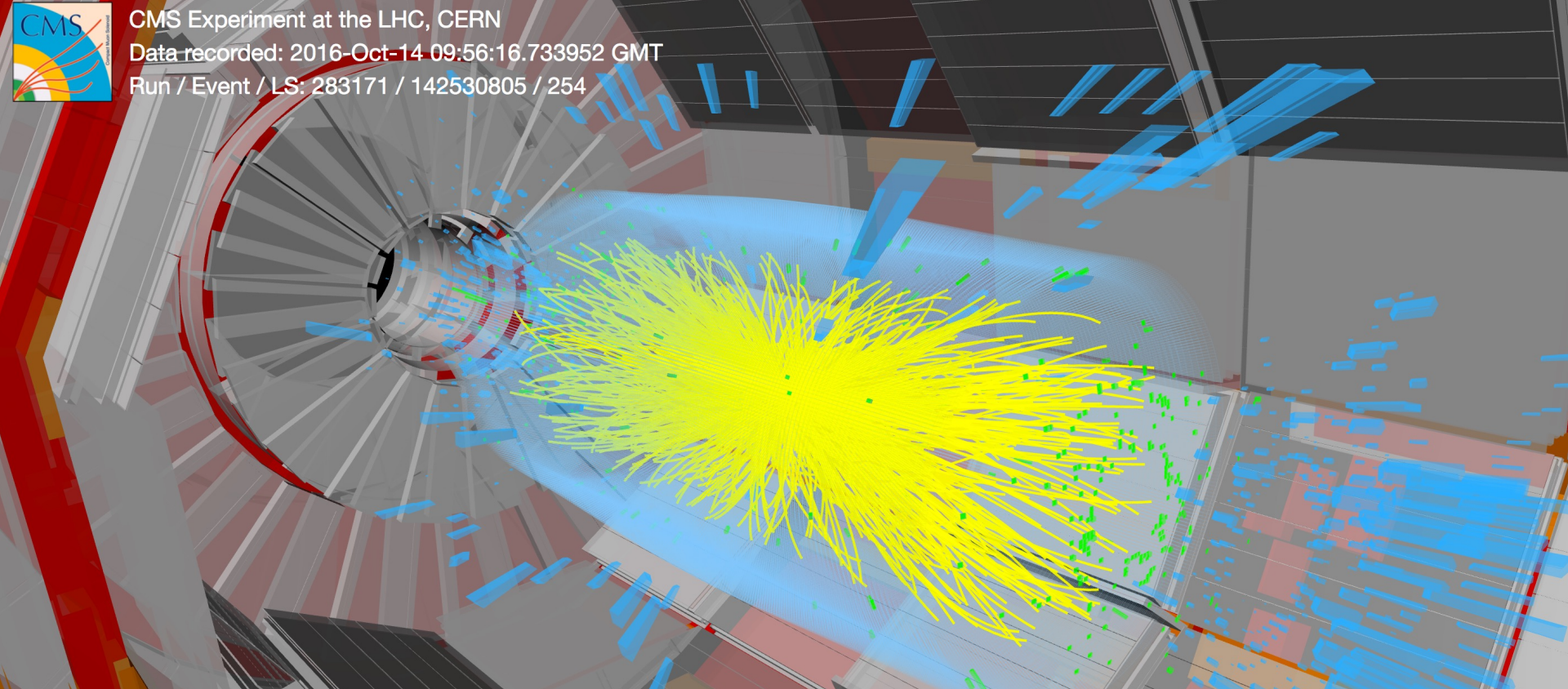


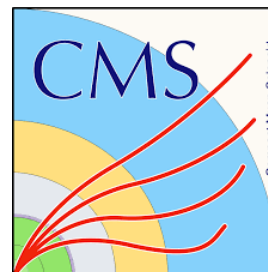


CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-14 09:56:16.733952 GMT
Run / Event / LS: 283171 / 142530805 / 254



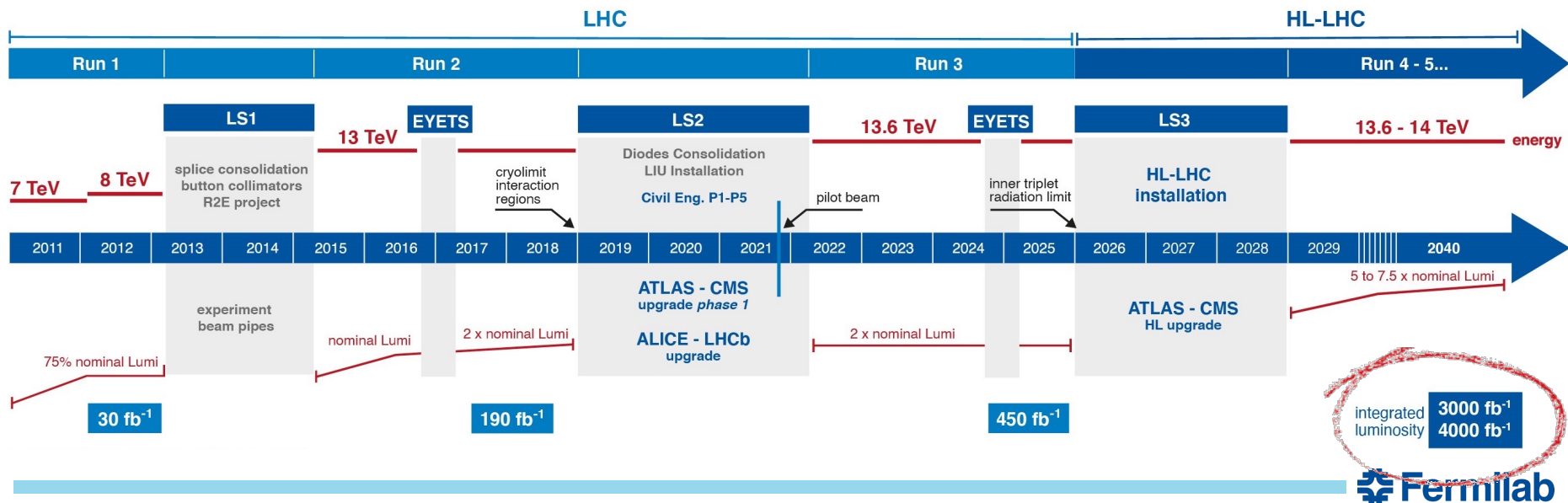
Physics at the High Luminosity LHC with ATLAS and CMS

Jennet Dickinson (Fermilab)
on behalf of the ATLAS and CMS collaborations
Snowmass Community Summer Study
July 23, 2022



High Luminosity LHC (HL-LHC)

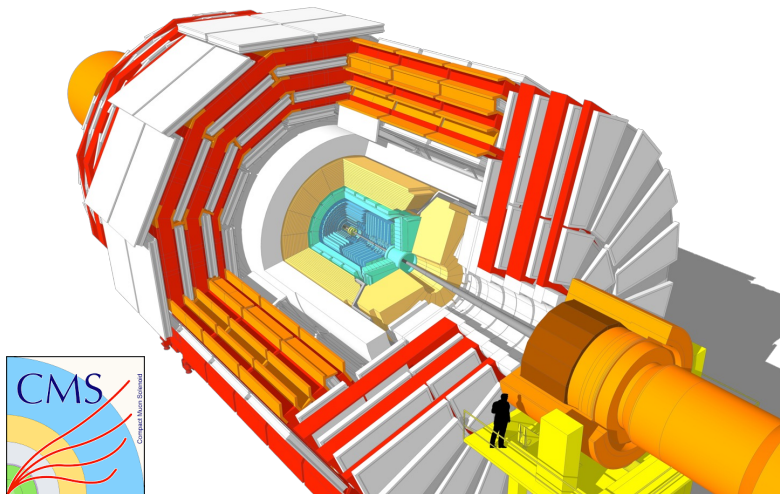
- Broad physics goals
 - Search for **rare processes** and make **more precise** measurements
- **HL-LHC** collider upgrade will provide more data than ever
 - Up to ~20x more integrated luminosity than we have now, ~100x more than we had at the time of the Higgs discovery
 - Associated challenges: complicated environments (**high pileup**), more radiation damage to detectors



HL-LHC detector upgrades

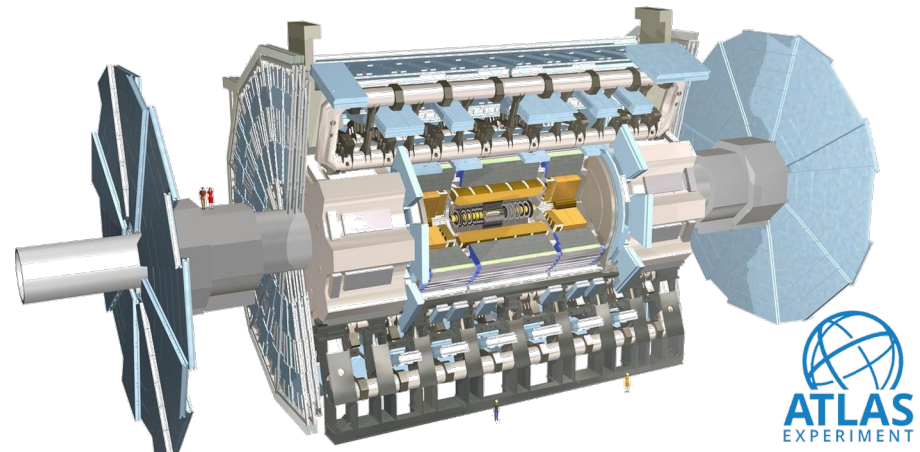
CMS detector

- New: MIP timing detector, additional muon detectors
- Fully replaced: silicon tracker, endcap calorimeters, trigger
- Upgraded: barrel calorimeters, forward calorimeters, muon chambers



ATLAS detector

- New: high granularity timing detector, additional muon detectors
- Fully replaced: silicon tracker, trigger
- Upgraded: liquid argon (EM) and tile (hadron) calorimeters, muon chambers



