Physics prospects for HL-LHC

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*on behalf of the ATLAS
and CMS collaborations*

LFC22 Trento
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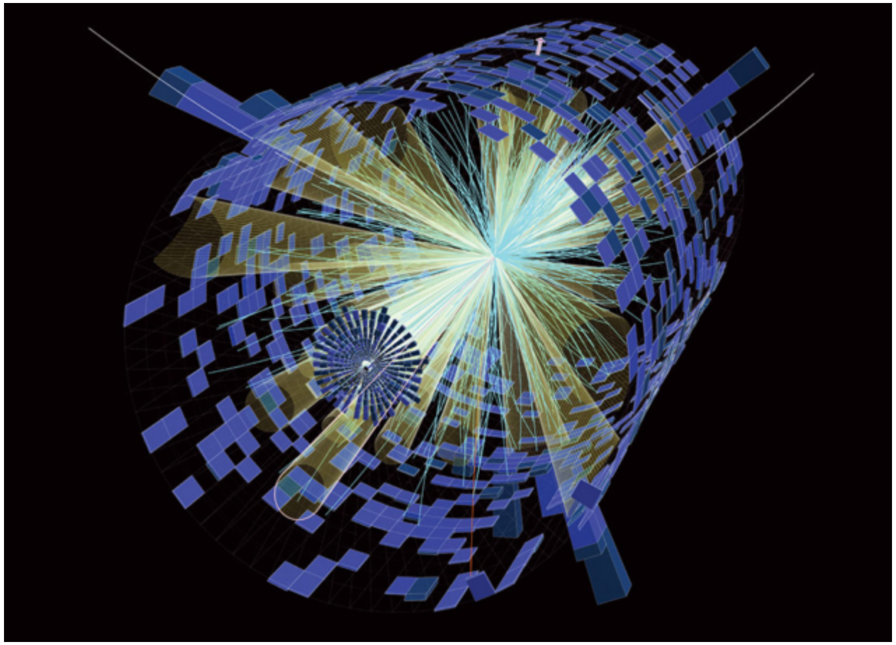
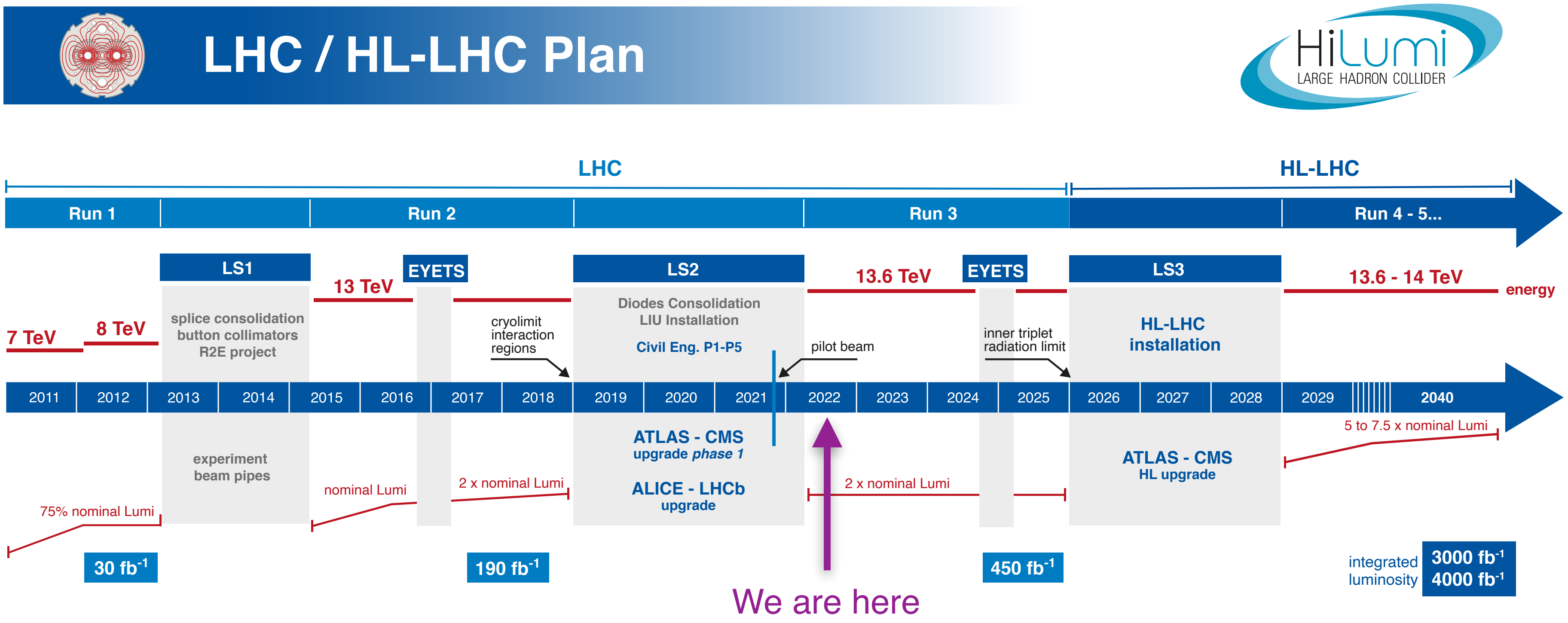


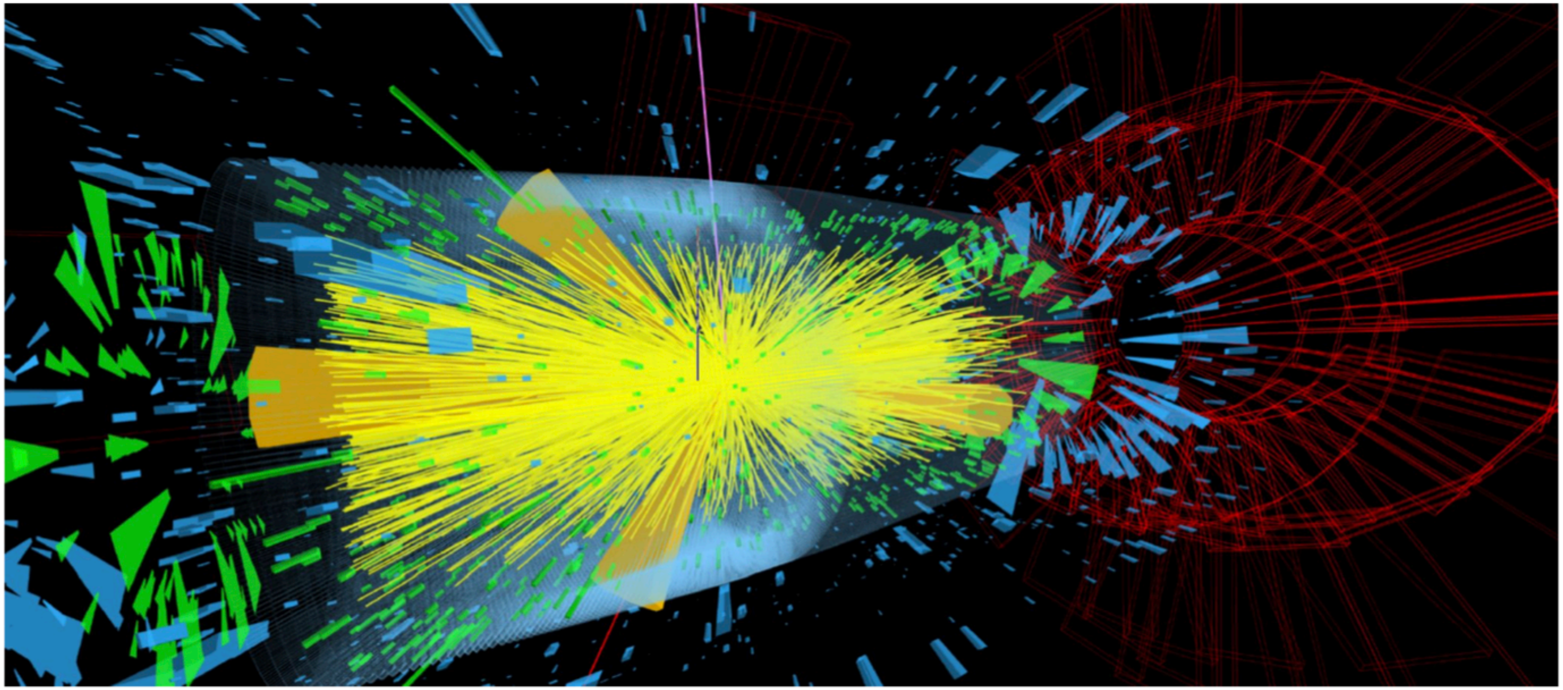
HL-LHC timeline



- **Run 3 just starting:** ATLAS and CMS datasets ~ x2 by 2025

- **Major boost in statistics expected with HL-LHC data-taking from 2029:**
  - 5-7.5x nominal instantaneous luminosity, <μ> = 140-200
  - integrated luminosity up to 4000 fb^{-1}, Run 1-3 dataset ~ 10% of total HL-LHC dataset

HL-LHC challenges



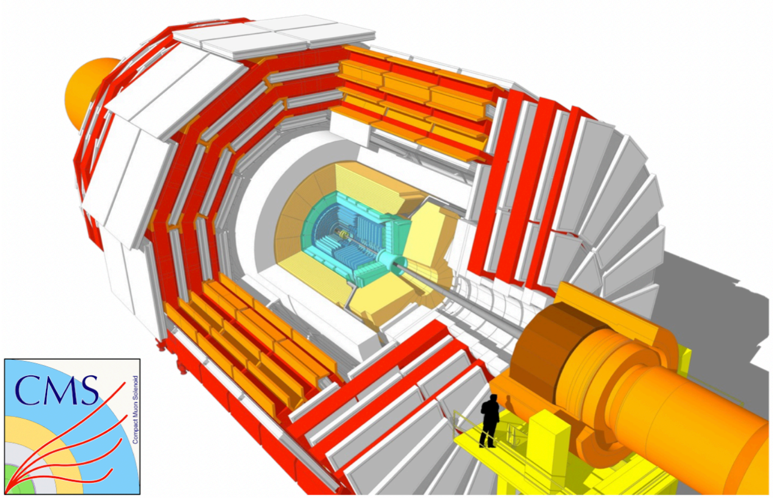
Simulated VBF H→ττ event in CMS (with pileup 200)

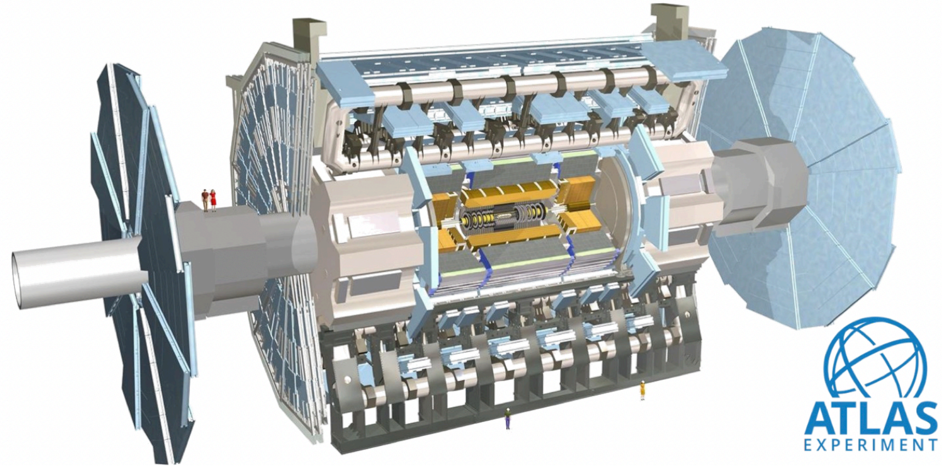
- **High luminosity + PU conditions particularly challenging for data-taking:** detector irradiation, higher occupancy, higher trigger rates

- **Require improvements for experiments in all areas:**
  - detectors themselves
  - trigger menu and hardware
  - object reconstruction
  - software & computing
  - physics analysis techniques

Detector upgrades

- **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 $|\eta|<4$
  - **new timing detectors** with central + forward / forward coverage
  - **improved muon coverage and trigger** in forward region
  - **upgraded electronics** for existing calorimeters + muon detectors
  - **new endcap high-granularity calorimeter**
- Aim at guaranteeing **equivalent** or better **performance as during Run 1-3:** assumption used in most physics projection results for HL-LHC



