MANCHESTER 1824
The University of Manchester

New directions for BSM searches at HL-LHC (with a special view to dark matter)

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European Research Council
Established by the European Commission

Outline

- Quick introduction to HL-LHC and its experiments
- Generic BSM searches
- Model-specific BSM searches
- Synergies with complementary experiments
- Conclusions

Disclaimer: This is not a summary talk on all HL-LHC BSM physics (see this document instead for a summary), but rather a few "new directions" ideas with examples

Sources: Much of the material comes from the inputs to the prioritisation to US particle physics panel P5, (Snowmass process), **all proceedings** can be found here.
Other useful sources:

Snowmass contribution from ATLAS/CMS on BSM at HL-LHC HL-LHC review, O. Bruning, H. Gray et al.

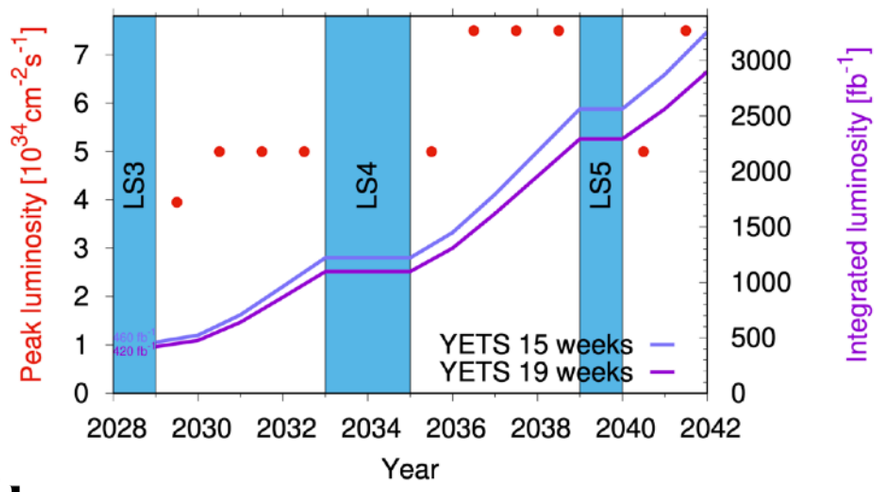
Snowmass Energy Frontier report Snowmass BSM report HL-LHC Yellow report for BSM

HL-LHC and its experiments

The collider

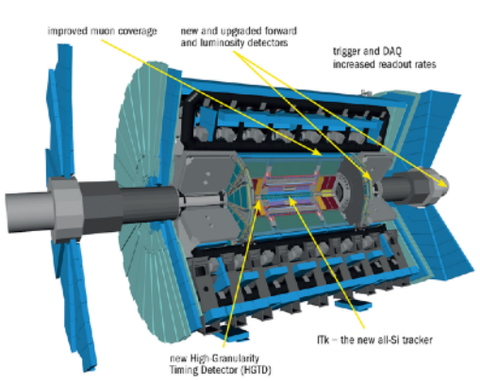
HL-LHC Technical Design Report

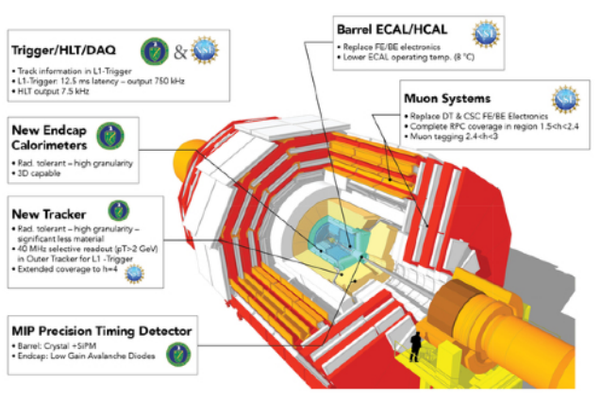
- 14 TeV center-of-mass energy
- Design integrated luminosity (∝ dataset size)
  - 3000/fb for ATLAS/CMS
  - 300/fb for LHCb (due to beam optics)
- Increase in dataset size → up to 200 simultaneous collisions (**pile-up**)

