RECENTERGHMGHTS **FROM THE LHC**

 Greg Landsberg Vulcano Workshop Ischia, Italy, 31.05.24 2024

LHC

CM

✦LHC Performance: Four Machines in One

- ✦30,000 Feet Highlights:
	- Standard Model Measurements
	- Searches for New Physics

✦Conclusions: Quo Vadis?

✦ Disclaimer: these are selected highlights of a large number of LHC results, with clear personal bias: they tell a story, rather than simply make up a shopping list... Priority is given to the results with direct connection to astrophysics and cosmology themes. All the links are clickable!

- ✦ For a full physics analysis landscape at the LHC, please refer to:
	- ๏ https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults
	- ๏ https://twiki.cern.ch/twiki/bin/view/AtlasPublic
	- ๏ <https://cms-results-search.web.cern.ch/>
	- ๏ https://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

Dedication: I'd like to dedicate this talk to the memory of Peter Ware Higgs (29.05.29-08.04.24), whose transformative and groundbreaking ideas laid the foundation for the physics of the standard model and the very particle named after him

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The LHC **Legacy**

Telescopes vs. Microscopes

Beautiful Instruments

Spectacular Launches

Deep Fields

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LHC - a Big Success!

- ✦ Nearly 300/fb of data have been delivered by the LHC in Runs 1-3 (2010-2023), at a c.o.m. of 7-13.6 TeV, exceeding the integrated luminosity projections
- ✦ Over 90% of the delivered data are fully certified for physics analyses
- ✦ Several heavy-ion and proton-lead runs at various energies, augmented by the proton-proton reference data at the same energies
- ✦ Thank you, LHC, for spectacular running!

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2.2-inch mono 4-in-1 print, copy, Four Machines Scan, fax 35-page auto smart in One!" document feede \bullet \bullet w HP Office let 5255 ◎ $\begin{array}{ccc} \hline \end{array} \begin{array}{ccc} \hline \end{array} \begin{array}{ccc} \hline \end{array} \begin{array}{ccc} \hline \end{array} \begin{array}{ccc} \hline \end{array}$ **IP OfficeJet 52**

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The LHC Legacy

- ✦ The LHC has figuratively replaced three machines in one go:
	- ๏ Tevatron (Higgs, BSM searches, top physics, and precision EW measurements)
	- ๏ BaBar/Belle B factories (precision B physics)
	- ๏ RHIC (heavy-ion physics)
- ✦ It also added one more machine:
	- xx collider (LbL scattering, Breit-Wheeler processes, searches for ALPs)
- ✦ The LHC experiments in general, and ATLAS & CMS in particular, are very successful and productive in all these four areas
- ✦ Would not be possible without theoretical and phenomenological breakthroughs of the past decade:
	- ๏ Higher-order calculations ("NLO revolution" → N3LO), modern Monte Carlo generators, reduced and better estimated PDF uncertainties
- ✦ Since it's impossible to cover all the aspects of this impressive program in one talk, I'll present a few highlights of recent LHC results in Higgs physics, SM physics, flavor physics, heavy-ion physics, and the discovery program, somewhat geared to the topics of this workshop

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Challenge: Big Data

- ✦ The amount of data produced by each LHC experiment is truly enormous: ~10 PB/year
- ✦ It takes some time to fully calibrate and align the detectors, and then reconstruct the data with the best possible calibrations
- ✦ As a result, most of the results presented in these talk are based on Run 2 (2015-2018, 13 TeV, ~140/ fb) data
- ✦ First results from Run 3 dataset at 13.6 TeV started to appear!
- ✦ Overall, a very fast turn-around compared to earlier generations of HEP experiments!

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Publish or Perish!

✦ Nearly 1,300 papers submitted by each ATLAS and CMS; over 700 by LHCb, and nearly 500 by ALICE!

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ATLAS+CMS Physics Reports

✦ ATLAS and CMS just submitted several Phys. Rept. articles on various aspects of the program • These are legacy Run 2 papers and a valuable resource on experimental techniques and results

✦ ATLAS:

- [arXiv:2403.02455](https://arxiv.org/pdf/2403.02455), The quest to discover supersymmetry at the ATLAS experiment
- ๏ [arXiv:2403.09292](https://arxiv.org/pdf/2403.09292), Exploration at the high-energy frontier: ATLAS Run 2 searches investigating the exotic jungle beyond the Standard Model
- ๏ [arXiv:2404.05498](https://arxiv.org/pdf/2404.05498), Characterising the Higgs boson with ATLAS data from Run 2 of the LHC
- ๏ [arXiv:2404.06829](https://arxiv.org/pdf/2404.06829), Electroweak, QCD and flavour physics studies with ATLAS data from Run 2 of the LHC
- ๏ [arXiv:2404.10674](https://arxiv.org/pdf/2404.10674), Climbing to the Top of the ATLAS 13 TeV data
- ๏ [arXiv:2405.04914](https://arxiv.org/pdf/2405.04914), ATLAS searches for additional scalars and exotic Higgs boson decays with the LHC Run 2 dataset

✦ CMS:

- ๏ [arXiv:2403.01313](https://arxiv.org/pdf/2403.01313), Review of top quark mass measurements in CMS
- ๏ [arXiv:2403.16926](https://arxiv.org/pdf/2403.16926), Searches for Higgs boson production through decays of heavy resonances
- [arXiv:2403.16134](https://arxiv.org/pdf/2403.16134), Enriching the physics program of the CMS experiment via data scouting and data parking
- [arXiv:2405.10785](https://arxiv.org/pdf/2405.10785), Overview of high-density QCD studies with the CMS experiment at the LHC
- ๏ [arXiv:2405.13778](https://arxiv.org/pdf/2405.13778), Dark sector searches with the CMS experiment
- ๏ [arXiv:2405.17605](https://arxiv.org/pdf/2405.17605), Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at \sqrt{s} = 13 TeV at the CMS experiment
- ๏ [arXiv:2405.18661](https://arxiv.org/pdf/2405.18661), Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns

Challenge: Pileup

- ✦ In ATLAS and CMS now a proton-proton event looks nearly as busy as a heavy-ion one!
- Average number of simultaneous interactions per bunch crossing (pileup, PU) is about 50 in the last two years
	- ๏ This by far exceeds the original LHC design PU number of 20
- Developed sophisticated tools to mitigate the effects of the PU: particle-flow reconstruction, machine-learning techniques

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Higgs Physics Highlights

Higgs Factory

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- ✦ LHC is the Higgs factory and the only place to study Higgs physics directly today
- ✦ At 13 TeV, the production cross section for the $_9$ \vee 00000 Higgs boson, dominated by gluon-gluon fusion, is ~50 pb
	- ๏ 14M Higgs bosons delivered by the LHC in Run 2!
	- ๏ By now ATLAS and CMS could have accumulated as many Higgs bosons as four LEP experiments accumulated Z bosons
	- ๏ With the cross section @13.6 TeV of ~60 pb another 11M have been already delivered in Run 3!
- ✦ But: triggering is a big challenge:
	- \bullet Most of gg \rightarrow H(bb) events were never put on tape, which is how half of the Higgs bosons are produced and decay

✦ Need to pursue aggressive triggering strategies and go for lower cross section production mechanisms to observe all possible Higgs boson decays and couplings

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Going Differential

- By now the number of recorded Higgs bosons is large enough to start measuring differential (and double-differential cross sections)
- Stress tests of higher-order theoretical calculations and parton shower generators

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Higgs Boson Couplings

Greg Landsberg - Recent LHC Highlights - Vulcano 2024 - Ischia **Slide** Greg Landsberg - Recent LHC Highlights - Vulcano 2024 - Ischia

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Slide

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Couplings to third-generation fermions and EW bosons have been measured; first evidence for coupling to muons

Exploring Higgs Potential

- \triangle One of the most important couplings is a Higgs boson self-coupling, λ
- Directly affects the shape of the Higgs potential, with implications for both early and late universe (e.g., EW vacuum stability)
- \blacklozenge Depends on λ (or, in the SM, m $_{\mathsf{H}} = \sqrt{2\lambda} \nu$), m $_{\mathsf{t}},$ and α_{s}
- Important to precisely measure all these parameters, including λ , to test the predictions of the Higgs mechanism 000000

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Higgs Boso

- \triangle New, more precise measureme CMS, with sub-permille precisi \triangle The two experiments also mea
	- on-shell and off-shell production $\frac{1}{124.6}$ $\frac{1}{124.8}$ $\frac{1}{125}$ $\frac{1}{125.2}$
		- \bullet $\Gamma_{\rm H}$ = 3.2^{+2.4}-1.7 MeV [CMS, Nat.
		- \bullet $\Gamma_{\rm H} = 4.5$ +3.3_{-2.4} MeV [ATLAS, PLB **846** (2023) 138223] $\mathsf{L}\mathsf{D}\mathsf{V}\mathsf{V}\mathsf{V}\mathsf{V}\mathsf{V}$ is denoted by $\mathsf{L}\mathsf{V}\mathsf{V}\mathsf{V}\mathsf{V}\mathsf{V}$ and the interval $\mathsf{L}\mathsf{V}\mathsf{V}\mathsf{V}\mathsf{V}\mathsf{V}$

 \triangleleft Measurements are in agreement with the SM prediction of $\Gamma_H = 4.1$ MeV confidence interval is indicated by the intersections of the horizontal line at 1 (4) with the log-likelihood curves.

ATLAS [PRL 131 \(2023\) 251802](https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.131.251802)*ATLAS* **Total** Stat. only **Combination Run 1:** \sqrt{s} = 7-8 TeV, 25 fb⁻¹, **Run 2:** \sqrt{s} = 13 TeV, 140 fb⁻¹ Total (Stat. only) **Run 1** $H \rightarrow \gamma\gamma$ 126.02 \pm 0.51 (\pm 0.43) GeV **Run 1** $H \rightarrow 4\ell$ 124.51 \pm 0.52 (\pm 0.52) GeV **Run 2** $H \rightarrow \gamma \gamma$ 125.17 \pm 0.14 (\pm 0.11) GeV **Run 2** $H \rightarrow 4\ell$ 124.99 \pm 0.19 (\pm 0.18) GeV **Run 1+2** $H \rightarrow \gamma\gamma$ ┡═┽ 125 22 \pm 0.14 (\pm 0.11) GeV **Run 1+2** $H \to 4\ell$ 124 94 \pm 0 18 (\pm 0 17) GeV **Run 1** Combined 125 38 \pm 0.41 (\pm 0.37) GeV **Run 2** Combined 125.10 \pm 0.11 (\pm 0.09) GeV **Run 1+2** Combined 125.11 \pm 0.11 (\pm 0.09) GeV ⊷ 123 124 125 126 127 128

 m_H [GeV]

