REBECA GONZALEZ SUAREZ - UPPSALA UNIVERSITY

PSI PARTICLE PHYSICS SUMMER SCHOOL – FROM LOW TO HIGH: PARTICLE PHYSICS AT THE FRONTIER

THE STANDARD MODEL AND BEYOND

Part II

THE STANDARD MODEL OF PARTICLE PHYSICS

- It is both true that:
  - **The SM works extremely well** → it is highly predictive and robust, and deviations are few and far in between
    - Last lecture
  - **The SM is broken** → we know it is hiding something, and it is hiding it very well
    - This one

The LHC was built as “discovery machine”

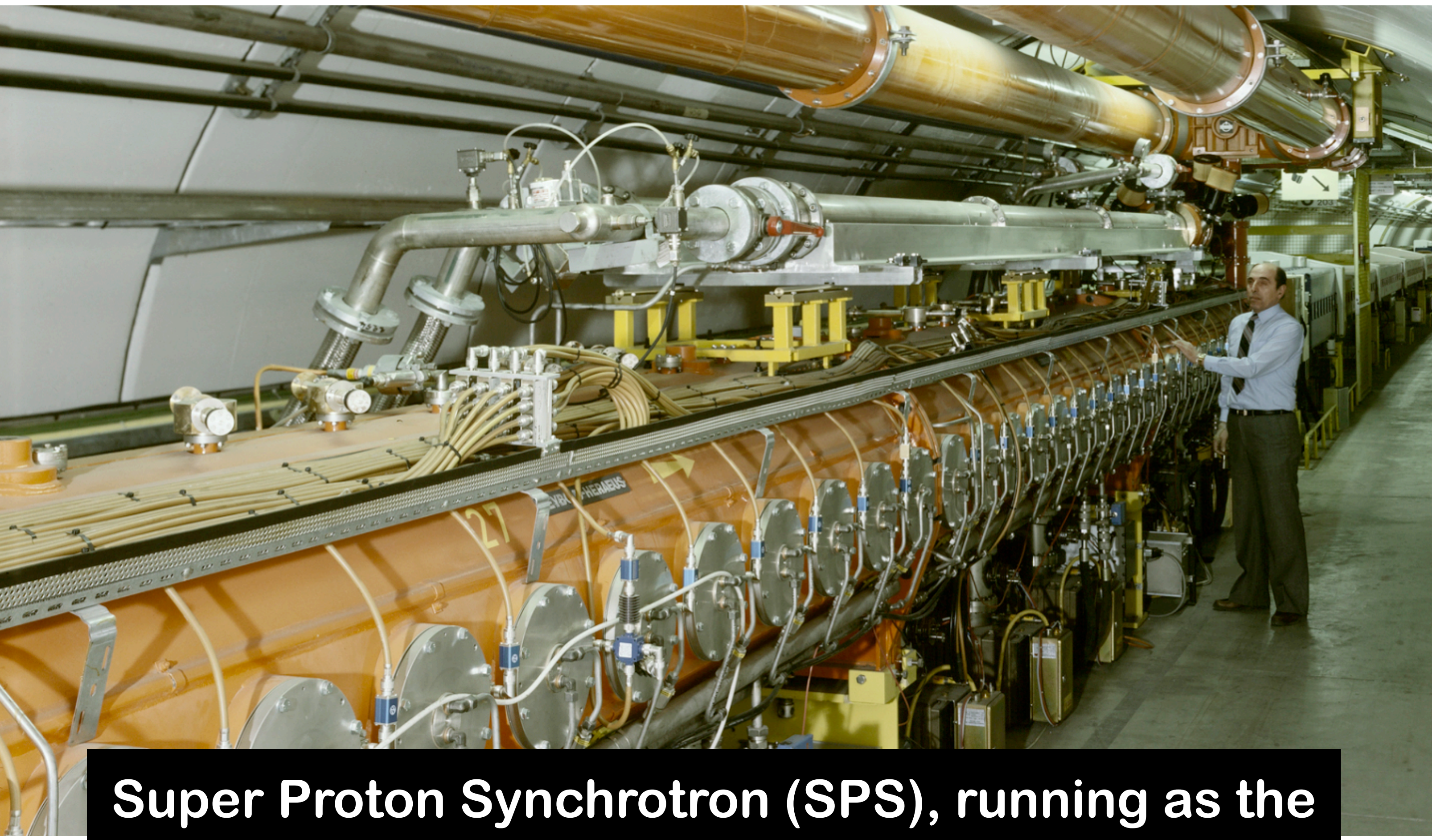
To push the “energy frontier”

WHEN INCREASING THE ENERGY

- When particles accelerated are close to the speed of light and collide, the collision energy becomes available mass to produce new particles ($E=mc^2$)
  - Heavier particles than those colliding can be produced
- When colliding protons (composite particles) we increase the chances to see something new

1983

W and Z bosons
80 and 90 GeV



Super Proton Synchrotron (SPS), running as the “Proton–Antiproton Collider” at CERN

540 GeV

1995

Top quark
173GeV

Tevatron at Fermilab

1 TeV

We did find a heavy particle!

2012

Higgs boson
125GeV

Large Hadron collider at CERN

13.6 TeV

THE LHC'S ACHIEVEMENTS

Not every collider finds new particles
Every collider gets us one step ahead

- After 14 years we have:
  - The Higgs boson
    - Found after decades of searches in multiple colliders
  - First observations of tons of never-seen-before SM processes
    - mostly multiple production of bosons and/or top quarks
  - About 3000 scientific papers
    - Approximately half of those being precision measurements
  - Un unparalleled battery of searches for BSM phenomena
    - Because the SM is great but…

WE STILL NEED TO GO

BEYOND THE STANDARD MODEL

LEON LEDERMAN'S LAUNDRY LIST

Nature Insight: The Large Hadron Collider
Vol. 448, No. 7151 pp 269-312 (2007)

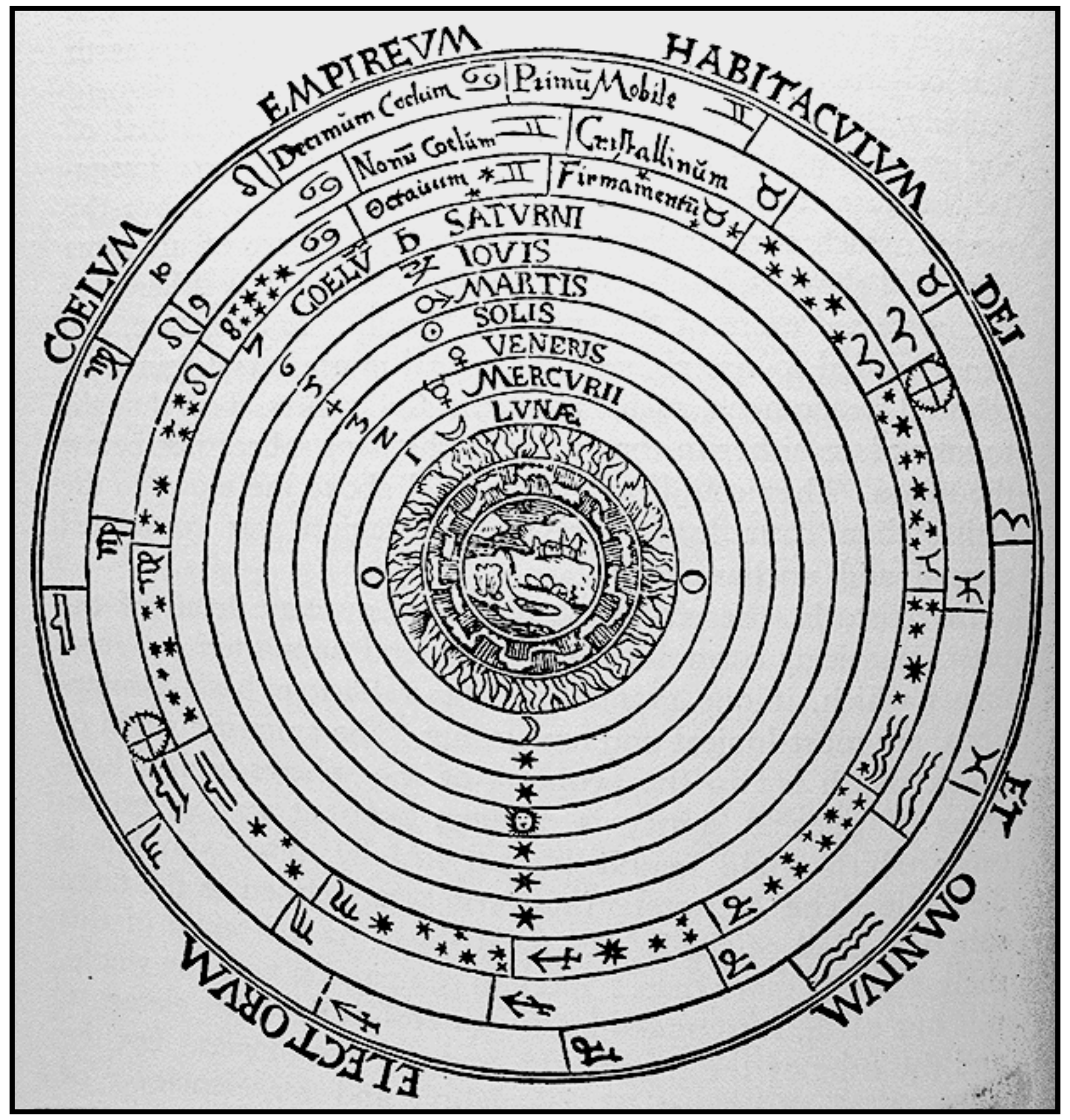
- ***“To me, these three factors —the Higgs particles, supersymmetric particles and new dimensions— are the discoveries most likely to emerge from the first five or so years of LHC operations. But there is a long, more speculative laundry list of objects that might be illuminated by the powerful beams of the LHC.”***

Expectations were high for the LHC
That is the “guaranteed discovery” people talk about

☑ Higgs boson
☐ SUSY
☐ Extra dimensions
☐ The origin of dark matter
☐ The origin of dark energy
☐ Compositeness
☐ Technicolor (new strong force)
☐ WW scattering
☐ Additional Higgs bosons
☐ Right-handed neutrinos
☐ Mini black holes

THE MANY PROBLEMS OF THE SM

The SM: the Aristotelian Ptolemaic system of our times

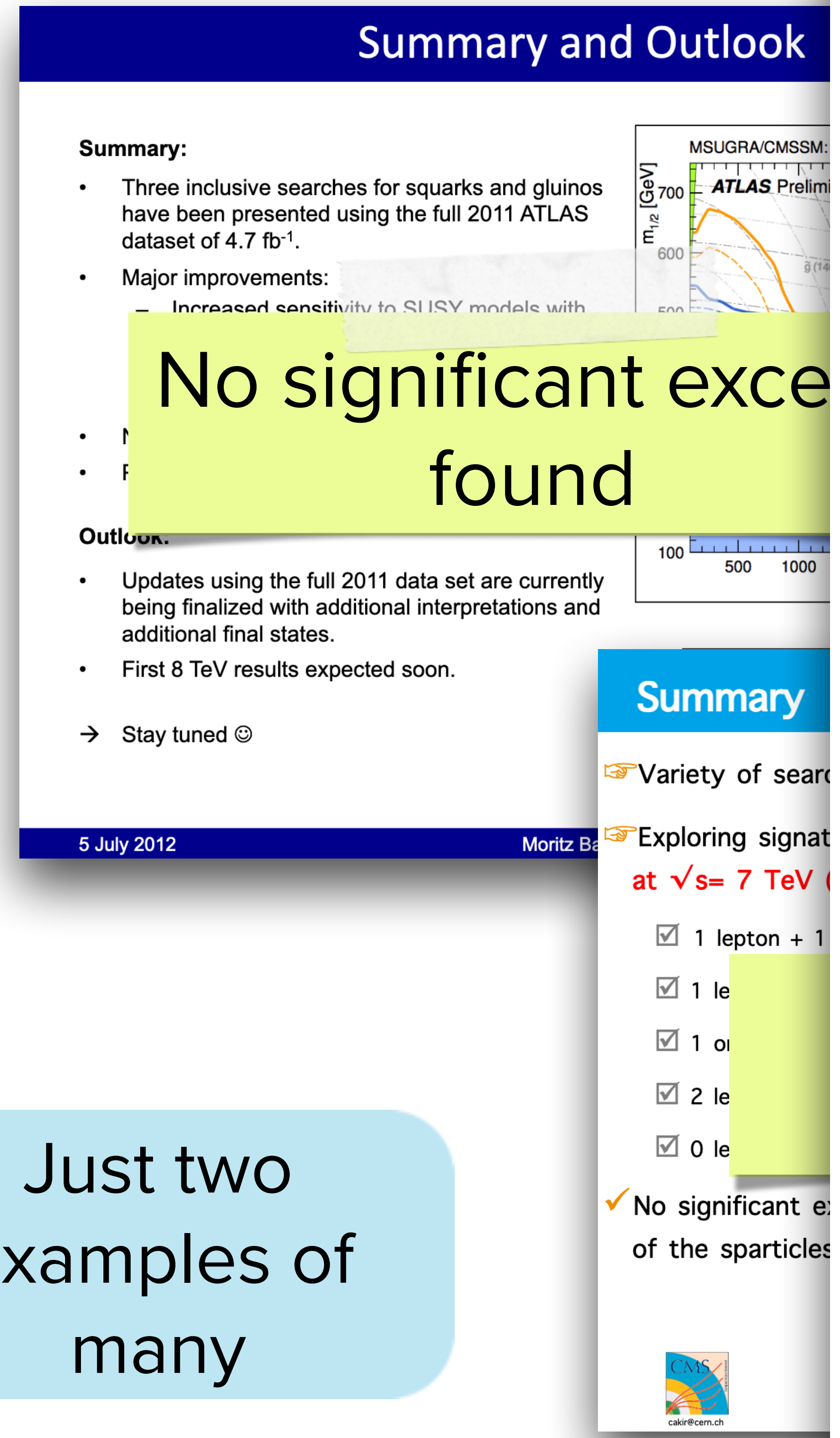


- The inexplicable neutrino masses
- The fact that dark matter exists but we have no idea what it is
- The fact that dark energy exists but we have even less idea
- The fact that we are made of matter and there is very little antimatter around
- We don’t know why we have 3 families of particles
- We don’t understand their masses
- There are a few parameters that cannot be predicted, we have to measure them and put them by hand
- The fact that we cannot connect gravity from the macroscopic to the fundamental
- …

FROM THE VERY BEGINNING

ICHEP2012 Melbourne

- SUSY was the



Summary and Outlook

Summary:

- Three inclusive searches for squarks and gluinos have been presented using the full 2011 ATLAS dataset of 4.7 fb^{-1}.
- Major improvements:
  - Increased sensitivity to SUSY models with

No significant exce found

Outlook:

- Updates using the full 2011 data set are currently being finalized with additional interpretations and additional final states.
- First 8 TeV results expected soon.

→ Stay tuned ☺

5 July 2012 Moritz Ba

Summary

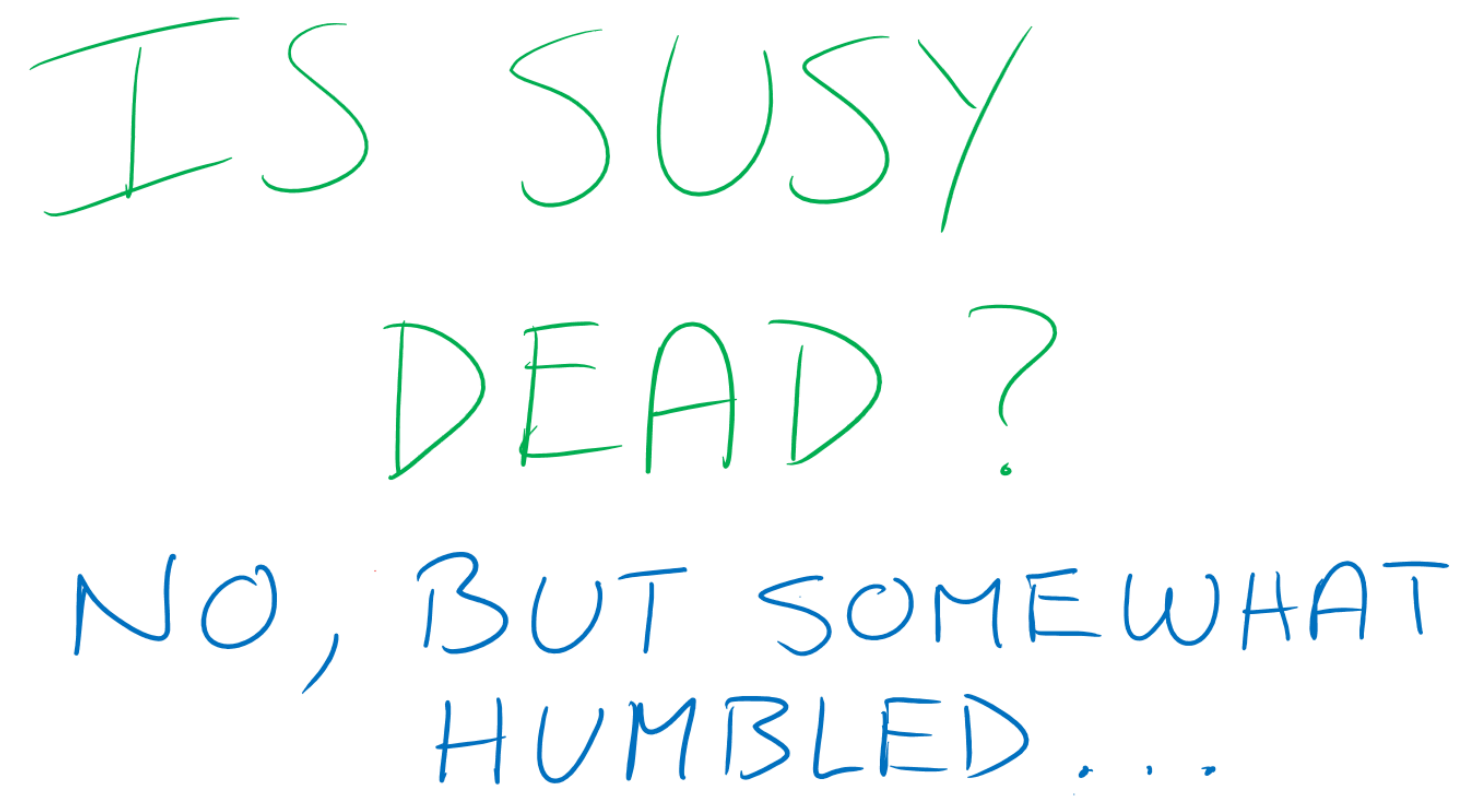
☞Variety of searc

☞Exploring signat
at $\sqrt{s}$= 7 TeV (

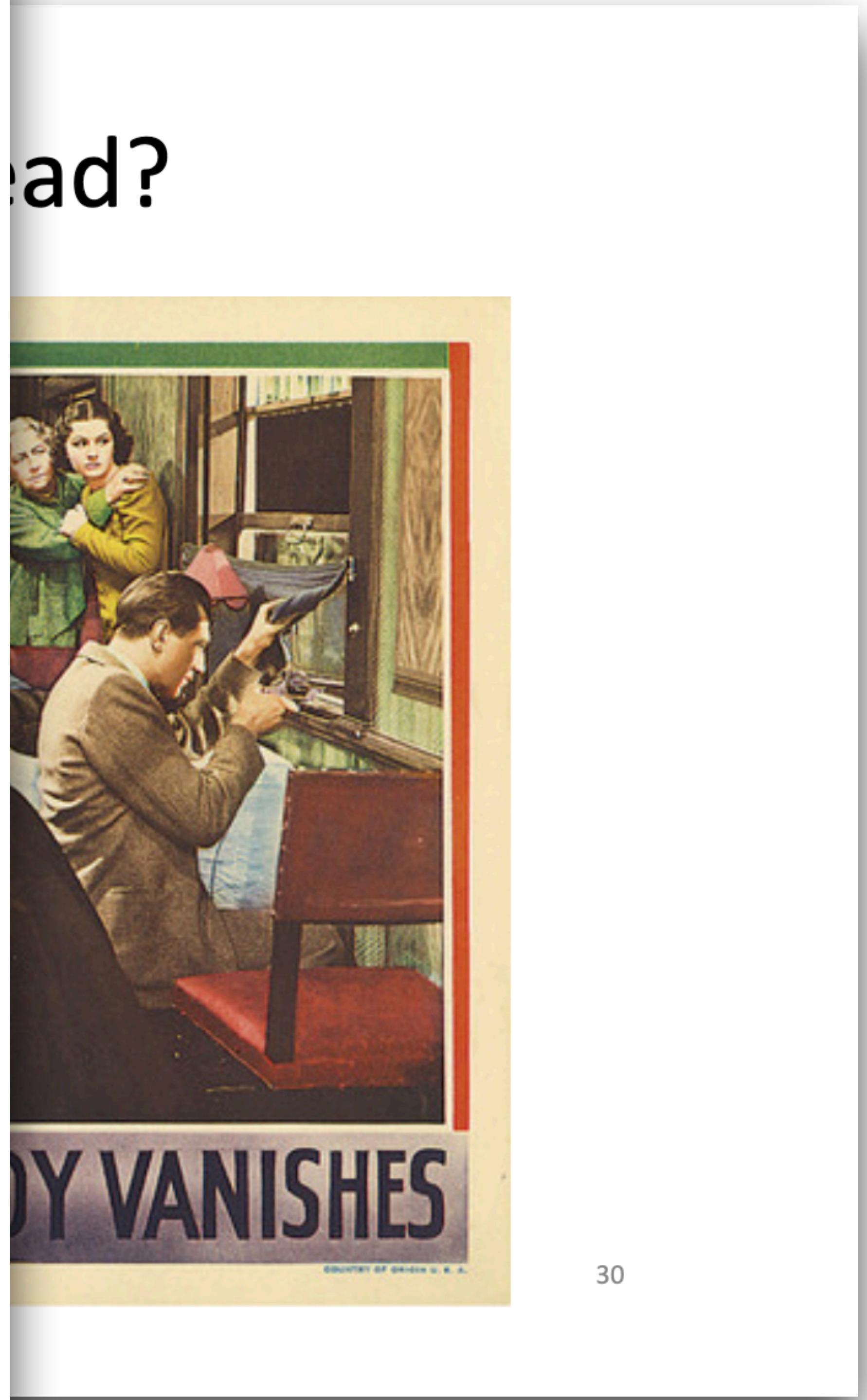
☑ 1 lepton + 1
☑ 1 le
☑ 1 o
☑ 2 le
☑ 0 le

✓ No significant e
of the sparticles

cakir@cern.ch



IS SUSY
DEAD?
NO, BUT SOMEWHAT
HUMBLED...

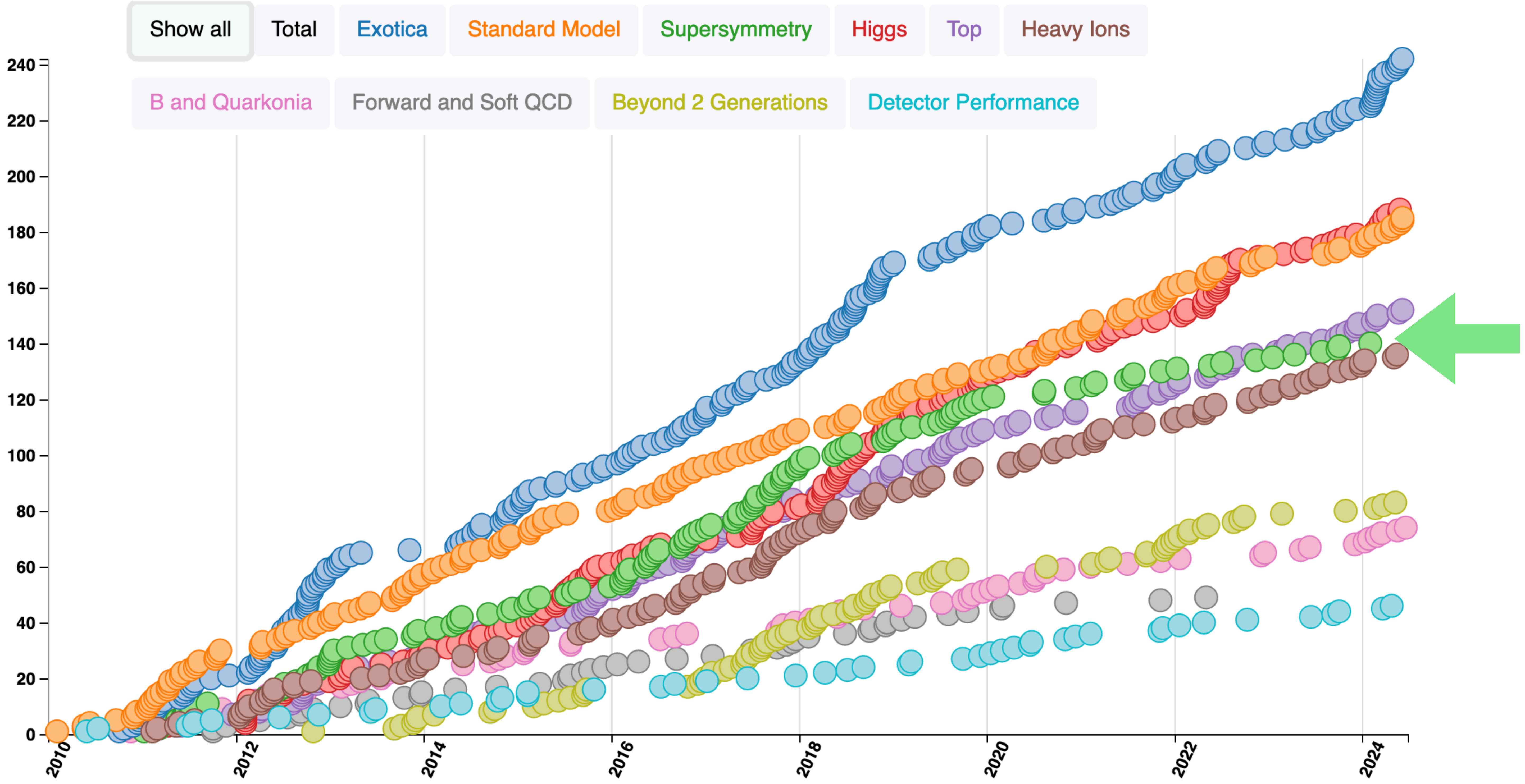


ad?

Just two examples of many

SUSY IS STILL NOT FULLY DEAD

- It will always be a fun ground to test interesting things
- CMS and ATLAS have about 300 SUSY papers

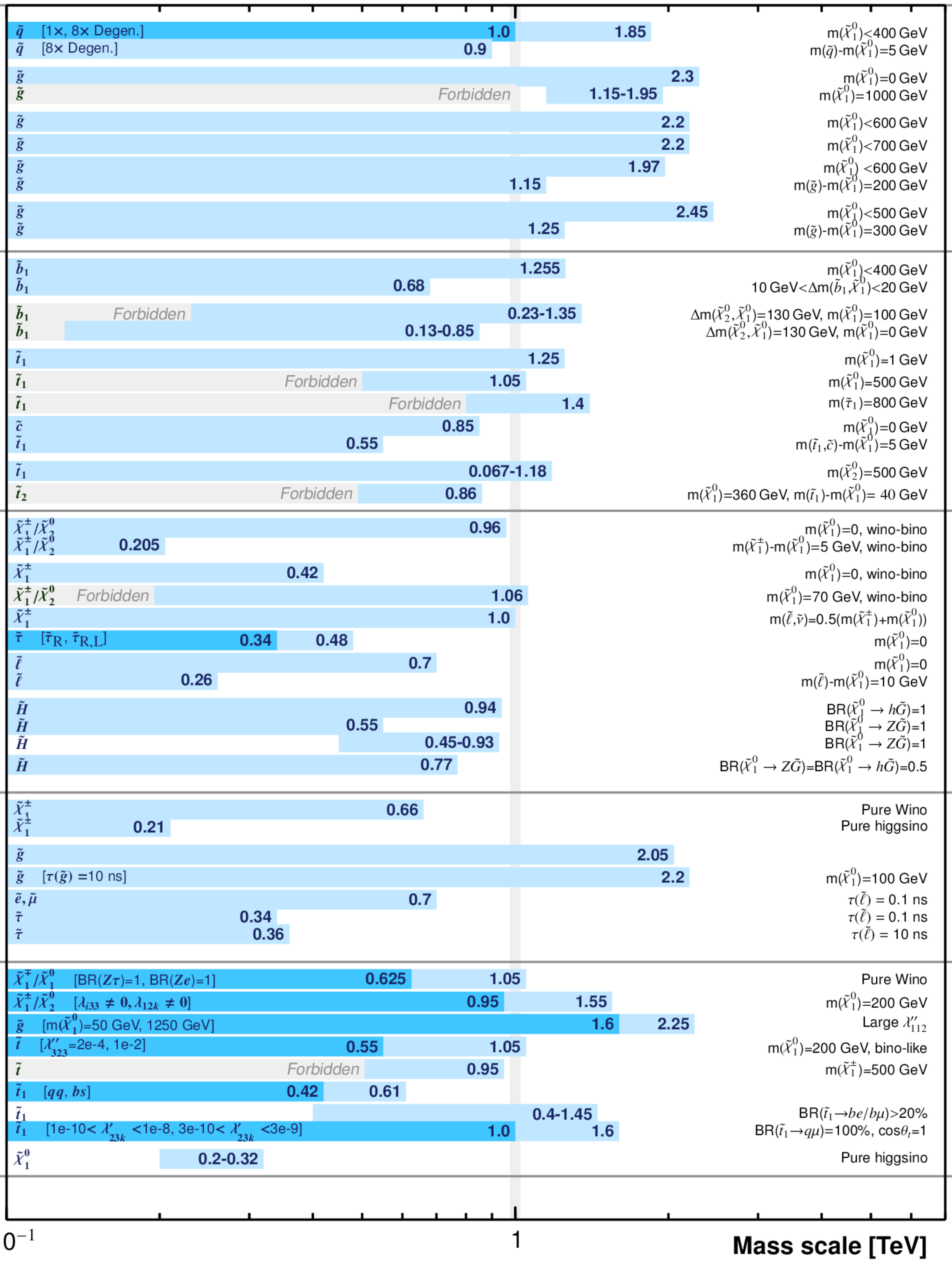


ATLAS SUSY Searches* - 95% CL Lower Limits

August 2023

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

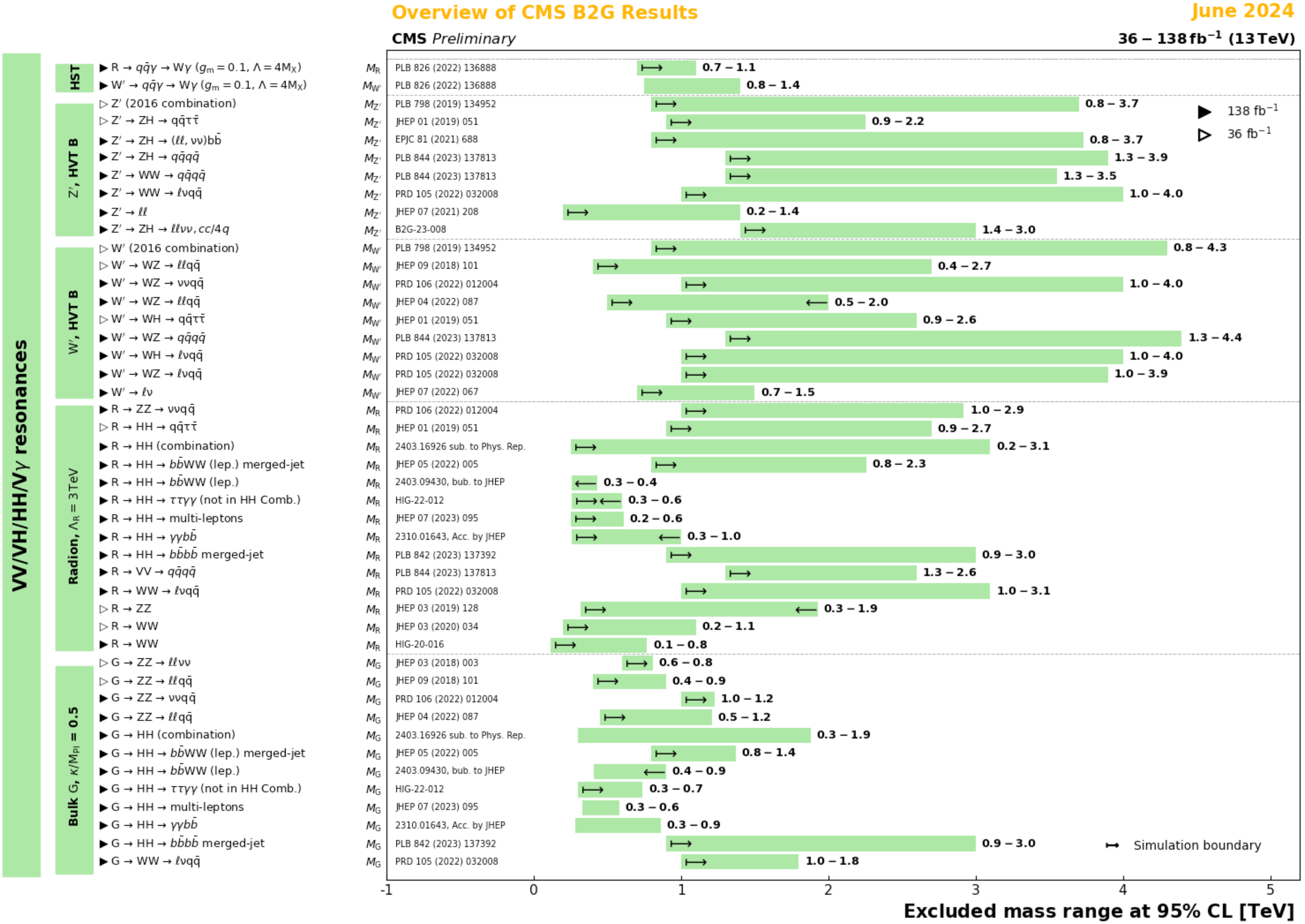


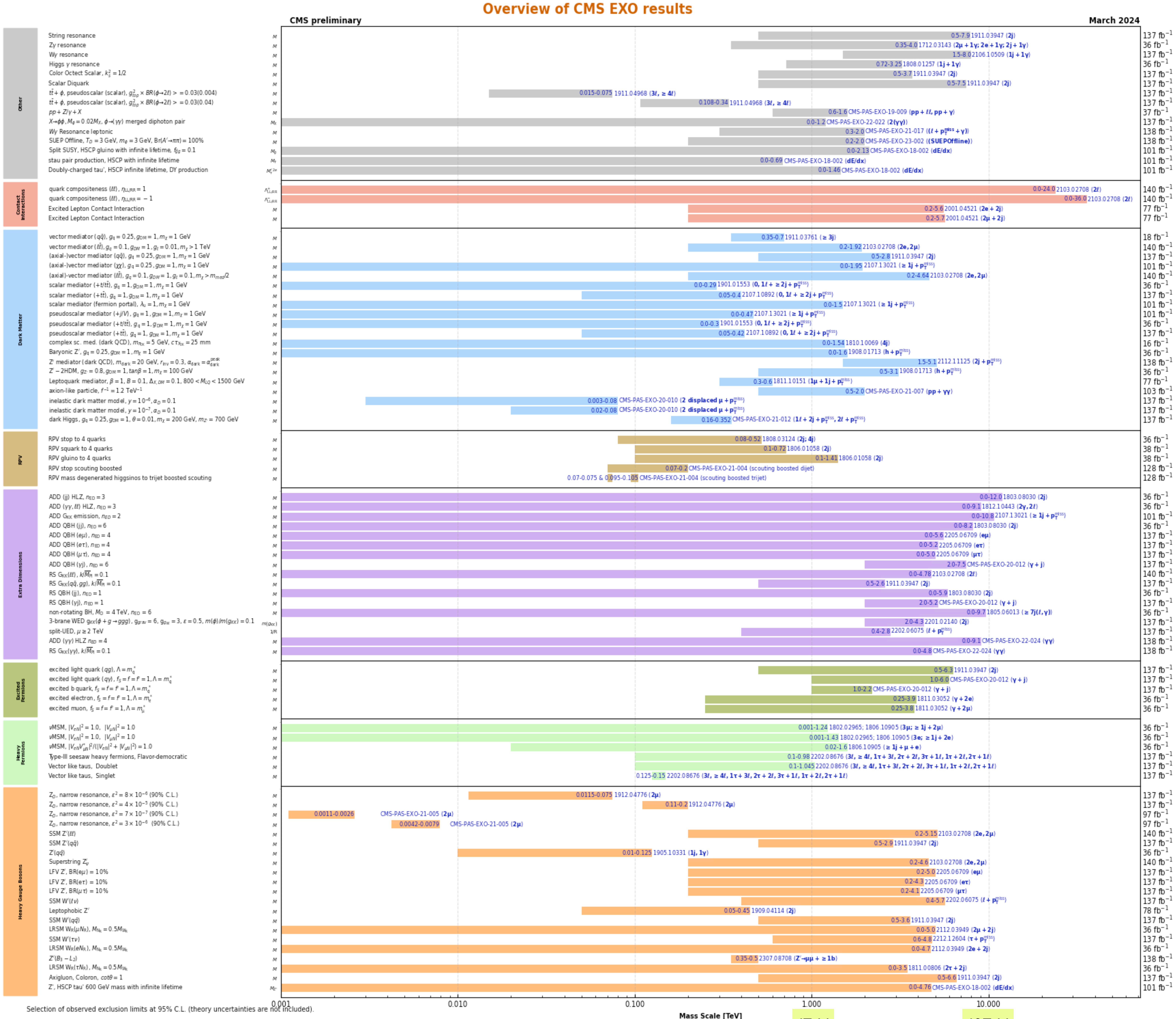
	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit				Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{q}$	[1×, 8× Degen.]	1.0 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	140	$\tilde{q}$	[8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{g}$		2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden	1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		140	$\tilde{g}$		2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	140	$\tilde{g}$		2.2	m($\tilde{\chi}_1^0$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	140	$\tilde{g}$		1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$		1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	140	$\tilde{g}$		2.45	m($\tilde{\chi}_1^0$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$		1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	140	$\tilde{b}_1$		1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$		0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	140	$\tilde{b}_1$	Forbidden	0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	140	$\tilde{b}_1$		0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{t}_1$		1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden	1.05	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799, ATLAS-CONF-2023-043
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden	1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$		0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	140	$\tilde{t}_1$		0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	140	$\tilde{t}_1$		0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	140	$\tilde{t}_2$	Forbidden	0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$		0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$		0.205	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$		0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	Forbidden	1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$		1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	140	$\tilde{\tau}$	[$\tilde{\tau}_R$, $\tilde{\tau}_{R,L}$]	0.34 0.48	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2023-029
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	140	$\tilde{\ell}$		0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\ell}$		0.26	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	140	$\tilde{H}$		0.94	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	To appear
		4 e,μ	0 jets	E_T^{miss}	140	$\tilde{H}$		0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	140	$\tilde{H}$		0.45-0.93	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	E_T^{miss}	140	$\tilde{H}$		0.77	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=BR($\tilde{\chi}_1^0\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$		0.66	Pure Wino	2201.02472
						$\tilde{\chi}_1^{\pm}$		0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$		2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}_1^0$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	140	$\tilde{e},\tilde{\mu}$		0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$		0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$		0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$	[BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	[$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$]	0.95 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		≥8 jets		140	$\tilde{g}$	[m($\tilde{\chi}_1^0$)=50 GeV, 1250 GeV]	1.6 2.25	Large λ''_{112}	To appear
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm}\to bbs$		$\geq 4b$		140	$\tilde{t}$	Forbidden	0.95	m($\tilde{\chi}_1^{\pm}$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$		0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0\to tbs$, $\tilde{\chi}_1^+\to bbs$	1-2 e,μ	≥6 jets		140	$\tilde{\chi}_1^0$		0.2-0.32	Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

THERE IS SO MUCH MORE THAN SUSY

Resonance searches
“bump hunt”





1TeV

10TeV

We are well above the TeV scale in heavy particle searches

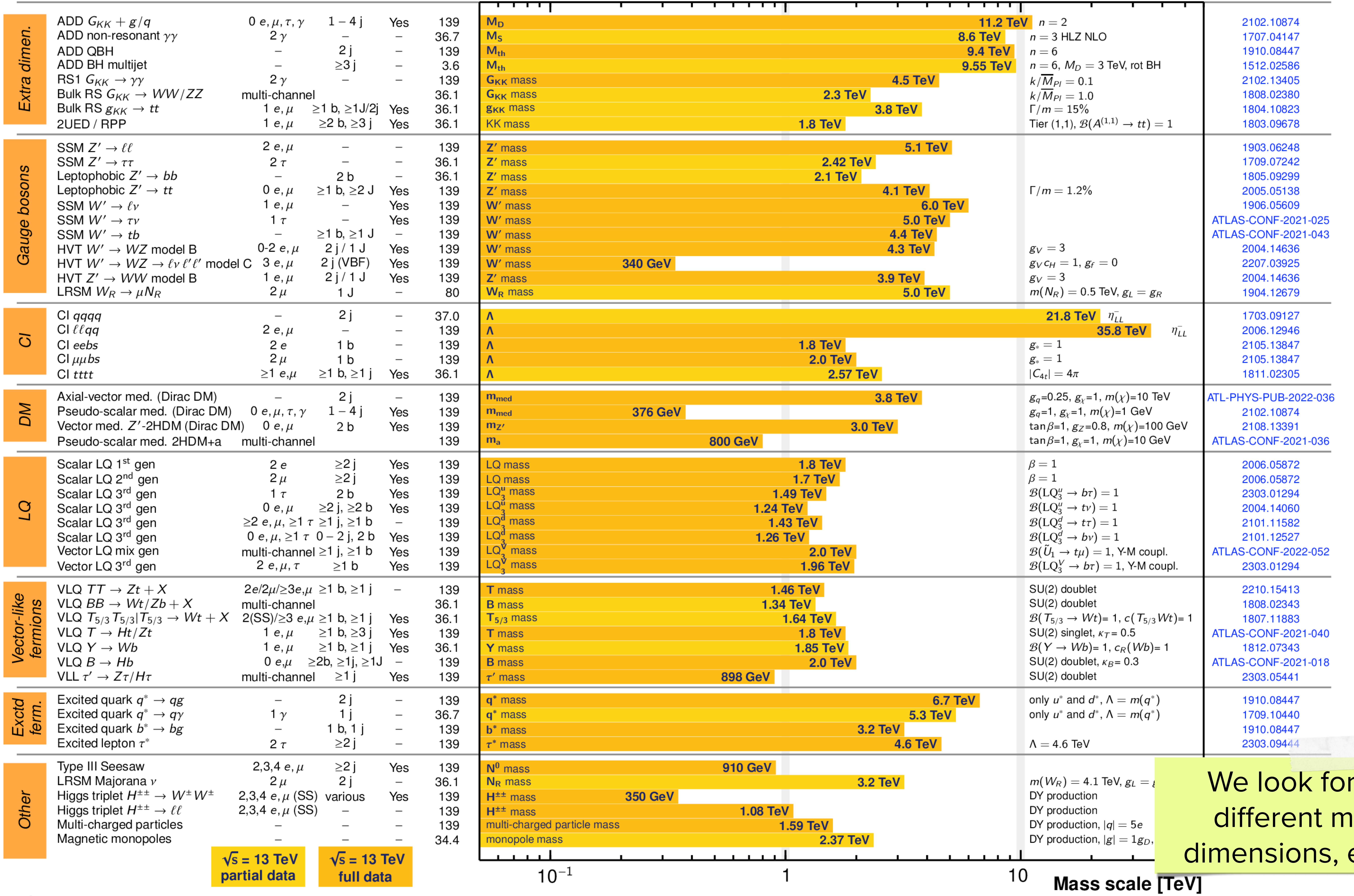
ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

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	$\mathrm{M_D}$	11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	$\mathrm{M_S}$	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	$\mathrm{M_{th}}$	9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	$\mathrm{M_{th}}$	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	$\mathrm{G_{KK}}$ mass	4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	$\mathrm{G_{KK}}$ 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	$\mathrm{g_{KK}}$ 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	0-2 e, μ	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	$\mathrm{W_R}$ 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 $tttt$	≥1 e,μ	≥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	$\mathrm{m_{med}}$	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	$\mathrm{m_{med}}$	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	$\mathrm{m_{Z'}}$	3.0 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	$\mathrm{m_a}$	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	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu$, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^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	$\mathcal{B}(\mathrm{LQ}_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥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 $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$\mathrm{T_{5/3}}$ 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,μ	≥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
Exctd ferm.	Excited quark $q^* \to qg$	–	2 j	–	139	$\mathrm{q^*}$ 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	$\mathrm{q^*}$ mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	$\mathrm{b^*}$ 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, μ	≥2 j	Yes	139	$\mathrm{N^0}$ mass	910 GeV		
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	$\mathrm{N_R}$ mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L =$	
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$\mathrm{H^{\pm\pm}}$ mass	350 GeV	DY production	
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$\mathrm{H^{\pm\pm}}$ mass	1.08 TeV	DY production	
	Multi-charged particles	–	–	–	139	multi-charged particle mass	1.59 TeV	DY production, $\lvert q\rvert = 5e$	
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert = 1g_D$,	

*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).

