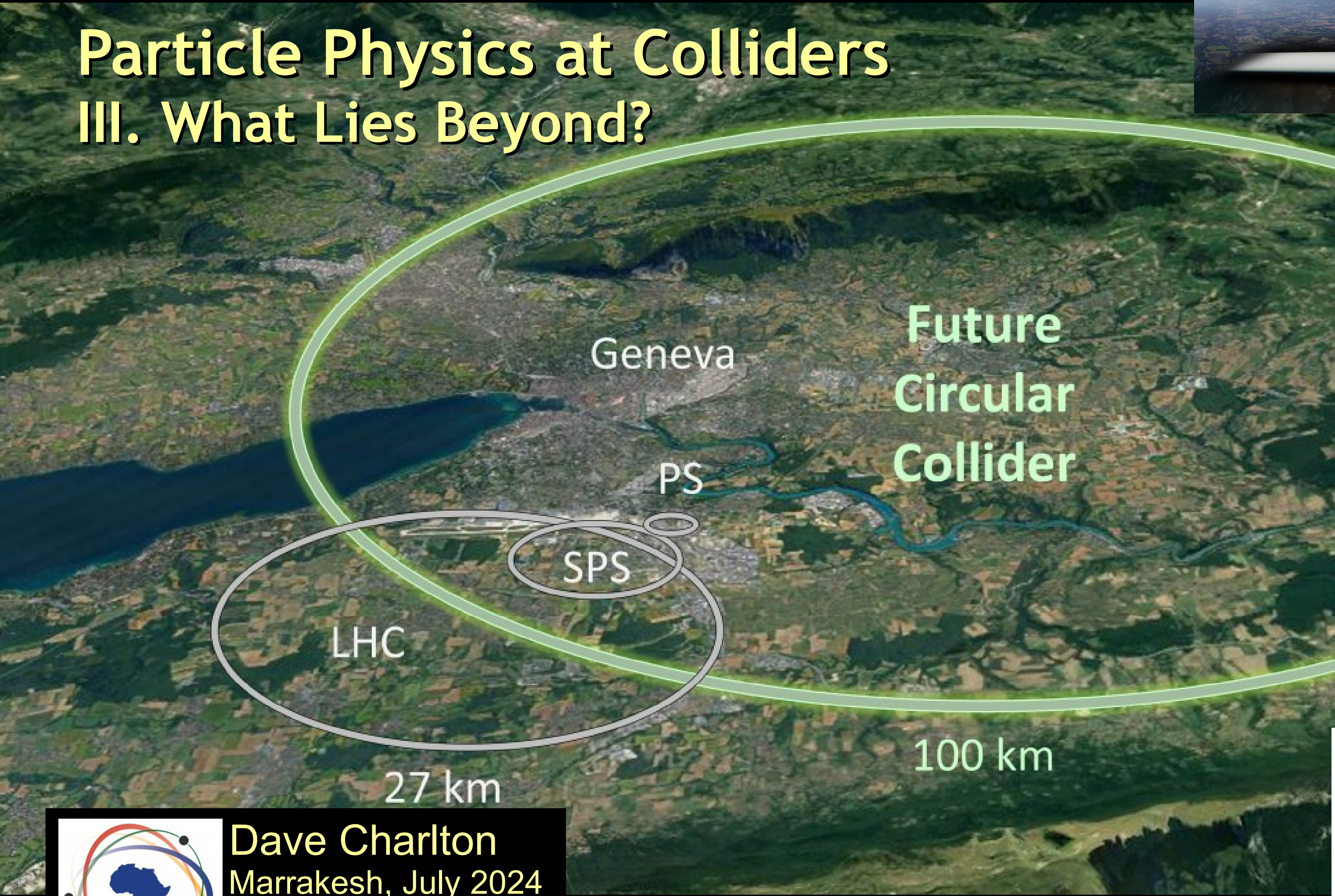
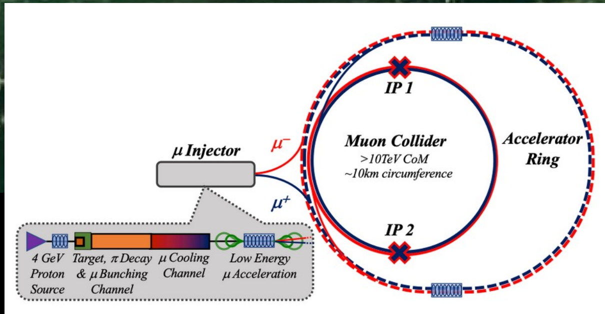
Particle Physics at Colliders
III. What Lies Beyond?





Dave Charlton
Marrakesh, July 2024
UNIVERSITY OF BIRMINGHAM

LHC physics with ATLAS and CMS

Very broadly, divide the ATLAS/CMS proton-proton programme into

- Measurements (Part II)
  - Make precise measurements of previously known processes in the new LHC energy regime
    - Masses, angular distributions, decay modes, momentum spectra ... ...
  - Test parts of SM not tested before – e.g. massive electroweak boson self-interactions
  - *Now* includes the measurements in the Higgs (scalar) sector
- Searching beyond (Part III)
  - Hunt for new physics beyond the Standard Model
    - LHC advantages: high energy, high intensity (integrated luminosity)
    - High energy -> many heavy objects (H, t, W/Z) – look for new physics coupling to these
  - Prospects in the HL-LHC era

Lecture 3 will also briefly touch on physics at future colliders, beyond the LHC

I generally show ATLAS results to illustrate, because it is easier for me – CMS has equally good and broad results!!!

Why "Beyond the SM" (BSM)?

SM explains physics beautifully at the 100 GeV energy-scale – the electroweak scale – and below

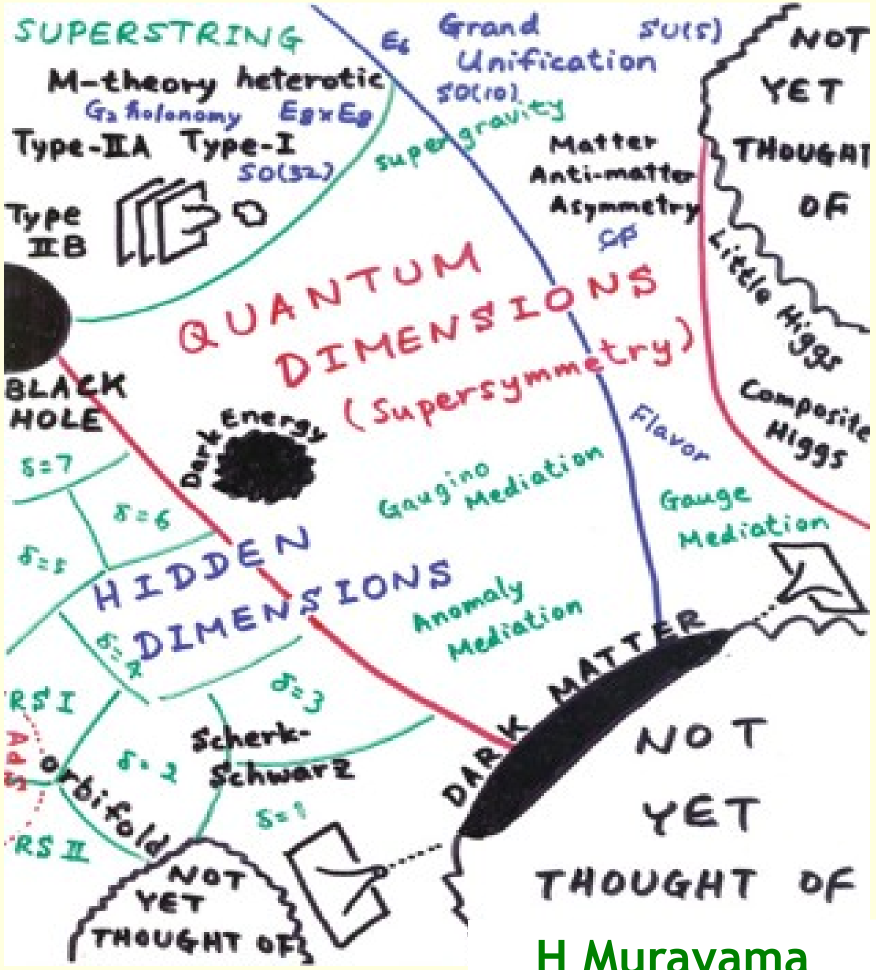
Fundamental questions remain, and must be addressed

- Why is the electroweak scale so much less than the Planck scale (10^{19} GeV)?
  - To go 17 orders of magnitude without new physics would be quite unprecedented! (cf. size of an atom vs. size of the earth)
- In the scalar (Higgs) sector...
  - Is the H(125) boson composite?
  - Are their more Higgs bosons?
  - Are there new massive particles coupling with the Higgs?
- Origin of fermion generations, mass values, mixings?
- What is the origin of neutrino mass?
- Why the matter - antimatter asymmetry we see in the universe (CP violation)?
- What is the nature of dark matter?

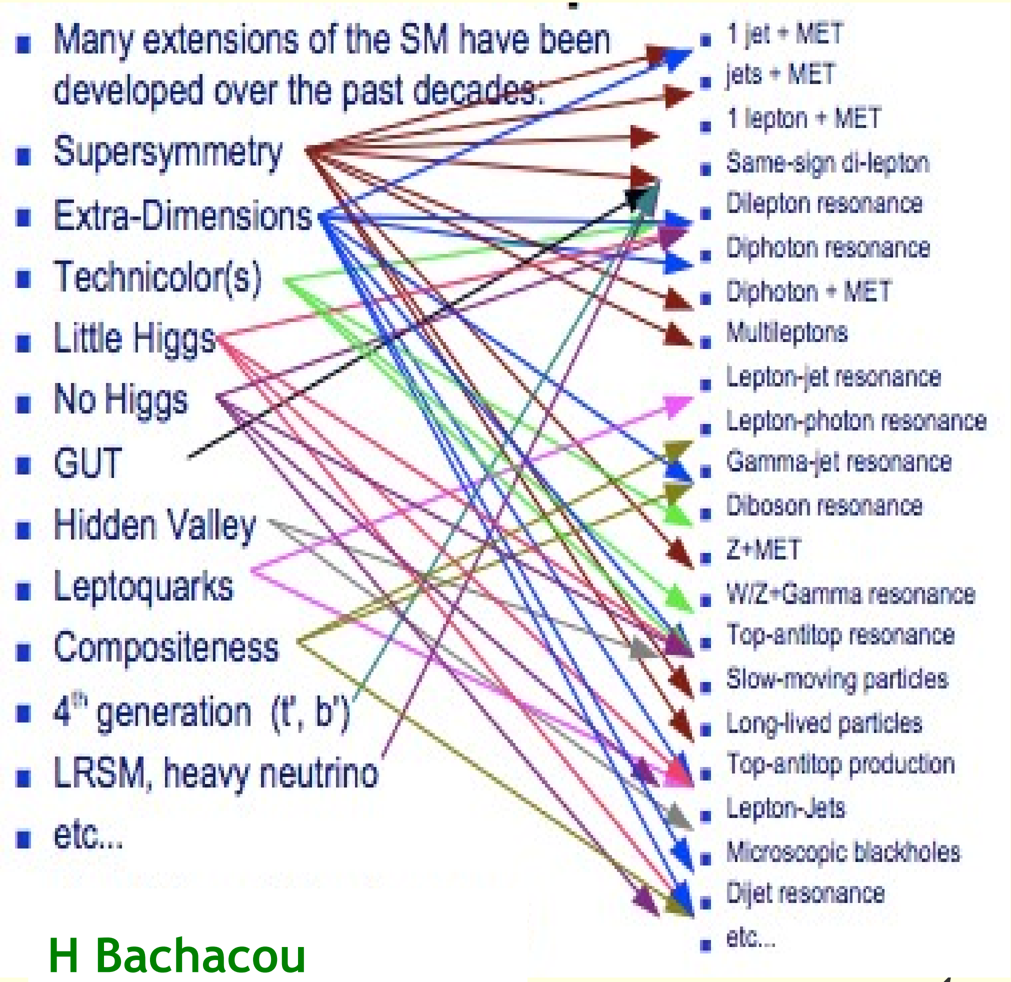
These arguments suggest that new physics will show up in the 0.1-10 TeV range – we must explore this region!

