## **Collider physics:** LHC prospects and beyond

Catania

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**Physics Letters B** 

#### 2012

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC  $\stackrel{\text{\tiny{$\stackrel{l}{2}$}}}{}$ 

#### ATLAS Collaboration\*

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.



2013



Physics Letters B

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆



### General properties and couplings: OK



The ATLAS Collaboration Nature, 607, 52–59 (2022), The CMS Collaboration Nature, 607, 60–68 (2022)







### The Higgs width (SM: 4.1 MeV) : OK

![](_page_4_Figure_1.jpeg)

 $\Gamma_H = 4.6 + 2.6 - 2.5$  MeV at 68% CL

![](_page_4_Figure_3.jpeg)

![](_page_4_Picture_4.jpeg)

![](_page_4_Picture_5.jpeg)

## The next steps in HEP build on

having important questions to pursue
creating opportunities to answer them
being able to constantly add to our knowledge, while seeking those answers

## beyond the Higgs: the important questions

## • Data driven:

- DM
- Neutrino masses
- Matter vs antimatter asymmetry
- Dark energy
- •

### • Theory driven:

- The hierarchy problem and naturalness
- Origin of inflation
- Quantum gravity

# • The flavour problem (origin of fermion families, mass/mixing pattern)

## The opportunities

- For none of these questions, the path to an answer is unambiguously defined.
- Two examples:
  - DM: could be anything from fuzzy  $10^{-22}$  eV scalars, to O(TeV) WIMPs, to multi-M<sub> $\odot$ </sub> primordial BHs, passing through axions and sub-GeV DM • a vast array of expts is needed, even though most of them will end up empty-handed...
  - Neutrino masses: could originate anywhere between the EW and the GUT scale • we are still in the process of acquiring basic knowledge about the neutrino sector: mass hierarchy, majorana nature, sterile neutrinos, CP violation, correlation with mixing in the charged-lepton sector ( $\mu \rightarrow e\gamma$ ,  $H \rightarrow \mu \tau$ , ...): as for DM, *a broad range of options* to explore, to find the right clues
- We cannot objectively establish a hierarchy of relevance among the fundamental questions. The hierarchy evolves with time (think of GUTs and proton decay searches!) and is likely subjective. It is also likely that several of the big questions are tied together and will find their answer in a common context (eg DM and hierarchy problem, flavour and nu masses, quantum gravity/ inflation/dark energy, ...)

![](_page_7_Figure_8.jpeg)

## But there is one central question to the progress of HEP, which can <u>only</u> be addressed by colliders

![](_page_8_Picture_1.jpeg)

## Where does this come from?

![](_page_8_Figure_3.jpeg)

## $V(H) = - \mu^2 |H|^2 + \lambda |H|^4$

![](_page_8_Picture_5.jpeg)

The SM Higgs mechanism (*á la Weinberg*) provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

Where these ingredients come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us ...

![](_page_9_Picture_2.jpeg)

## a historical example: superconductivity

- we would still lack a deep understanding of the relevant dynamics.

• The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But

• For superconductivity, this came later, with the identification of e-e- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and we must look beyond.

![](_page_10_Picture_5.jpeg)

## examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- Supersymmetry: the Higgs is a fundamental field and •  $\lambda^2 \sim g^2 + g'^2$ , it is not arbitrary (MSSM, w/out susy breaking, has one
  - parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - parameters of SUSY breaking

•

```
• EW symmetry breaking (and thus m_H and \lambda) determined by the
```

## **Other important open issues** on the Higgs sector

- $H^{\pm}, A^{0}, H^{\pm\pm}, \dots, EW$ -singlets, ....)?
  - Do all SM families get their mass from the **<u>same</u>** Higgs field?
  - fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour?  $H \rightarrow \mu \tau$ ?  $H \rightarrow e \tau$ ?  $t \rightarrow Hc$ ?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?
- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, which can only rely on the LHC and on a future generation of colliders

• Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g.

• Do  $I_3 = I/2$  fermions (up-type quarks) get their mass from the <u>same</u> Higgs field as  $I_3 = -I/2$ 

![](_page_12_Picture_15.jpeg)

## The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

In search of the origin of known departures from the SM

- Dark matter, long lived particles
- Neutrino masses
- Matter/antimatter asymmetry of the universe

<u>To explore alternative extensions of the SM</u>

- New gauge interactions (Z', W') or extra Higgs bosons
- Additional fermionic partners of quarks and leptons, leptoquarks, ...
- **Composite nature of quarks and leptons**
- Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, ...)
- **Extra dimensions**
- New flavour phenomena
- unanticipated surprises ...