We look for many other different models, extra dimensions, extra bosons…

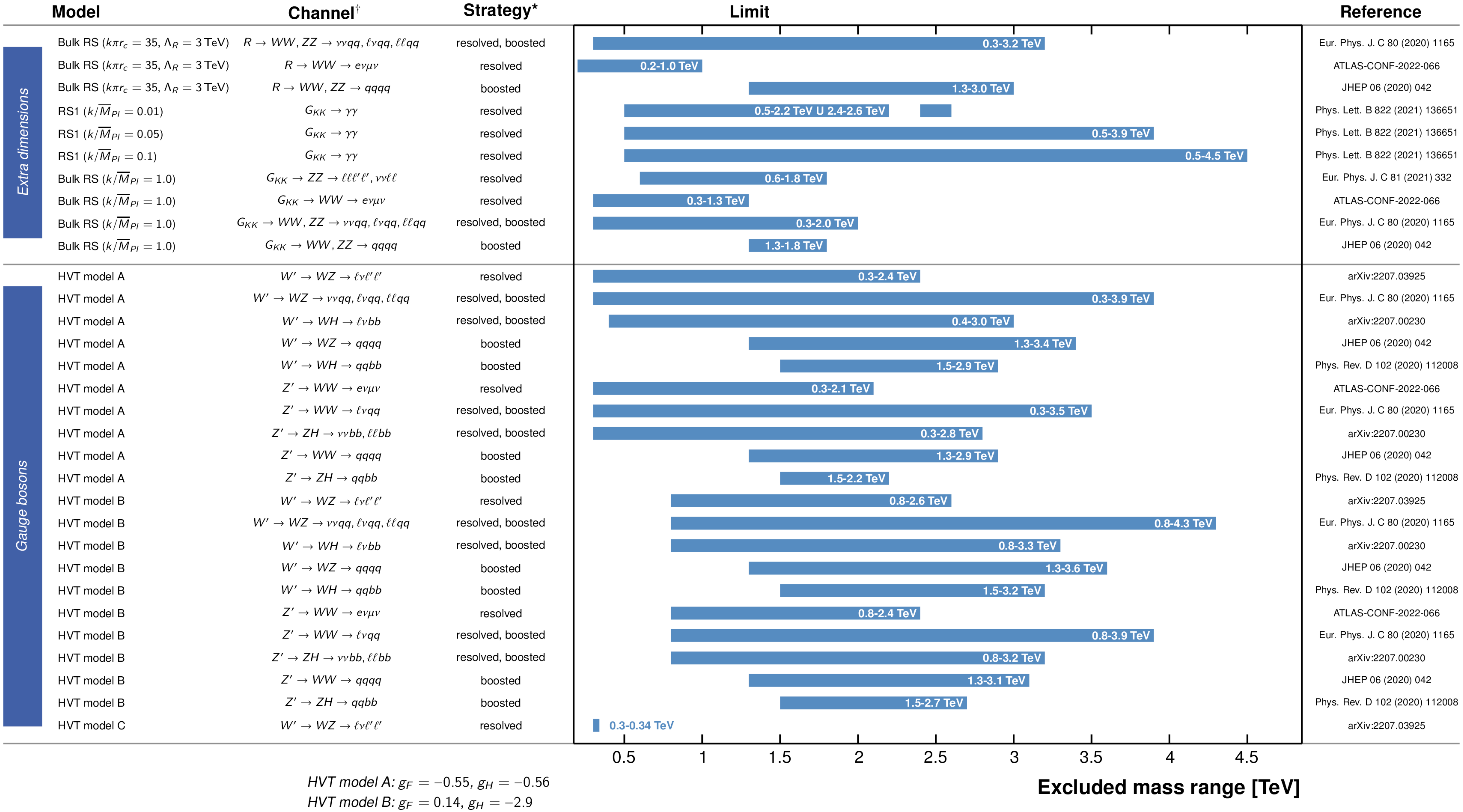
ATLAS Diboson Searches - 95% CL Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

$\mathcal{L}$ = 139 fb^{-1}



Model	Channel†	Strategy*	Limit	Reference
Extra dimensions				
Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.2 TeV	Eur. Phys. J. C 80 (2020) 1165
Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R \to WW \to e\nu\mu\nu$	resolved	0.2-1.0 TeV	ATLAS-CONF-2022-066
Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R \to WW, ZZ \to qqqq$	boosted	1.3-3.0 TeV	JHEP 06 (2020) 042
RS1 ($k/\overline{M}_{Pl} = 0.01$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-2.2 TeV U 2.4-2.6 TeV	Phys. Lett. B 822 (2021) 136651
RS1 ($k/\overline{M}_{Pl} = 0.05$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-3.9 TeV	Phys. Lett. B 822 (2021) 136651
RS1 ($k/\overline{M}_{Pl} = 0.1$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-4.5 TeV	Phys. Lett. B 822 (2021) 136651
Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to ZZ \to \ell\ell\ell'\ell', \nu\nu\ell\ell$	resolved	0.6-1.8 TeV	Eur. Phys. J. C 81 (2021) 332
Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW \to e\nu\mu\nu$	resolved	0.3-1.3 TeV	ATLAS-CONF-2022-066
Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-2.0 TeV	Eur. Phys. J. C 80 (2020) 1165
Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to qqqq$	boosted	1.3-1.8 TeV	JHEP 06 (2020) 042
Gauge bosons				
HVT model A	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.3-2.4 TeV	arXiv:2207.03925
HVT model A	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
HVT model A	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.4-3.0 TeV	arXiv:2207.00230
HVT model A	$W' \to WZ \to qqqq$	boosted	1.3-3.4 TeV	JHEP 06 (2020) 042
HVT model A	$W' \to WH \to qqbb$	boosted	1.5-2.9 TeV	Phys. Rev. D 102 (2020) 112008
HVT model A	$Z' \to WW \to e\nu\mu\nu$	resolved	0.3-2.1 TeV	ATLAS-CONF-2022-066
HVT model A	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.3-3.5 TeV	Eur. Phys. J. C 80 (2020) 1165
HVT model A	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.3-2.8 TeV	arXiv:2207.00230
HVT model A	$Z' \to WW \to qqqq$	boosted	1.3-2.9 TeV	JHEP 06 (2020) 042
HVT model A	$Z' \to ZH \to qqbb$	boosted	1.5-2.2 TeV	Phys. Rev. D 102 (2020) 112008
HVT model B	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.8-2.6 TeV	arXiv:2207.03925
HVT model B	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.8-4.3 TeV	Eur. Phys. J. C 80 (2020) 1165
HVT model B	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.8-3.3 TeV	arXiv:2207.00230
HVT model B	$W' \to WZ \to qqqq$	boosted	1.3-3.6 TeV	JHEP 06 (2020) 042
HVT model B	$W' \to WH \to qqbb$	boosted	1.5-3.2 TeV	Phys. Rev. D 102 (2020) 112008
HVT model B	$Z' \to WW \to e\nu\mu\nu$	resolved	0.8-2.4 TeV	ATLAS-CONF-2022-066
HVT model B	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.8-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
HVT model B	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.8-3.2 TeV	arXiv:2207.00230
HVT model B	$Z' \to WW \to qqqq$	boosted	1.3-3.1 TeV	JHEP 06 (2020) 042
HVT model B	$Z' \to ZH \to qqbb$	boosted	1.5-2.7 TeV	Phys. Rev. D 102 (2020) 112008
HVT model C	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.3-0.34 TeV	arXiv:2207.03925

HVT model A: $g_F = -0.55$, $g_H = -0.56$

HVT model B: $g_F = 0.14$, $g_H = -2.9$

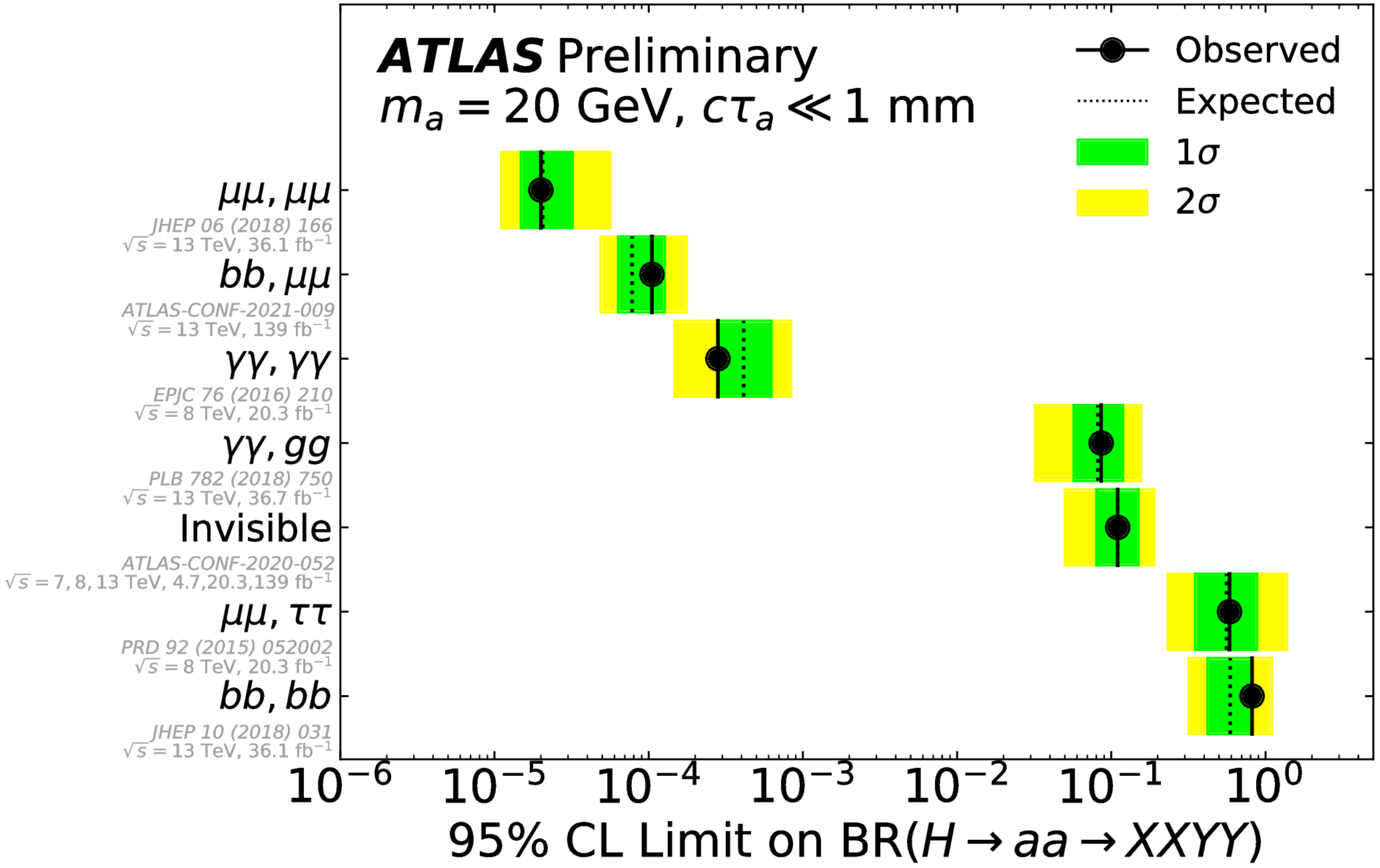
HVT model C: $g_F = 0$, $g_H = 1$

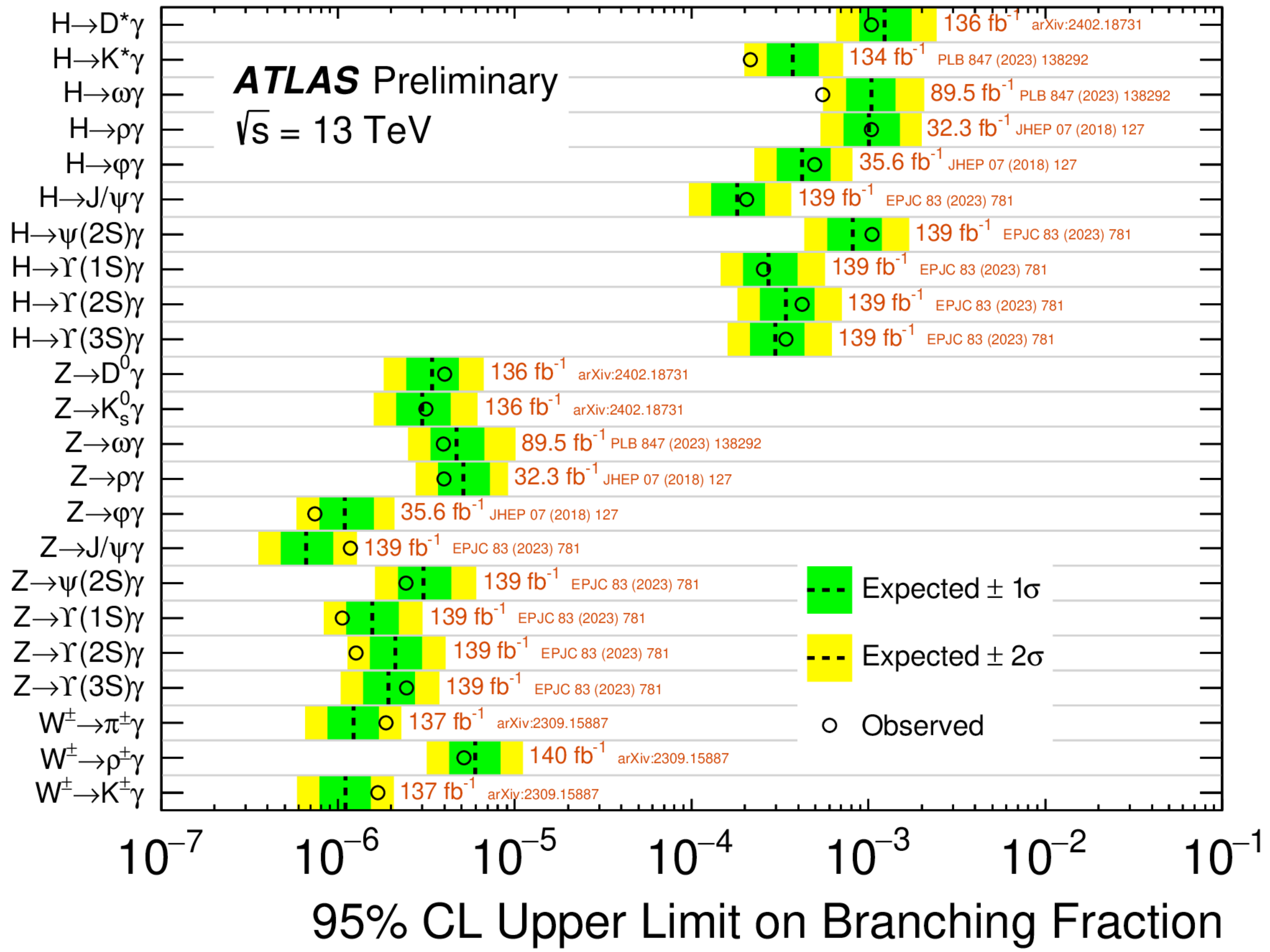
**small-radius (large-radius) jets are used in resolved (boosted) events*

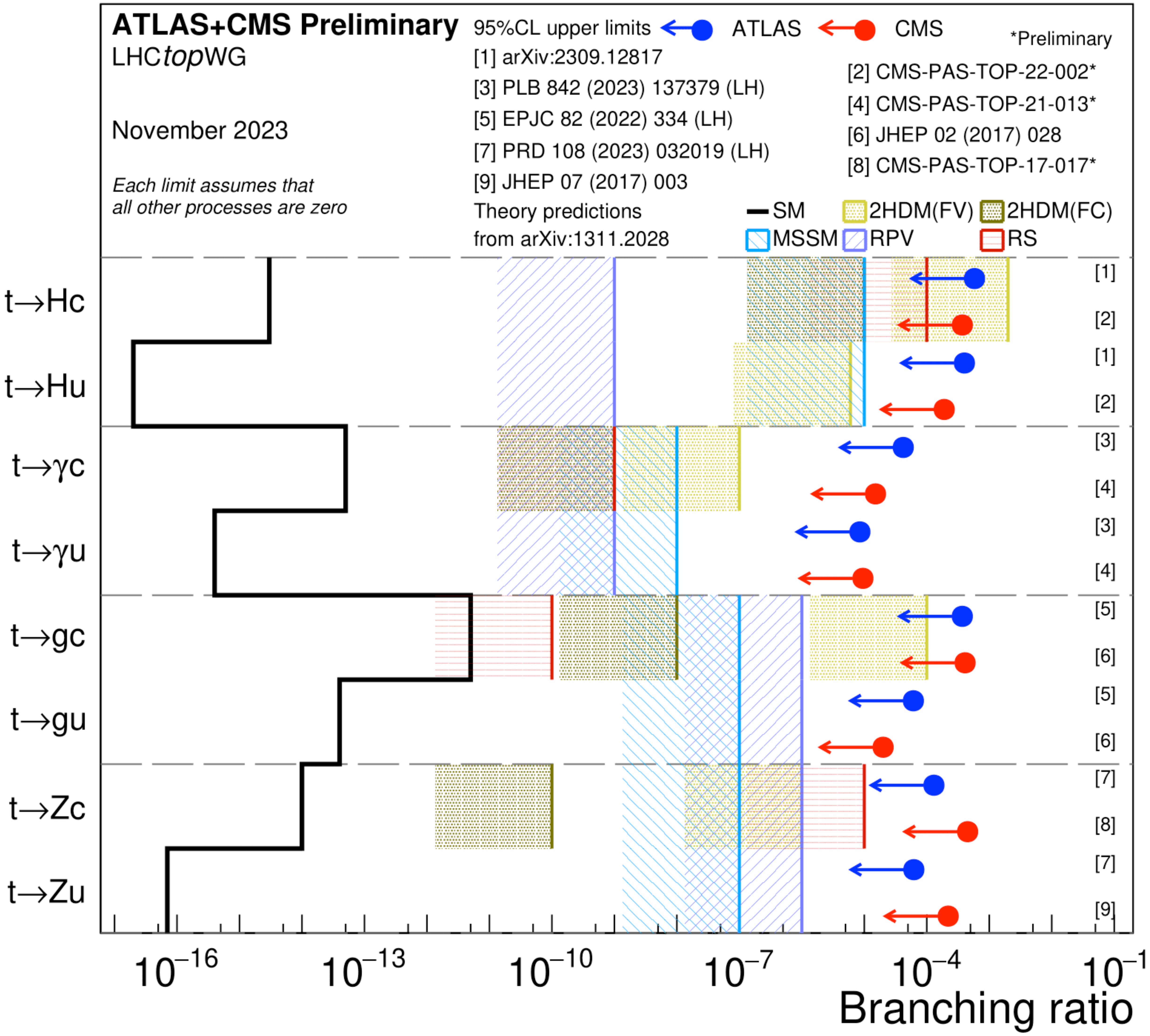
†with $\ell = \mu, e$

We look for exotic decays of the Higgs boson

March 2021



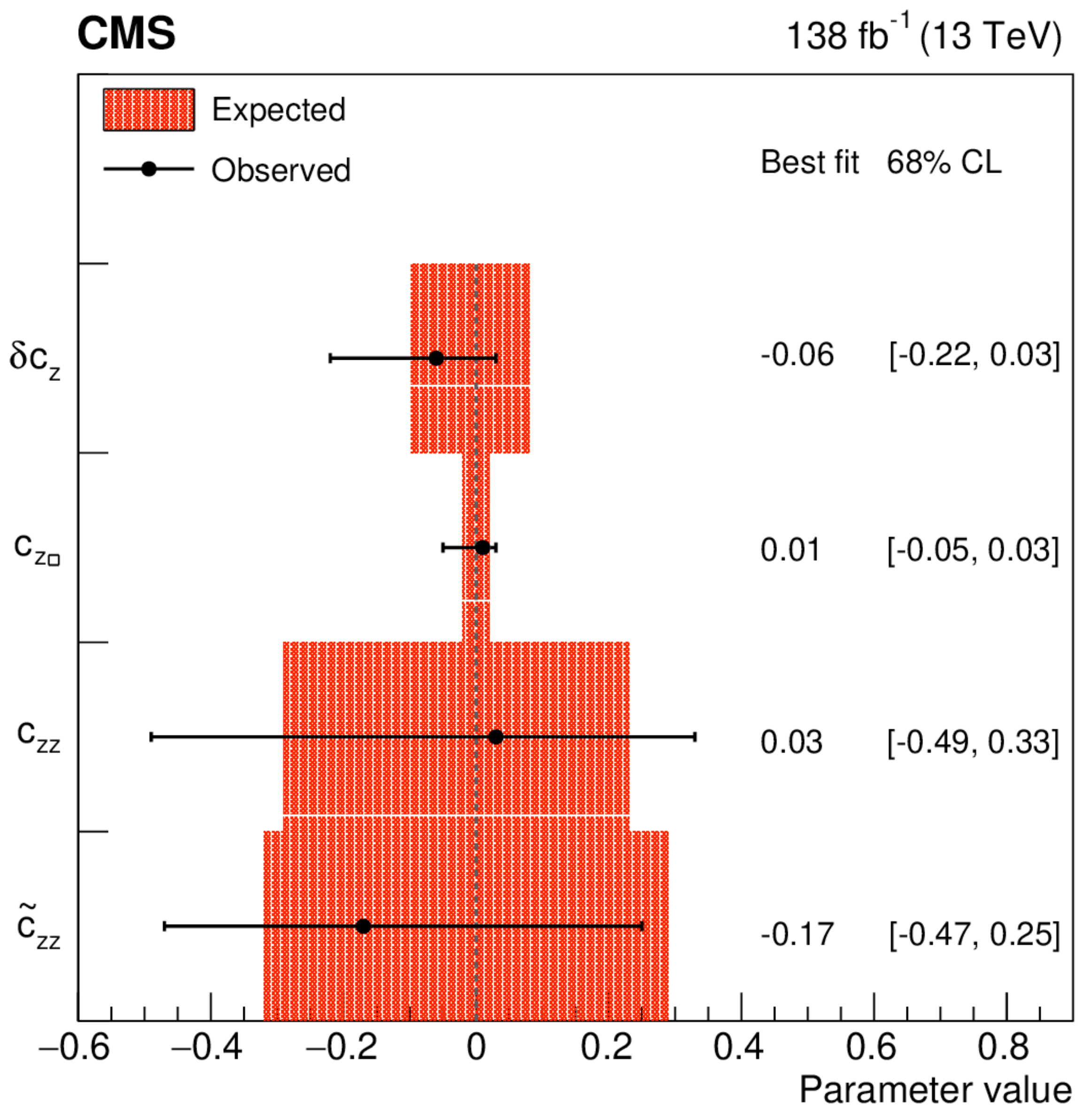


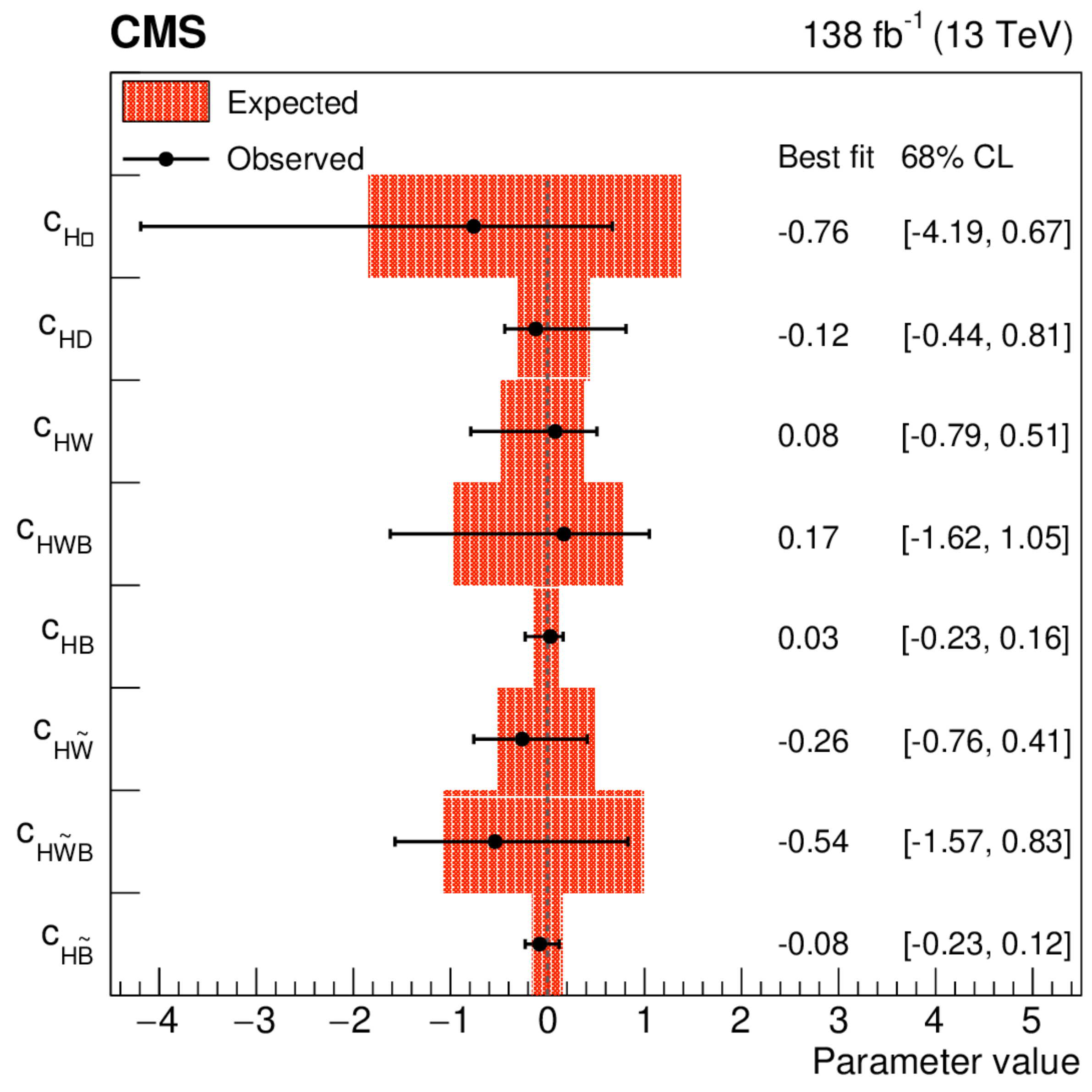


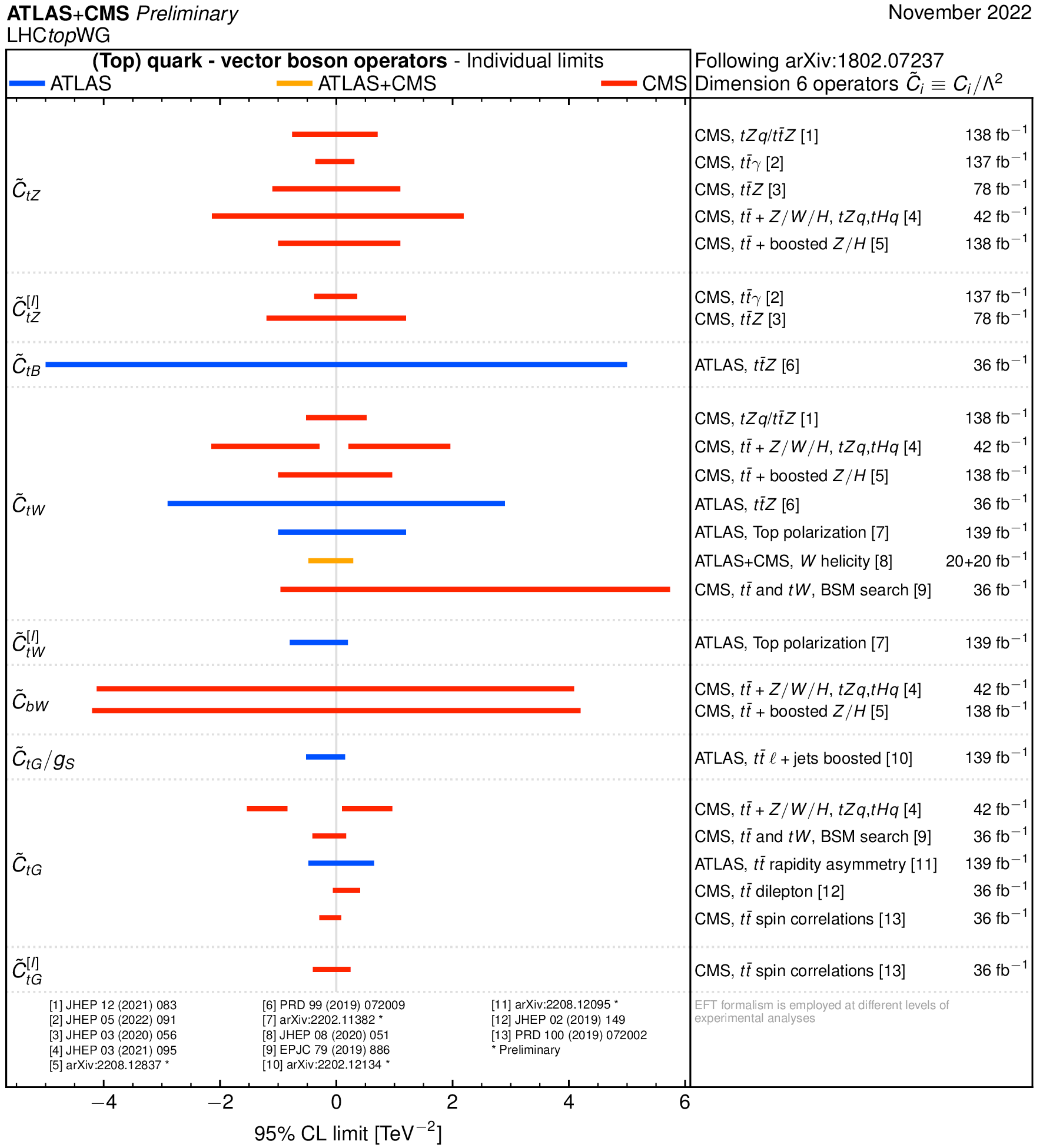
And of the top quark

WE LOOK AT PRECISION IN A DIFFERENT WAY

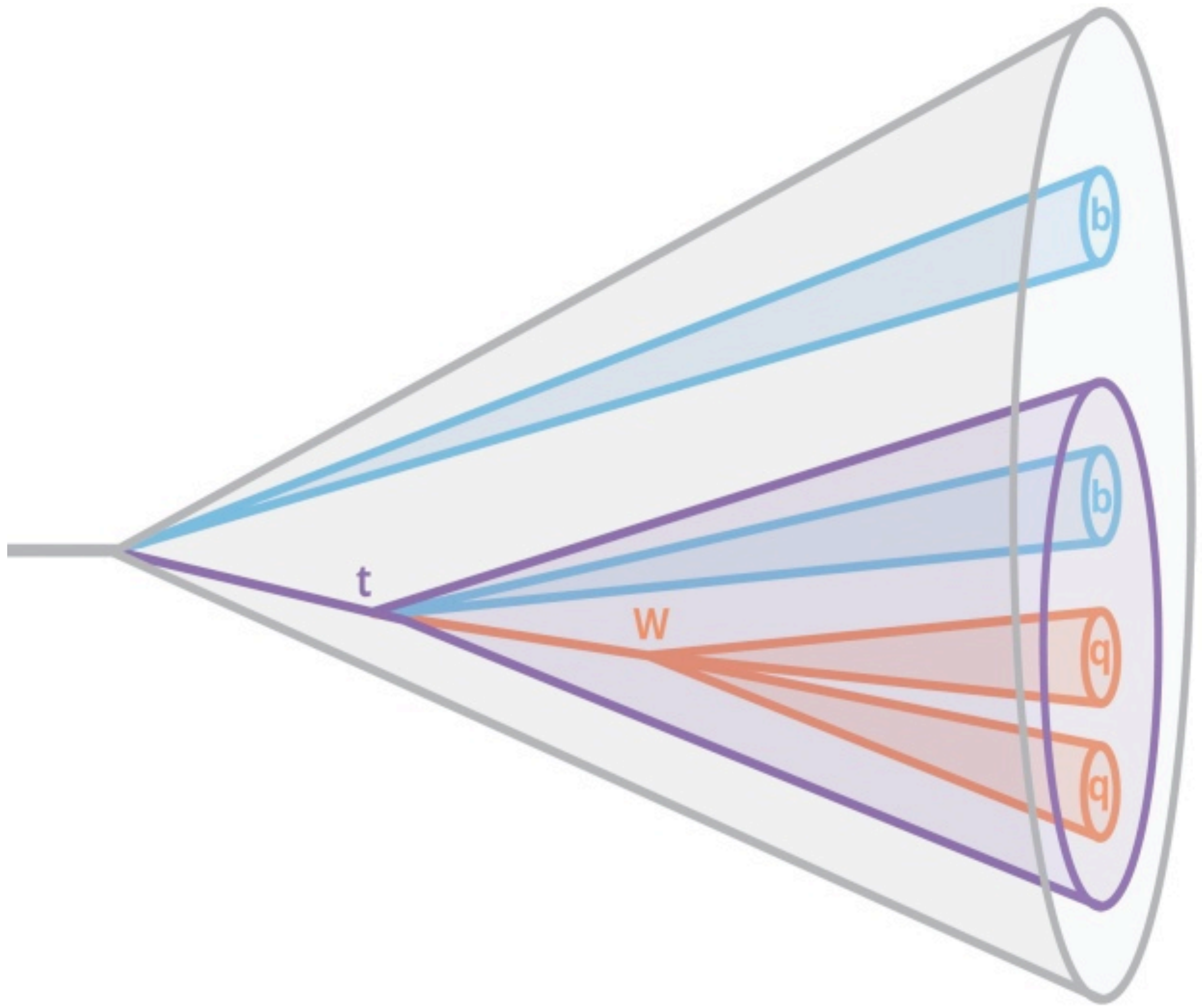
- Interpretating the LHC data in the context of effective field theories (EFTs)



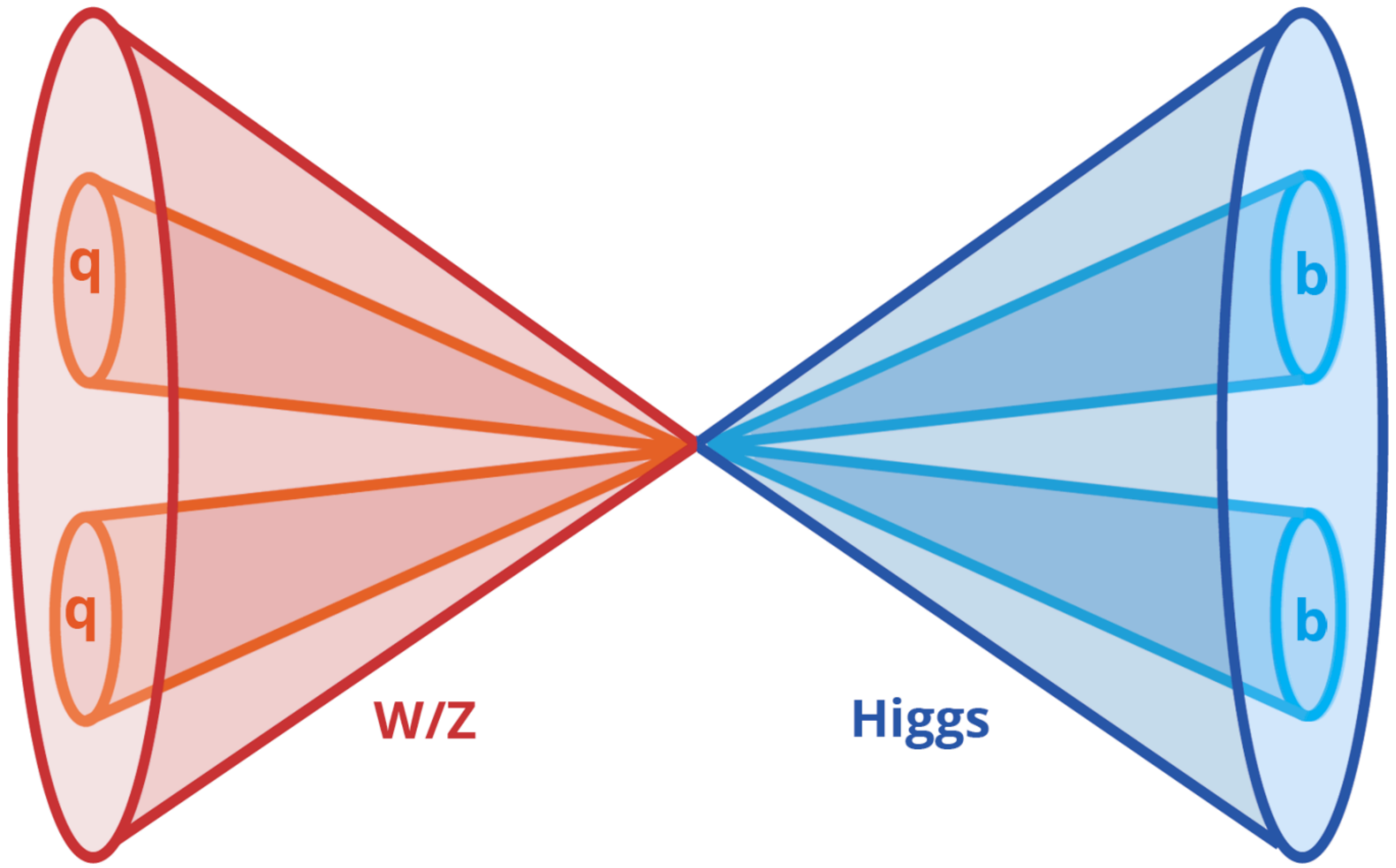




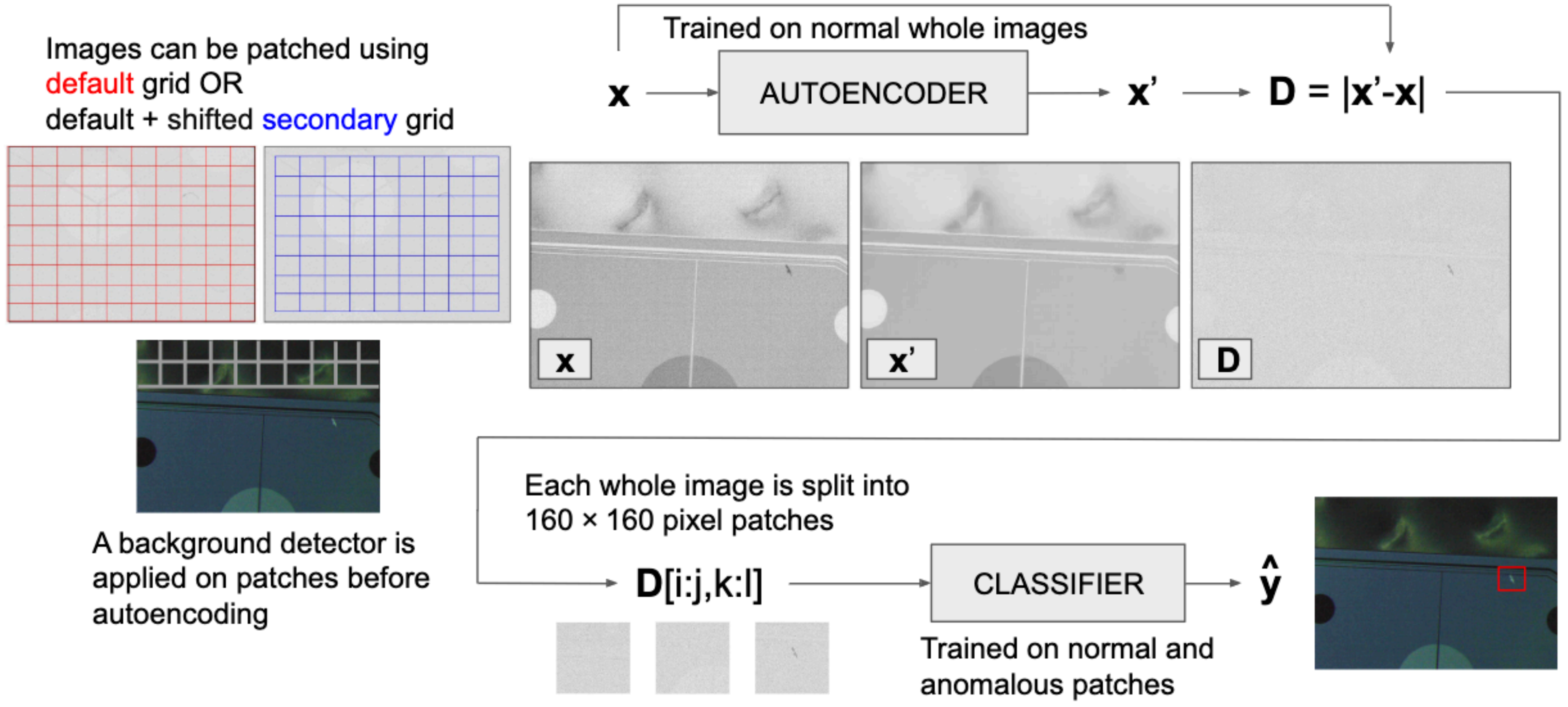
WE INCLUDE INCREASINGLY COMPLICATED INGREDIENTS



Like boosted objects, collimated decays, that can have substructure



AND INCREASINGLY COMPLICATED METHODS



Images can be patched using default grid OR default + shifted secondary grid

A background detector is applied on patches before autoencoding

Trained on normal whole images

x → AUTOENCODER → x' → D = |x'-x|

x

x'

D

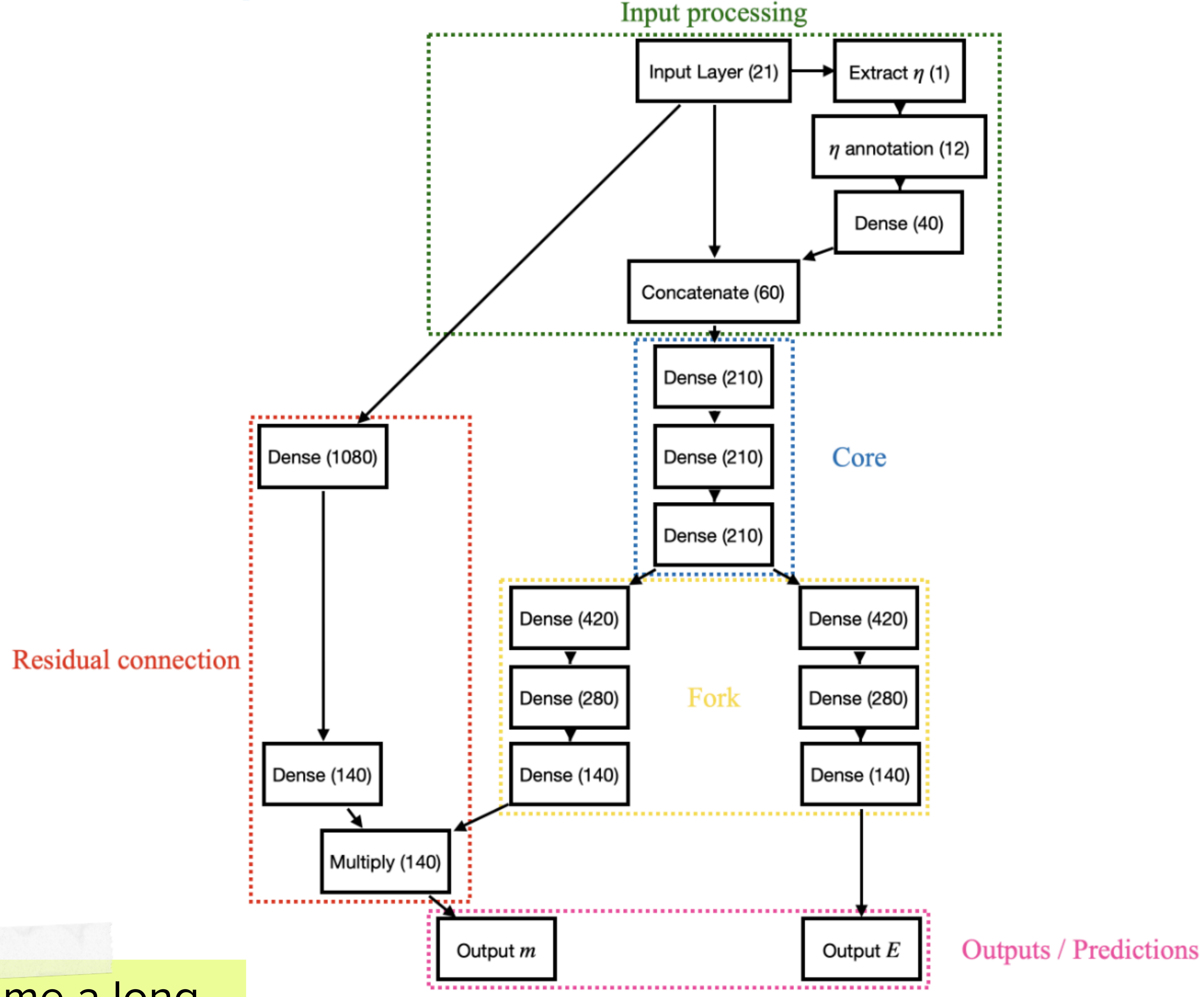
Each whole image is split into 160 × 160 pixel patches

D[i:j,k:l] → CLASSIFIER → ŷ

Trained on normal and anomalous patches

https://arxiv.org/pdf/2303.15319

We've come a long way from the cut-based analysis days



Input processing

Input Layer (21)

Extract η (1)

η annotation (12)

Dense (40)

Concatenate (60)

Core

Dense (210)

Dense (210)

Dense (210)

Residual connection

Dense (1080)

Dense (140)

Multiply (140)

Fork

Dense (420)

Dense (280)

Dense (140)

Dense (420)

Dense (280)

Dense (140)

Outputs / Predictions

Output m

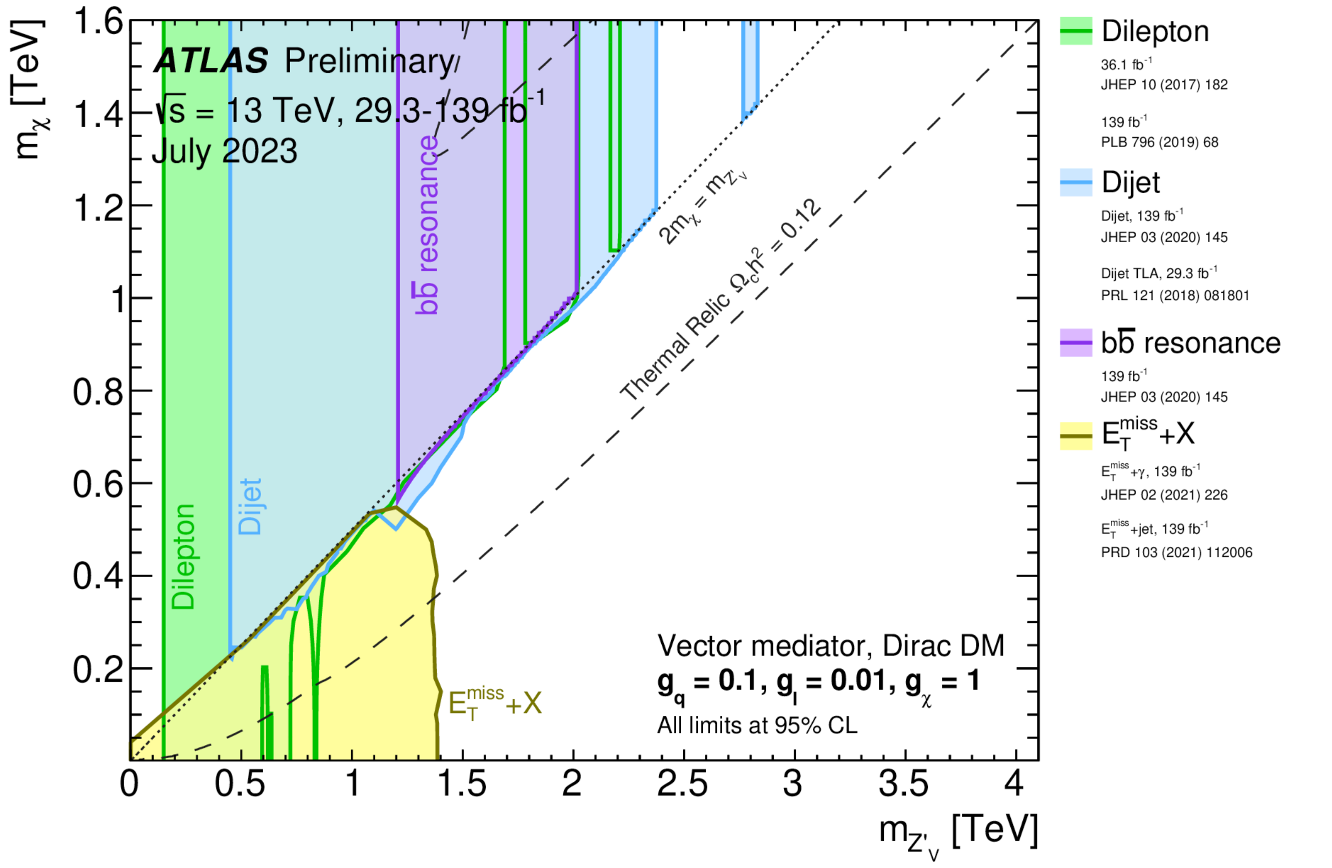
Output E

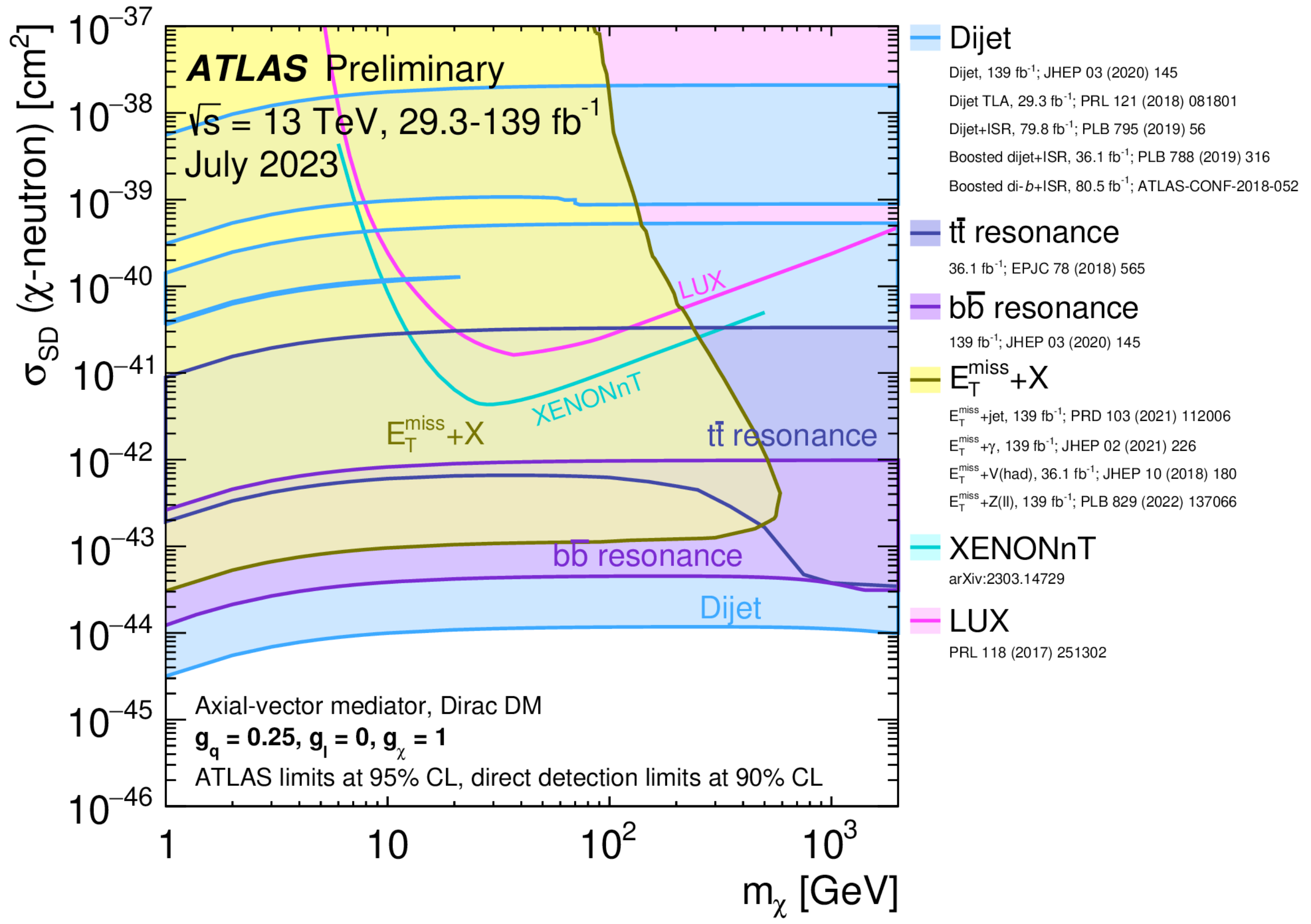
Figure 2: The architecture of the DNN.