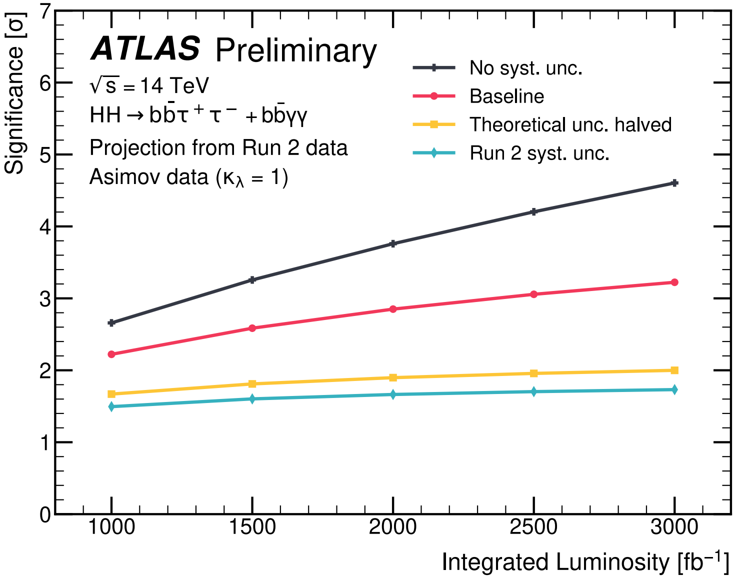


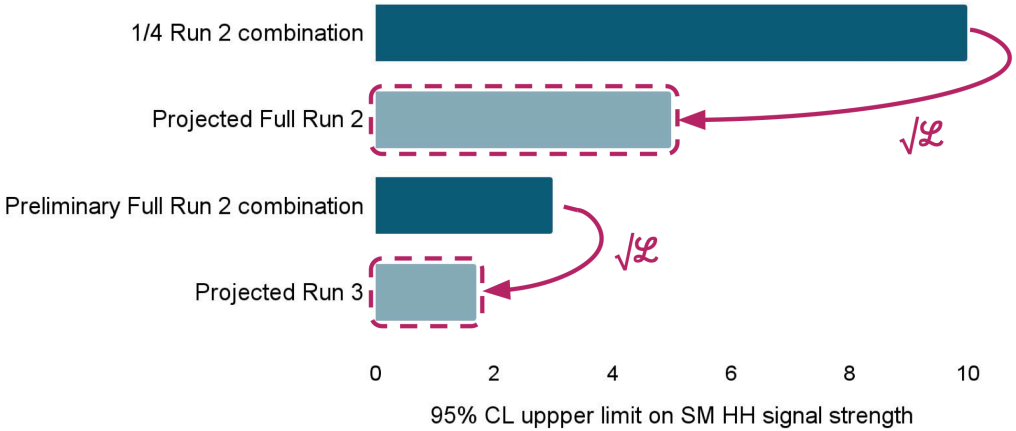
HL-LHC projections

- **Opportunity for ATLAS and CMS to update HL-LHC physics projections in Snowmass White Paper contribution** following last HL-LHC Yellow Report (2018)

- Increasing amount of measurements will be **limited by systematic uncertainties** with growing HL-LHC dataset

- Effort to determine **realistic estimates of uncertainties for physics projections for HL-LHC:**
  - **statistical uncertainty scaled as 1/√L**
  - **theory reduced by factor 2**
  - no MC stat. uncertainty
  - **most experimental uncertainties scaled as 1/√L**





- Previous experience shown that **knowledge gained with increasing datasets** can significantly improve reconstruction and analysis techniques

E. Brost - Higgs@10 Symposium

Higgs physics

Higgs properties

- **Most couplings measurements expected to be limited by theory uncertainties with HL-LHC datasets:** precision < 4%

- **H→μμ and H→Zɣ still limited by stat. uncertainty**

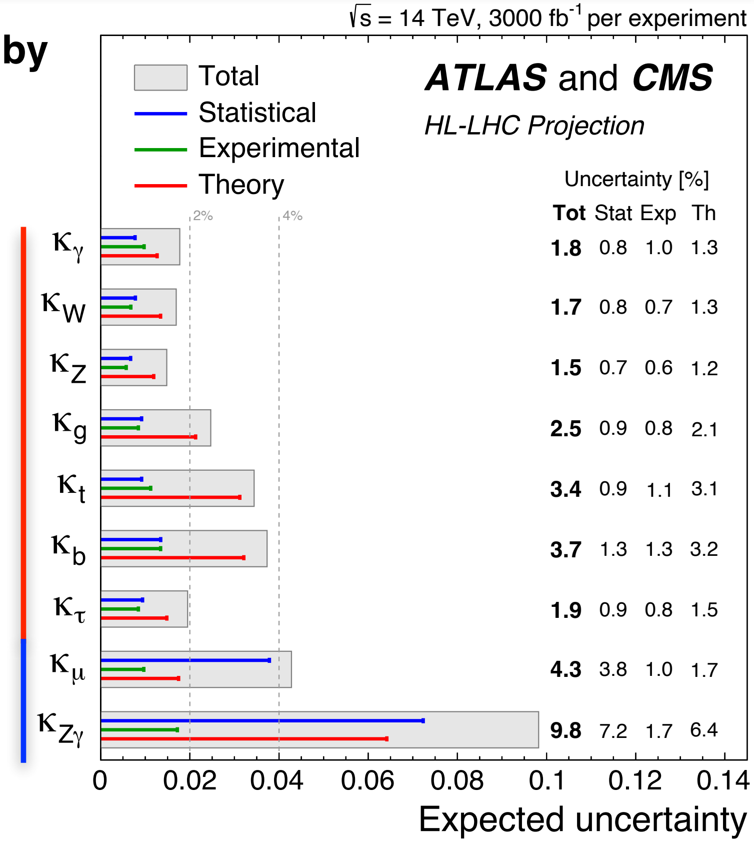
- **Precision on mass measurement + width also limited by systematics:**

  H→ɣɣ: $m_H = 125.38 \pm 0.02$ (stat.) ± 0.07 (sys.) GeV

  H→4l: $m_H = 125.38 \pm 0.02$ (stat.) ± 0.02 (sys.) GeV

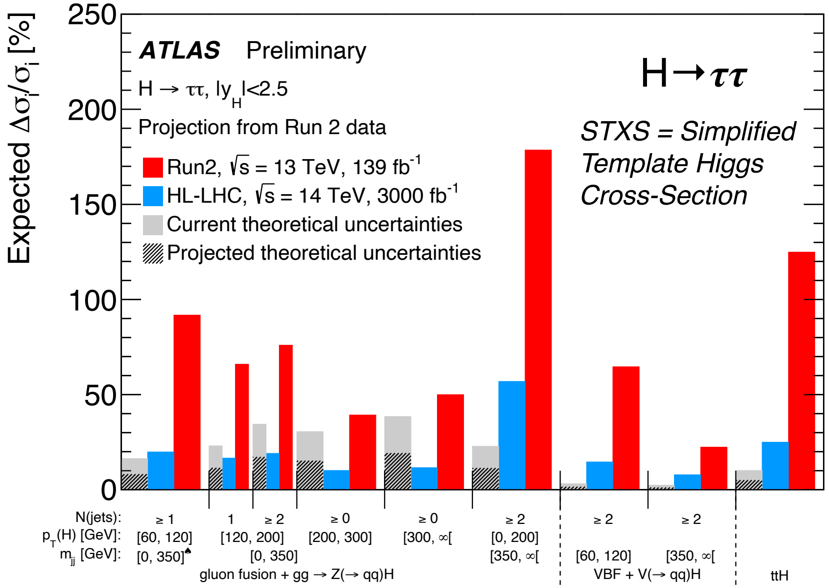
  $\Gamma_H < 177$ MeV from direct measurement

  CMS-PAS-FTR-21-007 + CMS-PAS-FTR-21-008



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4



H→ττ

STXS = Simplified Template Higgs Cross-Section

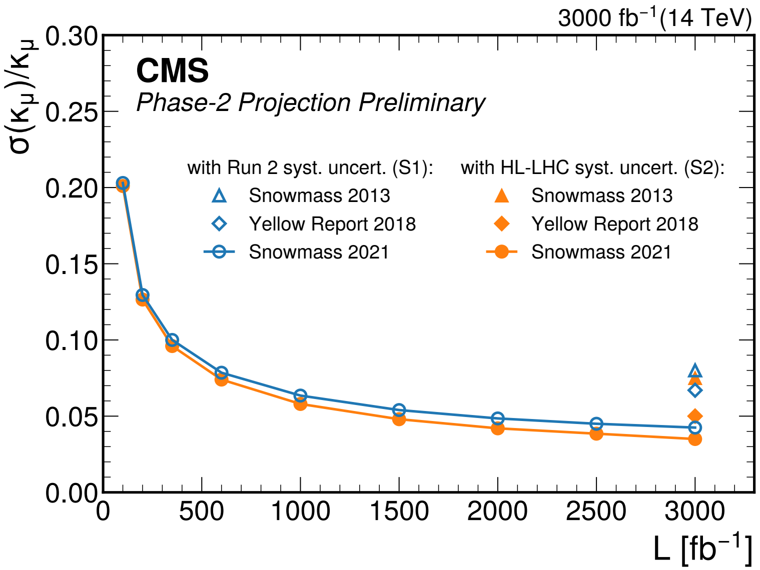
- **STXS measurements also studied** with Run 2 categories: **systematics dominated** except at high $p_T(H)$ or for subdominant production modes

  => STXS binning expected to evolve to optimally exploit large statistics available with HL-LHC dataset

ATL-PHYS-PUB-2021-039 + ATL-PHYS-PUB-2022-003

Higgs couplings to 2nd gen. fermions

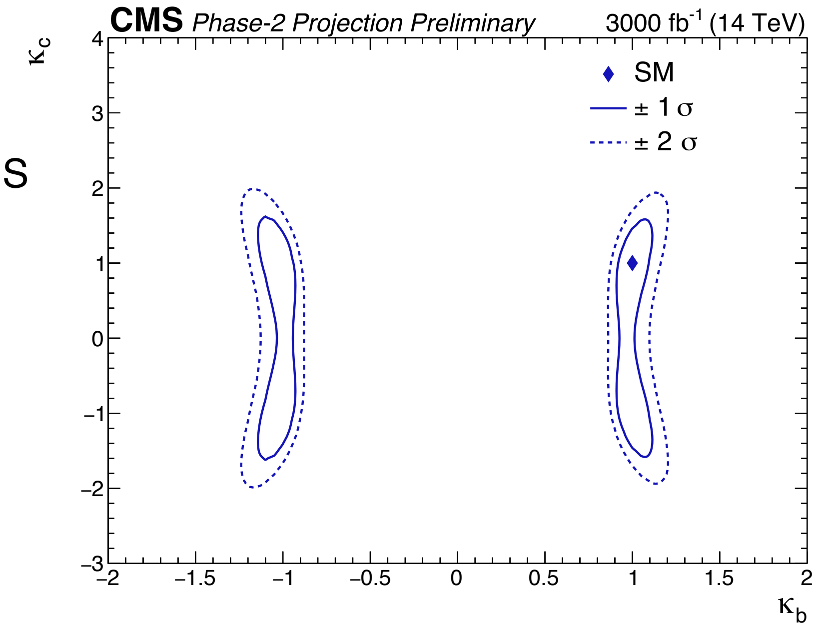
- **Very interesting prospects to probe Yukawa couplings to 2nd generation fermions**



- **Update of CMS H→μμ projection:**
  - takes into account improved acceptance + mass resolution with Phase-2 detector

=> uncertainty reduced from 5% with YR18 down to **3.5% with updated result**

CMS-PAS-FTR-21-006



- **Update on H→cc projections:**
  - sizeable boost in sensitivity achieved in CMS projection thanks to boosted category

ATLAS: μ(VH, H→cc) = 1.0 ± 2.0 (stat.) ± 2.5 (syst.)
CMS: μ(VH, H→cc) = 1.0 ± 0.6 (stat.) ± 0.5 (syst.)

=> direct measurement within reach at HL-LHC!

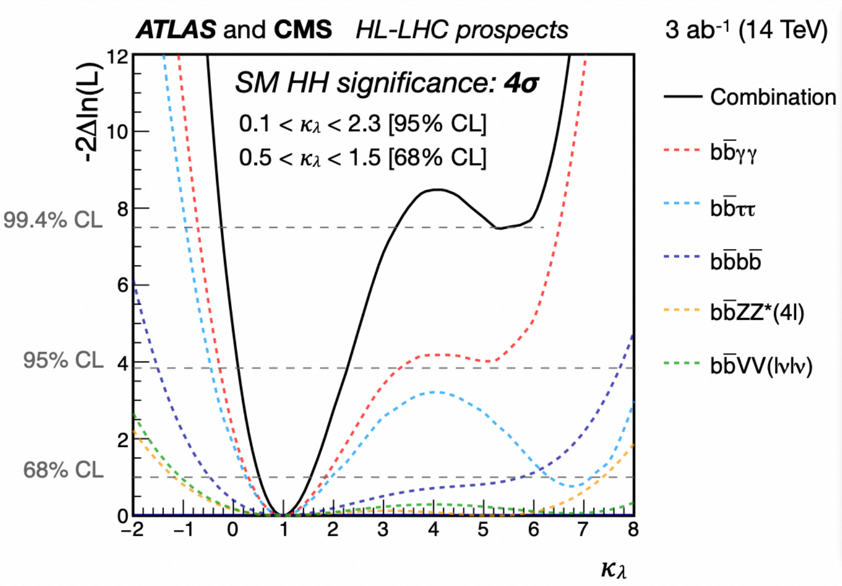
ATL-PHYS-PUB-2021-039 + CMS-HIG-21-008

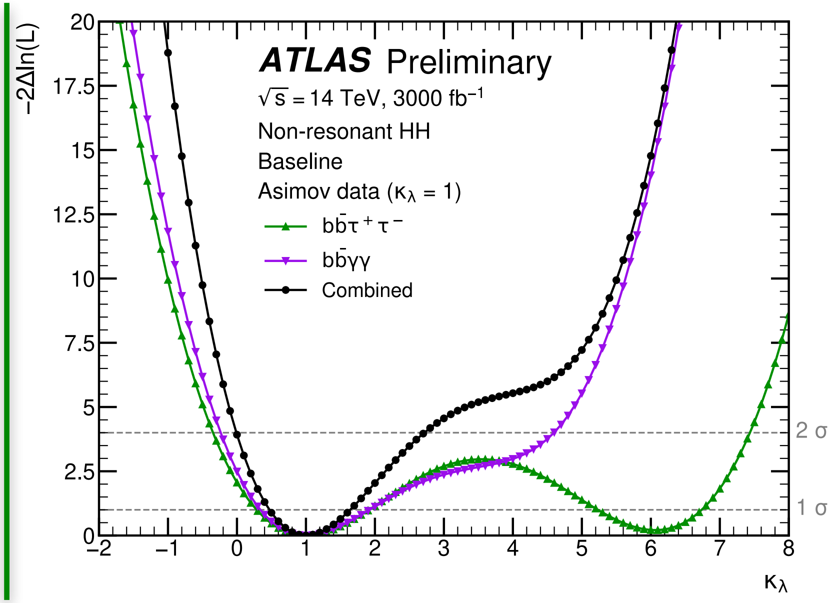
Higgs self-coupling

- Measurement of Higgs self-coupling important HL-LHC target to **improve our understanding of Higgs potential and EWSB**

