Future Physics with ATLAS and CMS at the HL-LHC



Vladimir Rekovic Vinca Institute, U. Belgrade On behalf of ATLAS and CMS DIS 2023, 26-30 March 2023 Michigan State University





Snowmass 2021: <u>https://snowmass21.org/</u>

- the US and its international partners.
- 10-year strategic plan.
- Organized in 10 frontiers: Energy, Neutrino, Rare processes & precision, Cosmic, Theory,
- Scientific results presented as white paper contributions (link)

ATLAS & CMS jointly contributed to the Energy Frontier

 White paper contribution: "Physics with the Phase-2 ATLAS and CMS Detectors" FTR-22-001, ATLAS-PHYS-PUB-2022-018, 17 March 2022.

• Particle physics community planning exercise: A scientific study bringing together the particle physics community to identify and document a scientific vision for the future of particle physics in

• The P5 (Particle Physics Project Prioritization Panel) takes the scientific input and develops a

Accelerator, Instrumentation, Computational, Underground facilities, Community engagement.





Snowmass White Paper Contribution: ATLAS & CMS

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10.1.5 Searches for scalar leptoquarks

10.1 Yellow Report summary

10.2 New results

- Summary of earlier results (mainly from the 2018-19) Yellow Reports (YRs) for the ESG).
- 1-page summaries of new results.









HL-LHC physics studies at ATLAS + CMS

ATLAS+CMS White Paper contents:

- 18 new studies by CMS: 12 new FTR PASes + 6 approved within Run2 analyses.
 - 3 more FTR PASes approved after WP,
- 7 new results by ATLAS.

Focus of studies:

- HL-LHC: 14 TeV, 3000 fb⁻¹
- Focus on new channels not (easily) accessible with the current data.
- Exploit enhanced detectors and coverage

Different methods to establish sensitivity:

- Projection from a present analysis: Use existing samples, scale results to cross section and higher luminosity for different systematics scenarios. -> ATLAS and CMS
- New analysis design: Use events with dedicated Phase-2 parametrized detector simulation **DELPHES**. -> only CMS.

Uncertainties treatment — different options used:

- Run 2 systematics: Use Run 2 values
- "YR18" systematics: A set of reduced uncertainties anticipated for Phase-2.
- Statistical-only uncertainties: The ultimately optimistic scenario with no systematics.
- Other analysis-specific scenarios.



Higgs prospects

Contributions to:

- EF01: Higgs boson properties and couplings
- EF02: Higgs boson as a portal to new physics

Plenary talk on Friday morning "Higgs Physics at HL-LHC" by Michaela Mlynarikova.

I will only give a few example teaser here.







Improved tracker lower material budget, Precision of HGCAL, PU suppress by MTD, Muon extend $|\eta| < 2.8$

Higgs mass and on-shell width results, by scaling X-section and luminosity from Run 2.

 $H \rightarrow ZZ \rightarrow 4I$: Improved uncertainties associated with mass resolution and lepton ID.

measure and correct the non-linear discrepancies in $E(\gamma)$ scale.

	Mass	(GeV)	Width		
	Run 2	Phase II	Run 2	Phase II	
$H \rightarrow ZZ \rightarrow 4I$	125.38		0.41	0.09	
	$\pm 0.20^{(stat)} \pm 0.08^{(sys)}$	± 0.03(stat) ± 0.02(sys)			
$H \rightarrow \gamma \gamma$	125.78				
	± 0.26 GeV	± 0.02(stat) ± 0.07(sys)			

- $H \rightarrow \mu\mu$: Improved p_T resolution (tracker) \implies Improved mass resolution by 30%,
 - Extended acceptance (sig 10%). Increased X-sec (13 to 14 TeV)
 - \implies Discovery 5 σ with 400 /fb using/DELPHES simulation3

CMS-PAS-FTR-21-007 (Simulation-assisted projection from CMS-HIG-19-001 and CMS-HIG-16-041) EF01: Higgs mass and on-shell width from $H \rightarrow ZZ / \gamma\gamma$, $H \rightarrow \mu\mu$

- Evaluate impact of detector Phase-2 upgrade on signal modeling and acceptance (DELPHES simulation)

 - $H \rightarrow \gamma\gamma$: Reduced photon E scale systematic (more accurate ECAL calibration, Improved method to









Projection from CMS-HIG-21-008, ATLAS-CONF-2021-21 EF01: Projection of the VH(H \rightarrow cc) search

- Difficult due to small X-sections, large QCD BGs, c-tagging in hadronic environments.
- Simultaneous measurement of VH(H \rightarrow bb) and VH(H \rightarrow cc).