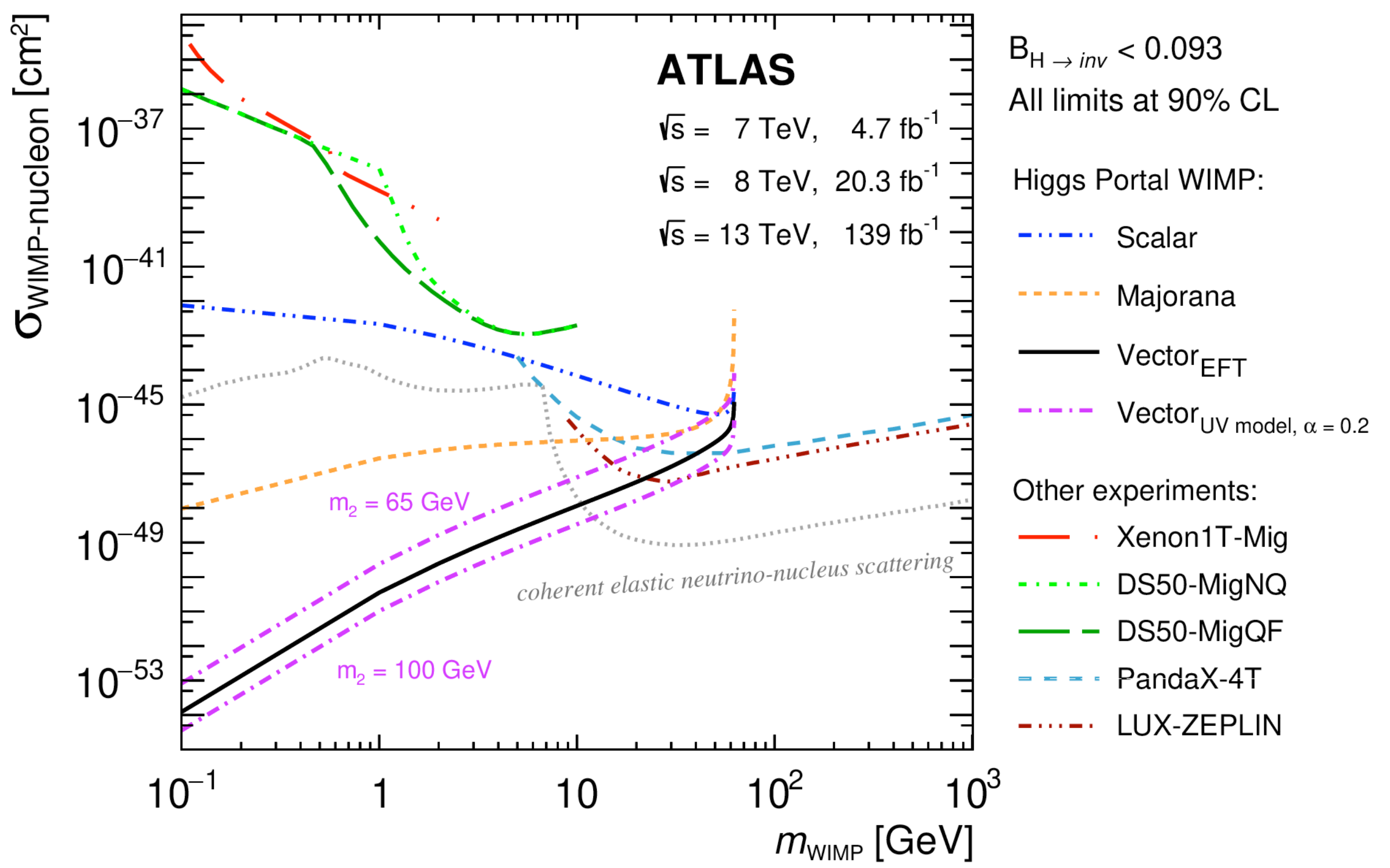
https://arxiv.org/pdf/2311.08885

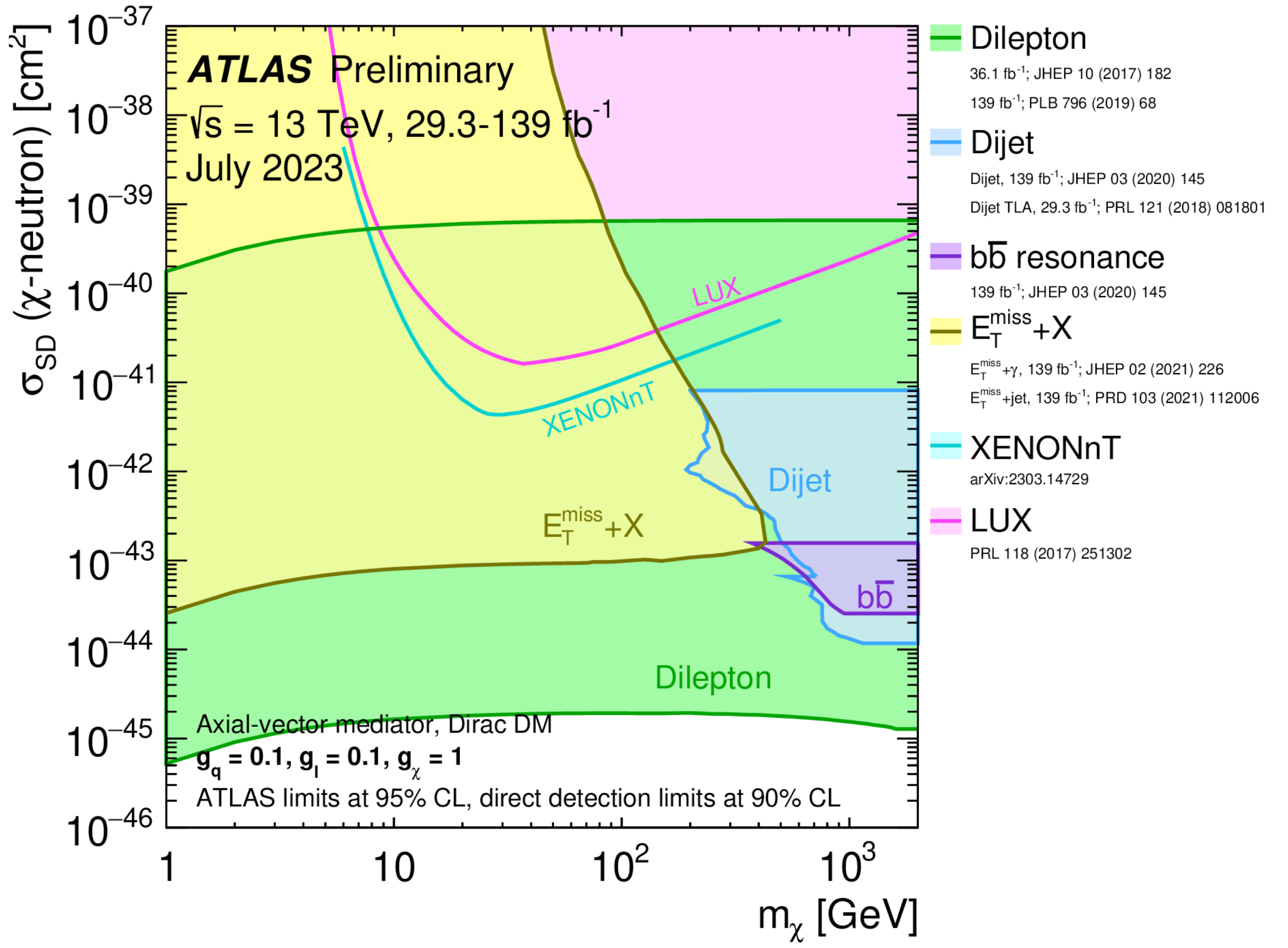
WE GO ACROSS PHYSICS FIELDS

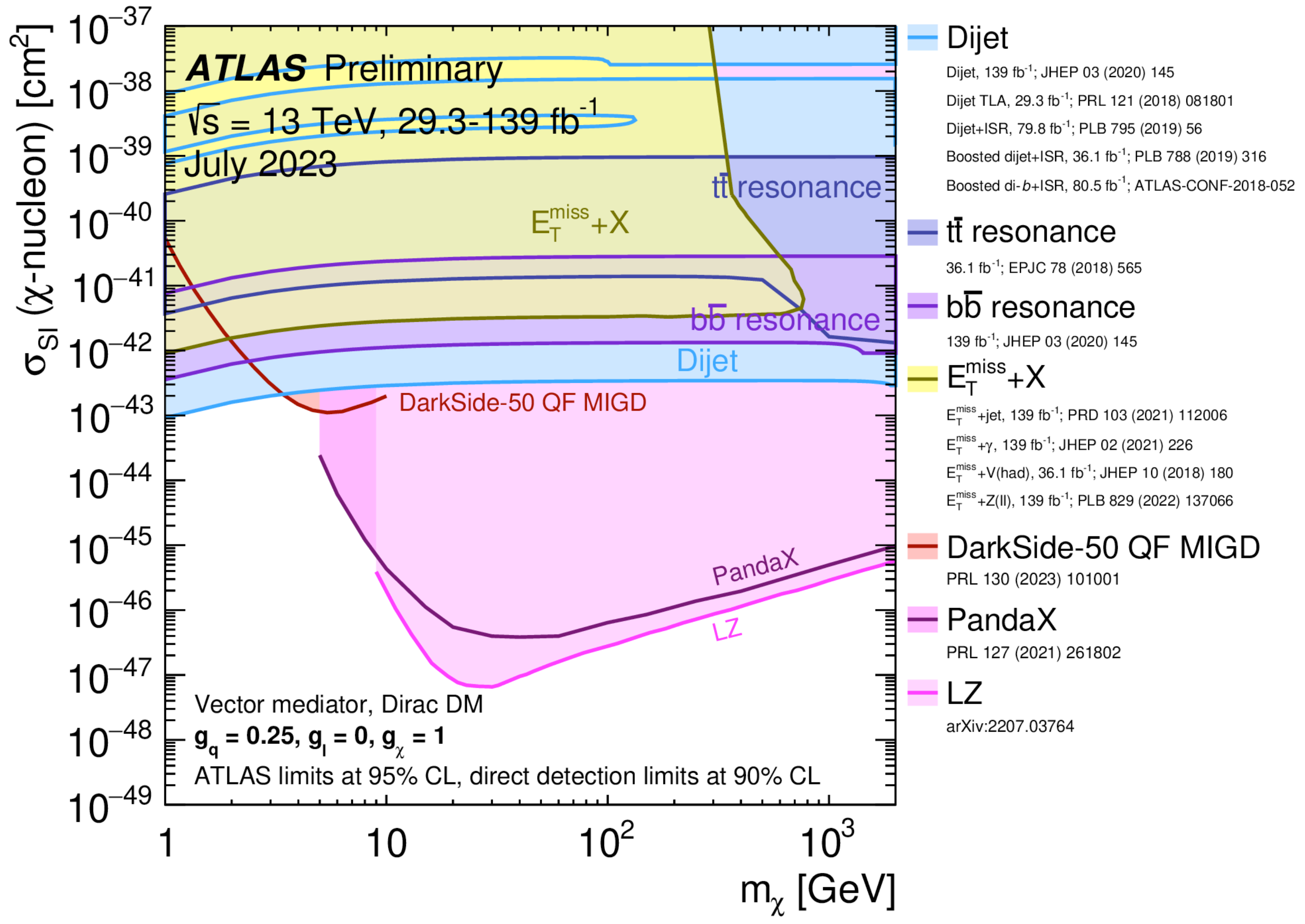
We look for dark matter in many different ways

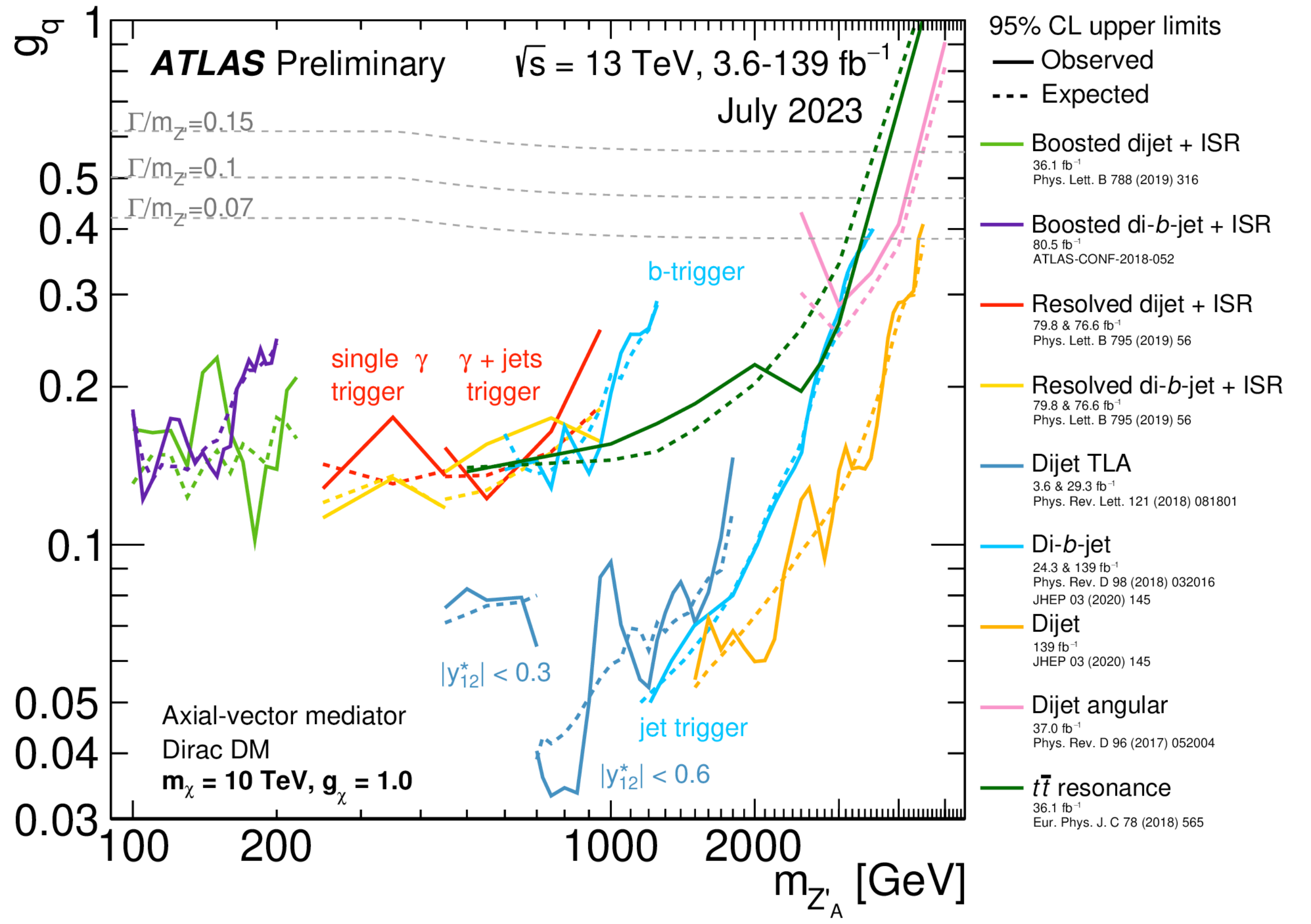




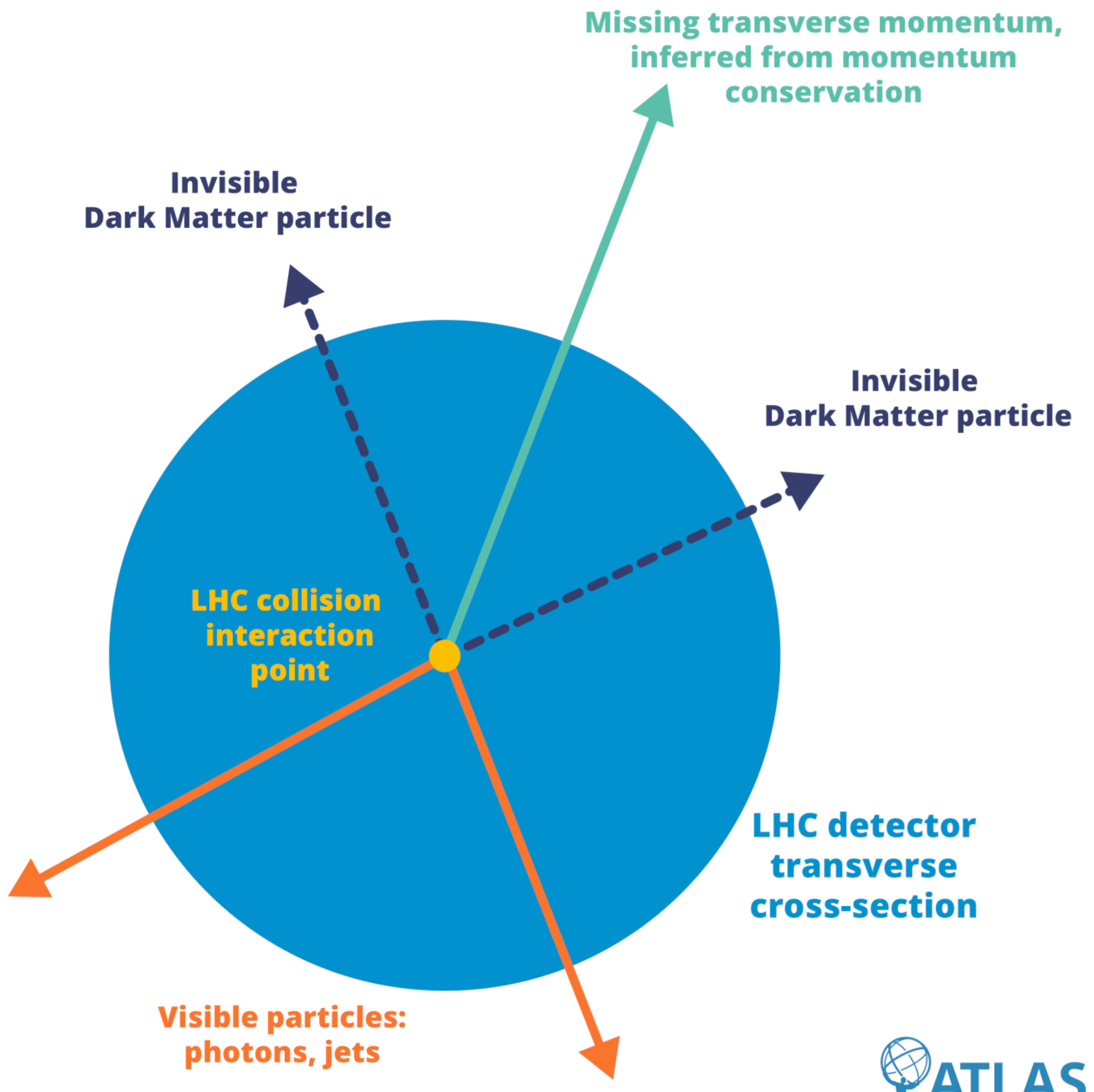


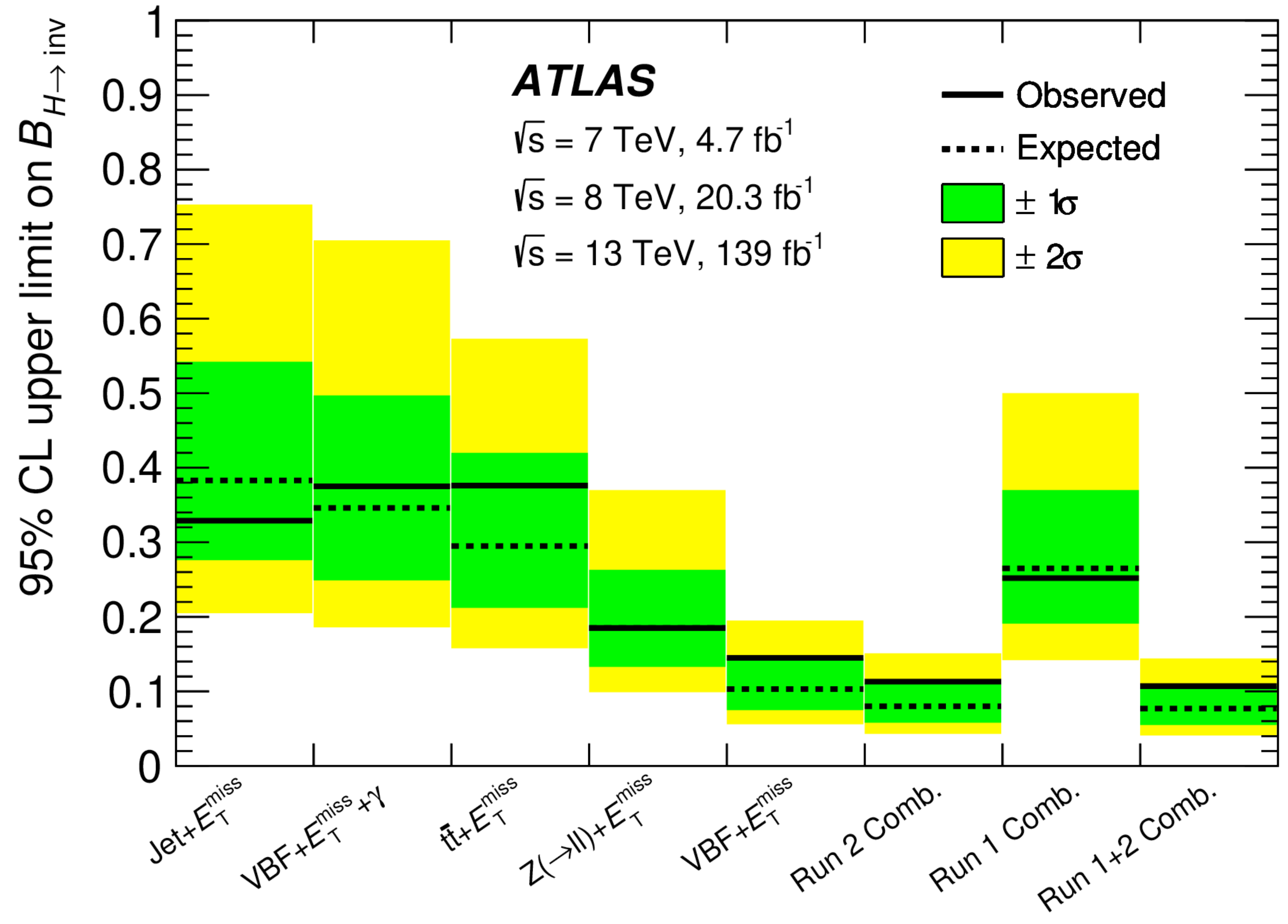


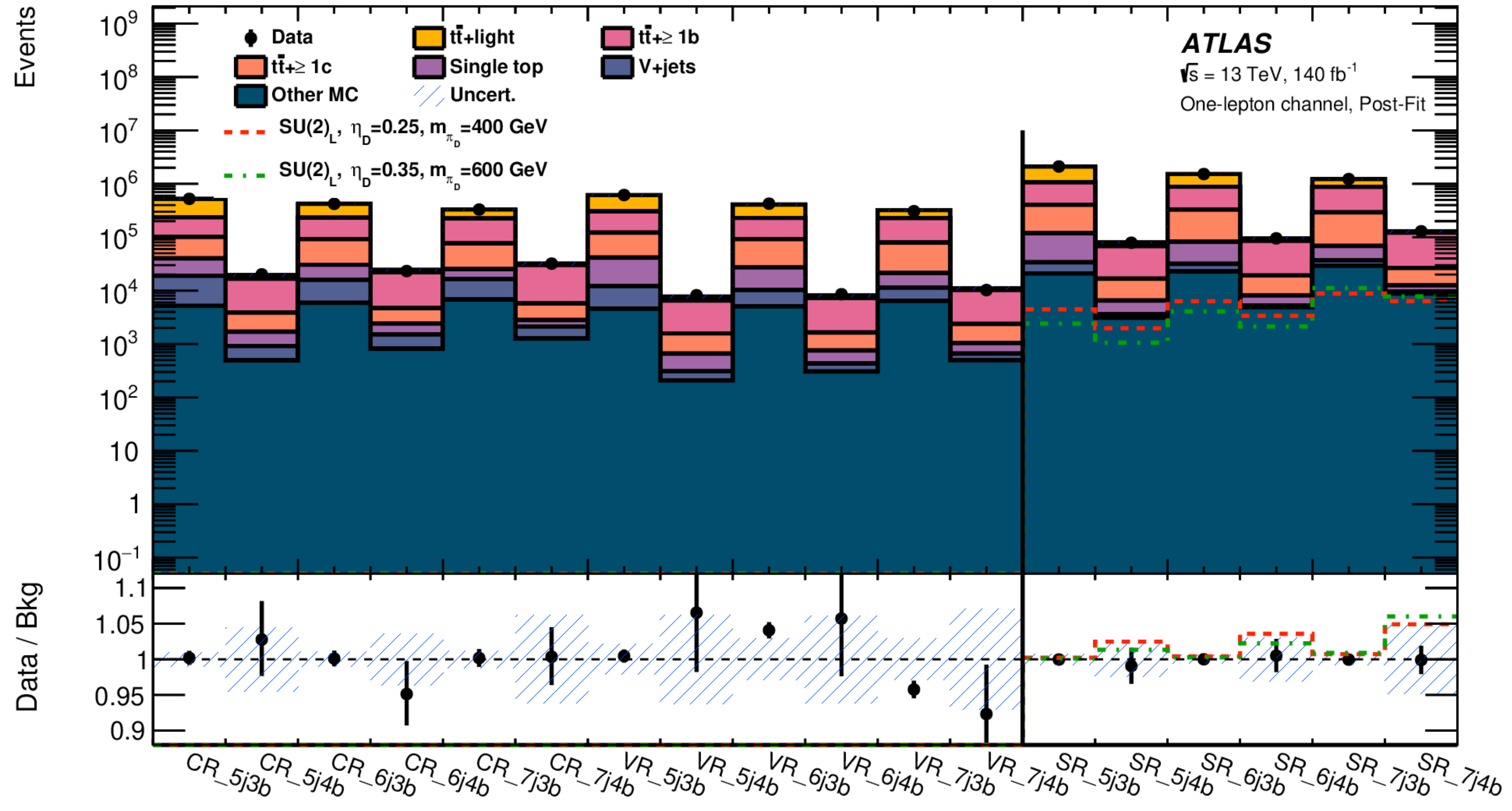




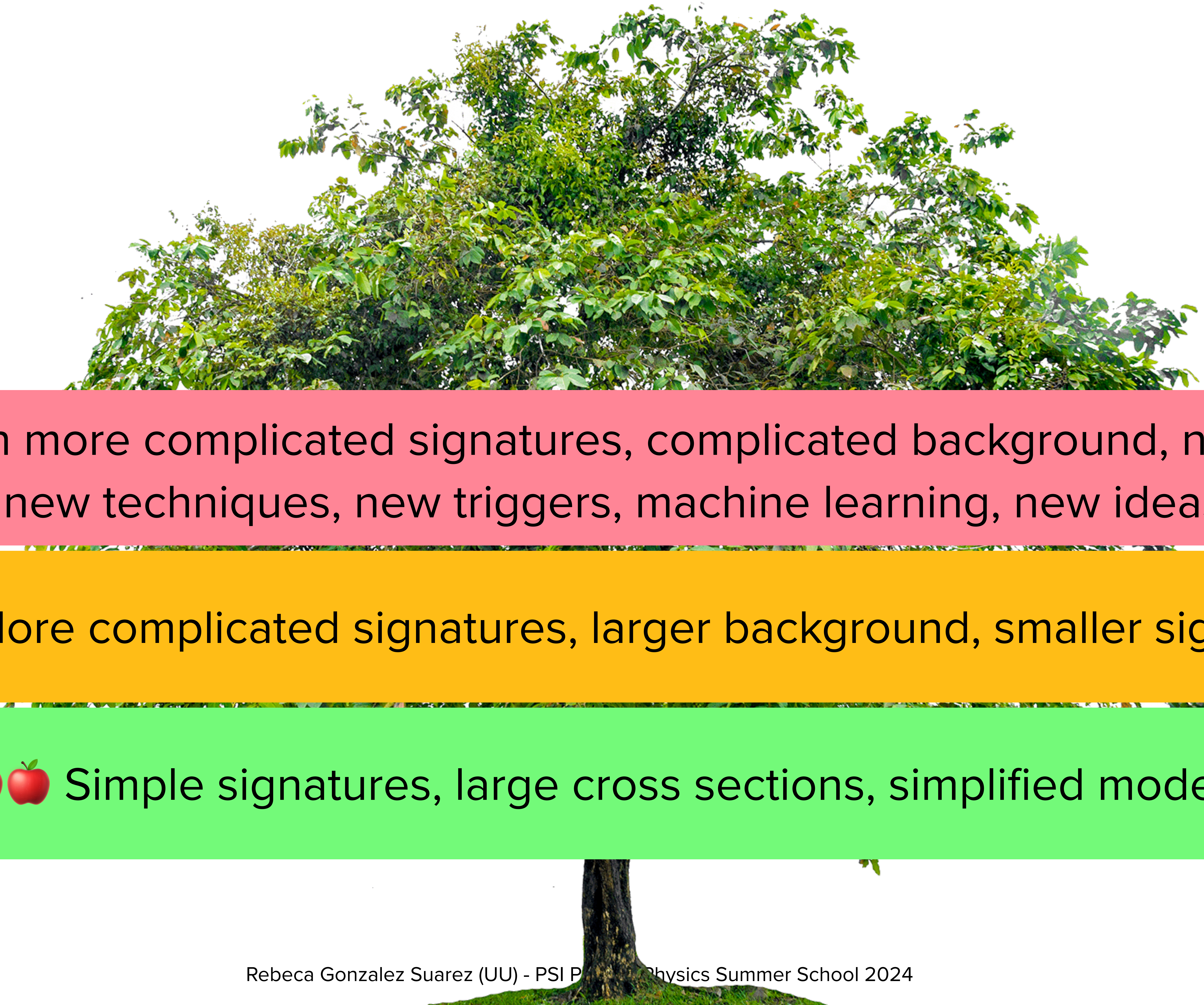
ALSO WITH INCREASED COMPLEXITY







At the very beginning, our dark matter searches were mostly “mono” things (a SM object + MET) or invisible decays of the Higgs boson but after many searches we have expanded the criteria to more complex models



🍎 Even more complicated signatures, complicated background, needs for new techniques, new triggers, machine learning, new ideas

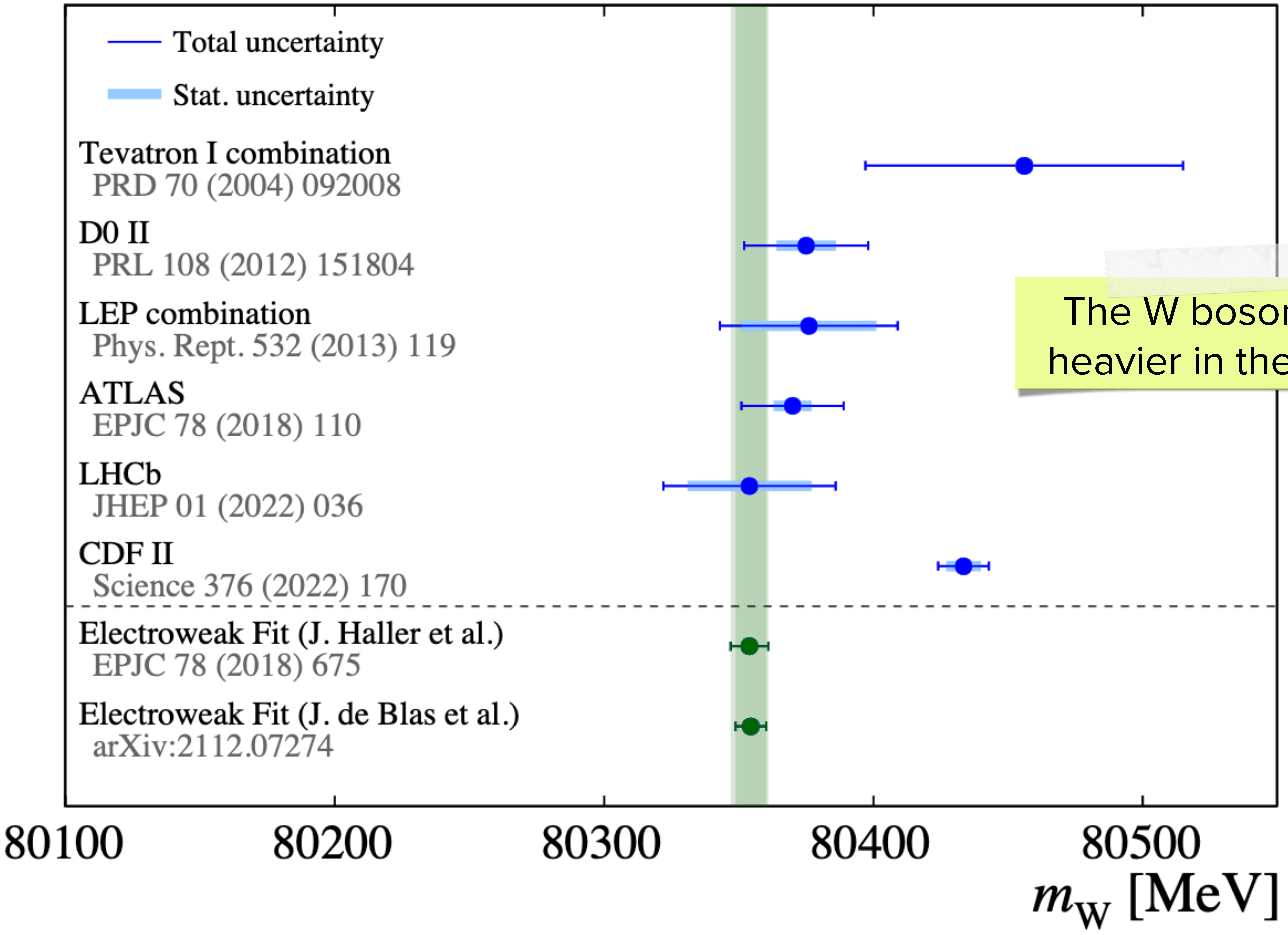
🍎🍎 More complicated signatures, larger background, smaller signals

🍎🍎🍎 Simple signatures, large cross sections, simplified models

Time

MORE TO INVESTIGATE

- Not only we have the general SM shortcomings we already discussed but we have additional interesting effects to investigate

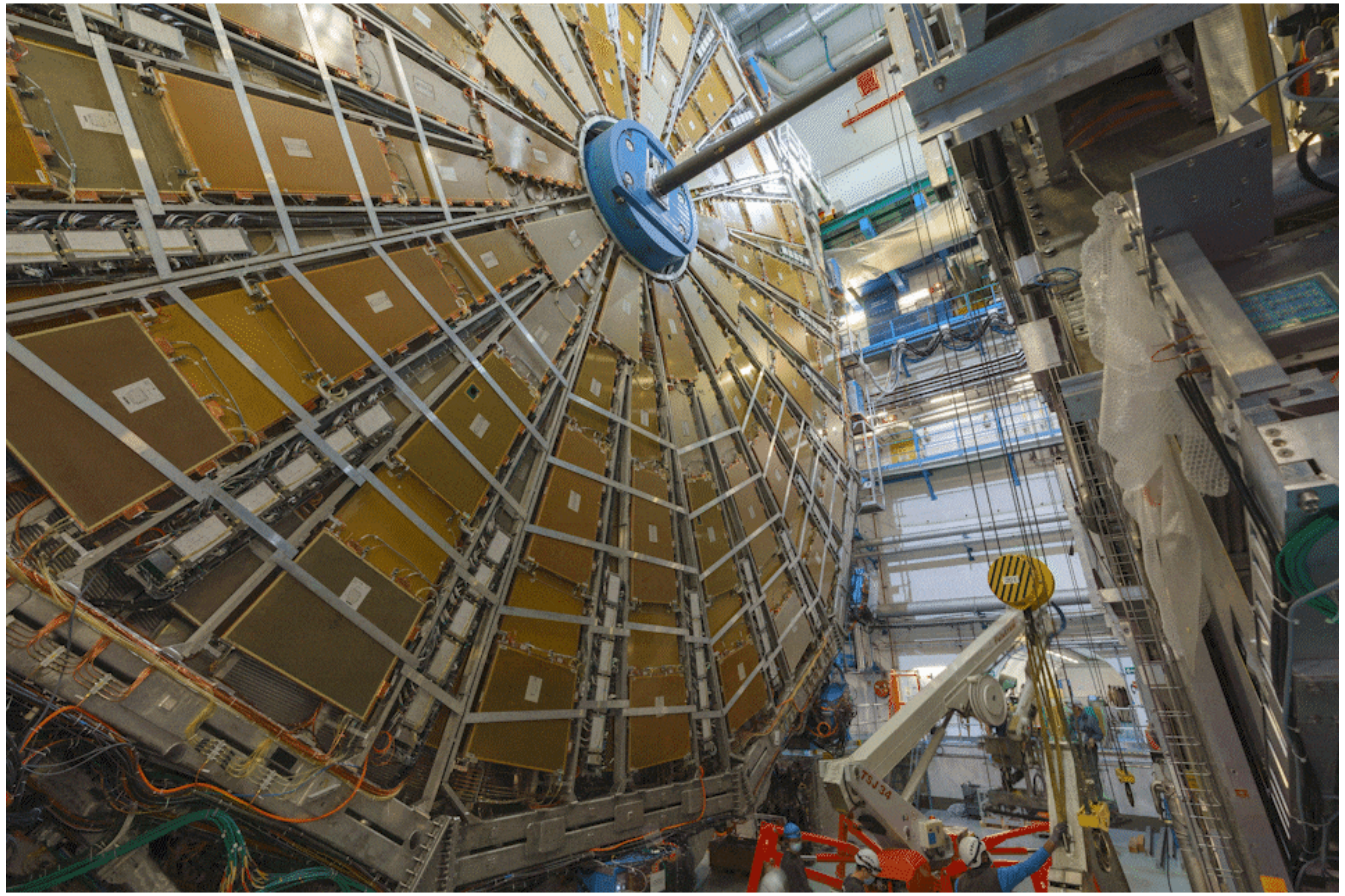


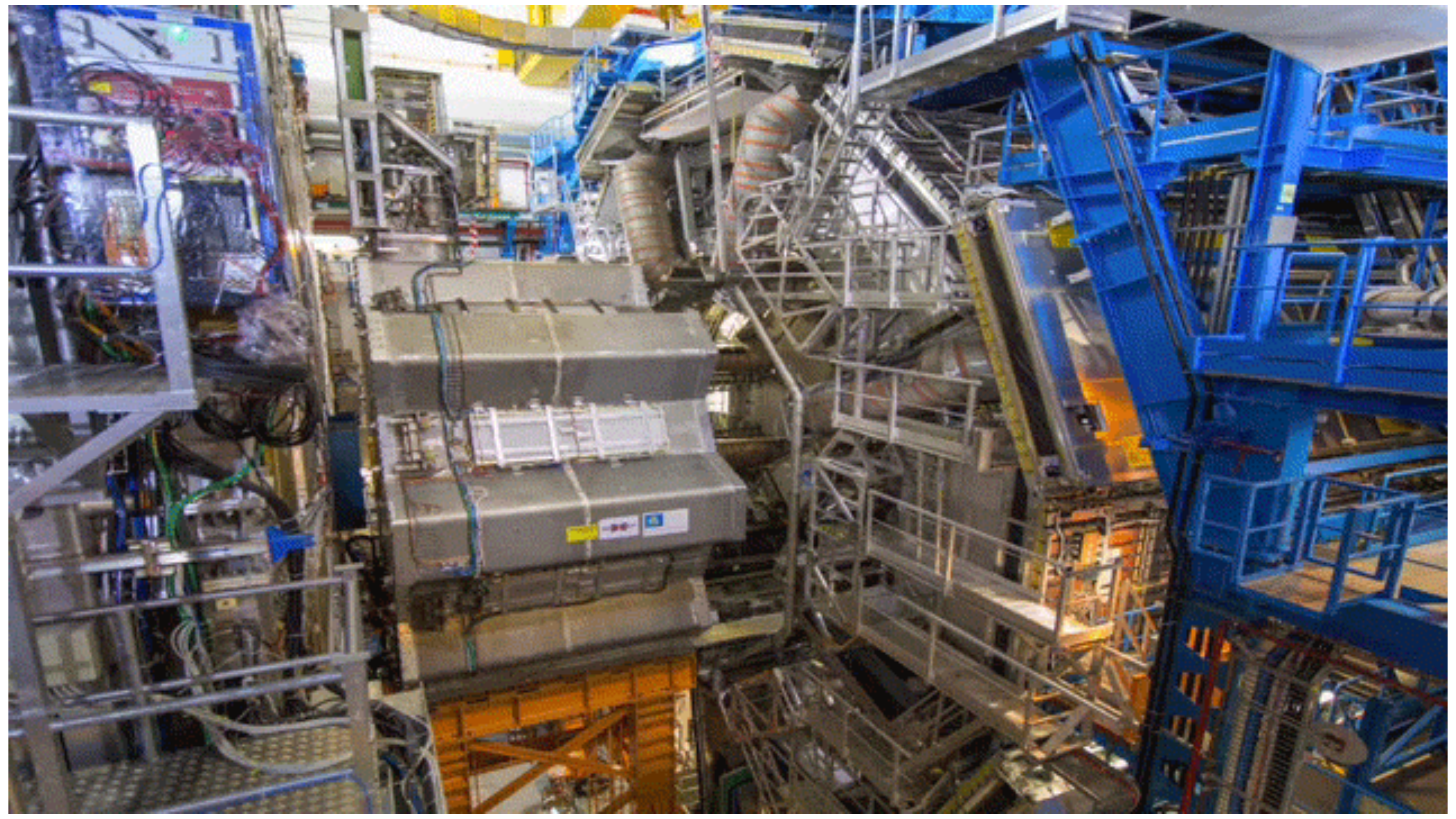
The W boson is heavier in the US

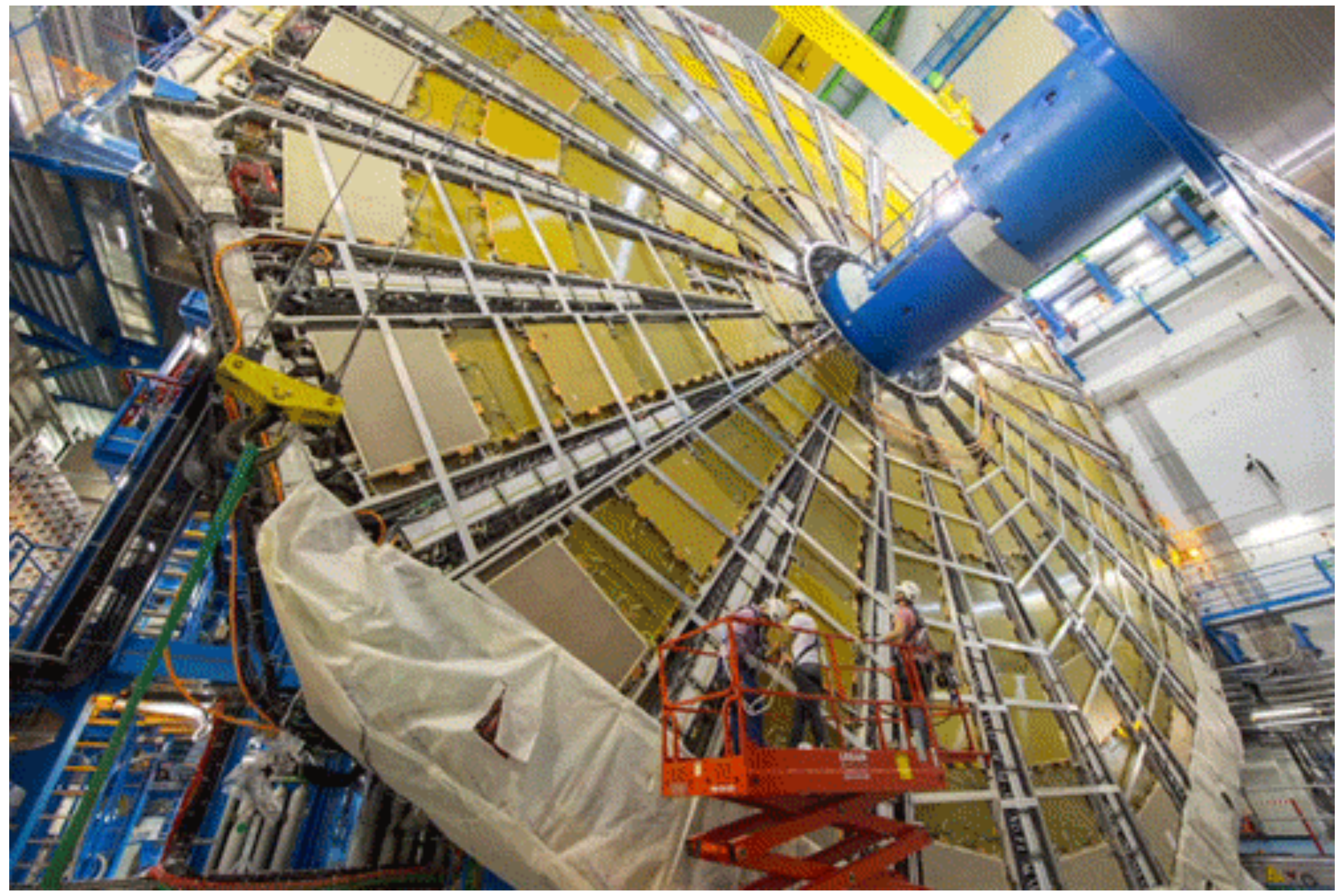
RUN-3

FEELS LIKE RUN 3 JUST STARTED

- Run-3 started after the second long shut-down (LS 2) in 2022
- Most ATLAS and CMS analysis use Run-2 data



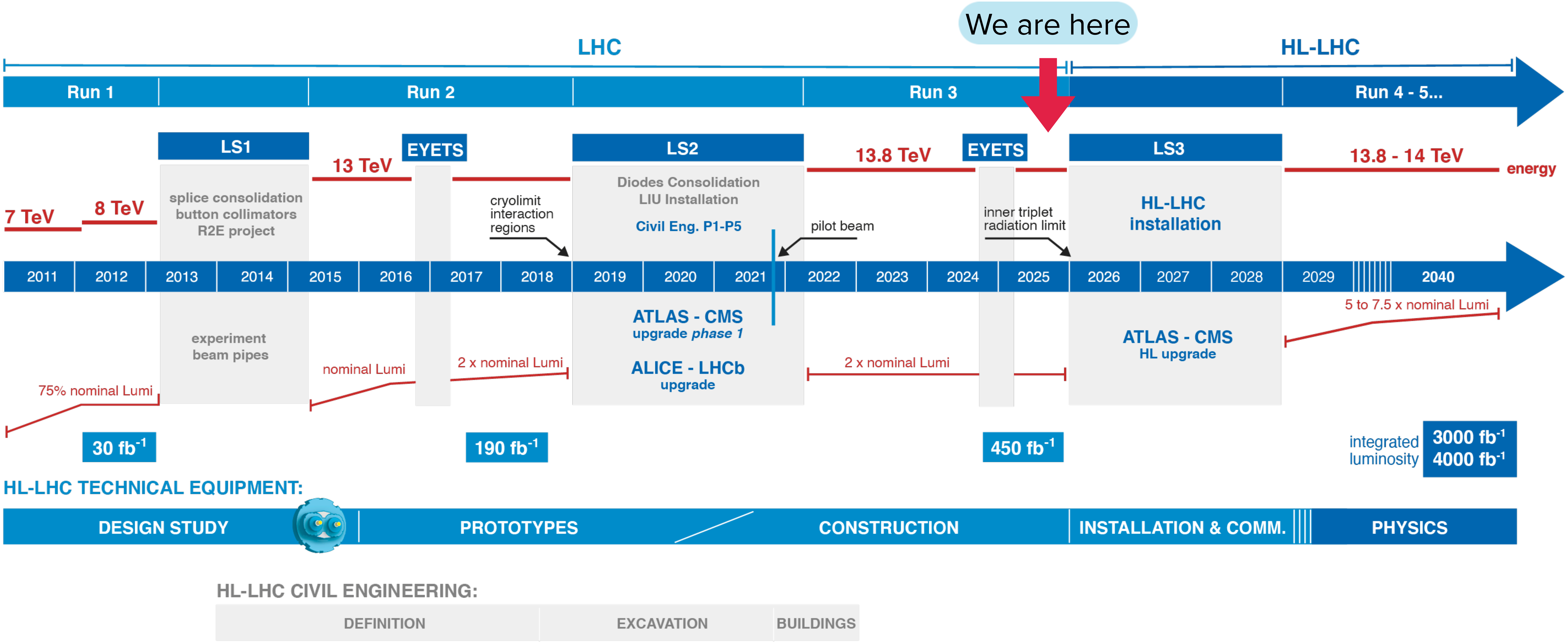




BUT RUN-3 IS THE LAST RUN OF THE LHC AS WE KNOW IT

- The goal for Run-3 is 250 fb^{-1} at 13.6 TeV
- Run-3 will finish next year (or maybe the one after?)
- Will be followed by a Long shut-down (LS3)
- To fully upgrade the LHC and the experiments
  - To the High-Luminosity LHC

LHC / HL-LHC Plan



We are here

LHC

HL-LHC

Run 1 | Run 2 | Run 3 | Run 4 - 5...

