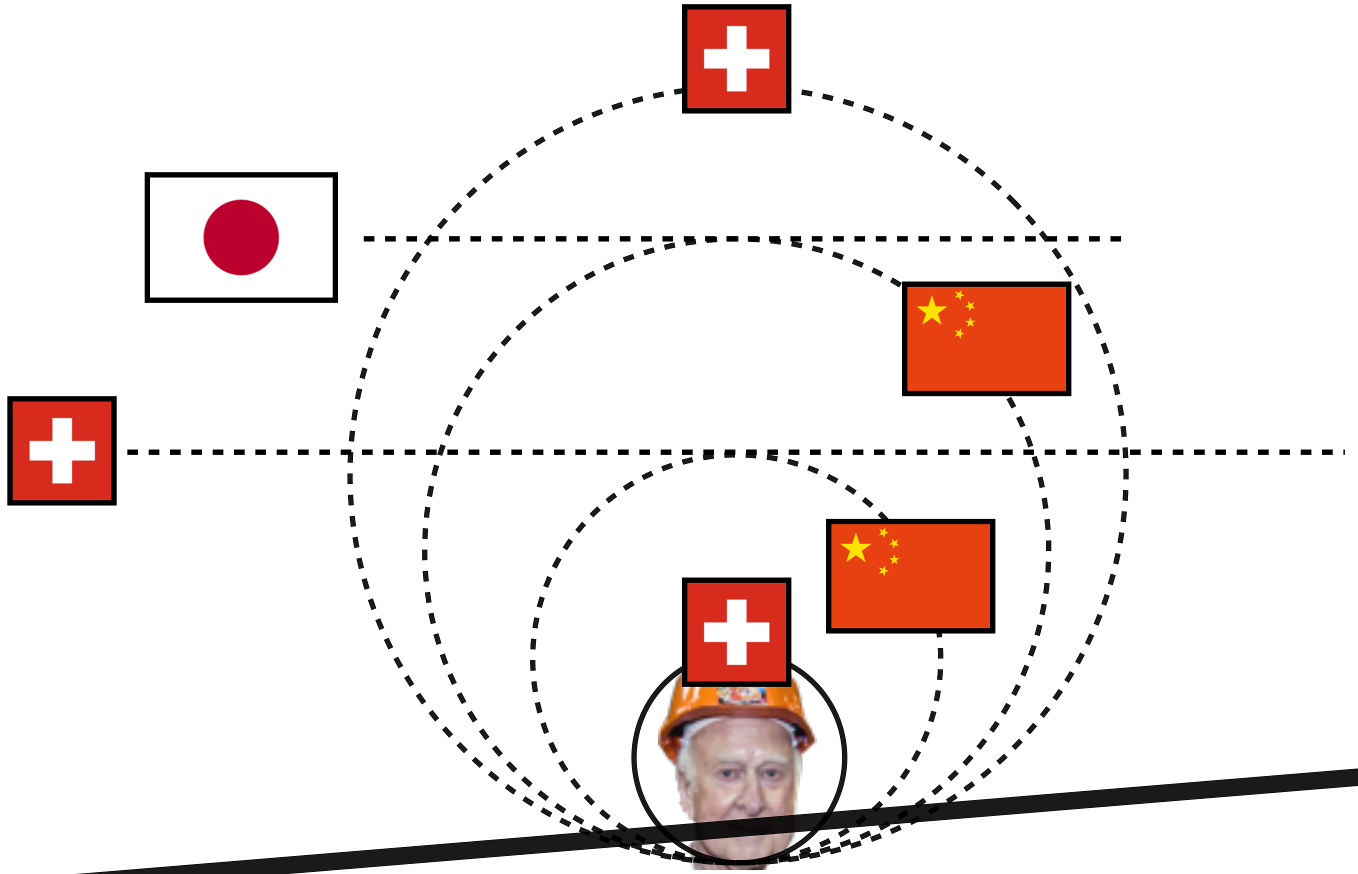
What's next in High-Energy Physics?

December 15, 2022

"Asymptotic Safety meets Particle Physics and Friends" workshop



Christophe Grojean

DESY (Hamburg)

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HEP after the Higgs Discovery

a string theorist

"The experiment worked better than expected and the analysis uncovered a very difficult to find signal"

Great success...

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...but the experimentalists haven't found what the theorists told them they will find in addition to the Higgs boson:
no susy, no BH, no extra dimensions, nothing ...

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Remember May 1, 2003

HEP after the Higgs Discovery

a string theorist

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Great success...

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Remember May 1, 2003

"Mission accomplished" speech by G.W. Bush

That was certainly not the end of the story and there were (are) still a lot things to do

Probing the Unknown

The Standard Model is not enough:

Many questions about the Universe (Dark Energy, DM, Matter-Antimatter) + anomalies (galactic center excess, H_0 tension);

Several puzzling colliders data (B-anomalies in particular, but flavour hierarchy and CP in general, g-2…);

And many theory questions (BH information paradox, unification, hierarchy, confinement…).

No doubt that there is something else beyond SM.

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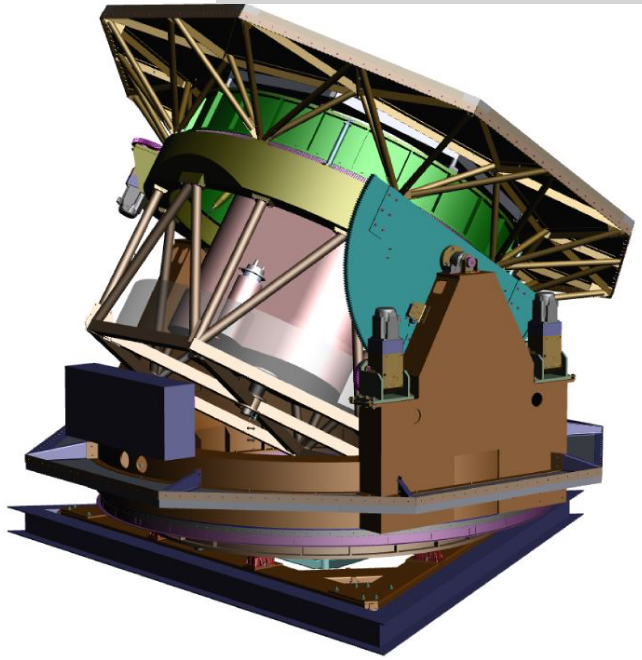
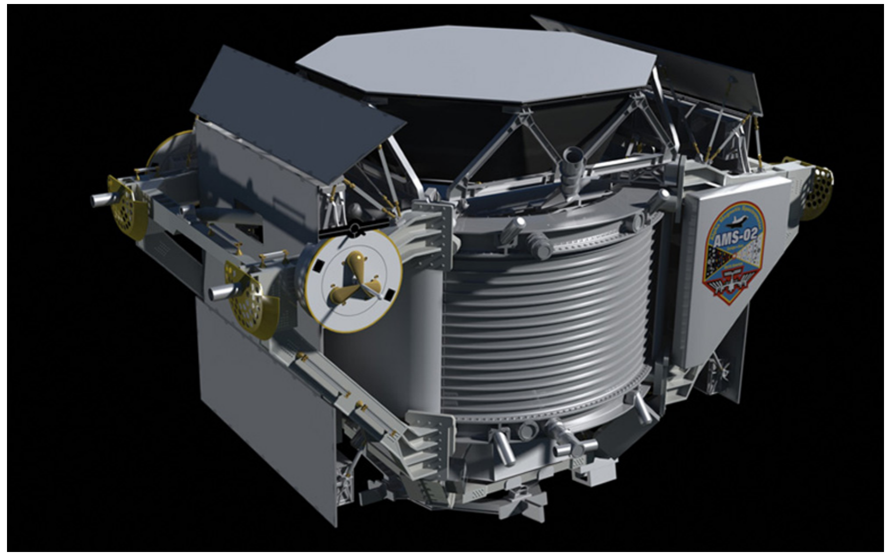
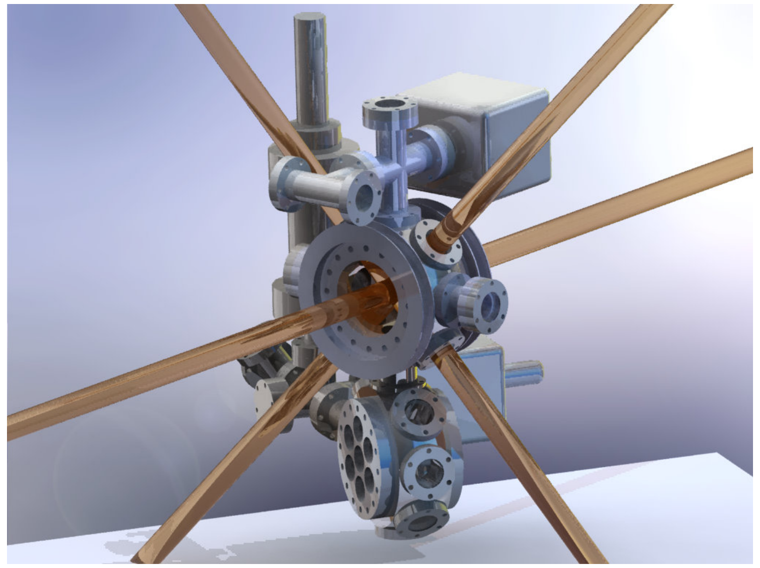
— no clear path BSM : new tools needed to explore different horizons —



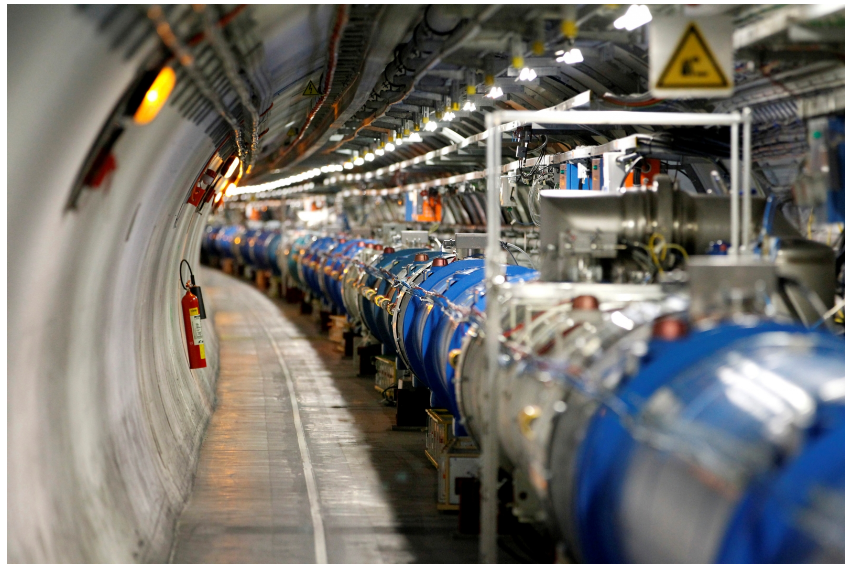
Cosmology frontier



Astroparticle frontier



Intensity frontier



Energy frontier

The LHC Legacy (so far)

- **SM confirmed to high accuracy up to energies of several TeV**
- **Higgs boson discovered**
- **Absence of new physics** ⟶
  - Traditional New Physics models are under siege
  - New approaches: relaxion, Nnaturalness, clockwork…

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Dark Sector/Cosmology might set the weak scale

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The remarkable and successful operation of the LHC

(made possible thanks to technological advancements, accelerator performance, detector resolution, high-performance computing and data handling, higher-order theoretical calculations)

also changed the nature of the LHC itself:

☺ not only an exploration machine but performs legacy precision measurements,

☺ a multi-messenger experiment on its own.

LHC Achievements

Flavour Physics

- B(s) $\rightarrow \mu\mu$
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase φ_s, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

QCD Dynamics

- Countless precise measurements of hard cross sections, and improved determinations of the proton PDF
- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in "small" systems (pA and pp)

EW Parameters and Dynamics

- m_W, m_{top}, $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)

1

LHC ≈ 100's scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities.

2

LHC advanced the knowledge acquired at previous facilities.

3

LHC complements future facilities

M. Mangano @ CERN Summer Students 2021

Message to outside world

We are not shooting in the dark.

Let's move away from "The SM is incomplete" and "we need to search everywhere"

Instead, we might say

We have made the following discoveries, which will enlarge our model of the Universe once we figure out how it fits into what we already know.

Highlights and Messages from the Snowmass Summer Study. Prisca Cushman

The experimental program (LHC and beyond) should have the opportunity to refine our "model" of the Universe and answer some of the open questions

- Infer the vacuum structure of the Universe
- Reveals the dynamics of the EW phase transition and infer the fate of the EW vacuum
- Identify DM, DE
- Understand the origin of flavor
- …

LHC: driving cultural change forward

Absence (so far) of new physics where it was expected (TeV)
&
progresses in string theory/quantum gravity (swampland, no global symmetries)

question our description of Nature in terms of effective quantum field theories
(non-locality, IR/UV correlation)

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IR parameters are functions of some fields whose value vary during the cosmological history or throughout a complex vacuum structure

Axion: $\mathcal{L}_{\text{dim}=4} = \frac{g_s^2}{32\pi^2}\,\bar{\theta} G^a_{\mu\nu} \widetilde{G}^{\mu\nu,a}$ $\quad \bar{\theta} \longrightarrow a$

Higgs mass: relaxion, etc. $\quad \mu|H|^2 \to g\Lambda\phi|H|^2$

"Weak Scale Triggers"

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"Weak Scale Triggers"

cosmological naturalness power counting

$$\frac{m_\phi^2}{\mu^2} \simeq \frac{\tilde{v}^{2q-j}v^j}{\Lambda_H^{2q}} \lesssim \frac{v^{2q}}{\Lambda_H^{2q}}$$

mass of the cosmological mediator → m_ϕ^2

its coupling to SM → μ^2

EW scale → v^{2q}

Higgs cutoff → Λ_H^{2q}

q = integer defines the BSM model

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"Weak Scale Triggers"

"Intensity frontier" is not only about precise measurements but
it could reveal light and weakly coupled structures as solution to the main open HEP questions.

What is the scale of New Physics?

“IR Simplicity”

High Scale Wishes

small FCNC:	$\frac{g F_{\mu\nu} \bar{\psi} H \sigma^{\mu\nu} \psi}{M_{\rm NP}^2}$	10^3TeV?
tiny neutrino masses:	$\frac{(LH)^2}{M_{\rm NP}}$	10^{14}GeV?
slow proton decay:	$\frac{UUDE}{M_{\rm NP}^2}$	10^{16}GeV?

↔

Low Scale Wishes

small EDMs: $\arg\det Y \leq 10^{-10}$

↪ axion?

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3}{\rm eV}\right)^4$

↪ ?

light Higgs boson: $m_H^2 \approx M_{\rm NP}^2 \gg (125{\rm GeV})^2$

↪ light susy?

“Naturalness”

We know for sure that New Physics exists.
But no clear indication of the energy scale to probe.
We need a broad, versatile and ambitious programme that
1. will achieve legacy precision measurements
2. can push the frontiers of the unknown
A new collider after LHC should combine these two aspects
More SENSIVITY, more PRECISION, more ENERGY

Why More Precision?

I Indirect sensitivity to New Physics (see quantitative concrete examples later)

LEP (10^6 Z) $\frac{c}{\Lambda^2} < \Delta$ → stat. dominated observables → FCC-ee/CEPC (10^{12} Z) $\frac{c}{\Lambda^2} < 10^{-3}\Delta$ i.e. improve bounds by

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m_W, m_Z ↔ Higgs couplings ✓

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lifetime of stars

(why $t_{Sun} \sim t_{life\ evolution}$?)

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- EW @ $t \sim 10^{-10}$s ↔ Higgs self-coupling ?

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- matter/anti-matter ↔ CPV in Higgs sector ?

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3 The values of the EFT interactions among SM fields will reveal the "selection rules" of the SM, with intimate links to new structure/symmetries

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

Dimensional arguments impose

$$c_i^{(D)} \sim (\text{coupling})^{n_i - 2}$$

n_i=number of fields in operator $\mathcal{O}_i^{(D)}$ (independant of D)

generically, (coupling ~ g_*) coupling of New Physics to SM
but there might exist **"selection rules"** that lead to other scaling

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Contino, Falkowski, Goertz, Grojean, Riva ‘16

Examples of symmetries leading to different selection rules

Operator	Naive (maximal) scaling with g_*	Symmetry/Selection Rule and corresponding suppression
$O_{y_\psi} = \|H\|^2 \bar\psi_L H \psi_R$	g_*^3	Chiral: y_f/g_*
$O_T = (1/2)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	g_*^2	Custodial: $(g'/g_*)^2$, $y_t^2/16\pi^2$
$O_{GG} = \|H\|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$ $O_{BB} = \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	g_*^2	Shift symmetry: $(y_t/g_*)^2$ Elementary Vectors: $(g_s/g_*)^2$ (for O_{GG}) $(g'/g_*)^2$ (for O_{BB}) Minimal Coupling: $g_*^2/16\pi^2$
$O_6 = \|H\|^6$	g_*^4	Shift symmetry: λ/g_*^2

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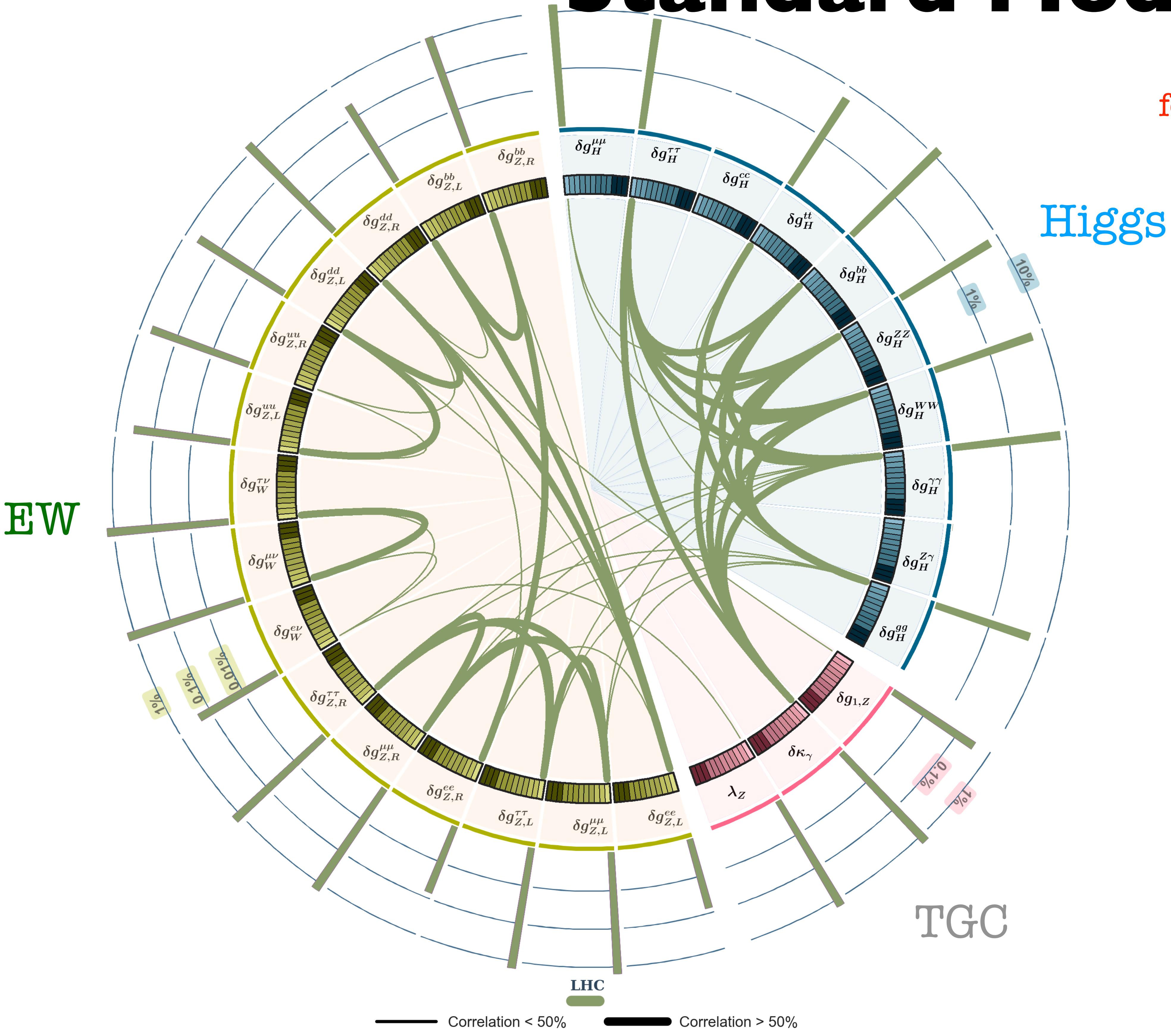
Precision physics exp. (EDMs, g-2…) usually constrains one operator.
Need a collider to have access to several of them and
then understand the underlying structure.

Standard Model Now



Many thanks to J. De Blas et al. (HEPfit)
for the analysis of current data (work in progress)
and to A. Paul for plotting the results

EW known at 0.1%
TGC known at 1%
Higgs known at 10%
This hierarchy limits the correlations
between the 3 sectors

The man of the game (still):

The man of the game (still): Mbappé/Messi?

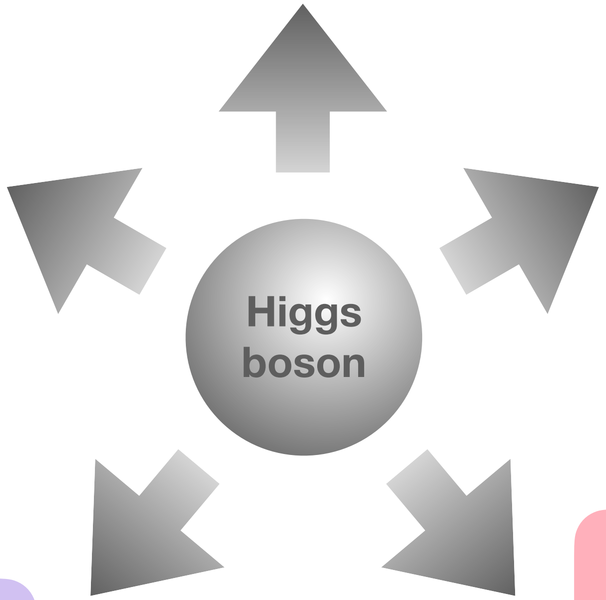
The man of the game (still): Higgs!

What is the origin of the early-universe inflation?

- Is the Higgs connected to the mechanism that drives inflation?
- Are there any imprints in cosmological observations?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs decay into pairs of quarks and leptons with distinct flavours (for example, $H \rightarrow \mu^+\tau^-$)?



Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs with the W and Z?

What is dark matter?

