Multi-Boson Interactions
CMS HL-LHC Multi-boson Physics Prospect

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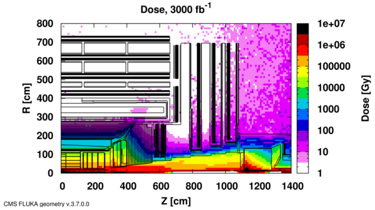
High Luminosity LHC

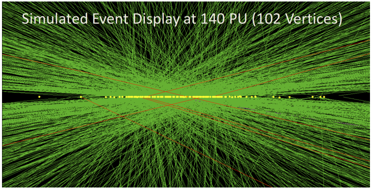
The High Luminosity LHC will shine a bright light on the dark corners of the SM.

The HL-LHC - A challenging environment

	Baseline Scenario	Upper limit
$\sqrt{s}$ (TeV)	14	14
Instan. L ($cm^{-2}s^{-1}$)	5×10^{34}	7.5×10^{34}
Integr. L (fb^{-1})	3000	4000
$< PU >$	140	200

5-7 times current Luminosity





CMS Phase II

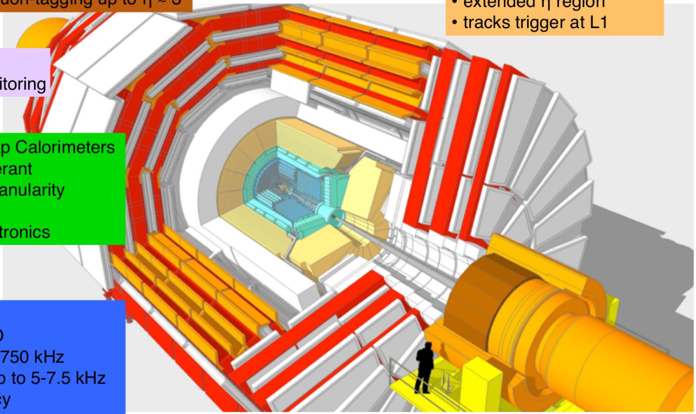
Muon System
- new DT FE electronics, CSC FEBs in inner rings
- extended η region (GEM & iRPC)
- investigate Muon-tagging up to η ~ 3

New luminosity and beam monitoring

Replace Endcap Calorimeters
- radiation tolerant
- increased granularity

Barrel ECAL
- new FE electronics

Trigger/DAQ
- new FE & RO
- L1 up to 500-750 kHz
- HLT output up to 5-7.5 kHz
- 12.5μs latency
- tracking @L1



Tracker
- higher granularity
- less material
- better p_T resolution
- extended η region
- tracks trigger at L1

MBI Physics Goals at HL

Gauge sector physics is central component of the SM HL program:

- High statistics studies of diboson states
- Observation of triple gauge boson production
- Observation of vector boson scattering
- Measurement of quartic gauge coupling constants ($WW\gamma\gamma$, $WWZ\gamma$, WWWW, WWZZ)
- Searches for higher mass scale physics through aTGC and aQGC

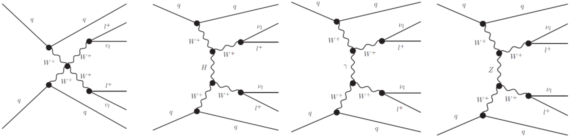
Higgs sector has multi-boson interaction within reach at HL:

- Measurement of di-Higgs production

CMS MBI studies for the HL-LHC

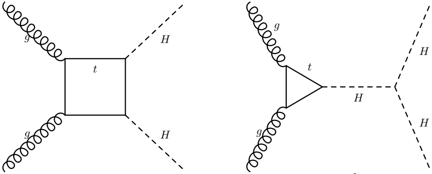
Vector Boson Scattering:

- Precision measurement in the electroweak sector with sensitivity to the electroweak symmetry breaking
- Test of the Higgs boson nature: $V_L V_L$ scattering unitarity relies on strong cancellations with Higgs diagrams

