The ATLAS experiment at CERN

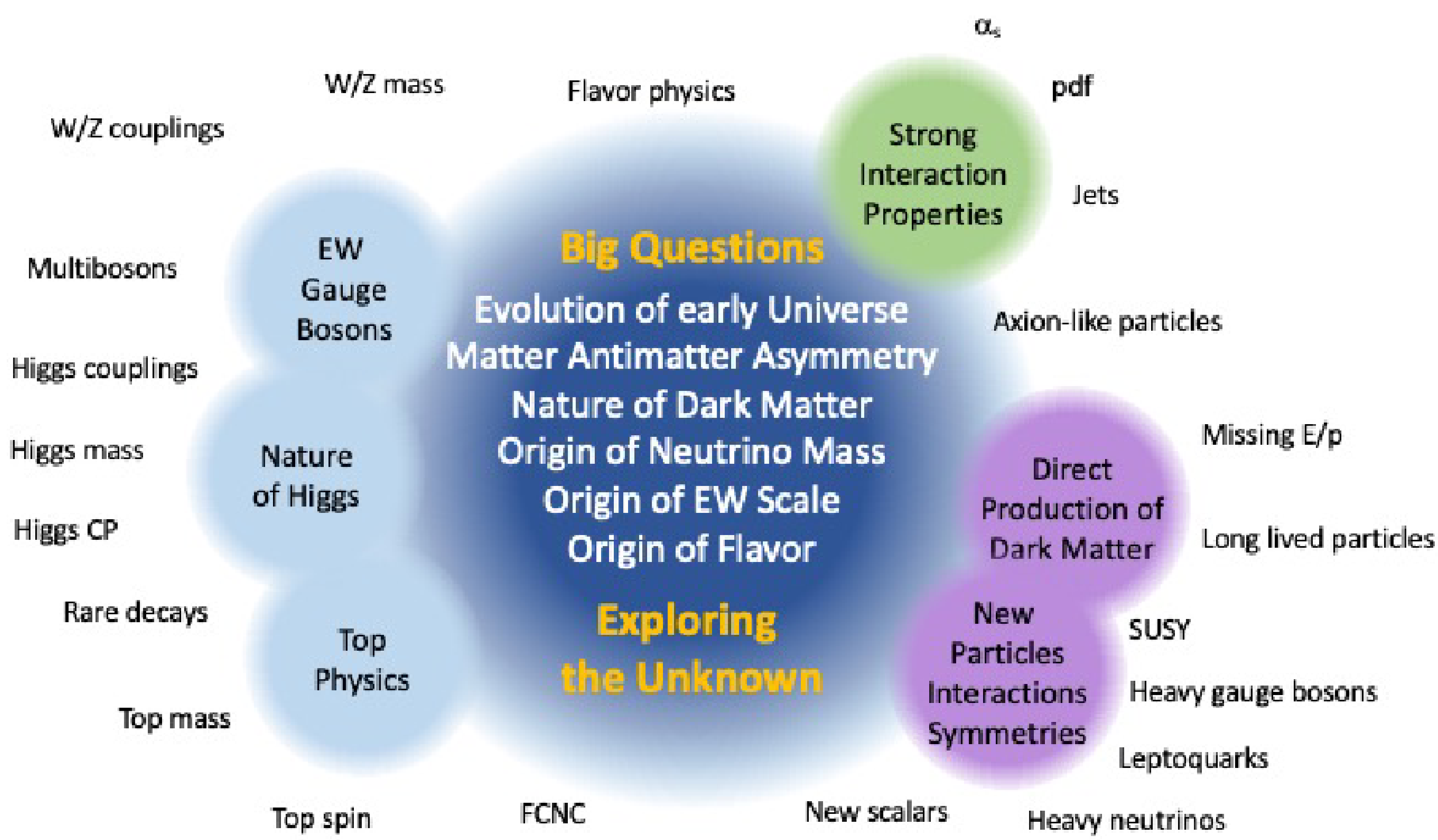
Elisabeth Petit
on behalf of the ATLAS-CPPM team

EN 2023, LE CPPM CÉLÈBRE SES 40 ANS
40
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM
AU CŒUR DE LA MATIÈRE ET DE L'UNIVERS