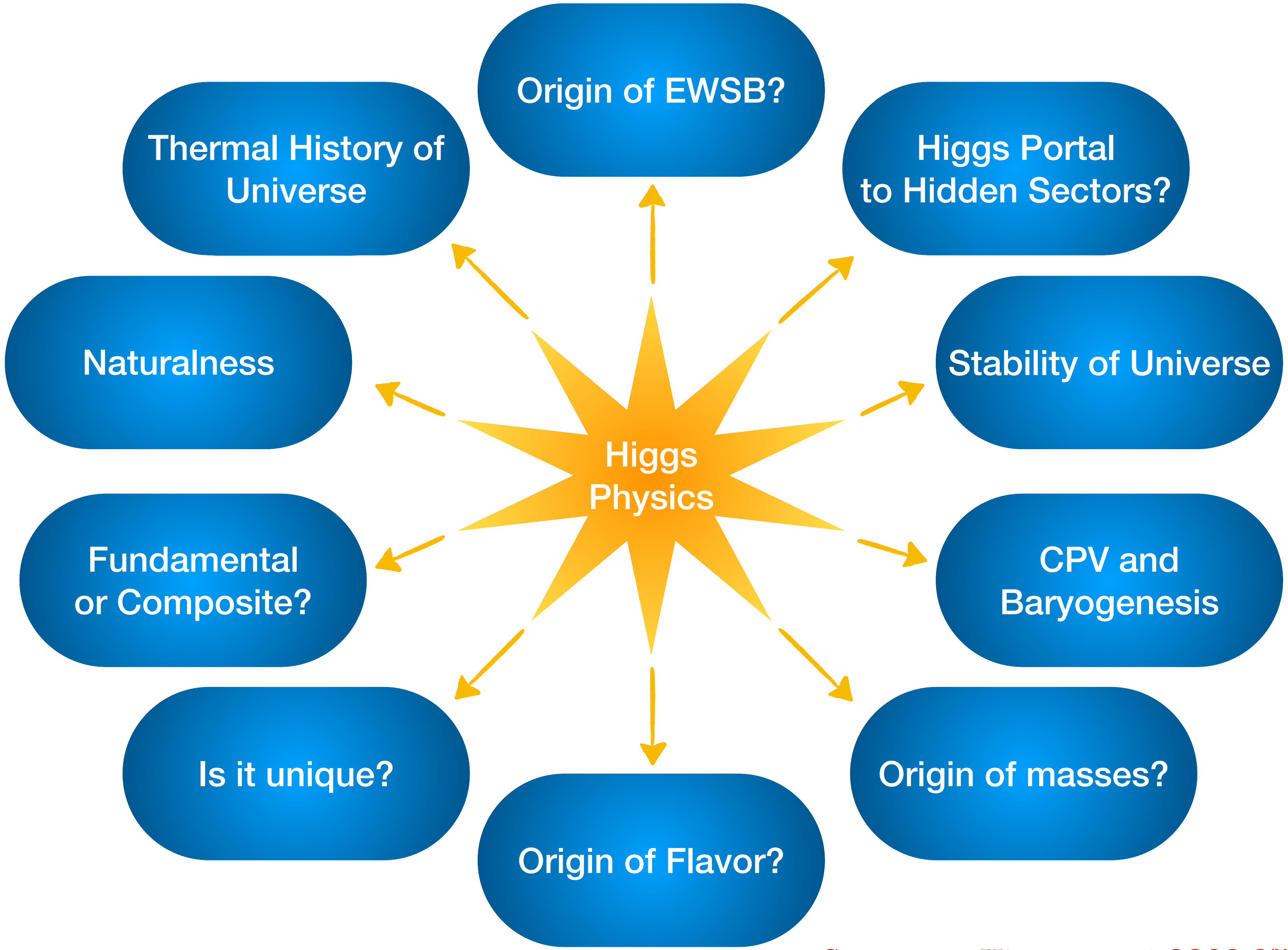
- Can the Higgs provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs?

Why is there more matter than antimatter in the universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-universe electroweak phase transition?
- Are there multiple Higgs sectors?

Nature 607 (2022) 7917

The man of the game (still): Higgs!



Snowmass Higgs report 2209.07510

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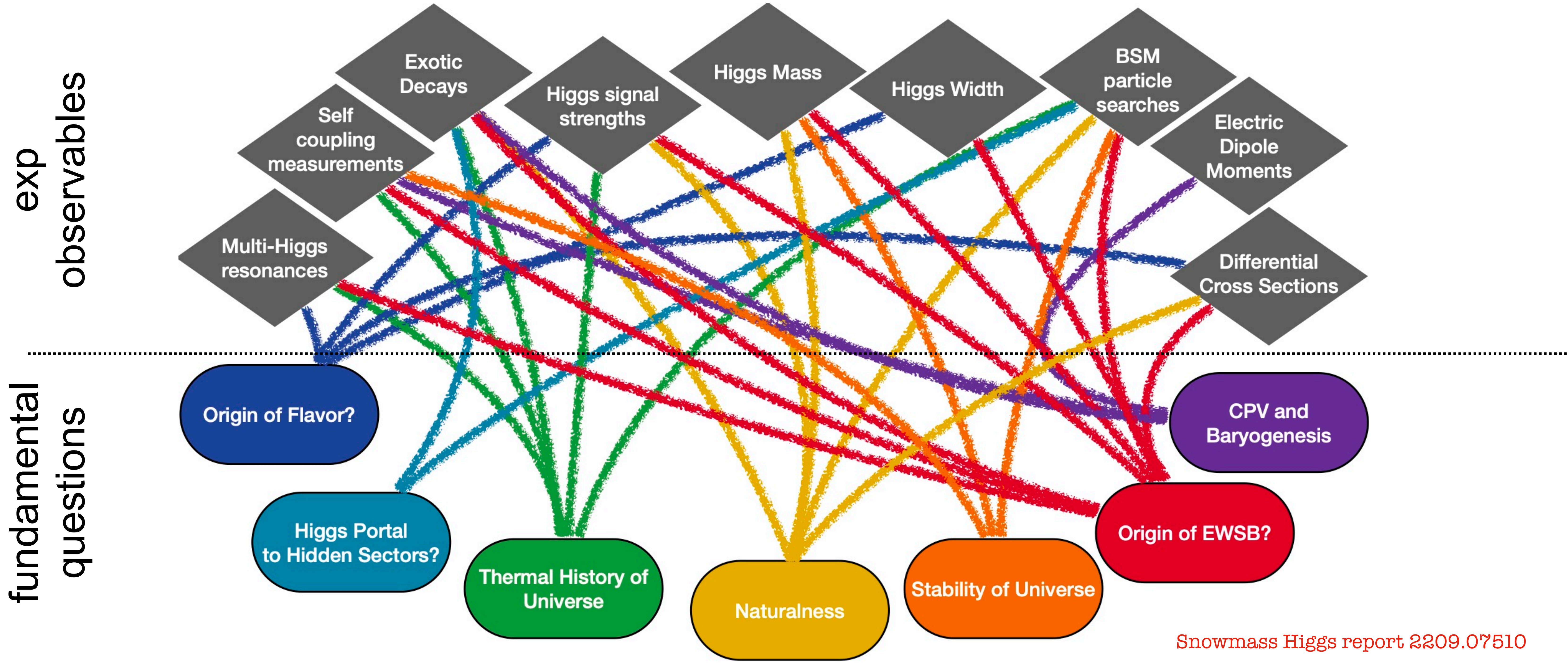


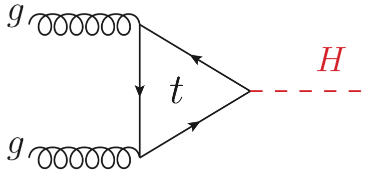
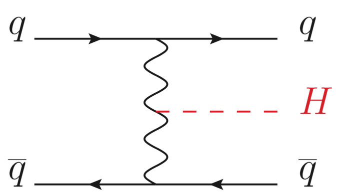
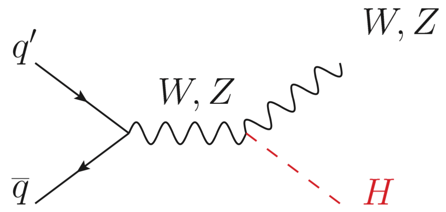
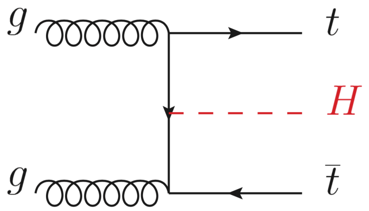
Snowmass Higgs report 2209.07510

The LHC Harvest

With the full Run 2 (140 fb-1 of pp collisions at 13 TeV)

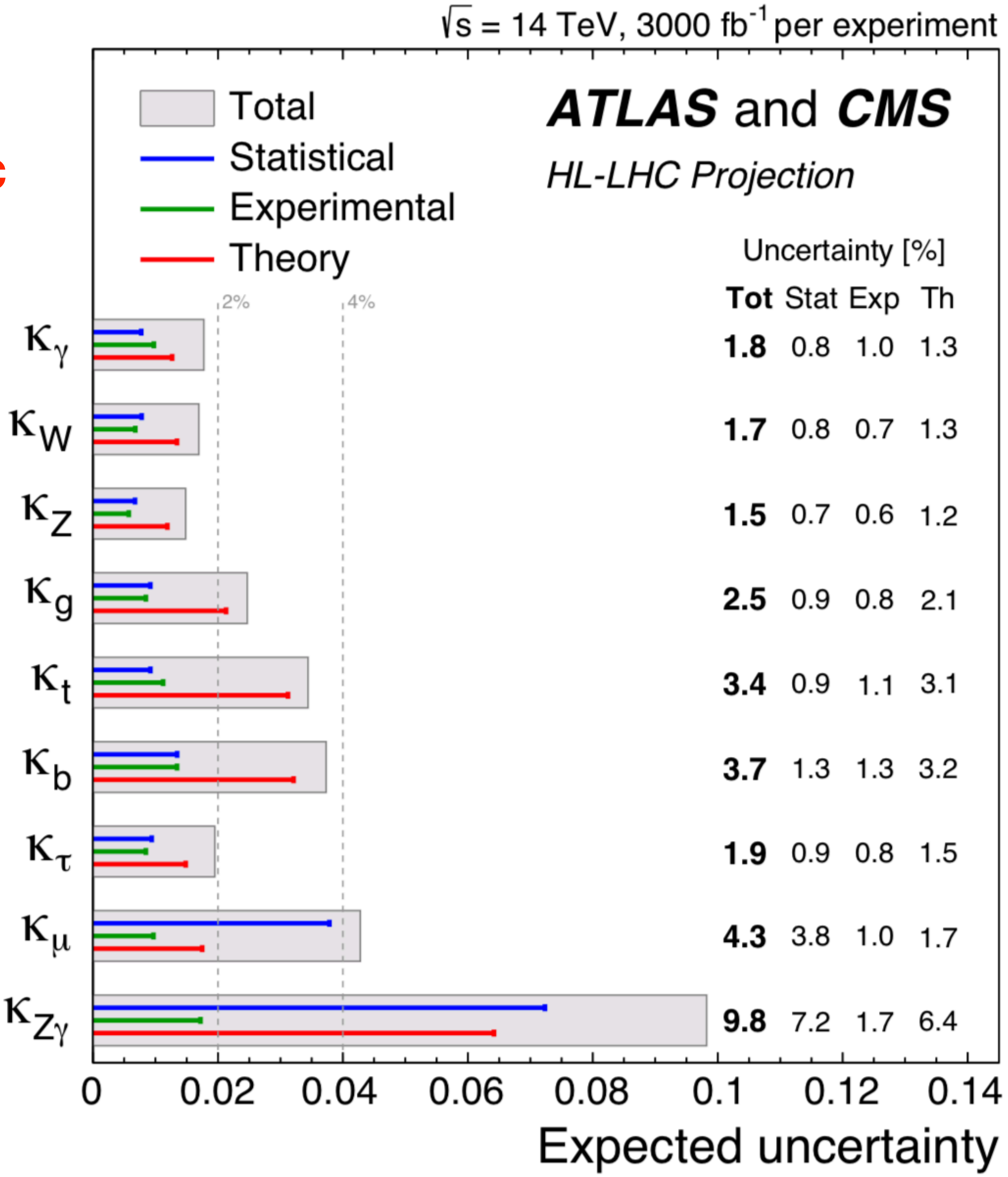
- 8 Million Higgs bosons produced
- 300 Million top quarks produced
- 8 Billion Z bosons with 300 Million per lepton flavour
- 30 Billion W bosons (3 billion per lepton flavour)
- 150 Trillion b quarks

The LHC Higgs Harvest

	Channel categories	Br	ggF	VBF	VH	ttH
			 ~8 M vets produced	 ~600 k vets produced	 ~400 k vets produced	 ~80 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

Higgs @ (HL)-LHC

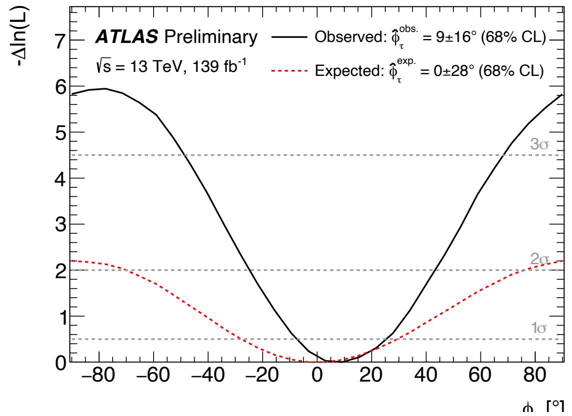
	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



TH Uncertainties dominant (assumed to be 1/2 of Run 2)

Beyond Inclusive Higgs

- CP properties of the tau Yukawa



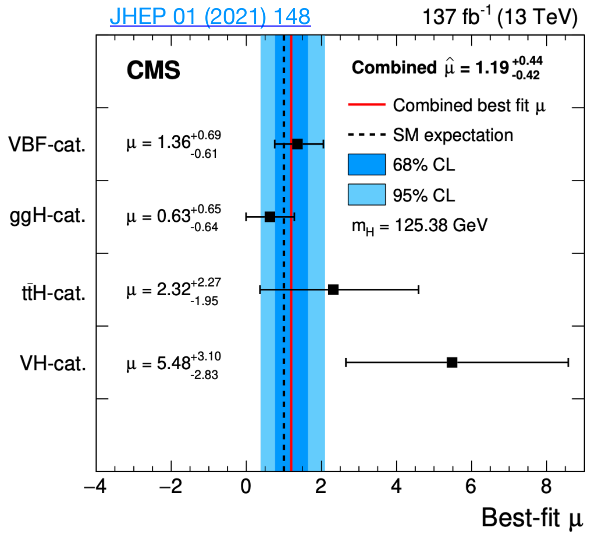
$\phi_\tau = 9^o \pm 5^o\,(\text{sys}) \pm 16^o\,(\text{stat})$

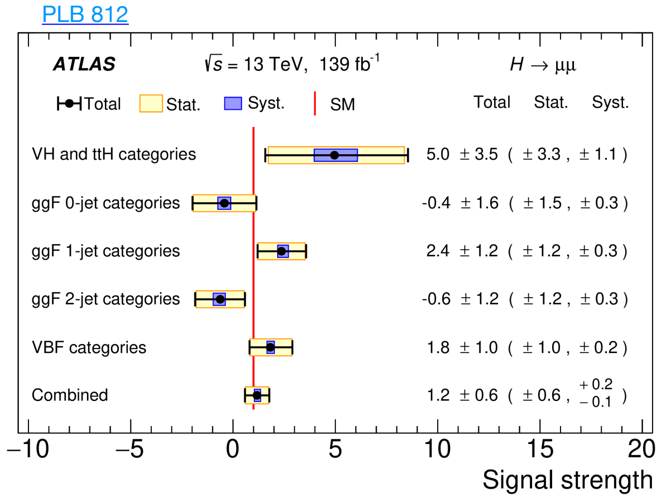
- Evidence for h→μμ

CMS Result

Expected 2.5σ
Observed 3.0σ

$\mu = 1.19 \pm 0.43$





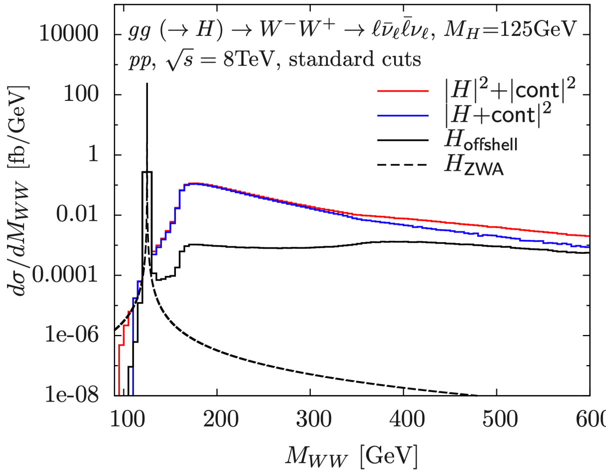
ATLAS Result

Expected 1.7σ
Observed 2.0σ

$\mu = 1.2 \pm 0.6$

- Evidence for h→γℓ⁺ℓ⁻

- Off-shell Higgs production (and Higgs width constraint)



$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

- Double Higgs production

Higgs Data — Future

I can see 5 main future exiting directions made possible thanks to *larger* data set:

- More differential measurements
- “Higgs couplings without the Higgs” programme
- Couplings to light fermions
- Study of CP violation in the Higgs sector
- Access to multi-Higgs channels

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} ↔ Does the Higgs have a size?

- Couplings to light fermions ↔ Does the Higgs make matter stable?
- Study of CP violation in the Higgs sector ↔ Did the Higgs create matter?
- Access to multi-Higgs channels ↔ Did the Higgs make the Universe boiling?

Future of HEP: Flagship Projects

ECFA Higgs study group '19

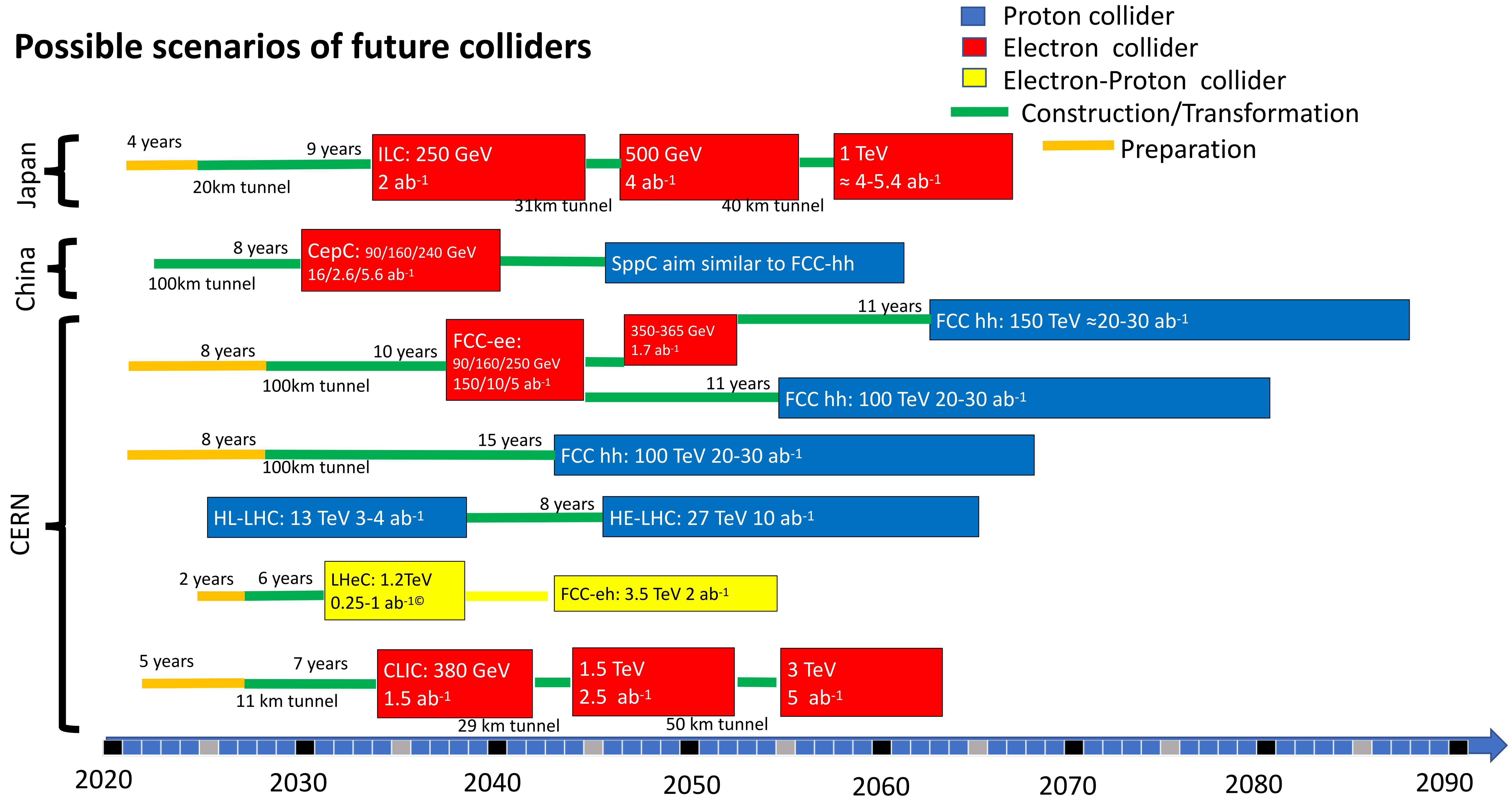
Subject to large uncertainty
1) need a scientific consensus
2) political approval

	Timeline (T_0, +5, +10, +15, +20, …, +26)	T_0
ILC	0.5/ab 250 GeV → 1.5/ab 250 GeV → 1.0/ab 500 GeV → 0.2/ab $2m_{top}$ → 3/ab 500 GeV	2032
CEPC	5.6/ab 240 GeV → 16/ab M_Z → 2.6 /ab $2M_W$ → SppC =>	2030
CLIC	1.0/ab 380 GeV → 2.5/ab 1.5 TeV → 5.0/ab => until +28 3.0 TeV	2035
FCC	150/ab ee, M_Z → 10/ab ee, $2M_W$ → 5/ab ee, 240 GeV → 1.7/ab ee, $2m_{top}$ → hh,eh =>	2037
LHeC	0.06/ab → 0.2/ab → 0.72/ab	2030
HE-LHC	10/ab per experiment in 20y	2040
FCC eh/hh	20/ab per experiment in 25y	2045

\+ muon-collider + gamma-gamma collider + …

Future of HEP: Flagship Projects

Possible scenarios of future colliders



Ursula Bassler, Granada 13.05.2019

Future of HEP: Flagship Projects

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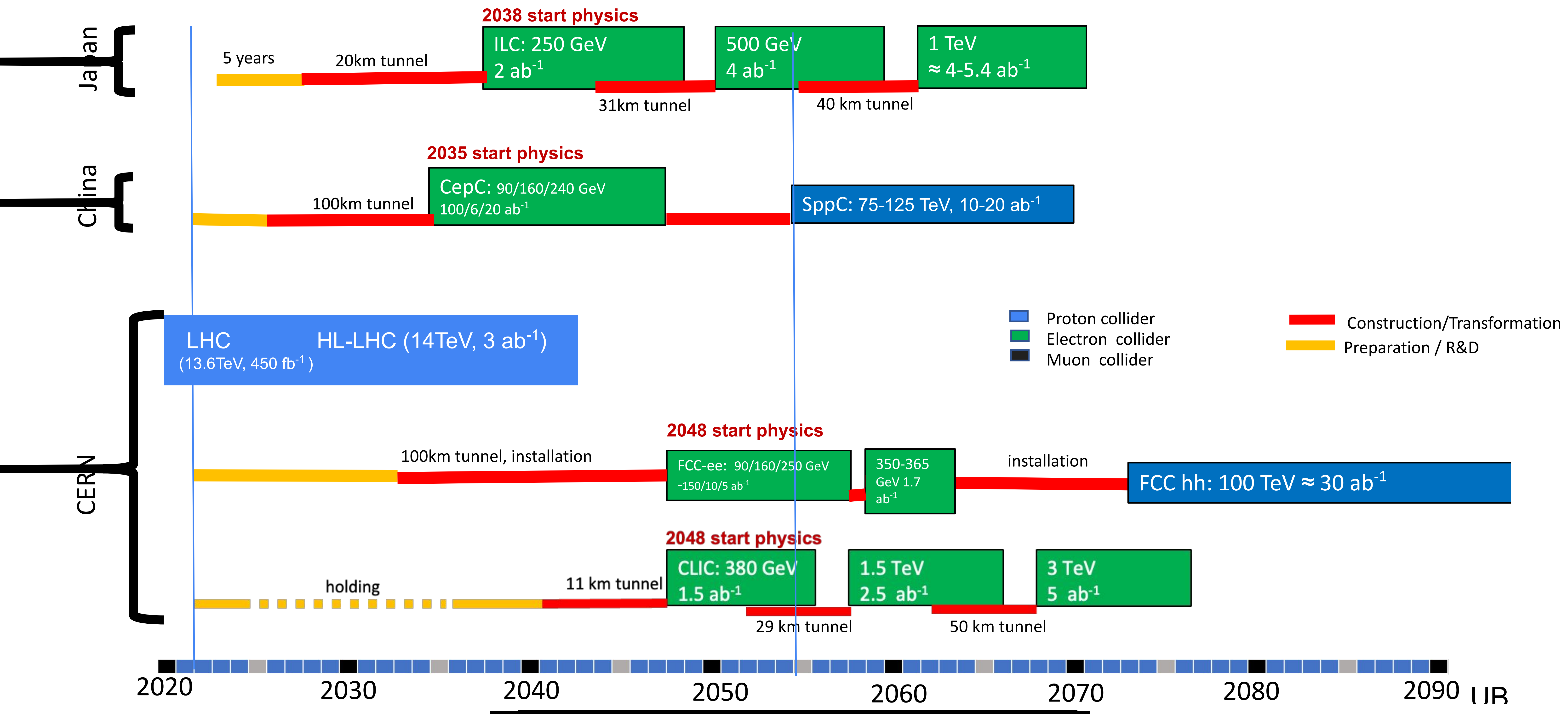
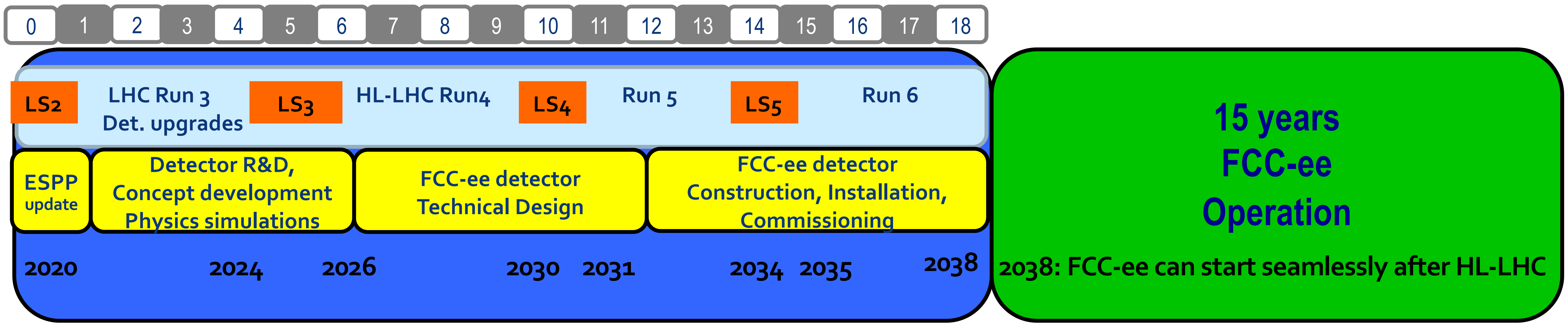


Menashki Narain, Snowmass 07.2022

Future of HEP: Flagship Projects

What is the necessary time interval between end of HL-LHC and start of FCC ? For LEP→LHC it was 10 years (same tunnel), but for SppS→LEP it was-2 years. Clear dependence on financial and human resources.

