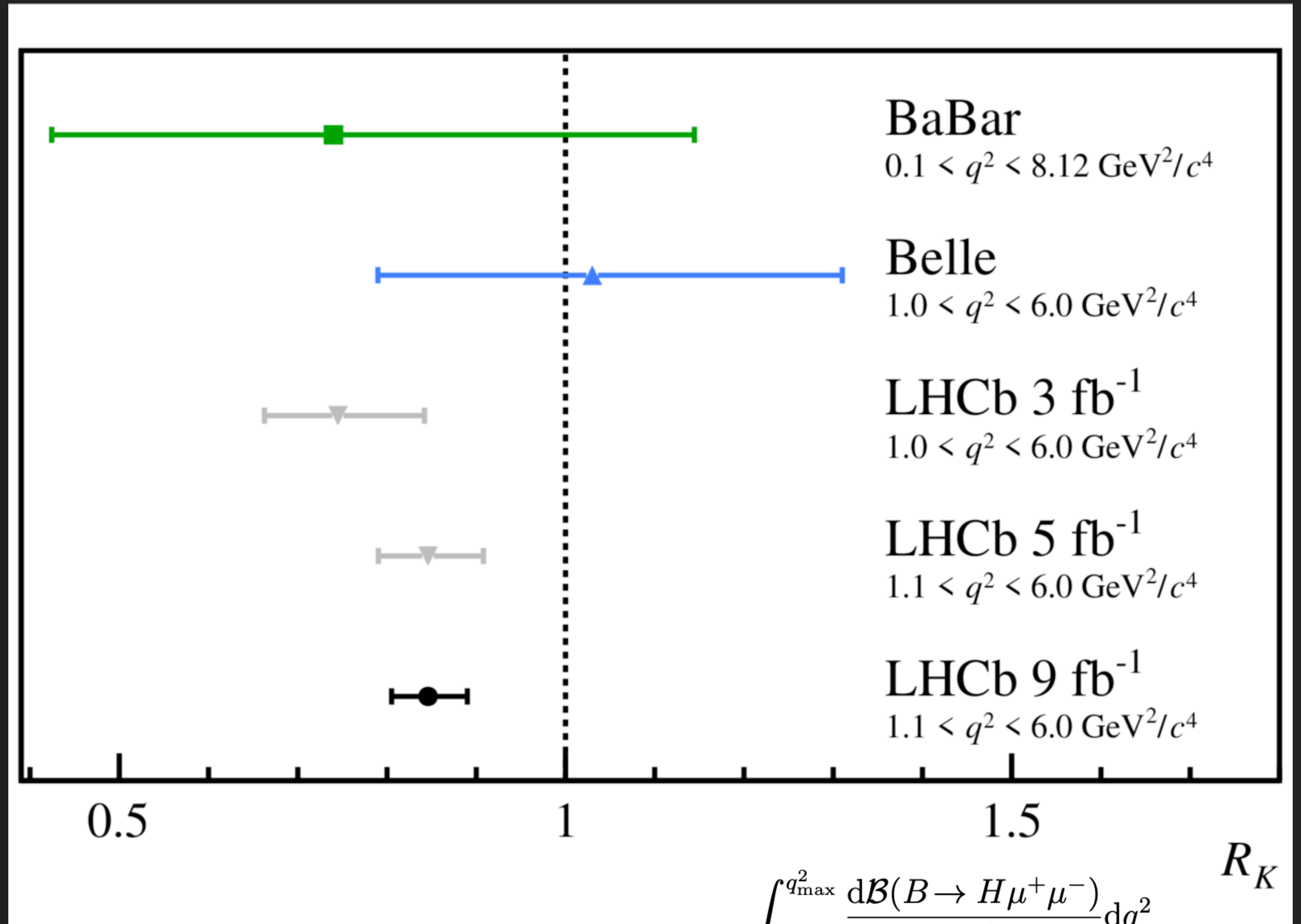
Higgs

THE BIG PICTURE: ELECTROWEAK

- EWK observables measured at percent precision (or better) at LEP, SLD, TeVatron, LHC,…
- Recent results on the W mass by LHCb and CDF II (intriguing tension)
- Hints of violation of the lepton flavor universality?



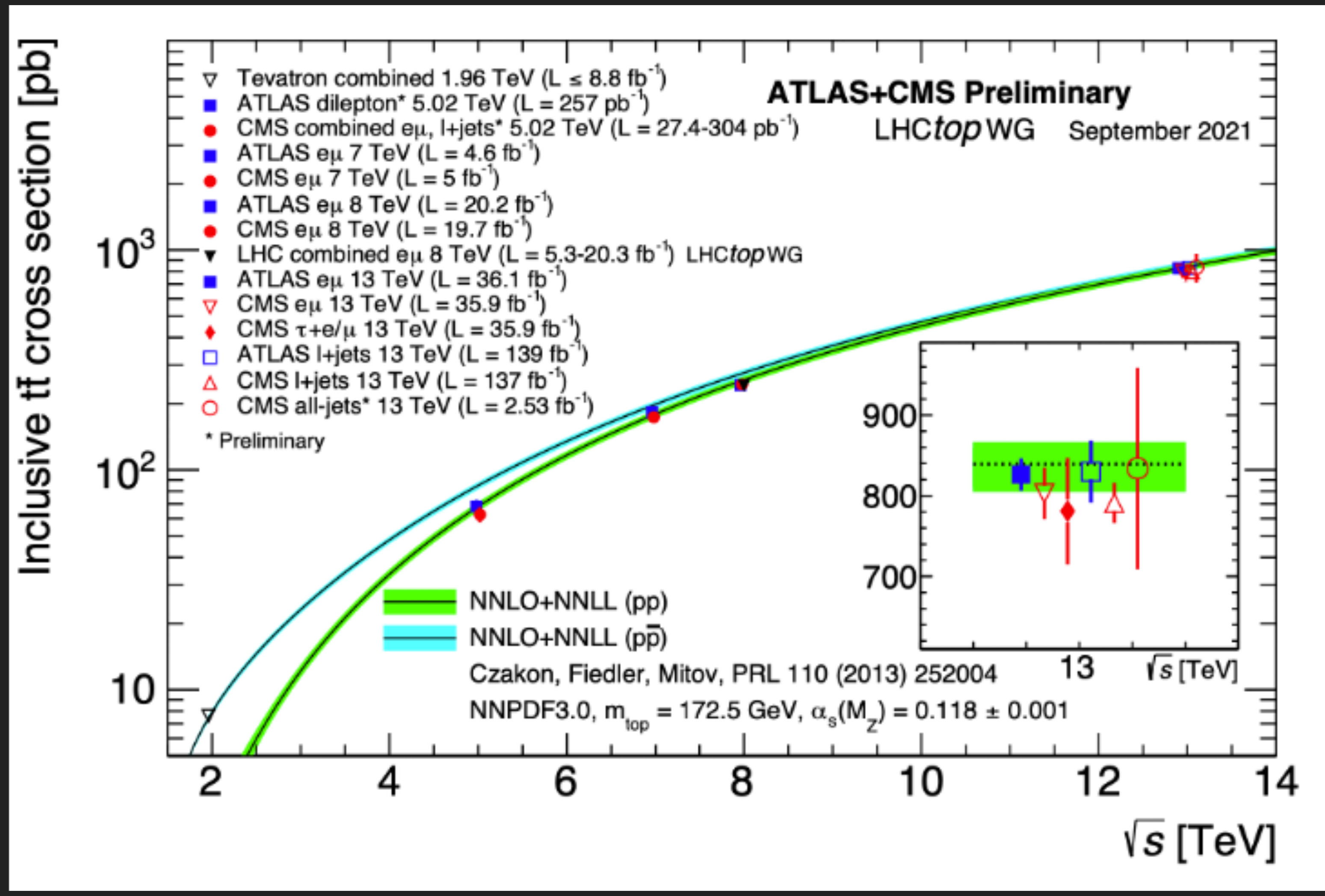




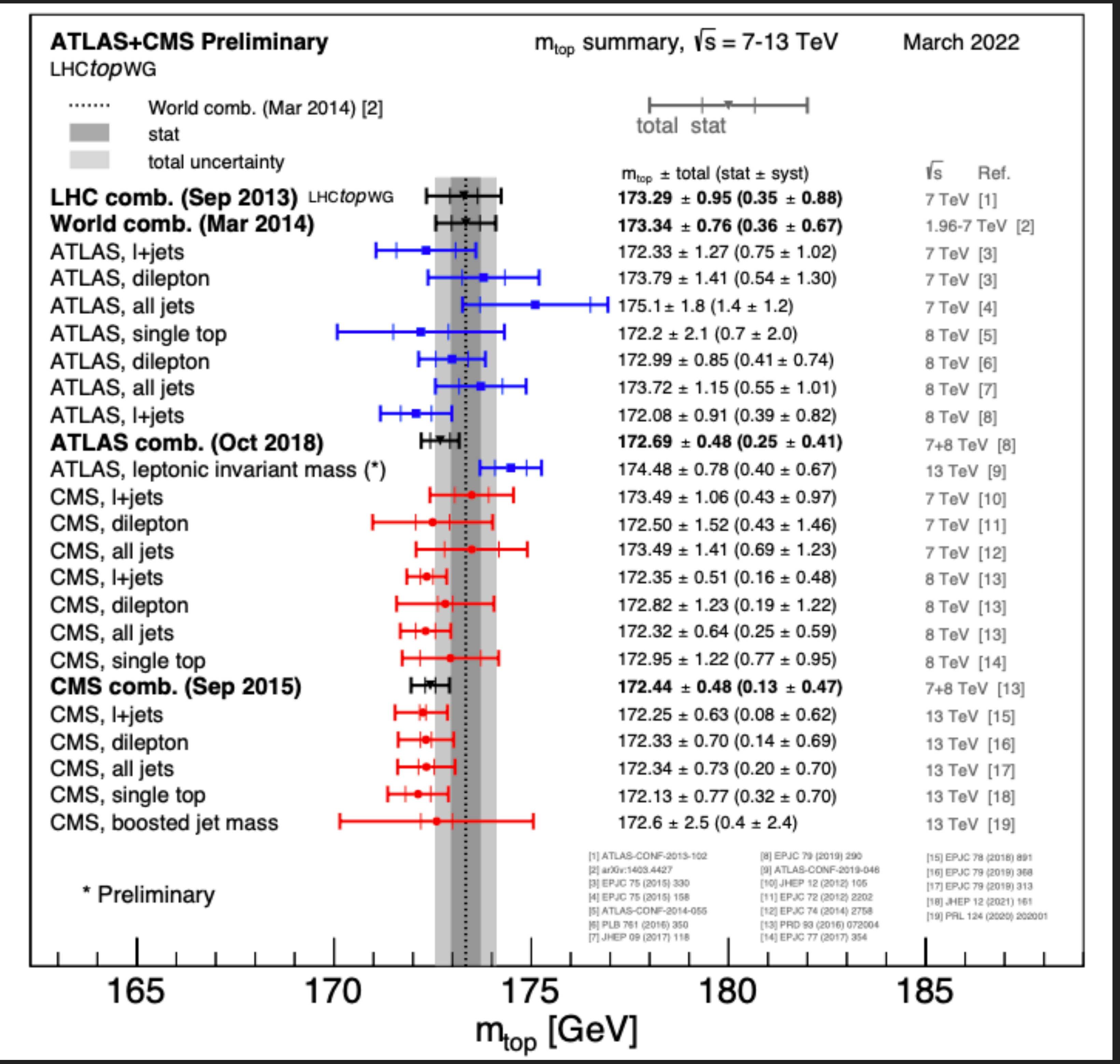
$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2}$$

THE BIG PICTURE: TOP

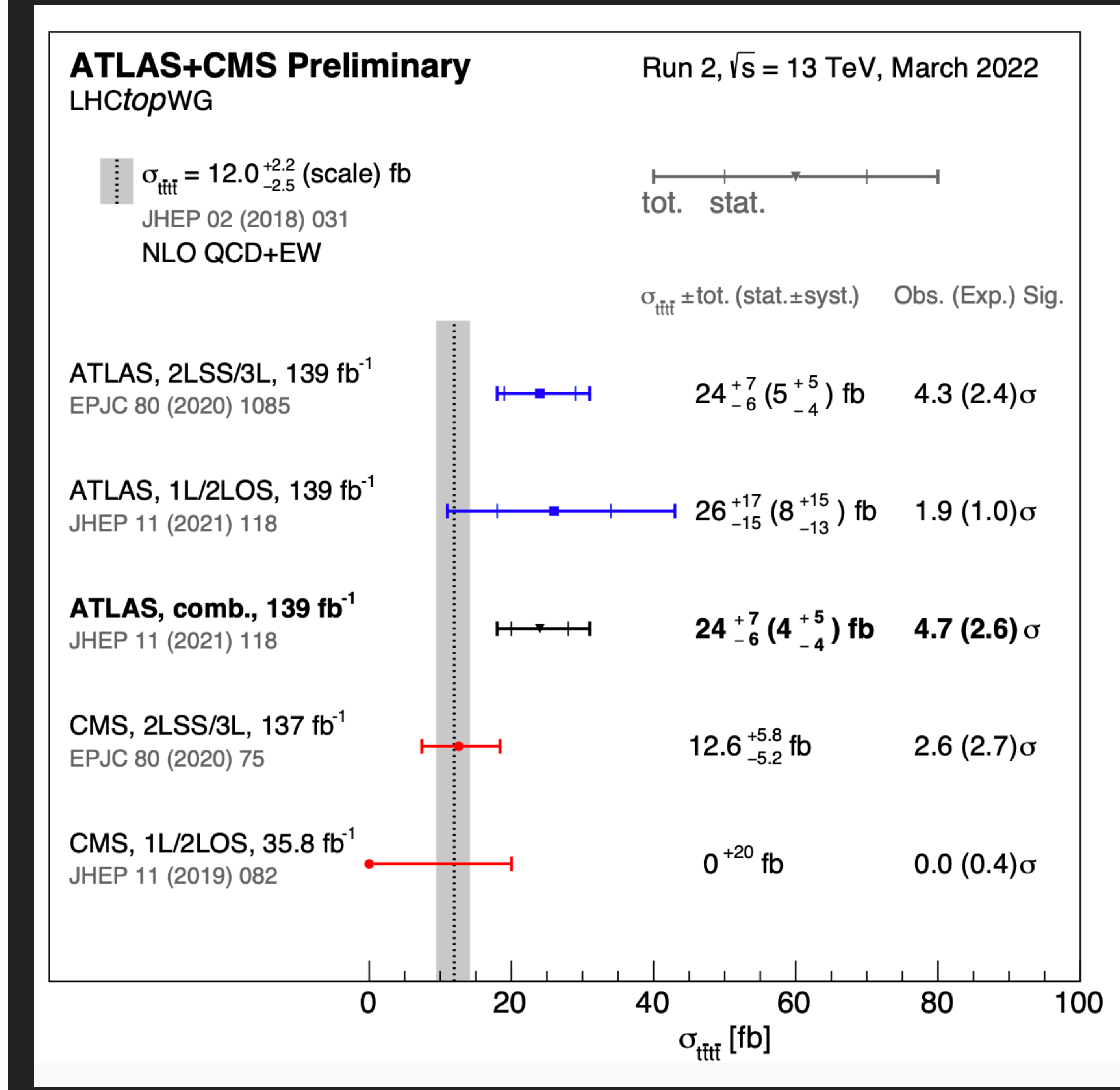
- Top quark: special role in EWSB?
- Knowledge of processes with top: limiting factor in many analyses