Visite des étudiants M1/M2 FunPhys
6^{th} of October 2023

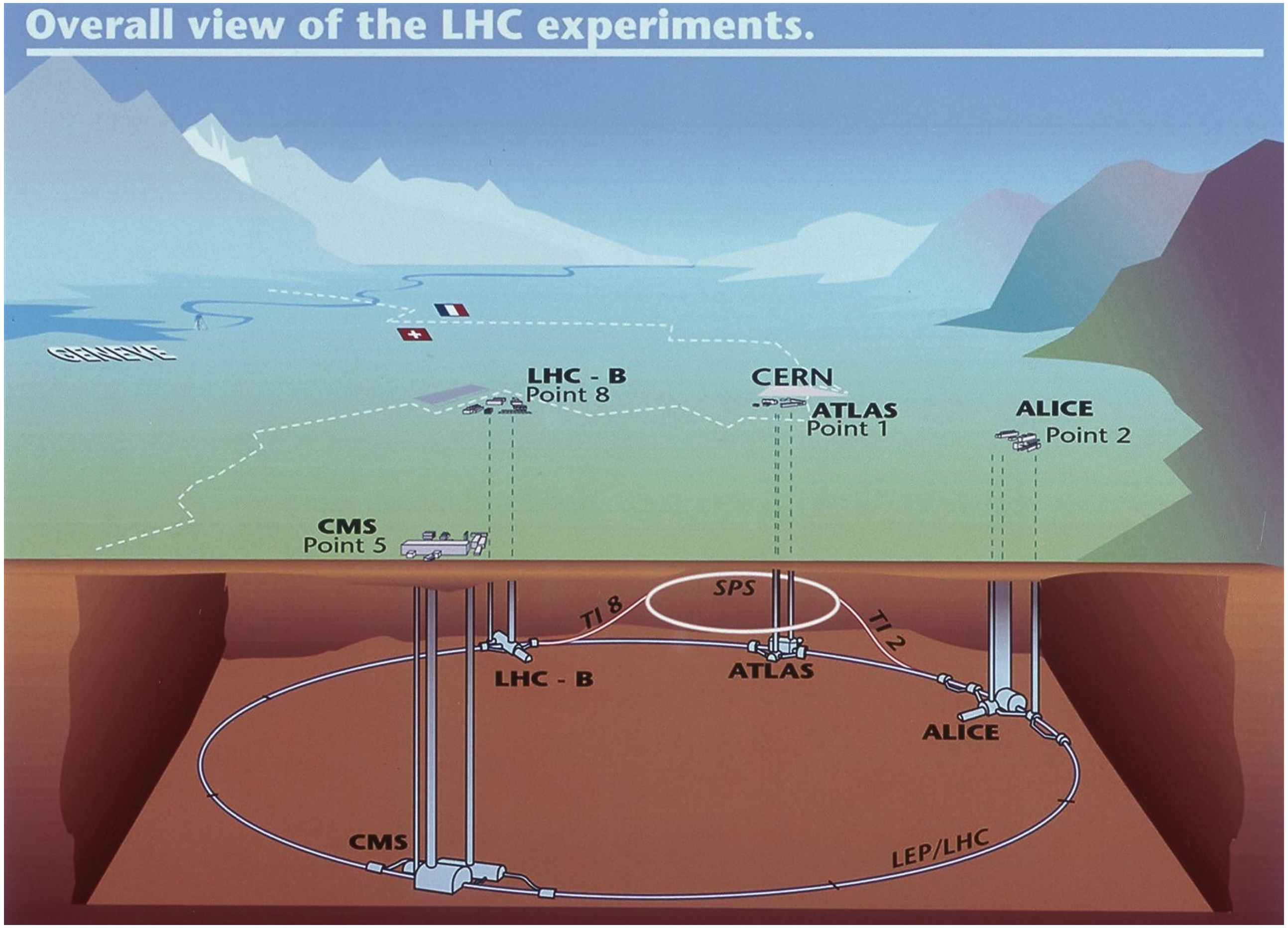
ATLAS EXPERIMENT

Energy frontier to address the big questions



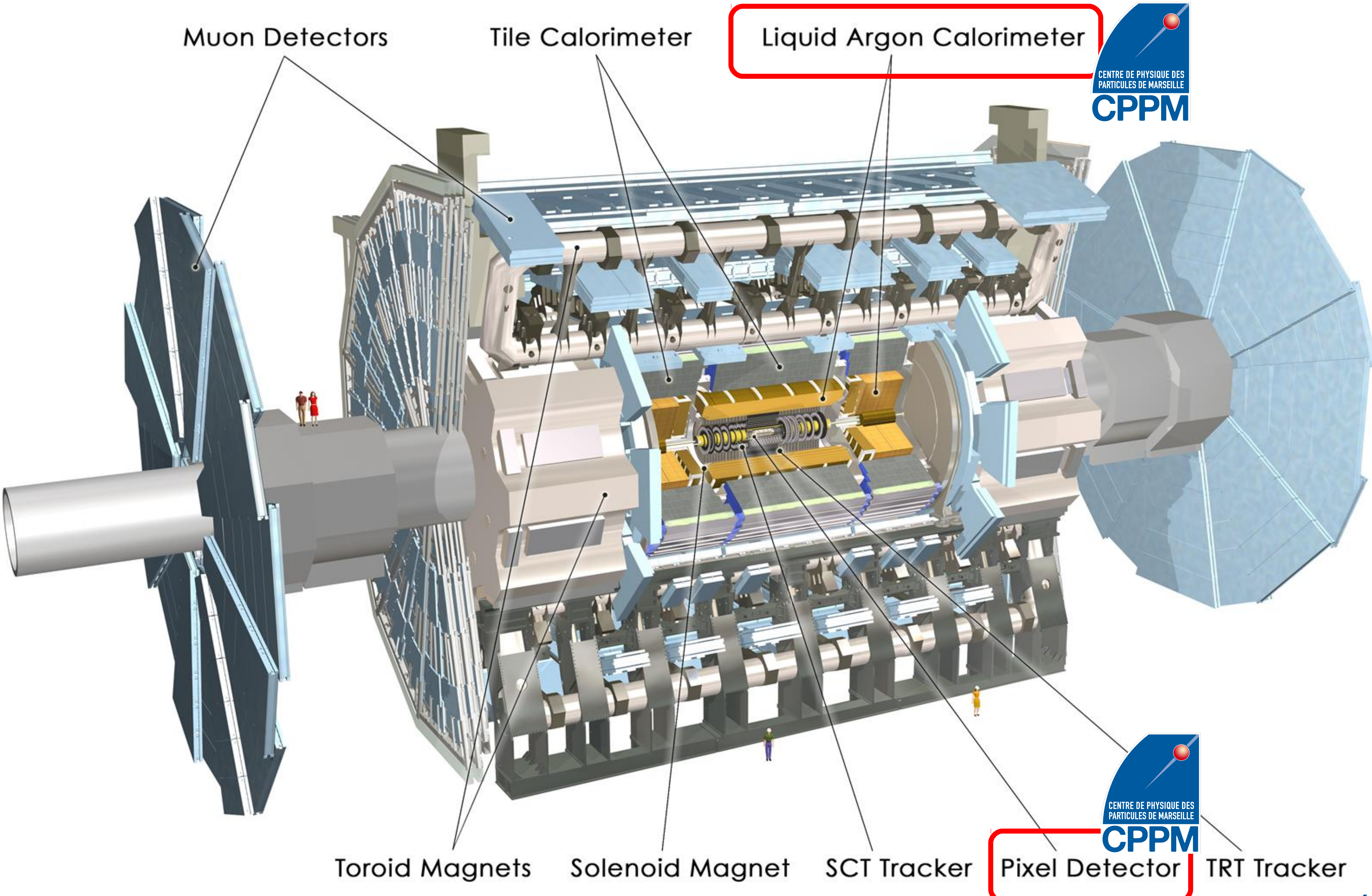
The LHC project

- Biggest accelerator ever!