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Probing Self-Coupling If we have the expected upper limit is 2.4 at 95% CL, and in the SM case the SM case the SM case the SM case t
The SM case the expected upper limit is 2.4 at 95% CL, and in the expected upper limit is 2.4 at 95% CL, and i

- $\frac{1}{4}$ \rightarrow Measurement of Higgs boson self-coupling λ is an ultimate goal of HL LHC
- $\frac{1}{3}$ + The cross section is very low, due to large negative interference between the diagrams $\frac{a}{\sqrt{4}}$ contributing to Higgs boson pair production $\frac{d}{d}$ continuating to rigge becompan production
- ✦ Enormous progress has been achieved using ML b-tagging techniques and multivariate methods $\frac{12}{18}$ + Enormous progress has been achieved using ML b-tagging tec $\frac{2}{\pi}$ are methods in individual searches and individual searches and individual searches and in the combination of $\frac{2}{\pi}$
- $\frac{3}{5}$ + Current 95% CL limits on $\mu = \sigma/\sigma_{SM}$ for HH production are <2.9 (2.4) in ATLAS and $\frac{1}{2}$ <3.4 (2.5) in CMS [already exceeded early HL LHC projections!

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Sensitivity to λ

Because of the negative interference, sensitivity to λ is non-trivial H ๏ Combination of single and double Higgs production $H \rightarrow - - - - \frac{1}{\kappa_{\lambda}}$ $\qquad \qquad \bullet$ $\qquad H \rightarrow - - - H \rightarrow \kappa_{\lambda}$ helps to constrain the self-coupling in a more model-independent way: **ATLAS [PLB 843 \(2024\) 137745](https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.131.251802)** H the Higgs boson self-interaction coupling modifier *kl* is in the range 1.24 to 6.49, while the and **CMS [PAS HIG-23-006](https://cds.cern.ch/record/2882424/files/HIG-23-006-pas.pdf)**t g q q $\frac{q}{200000}$ $\frac{1}{24}$ k³ (6.9 $\frac{q}{20}$ $\frac{3}{25\%}$ Ch_t **-1.24 < ^λ < 6.9 @ 95% CL** H • Here we focus on just HH analyses: H INSES: or \mathbf{A} significance of \mathbf{A} . \mathbf{A} s.d., \mathbf{A} or \mathbf{A} of \mathbf{A} of \mathbf{A} $\frac{1}{2}$ c $\frac{1}{2}$ c $\frac{1}{2}$ $\frac{1}{2}$ c $\frac{1}{2}$ c $\frac{1}{2}$ c $\frac{1}{2}$ c $\frac{1}{2}$ c $\frac{1}{2}$ c $\frac{1}{2}$ H 0.67 < x2<mark>V < 1.</mark>38 @ 95% GL _{II} κ_{λ} **-1.2 < λ < 7.2 @ 95% CL** $\frac{1}{\sqrt{2}}$ H g q **2V = 0 is excluded at 6.6σ!** q $0.57 < \kappa_{2V} < 1.48$ @ 95% CL t 138 fb⁻¹ (13 TeV) **CMS** 10^3 HH (incl.)) / fb د ۱۵۱۱ ج → HH (incl.)) / t $\kappa_t = \kappa_{2V} = \kappa_V = 1$ = κ $\begin{array}{r} \n\text{SUS} & \text{R.} & \text{R.} \\ \n\text{SUS} & \text{CIV} \\ \n\end{array}$ $\begin{array}{r} \n\text{SUS} & \text{CIV} \\ \n\text{SUS} & \text{CIV} \\ \n\end{array}$ $\begin{array}{r} \n\text{SUS} & \text{CIV} \\ \n\text{SUS} & \text{CIV} \\ \n\end{array}$ Median expected **ATLAS** Preliminary bbbb Theory prediction ----- 68% expected Multilepton $\overline{}$ \sqrt{s} = 13 TeV, 126-140 fb⁻¹ **ATLAS [CONF-2024-006](https://cds.cern.ch/record/2898670/files/ATLAS-CONF-2024-006.pdf)** $bb\ell + E^{\text{miss}}$ \longrightarrow $bb\tau^+\tau^-$ 95% expected HH combination κλ Obs. 95% CL Best fit (4.3, 0.92) H $10³$ → I . Exp. (SM) 95% CL $\hat{\mathbb{X}}$ SM prediction t (pp σ \bar{c} $|0^2$ (e) σ95% CL limit on 95% CL limit on Figure 2: Examples of one-loop _ -dependent diagrams for (a) the Higgs boson self-energy, and for single-Higgs production in the (c) \mathcal{L} \mathcal{L} and (e) \mathcal{L} circle. 10^{2} 10 SM predictions corrected for the _ -dependent NLO EW effects. A framework for a global fit to $\begin{array}{ccc} \hline \text{Excluded} & \text{N} & \text{C} \end{array}$ Excluded \vee Excluded \mathbb{Z}^n assumptions of the same references. In this parameterisation are described in the same references. In the same ref current work, inclusive production cross-sections, decay branching ratios and differential cross-sections are

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Kλ

 $e^{\frac{1}{2}}$ -6 -4 -2 0 2 4 6 8 10 $\sqrt{2}$ is the simplified template cross-section (STXS) framework described in Section II.3 of K_{λ}

λ κ

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 C

−2 −1 0 1 2 3 4

−6 −4 −2 0 2 4 6 8 10

Top Quark Mass Measurement

The most precise measurement of the top quark mass is currently from a recent Run 1 combination of ATLAS and CMS measurements: $m_t = 172.52 \pm 0.33$ GeV, with <2‰ precision A.6 Numerical details of the combination **17**

๏ The most precisely measured quark mass!