m_t known to 500 MeV

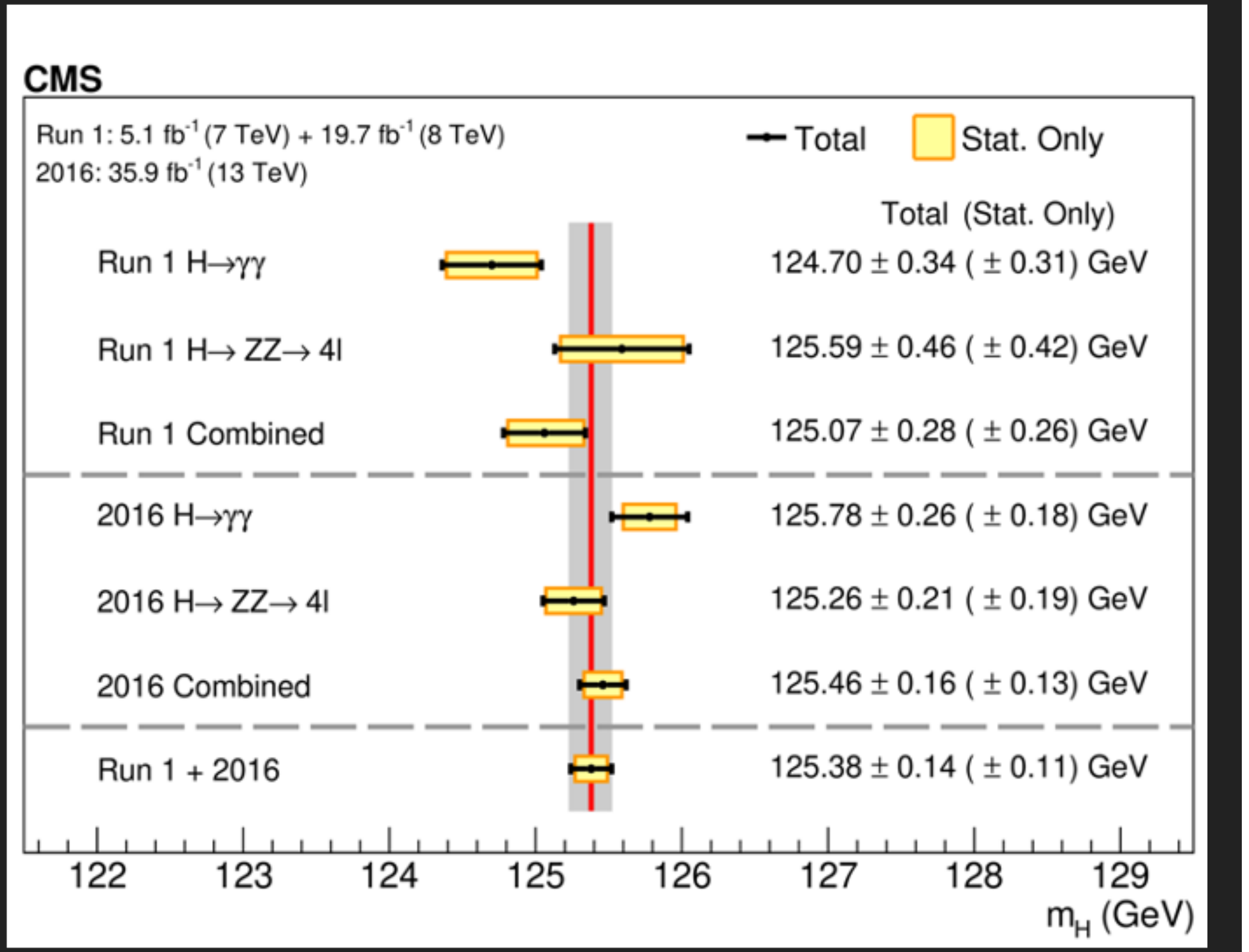


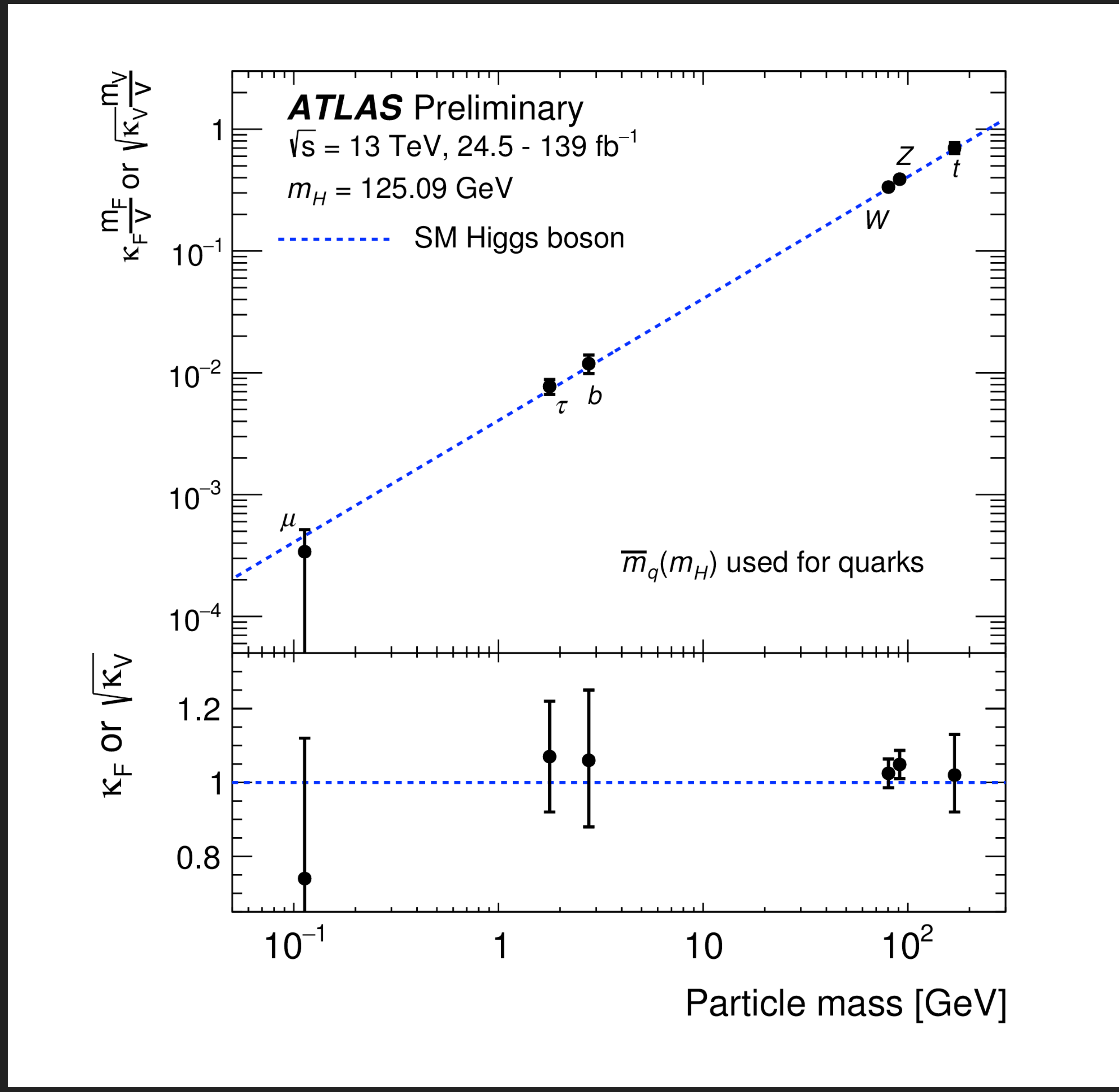
Elusive 4-top nearing the 3σ exp.



THE BIG PICTURE: HIGGS SECTOR

- Coupling to vector boson & 3rd generation fields known up to ~10%
- m_H=125.38 GeV with 0.11% precision & narrow width ($\Gamma_H = 3.2^{+2.8}_{-2.2}$ MeV)
- 0+ state favoured over other J^{PC} hypothesis





Direct search @ CMS (CMS-PAS-HIG-21-008)

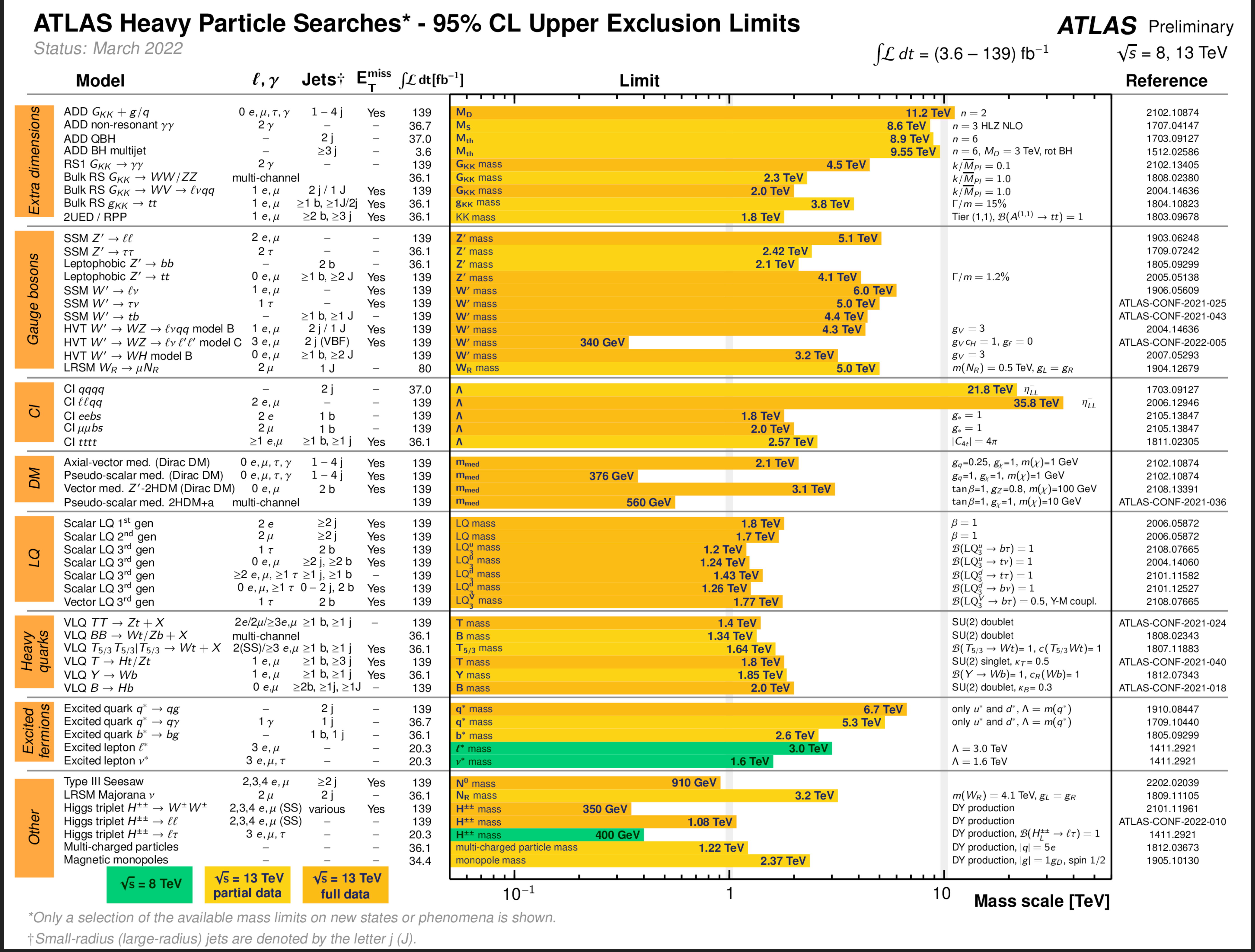
$1.1 < \kappa_c < 5.5$ obs. ($\kappa_c < 3.4$ exp.)

Indirect through Higgs boson $p_T^{\gamma\gamma}$ normalisation and shape @ ATLAS (arXiv:2202.00487):

$-2.7 < \kappa_c < 2.6$ obs. ($-3.2 < \kappa_c < 3.2$ exp.)