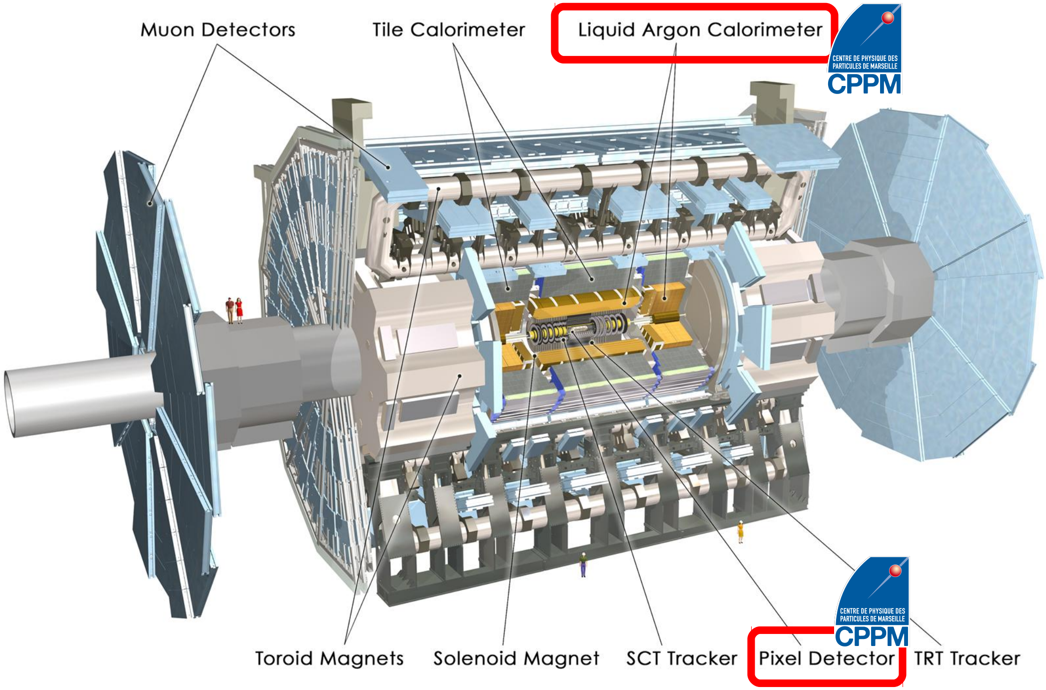


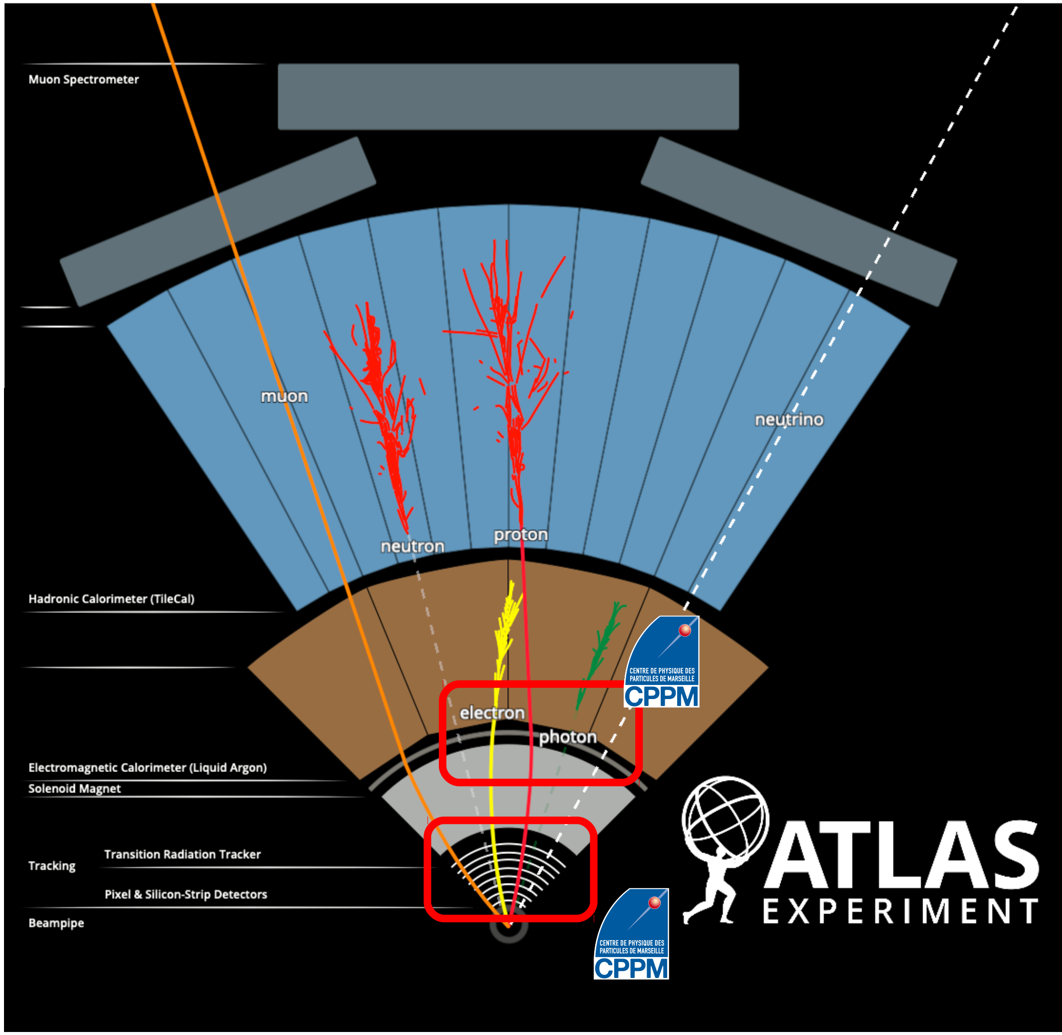
- pp (and heavy ions) collisions
- Centre-of-mass energy: 13.6 TeV
- Collision every 25 ns ⇒ 40 million collisions /s
  - 1 Higgs boson /h

The ATLAS experiment (1)



ATLAS experiment (2)





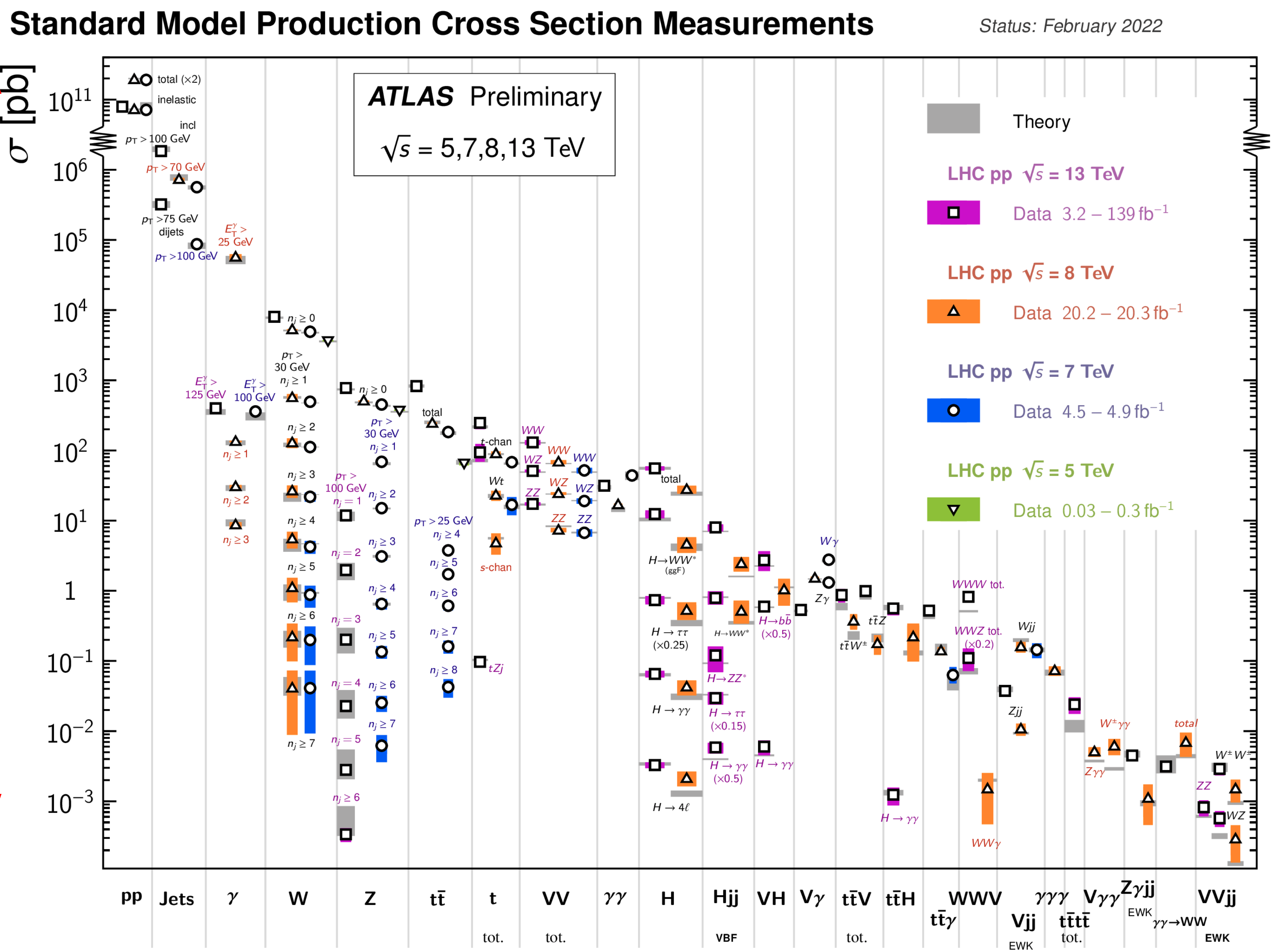
ATLAS Collaboration

ATLAS CPPM team

- 14 researchers
- 27 engineers and technicians
- 2 post-docs
- 7 PhD students

Physics at the LHC/ATLAS (1)

Tested over 14 orders of magnitude!!



Physics at the LHC/ATLAS (2)

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

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th} 9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ$ model B	$0\text{-}2\ e, \mu$	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\, \ell'\ell'$ model C	$3\ e, \mu$	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	2207.03925
	HVT $Z' \to WW$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	Z' mass 3.9 TeV	$g_V = 3$	2004.14636
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	$\geq 1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med} 3.8 TeV	g_q=0.25, g_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e, \mu$	2 b	Yes	139	$m_{Z'}$ 3.0 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a 800 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass 1.49 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	$\geq 2\ e, \mu, \geq 1\ \tau$	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu, \geq 1\ \tau$	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ^V mass 2.0 TeV	$\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	$2\ e, \mu, \tau$	≥1 b	Yes	139	LQ_3^V mass 1.96 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \to Zt + X$	$2e/2\mu/\geq 3e,\mu$	≥1 b, ≥1 j	–	139	T mass 1.46 TeV	SU(2) doublet	2210.15413
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} \mid T_{5/3} \to Wt + X$	$2(SS)/\geq 3\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3} Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	$1\ e, \mu$	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	$1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass 898 GeV	SU(2) doublet	2303.05441
Excited ferm.	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV		1910.08447
	Excited lepton τ^*	$2\ \tau$	≥2 j	–	139	τ^* mass 4.6 TeV	$\Lambda = 4.6$ TeV	2303.09444
Other	Type III Seesaw	$2,3,4\ e, \mu$	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	$2,3,4\ e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2,3,4\ e, \mu$ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	2211.07505
	Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV	DY production, $\lvert q \rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1905.10130