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Strong Coupling Measurement

Figure 12 shows the energy dependence predicted by the RGE (dashed line) using the α

s - Vulcano 2024 - Ischia

- ← Several new results from ATLAS and CMS, including ATLAS's novel N³LO extraction based on Z boson p_T spectrum, which is as precise as 2022 world average! [Submitted to Nature Physics.] (yellow band). The results from the *a*S(*Q*) determinations in the four subregions presented in SOIT DT SPECITUM, WHICH IS AS PIECISE AS d to indure Priysics.]
- ← The running of α _S(Q) has been probed at the LHC over nearly 3 orders of *magnitude in Q and agrees very well with the QCD NLO RGE evolution* corresponding to an average scale h*Q*i over each *p*^T interval.

Fundamental Physics

Top Quark Entanglement

- \triangle Top quark pair production is an excellen laboratory to look for fundamental QM effects, such as quantum entanglement
	- Top quark decays before it hadronizes and the spins of the two top quarks and their decay products are therefore correlated, leading to an entanglement

- Explore near-threshold tt production in the dilepton+jets final state
- ✦ The spin correlation matrix C can be used to define the entanglement condition [Peres–Horodecki condition, **Afik, de Nova, [EPJ+ 136 \(2021\) 907](https://link.springer.com/content/pdf/10.1140/epjp/s13360-021-01902-1.pdf)**

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- similar to Bell's
	- \bullet Entanglemen 0.4 in the tt rest f \bullet If D $<$ -1/3, the
		- 40 3.5 $-3\langle \cos\phi \rangle$, wh $\sum_{\infty}^{6.3}$ is the angle between $\frac{1}{2.5}$ two leptons from the top $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ 1.5 1.0 0.5 550 350 400 600 $M_{t\overline{t}}[\rm{GeV}]$

Observation of Entanglement

- New ATLAS result [submitted to Nature] is the first observation of quantum entanglement in the tt system: $D = -0.547 \pm 0.002$ (stat) \pm 0.021 (syst)
- \triangle Recently CMS confirmed this and showed that inclusion of the belowthreshold toponium resonance improves the agreement between the observed and predicted entanglement observed and predicted entanglement the inclusion of toponium causing a larger response in the shape of the cos *j* distribution at nproves the agreement between the from toponium.

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g-2 of the Tau Lepton **2**

 γ

 γ

 $p_2 \longrightarrow p_2' \longrightarrow p_2'$

2

 τ^-

 τ^+

✦ Anomalous magnetic moments are fundamental parameters sensitive to new physics $p_1 \longrightarrow p_1' \longrightarrow p_1'$

- ๏ Cf. Peter Winter's talk on the muon g-2 saga
- ✦ The magnetic moment of the tau lepton is known rather poorly
- ✦ New CMS analysis using photon-photon collisions [LHC as a photon collider!] in pp running to probe exclusive photoproduction of tau lepton pairs, which is sensitive to g-2
	- ๏ Based on the combination of hadronic and leptonic tau decays
	- Exclusivity is ensured by requiring primary vertex with no more than one extra track
- \rightarrow First observation of exclusive ττ production and the most stringent limit on g_τ 2: [-0.0042,0.0062], approaching sensitivity to the Schwinger term $\alpha/2\pi = 0.00116$ $\begin{bmatrix} 2 \ 1 \end{bmatrix}$ or separation distortion distortion distortion (right) to pologies are shown.

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1.05 1.1 1.05 **Lepton Flavor Universality**

- ◆ In the SM, couplings of gauge bosons to fermions are universal, which is an accidental symmetry of the SM 1.02
- pl<mark>l</mark> [GeV] 40 60 80 100 120 140 160 180 200 Data / Fit 0.98 1 LHCb claims of LFU violation in $6 \stackrel{80}{\rightarrow} 8$ $100 \stackrel{120}{\rightarrow} 140 \stackrel{160}{\rightarrow} 180 \stackrel{200}{\rightarrow} 200$ how understood to Data / Fit 0.98 ← Recent interest in lepton flavor universality (LFU) violation sparkled by the (b) be due to a missing background]
	- \mathbf{F} and \mathbf{F} channel divided by the 44 channel divided by the 44 channel as a function of divided by the 44 channel as a function of divided by the 44 channel as a function of direction of direction of direction • Higgs boson is the only known particle with non-flavor-universal couplings to leptons
- ← Recent precision test by ATLAS in W $\frac{100}{40}$ ev 140 16 ATLAS 40 60 80 100 120 140 160 180 200 **ATLAS [arXiv:2403.02133](https://arxiv.org/pdf/2403.02133)**
	- vs. μν decays
		- ๏ Uses tt production as a clean source of W events
		- ๏ Additionally uses the Z(ee)/Z(μμ) ratio, for which LFU has been firmly established by LEP and LHC, to reduce the uncertainty
- \triangleleft R^{µ/e}(W) = 0.9995 ± 0.0022 (stat) \pm 0.0036 (syst) \pm 0.0014 (ext)
- ✦ Most precise measurement to date