LS1: splice consolidation, button collimators, R2E project; experiment beam pipes

EYETS

LS2: Diodes Consolidation, LIU Installation, Civil Eng. P1-P5; ATLAS - CMS upgrade *phase 1*; ALICE - LHCb upgrade

EYETS

LS3: HL-LHC installation; ATLAS - CMS HL upgrade

7 TeV · 8 TeV · 13 TeV · 13.8 TeV · 13.8 - 14 TeV · energy

cryolimit interaction regions

pilot beam

inner triplet radiation limit

2011 · 2012 · 2013 · 2014 · 2015 · 2016 · 2017 · 2018 · 2019 · 2020 · 2021 · 2022 · 2023 · 2024 · 2025 · 2026 · 2027 · 2028 · 2029 · 2040

75% nominal Lumi · nominal Lumi · 2 x nominal Lumi · 2 x nominal Lumi · 5 to 7.5 x nominal Lumi

30 fb^{-1} · 190 fb^{-1} · 450 fb^{-1}

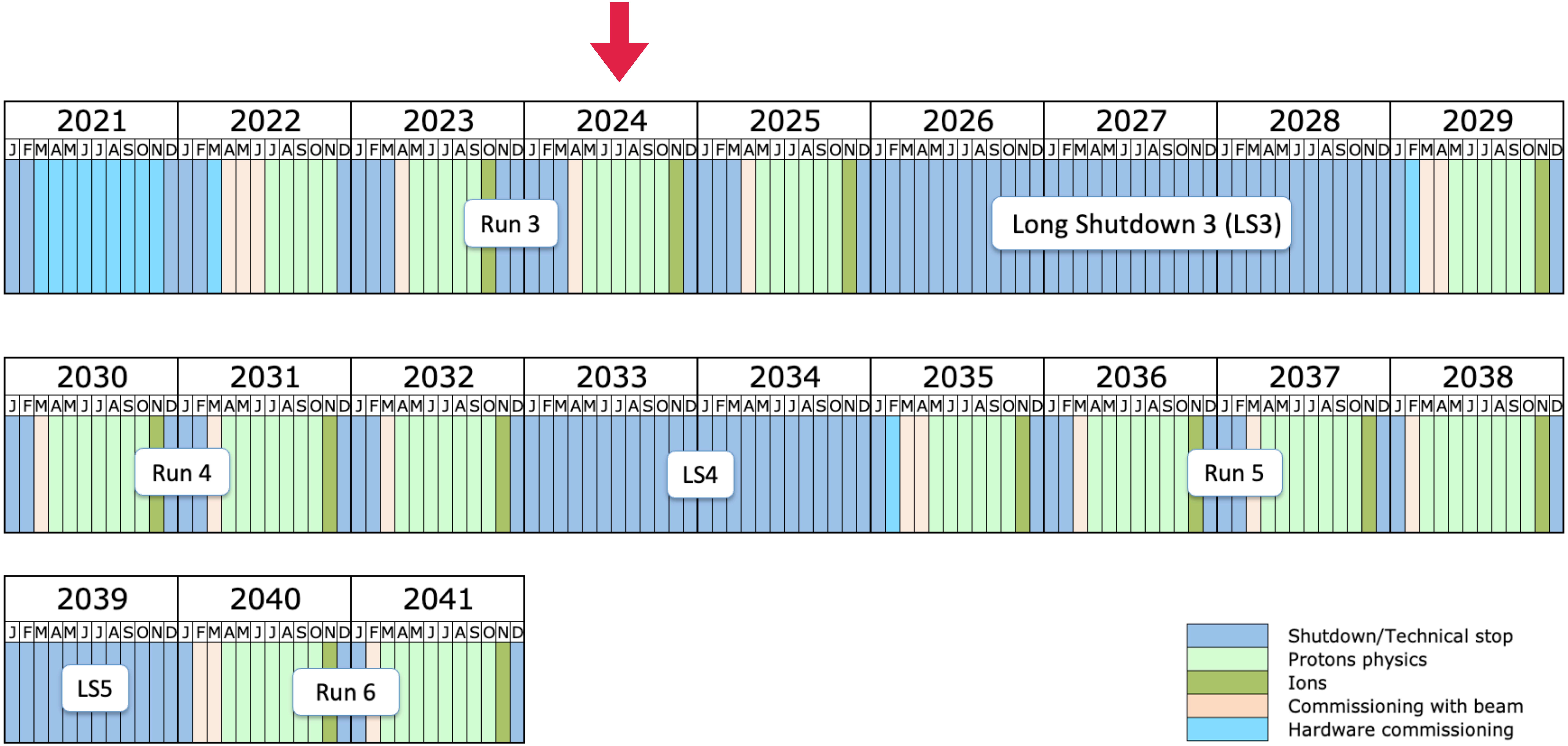
integrated luminosity: 3000 fb^{-1}, 4000 fb^{-1}

HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY · PROTOTYPES · CONSTRUCTION · INSTALLATION & COMM. · PHYSICS

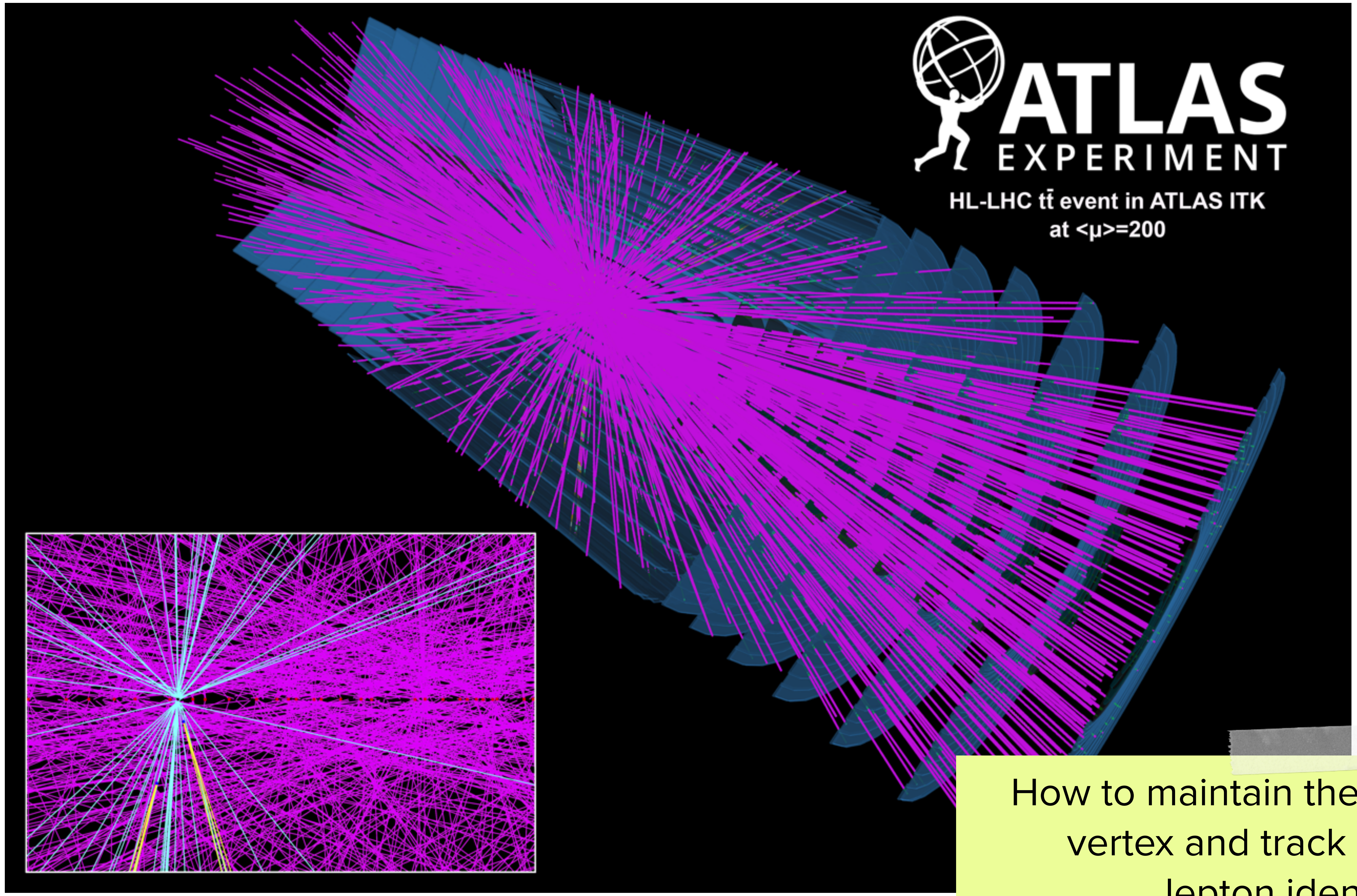
HL-LHC CIVIL ENGINEERING:

DEFINITION · EXCAVATION · BUILDINGS



Last update: April 2023

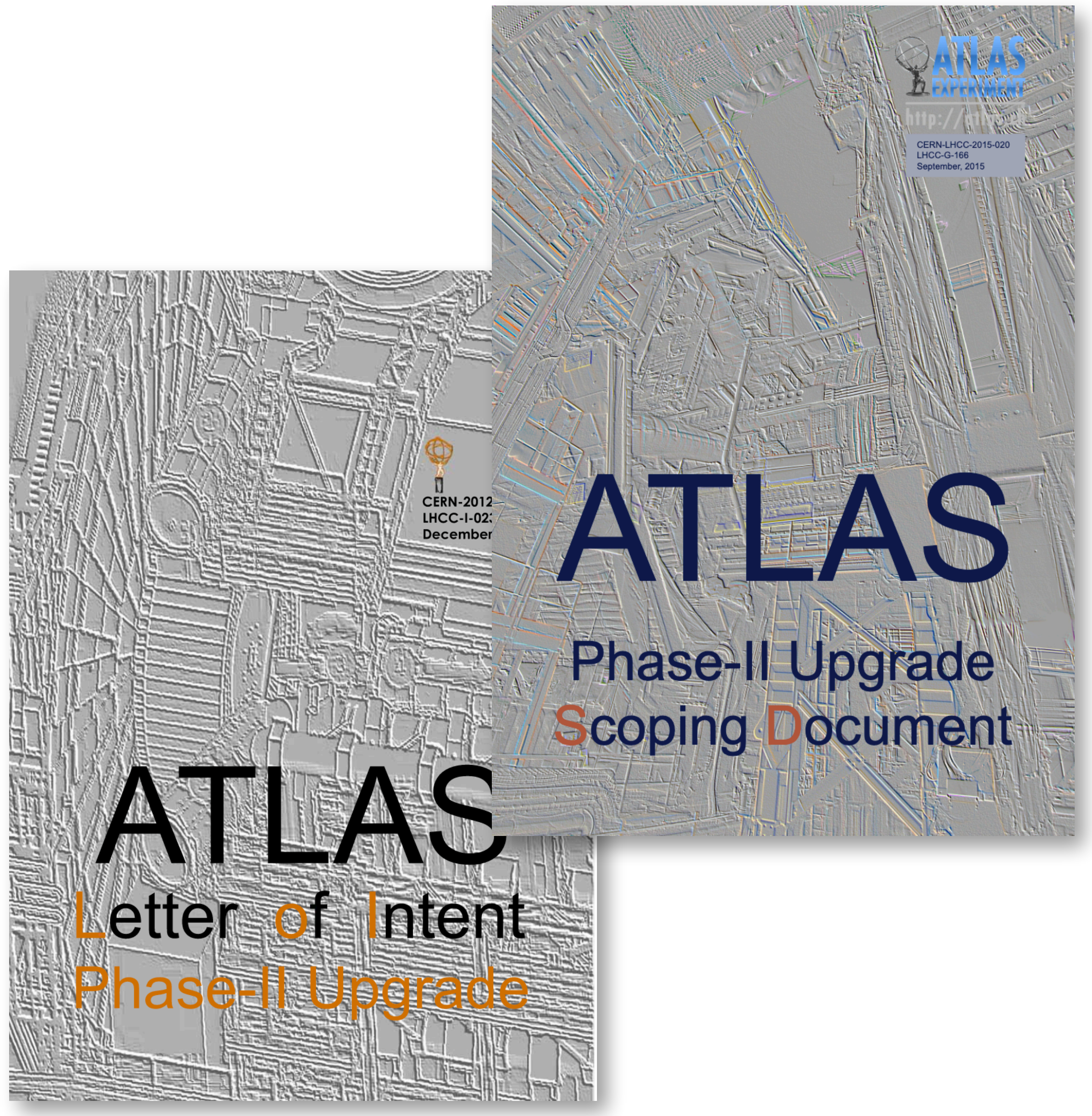
THE HL-LHC WILL BE TOUGH FOR THE DETECTORS



How to maintain the performance in
vertex and track reconstruction?
lepton identification?
heavy flavor tagging?

EVERY EXPERIMENT HAS A BATTERY OF UPGRADES

- E.g.: Three major detector upgrades for ATLAS
  - complete replacement of the inner tracking system
  - new radiation-tolerant read-out electronics for the tracking, calorimeter and muon systems
  - Trigger and Data Acquisition (TDAQ) architecture



THE DATA OF THE HL-LHC

- More than 10 extra years of running:
  - Targeting 3ab^{-1}
    - 3000fb^{-1} → to be compared with about 300fb^{-1} from Runs 1 to 3
    - 10x more events
  - Same center of mass energy, 13.6 TeV

0.5M Higgs bosons per experiment in Run 1
8M in Run 2
10M expected in Run 3
200M in HL-LHC

The High-Luminosity LHC

HiLumi
HL-LHC PROJECT

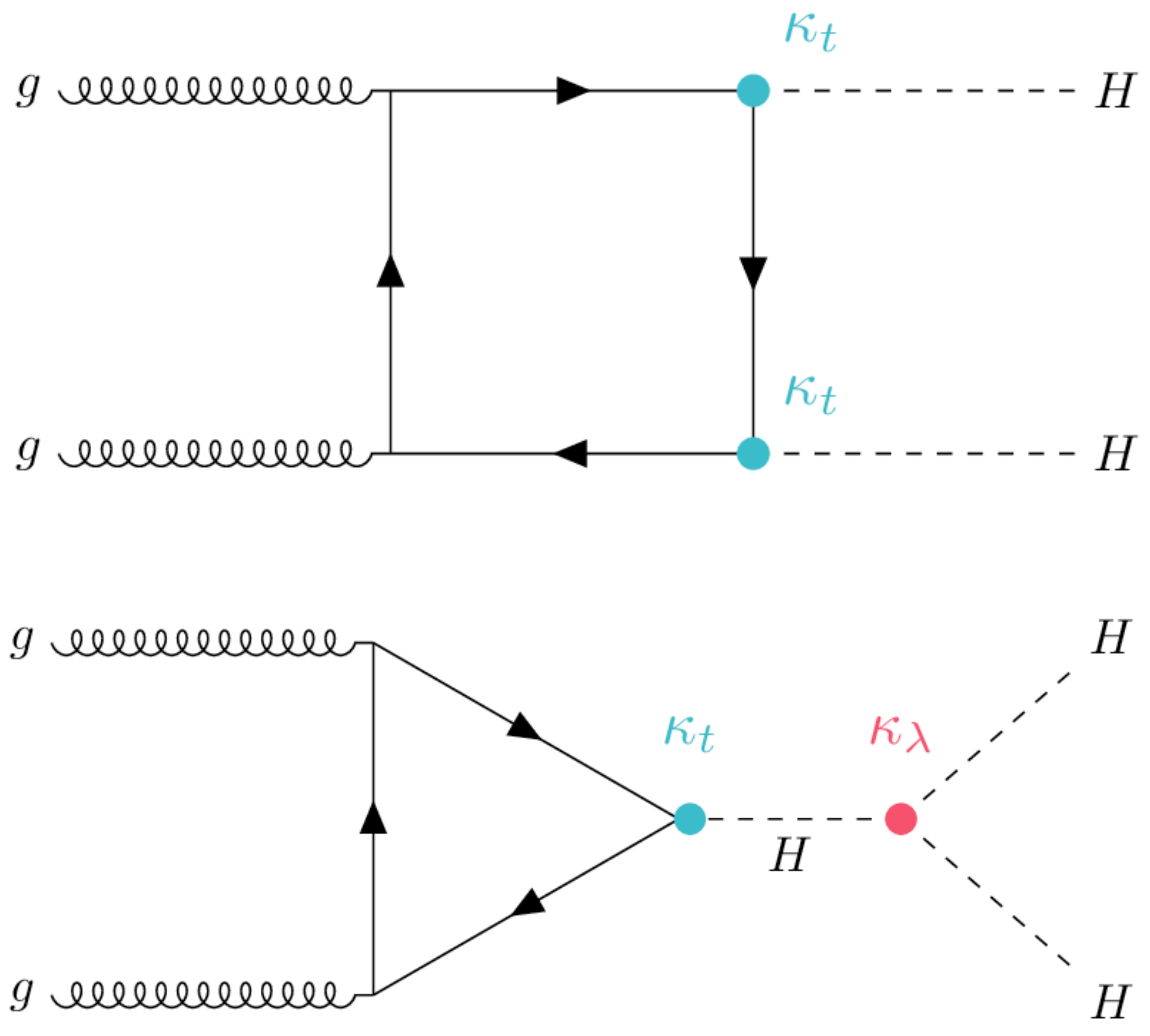

alpace.ch

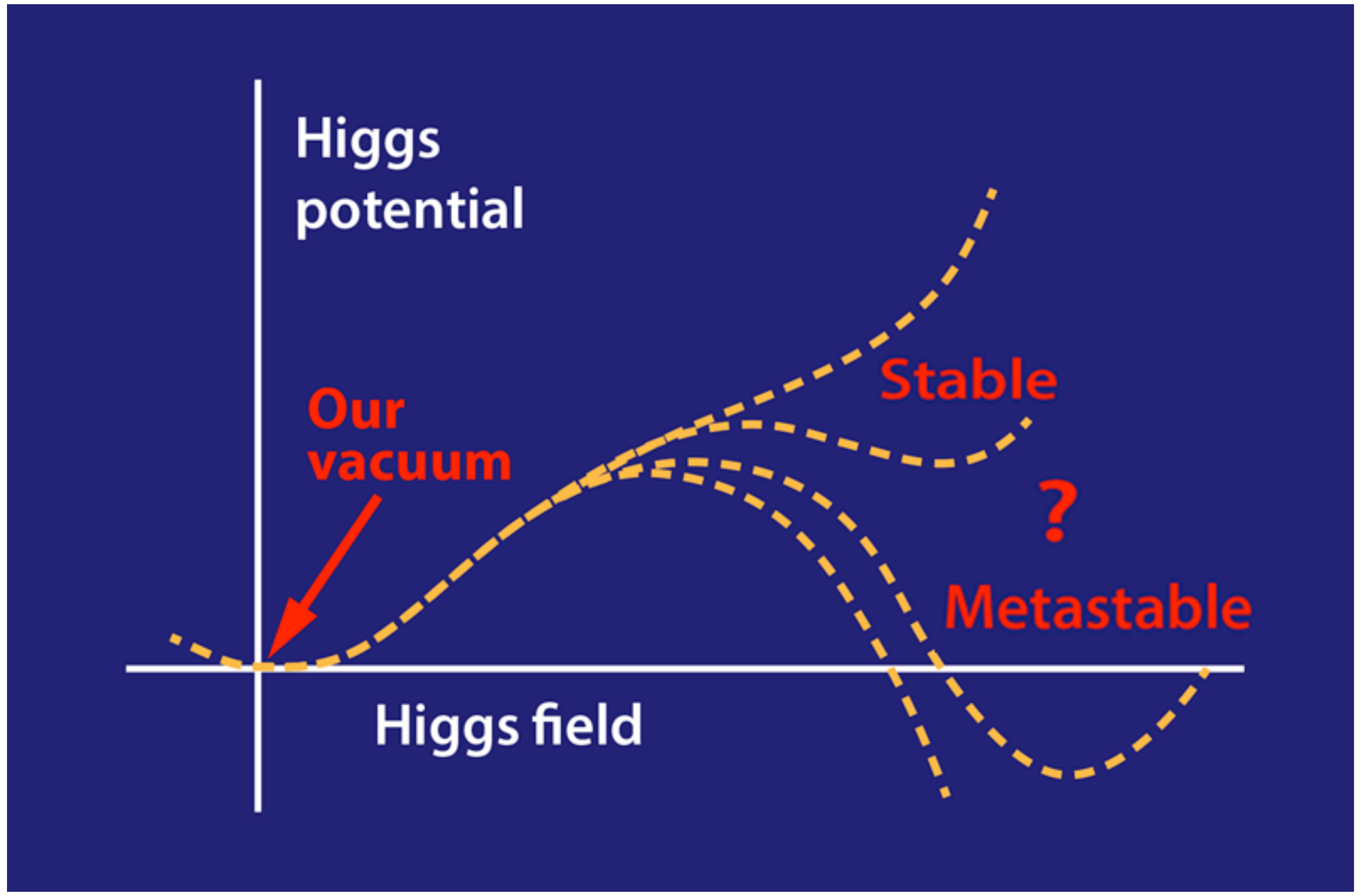

marti

THE PHYSICS CASE

OUR FIRST SHOT TO UNDERSTAND DOUBLE HIGGS PRODUCTION

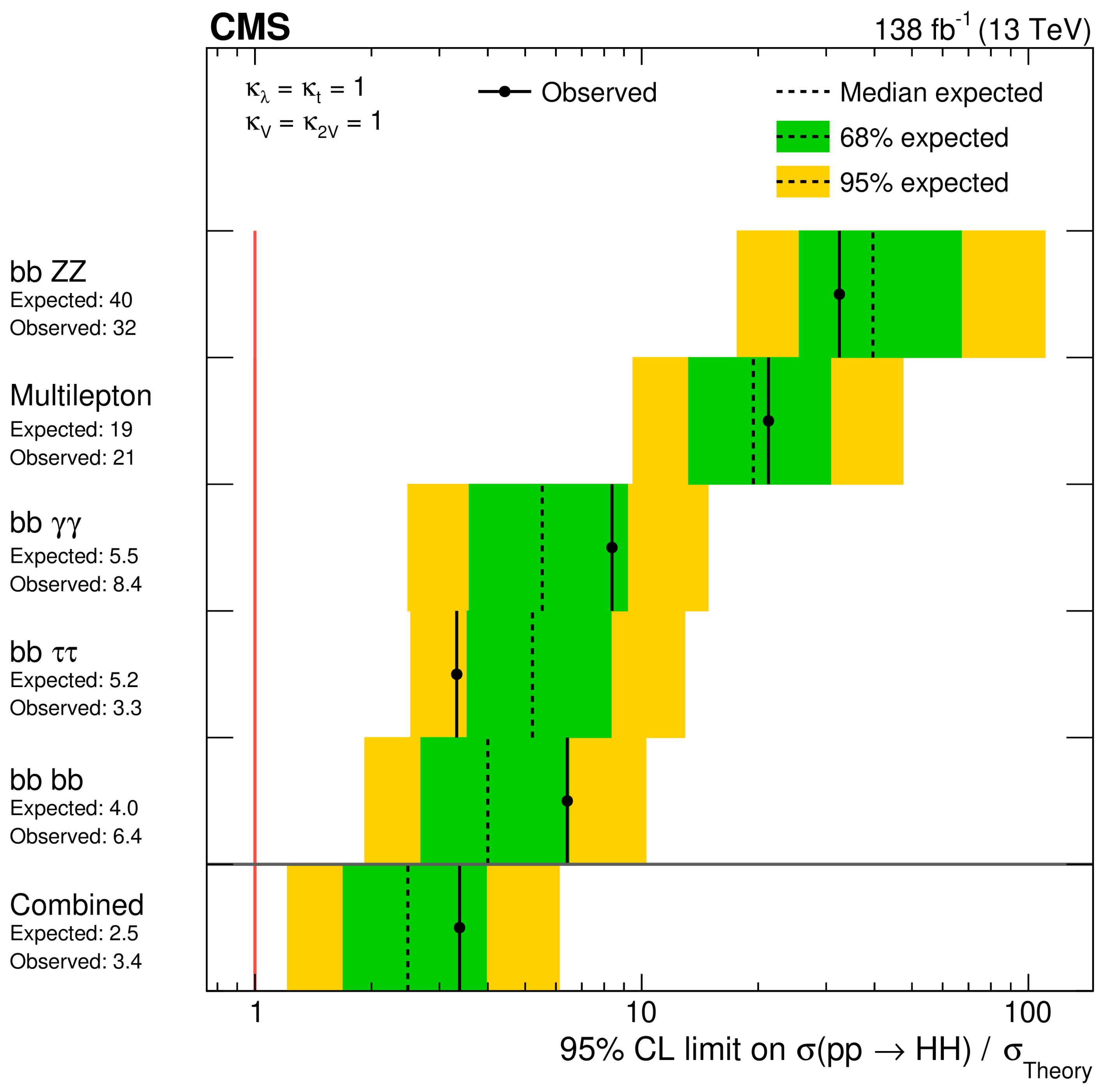
- All Higgs properties are interesting
- But di-Higgs production is particularly interesting
  - Shape of the Higgs potential (cosmological implications)

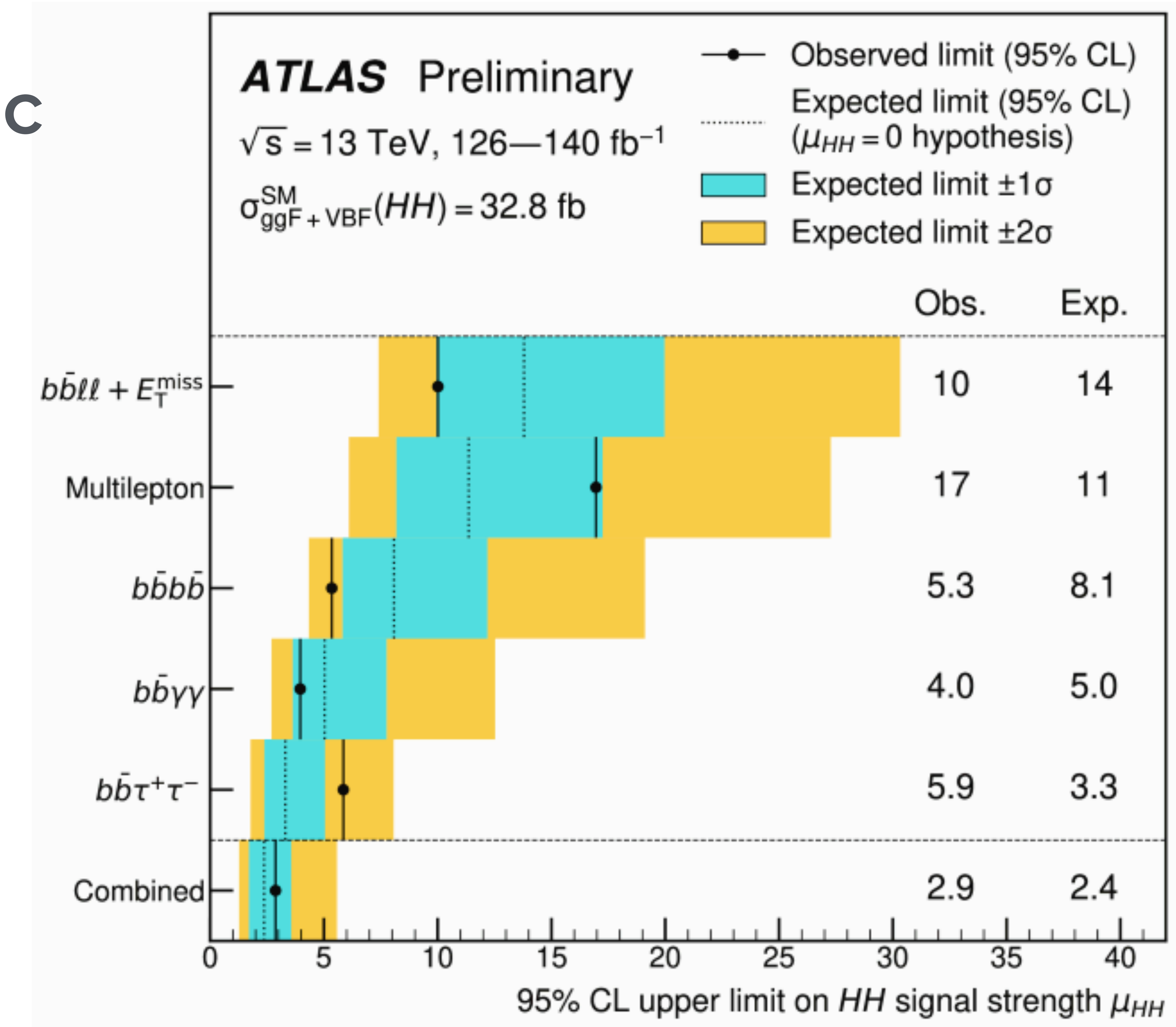




DI-HIGGS IS ONE OF THOSE THINGS

- That we thought was not possible at the LHC
- But we are getting closer every day

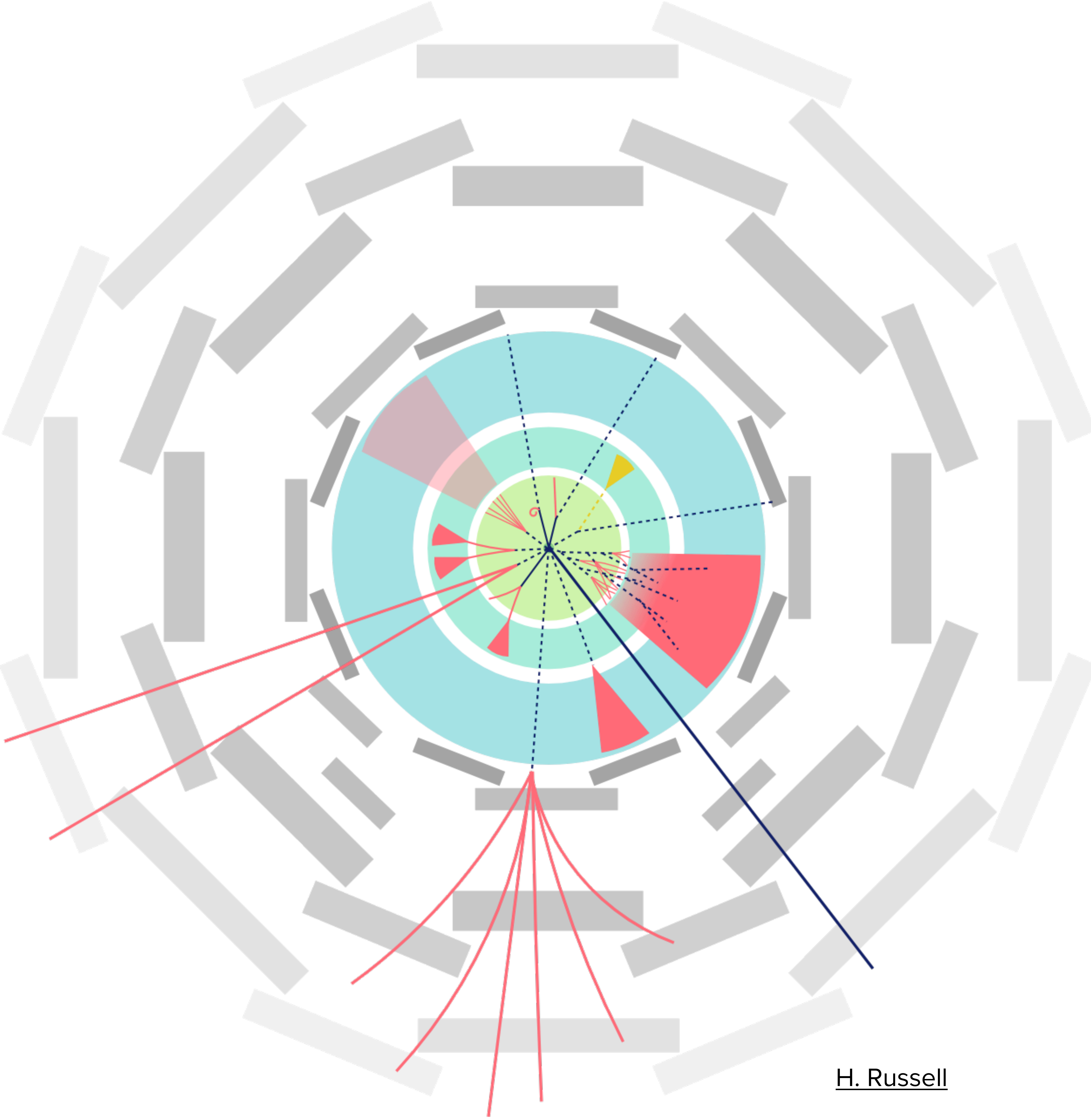




UNEXPLORED AREAS

- At the HL-LHC we will have more data
  - The opportunity to directly discover new particles and phenomena will increase
  - Especially background 0 searches

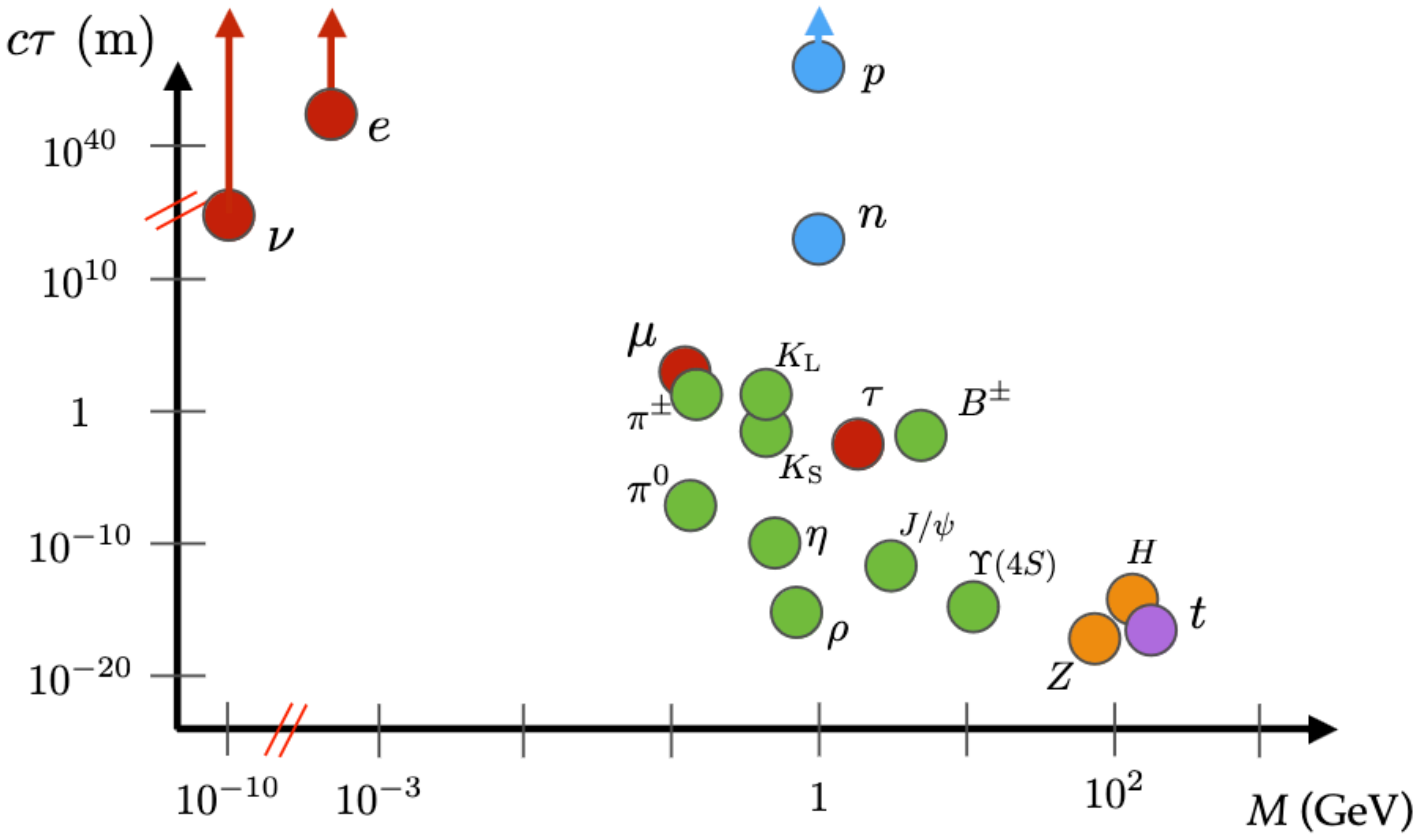
My favorite kind are searches for long-lived particles



H. Russell

ANOTHER DETOUR: LONG-LIVED PARTICLES

LONG-LIVED PARTICLES

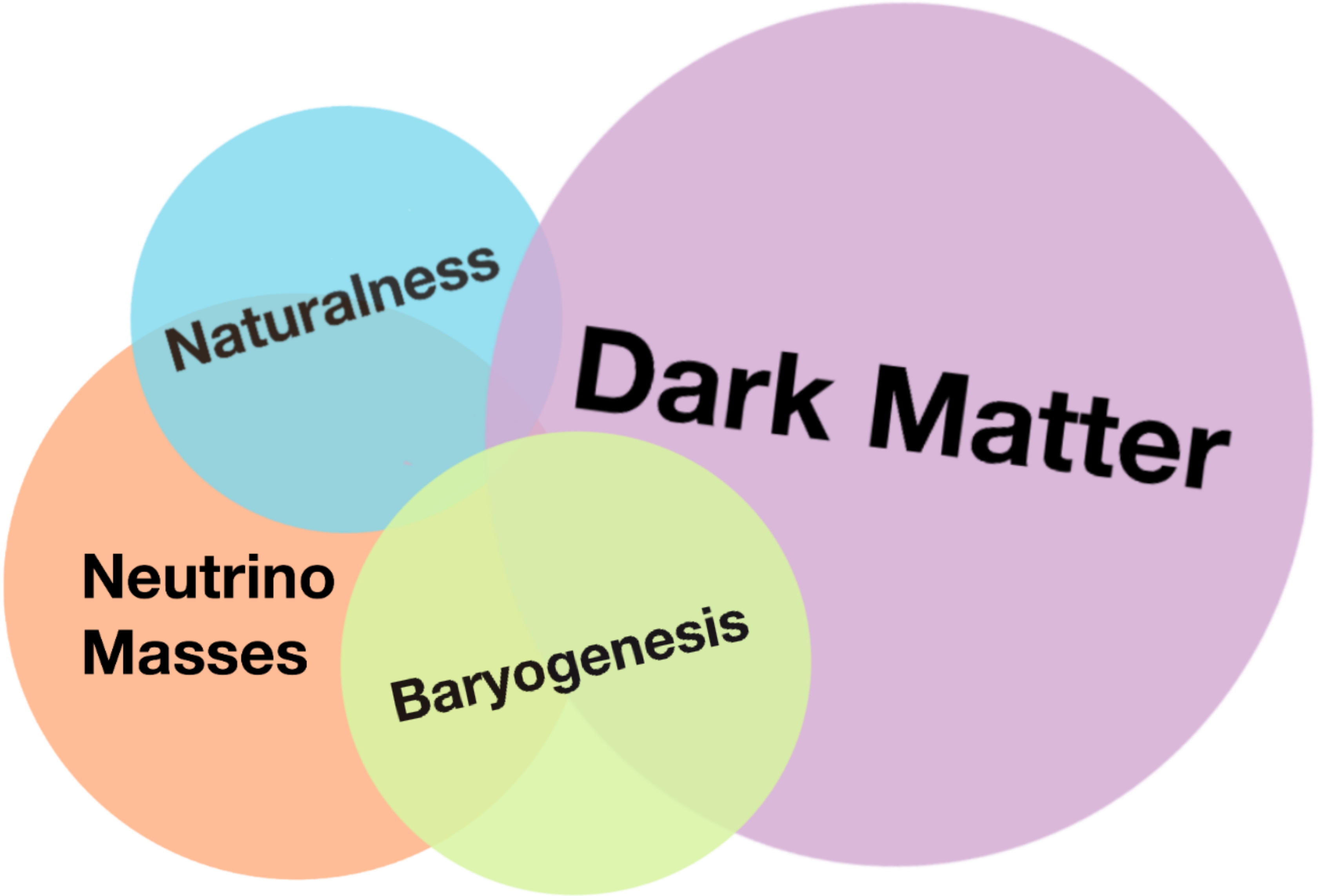


arXiv:1903.04497

- SM particles all have different lifetimes, even with similar masses
- Many of them are long-lived
  - Due to e.g. small couplings or a suppressed decay phase space
- But we use Long-lived particles (LLPs) as an umbrella term
  - New particles, that we have not discovered yet, with lifetimes long enough to travel measurable distances inside the detectors before decaying

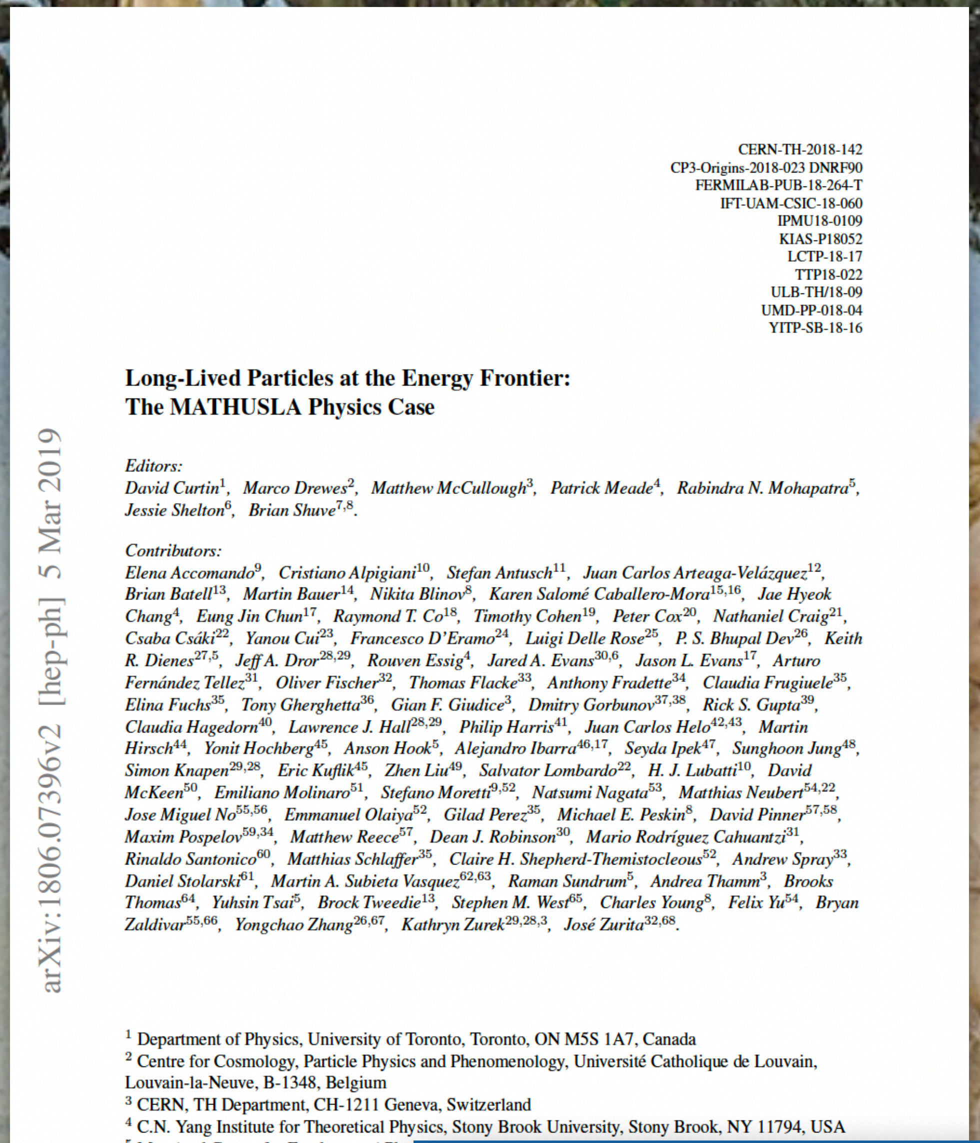
WHERE DO WE GET LLPS?