Starts with LHC & HL-LHC, must continue with future colliders

BSM models – and possible signatures



H Murayama



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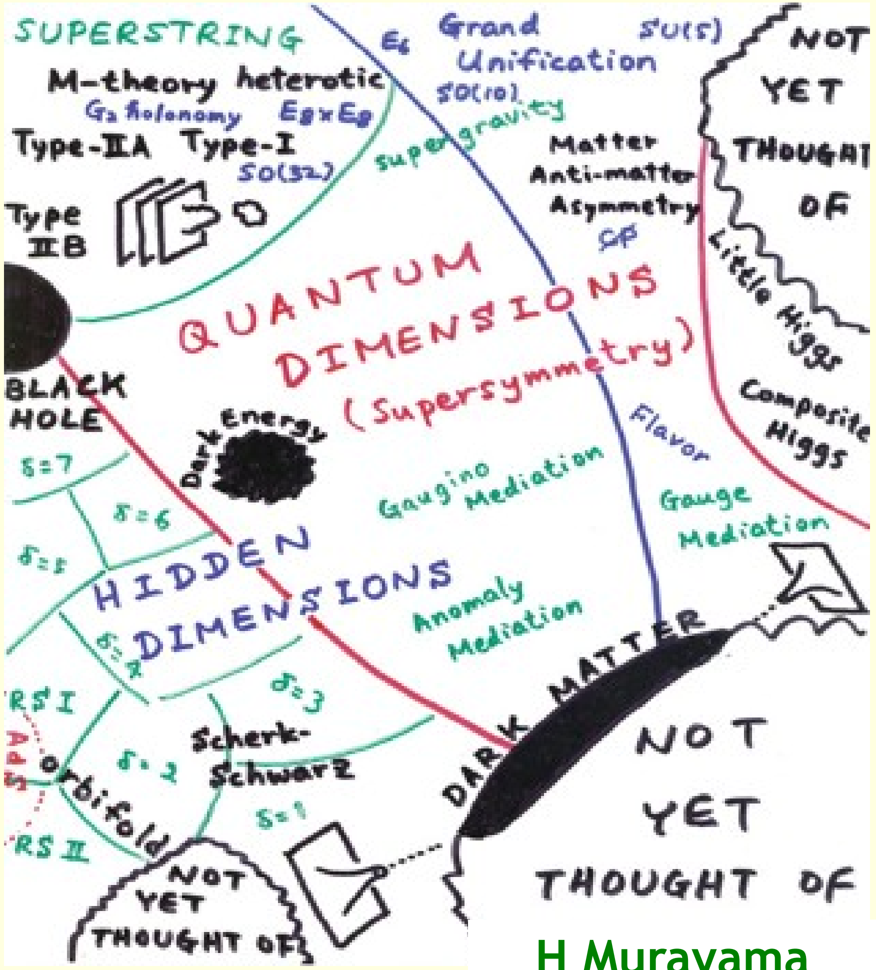
BSM models – and possible signatures



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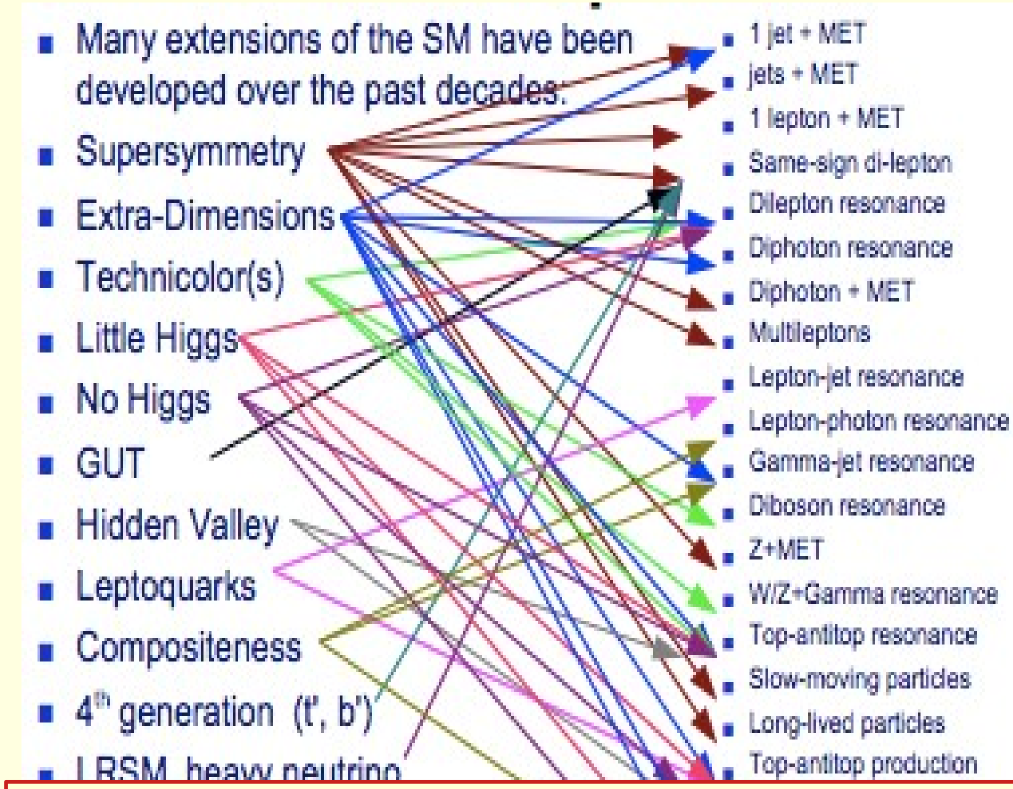


I'll give just a few examples...

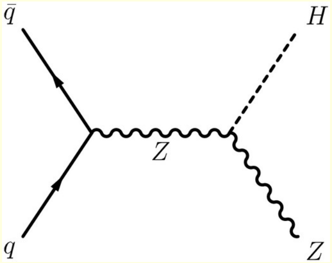
Invisible Higgs decays?

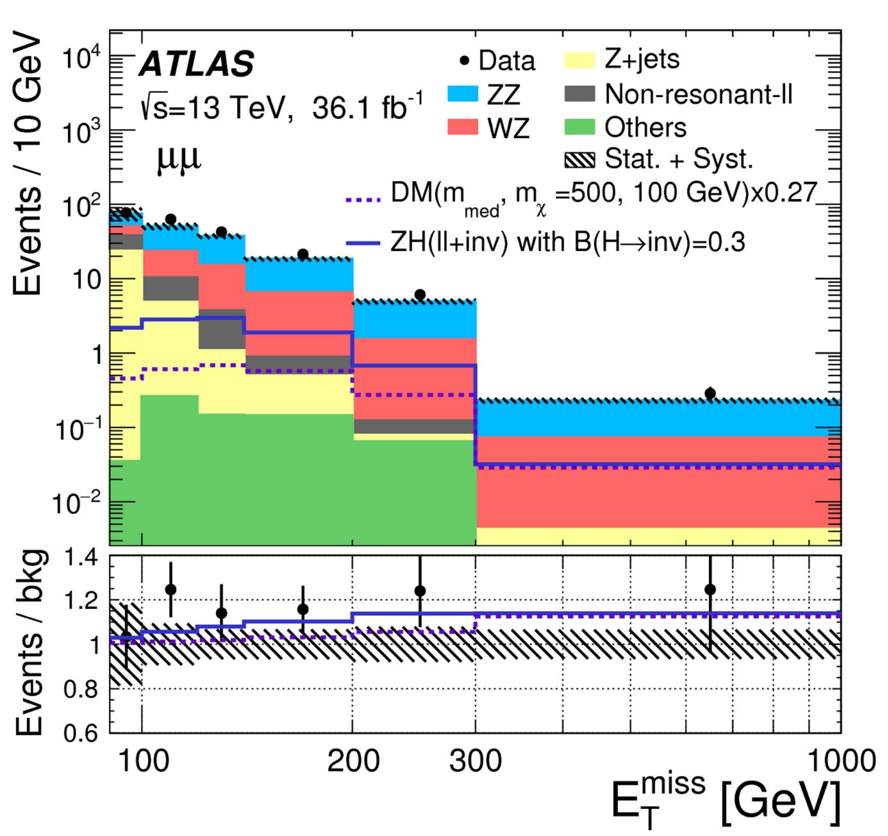
If the H couples to new BSM particles according to their mass, could give

- Modified H decay branching fractions
- Modified H couplings

E.g: does the H decay to new invisible particles?

- Can still select events with ZH or WH production, for example, from Z/W decay
- SM allows $H \to ZZ^* \to 4\nu$, but $B(H \to \text{invis.}) \sim 0.1\%$





ATLAS combination (full Run-2 data)

$B(H \to \text{invis.}) < 10.7\%$ at 95% CL

Need much better precision!

Dark Matter (DM)

Evidence for dark matter in the universe from astrophysical, cosmological measurements

- Galactic rotation curves
- Galaxy collisions (“Bullet cluster”)
- Early universe models (“ΛCDM”)
- Large scale structure of universe (e.g. “BAO”)

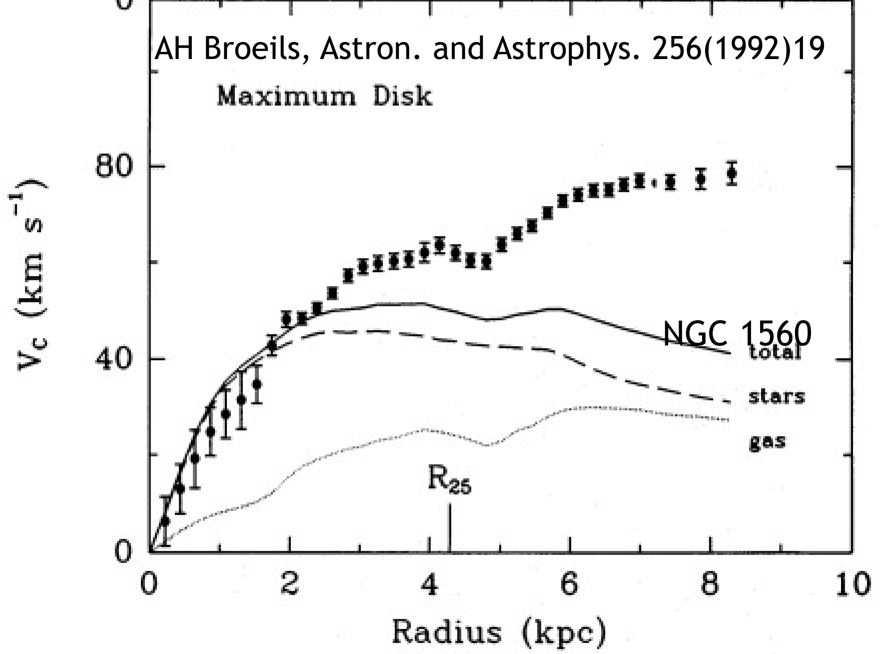
There seems to be a (big) problem – most of the matter in the universe is not identified

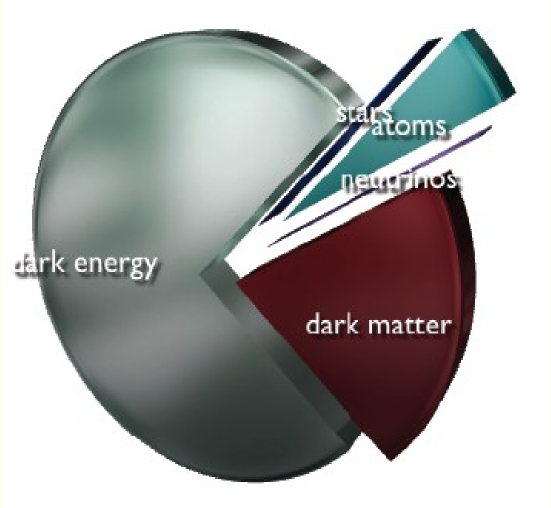
If the DM is non-baryonic, weakly interacting massive particles (**WIMPs**) are an attractive candidate

- models can provide sufficient mass to match the observations, if masses ~ electroweak scale
- Supersymmetry (SUSY) is a natural source

How to observe?