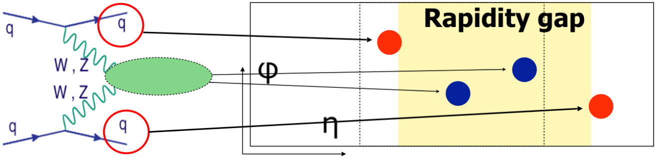


Higgs pair production:

- Measurement of the Higgs boson self coupling
- Probe third derivative Higgs field potential at its minimum to discriminate against BSM models



Vector Boson Scattering Topology

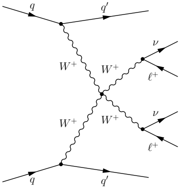


- Two highly energetic, forward 'tag jets' (identified as highest p_T jets) with large m_{jj} and $\Delta\eta_{jj}$
- Central leptons, MET
- Low amount of soft, hadronic activity in central-rapidity region

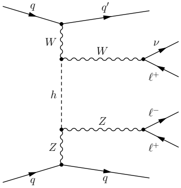
CMS Phase II: Measurement is enabled by improved forward jet reconstruction from tracker and calorimeter extensions and higher granularity.

VBS final states

Study of $W^{\pm}W^{\pm}$ and WZ scatting in the fully leptonic final states:



$$pp \rightarrow W^{\pm}W^{\pm}\ jj$$
$$\rightarrow l^{\pm}\nu\ l^{\pm}\nu\ jj$$



$$pp \rightarrow W^{\pm}Z\ jj$$
$$\rightarrow l^{\pm}\nu\ l^{+}l^{-}\ jj$$

$W^{\pm}W^{\pm}jj$ backgrounds:

- Jets misidentified as leptons (semi-leptonic $t\bar{t}$, W+jets)
- WW QCD, WZ and charge misassignment

$W^{\pm}Zjj$ backgrounds:

- Fake lepton background negligible ($\eta_{lep} < 2.5$)
- WZ QCD and ZZ

Benchmarks

- Cross section measurement
- Longitudinal scattering cross section:
  $V_L V_L \to V_L V_L$ unitarized through the presence of the Higgs boson
- Partial unitarization:
  In theories involving more than a single Higgs boson, unitarization of VBS is only partially operated by the Higgs boson.
- Anomalous couplings (EFT):
  New physics in the EWK sector at a high mass scale could lead to strong enhancements in the cross section at high energy

Detector configurations

To assess VBS sensitivity at the HL-LHC three scenarios are studied:

- Phase II, 140 PU
- Phase I aged, 140 PU:
  Without phase II upgrade and including radiation damage after 1 ab^{-1}
- Phase I, 50 PU:
  Current non-aged detector and data conditions

Target: Maintain the Phase I configuration performance throughout HL period

Detector simulation with Delphes:

- Fast multipurpose detector response simulation framework
- Simplified detector geometries and parameterization of efficiencies and resolutions
- Parameterizations tuned and verified by comparison to full CMS GEANT4-based simulation

Fake lepton background

Backgrounds containing a jet misidentified as a lepton (probability $\sim 10^{-5}$)

- Dominant background $W^{\pm}W^{\pm}$ scattering from semi-leptonic ttbar events

Measure fake lepton probability from detailed-simulation sample:

- step 1: Determine probability for a jet to be geometrically matched to a fake lepton (i.e. not produced by the generator)
- step 2: Correlation matrix between the matched jet P_T and the fake lepton P_T
- Both steps calculated separately for b jets and non-b jets

The results are cross-checked on several detailed-simulation samples.

To account for non-reliable normalization of the fake rate probability measured from simulation, results of the analysis are plotted as a function of a global fake rate scale factor.