$\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

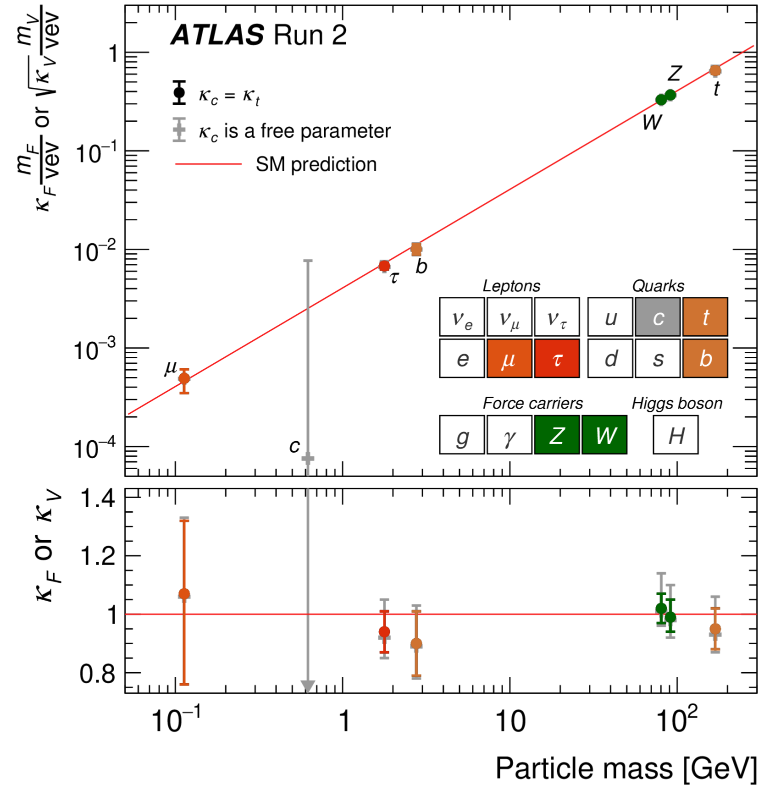
10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

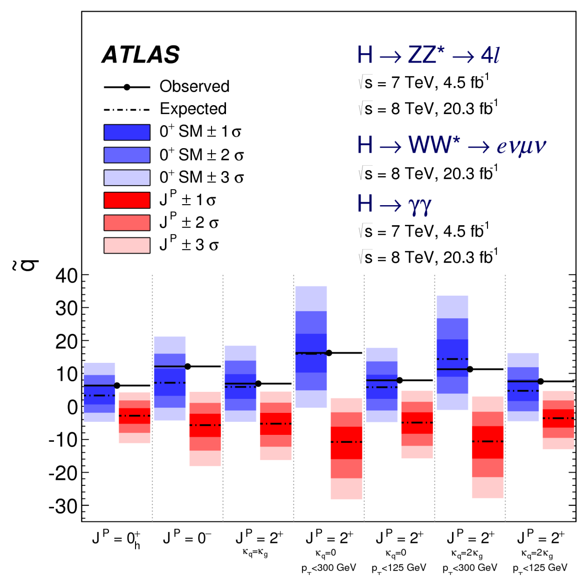
†Small-radius (large-radius) jets are denoted by the letter j (J).

Physics at the LHC/ATLAS (3)

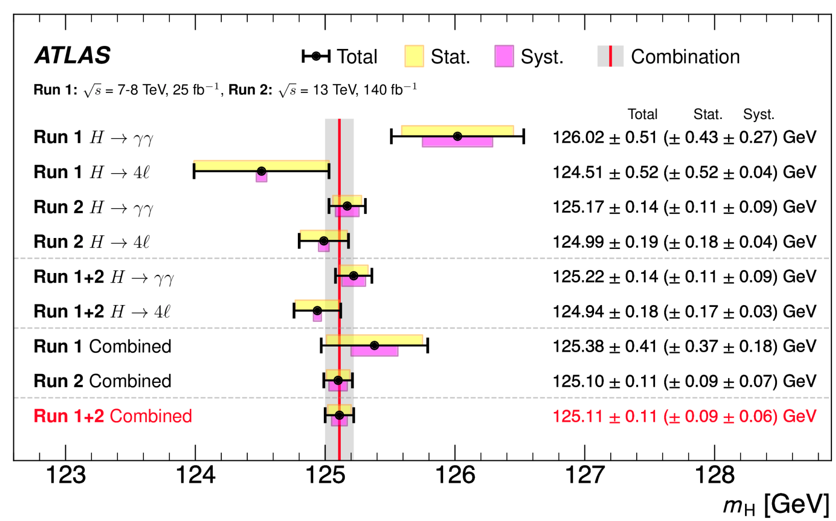
- Higgs boson discovered 11 years ago
- Couplings measured with a 10-50% precision



