Physics at Energy Frontier
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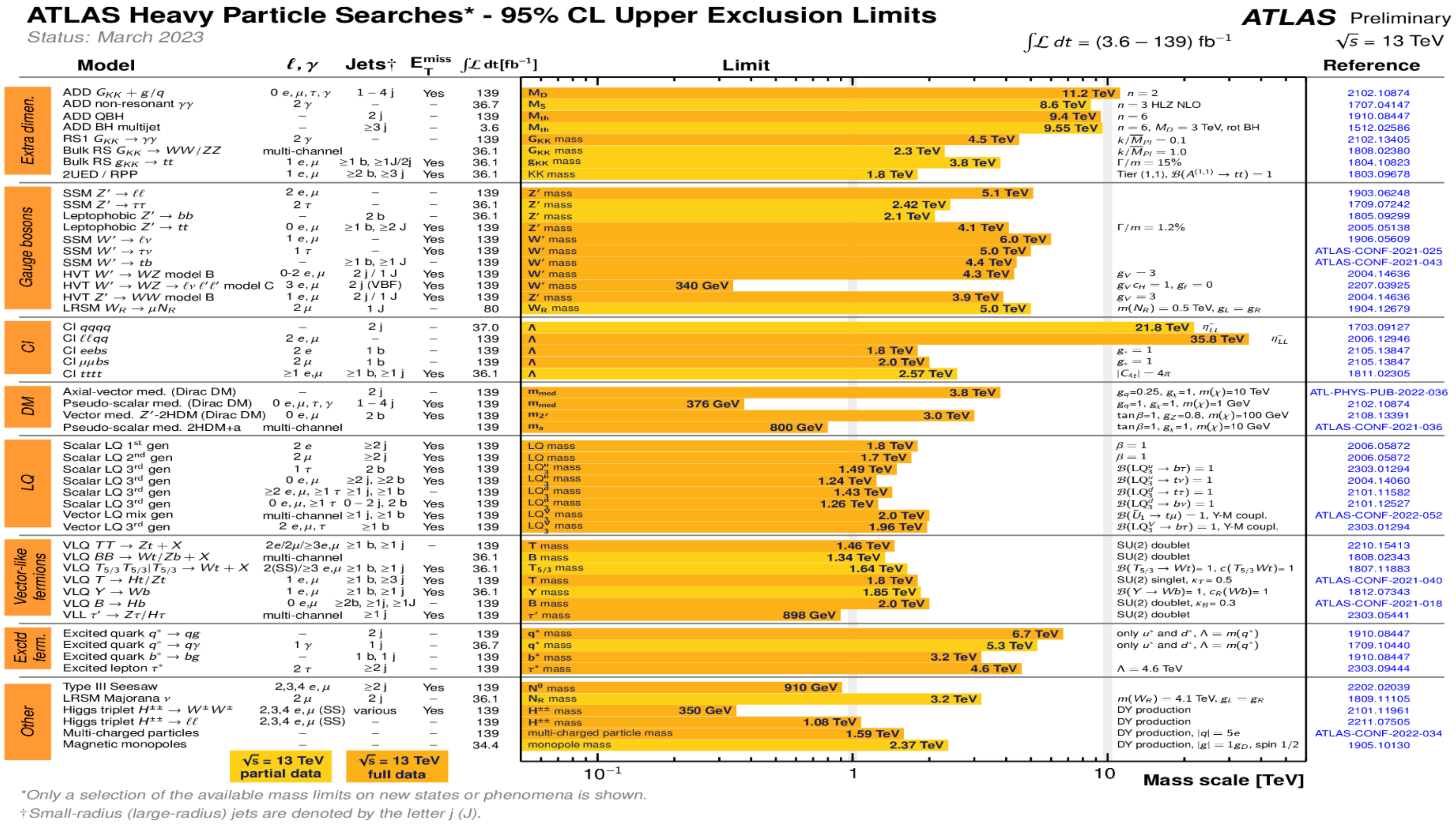
Problems in SM

- Dark Matter in the Universe
- \- Particle – antiparticle asymmetry in the Universe, numbers!
- CP violation CKM phase – too small efect
- \- Neutrino masses, mixing, oscillations
- \- Very small cosmological constant. Very weak gravity interaction
- \- Muon (g-2)μ anomaly (about 3.5 σ → 4.2 σ BNL)
- \- B-anomalies (about 4.5 σ)
- \- CDF W-mass anomaly (about 7 σ)



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,μ,τ,γ	1 – 4 j	Yes	139	M_D	11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	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 γ	–	–	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,μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e,μ	≥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,μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	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,μ	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	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,μ	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,μ	2 j / 1 J	Yes	139	Z' mass	3.9 TeV	$g_V = 3$	2004.14636
	LRSM $W_R \to \mu N_R$	2 μ	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,μ	–	–	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 μ	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	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,μ,τ,γ	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,μ	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 μ	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	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,μ	≥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	≥2 e,μ, ≥1 τ	≥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,μ, ≥1 τ	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_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,μ,τ	≥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/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 $T_{5/3}T_{5/3}\vert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥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,μ	≥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,μ	≥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	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	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 τ	≥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	N^0 mass	910 GeV		2202.02039
	LRSM Majorana ν	2 μ	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,μ (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,μ (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, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

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

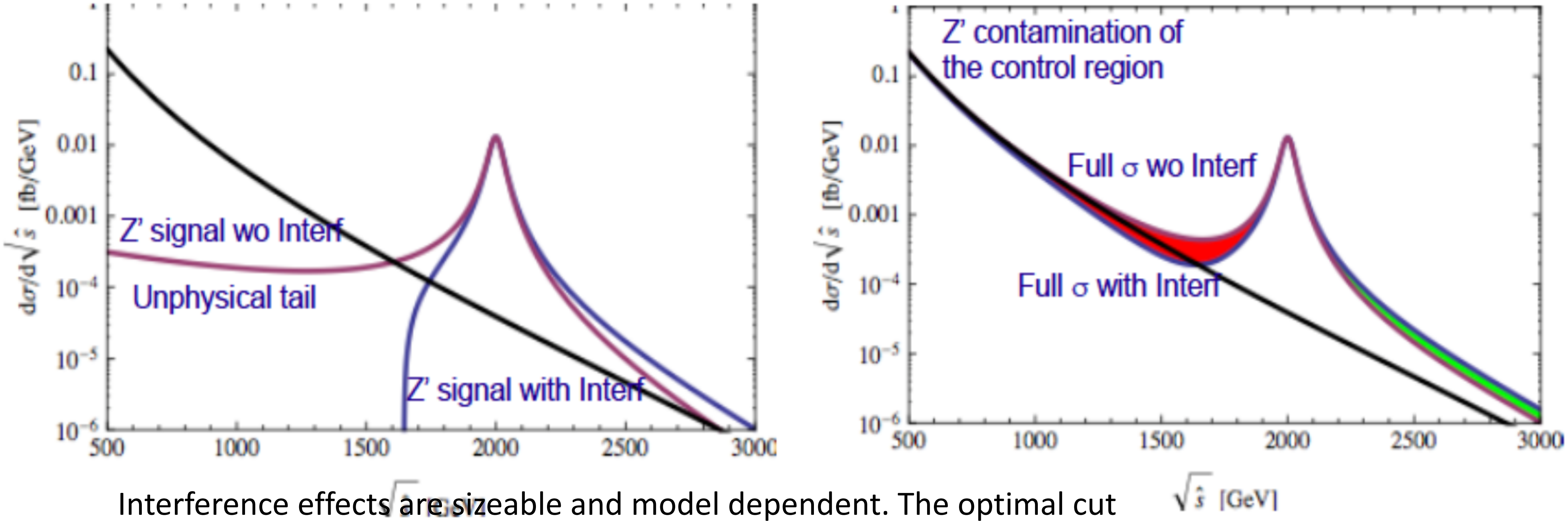
†Small-radius (large-radius) jets are denoted by the letter j (J).

More Problems in SM

- What is a generation? Why there are only 3 generations?
- How quarks and leptons related to each other, what is a nature of quark-lepton analogy?
- What is responsible for gauge symmetries, why charges are quantize?
- Are there additional gauge symmetries?
- What is responsible for a formation of the Higgs potential?
- To which accuracy the CPT symmetry is exact?
- Why gravity is so weak comparing to other interactions?

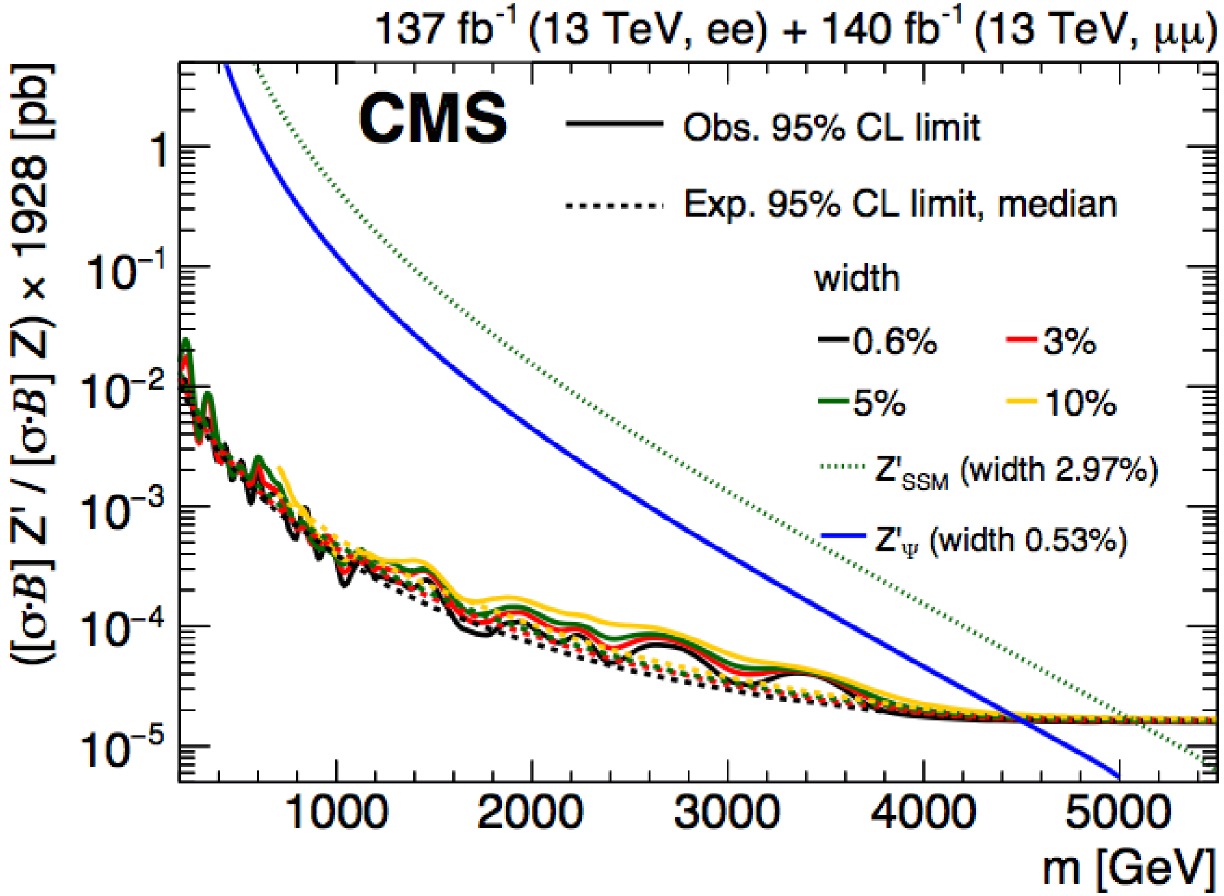
Z’-boson search strategy

pp → γ, Z, Z’ → lepton pair

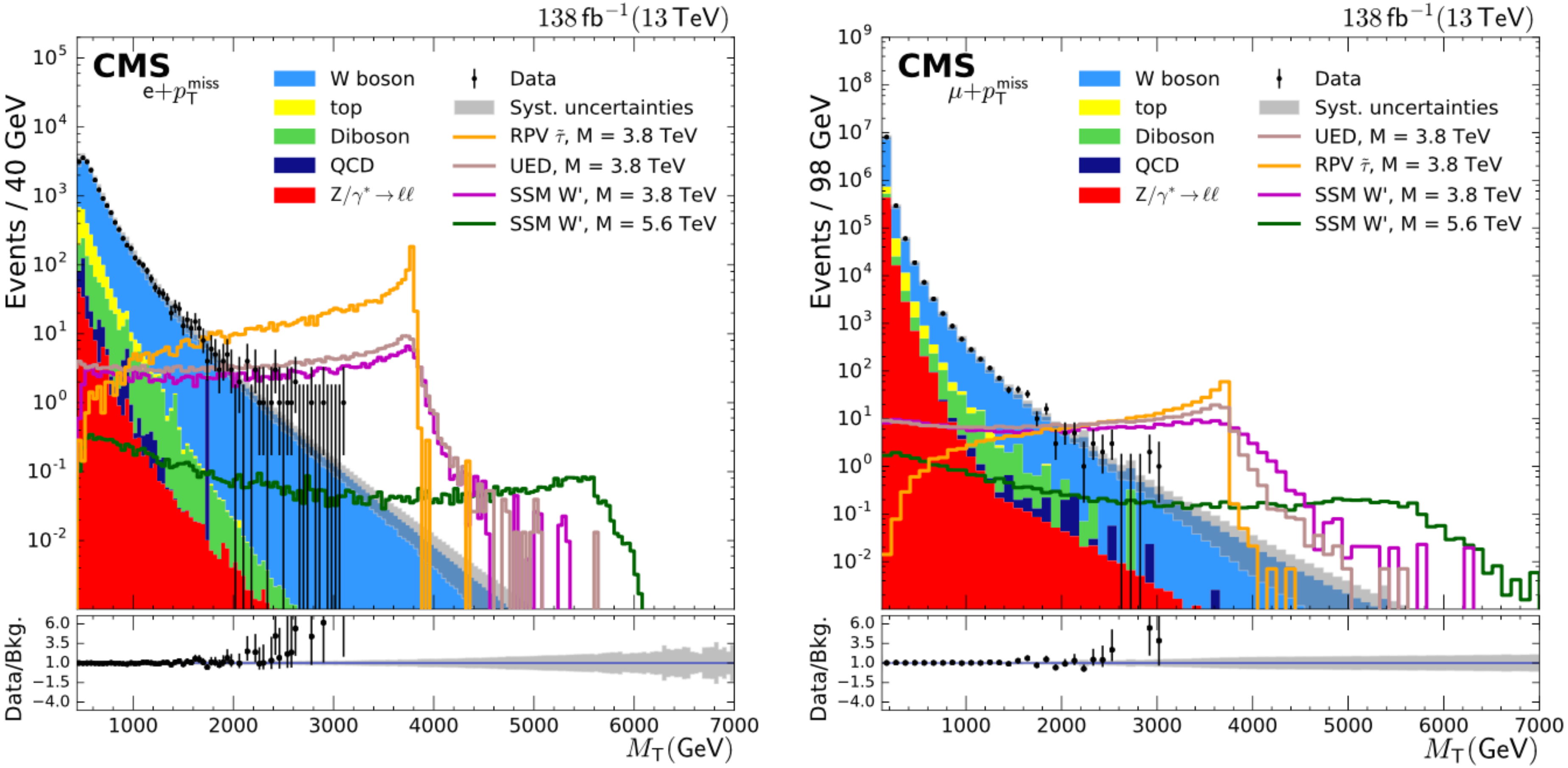


Interference effects are sizeable and model dependent. The optimal cut |M(ll)-MZ’| < 5% ELHC reduces them to O(10%) for all single narrow Z’s thus allowing
for model-independent analyses.

95% C.L. Exclusion Limits



W’-boson search strategy



Vector Like Quarks (VLQs)

- The “vector-like” part of their name means that they are not “chiral”. That is, the left-handed and right-handed versions of the them interact equally with the weak interaction, unlike the real quarks of the Standard Model, where only the left-handed ones do so. This modification means that vector-like quarks don’t have to get their mass from interactions with the Brout-Englert-Higgs field, and hence are not excluded by LHC measurements involving the Higgs boson.