(Some of the) Latest HL-LHC projections for Snowmass



Benefits from **luminosity**



Benefits from **detector upgrade**



Benefits from clever **algorithms**

Physics potential of the HL-LHC

- Overview in [ATLAS+CMS Snowmass white paper](#) (2022)
 - Includes results from [HL-LHC Yellow Report](#) (2019)
 - +28 **new projections** from the collaborations!
- Assumptions on uncertainties:
 - **Experimental** uncertainties reduced by $\sim \sqrt{\text{luminosity}}$
 - **Detector performance** as good or better than now, but with harsher pileup conditions
 - **Theory** uncertainties reduced by a factor of ~ 2

Physics potential of the HL-LHC

Contents

1	Introduction	8
2	EPH1: EW Physics: Higgs boson properties and couplings	7
2.1	Precision Higgs Measurements at the HL-LHC: Yellow Report Summary	7
2.1.1	Higgs boson production cross-sections and decay branching ratios: measurements and interpretations	8
2.1.2	Differential measurements	9
2.1.3	Higgs boson width and CP measurements	10
2.2	New results	10
2.2.1	Projection of the Higgs boson mass and on-shell width measurements in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel with CMS at the HL-LHC [200]	10
2.2.2	A projection of the precision of the Higgs boson mass measurement in the diphoton decay channel with CMS at the HL-LHC [151]	12
2.2.3	Study of sensitivity to the CP structure of the Yukawa coupling between the Higgs boson and t -quarks with CMS at the HL-LHC [201]	12
2.2.4	Prospects for the precise measurement of the Higgs boson properties in the $H \rightarrow Z\gamma$ decay channel with CMS at the HL-LHC [191]	13
2.2.5	Projection of the search for $VH(H \rightarrow \tau\tau)$ with CMS at the HL-LHC [171]	14
2.2.6	Search for new Higgs boson decays with resonant W bosons with CMS at the HL-LHC [201]	16
2.2.7	Prospects for the measurement of $\sigma(H, H' \rightarrow hh)$ production in the opposite-sign dileptonic channel with CMS at the HL-LHC [201]	18
2.2.8	Sensitivity to $H \rightarrow b\bar{b}$ and $H' \rightarrow c\bar{c}$ decays in VH production with ATLAS at the HL-LHC [161]	19
2.2.9	$H \rightarrow \tau\tau$ cross-section measurement results with ATLAS at the HL-LHC [67]	20
2.3	Higgs boson pair production and Higgs boson self-coupling: Yellow Report Summary	21
2.4	New results	24
2.4.1	Prospects for nonresonant HH production measurement in $hh\gamma\gamma$ final states with CMS at the HL-LHC [74]	24
2.4.2	Prospects for HH measurements in the $W^+W^- \gamma\gamma$ and $\tau^+\tau^- \gamma\gamma$ final states with CMS at the HL-LHC [75]	25
2.4.3	Search for the nonresonant HHH production in the semileptonic decay of the top quark pair and the Higgs boson pair decaying into h quarks with CMS at the HL-LHC [76]	26
2.4.4	Updated prospects of Higgs boson pair production in the $hh\gamma\gamma$ and $hhb\tau^+\tau^-$ final states with ATLAS at the HL-LHC [77–80]	28
3	EPH2: EW Physics: Higgs boson as a portal to new physics	32
3.1	Yellow Report summary	32
3.1.1	Invisible Higgs boson decays and Higgs portal interpretations	32
3.1.2	Exotic decays of the 125 GeV Higgs boson	33
3.1.3	Searches for additional Higgs bosons	33
3.1.4	Searches for new massive resonances decaying into Higgs boson pairs	34
3.2	New results	35
3.2.1	Search for high mass resonances decaying into W^+W^- in the dileptonic final state with CMS at the HL-LHC [111]	35
4	EPH3: EW Physics: Heavy flavor and top quark physics	37
4.1	Yellow Report summary	37
4.1.1	Top quark mass measurements	37
4.1.2	Differential d cross-section measurements	37
4.1.3	Study of rare processes involving top quarks	38
4.1.4	Constraints on flavor-changing neutral currents couplings	39
4.2	New results	40
4.2.1	Sensitivity to the measurement of the Standard Model low top quark cross-section with ATLAS at the HL-LHC [122]	40
5	EPH4: Weak decays of b and c quarks	42
5.1	Yellow Report summary	42
5.1.1	Sensitivity studies for rare B_u and B_d decays in two modes	43
5.1.2	f_2 sensitivity in the $B^0 \rightarrow K^{*0} \pi^0$ decay	43
5.1.3	CP violating phase θ_{bc} sensitivity in $B_c^0 \rightarrow J/\psi h$ decay	45
6	EPH5: EW Physics: EW precision physics and constraining new physics	46
6.1	Yellow Report summary	46
6.1.1	Weak mixing angle measurements	46
6.1.2	W boson measurements	48
6.1.3	Charged lepton flavor violation	52
6.1.4	W boson mass	52
6.2	New results	53
6.2.1	Prospects for the measurement of vector boson scattering production in leptonic WW and WZ diboson events with CMS at the HL-LHC [173]	53
7	EPH6: QCD and strong interactions: Precision QCD	55
7.1	Yellow Report summary	55
7.1.1	Inclusive cross-section measurements	55
7.1.2	Photon cross-section measurements	56
7.1.3	High- p_T jet measurements at the HL-LHC	57
8	EPH6: QCD and strong interactions: Hadronic structure and forward QCD	59
8.1	New results	59
8.1.1	Sensitivity to $\gamma\gamma \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu_\mu\nu_\mu$ with ATLAS at the HL-LHC [183]	59
9	EPH7: QCD and strong interactions: Heavy ions	61
9.1	Yellow Report summary	61
9.1.1	Jet modification studies	61
9.1.2	Heavy flavor hadrons	62
9.1.3	Particle collectivity in small and large systems	63
9.1.4	Hadron particle distribution functions	64
9.1.5	Ultra peripheral collisions	64
9.2	New results	65
9.2.1	Measurement of the $\gamma\gamma \rightarrow \tau^+\tau^-$ process with CMS at the HL-LHC [208]	65
10	EPH8: BSM: Model specific explorations	66
10.1	Yellow Report summary	66
10.1.1	Searches for selectron-like electroweakinos	68
10.1.2	Searches for compressed mass spectrum	71
10.1.3	Searches for staus	72
10.1.4	Searches for stops	72
10.1.5	Searches for selectron-like leptons	73
10.1.6	Search for a 2HDM model with low top quarks	74
10.2	New results	74
10.2.1	Hadronic electroweak supersymmetry search with CMS at the HL-LHC [221]	74
10.2.2	Search for top squarks in final states with one top quark and several light flavor jets with CMS at the HL-LHC [243]	75
10.2.3	Search for long-lived Z' resonances decaying to dijets in the dilepton plus missing transverse energy final state with CMS at the HL-LHC [246]	77
10.2.4	Search for dark matter production in association with dark matter	77
11	EPH9: BSM: More general explorations	80
11.1	Yellow Report summary	80
11.1.1	Compositeness	80
11.1.2	New gauge bosons and resonances	82
11.1.3	Long-lived particles and displaced signatures	84
11.2	New results	86
11.2.1	Sensitivity projections for a search for new phenomena at high dilepton mass with CMS at the HL-LHC [261]	86
12	EPH10: BSM: Dark matter at colliders	88
12.1	Yellow Report summary	88
12.1.1	Search for DM produced in association with a Z boson	88
12.1.2	W and Z and mono-photon final states	90
12.1.3	Monojets search for WIMPs	91
12.1.4	Single-top quark in association with invisible particles	92
12.1.5	Heavy quarks produced in association with dark matter	92
12.1.6	Search sensitivity for dark photons decaying to displaced muons	92
13	Summary	96