Measurement of the W Boson Mass

- ✦ The mass of the W boson is a fundamental parameter in the SM; also show the crucial for precision EW fits and experimental systematic uncertainties, grouped into categories. \blacksquare \blacktriangleright The mass of the W boson is a fundamental parameter in the SM; also
- ✦ At the LHC the measurements have been so far down by ATLAS and LHCb
- ◆ Recent update of the earlier analysis by ATLAS to include the latest constraints on parton distribution functions
- \bullet M_W = 80366.5 \pm 15.9 MeV (reduction of the uncertainty by 2.6 MeV)
- \triangleleft Also measured the W width $\Gamma_W = 2202 \pm 47$ MeV \triangle Alex 1888 20.11 2.9 \triangle 1.1 \triangle 1.

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CP Violation in Bs → J/**ѱ**φ Decays

- ✦ CP violation (CPV) is one of three Sakharov conditions for creation of matter-antimatter asymmetry in the universe
- flavor tagger to date, allowed to establish CPV in ✦ Recent result from CMS is based on the most performant $B_s \rightarrow J/\psi \phi$ decays
	- ๏ New tagger, based on DNNs achieved unprecedented tagging efficiency of 55.9% with the dilution factor of 10%, for a tagging power of 5.6%
- ✦ The result is consistent with the SM and LHCb measurement, and established for the first time

Figure 3: The two-dimensional one, two, and three standard deviations contours in the *fs*-DG*^s* plane for the combined results. The contours take into a contour statistical and system- $>$ 3σ evidence for the CPV phase ϕ_s to be non-zero

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CP Violation in Charm

- ✦ CPV has been observed in strange, beauty, and recently charm sectors
	- \bullet In charm sector CPV can occur in $D^0\leftrightarrow \overline{D}{}^0$ oscillations, directly in the decay, or in both
	- LHCb earlier observed CPV in the D⁰ \rightarrow K+K-, π + π decays
- \blacklozenge New LHCb result on a search for CPV in a charm decay: D^o \rightarrow K+ π -LHCb-PAPER-2024-008
	- \bullet Use D^{*} as a source of D⁰, tagged via the D^{*} → D⁰ π decay; 410M D⁰
	- No evidence for CPV in decay, mixing, or both

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CMS Experiment at the LHC, CERN

Data recorded: 2010-Nov-14 18:37:44.420271 GMT(19:37:44 CEST) Run / Event: 15107674405388

Heavy Ion **Highlights**

Observation of tt Production Jet energy scale +4.6 -4.1

- ◆ Top quark production in nucleus-nucleus collisions is an excellent probe of nuclear PDFs at low Bjorken x, particularly the gluon nPDF ICIEAT PDFS At IOW BJOTKEN
- ◆ A new ATLAS analysis focuses on both I+jets and dilepton decay channels of the tt system in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV (165 nb-1) new ATLAS analysis focuse ane at system in pPD comst
- ← Signal observed w/ >5σ significance in each channel, with cross section τ_t = 58.1 \pm 2.0 (stat) $^{+4.8}$ -4.4 (syst) nb consistent with the scaled pp NNLO $\frac{18}{5}$ cross section calculations gnal observed w/ >50 signi to 9% and is dominated by the systematic contribution.
	- ๏ Analysis approaches sensitivity necessary to probe nPDFs

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Resolving f₀(980) Puzzle

- ✦ For the first time, heavy ion collisions were used to probe the particle content of a potentially exotic state
- \triangle Since the 60-ies, the f₀(980) state, which is rather broad was speculated to be a tetraquark candidate, a molecular state, or an ordinary meson
- ✦ This is possible through the coalescence picture of bound state formation in nuclear collisions
	- ๏ Bound states are formed from particle with similar momenta and spatial positions
	- \bullet The elliptic flow of a state thus inherits the elliptic flow of the constituents, $v_2(p_T)\approx n_qv_{2,q}(p_T/n_q)$
- ✦ Consequently, measuring the elliptic flow of a specific state can tell how many quarks it contains
- \triangleleft CMS measurement excluded $n_q = 4$ over $n_q = 2$ by 7.7 σ , thus solving a half-a-century old puzzle! [Submitted to Nature Comm.]

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E Anti-³He Absorption in Matter

- ← Astrophysical observation of low-energy antinuclei, such as anti-³He, is one of the most promising signatures of DM annihilation
- ๏ Important question is the transparency of our galaxy to these antinuclei The second method, employed in the Pb–Pb data analysis at a centre-of-mass energy per nucleon pair [®] Important question is the transparency of our galaxy to these antinuclei
- \triangle ALICE has measured for the first time the cross section of anti-3He interactions as a function of momentum by measuring anti-³He absorption in several sub-detectors all the 3He candidates extracted from Pb–Pb collisions. As with the first method, this observable is absorption in scyclar sub-detectors
A full-sinel(3He) values.
- anti-³He/³He ratio method is used for pp collisions
- anti-³He disappearance in TRD is used for PbPb collisions

ALICE [Nature Phys. 19 \(2023\) 61](https://www.nature.com/articles/s41567-022-01804-8.pdf)

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Astrophysical Impact ME ASIC 1999 IN MATTER ALICE COLLABORATION IN MATTER ALICE COLLABORATION IN MATTER ALICE COLLABORATION IN MATTE