- **LLPs are a generic signature of BSM physics, connected to central questions**
  - R parity violating (RPV) and conserving (RPC) SUSY
  - Heavy Neutral leptons (right handed/sterile neutrinos)
  - Exotic Higgs decays
  - or new scalars, e.g. dark photon or Axion-Like Particles (ALPs)…
- In general, LLPs feature extensively in hidden sectors
- If light (<1 GeV) new particles exist, they must be very weakly coupled → LLPs



LLP searches have been going on for years at colliders in different ways
Looking for them is nothing new

But one could say that Long-Lived Particles are living a Renaissance



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IPMU18-0109
KIAS-P18052
LCTP-18-17
TTP18-022
ULB-TH/18-09
UMD-PP-018-04
YITP-SB-18-16

**Long-Lived Particles at the Energy Frontier:
The MATHUSLA Physics Case**

arXiv:1806.07396v2 [hep-ph] 5 Mar 2019

Editors:
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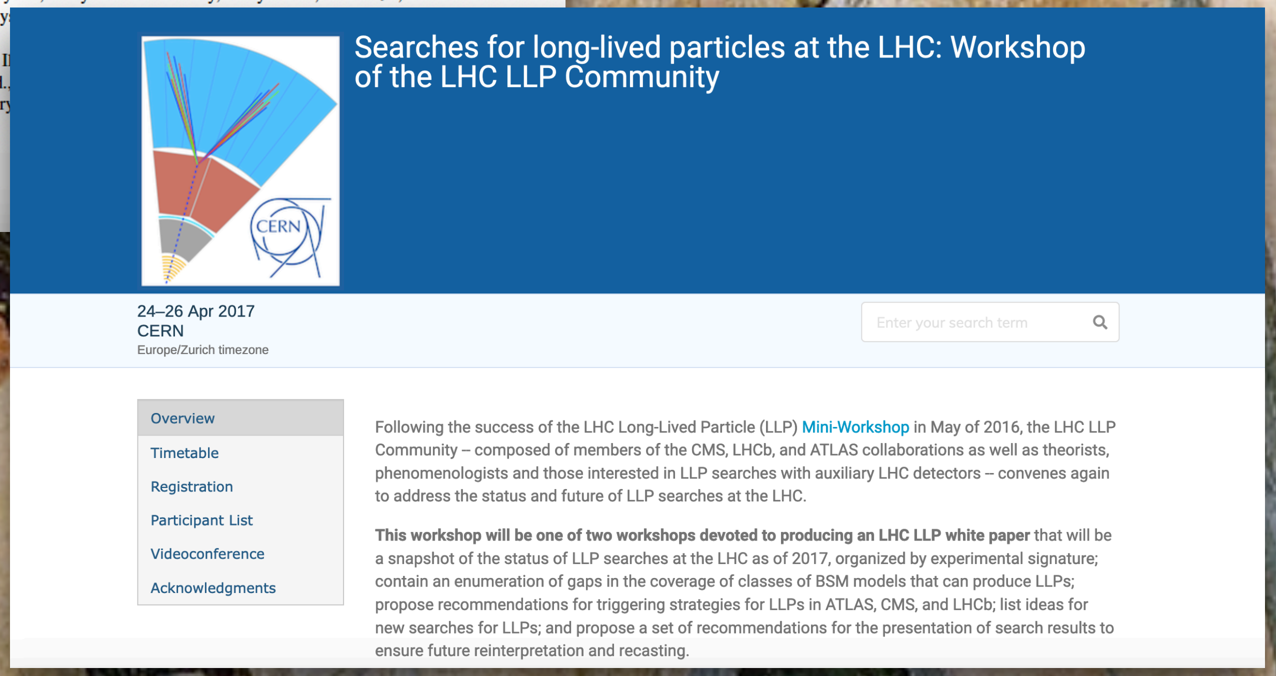
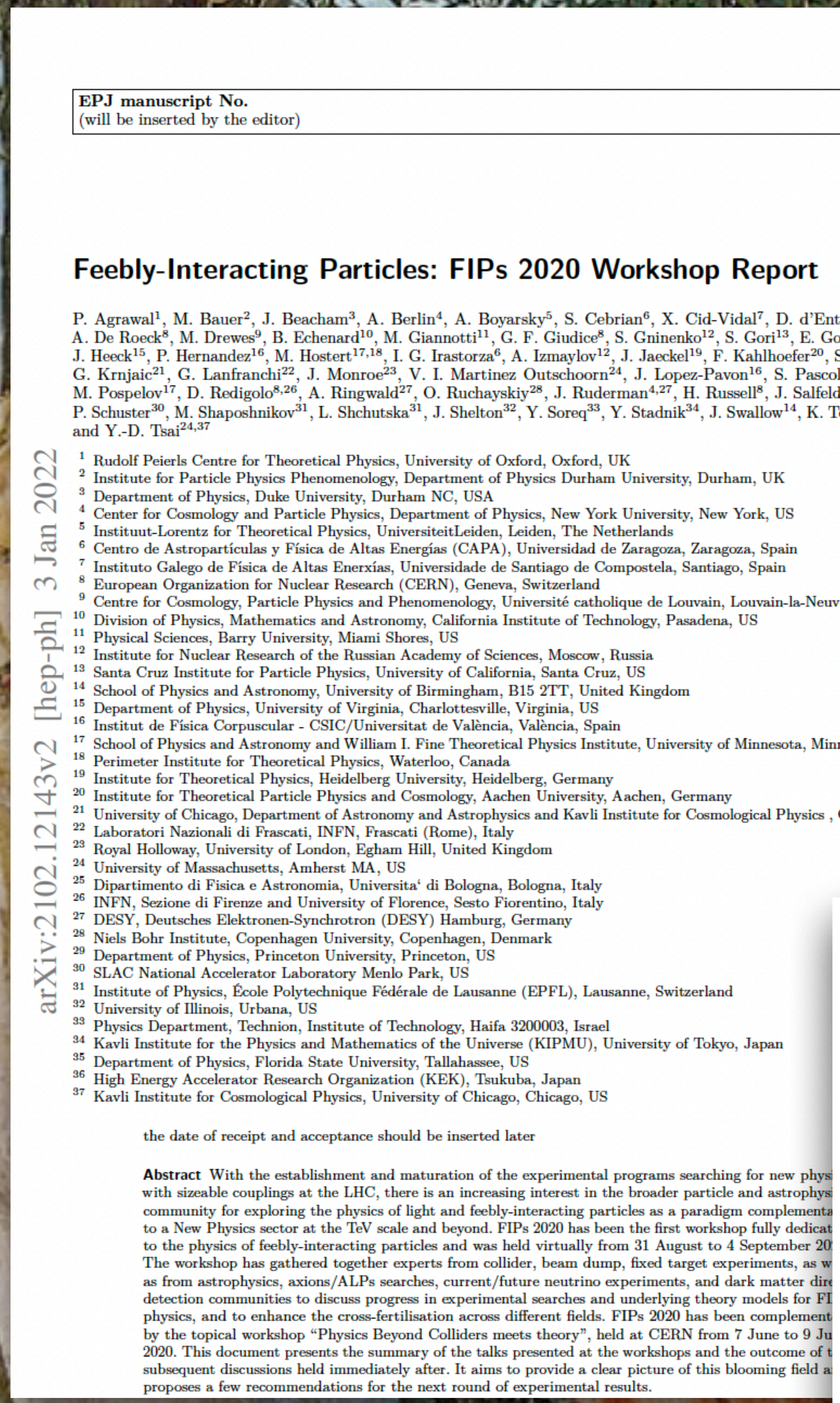


Searches for long-lived particles at the LHC: Workshop of the LHC LLP Community

24–26 Apr 2017
CERN
Europe/Zurich timezone

Following the success of the LHC Long-Lived Particle (LLP) Mini-Workshop in May of 2016, the LHC LLP Community – composed of members of the CMS, LHCb, and ATLAS collaborations as well as theorists, phenomenologists and those interested in LLP searches with auxiliary LHC detectors – convenes again to address the status and future of LLP searches at the LHC.

This workshop will be one of two workshops devoted to producing an LHC LLP white paper that will be a snapshot of the status of LLP searches at the LHC as of 2017, organized by experimental signature; contain an enumeration of gaps in the coverage of classes of BSM models that can produce LLPs; propose recommendations for triggering strategies for LLPs in ATLAS, CMS, and LHCb; list ideas for new searches for LLPs; and propose a set of recommendations for the presentation of search results to ensure future reinterpretation and recasting.



EPJ manuscript No.
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Feebly-Interacting Particles: FIPs 2020 Workshop Report

arXiv:2102.12143v2 [hep-ph] 3 Jan 2022

P. Agrawal[1], M. Bauer[2], J. Beacham[3], A. Berlin[4], A. Boyarsky[5], S. Cebrian[6], X. Cid-Vidal[7], D. d'Enterria[8], A. De Roeck[8], M. Drewes[9], B. Echenard[10], M. Giannotti[11], G. F. Giudice[8], S. Gninenko[12], S. Gori[13], E. Goudzovski[14], J. Heeck[15], P. Hernandez[16], M. Hostert[17,18], I. G. Irastorza[6], A. Izmaylov[12], J. Jaeckel[19], F. Kahlhoefer[20], S. Knapen[8], G. Krnjaic[21], G. Lanfranchi[22], J. Monroe[23], V. I. Martinez Outschoorn[24], J. Lopez-Pavon[16], S. Pascoli[2,25], M. Pospelov[17], D. Redigolo[8,26], A. Ringwald[27], O. Ruchayskiy[28], J. Ruderman[4,27], H. Russell[8], J. Salfeld-Nebgen[29], P. Schuster[30], M. Shaposhnikov[31], L. Shchutska[31], J. Shelton[32], Y. Soreq[33], Y. Stadnik[34], J. Swallow[14], K. Tobioka[35,36], and Y.-D. Tsai[24,37]

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the date of receipt and acceptance should be inserted later

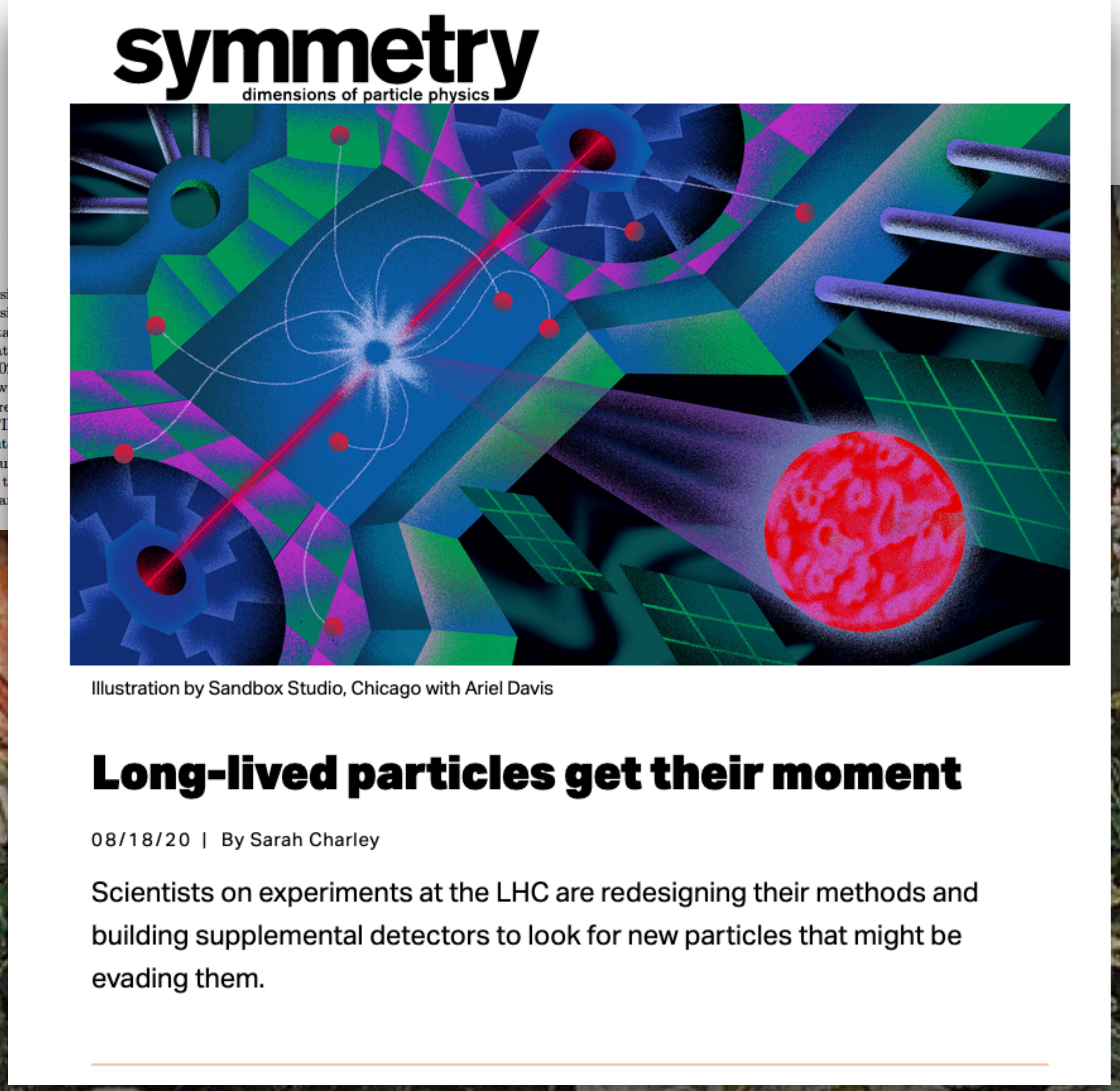
Abstract With the establishment and maturation of the experimental programs searching for new phys
with sizeable couplings at the LHC, there is an increasing interest in the broader particle and astrophys
community for exploring the physics of light and feebly-interacting particles as a paradigm complementa
to a New Physics sector at the TeV scale and beyond. FIPs 2020 has been the first workshop fully dedicat
to the physics of feebly-interacting particles and was held virtually from 31 August to 4 September 20
The workshop has gathered together experts from collider, beam dump, fixed target experiments, as w
as from astrophysics, axions/ALPs searches, current/future neutrino experiments, and dark matter dir
detection communities to discuss progress in experimental searches and underlying theory models for FI
physics, and to enhance the cross-fertilisation across different fields. FIPs 2020 has been complement
by the topical workshop "Physics Beyond Colliders meets theory", held at CERN from 7 June to 9 Ju
2020. This document presents the summary of the talks presented at the workshops and the outcome of t
subsequent discussions held immediately after. It aims to provide a clear picture of this blooming field a
proposes a few recommendations for the next round of experimental results.

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

March 6, 2019

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly decaying particles that are targeted by the majority of searches for new physics at the LHC, often requiring customized techniques to identify, for example, significantly displaced decay vertices, tracks with atypical properties, and short track segments. Given their non-standard nature, a comprehensive overview of LLP signatures at the LHC is beneficial to ensure that possible avenues of the discovery of new physics are not overlooked. Here we report on the joint work of a community of theorists and experimentalists with the ATLAS, CMS, and LHCb experiments — as well as those working on dedicated experiments such as MoEDAL, milliQan, MATHUSLA, CODEX-b, and FASER — to survey the current state of LLP searches at the LHC, and to chart a path for the development of LLP searches into the future, both in the upcoming Run 3 and at the High-Luminosity LHC. The work is organized around the current and future potential capabilities of LHC experiments to generally discover new LLPs, and takes a signature-based approach to surveying classes of models that give rise to LLPs rather than emphasizing any particular theory motivation. We develop a set of simplified models; assess the coverage of current searches; document known, often unexpected backgrounds; explore the capabilities of proposed detector upgrades; provide recommendations for the presentation of search results; and look towards the newest frontiers, namely high-multiplicity "dark showers", highlighting opportunities for expanding the LHC reach for these signals.

Editors:
Juliette Alimena(1) (Experimental Coverage, Backgrounds, Upgrades), James Beacham(2) (Document Editor, Simplified Models), Martino Borsato(3) (Backgrounds, Upgrades), Yangyang Cheng(4) (Upgrades), Xabier Cid Vidal(5) (Experimental Coverage), Giovanna Cottin(6) (Simplified Models, Reinterpretations), Albert De Roeck(7) (Experimental Coverage), Nishita Desai(8) (Reinterpretations), David Curtin(9) (Simplified Models), Jared A. Evans(10) (Simplified Models, Experimental Coverage), Simon Knapen(11) (Dark Showers), Sabine Kraml(12) (Reinterpretations), Andre Lessa(13) (Reinterpretations), Zhen Liu(14) (Simplified Models, Backgrounds, Reinterpretations), Sascha Mehlhase(15) (Backgrounds), Michael J. Ramsey-Musolf(16,126) (Simplified Models), Heather Russell(17) (Experimental Coverage), Jessie Shelton(18) (Simplified Models, Dark Showers), Brian Shuve(19,20) (Document Editor, Simplified Models, Simplified Models Library), Monica Verducci(21) (Upgrades), Jose Zurita(22,23) (Experimental Coverage)



symmetry
dimensions of particle physics

Illustration by Sandbox Studio, Chicago with Ariel Davis

Long-lived particles get their moment

08/18/20 | By Sarah Charley

Scientists on experiments at the LHC are redesigning their methods and building supplemental detectors to look for new particles that might be evading them.

---

matches for "long-lived" in the indico agenda
ICHEP 2012: 11
ICHEP 2022: 53

WHY IS THIS HAPPENING?

- There are a few reasons for why LLPs are so interesting nowadays:
  - Searches for LLPs cover intermediate areas, gaps of sensitivity between experiments (eg. dark matter searches between colliders and astro)
  - They address the lack of prompt BSM signals → providing accessible new areas where BSM could be hiding
  - LLP searches offer us the opportunity to think outside the box, to be creative and to propose new ways to solve problems
    - Innovation: in methods and experimental setups

AT HIGHER ENERGIES

- We gain access to more massive particles that in turn tend to be shorter-lived

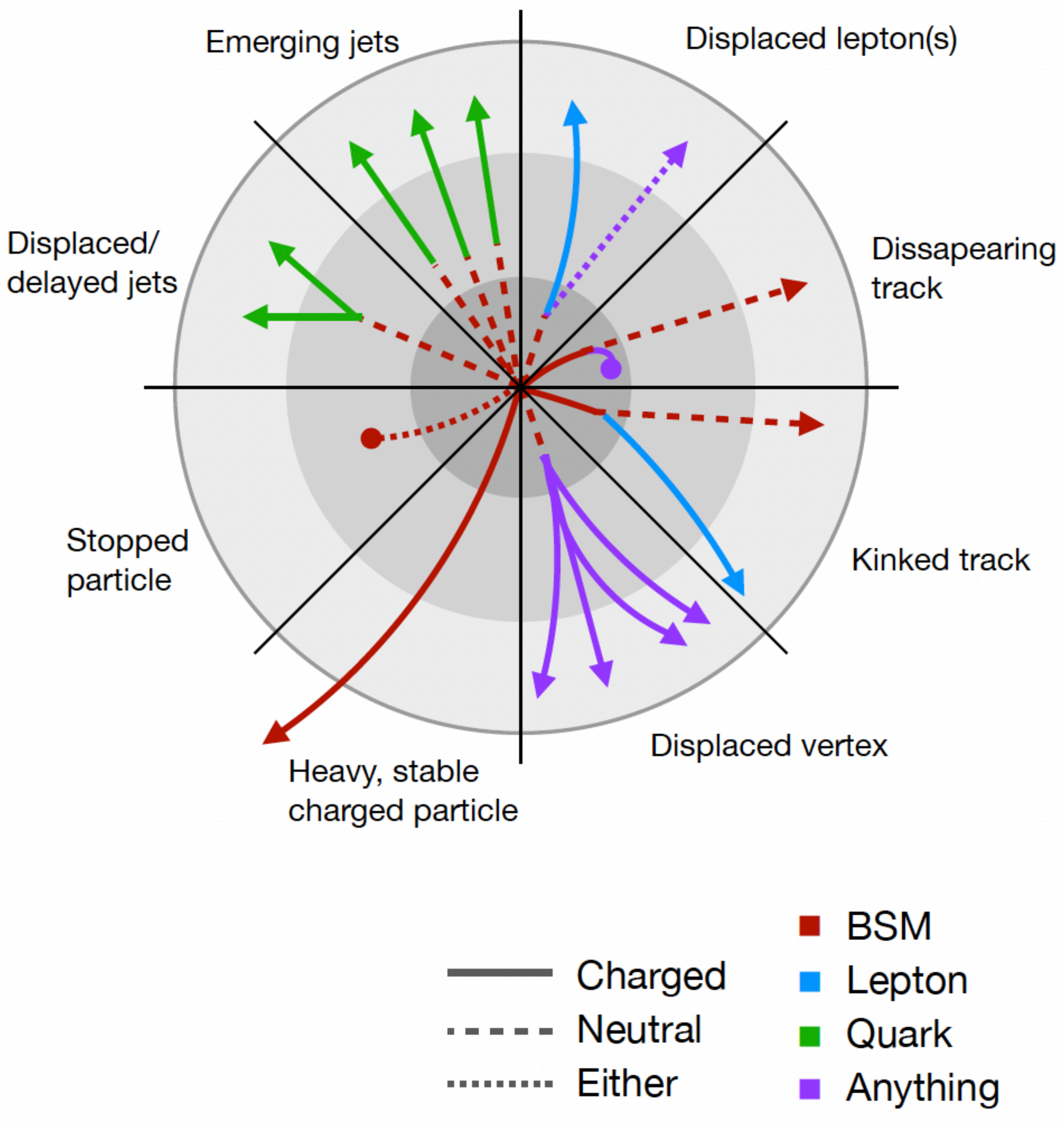
Main offenders

The Higgs boson
2012 - LHC
Sort-Lived
10^{-22} seconds
You blink and you miss it!

The top quark
1995 - Tevatron
Sort-Lived
10^{-25} seconds
So short-lived it does not even have time to form hadrons!

- And we naturally optimize our detectors, trigger, and reconstruction methods to find them
  - LLPs could be regularly produced in collisions and we wouldn't know it
- LLPs produce unconventional signatures in colliders
  - clearly different from other processes (easy to spot!), but potentially invisible to current data-acquisition methods → we could be throwing them away

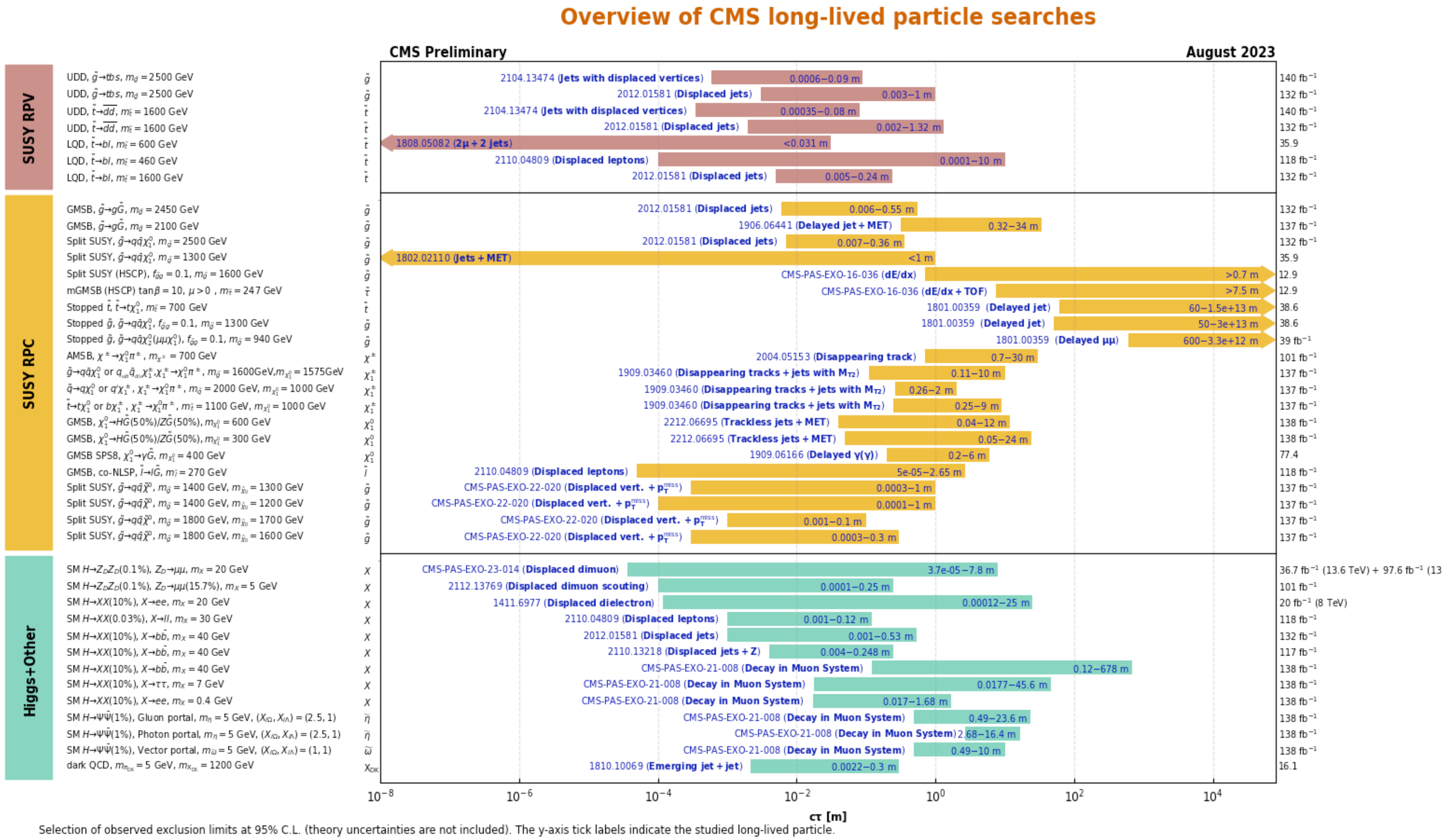
NON-STANDARD EXPERIMENTAL SIGNATURES

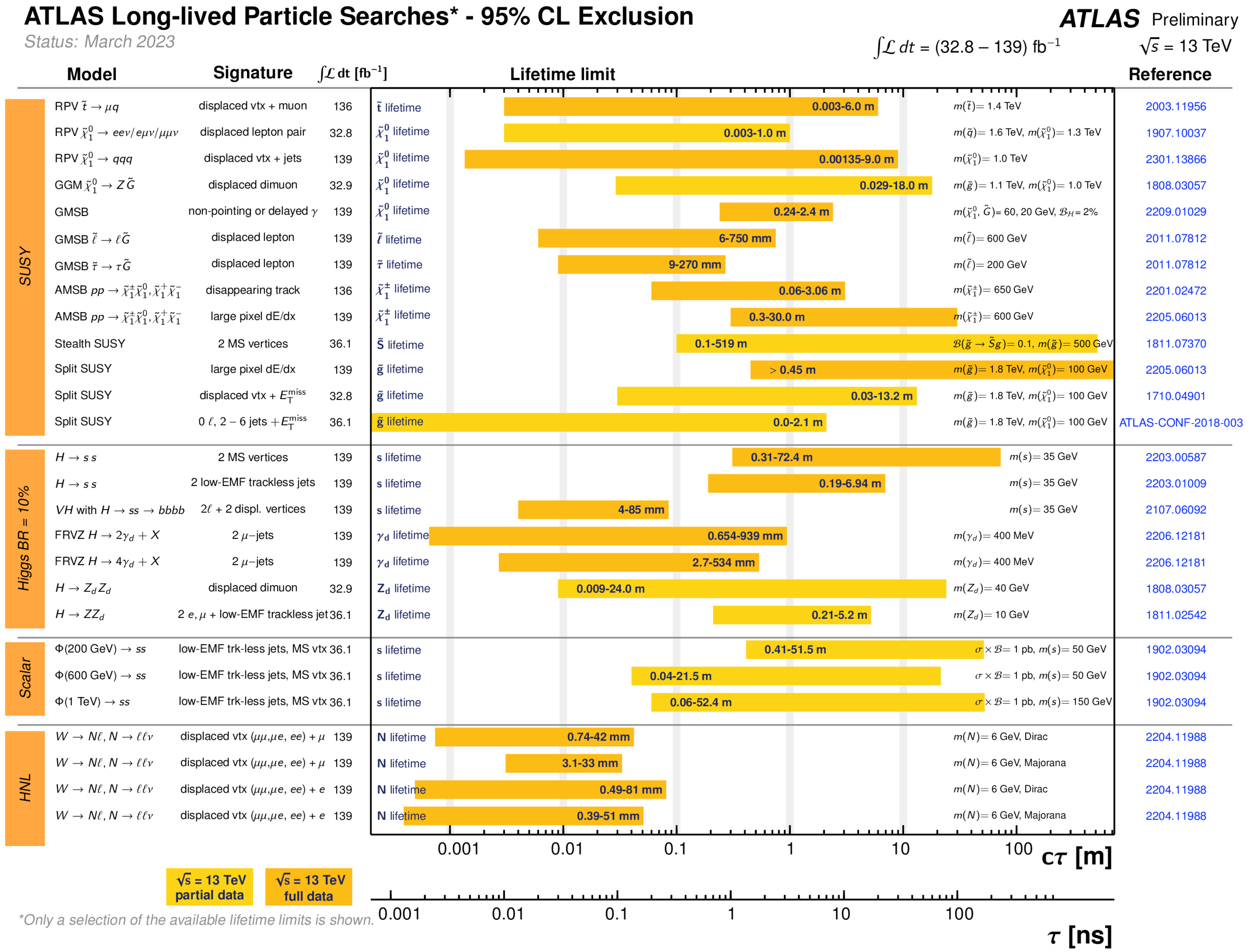


- We are talking about
  - displaced and/or delayed objects (leptons, photons, jets); disappearing tracks; nonstandard tracks produced by monopoles, quirks or heavy stable charged particles (HSCPs); nonstandard jets produced in dark showers…
- LLP analyses at the LHC experiments:
  - require customisation: dedicated triggers, object reconstruction, background estimation and in general analysis methods
  - are affected by challenging backgrounds near the collision points → motivate dedicated experiments

ATLAS AND CMS

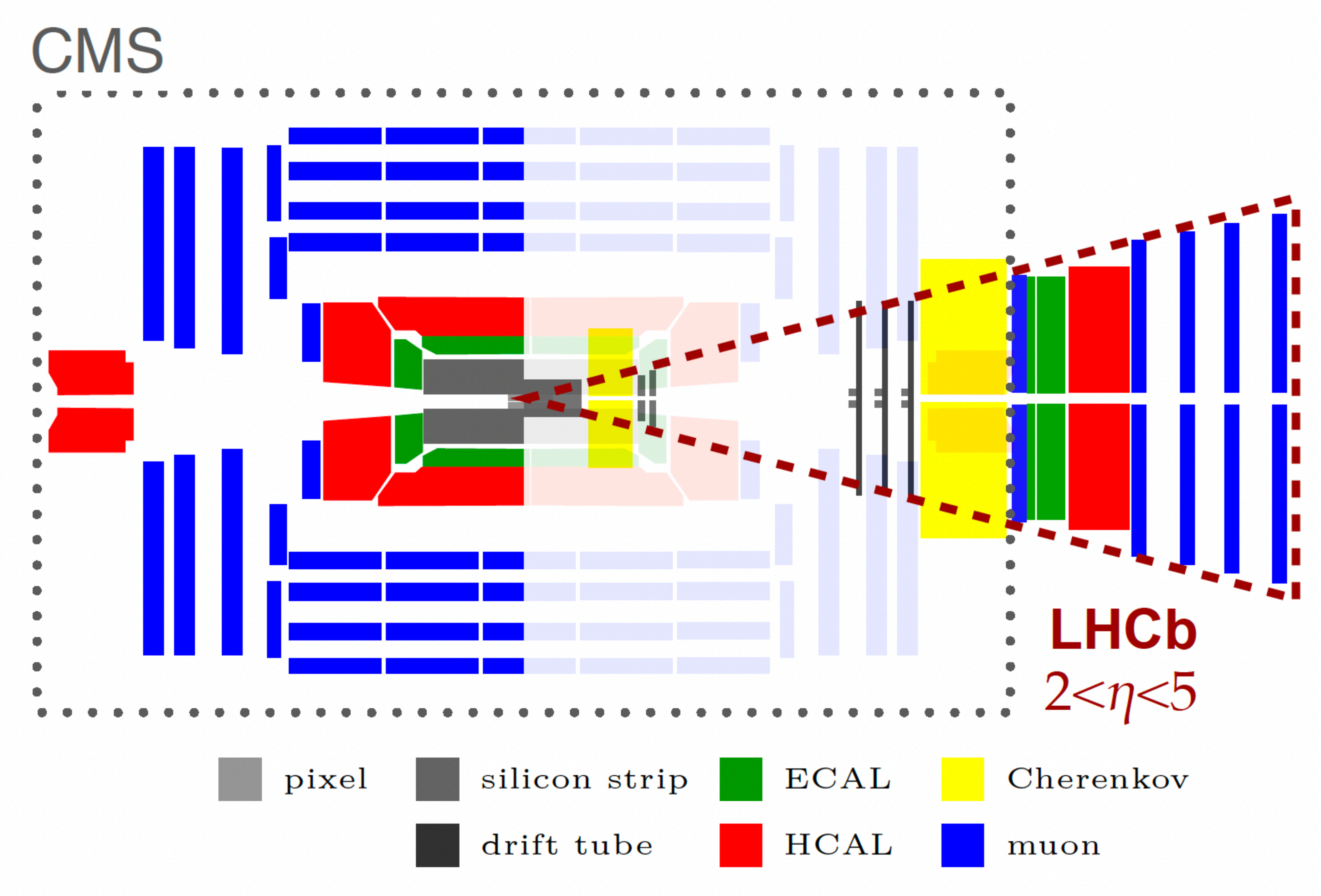
- Vibrant scene of long-lived searches in the exotics and SUSY groups

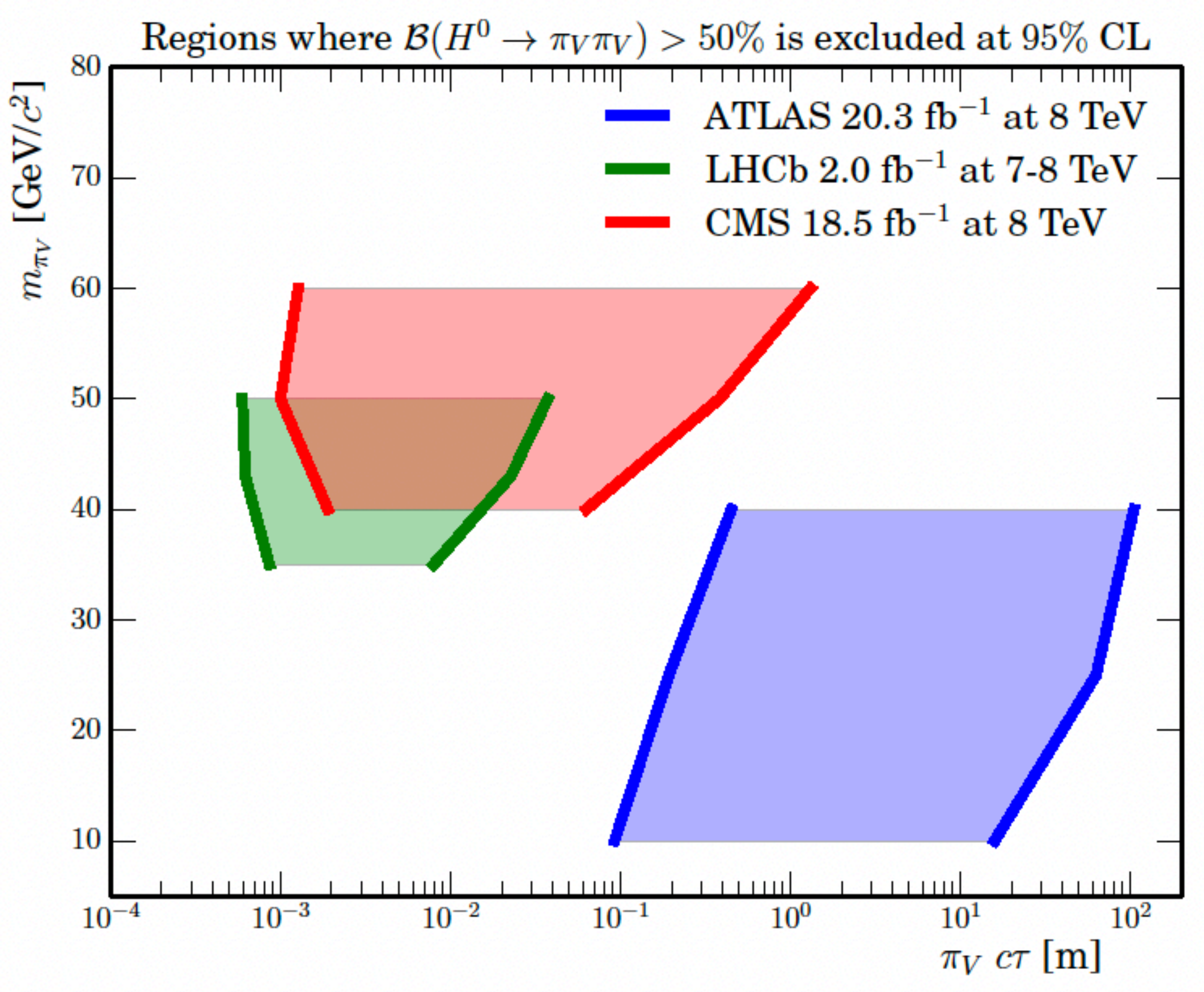




LHCb

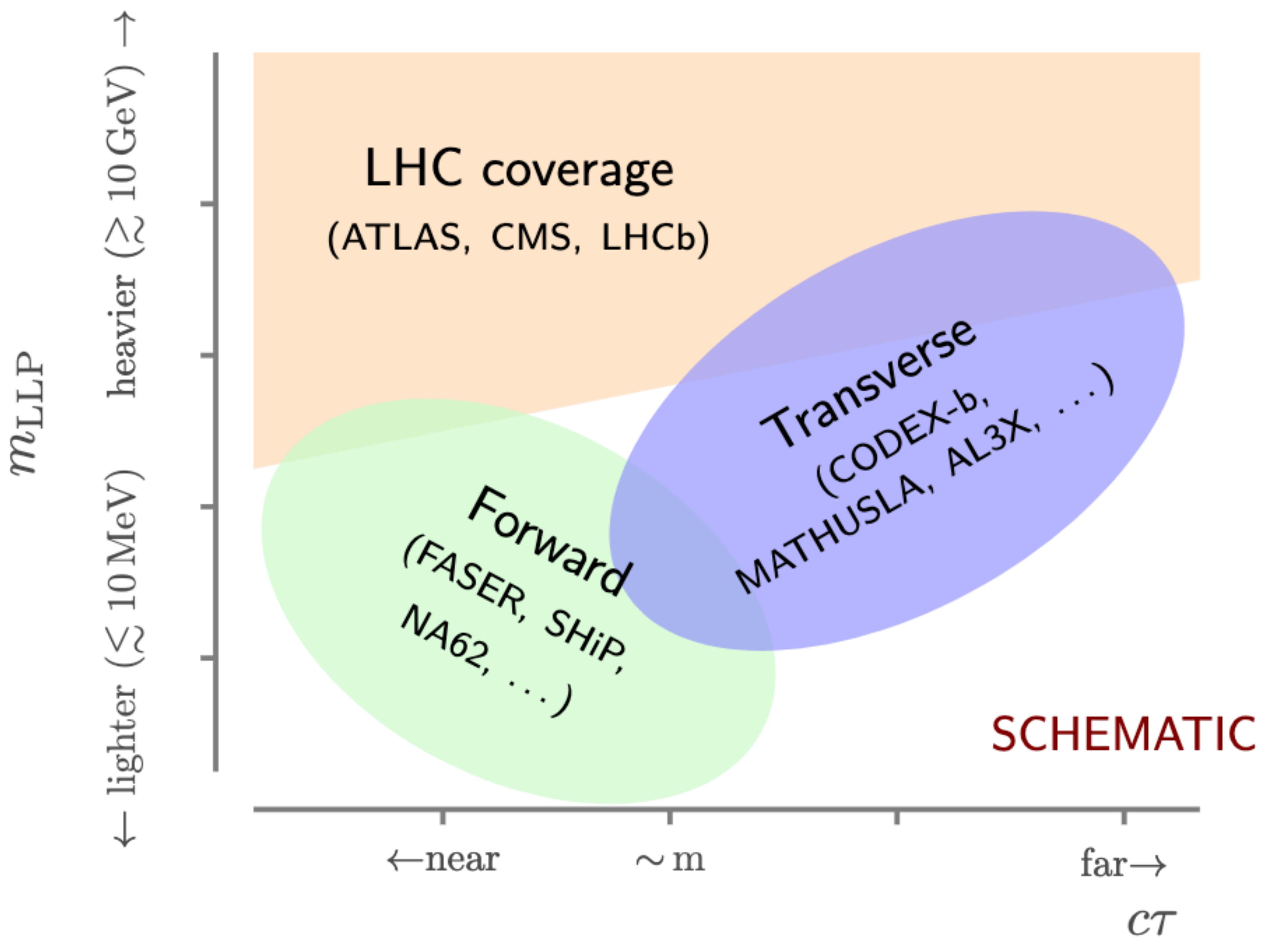
- Existing results on dark photons, exotic Higgs decays, HNLs…
- Complementary coverage to ATLAS and CMS
- First fully GPU trigger in HEP opens new possibility for LLPs

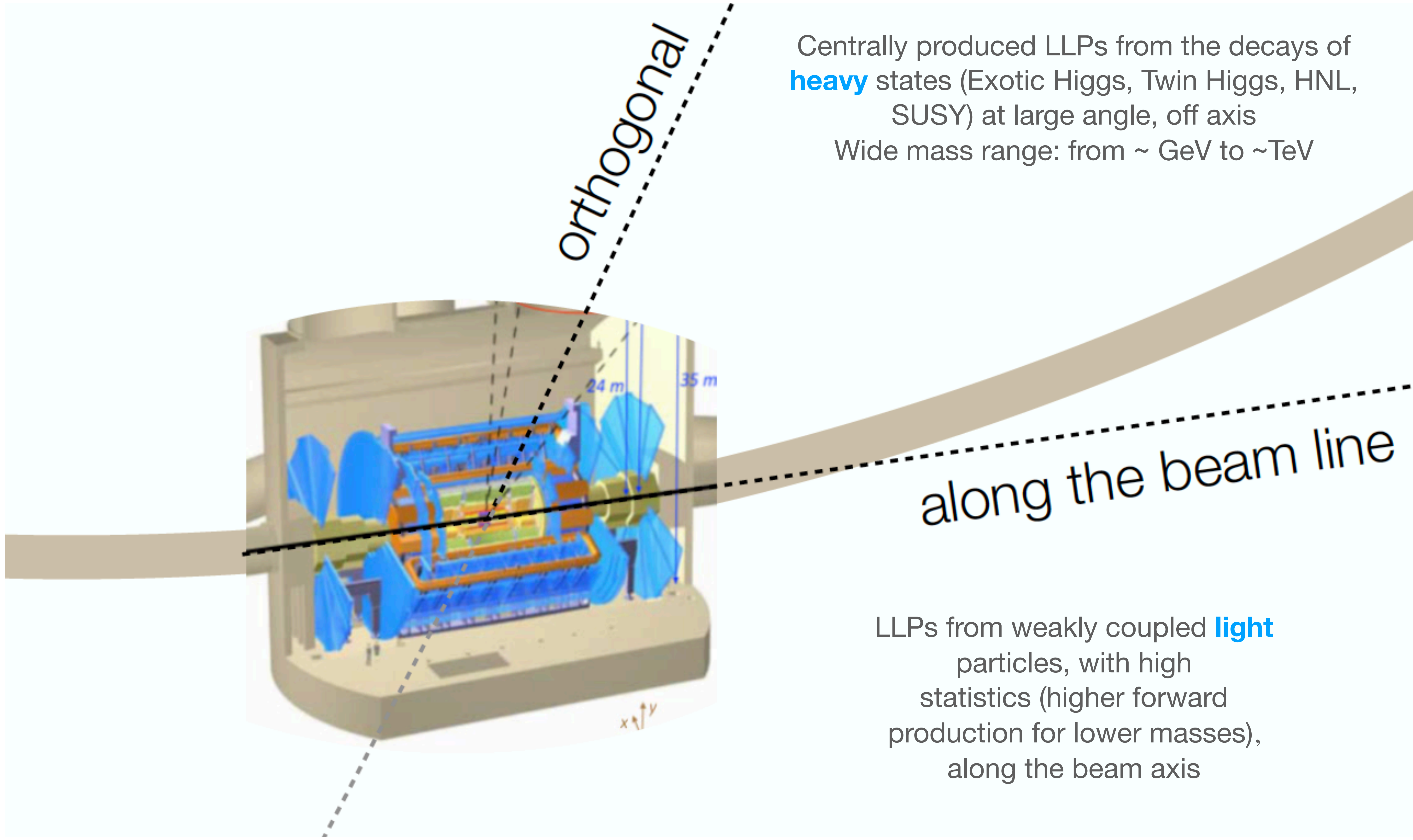




THINKING OUTSIDE THE LHC DETECTORS

- We can supplement them with external detectors optimized for LLPs
  - Access to longer decay lengths
  - Less background (shielding)
  - Easy trigger (or trigger-less)





Centrally produced LLPs from the decays of **heavy** states (Exotic Higgs, Twin Higgs, HNL, SUSY) at large angle, off axis
Wide mass range: from ~ GeV to ~TeV

LLPs from weakly coupled **light** particles, with high statistics (higher forward production for lower masses), along the beam axis