Physics potential of the HL-LHC

Contents

1	Introduction	8
2	EPFL: EW Physics: Higgs boson properties and couplings	7
2.1	Precision Higgs Measurements at the HL-LHC: Yellow Report Summary	7
2.1.1	Higgs boson production cross-sections and decay branching ratios: measurements and interpretations	8
2.1.2	Differential measurements	9
2.1.3	Higgs boson width and CP measurements	10
2.2	New results	10
2.2.1	Projection of the Higgs boson mass and on-shell width measurements in the $H \rightarrow Z\gamma \rightarrow 4\ell$ decay channel with CMS at the HL-LHC [200]	10
2.2.2	A projection of the precision of the Higgs boson mass measurement in the dilepton decay channel with CMS at the HL-LHC [201]	12
2.2.3	Study of sensitivity to the CP structure of the Yukawa coupling between the Higgs boson and t quarks with CMS at the HL-LHC [202]	12
2.2.4	Prospects for the precise measurement of the Higgs boson properties in the $H \rightarrow Z, \gamma\gamma$ decay channel with CMS at the HL-LHC [203]	13
2.2.5	Projection of the search for $V(H \rightarrow \gamma\gamma)$ with CMS at the HL-LHC [204]	14
2.2.6	Search for new Higgs boson decays with CMS at the HL-LHC [205]	16
2.2.7	Prospects for the measurement of $\sigma(H, H \rightarrow hh)$ production in the opposite-sign dilepton channels with CMS at the HL-LHC [206]	18
2.2.8	Search for $H \rightarrow hh$ and $H \rightarrow \gamma\gamma$ decays in VH production with ATLAS at the HL-LHC [207]	19
2.2.9	$H \rightarrow \gamma\gamma$ cross-section measurement results with ATLAS at the HL-LHC [208]	20
2.3	Higgs boson pair production and Higgs boson self-coupling: Yellow Report Summary	21
2.4	New results	24
2.4.1	Prospects for measuring HH production measurement in heavy final states with CMS at the HL-LHC [209]	24
2.4.2	Prospects for HH measurements in the $W^+W^- \gamma\gamma$ and $\gamma^*\gamma^* \gamma\gamma$ final states with CMS at the HL-LHC [210]	25
2.4.3	Search for the measurement HH production in the semileptonic decay of the top quark pair and the Higgs boson pair decaying into 4 quarks with CMS at the HL-LHC [211]	26
2.4.4	Updated prospects of Higgs boson pair production in the $hh\gamma\gamma$ and $hhb\gamma^*\gamma^*$ final states with ATLAS at the HL-LHC [212-213]	28
3	EPFL: EW Physics: Higgs boson as a portal to new physics	32
3.1	Yellow Report summary	32
3.1.1	Illustrative Higgs boson decays and Higgs portal interpretations	32
3.1.2	Exotic decays of the 125 GeV Higgs boson	33
3.1.3	Searches for additional Higgs bosons	33
3.1.4	Searches for new massive resonances decaying into Higgs boson pairs	34
3.2	New results	35
3.2.1	Search for high mass resonances decaying into W^+W^- in the dileptonic final state with CMS at the HL-LHC [111]	35
4	EPFL: EW Physics: Heavy flavor and top quark physics	37
4.1	Yellow Report summary	37
4.1.1	Top quark mass measurements	37
4.1.2	Differential d cross-section measurements	37
4.1.3	Study of rare processes involving top quarks	38
4.1.4	Constraints on flavor-changing neutral currents couplings	39
4.2	New results	40
4.2.1	Sensitivity to the measurement of the Standard Model low top quark cross-section with ATLAS at the HL-LHC [122]	40
5	EPFL: Weak decays of b and c quarks	42
5.1	Yellow Report summary	42
5.1.1	Sensitivity studies for rare B_s and B_d decays in two modes	43
5.1.2	C sensitivity in the $B^0 \rightarrow K^{*0} \pi^0$ decay	43
5.1.3	CP violating phase ϕ_s sensitivity in $B_s^0 \rightarrow \ell^+\ell^- \mu^+\mu^-$ decay	45
6	EPFL: EW Physics: EW precision physics and constraining new physics	48
6.1	Yellow Report summary	48
6.1.1	Weak mixing angle measurements	48
6.1.2	W -boson measurements	48
6.1.3	Charged lepton flavor violation	52
6.1.4	W boson mass	52
6.2	New results	53
6.2.1	Prospects for the measurement of vector boson scattering production in leptonic WW and WZ diboson events with CMS at the HL-LHC [175]	53
7	EPFL: QCD and strong interactions: Precision QCD	58
7.1	Yellow Report summary	58
7.1.1	Jet cross-section measurements	58
7.1.2	Photon cross-section measurements	58
7.1.3	High- p_T jet measurements at the HL-LHC	57
8	EPFL: QCD and strong interactions: Hadronic structure and forward QCD	59
8.1	New results	59
8.1.1	Sensitivity to $\gamma\gamma \rightarrow W^+W^- \rightarrow e^+e^+\mu^+\mu^-$ with ATLAS at the HL-LHC [183]	59
9	EPFL: QCD and strong interactions: Heavy ions	61
9.1	Yellow Report summary	61
9.1.1	Jet modification studies	61
9.1.2	Heavy flavor hadrons	62
9.1.3	Particle collectivity in small and large systems	63
9.1.4	Two-to-particle distribution functions	64
9.1.5	Ultra-peripheral collisions	65
9.2	New results	65
9.2.1	Measurement of the $\gamma\gamma \rightarrow e^+e^-$ process with CMS at the HL-LHC [208]	65
10	EPFL: BSM: Model specific explorations	68
10.1	Yellow Report summary	68
10.1.1	Searches for selectron-like electroweakinos	68
10.1.2	Searches for compressed mass spectrum	71
10.1.3	Searches for staus	72
10.1.4	Searches for stops	72
10.1.5	Searches for selectron-like electroweakinos	73
10.1.6	Search for a Higgs-like state with low top quarks	74
10.2	New results	74
10.2.1	Hadronic electroweak supersymmetry search with CMS at the HL-LHC [221]	74
10.2.2	Search for top squarks in final states with one top quark and several light flavor jets with CMS at the HL-LHC [243]	75
10.2.3	Search for long-lived Z' resonances decaying to dijets in the dilepton plus missing transverse energy final state with CMS at the HL-LHC [246]	77
10.2.4	Search for dark matter production in the dilepton plus missing transverse energy final state with CMS at the HL-LHC [247]	78
11	EPFL: BSM: Mass general explorations	80
11.1	Yellow Report summary	80
11.1.1	Compositeness	80
11.1.2	New gauge bosons and resonances	82
11.1.3	Long-lived particles and displaced signatures	84
11.2	New results	86
11.2.1	Sensitivity projections for a search for new phenomena at high dilepton mass with CMS at the HL-LHC [261]	86
12	EPFL: BSM: Dark matter at colliders	88
12.1	Yellow Report summary	88
12.1.1	Search for DM produced in association with a Z boson	88
12.1.2	W - W and W - W and W - W and W - W final states	89
12.1.3	Missing energy search for WIMPs	91
12.1.4	Single-top quark in association with invisible particles	92
12.1.5	Heavy quarks produced in association with dark matter	92
12.1.6	Search sensitivity for dark photons decaying to displaced muons	92

Higgs boson

Sapta's talk

Standard Model

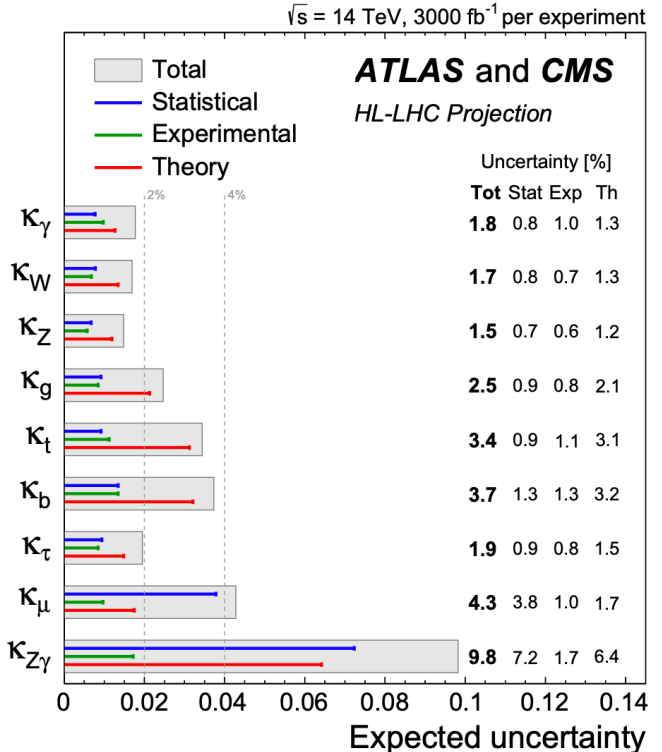
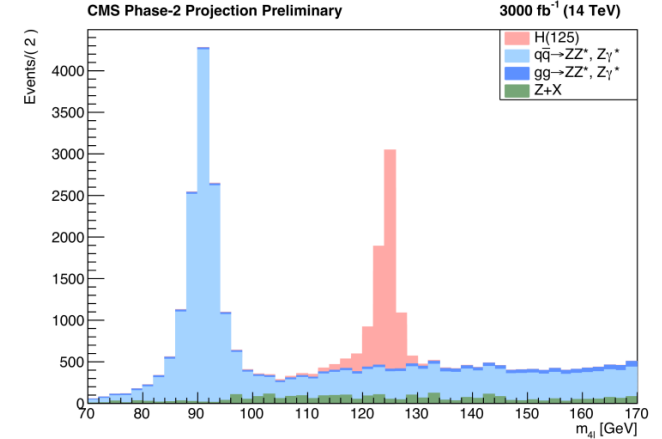
Beyond the SM