Event Selection

Basic objects:

- tight leptons with $p_T > 20$ GeV and $|\eta| < 2.5$
- At least 2 jets with $p_T > 30$ GeV
- MET > 30-40 GeV
- extra loose lepton veto

VBS topology cuts:

- $m_{jj} > 625 - 850$ GeV
- $\Delta\eta_{jj} > 3 - 4$

WW cuts:

- Z mass veto
- b veto (loose b-tagging WP)
- soft muon veto (in jet cone)
- η_{l1} and η_{l2} between η_{jets}
- H_T (track jets) < 125 GeV (150GeV for phase II)
- $m_{ll} > 40$ GeV
- $\Delta R(JJ, LL) < 6$
- $\Delta\eta_{ll} < 2$

WZ cuts:

- Z mass selection
- $m_{ll} > 20$ GeV for same flavour opposite charge lepton pairs

Analysis strategy

Classify events according to lepton flavour and charge:

WW:

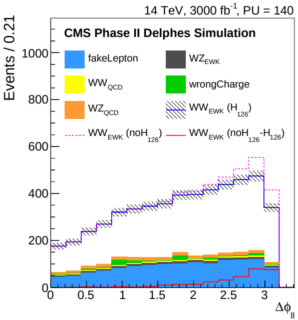
- Flavour: EE/MM/EM/ME
- Charge: ++ / − −

WZ:

- Flavour: EEE/UUU/EEU/UUE

Perform 2D binned fit for each category and for every benchmark

- Best variables chosen with a scan on a large set of combinations



Cross section results

EWK $W^{\pm}W^{\pm}jj$ XS uncertainty at the order of 5%, close to the systematic limit, after 3ab^{-1}

EWK WZ scattering XS uncertainty at the order of 10% after 3ab^{-1}

Systematics:

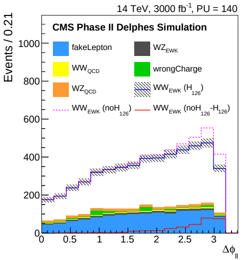
- Theoretical uncertainties are taken from RunI analysis
- Experimental uncertainties:

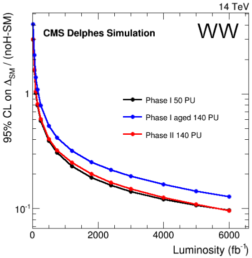
  PhaseI and PhaseII:
  uncertainties from RunI analysis

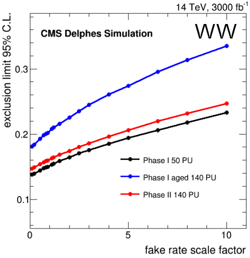
  Phase I aged:
  several systematics are downgraded (from detailed simulation comparison)

Partial unitarization results

- Use (noH - H) excess as signal and SM contribution as background
- Expected 95% CL exclusion limit can be calculated on fraction of difference $\Delta_{SM}/(noH - SM)$
- Excluded signal strength is well below 1 for $3ab^{-1}$







Samples generated with Phantom

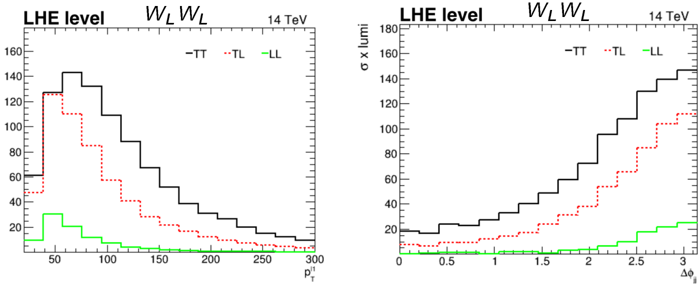
Combined WW and WZ result:

	Phase I	Phase II	Phase I aged
noH 95% CL exclusion	0.14	0.14	0.20

Phase II scenario recovers performance phase I scenario.