- **Main sensitivity from HH production** but single-Higgs measurements can also contribute to measurement

- **ATLAS+CMS combination of several HH channels for YR18**: 4σ significance for HH process, 50% uncertainty on κ_λ





ATL-PHYS-PUB-2022-005

- **Recent updates on ATLAS bbγγ+bbττ projections** + other CMS individual channels
  - 3.2σ significance on those two ATLAS channels alone

    => 5σ observation possible with full ATLAS+CMS combination

- **This HL-LHC κ_λ measurement will likely stay the most precise for many years** until ee collider runs above HH thresholds or new hadron colliders

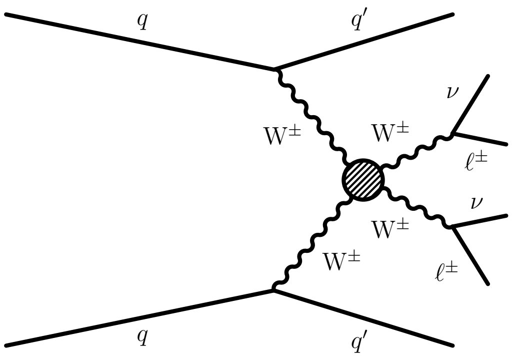
Standard Model

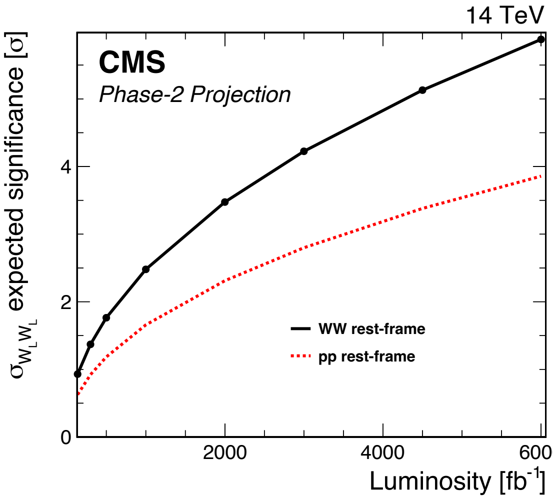
Electroweak physics

- **Vector Boson Scattering (VBS) observations recently reported by ATLAS and CMS**

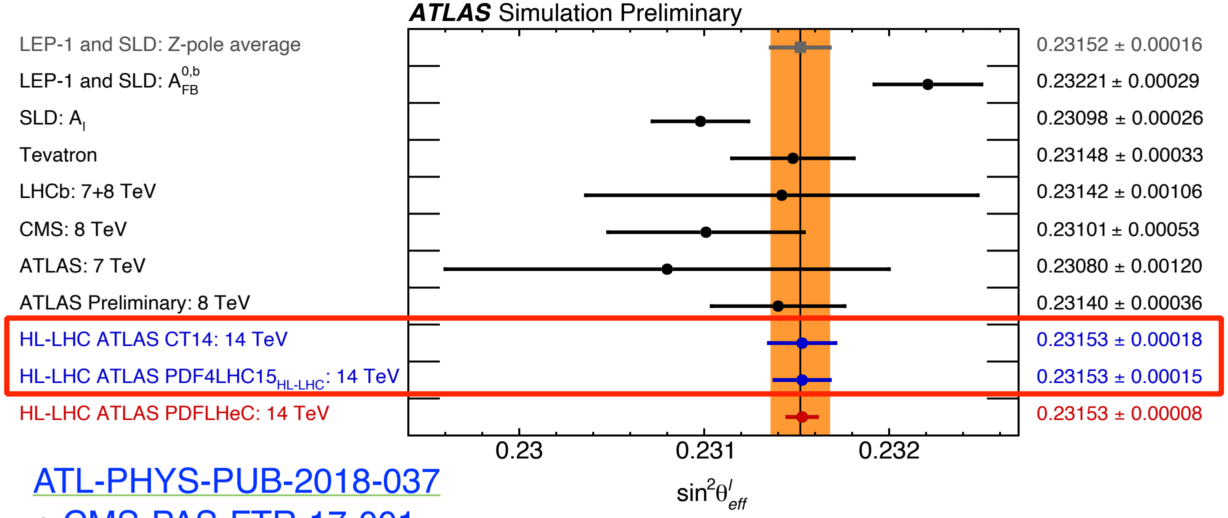
- Processes quite sensitive to BSM effects, in particular for **longitudinally polarised V_LV_L scattering** unitarised by Higgs diagrams in SM (6-7% of inclusive cross-section)

- **Projection studies for various final states** (multilepton channels most sensitive): **5σ observation of V_LV_L scattering** expected with ATLAS-CMS combination





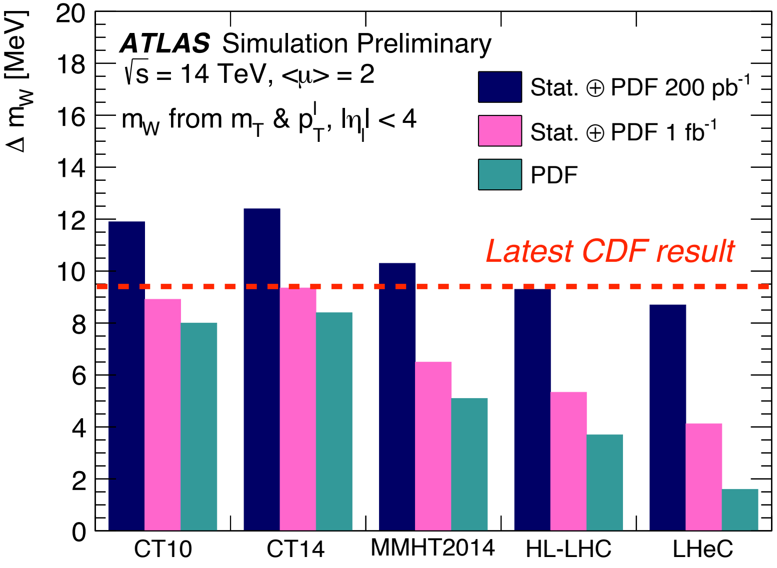
CMS-PAS-FTR-21-001



ATL-PHYS-PUB-2018-037
+ CMS-PAS-FTR-17-001

- **$\sin^2\theta_{eff}$ precision measurement** to be performed using **forward-backward asymmetry in Drell-Yan** dilepton events: benefits from improved forward lepton reconstruction + statistics
  => better precision than individual LEP-1 and SLD measurements (3σ discrepancy)

W and top mass measurements



ATL-PHYS-PUB-2018-026

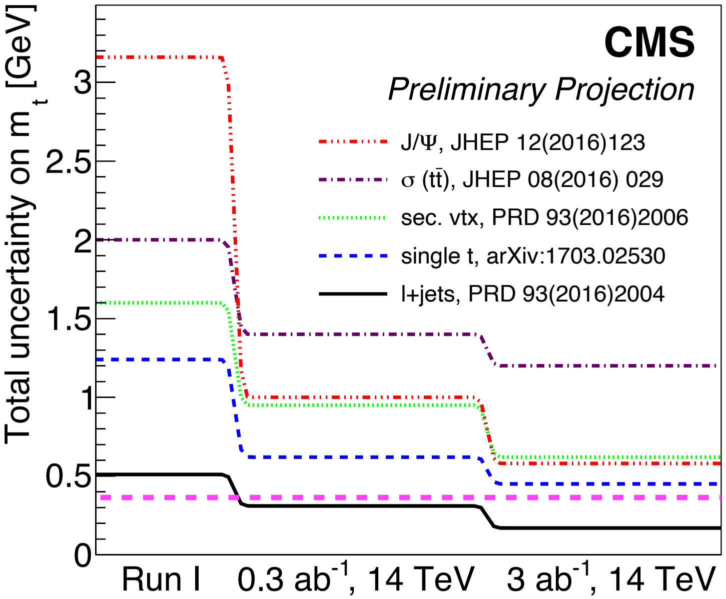
- Top, W and Higgs masses connected through loop corrections: **accurate measurements provide stringent of the SM**

- **W mass measurement at low μ will benefit from:**
  - extended tracking coverage: -25% uncertainty
  - improved PDF precision: -50% on PDF systematic
  - larger dataset: 200 pb^{-1} per week at <μ>=2

=> with 200 pb^{-1} precision of 8.6 (stat) + 3.7 (PDF syst) = 9.3 MeV / 5 MeV with 1 fb^{-1}

- Various techniques investigated for **top mass measurements**:
  - **l+jets** expected to yield most precise result with **0.17 GeV uncertainty**
  - **σ(tt)** less precise but gives access to mt in a well-defined renormalisation scheme
  - **additional methods** expected to improve further precision in a combination

CMS-PAS-FTR-16-006



Latest CMS result 0.38 GeV

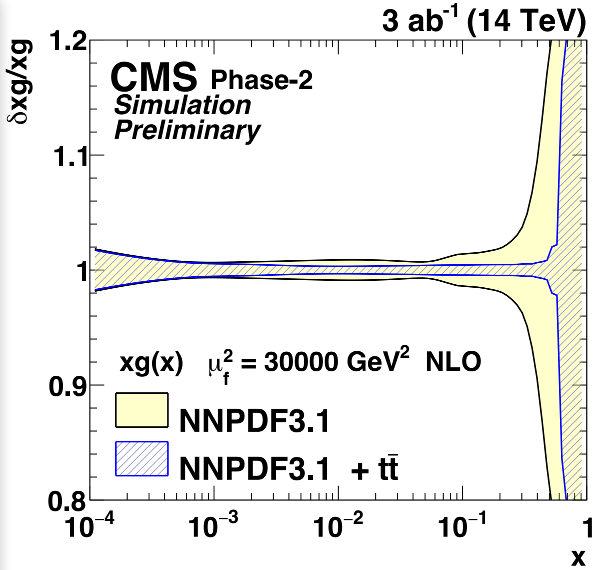
CMS-PAS-TOP-20-008

Top physics

- **All top measurements will directly benefit from:**
  - improved JES + b-tagging experimental systematics
  - extended η coverage

- **Differential cross-section** fine-binned measurements

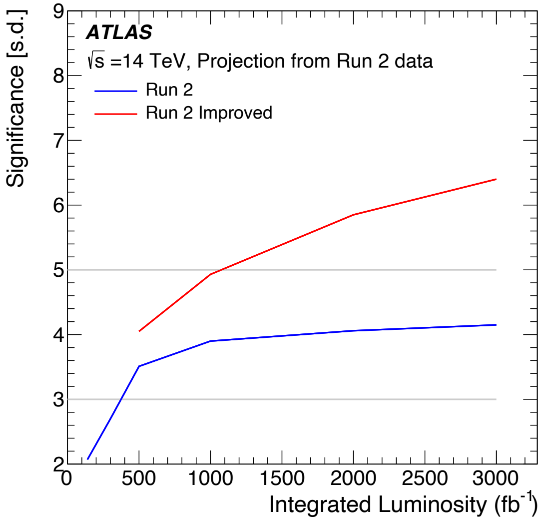
- Direct improvement on **precision of gluon PDFs**



CMS-PAS-FTR-18-015

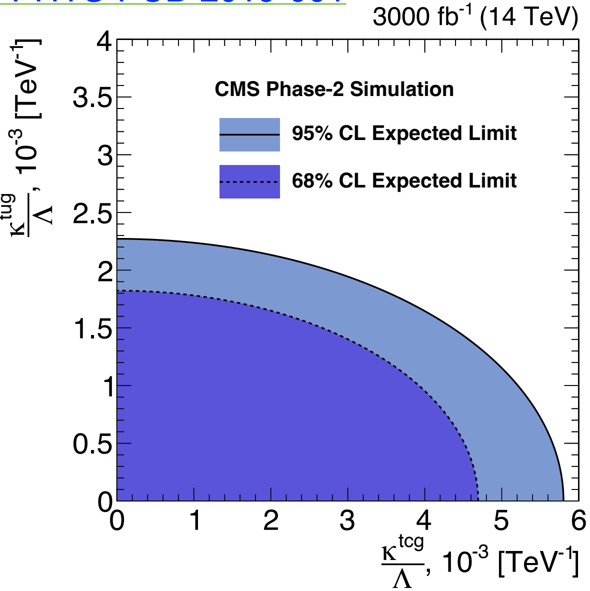
- Study of rare processes w/ cross-sections down to O(10) fb: tt+V, **4-tops**