Measurement of 3He nuclei absorption in matter \mathcal{A}_1 absorption in matter \mathcal{A}_2

- $\frac{1}{2}$ \rightarrow These cross section measurements allowed to model our galaxy **EXECUTE:** Transparency to anti-³He produced in DM annihilation in the center of Milky **Way** $\frac{w}{\sqrt{2}}$ consparency to anti-fire produced in DM similar ing mass of 100 GeV/*c* and 200 GeV/*c* and 200 GeV/*c* and *W*₂ and *C* and *C* and *W* pairs followed by the *W* $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ are determined by $\frac{1}{2}$ are determined by $\frac{1}{2}$
- $\frac{16}{2}$ \star Various processes are considered, along with the effect of solar modulation phase space in a considered in Methods about the cosmic term in Methods and DM sources are discussed in Methods are discussed in Methods and DM sources are discussed in Methods and DM sources are discussed in Methods and D
- $\frac{3}{5}$ + Prediction for a 100 GeV WIMP are made and are about 1 order of $\frac{1}{2}$ magnitude below the current AMS-02 and GAPS sensitivity \leq \leq

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$2 - \frac{1}{3} F_{av} F^{\prime\prime}$ $+ i \nabla \mathcal{B} \psi + k_c$ $+ \times$: $y_{ij}y_{ij}\phi + k$

Standard Model **Highlights**

"Stairway to Heaven"

Mind-boggling precision on so many SM processes!

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gravistairway to Heaven" tions. Shaded hashed bars indicate the excluded cross section region for a production process with the measured 95% CL upper limit on the process indicated by the process indicated by the same of the same \sim

◆ Mind-boggling precision on so many SM processes! bols and the coloured bands indicate the combined statistical and systematic uncertainty of the

Searches for New Physics

Looking for Unknown

- ✦ The LHC has been successfully operating for nearly 15 years, transforming the entire landscape of searches for new physics
- ✦ Despite a number of tantalizing hints seen by ATLAS, CMS, and LHCb over the years, apart from the observation of the Higgs boson and a number of QCD states, none of them raised to the discovery level yet; many are now gone
- ✦ So, why are we still looking for new physics at the LHC and where should we look for it if we are to continue?
- ✦ Why are we still covering something like a territory of Brazil with the "Brazilian flag" exclusion plots?

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Looking for Unknown

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The Why

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- Many things are missing from the standard model (SM), hinting that it is likely incomplete
	- ✤ Physics issues: no gravity; no dark matter; no connection between the three generations of quarks and leptons; no quantitative explanation of the matter-antimatter asymmetry in the universe; no neutrino oscillations
	- ✤ Math issues: naturalness, which became a real problem since the discovery of the Higgs boson; "arbitrary" fermion masses; strong CP problem
- ๏ Most of viable SM extensions that cure some of the above problems require new particles, dimensions, symmetries
- ๏ Many lead to the phenomenology within the reach of the LHC, although there is no guarantee anymore
- ๏ Many exclusions, while appear strong, are based on simplifying assumptions, which are often arbitrary (e.g., $Br = 1$) - read the fine print!

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Read the fine print!

The Where

Given that the LHC has reached its ultimate energy, looking for heavy particles is a game of a diminishing return - it will take many years to discover something in this regime, if we haven't seen a hint so far

• No more low-hanging fruit!

✦ The focus shifts to much more complicated signatures, which haven't been exploited thus far, as well as significantly more sophisticated analyses than we pursued during the earlier years

✦ Doubling time has doubled since Run 2; it is now about three years

๏ Compatible with a "lifetime" of a graduate student in an LHC experiment, allowing for a well-designed and sophisticated analysis rather than a "luminosity chase"

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Stairway to Hell

New Tools for the New Paradigm

- ✦ Use of new triggers not available earlier in the LHC running
	- ๏ A variety of triggers optimized for long-lived particles
	- ๏ Trigger-level analysis (TLA), aka data scouting ATLAS and CMS, and triggerless design with real-time alignment and calibration (LHCb)
		- ✤ Extensive use of GPU in the trigger
	- ๏ ISR-based triggers with jet substructure and massdecorrelated subjet taggers
	- ๏ Data parking
- ✦ Novel approaches with machine learning (ML) techniques: weakly supervised and unsupervised ML

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FRITOWard Small Masses: TLA has an integrated luminosity of up to 29.3 fb−1 and was recorded at a center-of-mass energy of 13 TeV. particles and on a model of dark-matter particles with axial-vector couplings to quarks.

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Trigger-level analysis (TLA) is **E** based only on the high-level $\frac{1}{2}$ trigger (HLT) objects resulting $\frac{S}{2}$ in a very compact event size $\frac{1}{3}$ and vastly increased rate per $\frac{1}{2}$ bandwidth for the TLA data $\frac{5}{5}$ stream jets [13,14]. In these cases, additional features in the events and vasuy increased rate per $\frac{1}{2}$ reduced set of information from the trigger system is $\frac{1}{2}$

 $\frac{dP}{dt}$ \bullet Avoids the use of (large) trigger prescales using the standard approach, while using less than 1% of PHYSICAL REVIEW LETTERS 121, 081801 (2018) σ and a peak rate to the total rate of σ

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Toward Small Masses: ISR Small-radius jets Large-radius jet q