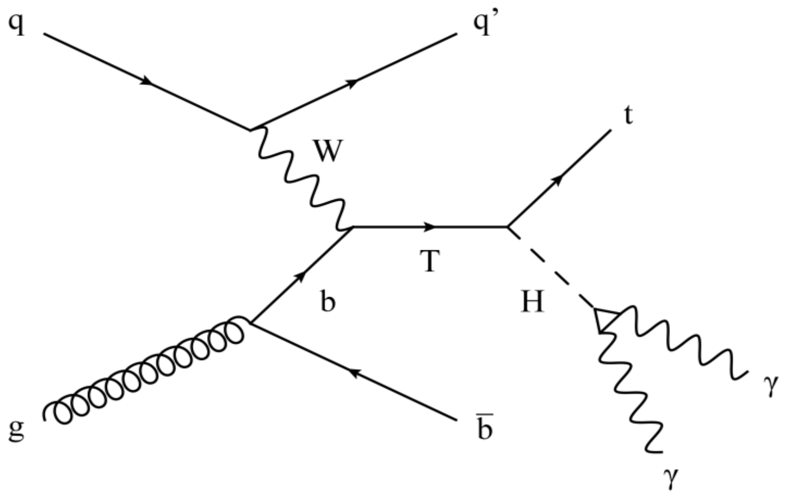
Vector Like Quarks (VLQs)

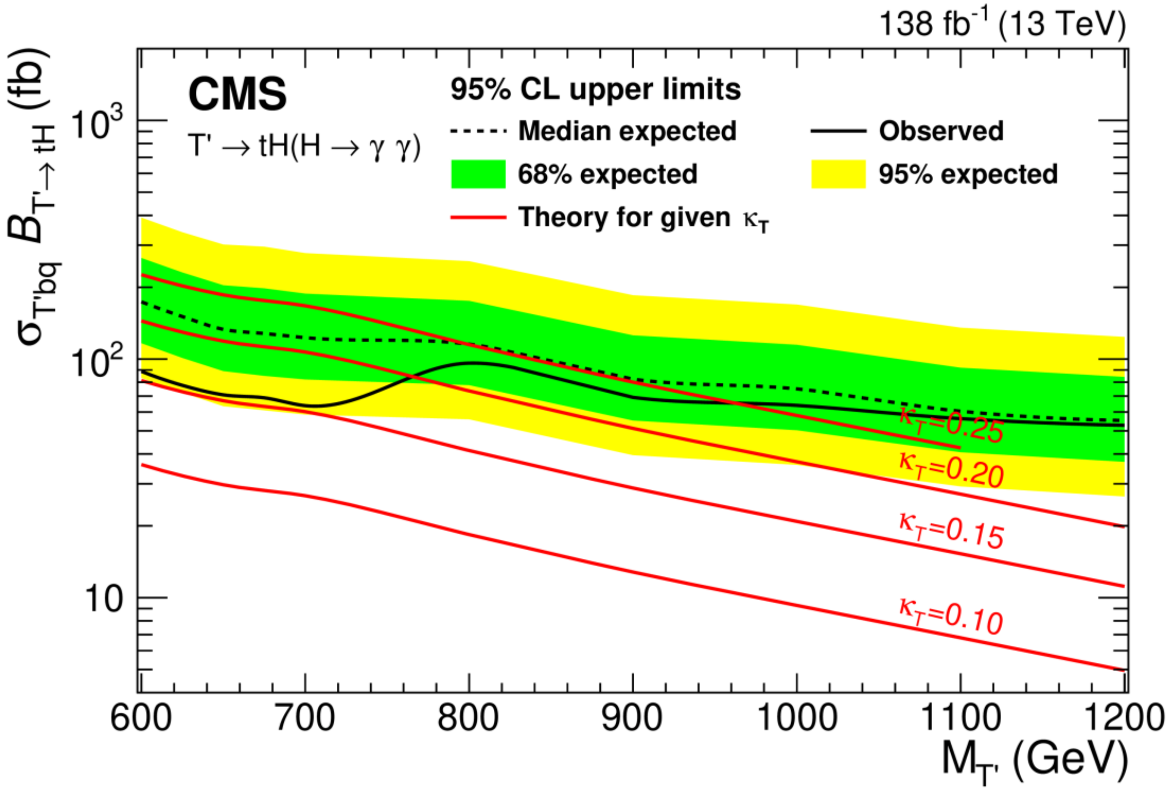
- Yukawa are completely free parameters) and to the Higgs mass stability itself (divergence of radiative corrections), which can probably be explained, extending the SM to encompass new, yet undiscovered, states.
- Vector like quarks (VLQ): colored 1⁄2 spin particles, left and right components are symmetric
- Decays to heavy SM objects, H/W/Z/Top

Vector Like Quarks (VLQs)

- In minimal models, VLQs exist as either singlets(T and B) or as a doublet(T, B), each with different **B**ranching **F**ractions:
- singlet **50 %** ($T \rightarrow bW, B \rightarrow tW$),
- **25%**($T \rightarrow tH$ and $\rightarrow tZ, B \rightarrow bW$ and $\rightarrow bZ$)
- doublet **50%**($T \rightarrow tH \text{and} \rightarrow tZ, B \rightarrow bW \text{and} \rightarrow bZ$)

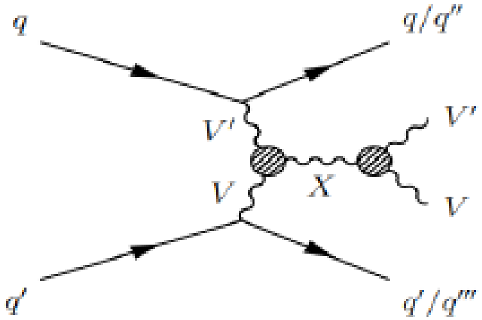
$T \rightarrow tH(H \rightarrow \gamma\gamma)$



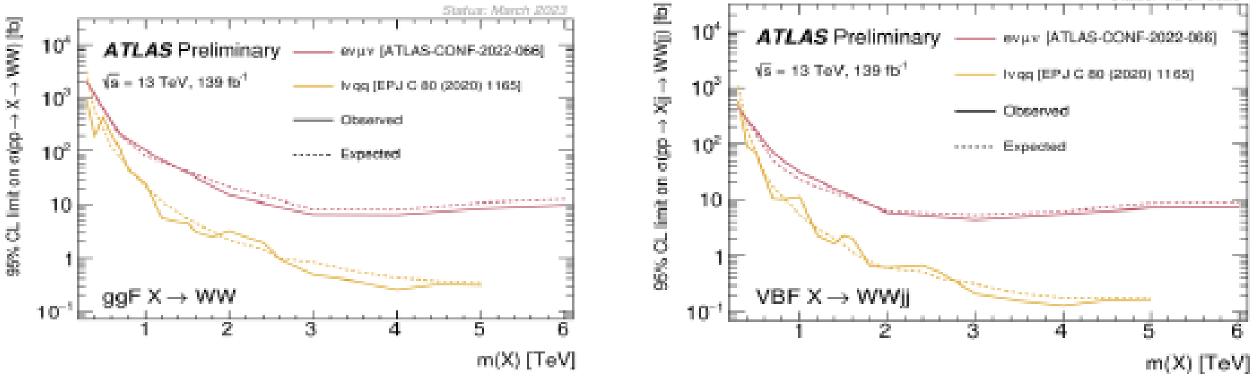


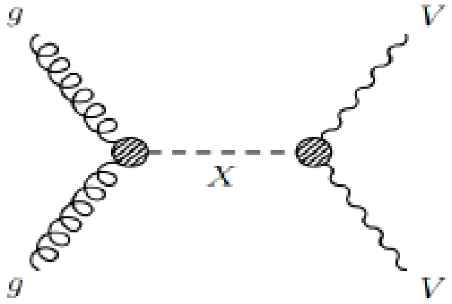
Di-boson Resonance Summary

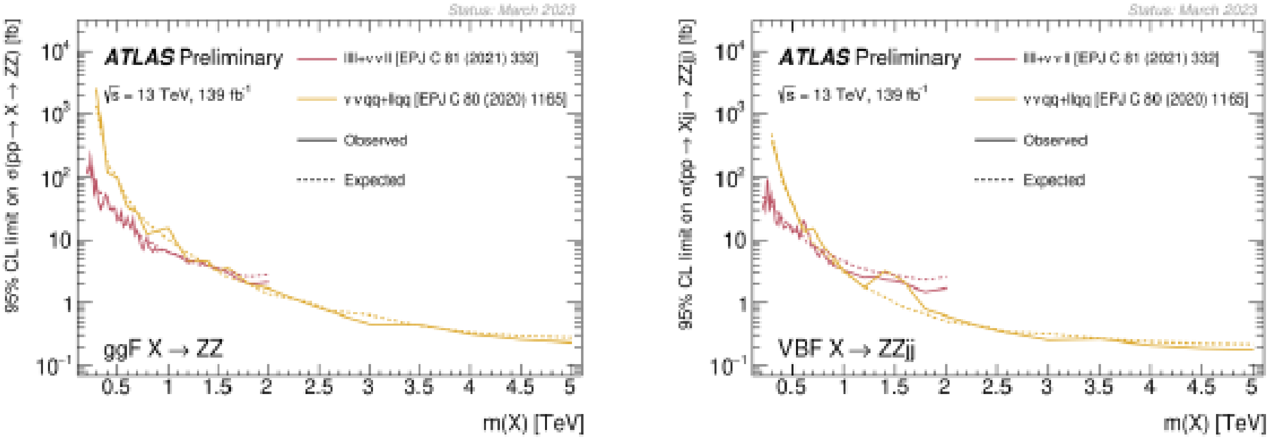
- Summary of all ATLAS Run-2 di-boson searches
  - **WW**, WZ, **ZZ**, WH, ZH, $\gamma\gamma$. ATL-PHYS-PUB-2023-007



95% CL-Exclusion limits for X→WW in ggF (Left) and VBF (Right) production. (Interpreted in context of RS-model)







95% CL-Exclusion limits for X→ZZ in ggF (Left) and VBF (Right) production. (Interpreted in context of narrow-width X approximation)

Heavy Neutral Leptons - Motivation

- SM neutrinos have mass:
  - need right-handed neutrino for mass terms
- **SM** + **n $\geq$ 1 *sterile* right handed neutrinos**
  - **Heavy Neutral Leptons (HNL)**
    - O(1-100) GeV sterile neutrino
    - **see-saw mechanism**
  - O(keV) sterile neutrino - **Dark matter candidate**
  - **Early universe CP violation enhancement**

LHC HNL Searches

- **Run2 searches!**

- **Low mass displaced - SM + ν_R**
  - **ATLAS:** HNL decays to displaced dilepton vertex search - arXiv:2204.11988
  - **CMS:** HNL decays to displaced dilepton vertex - arXiv:2201.05578
    HNL decays to displaced lepton + jets search - CMS-PAS-EXO-21-013

Moriond 2023

- **High mass - W_R and WW scattering**
  - **ATLAS:** Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with charged leptons and jets - arXiv:1809.11105
  - **CMS:** Search for a right-handed W boson and a heavy neutrino **-** arXiv:2112.03949
  - **ATLAS:** Search for Majorana neutrinos in same-sign WW scattering events **-** EXOT-2020-06
  - **CMS:** heavy Majorana neutrinos and the Weinberg operator through vector boson fusion arXiv:2206.08956

NEW!

Tracker DV searches – ATLAS & CMS

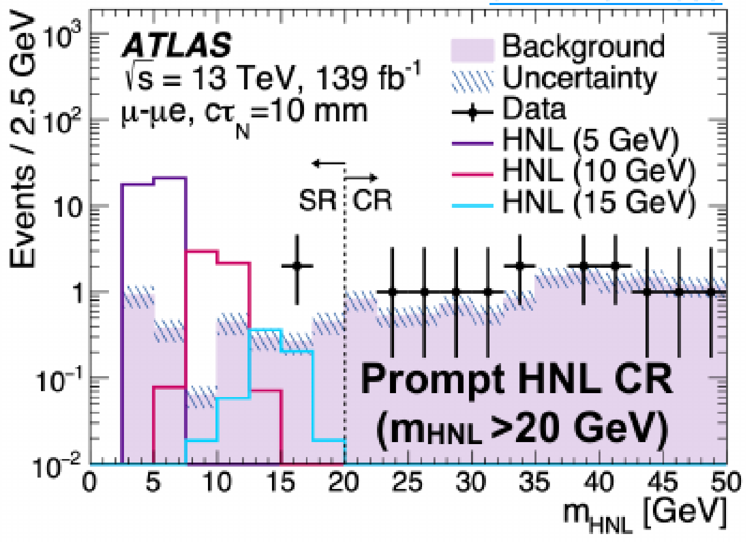
ATLAS

Large radius tracking:

Dedicated DV algorithm, sequential Kalman filter

- Background: Prompt ℓ + DV uncorrelated pairs

arXiv:2204.11988

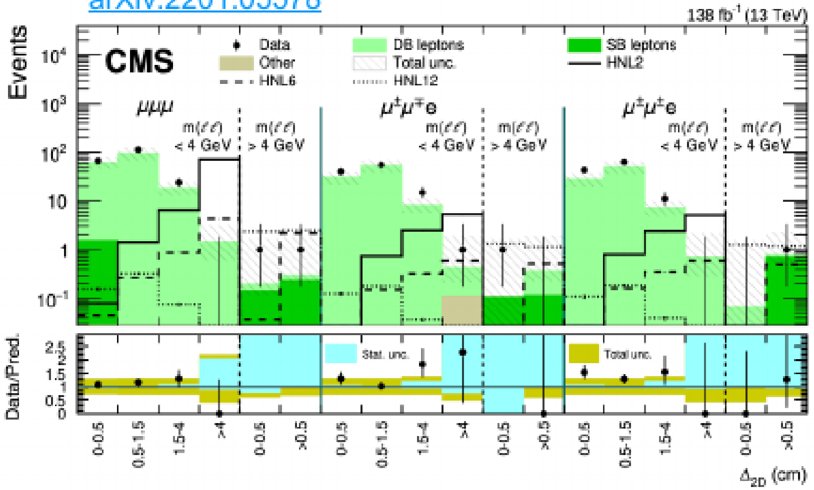


Ra

CMS

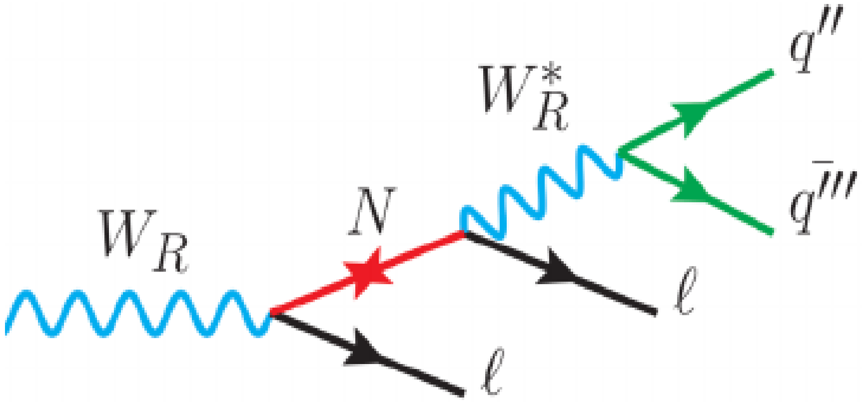
- $m_{\ell'\ell''} \times \Delta_{2D}^{\ell'\ell''}$ categories:
  - Kinematics x lifetime signal enhancements
- Δ_{2D} is DV transverse displacement

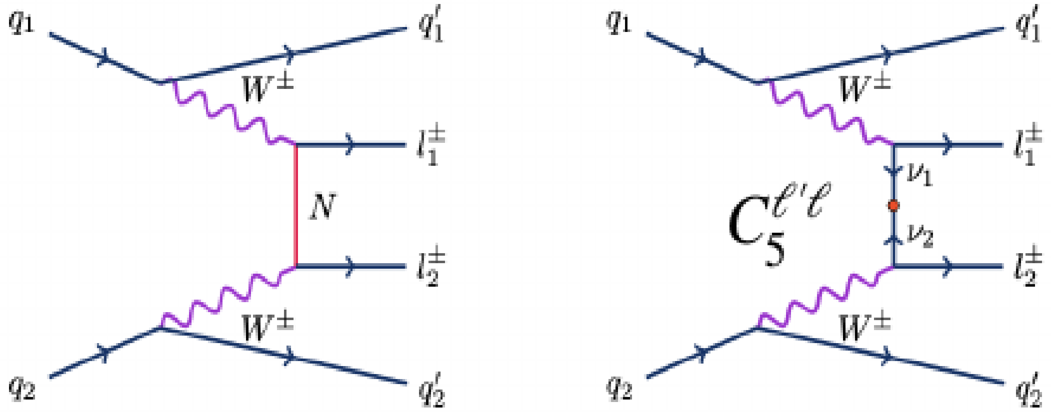
arXiv:2201.05578



m_{HNL} in multi-TeV scale

- **SM + SU(2)$_{R}$:** $W_R \to N + \ell$
- **SMEFT -** N **OR** Weimberg $C_5^{\ell'\ell}$





complementary final states

If $M_{W_R} \gg m_N$ - Boosted regime:

2 leptons + 2 jets

High $\Delta\eta$ jets separation

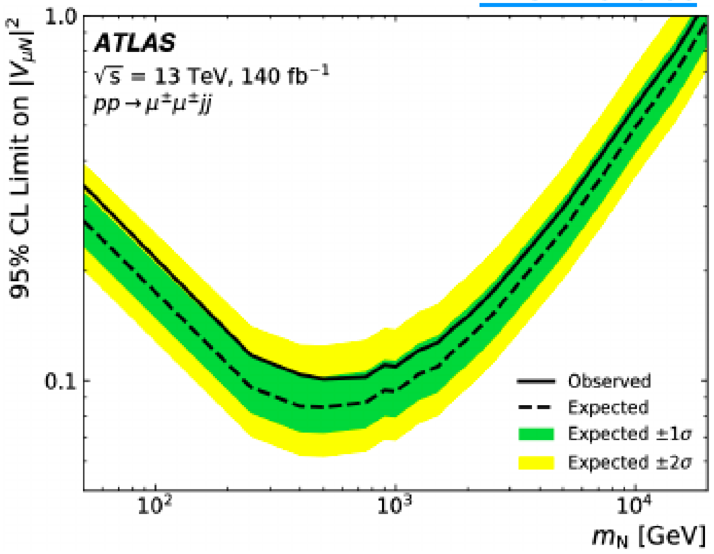
lepton(s) + 1 jet

μ signatures only

W±W± scattering results

ATLAS

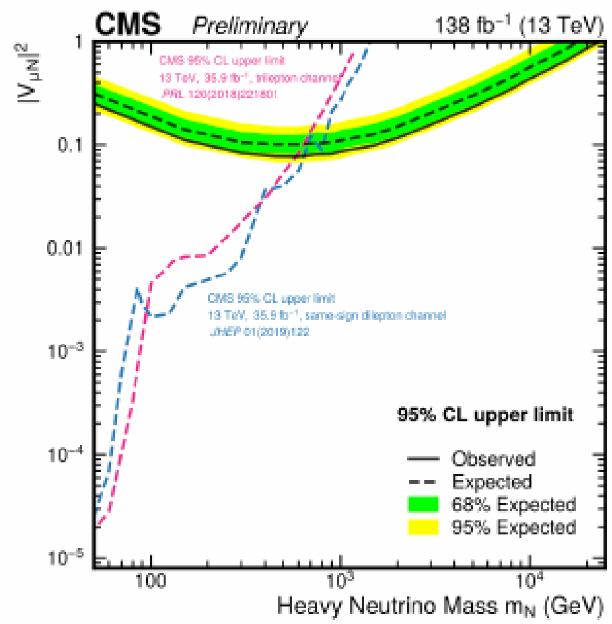
EXOT-2020-06



Competitive exclusions
for multi-TeV scale

$m_{\mu\mu}^{\mathrm{EFT}}$**(observed) upper limit 16.7 GeV**

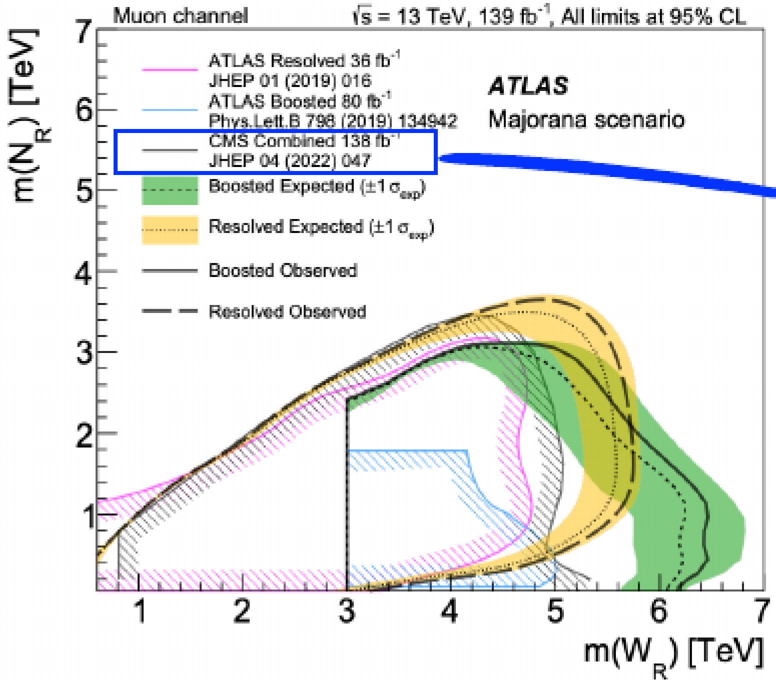
CMS arXiv:2206.08956



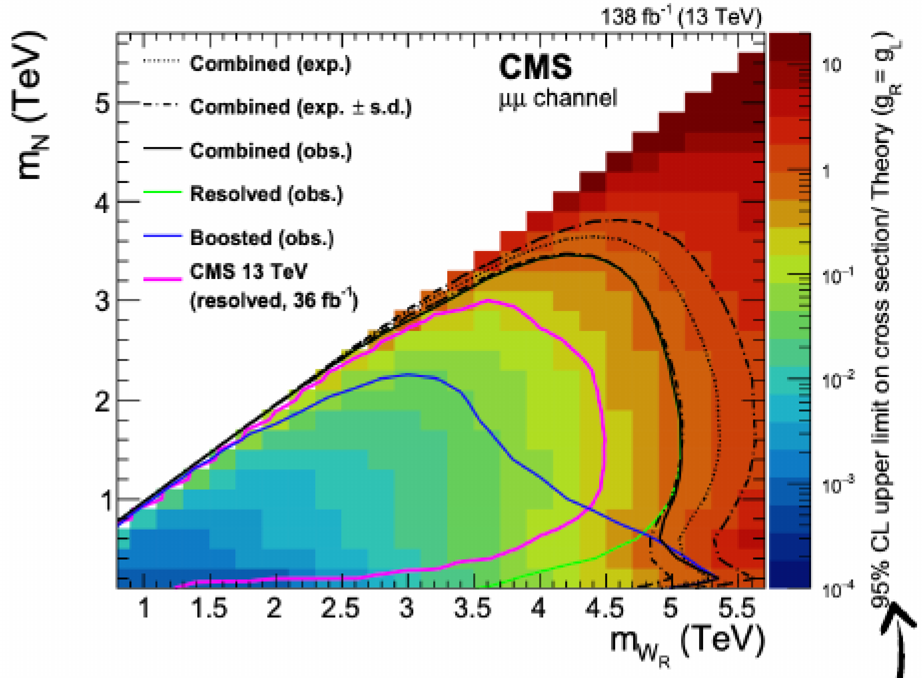
$m_{\mu\mu}^{\mathrm{EFT}}$**(observed) upper limit 10.84 GeV**