- “Direct detection” (typically underground experiments, no beam)
- Production searches (LHC)

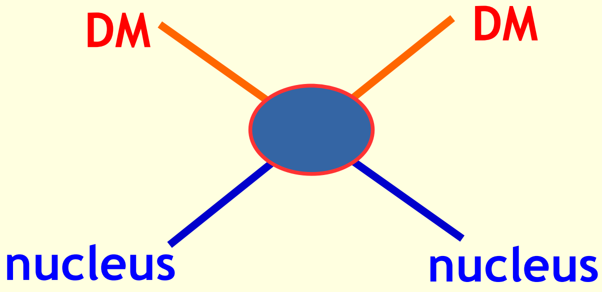




DM direct detection searches

Look to see evidence of dark matter scattering off normal matter

- Rely on “ambient” dark matter in the local vicinity of the solar system
- Similar in nature to neutrino scattering – but heavier, slower, invisible particle, no beam
- Techniques to spot low-E nuclear recoil



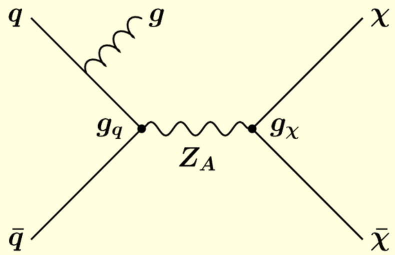
→ Lectures by Prof Gopolang Mohlabeng on this tomorrow, so I will not discuss further here

LHC DM searches

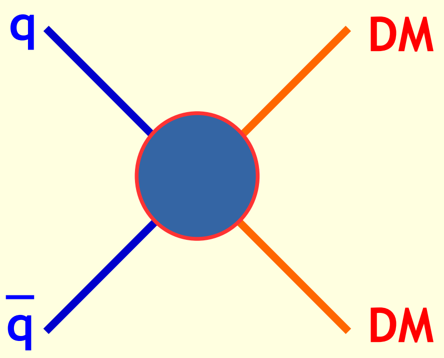
“Crossed” process: pair production of DM particles

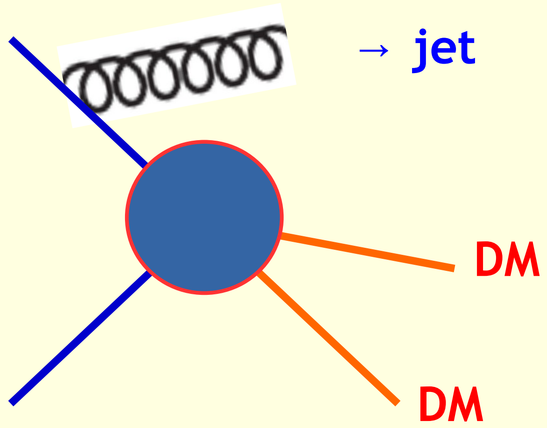
“Physics in the blob” is more important at LHC (especially to compare with direct detection experiments)

Models typically have at least one unknown “mediator” particle which is “inside the blob”, e.g.

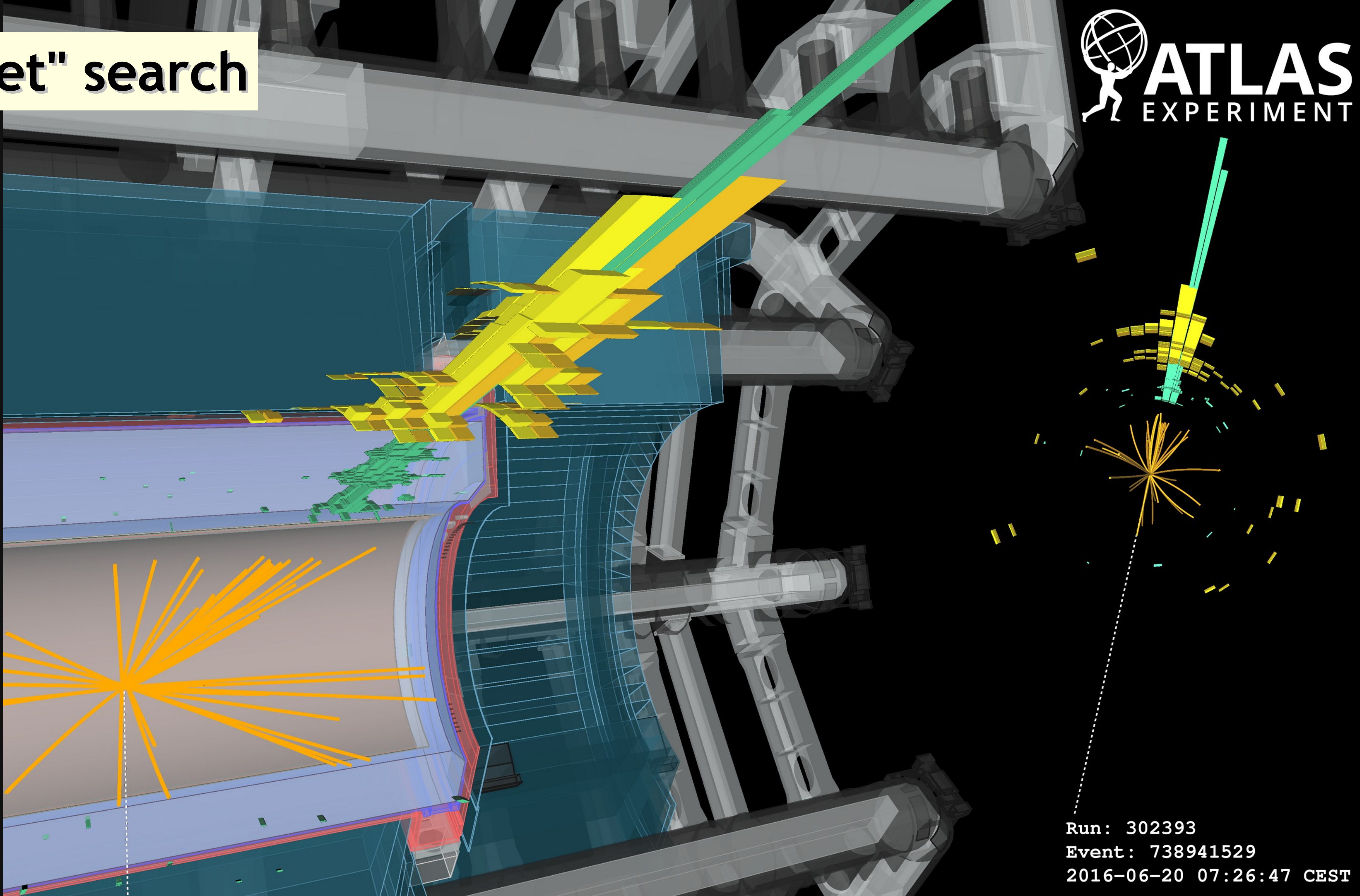


There are many searches for DM at the LHC: one very general search looks for an initial-state-radiation jet plus E_T^{miss} from the unobserved DM particles → “mono-jets”





"Mono-jet" search

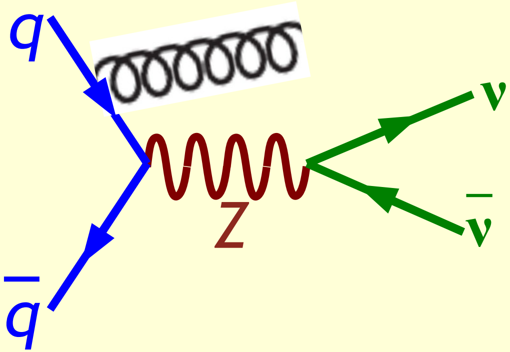


"Mono-jet" search

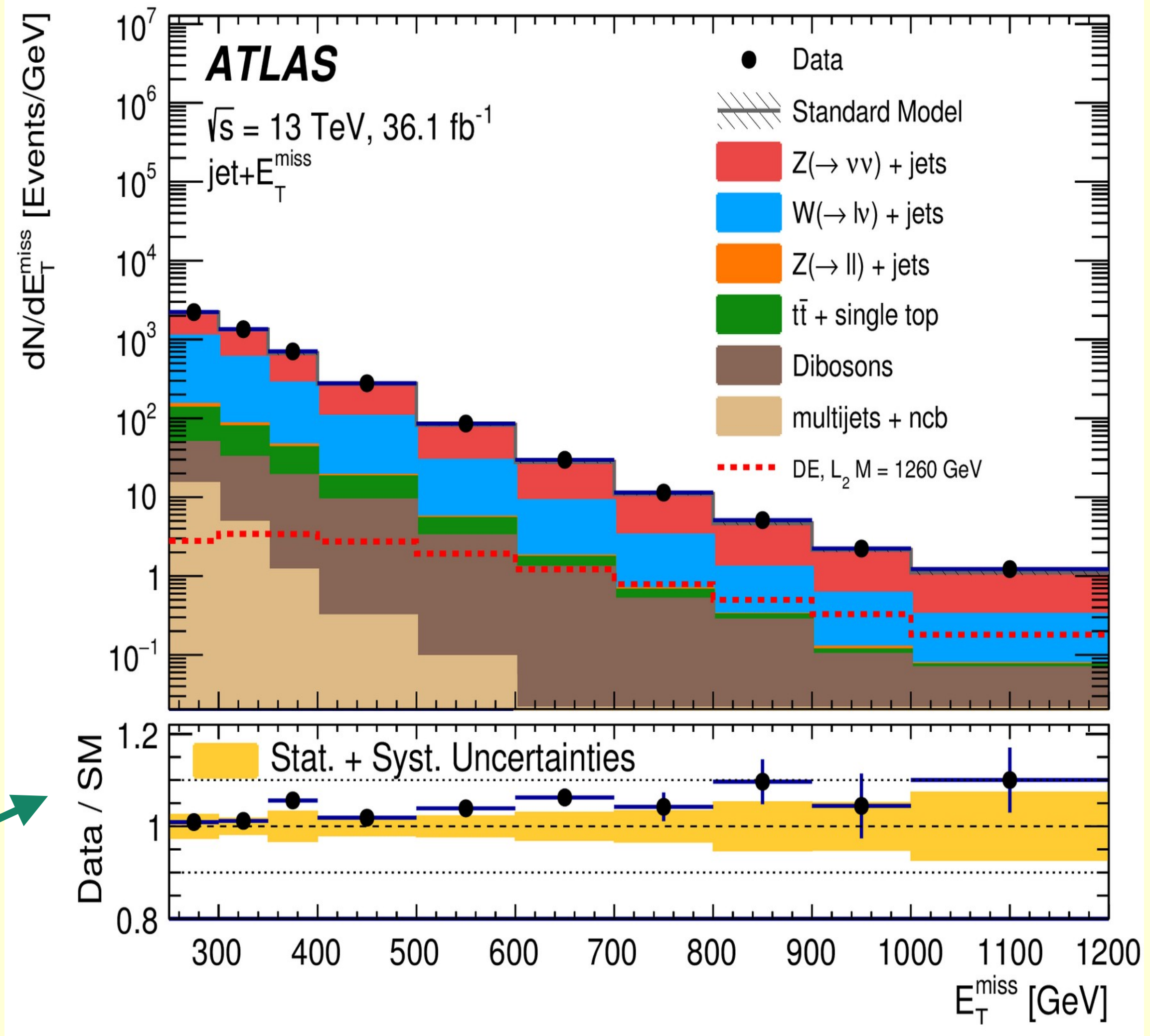
Nice event!