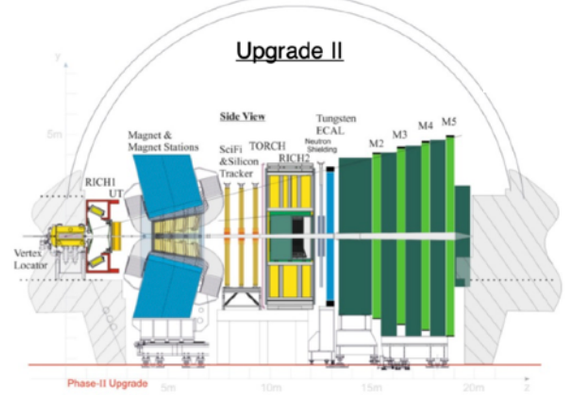


The main experiments in this talk

click on the experiment for more info on upgrades







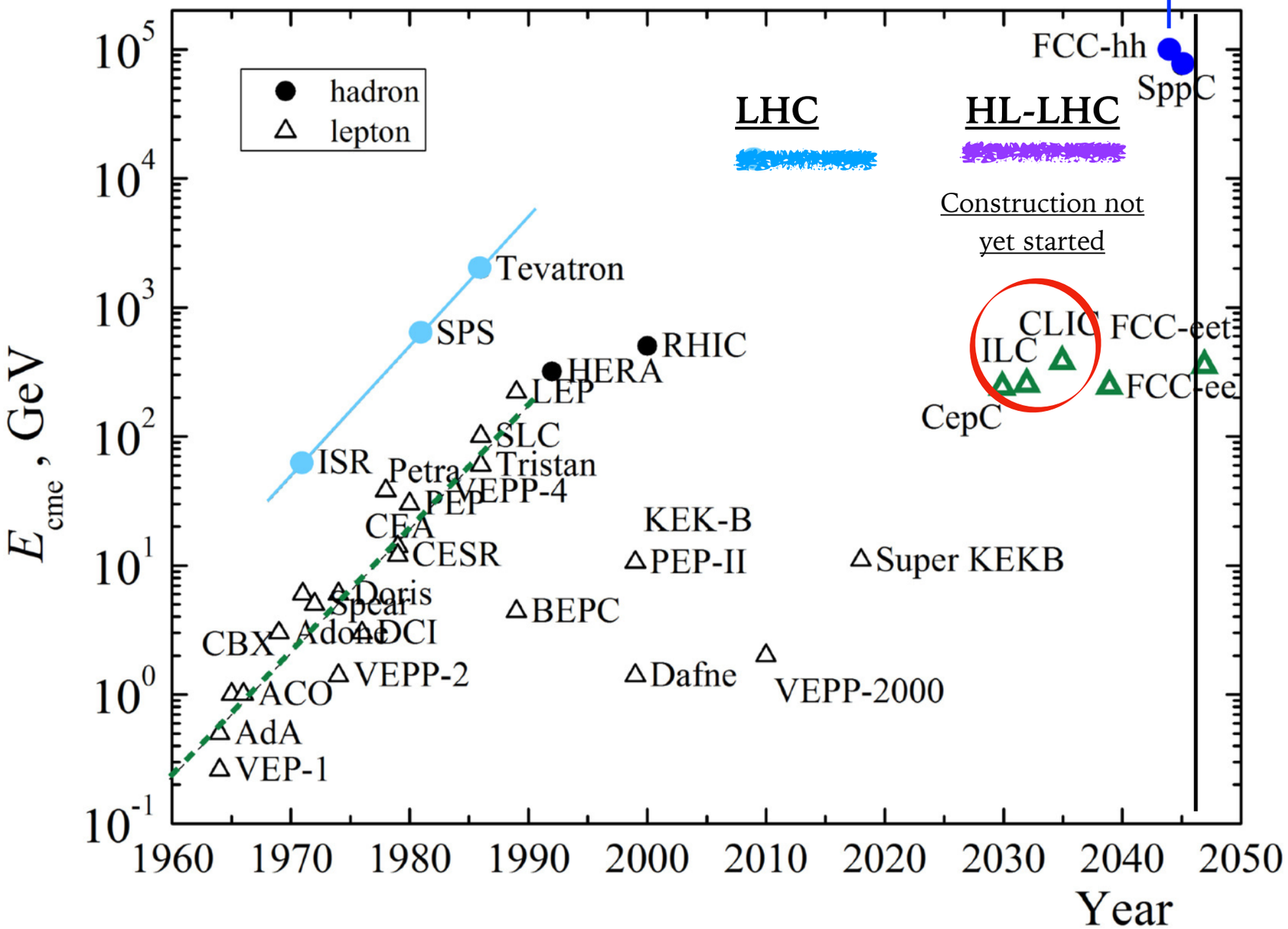
- Major upgrades for all experiments mentioned here:
  - Higher-bandwidth/rate **data acquisition/selection** (DAQ/trigger)
  - More performant **tracking detectors**
  - New **timing detectors** with picosecond precision

needed to **cope with pile-up** conditions
but also
provide **new opportunities** for BSM searches