THERE ARE MANY EXPERIMENTS

Running

FASER

MAPP
MoEDAL

NA62
P326

LHC
Scattering and Neutrino Detector
at the LHC

THE MILLIQAN EXPERIMENT

Proposed

MATHUSLA

SHiP
Search for Hidden Particles

CODEX-b

FPF
Forward Physics Facility

AL3X ANUBIS

SHADOWS FACET

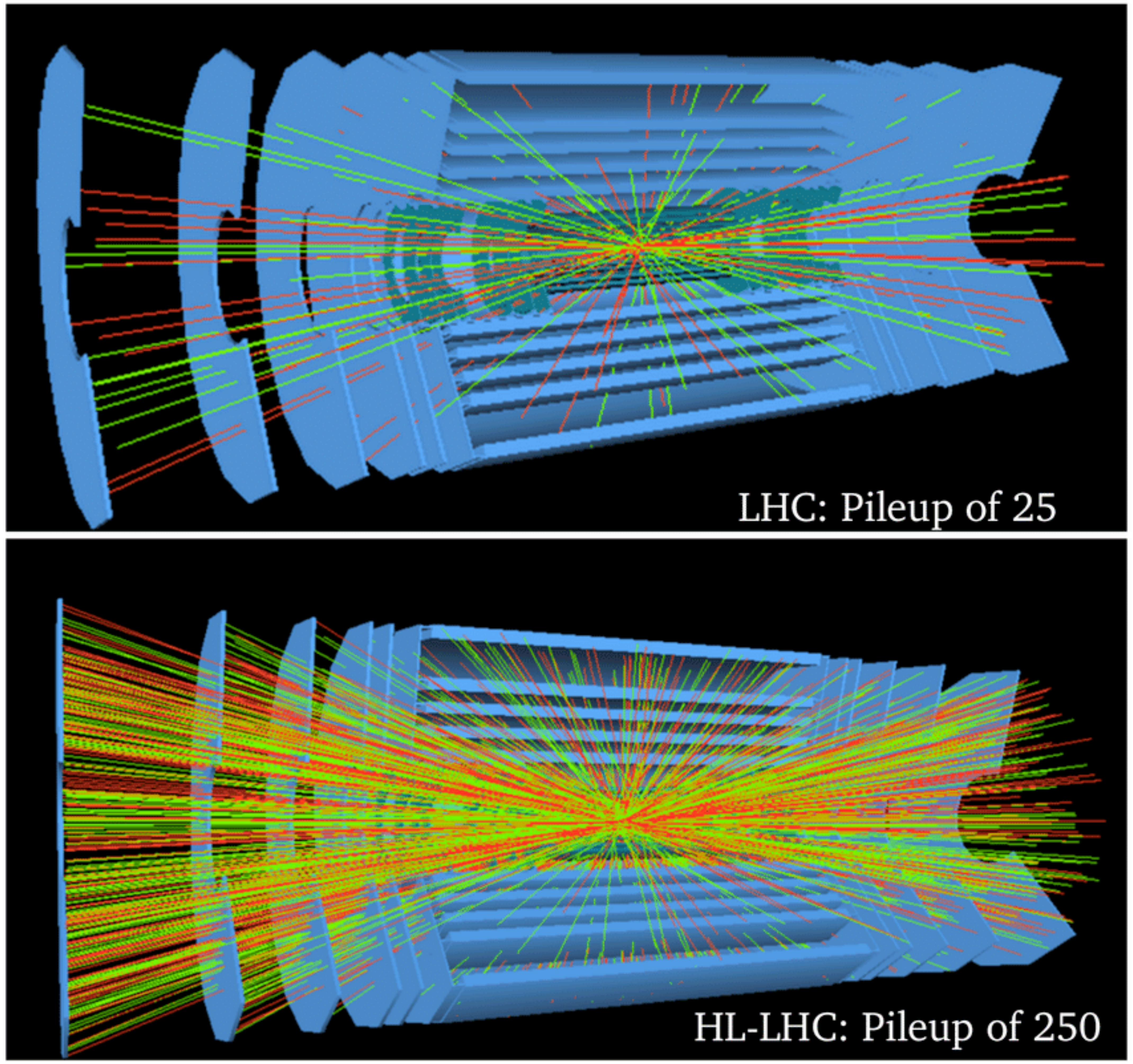
FORMOSA

Your experiment here

THE HL-LHC WON'T BE THE END OF THE STORY

- At the HL-LHC we will have more data
  - We will keep probing SM processes, with higher precision
    - Higher chance to find deviations with respect to the predictions
- Most of our current analyses are NOT statistically limited
- No increase of the center of mass energy, HL-LHC will stay at 13.6 TeV
- The pileup will be brutal

There is potential for a surprise but a surprise will be surprising

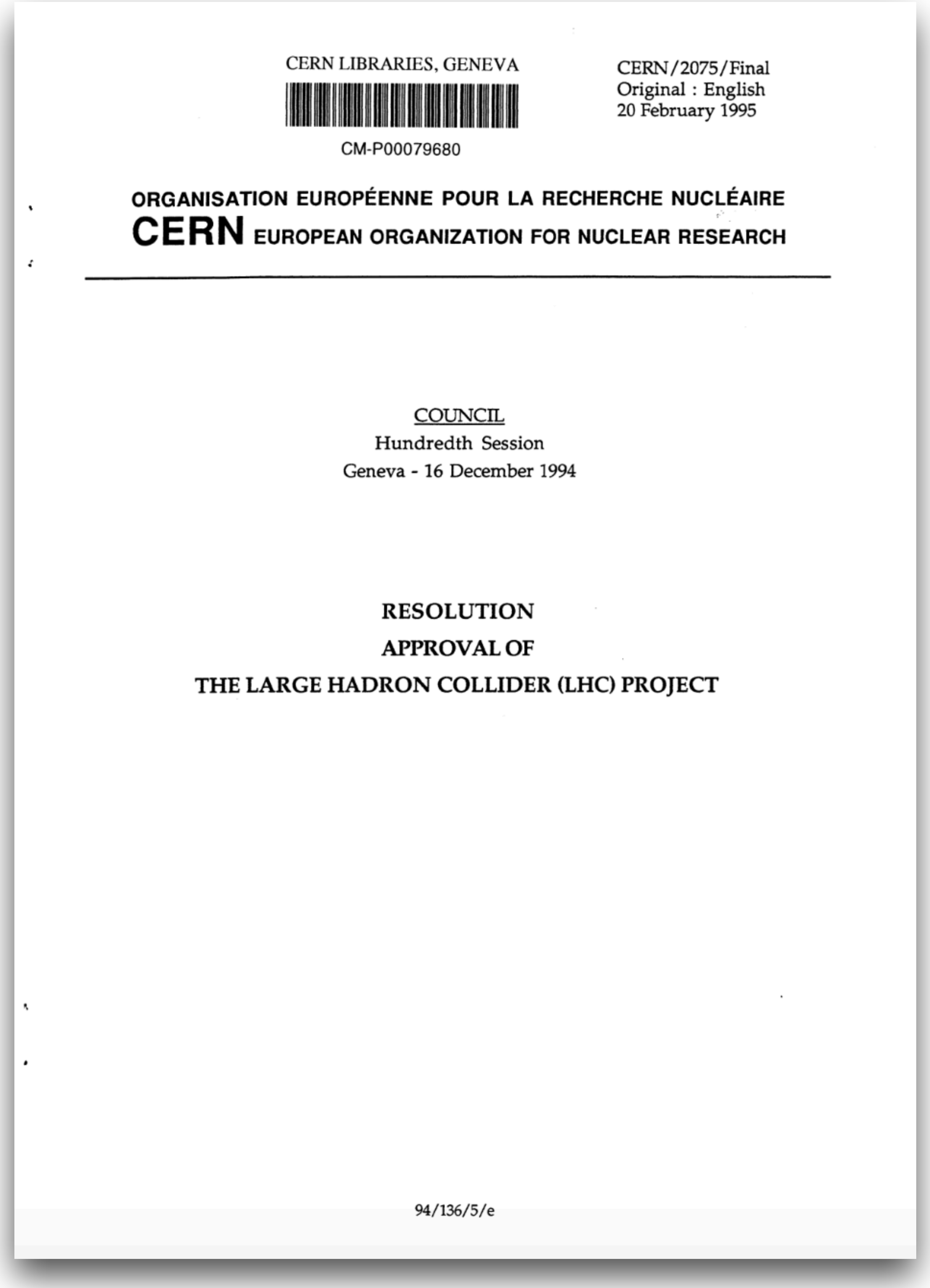


https://arxiv.org/abs/1201.5469

SO, WHAT'S NEXT?

WELL, WE DON’T KNOW

BUT THE CYCLES OF COLLIDER PHYSICS ARE LONG



CERN/2075/Final
Original : English
20 February 1995

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

COUNCIL
Hundredth Session
Geneva - 16 December 1994

RESOLUTION
APPROVAL OF
THE LARGE HADRON COLLIDER (LHC) PROJECT

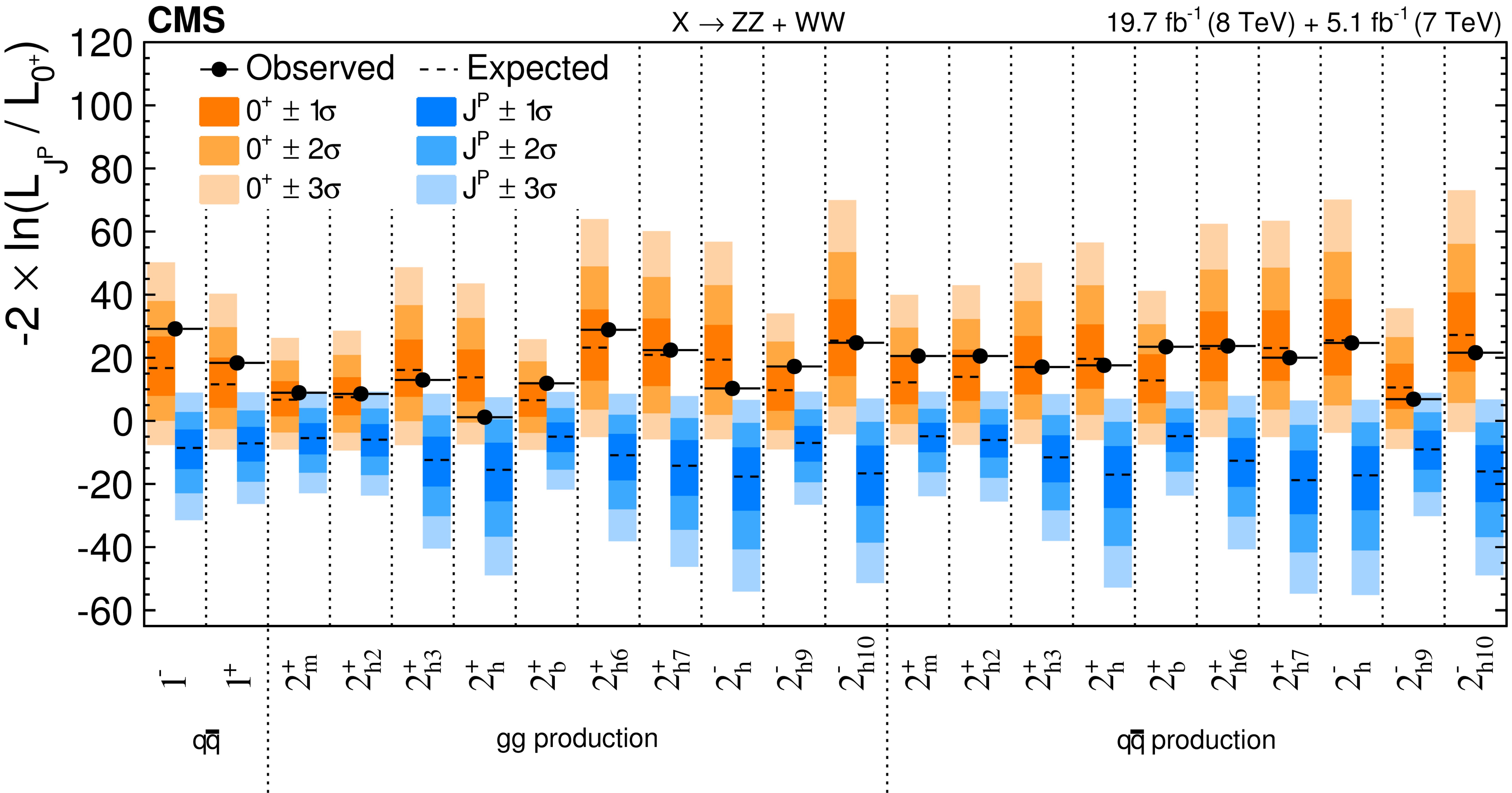
94/136/5/e

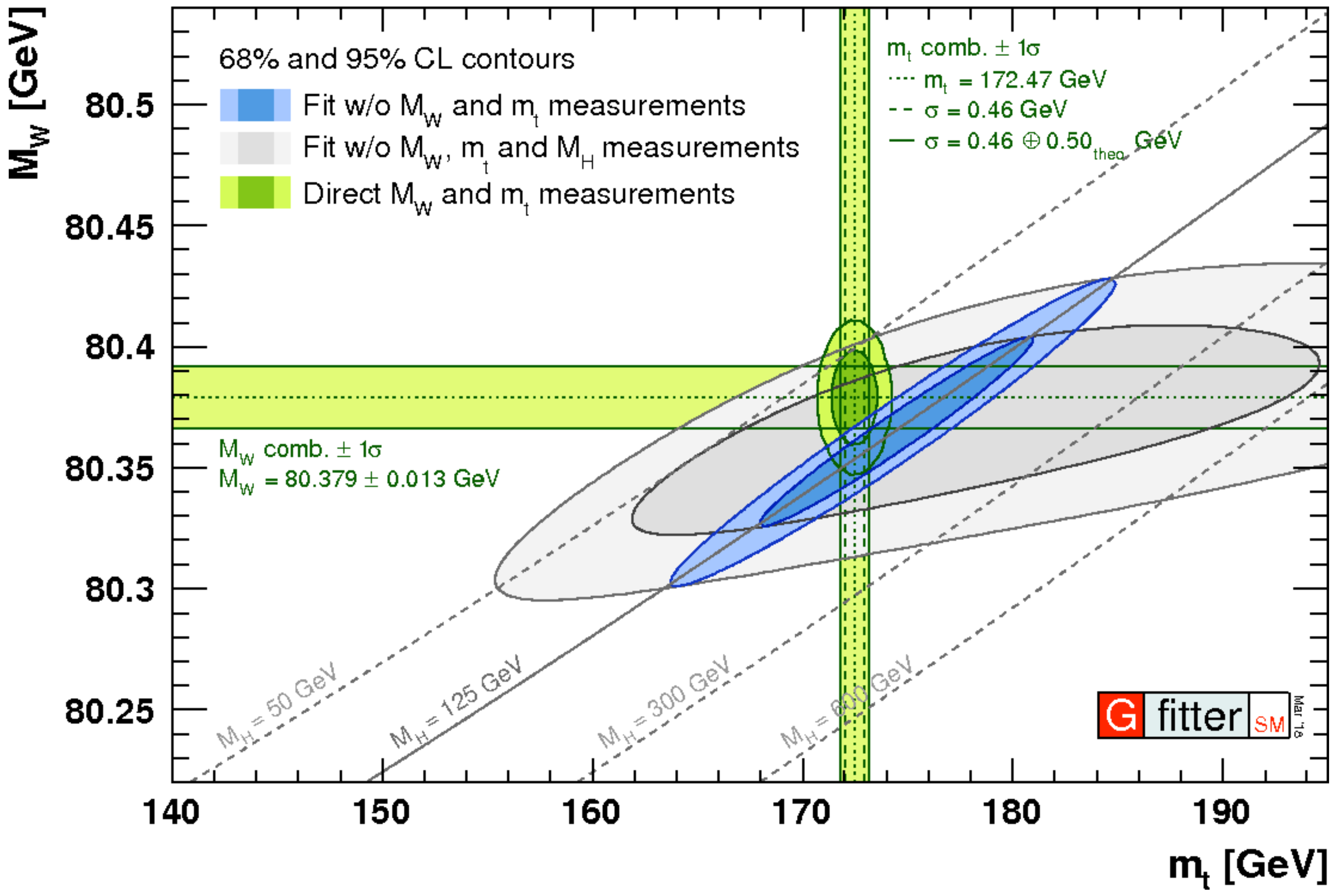
- The LHC was approved in 1994 → started running in 2009 (15 years) → will run until 2041 (32 years)
  - The Tevatron was approved in 1978 → started running in 1985 (7 years) → run until 2009 (14 years)
- If we want something to be running shortly after the HL-LHC, now is the time to approve it

The spokespersons of the future colliders
are walking among us, already in the field!
They could be any of you

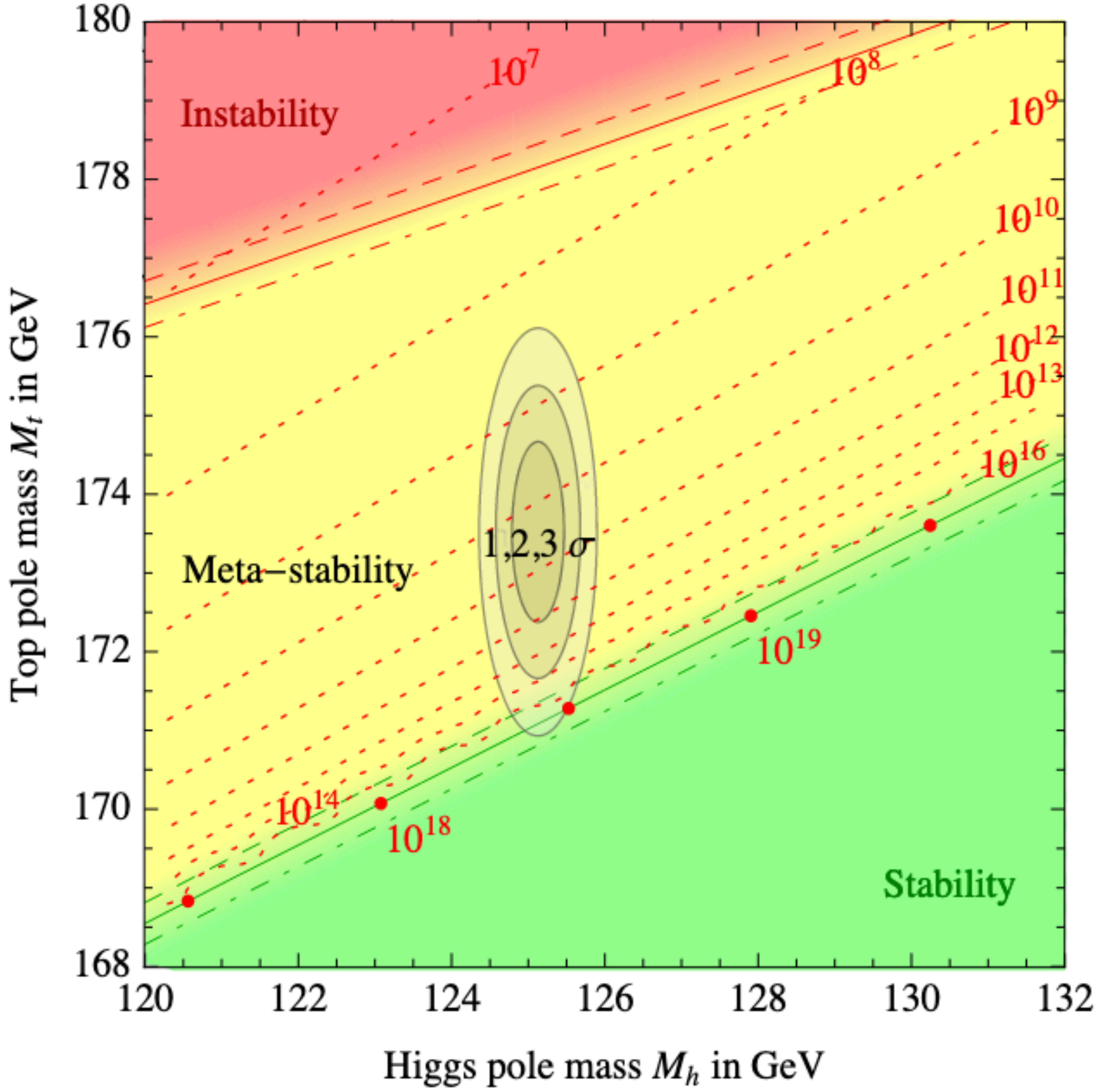
WHAT DO WE HAVE TODAY?

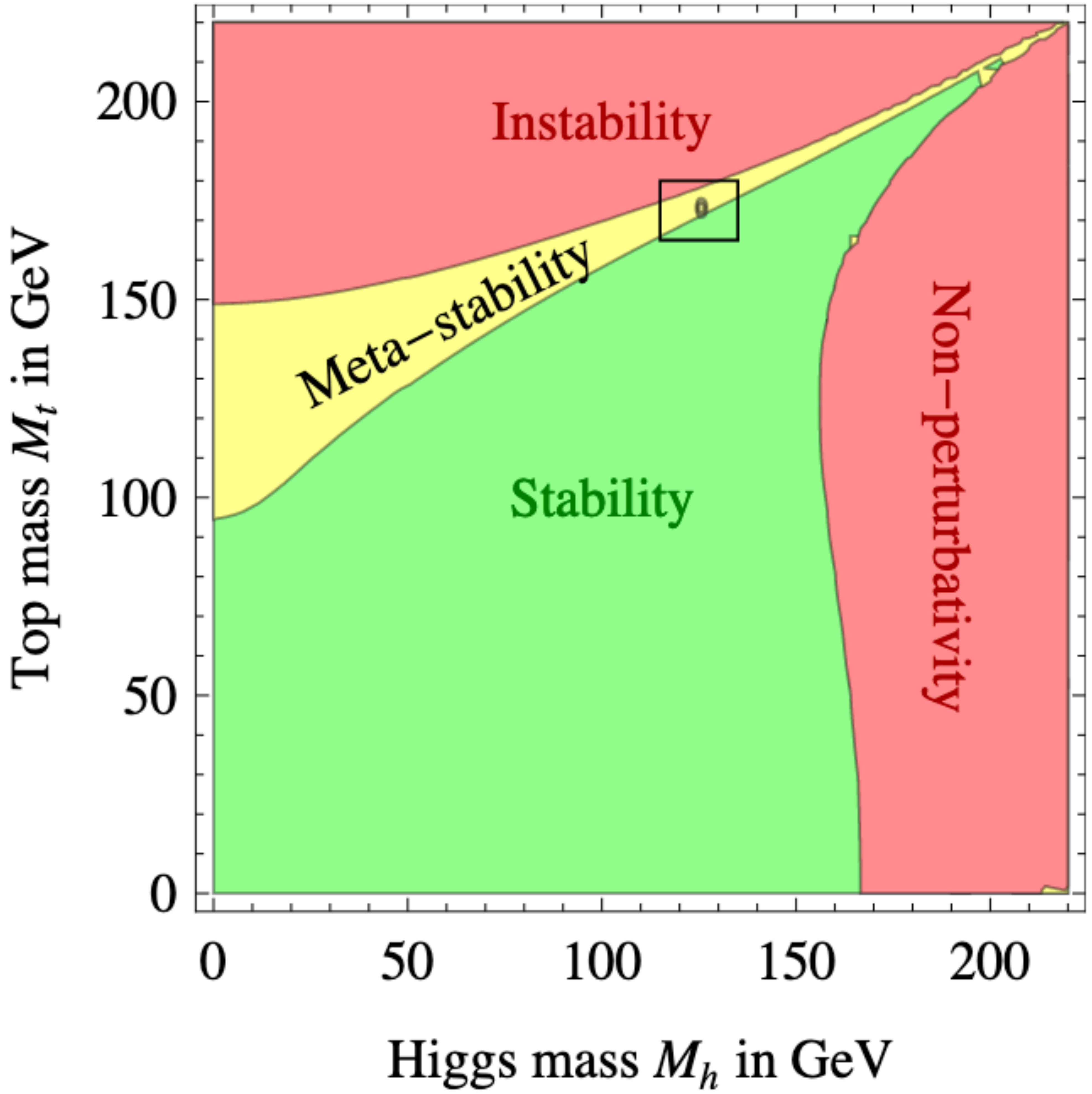
- A relatively new particle that is very special, an exploration tool.





The value of the Higgs mass of 125GeV is very interesting.
When combined with the masses of the top quark and the W boson, it hints at something beyond the standard model.





The value of the Higgs mass of 125GeV is very interesting.
When combined with the masses of the top quark and the W boson, it hints at something beyond the standard model.

AND WE ALSO HAVE

- Various options on the table.
- Decades of collider expertise.
- The largest community we ever had.
- Priorities

2020 update of the European Strategy for Particle Physics

“An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.”

Working towards the 2025 strategy update

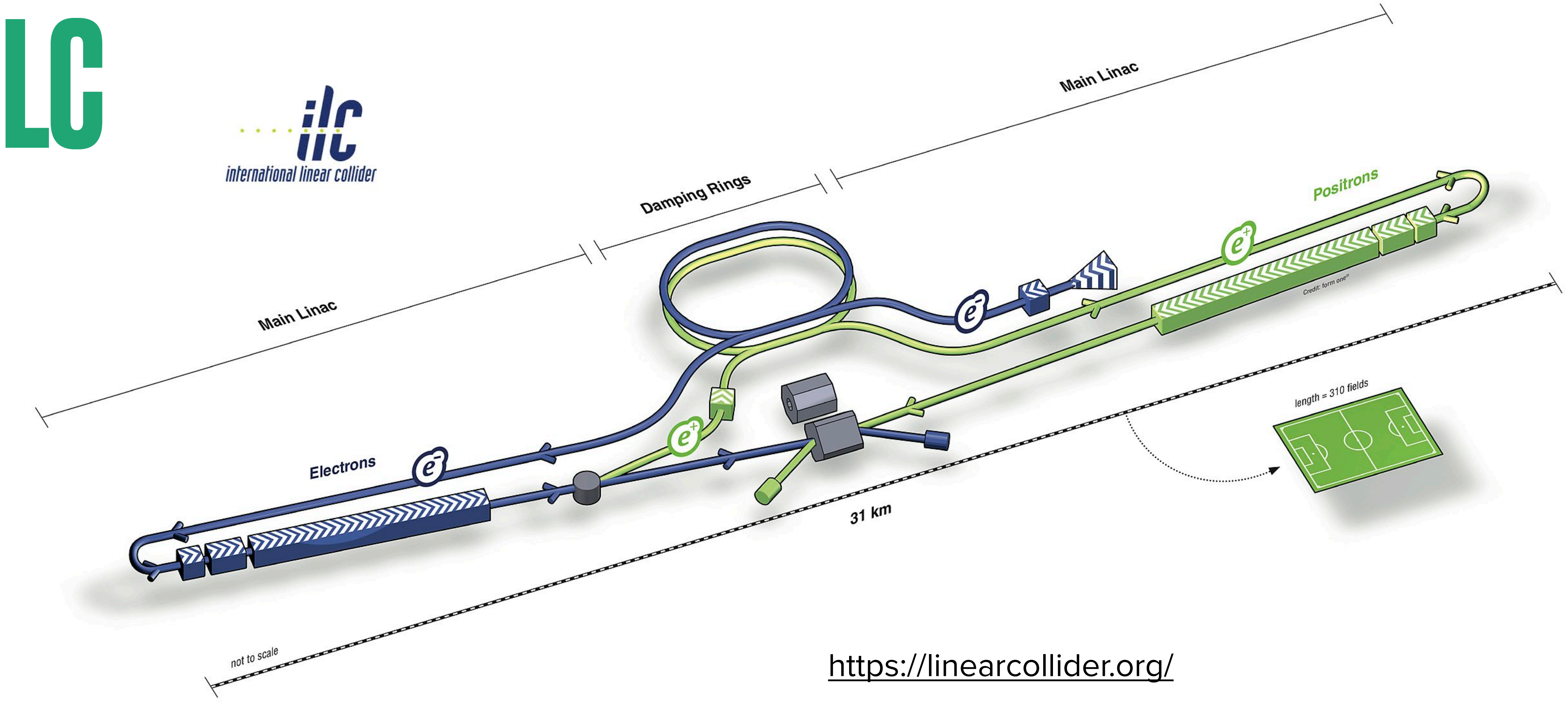
2023 US P5 Report

Advocates for substantial US participation and effort to support development of an offshore Higgs factory, with the goal of leading and potentially hosting a muon (!) collider beyond it.

LET’S DIVE A LITTLE DEEPER

LINEAR e^+e^- COLLIDERS: ILC

ilc
international linear collider

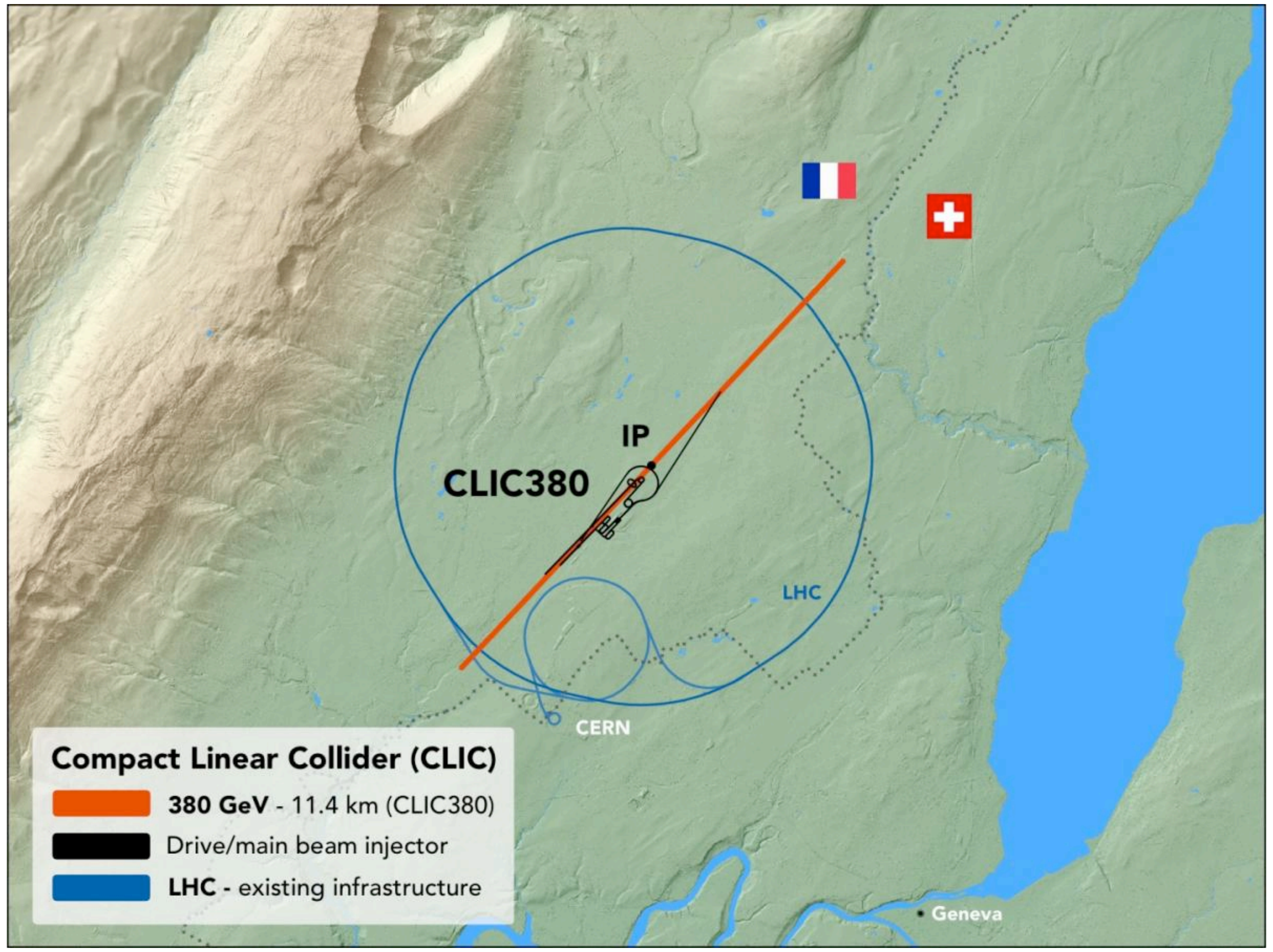


https://linearcollider.org/

- 250 GeV (could be upgraded to 500)
- 30-km-long
- TDR in 2012
- In Japan originally (before that Germany), currently: location pending
- One collision zone: up to two experiments

LINEAR e^+e^- COLLIDERS: CLIC

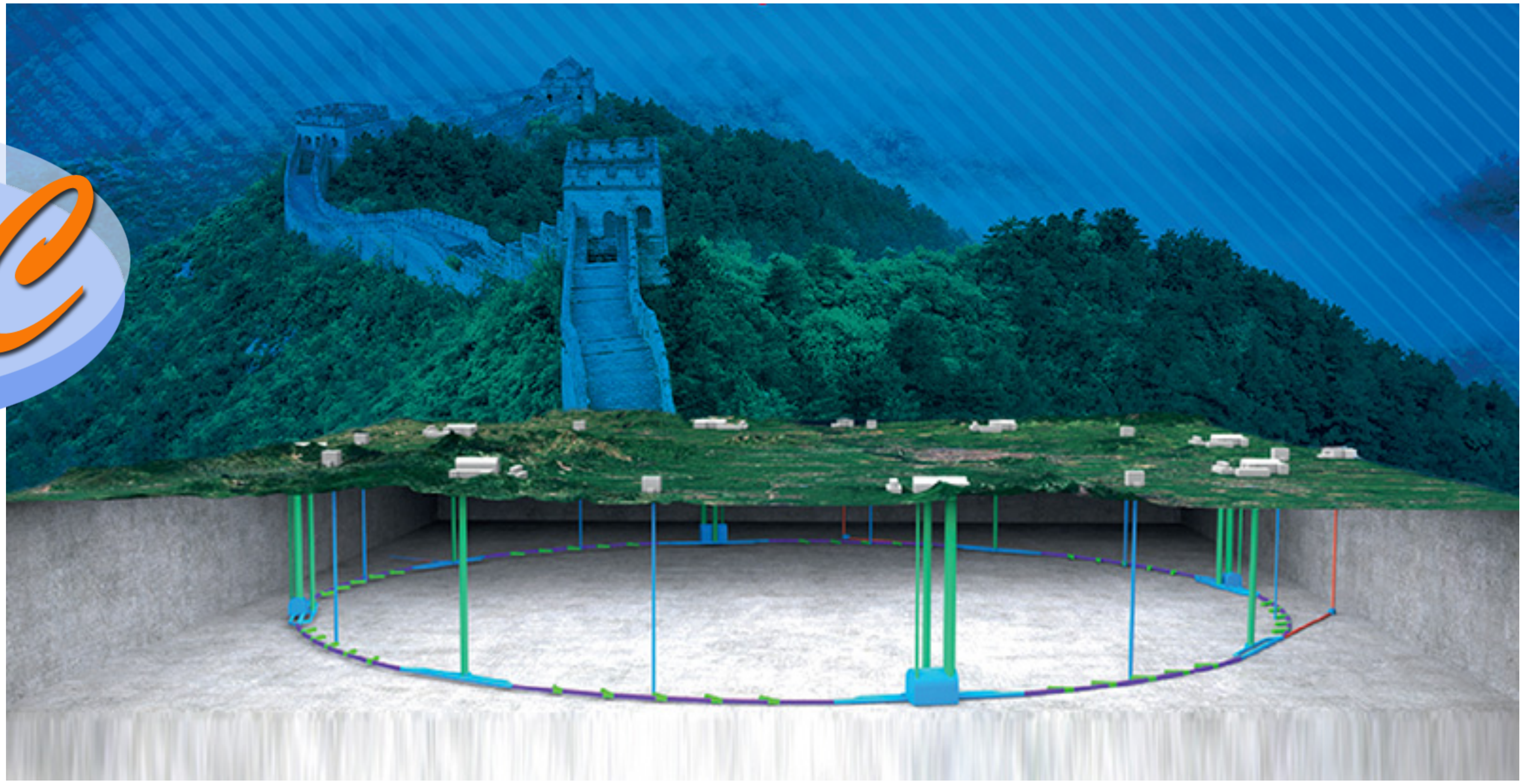
https://clicdp.web.cern.ch/



- 380 GeV (up to 3TeV)
- compact: 11 km total length
  - ~LHC diameter
- CDR in 2013
- at CERN
- One interaction region

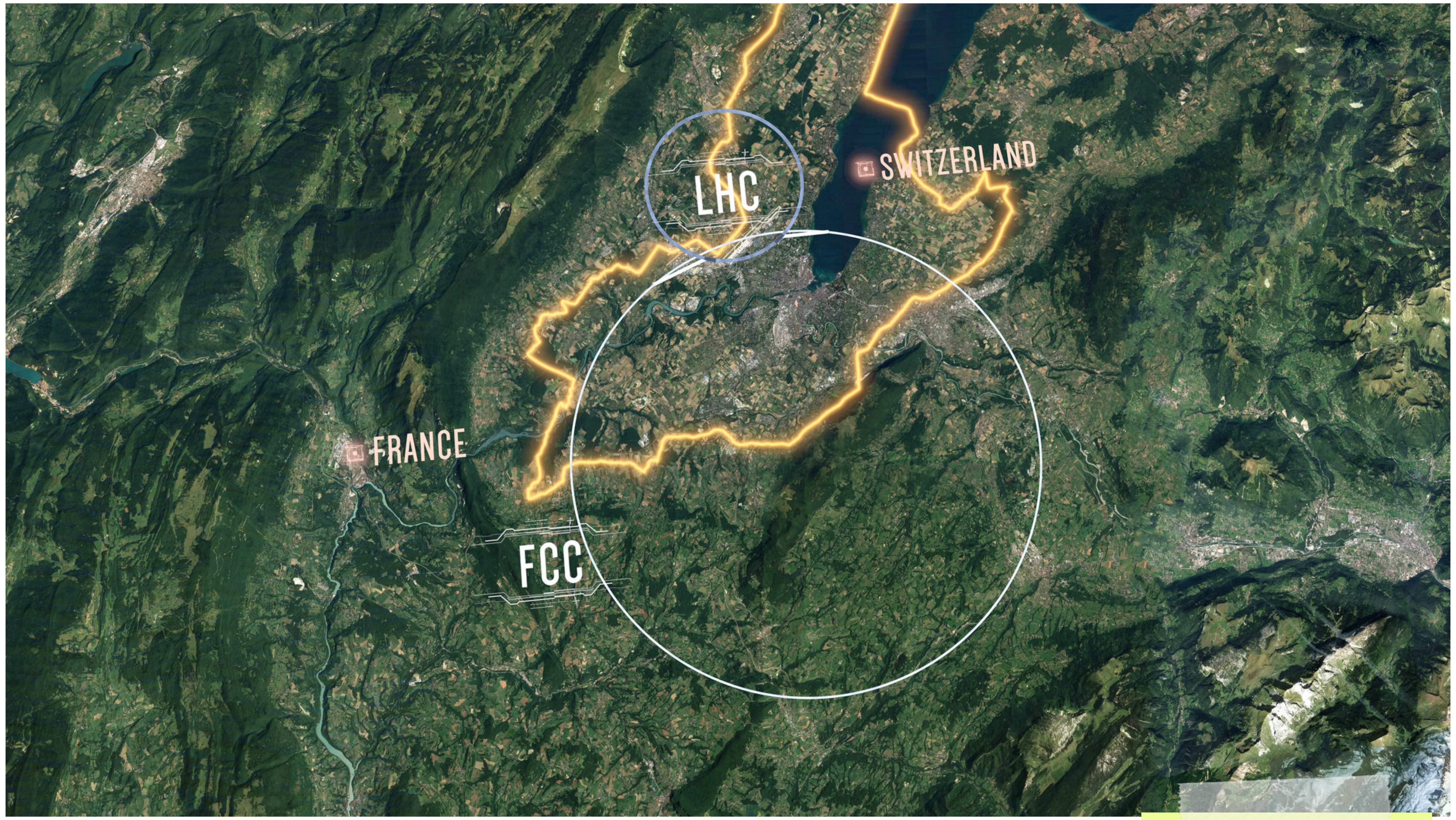
CIRCULAR e^+e^- COLLIDERS: CEPC

http://cepc.ihep.ac.cn/



- 90-365 GeV
- underground tunnel of 100 km of circumference, double-ring collider
- TDR in 2023
- To be hosted in China, exact location tbc
- Two (4?) interaction points (IPs)

CIRCULAR e^+e^- COLLIDERS: FCC-ee



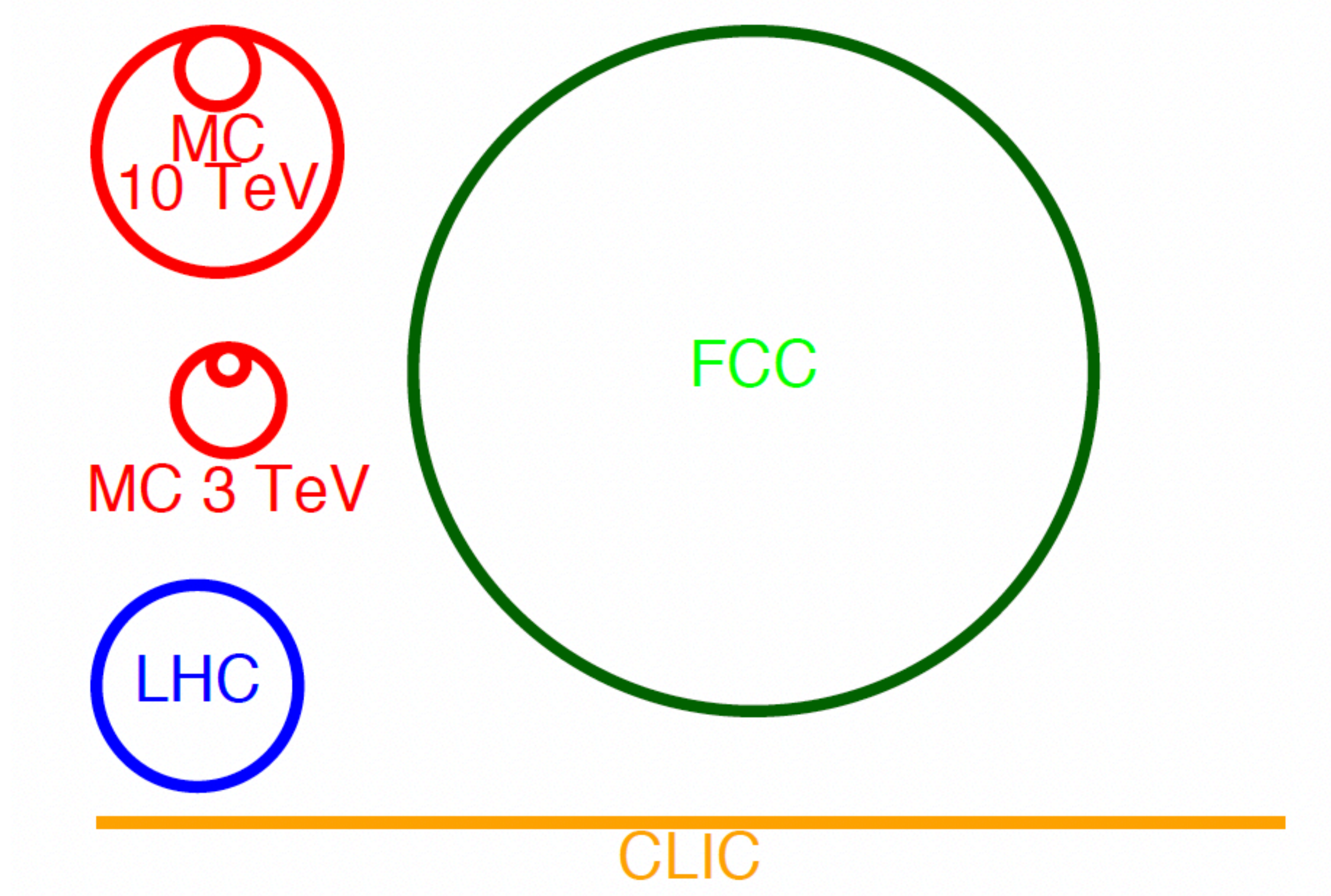
More on this one in a minute

FUTURE CIRCULAR COLLIDER

https://fcc-ee.web.cern.ch/

THE WILDCARD: A MUON COLLIDER

- The coolest kid on the block
- Requires a lot of R&D in the coming years
- US (or Europe?)