But there is a Standard Model signal source (and backgrounds):

jet+Z production with $Z \rightarrow \nu\bar{\nu}$

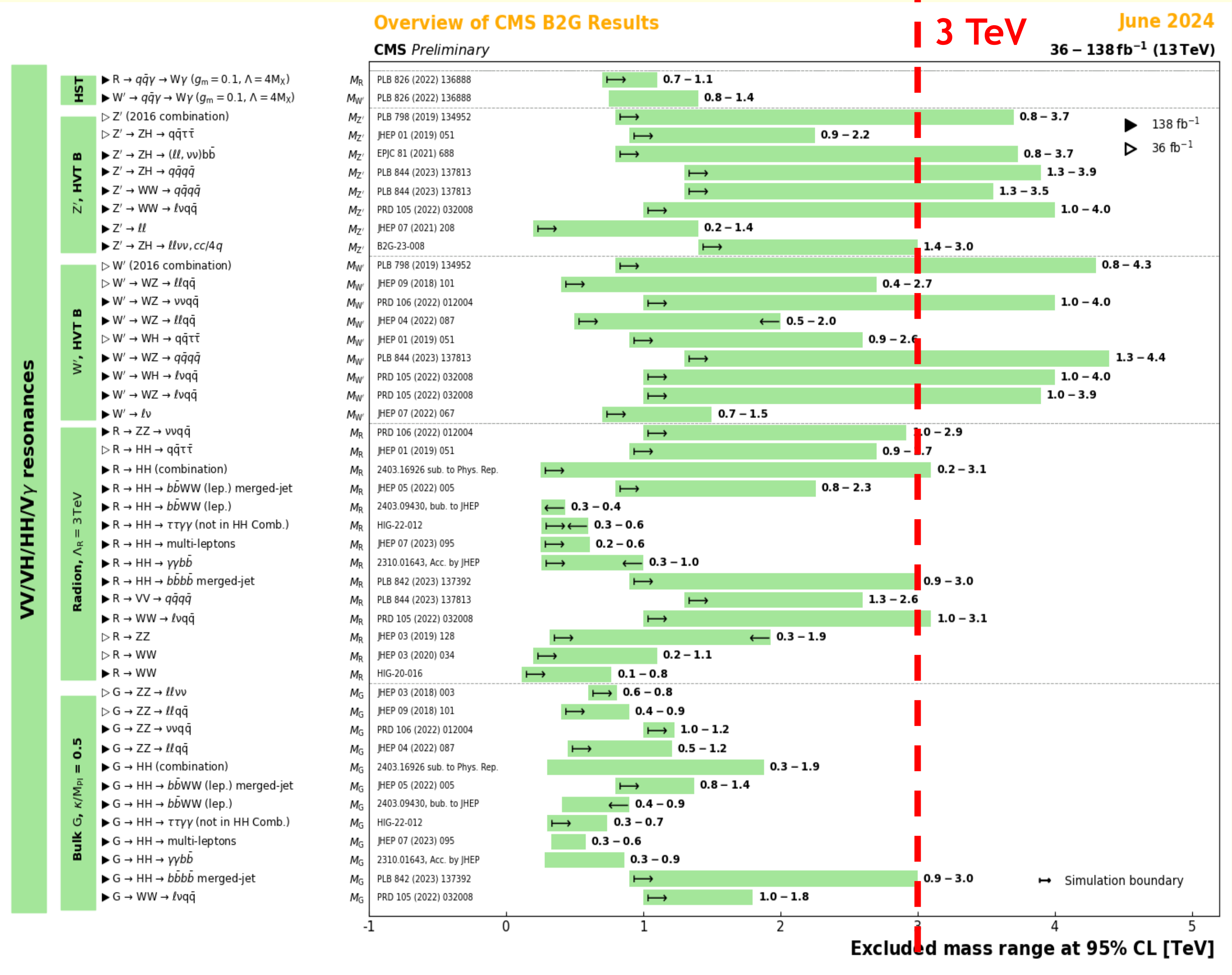


Study of E_T^{miss} in events with an energetic jet – no excess seen



Many more searches for new particles

Many favoured scenarios ruled out at TeV scale, and some well beyond



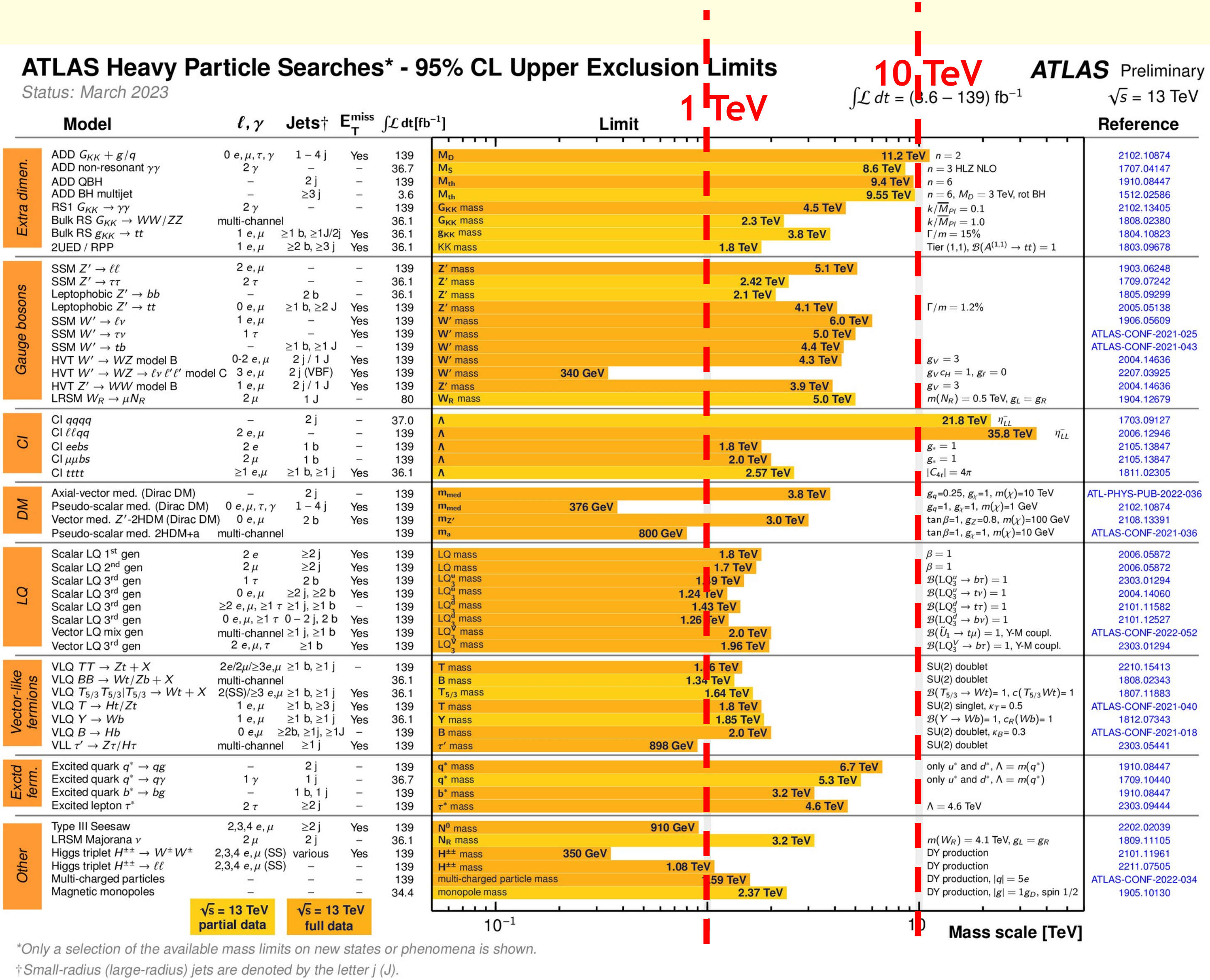
Many more searches for new particles

Many favoured scenarios ruled out at TeV scale, and some well beyond

Changes thinking for the future

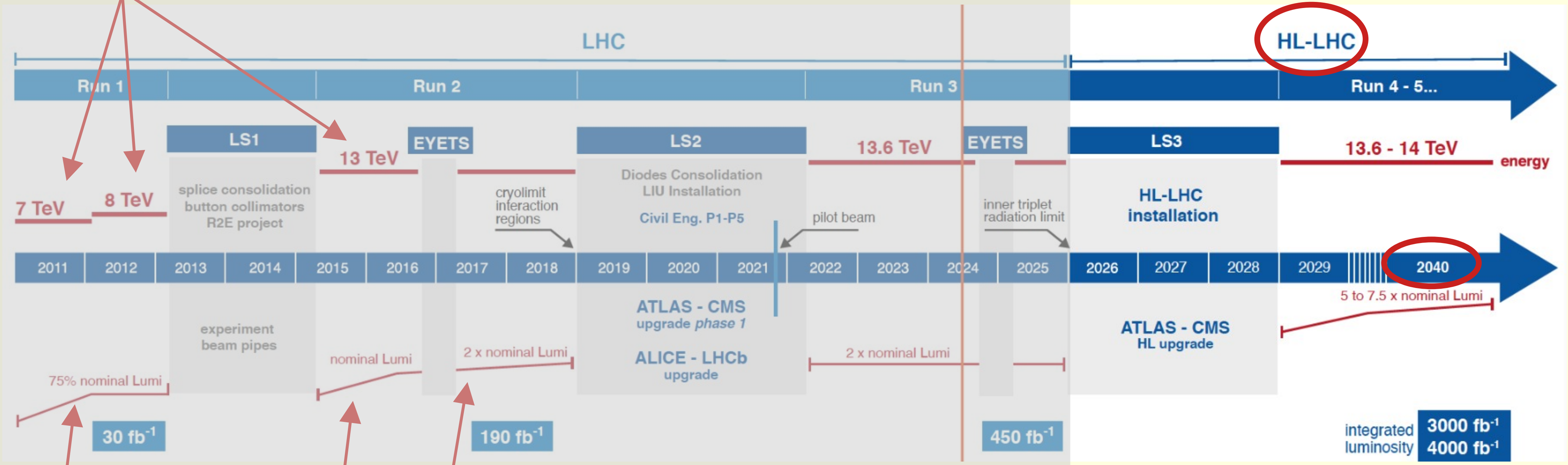
- Feebly interacting particles?
- SUSY with very similar masses ("compressed")?
- Higgs portal models?
- Complex dark sector → "long"-lived new particles?