- Can be exploited to **constrain EFT operators**



ATL-PHYS-PUB-2022-004 + CMS-PAS-FTR-18-031

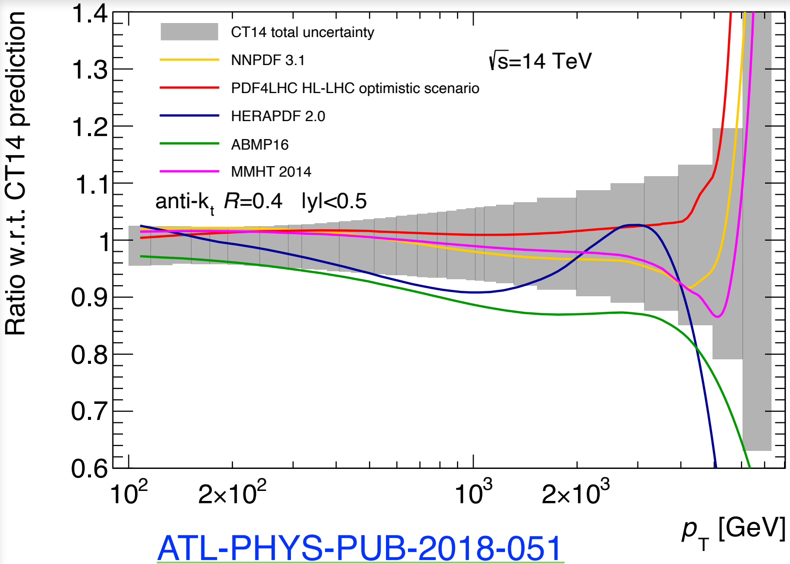
CMS-PAS-FTR-18-004 + ATL-PHYS-PUB-2019-001



- Constrains on **BSM FCNC operators** through top decays: tqZ, **tqg**
  - B(t→uZ) < 4.6 x 10^{-5}
  - B(t→cZ) < 5.5 x 10^{-5}
  - B(t→ug) < 3.8 x 10^{-6}
  - B(t→cg) < 3.2 x 10^{-5}

- Improvements by 1 order of magnitude expected wrt current BSM branching ratios constraints

QCD physics

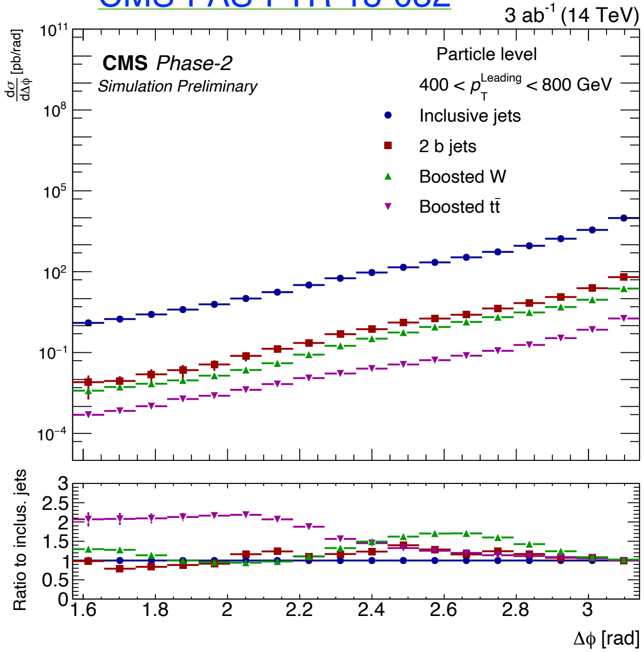


ATL-PHYS-PUB-2018-051

- **Significant increase in reach of differential QCD measurements** expected with HL-LHC dataset:
  - single-jet p_T 3.5 → 5 TeV
  - dijet m_{jj} 9 → 11.5 TeV
  - γ+jet $E_T(\gamma)$, p_T(jet) 1.5→ 3.5 TeV, m(γ+jet) 3.3→ 7 TeV

- Large differences between various PDF predictions at high pT **=> strong impact of HL-LHC measurements improve determination of proton PDFs**

CMS-PAS-FTR-18-032

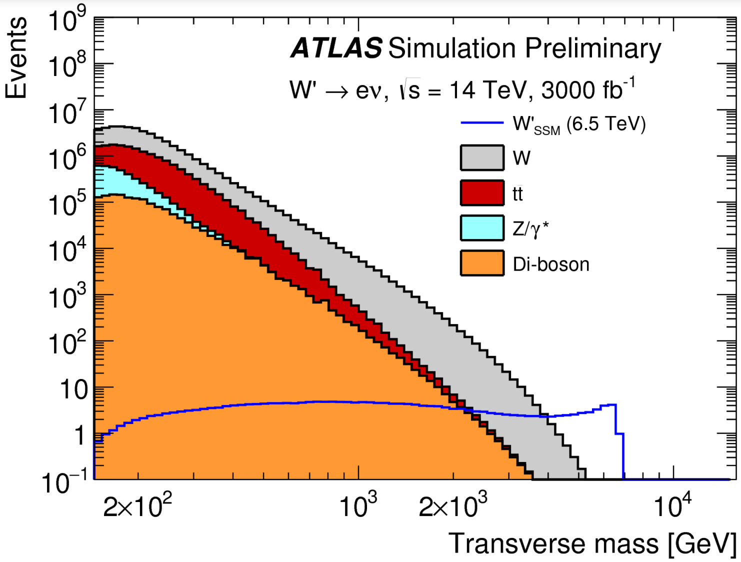


- **High-pT jet measurements** also considered separately for **various boosted object flavours:** strongly relying on b-tagging + boosted W-top tagging performance
  => expected reach up to p_T ~ 3 / 2.5 / 2 TeV for b / W / top

- **Angular correlations** also sensitive to **colour connection**
  => measurements can help **improving computations of soft gluon resummation**

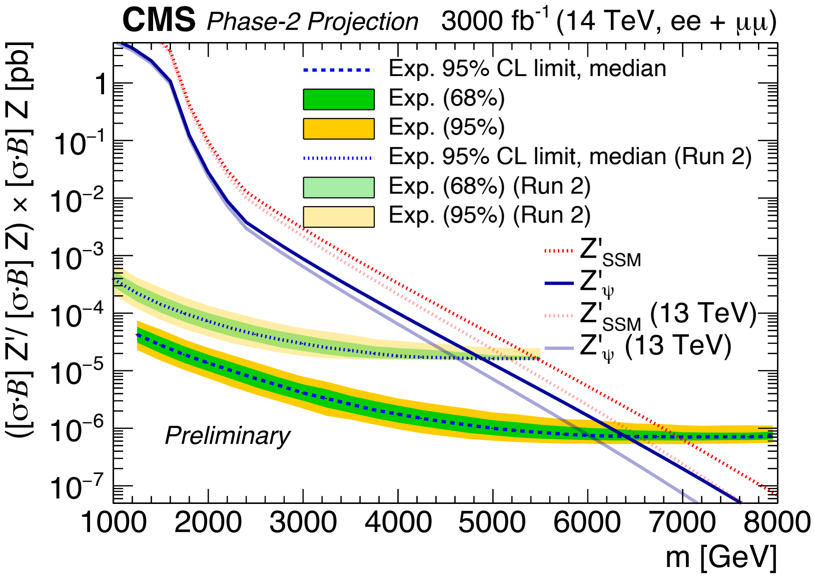
Beyond the Standard Model

BSM resonance searches



- **Many BSM models predict heavy resonances manifesting as bump in tail of mass spectrum:** heavy gauge bosons, excited leptons, Majorana neutrinos…
- **Leptonic channels typically exhibit best sensitivity:** often rely on dedicated lepton reco. / identification
- **HL-LHC will increase reach of searches to weaker couplings and higher masses** (≳ 6TeVs)

Model	***Run-2 exclusion***	***HL-LHC exclusion***
Excited lepton** $\ell\ell\gamma$ **[1]	*3.8-3.9 TeV*	*5.8 TeV*
Heavy Majorana neutrino** $\ell\ell$**qq [2]	*4.6-4.7 TeV*	*8 TeV*
RS gluon tt [3]	*4.5 TeV*	*6.6 TeV*
W'_R tb [4]	*3.15 TeV*	*4.9 TeV*
SSM W' τ+MET [5]	*4.6 TeV*	*6.0 TeV*
SSM W' ℓ+MET [4]	*5.6 TeV*	*7.9 TeV*
SSM Z' $\ell\ell$ [4-7]	*5.1 TeV*	*6.8 TeV*



[1] CMS-PAS-FTR-18-029 + [2] 18-006 + + [3] 18-009 + [5] 18-030 + [7] 21-005 + [4] ATL-PHYS-PUB-2018-044

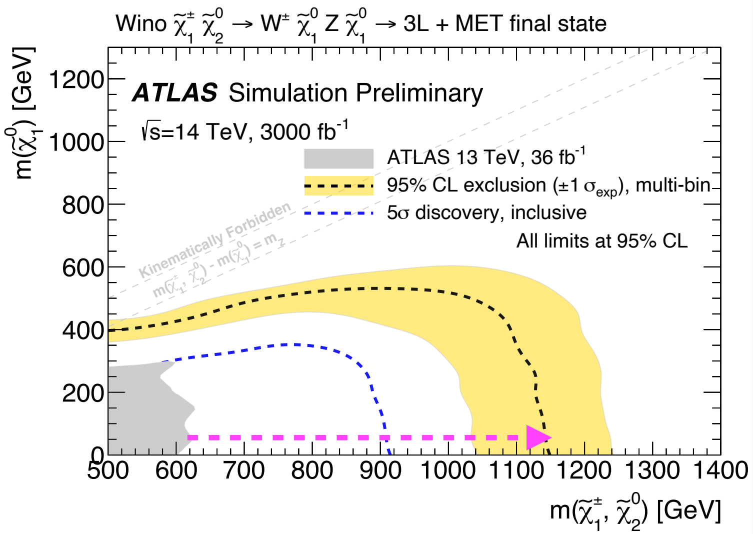
SUSY searches

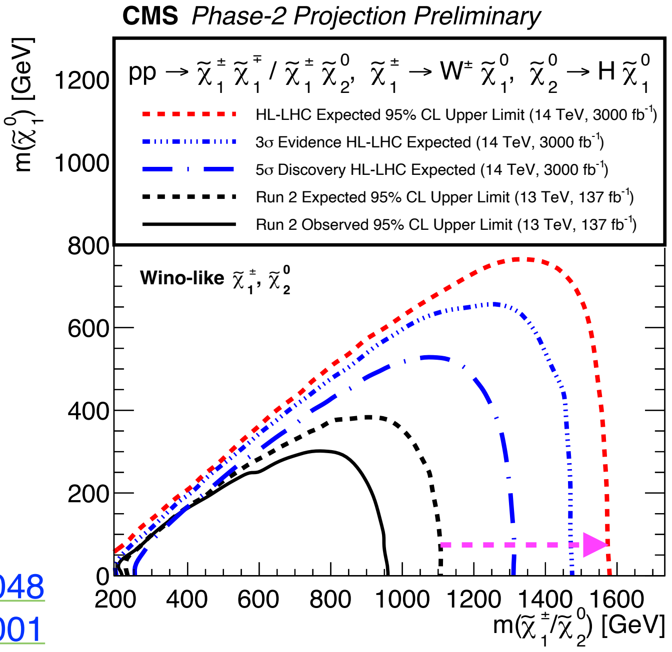
- **Strong SUSY production:** many scenarios already excluded up to 1 TeV

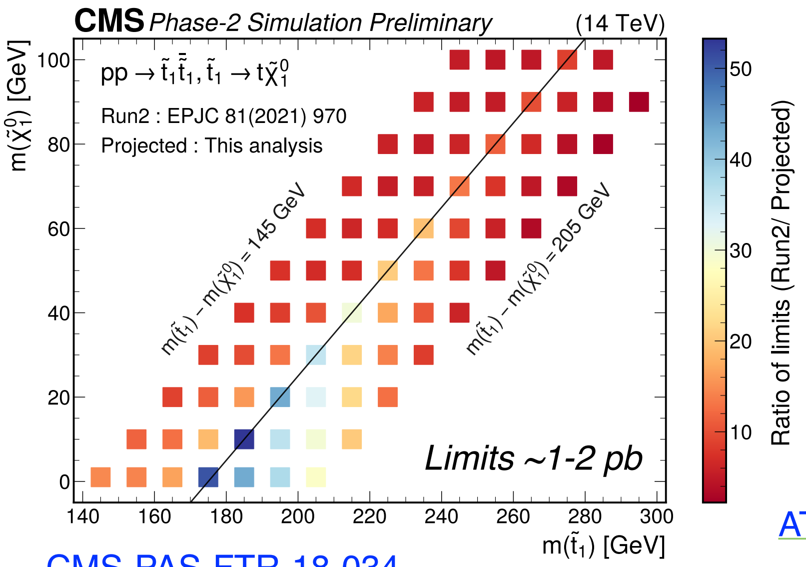
- **EWK SUSY production:** larger benefit from HL dataset due to smaller cross-sections

  => many final states to be probed, sensitivity extended by ~500 GeV for light LSP

- **Scenarios with compressed mass spectra** also particularly challenging but **use of dedicated analysis techniques** (top spin correlation, disappearing tracks…) can significantly boost existing limits