THE BIG PICTURE: BEYOND THE SM

- No new particle discovered so far…

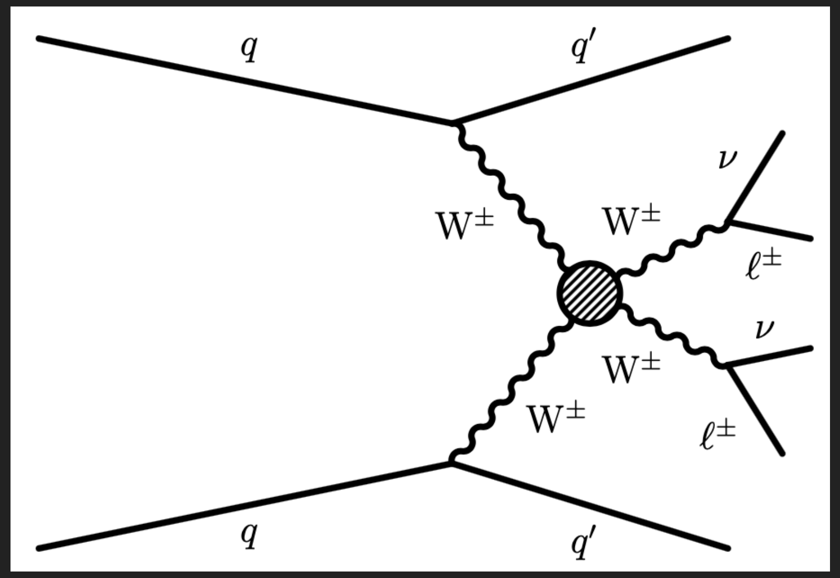


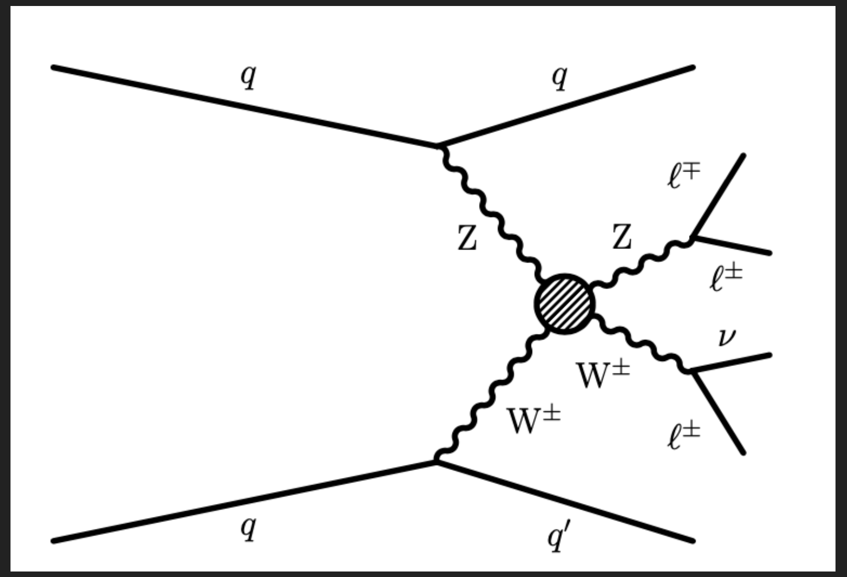
PROSPECTS ON SM PHYSICS

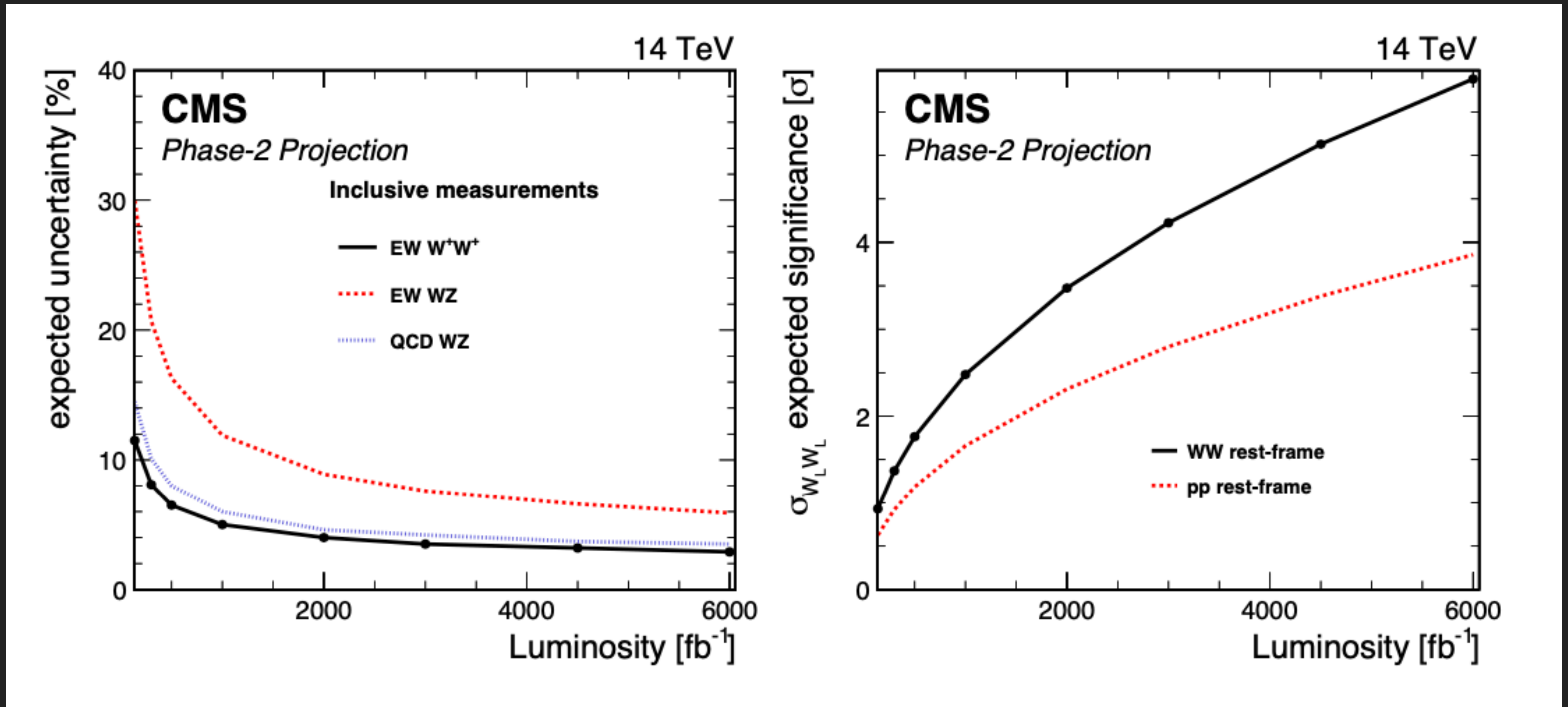
- The increased dataset will allow to improve sensitivity in statistically limited measurements
- The systematically limited measurements will benefit too!
  - More data = better understanding of experimental systematic uncertainties
  - Theoretical uncertainties may become dominant in some measurements
- Also benefit from detector upgrades, e.g. the inner detector improved forward coverage in ATLAS and CMS

SM: MULTIBOSON PRODUCTION (STATISTICALLY LIMITED)

- Purely electroweak diboson production VVjj - sensitive to the nature of mass generation as well as quartic-gauge interactions
- Very low cross section - only possible to investigate at the HL-LHC
- The final state in which the two bosons are longitudinally polarized directly probes the unitarization mechanism of the vector boson scattering amplitude production through Higgs boson



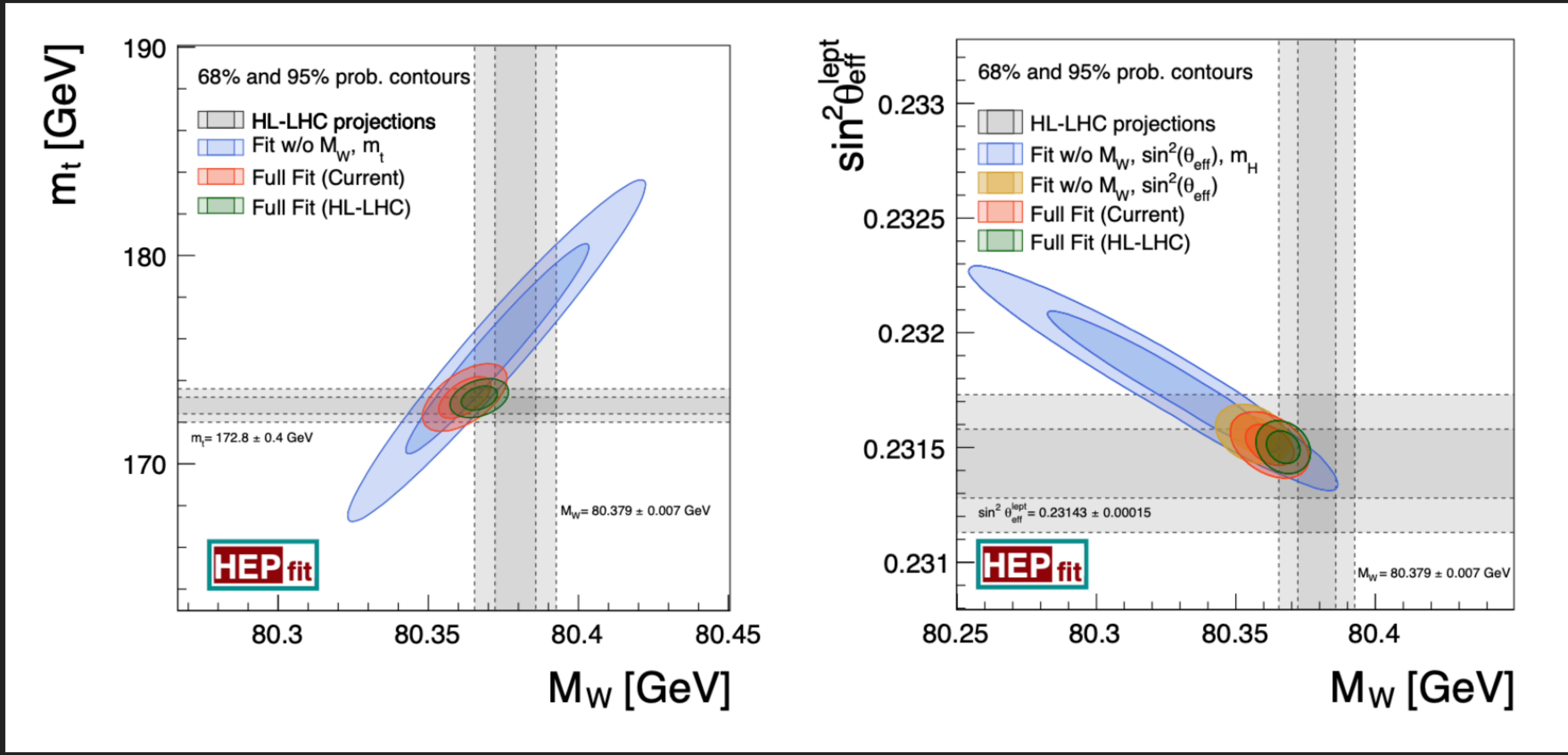




=> should be available at HL-LHC through combination of CMS and ATLAS

SM: GLOBAL EW FIT (ACCEPTANCE / SYSTEMATIC IMPROVEMENTS)

- Global fit to EW precision observables with HEPFit for current and expected HL-LHC results:



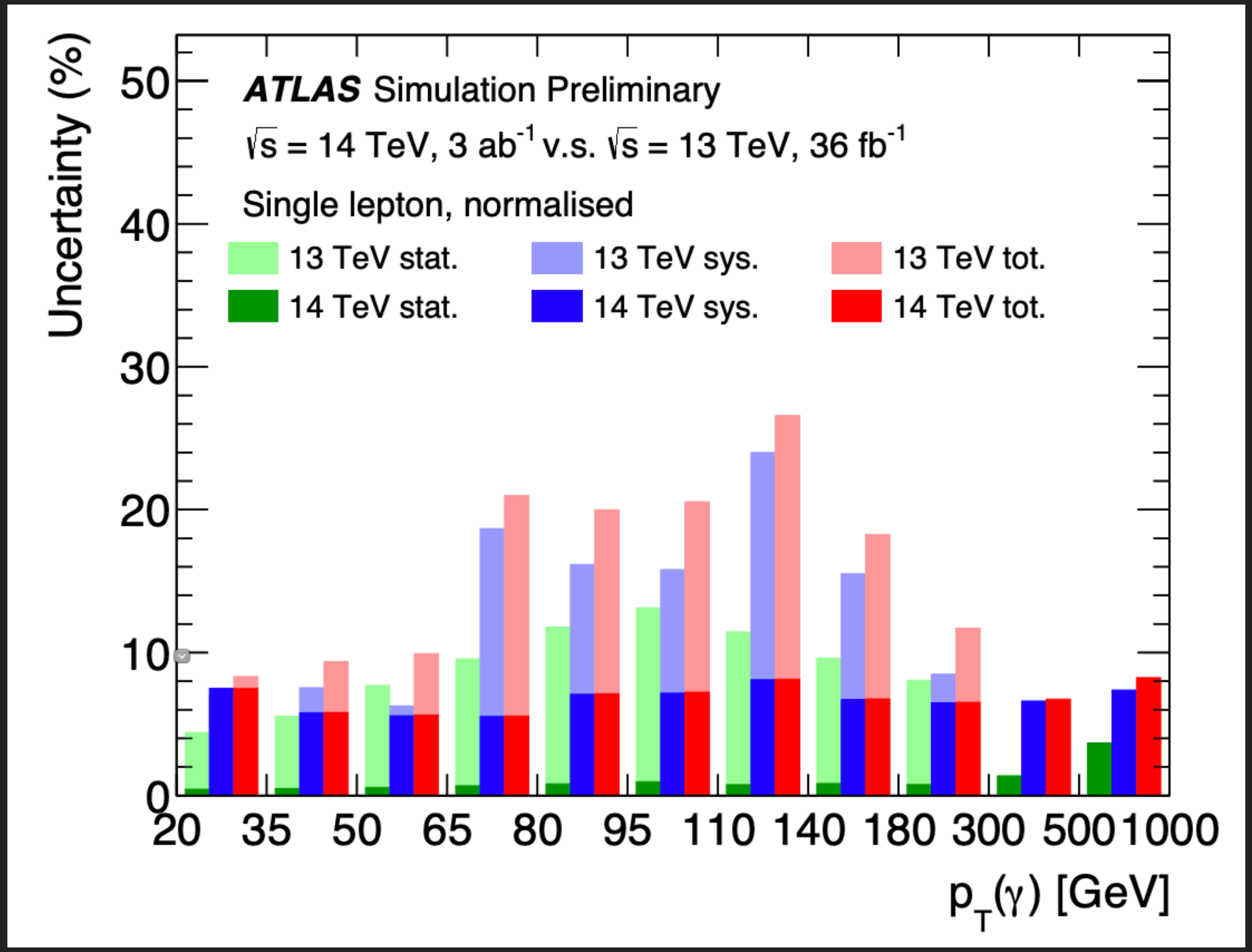
Improvement on W mass: special low-lumi runs + larger acceptance from upgrade (lower PDF uncert.)