![](_page_13_Picture_15.jpeg)

### So far, no conclusive signal of physics beyond the SM

#### **ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits**

Status: July 2022

	Model	$\ell, \gamma$	Jets†	E <sup>miss</sup> T	∫£ dt[fb	-1]
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell \nu q q$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu, \tau, \gamma \\ 2 \ \gamma \\ - \\ 2 \ \gamma \\ multi-channel \\ 1 \ e, \mu \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array}$	1 – 4 j 2 j ≥3 j - 2 j / 1 J ≥1 b, ≥1J/2 ≥2 b, ≥3 j	Yes – – – Yes Yes Yes	139 36.7 139 3.6 139 36.1 139 36.1 36.1	M <sub>D</sub> M <sub>S</sub> Mth         GKK mass         GKK mass         GKK mass         GKK mass         KK mass         KK mass
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{Leptophobic} Z' \to bb \\ \operatorname{Leptophobic} Z' \to tt \\ \operatorname{SSM} W' \to \ell\nu \\ \operatorname{SSM} W' \to \tau\nu \\ \operatorname{SSM} W' \to tb \\ \operatorname{HVT} W' \to WZ \to \ell\nu qq \operatorname{mode} \\ \operatorname{HVT} W' \to WZ \to \ell\nu \ell'\ell' \operatorname{mode} \\ \operatorname{HVT} W' \to WZ \to \ell\nu \ell'\ell' \operatorname{mode} \\ \operatorname{HVT} W' \to WH \to \ell\nu bb \operatorname{mode} \\ \operatorname{HVT} Z' \to ZH \to \ell\ell/\nu\nu bb \operatorname{mode} \\ \operatorname{HVT} Z' \to ZH \to \ell\ell/\nu\nu bb \operatorname{mode} \\ \operatorname{LRSM} W_R \to \mu N_R \end{array}$	$\begin{array}{c} 2 \ e, \mu \\ 2 \ \tau \\ - \\ 0 \ e, \mu \\ 1 \ e, \mu \\ 1 \ \tau \\ el \ B \\ del \ C \\ 3 \ e, \mu \\ el \ B \\ 1 \ e, \mu \\ del \ B \\ 0, 2 \ e, \mu \\ 2 \ \mu \end{array}$	- 2 b ≥1 b, ≥2 J - ≥1 b, ≥1 J 2 j / 1 J 2 j (VBF) 1-2 b, 1-0 j 1-2 b, 1-0 j 1 J	- Yes Yes Yes Yes Yes Yes Yes	139 36.1 36.1 139 139 139 139 139 139 139 139 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass W' mass W' mass W' mass W' mass Z' mass Z' mass W <sub>R</sub> mass
CI	Cl qqqq Cl ℓℓqq Cl eebs Cl μμbs Cl tttt	_ 2 e, μ 2 e 2 μ ≥1 e,μ	2 j - 1 b 1 b ≥1 b, ≥1 j	- - - Yes	37.0 139 139 139 36.1	Λ Λ Λ Λ
MQ	Axial-vector med. (Dirac DM) Pseudo-scalar med. (Dirac DM) Vector med. Z'-2HDM (Dirac I Pseudo-scalar med. 2HDM+a	0 e, μ, τ, γ I) 0 e, μ, τ, γ DM) 0 e, μ multi-channel	1 – 4 j 1 – 4 j 2 b	Yes Yes Yes	139 139 139 139	m <sub>med</sub> m <sub>med</sub> m <sub>med</sub>
70	Scalar LQ 1 <sup>st</sup> gen Scalar LQ 2 <sup>nd</sup> gen Scalar LQ 3 <sup>rd</sup> gen Scalar LQ 3 <sup>rd</sup> gen Scalar LQ 3 <sup>rd</sup> gen Scalar LQ 3 <sup>rd</sup> gen Vector LQ 3 <sup>rd</sup> gen	$\begin{array}{c} 2 \ e \\ 2 \ \mu \\ 1 \ \tau \\ 0 \ e, \mu \\ \geq 2 \ e, \mu, \geq 1 \ \tau \\ 0 \ e, \mu \leq 1 \ \tau \\ 1 \ \tau \end{array}$	$ \begin{array}{c} \geq 2 \ j \\ \geq 2 \ j \\ 2 \ b \\ \geq 2 \ j, \geq 2 \ b \\ \geq 1 \ j, \geq 1 \ b \\ 0 - 2 \ j, 2 \ b \\ 2 \ b \end{array} $	Yes Yes Yes - Yes Yes	139 139 139 139 139 139 139 139	LQ mass LQ mass LQ <sup>u</sup> mass LQ <sup>d</sup> mass LQ <sup>d</sup> mass LQ <sup>d</sup> mass LQ <sup>d</sup> mass
Vector-like fermions	$\begin{array}{l} VLQ \ TT \to Zt + X \\ VLQ \ BB \to Wt/Zb + X \\ VLQ \ T_{5/3} \ T_{5/3}   T_{5/3} \to Wt + X \\ VLQ \ T \to Ht/Zt \\ VLQ \ T \to Ht/Zt \\ VLQ \ Y \to Wb \\ VLQ \ B \to Hb \\ VLL \ \tau' \to Z\tau/H\tau \end{array}$	$2e/2\mu/\geq 3e,\mu$ multi-channel X 2(SS)/ $\geq 3e,\mu$ 1 $e,\mu$ 1 $e,\mu$ 0 $e,\mu \geq$ multi-channel	≥1 b, ≥1 j ≥1 b, ≥1 j ≥1 b, ≥3 j ≥1 b, ≥1 j 2b, ≥1j, ≥1 ≥1 j	- Yes Yes J - Yes	139 36.1 36.1 139 36.1 139 139	T mass B mass T <sub>5/3</sub> mass T mass Y mass B mass τ' mass
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton $\ell^*$ Excited lepton $\nu^*$	1γ - 3 e,μ 3 e,μ,τ	2 j 1 j 1 b, 1 j - -		139 36.7 139 20.3 20.3	q* mass q* mass b* mass ℓ* mass v* mass
Other	Type III Seesaw LRSM Majorana $v$ Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ Multi-charged particles Magnetic monopoles	2,3,4 e, $\mu$ 2 $\mu$ 2,3,4 e, $\mu$ (SS 2,3,4 e, $\mu$ (SS 3 e, $\mu$ , $\tau$	≥2 j 2 j ) various ) – – –	Yes  Yes _ _ _ _	139 36.1 139 139 20.3 139 34.4	N <sup>0</sup> mass N <sub>R</sub> mass H <sup>±±</sup> mass H <sup>±±</sup> mass H <sup>±±</sup> mass multi-charged particl monopole mass
	√s = 8 TeV	vs = 13 TeV partial data	√s = 13 full da	TeV ata		10 <sup>-1</sup>