W_R -> N + l results

arXiv:1809.11105 **Moriond 2023**



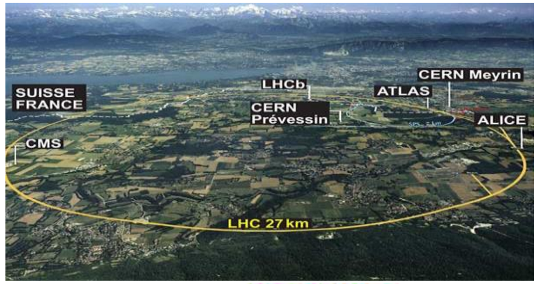
arXiv:2112.03949



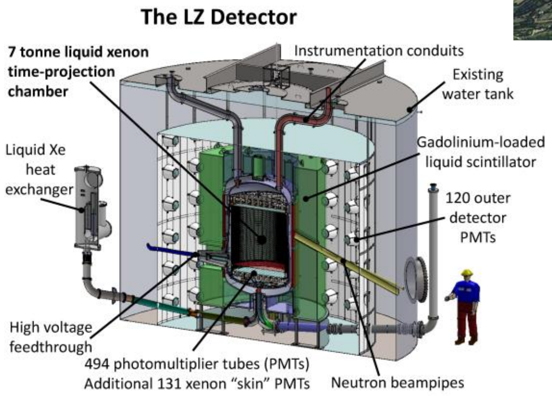
Most stringent limit to date to W_R N events

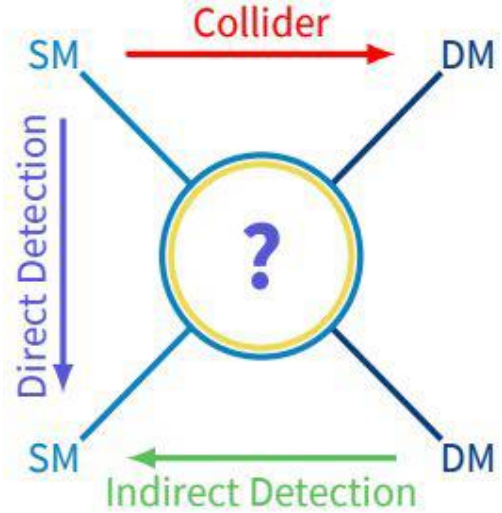
$\sigma_{95\%C.L}/\sigma_{SM}$ **scan**

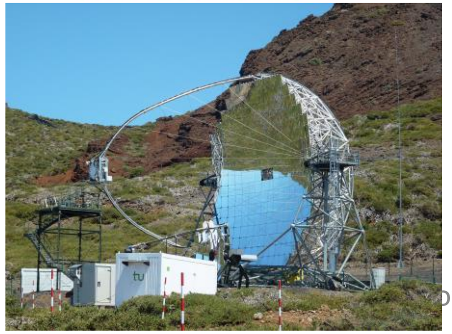
Searches for Dark Matter (DM)



Direct production
of DM
ATLAS, CMS







Indirect detection
Detect ordinary matter resulting
from decay/annihilation of dark
matter (ICECUBE, HESS)

Dark matter candidates:

- stable (non-interacting directly, MET signatures) or with a lifetime high enough (LLP signatures)
- electrically neutral
- with a mass reachable at the LHC

DM signatures (two substances – DM particle and mediator):

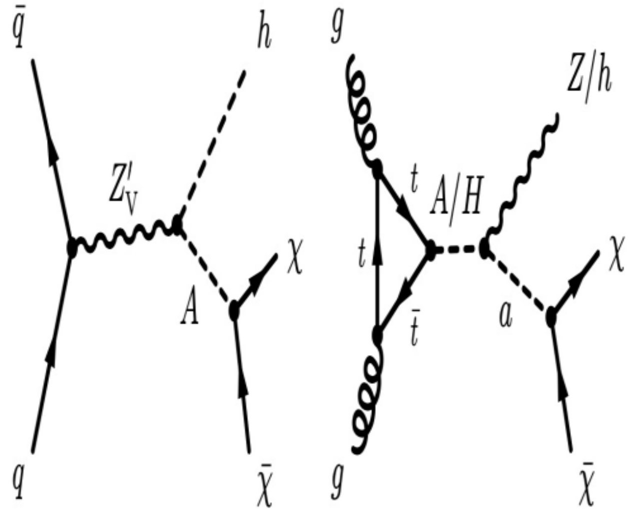
- fully visible (mediator only, a new resonance

  in dijet/dilepton/diboson etc. spectra)
- MET - decay to DM particle pair (+ a visible “tag”)
- non-standard properties of SM particles
- (higgs sector – higgs boson pair production, h125 to invisible…)

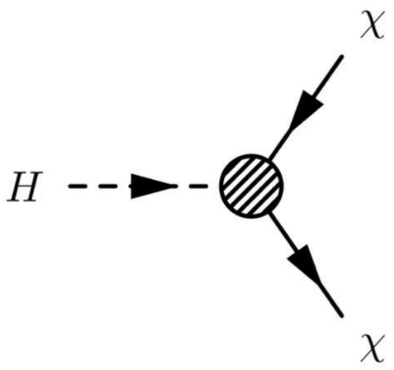
There are three complementary philosophies to search for DM at the LHC

- Effective Field Theory (EFT)-typically depends on two Degrees of Freedom (M_DM and M* -UV cut off scale)
- Simplified (or simple) models-minimal number of DOF, typically 4 or more
- Complete models like SUSY, possibly with a smaller, phenomenologically motivated parameter set like the pMSSM.

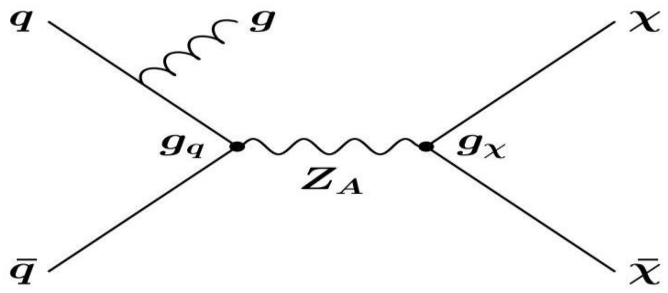
Dark matter models



Simplified models



Higgs portal



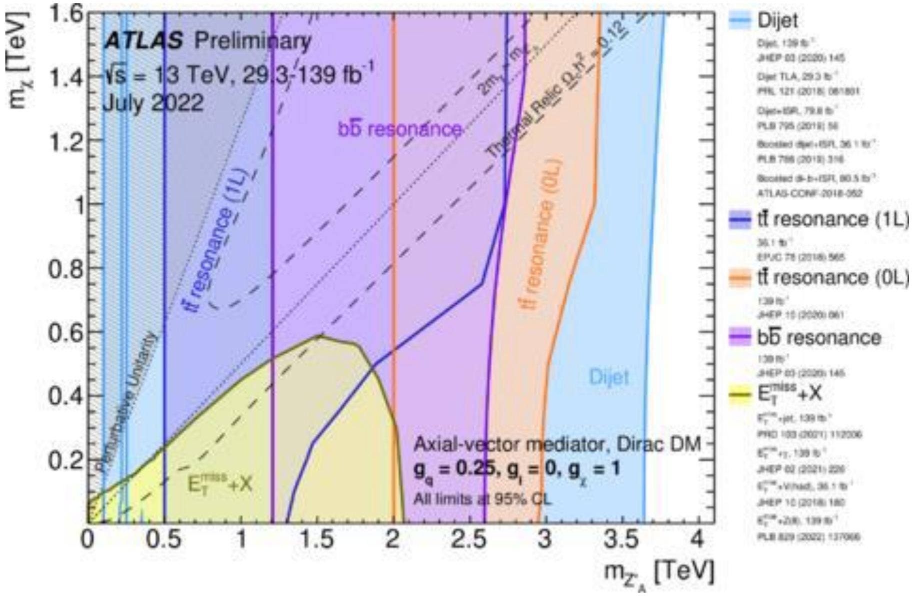
Extended
Higgs sector

Experimental signatures

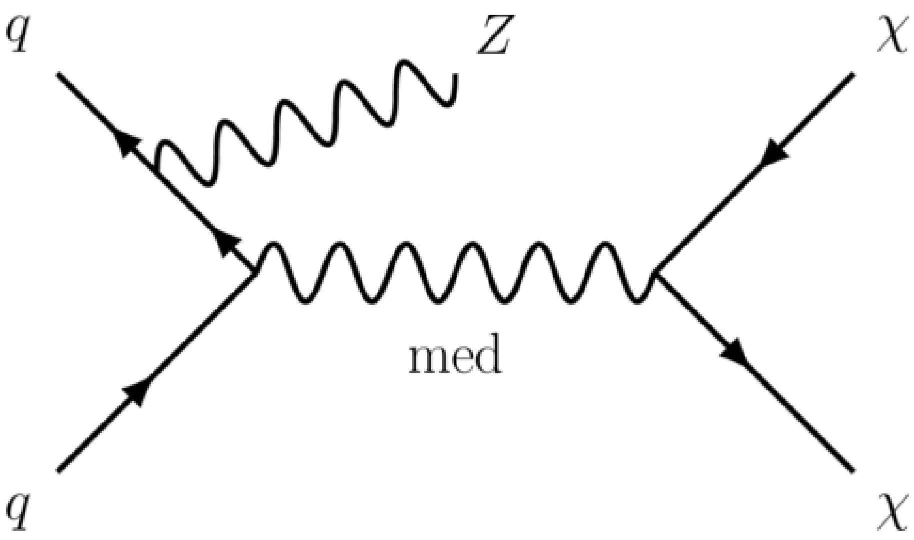
- searches for missing transverse momentum (EmissT) plus X signatures (mono-X, where the Et_miss resulting from the DM particles leaves the detectors unnoticed and the visible, i.e. detectable,final state X is used for triggering
- containing only visible particles such as pairs of leptons or jets that aim to detect the particles mediating the interactions between the DM and the SM particles through observation of a new resonance or a modification of the kinematics of the final-state particles

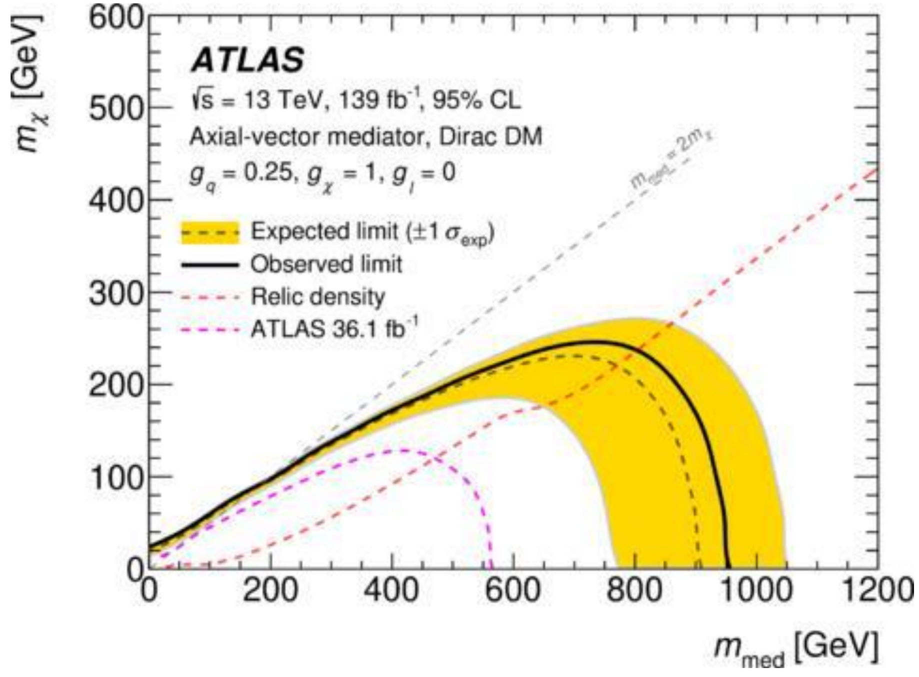
Simplified DM model summary (ATL-PHYS-PUB-2022-036) summary plots for s-channel, 2HDM+a and Dark Higgs models

Regions in the (mediator-mass, DM-mass) plane excluded at 95% CL by visible and invisible searches, for leptophobic axial-vector mediator simplified models.



Zll+ ET_miss, Phys. Lett. B 829 (2022) 137066



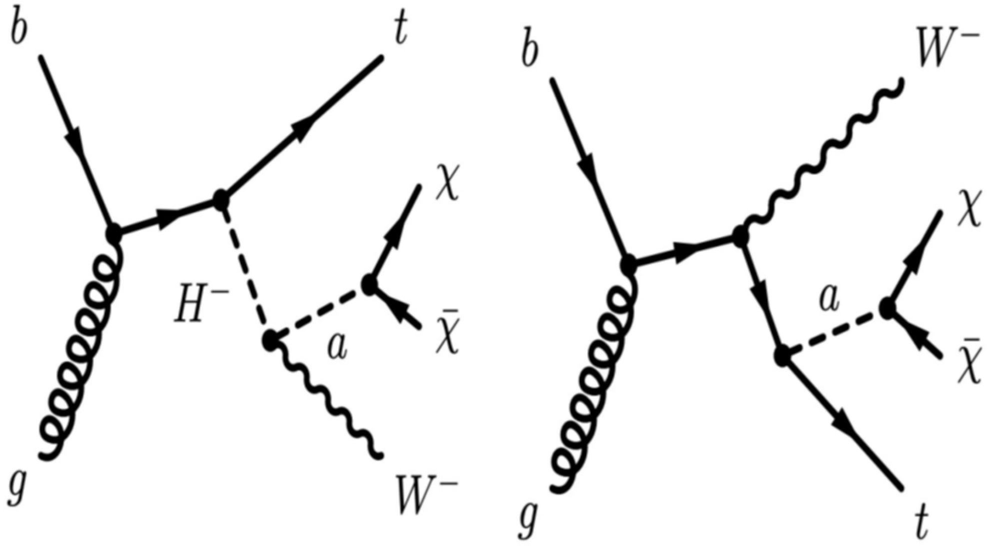


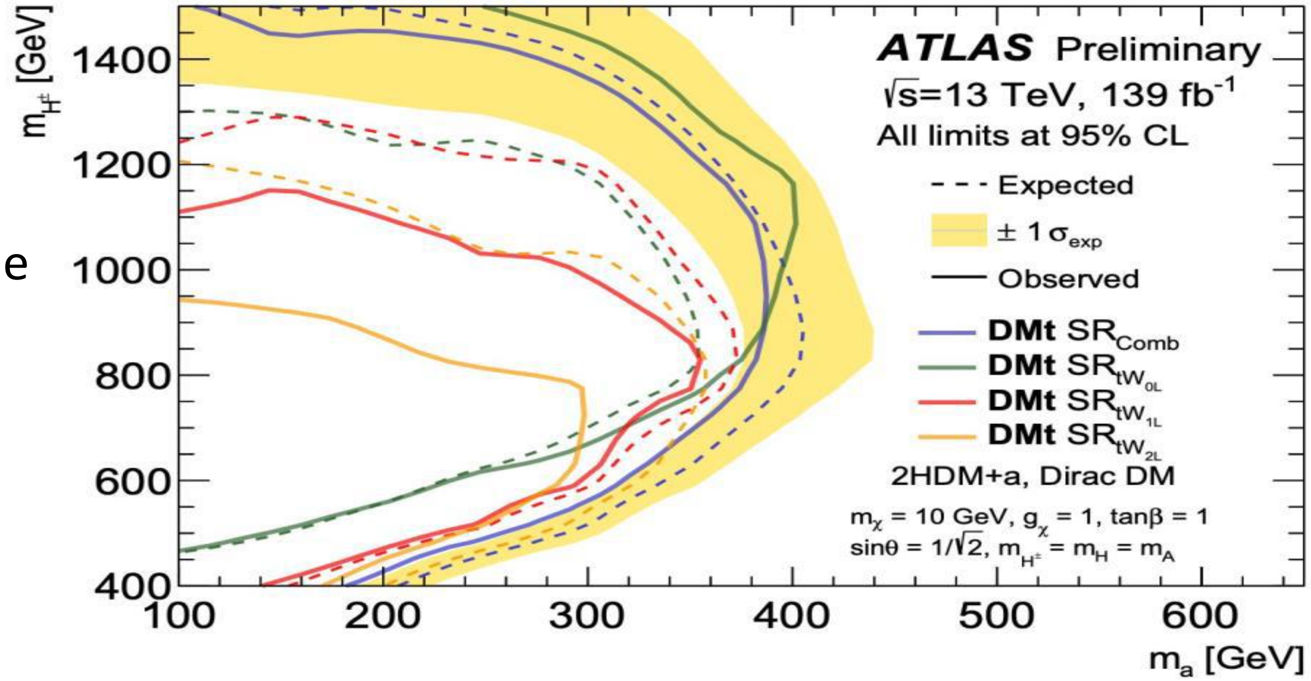
Sensitive to many types of models; particularly competitive for $H \to inv$ and 2HDM+a