— 2019 Schedule —



well-coordinated schedule between HL-LHC running and FCC-ee construction while R&D for FCC-hh is actively pursued

Future of HEP: Flagship Projects

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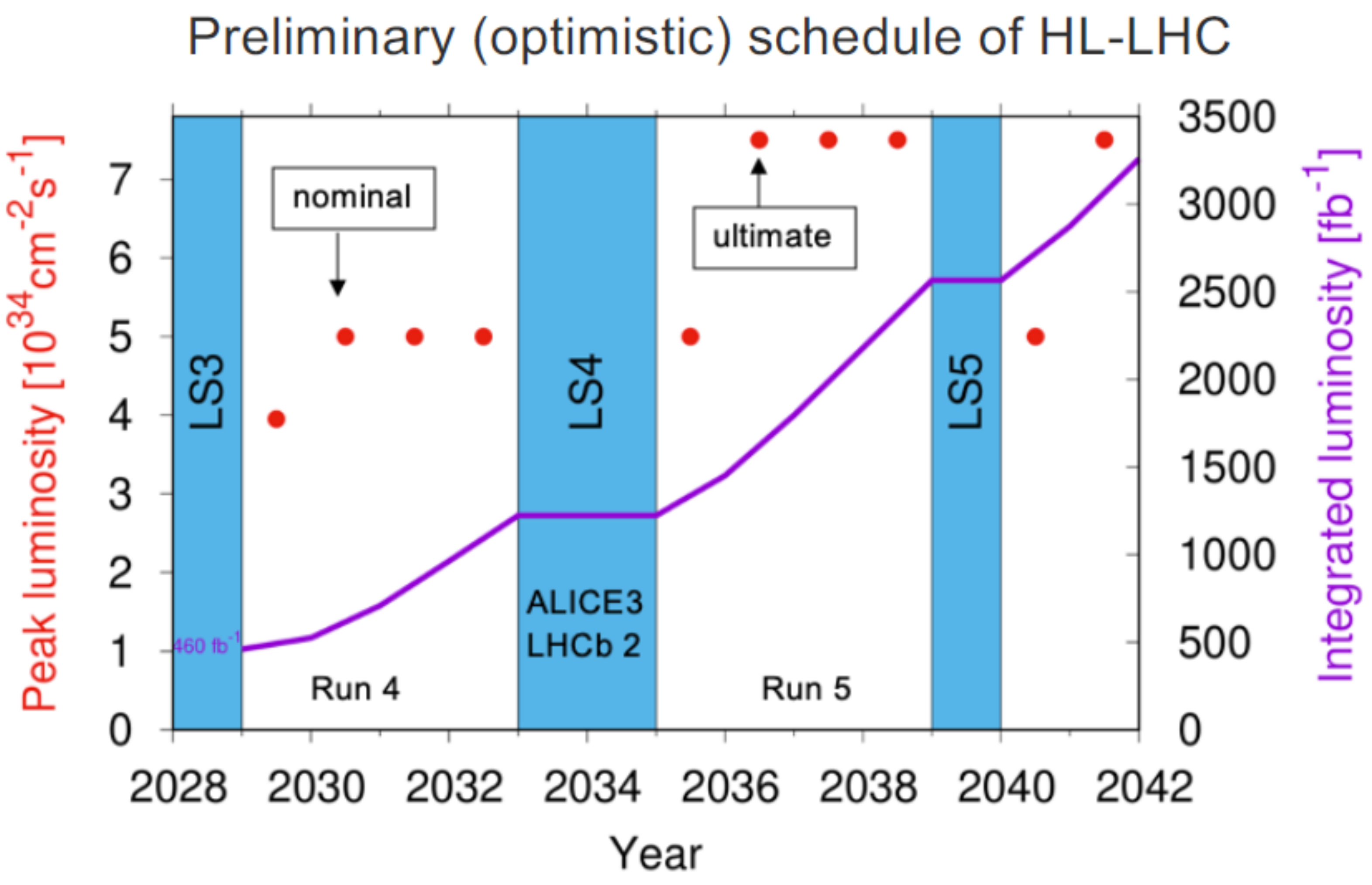
— 2021 Schedule —



Future of HEP: Flagship Projects

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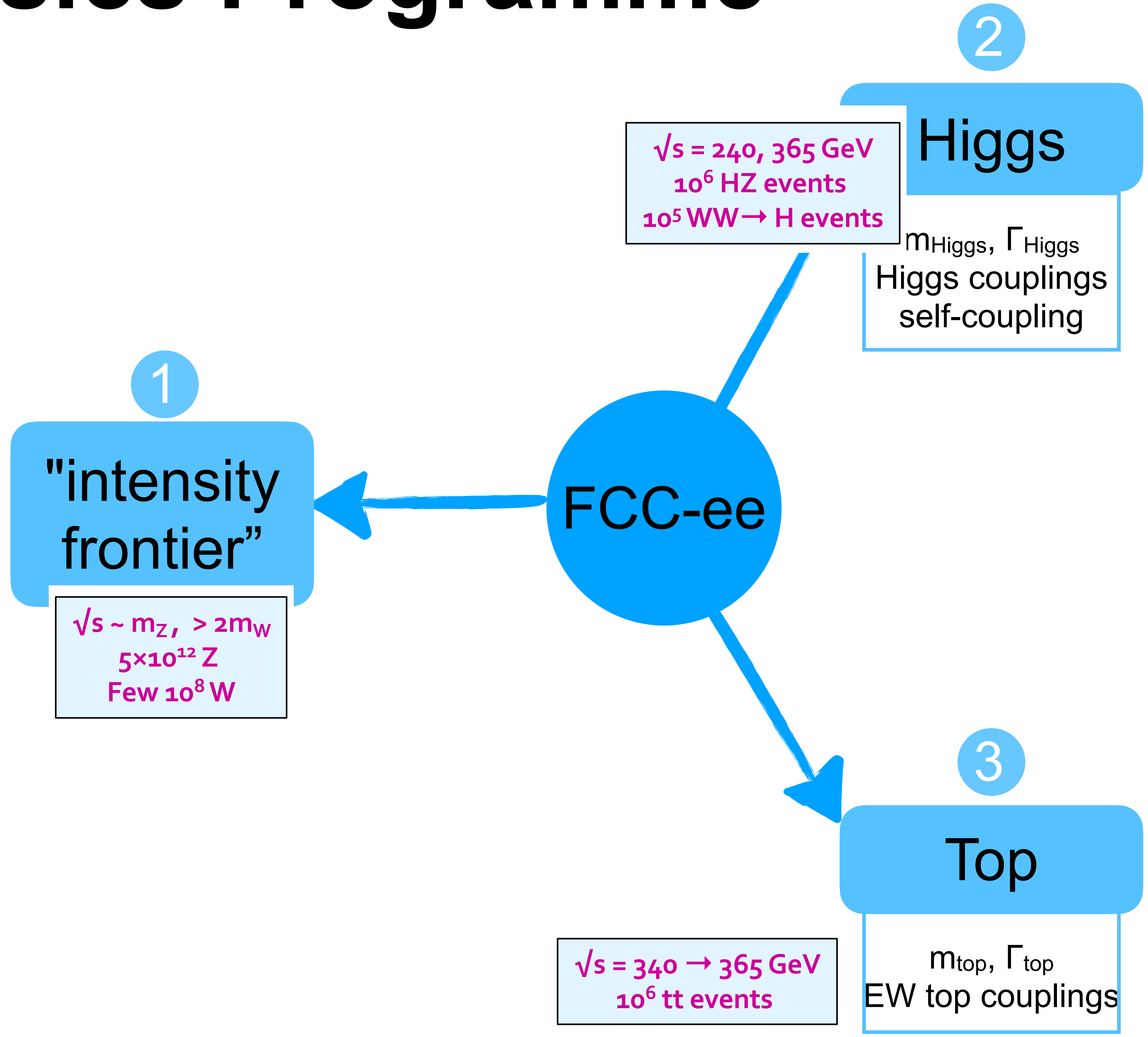
Stay safe/healthy and live long!

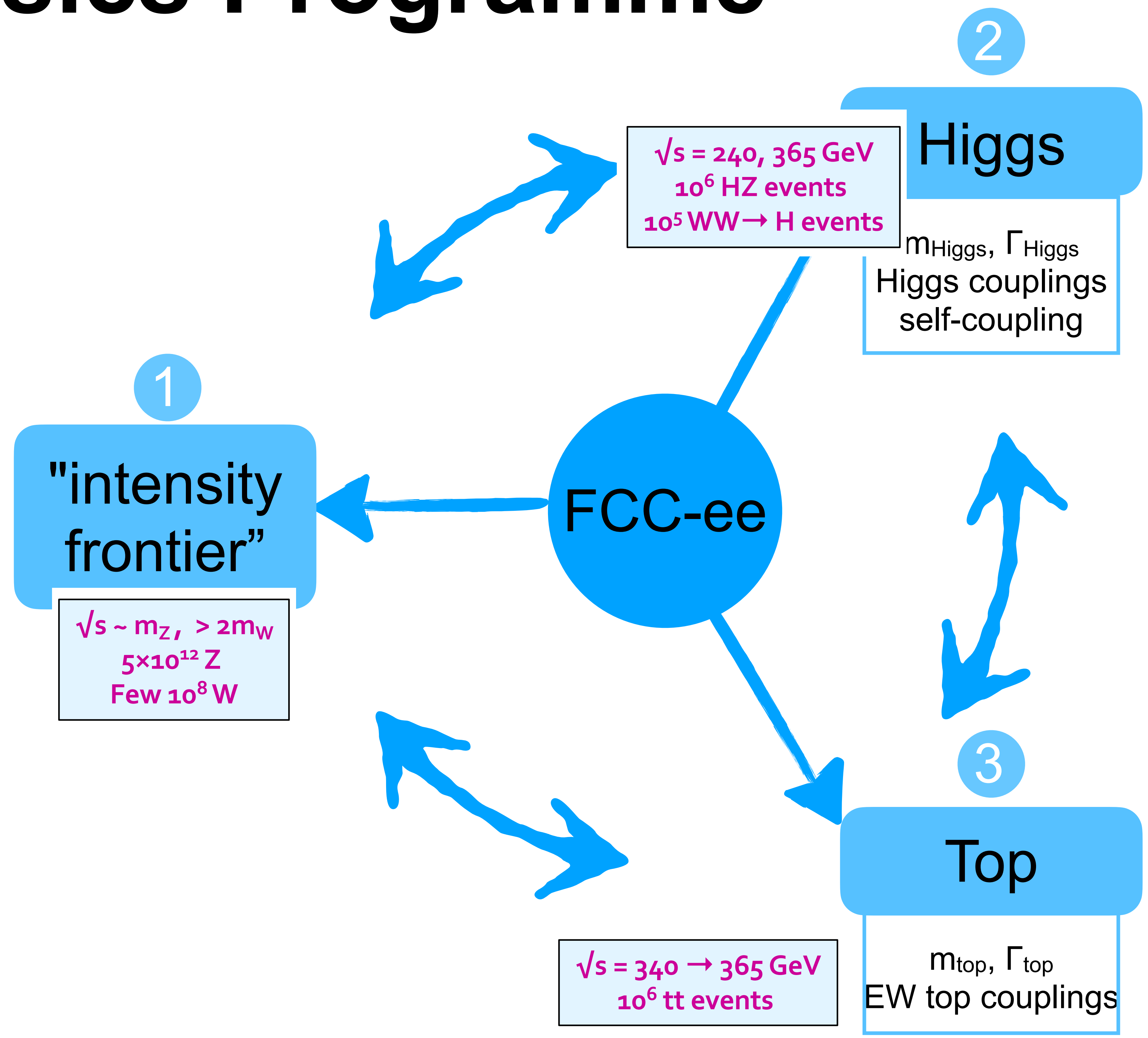
FCC-ee Physics Programme

FCC-ee

FCC-ee Physics Programme



FCC-ee Physics Programme



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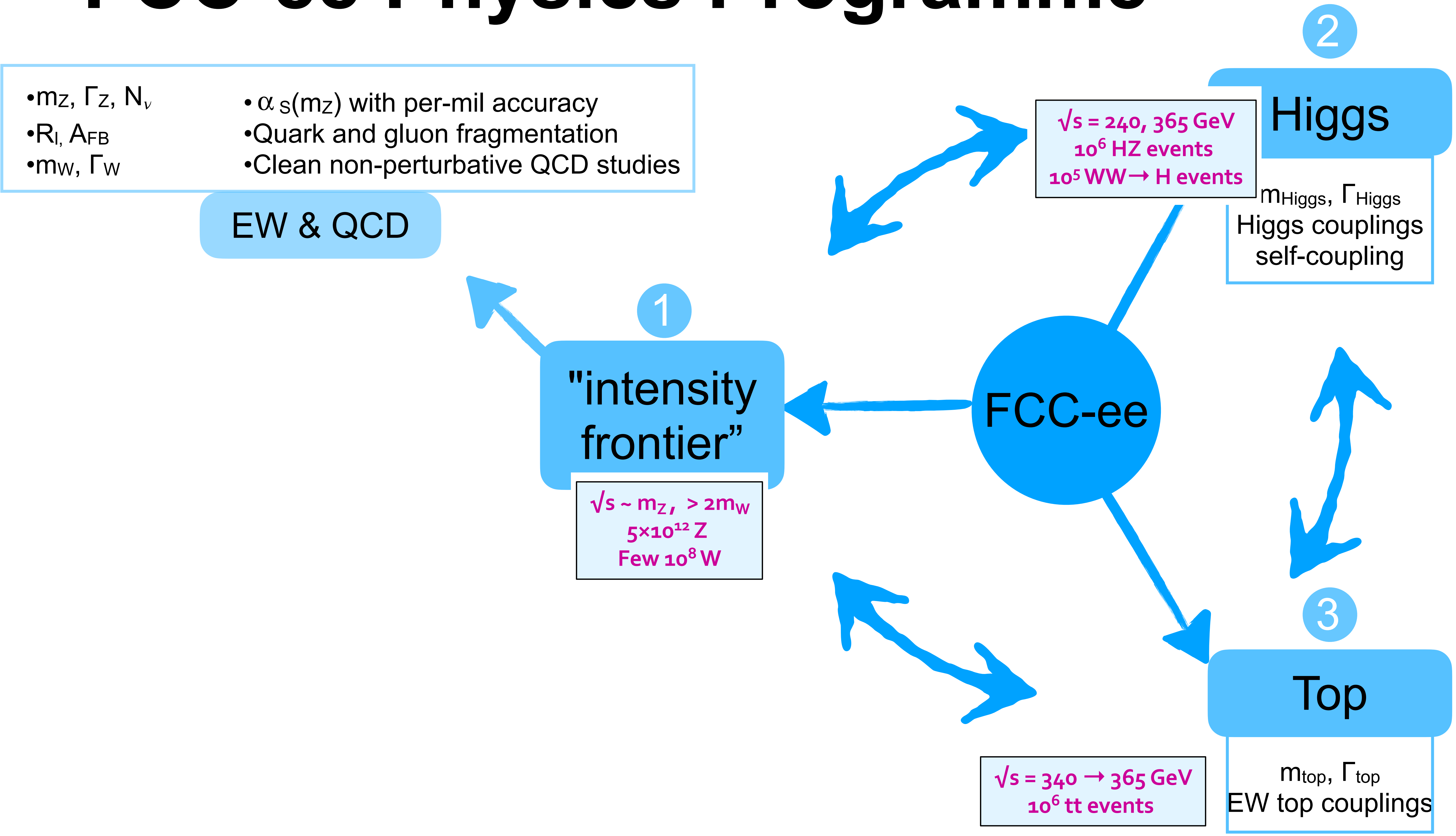

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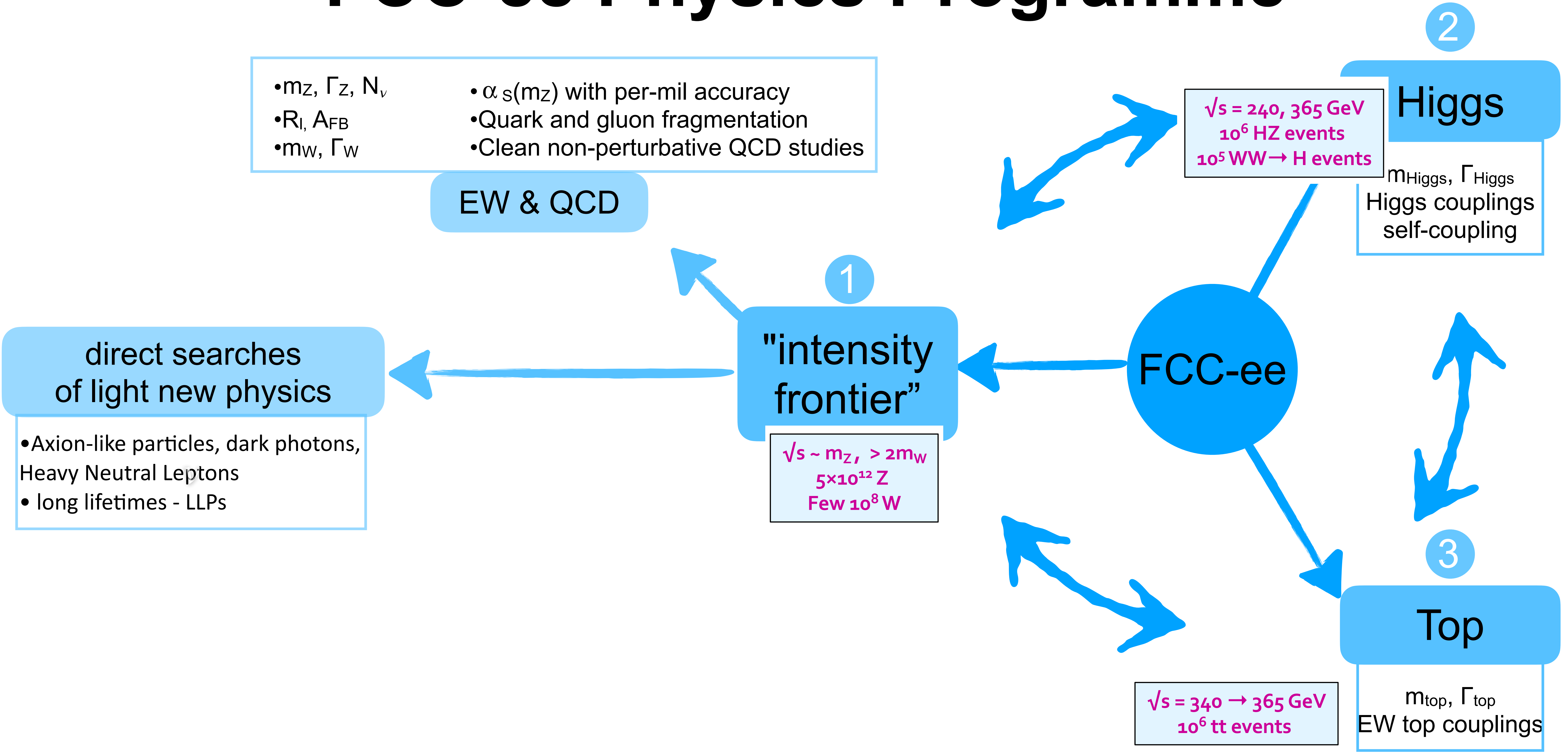

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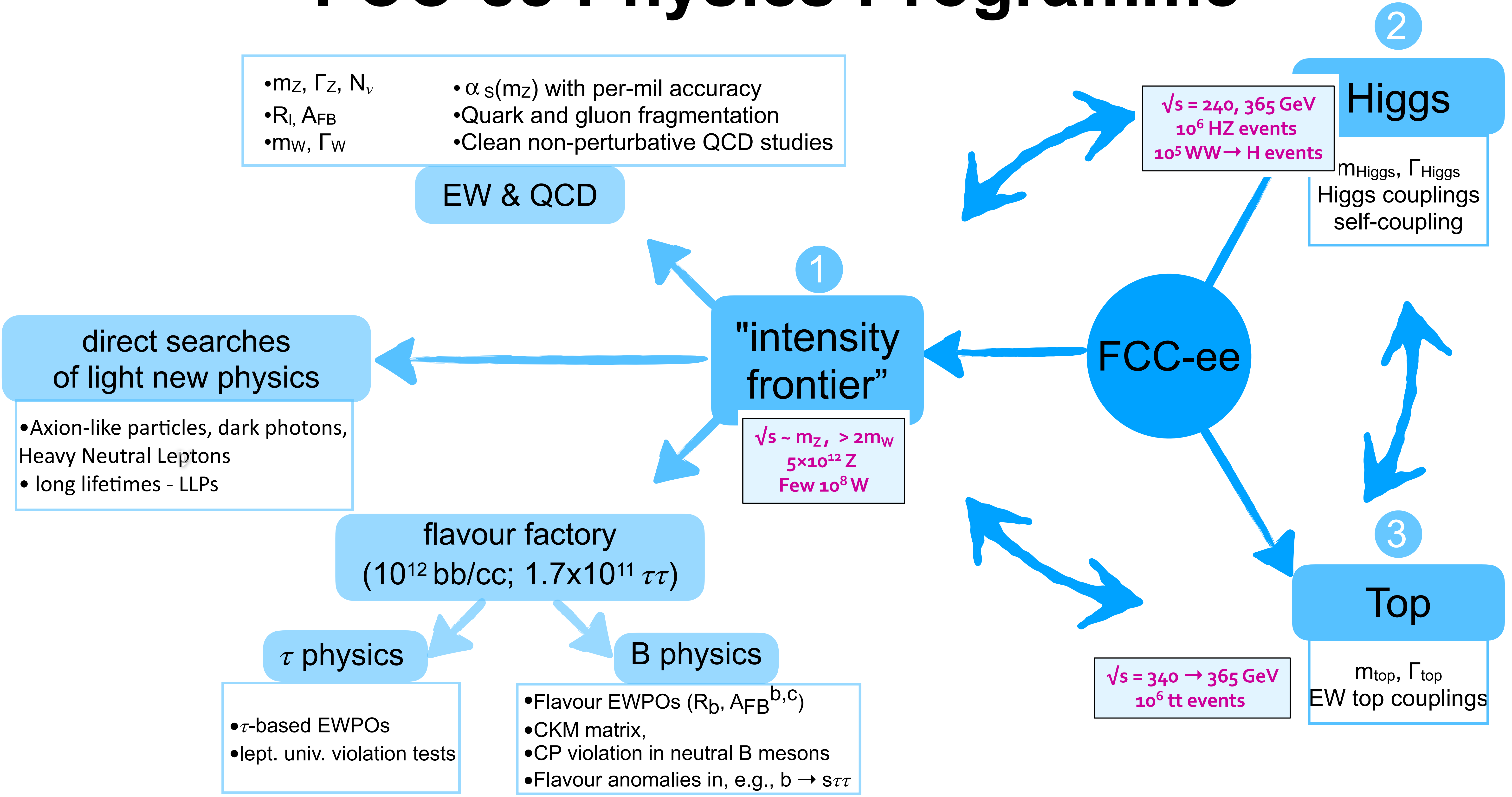