\*Only a selection of the available mass limits on new states or phenomena is shown. †Small-radius (large-radius) jets are denoted by the letter j (J).

#### **ATLAS** Preliminary

 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$ 

 $\sqrt{s} = 8, 13 \text{ TeV}$ 

Limit Reference **11.2 TeV** *n* = 2 2102.10874 **8.6 TeV** *n* = 3 HLZ NLO 1707.04147 **9.4 TeV** *n* = 6 1910.08447 **9.55 TeV**  $n = 6, M_D = 3$  TeV, rot BH 1512.02586  $k/\overline{M}_{Pl} = 0.1$ 4.5 TeV 2102.13405 2.3 TeV  $k/\overline{M}_{Pl} = 1.0$ 1808.02380  $k/\overline{M}_{Pl} = 1.0$ 2.0 TeV 2004.14636  $\Gamma/m = 15\%$ 1804.10823 3.8 TeV Tier (1,1),  $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 1.8 TeV 1803.09678 5.1 TeV 1903.06248 2.42 TeV 1709.07242 2.1 TeV 1805.09299 4.1 TeV  $\Gamma/m = 1.2\%$ 2005.05138 6.0 TeV 1906.05609 ATLAS-CONF-2021-025 5.0 TeV 4.4 TeV ATLAS-CONF-2021-043 4.3 TeV  $g_V = 3$ 2004.14636 340 GeV ATLAS-CONF-2022-005  $g_V c_H = 1, g_f = 0$ 3.3 TeV  $g_V = 3$ 2207.00230 3.2 TeV  $g_V = 3$ 2207.00230  $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$ 5.0 TeV 1904.12679 **21.8 TeV** η<sub>LL</sub> 1703.09127 35.8 TeV  $\eta_{LL}^-$ 2006.12946 1.8 TeV  $g_{*} = 1$ 2105.13847 2.0 TeV  $g_{*} = 1$ 2105.13847  $|C_{4t}| = 4\pi$ 2.57 TeV 1811.02305  $g_q=0.25, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 2.1 TeV 2102.10874  $g_q=1, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 376 GeV 2102.10874  $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$ 3.1 TeV 2108.13391  $\tan\beta=1, g_{\chi}=1, m(\chi)=10 \text{ GeV}$ ATLAS-CONF-2021-036 560 GeV 1.8 TeV  $\beta = 1$ 2006.05872 1.7 TeV  $\beta = 1$ 2006.05872  $\mathcal{B}(\mathrm{LQ}_3^u \to b au) = 1$  $\mathcal{B}(\mathrm{LQ}_3^u \to t
u) = 1$ 1.2 TeV 2108.07665 1.24 TeV 2004.14060  $\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$ 1.43 TeV 2101.11582  $\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$ 1.26 TeV 2101.12527 1.77 TeV  $\mathcal{B}(LQ_3^V \to b\tau) = 0.5$ , Y-M coupl. 2108.07665 1.4 TeV SU(2) doublet ATLAS-CONF-2021-024 1.34 TeV SU(2) doublet 1808.02343 1.64 TeV  $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 1807.11883 1.8 TeV SU(2) singlet,  $\kappa_T = 0.5$ ATLAS-CONF-2021-040 1.85 TeV  $\mathcal{B}(Y \to Wb) = 1, c_R(Wb) = 1$ 1812.07343 SU(2) doublet,  $\kappa_B = 0.3$ 2.0 TeV ATLAS-CONF-2021-018 898 GeV SU(2) doublet ATLAS-CONF-2022-044 6.7 TeV only  $u^*$  and  $d^*$ ,  $\Lambda = m(q^*)$ 1910.08447 5.3 TeV only  $u^*$  and  $d^*$ ,  $\Lambda = m(q^*)$ 1709.10440 3.2 TeV 1910.0447 3.0 TeV  $\Lambda = 3.0 \text{ TeV}$ 1411.2921 1.6 TeV  $\Lambda = 1.6 \text{ TeV}$ 1411.2921 910 GeV 2202.02039  $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 3.2 TeV 1809.11105 DY production 350 GeV 2101.11961 DY production ATLAS-CONF-2022-010 1.08 TeV DY production,  $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ 400 GeV 1411.2921 DY production, |q| = 5e1.59 TeV ATLAS-CONF-2022-034 mass DY production,  $|g| = 1g_D$ , spin 1/2 2.37 TeV 1905.10130 10