Exclusion limits for simplified DM models with gχ= 1.0, gq= 0.25, and gℓ = 0, when assuming (a) an axial-vector mediator or (b) a vector mediator.

tW + ***ET_miss*** (ATLAS-CONF-2022-012) 2HDMa

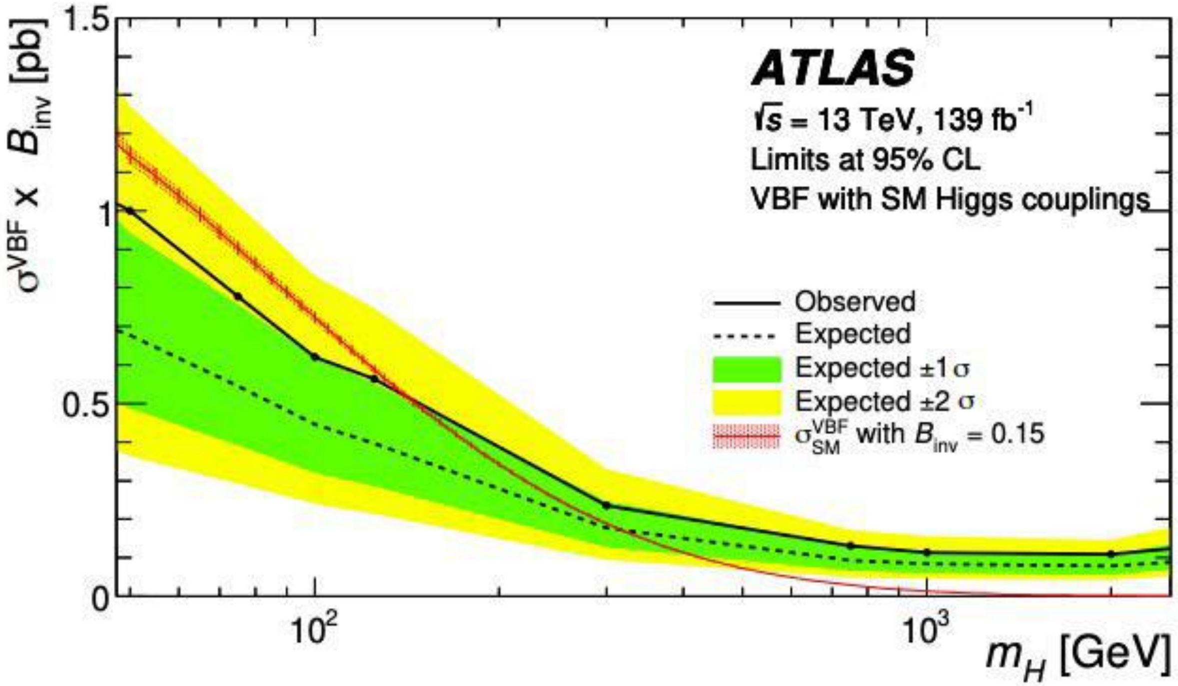
Combined with tW2L channel (Eur. Phys. J. C 81 (2020) 860)
The dominant single top-quark final state for the 2HDM+a model,



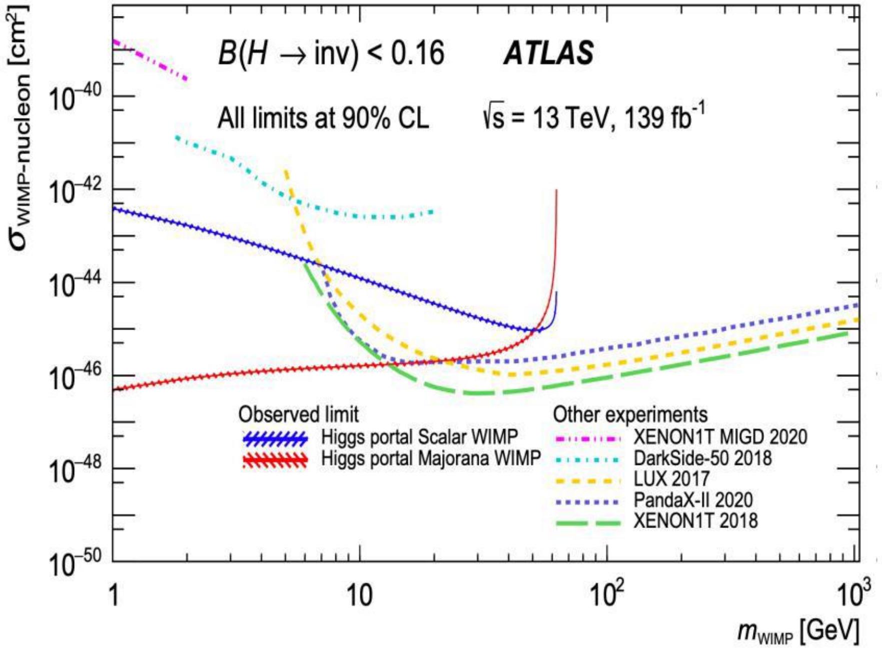


The expected and observed exclusion contours as a function of m

VBF Higgs + ***ET_miss*** (JHEP 08 (2022)



Upper limit on cross section times branching ratio to invisible particles for a scalar mediator as a function of its mass



Upper limits on the spin-independent WIMP-nucleo cross section using Higgs portal interpretations of Binv at 90% CL vs mWIMP

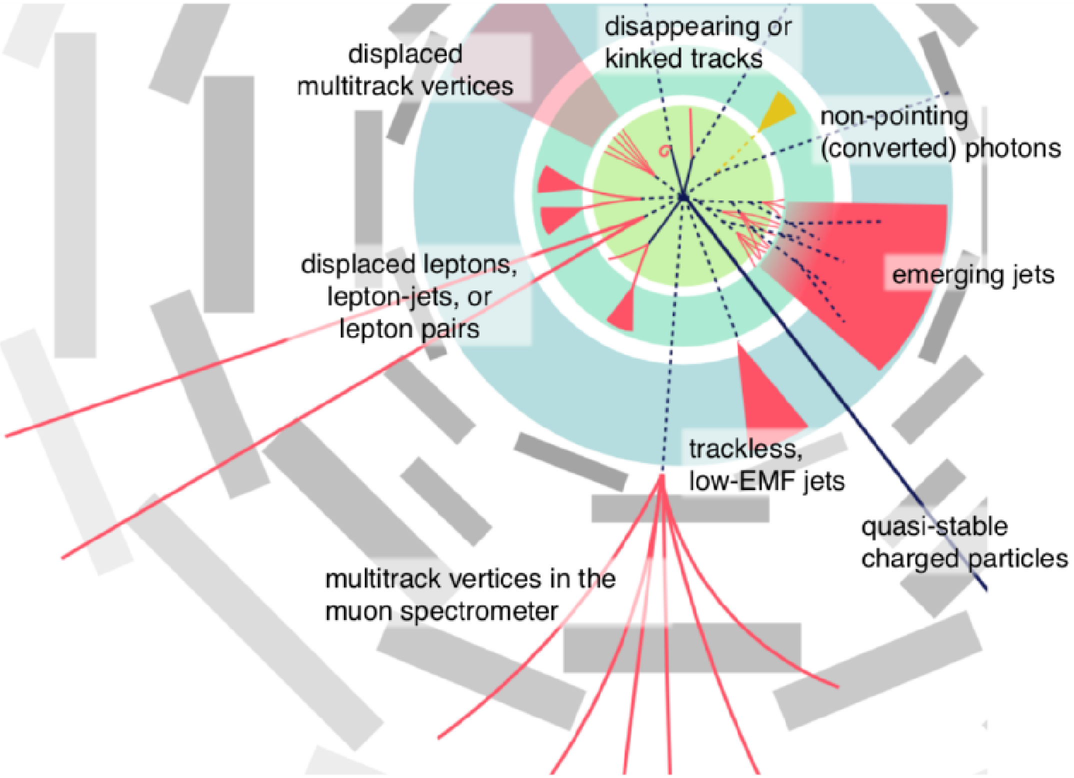
Dark sector with Long-Lived Particles at the LHC

LLP:
a proper lifetime cτ0 is greater than or comparable to the characteristic size of the (sub)detectors

small cτ0 that comparable to the inner tracker size, no displaced tracks ⍰ “standard” prompt decay

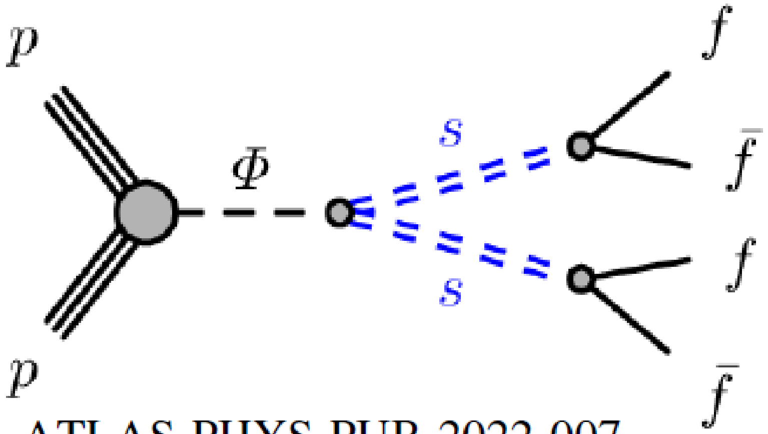
intermediate cτ0 LLP

very large/infinite large cτ0 ⍰ stable particles, “standard” MET signatures

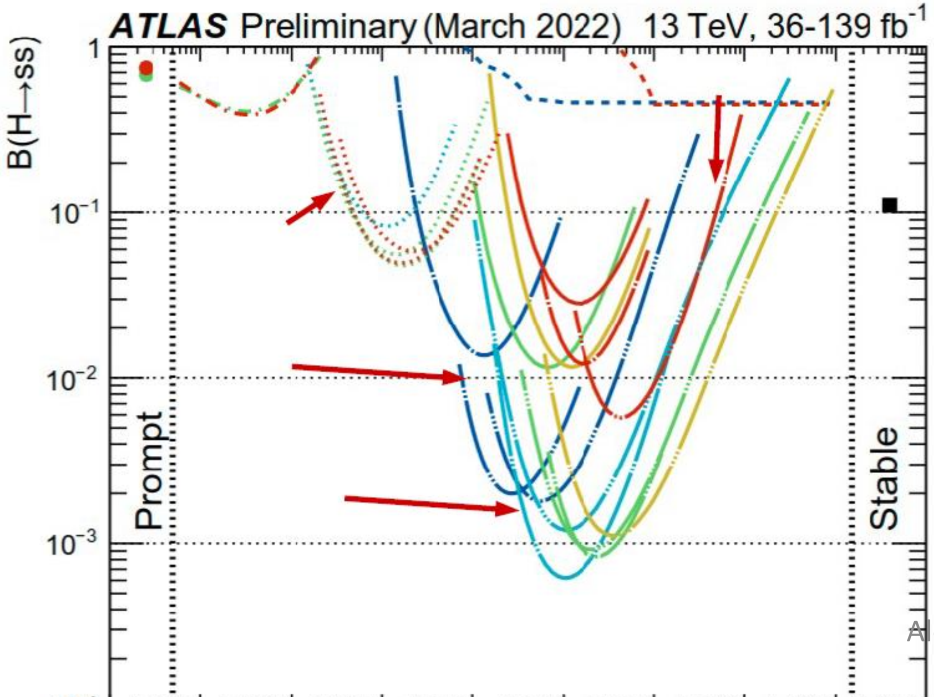


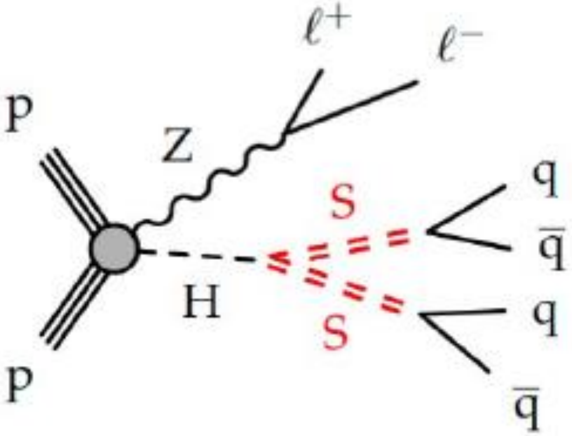
Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP signatures with displaced vertexes

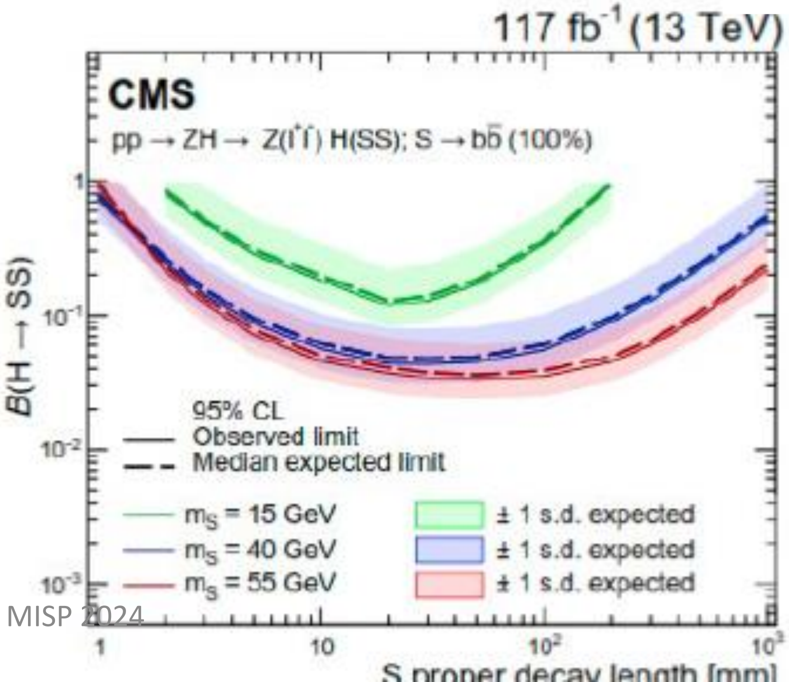


ATLAS-PHYS-PUB-2022-007





JHEP 03 (2022) 160

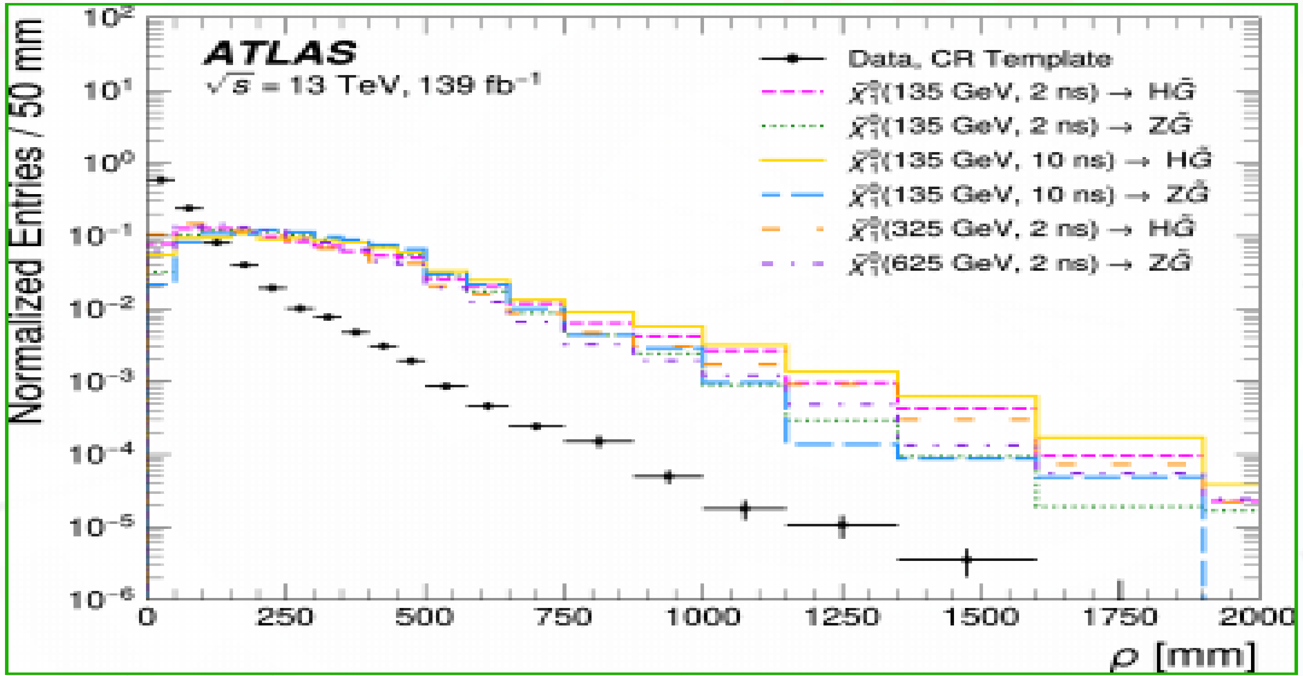


Non-prompt photons from BSM decays before EM Calo

1. Photons from same decays

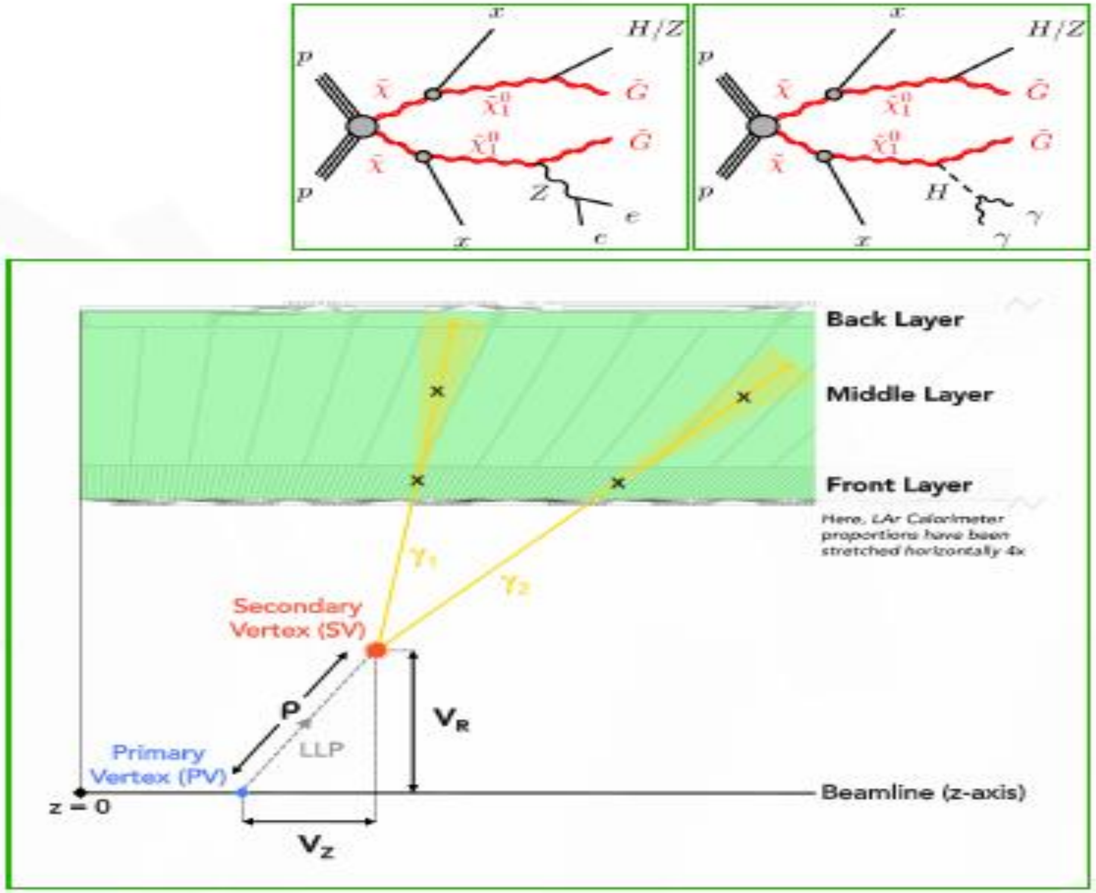
- LLP particles, originating displaced $H \to \gamma\gamma$ or $Z \to ee$ decays
- two photons produced in decay of same LLP → Di-photon trigger
- trajectory based on shower shape
- signal region for high missing energy and at least 2 trigger matched photons
- exploit LAr arrival time (t_{avg}) as well as the mass and 2D position (ρ) of the displaced vertex → average timing in calo $t_{avg} = (t_{\gamma 1} + t_{\gamma 2})/2$