The larger acceptance will also help the weak angle measurement through dileptonic A_{FB}

- Same input SM central values + reduced exp. uncert. + more precise EW measurements : could significantly increase the tension between the indirect and direct determinations of m_Z, m_t, and m_H

SM: DIFFERENTIAL MEASUREMENTS

- Significant improvement expected: increased precision, reduced bin size, new phase space at higher momentum
  - Look for deviations from BSM, improve on the PDF uncertainties,…
- As an example: the $tt\gamma$ production - the photon p_T distribution can probe for anomalous dipole moments of the top quark

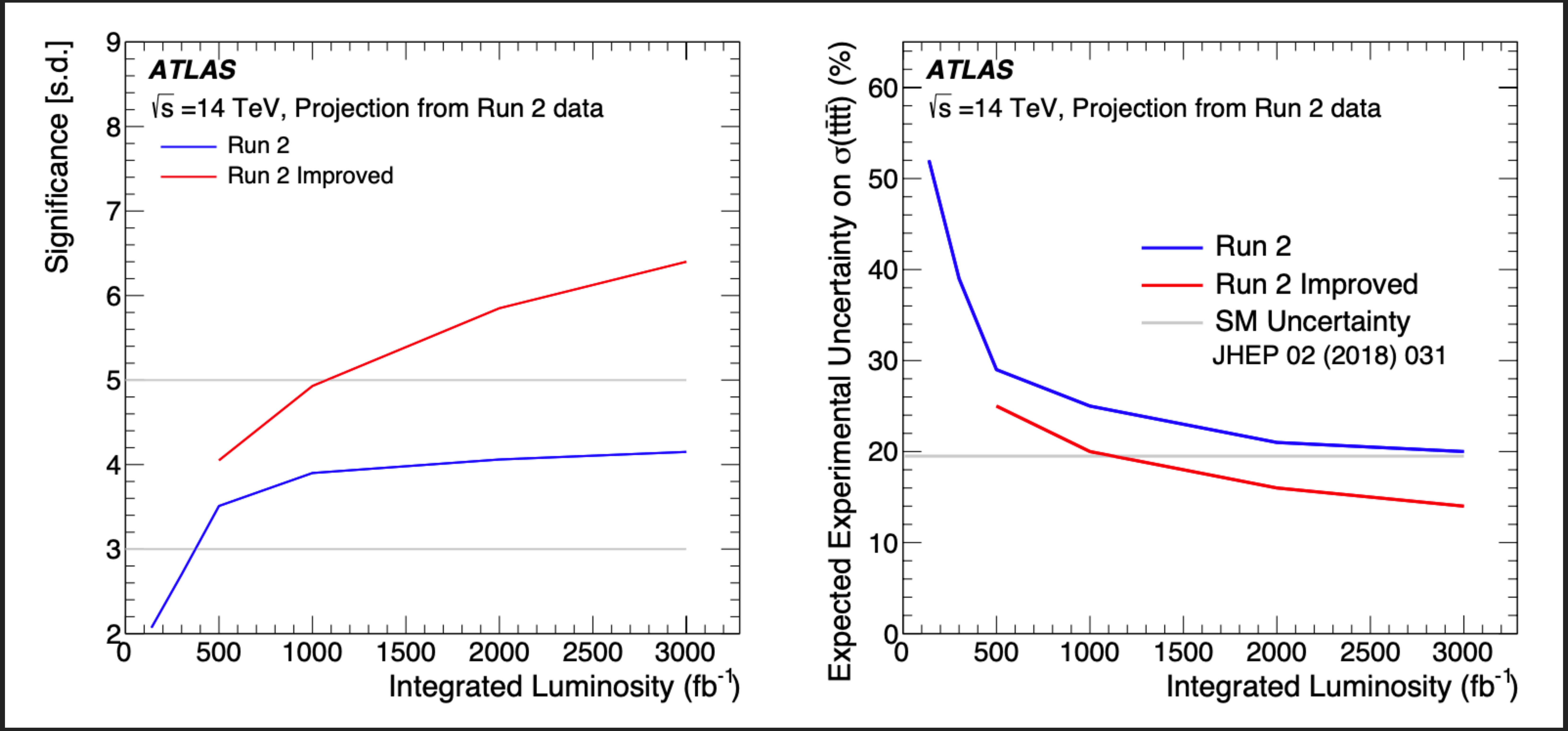


Significant reduction of the uncertainties @ HL-LHC + new bins at high values

SM: 4TOP

ATL-PHYS-PUB-2022-004

- Extrapolation of the full Run-2 analysis to the HL-LHC
  - ≥ 2 leptons (2 of same charge or ≥3), ≥ 6 jets of which ≥2 are b-tagged, high H_T > 500 GeV

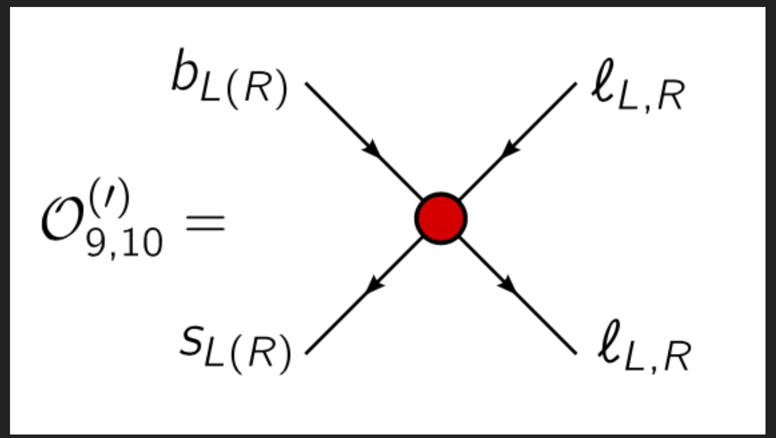


Run 2 Improved scenario driven by smaller uncertainties assumed for the 4top and ttV+jets modeling

14% uncertainty on the measured cross section at the end of the HL-LHC

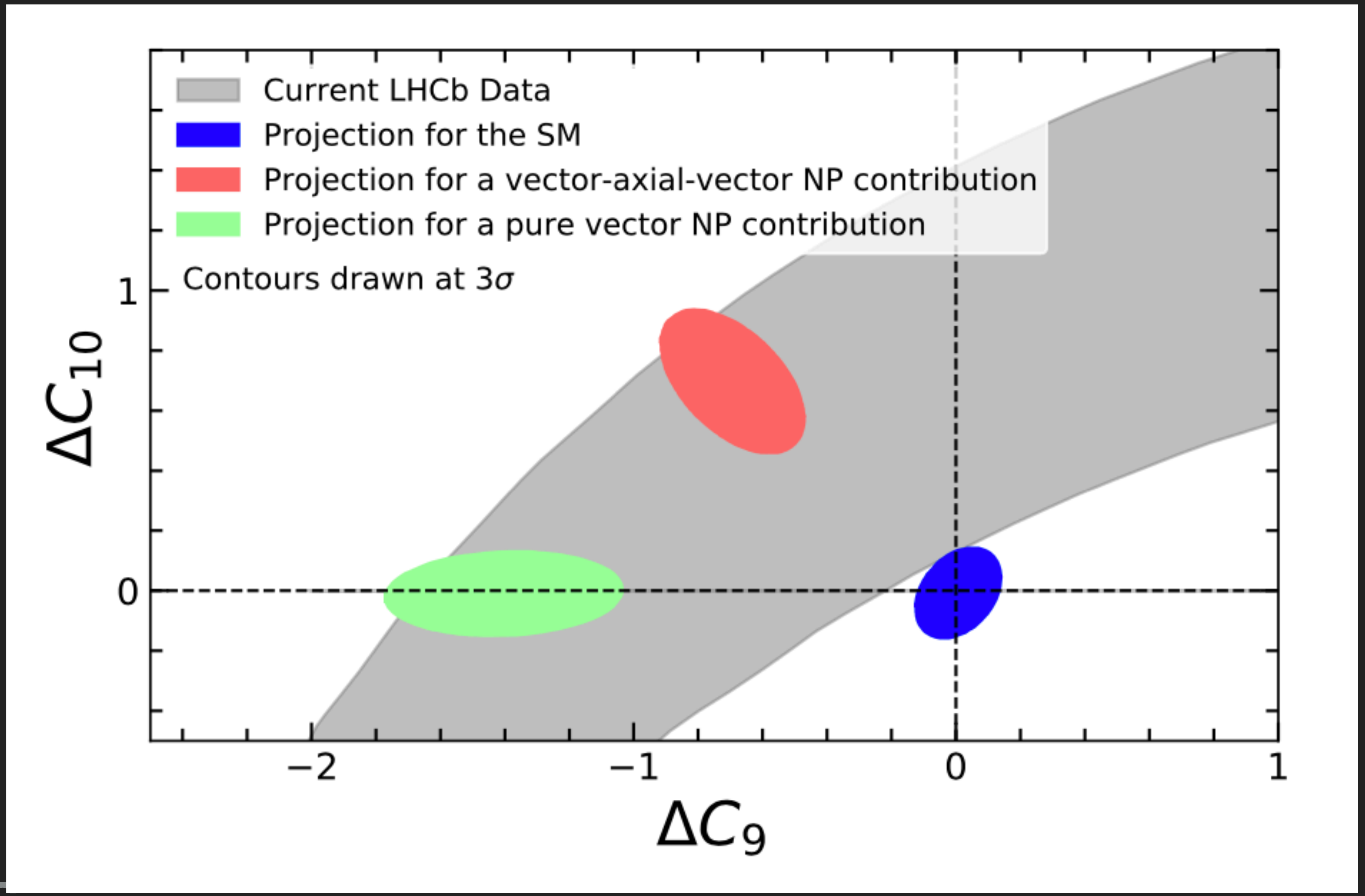
SM: LEPTON FLAVOUR UNIVERSALITY TESTS

- Exact LFU in the SM gauge couplings & corrections due to mass effects are calculable to good precision: excellent probe for some BSM theories
  - With 300 fb^{-1} @ LHCb will also allow to compare angular distributions for $b \to s\mu^+\mu^-$ and $b \to se^+e^-$: axial or vector nature of a potential BSM particle
  - Will not only allow a potential BSM contribution to be established with an overwhelming significance, but also provide a characterisation of the BSM that will be essential to distinguish between theoretical models



$\mathcal{O}^{(\prime)}_{9} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$

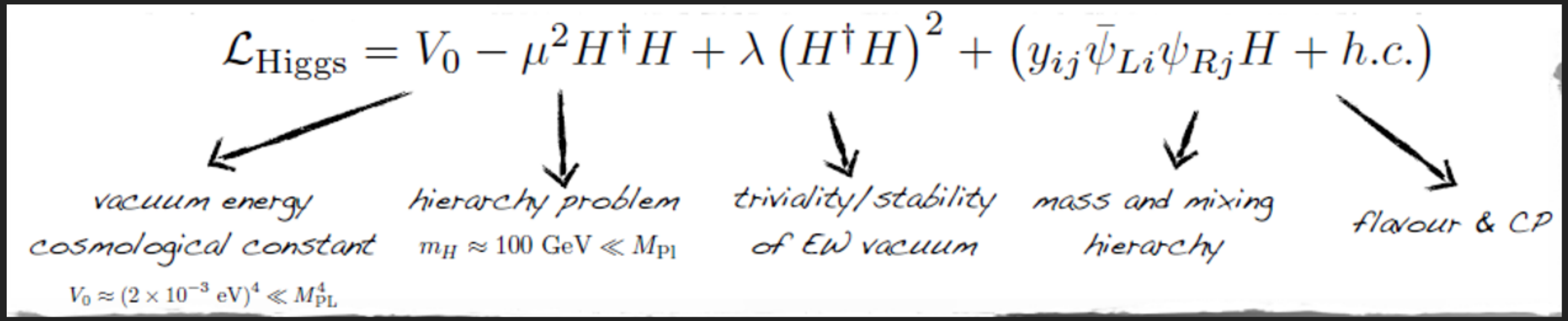
$\mathcal{O}^{(\prime)}_{10} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$



Grey region: current 3-sigma uncertainty

PROSPECTS ON HIGGS PHYSICS

- The Higgs boson is a fundamental scalar particle and its theory is unlike anything else we have seen in nature
- It is linked to several deep problems in High Energy Physics:

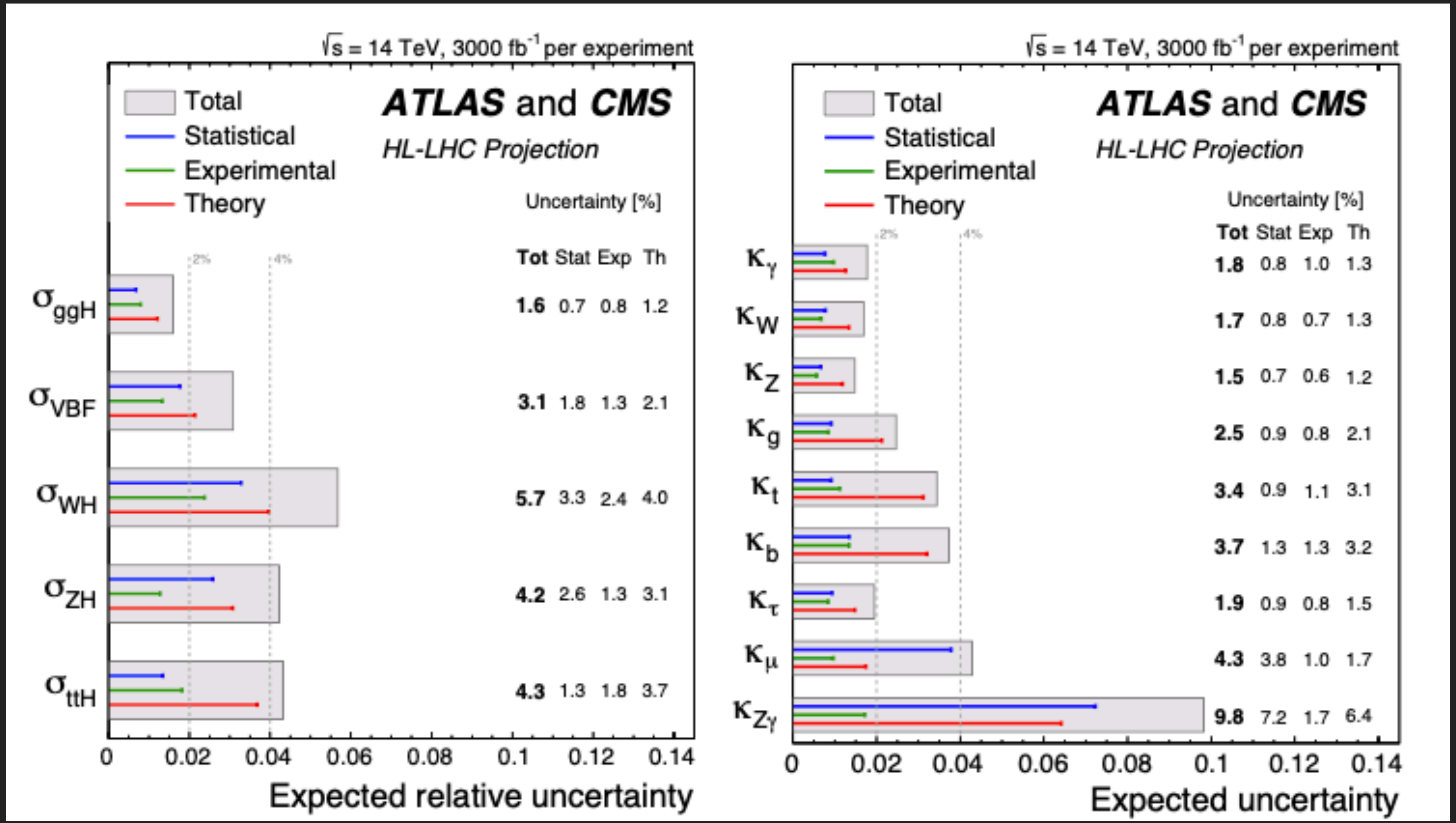


From C. Grojean

- While the results obtained so far are in agreement with the SM, the current precision is not enough to significantly challenge many BSM models

CERN-2019-007
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001

HIGGS: CROSS SECTION, COUPLINGS, MASS & WIDTH

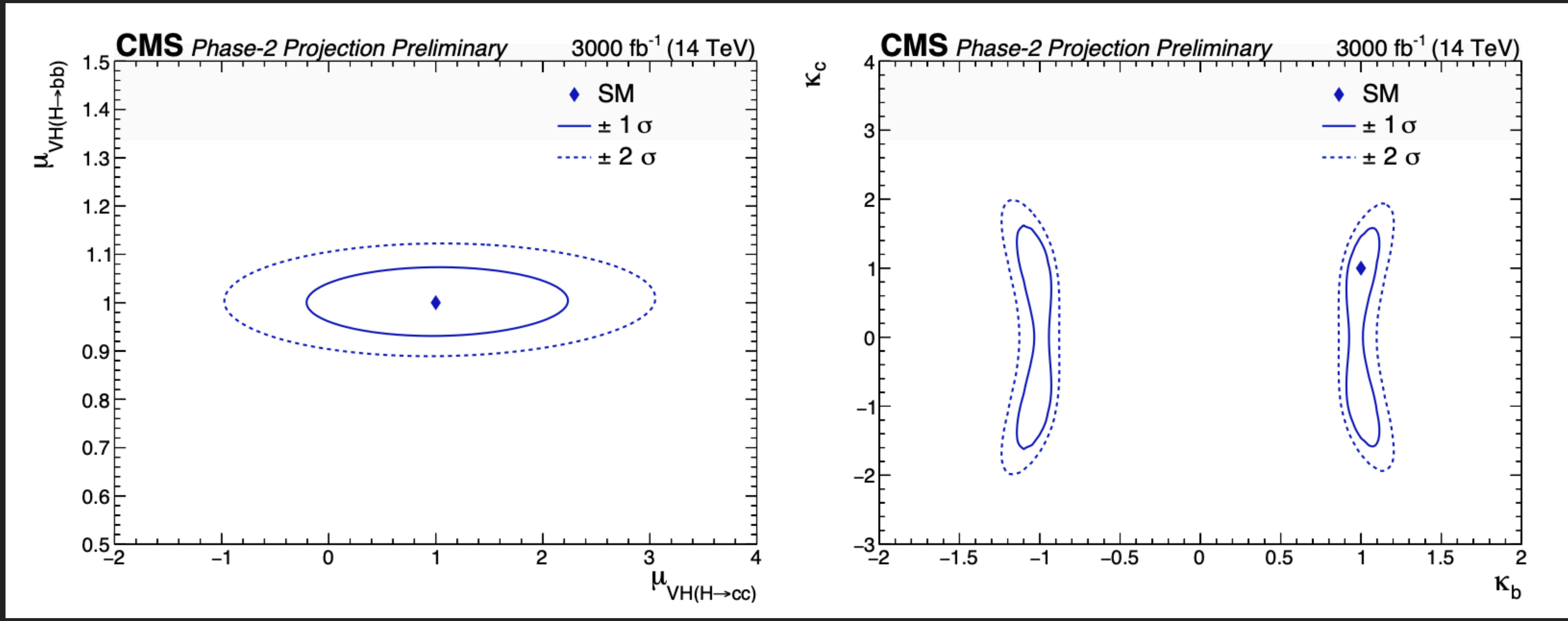


- In the diphoton channel, CMS predicts an expected mass measurement of m_H = 125.38 ± 0.02 (stat) ± 0.07 (syst) GeV
- Constraining the width Γ/Γ_{SM}:
  - from a fit to the couplings (assume $|\kappa_V| \leq 1$) : 4% uncertainty at HL-LHC from CMS projection
  - from a comparison of the on-shell and off-shell $H \to ZZ$ production (assume that the gluon and Z couplings evolve off-shell as in the SM): ATLAS+CMS projection at $4.1^{+0.7}_{-0.8}$ MeV (dominated by theory uncertainties)

HIGGS: COUPLING TO CHARM

ATL-PHYS-PUB-2022-018, CMS PAS FTR-22-001

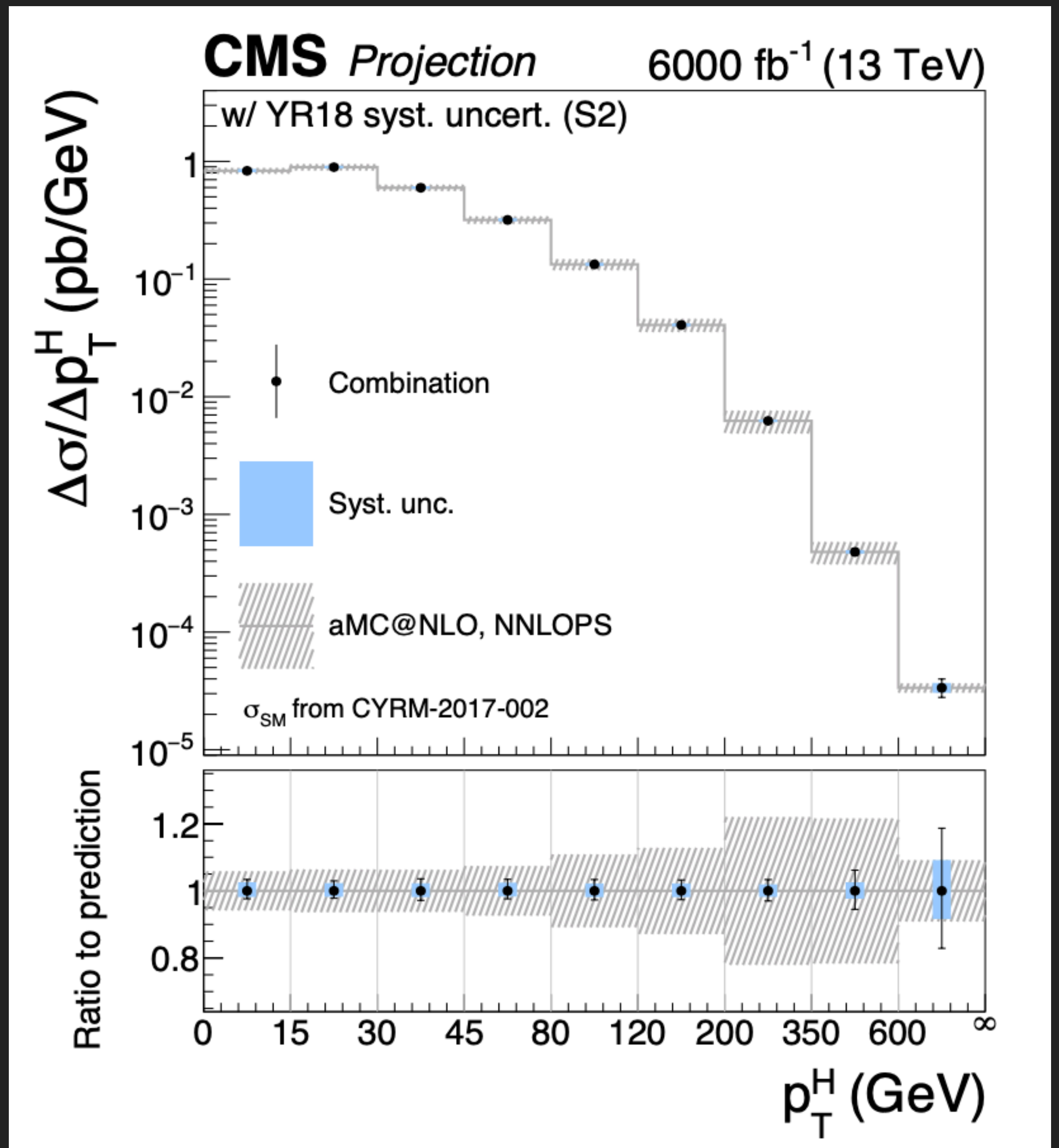
- Probing the coupling to the charm quark directly through $H \rightarrow c\bar{c}$ searches
  - future development in charm tagging techniques could result in a significant increase of the sensitivity
- Projection to HL-LHC using the boosted Higgs category analysis of the recent Run 2 CMS result
  - HL-LHC systematics used except for the b and c-tagging efficiencies which will be constrained using VZ(Z→bb) and VZ(Z→cc)
  - Combined fit of bb- and cc-enriched categories to simultaneously measure VH(H→bb) and VH(H→cc)



HIGGS: DIFFERENTIAL MEASUREMENTS

CERN-2019-007

- Potential BSM physics may reside in the tails of distributions, which cannot be measured in inclusive measurements
  - measure the p_T^H distribution
- Can improve the constraint on the top Yukawa coupling by looking at top channels where the Higgs momentum can be reconstructed (e.g. $t\bar{t}H$ with $H \to \gamma\gamma$ or $H \to bb$)
- Used of improved jet substructure tools to reconstruct boosted Higgs can significantly enhance the sensitivity of these analyses



Combination of
$H \to \gamma\gamma$ (ATLAS+CMS)
$H \to ZZ$ (ATLAS+CM)
$H \to bb$ (CMS)

Precision per bin:

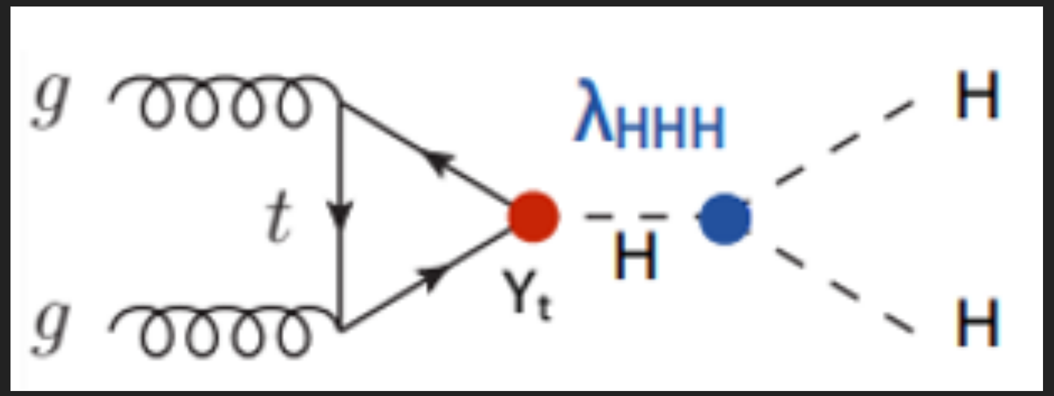
p_T^H [GeV]	0-10	10-15	15-20	20-30	30-45	45-60	60-80	80-120	120-200	200-350	350-1000	
Combination	2.9%		2.6%		3.2%	2.9%		3.0%	2.9%	3.2%	5.8%	17.9%