Mass scale [TeV]

![](_page_14_Picture_11.jpeg)

The value of diversity in collider physics

![](_page_15_Picture_1.jpeg)

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## LHC scientific production

Over 3000 papers published/submitted to refereed journals by the 7 experiments that operated in Run 1 and 2 (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)... and the first papers are appearing by the new experiments started in Run 3 (FASER, SND@LHC)

Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~30% on searches for new physics (35% if ATLAS+CMS only)

~60% of the papers on SM measurements (jets, EW, top, b, HIs, ...)

![](_page_16_Picture_6.jpeg)

![](_page_16_Picture_7.jpeg)

### **Flavour physics**

- $B(s) \rightarrow \mu \mu$
- D mixing and CP violation in the D system
- Measurement of the  $\gamma$  angle, CPV phase  $\phi$ s, ...

### **QCD** dynamics

- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- sensitivity to glueballs
- ...) in "small" systems (pA and pp)

### EW param's and dynamics

- $m_W$ ,  $m_{top}$  171.77 ± 0.37 GeV, (CMS <u>https://arxiv.org/pdf/2302.01967.pdf</u>) sin<sup>2</sup> $\Theta_W$
- EW interactions at the TeV scale (DY,VV,VVV,VBS,VBF, Higgs, ...)

Lepton flavour universality in charge- and neutral-current semileptonic B decays = possible anomalies?

Countless precise measurements of hard cross sections, and improved determinations of the proton PDF

Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected

Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement,

![](_page_17_Picture_20.jpeg)

![](_page_17_Picture_21.jpeg)

# QCD production dynamics

![](_page_18_Picture_2.jpeg)

#### Standard Model Production Cross Section Measurements

![](_page_19_Figure_1.jpeg)

Excellent agreement between data and theoretical predictions, over 10 orders of magnitude, culminating 30 years of progress in higher-order perturbative calculations, which have now reached next-to-leading order as routine, NNLO as benchmark for most processes, and NNNLO available for only some (very important!) cases, but rapidly expanding beyond

Status: May 2017

![](_page_19_Picture_4.jpeg)

![](_page_20_Picture_0.jpeg)

![](_page_20_Figure_1.jpeg)

![](_page_20_Picture_2.jpeg)

## **4 top production**

![](_page_20_Figure_4.jpeg)

![](_page_20_Picture_5.jpeg)

![](_page_20_Picture_6.jpeg)

#### https://arxiv.org/abs/2303.15061

![](_page_21_Figure_1.jpeg)

![](_page_21_Figure_2.jpeg)

#### Combined

![](_page_21_Figure_5.jpeg)

![](_page_21_Picture_6.jpeg)

## as from Z pt spectrum

![](_page_22_Figure_1.jpeg)

#### ATLAS-CONF-2023-015

![](_page_22_Figure_3.jpeg)

![](_page_22_Picture_4.jpeg)

![](_page_22_Picture_5.jpeg)

![](_page_22_Picture_6.jpeg)

### **Example: PDF fits from LHC data**

ATLASpdf21 fit, https://arxiv.org/pdf/2112.11266.pdf including HERA and ATLAS data

