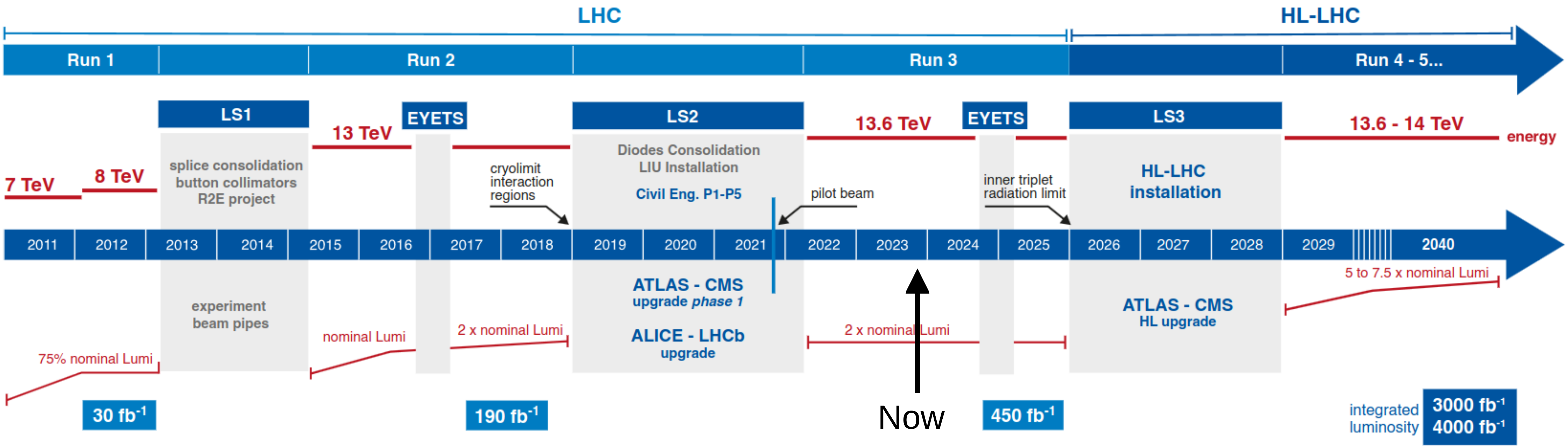
Prospects at HL-LHC

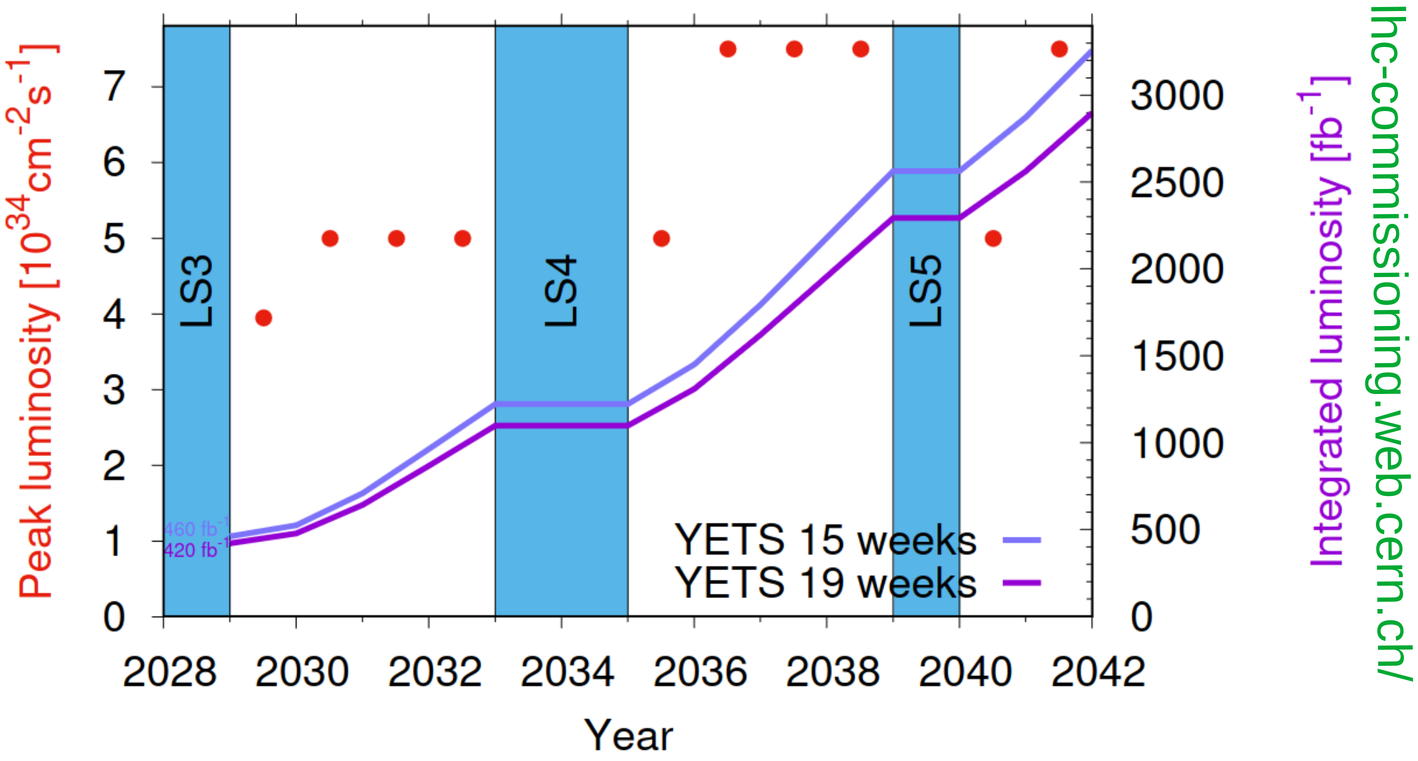
Monika Wielers
STFC-RAL

HL-LHC Timeline, Energy & Integrated Luminosity



- The LHC accelerator will undergo a major upgrade in 2026 - 2028
  - >5 times the initial nominal instantaneous luminosity (i.e. up to 5-7.5 x 10^{34} $cm^{-2}s^{-1}$)
  - Increase of the average pile up from current μ~50 to μ=200
  - Centre-of-mass energy $\sqrt{s}$ = 13.6 - 14 TeV

HL-LHC Integrated Luminosity

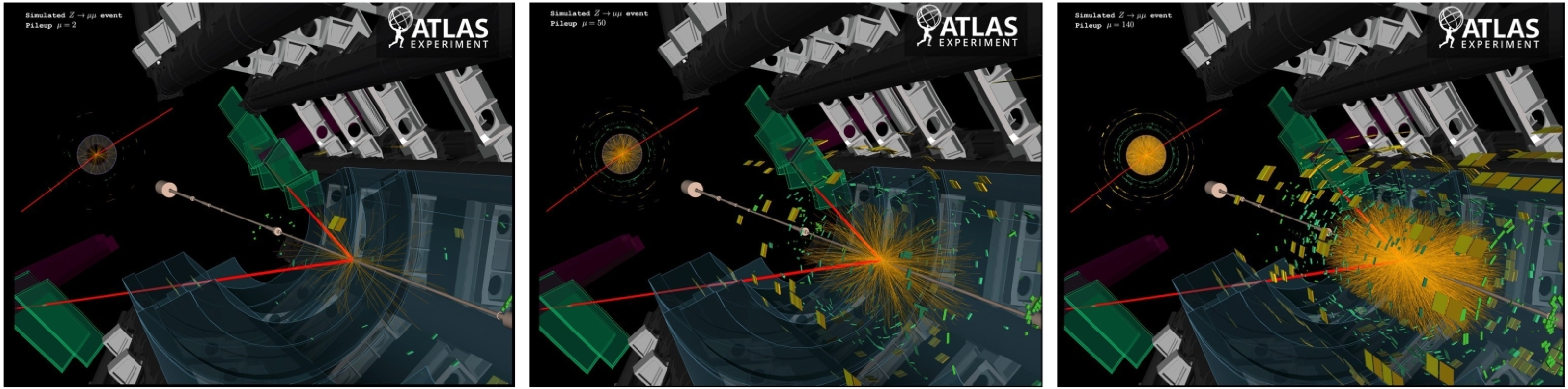


pp collisions		
√s [TeV]	When	Luminosity delivered by LHC [fb^{-1}]
7	2010-2011	6
8	2012	23
13	2015 - 2018	156
13.6	Since 2022	70
Total	Since 2010	255

- Integrated luminosity expectation for ATLAS/CMS: 2.9 - 3.2 ab^{-1}
  - Run 1 – 3 correspond to ~10% of total LHC + HL-LHC dataset
- This will be major boost in statistics
- Data will be essential to improve the knowledge of the Higgs couplings; measure the Higgs self coupling, rare decays etc