Searches are refocussing, e.g. using new trigger strategies



The future at the LHC - "High-Lumi LHC", HL-LHC

Centre-of-mass energy, √s

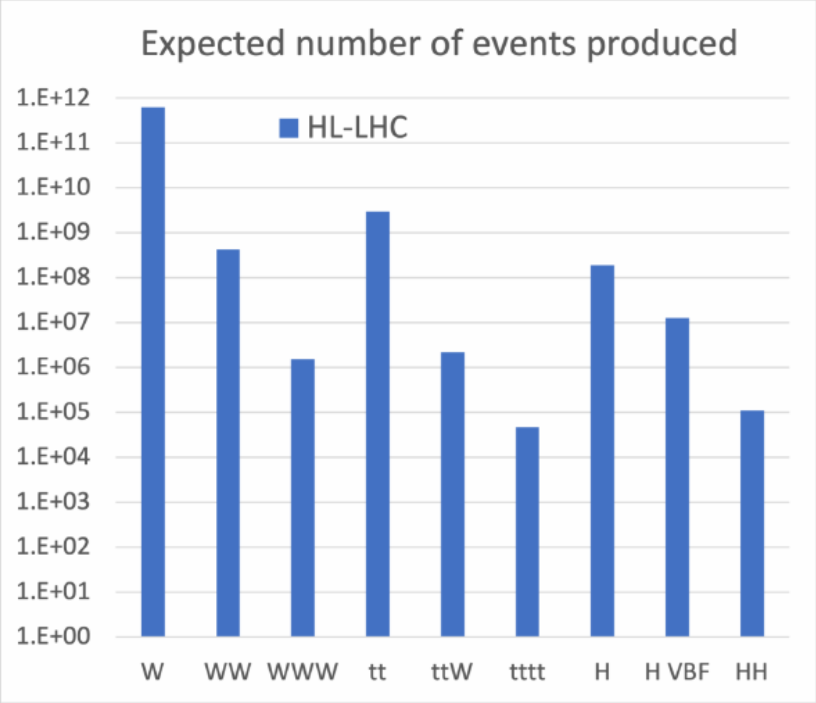


Peak instantaneous luminosity (nominal 10^{34} cm^{-2} s^{-1})

10× data we have now
Better detectors
Better triggers

HL-LHC is a Higgs factory (and a W, Z, top, etc. factory)

- **Huge statistical power for heavy particles**
  - Number of particles produced for each of ATLAS & CMS with 3,000 fb^{-1} at $\sqrt{s} = 14$ TeV
    - ~600,000,000,000 W bosons
    - ~3,000,000,000 $t\bar{t}$ pairs
    - ~190,000,000 Higgs bosons
    - ~120,000 HH pairs
  - Gives access to "rare" processes
    - ~50,000 $t\bar{t}t\bar{t}$
    - exotic Higgs decays down to BF ~10^{-5} — 10^{-6} (e.g. $H \to aa \to \mu\mu\tau\tau$) + extremely rare Z or top decays

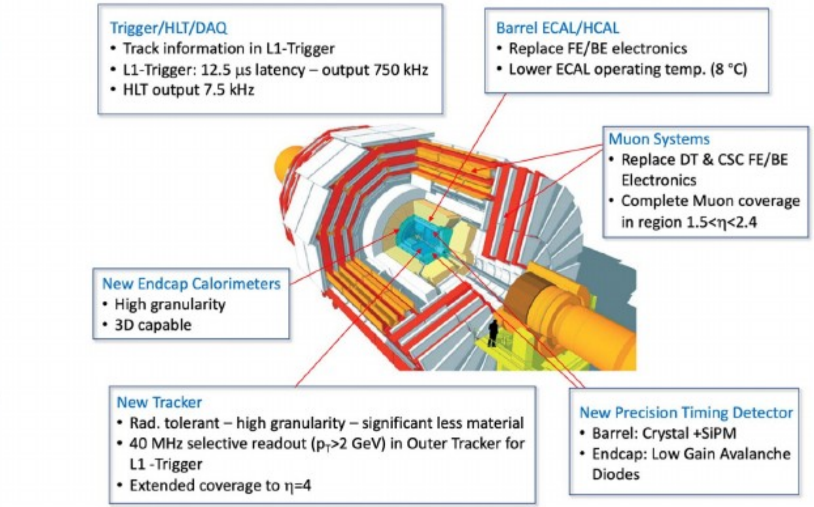


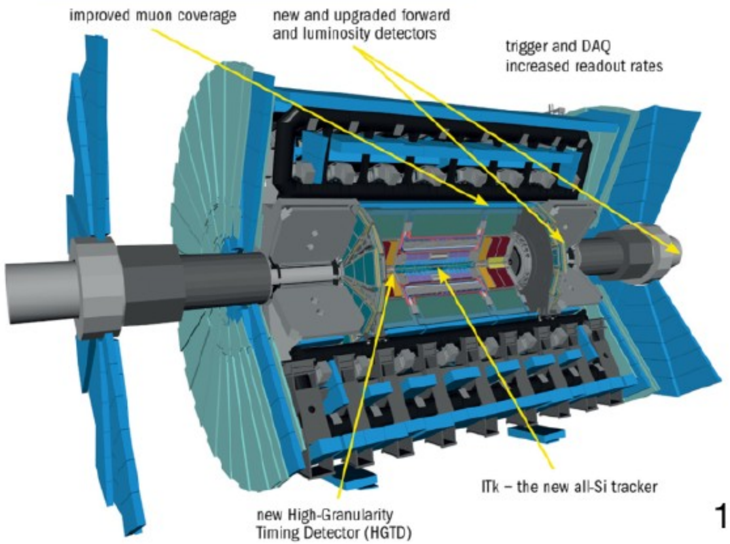
- **HL-LHC allows exploration at both energy frontier and intensity frontier**
- **Challenges:** high pileup (μ = 200 vs. 34 in Run 2) and high radiation doses

S Willocq / LHCP2024

ATLAS and CMS detector upgrades for HL-LHC

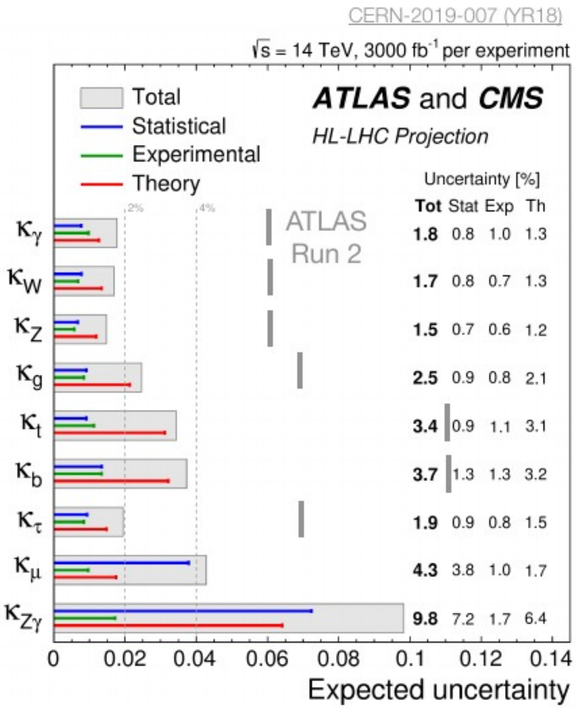
- **ATLAS and CMS Phase-II upgrades for Runs 4, 5 & 6**
  - Challenge: pileup μ = 200
    data acquisition rates 10x higher than LHC
    maintain or lower trigger thresholds
  - Significant enhancement to sensitivity with
    - higher-resolution tracking systems (extending to $|\eta| = 4$)
    - improved calorimetry
    - increased muon coverage
    - enhanced trigger capability
    - novel timing systems
  - Aggressive R&D in trigger, software and computing
    - exploit AI/ML techniques online and offline
    - develop software for heterogeneous computing technologies



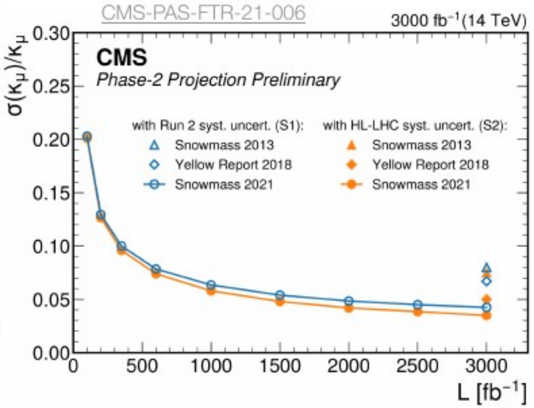


Higgs couplings @HL-LHC

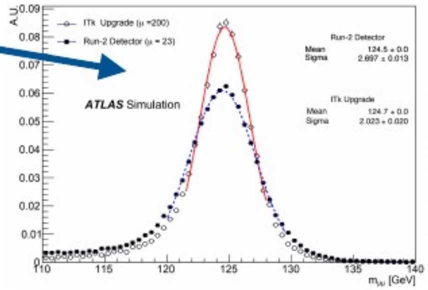
- Combination of ATLAS and CMS measurements extrapolated from (early) Run 2 analyses for YR18
- Precision on tree-level coupling modifiers (κ_i)
    - 1.5 - 1.8% for couplings to bosons (γ, W, Z)
    - 1.9 - 4.3% for couplings to fermions (μ, τ, b, t)



- Access to couplings to 2nd generation fermions via $H \rightarrow \mu^+\mu^-$
  Given $B(H \rightarrow \mu\mu) = 2 \times 10^{-4}$, statistics dominate even with 3,000 fb^{-1}



- New tracking system: 30% improvement in $m(\mu\mu)$ resolution
- Uncertainty reduced from 5.0% (YR18) to 3.5% by extrapolating full Run 2 analysis



- Coupling to charm difficult due to $B(H \rightarrow c\bar{c}) = 2.9\,\%$, large background and c-tagging performance

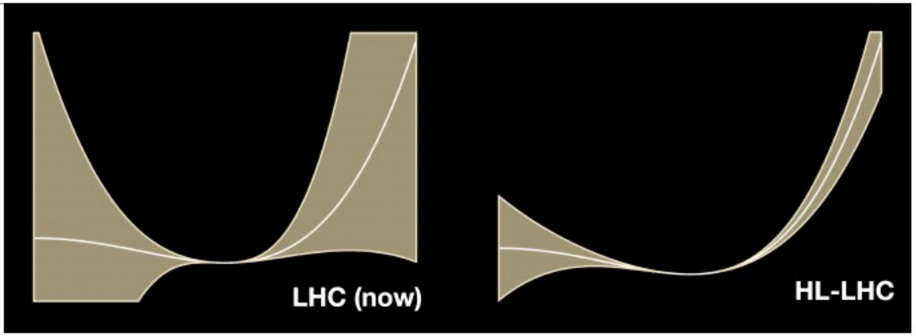
Snowmass 2021

$\kappa_c < 1.75$ (95% CL)

Higgs potential

EW phase transition resp. for baryon asymmetry? Vacuum stable?

N. Craig (Dec 2022)

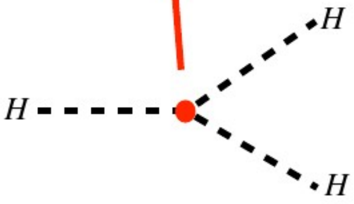


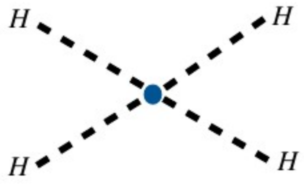
- **Measurement of Higgs potential a *science driver* for HL-LHC,** largely unconstrained so far
- Shape of potential key to understand **EW phase transition in early universe**
- Shape of potential determines **vacuum stability**

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$

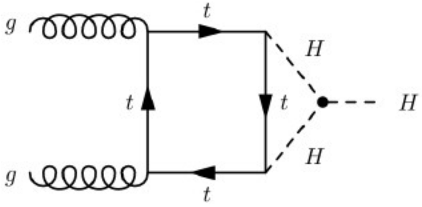
$$\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2v^2}$$

Higgs mass already measured at LHC with ~per-mill precision



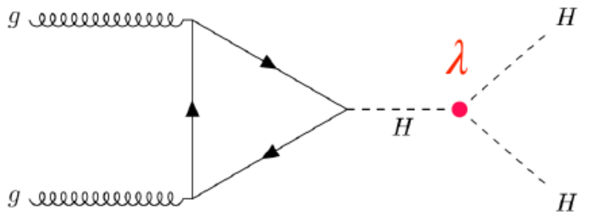


- Cubic (aka tri-linear) coupling λ ($\equiv \lambda_3$) via Higgs pair production
- Single Higgs measurements sensitive to λ via higher-order corrections



Higgs self-coupling @HL-LHC

- Tri-linear coupling λ directly accessible via Higgs pair production
- $pp \rightarrow HH$ cross section 3 orders of mag. lower than single Higgs
- Improved trackers and ML key for HH studies (e.g. b tagging)