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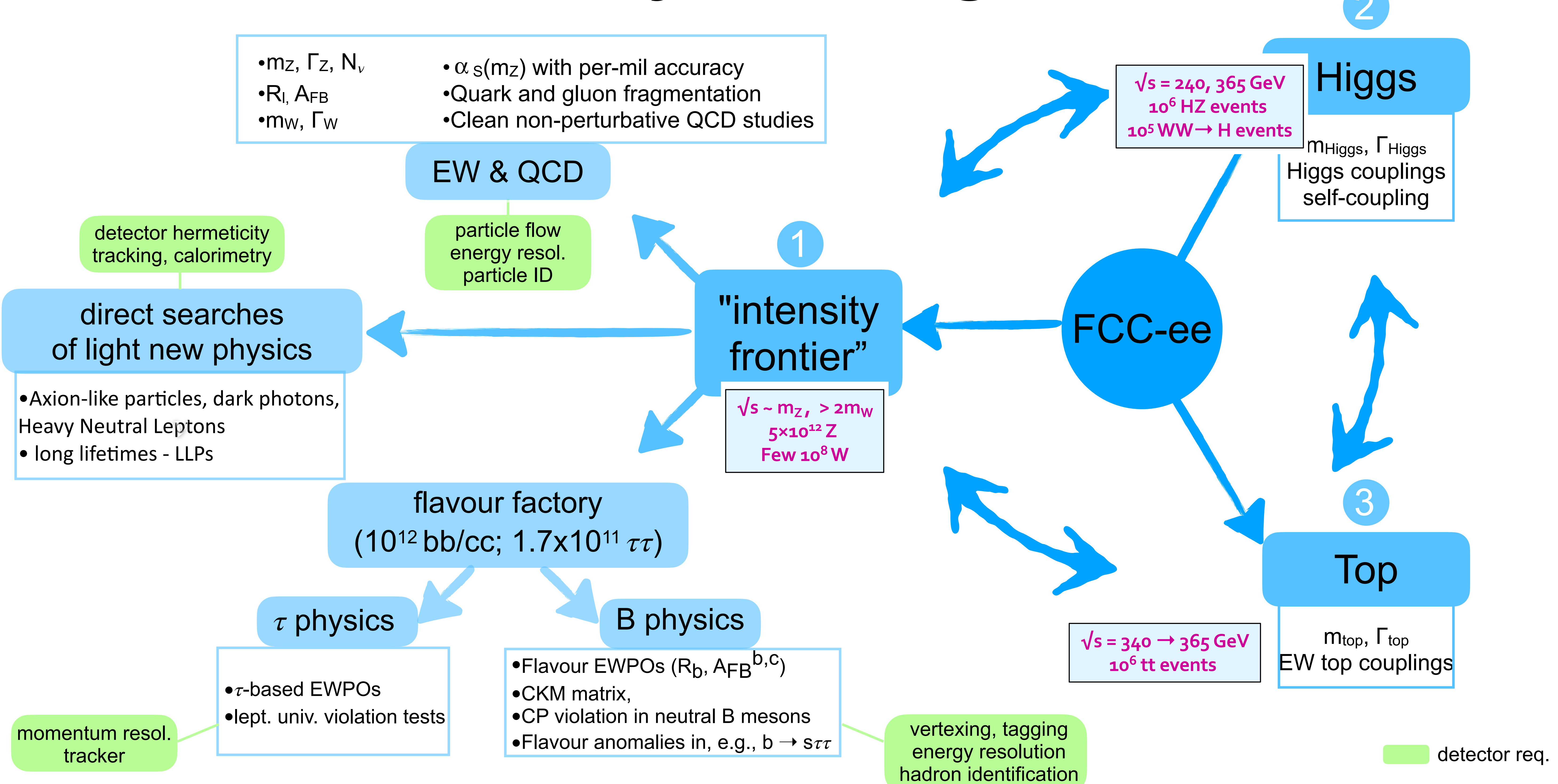


BSM @ TeV

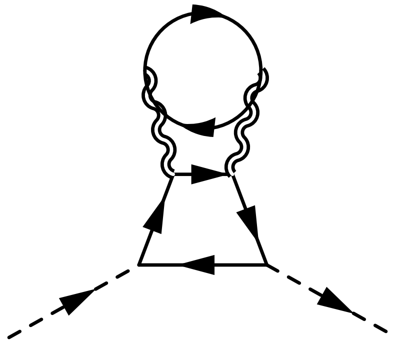
What's Next?

The potential of an elementary scalar field is highly sensitive to UV physics:
Is the EW vacuum compatible with new physics at higher energy (aka **hierarchy/naturalness** problem)?

Conspiracy/intelligent design

Arrange high-scale physics,
including quantum gravity,
to give small enough corrections
to Higgs potential

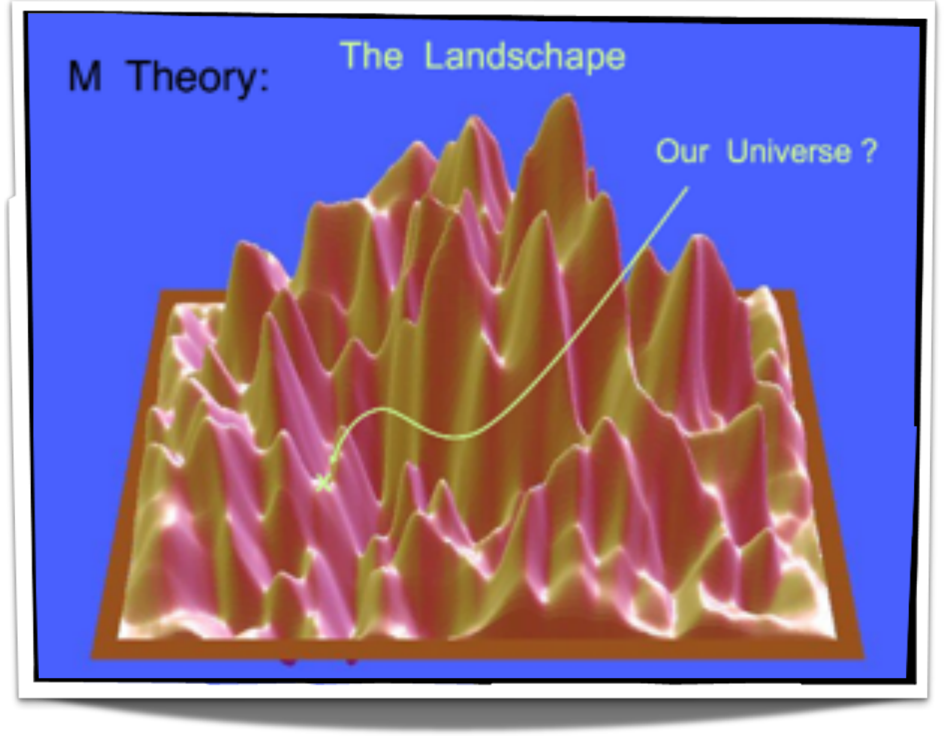
— Challenge —



$$\delta m_H^2 \sim \frac{6y_t^2}{(16\pi^2)^3}\frac{m_\Psi^6}{M_{Pl}^4}$$

Even new physics
only gravitationally coupled to SM
can generate large corrections
because off-shell couplings to gravitons

Anthropic selection in multiverse



Particles and fields are not
the building blocks of matter.
Strings and D-branes are.
Non-trivial fluxes generate multiverse

Dynamical screening

More conservative approach

Add new physics
to stabilise the EW vacuum

- New spacetime symmetry (supersymmetry)
- New forces/new particles (composite Higgs)
- New vacua

One-Vacuum Natural Models

Dynamical screening of the UV corrections to Higgs potential

- **Single vacuum**

New particles
with couplings related to SM ones by
symmetry cancel the large corrections

1. a symmetry (**Susy, PQ**)
2. a form factor (**composite Higgs**)

Low scale of quantum gravity

1. Large extra dimensions (**ADD**)
2. Gravitational sequestering (**RS**)

Combination of the above

TeV scale new physics

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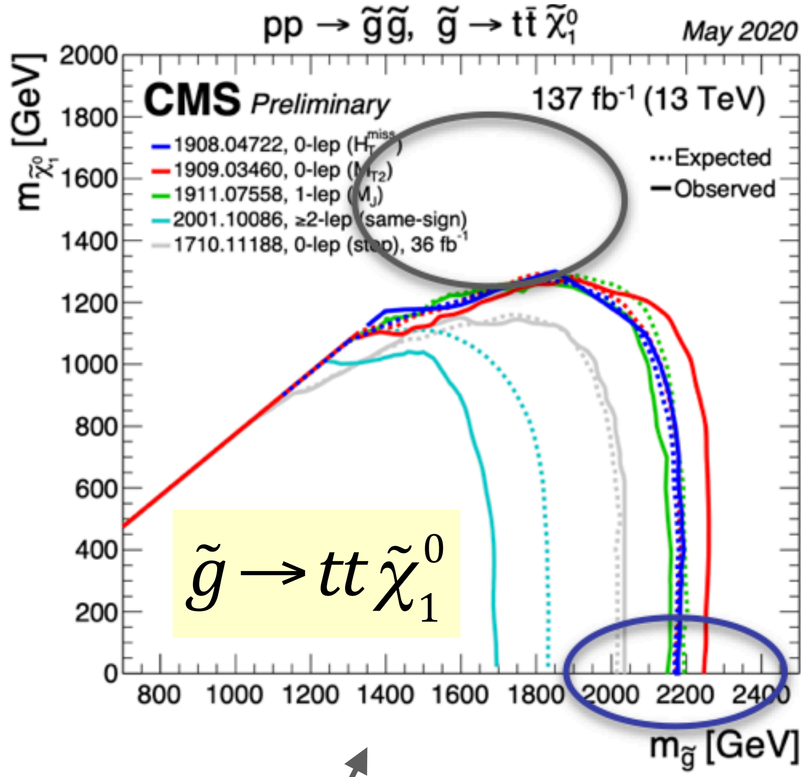
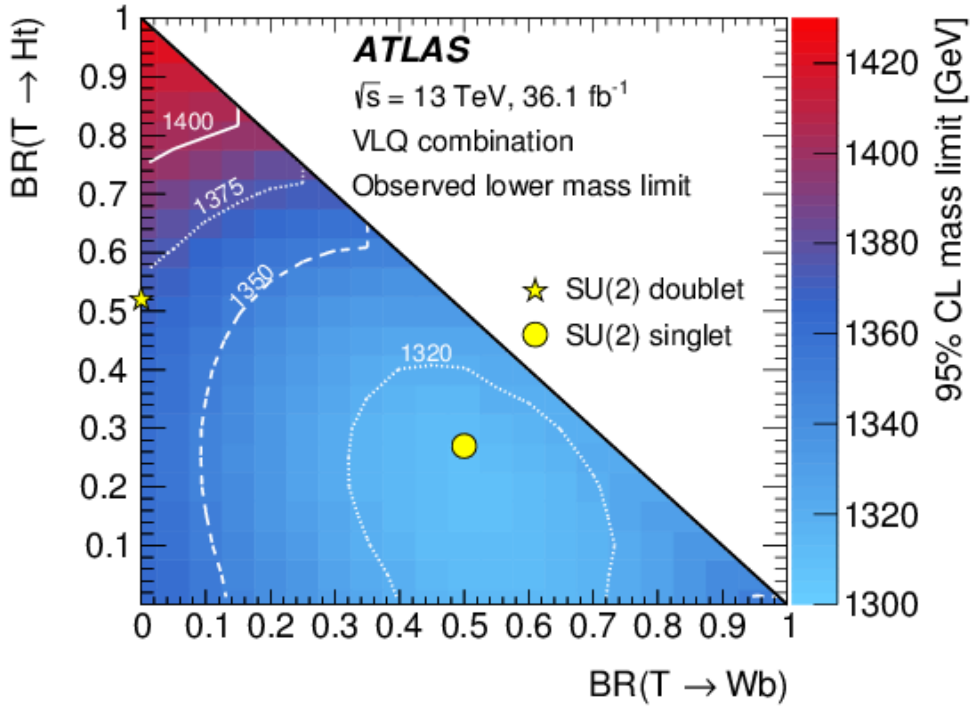
SUSY Searches



Vanilla models are getting in their tuned region

Composite Higgs top partners searches



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New Natural Models

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB/RS composite
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	???	Twin Higgs

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Neutral Naturalness

new "exotic" signatures
- displaced vertices
- emerging jets

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Neutral Naturalness

new "exotic" signatures

- displaced vertices
- emerging jets

Last model building opportunities filled up recently

Singlet scalar top partners from accidental supersymmetry

Hsin-Chia Cheng,[a,b] Lingfeng Li,[a] Ennio Salvioni[c] and Christopher B. Verhaaren[a]

The Hyperbolic Higgs

Timothy Cohen,[a] Nathaniel Craig,[b] Gian F. Giudice[c] and Matthew McCullough[c]

Multi Vacua Natural Models

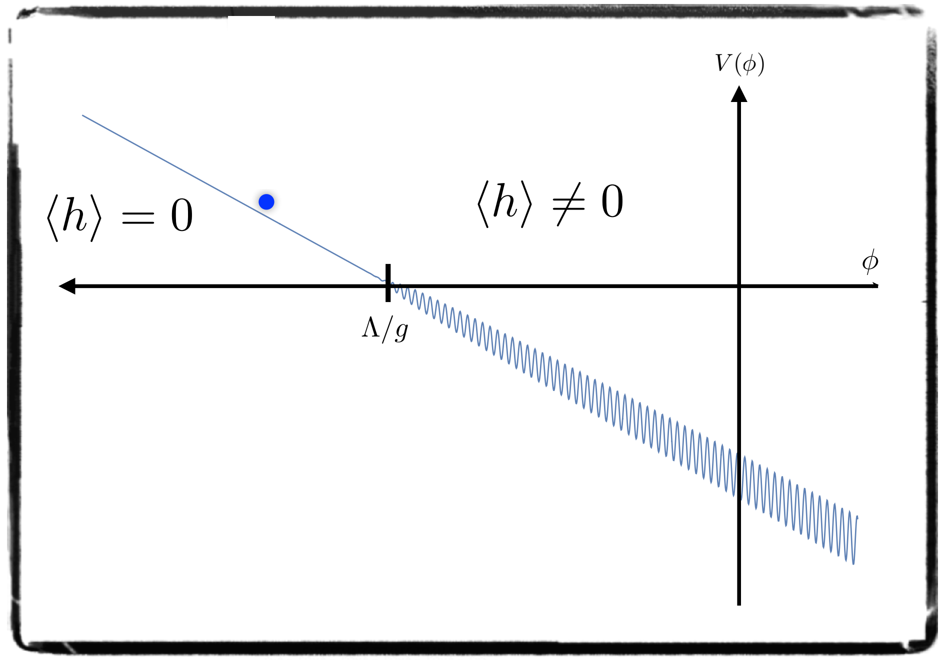
Dynamical screening of the UV corrections to Higgs potential

- **Multiple vacua**

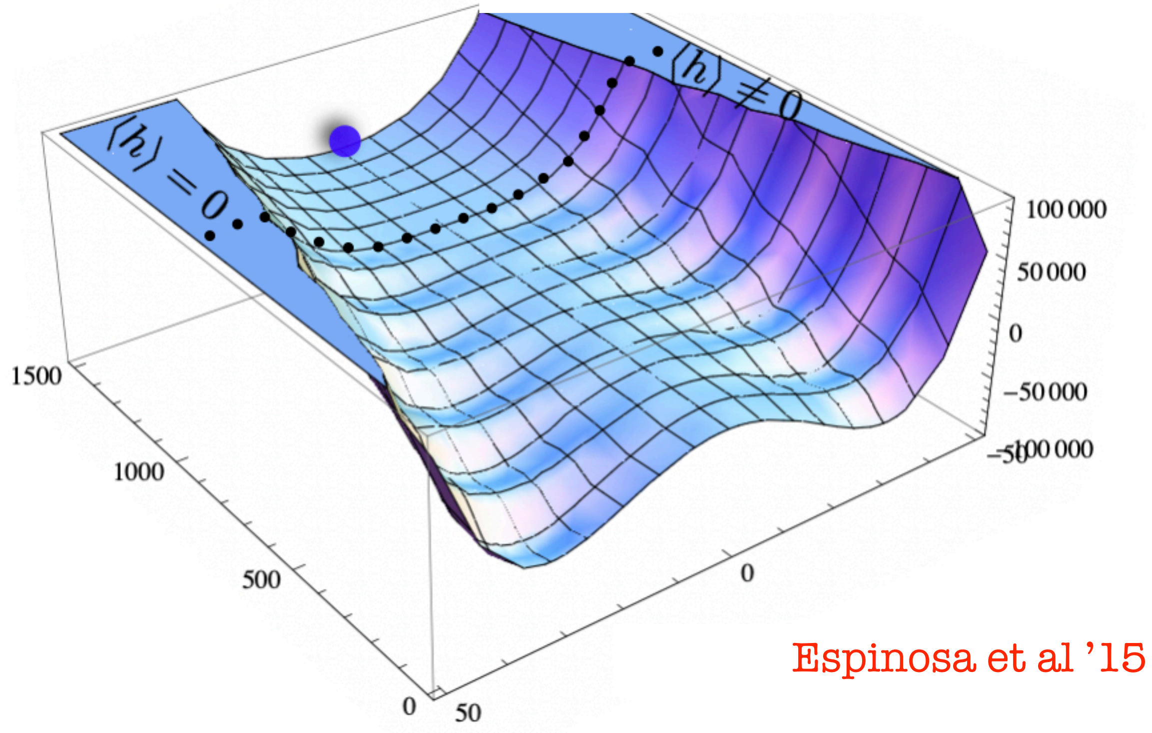
many metastable vacua with a vast range of values for m_H

Dynamical selection of $m_H \ll \Lambda$

1. **NNaturalness**: The patches with different Higgs VEVs expand differently: either they shrink to nothing or they expand too fast and no particle reheating possible. The patch with the right EW vacuum is selected.
2. **Relaxion**: Cosmological scanning with non-trivial back reaction that stops the exploration of the vacuum manifold at the right place



Graham, Kaplan, Rajendran '15



Espinosa et al '15

Paradigm shift

light new physics expected to address the hierarchy problem

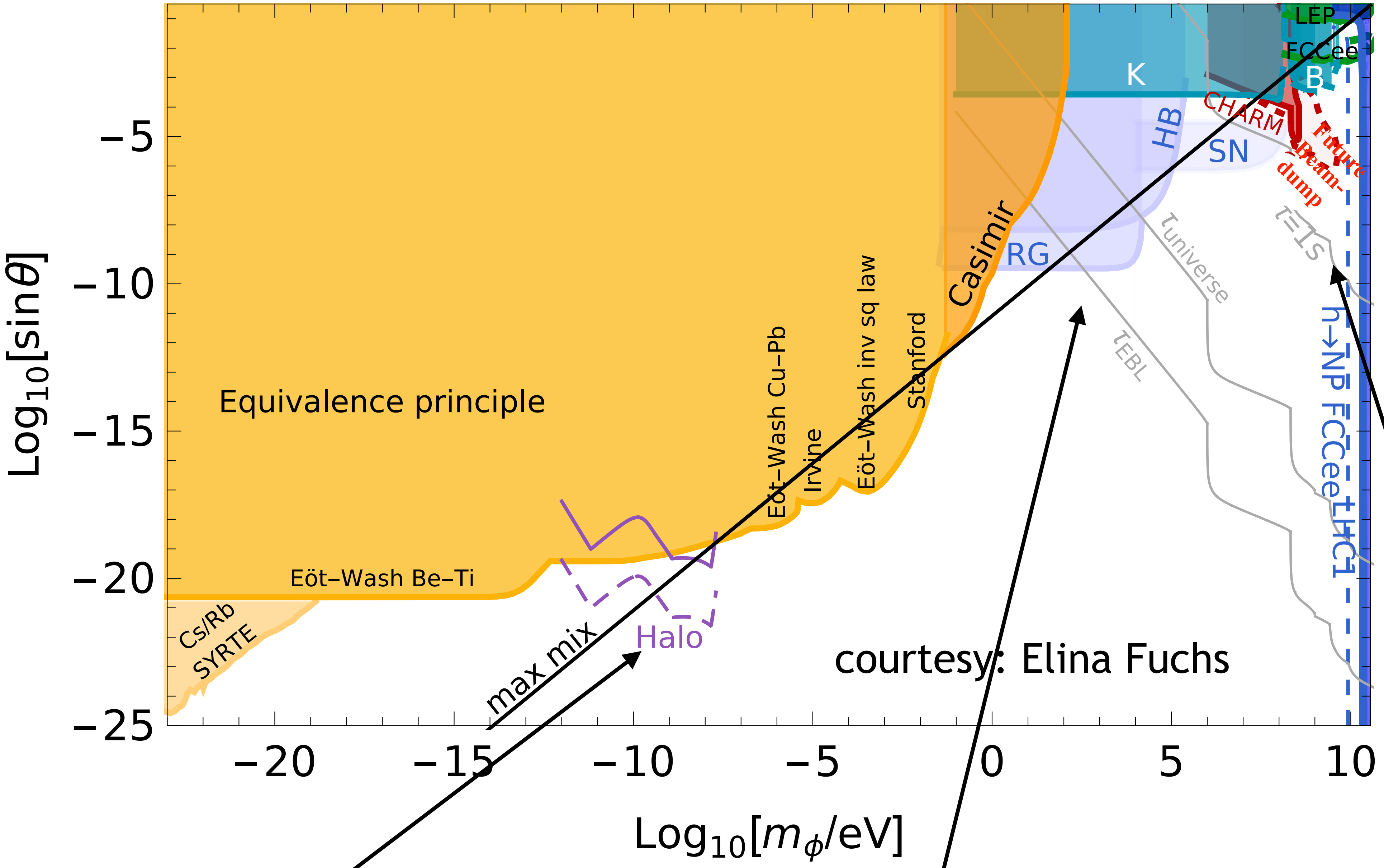
LHC/energy frontier is not the unique place to probe "natural" models