HL-LHC challenges for the detectors

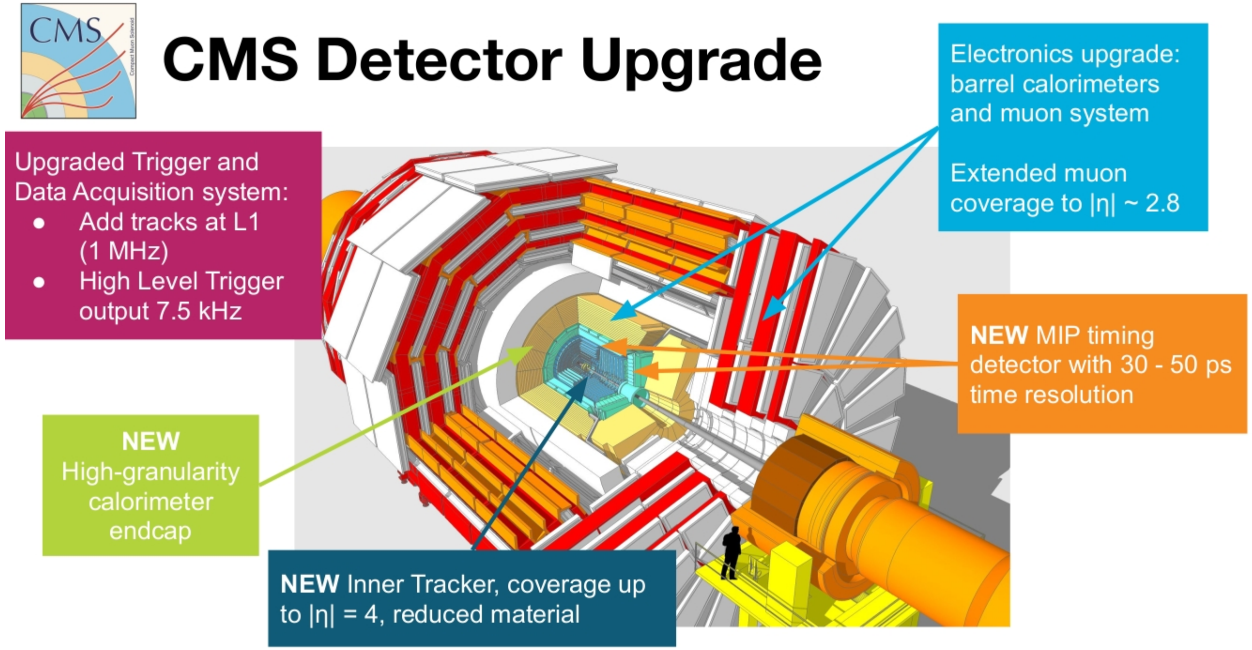
Pile-up = 2 | Pile-up = 50 | Pile-up = 140

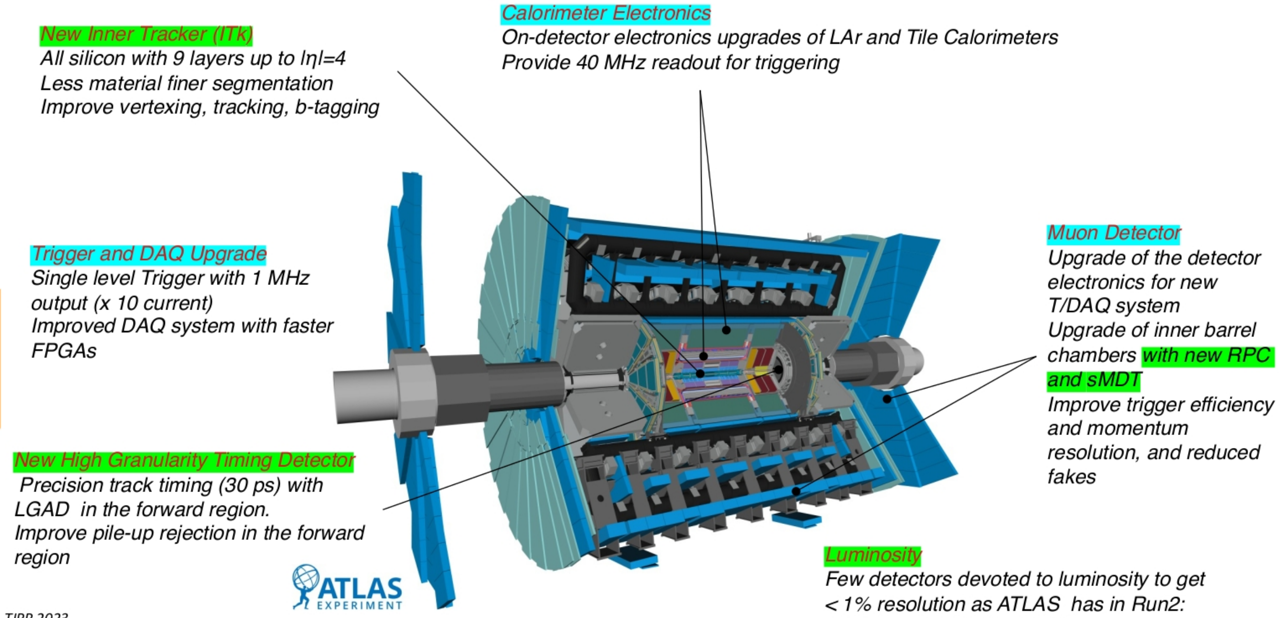


- Detectors need to deal with more “messy” events, and more radiation damage
- Major upgrades needed to
  - Improve radiation hardness and replace detectors at end-of-life
  - Provide handles for mitigating pileup (high granularity, fast timing)
  - Allow higher event rates to maintain/improve trigger acceptance
- To fulfill physics goals it is essential to maintain or improve over current performance

HL-LHC challenges for the detectors

- **Ambitious upgrade programme both for CMS and ATLAS:**
  - **upgrade Trigger and DAQ:** hardware trigger 100 kHz → 750 kHz including tracks / 1 MHz, software trigger 1 kHz → 7.5 kHz / 10 kHz
  - **new all-silicon inner trackers** with extended coverage up to |η|<4
  - **new timing detectors** with central + forward / forward coverage
  - **improved muon coverage and trigger** in forward region
  - new endcap high-granularity calorimeter
  - **upgraded electronics** for existing calorimeters + muon detectors



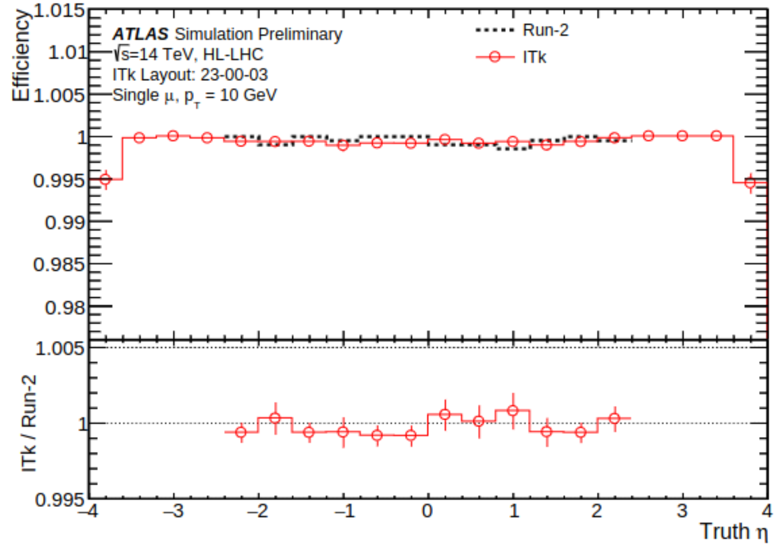


TIPP 2023
C. Gemme

Analysis techniques

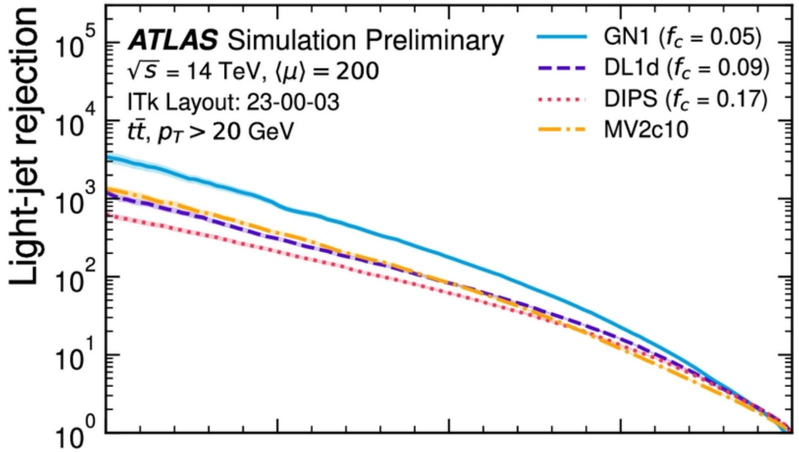
- Three main approaches for HL-LHC studies
  - Full simulation (i.e. for assessing detector performance)
  - Analysis with parameterised detector performance
    - ATLAS: smearing of generated particle energy and p_T, identification eff., mis-tag rates etc
    - CMS: DELPHES with up-to-date detector performance
    - Analysis guided by present analysis. Limited optimisation for HL-LHC environment
  - Projections using Run-2 signal/bkd samples scaled to 3000 fb^{-1} of data and $\sqrt{s}$ =14 TeV