THE OPTION I AM WORKING ON

FUTURE CIRCULAR COLLIDER (FCC) AT CERN

- A versatile, next-generation particle collider housed in a 90km underground ring
- Linked to the LHC accelerator chain
- Implemented in stages, one e^+e^- machine, followed by a high-energy hadron collider

FCC PUSHES TWO FRONTIERS

- **1st stage collider, e+e-**
  - FCC-ee
  - electron-positron collisions
  - 90-365 GeV
  - Higgs, EW, top factory
  - Construction starts: 2033
  - Physics starts: 2048 (45 if accelerated)

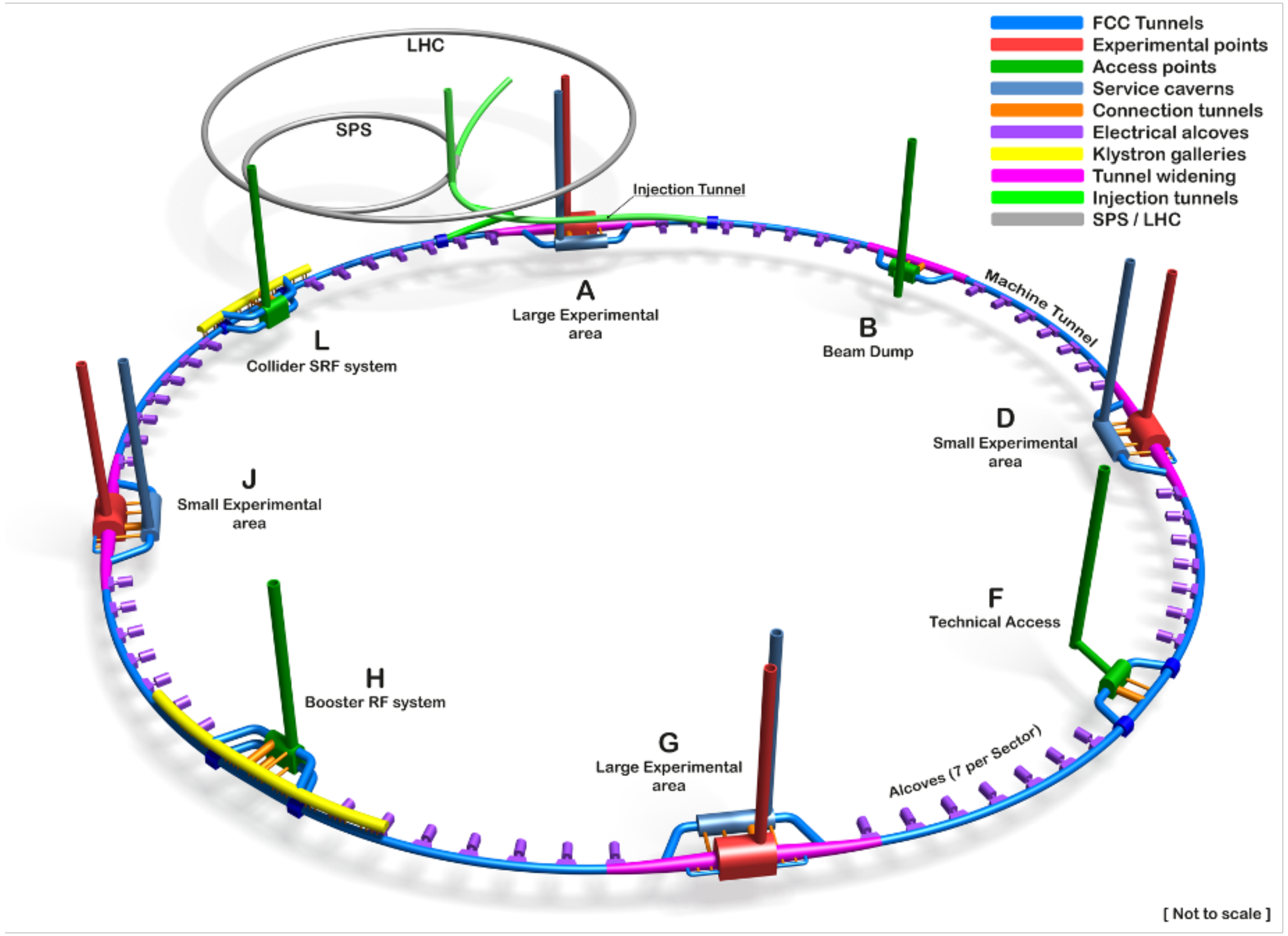
- **2nd stage collider, pp**
  - FCC-hh
  - proton-proton collisions
  - ≥ 100 TeV
  - Discovery machine
  - Physics operation: ~ 2070

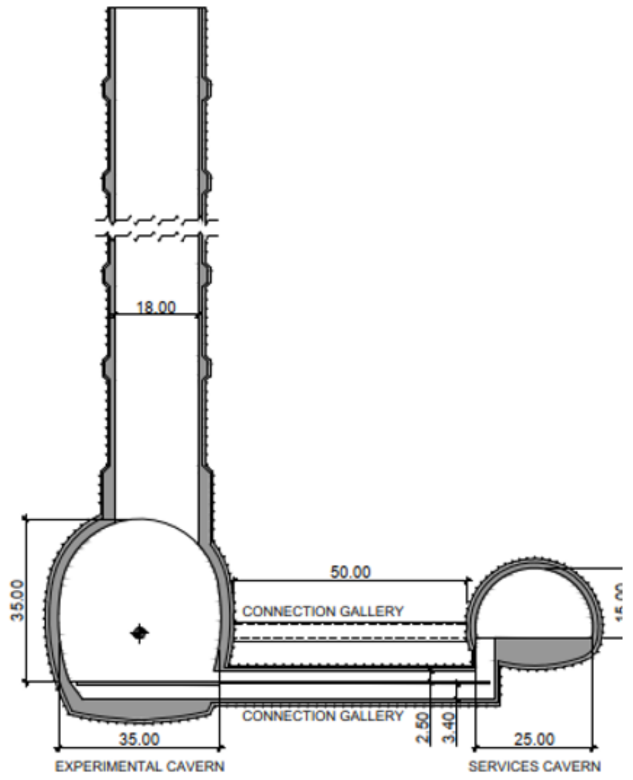
Additional modes
supported
Heavy ions, eh

Complementary
Synergetic
All-in-one facility

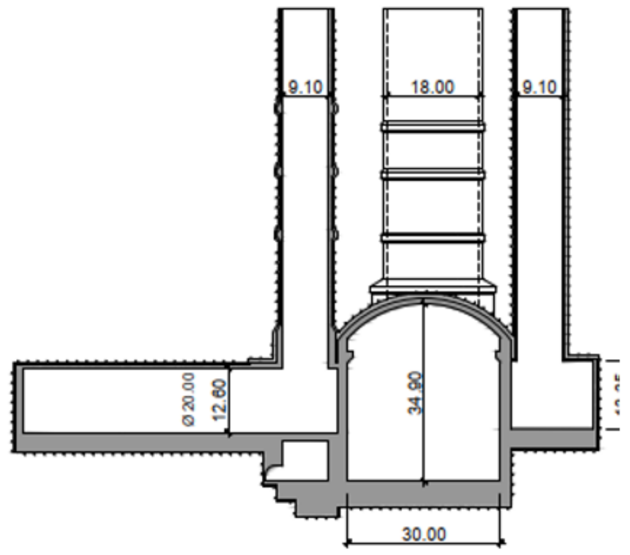
COMMON INFRASTRUCTURE

- Making use of the current acceleration chain
- Using one tunnel (and one set of caverns) for both stages
  - 90.7 km ring, 8 surface points

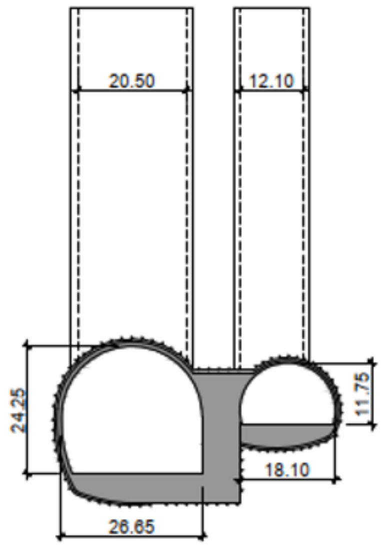




FCC



ATLAS

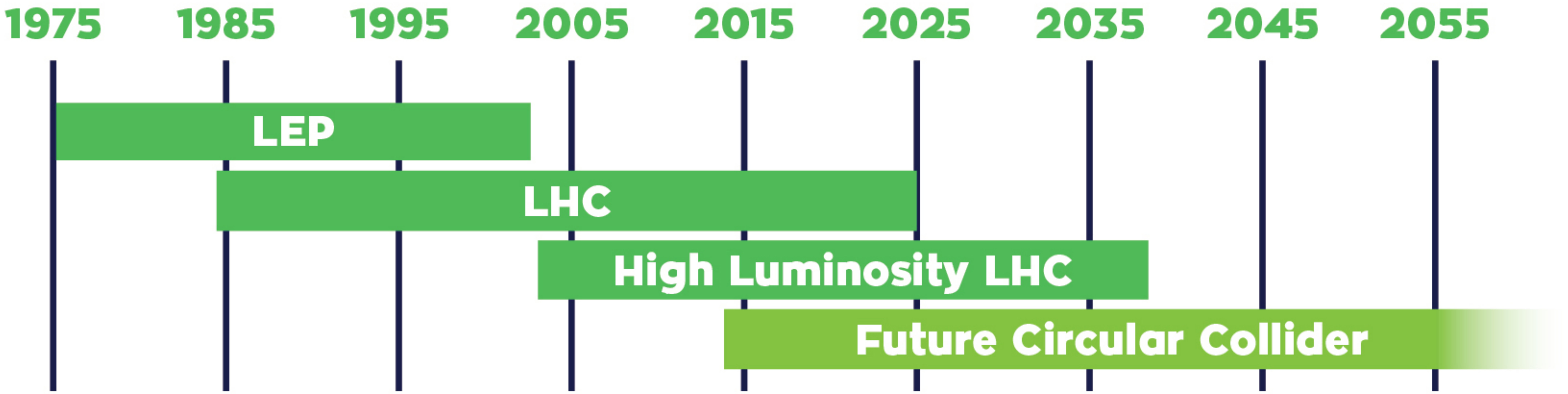


CMS

- 4 Experimental areas 2 large (> ATLAS) & 2 small (~CMS)
- Deepest shaft: 400m
- Average shaft depth: 243m

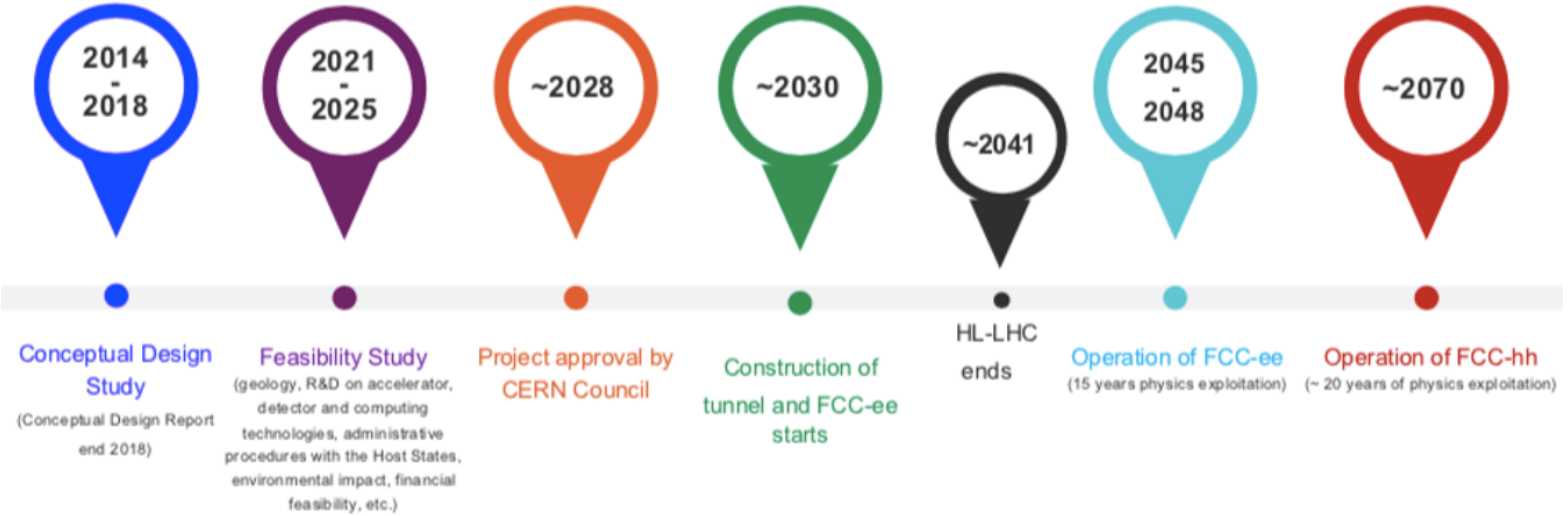
CONTINUITY

- FCC-ee technology is mature and ready ➔ construction in parallel to HL-LHC operation
- Physics a few years after the HL-LHC
  - Guarantees continuity for generations of high energy physicists
  - Can accommodate the size of the CERN community



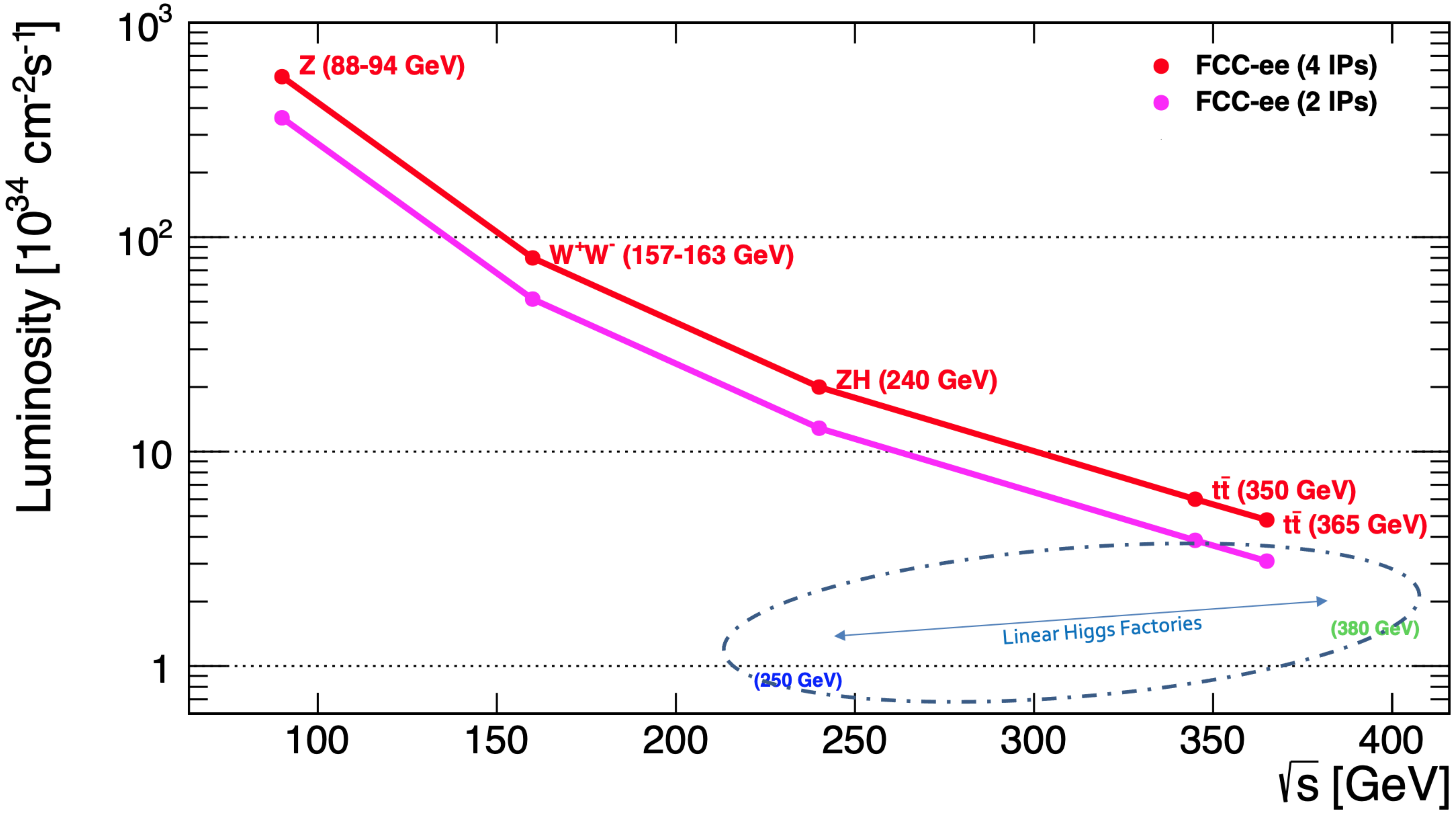
STAGED APPROACH

- Two-stage approach
  - Allows to spread the cost of the more expensive FCC-hh over more years
  - 20 years of R&D work towards optimal and affordable magnets
  - Optimization of overall investment by reusing civil engineering and large part of the technical infrastructure



LUMINOSITY

- **FCC-ee: highest luminosities of all proposed Higgs and EW factories, clean experimental conditions, and a range of energies that cover Z, WW, ZH, and tt.**

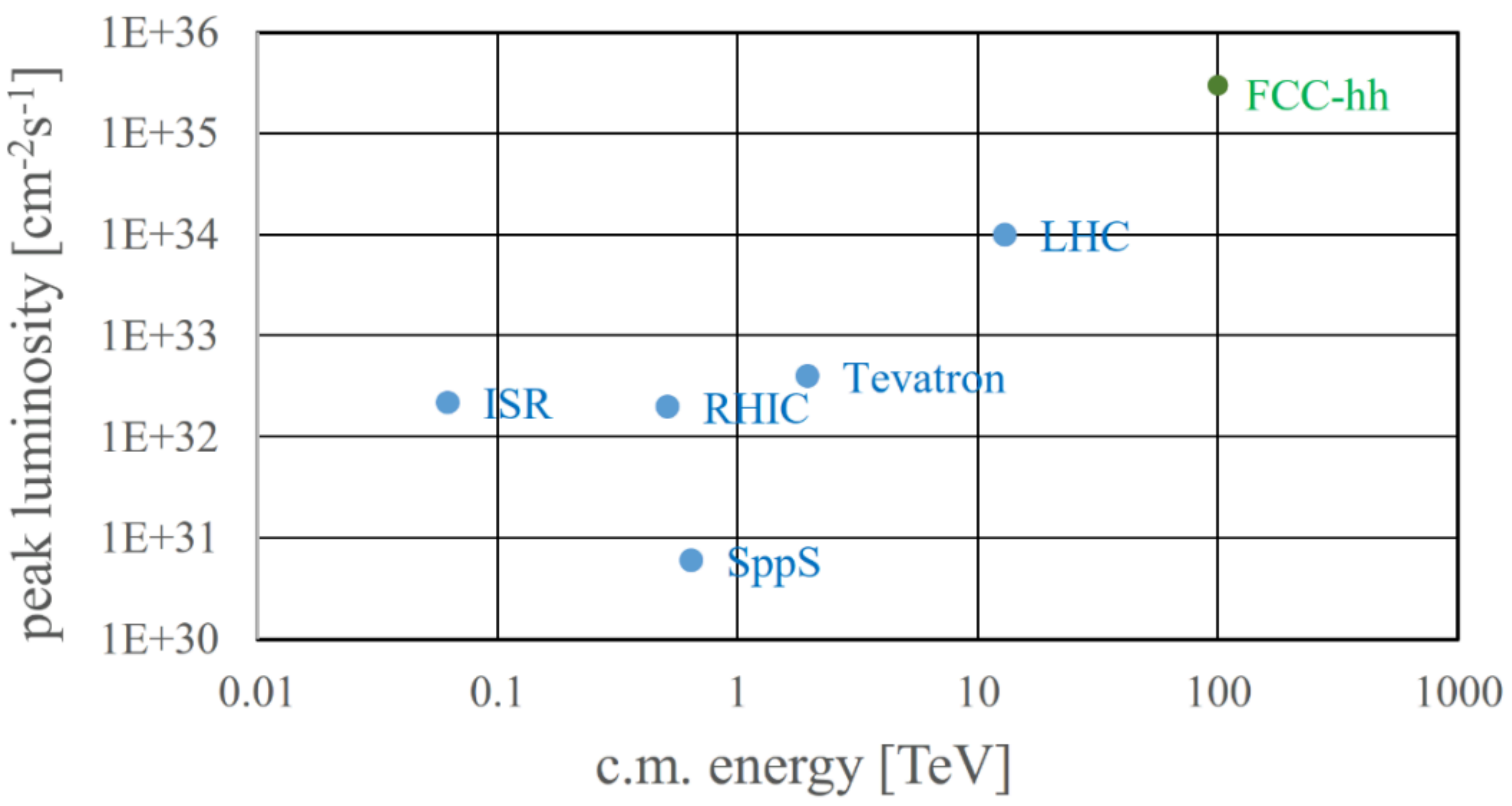


FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

combining successful ingredients of several recent colliders → highest luminosities & energies

ENERGY

- FCC-hh: Able to directly reach the next energy frontier (~ x10 LHC)
  - order of magnitude performance increase in both energy & luminosity wrt the LHC



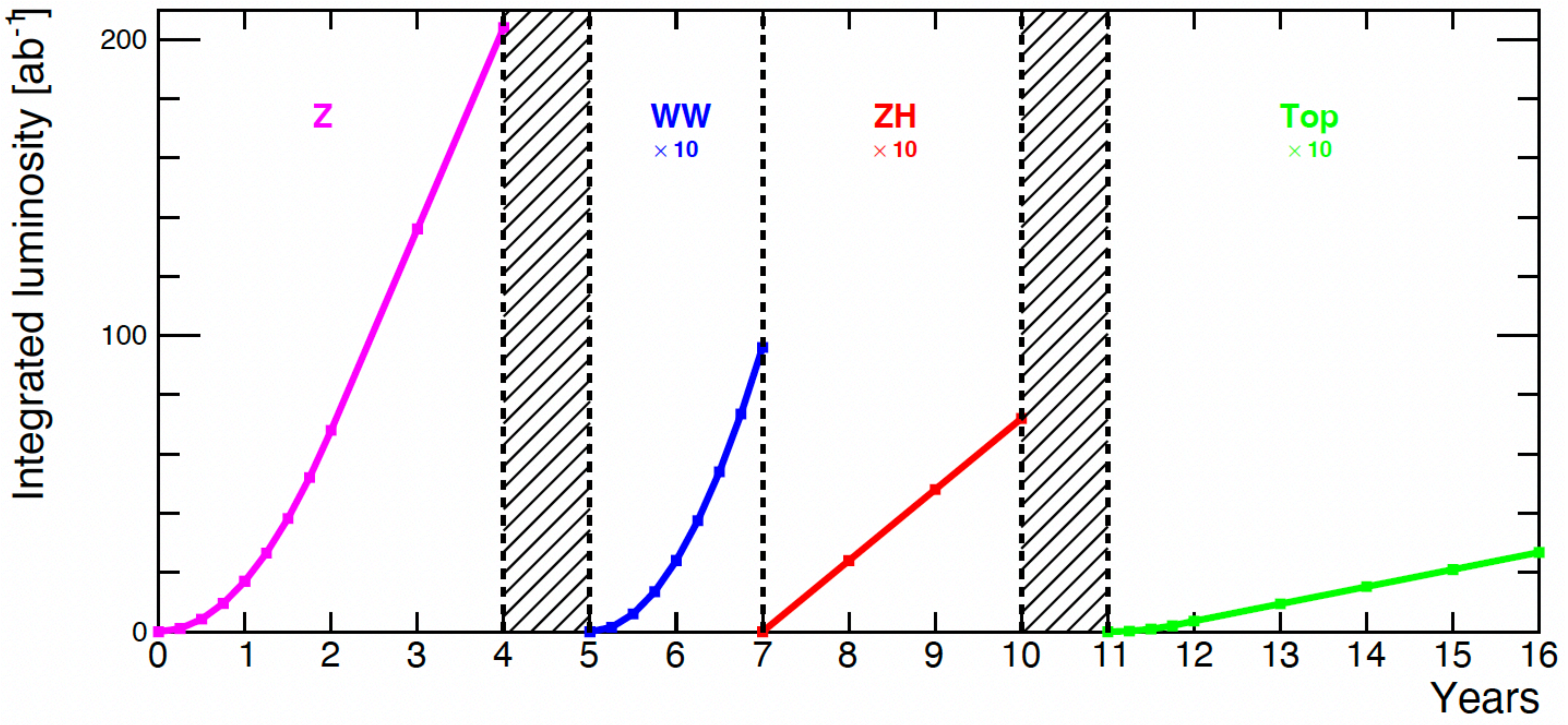
parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 119	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

[Frank Zimmermann - ICFA Seminar 2023]

That's not all!
Heavy-ion collisions and, possibly, ep/e-ion collisions, additional experiments and e.g. a FPF could be there from the beginning

FCC-ee

- **16 years, 4 IPs**
- **Flexibility in the run scenario: in order and operation periods.**
  - **Additional runs, e.g. 125GeV possible**
- **Stringent experimental requirements**



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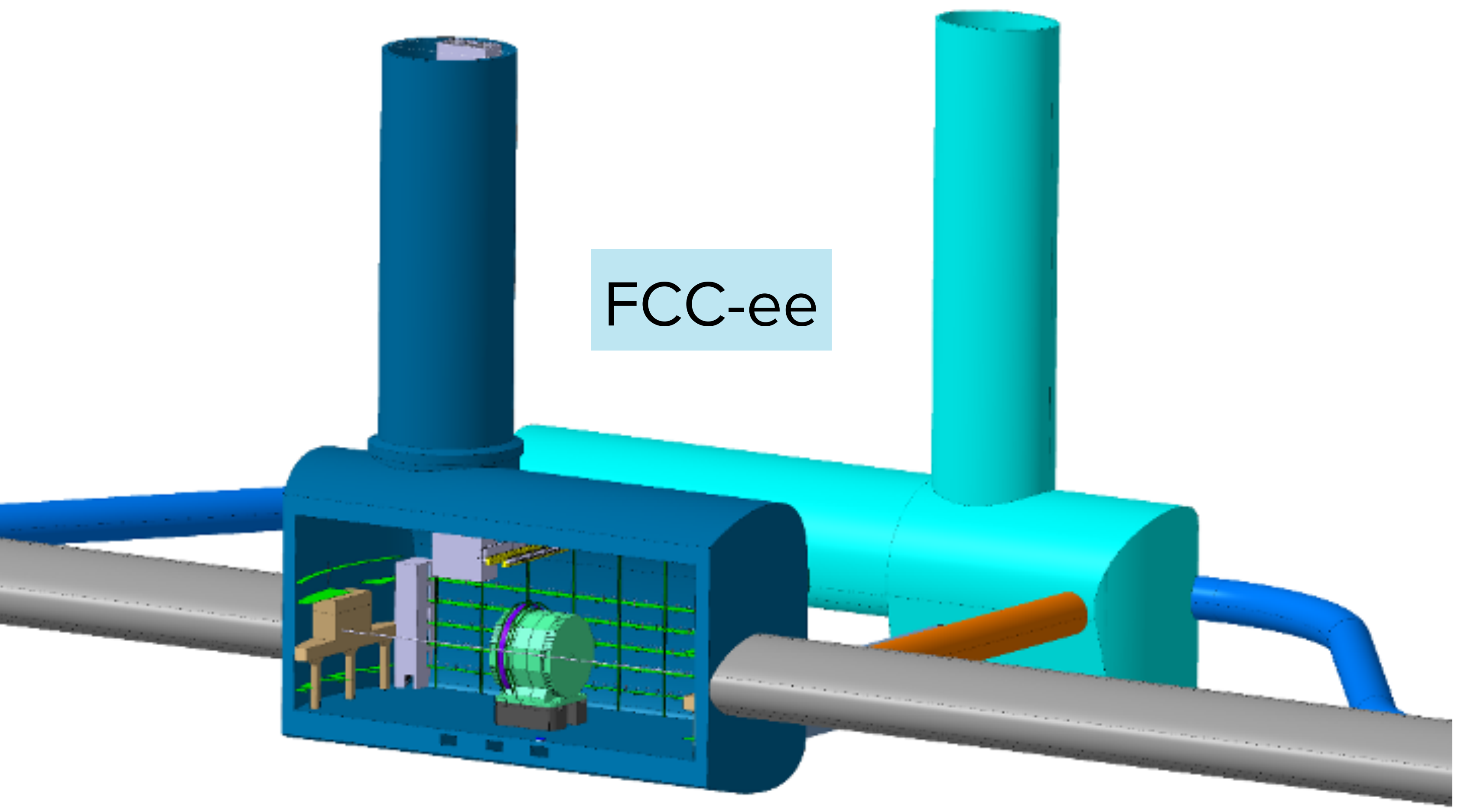
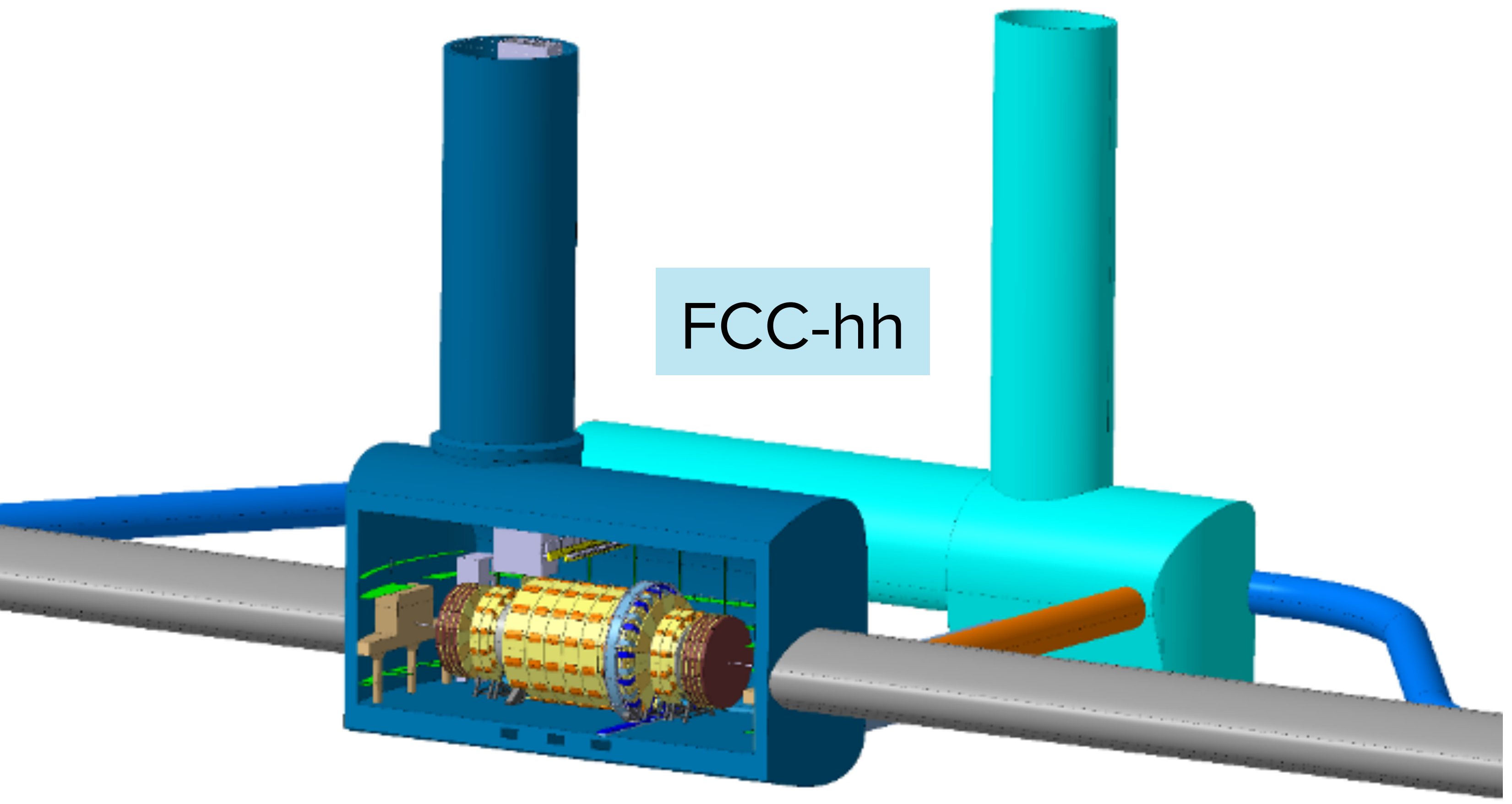
Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\to$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\to$ H	

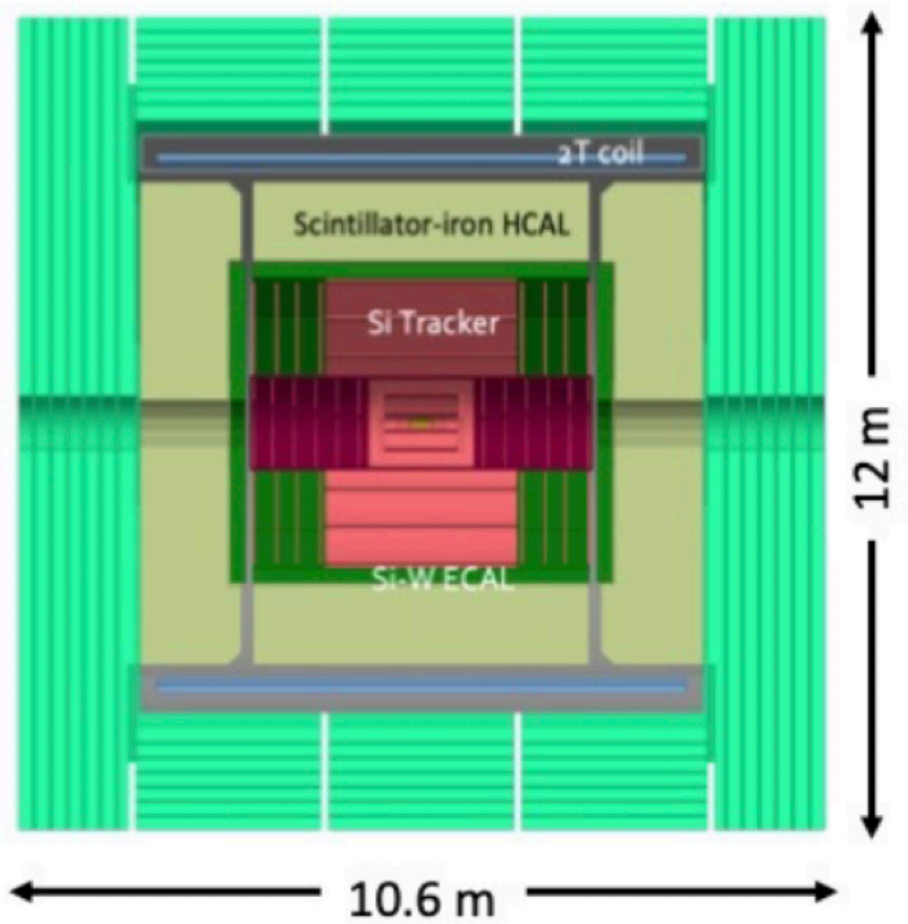
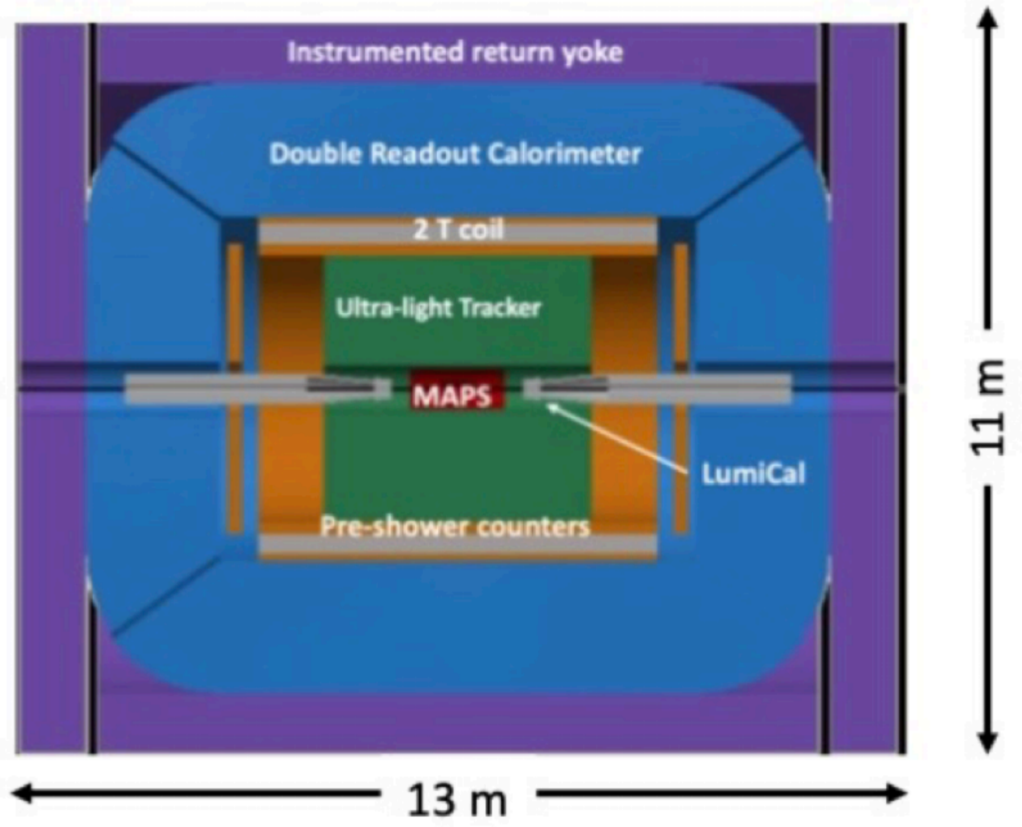
integrated luminosity per year summed over 4 IPs corresponding to 185 days of physics per year and 75% efficiency

all the data of LEP1 in minutes

DETECTOR CONCEPTS





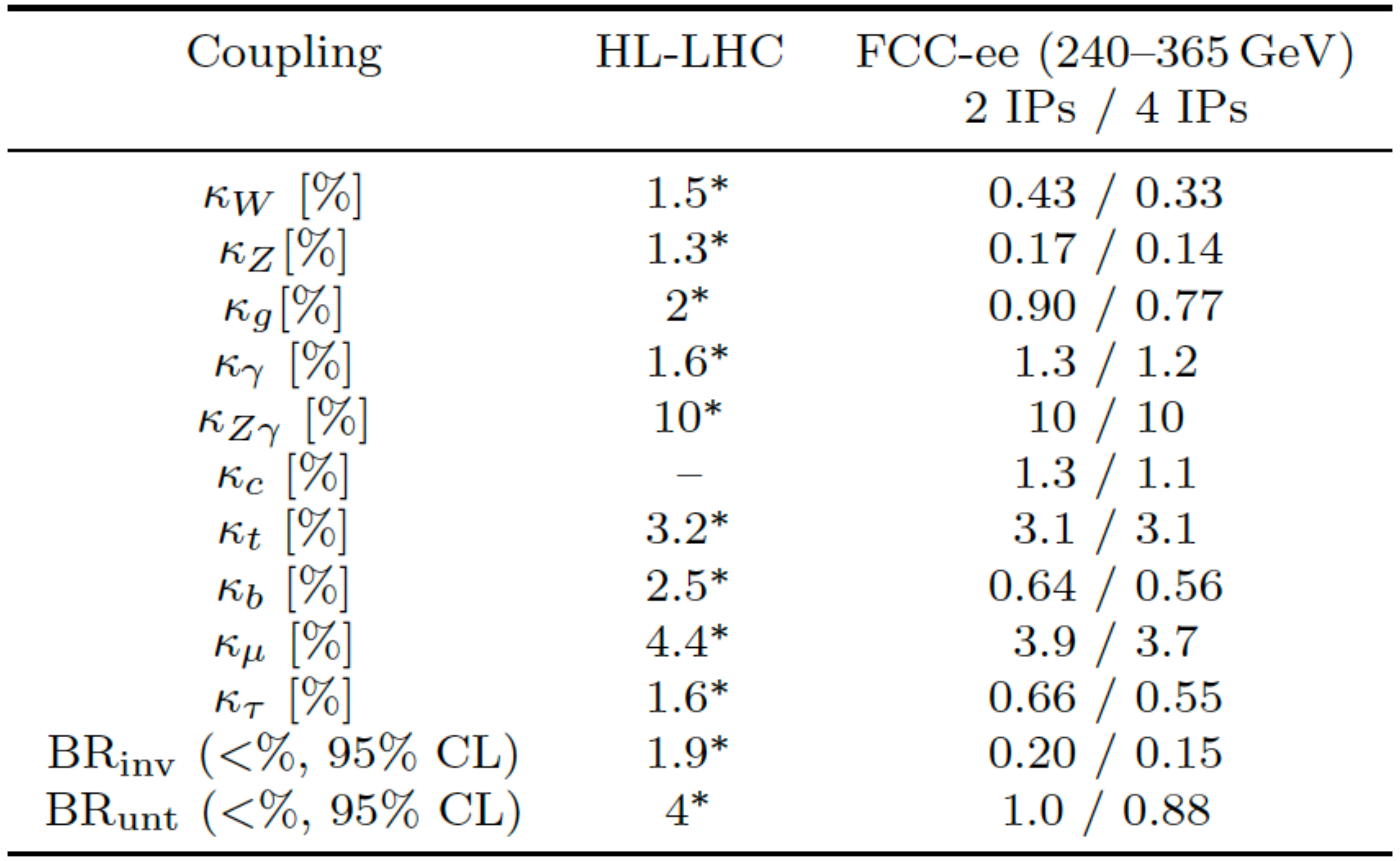
CLD	IDEA	ALLEGRO
		
Based on CLIC detector design, arXiv:1911.12230 Full silicon vertex detector and tracker 3D-imaging highly-granular calorimeter system Coil outside calorimeter system	Innovative, possibly cheaper than CLD https://pos.sissa.it/390/819 Baseline in many ongoing studies Silicon vertex detector Short-drift, ultra-light wire chamber Dual-readout calorimeter Thin and light solenoid coil inside calorimeter system	GranuLAr WS, IJCLab 2022 – Martin Aleksa Highly granular noble-liquid calorimeter Thin 2T solenoid in the calorimeter cryostat.

More complementary options possible (4 IP!) ➔ Can we optimize detector designs for the complete physics program? Yes! opportunities to contribute

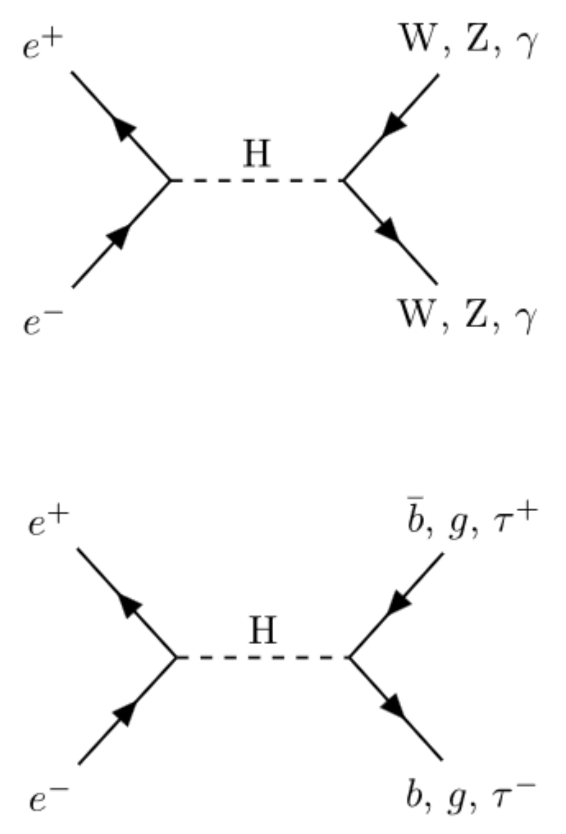
HIGGS UNDER THE MICROSCOPE

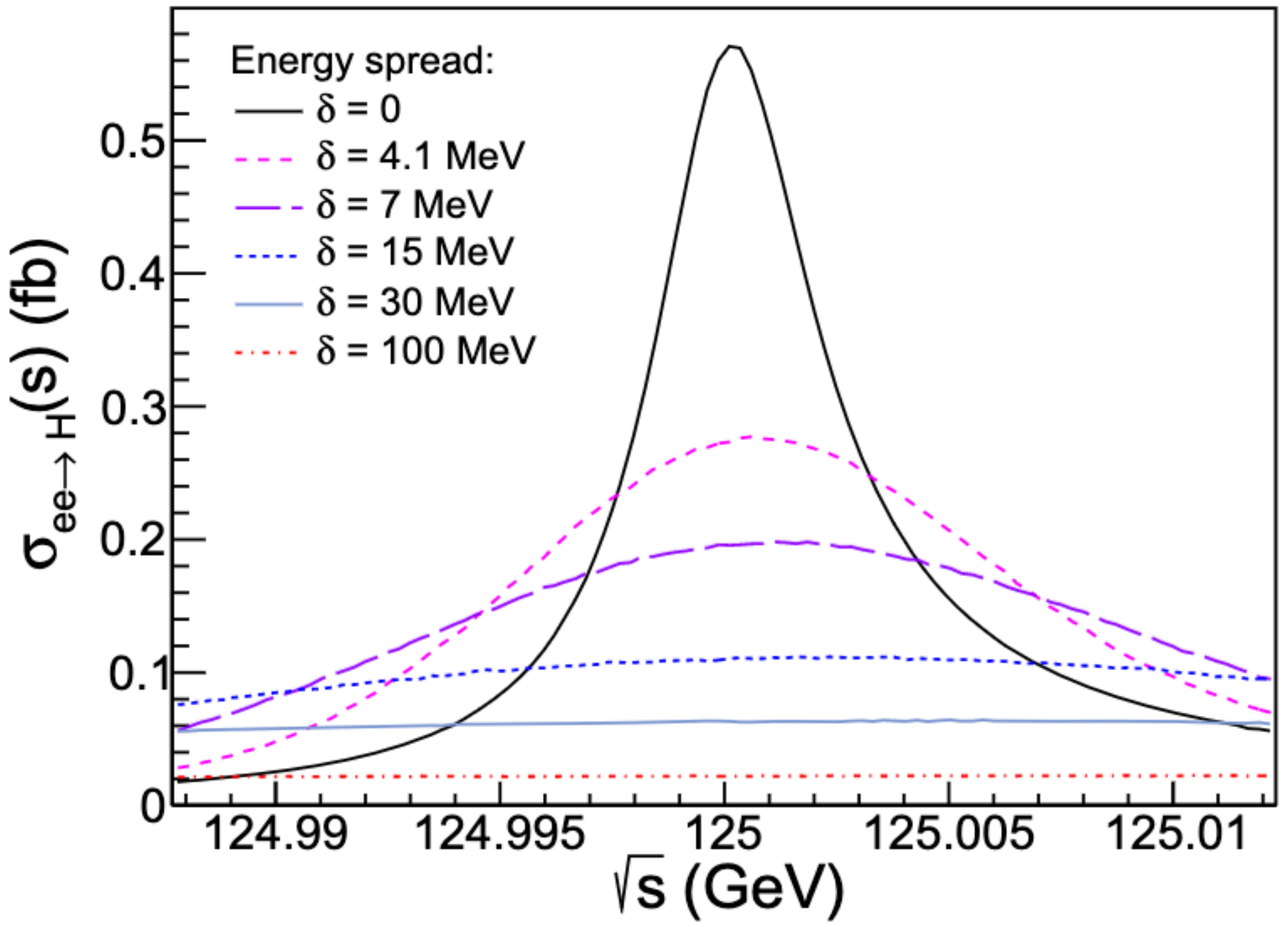
- We will be able to map all the Higgs properties with accuracy
- Improvement in the precision of several Higgs boson couplings of about one order of magnitude wrt the end of the HL-LHC
    - sub-% measurement of couplings to W, Z, b, τ , % to gluon and charm
- absolute measurement width/couplings
- Recoil method
- Access to direct Higgs production at 125GeV

FCC feasibility Mid-term report -
Deliverable #8, physics and Experiments



Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88



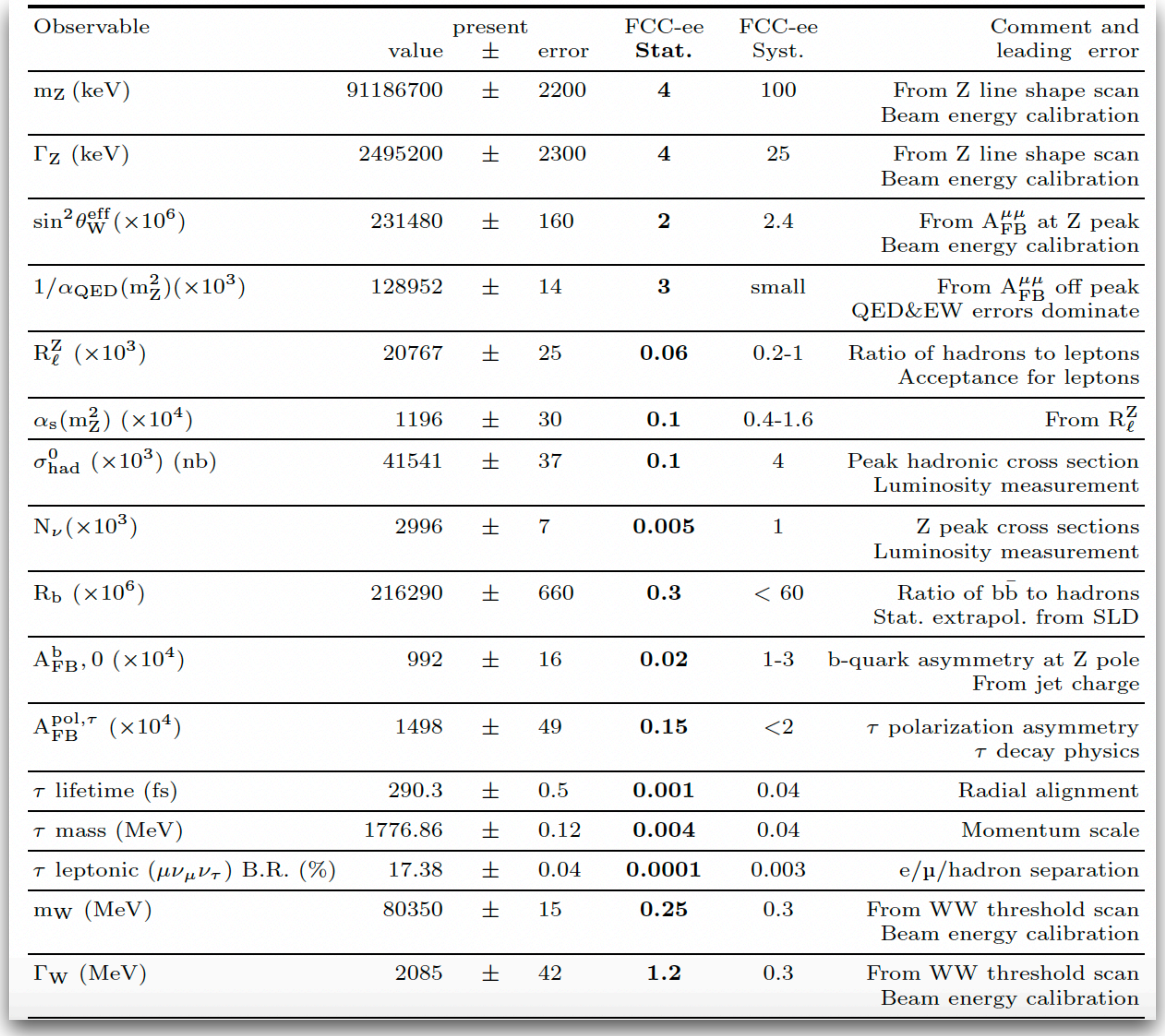


Eur. Phys. J. Plus (2022) 137:201

ELECTROWEAK

- Dedicated W and Z runs with unprecedented statistics
  - Z pole run → LEP Statistical uncertainties divided by ~1000
- Comprehensive measurements of the Z lineshape and many Electroweak Precision Observables
  - 50x improved precision→ 7x jump in indirect sensitivity to BSM effects
- Direct and uniquely precise determinations of $\alpha_{QED}(m_Z)$ (for the first time) and $\alpha_S(m_Z)$