- Spin/parity: $J^{PC} = 0^{++}$
  - spin 1 and 2 excluded at > 99% CL



- Mass measured with a 0.09% precision



Is it the end?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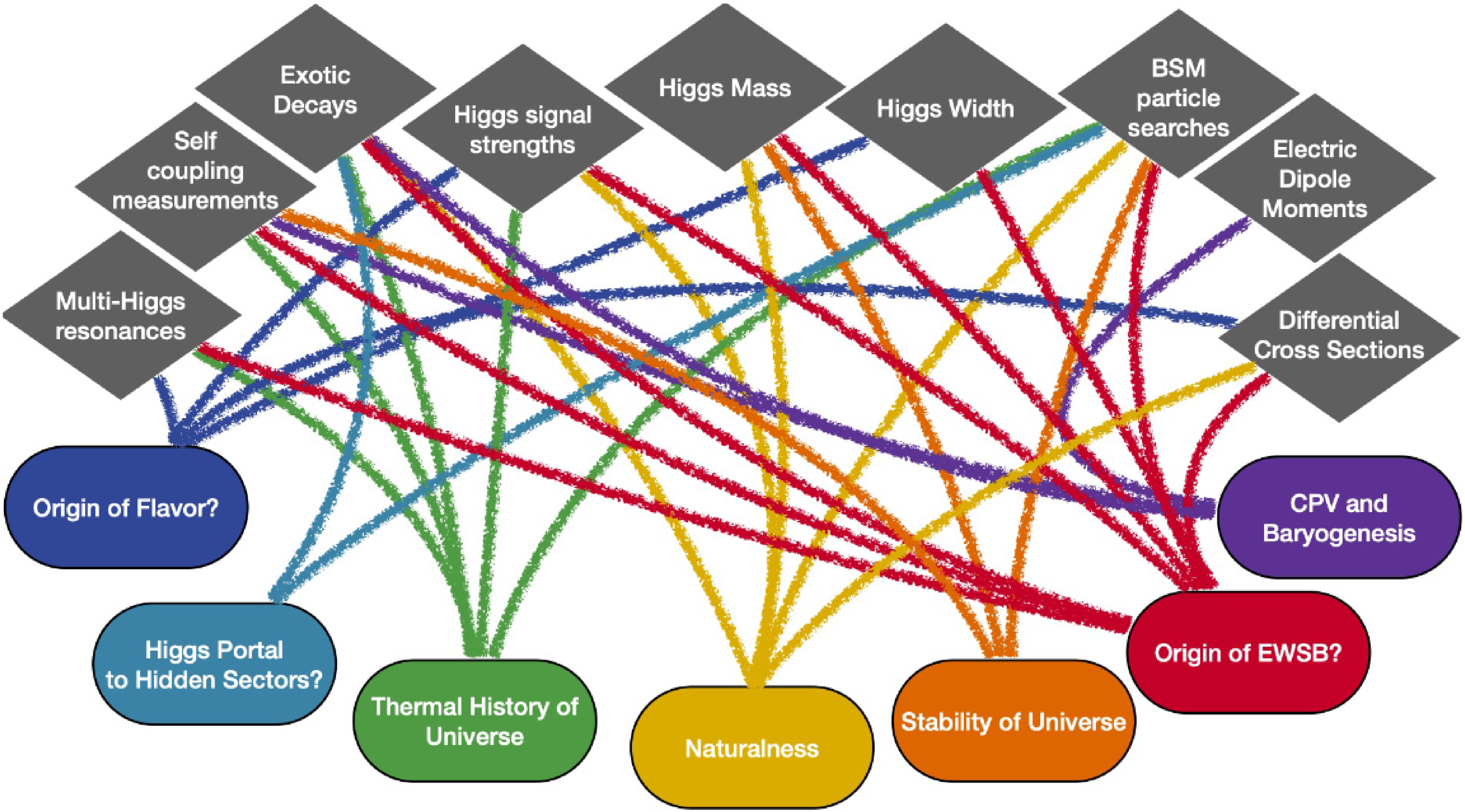
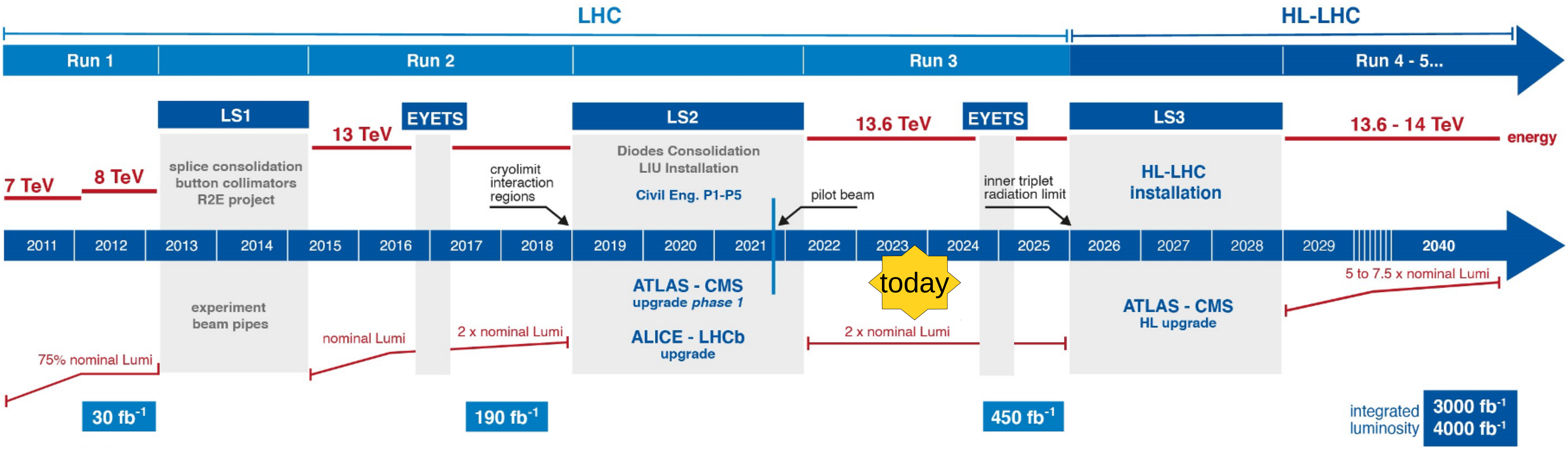
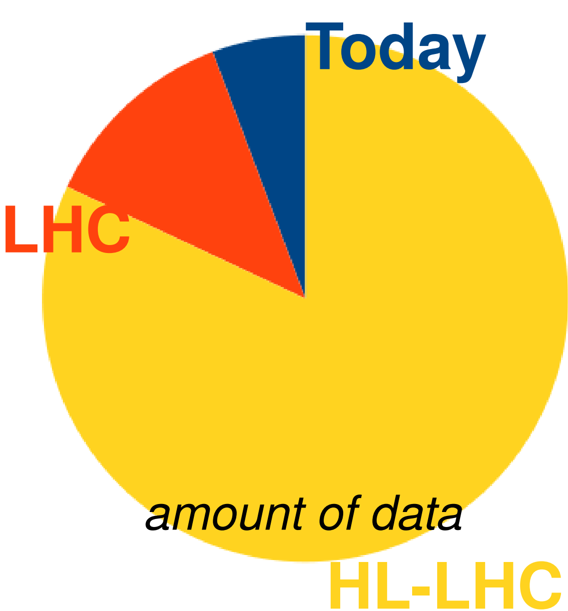


Exotic Decays
Higgs signal strengths
Higgs Mass
Higgs Width
BSM particle searches
Self coupling measurements
Electric Dipole Moments
Multi-Higgs resonances
Differential Cross Sections
Origin of Flavor?
CPV and Baryogenesis
Higgs Portal to Hidden Sectors?
Thermal History of Universe
Naturalness
Stability of Universe
Origin of EWSB?

LHC program

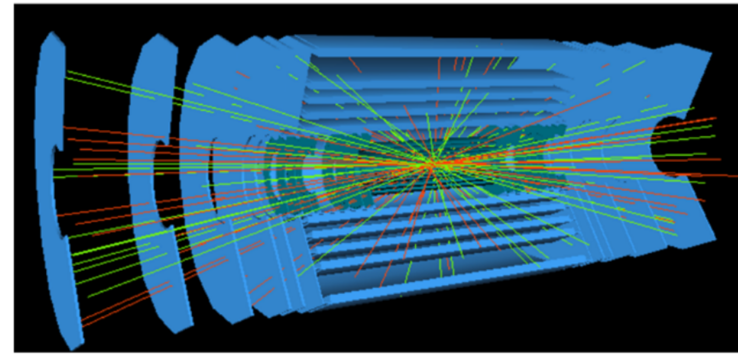


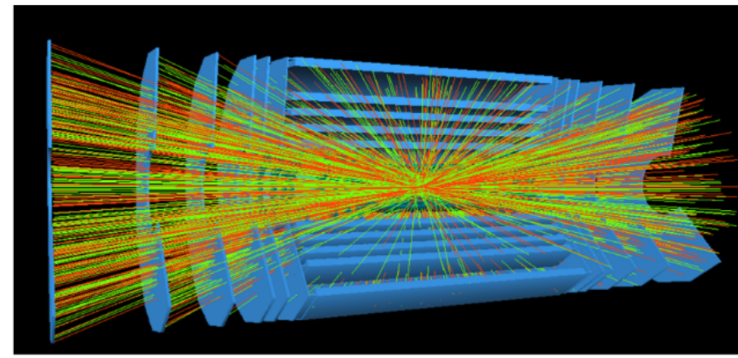


- Talented researchers make the difference
  - top-Higgs coupling
    - 2013: expected precision with the HL-LHC: 7-10%
    - 2019, with innovated experimental and theoretical techniques: 4%
  - charm-Higgs coupling
    - until recently thought it was not measurable
    - now prospects thanks to new c-tagging

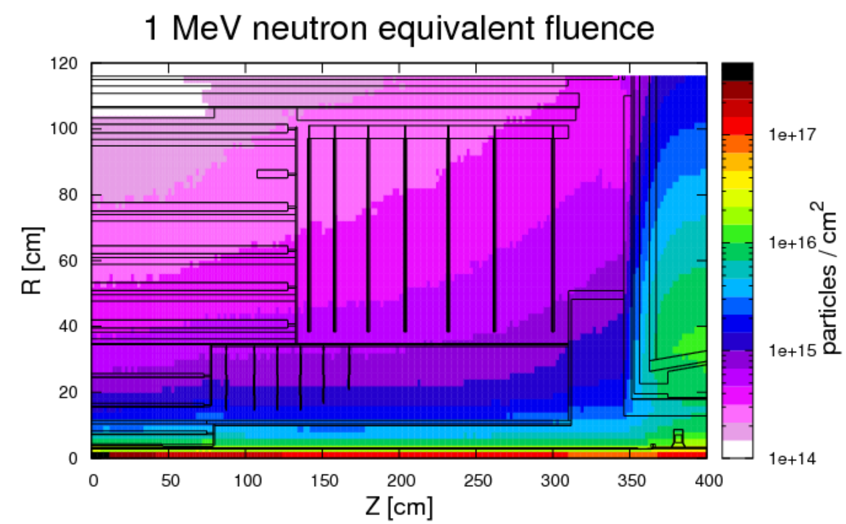
Why we need upgrades for the HL-LHC

- Expected number of interactions /bunch crossing (pile-up): 200
  - ATLAS design value: 25
  - better detector needed to maintain tracking, vertexing, b-tagging performance