Tracking efficiency for p_T=10 GeV μ (no pu)



ATL-PHYS-PUB-2021-024

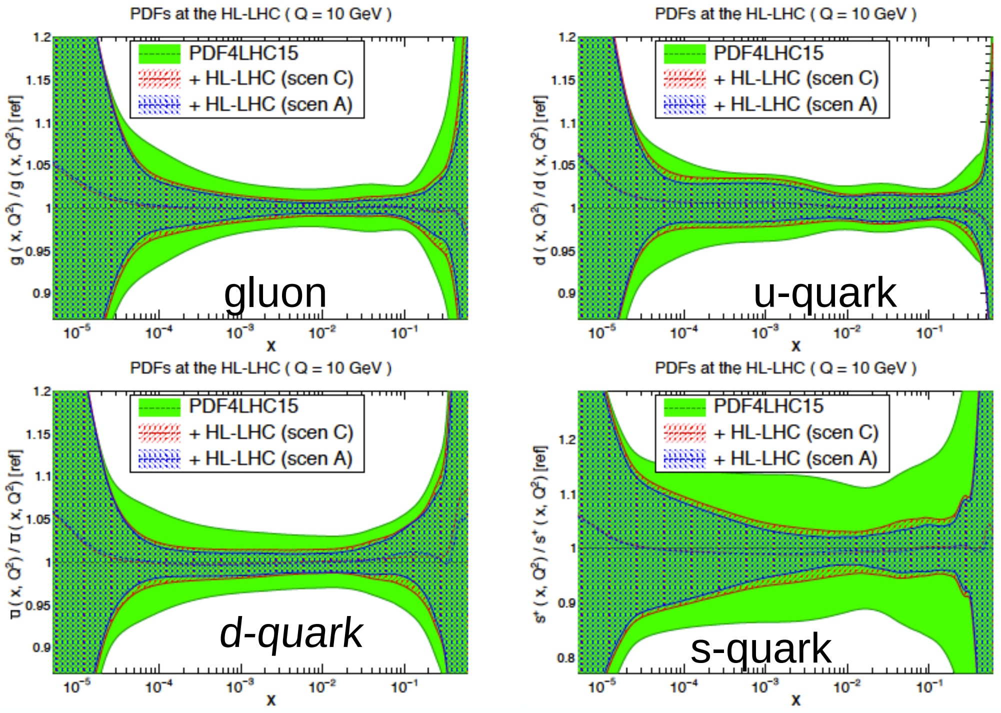
Light jet rejection in ttbar events



ATL-PHYS-PUB-2022-047

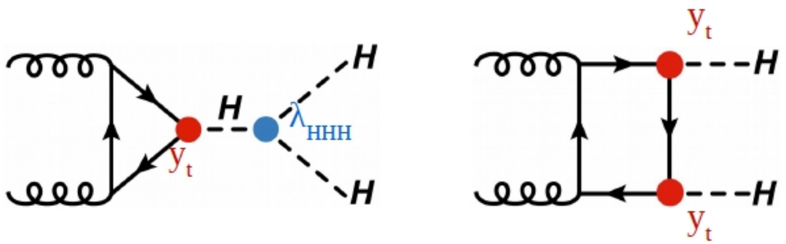
Systematics

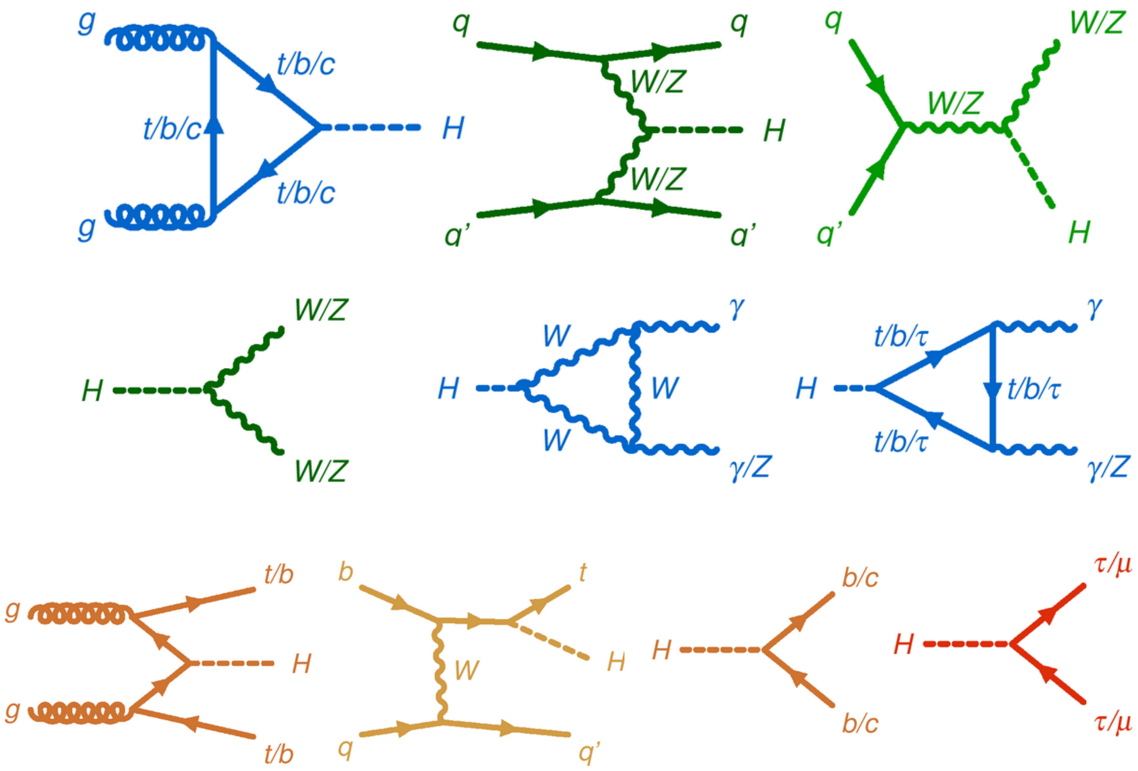
- General “rule of thump”
  - Detector and trigger performance comparable to Run 2
  - Experimental uncertainties scaled down by √L until they reach a defined lower limit.
  - Most theoretical uncertainties scaled down by a factor ½
  - Modelling uncertainties to be halved
  - Uncertainties due to the finite number of simulated events are neglected
  - Luminosity uncertainty: 1%
- Example: PDF uncertainties
  - Significant reduction in PDF uncertainties



HL-LHC overview of Higgs physics programme

- HL-LHC is Higgs factory
  - Expect 170×10^6 Higgs bosons
  - Typically > 1×10^6 for each of the main production modes
  - ~100 k HH events



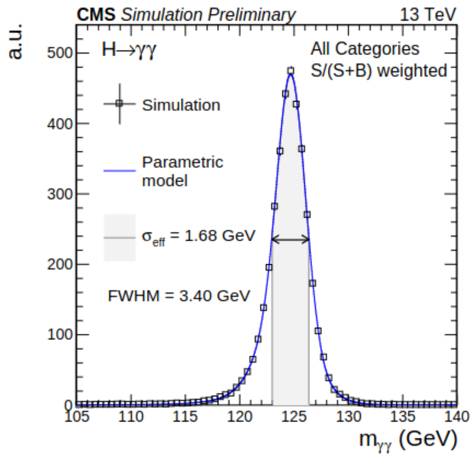


- Broad Higgs physics programme
  - Exploration of Higgs potential (HH production)
  - Precision measurements (O(few %))
  - Sensitivity to rare decays involving new physics
  - Extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotics decays…)

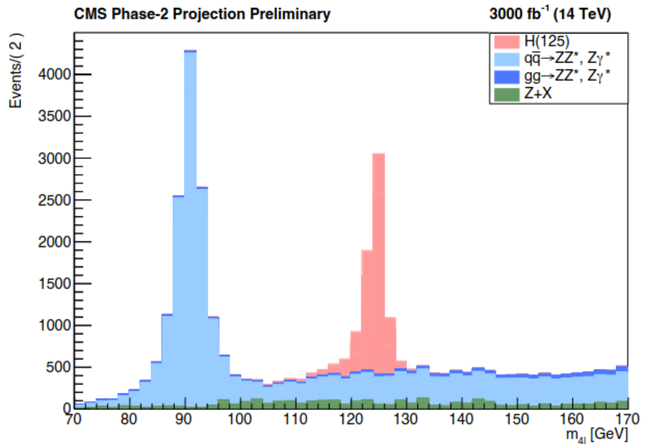
Higgs Boson Properties: Mass

- LHC run-2 measurement:
  - CMS H→4ℓ: m_H = 125.04 ± 0.12 [±0.11(stat.) ± 0.05(sys.)] GeV CMS-PAS-HIG-21-019
  - ATLAS H→4ℓ+H→γγ: m_H = 125.11 ± 0.11 [±0.09 (stat.) ± 0.06 (sys.)] GeV arXiv:2308.04775
- CMS HL-LHC projections
  - H→4ℓ: m_H = 125.38 ± 0.03 GeV [0.022 (stat.) ± 0.020 (sys.)] GeV CMS-PAS-FTR-21-007