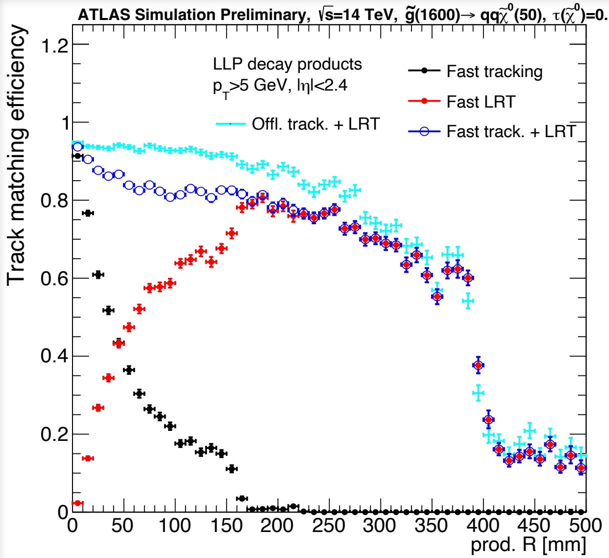


CMS-PAS-FTR-18-034

ATL-PHYS-PUB-2018-048

CMS-PAS-FTR-22-001

LLP searches



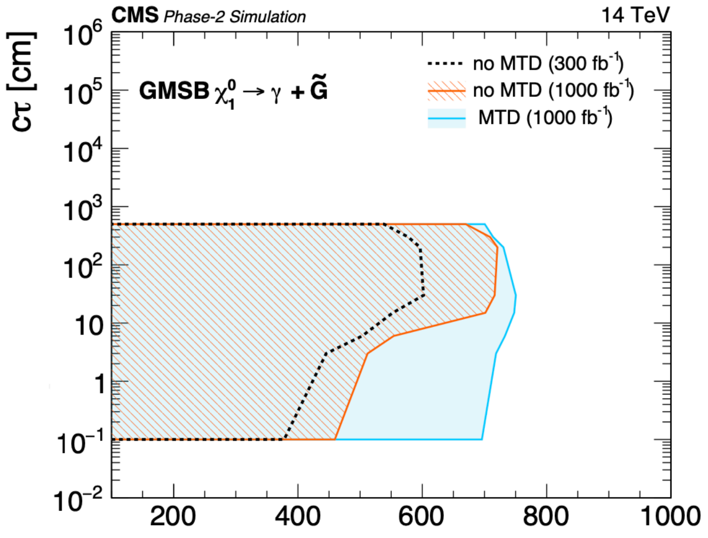
Offline reconstruction = default + LRT

Trigger reconstruction = default + LRT

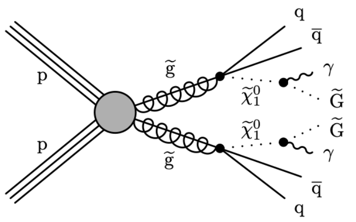
ATLAS-TDR-029-ADD-1

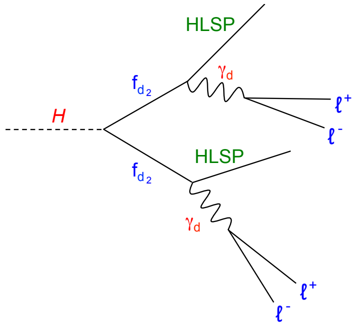
- **More and more models predict LLP**
- Standard reco. algo. tailored for reconstruction of prompt particles but new algo. developed during Run 2-3: **can be successfully adapted for HL-LHC detectors**
- **Phase-2 upgrades** (MTD, muon triggers) also opportunities to **exploit new capabilities for trigger and reco.**

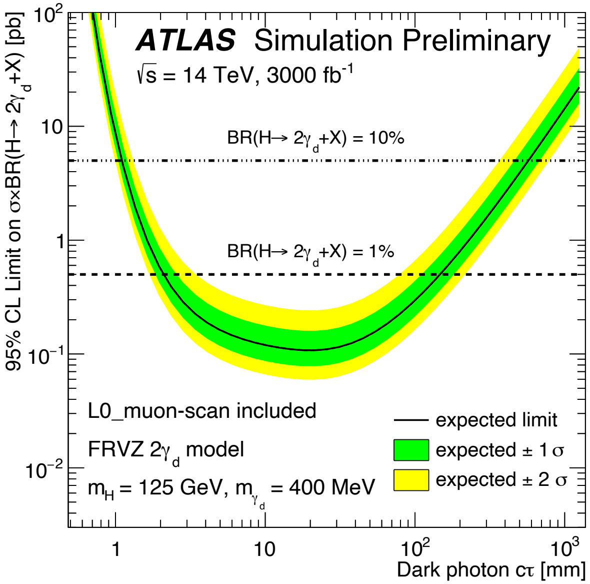
ATL-PHYS-PUB-2019-002



CMS-TDR-020



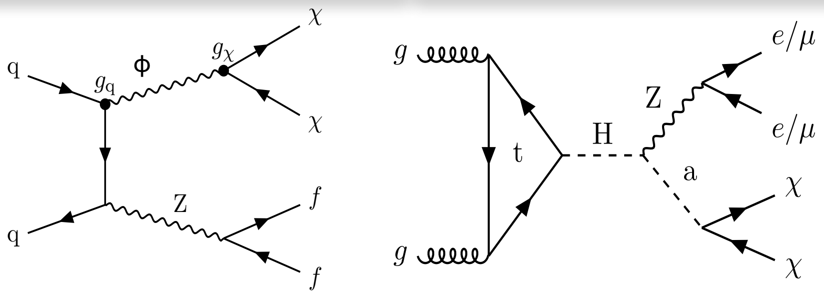




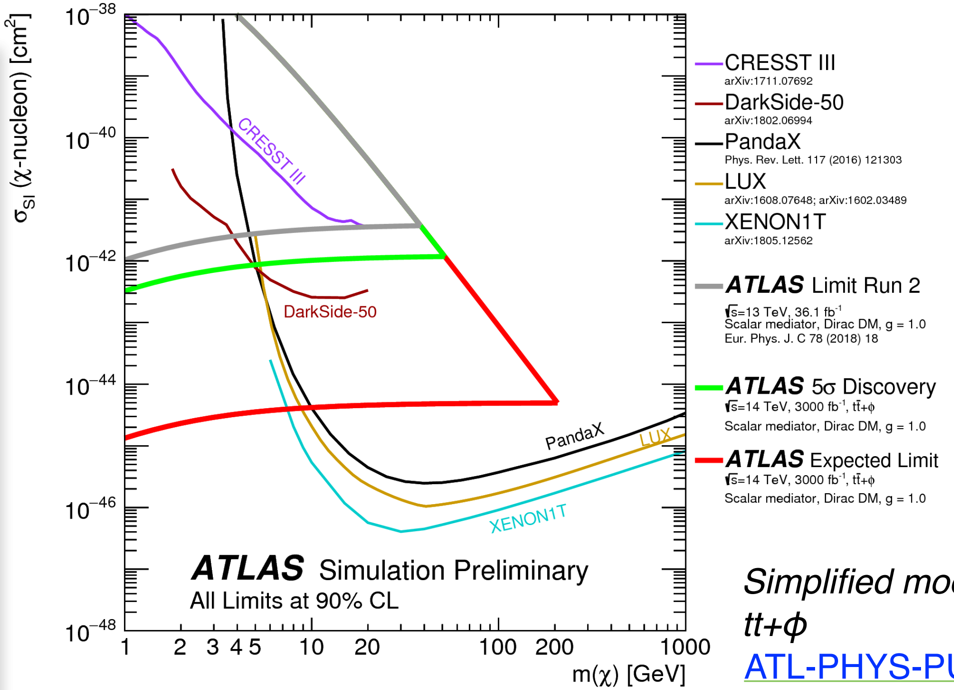
Dark matter searches

- **Search for associated production of DM with SM detectable particles** (e.g. mono-X, X=Z/H/top): look for excess in tail of MET or m_T distributions

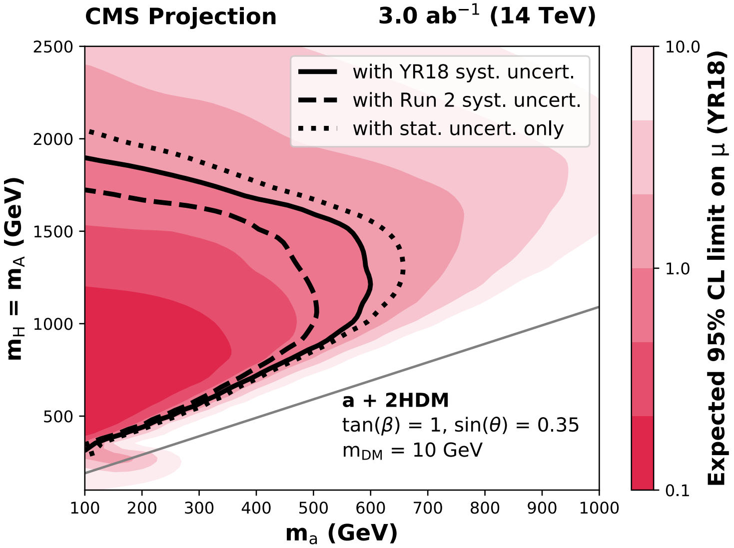
- Most interpretations in **simplified (ϕ→χχ)** or **2HDM+a models**: more than two parameters involved



- Sizeable improvements wrt Run 2 possible thanks to **increased dataset + improved systematics: complementary to direct detection experiments**



Simplified model
tt+ϕ
ATL-PHYS-PUB-2018-024



Mono-Z→ll
CMS-PAS-FTR-18-007

Conclusion

- **HL-LHC data-taking will represent an unprecedented challenge for ATLAS & CMS experiments:**
  - major detector upgrades
  - updated object reconstruction
  - huge amount of data to be analysed

  to be prepared in parallel to Run 3 data-taking

  => major effort from collaborations to make this a success

- **Sensitivity of HL-LHC analyses will definitely benefit from:**
  - large luminosity to be collected
  - improved systematic uncertainties
  - new trigger and reconstruction techniques possible thanks to detector upgrades

- **Extremely rich and exciting physics program ahead:**
  - **Higgs physics:** precise determination of Higgs properties, probing of small Higgs couplings
  - **Standard Model:** ultimate precision measurement of fundamental SM parameters, constraints on new physics through EFT interpretations
  - **Beyond Standard Model:** direct improvement in mass reach for many models, new analysis techniques can help close gaps in unexplored regions of phase space

  \+ **flavor physics + heavy-ion physics** (unfortunately not shown here for time constraints)

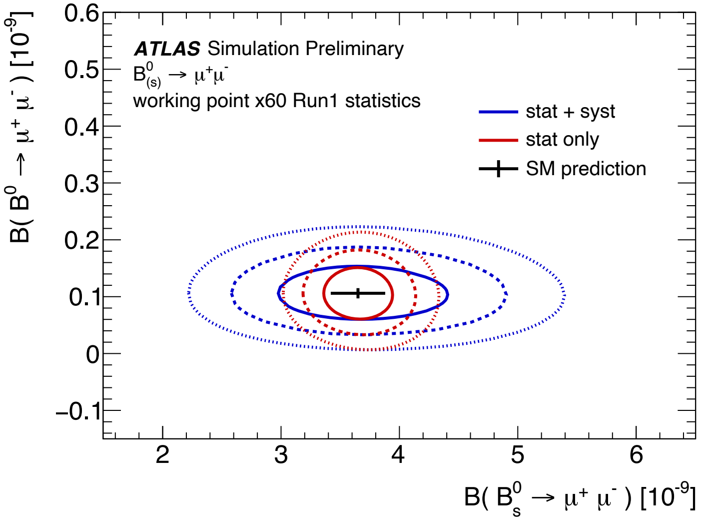
Back-up

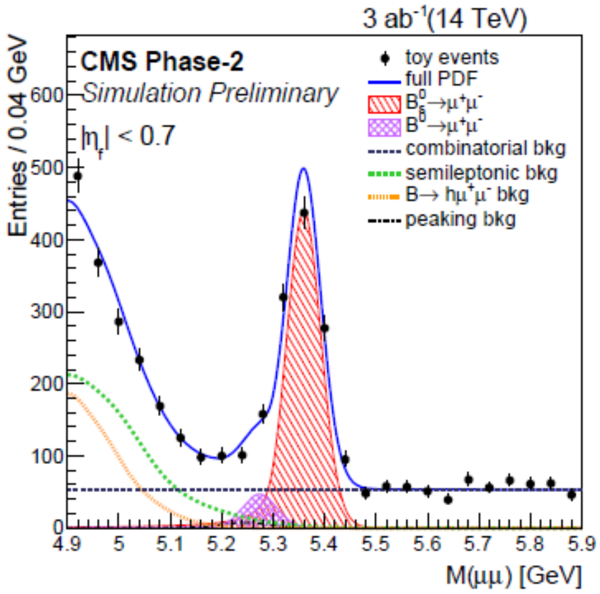
Flavor physics

Potential $B^0_d \to \mu\mu$ 5σ observation

ATL-PHYS-PUB-2018-005

[CMS-PAS-FTR-18-013](CMS-PAS-FTR-18-013)