Longitudinal scattering

- $V_L V_L$ component is considered as signal, $V_L V_T$ and $V_T V_T$ as backgrounds
- Signal is much reduced w.r.t. the total EWK scattering

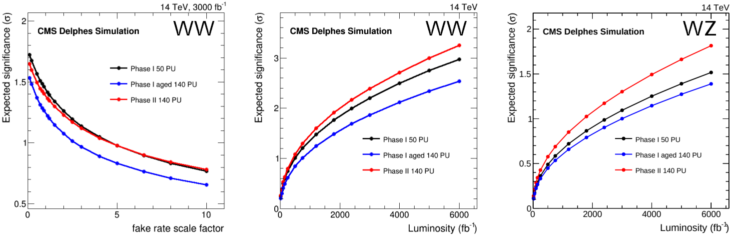


Madgraph v5.2.2.3 + decay package

Sensitivity from the low lepton P_T region.

Electroweak $V_L V_L\ jj$ results

- Expected significance after $3ab^{-1}$ at the level of 2σ for $W^{\pm}W^{\pm}jj$ and 1σ for $WZjj$



Combined result:

	Phase I	Phase II	Phase I aged
$V_L V_L$ scattering significance (σ)	2.50	2.75	2.14

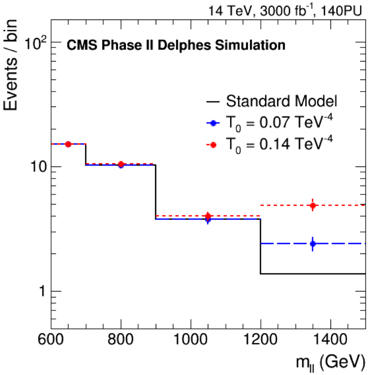
Phase II performs better due to improved lepton reconstruction for low P_T leptons.

$W^{\pm}W^{\pm}jj$ EFT

- New physics effects are parametrized by including higher dimension operators (8th order) in SM Lagrangian
- Exclusion limits on associated coefficients set through binned template fit on m_{ll}

$$\mathcal{L} = \mathcal{L}_{SM}\left(+\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}\right) + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

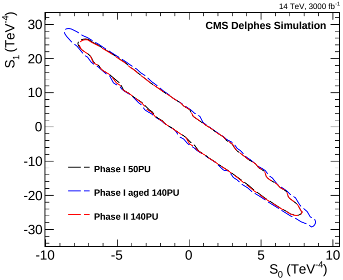
$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$



$W^{\pm}W^{\pm}jj$ EFT results

- Expected upper 95% CL limits on the coefficients for the dimension eight operators
- Combination S0-S1: only modifies SM quartic gauge coupling

	phase I	phase II	phase I aged
S_0	1.06	1.07	1.17
S_1	3.51	3.55	3.87
M_0	0.78	0.75	0.82
M_1	1.10	1.06	1.14
M_6	1.56	1.49	1.63
M_7	1.37	1.32	1.45
T_0	0.067	0.077	0.083
T_1	0.036	0.033	0.036
T_2	0.119	0.111	0.119



Limits from the 8 TeV analysis are 30 - 60 times higher

VBS expectations

Run 2 (100fb^{-1}):

- Expected discovery of EWK $W^{\pm}W^{\pm}$jj production

Run 3 (300fb^{-1}):

- Expected discovery of EWK WZjj production
- Precision on the total XS of the EWK VBS processes at the order of $10-20\%$,
  Sensitivity to partially-unitarized models is expected:
  95% CL exclusion for 0.6 times the (noH - H) difference

HL-LHC (3000fb^{-1}):

- Sensitivity to partially-unitarized models:
  95% CL exclusion for 0.14 times the (noH - H) difference
- Sensitivity to aQGC strongly enhanced
- Detecting the longitudinal component of the VV scattering remains challenging, expected significance of 2.75 σ

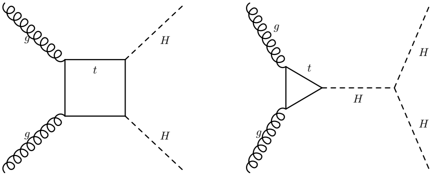
Room for improvements:

- Conservative estimates for pixel detector performance, possible improvements in reconstruction algorithms
- b-tagging only up to $|\eta| < 2.5$
- Longitudinal scattering analysis strategy
- Semi-leptonic final states unexplored

Di-Higgs final states

Study of Higgs pair production in three final states

- Destructive interference gives very low NNLO cross section of $\sim 40\text{fb}^{-1}$ in gluon fusion production mode, 1000 times smaller than single Higgs production
- Without Higgs self-coupling cross section x 2



$HH \to bb\gamma\gamma$

- Exp. events (3ab^{-1}): 320
- MC with smearing functions

$HH \to bb\tau\tau$

- Exp. events (3ab^{-1}): 9000
- Combination of MC and Delphes

$HH \to bbWW$
$\to bbl\nu l\nu$

- Exp. events (3ab^{-1}): 1500
- Delphes simulation

$HH \to bb\gamma\gamma$

Backgrounds:

- Resonant: ZH, $t\bar{t}H$, $b\bar{b}H$
- Non-resonant: $b\bar{b}\gamma\gamma$, $jj\gamma\gamma$, $b\bar{b}j\gamma$, $b\bar{b}jj$, $jjjj$ and $t\bar{t}(\gamma)$
  Produced at generator level and weighted by mis-tagging efficiencies and mis-identification rates.

$g \to \gamma$	10^{-4}
$q \to \gamma$	5×10^{-4}
light $j \to b$	1%
$c \to b$	20%
$e \to \gamma$	1%

k-factor ~ 2

Two categories:

- 2 photons in barrel / at least 1 photon in endcap
- Dominant backgrounds: $b\bar{b}\gamma\gamma$, $b\bar{b}j\gamma$ / $b\bar{b}j\gamma$, $b\bar{b}jj$

Event Selection:

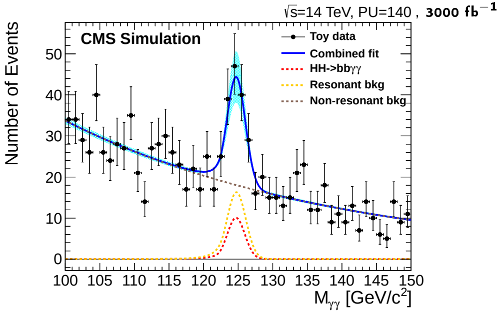
- 2 photons with $P_T > 40$, 25 GeV and $|\eta| < 2.5$
- 2 b-tagged jets with $P_T > 30$ GeV and $|\eta| < 2.4$
- loose lepton veto
- #jets < 4
- $\Delta R_{\gamma,\gamma} < 2.0$
  $\Delta R_{bb} < 2.0$
  $min\left(\Delta R_{\gamma b}\right) > 1.5$

$HH \to bb\gamma\gamma$ - Signal Extraction

Fitting the double Higgs peak:

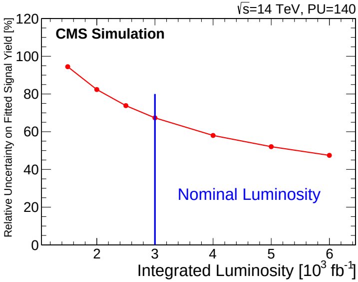
- 2D maximum likelihood fit on $M_{\gamma\gamma}$ and M_{bb}
- PDF's fitted on MC:
  Crystal Ball for resonances, decaying exponential for non-resonant backgrounds
- Correlation $M_{\gamma\gamma}$ and M_{bb} assumed to be negligible

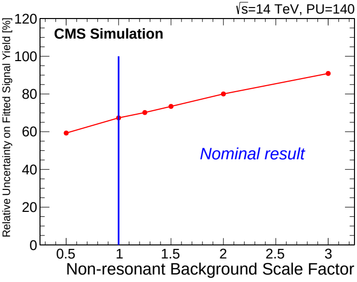
Example toy experiment for category with two photons in barrel:



$HH \to bb\gamma\gamma$ - Results

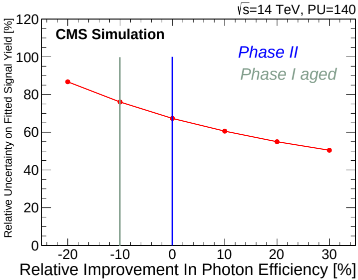
Relative uncertainty on fitted signal yield (%):





- Expected significance at 3ab^{-1}: 1.6σ
- Result dominated by statistical uncertainties

$HH \rightarrow bb\gamma\gamma$ - CMS upgrade



Small improvement to the selection efficiencies would have significant impact on the analysis sensitivity.

$HH \rightarrow bb\tau\tau$

Backgrounds:

- Resonant: ZH, $t\bar{t}H$
- Non-resonant: $t\bar{t}$, DY, tV, $t\bar{t}V$, VV
  Combination of Delphes and generator level weighted by efficiencies.

Two categories:

- $\tau_h\tau_h$ / $\tau_h\tau_\mu$
  τ_h: Hadronic tau decays
  τ_μ: Tau decays to μ

Event Selection:

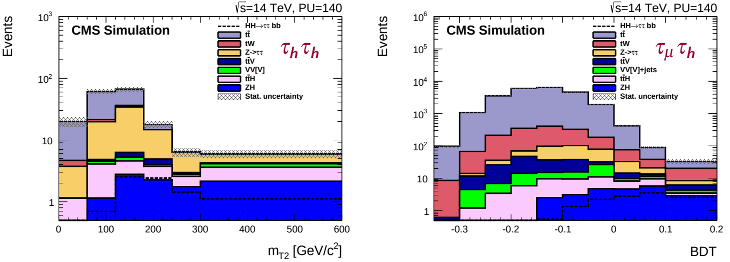
≥ 2 b-tagged jets with $p_T > 30$GeV, $\lvert\eta\rvert < 2.4$
$\tau_h\tau_h$ final state ≥ 2 isolated τ_h-s with $p_T > 60$GeV or $p_T > 90/45$GeV, $\lvert\eta\rvert < 2.1$
$\tau_\mu\tau_h$ final state An isolated τ_h with $p_T > 30$GeV, $\lvert\eta\rvert < 2.1$ and an isolated τ_μ with $p_T > 30$GeV, $\lvert\eta\rvert < 2.5$
90GeV $< m_{bb} <$ 130GeV and 110GeV $< m_{\tau\tau} <$ 140GeV

$m_{\tau\tau}$ reconstructed with likelihood based technique (SVFIT), important to discriminate against $Z \rightarrow \tau\tau$.

$HH \to bb\tau\tau$ - Analysis strategy

Define kinematic bounding variable m_{T2} to discriminate against $t\bar{t}$:

- Maximal possible mass of the parent particle (t or H) consistent with the constraints
- Bounded above by the top mass for $t\bar{t}$ events, unbounded for di-Higgs signal events



To further exploit the boosted kinematics of di-Higgs production, a BDT is trained on masses, P_T, ΔR and m_{T2}

$HH \to bb\tau\tau$ - Results

Signal extraction:

- $\tau_h \tau_h$: Maximum likelihood fit on m_{T2}
- $\tau_\mu \tau_h$: Has a much larger leptonic $t\bar{t}$ background
  Maximum likelihood fit on BDT output

Expected significance:

- 0.5 and 0.7σ for $\tau_\mu \tau_h$ and $\tau_h \tau_h$
- Total: 0.9σ

Strong dependance on capability to trigger at level 1 on charged particles with the Phase II CMS detector, otherwise sensitivity reduced by $\sim$40%.