HIGGS: TRILINEAR SELF-INTERACTION

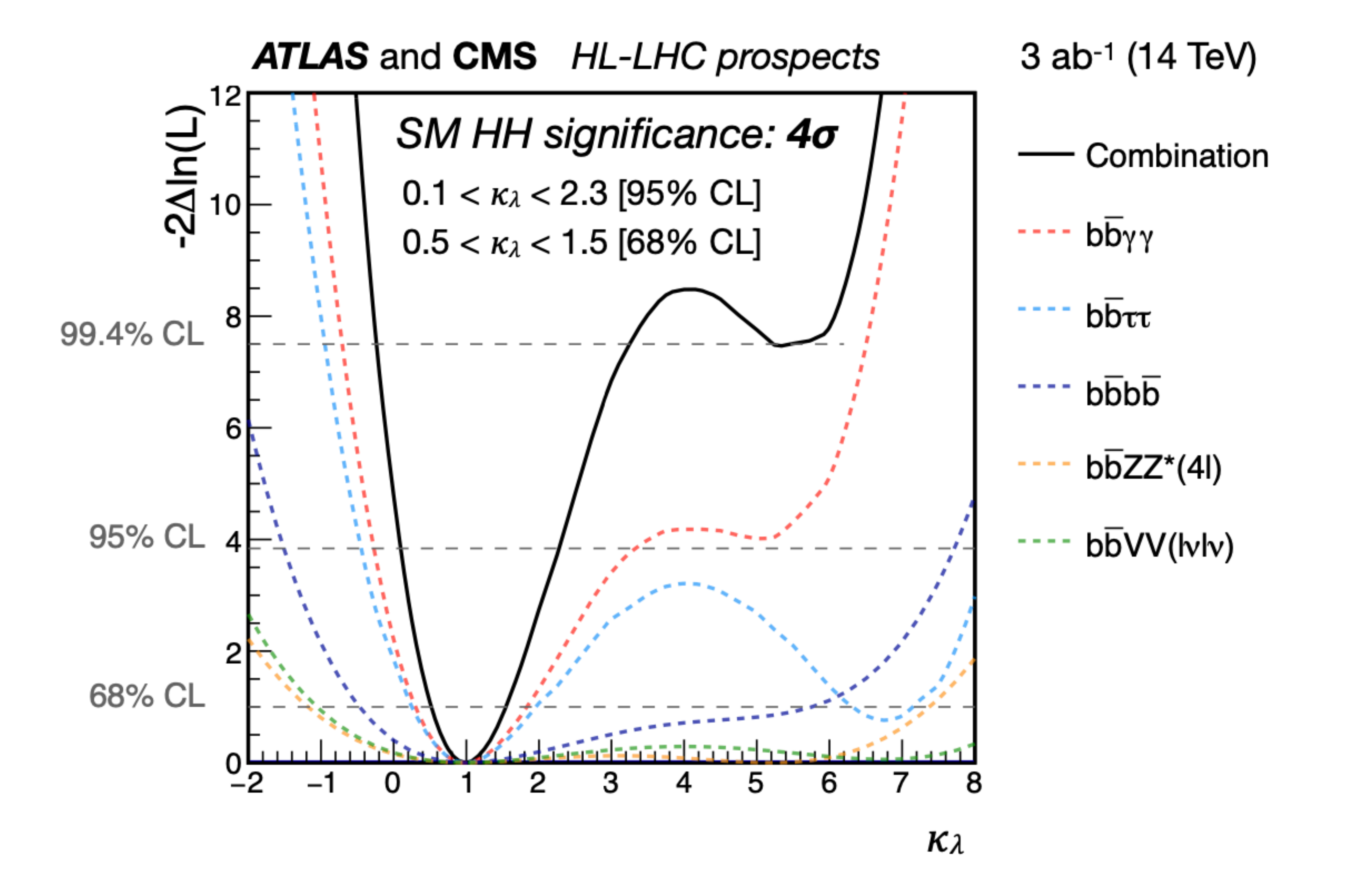
CERN-2019-007

ATL-PHYS-PUB-2022-018, CMS PAS FTR-22-001

- Directly measuring the coupling ($\lambda_{HHH} = m_H{}^2 / 2v^2$) with HH production* will constrain the shape of the Higgs potential and verify the EWSB mechanism



- Mainly $HH \rightarrow bbbb$ (33.9%), $HH \rightarrow bb\tau\tau$ (7.3%) and $HH \rightarrow bb\gamma\gamma$ (0.26%)



+ Snowmass updated projections leading to even higher significances:

For ex.: ATLAS extrapolation from full Run 2 analyses, benefiting from updated reconstruction algorithms and analysis methods

- $bb\tau\tau$: $2.1\sigma \rightarrow 2.8\sigma$
- $bb\gamma\gamma$: $2.0\sigma \rightarrow 2.2\sigma$

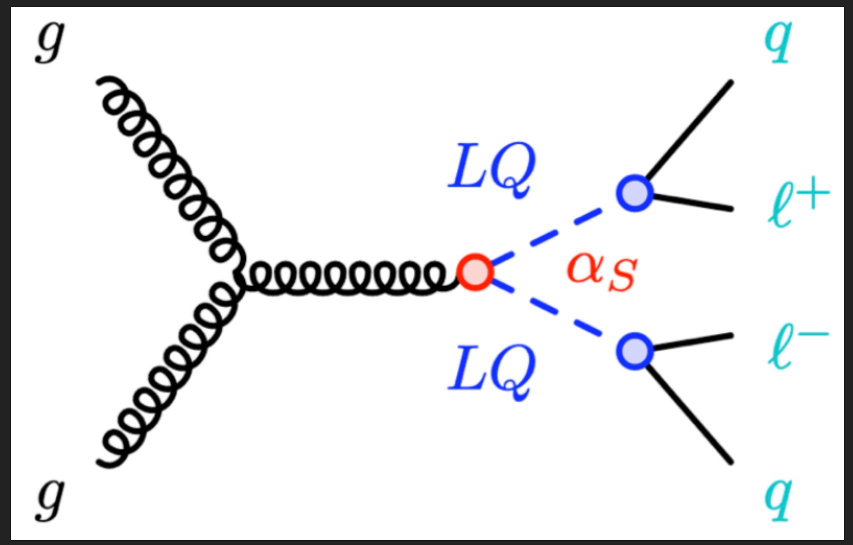
*1000x smaller than single H production!

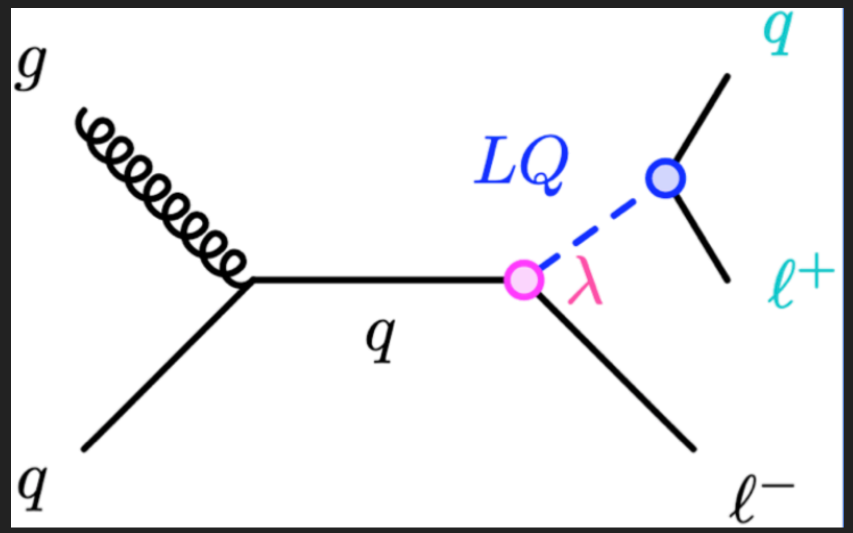
PROSPECTS FOR BSM PHYSICS

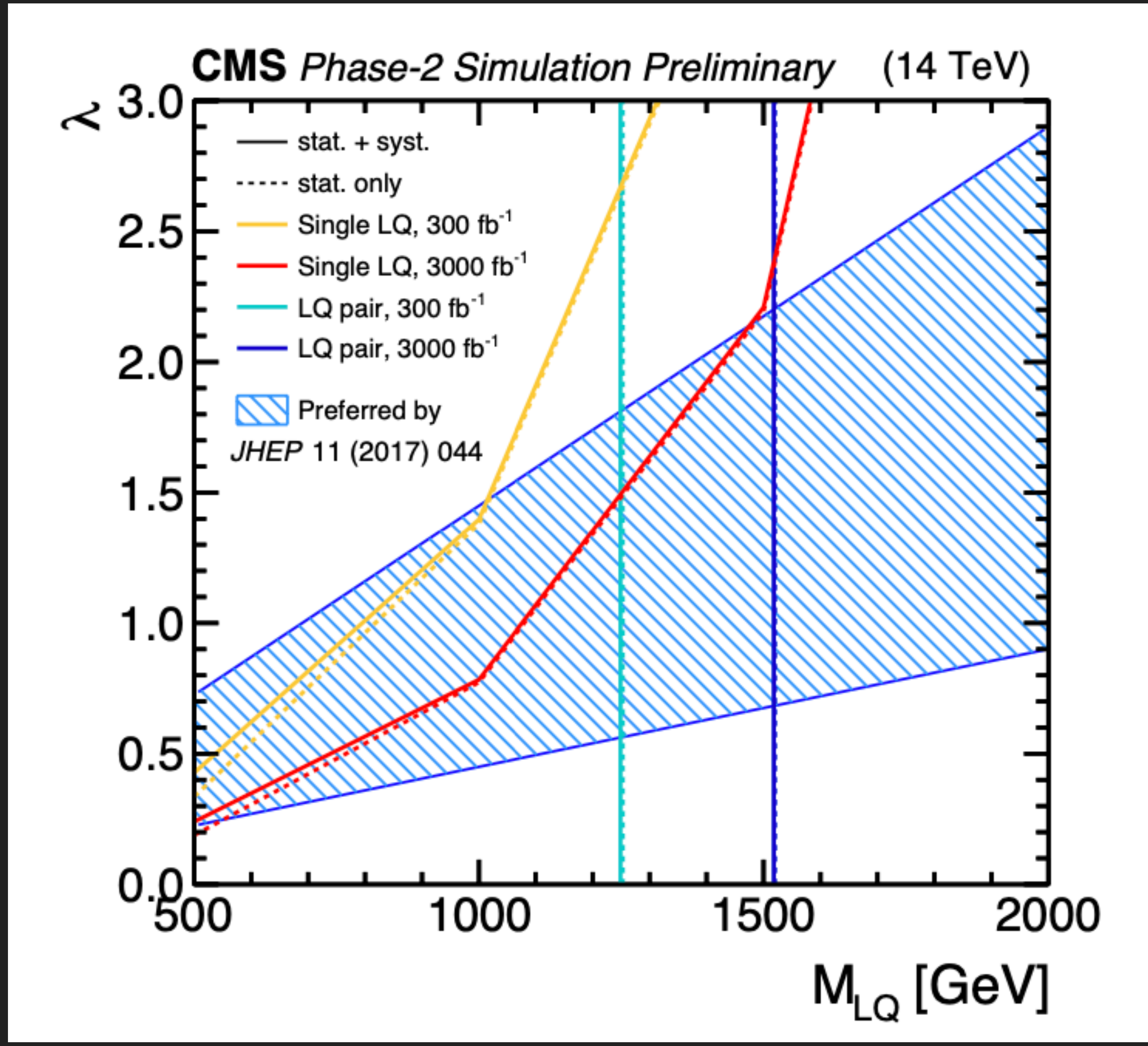
- No clear deviation seen so far, but only 5% of the expected data analysed
  - The sensitivity should improve at sqrt(L) *or as L for searches with no BG (interesting avenue in the first years of new runs!)*
  - Not only improving by stats only as already noted before: bigger samples should benefit performance studies, reducing systematics as well
- Probe for BSM:
  - At higher masses (resonances in spectrum, kinematic tail deviations,…)
  - At low masses (could have escaped detection due to low couplings!) - need innovative methods to reduce BG / trigger on these events!
  - Explore new channels
  - Upgraded detectors and innovative analysis approaches (eg ML)

BSM: PROBING HIGHER MASSES

- Standard benchmark: heavy vector boson as a resonance over a smoothly falling BG
  - SSM bosons: ee + μμ channels discovery reach (CMS): Z′ up to 6.8 TeV or W′(τν) up to 6.4 TeV
  - Right-handed W′ (ATLAS): up to 4.3 TeV in the tb channel
- Renewed interest in direct searches for leptoquarks from hints of flavour anomalies







Scalar LQ to bτ could be probed up to 1.5 TeV (500 GeV improvement)