displacement $\rho = \sqrt{V_R^2 + V_Z^2}$



Photons from same decay

arXiv:2304.12885



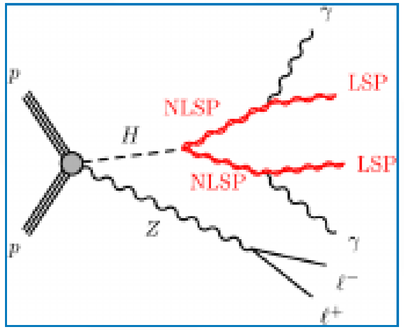
Here, LAr Calorimeter proportions have been stretched horizontally 4x

Non-prompt photons from BSM decays before EM Calo

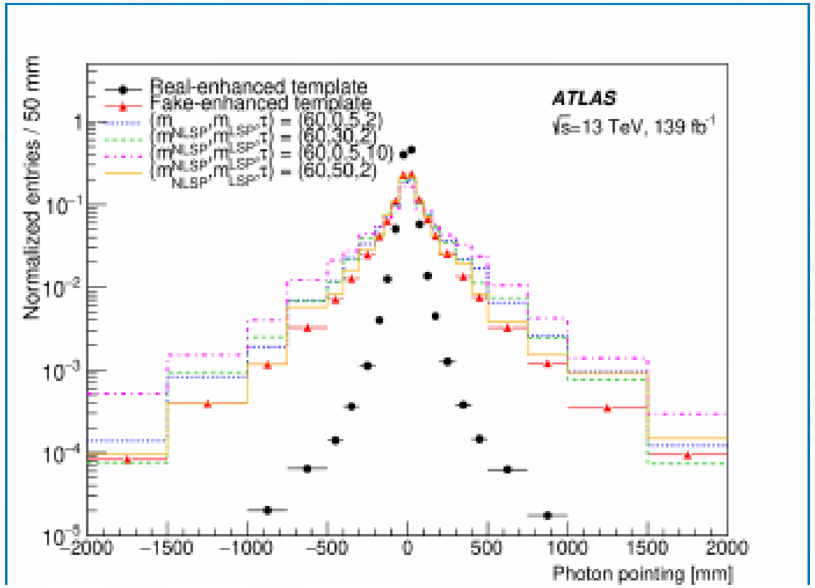
arXiv:2209.01029

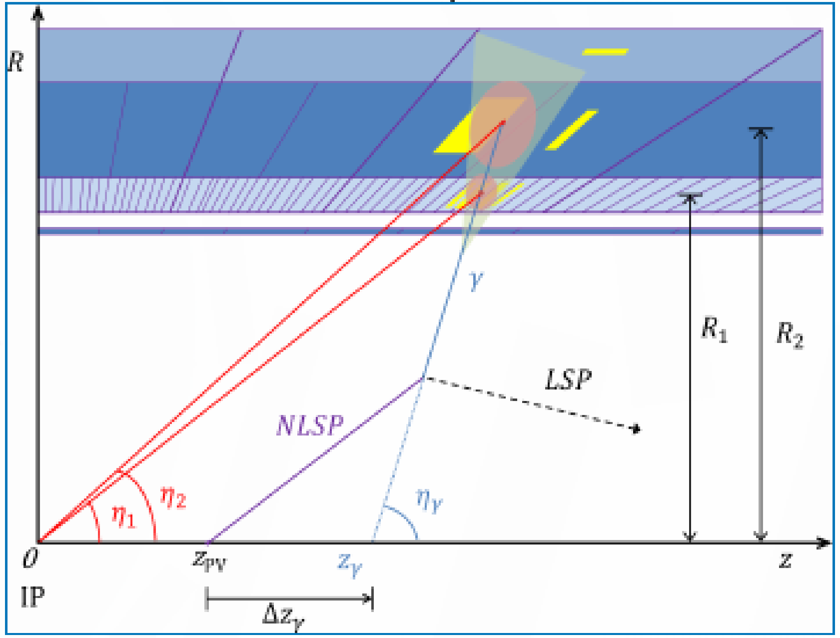
2. Photons from different decays

- two non pointing photons coming from different of LLPs in association with leptons
  - → per photon timing in calo tγ, single lepton trigger
- exploited EM calorimeter info for precise pointing and timing measurements
- signal region for 1 and ≥ 2 photons
- isolated photons, ≥1 lepton and high missing energy

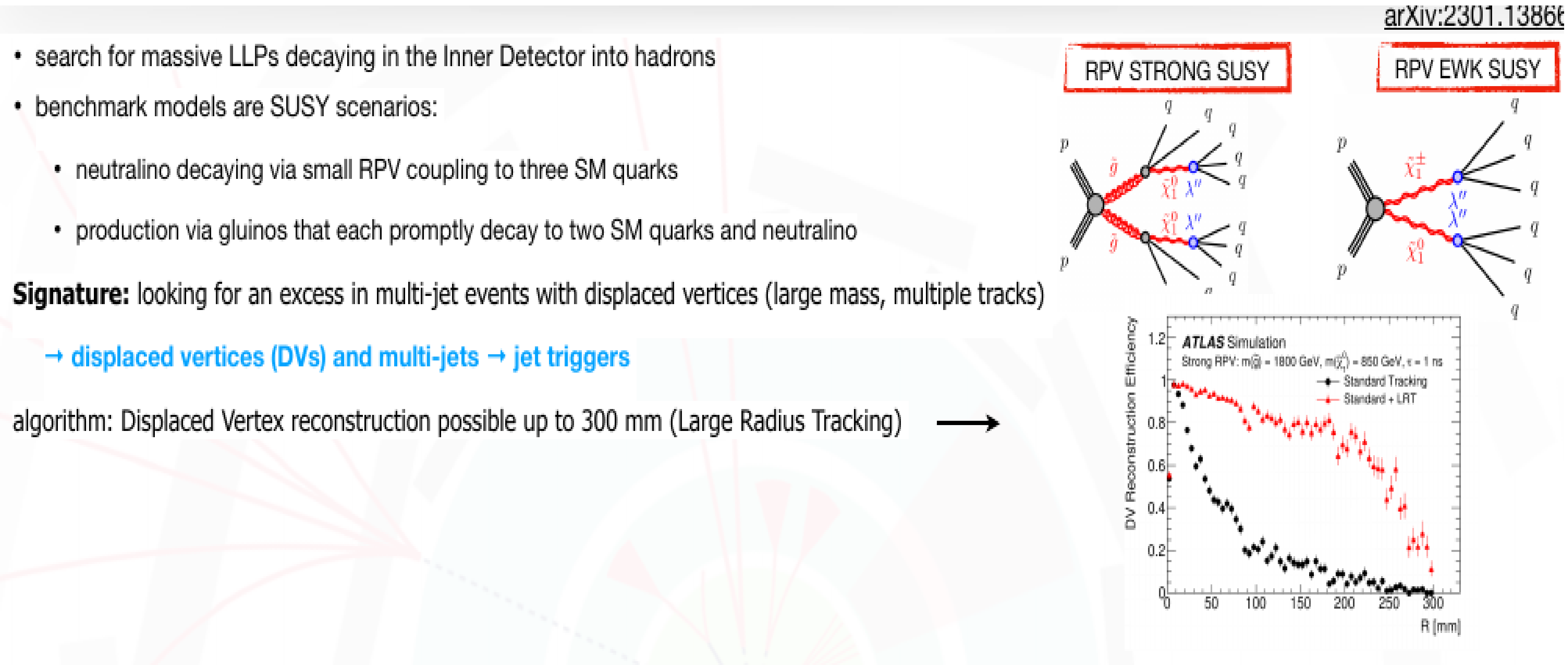


pointing $\Delta z_\gamma = |z_\gamma - z_{PV}|$





Displaced Vertex + Jets



arXiv:2301.1386

- search for massive LLPs decaying in the Inner Detector into hadrons
- benchmark models are SUSY scenarios:
  - neutralino decaying via small RPV coupling to three SM quarks
  - production via gluinos that each promptly decay to two SM quarks and neutralino

Signature: looking for an excess in multi-jet events with displaced vertices (large mass, multiple tracks)

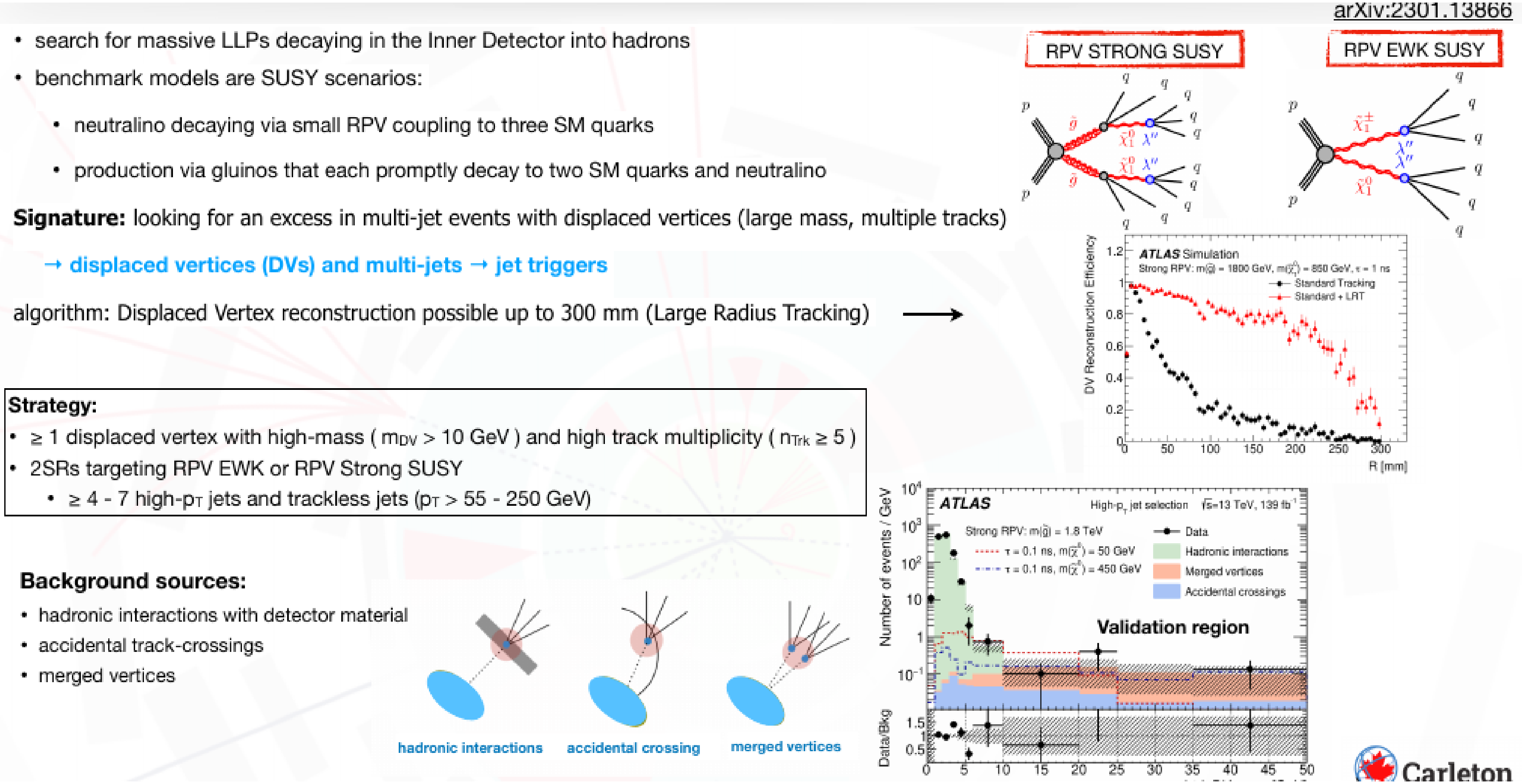
→ displaced vertices (DVs) and multi-jets → jet triggers

algorithm: Displaced Vertex reconstruction possible up to 300 mm (Large Radius Tracking) ⟶

RPV STRONG SUSY

RPV EWK SUSY

Displaced Vertex + Jets



arXiv:2301.13866

- search for massive LLPs decaying in the Inner Detector into hadrons
- benchmark models are SUSY scenarios:
    - neutralino decaying via small RPV coupling to three SM quarks
    - production via gluinos that each promptly decay to two SM quarks and neutralino

Signature: looking for an excess in multi-jet events with displaced vertices (large mass, multiple tracks)

→ displaced vertices (DVs) and multi-jets → jet triggers

algorithm: Displaced Vertex reconstruction possible up to 300 mm (Large Radius Tracking) →

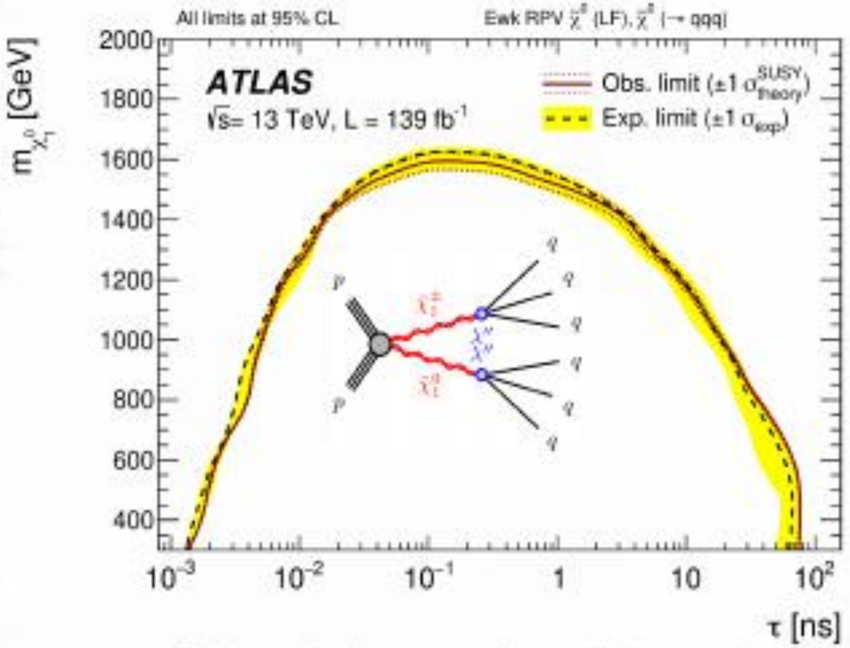
Strategy:
- ≥ 1 displaced vertex with high-mass (m_{DV} > 10 GeV) and high track multiplicity ($n_{Trk} \geq 5$)
- 2SRs targeting RPV EWK or RPV Strong SUSY
    - ≥ 4 - 7 high-p_T jets and trackless jets (p_T > 55 - 250 GeV)

Background sources:
- hadronic interactions with detector material
- accidental track-crossings
- merged vertices

Displaced Vertex + Jets

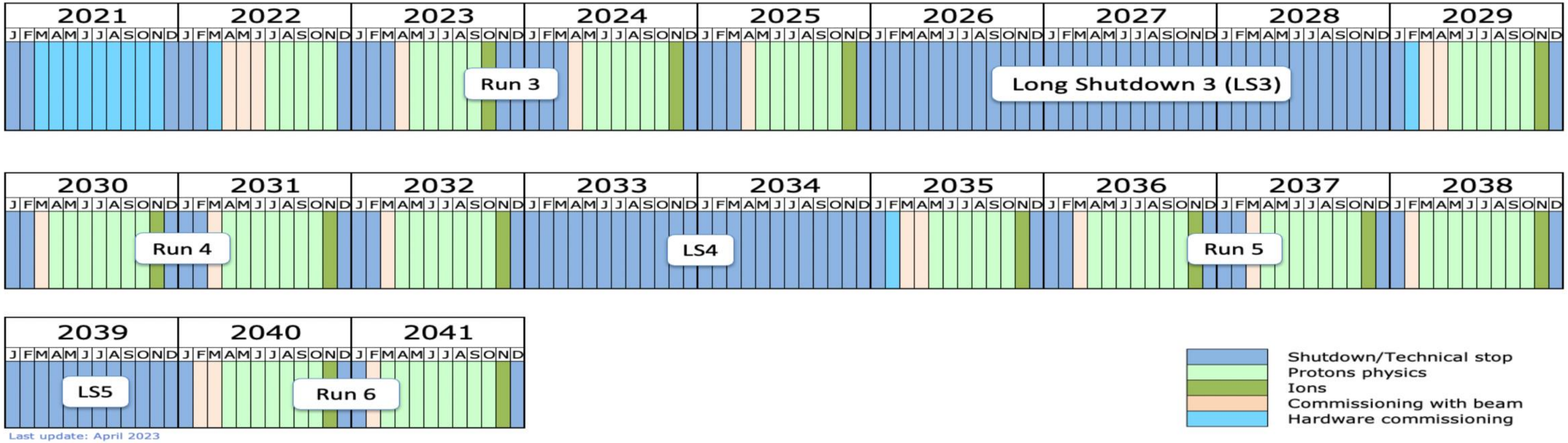
- observed event yields consistent with the background-only hypothesis
  → limits are set on the SUSY benchmark models.