Higgs boson physics at the HL-LHC





Contents

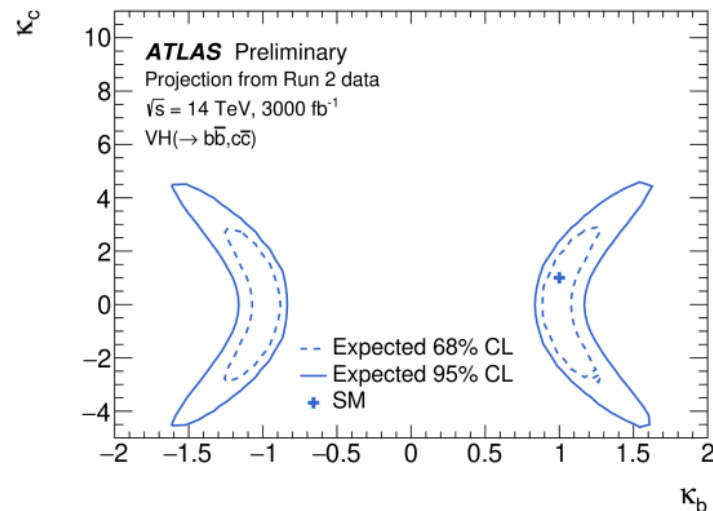
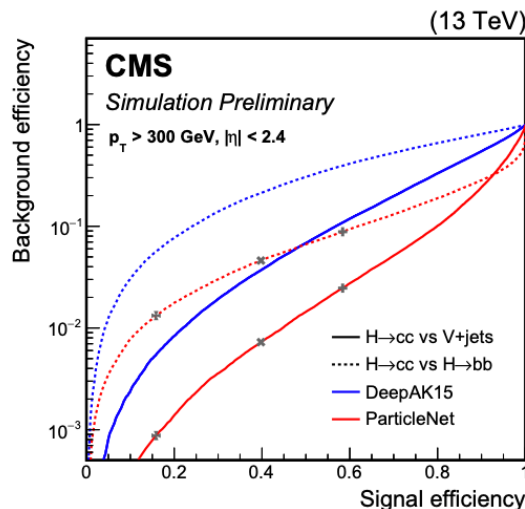
1	Introduction	8
2	EPFL: EW Physics: Higgs boson properties and couplings	7
2.1	Precision Higgs Measurements at the HL-LHC: Yellow Report Summary	7
2.1.1	Higgs boson production cross-sections and decay branching ratios: measurements and interpretations	8
2.1.2	Differential measurements	9
2.1.3	Higgs boson width and CP measurements	10
2.2	New results	10
2.2.1	Projection of the Higgs boson mass and on-shell width measurements in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel with CMS at the HL-LHC [200]	10
2.2.2	A projection of the precision of the Higgs boson mass measurement in the diphoton decay channel with CMS at the HL-LHC [201]	12
2.2.3	Study of sensitivity to the CP structure of the Yukawa coupling between the Higgs boson and top quarks with CMS at the HL-LHC [202]	12
2.2.4	Prospects for the precise measurement of the Higgs boson properties in the $H \rightarrow \gamma\gamma$ decay channel with CMS at the HL-LHC [203]	14
2.2.5	Projection of the search for $VH(H \rightarrow \gamma\gamma)$ with CMS at the HL-LHC [171]	14
2.2.6	Search for new Higgs boson decays with CMS at the HL-LHC [204]	16
2.2.7	Prospects for the measurement of $\sigma(H, H \rightarrow hh)$ production in the opposite-sign dilepton channel with CMS at the HL-LHC [205]	18
2.2.8	Search for $H \rightarrow \mu\mu$ decay in VH production with ATLAS at the HL-LHC [206]	19
2.2.9	$H \rightarrow \mu\mu$ cross-section measurement results with ATLAS at the HL-LHC [207]	20
2.3	Higgs boson pair production and Higgs boson self-coupling: Yellow Report Summary	21
2.4	New results	24
2.4.1	Prospects for measuring HH production measurement in heavy final states with CMS at the HL-LHC [208]	24
2.4.2	Prospects for HH production in the $W^+W^- \gamma\gamma$ and $\gamma^*\gamma^*$ final states with CMS at the HL-LHC [209]	25
2.4.3	Search for the measurement of HH production in the semileptonic decay of the top quark pair and the Higgs boson pair decaying into a quark with CMS at the HL-LHC [210]	26
2.4.4	Updated prospects of Higgs boson pair production in the $hh\gamma\gamma$ and $hh\ell^+\ell^-$ final states with ATLAS at the HL-LHC [211]	28
3	EPFL: EW Physics: Higgs boson as a portal to new physics	32
3.1	Yellow Report Summary	32
3.1.1	Searches for Higgs boson decays and Higgs portal interactions	32
3.1.2	Searches for Higgs boson decays into invisible particles	33
3.1.3	Searches for additional Higgs bosons	33
3.1.4	Searches for new massive resonances decaying into Higgs boson pairs	34
3.2	New results	35
3.2.1	Search for high mass resonances decaying into W^+W^- in the di-lepton final state with CMS at the HL-LHC [111]	35
4	EPFL: EW Physics: Heavy flavor and top quark physics	37
4.1	Yellow Report Summary	37
4.1.1	Top quark mass measurements	37
4.1.2	Differential t -cross-section measurements	37
4.1.3	Study of rare processes involving top quarks	38
4.1.4	Constraints on flavor-changing neutral currents couplings	39
4.2	New results	40
4.2.1	Sensitivity to the measurement of the Standard Model low top quark cross-section with ATLAS at the HL-LHC [122]	40
5	EPFL: Weak decays of b and c quarks	42
5.1	Yellow Report Summary	42
5.1.1	Sensitivity studies for rare B_u and B_c decays in two modes	43
5.1.2	Sensitivity to the $B^0 \rightarrow K^{*0} \gamma$ decay	43
5.1.3	CP violating phase A_u sensitivity in $B_c^0 \rightarrow \ell^+\ell^-\gamma$ decay	45
6	EPFL: EW Physics: EW precision physics and constraining new physics	48
6.1	Yellow Report Summary	48
6.1.1	Weak mixing angle measurements	48
6.1.2	α_s observables measurements	49
6.1.3	Charged lepton flavor violation	52
6.1.4	W boson mass	53
6.2	New results	53
6.2.1	Prospects for the measurement of vector boson scattering production in lepton WW and WZ diboson events with CMS at the HL-LHC [175]	53
7	EPFL: QCD and strong interactions: Precision QCD	58
7.1	Yellow Report Summary	58
7.1.1	Jet cross-section measurements	58
7.1.2	Photon cross-section measurements	58
7.1.3	High p_T jet measurements at the HL-LHC	57
8	EPFL: QCD and strong interactions: Hadronic structure and forward QCD	59
8.1	New results	59
8.1.1	Sensitivity to $\gamma\gamma \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu\bar{\nu}$ with ATLAS at the HL-LHC [183]	59
9	EPFL: QCD and strong interactions: Heavy ions	61
9.1	Yellow Report Summary	61
9.1.1	Jet modification studies	61
9.1.2	Heavy flavor hadrons	62
9.1.3	Particle collectivity in small and large systems	63
9.1.4	Longitudinal parton distribution functions	64
9.1.5	Ultra peripheral collisions	65
9.2	New results	65
9.2.1	Measurement of the $\gamma\gamma \rightarrow \gamma^* \gamma^*$ process with CMS at the HL-LHC [208]	65
10	EPFL: BSM: Model specific explorations	68
10.1	Yellow Report Summary	68
10.1.1	Searches for stop-like electroweakinos	68
10.1.2	Searches for compressed mass spectrum	71
10.1.3	Searches for staus	72
10.1.4	Searches for stops	72
10.1.5	Searches for scalar top squarks	74
10.2	New results	74
10.2.1	Hadronic electroweak supersymmetry search with CMS at the HL-LHC [221]	74
10.2.2	Search for top squarks in final states with two top quarks and several light flavor jets with CMS at the HL-LHC [245]	75
10.2.3	Search for long-lived Z' resonances decaying to dijet or dilepton plus missing transverse energy final state with CMS at the HL-LHC [246]	77
10.2.4	Search for dark matter production in association with Higgs boson at the HL-LHC [247]	77
11	EPFL: BSM: Mass general explorations	80
11.1	Yellow Report Summary	80
11.1.1	Compositeness	80
11.1.2	New gauge bosons and resonances	82
11.1.3	Long-lived particles and dark matter	84
11.2	New results	86
11.2.1	Sensitivity projections for a search for new phenomena at high dilepton mass with CMS at the HL-LHC [261]	86
12	EPFL: BSM: Dark matter at colliders	88
12.1	Yellow Report Summary	88
12.1.1	Search for DM produced in association with a Z boson	88
12.1.2	W - W' and new-physics final states	90
12.1.3	Monojet search for WIMPs	91
12.1.4	Single-top quark in association with invisible particles	92
12.1.5	Heavy quarks produced in association with dark matter	92
12.1.6	Search sensitivity for dark photons decaying to displaced muons	92
13	Summary	96

- Precise measurements of mass and width
 - $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
- Precise measurements of couplings to SM particles
 - Increased sensitivity to rare production and decay modes
- Evidence (or more) of Higgs self-coupling
- Measurements of differential distributions
 - Higgs p_T , Simplified Template Cross Sections, etc.



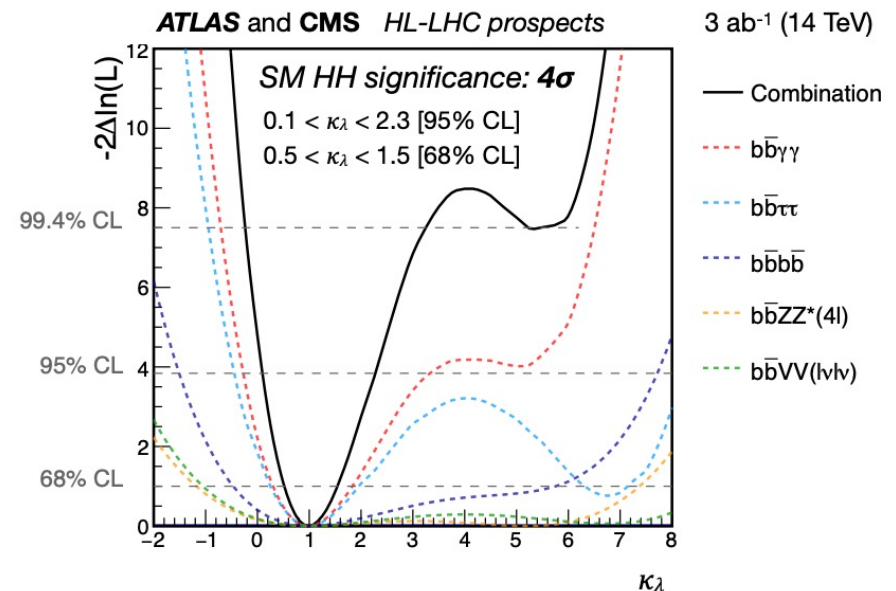
Higgs coupling to second generation fermions

- $H \rightarrow \mu\mu$ in ggF and VBF
 - Evidence in Run 2 at 3σ level. Project 5σ discovery of SM with $\sim 400 \text{ fb}^{-1}$
 -  New techniques brought us farther in Run 2 than we expected!
 -  Big gains from tracking upgrade in $m_{\mu\mu}$ resolution, extended η coverage
- $H \rightarrow cc$ in high p_T VH
 - Challenging search! rare process, large QCD background, charm tagging
 - Simultaneous measurement of $H \rightarrow bb$ and $\rightarrow cc$
 -   Gains from boosted jet reco, new charm-tagging algorithms