    Significant reduction in Higgs mass uncertainty in 4ℓ final state
  - H→γγ: m_H = 125.38 ± 0.07 GeV [0.02 (stat.) ± 0.07 (sys.) GeV] CMS-PAS-FTR-21-008



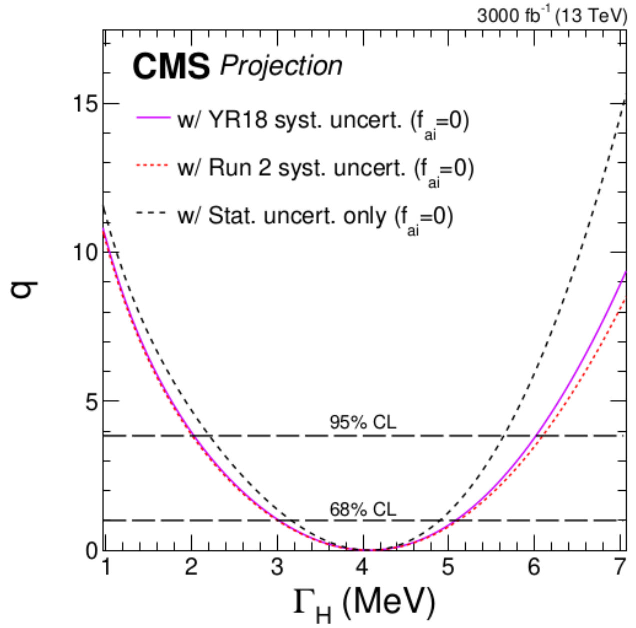
CMS-PAS-FTR-21-008



CMS-PAS-FTR-21-007

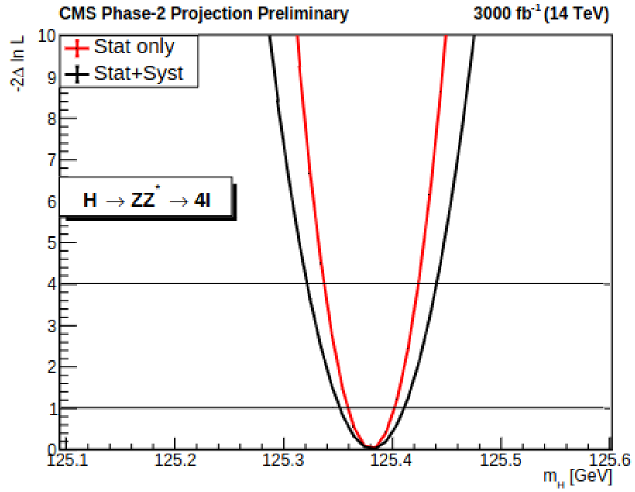
Higgs Boson Properties: Width

- Very challenging as detector resolution >> natural Higgs width
- Access to natural width: look at off-shell prod. in H→4l final state
- Assumptions:
  - Higgs couplings to gluons and ZZ evolve off-shell as in the SM
  - Couplings to vector bosons are not larger than SM ones ($\kappa_V \leq 1$)
- CMS Run-2 measurement:
  - H→4ℓ or 2ℓ2ν: $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV at 68% CL CMS-PAS-HIG-21-019
- HL-LHC extrapolation CERN-2019-007
  - H→4ℓ: $\Gamma_H = 4.1^{+1.0}_{-1.1}$ MeV CMS, $\Gamma_H < 4.1^{+0.7}_{-0.8}$ MeV CMS+ATLAS at 68% CL
  - Approaching the natural width expected by SM



CMS-PAS-FTR-21-007

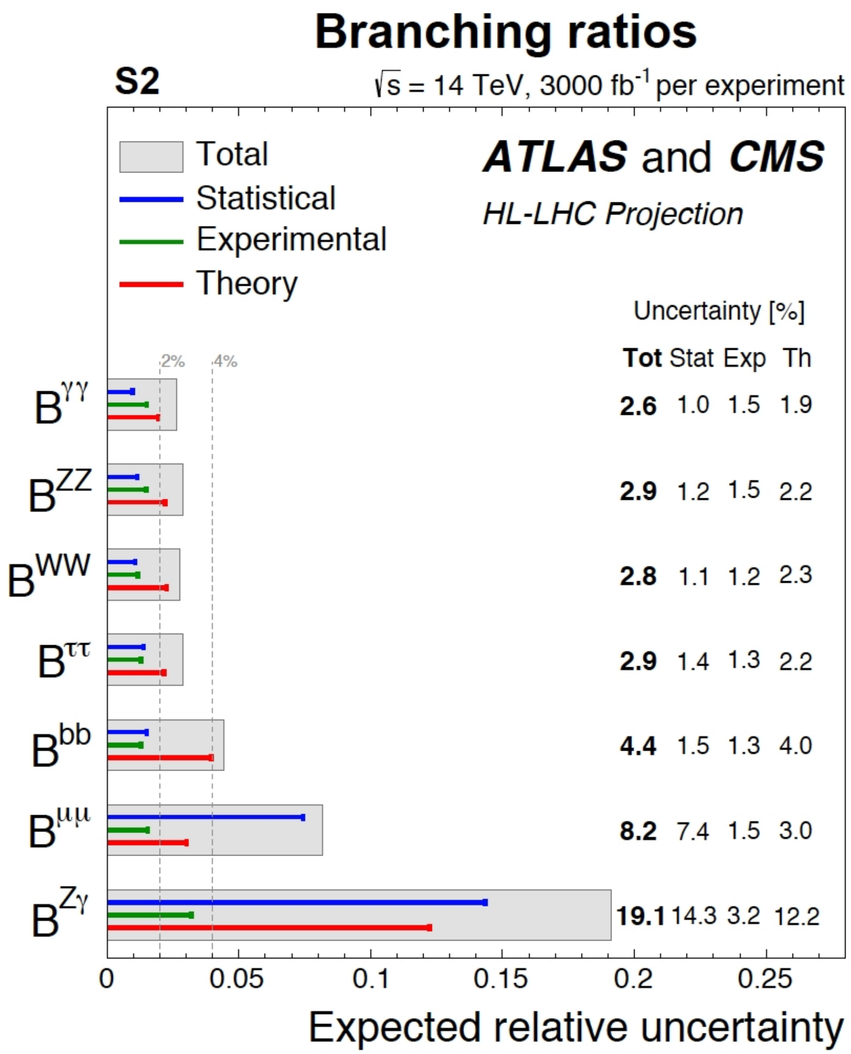
- To be complemented with direct width measurement, CMS result:
  - $\Gamma_H < 177$ MeV (stat.+sys.) and $\Gamma_H < 94$ MeV (stat.) at 95% CL



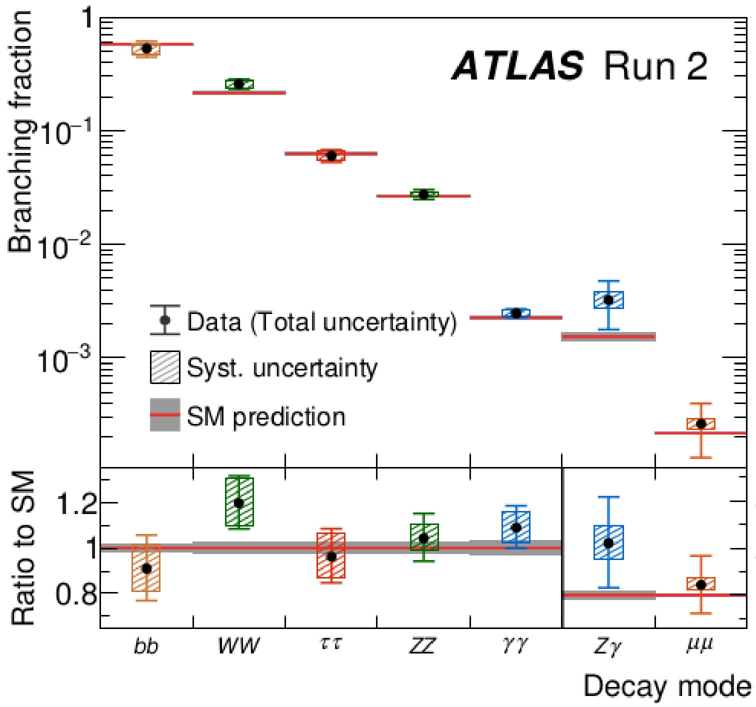
Higgs Boson Properties: Branching ratios