Signal Region	Expected	Observed
High-p_T jet SR	$0.46^{+0.27}_{-0.30}$	1
Trackless jet SR	$0.83^{+0.51}_{-0.53}$	0



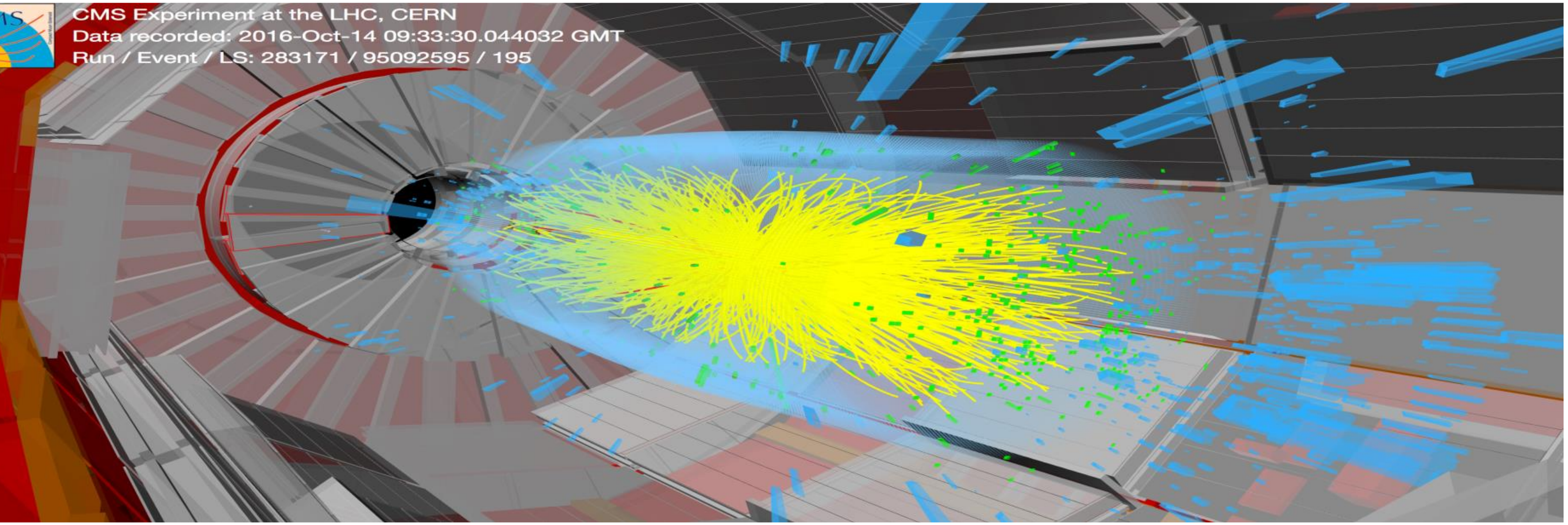
- The pair-production of electroweakinos with masses below 1.5 TeV is excluded for mean proper lifetimes in the range from 0.03 ns to 1 ns.

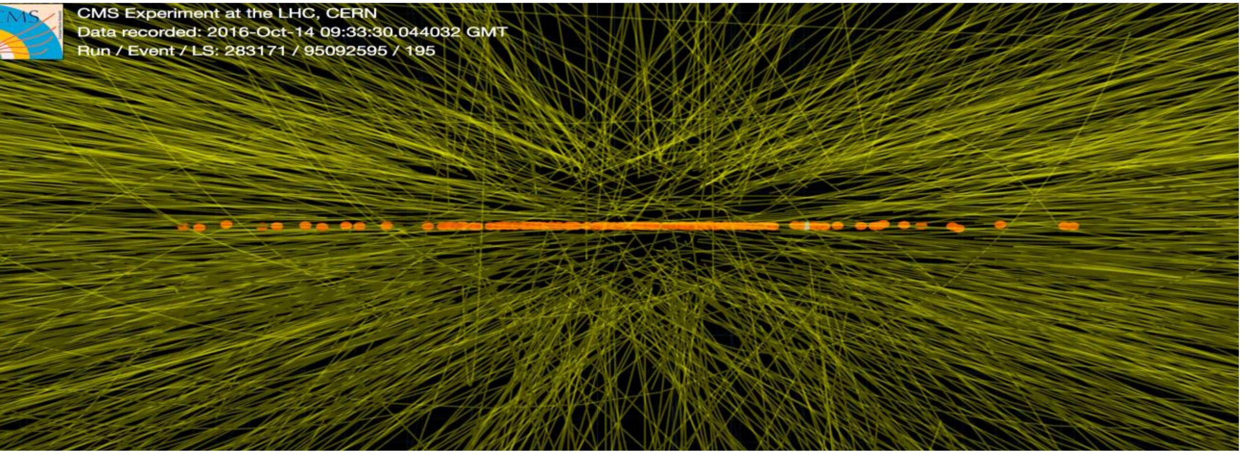
HL-LHC



Run 2: 140/fb
Run 3: ~450/fb
HL-LHC: ~3000/fb
(~20 x today's dataset)

PU in Run2 and HL-LHC

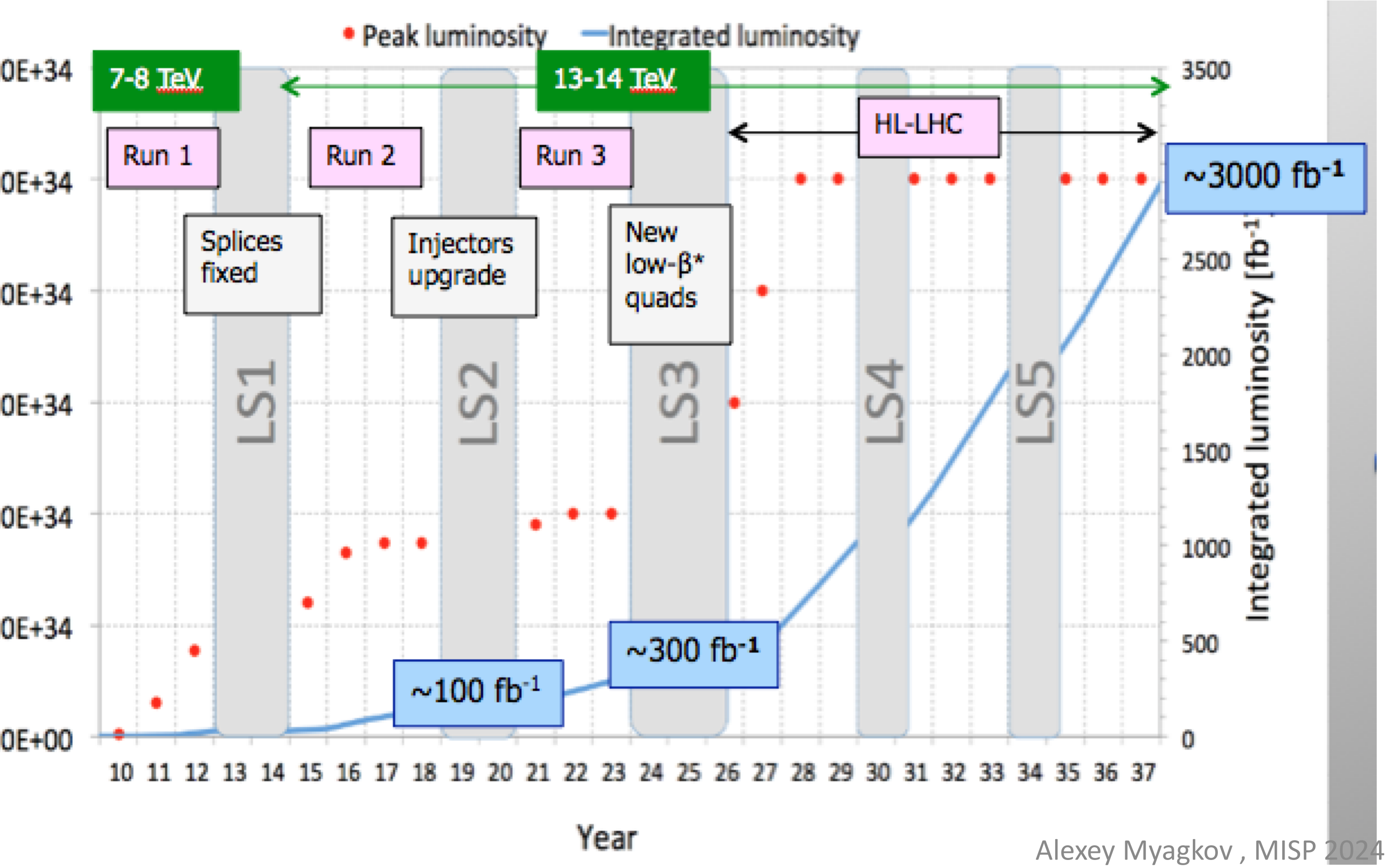




At Run 2 average PU per event was approximately 40.

Expected PU at HLLHC 140-200

Expected schedule



LHC will run till ~2037

Only ~5% of the collisions

Delivered so far…

Then a high energy LHC (28 TeV)?

This option is discussed @ CERN..

HE-LHC

- HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (√s~ 30TeV)
- uses existing tunnel and infrastructure; can be built at fixed budget
- strong physics case if new physics from LHC/HL-LHC
- powerful demonstration of the FCC-hh magnet technology

Main expected measurements

Higgs Boson Physics will be a major component, main measurements:

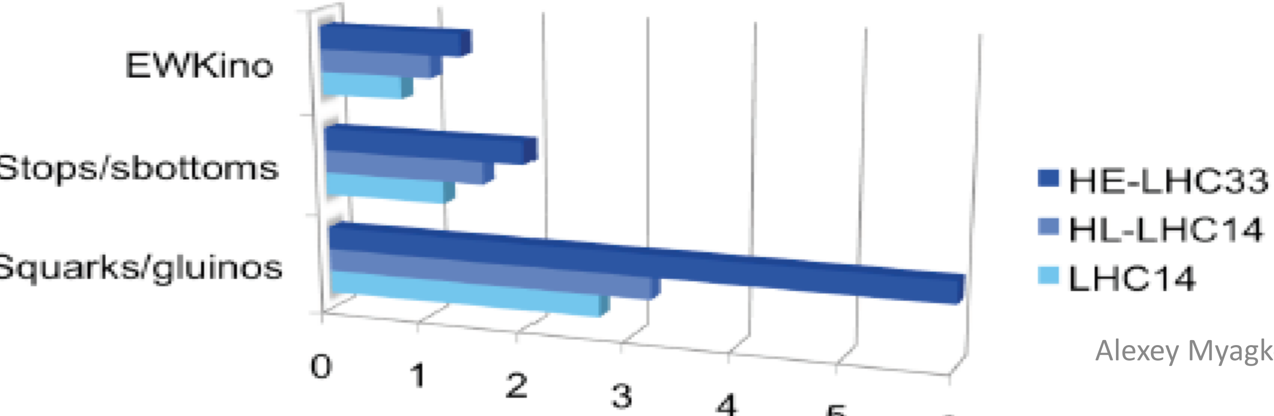
- Higgs couplings and self-coupling
- Higgs differential distributions
- Rare Higgs decays
- Heavy Higgs searches

From ECFA 2013

14 TeV, 3/ab

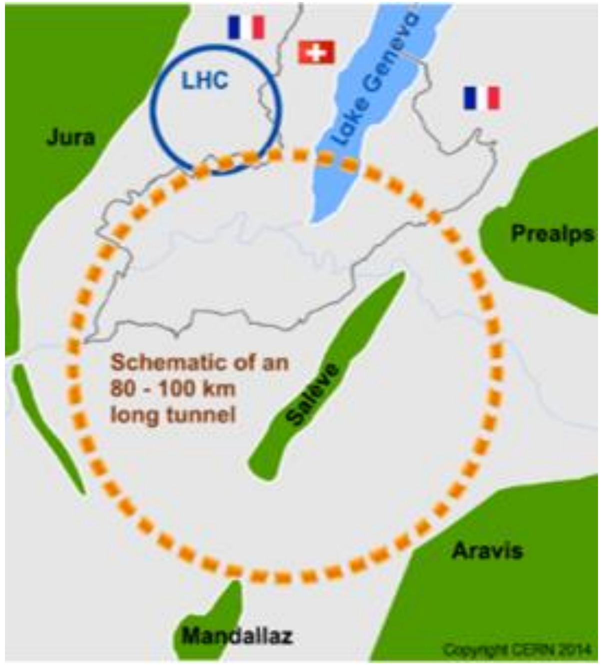
Support for rich program in **Standard Model (SM) and Flavour Physics**

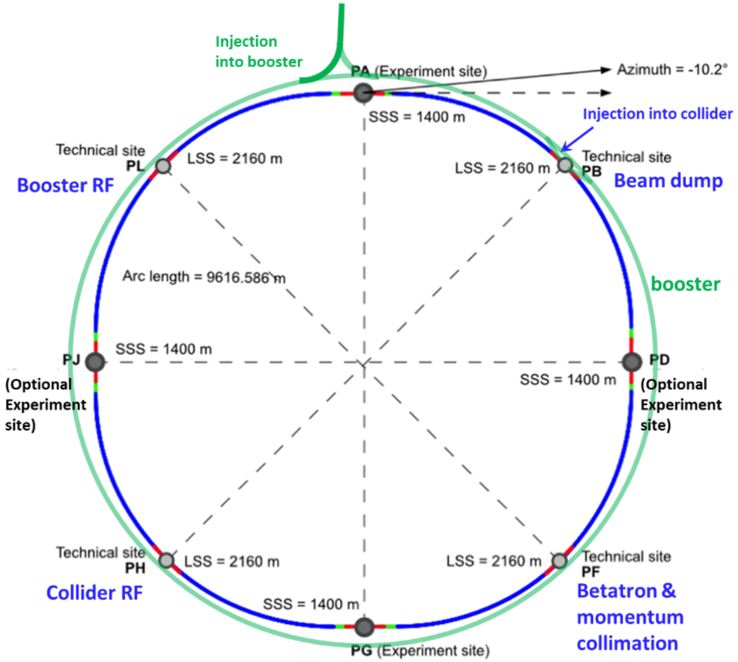
Extended sensitivity for **Beyond the Standard Model Physics**

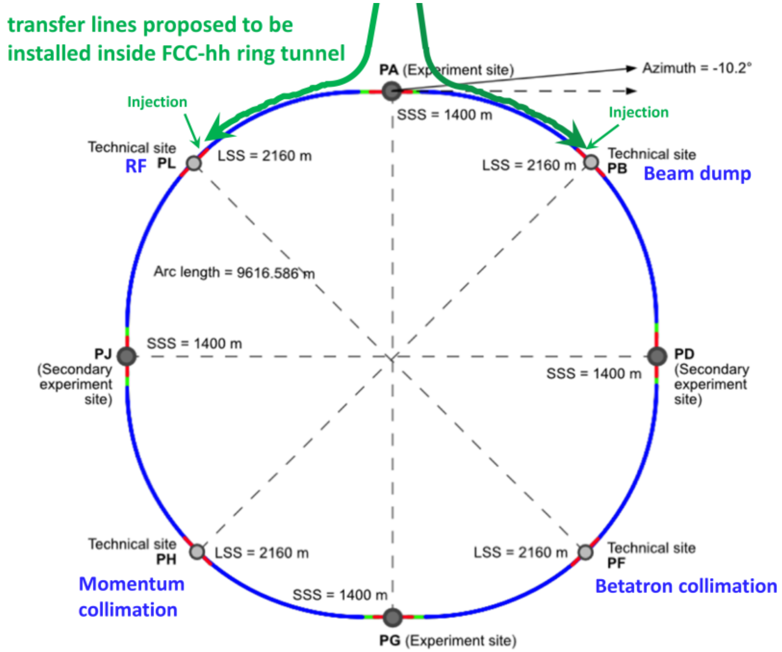


FCC Integrated Programme (Michael Benedikt and Frank Zimmermann, CERN)

comprehensive long-term program maximizing physics opportunities
stage 1: FCC-ee (Z, W, H, "t" "t"¯) as Higgs factory, electroweak & top factory at highest luminosities
stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option