BSM @ Intensity Frontiers

The *log* Crisis of the Higgs

G. Perez et al ’17-‘19

Overview plot: the relaxion 30-decade-open parameter space



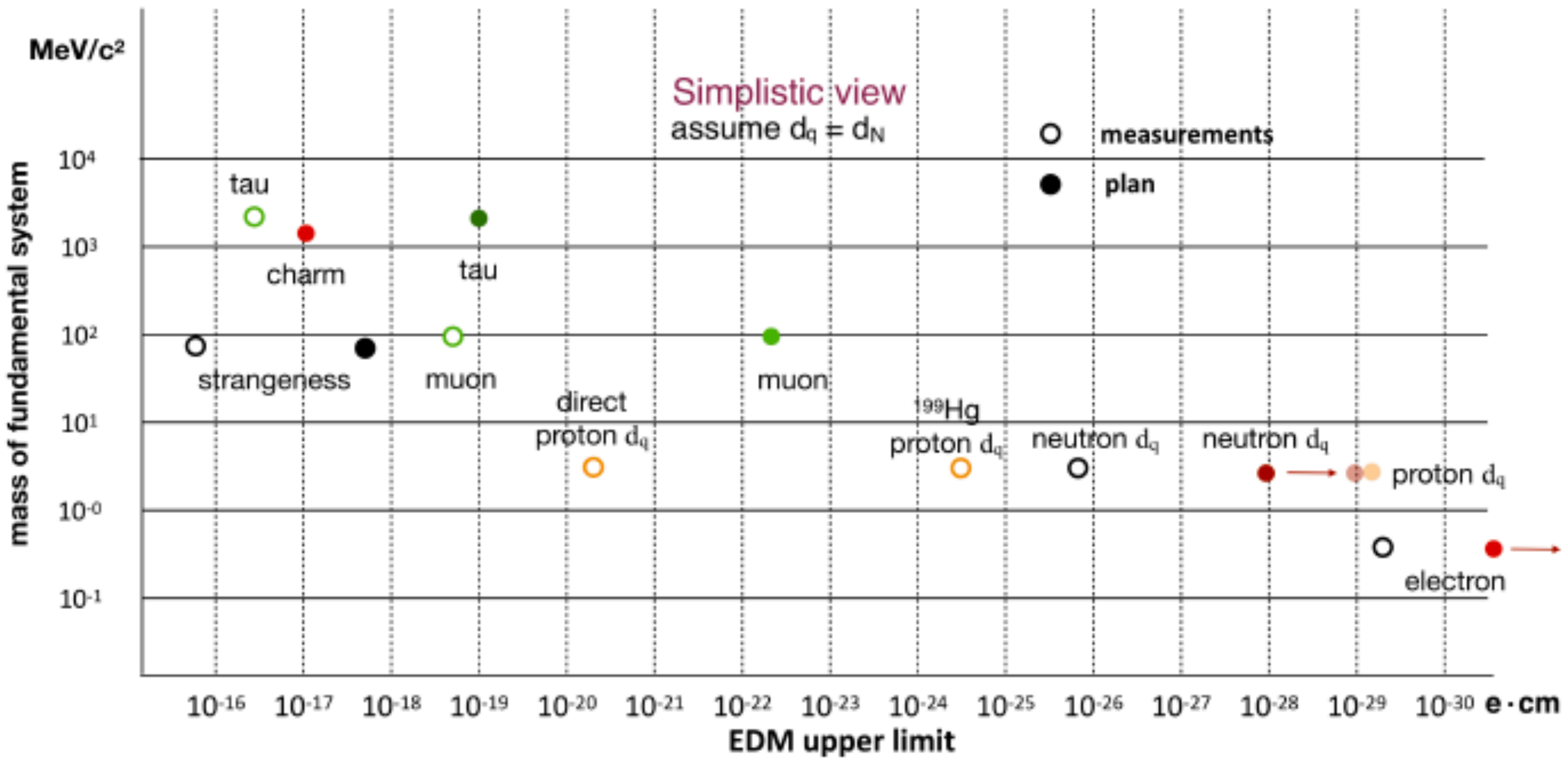
Rich opportunities at different scales

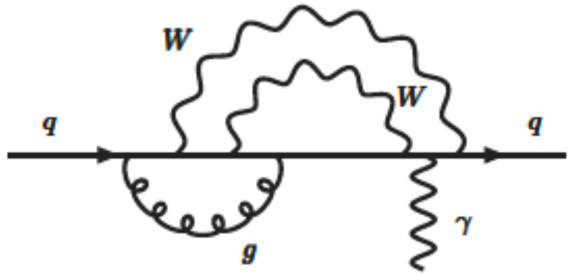
“fun signatures”

Precision frontier	Astro frontier	Collider frontier
Higgs vev oscillates	DM halo, super radiance	Invisible Higgs decays

Precision Probes BSM

EDM



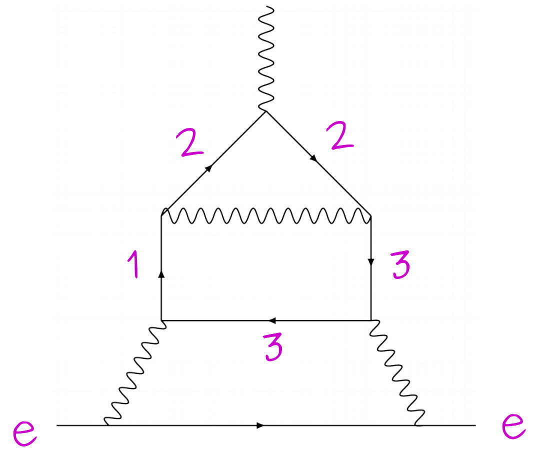


$$\mathcal{L}_{dipole} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - \frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}i\gamma^5 F_{\mu\nu}\Psi$$

Non-relativistic limit

$$H = -\mu\,\vec{B}\cdot\frac{\vec{S}}{S} - d\,\vec{E}\cdot\frac{\vec{S}}{S}$$

SM predictions



$\rightarrow d_e/e \sim 10^{-40}\ cm$

SM contribution is ridiculously small
EDM is clear signal of New Physics

$|d_e| < 9.4 \cdot 10^{-29}\, e\,\mathrm{cm}$ (ACME @ 90% CL)

$|d_e| \lesssim 0.5 \cdot 10^{-29}\, e\,\mathrm{cm}$ (ACME II)

$|d_e| \lesssim 0.3 \cdot 10^{-30}\, e\,\mathrm{cm}$ (ACME III)

Pushing the EDM Frontier

M. Reece @ Pheno2020

Snowmass LOI

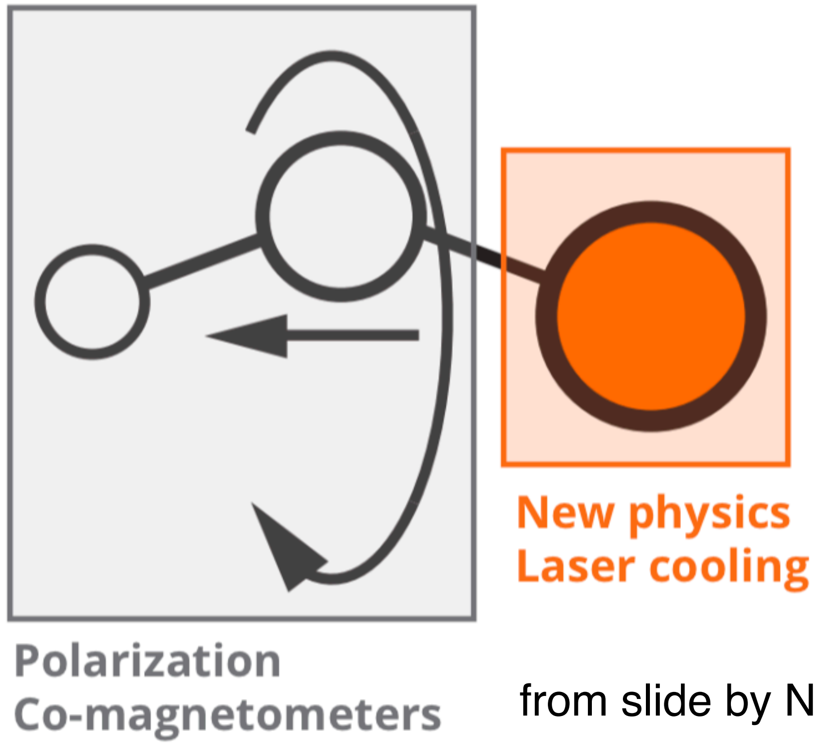
To improve, need more molecules, longer coherence times. Need special molecules:

Laser cooling can produce many slow-moving molecules to study. Avoid exciting molecular rotational, vibrational modes.

EDM systematics need "internal co-magnetometer."

Hutzler & Kozyryev 2017: **polyatomic molecules can give both! (ex: YbOH)**

Polyatomic EDM



from slide by N. Hutzler

Time scale of 5-10 years:

$$|d_e| \lesssim 10^{-32}\, e\, \mathrm{cm}$$

1-loop, PeV scale sensitivity

Other planned experiments: trapped molecular ions (Cornell, Ye, JILA), YbF (Hinds, Imperial), EDM^3 (Vutha, Horbatsch, Hessels, Toronto/York), …

EDM Probes BSM

e.g., EDM can help testing the presence of top partners in composite Higgs models far beyond direct reach

arXiv:1712.06337

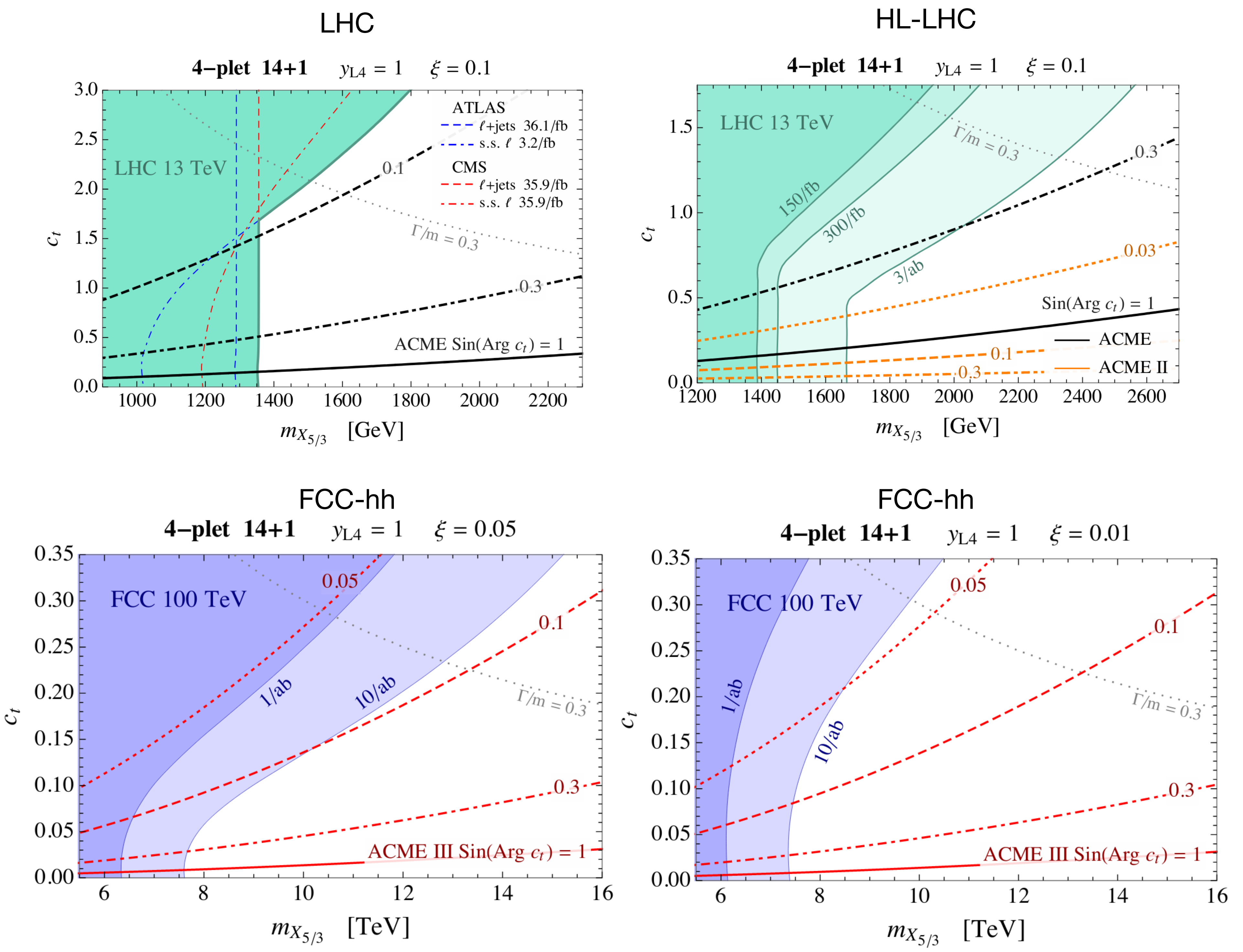
$$g_{W X_{5/3} t_R} = \frac{g}{\sqrt{2}} c_t \frac{v}{f}$$

$$\xi = \frac{v^2}{f^2}$$

$$\xi = 0.1 \leftrightarrow f \approx 800\,\mathrm{GeV}$$

$$\xi = 0.05 \leftrightarrow f \approx 1100\,\mathrm{GeV}$$

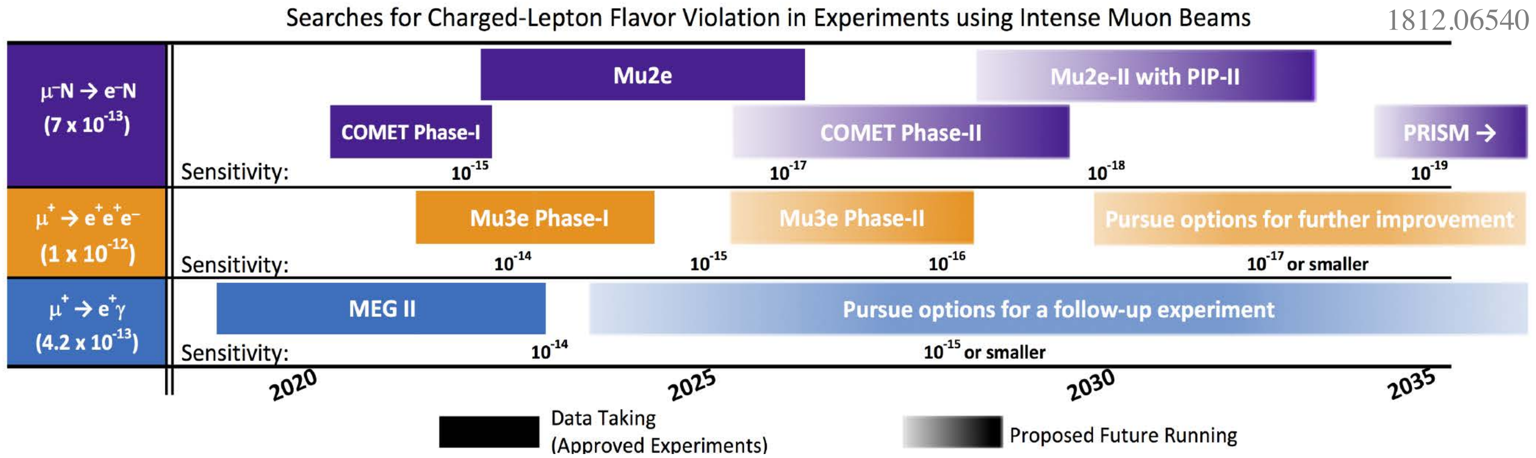
$$\xi = 0.001 \leftrightarrow f \approx 8000\,\mathrm{GeV}$$



Precision Probes BSM

ESU, arXiv:1910.11775

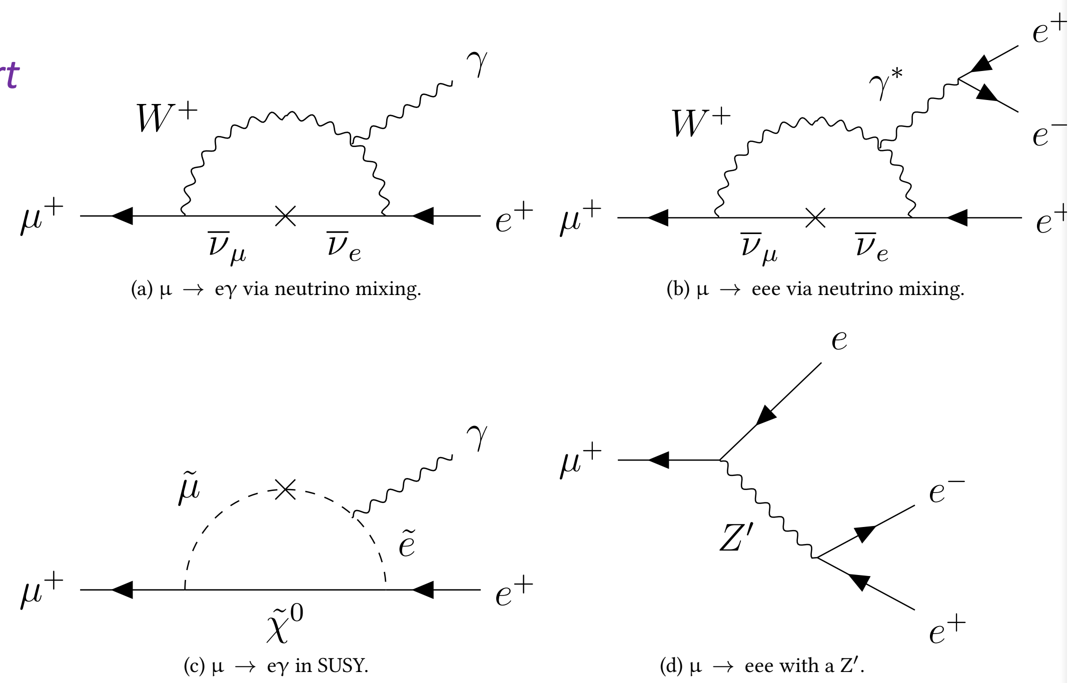
LFV



Figures from A-K Perrevoort

SM: BR<10^{-54}

BSM



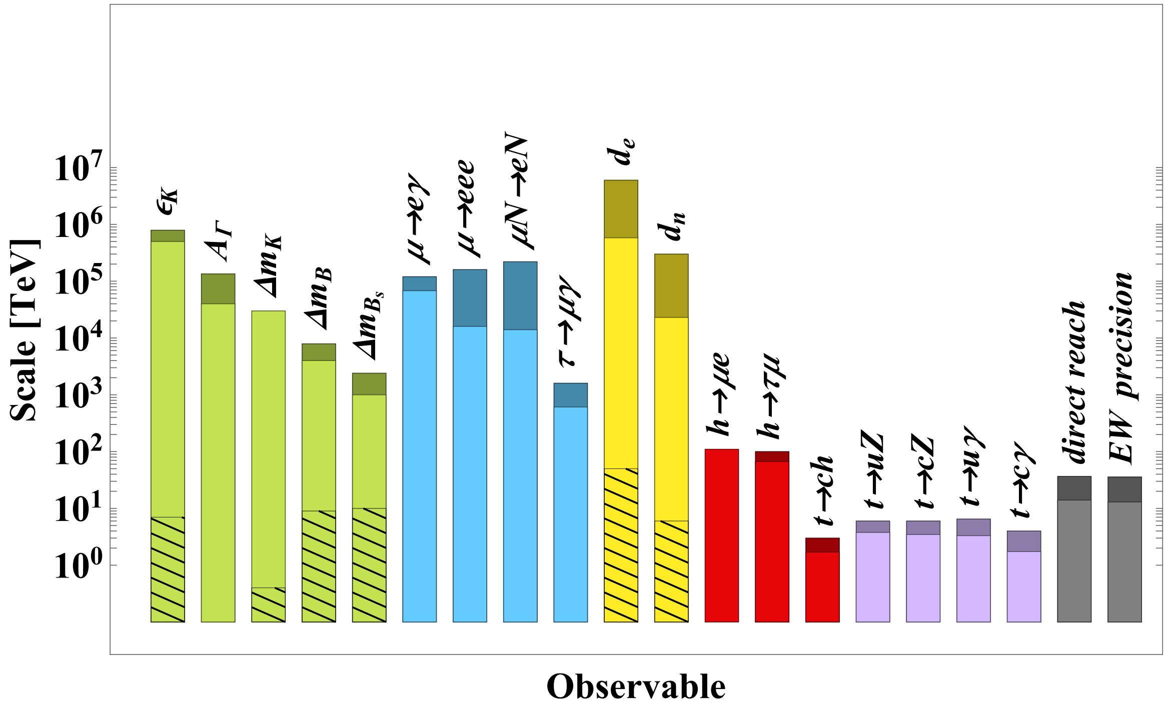
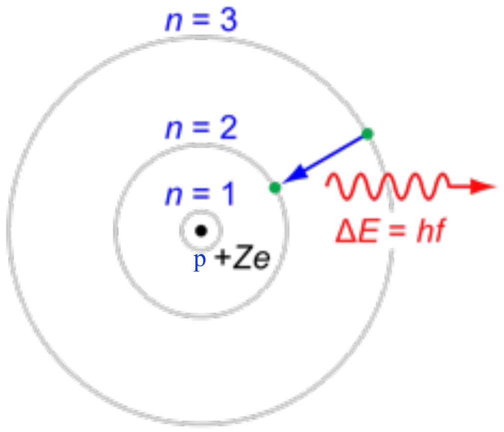


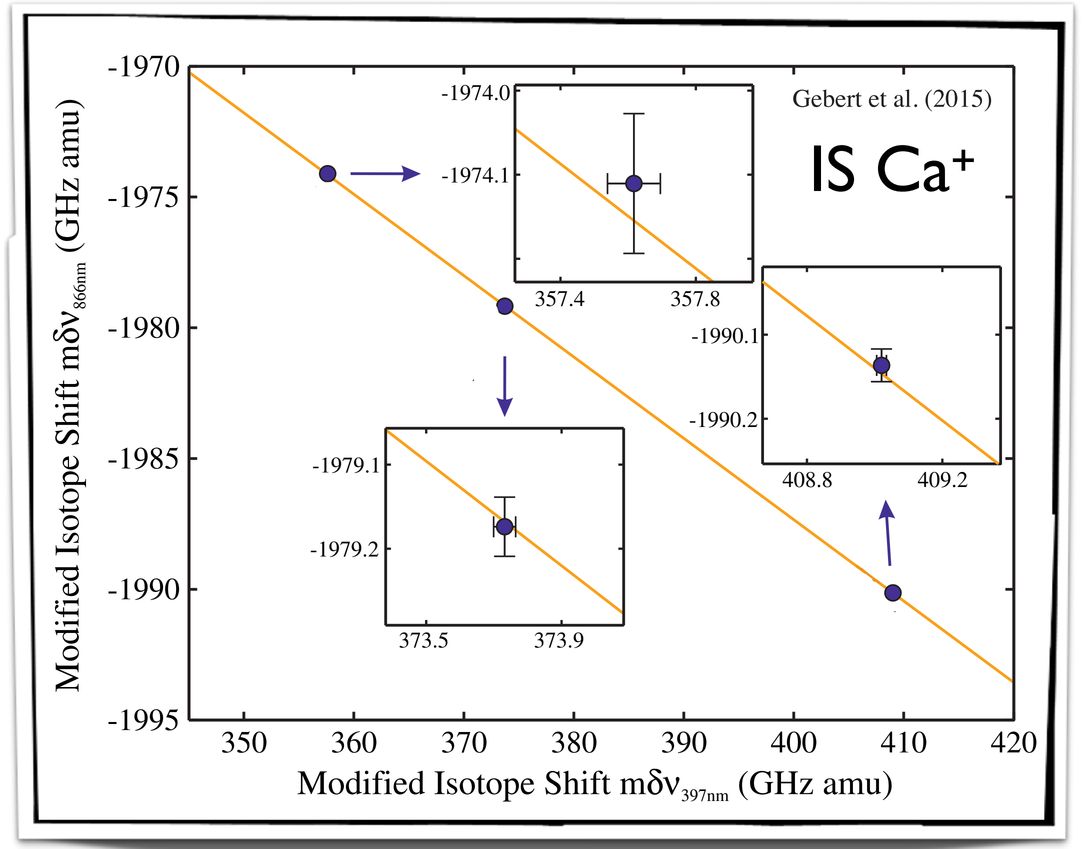
Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).