- Branching ratios can be measured with a very good precision
  - Most measurements limited by theory uncertainties
    - Precision 2-5%
  - Branching ratio of H→μμ and H→Zɣ still limited by stat. uncertainty

CERN-2019-007



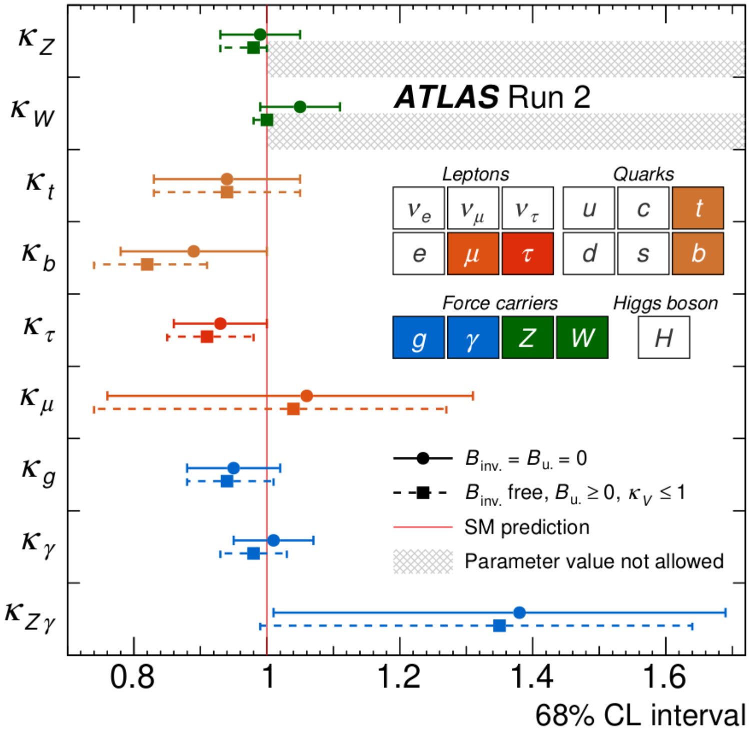
Nature 607, 52 (2022)



Higgs Boson Properties: Couplings

- "κ framework": Consider coupling modifiers $\kappa_j^2 = \sigma_j/\sigma_j^{SM}$, or $\kappa_j^2 = \Gamma_j/\Gamma_j^{SM}$
  - Parametrises potential deviations from the SM predictions
- Higgs couplings move into precision regime
  - Most measurements limited by theory uncertainties with HL-LHC datasets
    - Precision 2-4%
  - κ(μ) and κ(Zɣ) still limited by stat. uncertainty

Nature 607, 52 (2022)



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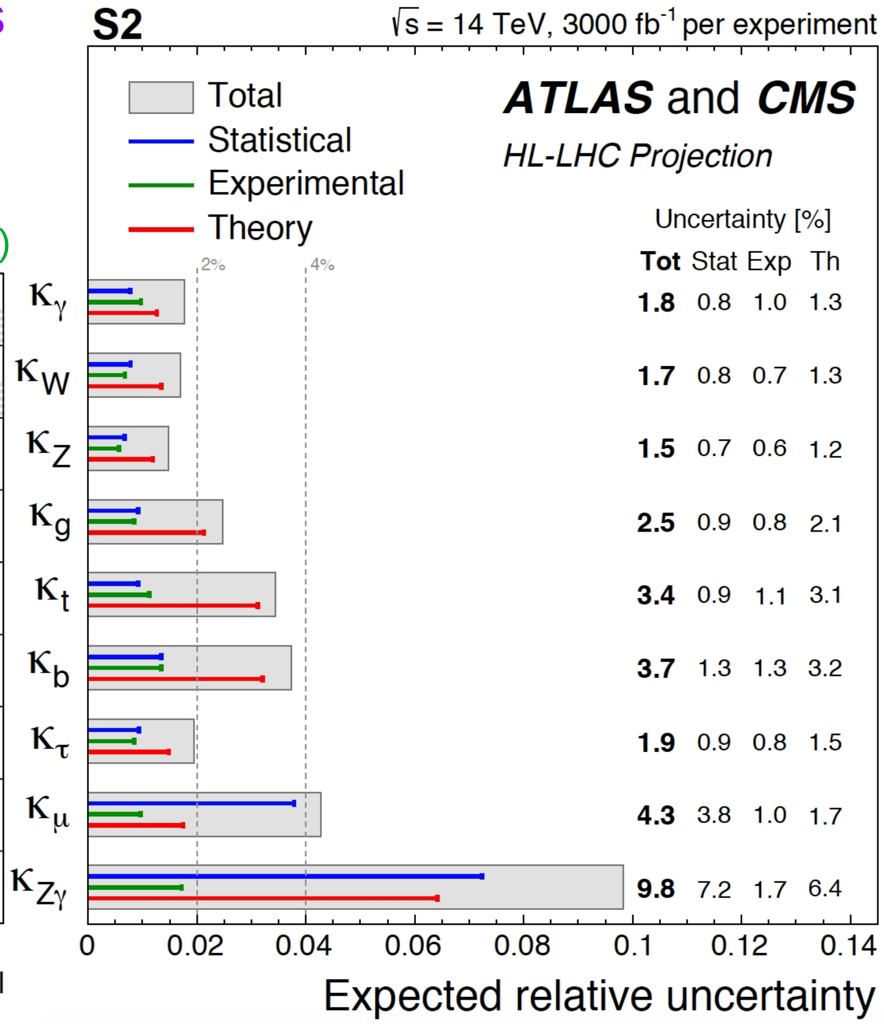
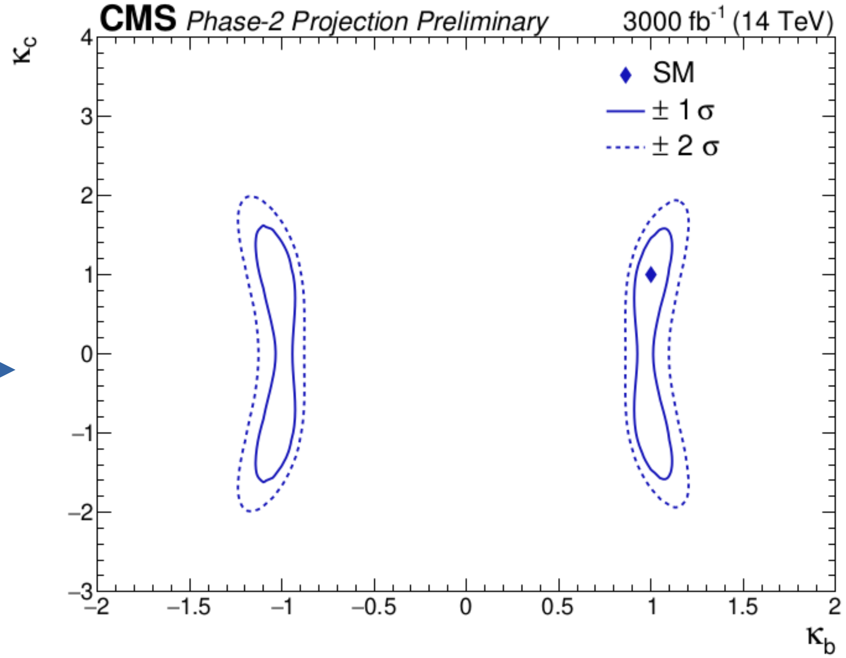


Higgs couplings to 2nd generation fermions: H→cc

- Most sensitive production mode is VH
  - ATLAS: $|\kappa_c| < 8.5$ at 95% CL ATLAS-CONF-2021-021
  - CMS: $1.1 < |\kappa_c| < 5.5$ at 95% CL Phys. Rev. Lett. 131, 061801
    - Compared to ATLAS, also boosted c-jets considered
  - LHCb Run 1: $|\kappa_c| < 80$ LHCb-CONF-2016-006
- Extrapolation to HL-LHC
  - CMS: Precision of $|\kappa_c/\kappa_b|$ CMS-HIG-21-008
  - ATLAS: $|\kappa_c| < 3$ ATL-PHYS-PUB-2021-039
  - LHCb with 300 fb^{-1}: $|\kappa_c| < 2$-3 LHCB-PUB-2018-009



- Direct measurement within reach at HL-LHC!
  - New analysis techniques, such as the use of multivariate techniques and jet substructure variables, are improving results significantly already now, combination could reach $|\kappa_c| \sim 1$
  - Additional information from rare decays or studying p_T spectrum