Data set	$\sqrt{s}$ [TeV]	Luminosity [fb <sup>-1</sup> ]	Decay channel	Observables entering the fit
Inclusive $W, Z/\gamma^*$ [9]	7	4.6	$e, \mu$ combined	$\eta_{\ell}$ (W), $y_{Z}$ (Z)
Inclusive $Z/\gamma^*$ [13]	8	20.2	$e, \mu$ combined	$\cos \theta^*$ in bins of $y_{\ell\ell}, m_{\ell\ell}$
Inclusive W [12]	8	20.2	$\mu$	$\eta_{\mu}$
$W^{\pm} + jets [24]$	8	20.2	е	$p_{\mathrm{T}}^W$
Z + jets [25]	8	20.2	e	$p_{\rm T}^{\rm jet}$ in bins of $ y^{\rm jet} $
tī [26, 27]	8	20.2	lepton + jets, dilepton	$m_{t\bar{t}}, p_{\mathrm{T}}^{t}, y_{t\bar{t}}$
<i>tt</i> <sup>¯</sup> [15]	13	36	lepton + jets	$m_{t\bar{t}}, p_{T}^{t}, y_{t}, y_{t\bar{t}}^{b}$
Inclusive isolated $\gamma$ [14]	8,13	20.2, 3.2	-	$E_{\rm T}^{\gamma}$ in bins of $\eta^{\gamma}$
Inclusive jets [16–18]	7, 8, 13	4.5, 20.2, 3.2	r <b>-</b> .	$p_{\rm T}^{\rm jet}$ in bins of $ y^{\rm jet} $

Strange quark / light antiquarks ratio

![](_page_23_Figure_4.jpeg)

![](_page_23_Figure_5.jpeg)

![](_page_23_Picture_6.jpeg)

### Not everything is perfect though! Ex: ttW cross section....

![](_page_24_Figure_1.jpeg)

arXiv:2208.06485

![](_page_24_Figure_3.jpeg)

Study of QCD dynamics in previously unexplored dynamical regimes

![](_page_25_Picture_1.jpeg)

### **Collective QCD phenomena in high-T, high-density** and other extreme environments

consolidation of known phenomena, with higher precision and broader coverage: (ALICE, https://inspirehep.net/literature/2165947)

![](_page_26_Figure_2.jpeg)

discovery of new dynamical behaviour, with collective phenomena typical of QGP appearing already in highmultiplicity final states of pp and pA

![](_page_26_Figure_4.jpeg)

#### First experimental evidence for odderon exchange made possible by comparison of pp TOTEM data with ppbar D0 data

hh elastic scattering dominated by exchange of leading Regge poles:
pomeron (CP even, contributes w. same sign to pp and ppbar amplitudes)
odderon (CP odd, contribute w. opposite signs to pp and ppbar amplitudes)

![](_page_27_Figure_2.jpeg)

#### Phys.Rev.Lett. 127 (2021) 6, 062003

![](_page_27_Picture_4.jpeg)

![](_page_28_Picture_0.jpeg)

![](_page_28_Picture_1.jpeg)

![](_page_28_Picture_2.jpeg)

![](_page_29_Picture_0.jpeg)

	Overview of m <sub>w</sub> Measureme
LEP Combination	ATLAS Prelimin
	√s = 7 TeV, 4.6 fb <sup>-1</sup>
D0 (Run 2) arXiv:1203.0293	
CDF (Run 2) FERMILAB-PUB-22-254-PP	D
LHCb 2022 arXiv:2109.01113	
ATLAS 2017 arXiv:1701.07240	<ul> <li>Measurement</li> <li>Stat. Unc.</li> </ul>
ATLAS 2023 this work	Total Unc.
8	0200 803

## W mass

![](_page_29_Figure_3.jpeg)

![](_page_29_Picture_4.jpeg)

## Lepton universality of W couplings

ATLAS 2020: <u>arXiv:2007.14040</u>

![](_page_30_Figure_2.jpeg)

CMS 2022: <u>arXiv:2201.07861</u>

![](_page_30_Picture_4.jpeg)

![](_page_31_Figure_0.jpeg)

M<sub>W</sub> and sin<sup>2</sup>θ<sub>W</sub> precision must still improve to match the accurate SM prediction

PS: note the big impact in the SM precision due to the knowledge of  $M_H$ 

![](_page_31_Picture_3.jpeg)

## Exotic Spectroscopy, nuclear physics and more

![](_page_32_Picture_1.jpeg)

### Continued progress, and novelties, in spectroscopy

CMS, <u>Phys. Lett. B 803 (2020) 135345</u>

![](_page_33_Figure_2.jpeg)

![](_page_33_Figure_3.jpeg)

![](_page_33_Picture_4.jpeg)

A usual baryon:

![](_page_34_Picture_1.jpeg)

### A baryon with two heavy q's:

### Similar to a heavy meson, eg $B_u$

but here the core is a fermion, while in a doubly-heavy baryon the core is a boson (different hyperfine splitting structures, etc)

 $\Rightarrow$  rewarding for theory and experiment to challenge each other's ability to predict/measure!!