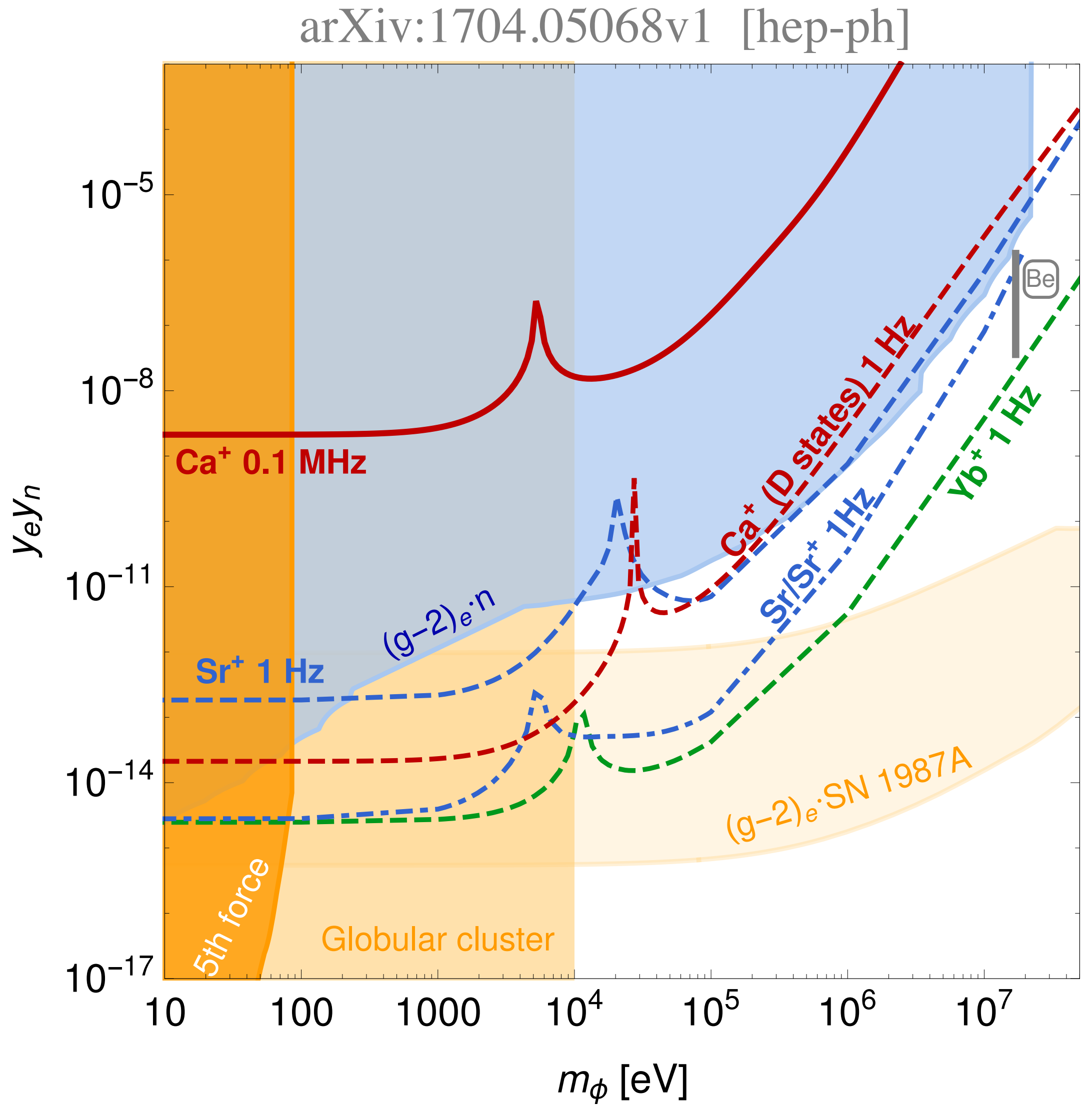
LFV processes give strongest constraints on MVF models

HEP Meets AMO

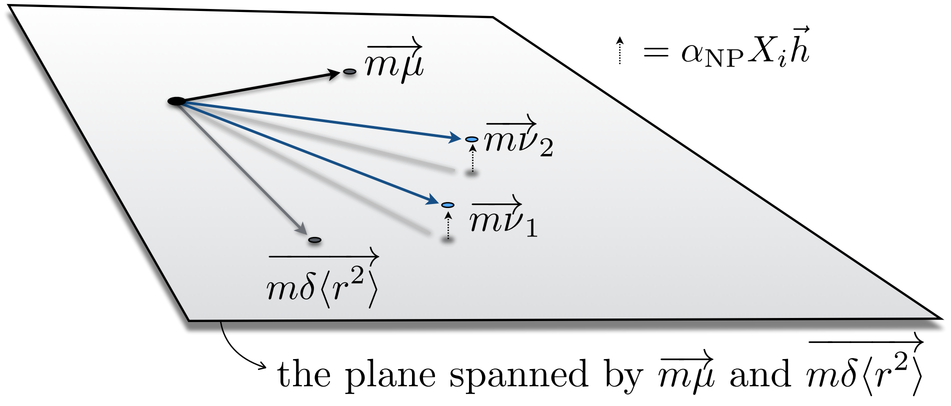
O(10^{-18}) sensitivity in atomic clock measurements
can be used to detect new (long range) forces







can only probe long-range force
(no bound on e- Yukawa, unfortunately)



Spectacular experimental progress very recently

2004.11383
Yb+ King plot (300 Hz)

2005.00529
Ca+ King plot (20 Hz)

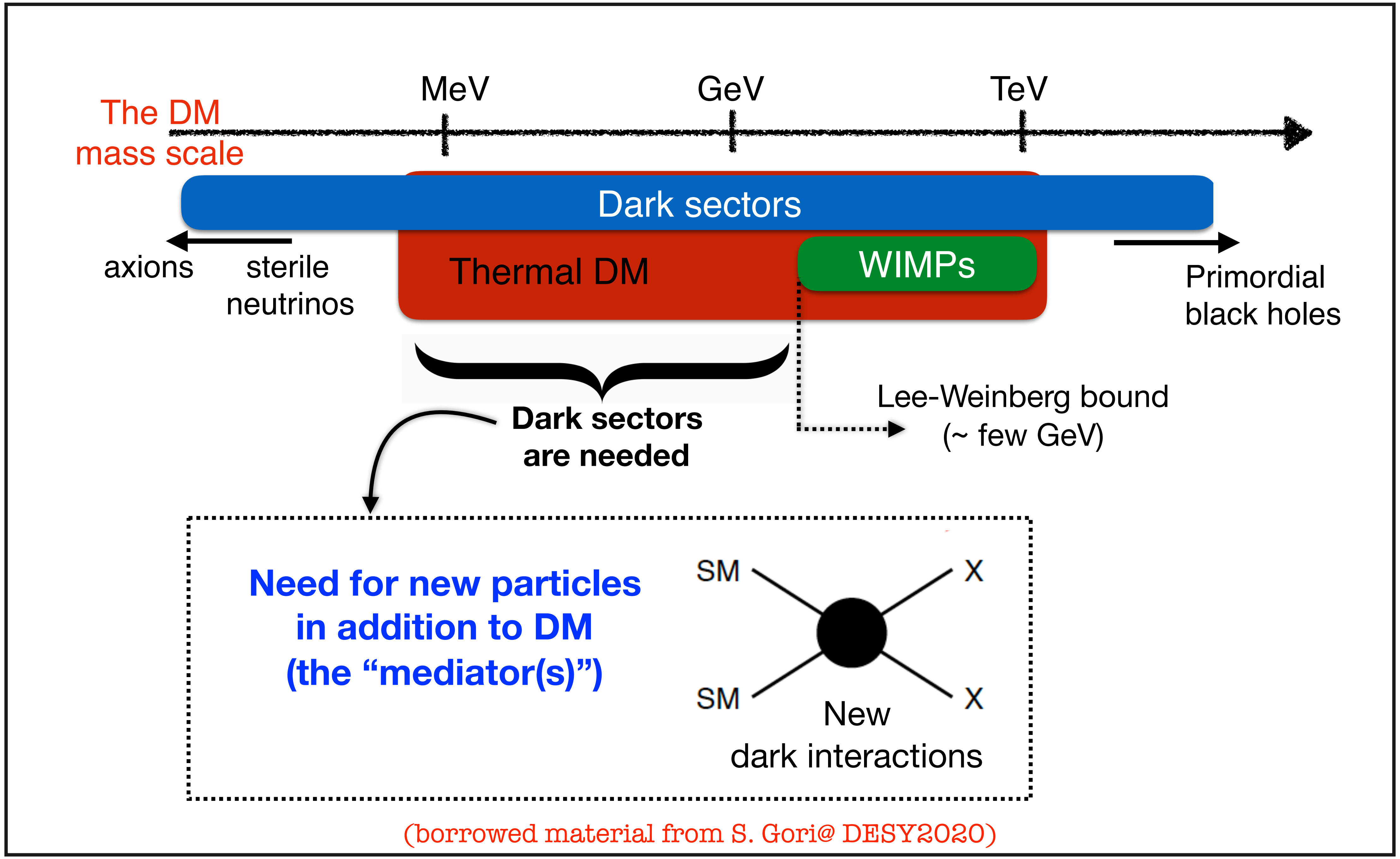
BSM in the Dark Sector

Scale of DM

The prediction about the mass scale of DM comes with large error bars:

$$10^{-22}\,\text{eV} < m_{DM} < 10^{20}\,\text{GeV}$$

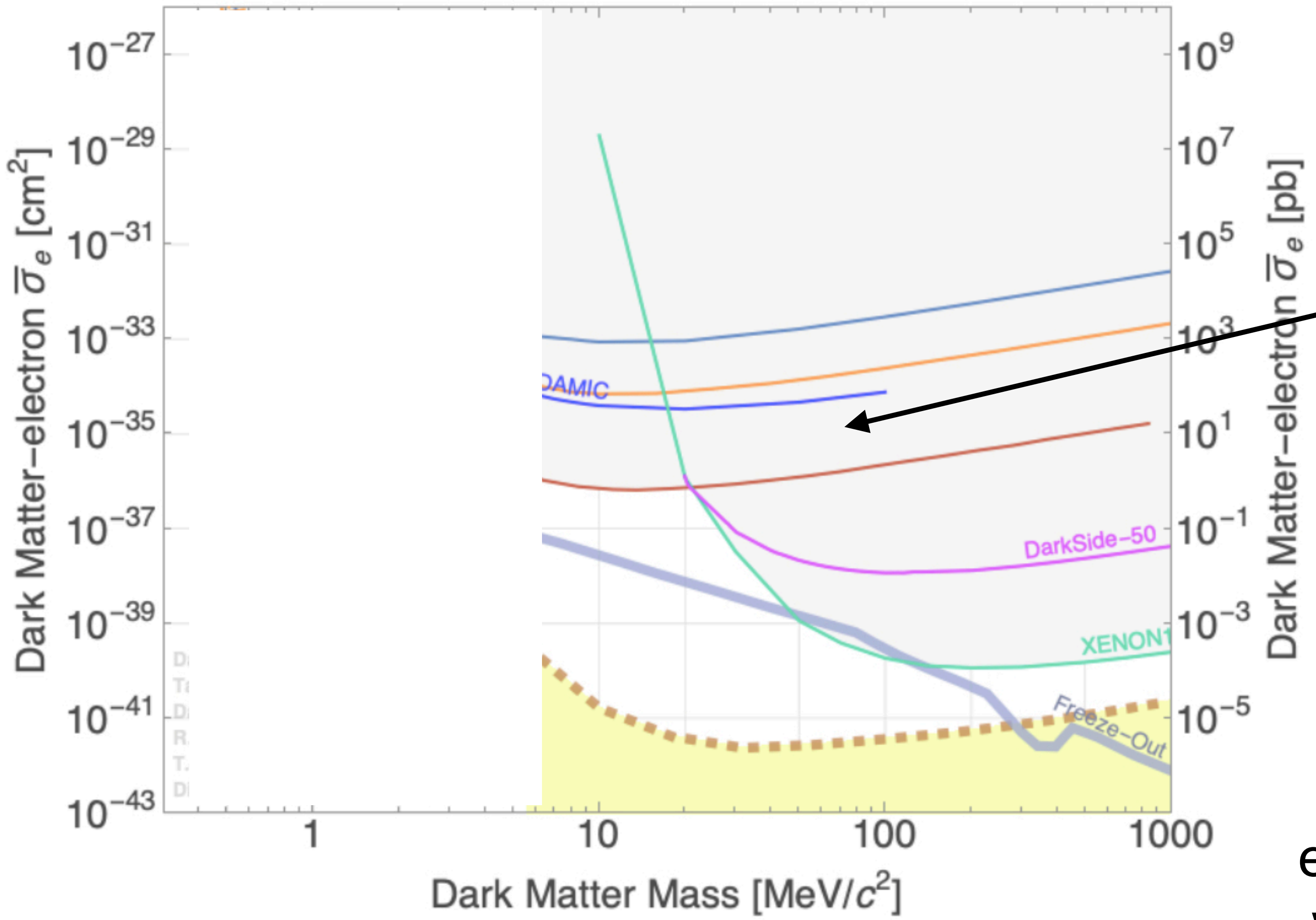
(ALPs) (Wimpzillas, Q-balls)



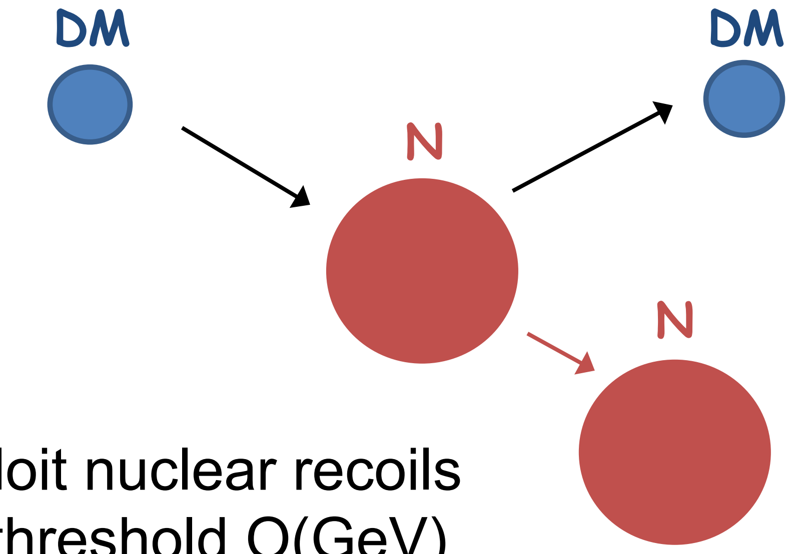
WIMP and Beyond

WIMP miracle/accident: DM can can be naturally linked to the weak scale

thermal freeze-out: $$\Omega_{DM} \sim 0.3 \, \frac{g^2_{\text{DM-SM}}}{4\pi\,\alpha} \left(\frac{100\,\text{GeV}}{m_{DM}}\right)^2$$



WIMP region is well explored and no signal (yet)



exploit nuclear recoils w/ threshold O(GeV)

(borrowed material from Y. Hochberg @ DESY2020)

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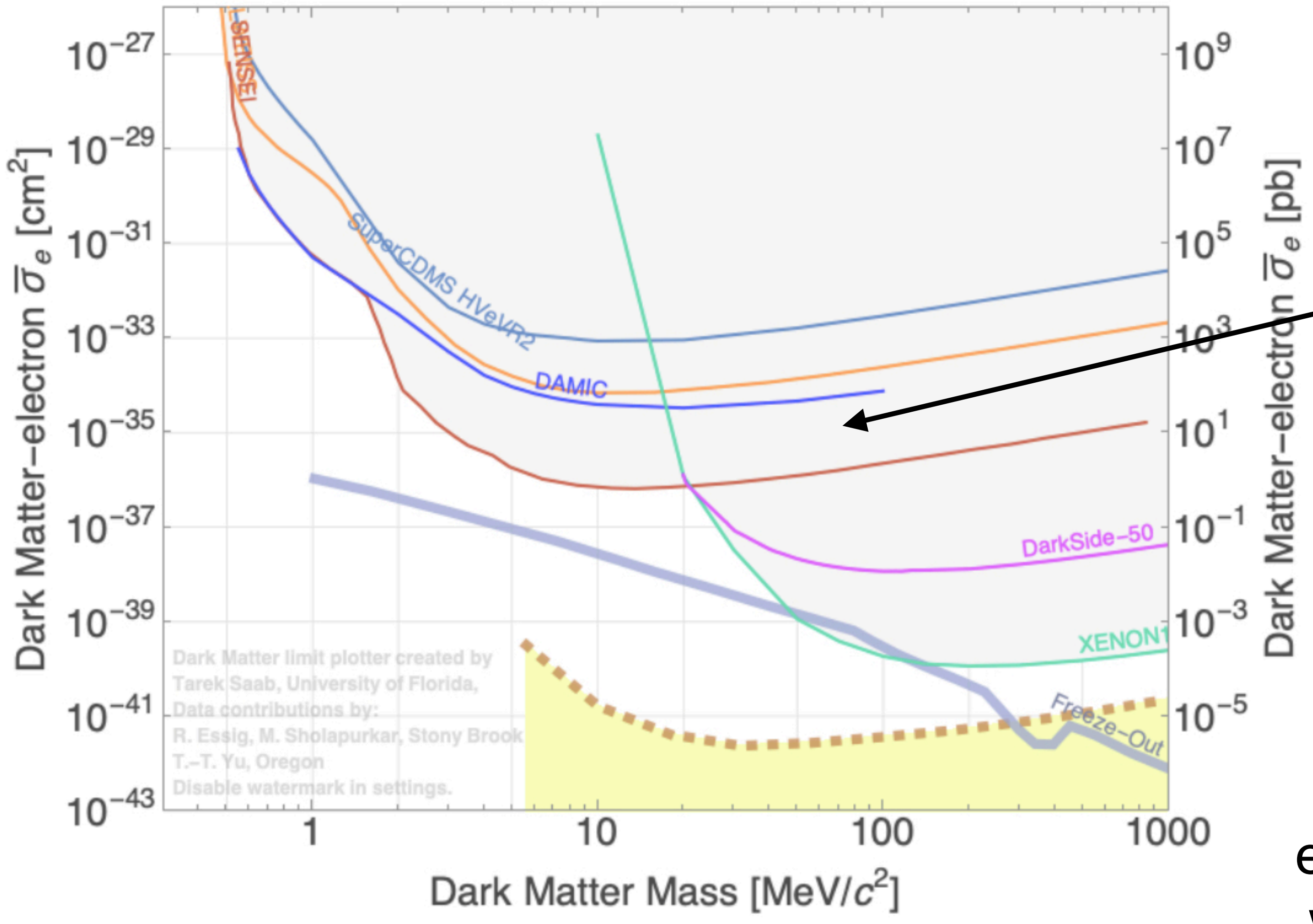

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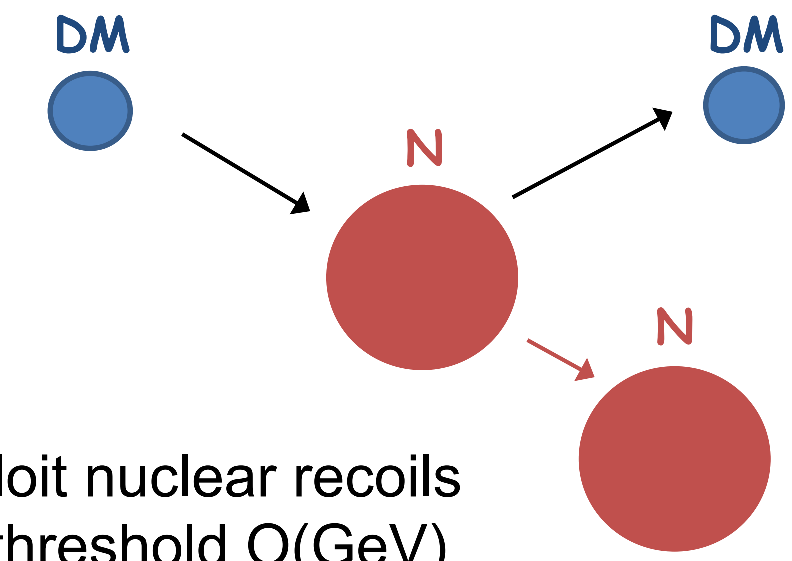

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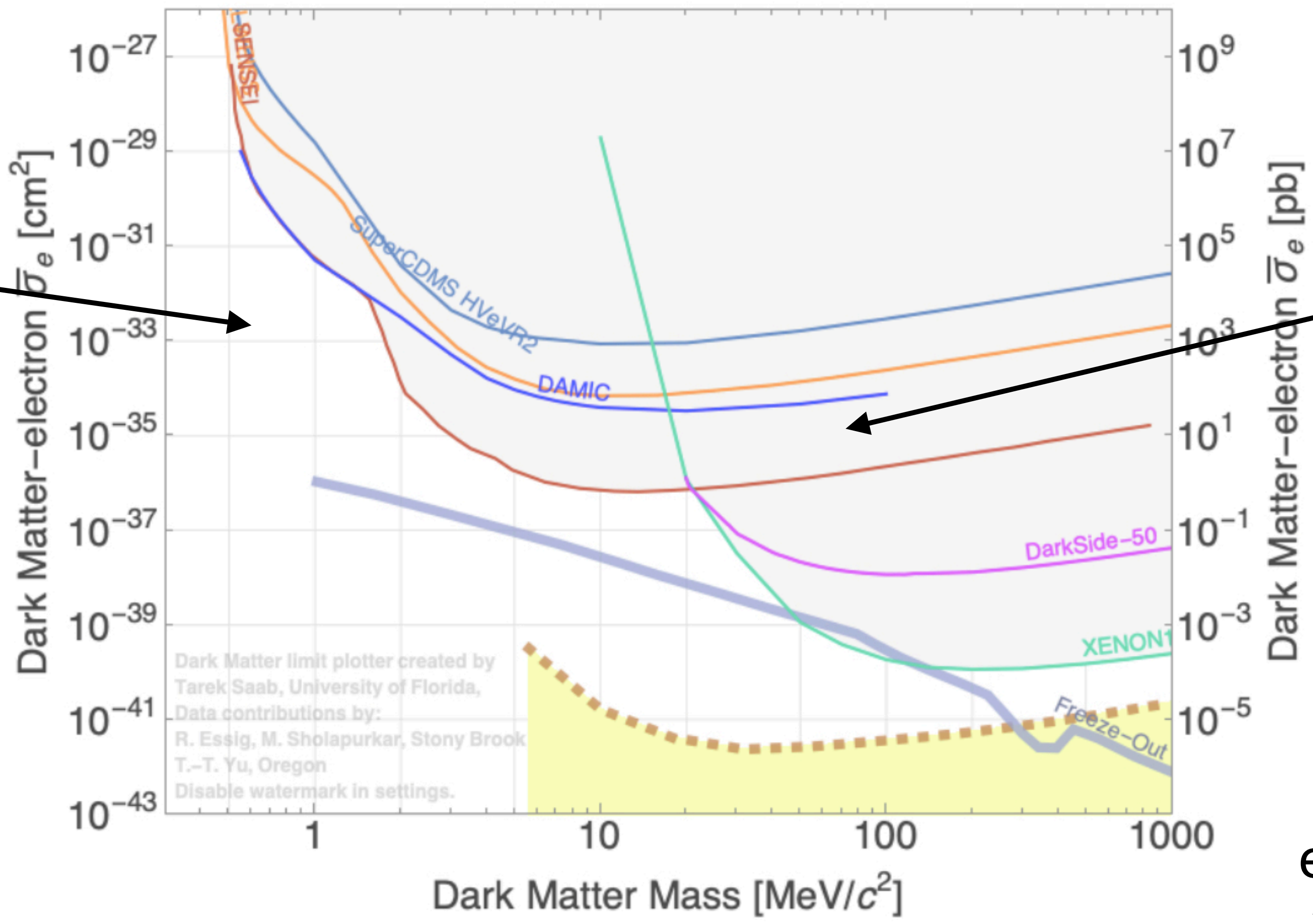
light DM
region is subject
to weaker constraints



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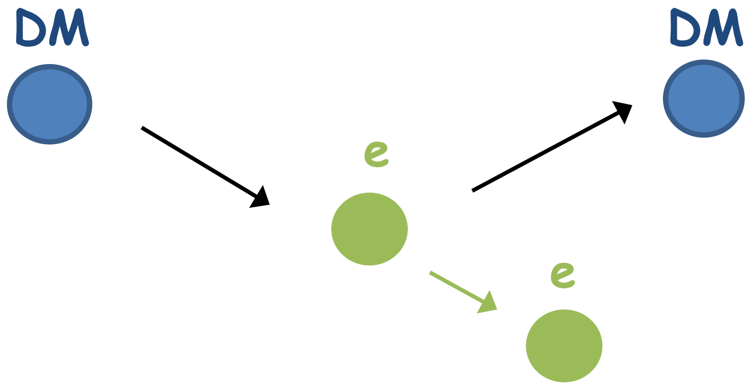
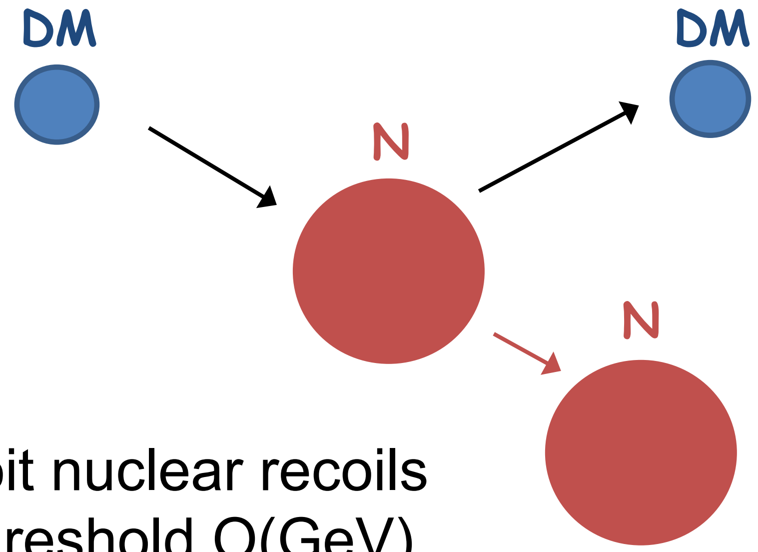


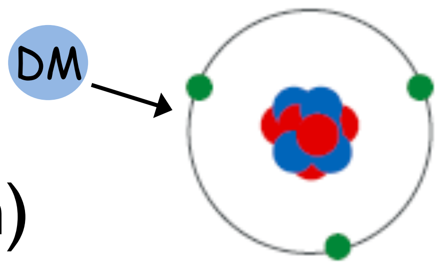
exploit electron recoils
w/ threshold O(keV)