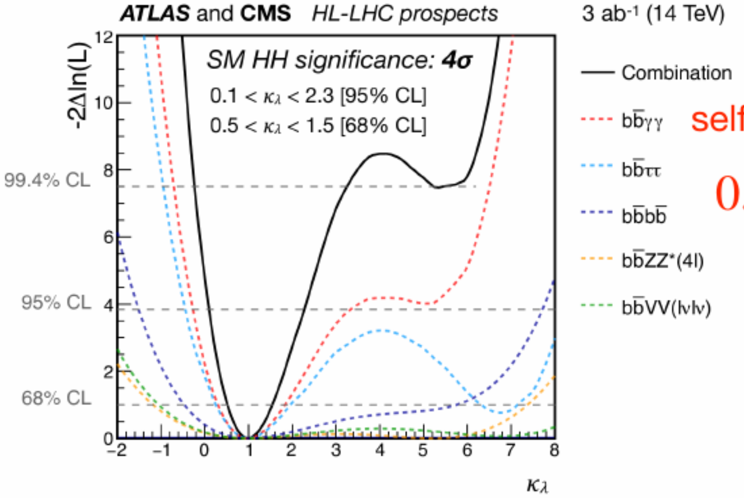


destructive interference with box diagram

- **ATLAS+CMS Yellow Report 2018**

  $pp \rightarrow HH$ significance = 4.0 σ (4.5 σ stat only)

CERN-2019-007 (YR18)



self-coupling modifier

$0.52 < \kappa_\lambda < 1.5$

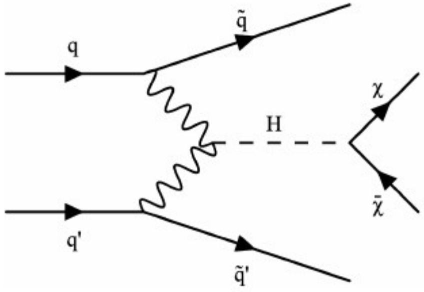
(68% Cl)

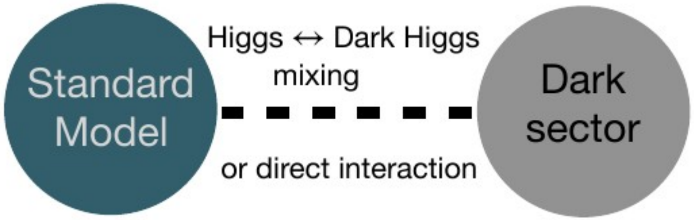
Estimates of HL-LHC sensitivity here are a bit old – latest numbers suggest we can get to 5σ observation of HH production

Constraints on the self-coupling, but need more precision → future colliders, long-term

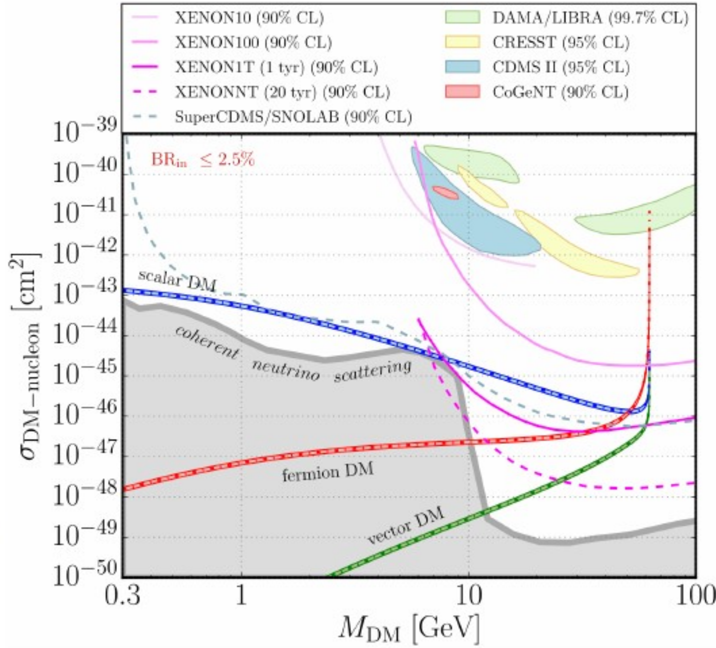
BSM: Higgs portal @HL-LHC

- Higgs **portal to dark sector** of new particles and interactions
  - Lowest-dimension operator $H^\dagger H \mathcal{O}_{DS}$
  - Search for $H \to \text{invisible}$ in VBF and ZH production
    SM rate: $B(H \to ZZ^* \to \nu\bar{\nu}\nu\bar{\nu}) \simeq 0.1\,\%$
  - Pileup mitigation techniques, timing, increased tracking acceptance key to identify forward jets and preserve E_T^{miss} resolution
  - Model-independent $B(H \to \text{inv}) < 2.5\,\%$ (95% CL ATLAS+CMS)
  - HL-LHC sensitivity exceeds direct detection expts in minimal Higgs portal model for $m_{DM} \lesssim 30$ GeV
- Significant gains in BSM with low XS or BF from large luminosity
  - Electroweak SUSY, compressed spectra
  - Feeble interactions, dark sector portals, long-lived particles





CERN-2019-007 (YR18)



Beyond the LHC

A few clear priorities:

- Improve measurements of Higgs properties and couplings
  - Higgs total width – probe for unobserved decay modes, visible or invisible
  - Higgs self-coupling
- Go an order of magnitude beyond LHC E scale to probe for BSM physics ("10 TeV partonic CM energy" / "10 TeV pCM")
  - Look for new higher energy processes and higher mass particles
  - Especially whether Higgs is a portal to new physics
- Understand / discover dark matter – this is a shared endeavour, colliders just one prong
  - "All" we know about dark matter is that it has (gravitational) mass
  - Won't it couple to the Higgs, as that generates fundamental particle masses in SM?
  - Why should DM be a single particle?
    - When something found, we want to explore the dark sector

Future colliders

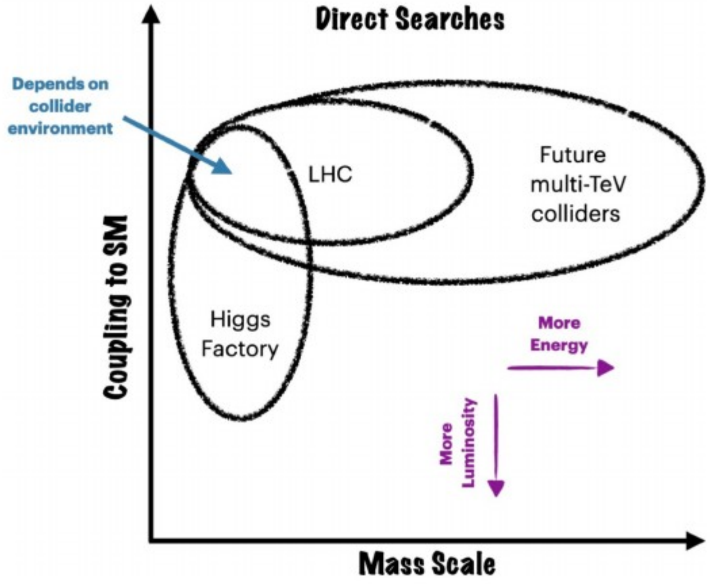
- Next priority: **e⁺e⁻ Higgs factory**

	Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{int}$ ab^{-1} /IP
	HL-LHC	pp	14 TeV		3
linear ee	ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2
			350 GeV	$\pm80/\pm30$	0.2
			500 GeV	$\pm80/\pm30$	4
			1 TeV	$\pm80/\pm20$	8
	CLIC	ee	380 GeV	$\pm80/0$	1
circular ee	CEPC	ee	M_Z		50
			$2M_W$		3
			240 GeV		10
			360 GeV		0.5
	FCC-ee	ee	M_Z		75
			$2M_W$		5
			240 GeV		2.5
			$2\ M_{top}$		0.8
μμ	μ-collider	$\mu\mu$	125 GeV		0.02

Different $\sqrt{s}$: e⁺e⁻ at Z, WW, ZH, tt, up to 1 TeV

μ-collider at H pole (E_{beam} spread challenge)

(e⁺e⁻ perhaps at H pole also)



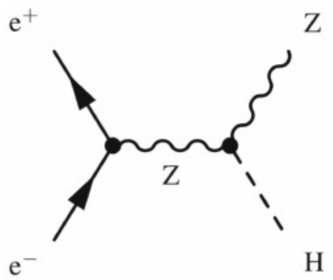
Snowmass EF report

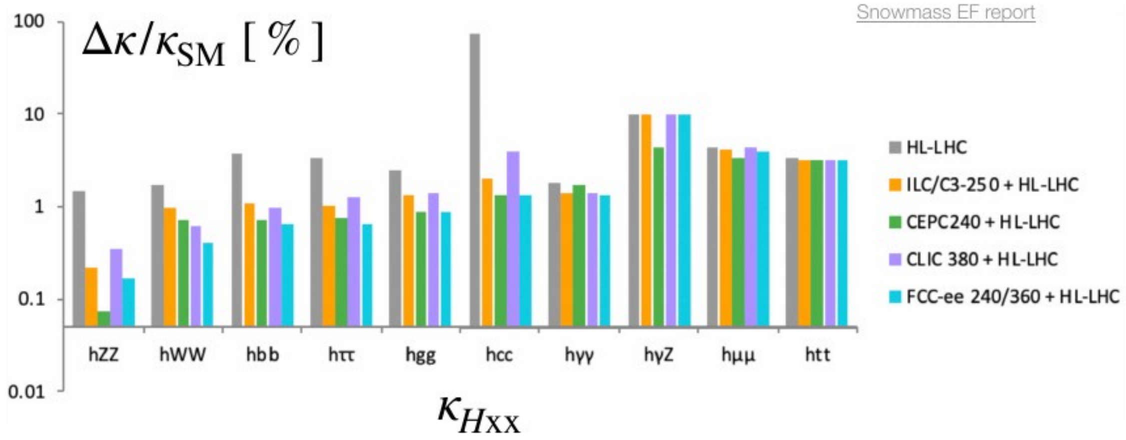
- Longer term: **multi-TeV collider**

Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{int}$ ab^{-1}/IP
HE-LHC	pp	27		15
FCC-hh	pp	100		30
SPPC	pp	75-125		10-20
LHeC	ep	1.3		1
FCC-eh		3.5		2
CLIC	ee	1.5	$\pm80/0$	2.5
		3.0	$\pm80/0$	5
μ-collider	$\mu\mu$	3		1
		10		10

e^+e^- : Higgs boson

- *Fully inclusive* Higgs sample via recoil mass in ZH production (~1 M events)



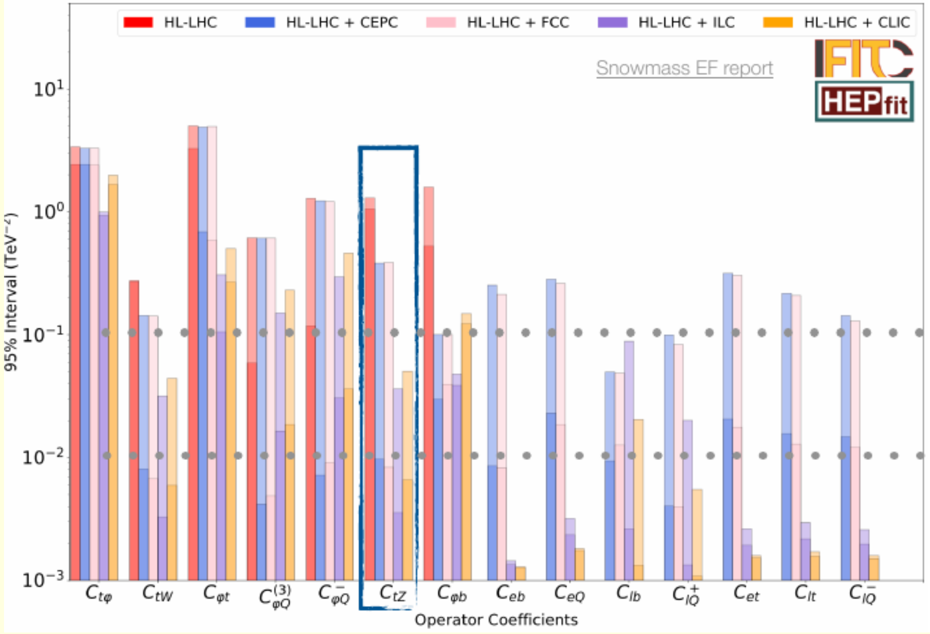


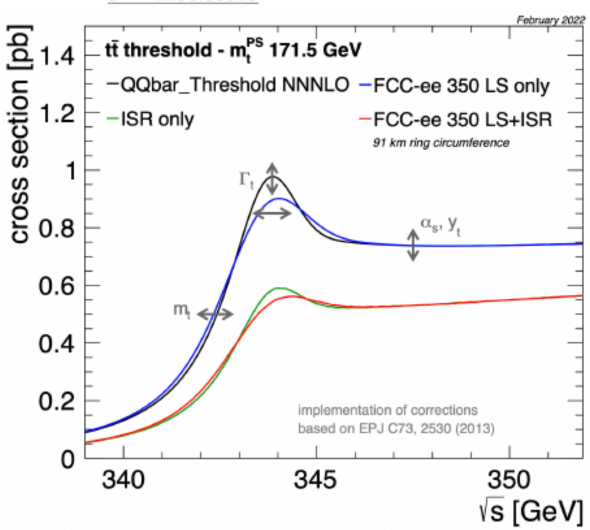
- **Absolute** measurement of g_{HZZ} with 0.05% statistical precision reachable
  - Allows to translate cross-section ratios from HL-LHC into model-independent coupling measurements