![](_page_34_Figure_6.jpeg)

![](_page_34_Picture_9.jpeg)

![](_page_35_Figure_1.jpeg)

![](_page_35_Figure_4.jpeg)

![](_page_35_Picture_7.jpeg)

## Impact on astroparticle physics

countless searches for dark matter candidates covering a huge domain of plausible model space

... plus:

![](_page_36_Picture_4.jpeg)

![](_page_37_Picture_0.jpeg)

Probing the spectrum of most energetic particles forward-produced => model development of highest-energy cosmic ray showers in the atmosphere

![](_page_37_Figure_2.jpeg)

photons~π<sup>0</sup>~π<sup>+-</sup>

Phys.Lett.B 780 (2018) 233

neutrons

JHEP 07 (2020) 016

![](_page_37_Picture_7.jpeg)

![](_page_38_Figure_0.jpeg)

![](_page_38_Picture_1.jpeg)

#### Article

#### Measurement of anti-<sup>3</sup>He nuclei absorption in matter and impact on their propagation in the Galaxy

![](_page_39_Figure_3.jpeg)

### **Measuring antinuclei fluxes**

![](_page_39_Figure_8.jpeg)

Laura Šerkšnytė CERN seminar

#### **Method: ALICE as a target**

![](_page_39_Figure_13.jpeg)

#### Antimatter-to-matter ratio

• Measure reconstructed  ${}^{3}\overline{\text{He}}/{}^{3}\text{He}$  and compare with MC simulations

![](_page_39_Figure_16.jpeg)

#### **TOF-to-TPC-matching**

• Measure reconstructed  ${}^{3}\overline{\text{He}}_{\text{TOF}}/{}^{3}\overline{\text{He}}_{\text{TPC}}$ and compare with MC simulations

![](_page_39_Figure_19.jpeg)

![](_page_39_Picture_20.jpeg)

• AMS-02: Magnetic spectrometer on ISS; 9 antihelium candidates; not published yet • GAPS: Antarctic balloon mission; low energy antinuclei; planned at the end of 2023 • AMS-100: Next generation magnetic spectrometer; x1000 sensitivity; estimated launch 2039

![](_page_39_Picture_22.jpeg)

## Neutrino Physics: FASERv and SND@LHC

Among other goals:

measure neutrino cross sections in energy ranges never explored before, of relevance to cosmic neutrino studies, and flavour-tagged

![](_page_40_Figure_3.jpeg)

![](_page_41_Figure_1.jpeg)

![](_page_41_Picture_2.jpeg)

### **FASER/FASERv**

• Analysis of FAESRv emulsion detector underway

![](_page_41_Figure_6.jpeg)

Candidate	Events			
<b>n</b> <sub>0</sub>	<b>153</b> (151 ± 4			
<b>n</b> <sub>10</sub>	4			
<b>n</b> <sub>01</sub>	6			
n <sub>2</sub>	64014695			

![](_page_41_Picture_8.jpeg)

![](_page_41_Picture_9.jpeg)

![](_page_42_Figure_1.jpeg)

## SND@LHC

- About 480 m from ATLAS interaction
- - Used in the past as transfer line
- Shielded by 100 m of rock and LHC
- Angular acceptance:  $7.2 < \eta < 8.4$
- First phase: collect 250 fb<sup>-1</sup> in Run 3

![](_page_42_Picture_10.jpeg)

![](_page_42_Picture_11.jpeg)

## Remarks

- These 3000 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities
- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities
  - HERA  $\rightarrow$  PDFs, B-factories  $\rightarrow$  flavour, RHIC  $\rightarrow$  HIs, LEP/SLC  $\rightarrow$  EWPT, etc
- Even in the perspective of new dedicated facilities, eg SuperKEKB or EIC, LHC maintains a key role of competition and complementarity

from the data, that are unexpected, surprising, or simply poorly understood.

phenomena.

"New physics" is emerging every day at the LHC!

- I have a broad concept of "new physics", which includes SM phenomena, emerging
- I consider as "new", and as a discovery, everything that is not obviously predictable, or that requires deeper study to be clarified, even if it belongs to the realm of SM

![](_page_43_Picture_11.jpeg)

![](_page_43_Picture_12.jpeg)

## The LHC future: High-Luminosity LHC

![](_page_44_Figure_1.jpeg)

![](_page_44_Picture_2.jpeg)

Gluino mass exclusion search sensitivity, vs luminsoty: still plenty of room for discovery at HL-LHC!