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- \triangleleft Use high-p_T single-photon or single jet triggers to record the events, require a substructure in the recoiling AK8 jet, and search for narrow resonances in the recoiling jet trimmed mass spectrum ne
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- ✦ Allows to go as low as 10 GeV in the resonance mass! Boosted jets: Increase transverse momentum, pT and the second service momentum of the service momentum, pT and the service of the se $\frac{2}{5}$ $\frac{1}{10}$ $\frac{1}{10}$ $\frac{1}{10}$ $\frac{1}{10}$ $\frac{1}{2}$ in the resonance *I* α is a sequence in asset of the single sequence in the single sequence as a single jet of the single jet of the single sequence in the single sequence α single α single sequence in the single sequence in th

Figure 1: The soft drop [38, 39] jet mass distribution of the signal region after the main back-

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Lorentz boost (ɣ) ɣ ~ 4, α ~ 0.5 - a single jetp_T(ISR) ~ 100 GeV m(X) ~ 25 GeV

Toward Small Masses: ISR [268] 36 Mono-photon *m*Z⁰ *>* 0.95 [270] 36 Mono-H(bb) *m*Z⁰ *>* 1.60

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48

 \triangleleft Use high-p_T single-photon or single jet triggers to record the events, require a substructure in the recoiling AK8 jet, and search for narrow resonances in the recoiling jet trimmed mass spectrum

Allows to go as low as 10 GeV in the resonance mass!

*m*Z⁰ *>* 0.80 Axial coupling

Toward Low Masses: ISR+Scouting

- One could also combine the two techniques, adding extra sensitivity
- ๏ The idea behind a CMS search for dijet resonances in three-jet events collected by a low-H_T scouting trigger (4 kHz $@$ 10³⁴ cm⁻²s⁻¹) available $\frac{q}{q}$ for ~half of 2016 data taking (18 fb-1) data in the mass range 290 *< m*jj *<* 1000 GeV. The chi-square per number of degrees of free-
- **EXECUSE IS A CONDUCT EXAMPLE 1.1** SUSTEMBLE FIGURE EXPONDING TO USE ISSUES Of USE Of 1.1) jets offline to improve resolution and acceptance ϵ expected distributions of a resonance signal for the resonance signal for ϵ
- $\frac{2}{3}$ \bullet Limits set in the 350-700 GeV range as low as 1/3 of EM coupling there is no evidence for a dijet resonance.

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Toward Low Masses: ISR+Scouting **90** ^T -based DM

searches in the leptophobic vector and axial-vector model. For α

- ◆ One could also combine the two techniques, adding extra sensitivity two techniques adding ϵ
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- **EXECUSE IS A CONDUCT EXAMPLE 1.1** SUSTEMBLE FIGURE EXPONDING TO USE ISSUES Of USE Of 1.1) jets offline to improve resolution and acceptance ϵ expected distributions of a resonance signal for the resonance signal for ϵ [263] 36 Mono-t *m*Z⁰ *<* 0.20 Portal is FCNC d accer
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- ✦ Nice complementarity between the two sets **of results, interpreted as dark Z boson or in** \sum_{E} **E** $\sum_{E \in C \text{ for } |E| \text{ for } E \text{ for } E}$ **E** Electroweak fit constraints (95% CL) [UHEP 02 (2015) 157] $\frac{1}{2}$ the context of 2HDM + complex singlet $\frac{1}{10^{5}}$ and the compared with the compared with the compared with the existing limits are compared with the existing limits and the existing limits are compared with the existing limits and the existing limits at 90% CL provided b
- $\frac{5}{5}$ \rightarrow New search based entirely on a scouting trigger allowed to lower the mass reach below the Y resonances in the same models **CMS, PRL 124 (2020) 131802**

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Toward Long Lifetimes

✦ Plethora of models and experimental results

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Cf. an excellent talk by Claudia Seltz

Dark Matter Searches

Conclusions: Quo Vadis?

- ✦ LHC is an amazing machine, with a spectacular performance by far exceeding the expectations
- ✦ Discovery of the Higgs boson in 2012 has completed the standard model of particle physics and paved an avenue to decades of exploration
	- ๏ Cf. the richness of top quark physics now, nearly 30 years after the discovery!
- ✦ Precision standard model measurements, supported by the latest theory developments, continue to be very exciting and important
- ✦ Direct searches for new physics have unexpectedly failed so far, but not for the lack of trying!
	- ๏ Redirect searches away from theoretical lampposts, and toward challenging signatures and most sophisticated analysis techniques
	- If no observation: LHC will do for dim-6 operators what LEP did for the dim-4 ones (SMEFT approach)
- ✦ It's too early to throw a towel in: there are still hints for possible BSM physics and we will follow up on them diligently
- ✦ Stay tuned for many new results from Run 3 data to come soon!

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NON SEQUITUR

Thank You!