- Sharp improvement wrt HL-LHC for Higgs coupling to Z, W, b, **c**, τ (factor 10 for Z or H_{inv})
- **Higgs width precision**
  - 1% combining e^+e^- with HL-LHC
  - 1.7% direct measurement via line-shape at μC
- FCC-ee exploring running at $\sqrt{s} = 125$ GeV to measure coupling to electrons

e+e− : Top quark

- **Top quark:** key role in SM
  - Yukawa coupling $y_t \simeq 1$, quadratic corr^s to m_H, vacuum stability
  - Only quark that does not hadronize before decay
- Expect ~2M $t\bar{t}$ events w/ clean environment + ability to scan $\sqrt{s}$
- Top-mass precision: 40-75 MeV from scan
- Sharply improved ttZ coupling + EFT constraints on top couplings





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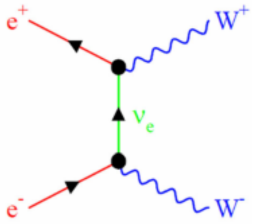
e^+e^- : Precision Electroweak

- **Giga-Z (ILC) & Tera-Z (FCC-ee, CEPC) runs**: up to 6 x 10^{12} Z bosons
  —> 5+ orders of magn. more than LEP
  - **Reduced statistical uncertainties by factor up to ~500**
  - Requires theory calculations at next order or higher + improved $\alpha_s, \alpha_{EM}, m_t$
- **WW threshold**: 2 x 10^8 WW boson pairs
  —> 3 orders of magn. more than LEP



Snowmass EF report

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{had}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b ($\times 10^3$)	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

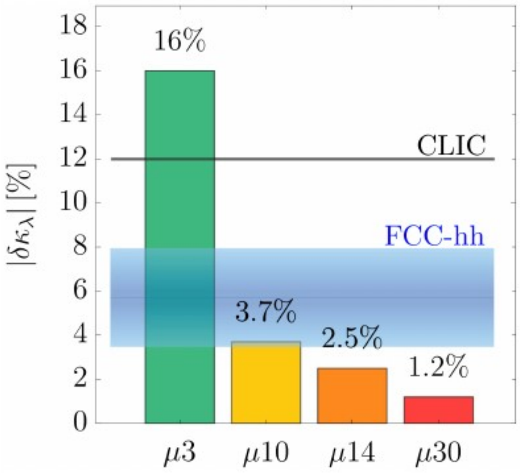
Stat. (exp. syst.) uncertainties improve by up to factors of 20-50

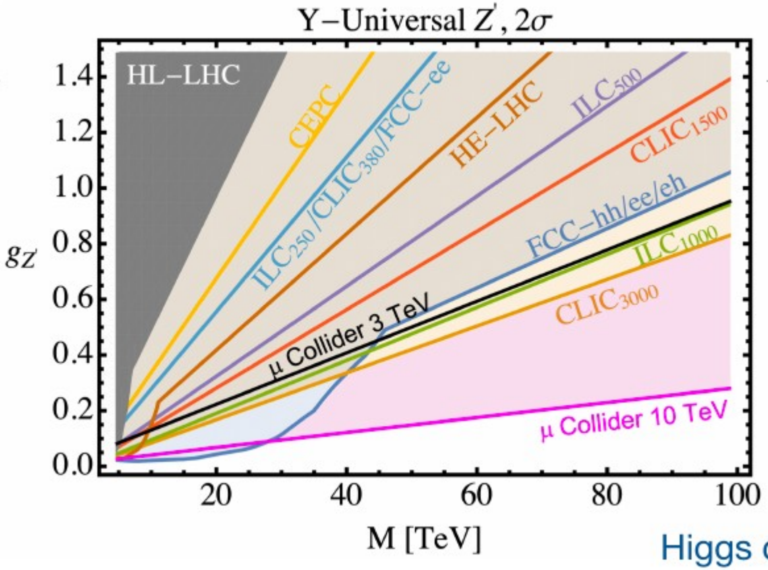
  - W mass and width from line shape —> $\delta m_W = 0.4$ MeV, $\delta\Gamma_W = 1.2$ MeV
- **EFT study w/ dim-6 operators for Higgs + EW:** indirect BSM sensitivity up to 70 TeV (Tera-Z)

Multi-TeV colliders

- **Higgs potential via self-coupling** precision of
  ~5% (100 TeV *hh*)
  ~4% (10 TeV μC)

arXiv:2303.08533



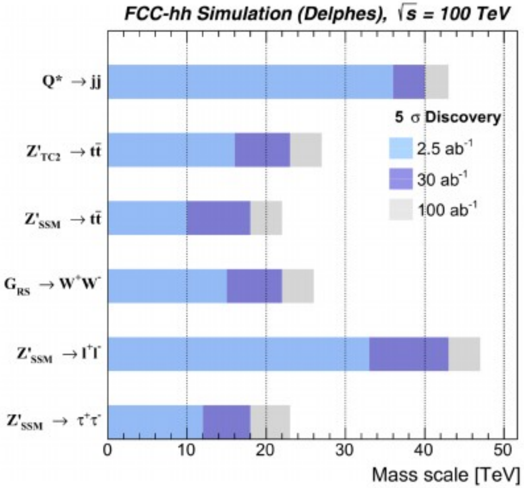


Snowmass EF report

Vector resonances reach to ~100 TeV

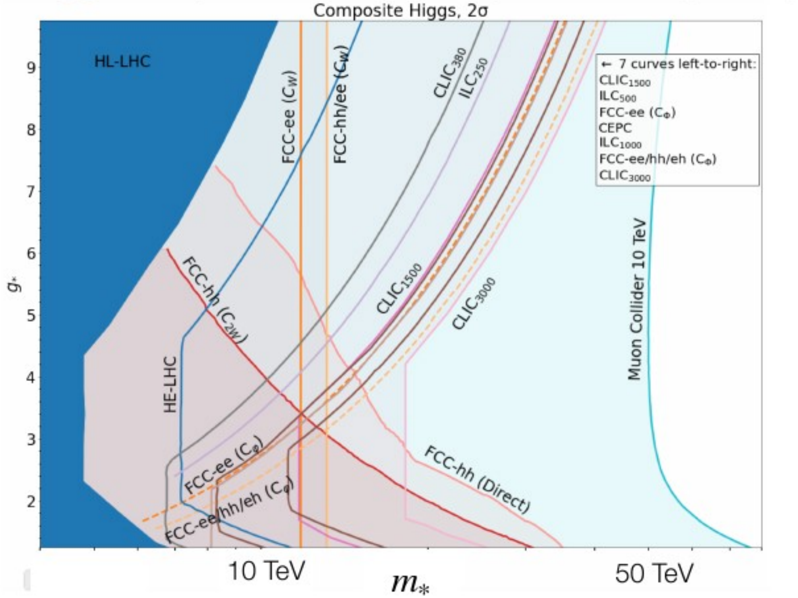
Complementarity of direct and indirect searches

Heavy resonances up to 40 TeV



arXiv:2209.13128

Higgs compositeness scale up to 50 TeV (μ-coll.)

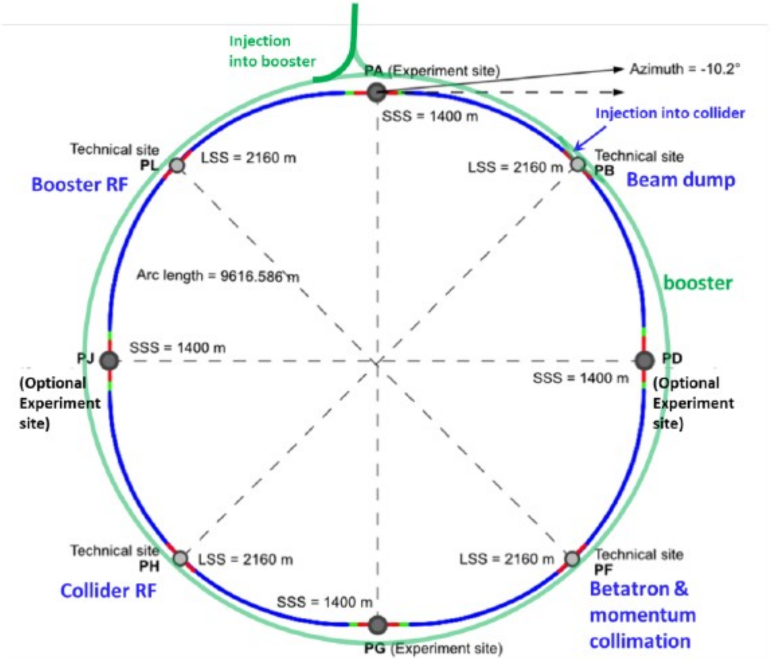


FCC Ring Parameters and Placement

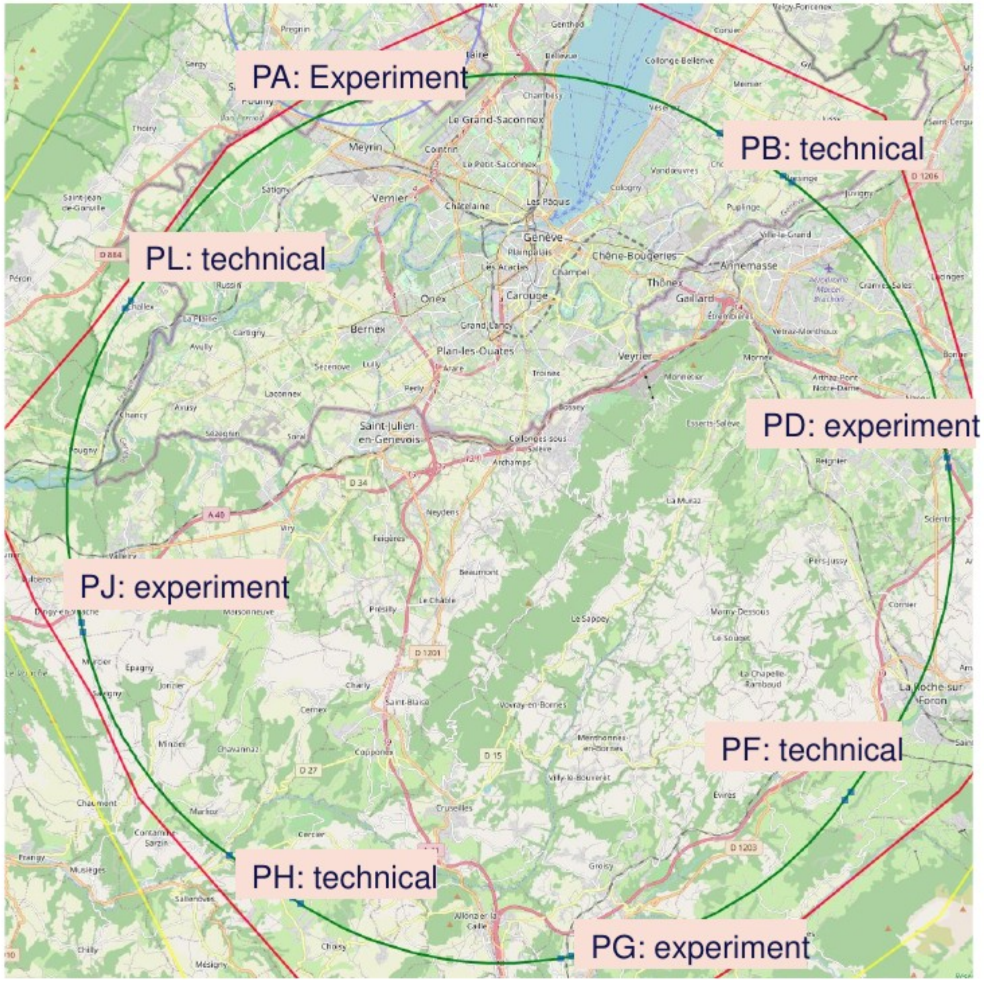
Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