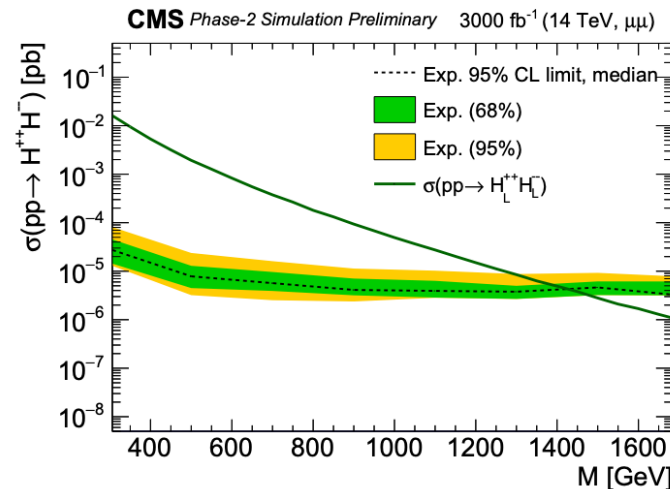
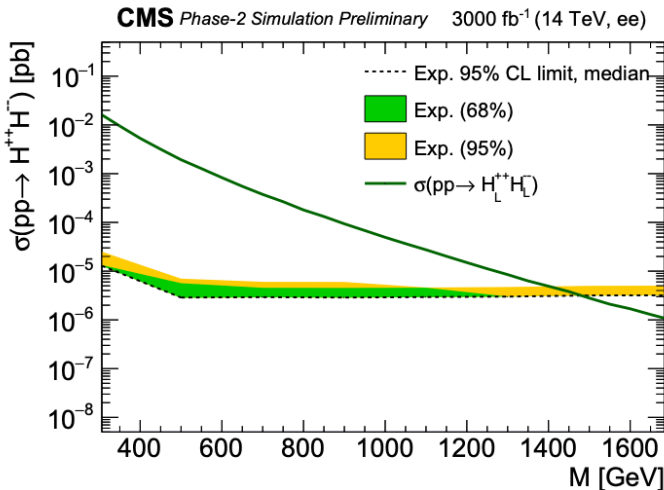
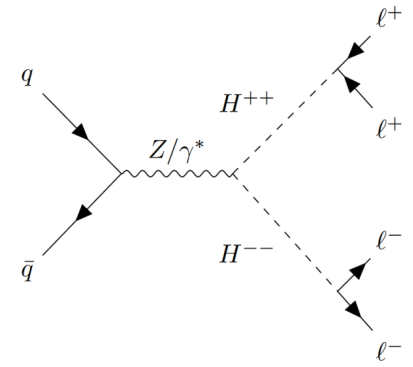
Di-Higgs production 🌞

- Current projection: **4 σ combined sensitivity** to SM HH
 - 🧠 Constantly improving with analysis of current data
- Number of channels explored is constantly growing
 - New projections for decays $HH \rightarrow b\bar{b}\gamma\gamma, WW\gamma\gamma, \tau\tau\gamma\gamma, b\bar{b}\tau\tau$
 - New projection for $t\bar{t}HH$ production with semi-leptonic top decay
- Pursuit of the **Higgs boson self-coupling**, κ_λ
 - Combined limits from ATLAS and CMS with full HL-LHC luminosity: $0.5 \leq \kappa_\lambda < 1.5$
 - Expect to exclude $\kappa_\lambda = 0$ at 95% CL



BSM Higgs

- Search for **doubly charged Higgs** ([new](#))
 - Prediction of type II seesaw mechanism
 - $H^{++} \rightarrow e^+e^+$ and $H^{++} \rightarrow \mu^+\mu^+$
 - Nearly background-free search, especially at large H^{++} mass
 - Expected exclusion $M < 1400$ GeV (compared to 750-870 GeV in Run 2)



- Another study of the seesaw mechanism at the HL-LHC can be found [here](#)

Standard Model physics at the HL-LHC

Contents

1	Introduction	8
2	EPIC: EW Physics: Higgs boson properties and couplings	7
2.1	Precision Higgs Measurements at the HL-LHC: Yellow Report Summary	7
2.1.1	Higgs boson production cross-sections and decay branching ratios: measurements and interpretations	8
2.1.2	Differential measurements	9
2.1.3	Higgs boson width and CP measurements	10
2.2	New results	10
2.2.1	Projection of the Higgs boson mass and on-shell width measurements in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel with CMS at the HL-LHC [206]	10
2.2.2	A projection of the precision of the Higgs boson mass measurement in the diphoton decay channel with CMS at the HL-LHC [205]	12
2.2.3	Study of sensitivity to the CP structure of the Yukawa coupling between the Higgs boson and t quarks with CMS at the HL-LHC [205]	12
2.2.4	Prospects for the precise measurement of the Higgs boson properties in the $H \rightarrow Z\gamma$ decay channel with CMS at the HL-LHC [205]	14
2.2.5	Projection of the search for $VH(H \rightarrow \tau\tau)$ with CMS at the HL-LHC [175]	14
2.2.6	Search for new Higgs boson decays with sensitivity with CMS at the HL-LHC [201]	16
2.2.7	Prospects for the measurement of $\sigma(H, H \rightarrow hh)$ production in the opposite-sign dilepton channel with CMS at the HL-LHC [201]	18
2.2.8	Sensitivity to $H \rightarrow hh$ and $H \rightarrow \tau\tau$ decays in VH production with ATLAS at the HL-LHC [65]	19
2.2.9	$H \rightarrow \tau\tau$ cross-section measurement results with ATLAS at the HL-LHC [67]	20
2.3	Higgs boson pair production and Higgs boson self-coupling: Yellow Report Summary	21
2.4	New results	24
2.4.1	Prospects for measuring HH production measurement in heavy final states with CMS at the HL-LHC [78]	24
2.4.2	Prospects for HH measurements in the $W^+W^- \gamma\gamma$ and $\tau^+\tau^- \gamma\gamma$ final states with CMS at the HL-LHC [78]	25
2.4.3	Search for the measurement of HH production in the semileptonic decay of the top quark pair and the Higgs boson pair decaying into 4 quarks with CMS at the HL-LHC [76]	26
2.4.4	Updated prospects of Higgs boson pair production in the $hh\gamma\gamma$ and $hh\tau^+\tau^-$ final states with ATLAS at the HL-LHC [77–80]	28
3	EPIC: EW Physics: Higgs boson as a portal to new physics	32
3.1	Yellow Report summary	32
3.1.1	Exotic Higgs boson decays and Higgs portal interpretations	32
3.1.2	Exotic decays of the 125 GeV Higgs boson	33
3.1.3	Searches for additional Higgs bosons	33
3.1.4	Searches for new massive resonances decaying into Higgs boson pairs	34
3.2	New results	35
3.2.1	Search for high mass resonances decaying into W^+W^- in the di-lepton final state with CMS at the HL-LHC [111]	35
4	EPIC: EW Physics: Heavy flavor and top quark physics	37
4.1	Yellow Report summary	37
4.1.1	Top quark mass measurements	37
4.1.2	Differential t -cross-section measurements	37
4.1.3	Study of rare processes involving top quarks	38
4.1.4	Constraints on new decaying particles from top quark decays	39
4.2	New results	40
4.2.1	Sensitivity to the measurement of the Standard Model top quark cross-section with ATLAS at the HL-LHC [122]	40
5	EPIC: Weak decays of b and c quarks	42
5.1	Yellow Report summary	42
5.1.1	Sensitivity studies for rare B_u and B_c decays in two modes	43
5.1.2	Sensitivity to the $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decay	43
5.1.3	CP violating phase ϕ_1 sensitivity in $B_c^0 \rightarrow \ell^+ \ell^-$ decay	45
6	EPIC: EW Physics: EW precision physics and constraining new physics	48
6.1	Weak mixing angle measurements	48
6.1.1	WW observables measurements	48
6.1.2	WW observables measurements	48
6.1.3	Charged lepton flavor violation	52
6.1.4	W boson decays	52
6.2	New results	53
6.2.1	Prospects for the measurement of vector boson scattering production in lepton WW and WZ observables with CMS at the HL-LHC [175]	53
7	EPIC: QCD and strong interactions: Precision QCD	58
7.1	Yellow Report summary	58
7.1.1	Inclusive cross-section measurements	58
7.1.2	Particle cross-section measurements	58
7.1.3	High p_T jet measurements at the HL-LHC	57
8	EPIC: QCD and strong interactions: Hadronic structure and forward QCD	59
8.1	New results	59
8.1.1	Sensitivity to $\gamma\gamma \rightarrow W^+W^- \rightarrow \ell^+\ell^+ \ell^-\ell^-$ with ATLAS at the HL-LHC [183]	59
9	EPIC: QCD and strong interactions: Heavy ions	61
9.1	Yellow Report summary	61
9.1.1	Jet modification studies	61
9.1.2	Heavy flavor hadrons	61
9.1.3	Particle collectivity in small and large systems	63
9.1.4	Hadron production distribution functions	64
9.1.5	Ultra-peripheral collisions	64
9.2	New results	65
9.2.1	Measurement of the $\gamma\gamma \rightarrow \tau^+\tau^-$ process with CMS at the HL-LHC [208]	65
10	EPIC: BSM: Model specific explorations	68
10.1	Yellow Report summary	68
10.1.1	Searches for new-like electroweak bosons	68
10.1.2	Searches for compressed mass spectrum	71
10.1.3	Searches for stops	72
10.1.4	Searches for stops	72
10.1.5	Searches for vector leptoquarks	73
10.1.6	Search for a 2HDM model with low top quarks	74
10.2	New results	74
10.2.1	Hadronic electroweak supersymmetry search with CMS at the HL-LHC [221]	74
10.2.2	Search for top squarks in final states with two top quarks and several light flavor jets with CMS at the HL-LHC [245]	75
10.2.3	Search for long-lived Z' resonances decaying to dijets in the dilepton plus missing transverse energy final state with CMS at the HL-LHC [246]	77
10.2.4	Search for dark matter production in final states with CMS at the HL-LHC [247]	77
11	EPIC: BSM: More general explorations	80
11.1	Yellow Report summary	80
11.1.1	Complement	80
11.1.2	New gauge bosons and resonances	82
11.1.3	Long-lived particles and displaced signatures	84
11.2	New results	86
11.2.1	Sensitivity projections for a search for new phenomena at high dilepton mass with CMS at the HL-LHC [261]	86
12	EPIC: BSM: Dark matter at colliders	88
12.1	Yellow Report summary	88
12.1.1	Search for DM produced in association with a Z boson	88
12.1.2	W - W and W - W and W - W final states	89
12.1.3	Monopole search for WIMPs	91
12.1.4	Single-top quark in association with invisible particles	91
12.1.5	Heavy quarks produced in association with dark matter	92
12.1.6	Search sensitivity for dark photons decaying to displaced muons	92
13	Summary	96