CMS Run 2: $\mu_{VH(H - > cc)}$: 14 (7.6^{+3.4}-2.3) obs (exp) new jet reco, merged jets, ML c-tagging

- Event categories:
- MVA for 2 resolved jets.
- Substructure for "boosted" topology

Phase-2 Projection

Use only the merged jet categories 3 cc + 3 bb

ATLAS Run 2: $\mu_{VH(H - > cc)}$: 26 (31⁺¹²-8) obs (exp) Event categories:

- V momentum, jet multiplicity,
- signal/control regions with BDT descriminant Phase-2 projection

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2D profile likelihood scans of signal strength and coupling modifiers





CMS: **DELPHES** studies of ggHH and VBFHH:

- DNNs for signal/bg discrimination in event selection. Updated analysis (139 /fb)
- Signal significance extracted with a simultaneous fit to m_{bb} and m_{yy} distributions.



 $HH \rightarrow bb\gamma\gamma$: 2.16 σ_{I} (for ggHH+VBFHH)

ATLAS: Projections from Run2 results:

Modified mass

 $M_{bbyy} = m_{bbyy} - (m_{bb} - 125 \text{ GeV}) - (m_{yy} - 125 \text{ GeV})$



 $HH \rightarrow bb\gamma\gamma : 2.2 \sigma$. Similarly HH \rightarrow bbtt : 2.8 σ







SM prospects

Contributions to:

- EF04: EW precision physics and constraining new physics
- EF07: QCD and strong interactions: Heavy ions
- EF03: Heavy flavor and top quark physics







- ATLAS (CMS) had first observations of several EW VBS with Run-2 data - leptonic decays of VBS WW, WZ, ZZ.
- Phase 2 projected sensitivity to VBS X-section and polarization. with signatures: 2 same-charge leptons or 3 leptons with total charge 1.
- Simultaneous measurement of EW WW, EW WZ and QCD WZ production X-sections, with uncertainty 6%(3%) and (4%) Benefit from large stats and forward acceptance of leptons and jets.
- Simultaneous measurement of longitudinal and transverse polarized components in the WW channel.
 - unitirized in SM, BSM?

Expected significance for the EW W_LW_L^{...}

1.8 σ (2.7 σ)

Small X-sec (7% of tot), challenge but important for ATLAS (CMS)



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Phase-2 Projection

CMS







Ultra-peripheral heavy ion collisions: No hadronic collisions between the ions. \implies Clean environment to study yy-induced processes.

 \implies Sensitive to BSM \iff improved constraints on $(g-2)_{\tau}$.

Projection of the Run 2 search for $\gamma\gamma \rightarrow \tau^+\tau^-$ with 1 muon + 3 charged particles.

• 13 nb⁻¹ PbPb luminosity, $sqrt(S_{NN}) = 5.02$ TeV. Backgrounds (leptonic and hadronic)

 $\gamma\gamma \rightarrow I+I-$ supressed by track impact pararm for τ

 $\gamma\gamma \rightarrow qq^{-}$ estimated from data

Phase-2 expected $\gamma\gamma \rightarrow \tau^+\tau^-$ xsect. uncertainties: 4.8 ± < 0.1 ± 0.2 μb. Total: 4%

~x4 improvement wrt Run 2 prediction: $4.8 \pm < 0.6 \pm 0.5 \ \mu b$

Including more decay channels and improved analyses (e.g. shape analysis), precision on $(g-2)_{\tau}$ will surpass the existing measurements.



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Spin correlation very sensitive to presence of stop. $\Rightarrow \Delta \phi(l^+, l^-)$) the most accurate spin corr. observable with 3% precision (among 22 studied)



Phase-2 exclusion limits on the stop-stop Ratio of Phase-2 / Run 2 expected exclusion cross section. m_{stop} exclusion up to 600 GeV. limits on cross section.

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- Project measurement of the top quark spin correlations with opposite charge $e\mu + \ge 2$ jets $+ \ge 1$ b-jet.
- Use spin corr. variables in a DNN to search for top squarks in the "top corridor", $\Delta(m_{stop} m_{LSP}) \sim m_{top}$.





BSM prospects

Contributions to:

- EF08: Model-specific explorations
- EF09: More general explorations
- EF10: Dark matter at colliders







Project search for EW-produced chargino / neutralino decaying to boosted hadronic W/Z/h + LSP:

- Final states: WW, WH, WZ, $ZH + E_T^{miss} > 200$ GeV. 2 AK8 jets with pT > 200 GeV and W/Z/h tagging.
- Scaled luminosity and cross sections.



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1000 1200 1400 1600 m(χ̃ [±]₁/χ̃ ⁰₂) [GeV]

Interpret in scenarios with bino-like LSP and wino-like or Higgsino-like NSLP m_{NLSP} exclusion limits difference Phase-2 expected - Run 2 observed :

650 - 750 GeV

 $pp \to \widetilde{\chi}_{1}^{\pm} \widetilde{\chi}_{1}^{\mp} / \widetilde{\chi}_{1}^{\pm} \widetilde{\chi}_{2}^{0}, \ \widetilde{\chi}_{1}^{\pm} \to W^{\pm} \widetilde{\chi}_{1}^{0}, \ \widetilde{\chi}_{2}^{0} \to H \widetilde{\chi}_{1}^{0}$ HC Expected 95% CL Upper Limit (14 TeV, 3000 fb⁻¹ 3σ Evidence HL-LHC Expected (14 TeV, 3000 fb⁻¹) 5σ Discovery HL-LHC Expected (14 TeV, 3000 fb⁻¹) Run 2 Expected 95% CL Upper Limit (13 TeV, 137 fb⁻¹) Run 2 Observed 95% CL Upper Limit (13 TeV, 137 fb⁻¹)



CMS Phase-2 Projection Preliminary





Projection of a search for stop pair production in R-parity violating or Stealth SUSY models:

- 2 tops + additional jets ->1 lepton + ≥ 7 jets (no E_T^{miss}).
- Bkg:tt-pair + jets production
- Use high jet multiplicity to differentiate sig/bg - Binary classifier neural networks.
- Projection at 13 TeV by scaling the luminosity.