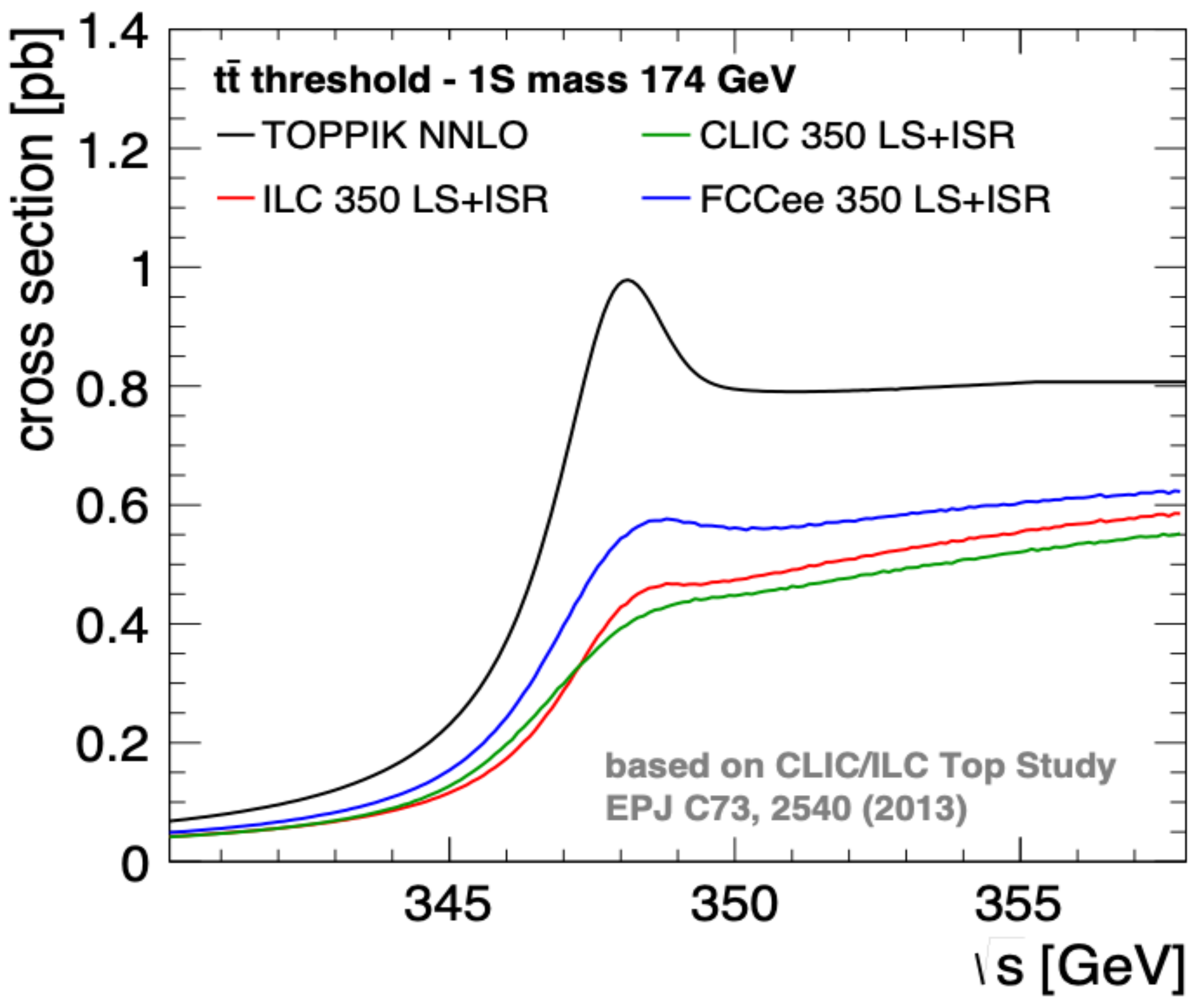
FCC feasibility Mid-term report -
Deliverable #8, physics and Experiments



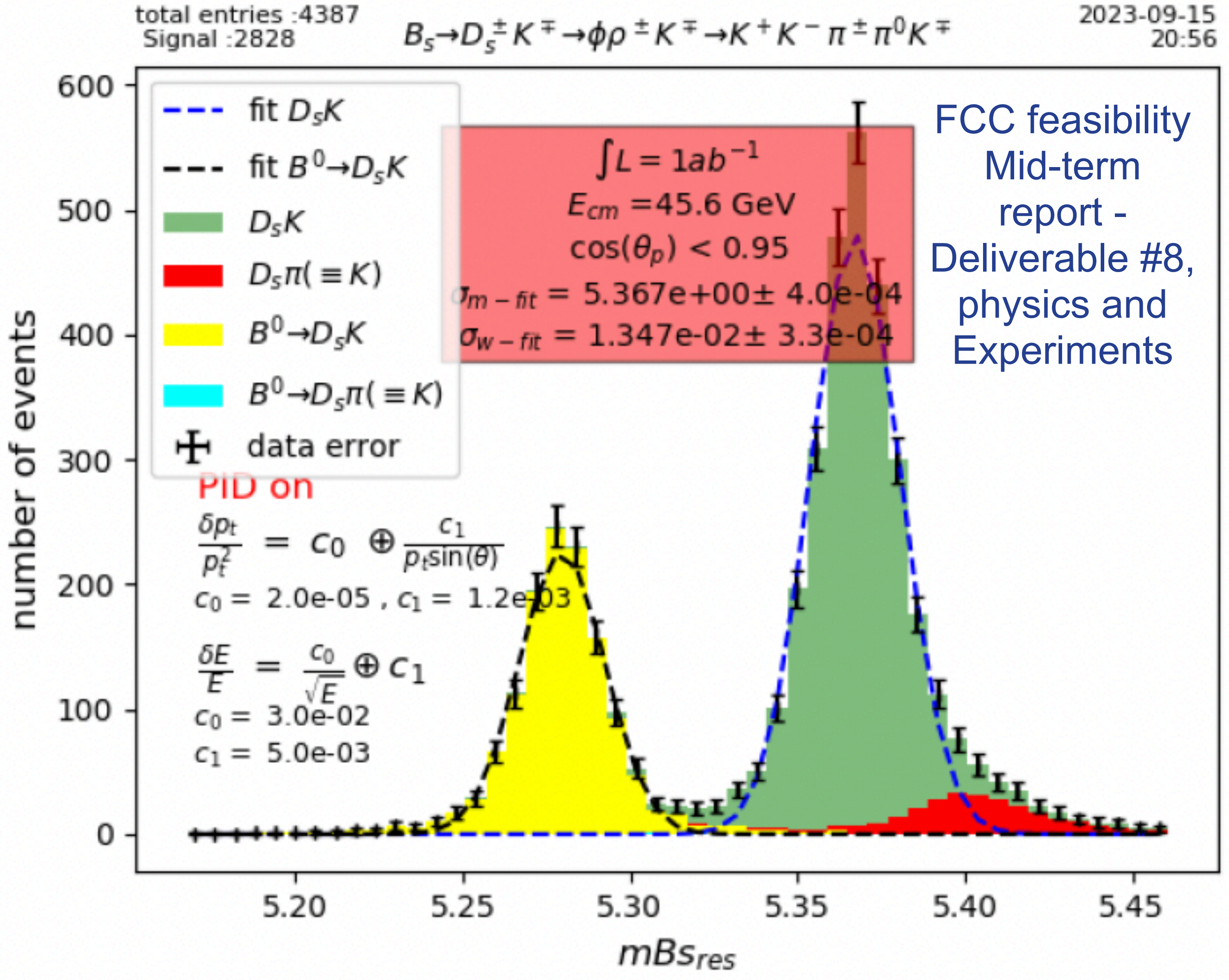
Observable	present value	±	error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration

TOP AND FLAVOUR

- Threshold region: most precise measurements of top quark mass and width, FCNC…
- Flavour factory
  - Clean environment, precise momentum of b/c/τ pairs from Z decays (like in B-factories), ~10 times more bb/cc than final Belle-II statistics
- Potential in boosted b/τ
  - Higher efficiency than at B factories for modes with missing energy (especially multi-ν) and inclusive modes, smaller uncertainties in lepton ID efficiencies.
- Interesting opportunities:
  - e.g. decays of: Rare b-hadron with ττ pairs in the final state and charged-current b-hadrons with τν in the final state; lepton flavour violating τ decays, or lepton-universality tests in τ decays.



based on CLIC/ILC Top Study EPJ C73, 2540 (2013)



FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

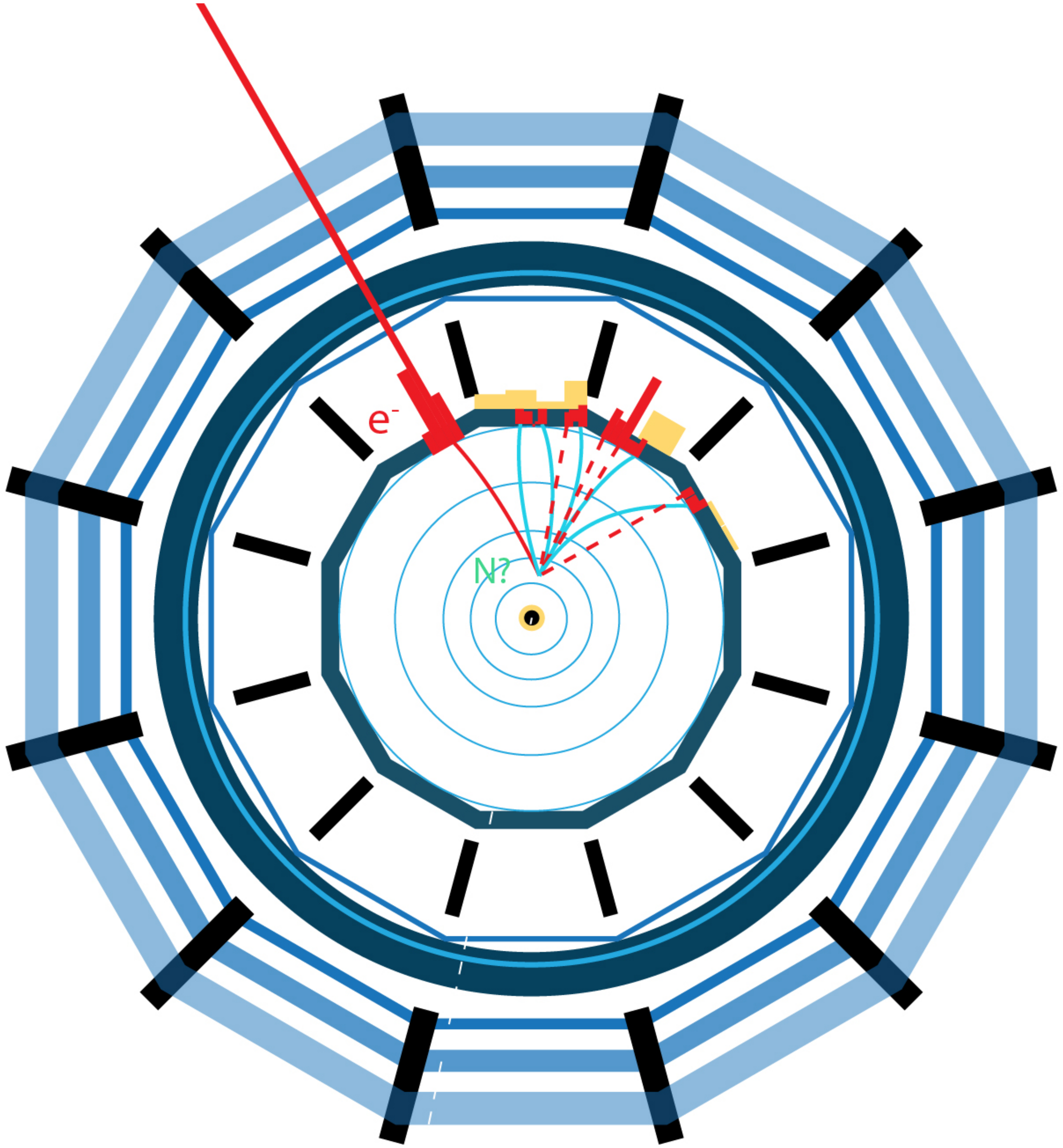
Reconstructed Bs system, 3% energy resolution in the calorimeter

BEYOND THE STANDARD MODEL

- Potential for indirect BSM exploration: SMEFT, and other precision/search cases
- But also direct searches:
  - Clean environment, high luminosity, and large acceptance, direct scrutiny of O(1-100) GeV mass range for new particles
    - Dark/hidden sectors that connect feebly to the SM via mediators (dark photon)
    - Exotic decays of the Z or Higgs boson
  - Specially interesting are signature-driven searches for non-mainstream signals
    - Here come **long-lived particles** again!

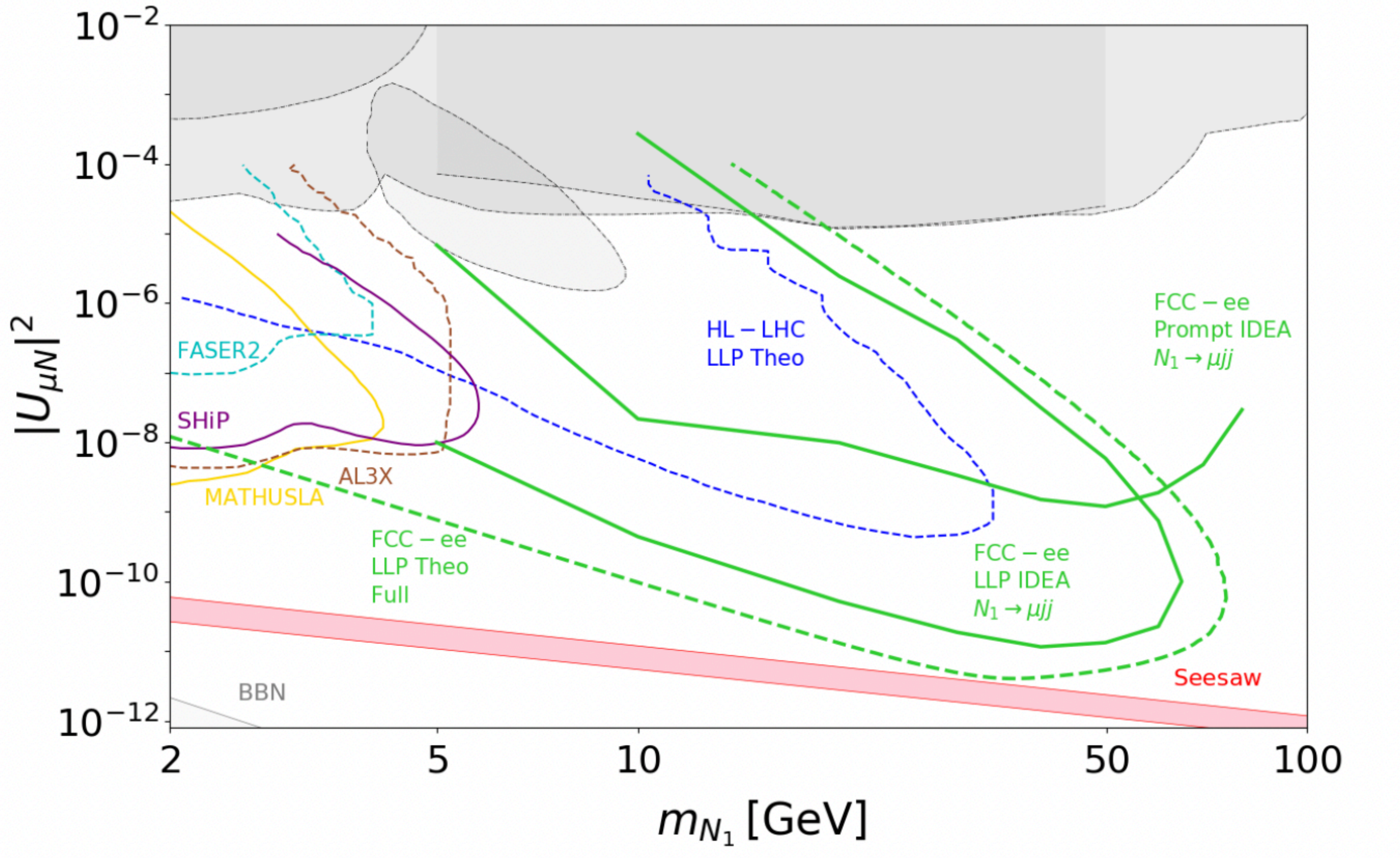
THE FLAGSHIP, HNLs

- Sterile/right-handed neutrinos
  - Could give many answers: neutrino masses, DM, BAU
- Many of the current limits cover large neutrino mixing angles.
  - For small values of the mixing angle → LLP signature (displaced vertex search)
- The FCC-ee will offer a fantastic reach for HNL at the Z-Pole
  - FCC will probe space not constrained by astrophysics or cosmology, complementary to other dedicated experiments



HEAVY NEUTRAL LEPTONS

- Working towards a complete sensitivity analysis implemented in FCC software
- A few channels (eeν, μjj, μμν) considered prompt and long-lived



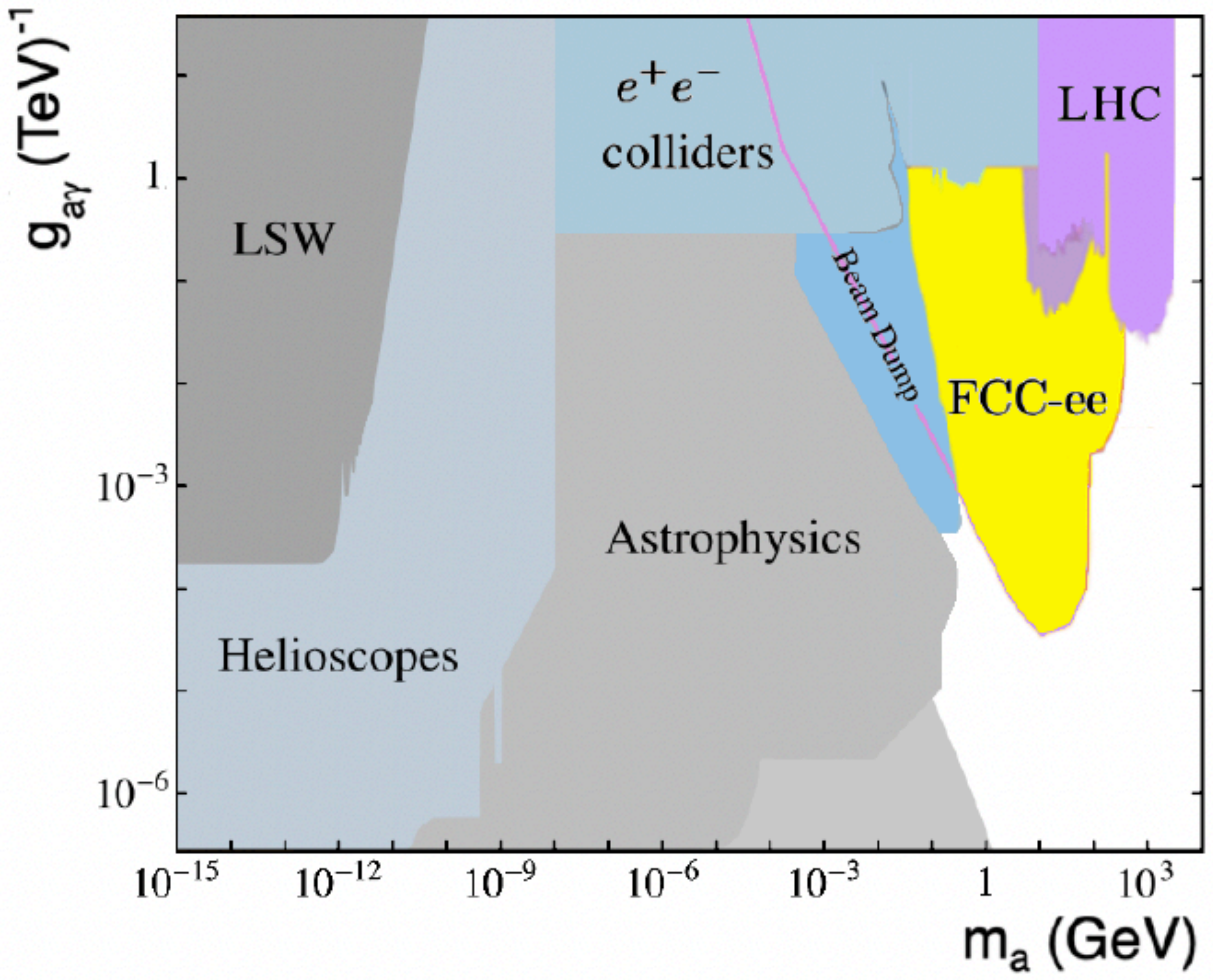
FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

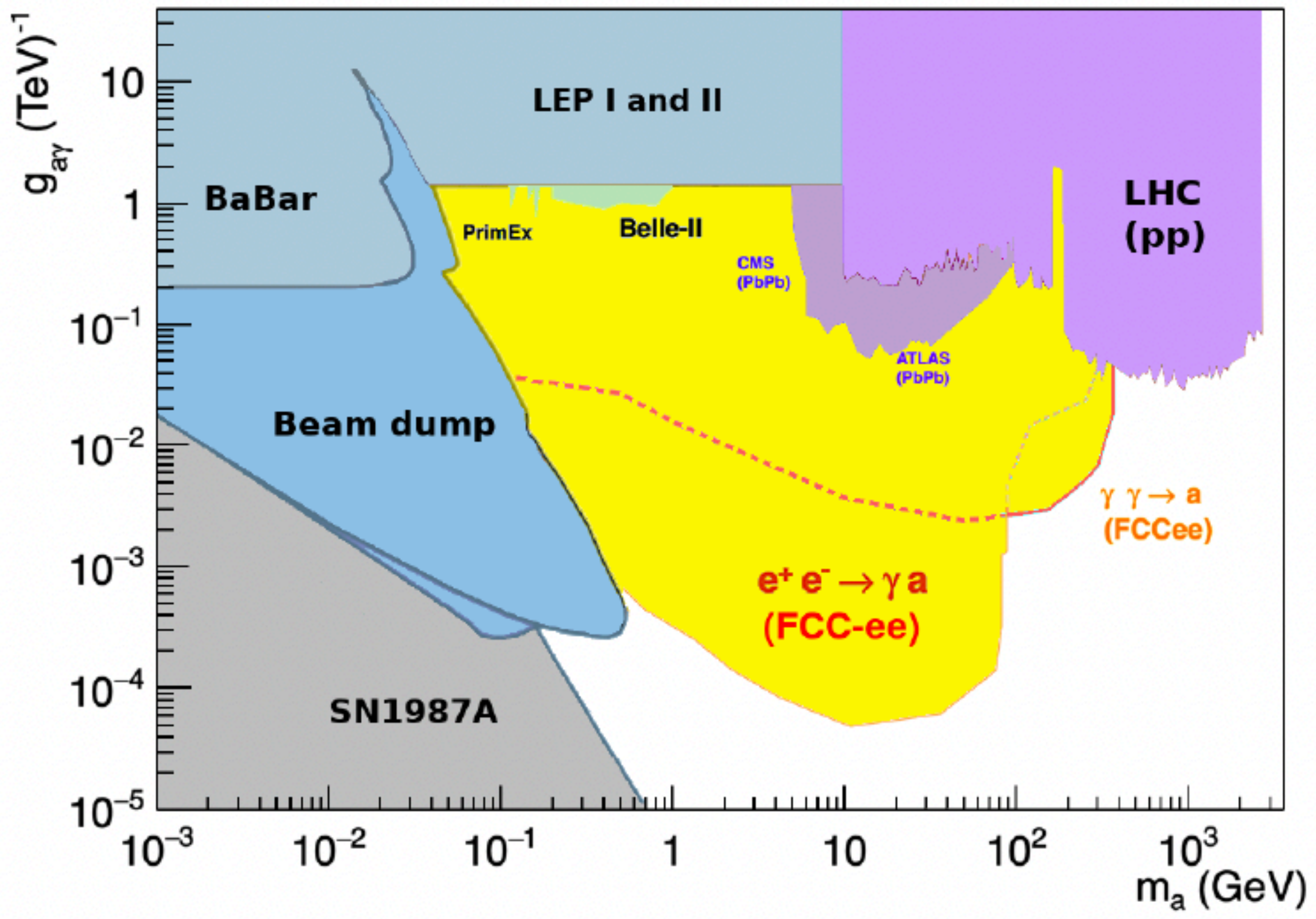
arXiv:2203.05502

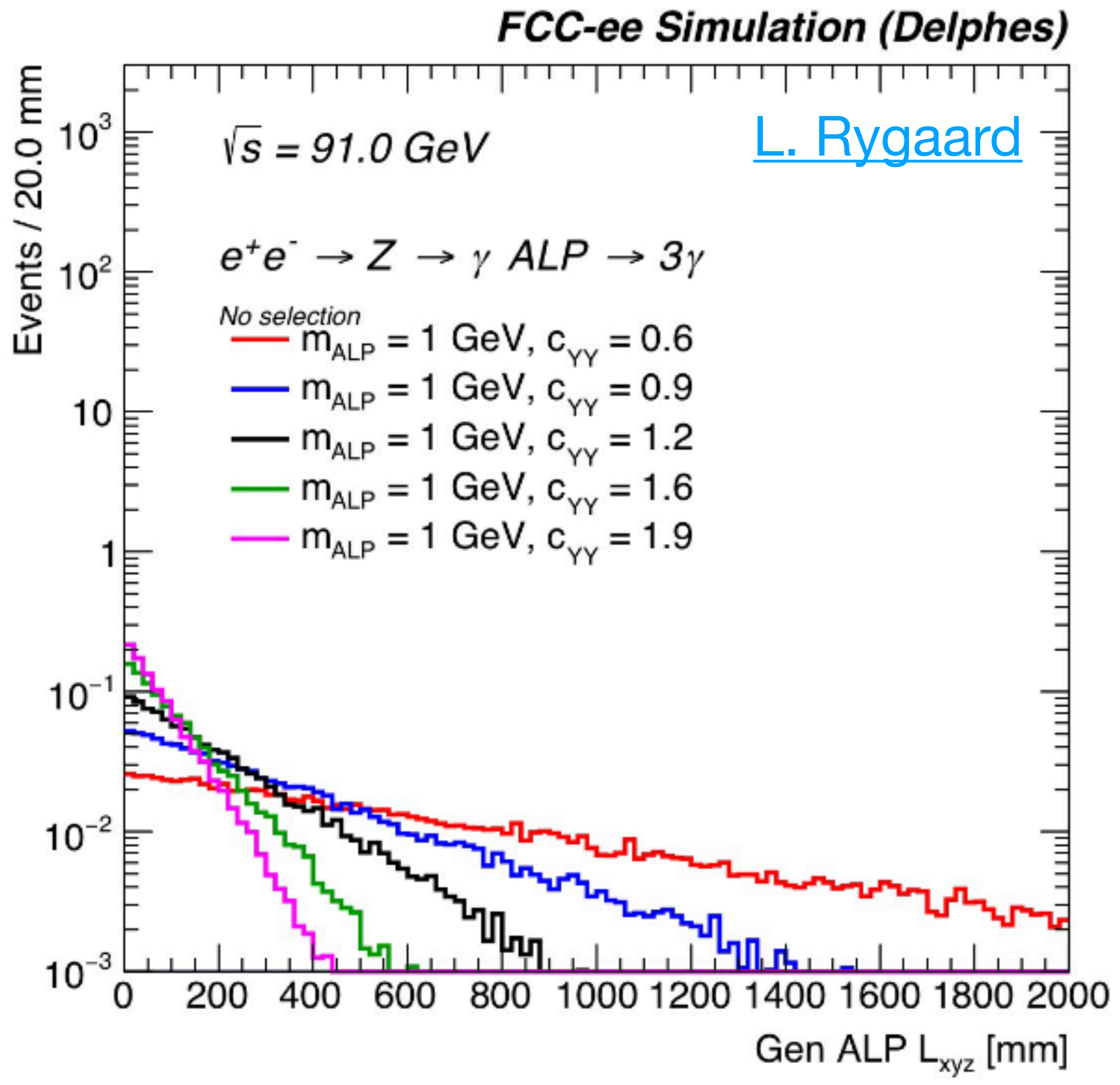
AXION-LIKE PARTICLES

extending current limits > than 3 orders of magnitude

- **Unconstrained mass range (0.1 – 100 GeV) accessible via e+e– → aγ and e+e–→ a, a → γγ. Sensitivity to couplings to < 10–4 TeV-1**
- **At small coupling values → macroscopic decay lengths**





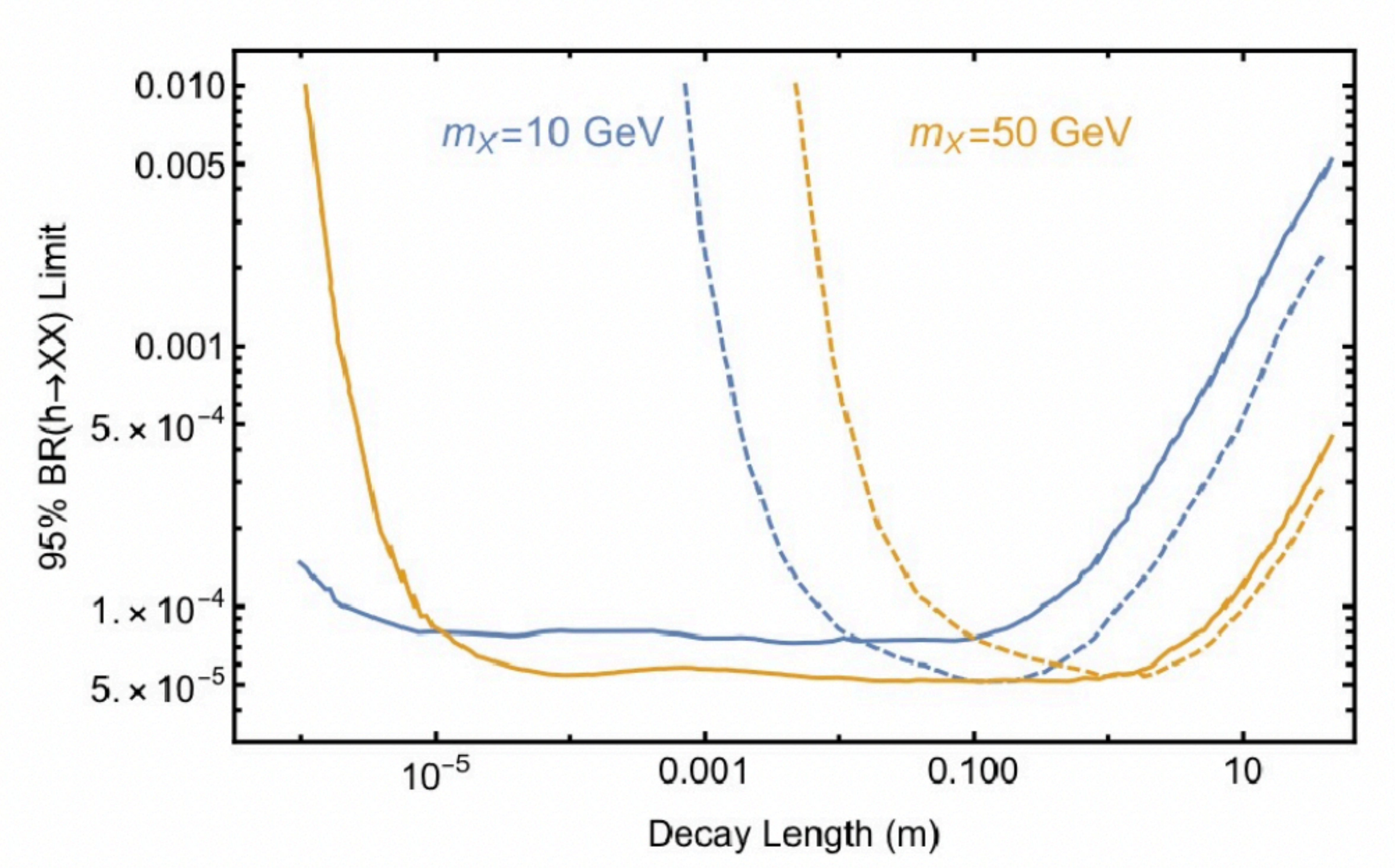


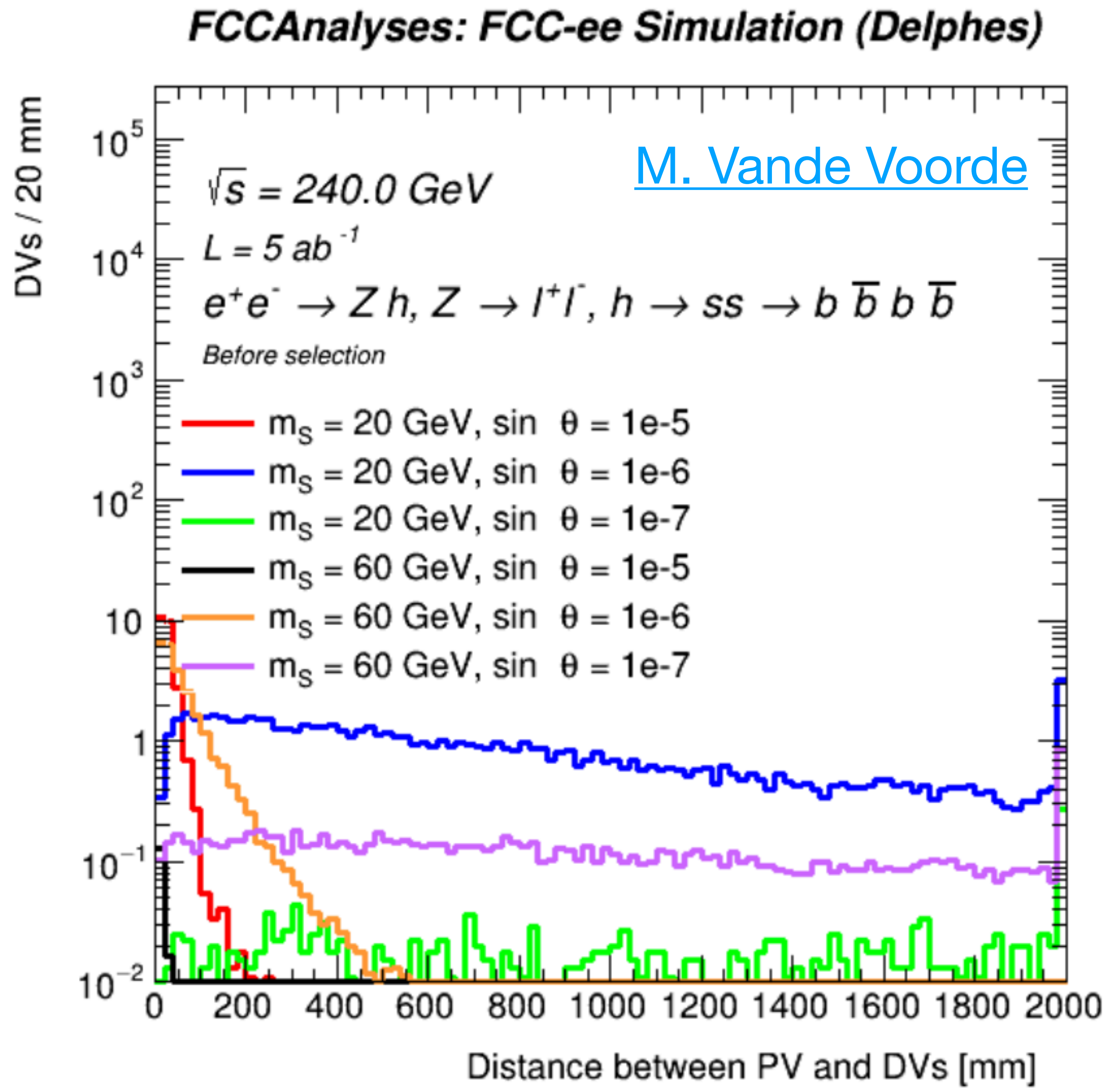
Truth-level decay length of the ALP

FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

EXOTIC HIGGS BOSON DECAYS

- Possible and present in many models:
  - SM extensions with scalars/fermions/ vectors, MSSM, NMSSM, Hidden Valleys, Twin Higgs (arXiv:1312.4992, arXiv:1812.05588, arXiv:1712.07135)





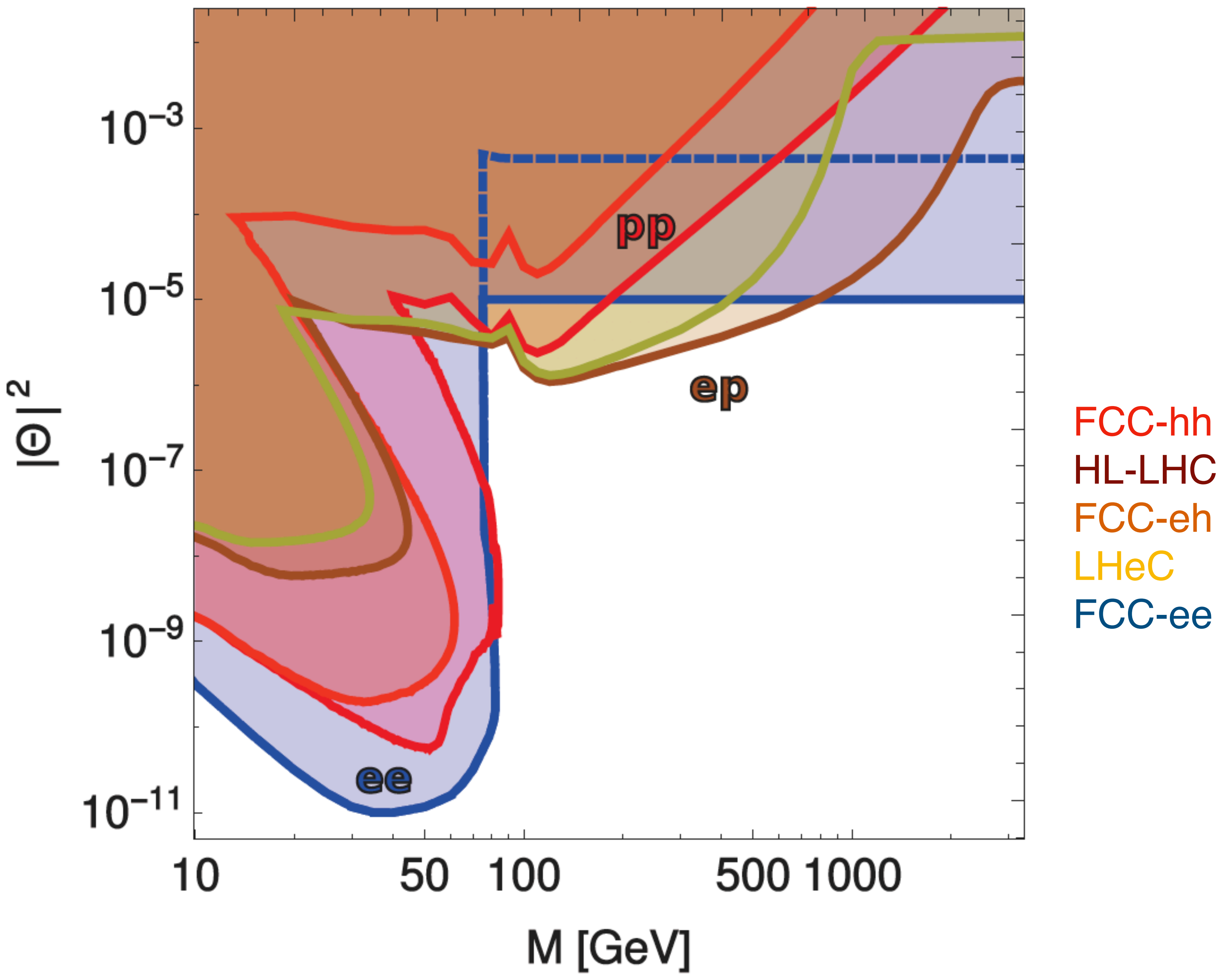
M. Vande Voorde

FCC feasibility Mid-term report - Deliverable #8, physics and Experiments

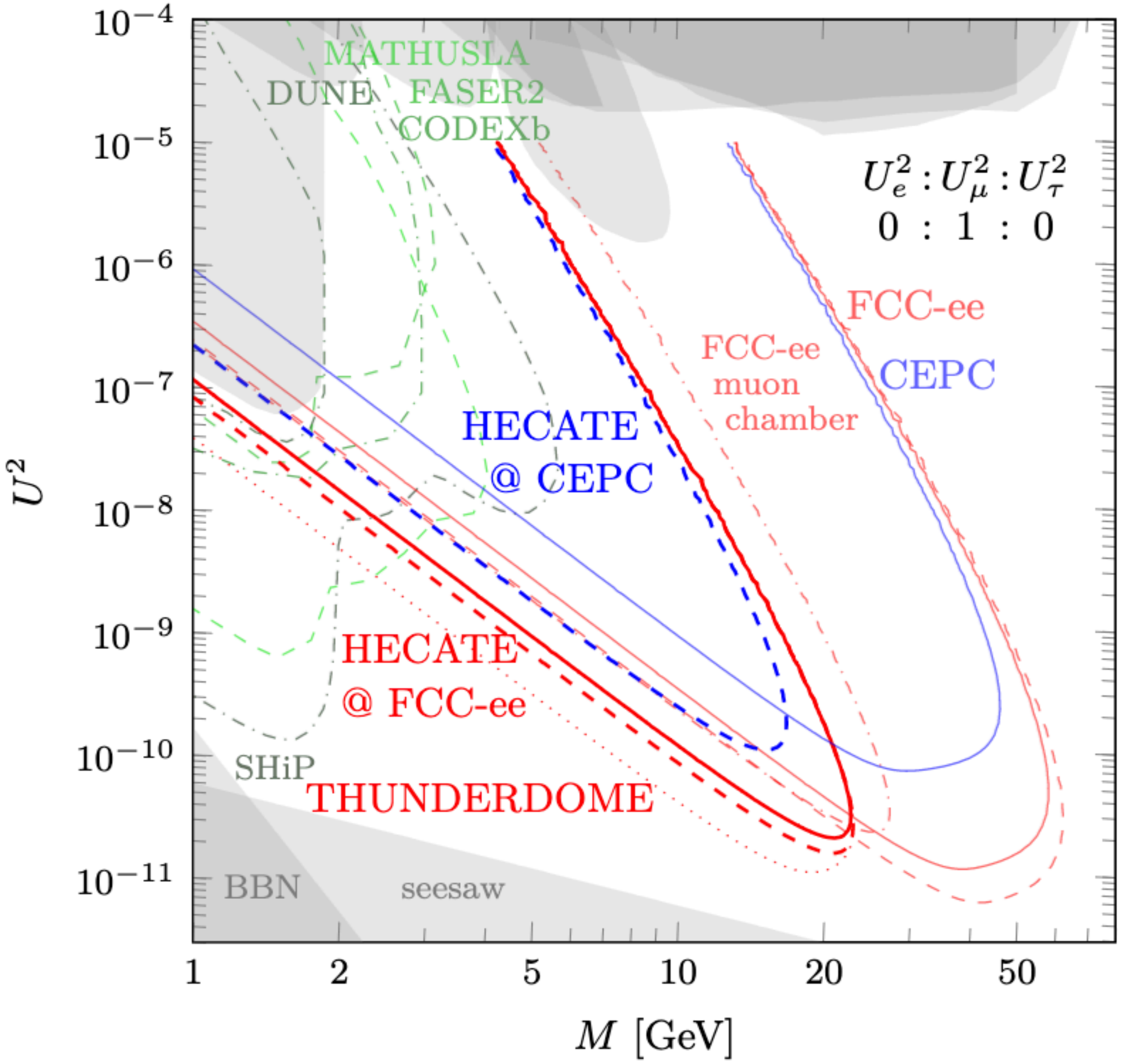
SYNERGIES ACROSS STAGES, RUNNING SCENARIOS

- In FCC-ee: precision measurements in W and Z will have a positive impact in the Higgs couplings measurements in the Higgs runs
- Precision Higgs measurements in FCC-ee will have an impact in the Higgs self-coupling studies in FCC-hh
- Coverage for prompt and long-lived searches will be very different in the different stages

arXiv:1612.02728



EXTRA DETECTORS!



- Following the plans for different additional LLP experiments at the HL-LHC it is possible to also envision similar concepts at other future colliders
- HECATE: A long lived particle detector concept for the FCC-ee or CEPC: arXiv:2011.01005
- The civil engineering of the FCC-ee will have much bigger detector caverns than needed for a lepton collider (to use them further for a future hadron collider)
- We could install extra instrumentation at the cavern walls to search for new long lived particles

FAr Detectors
arXiv:1911.06576
for ALPs at FCC-ee, CepC
arXiv:2201.08960

BUT THIS IS JUST ONE OPTION

Timeline for the update of the European Strategy for Particle Physics

End September 2024

Council appointment of the members of the **PPG** and decision on the venue for the **Open Symposium**

December 2024

Council decision on the venue for the **ESG Strategy Drafting Session**

31 March 2025

Deadline for the submission of main input from the community

26 May 2025

Deadline for the submission of additional national input in advance of the **Open Symposium**

23-27 June 2025

Open Symposium

End September 2025

Submission of the “Briefing Book” to the **ESG**

14 November 2025

Deadline for the submission of final national input in advance of the **ESG Strategy Drafting Session**

1-5 December 2025

ESG Strategy Drafting Session

End January 2026

Submission of the draft strategy document to the Council

March and June 2026

Discussion of the draft strategy document by the Council and **updating of the Strategy**

LET’S RECAP

WE HAVE EXPLORED

- We had a look at our current best tool for discovery and precision measurements (the LHC)
- We reviewed briefly how the general purpose LHC experiments work
- And how they take data
- We have taken stock on how much data we have available and how much is coming
- We had gone back in time to the early LHC data
- We have looked at the early SM measurements
- We started simple and by now have entered precision regime in many areas
- We mentioned the Higgs boson discovery

BUT TOGETHER WITH THE HIGGS: NO OTHER PARTICLE

- The LHC is made for searches an we certainly are searching
- We started by the easier cases and built to more and more complicated ones
- We are setting limits and cornering many new physics models
- We are on the brink of the high-luminosity upgrade of the LHC
- We will get enough lumi to see Higgs bosons produced in pairs
- There are exciting options for searches too
- However, the HL-LHC will be limited
- And so we are planning on the next collider

It could be YOUR collider, get involved!

CREDITS

Future colliders:
https://ecfa.web.cern.ch/
https://fcc-ped.web.cern.ch/
https://clicdp.web.cern.ch/
https://linearcollider.org/
http://cepc.ihep.ac.cn/
https://muoncollider.web.cern.ch/

Most of the pictures in this lecture belong to CERN and can be found in the document server:
https://cds.cern.ch/
https://home.cern/

Physics results from the main LHC experiments can be access in their websites:
https://atlas.cern/
https://cms.cern/
http://lhcb.web.cern.ch/
https://alice.cern/

And the public repositories of results:
https://arxiv.org/
https://inspirehep.net/

I have re-used some of my material from other lectures (at schools and in Uppsala University) and slides presented at seminars/workshops/conferences as well as outreach talks.

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