![](_page_45_Figure_1.jpeg)

ŀ	IL/HE-LHC	SUSY	Searche	HL-LHC, $\int \mathcal{L} dt = 3ab^{-1}$ ; for $d$ HE-LHC, $\int \mathcal{L} dt = 15ab^{-1}$ ; for $d$	soavery (95% CLexclusion) isoavery (95% CLexclusion)	S	Simulation Prelimina $\sqrt{s} = 14,27$ Te
	Model	$e, \mu, \tau, \gamma$	Jets	Mass limit			Section
Gluino	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_1^0$	0	4 jets	2	2.9 (3.2) TeV	m( $\bar{\ell}_{1}^{0}$ )=0	2.1.1
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0	4 jets	ž	5.2 (5.7) TeV	$m(\tilde{\chi}_1^0)=0$	2.1.1
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\lambda}_1^0$	0	Multiple	ž	2.3 (2.5) TeV	m( $\bar{\chi}_{1}^{0}$ )=0	2.1.3
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{c} \tilde{\chi}_{1}^{0}$	0	Multiple	ž	2.4 (2.6) TeV	m( $\hat{\chi}_{1}^{0}$ )=500 GeV	2.1.3
	NUHM2, $\tilde{g} \rightarrow t\tilde{t}$	0	Multiple/2b	ž	5.5 (5.9) TeV		2.4.2
do	$\tilde{x}_1 \tilde{x}_1, \tilde{x}_1 \rightarrow t \tilde{\chi}_1^0$	0	Multiple/2b	ĩ,	1.4 (1.7) TeV	m(X <sup>0</sup> 1)=0	2.1.2, 2.1.3
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0	Multiple/2b	T <sub>1</sub>	0.6 (0.85) TeV	$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(t)$	2.1.2
S	$\tilde{\imath}_1\tilde{\imath}_1,\tilde{\imath}_1{\rightarrow}b\tilde{\chi}^a/\imath\tilde{\chi}^0_1,\tilde{\chi}^0_2$	0	Multiple/2b	ĩ	3.16 (3.65) TeV		2.4.2
	$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ {\rightarrow} W^* \tilde{\chi}_1^0$	2 e.µ	0-1 jets	$\tilde{X}_{1}^{\pm}$	0.66 (0.84) TeV	m(x10)=0	2.2.1
pino, alino	$\tilde{\chi}_1^* \tilde{\chi}_2^0$ via $WZ$	3 e, µ	0-1 jets	$\bar{X}_{1}^{*}/\bar{X}_{2}^{0}$	0.92 (1.15) TeV	$m(\tilde{\chi}_{1}^{0})=0$	2.2.2
harg	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh, Wh $\!$	1 e, µ	2-3 jets/2b	$\bar{X}_{1}^{*}/\bar{X}_{2}^{0}$	1.08 (1.28) TeV	$m(\tilde{t}_1^0)=0$	2.2.3
0 6	$\tilde{\chi}_2^{\pm} \tilde{\chi}_4^0 \rightarrow W^{\pm} \tilde{\chi}_1^0 W^{\pm} \tilde{\chi}_1^{\pm}$	2 e,µ	7	$\bar{\chi}_{2}^{\pm}/\bar{\chi}_{4}^{0}$	0.9 TeV	m(\$\tilde{\text{t}}_1^0)=150, 250 \text{ GeV}	2.2.4
0	$\tilde{\mathcal{X}}_1^{\pm} \tilde{\mathcal{X}}_2^0 + \tilde{\mathcal{X}}_2^0 \tilde{\mathcal{X}}_1^0, \tilde{\mathcal{X}}_2^0 {\rightarrow} Z \tilde{\mathcal{X}}_1^0, \tilde{\mathcal{X}}_1^{\pm} {\rightarrow} W \tilde{\mathcal{X}}_1^0$	2 e,µ	1 jet	$\hat{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.25 (0.36) TeV	m(x10)=15 GeV	2.2.5.1
Higgsine	$\tilde{\mathcal{X}}_1^{\pm} \tilde{\mathcal{X}}_2^0 + \tilde{\mathcal{X}}_2^0 \tilde{\mathcal{X}}_1^0, \tilde{\mathcal{X}}_2^0 {\rightarrow} Z \tilde{\mathcal{X}}_1^0, \tilde{\mathcal{X}}_1^{\pm} {\rightarrow} W \tilde{\mathcal{X}}_1^0$	2 e,µ	1 jet	$\bar{X}_{1}^{n}/\bar{X}_{2}^{0}$	0.42 (0.55) TeV	m( $\bar{\chi}_{1}^{0}$ )=15 GeV	2.2.5.1
	$\tilde{\boldsymbol{\chi}}_{2}^{0} \tilde{\boldsymbol{\chi}}_{1}^{*}, \tilde{\boldsymbol{\chi}}_{1}^{*} \tilde{\boldsymbol{\chi}}_{1}^{*} \tilde{\boldsymbol{\chi}}_{1}^{\mp}, \tilde{\boldsymbol{\chi}}_{1}^{*} \tilde{\boldsymbol{\chi}}_{1}^{0}$	2 μ	1 jet	$\tilde{X}_{2}^{0}$	0.21 (0.35) TeV	$\Delta m({ar \chi}^0_2,{ar \chi}^0_1){=}5{ m GeV}$	2.2.5.2
Wino	$\tilde{\chi}_2^*\tilde{\chi}_4^0$ via same-sign $WW$	2 e.µ	0	Wino	0.86 (1.08) TeV		2.4.2
	$\tilde{\tau}_{L,R}\tilde{\tau}_{L,R}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$	2 τ	-	e	0.53 (0.73) TeV	m( $\bar{\chi}_{1}^{0}$ )=0	2.3.1
stau	77	$2\tau,\tau(e,\mu)$	-	÷	0.47 (0.65) TeV	$m(\tilde{\chi}_1^0) = 0,  m(\tilde{\tau}_L) = m(\tilde{\tau}_R)$	2.3.2
0	77	$2\tau,\tau(e,\mu)$		P	0.81 (1.15) TeV	$m(\tilde{\chi}_1^0)=0, m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$	2.3.4
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \tilde{\chi}_1^0, \operatorname{long-lived} \tilde{\chi}_1^{\pm}$	Disapp. trk.	1 jet	$\hat{X}_1^{\pm} = [\tau(\hat{X}_1^{\pm}) = 1 \text{ns}]$	0.8 (1.1) TeV	Wino-like $\tilde{\chi}_1^a$	4.1.1
	$\tilde{\mathcal{X}}_1^* \tilde{\mathcal{X}}_1^*, \tilde{\mathcal{X}}_1^* \tilde{\mathcal{X}}_1^0, \operatorname{long-lived} \tilde{\mathcal{X}}_1^*$	Disapp. trk.	1 jet	$\hat{X}_1^{\pm} = [\tau(\hat{X}_1^{\pm}) = 1 \text{ns}]$	0.6 (0.75) TeV	Higgsino-like $\hat{\chi}_1^a$	4.1.1
	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.88 (0.9) TeV	Wino-like DM	4.1.3
n g	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	2.0 (2.1) TeV	Wino-like DM	4.1.3
1-live ticles	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.28 (0.3) TeV	Higgsino-like DM	4.1.3
Long	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.55 (0.6) TeV	Higgsino-like DM	4.1.3
	$\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\ell}_1^0$	0	Multiple	$\tilde{g} = [r(\tilde{g}) = 0.1 - 3 \text{ ns}]$	3.4 TeV	m( $\tilde{t}_{1}^{0}$ )=100 GeV	4.2.1
	$\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	0	Multiple	$\tilde{g} = [r(\tilde{g}) = 0.1 - 10 \text{ ns}]$	2.8 TeV		4.2.1
	GMSB $\bar{\mu} \rightarrow \mu \bar{G}$	displ. $\mu$		$\tilde{\mu}$	0.2 TeV	cr =1000 mm	4.2.2
							arXiv:1812.07831
10 <sup>-1</sup>			0 <sup>-1</sup> 1	Mass scale [TeV]			
					3 TeV	н	L-LHC YR