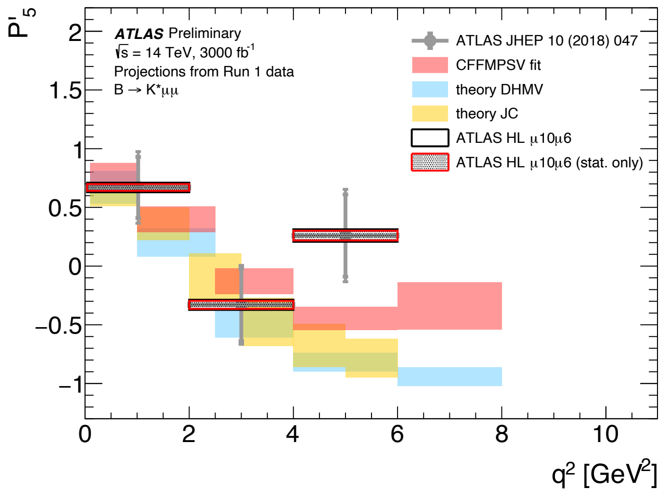


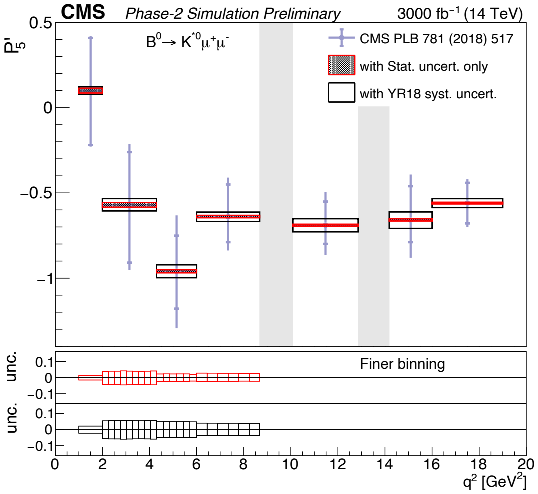


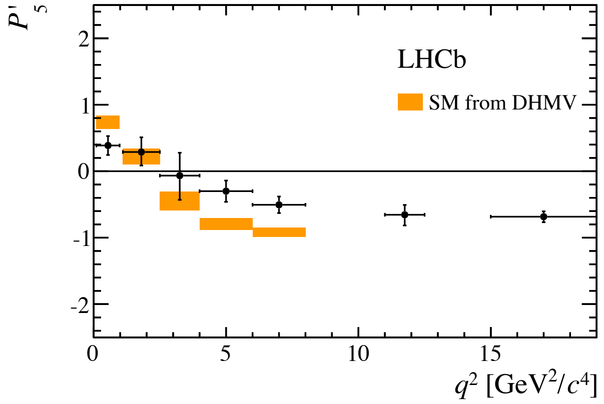
Improved precision for P'_5 measurement in $B^0 \to K^{*0}\mu\mu$

ATL-PHYS-PUB-2019-003

[CMS-PAS-FTR-18-033](CMS-PAS-FTR-18-033)







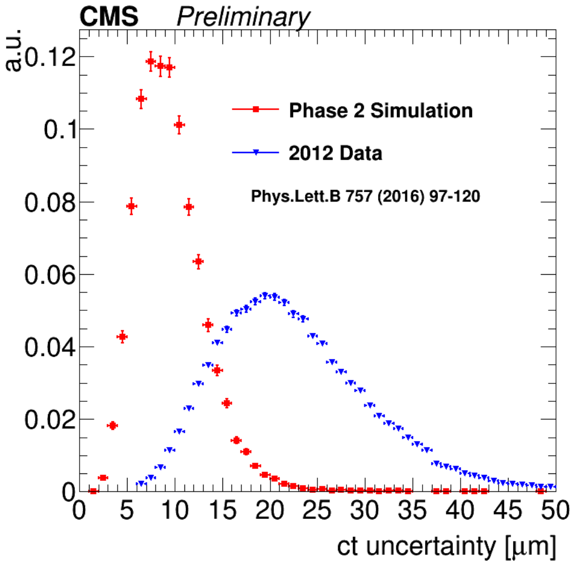
LHCb-PAPER-2015-051

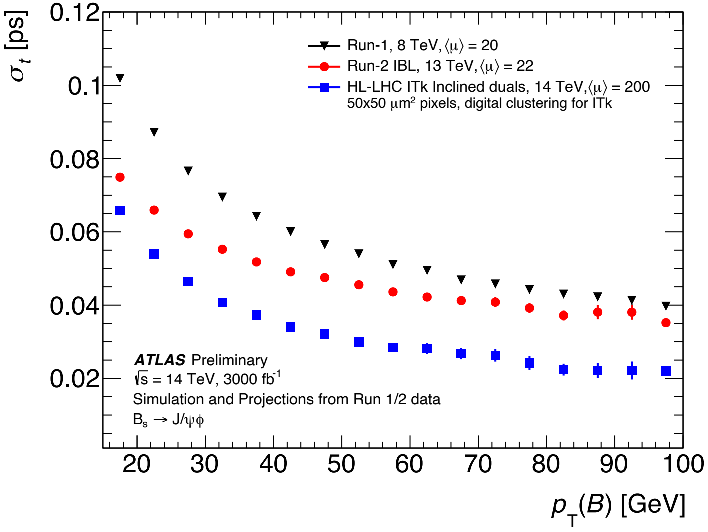
Flavor physics

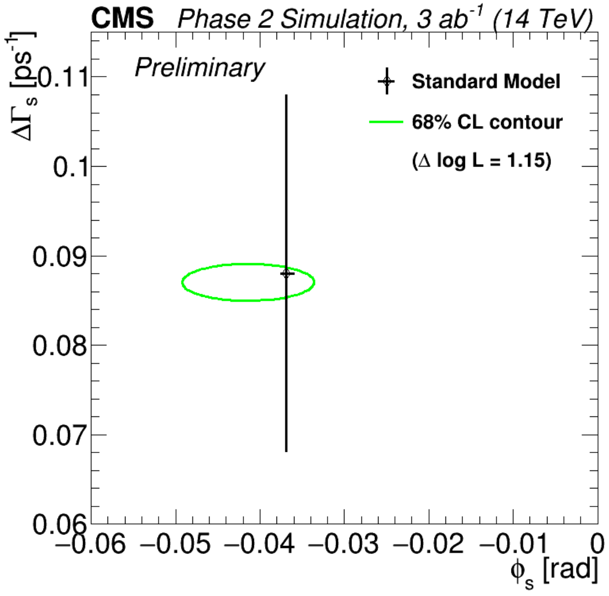
Improvement in CP-violating phase measurement from $B^0_s \to J/\psi\phi$ decays