Higgs couplings to 2nd generation fermions: H→μμ

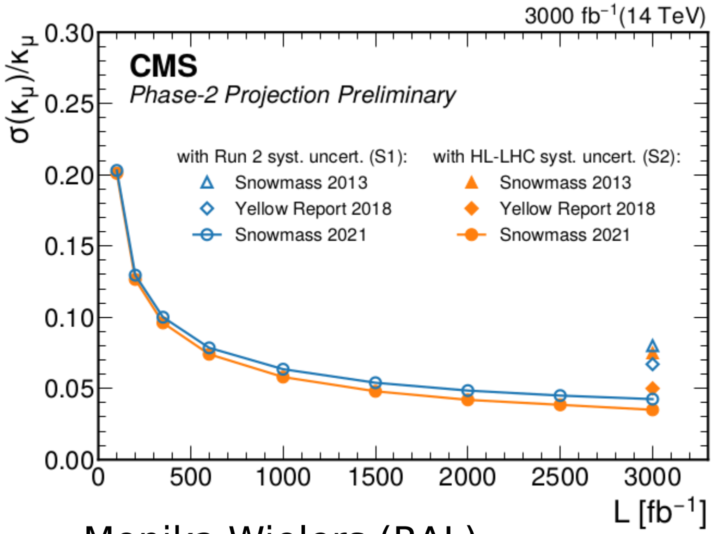
JHEP01(2021)148
Phys. Lett. B 812 (2021)

- So far: Evidence at 3σ using Run 1 and 2 data in CMS, 2σ for ATLAS run-2 data
- Extrapolation from Run 2, with improved expected reco. Higgs mass width
  - S1: Run-2 uncertainties, S2: HL-LHC uncertainties
- Uncertainty of $\sigma(H\rightarrow\mu\mu)/\sigma_{SM}(H\rightarrow\mu\mu)$
  - CMS: 7% CMS-PAS-FTR-21-006
  - ATLAS: 13% ATL-PHYS-PUB-2018-006

CMS		Statistical	Experimental	Theoretical	Total
S1	Snowmass 2013	-	-	-	20.0%
	YR 2018	9.1%	7.6%	4.8%	12.8%
	Snowmass 2021	6.4%	3.7%	4.2%	8.5%
S2	Snowmass 2013	-	-	-	14.0%
	YR 2018	9.1%	1.7%	2.7%	9.6%
	Snowmass 2021	6.4%	2.0%	2.0%	7.0%

- Precision of κ_μ : 3.5% for CMS
  - κ_μ uncertainty shown few slides ago, is already now slightly improved

CMS		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

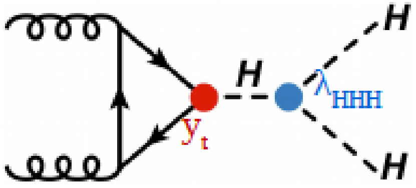
Even rarer: $H \rightarrow Z\gamma$

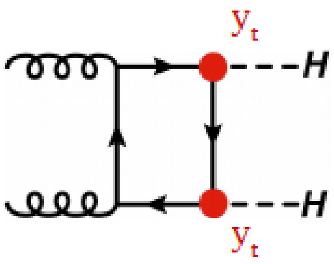
- Extrapolation from 36 fb^{-1} of ATLAS Run-2 data: ATL-PHYS-PUB-2018-054
  - Expected significance: 4.9σ
    - We will be able to observe this decay either per experiment or by combining results!
  - Expected precision on $\sigma \times BR$

Scenario	Δ_{tot}/σ_{SM}	$\Delta_{stat}/\sigma_{SM}$	$\Delta_{syst}/\sigma_{SM}$
HL-LHC S1	0.23	0.20	0.11

    - Systematic uncertainty dominated by missing higher order corrections

Di-Higgs production

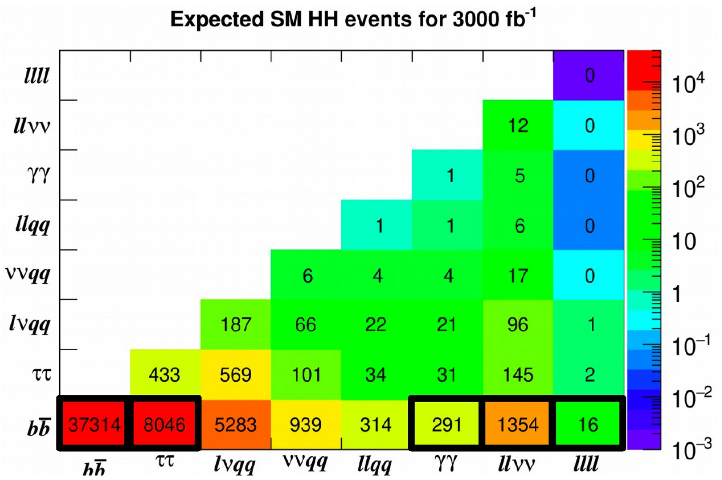




- Rare process of the SM
  - σ(gg→HH) ≈ 0.1%×σ(gg→H)
- Gateway to improve our understanding of Higgs potential and EWSB
- BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section:

  $\kappa_\lambda = c_{hhh} = \lambda_{HHH}\ \lambda^{SM}_{HHH},\ \lambda_{HHH} = m_H^2/(2\,\upsilon\,)$

- Either extrapolations from Run-2 analyses, or dedicated studies with smeared/parametric detector response



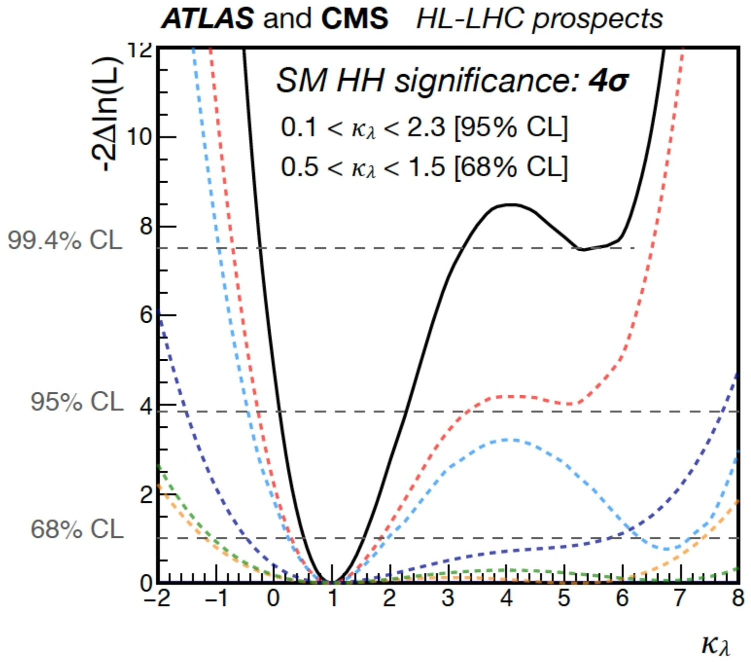
CERN-2019-007

	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric	Very small BR ☹ Very small bkg ☺

Di-Higgs production

- Expected significance (SM) with (without) systematics at HL-LHC CERN-2019-007
  - 4σ (4.5σ) expected with ATLAS+CMS!
- Measurement of κ_λ
  - Precision: 50% at 68% CL
  - 2nd minimum excluded at 99.4% CL
    - 2nd minimum from increase in cross section vs coupling strength, signal acceptance (m_{HH} window used in ATLAS in bbγγ channel)

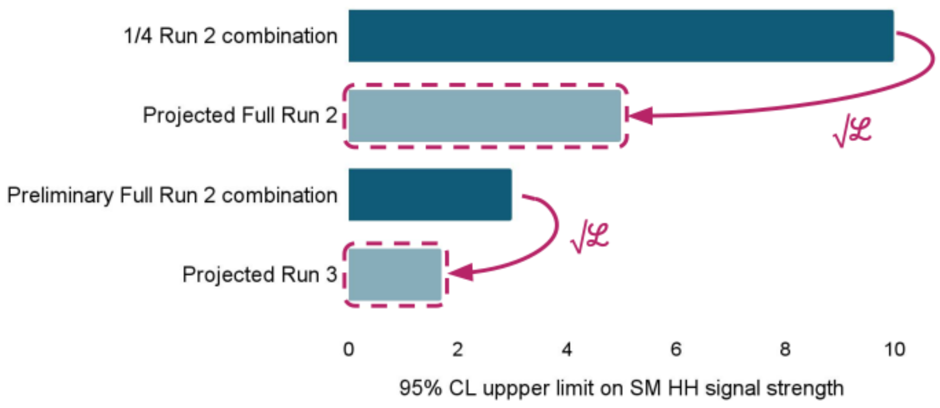
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



CERN-2019-007

Since then...