2 Search for Inelastic DM k konowledge of efficiencies, energy corrections, and the k integrated luminosity [60–62]. The total signal systematic uncertainties averaged over all years are approximately TABLE II. SYSTEMATIC UNCERTAINMENT uncertainties are larger in 2017 because of noise issues with the ECAL end cap. The tracking inefficiency in 2016 is caused by

◆ Originally models of inelastic DM (IDM) were $\frac{1}{6}$ proposed to explain the DAMA anomaly; nevertheless they are generally viable models $\frac{3}{8}$ involving dark sectors - first IDM search at the LHC $\frac{1}{2}$ proposed to explain the DAMA anomaly; reduce the likelihood of *p*miss **F** by a consider the from an and the set of the selection $\frac{1}{2}$ $\mathcal{T}_{\mathcal{A}}$ two rows give the uncertainty per PF muon. Thus, for the uncertainty per PF muon. Thus, fo astic Divi (IDIVI) were uncertainty 2016 2017 2018 2019 \inf IDM search at the LHC $\,$ DSA displaced reco. 2 2 2 Total

Figure 1: Figure 1: Figure 1: Δ in proton-proton- $\frac{12}{35}$ \star Probe a model w/ 2 nearly mass-degenerate DM states, χ_1 and χ_2 (m₂ - m₁ = Δ = IT IT CONTROLLED IN SIG

3

- $\frac{3}{5}$ (0.1-0.4)m₁), as well as a dark photon mediator A' (m_{A'} = 3m₁), which is long-lived $t_{\rm eff}$ coordinate system used and the relevant kinematic variables, can be found in Ref. [17]. The $\frac{3}{5}$ (0.1-0.4)m₁), as well as a dark photon mediator A' (m . dark photon mediator A[.] Im Trigger 1.5 1.5 1.5 Total
- ϵ aligned with n-miss (algo used for $\frac{1}{5}$ + The signature is two collimated displaced muons aligned with p_T^{miss} (also used for **Fig.** 2, the reconstruction effect of disconstruction effect of disconstruction effect of details and global recon- $\frac{12}{12}$ \rightarrow The signature is two collimated displaced muons aligned $\frac{1}{2}$, which requires both tracker and muon chamber in $\frac{1}{2}$ iteg aisplaced induits aligne \triangle The signature is two colling uncertainties are larger in 2017 because of noise issues with the E the unexpected saturation of photodiode signals in the tracker. Jue anunce die produce in the terminal mated displaced mache ally
- of oxtopding consitivity to lerge of $\frac{1}{6}$ + Special displaced muon reconstruction capable of extending sensitivity to large ct the transverse plane between the muon-pair vertex and the vertex with the vert categories, respectively (with a yearly breakdown shown show onstruction capable of exter The first two rows give the uncertainty per PF muon. Thus, for the uncertainty per Γ \rightarrow Special displaced muon row and two-match categories, respectively.
- in sensitivity around $m(A') = m(\angle)$ \triangle A' is mixed both with photon and Z, hence peak in sensitivity around m(A') = m(Z) \mathbb{F} \mathbb{Z} the tracker when the standard effect of \mathbb{Z} hypotheses, unlike the statistical uncertainty, which n and $7\,$ hence neak in se $T_{\text{max}} = \frac{1}{2}$ \triangle Al is mixed bath with photon and Z hones peok in a reasonable background \triangle Uncertainty 2016 2017 2018 Correlation olon and

EXAMPLE ATLASS FOR DIMUONS (`˜') of any lifetime for masses less than 96.3 GeV [19–23]. Previous searches for long-lived sleptons have 620 GeV respectively, for a lifetime of 100 ps.

possible blind spot in BSM searches at the LHC [18]. Figure 1 shows a diagram of the targeted signal. A combination of results from the LEP experiments exclude the superpartners of the superpartners of the right-handed muons \mathcal{L}_max

$0.1 < d_0$ ^{\pm} < 0.3 mm control regions $n = 1$ the signal contains $\frac{1}{2}$ smuon signal containing $\frac{1}{2}$ $t_{\rm cl}$ \sim $t_{\rm cl}$ \sim 0.3 mm control regions and Δ \sim \sim \sim \sim

- $\frac{d}{dx}$ + Data agree well w/ expectations in 3 signal $\frac{1}{2}$ regions corresponding to different dimuon $\frac{1}{6}$ threshold masses are valued. $\frac{1}{10}$ Y Data ay be well with the positivities in 0 sign 200 GeV, the invariant mass of the two muons must be greater than 200 GeV for the regions on the right. A, B, C, shows the results of a model-independent fit, performed using the Historic package $[51, 51]$ Data agree well w/ expectations in 3 signal regions corresponding to different dimuon $\frac{1}{2}$ in the SRS. The processes in the corresponding to different different and the $\frac{1}{2}$
- $\frac{16}{10}$ + The new result bridges the prompt searches $\frac{g}{g}$ (d₀ < 0.3 mm) and the dimuon LLP analysis **E** $(0.3 \text{ cm} < d_0 < 300 \text{ cm})$ 10⁻¹ $\frac{15}{2}$ (d₀ < 0.3 mm) and the dimuon LLP analysis 2 and 3 refer to the boundaries used to subdivide the planes in |30| as depicted in Figure 2 for Set of Regions 1. The new result bridges the prompt searches $_{10}$ $\frac{1}{2}$ exposition the expectation of the expectation of the expectation of $\frac{1}{2}$ $\sqrt{0.00 \text{ cm}}$, $\sqrt{0.00 \text{ cm}}$, cap

Figure 1: Decay topology of the simplified model considered where smuons (`˜) are pair produced and each smuon **ATLAS [PLB 846 \(2023\) 138172](https://www.sciencedirect.com/science/article/pii/S0370269323005063/pdfft?md5=81c96022aaf1ff95bc5343ec4ddb90d9&pid=1-s2.0-S0370269323005063-main.pdf)**