Overall lowest risk baseline: 90.7 km ring, 8 surface points
< 40 ha of land needed and < 4 km of additional roads

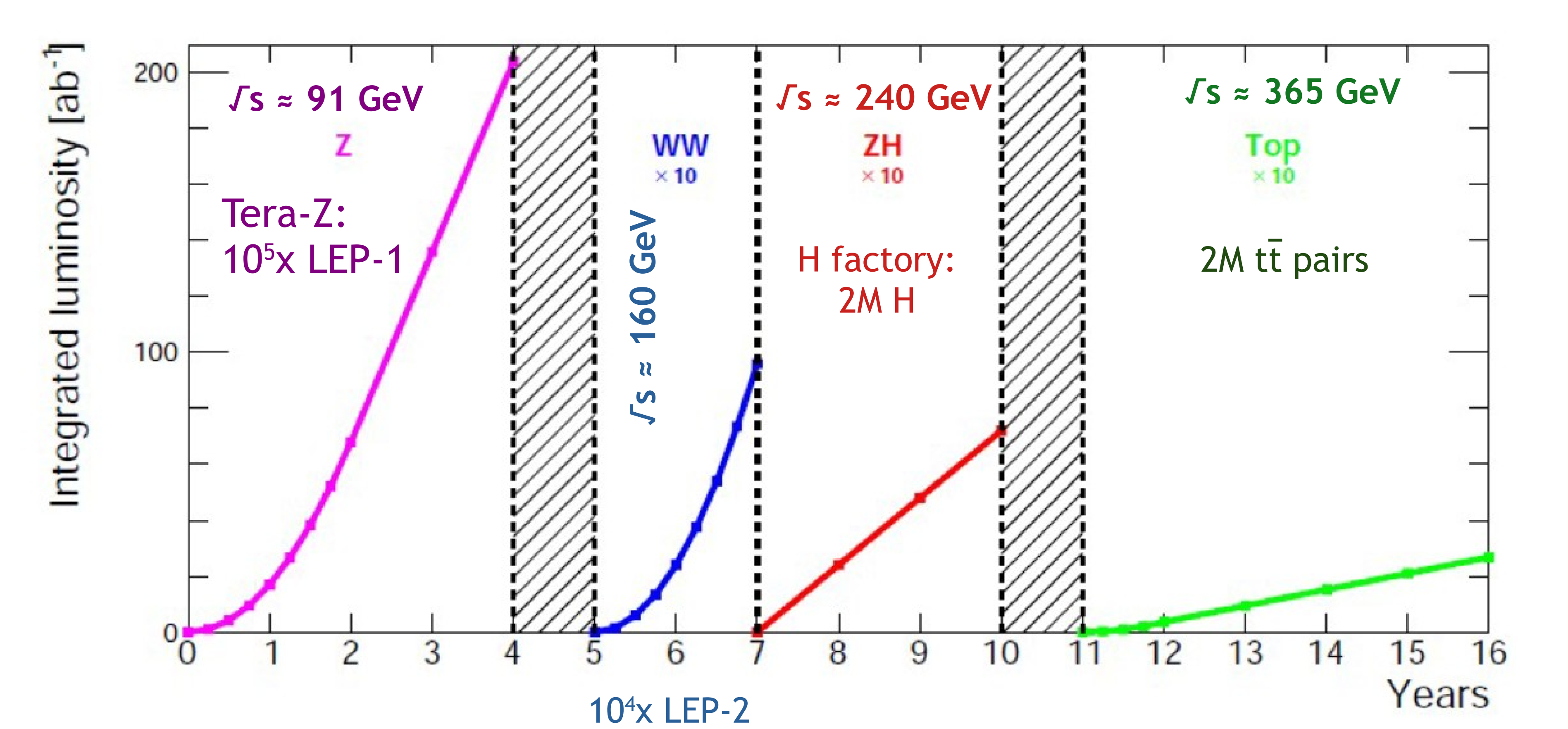
Whole project has been adapted to this placement



Manfred Krammer



FCC-ee possible operation sequence



Year-0? CERN realistic schedule says 2045-2048 (with HL-LHC ending 2041)

FUTURE CIRCULAR COLLIDER

FCC-hh main machine parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 120	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]	1100 - 4570	7.3	3.6
SR power / length [W/m/ap.]	14 - 58	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]	6.3 – 9.2	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

Realistic start date around 2070(?)

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:

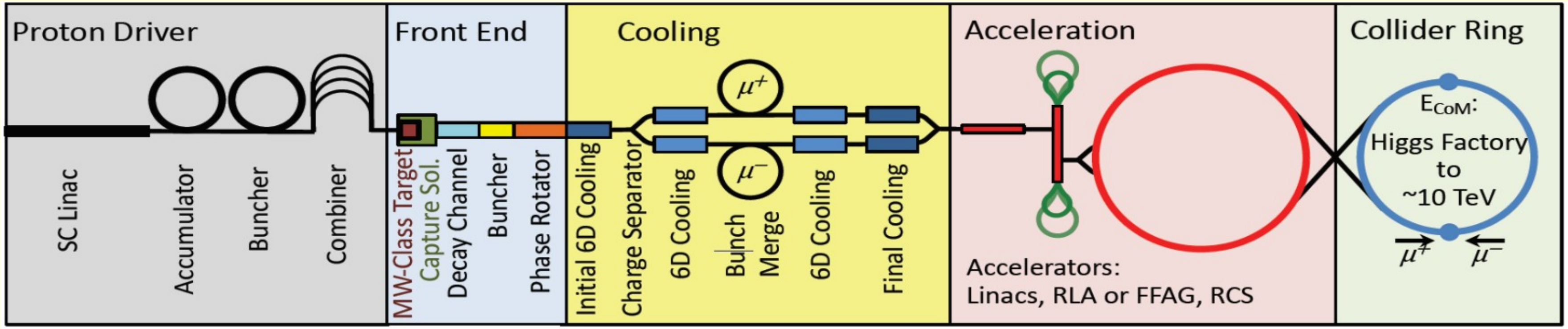
- Direct discovery potential up to ~ 40 TeV
- Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays (γγ, Zγ, μμ)
- Final word about WIMP dark matter

F. Gianotti

Muon collider

Concept is to make a muon collider ring at high energy

- Advantage that muons radiate much less synchrotron radiation than electrons
  → much smaller ring to achieve $\sqrt{s} \sim 10$ TeV
- Disadvantage that muons decay with (restframe) lifetime τ~2.2 μs!



Short, intense proton bunch

Protons produce pions which decay into muons
muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Muon collider

International MUON Collider Collaboration

Concept is to make a muon collider ring at high energy

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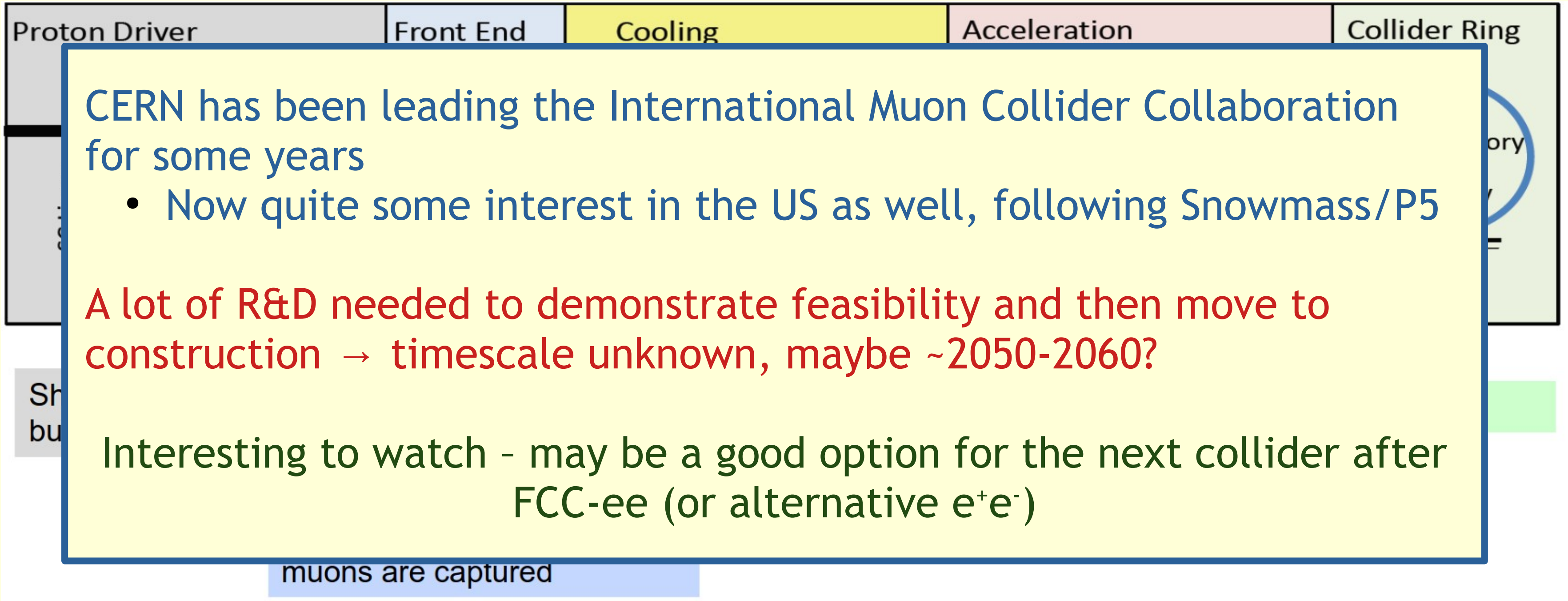

CERN has been leading the International Muon Collider Collaboration for some years

- Now quite some interest in the US as well, following Snowmass/P5

A lot of R&D needed to demonstrate feasibility and then move to construction → timescale unknown, maybe ~2050-2060?

Interesting to watch – may be a good option for the next collider after FCC-ee (or alternative e^+e^-)

Final words

Through these lectures, we have seen

- The physics need for large colliders, both the LHC – and future machines
- The huge physics range of these facilities
- The exciting prospects beyond the LHC

In the medium term (10y), (HL-)LHC will be the world's forefront collider

- There is a huge amount of frontier physics to be done!
- Completely international collaborations, especially in terms of member nationalities!

There are lots of good ideas what to do after the LHC – currently FCC gaining traction

- All options are expensive (€10 billion-scale)

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All the best to all of you with your studies and research - I hope to see some of you working at the LHC!