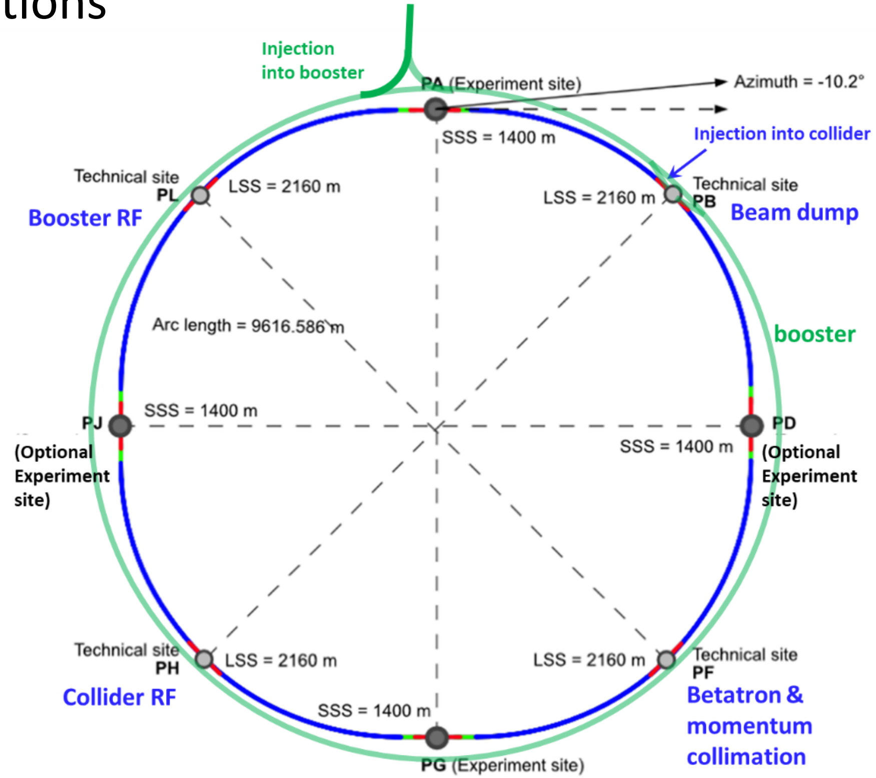


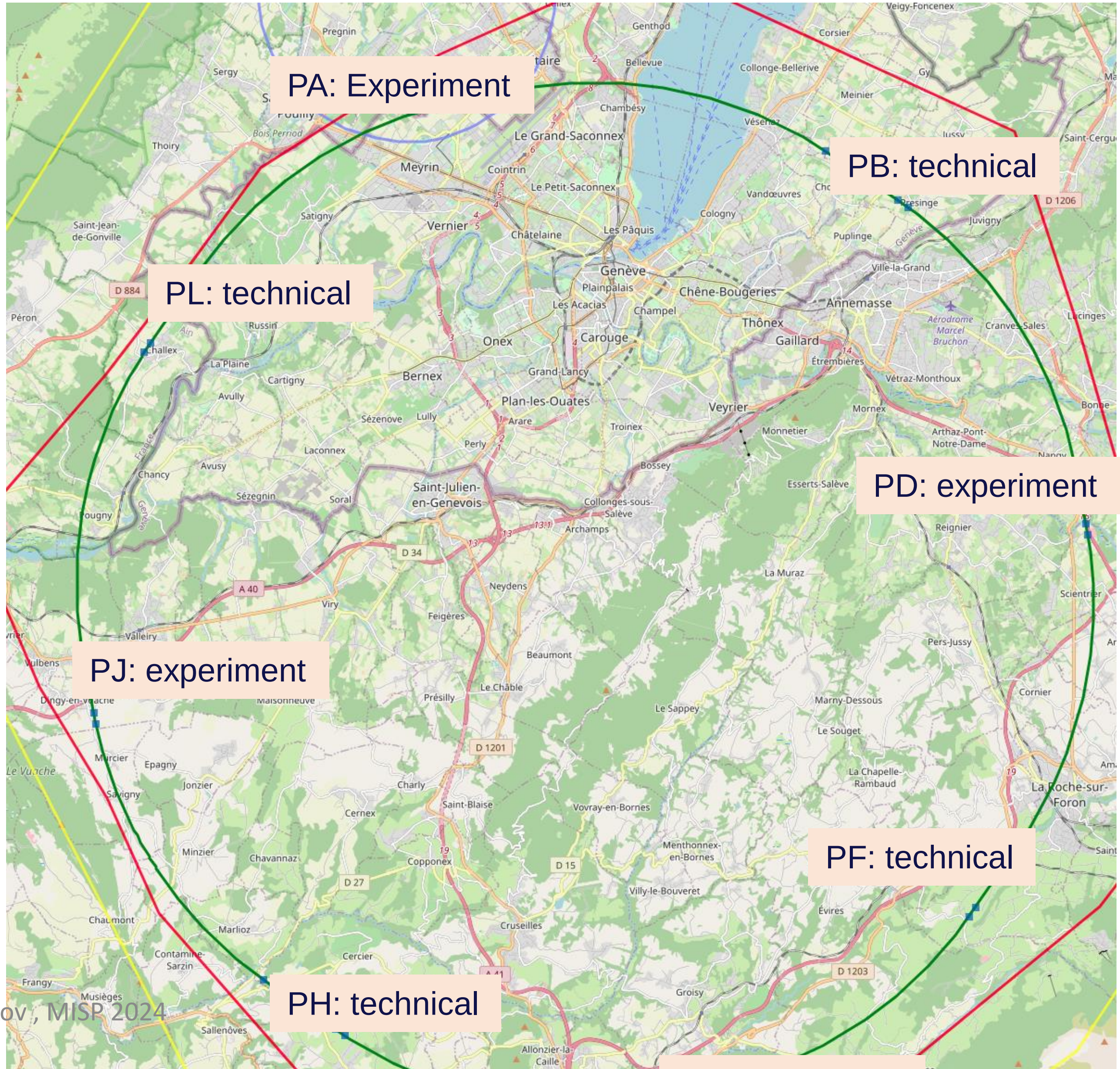




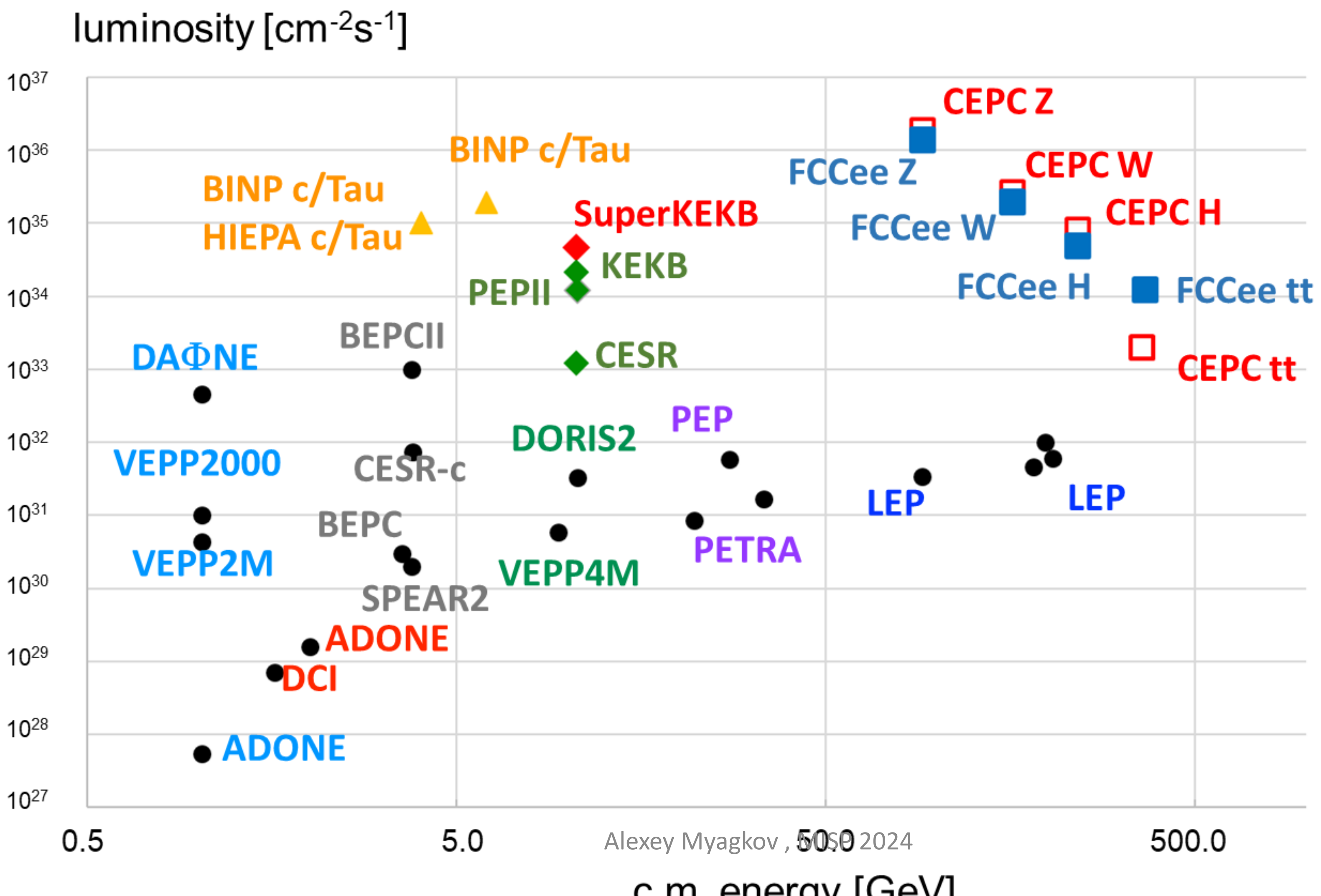
Layout chosen out of ~ 100 initial variants, based on geology and surface constraints (land availability, access to roads, etc.), environment (protected zones), infrastructure (water, electricity, transport), machine performance etc.

“Avoid-reduce -compensate” principle of EU and French regulations





Stage 1: FCC-ee – 2nd highest luminosity collider



FUTURE
CIRCULAR
COLLIDER

FCC-ee: main machine parameters

F. Gianotti

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

4 years
5 x 10^{12} Z
LEP x 10^5

2 years
> 10^8 WW
LEP x 10^4

3 years
2 x 10^6 H

5 years
2 x 10^6 tt pairs

- ☐ x 10-50 improvements on all EW observables
- ☐ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ☐ x10 Belle II statistics for b, c, τ
- ☐ indirect discovery potential up to ~ 70 TeV
- ☐ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

Stage 2: FCC-hh – parameters

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	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

Formidable challenges:

- ☐ high-field superconducting magnets: 14 - 20 T
- ☐ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ☐ stored beam energy: ~ 9 GJ → machine protection
- ☐ pile-up in the detectors: ~1000 events/xing
- ☐ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ☐ Direct discovery potential up to ~ 40 TeV
- ☐ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ☐ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, $Z\gamma$, μμ)
- ☐ Final word about WIMP dark matter

F. Gianotti

Why FCC ?

Physics : best overall physics potential of all proposed future colliders
FCC-ee : ultra-precise measurements of the Higgs boson, indirect exploration of next energy scale (~ x10 LHC)
FCC-hh : only machine able to explore next energy frontier directly (~ x10 LHC)
Heavy-ion collisions and, possibly, ep/e-ion collisions
4 collision points robustness; increased dataset for same machine power; specialized experiments for maximum physics output

2) Timeline

FCC-ee technology is mature construction can proceed in parallel to HL-LHC operation and physics can start few years after end of HL-LHC operation ⍰ This would keep the community, in particular the young people, engaged and motivated.

FCC-ee before FCC-hh would also allow:
- cost of the (more expensive) FCC-hh machine to be spread over more years
- 20 years of R&D work towards affordable magnets providing the highest achievable field (HTS)
- optimization of overall investment : FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure

3) It’s the only facility commensurate with the size of the CERN community (4 major experiments)

LC projects discussed

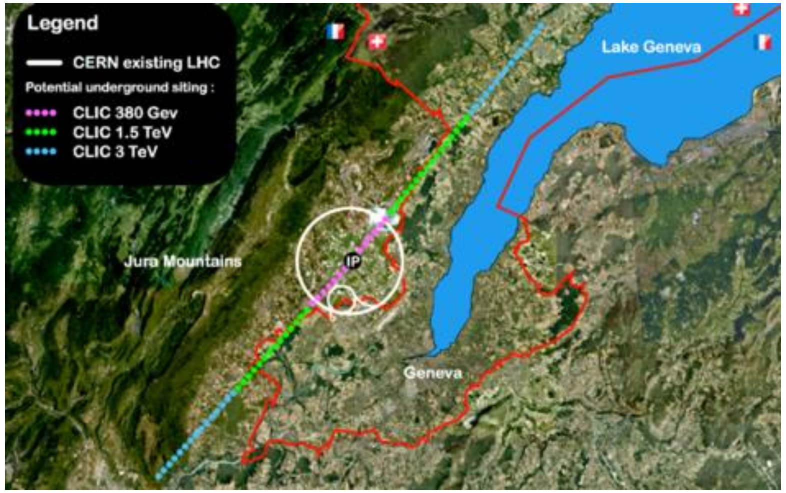
ILC in Japan

Initially e+e- collisions at least at 250 GeV

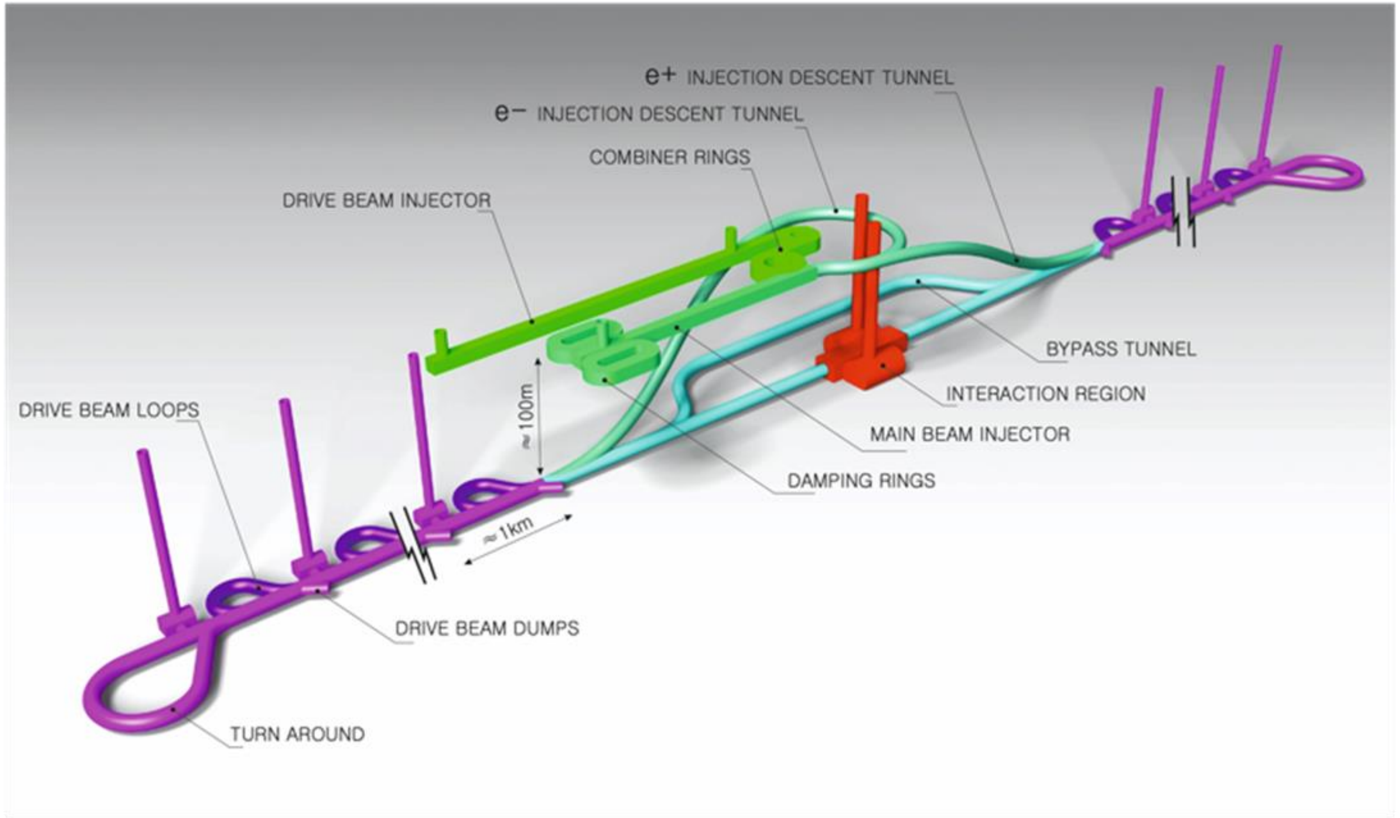
Linear colliders: 11 (Higgs) -> 50 (max) km for higher energies later

Four different RF solutions drive the designs

CLIC at CERN



The Compact Linear Collider (CLIC)



Timeline: Electron-positron linear collider at CERN for the era beyond HL-LHC

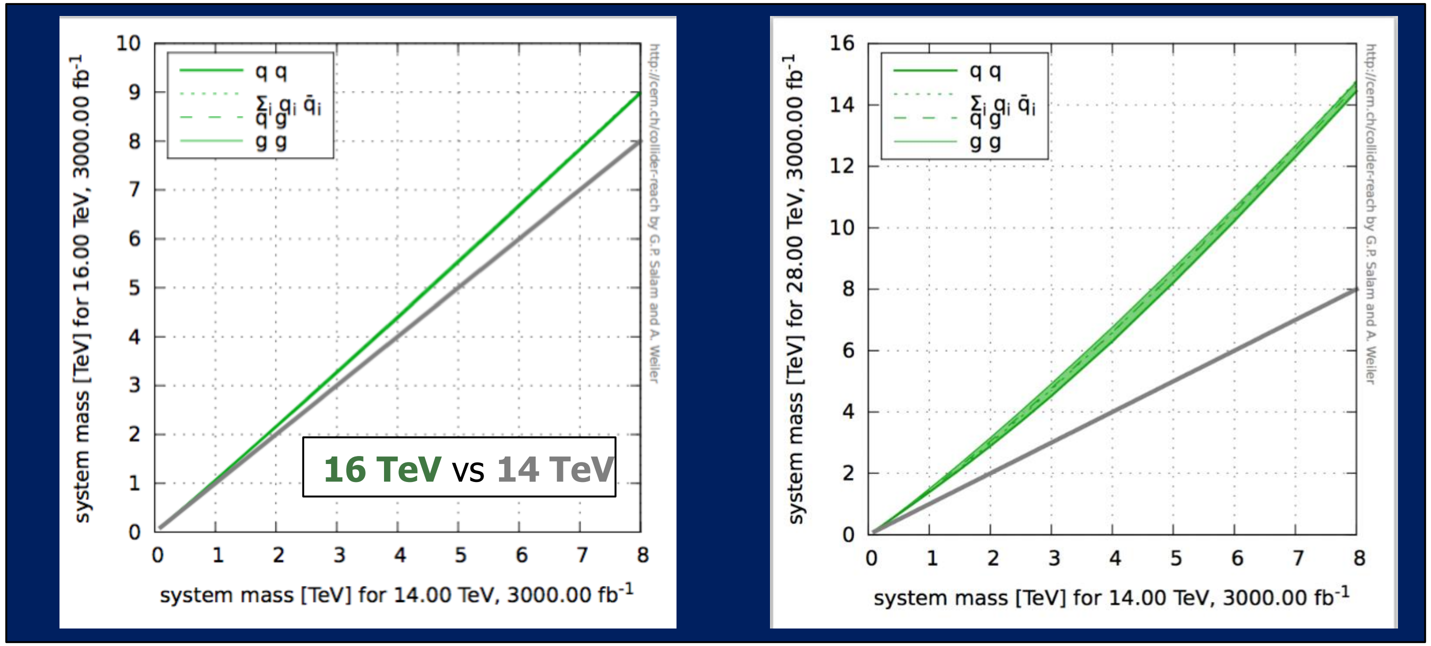
Compact: Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase

Expandable: Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

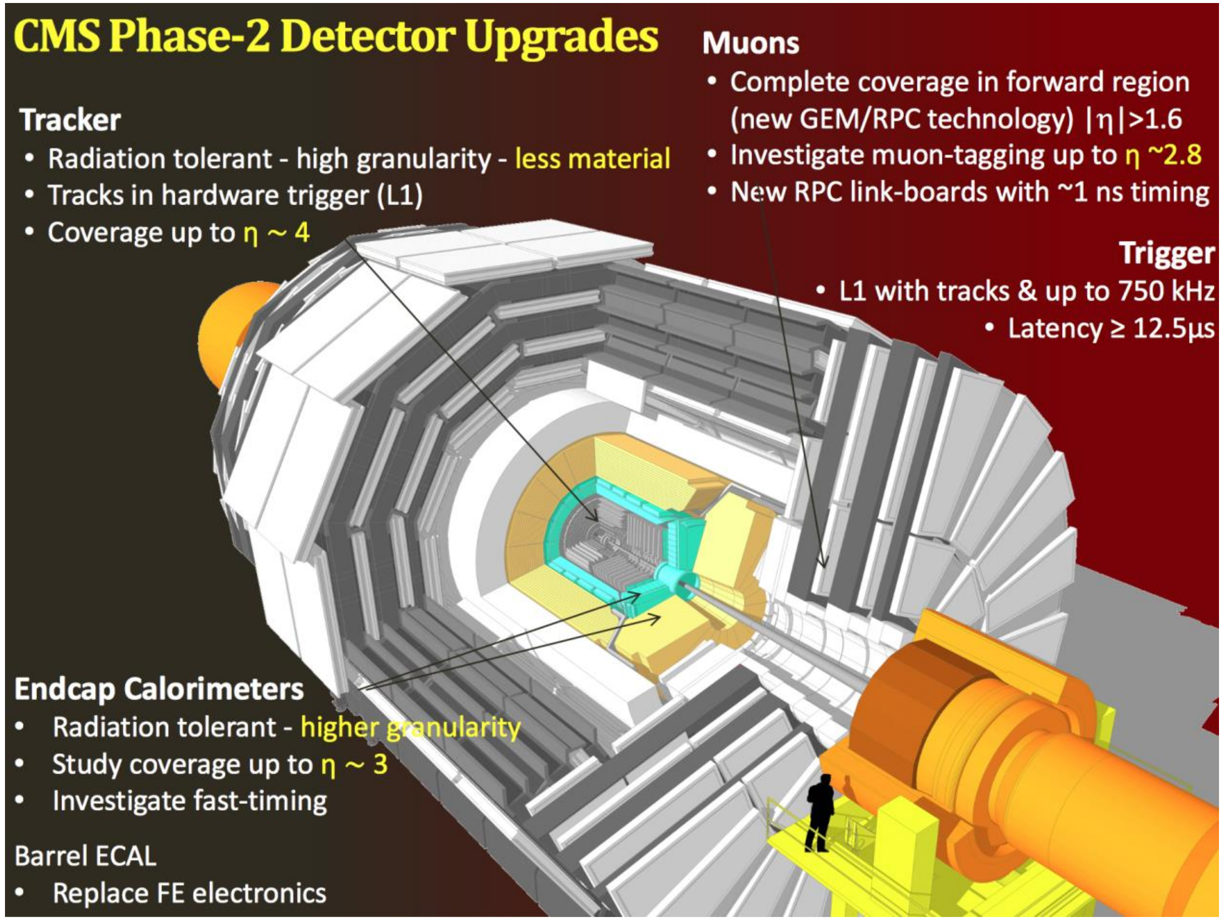
CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

Thank you for your attention!

- F. Gianotti
- FCC meeting
- Rome April 2016



- WG set up to explore technical feasibility of pushing LHC energy to:
- design value: 14 TeV
- ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
- beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb3Sn magnets)
- Identify open risks, needed tests and technical developments, trade-off
- between energy and machine efficiency/availability
- Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)



CMS Phase-2 Detector Upgrades

Tracker

- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons

- Complete coverage in forward region (new GEM/RPC technology) |η|>1.6
- Investigate muon-tagging up to η ~2.8
- New RPC link-boards with ~1 ns timing

Trigger

- L1 with tracks & up to 750 kHz
- Latency ≥ 12.5μs

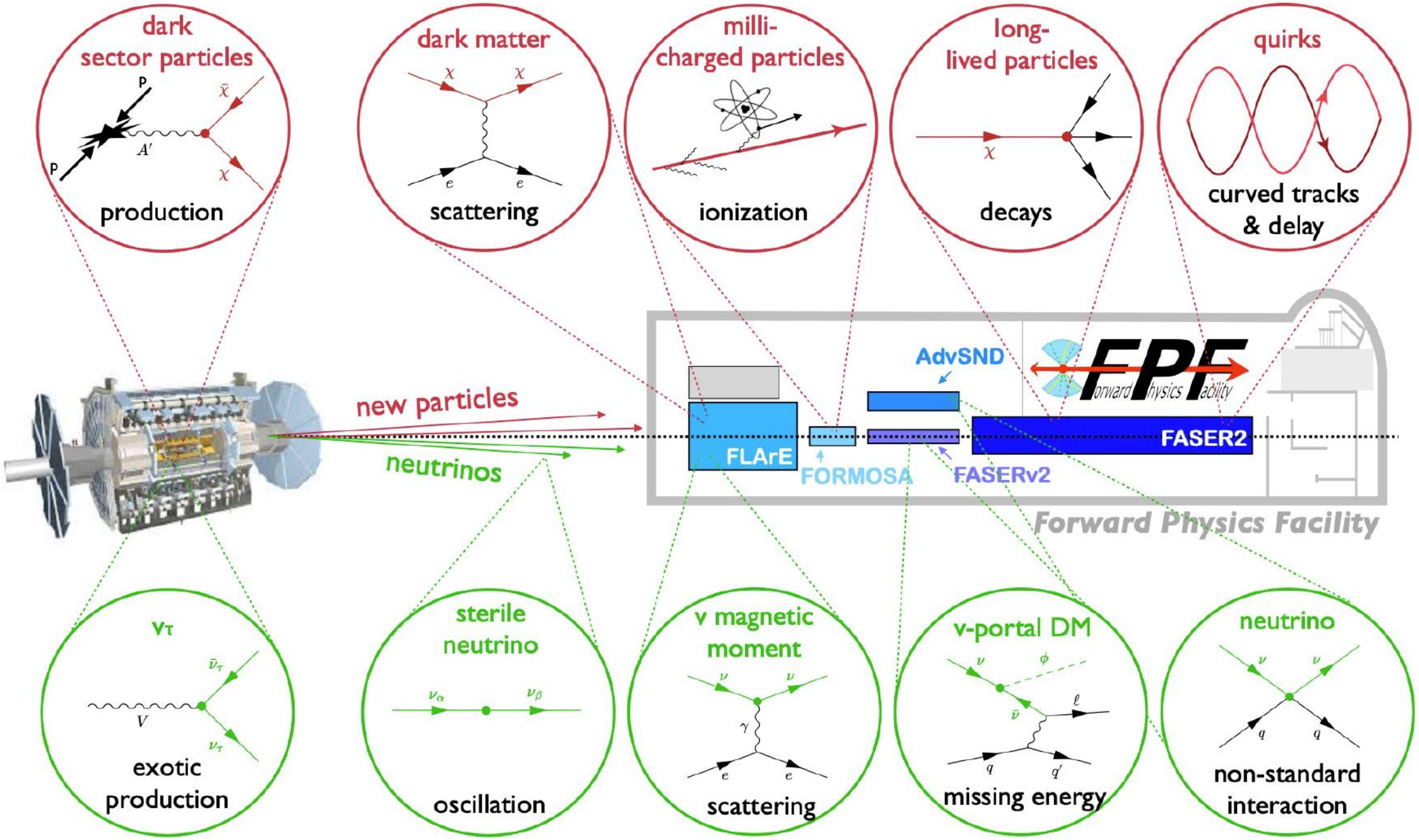
Endcap Calorimeters

- Radiation tolerant - higher granularity
- Study coverage up to η ~ 3
- Investigate fast-timing

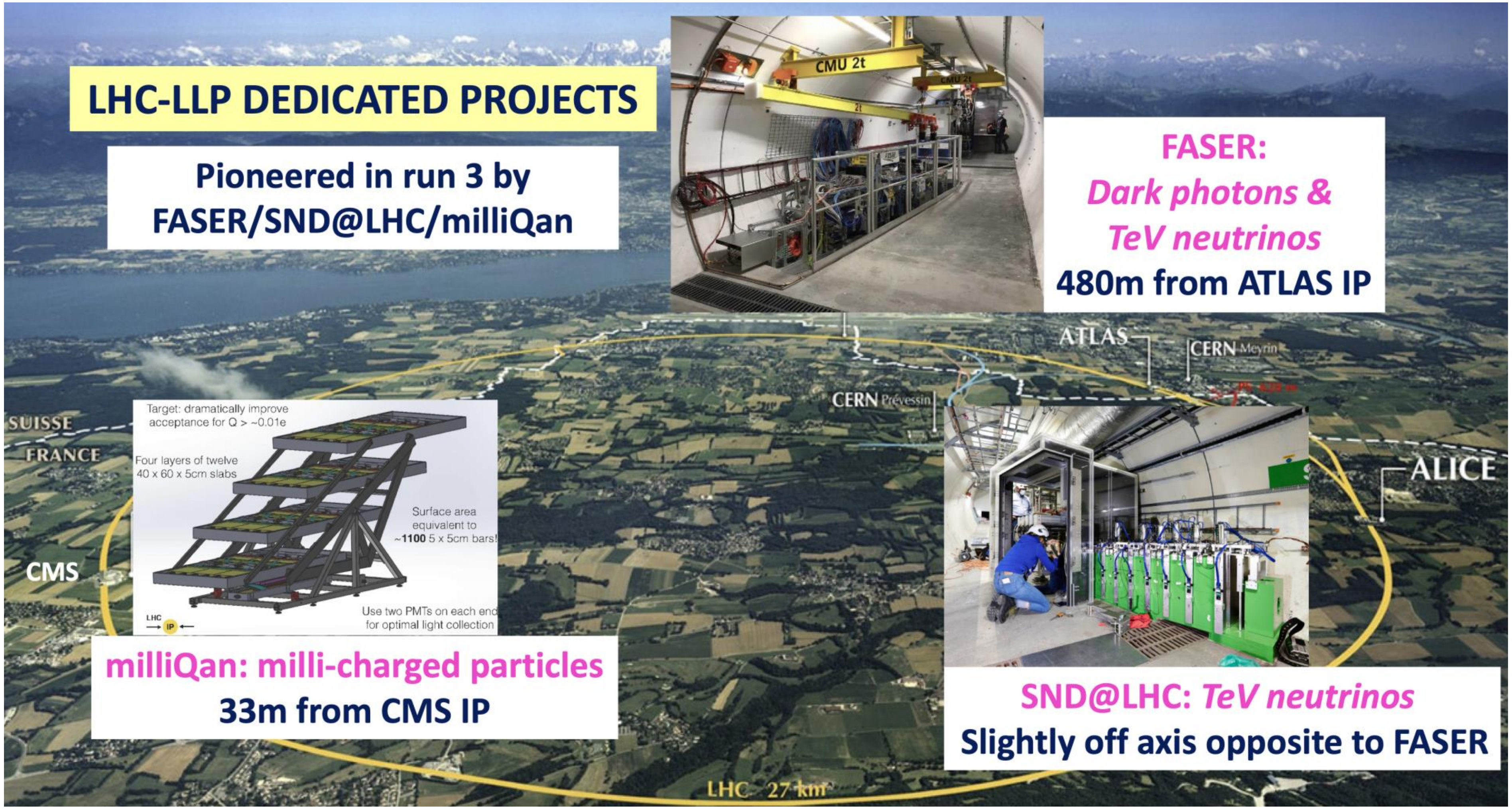
Barrel ECAL

- Replace FE electronics

FPF - BSM Physics Studies



LHC LLP – Run 3



LHC-LLP DEDICATED PROJECTS

Pioneered in run 3 by FASER/SND@LHC/milliQan

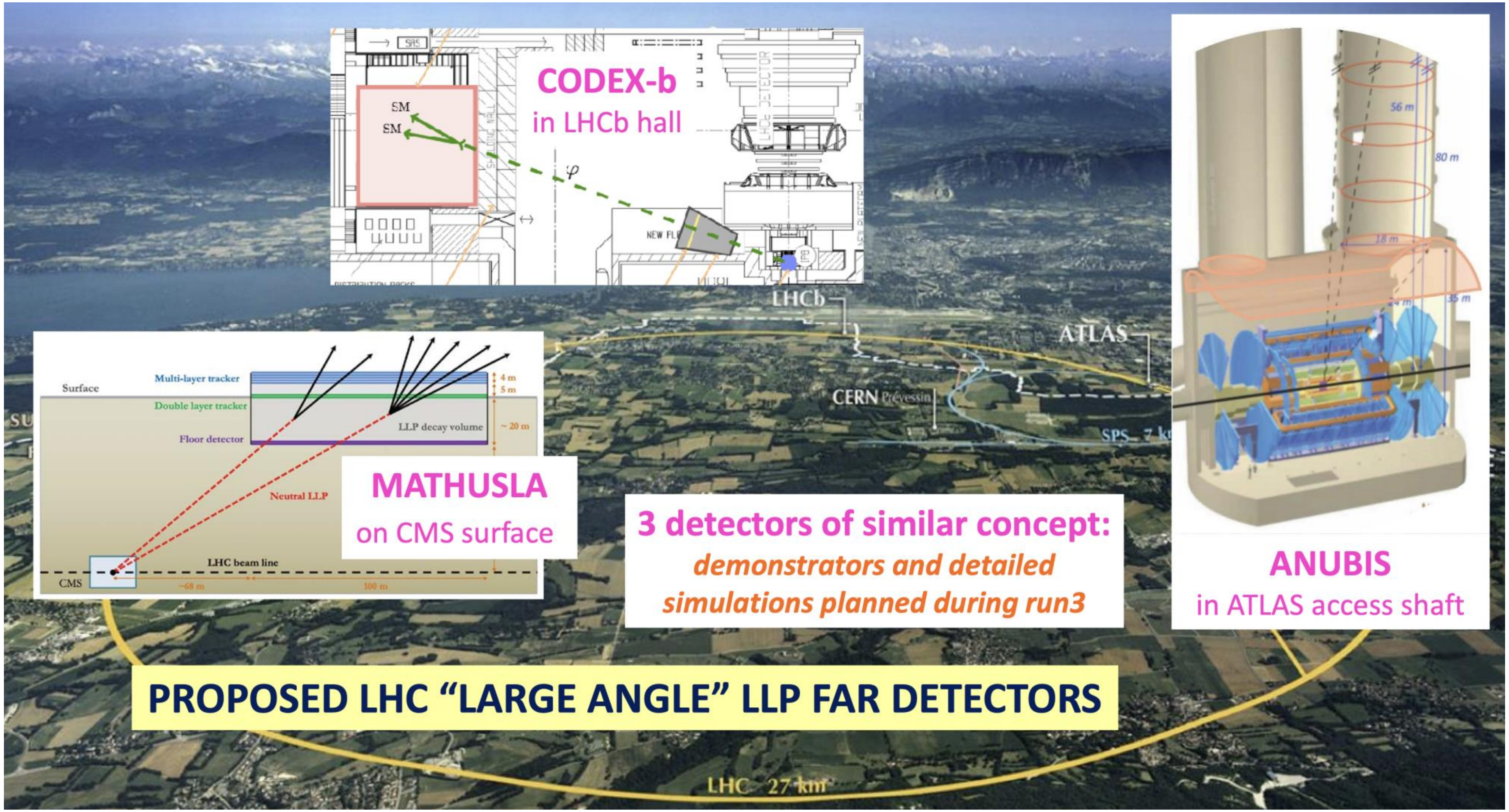
FASER:
Dark photons & TeV neutrinos
480m from ATLAS IP

milliQan: milli-charged particles
33m from CMS IP

SND@LHC: *TeV neutrinos*
Slightly off axis opposite to FASER

These are cost-effective implementations based on existing tunnels and infrastructures.

LHC LLP proposals



CODEX-b
in LHCb hall

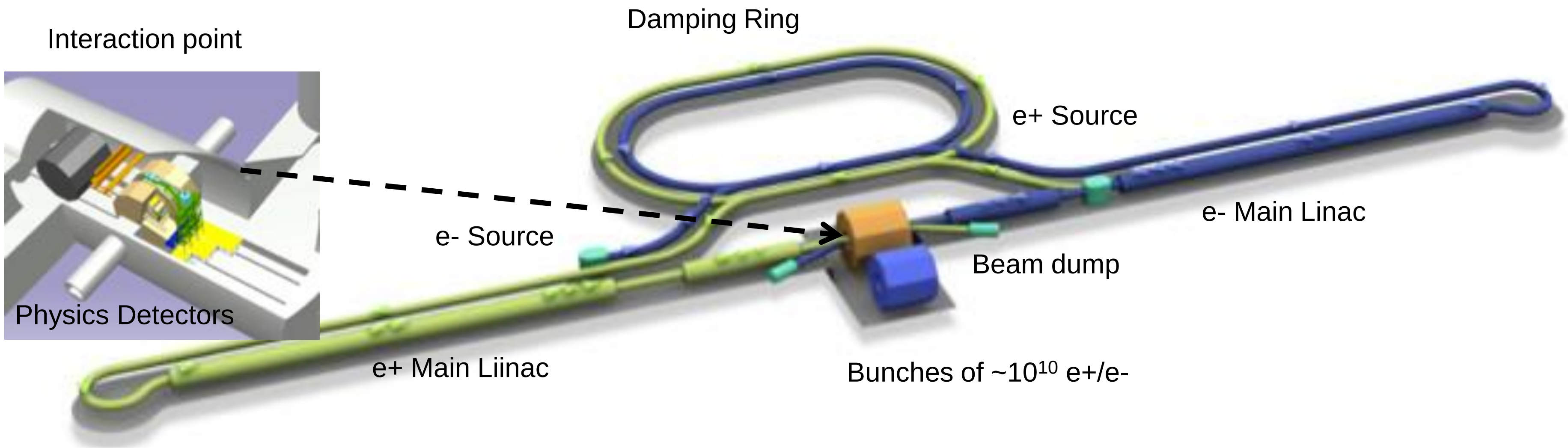
MATHUSLA
on CMS surface

3 detectors of similar concept:
demonstrators and detailed simulations planned during run3

ANUBIS
in ATLAS access shaft

PROPOSED LHC "LARGE ANGLE" LLP FAR DETECTORS

The ILC250 accelerator facility



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G.	31.5 MV/m (35 MV/m)