- Reanalysis of ATLAS bbγγ+bbττ analyses ATL-PHYS-PUB-2022-005
  - Full ATLAS Run-2 yielded a factor of ~1.7 improvement in results due to improved reconstruction and analysis techniques w.r.t. previous results (compared to simple projection based on $\sqrt{\mathscr{L}}$)
  - Expected significance: 3.2σ
- Reanalysis of CMS bbγγ analysis CMS-PAS-FTR-21-004
  - Expected significance: 2.16σ
- New analysis HH→WWγγ or HH→ττγγ CMS-PAS-FTR-21-003
  - Expected significance: 0.2σ
- Expected (back of the envelop) combined significance ATLAS+CMS: 4.6σ
  - Excellent progress towards 5σ



Talk by E. Brost

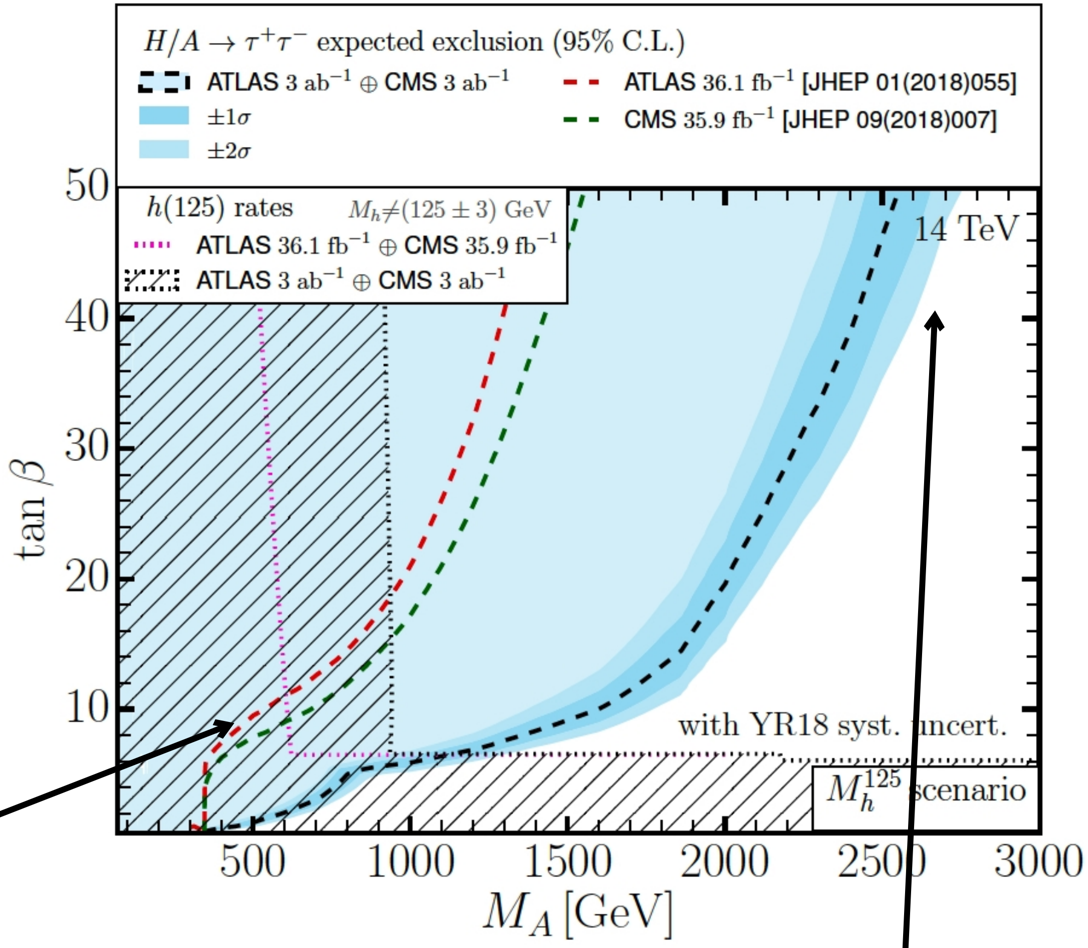
ATLAS	Significance	
Channel	Yellow Report	Snowmass
bbγγ	2.0σ	2.2σ
bbττ	2.1σ	2.8σ

CMS	Significance	
Channel	Yellow Report	Snowmass
bbγγ	1.8σ	2.16σ
WWγγ + ττγγ		0.2σ

Searches for additional Higgs bosons

Searches for additional Higgs bosons

- Example: search for A/H →ττ within MSSM model
  - MSSM predicts 5 Higgs bosons: h_0, H, A, H^+, H^-



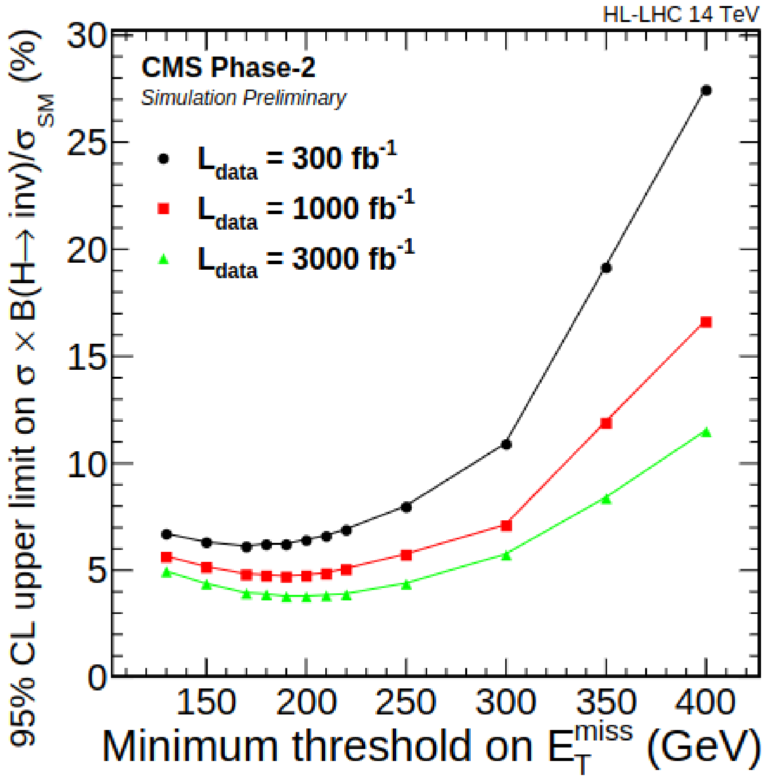
Excluded region from Higgs precision coupling measurements

Probe up to 2.5 TeV for tanβ>50

Searches for H→invisible

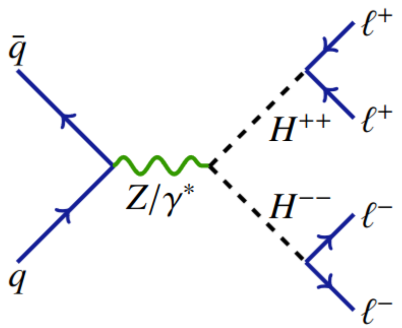
- SM B(H→inv.) is below current experimental limits
  - $B_{SM}(H \to ZZ \to 4\nu) \sim 0.1\%$
- Higgs could decay into BSM particles:
  - Light pseudoscalars, LLP, Dark photons, Dark matter, etc
- Current Run-2 limits:
  - Atlas: B(H→inv.) < 10.7% using VBF, ttbar, Z(→ℓℓ) or jet + E_T^{miss} signature Phys. Lett. B 842 (2023) 137963
  - CMS: B(H→inv.) < 18% using VBF + E_T^{miss} Phys. Rev. D 105 (2022) 092007
- HL-LHC extrapolation
  - CMS in VBF channel: BR(H→inv.) < 3.8% with E_T^{miss}>190 GeV CMS-FTR-18-016
  - ATLAS in Z(→ℓℓ)H: BR(H→inv.) < 8% with E_T^{miss}>190 GeV ATL-PHYS-PUB-2013-014
  - (Back of envelope) combination ATLAS/CMS in VBF, Z(→ℓℓ) channel: BR(H→inv.) < 2.5% CERN-2019-007