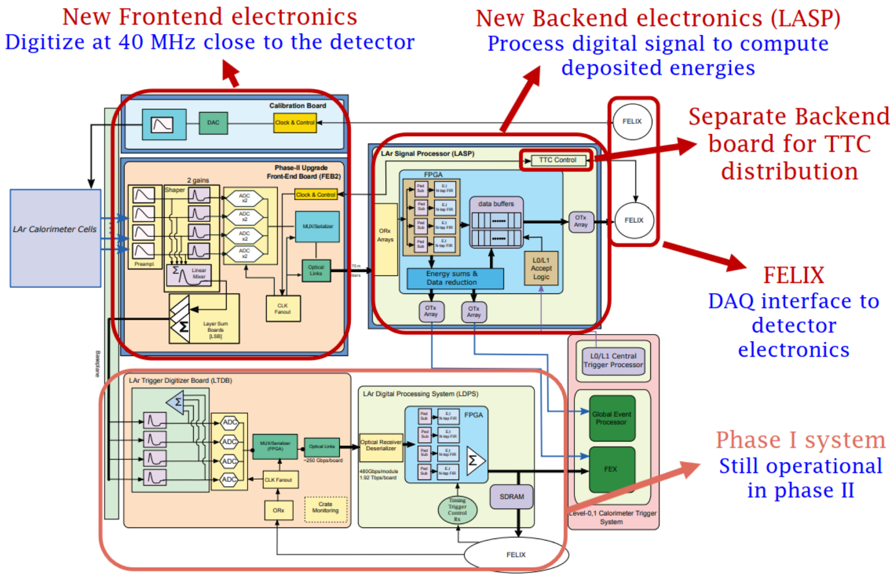
- Much higher radiation environment
  - total ionisation dose: 7.7 MGy
  - end of Run 3: 1.5 MGy → ATLAS design



- Trigger rate
  - Run 2-3: 100 kHz
  - HL-LHC: 1 or 4 MHz

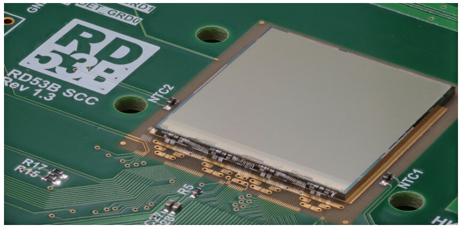
Upgrade projects at CPPM

- LAr calorimeter
  - the detector itself can sustain the growing amount of radiation
  - replacement of the entire data acquisition electronics

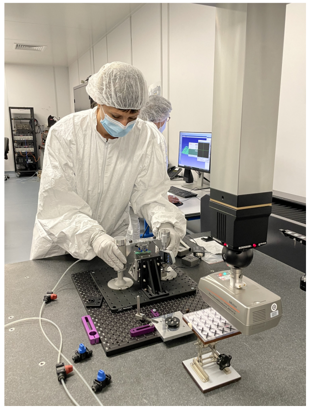


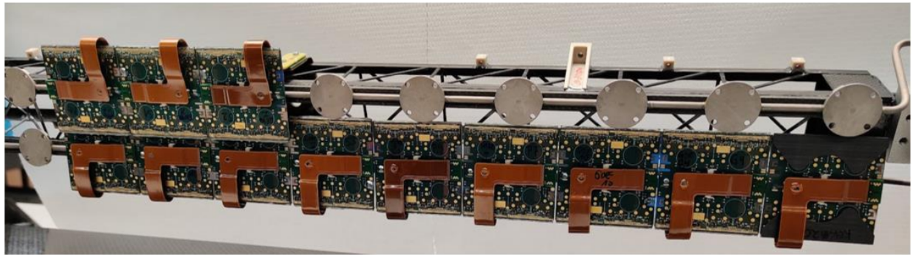
  - use the best available (future) technologies: AIDAQ: Development of neural networks for energy reconstruction in the LASP board

- ITk (new Inner Tracker)
  - micro-electronics



  - development of mechanical parts, module loading, participation to production

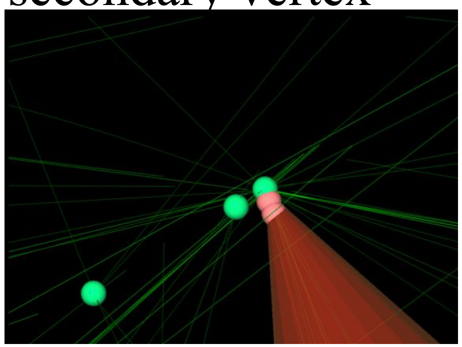




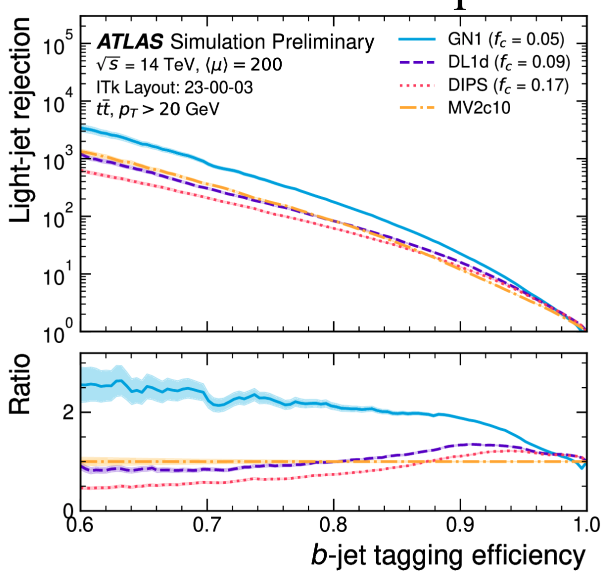
  - development of new pixel sensors (depleted CMOS)

Performance program at CPPM

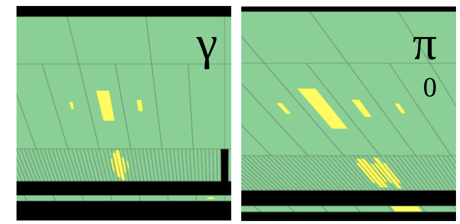
- **b-tagging**
  - distinguish b-jets from c-jets or light-jets
  - b-hadron lifetime of 1.5 ps
    ⇒ flight path of a few mm
    ⇒ secondary vertex



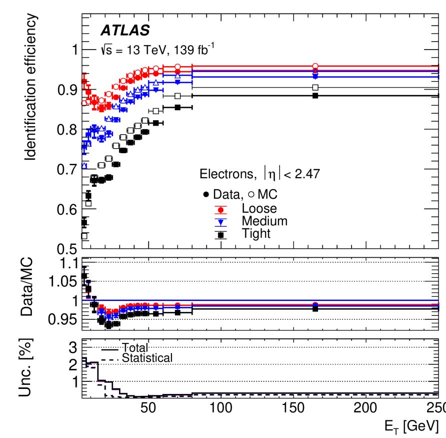
  - at trigger-level
  - new MVA techniques for HL-LHC



- **Electrons/photons**
  - distinguish from jets
  - shower shape in the calorimeter