$HH \to bbWW \to bbl\nu l\nu$

Backgrounds:

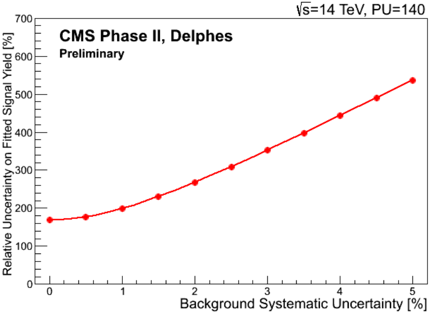
- Dominant background: $t\bar{t}$ production with fully leptonic decay
- Other backgrounds negligible
- Detector simulation with Delphes

Event Selection:

- 2 opposite sign leptons, muon $P_T > 20$ GeV, electron $P_T > 25$ GeV and $|\eta| < 2.5$
- 2 b-tagged jets with $P_T > 30$ GeV and $|\eta| < 2.5$
- $m_{ll} > 85$ GeV
- 60 GeV $< m_{bb} <$ 160 GeV
- $\Delta R_{ll} < 2.0$
  $\Delta R_{bb} < 3.1$
  $\Delta\phi_{bb,ll} > 1.7$

$HH \to bbWW \to bbl\nu l\nu$ Results

A neural network is trained on the kinematic properties, taking into account the correlations



- Result from cut and count on NN discriminator
- Small contribution to significance when combined with the other final states

Higgs Pair production expectations

HL-LHC ($3000 fb^{-1}$):

- Combining $bb\gamma\gamma$ and $bb\tau\tau$ final states, the expected significance is 1.9σ
- Observation might be possible, after improvements and combining CMS and ATLAS results

Room for improvements:

- More sophisticated reconstruction and analysis techniques
- Additional di-Higgs boson production and decay modes remain unexplored, especially promising *bbbb* final state when using boosted b-tagging techniques

Conclusions

Many interesting future MBI results with the LHC. At the short term:

- Observation of triple gauge boson states
- Discovery of EWK VV+2j production
- Improved measurements of the anomalous triple and quartic gauge couplings

At longer term, HL-LHC:

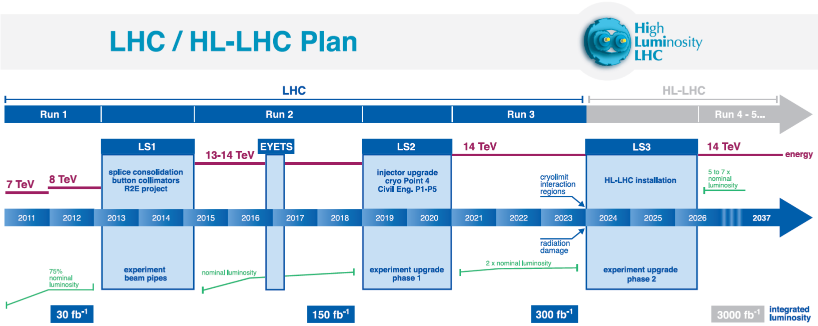
- Sensitivity to partially-unitarized models
- Possibility of discovering longitudinal vector boson scattering and di-Higgs production, but further study is required

Analyses will benefit from HL LHC and phase 2 upgrades:

- Tracker extension improves tag-jets identification in scattering analysis
- The ability to measure the di-Higgs production in the most promising final states will largely depend on the identification and momentum resolution performance for b-jet, photons and τ

Backup

HL-LHC plan


LHC / HL-LHC Plan
High Luminosity LHC
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13-14 TeV
14 TeV
14 TeV
energy
splice consolidation button collimators R2E project
injector upgrade cryo Point 4 Civil Eng. P1-P5
cryolimit interaction regions
HL-LHC installation
5 to 7 x nominal luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
radiation damage
75% nominal luminosity
experiment beam pipes
nominal luminosity
experiment upgrade phase 1
2 x nominal luminosity
experiment upgrade phase 2
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated luminosity