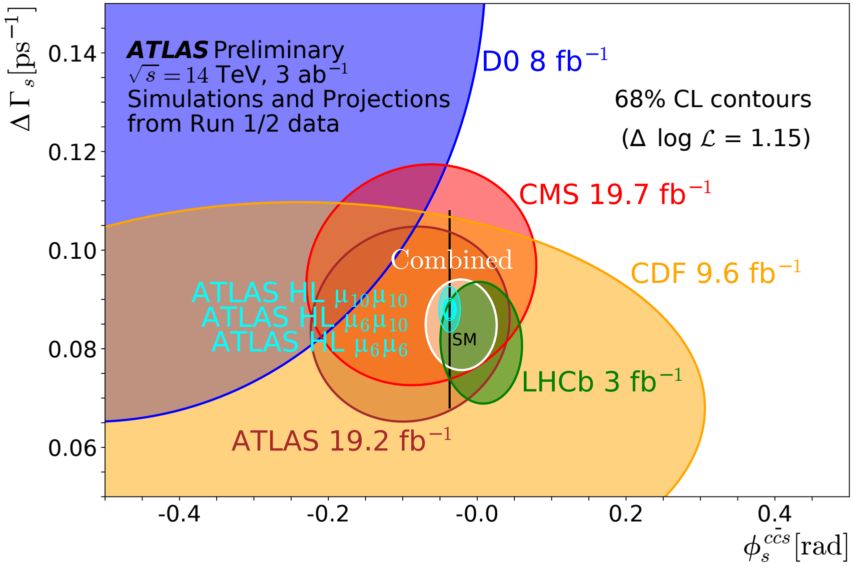
ATL-PHYS-PUB-2018-041

CMS-PAS-FTR-18-041

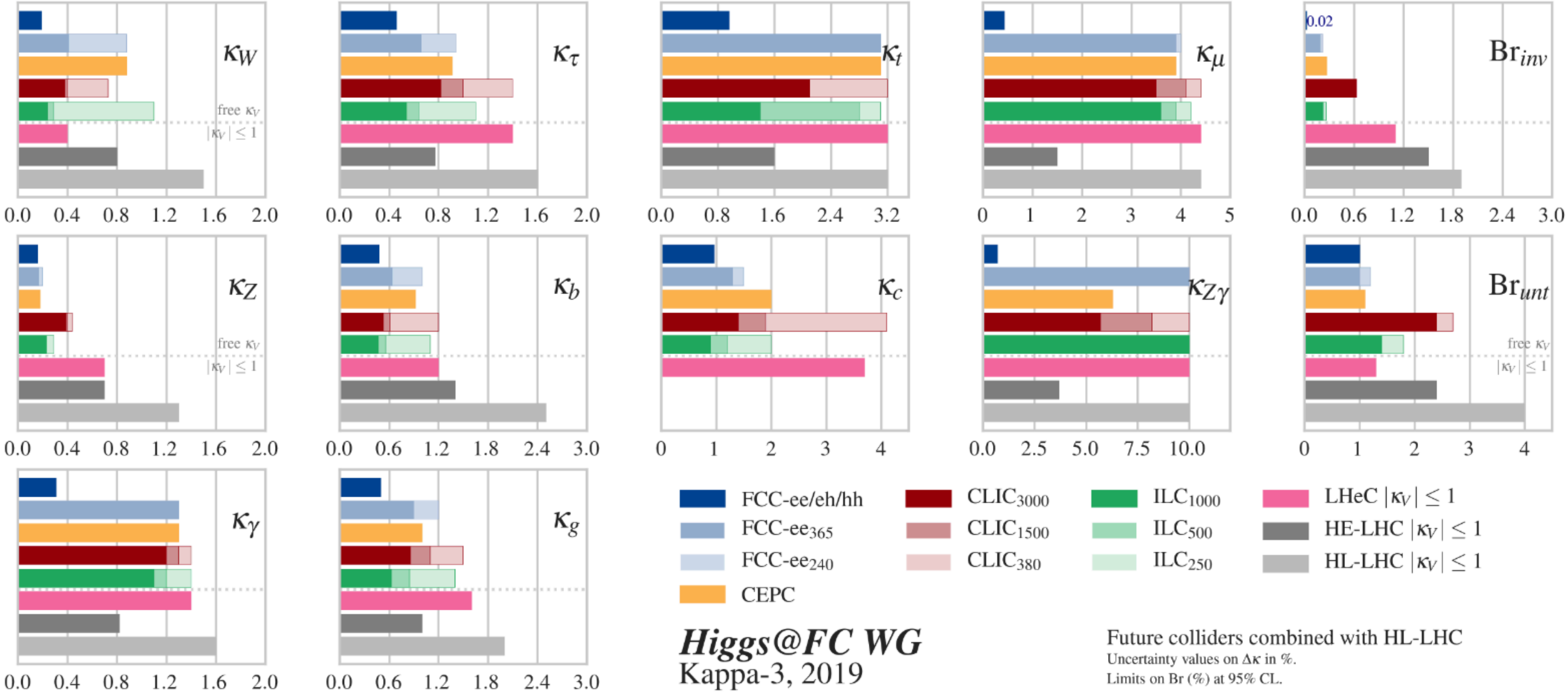






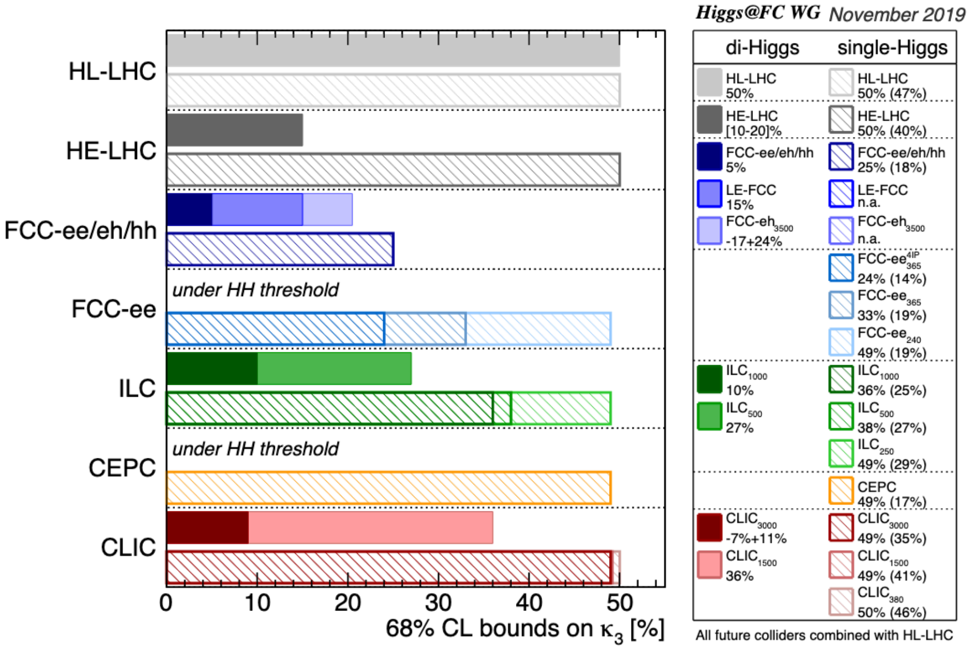


Higgs properties



https://arxiv.org/abs/1905.03764

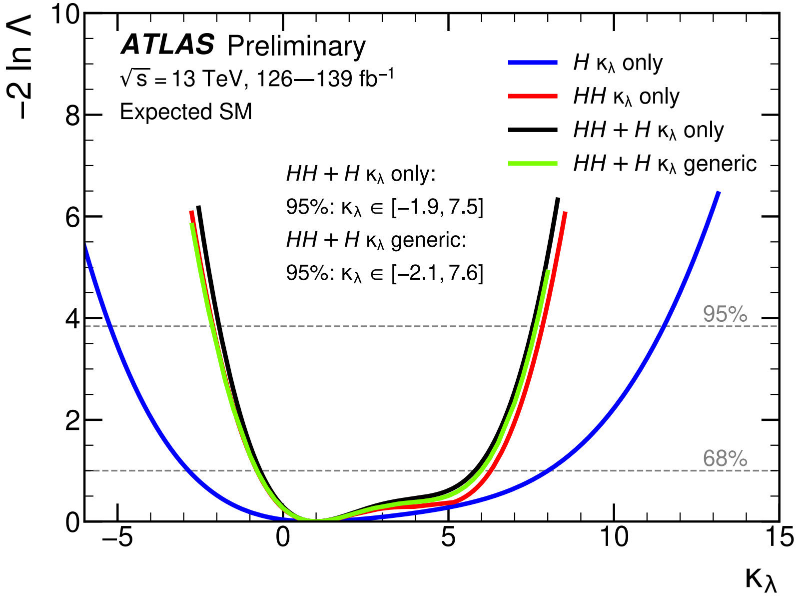
Higgs self-coupling



https://arxiv.org/abs/1905.03764

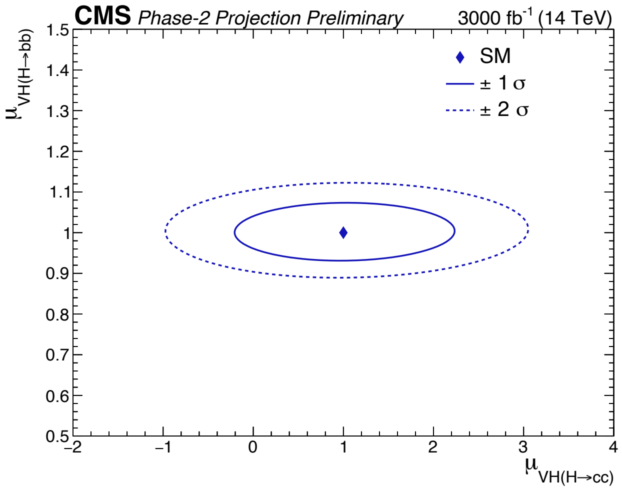
Single-Higgs vs di-Higgs sensitivity

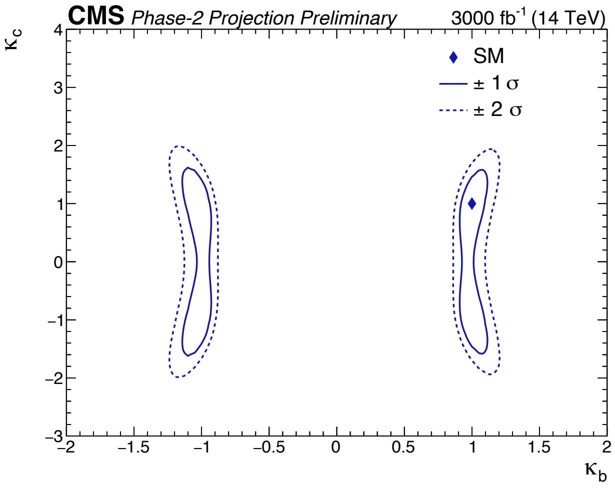
ATLAS-CONF-2022-050

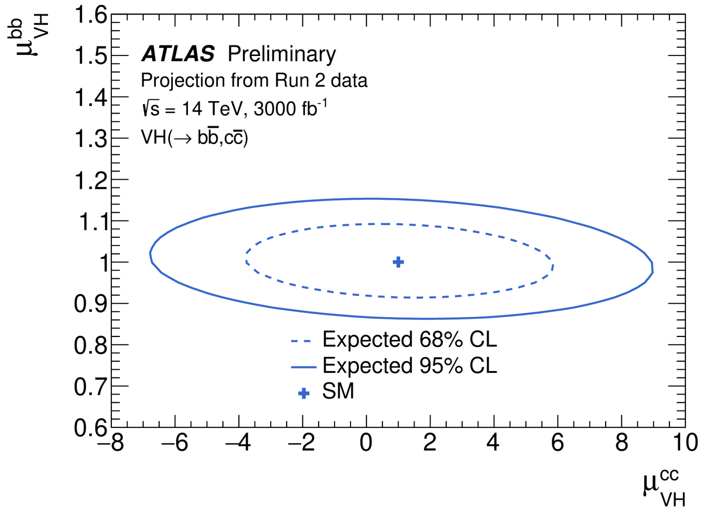


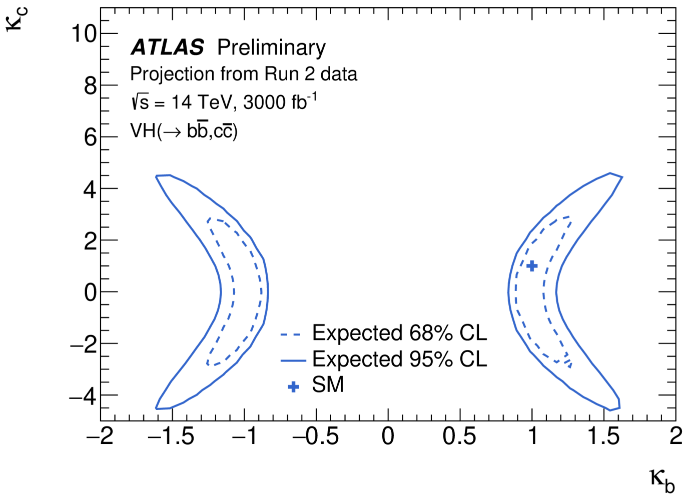
Higgs couplings to 2nd gen. fermions

Update on H→cc projections ATL-PHYS-PUB-2021-039 + CMS-HIG-21-008

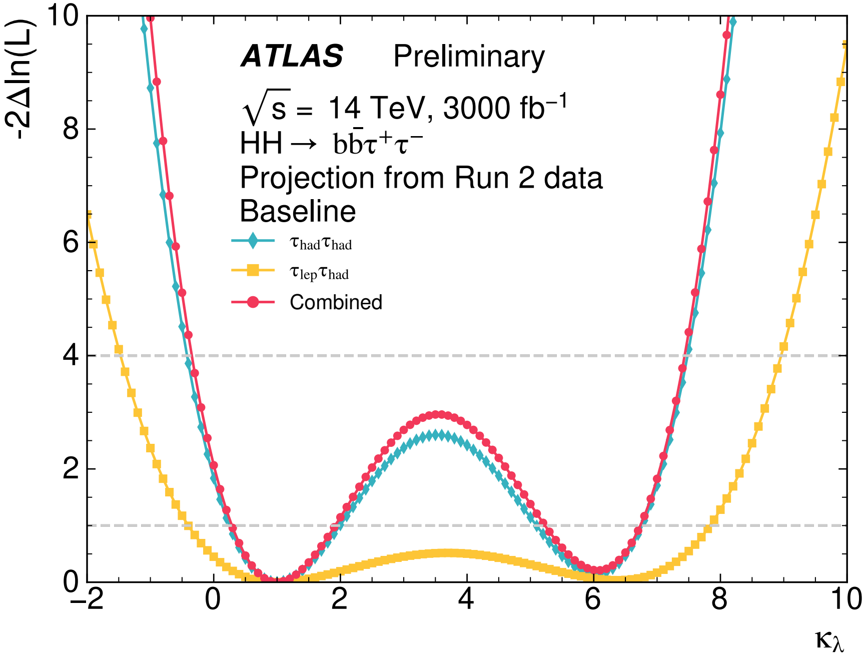




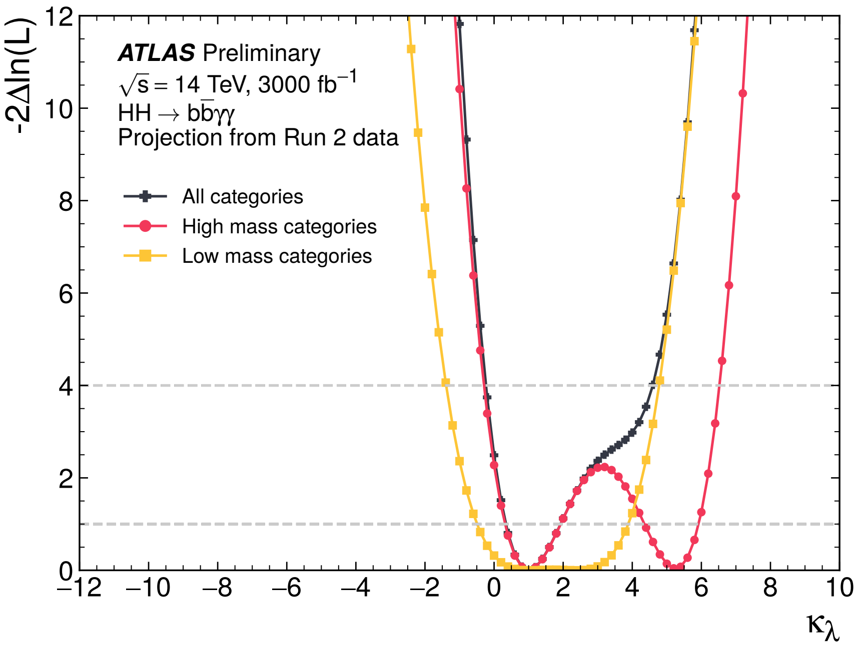




Higgs self-coupling



ATL-PHYS-PUB-2021-044

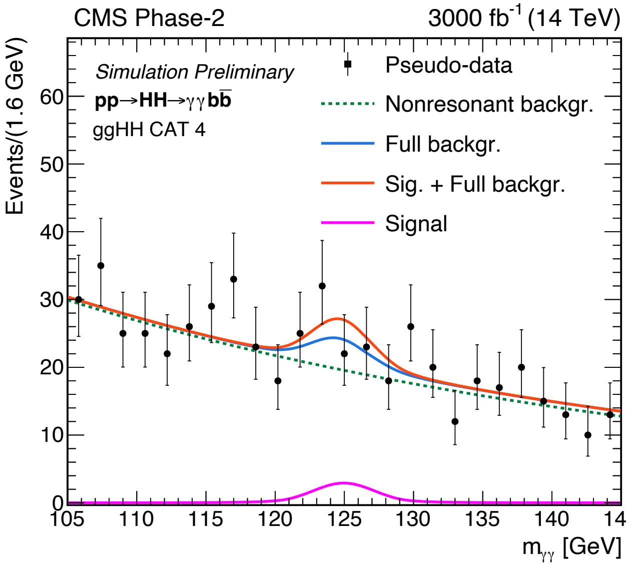


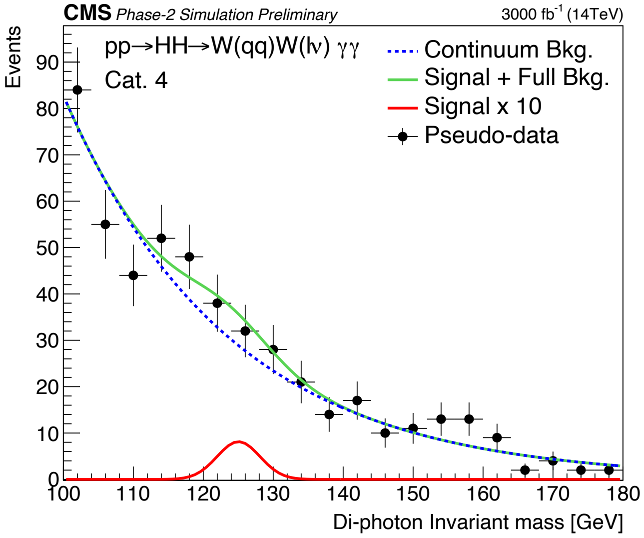
ATL-PHYS-PUB-2022-001

	Significance [σ]			Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination	strength precision [%]
No syst. unc.	2.3	4.0	4.6	$-23/+23$
Baseline	2.2	2.8	3.2	$-31/+34$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$