  - local expertise on electron reconstruction and photon identification

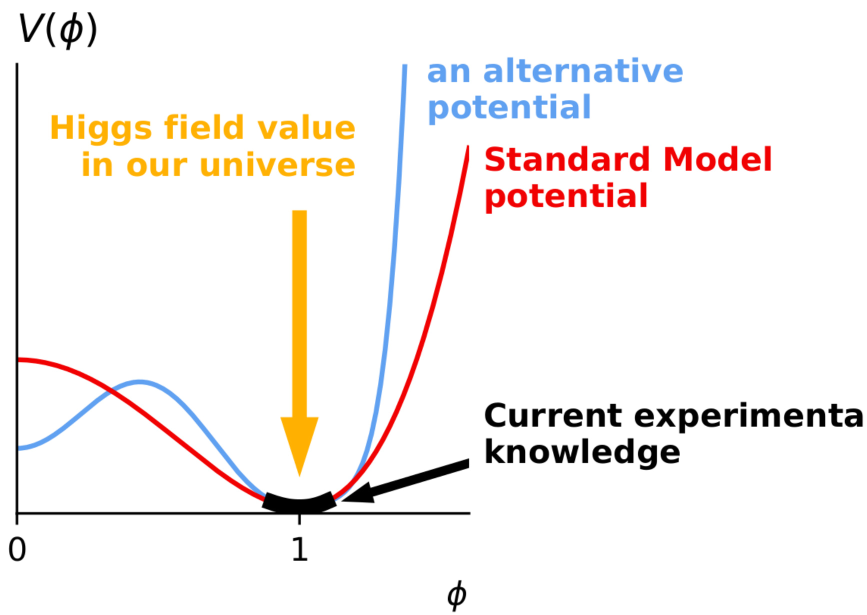


  - towards HL-LHC: impact of new calorimeter energy reconstruction on photons and electrons

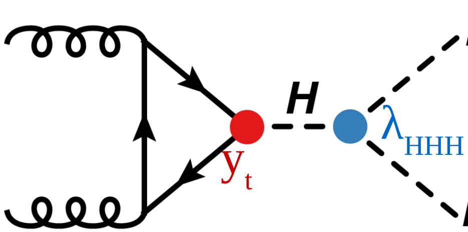
Physics program at CPPM (1)

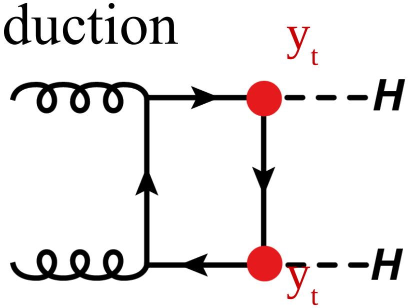
- Higgs boson has a mass ⇒ it couples to itself!
  - but not measured yet
- Potential of the Higgs boson “Mexican Hat”: $V(\Phi)=\frac{1}{2}\mu^2\Phi^2+\frac{1}{4}\lambda\Phi^4$
- Approximation around the v.e.v:

$$V(\Phi)\approx\underbrace{\lambda v^2 h}_{\text{mass term}}+\underbrace{\lambda v h^3+\frac{1}{4}\lambda h^4}_{\text{self-coupling terms}}$$



- Higgs self-coupling can be measured thanks to HH production



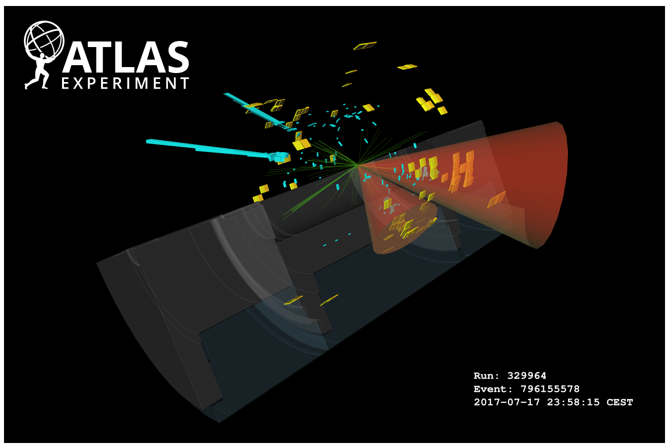


  - very rare process: σ(HH)/σ(H) = 0.1% ⇒ 100k HH events at the end of HL-LHC

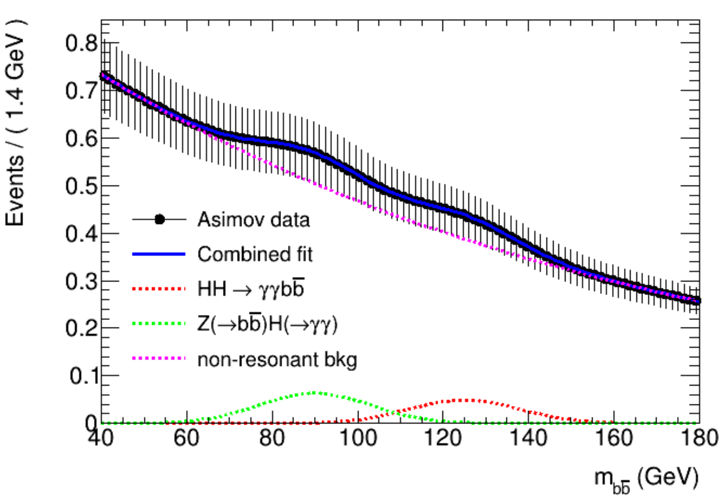
- Relationship to electroweak phase transition: matter-antimatter asymmetry, gravitational waves, etc

Physics program at CPPM (2)

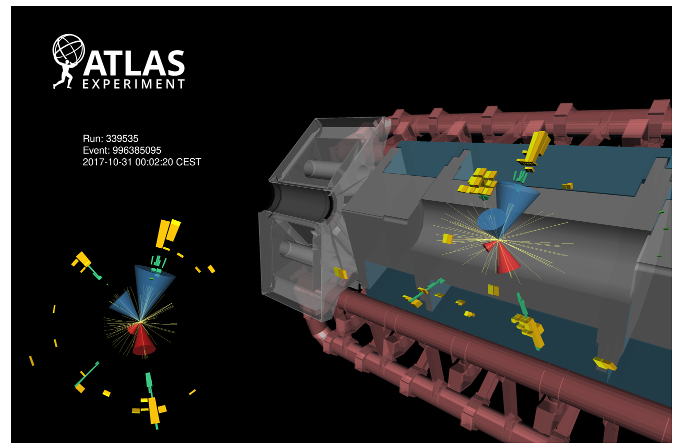
- Two main decay channels for HH:
- $HH \to b\bar{b}\gamma\gamma$ (since 2019)
  Small BR ☹
  Good diphoton resolution ☺
  Relatively small background ☺



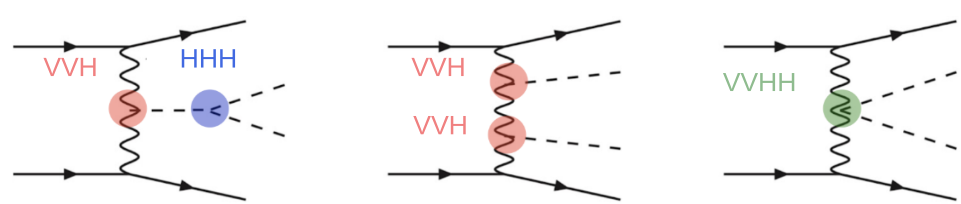
– Run 3: ZH and HH measurement



- $HH \to b\bar{b}\tau\tau$
  Sizeable BR ☺
  Relatively small background ☺

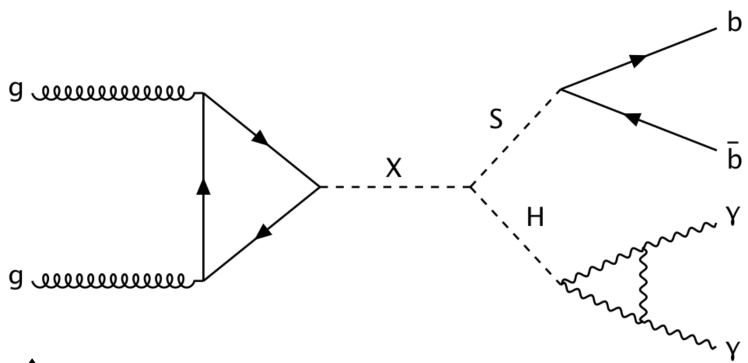


– New involvement for Run 3
  - concentrate on VBF production

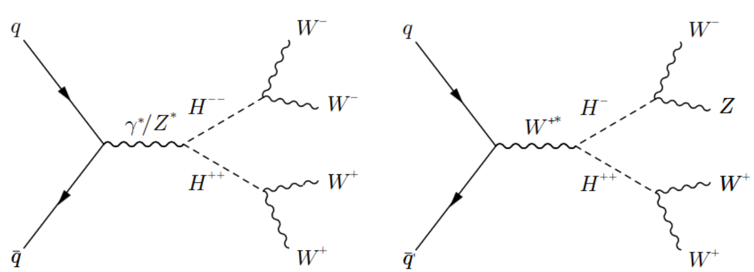


Physics program at CPPM (3)