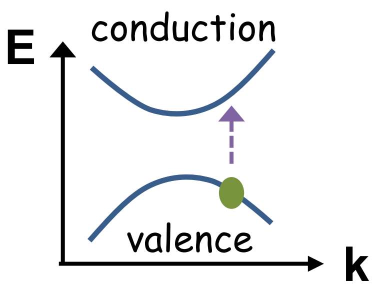
exploit nuclear recoils
w/ threshold O(GeV)

(borrowed material from Y. Hochberg @ DESY2020)

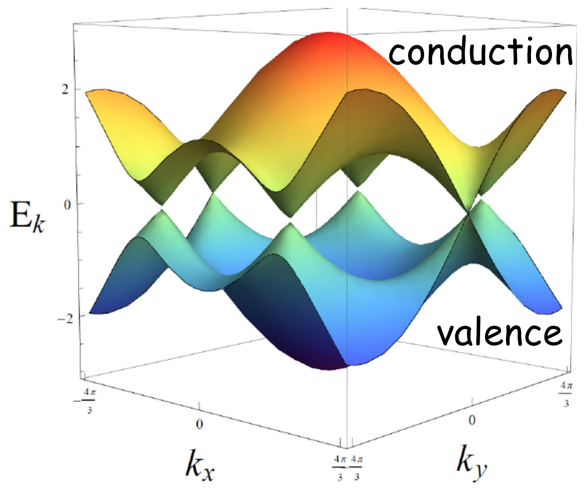
The light DM frontier

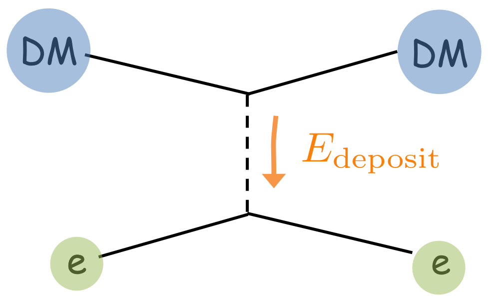


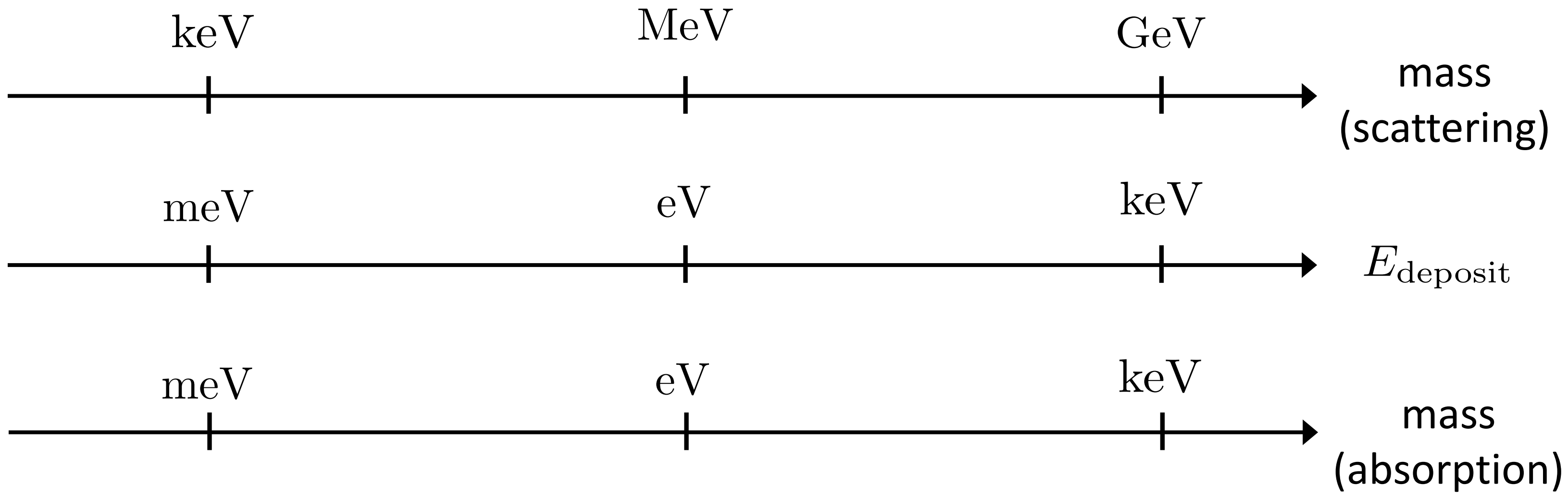
- Atomic ionization (Xenon)
- Semiconductors (Sensei)

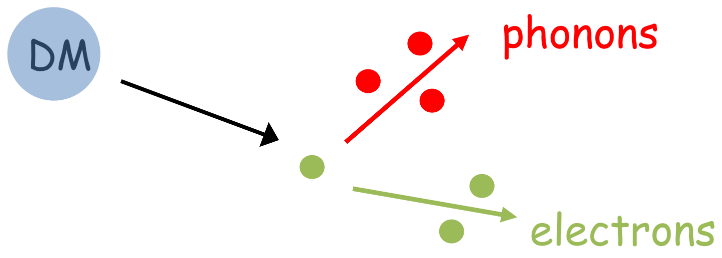


- Superconductors (SNSPDs) DM scatters on Cooper pairs and break them
- Graphene/vanishing bandgap (Ptolemy): DM scatters with valence e⁻ and eject them
- Dirac material









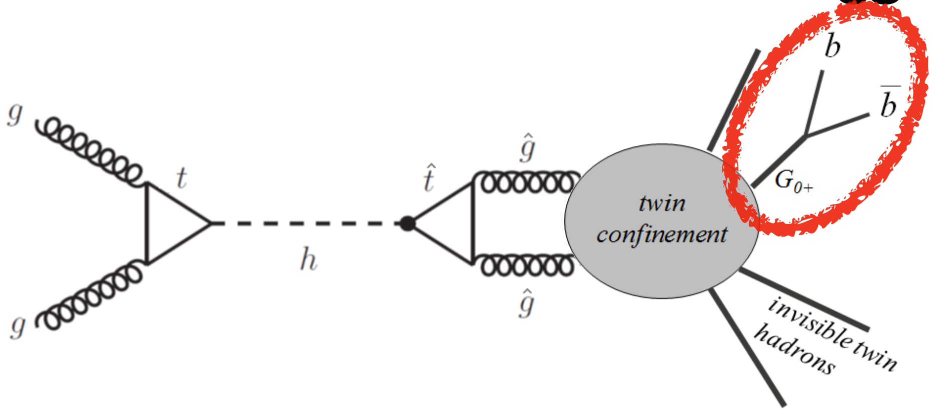
(see Y. Hochberg @ DESY2020)

Searches for the light dark states

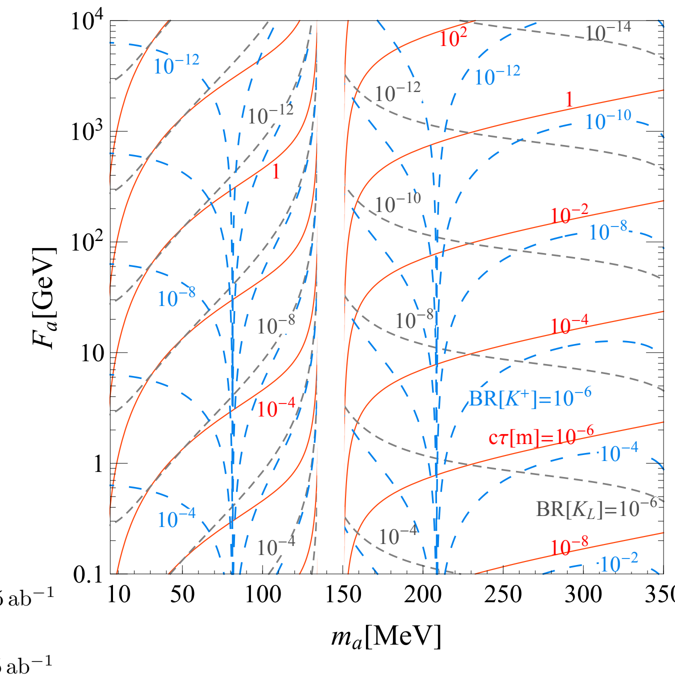
(see S. Gori @ DESY2020)

- **LLP searches with displaced vertices**
  e.g. in twin Higgs models glueballs that mix with the Higgs and decay back to b-quarks

arXiv:1501.05310



Mathulsa, Faser…
or precise timing detector @ ATLAS/CMS



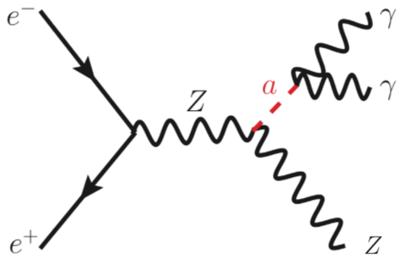
arXiv:2005.05170

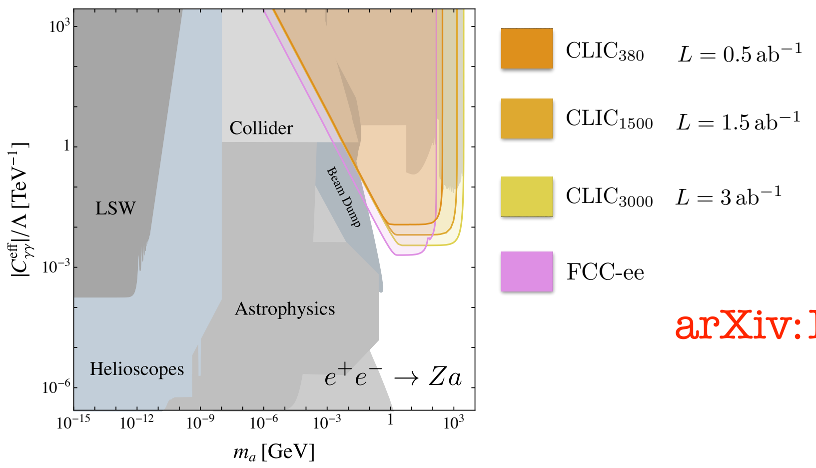
- **Rare decays**
  e.g. ALP mixing w/ SM mesons:

$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \text{ (KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \text{ (NA62)}$$

$$\mathcal{L} = \frac{\alpha_s}{8\pi F_a} a G_{\mu\nu} \tilde{G}^{\mu\nu}$$

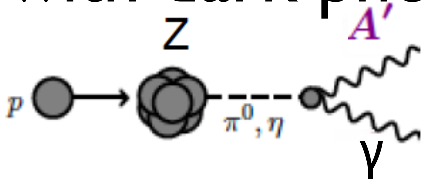
- **ALPs@ colliders**
  e.g. $e^+e^- \to Za$
  $e^+e^- \to ha$





arXiv:1808.10323

- **Beam-dump experiments**
  e.g. kinetic mixing with dark photon



e.g. SHiP: arXiv:1504.04855

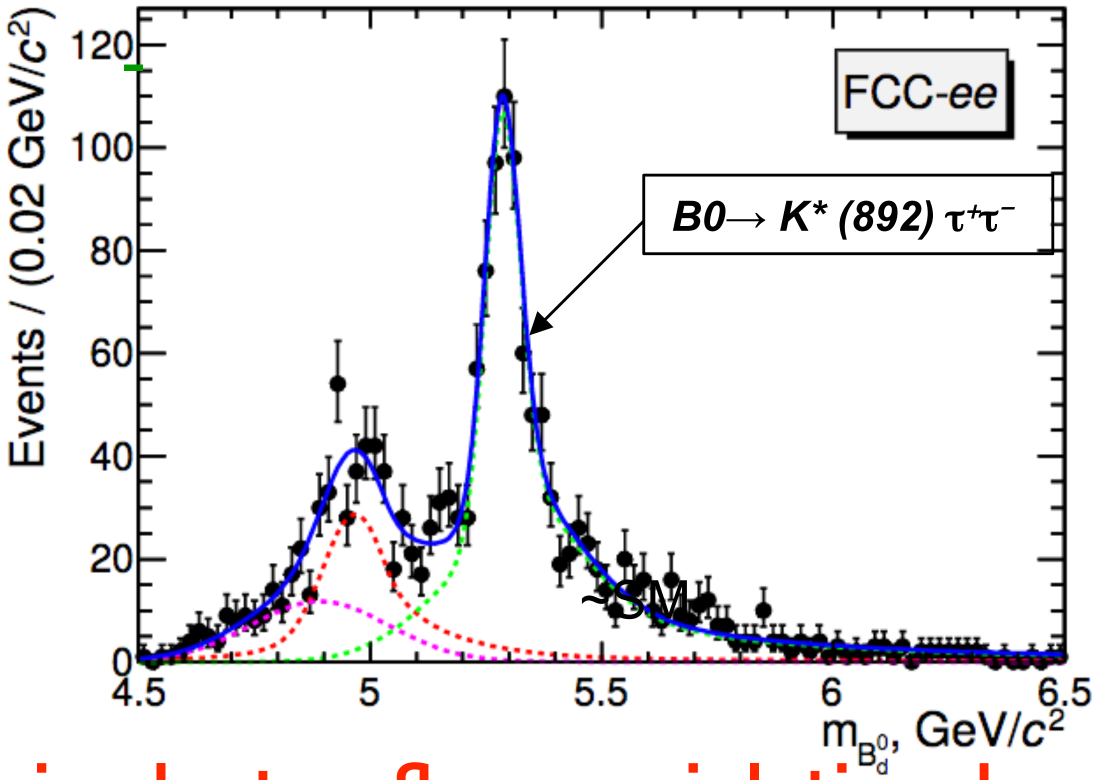
SHiP, DarkQuest

Z-Factories are also Flavour Factories

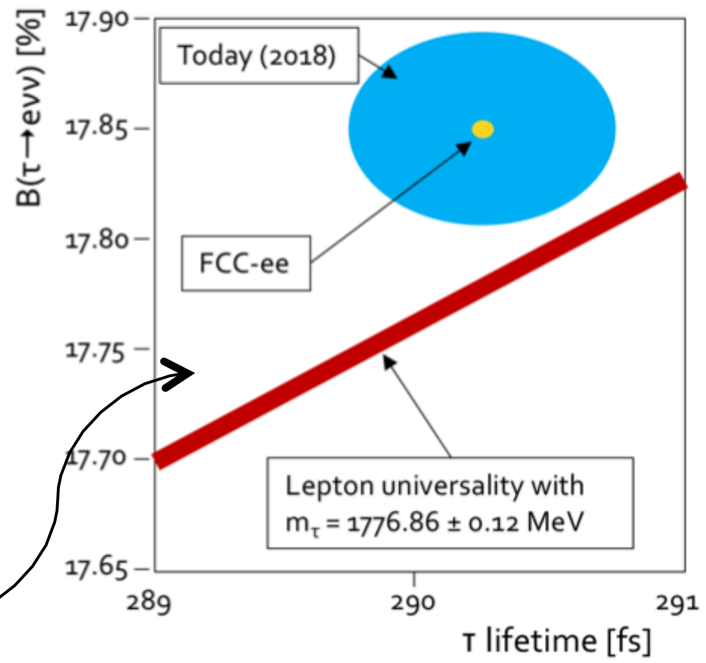
- **Lepton flavour universality is challenged in b $\rightarrow$ s $\ell^+\ell^-$ transitions @ LHCb**
  - This effect, if real, could be enhanced for $\ell = \tau$, in $B \rightarrow K^{(*)} \tau^+\tau^-$
    - Extremely challenging in hadron colliders
    - With 10^{12} Z → bb, FCC-ee is beyond any foreseeable competition
      - ➨ Decay can be fully reconstructed; full angular analysis possible

Material from P. Janot

J.F. Kamenik et al.
arXiv:1705.11106



Also 100,000 $B_S \rightarrow \tau^+\tau^-$ @ FCC-ee
Reconstruction efficiency under study



- **Not mentioning lepton-flavour-violating decays**
  - BR(Z → eτ, μτ) down to 10^{-9} (improved by 10^4)
  - BR(τ → μγ, μμμ) down to a few 10^{-10}
  - τ lifetime vs BR($\tau \rightarrow e\nu_e\nu_\tau, \mu\nu_\mu\nu_\tau$) : lepton universality tests

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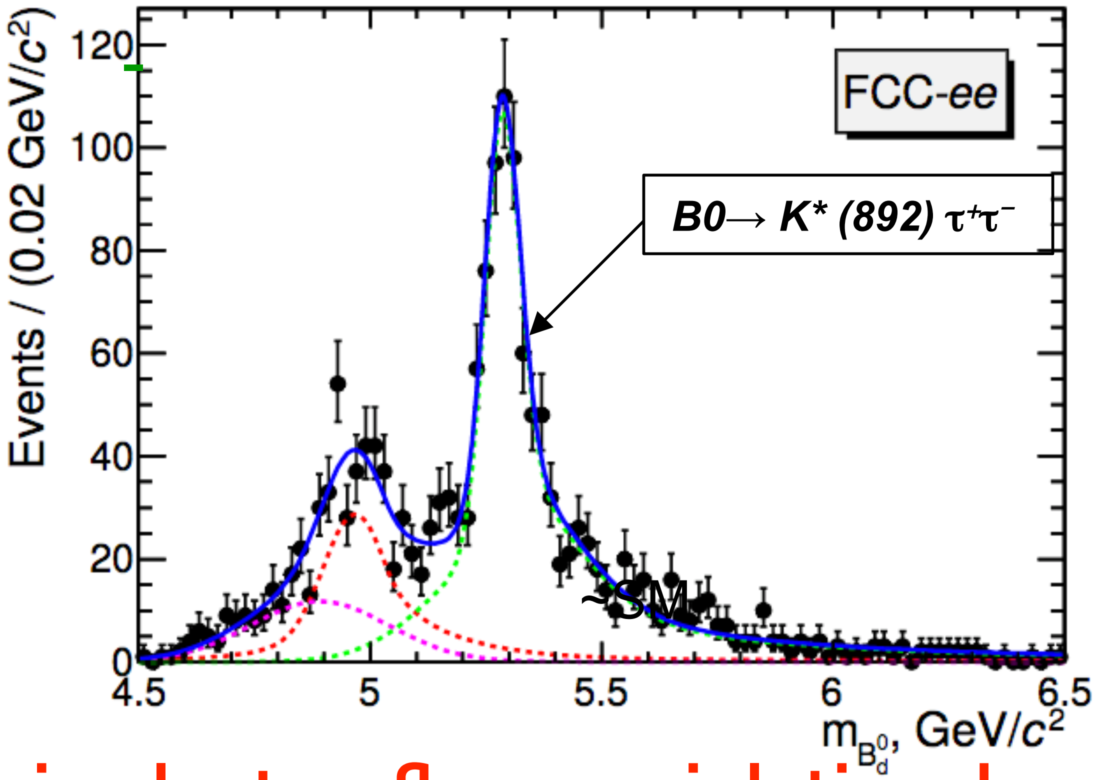

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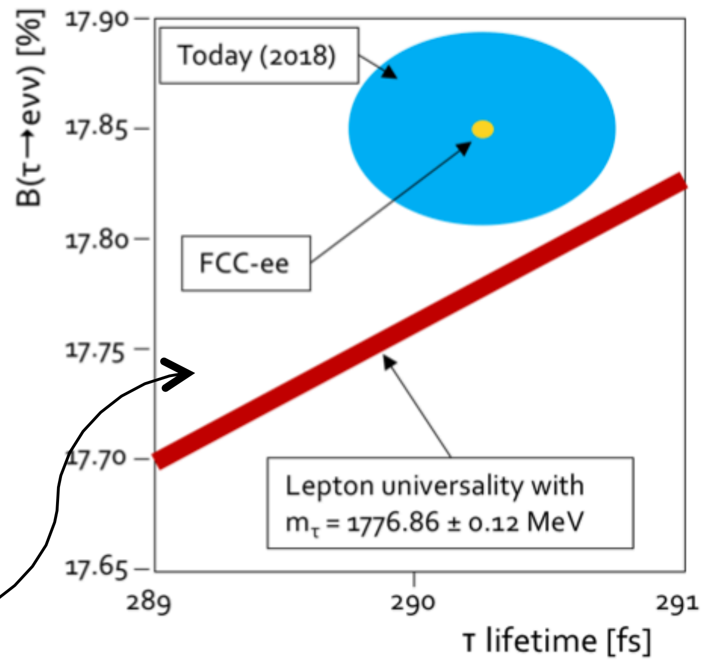

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Z-Factories are also Flavour Factories

See S. Monteil, FCC CDR overview '19

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\overline{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	1000	1000	250	250	1000	500

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu_{mu}$	5%	–	–	3%
$B^+ \to \tau^+\nu_{tau}$	7%	–	–	2%
$B_c^+ \to \tau^+\nu_{tau}$	n/a	–	–	5%
CP / hadronic decays				
$B^0 \to J/\Psi K_S$ ($\sigma_{\sin(2\phi_d)}$)	$\sim 2. * 10^6$ (0.008)	41500 (0.04)	$\sim 0.8 \cdot 10^6$ (0.01)	$\sim 35 \cdot 10^6$ (0.006)
$B_s \to D_s^{\pm}K^{\mp}$	n/a	6000	~ 200000	$\sim 30 \cdot 10^6$
$B_s(B^0) \to J/\Psi\phi$ (σ_{ϕ_s} rad)	n/a	96000 (0.049)	$\sim 2.10^6$ (0.008)	$16 \cdot 10^6$ (0.003)

GW probe of BSM

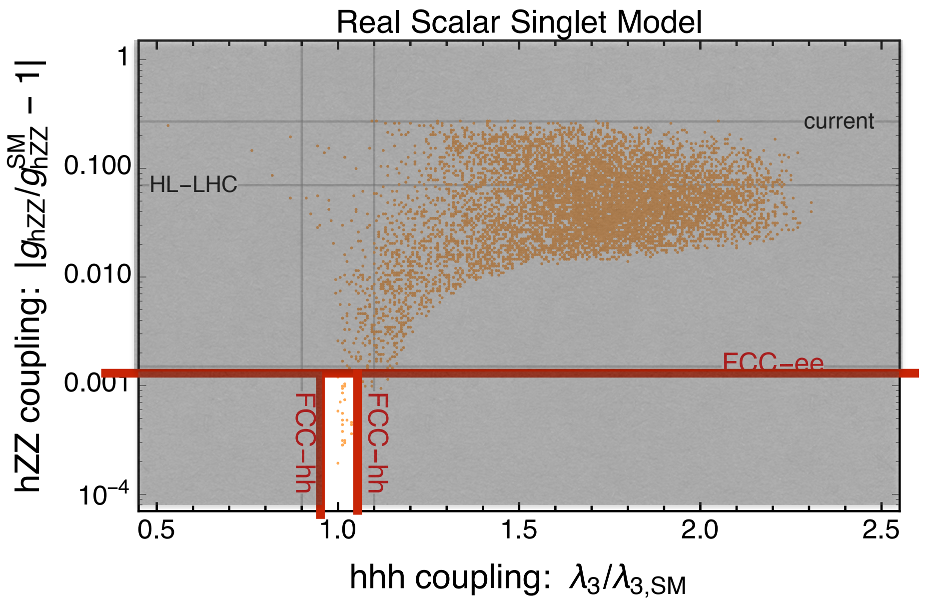
Which GW?