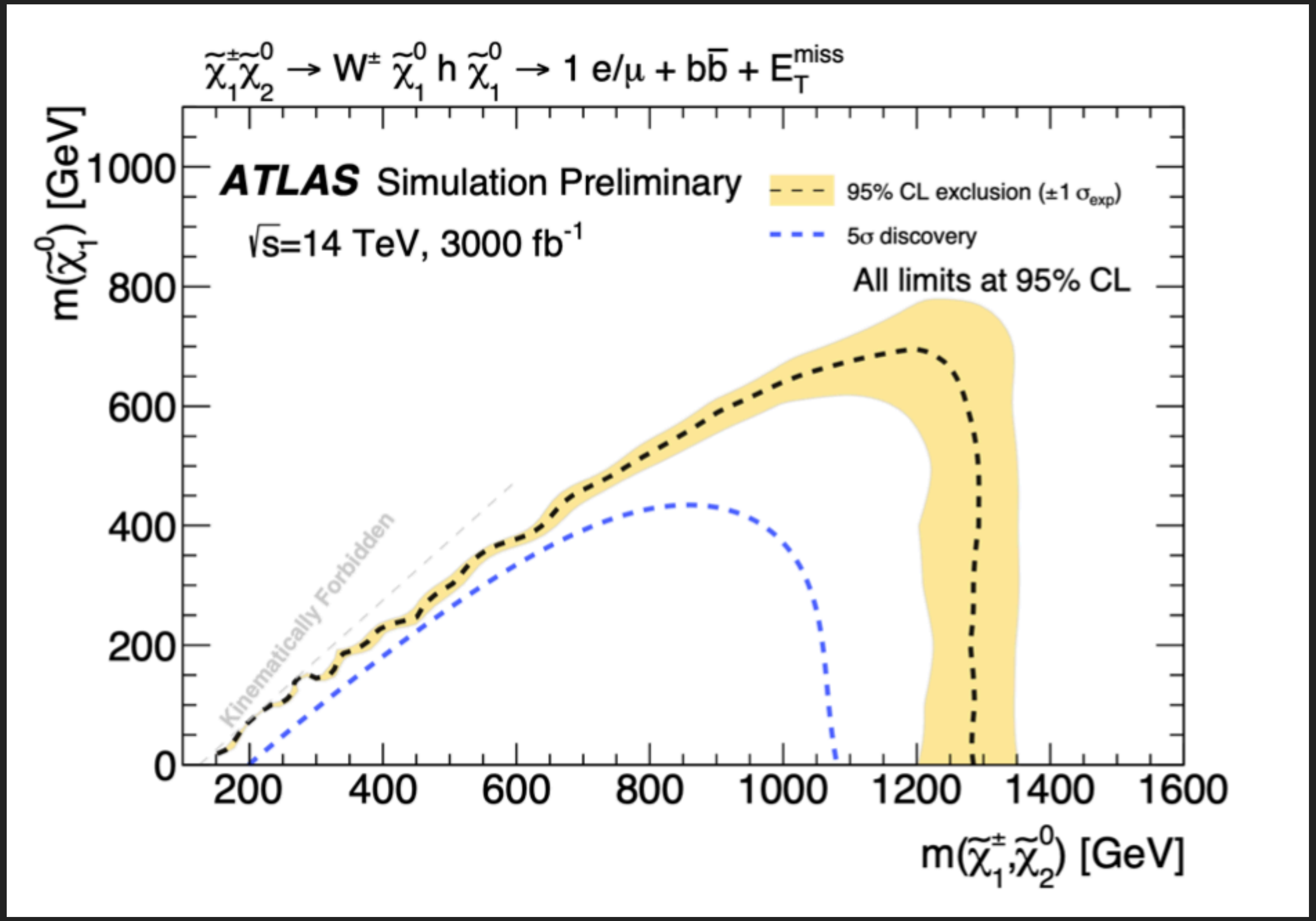
BSM: PROBING LOWER MASSES & COUPLINGS

- Could have evaded detection so far due to small couplings and/or small production cross section and overwhelming backgrounds
- In the previous LHC runs: development of trigger-level (scouting) analyses
  - increase bandwidth by writing out very few information about specific objects, instead of full events for some triggers (dijet, dimuon resonance searches)
  - ATLAS/CMS: upgraded trigger systems will allow this program to continue, likely including additional final states.
  - LHCb:"triggerless" approach for the HL-LHC upgrade => complementary similar analyses in the forward rapidity region

CERN-2019-007

BSM: ELECTROWEAK SUPERSYMMETRY

- If gluinos/squarks at > 3–4 TeV, charginos and neutralinos may dominate the SUSY production at HL-LHC
- Example: final state of E_T^{miss} + 2 b-tagged jets with Higgs-like m_{bb} boson + W decaying leptonically



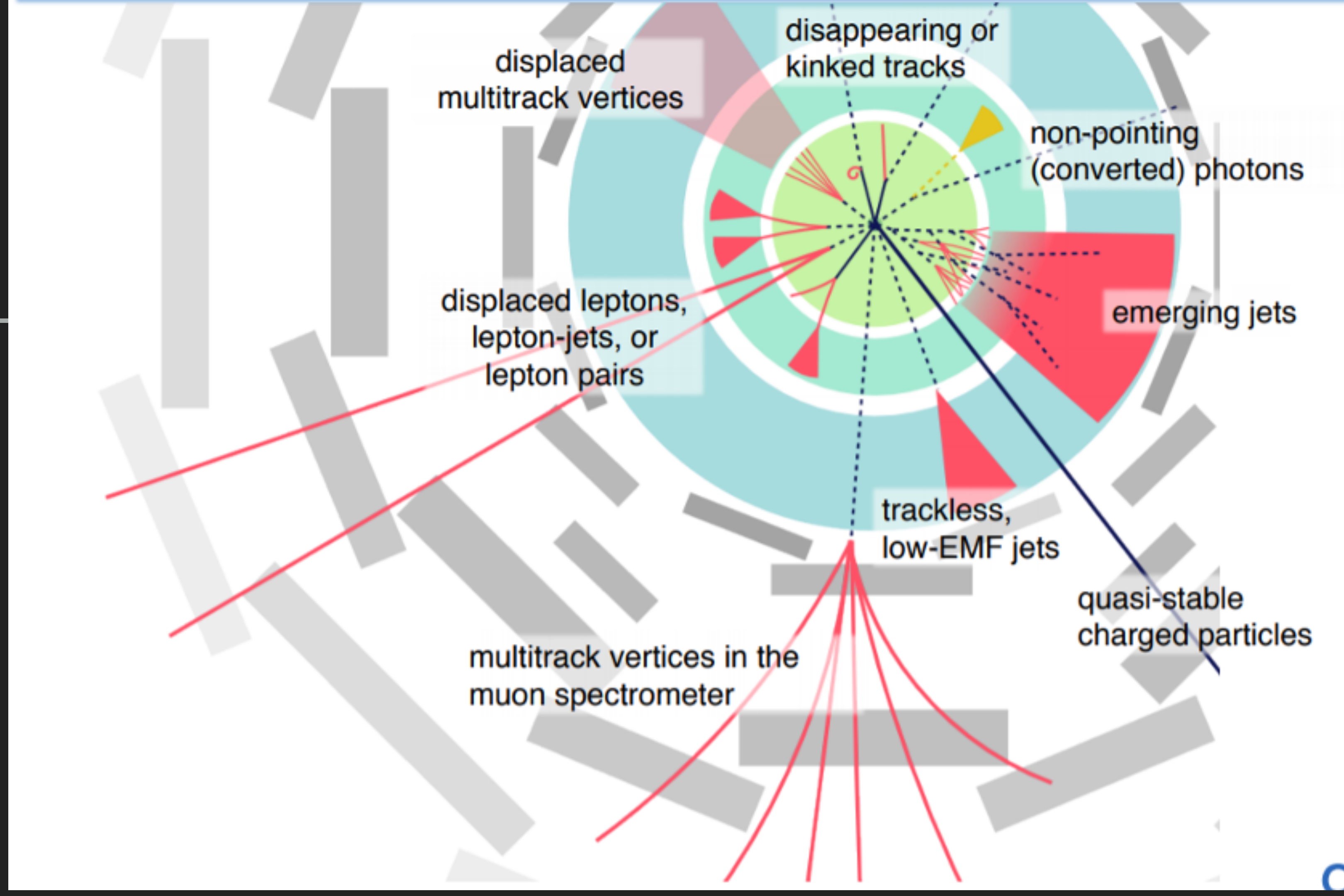
3 BDTs trained against top BG for different mass compression scenarios

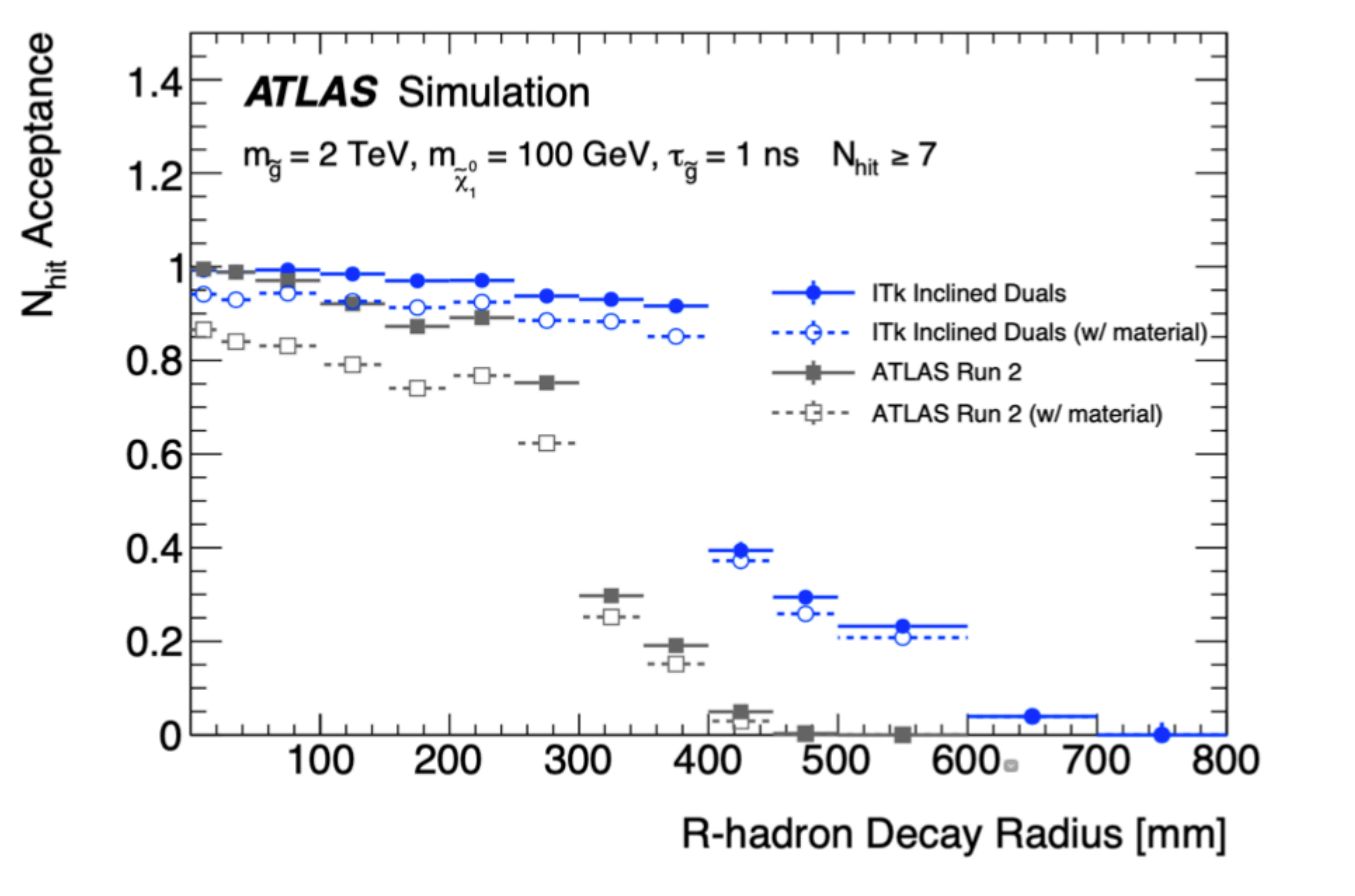
Conservative reach as fully-hadronic channel later found in Run 2 to be more sensitive (fast evolution)

Masses at the TeV scale will be within reach even in scenarios of electroweak production!

BSM: LONG-LIVED PARTICLES

- LLPs occur in many BSM theories (heavy mediators, small couplings, compressed mass spectra) => decays away from the interaction point (eg displaced vertices)
  - Growing interest but need dedicated and complex reconstruction algorithms
  - Will benefit from upgraded detectors (ITk in ATLAS, MTD in CMS…)
    - And from new dedicated detectors (eg FASER)!





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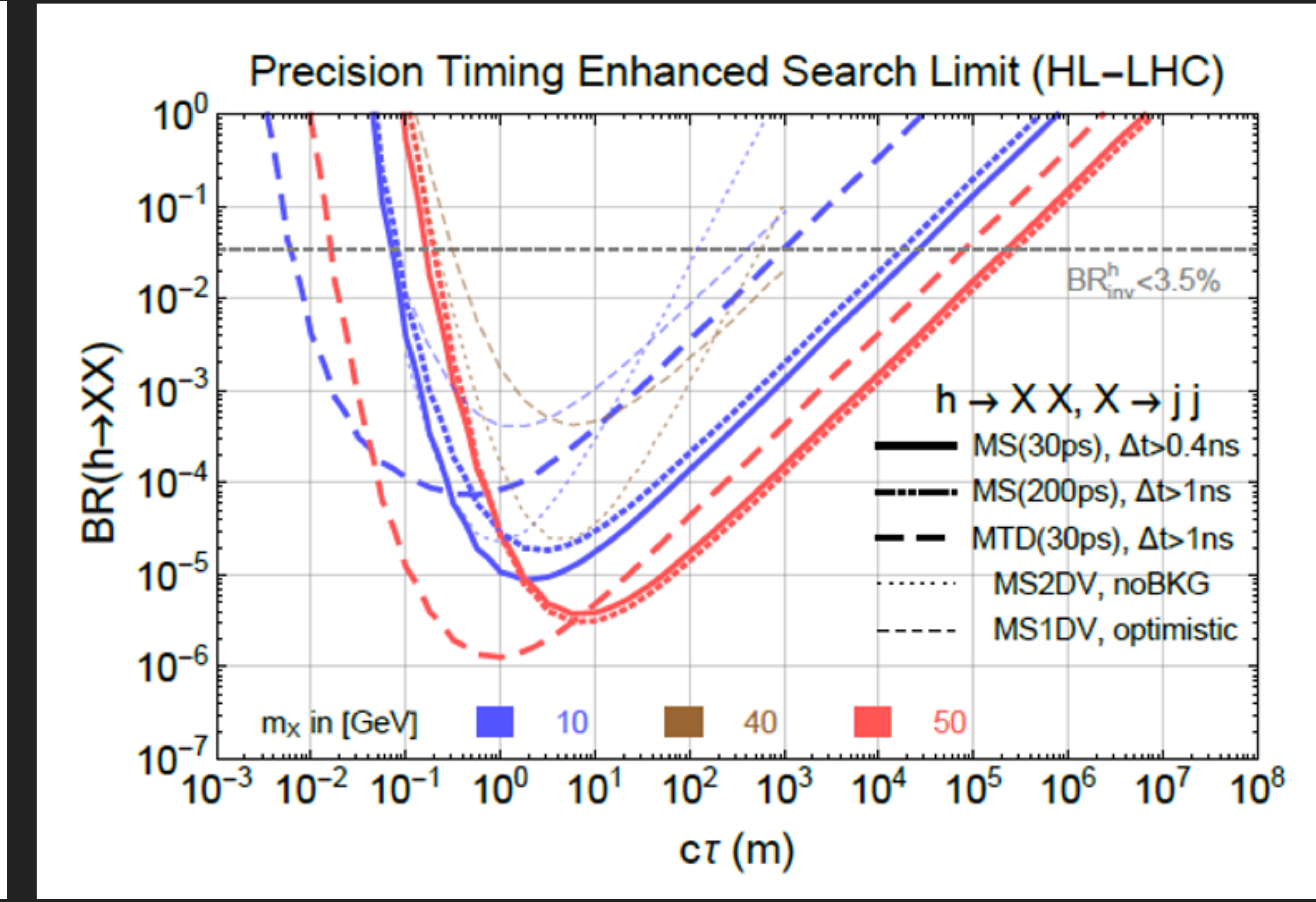