![](_page_45_Picture_4.jpeg)

![](_page_45_Picture_5.jpeg)

ī

## Examples of new opportunities

![](_page_46_Picture_1.jpeg)

![](_page_47_Picture_0.jpeg)

![](_page_47_Figure_2.jpeg)

- - Also taking into account new preliminary NA62 result (see backup)

## **FASER BSM searches**

CERN-FASER-CONF-2023-001

![](_page_47_Picture_10.jpeg)

## CMS light dimuon resonance searches with data scouting

- Mass range 1.1-2.6 GeV and 4.2-7.9 GeV
- Stores events with 2  $\mu$  of pt>3 GeV
- Selects  $\mu + \mu$  pairs with pt>4  $|\eta| < 1.9$

![](_page_48_Figure_5.jpeg)

### Improves on LHCb and Belle/Babar sensitivity

![](_page_48_Picture_8.jpeg)

![](_page_48_Picture_9.jpeg)

# enhance or evaporate

- architectures
- signatures

• Plenty of excesses and anomalies exist here and there, which higher luminosity can

• focus on development of new analysis strategies, relying on advanced machinelearning techniques, new detector capabilities (eg timing), advences in trigger

• The exploration of the highest mass region (where already now signal eff $\sim O(1)$  and S/B>>1) is already close to saturation, but plenty of room for significant improvement in sensitivity below the phase-space threshold, especially for rare and/or elusive

![](_page_49_Picture_6.jpeg)

![](_page_49_Picture_7.jpeg)

## **Key take-home messages**

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- The LHC has proven the immense and unique versatility and precision of a high-energy pp collider.
- The spectrum of observables and diverse phenomena that it has access to, the precision of the measurements, the groundwork for first-principles interpretations in the context of the Standard Model or beyond, have no equals in the history of our field
- The LHC forthcoming upgrades in luminosity and detector performance with expand even more its broad and deep potential, opening the way to possible discoveries, and more surprises

![](_page_50_Figure_6.jpeg)

![](_page_50_Figure_7.jpeg)