RPV: 670 GeV (Run 2) -> 870 GeV (Phase-2) Stealth: 870 GeV (Run 2) -> 1190 GeV (Phase-2) Vladimir Rekovic, DIS 2023



IIIIIII REREERE

RPV











CMS-PAS-FTR-21-011 (Dedicated search - studied first time in CMS) EF08: Leptophobic Z' to charginos in Il +MET



Search for leptophobic Z' decaying to two charginos, which subsequently decay to leptonically decaying Ws and neutralinos using Delphes.

- Bkg; dileptonic decays of $t\bar{t}$ +jets, Drell-Yan+jets with m_{ll} >100GeV,
- Select events with ee, $\mu\mu$, $e\mu$ (high p_T , opposite-charged) and $E_T^{miss} > 80$ GeV.
- Signal extraction via DNNs per each signal point.

3 ab⁻¹(14 TeV)

masses in GeV

- m(Z')=2500, m(χ[±])=1095

stat.+sys. unc.

Signal class DNN score

Input variables exploiting the resonance nature of the Z'.



0.6

0.2

0.4





Phase-2 exclusion for Z' xsec:

Can exclude m_Z[,] up to 4.5 TeV.







[500,Inf)

LT

[600,Inf)

0e3µ

[500, Inf)

LT

[600,Inf)

SS1e2µ

[500,Inf)

LT

[600,Inf)

SS2e1µ

[500, Inf)

LT

[600, Inf)

2e2µ

[500,Inf)

LT

[600,Inf)

0e4µ

[500, Inf)

LT

[600, Inf)

3e0µ

[500,Inf)

LT

[600,lnf)

4e0µ

[300,500)

LT

[600,Inf)

0e3µ

Search for Type-I and Type-II seesaw models (explaining neutrino masses) using Delphes.

- Final states with exactly 3 or 4 leptons, $p_T > 40$ GeV
- Discriminating variables: $L_T = sum(p_T \text{ leptons}), min(m_{\parallel})$
- 87 bins of lepton flavor, L_T , max(m_{II}).



[300,500)

LT

[600,Inf) SS2e1µ

Vladi

[300,500)

LT

[600,Inf)

SS1e2µ







Search for boosted mono Higgs, with $h \rightarrow bb + dark$ matter using Delphes:

- ML-based boosted Higgs tagging on AK8 jets ; $E_T^{miss} > 200$ GeV.
- Upgraded detector + improved timing + improved heavy particle taggers + ML methods will enhance Phase-2 sensitivity.
- Interpretation in terms of a Type-II 2HDM+a model: $\tan\beta = 1$, $\sin\theta = 0.35$, $m\chi = 10$ GeV.

Phase-2 limit on signal strength: Exclude masses $1 < m_A < 2 \text{ TeV}$ for $m_a < 500$ GeV



Not in WP, approved.



Phase-2 significance: 5σ disc. for CP-even pseudoscalars heavy $m_A \sim 1-1.6$ TeV, light $m_a = 250 \text{ GeV}$

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- Studies for the Yellow Report and White Paper covered a substantial part of the HL-LHC physics phase space.
- Exploring new ideas is encouraged, in particular final states only accessible at HL-LHC and studies exploiting Phase-2 detector features.
 - di-Higgs and long-lived particles are obvious examples.
 - Wherever new physics reach available with Phase-2 Upgraded Detectors
 - e.g. CMS Phase2 Level-1 Trigger (CMS-TDR-021)
 - Track Trigger
 - Particle Flow



Extra slides







Phase-2 upgrade for the CMS detector

Improved muon coverage and trigger

increased RPC coverage (1.5 < $|\eta|$ < 2.4) new electronics

CMS-TDR-016

New precision timing detector

Timing resolution of 30-40 ps for MIPs full coverage of $|\eta| < 3.0$

New inner tracker

all silicon tracker 4 layers of pixels 5 layers of strips coverage to |n| < 4



Beam Radiation Instrumentation and Luminosity Detectors CMS-TDR-023

New endcap calorimeters

high granularity can reconstruct showers in 3D

CMS-TDR-019

Updates to calorimeter and trigger

higher granularity electronics for trigger CMS-TDR-015

L1: CMS-TDR-021 DAQ/HLT: CMS-

Upgrade to trigge 2and DAQ

L1 rate increased to 750 kHz High Level trigger rate to 7.5 kHz Track information at L1