• Heavy flavor and top quark physics

– Particle properties and rare processes

• Precision electroweak measurements

– $\sin^2 \theta_{\text{eff}}, m_W$

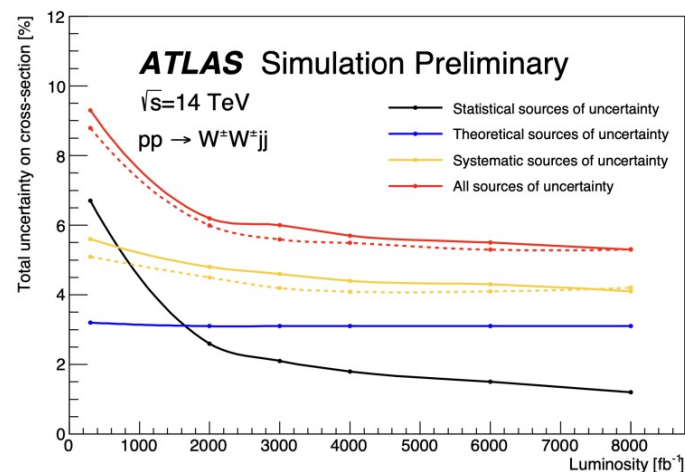
– Vector boson scattering

• QCD measurements

– Can constrain PDFs and the running of α_s

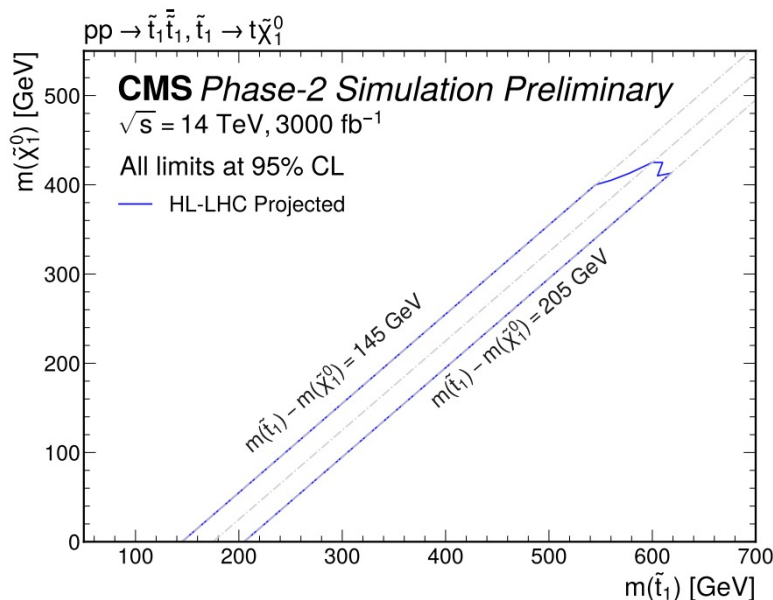
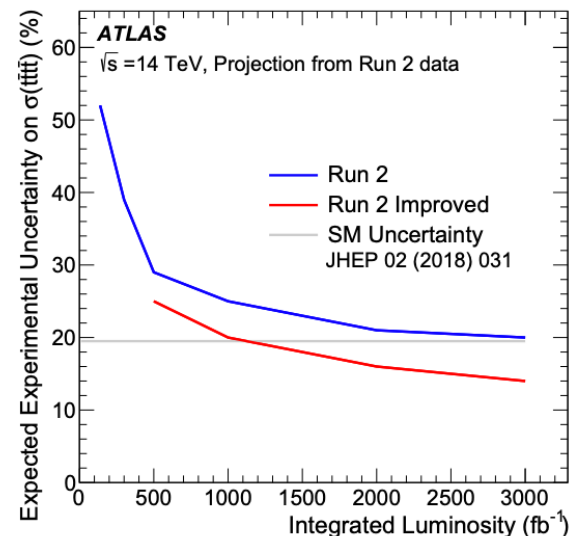
– Better understanding of backgrounds for many other analyses

• The HL-LHC as a photon collider




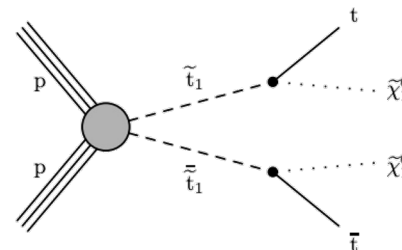
Top quark physics

- Projected measurement of the **four top** cross section
 - SM cross section = $16 \text{ fb}^{+18\%}_{-21\%}$
 - Enhancement predicted by many BSM processes (gluinos, scalar gluons, heavy boson + tt)
 - Expect $4\text{-}5\sigma$ sensitivity to SM process



Top quark **spin correlations** ([new](#))

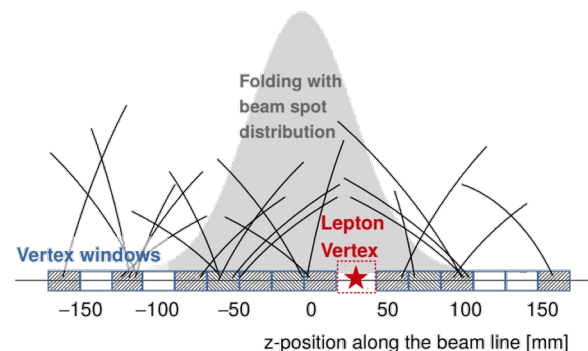
- Opposite sign $e\mu$ final state
- Systematics dominated by theory
-  Used in a multivariate search for stop squark pair production where $|\text{Im}(\text{stop}) - m(\chi_1^0)| \sim m(\text{top})$



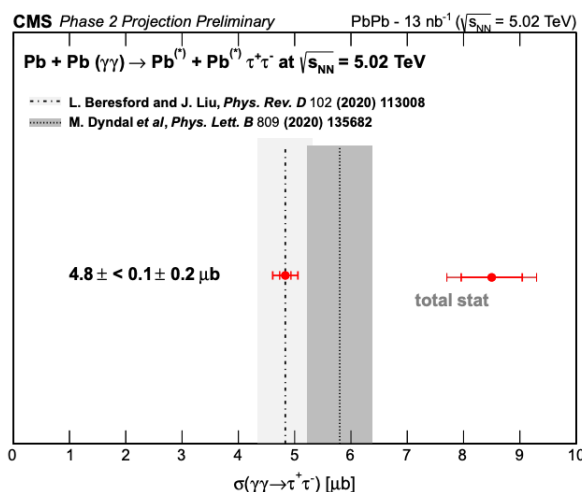
Photon-photon collisions ☀

- **Exclusive WW** in pp ($\gamma\gamma \rightarrow WW \rightarrow e\nu \mu\nu$)

- Sensitive to anomalous gauge boson couplings
- Allow no tracks aside from W boson decay. Pileup makes this really hard!
- 🧠🔧 Investigation of how to maximize detector upgrades for low p_T tracking, rejection of fake tracks, η coverage
- Expect total uncertainty reduction of $\sim 50\%$ at high dilepton mass



- Ultra-peripheral collisions of **$\gamma\gamma \rightarrow \tau\tau$ in Pb-Pb**



- Final state with $\mu + 3$ charged particles
- 4x more precise cross section at HL-LHC vs. Run 2
- Sensitive to anomalous magnetic moment of the tau $(g-2)_\tau$
- 🧠 With new analysis ideas & channels, could surpass existing constraints on $(g-2)_\tau$