ATL-PHYS-PUB-2022-005

Higgs self-coupling





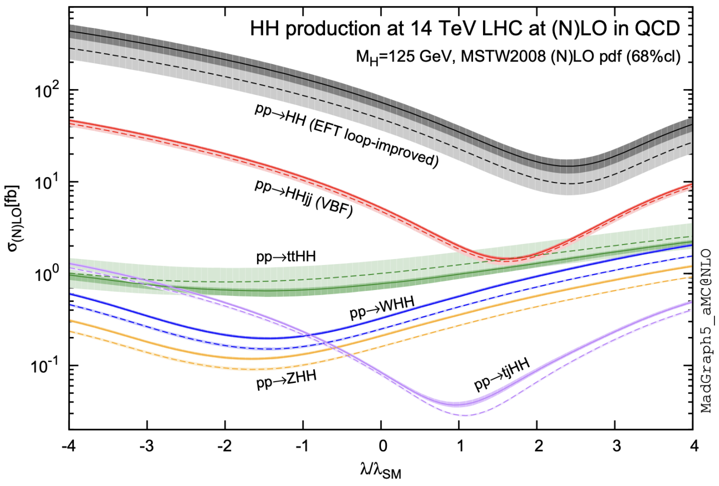
$HH \to bb\gamma\gamma$ 2.16σ

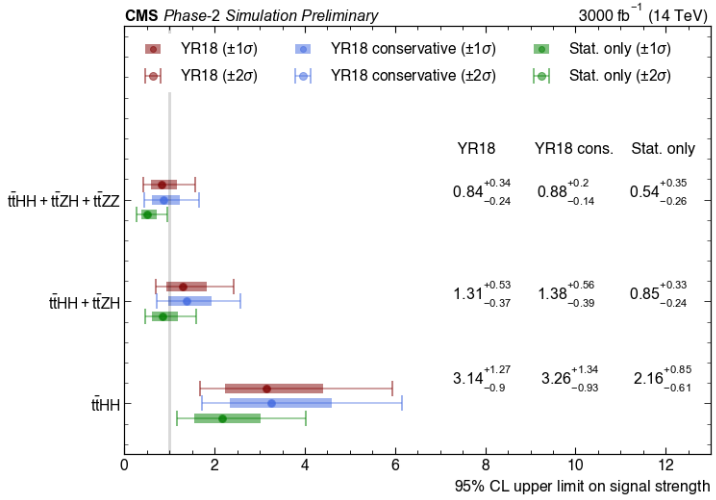
CMS-PAS-FTR-21-004

$HH \to WW\gamma\gamma$ 0.21σ

$HH \to \tau\tau\gamma\gamma$ 0.08σ

CMS-PAS-FTR-21-003





$ttHH \to 4b$

CMS-PAS-FTR-21-010

BSM Higgs searches

- **Higgs decays into BSM particles:**
  - light pseudoscalars
  - LLP
  - dark photons
  - **dark matter**

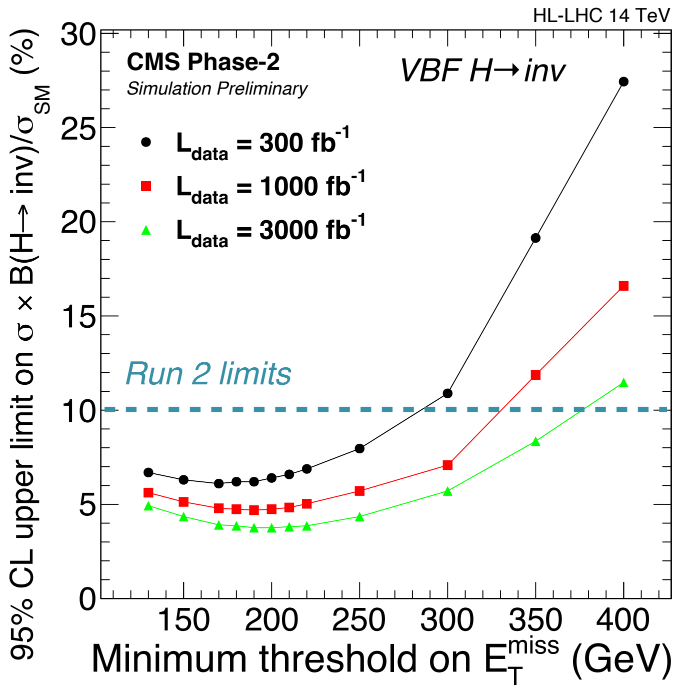
  => B(H→inv) < 2.5% combining ATLAS+CMS

- **Searches for additional Higgs bosons:**
  - charged Higgs in broken LRS, type II seesaw
  - **neutral Higgs in 2HDM**

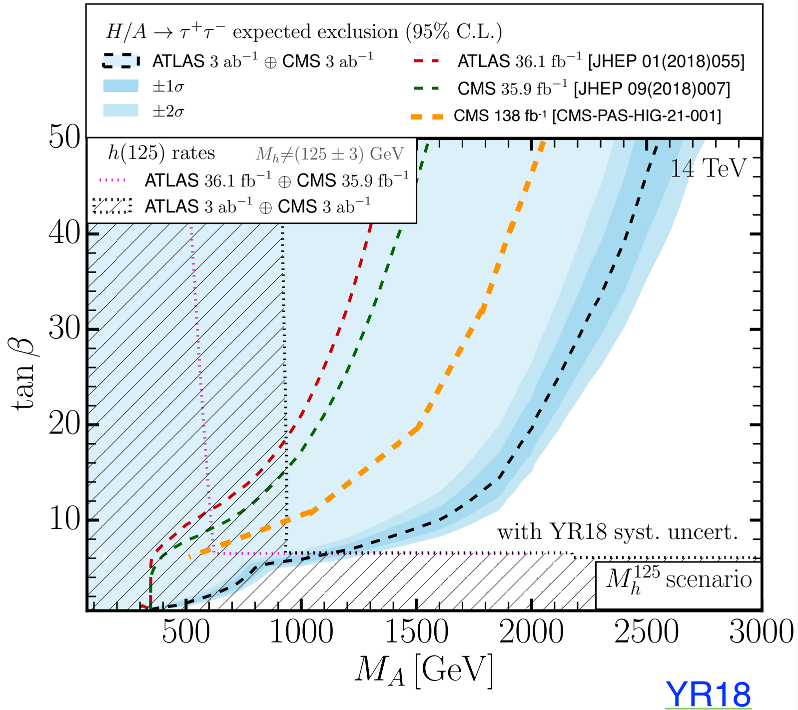
  => +O(500) GeV for H/A→ττ limits wrt best Run 2 limits

- **Searches for heavy resonances decaying into Higgs bosons:**
  - KK gravitons→HH→4b

    => mG < 2-3 TeV
  - will benefit from continuous improvements in boosted object tagging

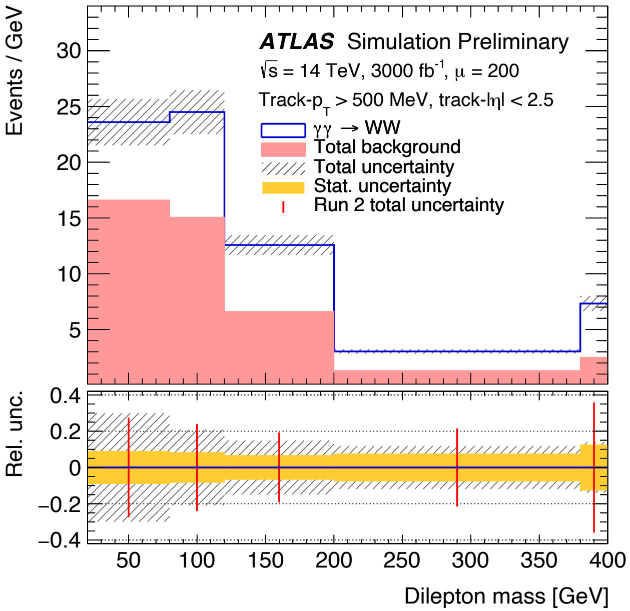


CMS-PAS-FTR-18-016



YR18

HL-LHC as photon collider



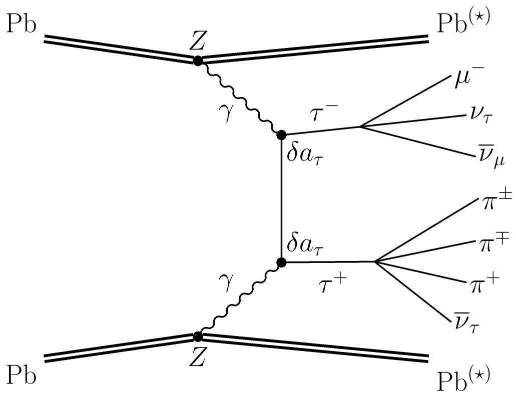
pp $\gamma\gamma \to WW$

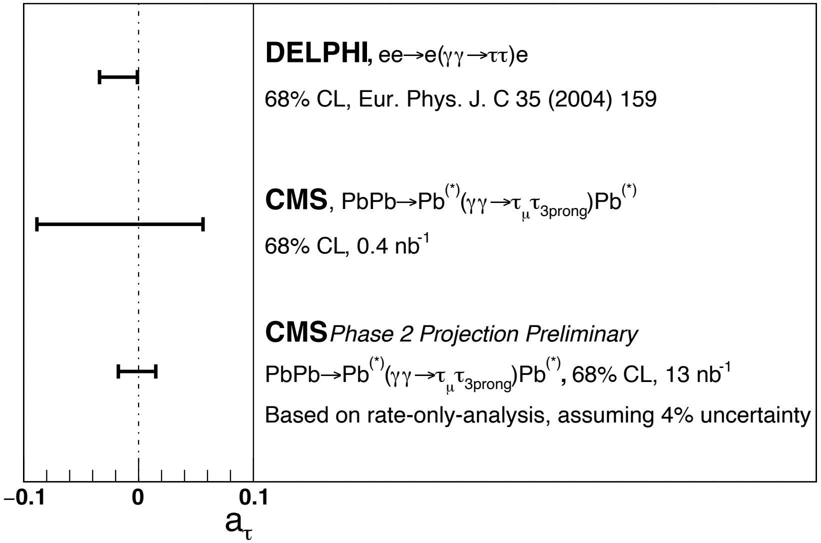
ATL-PHYS-PUB-2021-026

Configuration	$N_{\mathrm{sig.}}$	$N_{\mathrm{bkgd.}}$	$\sigma_{\mathrm{stat.}}/N_{\mathrm{sig.}}$	$\sigma_{\mathrm{tot.}}/N_{\mathrm{sig.}}$
Run 2	174	132	0.10	0.14
1 mm window				
HL-LHC baseline, track-$\|\eta\| < 2.5$	929	2 840	0.07	0.37
HL-LHC baseline, track-$\|\eta\| < 4.0$	209	281	0.11	0.19
Track-$p_{\mathrm{T}} > 500\ MeV$, track-$\|\eta\| < 2.5$	611	323	0.05	0.08
0.2 mm window				
HL-LHC baseline, track-$\|\eta\| < 2.5$	2 930	15 300	0.05	0.63
HL-LHC baseline, track-$\|\eta\| < 4.0$	934	3 560	0.07	0.46
Track-$p_{\mathrm{T}} > 500\ MeV$, track-$\|\eta\| < 2.5$	1 684	2 410	0.04	0.18

Heavy Ions $\gamma\gamma \to \tau\tau$

CMS-HIN-21-009





DELPHI, ee→e(γγ→ττ)e

68% CL, Eur. Phys. J. C 35 (2004) 159

CMS, PbPb→Pb$^{(*)}$(γγ→$\tau_\mu\tau_{3prong}$)Pb$^{(*)}$

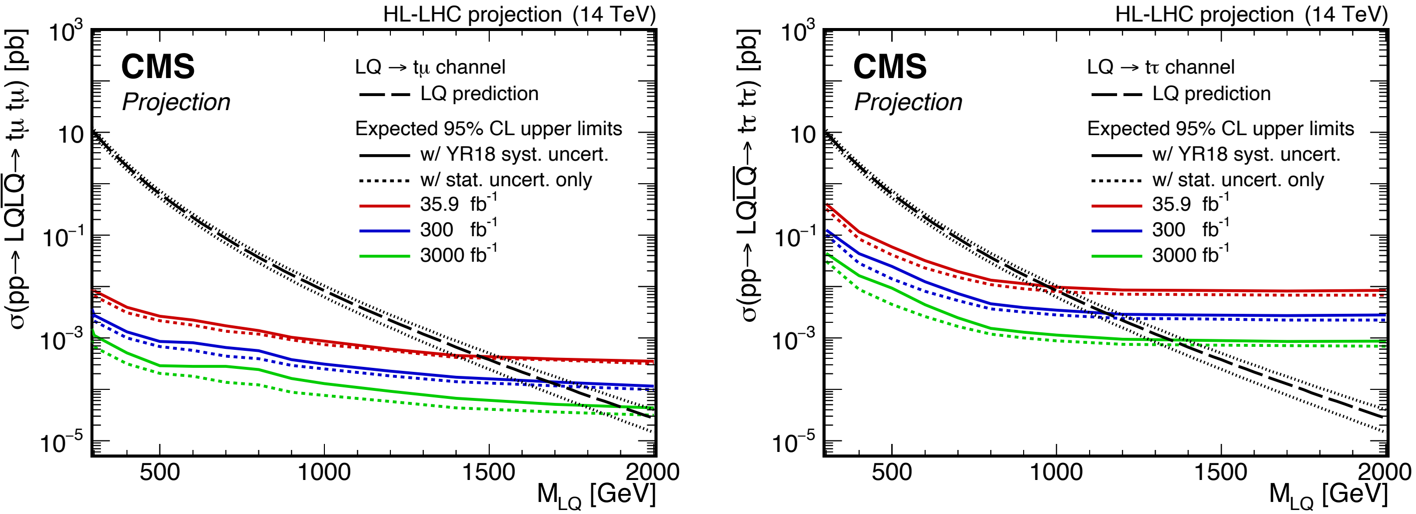
68% CL, 0.4 nb^{-1}

CMS *Phase 2 Projection Preliminary*

PbPb→Pb$^{(*)}$(γγ→$\tau_\mu\tau_{3prong}$)Pb$^{(*)}$, 68% CL, 13 nb^{-1}

Based on rate-only-analysis, assuming 4% uncertainty

BSM searches for leptoquarks



LQ→t+μ/τ

CMS-PAS-FTR-18-008

LQ→b+τ

CMS-PAS-FTR-18-028