cosmological origin

- inflation/initial quantum fluctuations
- cosmological phase transition
- topological defects

unique information about early universe

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh

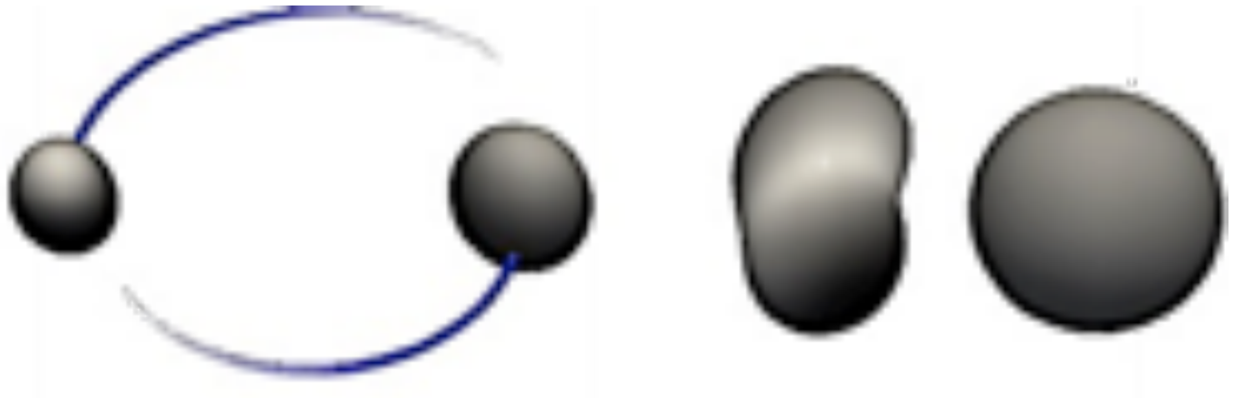


Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

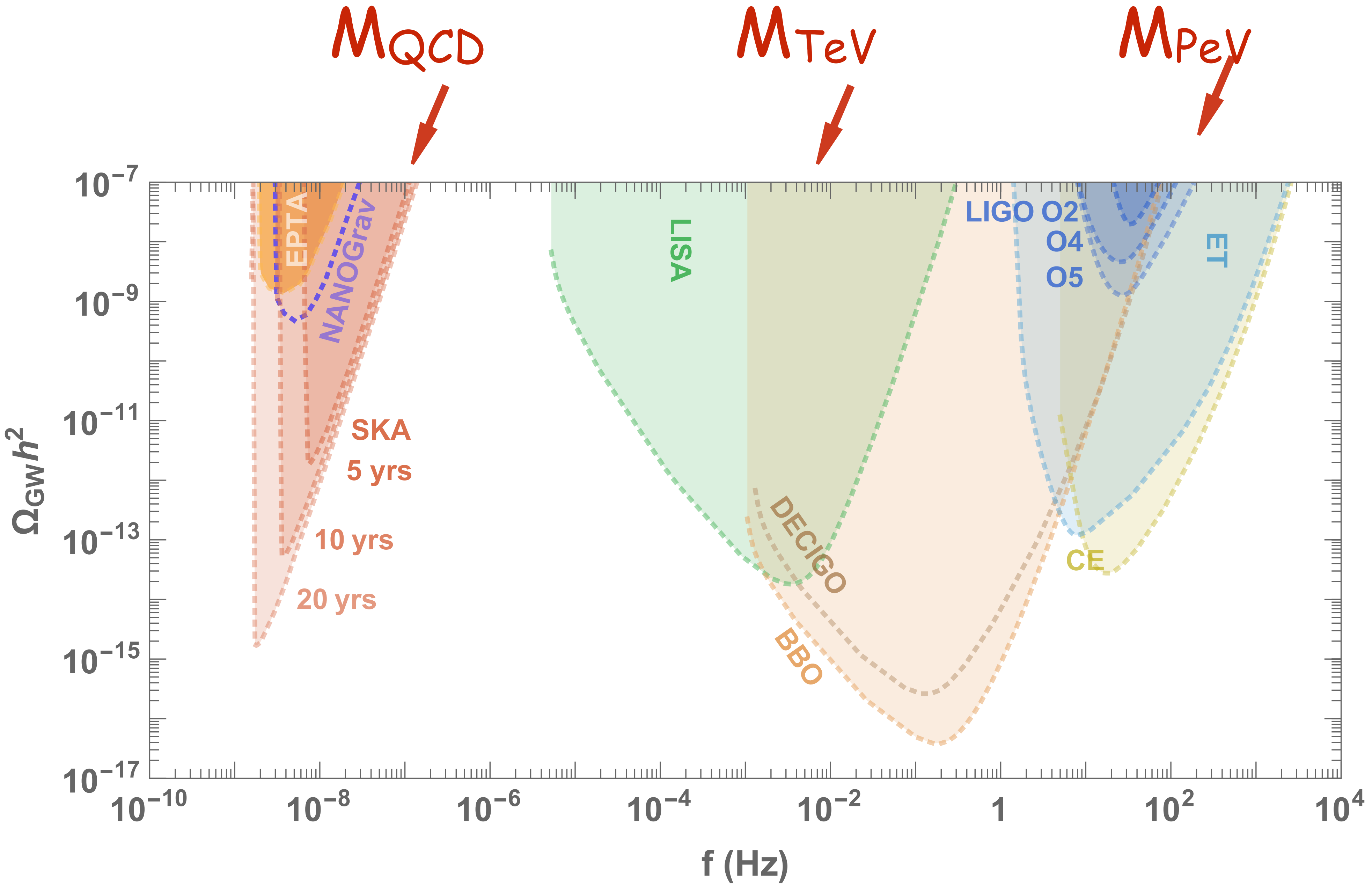
astrophysics origin

- BH/NS mergers
-

unique information strong gravity regime
tests GR



Cosmological GW and Early Universe

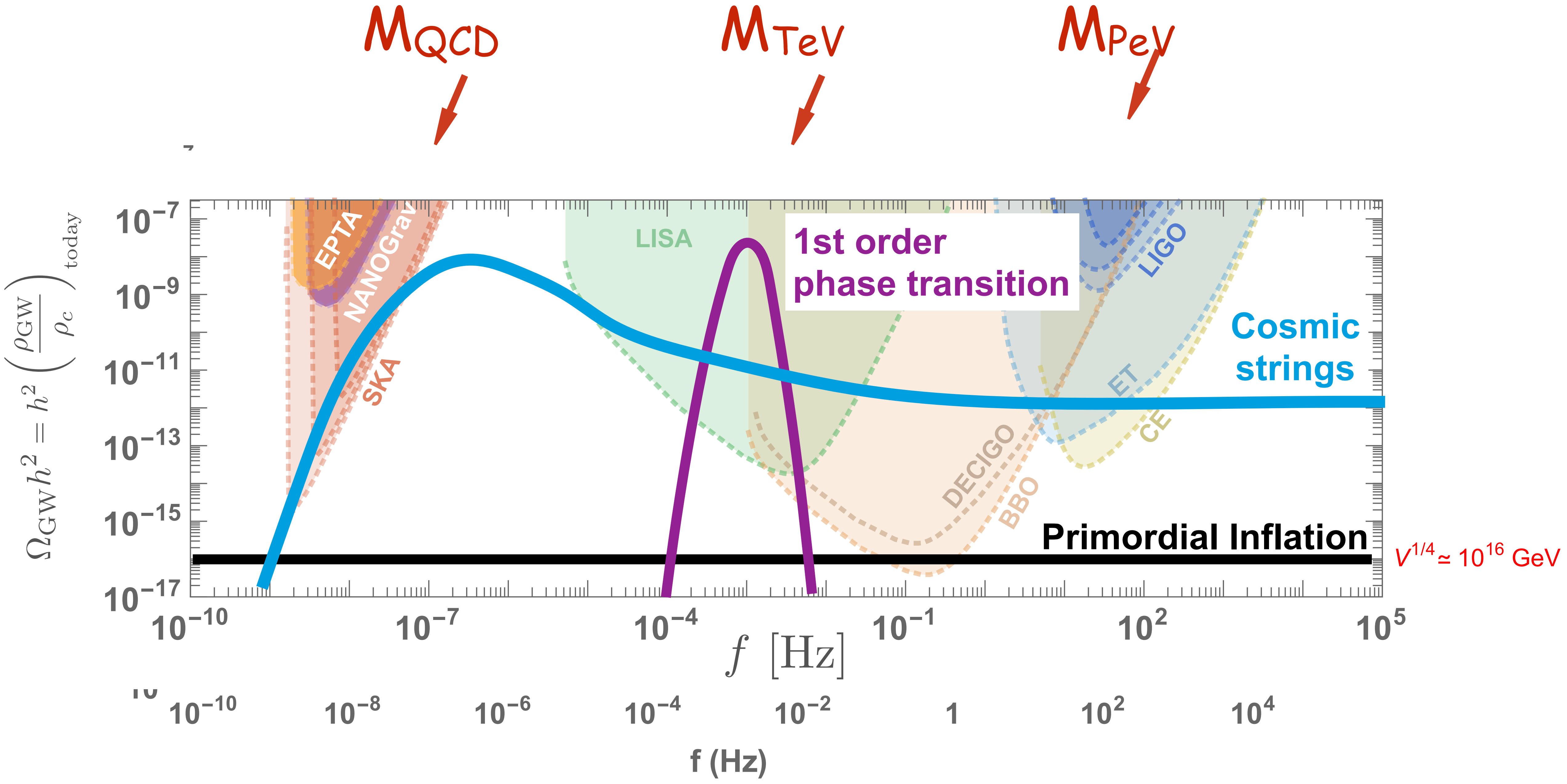


pulsar-timing arrays

space-based interferometers

ground-based interferometers

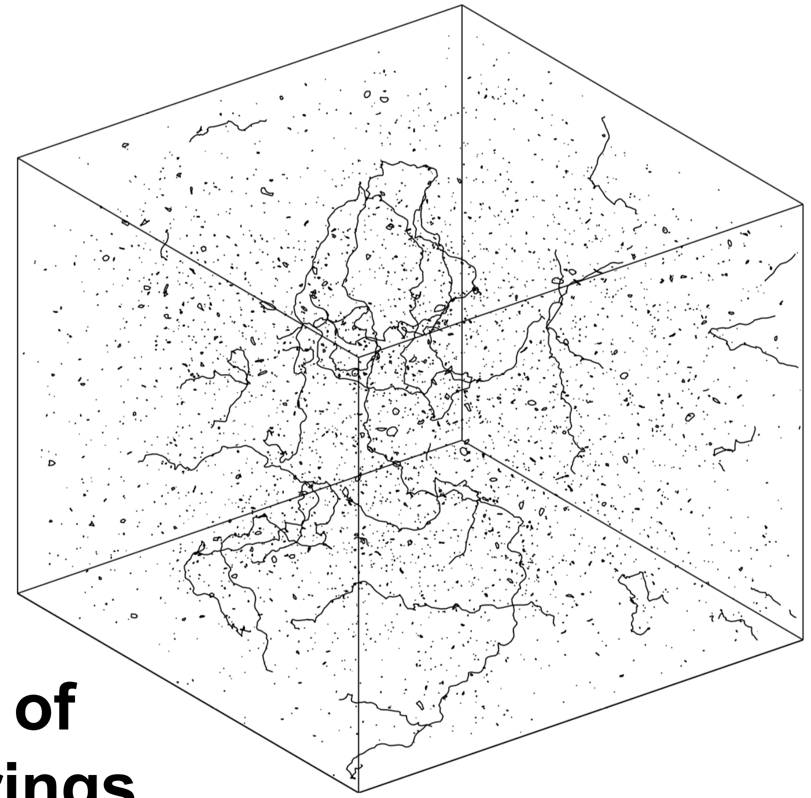
Cosmological GW and Early Universe



pulsar-timing arrays | **space-based interferometers** | **ground-based interferometers**

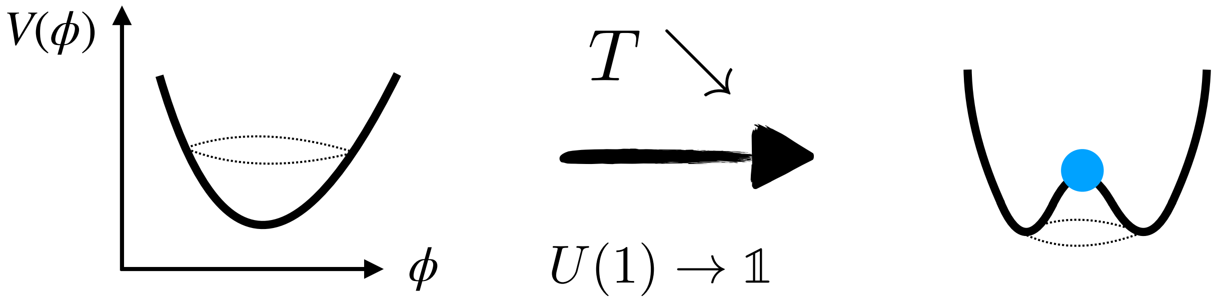
GW from cosmic strings

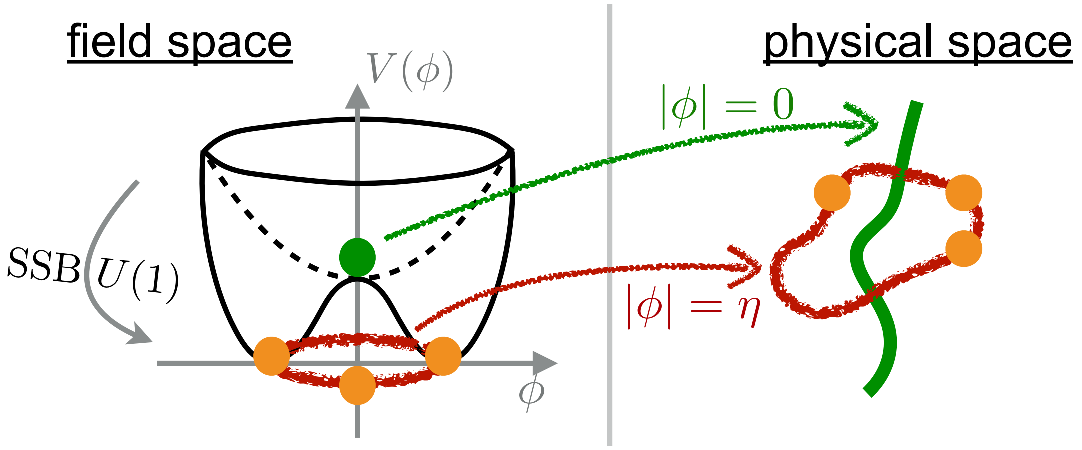
Topological defects generated during a **spontaneous symmetry-breaking phase transition with** $\pi_1(G/H) \neq 1$ [Kibble1976]



Network of cosmic strings

[Allen & Shellard, 1990]





string network acts as a long-lasting GW source
probe the entire cosmic history

…non-standard cosmology, modified equation of state of the universe with respect to radiation domination (early matter or kination eras, secondary short intermediate inflation era…

Astrophysical GW: Tests of GR

∃ inconsistencies between gravity and QM:
e.g. BH information paradox & existence of naked singularities in classical GR

- Recent progress: entanglement entropy and geometry, soft theorems, asymptotic symmetries
- GW propagation and graviton mass (alternative to Dark Energy?)
- GW from BH: imprints in the gravitational waveform → probe of modified GR

- hairy BH in f(R) gravity/Chern-Simons gravity

- quantum modifications on horizon scales for macroscopic BHs: features of the near-horizon region, tidal deformability, and energy dissipation at the horizon characteristic imprints in the gravitational waveforms

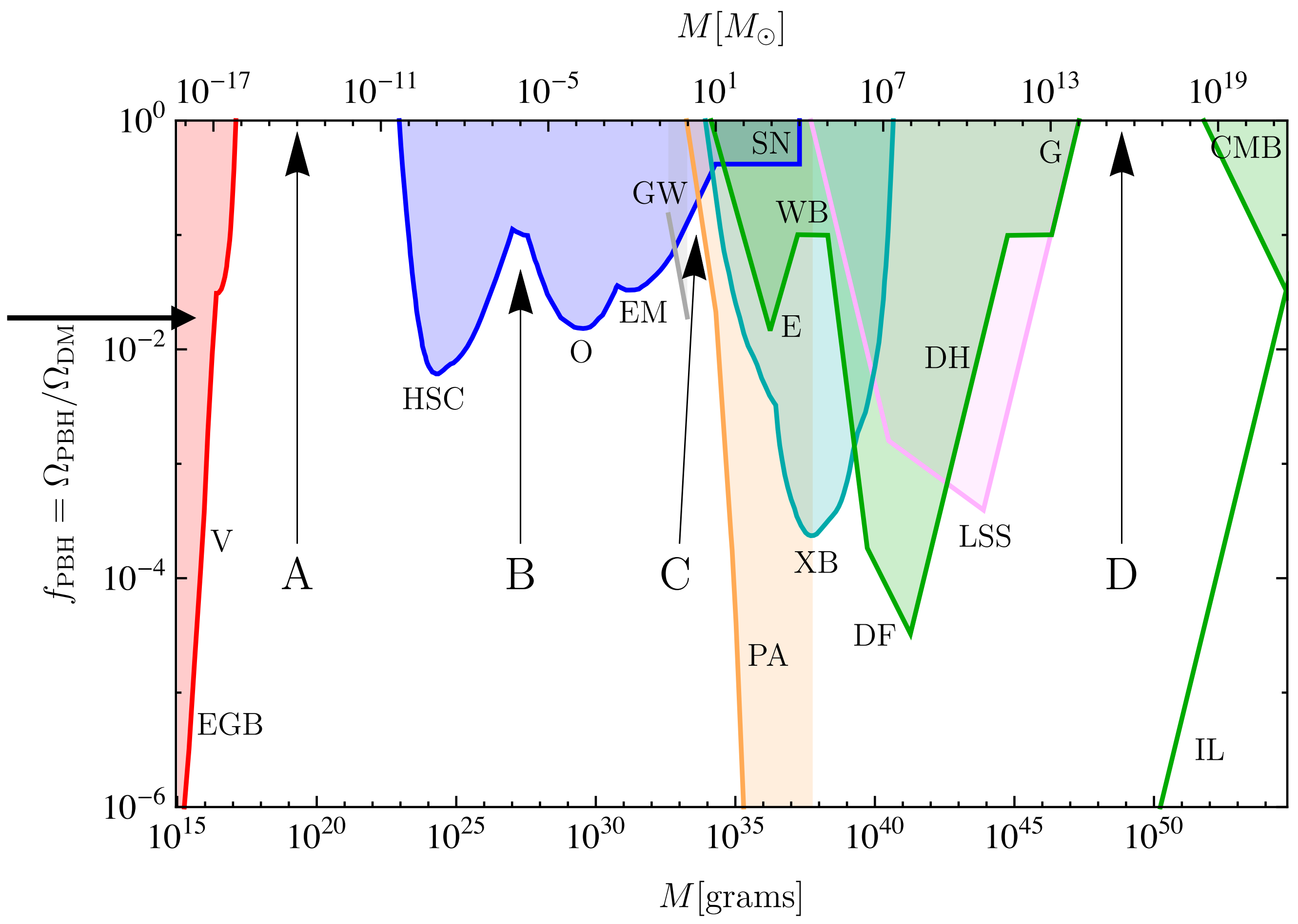
A precise monitoring of the phase of inspiralling binaries can constrain

- equation of states of compact objects (Neutron stars…)
- new additional propagating fields
- local environment (local dark matter density → dynamical friction)

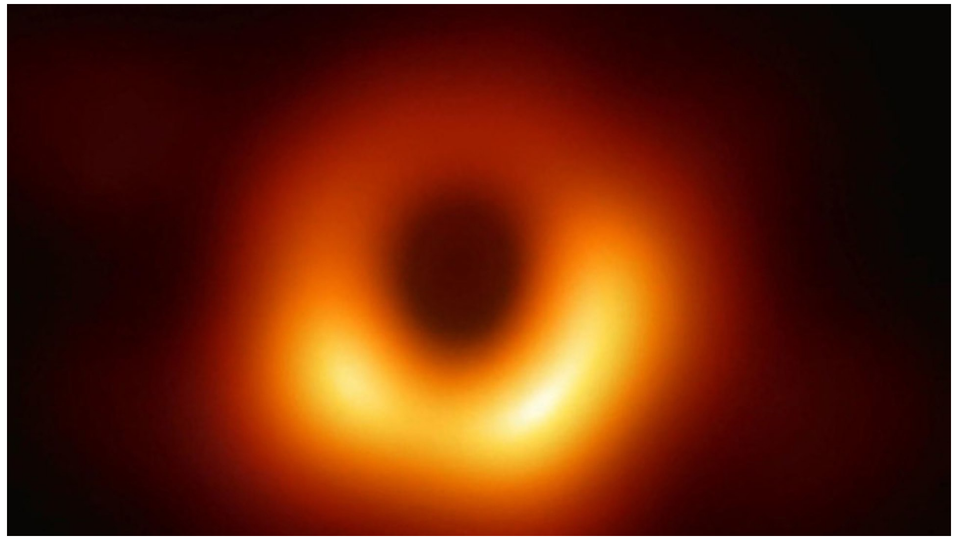
BH and DM

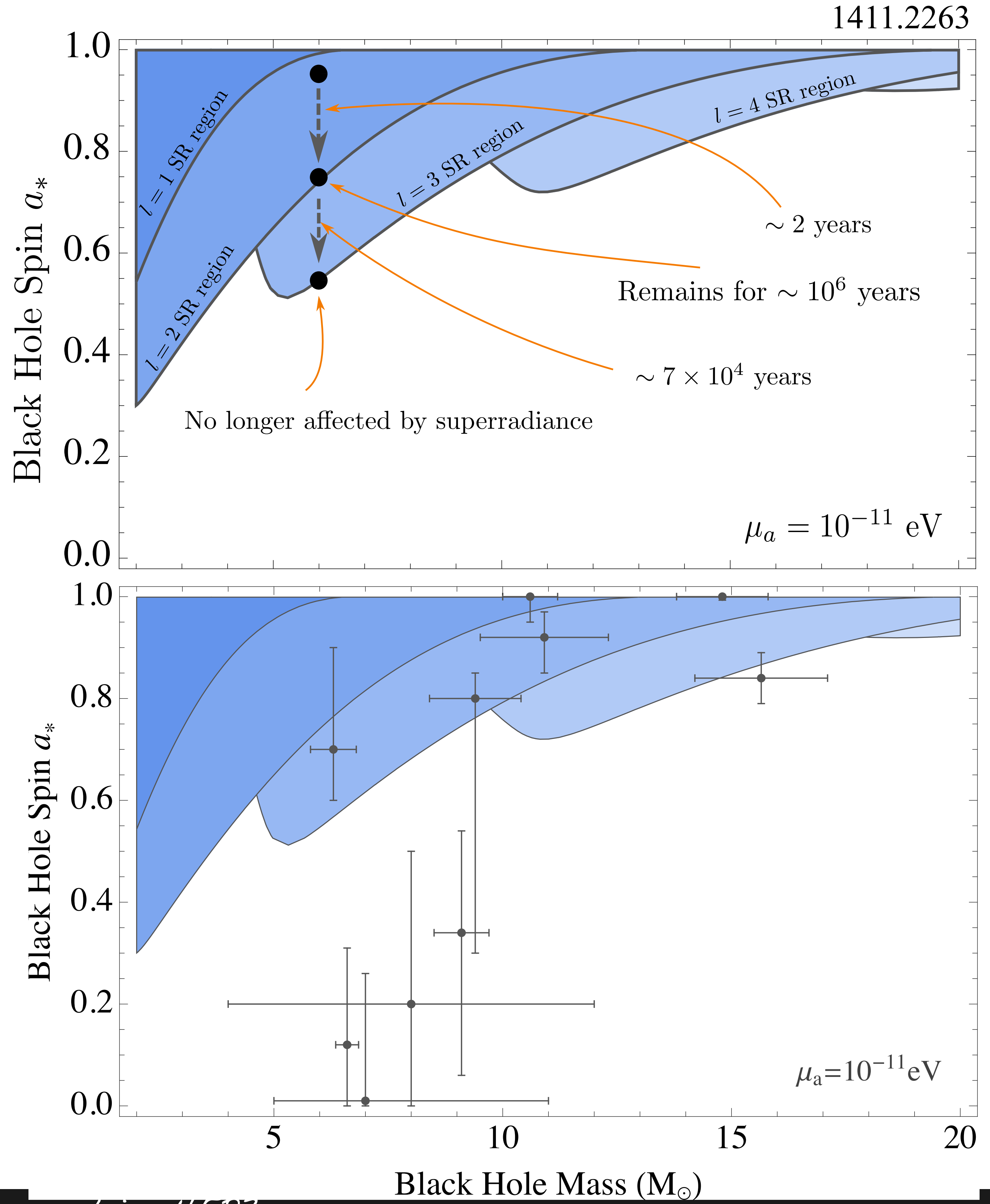
- Gravitational waveforms from BH mergers are sensitive to local environment → use BH to measure local DM density
- Ultra-light particles (axions…) → superradiance (spin distributions of BHs), BH surrounded by "boson" clouds
- primordial BHs as DM

Hawking radiation



Superradiance


Event Horizon Telescope, Astrophys.J. 875 (2019) no.1, L6



BH mass vs. spin

BH spin distribution can probe the existence of very light scalars

Conclusions

We don't know what BSM is! So we should keep searching:

" Looking and not finding is different than not looking! "

There is a vigorous experimental program on a vast range of energy scales.

It will surely guide us to a new understanding of nature.

LHC turned out to be a very diverse machine exploring many different fronts in a correlated way.

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LHC turned out to be a very diverse machine exploring many different fronts in a correlated way.

Data always brings new understanding.
We need facts and data: Physics is a natural science!
We have profound questions and we need create opportunities to answer them.