Physics beyond the SM at the HL-LHC

Contents

1	Introduction	8
2	EW Physics: Higgs boson properties and couplings	7
2.1	Precision Higgs Measurements at the HL-LHC: Yellow Report Summary	7
2.1.1	Higgs boson production cross-sections and decay branching ratios: measurements and interpretations	8
2.1.2	Differential measurements	9
2.1.3	Higgs boson width and CP measurements	10
2.2	New results	10
2.2.1	Projection of the Higgs boson mass and on-shell width measurements in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel with CMS at the HL-LHC [206]	10
2.2.2	A projection of the precision of the Higgs boson mass measurement in the diphoton decay channel with CMS at the HL-LHC [205]	12
2.2.3	Study of sensitivity to the CP structure of the Yukawa coupling between the Higgs boson and t -quarks with CMS at the HL-LHC [207]	12
2.2.4	Prospects for the precise measurement of the Higgs boson properties in the $H \rightarrow Z\gamma$ decay channel with CMS at the HL-LHC [208]	13
2.2.5	Projection of the search for $VH(H \rightarrow c\bar{c})$ with CMS at the HL-LHC [171]	14
2.2.6	Search for Higgs boson decays with neutralinos with CMS at the HL-LHC [209]	16
2.2.7	Prospects for the measurement of $(\delta H, H \rightarrow hh)$ production in the opposite-sign dilepton channel with CMS at the HL-LHC [201]	18
2.2.8	Sensitivity to $H \rightarrow h\bar{h}$ and $H \rightarrow c\bar{c}$ decays in VH production with ATLAS at the HL-LHC [85]	19
2.2.9	$H \rightarrow \tau\tau$ cross-section measurement results with ATLAS at the HL-LHC [67]	20
2.3	Higgs boson pair production and Higgs boson self-coupling: Yellow Report Summary	21
2.4	New results	24
2.4.1	Prospects for measuring Higgs production measurement in heavy final states with CMS at the HL-LHC [74]	24
2.4.2	Prospects for Higgs measurements in the $W^+W^- \gamma\gamma$ and $\gamma^*\gamma^* \gamma\gamma$ final states with CMS at the HL-LHC [75]	25
2.4.3	Search for the measurement HH production in the monophoton decay of the top quark pair and the Higgs boson pair decaying into a quark with CMS at the HL-LHC [76]	26
2.4.4	Updated prospects of Higgs boson pair production in the $hh\gamma\gamma$ and $hh\nu\bar{\nu}$ final states with ATLAS at the HL-LHC [77–80]	28
3	EW Physics: Higgs boson as a portal to new physics	32
3.1	Yellow Report summary	32
3.1.1	Searches for Higgs boson decays and Higgs portal interpretations	32
3.1.2	Exotic decays of the 125 GeV Higgs boson	33
3.1.3	Searches for additional Higgs bosons	33
3.1.4	Searches for new massive resonances decaying into Higgs boson pairs	34
3.2	New results	35
3.2.1	Search for high mass resonances decaying into W^+W^- in the dilepton final state with CMS at the HL-LHC [111]	35
4	EW Physics: Heavy flavor and top quark physics	37
4.1	Yellow Report summary	37
4.1.1	Top quark mass measurements	37
4.1.2	Differential d -cross-section measurements	37
4.1.3	Study of rare processes involving top quarks	38
4.1.4	Constraints on flavor-changing neutral-current couplings	39
4.2	New results	40
4.2.1	Sensitivity to the measurement of the Standard Model low top quark cross-section with ATLAS at the HL-LHC [122]	40
5	EW Physics: Weak decays of b and c quarks	42
5.1	Yellow Report summary	42
5.1.1	Sensitivity studies for rare B_u and B_s decays in two modes	43
5.1.2	Sensitivity to the $B^0 \rightarrow K^{*0} \gamma$ decay	43
5.1.3	CP violating phase ϕ_1 sensitivity in $B_s^0 \rightarrow J/\psi$ decay	45
6	EW Physics: EW precision physics and constraining new physics	48
6.1	Yellow Report summary	48
6.1.1	Weak mixing angle measurements	48
6.1.2	W -boson measurements	50
6.1.3	Charged lepton flavor violation	52
6.1.4	W boson mass	52
6.2	New results	53
6.2.1	Prospects for the measurement of neutrino scattering production in leptonic WW and WZ diboson events with CMS at the HL-LHC [175]	53
7	EW Physics: QCD and strong interactions: Precision QCD	58
7.1	Yellow Report summary	58
7.1.1	Jet cross-section measurements	58
7.1.2	Photon cross-section measurements	58
7.1.3	High- p_T jet measurements at the HL-LHC	57
8	EW Physics: QCD and strong interactions: Hadronic structure and forward QCD	59
8.1	New results	59
8.1.1	Sensitivity to $\gamma\gamma \rightarrow W^+W^- \rightarrow \ell^+\ell^-\nu\bar{\nu}$ with ATLAS at the HL-LHC [183]	59
9	EW Physics: QCD and strong interactions: Heavy ions	61
9.1	Yellow Report summary	61
9.1.1	Jet modification studies	61
9.1.2	Heavy flavor hadrons	61
9.1.3	Particle collectivity in small and large systems	63
9.1.4	Flow for particle distribution functions	64
9.1.5	Ultra peripheral collisions	64
9.2	New results	65
9.2.1	Measurement of the $\gamma\gamma \rightarrow \ell^+\ell^-$ process with CMS at the HL-LHC [208]	65
10	EW Physics: BSM: Model specific explorations	68
10.1	Yellow Report summary	68
10.1.1	Searches for new-like electroweak bosons	68
10.1.2	Searches for compressed mass spectrum	71
10.1.3	Searches for stops	72
10.1.4	Searches for stops	72
10.1.5	Searches for vector leptoquarks	73
10.1.6	Search for a ZH-like model with top quarks	74
10.2	New results	74
10.2.1	Hadronic electroweak supersymmetric search with CMS at the HL-LHC [221]	74
10.2.2	Search for top quarks in final states with two top quarks and several light-flavor jets with CMS at the HL-LHC [245]	75
10.2.3	Search for long-lived Z' resonances decaying to dijets in the dilepton plus missing transverse energy final state with CMS at the HL-LHC [246]	77
10.2.4	Resonance model searches using multiplicity final states with CMS at the HL-LHC [247]	78
11	EW Physics: BSM: Mass general explorations	80
11.1	Yellow Report summary	80
11.1.1	Compositeness	80
11.1.2	New gauge bosons and resonances	82
11.1.3	Long-lived particles and displaced signatures	84
11.2	New results	86
11.2.1	Sensitivity projections for the search for new phenomena at high dilepton mass with CMS at the HL-LHC [250]	86
12	EW Physics: BSM: Dark matter at colliders	88
12.1	Yellow Report summary	88
12.1.1	Search for DM produced in association with a Z boson	88
12.1.2	W - WZ and W - WW production final states	89
12.1.3	Monophoton searches for WIMPs	91
12.1.4	Single-top quark in association with invisible particles	92
12.1.5	Heavy quarks produced in association with dark matter	92
12.1.6	Search sensitivity for dark photons decaying to displaced muons	92
13	Summary	96

• Supersymmetry

– Strong SUSY is well constrained by the LHC, but HL-LHC probes smaller cross sections, mass splittings

– Potential increase of 20x in sensitivity to electroweak SUSY

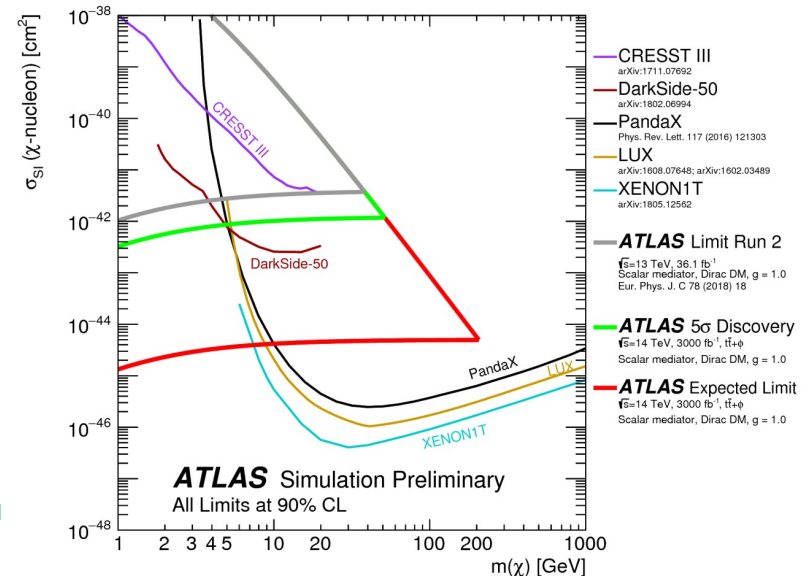
• Heavy resonances

• Long-lived particles



– Requires dedicated triggers and reconstruction algorithms

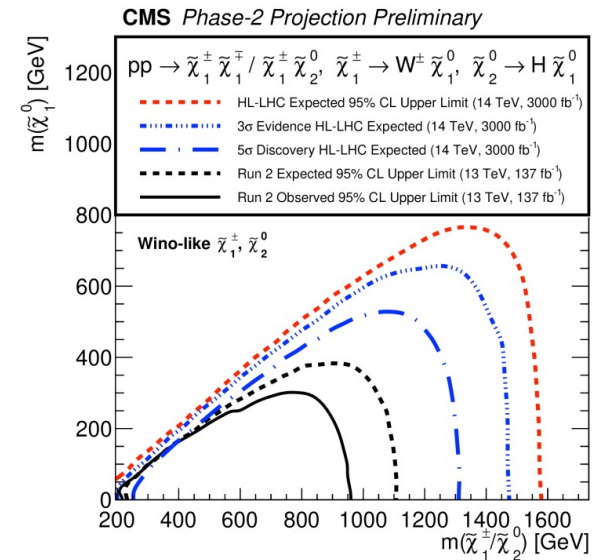
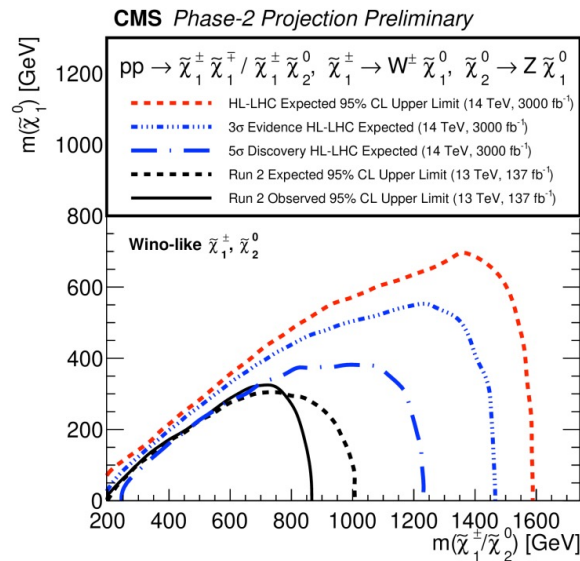
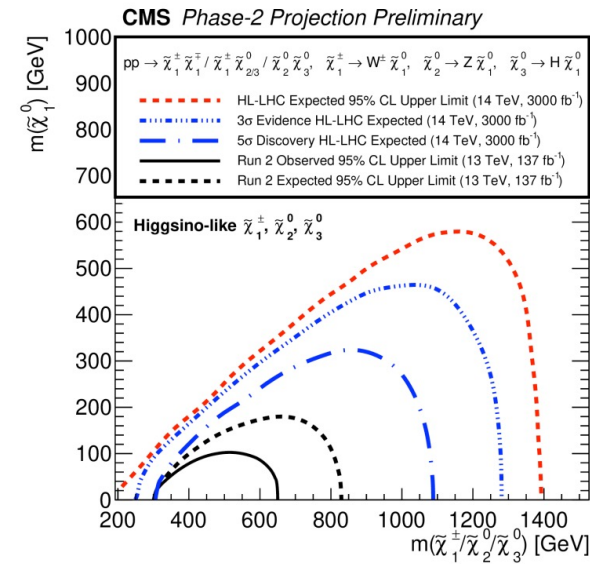
• Dark matter