Phys Rev Lett 122 131801

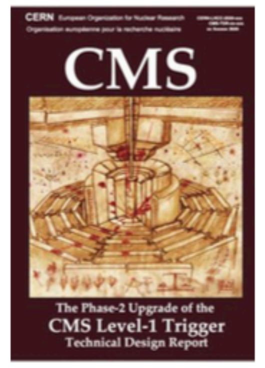
NEW ANALYSIS TECHNIQUES

- Machine learning techniques used in HEP for a long time, but recent increase in frequency and breadth
- Some ML can target theories better than simple “cut-and-count” analyses, but the results obtained can highly depend on the model under study
- Exciting recent avenue: search for anomalies in the data themselves
  - Search for anomalies in objects with respect to a data-based training sample - no need for a prior knowledge of the signal characteristics
    - See eg ATLAS search for dijet resonances with weak supervision (Phys. Rev. Lett. 125, 131801 (2020))
  - Gaining momentum, likely have become one of the standard search tools by HL-LHC

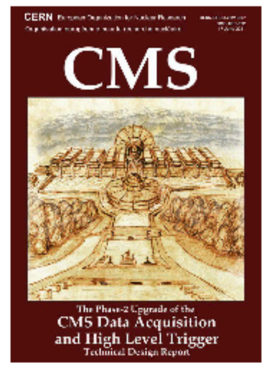
CONCLUSIONS

- Just summarized a handful of projections, showing very nice prospects!
  - Many others exist and some areas (eg low-mass BSM or LLP) do not have many projections made yet
- The assumptions made are typically conservative given the rapid progress continuously achieved by the LHC analyses
    - Some recent full Run-2 results are already competing with older HL-LHC projections!
    - Expected to be further refined by the start of the HL-LHC data-taking, following developments in the object reconstruction performance and analysis methods
- The program of the (HL-)LHC will continue to span a very wide range of physics topics, within the Standard Model and beyond, with unprecendented sensitivities

The CMS Phase-2 Upgrade

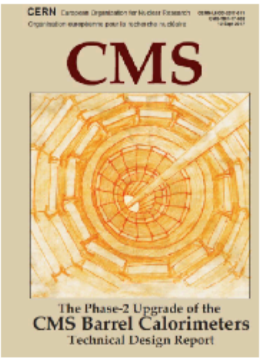


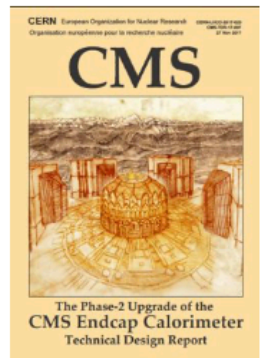
Level-1 Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



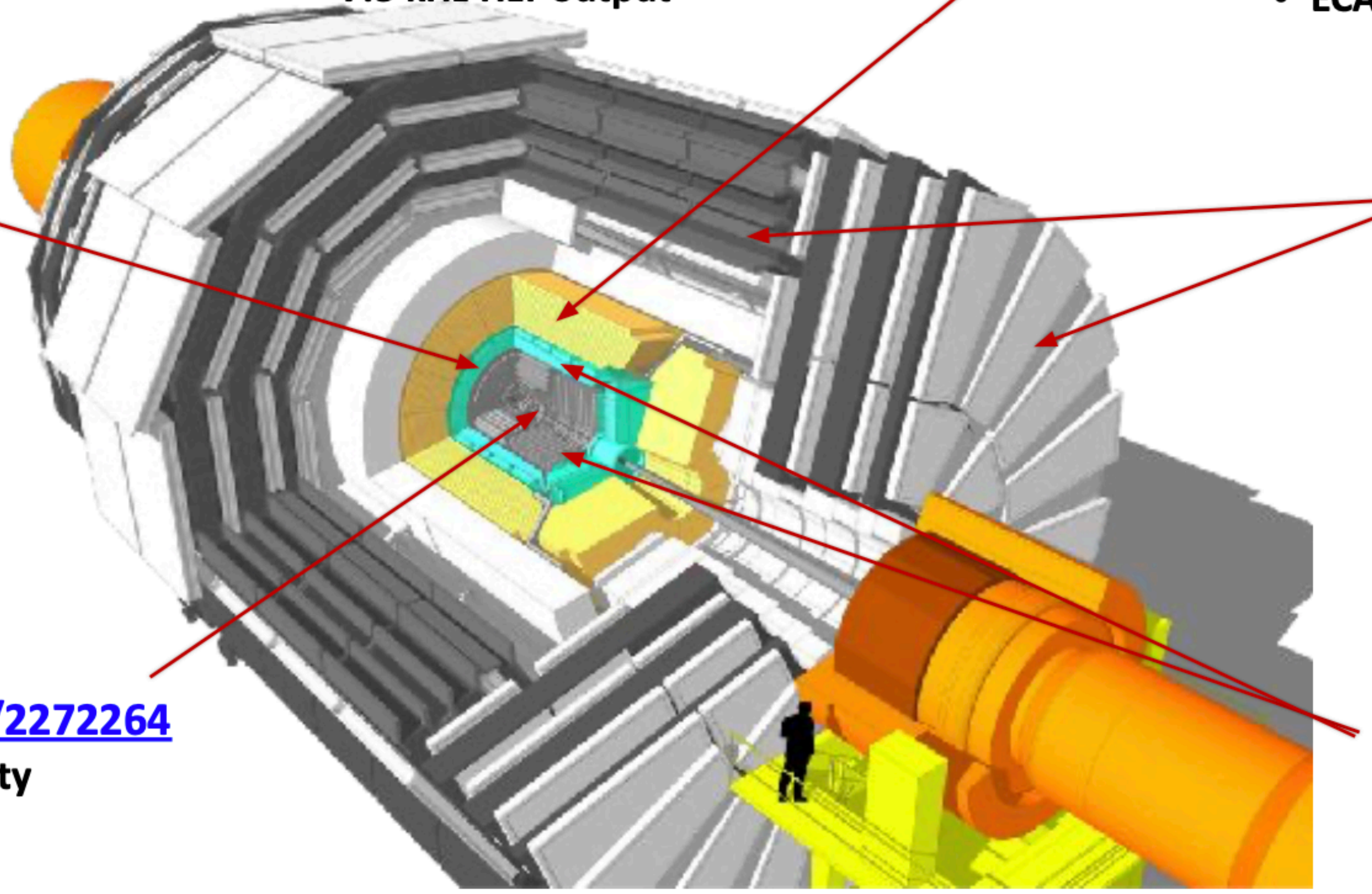
DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL single crystal granularity readout at 40 MHz with precise 30 ps timing for e/γ at 30 GeV
- Spike rejection
- ECAL and HCAL new Back-End boards

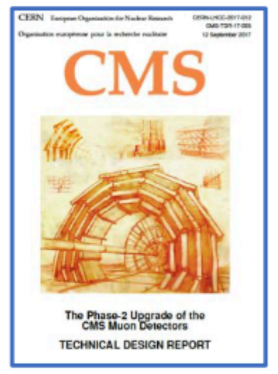


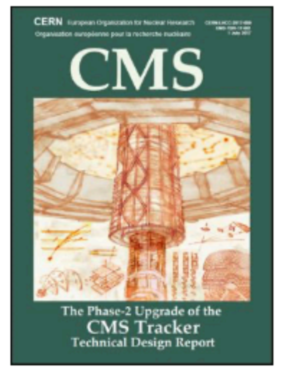


High-Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/Cu-W/SS



Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC BE electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \approx 3$

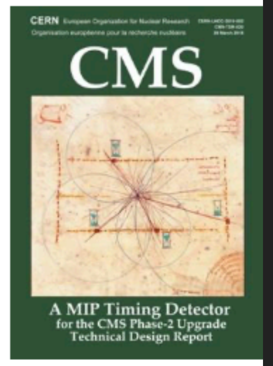


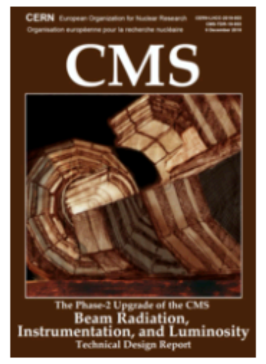


Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to $\eta \approx 4$
- Design for tracking in L1 Trigger

MIP Timing Detector
https://cds.cern.ch/record/2667167

Precision timing with:
- Full coverage to $\eta \approx 3$
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes





Beam Radiation Instrumentation and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

Gabriella Pásztor

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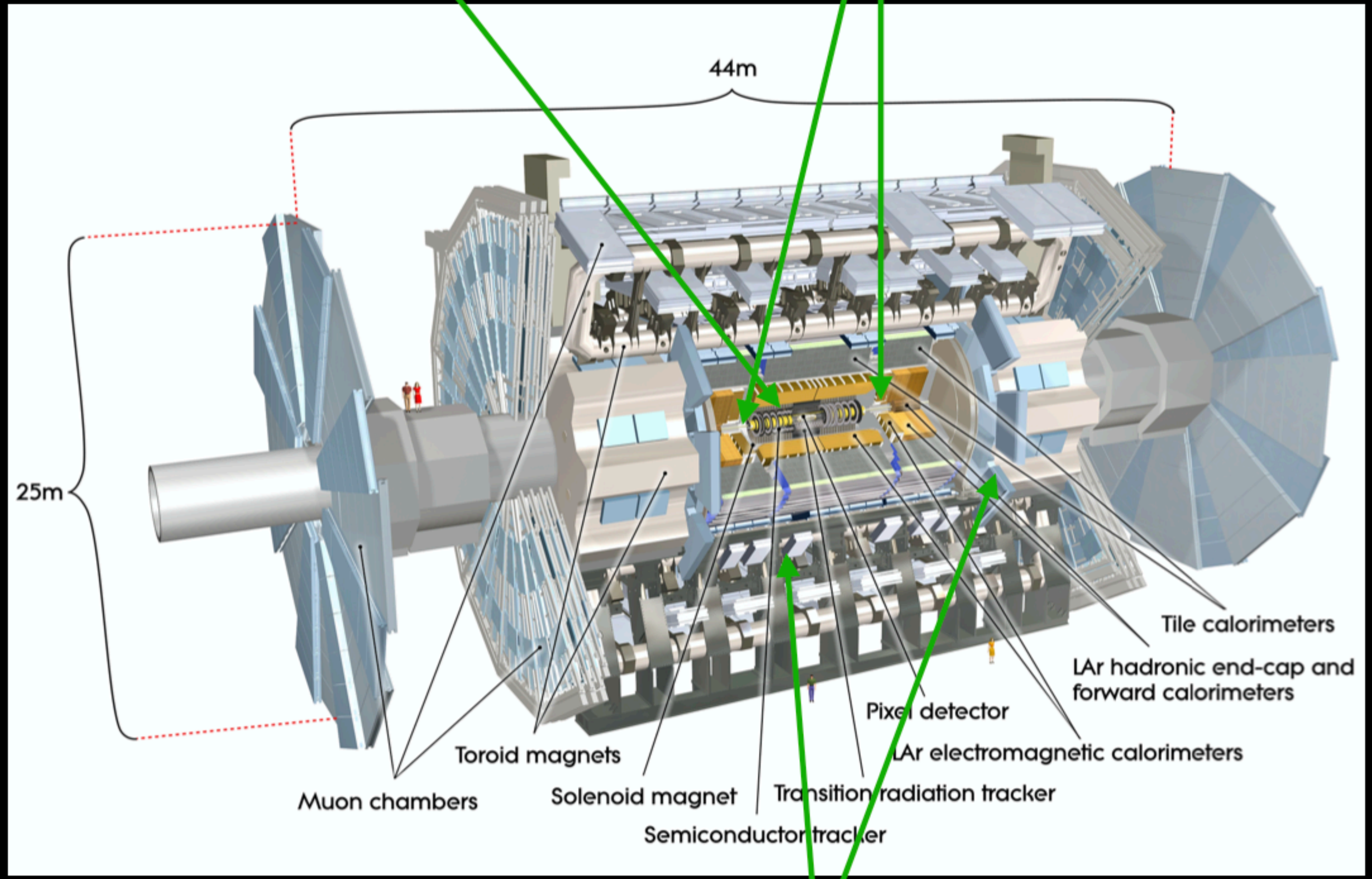
ATLAS upgrades for Run4

- New systems in the cavern:
  - ITk: silicon inner tracker (pixels + strip detector) with eta coverage up to 4
  - RPC and sMDT muon detector in the barrel inner region, sTGC in the end-cap inner region
  - High Granularity Timing Detector in the forward region
  - Calorimeters and muon detectors (TGC/RPC/MDT) front-end readout at 40 MHz
  - Upgrades of luminosity and forward detectors
- New TDAQ off-detector electronics:
  - Level-0 hardware trigger: calorimeter, topological, muon, global, CTP (FPGA-based boards)
  - Readout: FELIX for all ATLAS detectors
  - Event Filter processor farm and hardware tracking

New High Granularity Timing Detector (HGTD)

New inner tracker (ITK)



New muon detectors (RPC + sMDT + TGC)

Front-end replaced for calorimeters and muon detectors

LHCb Phase-II Upgrade detector

CERN-LHCC-2017-003