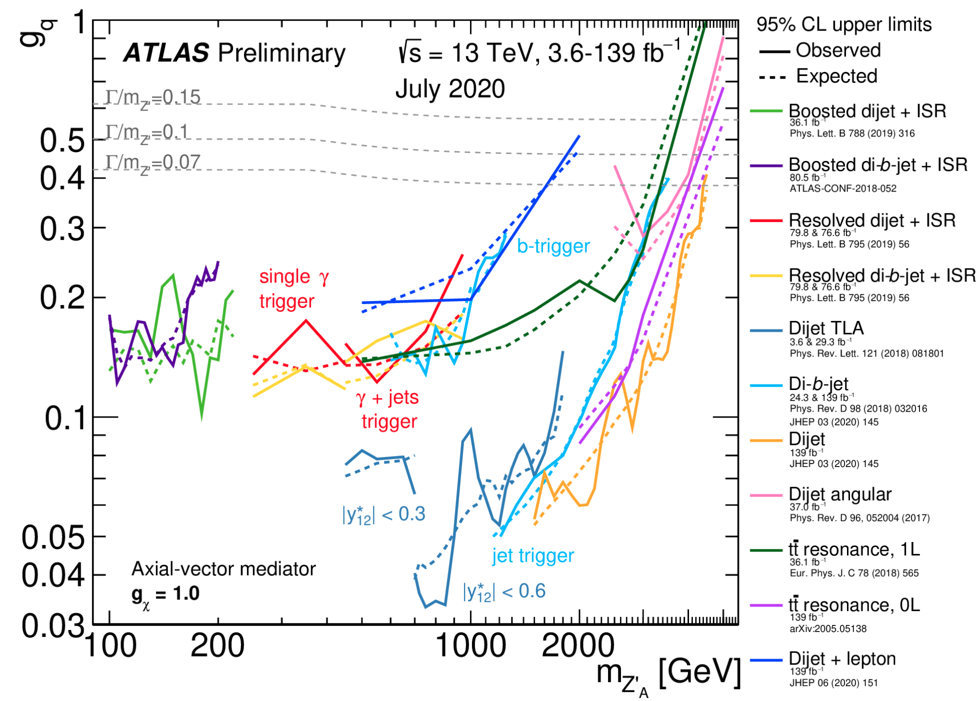
- HH spin-off analysis
  - high-mass (250-1000 GeV) scalar particle decaying to $b\bar{b}\gamma\gamma$



- Charged Higgs
  - spin-off analysis of previous ttH analysis
  - many models predict additional Higgs bosons: $H^{\pm\pm}$, $H^{\pm}$, A^0 (CP odd), H^0 (CP even), h^0 (SM Higgs)
    - neutrino masses through the type-II seesaw mechanism



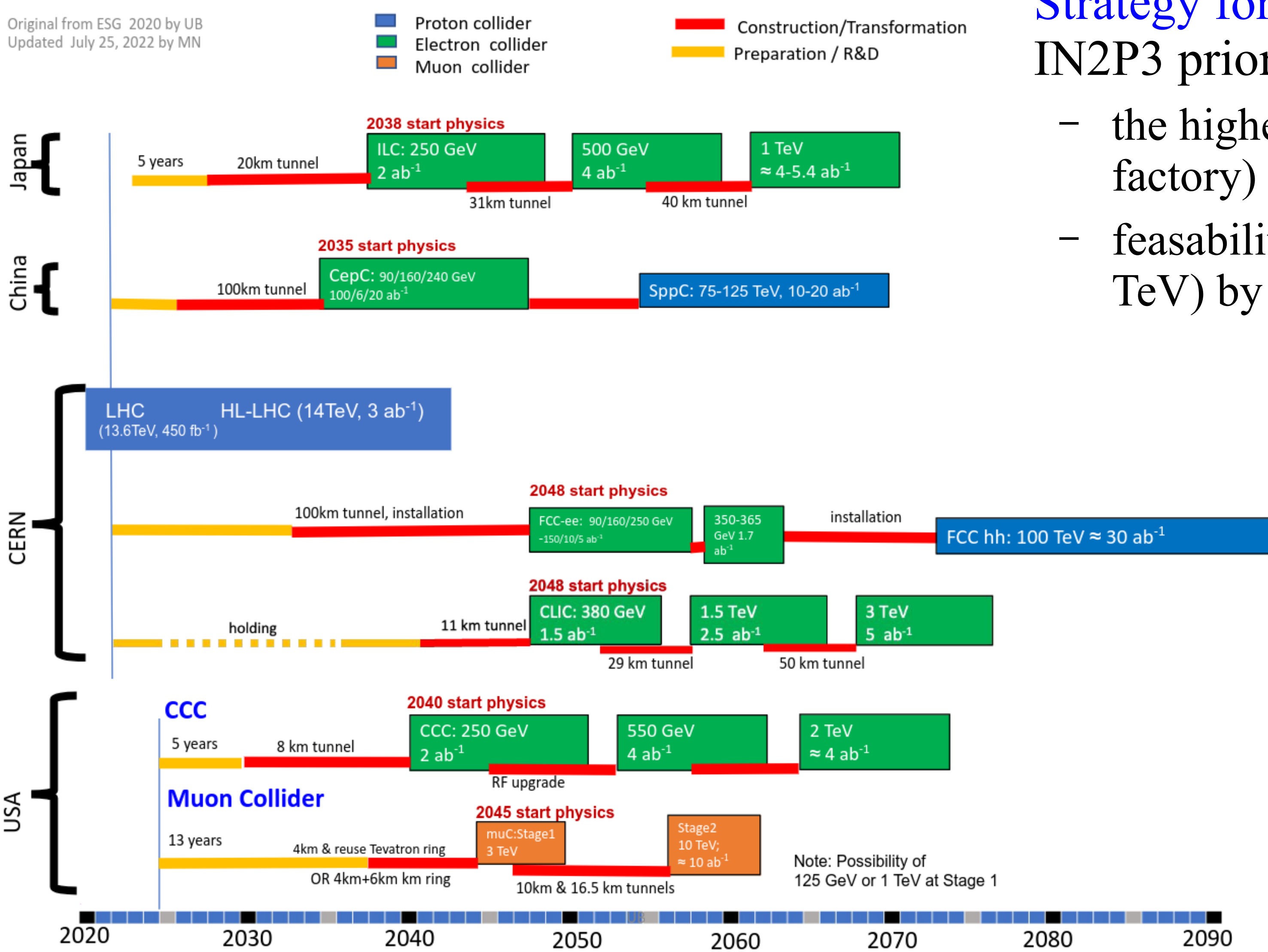
- Low m_{bb} resonances
  - new!
  - many of these models predict resonances in di-quark events



  - regions below 100 GeV are still unexplored
  - needs trigger-level analysis

Beyond LHC

- Many Future Colliders projects:



- 2020 update of the European Strategy for Particle Physics and IN2P3 priorities:
  - the highest-priority: FCCee (Higgs factory) next collider
  - feasability of FCChh ($\sqrt{s} \geq 100$ TeV) by 2025

Thank you!


SUSY Workshop
Beams Workshop
WORKSHOP OF RARITIES
WWW Workshop
Higgs Workshop

Back-up

Sources

- DeJongERC
- Ursula SFP
- 10ans Higgs
- IN2P3 prospects
- Cours Techniques base Détecteurs (eg LHC timeline)