- Searches for DM accompanied by SM particle(s)
- Complementary to direct detection experiments





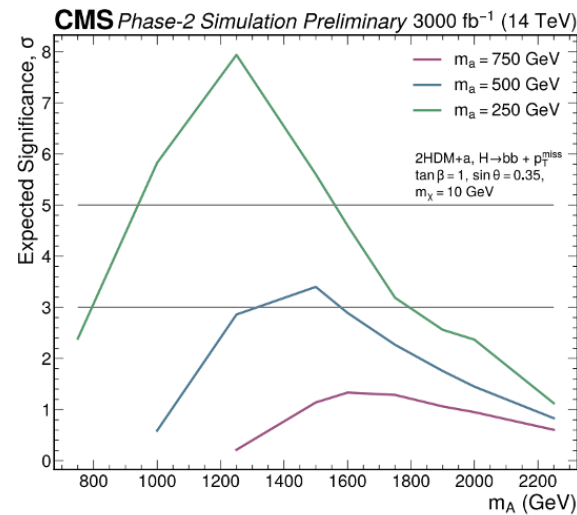
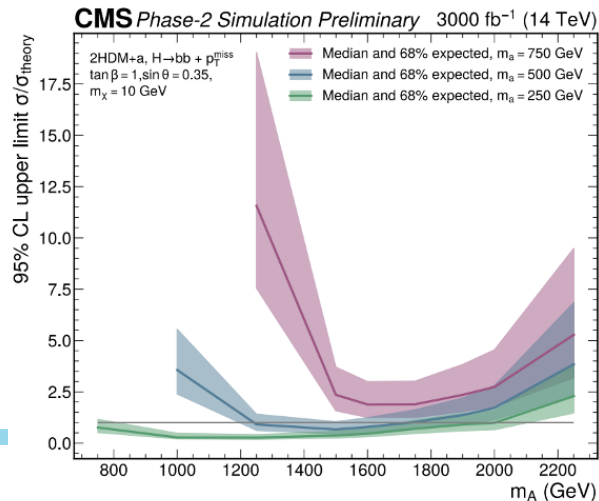
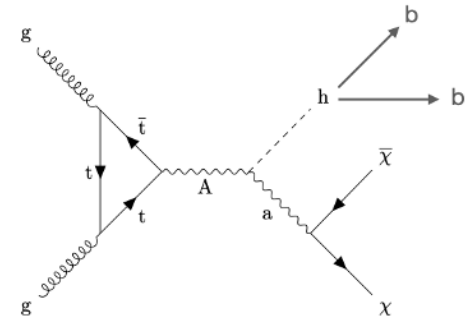
EWK SUSY with hadronic probes

- Pair production of NLSP: charginos, heavy neutralinos
 - $\chi_1^+ \rightarrow W^+ \chi_1^0$, $\chi_2^0 \rightarrow Z \chi_1^0$, $\chi_2^0 \rightarrow H \chi_1^0$
 - Then hadronic W, Z, H decays (  boosted jet reco and flavor tagging)
- Coverage in NLSP mass extended by 600-750 GeV compared to Run 2



Dark matter with boosted mono-Higgs

- Boosted $H \rightarrow bb$ decay + missing transverse energy ([new](#))
 -   Gains from boosted jet tagging, improved vertexing (e.g. tracking, precision timing)
- Interpreted in type II 2HDM + additional light pseudoscalar boson (a)
 - For lighter a , get more boosted H and higher acceptance
 - Projections could exclude 1-2 TeV m_A for $m_a < 500$ GeV
 - 5σ discovery reach: m_A 1-1.6 TeV for $m_a = 250$ GeV

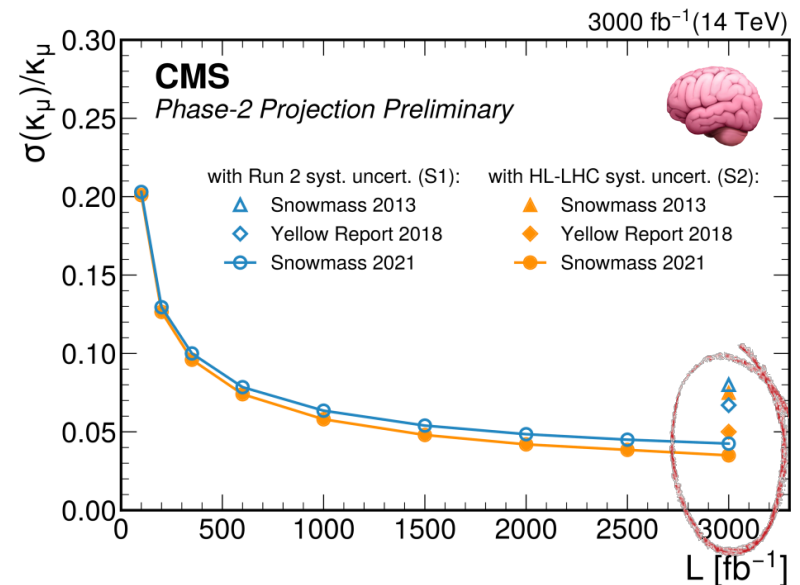


Conclusions

- The HL-LHC is the **immediate future** of physics on the energy frontier
- Along with accompanying upgrades, will be very powerful for physics across **Higgs**, **SM**, and **BSM**
 - Gains from high **luminosity**, **detector upgrades**, and new clever **algorithms**
- We've barely begun and are always improving!
- HL-LHC will provide a massive amount of new knowledge
 - Legacy will last for decades to come




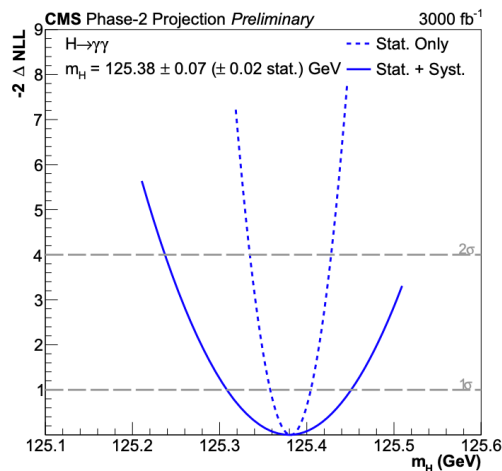
The future is bright!





Extras

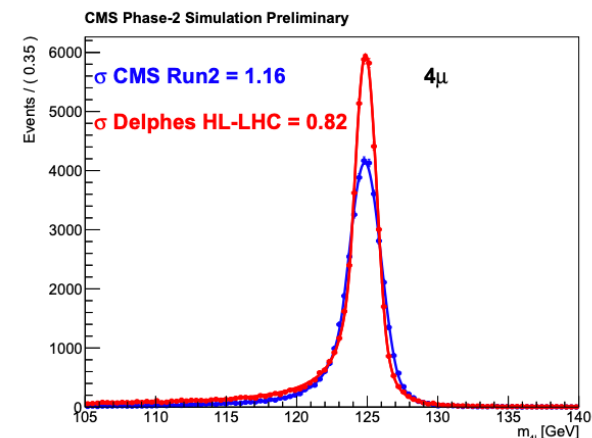
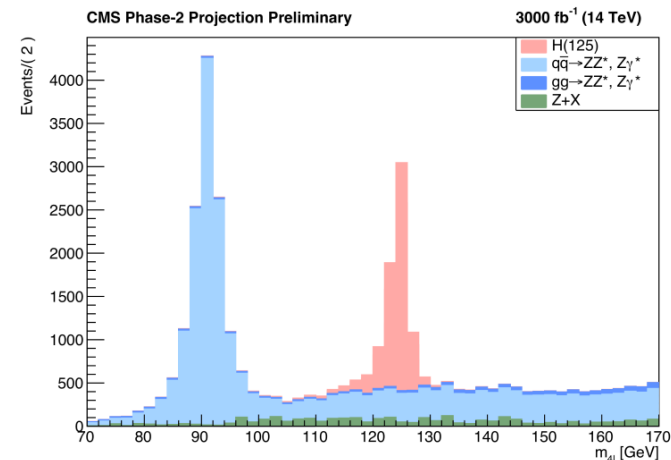
Higgs mass and width

- With run 2 data, combined $m_H = 125.38 \pm 0.14$ GeV
- $H \rightarrow ZZ \rightarrow 4\ell$
 - Channels: $4e, 4\mu, 2e2\mu, 2\mu2e$
 - $m_H = 125.38 \pm 0.03(\text{stat}) \pm 0.02(\text{sys})$ GeV
 - $\Gamma_H < 0.09$ (0.18) GeV at 68% (95%) CL
 -  Detector upgrades give better mass resolution, especially 4μ



• $H \rightarrow \gamma\gamma$

- $m_H = 125.38 \pm 0.02$ (stat) ± 0.07 (syst) GeV
- Benefits from  tracker and HGCAL upgrades,  photon energy calibration
- Systematics dominated by photon energy scale



BSM Higgs 🌞

- **Heavy Higgs** \rightarrow **WW**, $W \rightarrow e\nu$, $W \rightarrow \mu\nu$
 - 🧠 Multivariate analysis rejects background
 - Interpreted in several BSM scenarios, including MSSM and THDM
 - THDM run 2 limit at $m_H \sim 700$ GeV