CMS-FTR-18-016

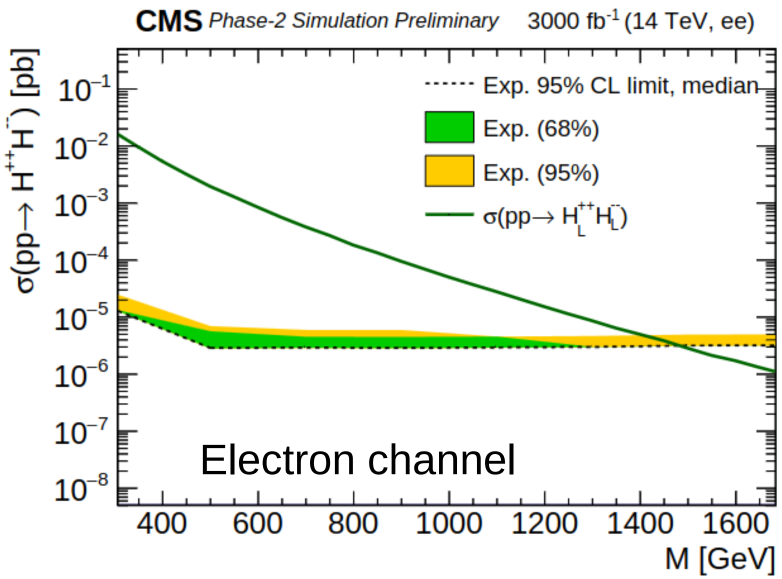


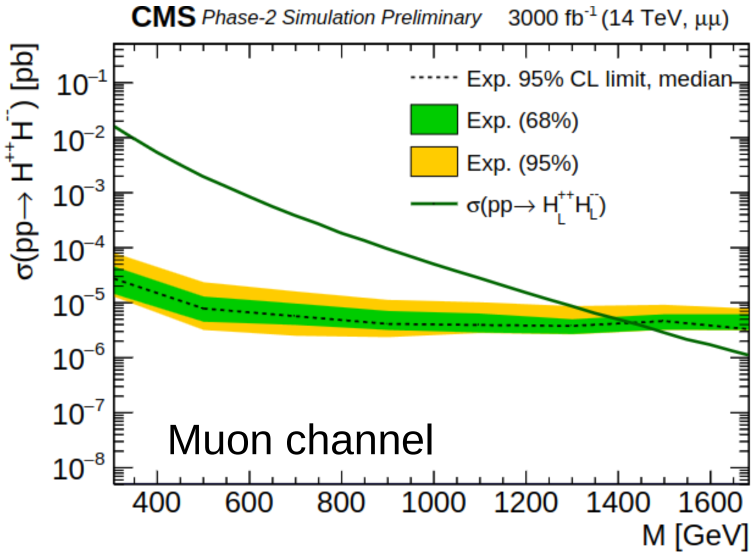
Doubly charged Higgs

CMS-PAS-FTR-22-006



- Predicted by
  - Left-right symmetric (LRS) models, Higgs triplet models, little Higgs model, type-II see-saw models, etc
- Example: Search for $H_L^{\pm\pm}$ with $BR(H_L^{\pm\pm} \rightarrow 2\mu\ (2e)) = 100\%$ in LRSM
  - 4μ or 4e final state is nearly background-free, especially at large $H^{\pm\pm}$ mass
  - Expected exclusion: M < 1400 GeV (compared to 870 GeV in Run 2 Eur. Phys. J. C78 (2018) 199)





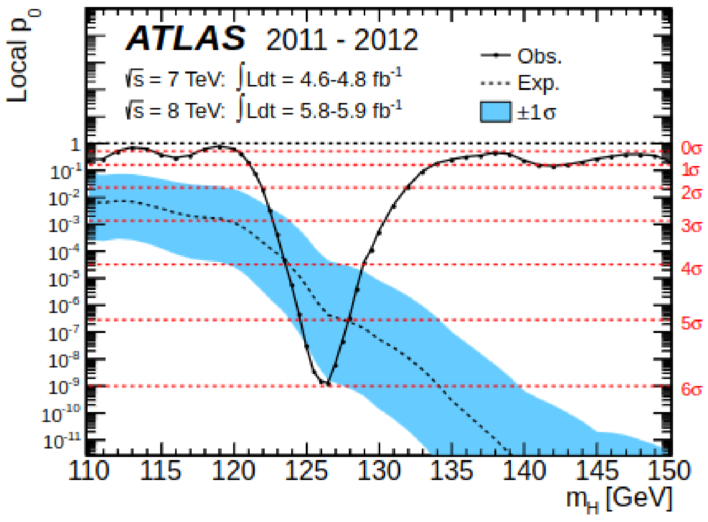
CMS-PAS-FTR-22-006

Conclusions

- Main goal: determination of Higgs boson properties, and their connection to electroweak symmetry breaking
- Higgs properties can be measured with high precision in all channels besides rare ones
- First direct constraints on the Higgs trilinear self-coupling and the natural width expected
- Direct and indirect searches for BSM physics will extend the current search reach into new territory, only showed few examples here for direct searches
- Many more results available in
  - CERN Yellow Report for European Strategy Update (2018-2020)
  - Snowmass White Paper (2020 – 2022)

We have come a long way...

- Performance we expected in ATLAS TDR (1999)
  - With 30 fb^{-1} of 14 TeV low lumi data: ~6σ significance for Higgs with m_H=125 GeV
- In 2012 using 4.8 fb^{-1} of $\sqrt{s}$=7 TeV data and 5.8 fb^{-1} of $\sqrt{s}$=8 TeV data
  - Higgs discovered by ATLAS with 5.9σ Phys.Lett. B716 (2012) 1-29
  - ~3 times less statistics and cross sections ~3 times lower
  - Improvement of O(10) to what we expected in TDR
- Continuously improving our analyses methods and object performances



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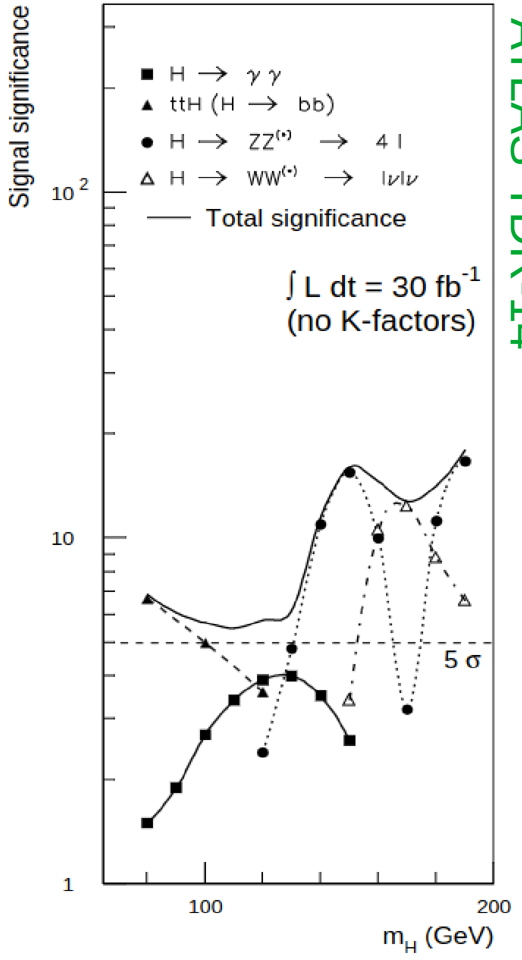
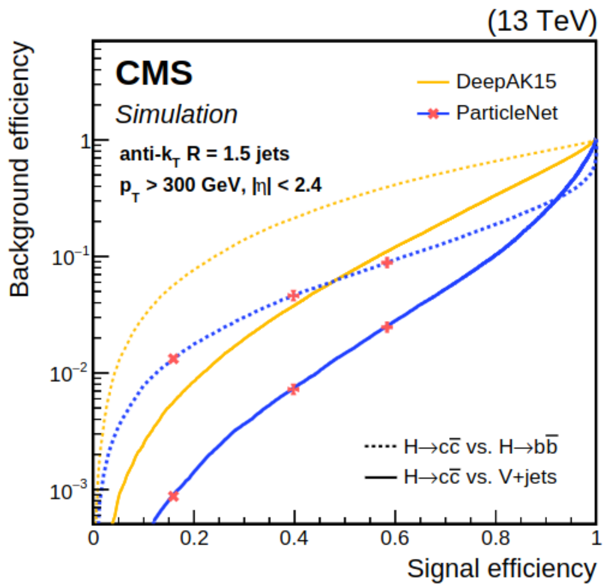


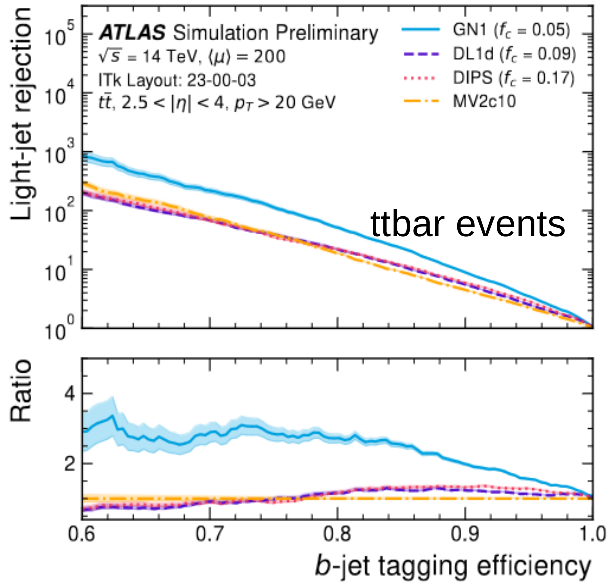
ATLAS-TDR-14

Outlook

- Example: neural networks are now becoming very powerful
  - Will improved the reconstruction/identification of physics objects and yield better background rejections for given efficiency



CMS
VH→ℓℓ'cc
Look for 2 c-jets in ΔR=0.8 jets using graph neural network (DeepAK15)
CMS-HIG-21-008



ATLAS
b-jet tagging improvements using graph neural network (GN1)
ATL-PHYS-PUB-2022-047

- Higgs results expected to be better at the time of HL-LHC than the projections shown in this talk

Backup

Documentation

- CERN Yellow Report for European Strategy Update (2018-2020)
- Snowmass White Paper (2020 – 2022)
- ATLAS public results
- CMS public results