The collider landscape

- See P. Azzi's talk later for more about FCC

H. Gray, Reviews in Physics 6 (2021) 100053

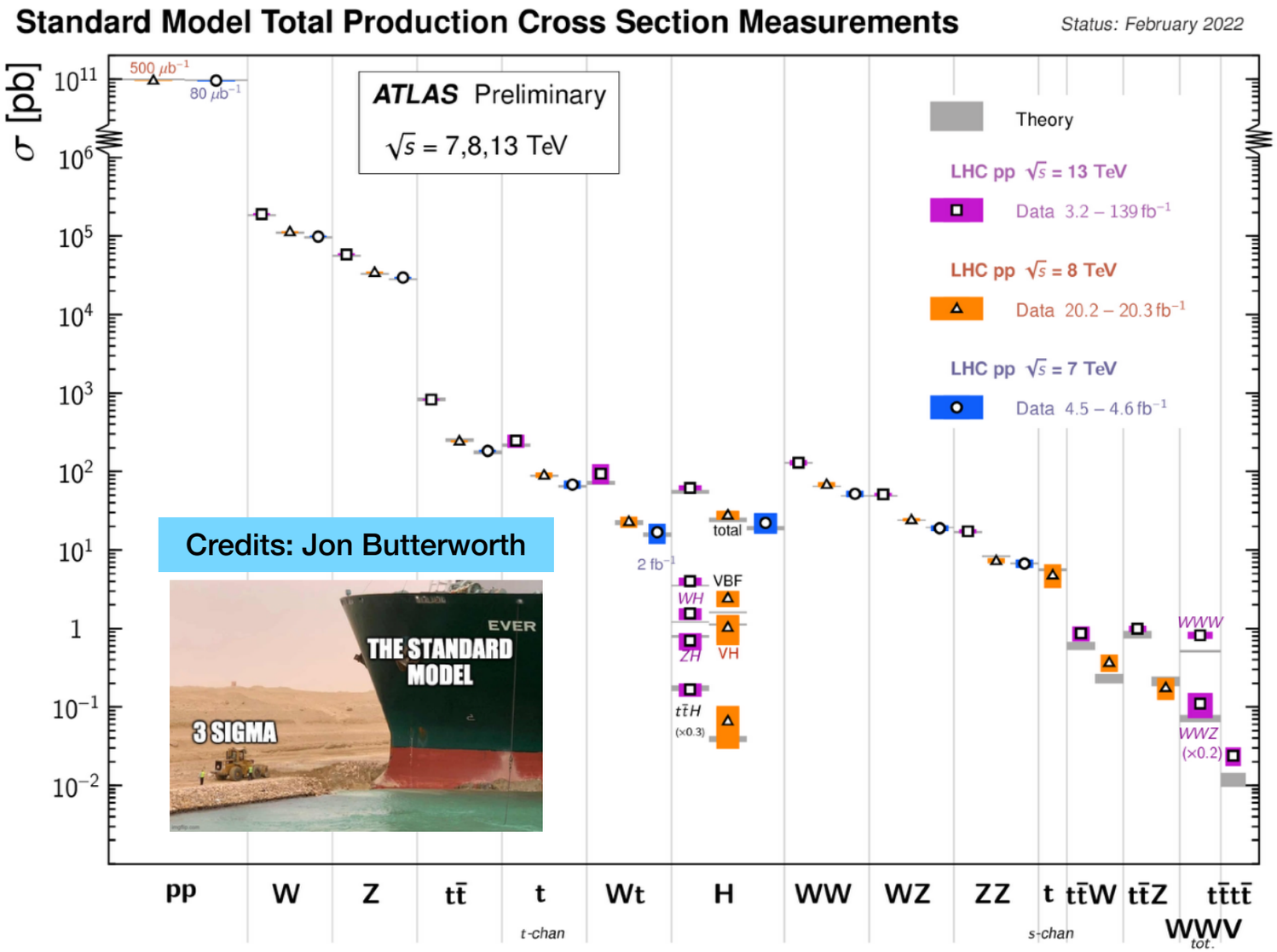


- HL-LHC: only **high-energy collider** that will be **taking data in the next decade**

Further considerations relevant for BSM/DM searches:

- **Different regime** wrt early **LHC** data taking: accumulating / analysing data will take **longer** and will be more challenging
- However: we already did **many innovative searches** at the **LHC** (see J. Berlingen's talk today) → expect surprises

The physics landscape

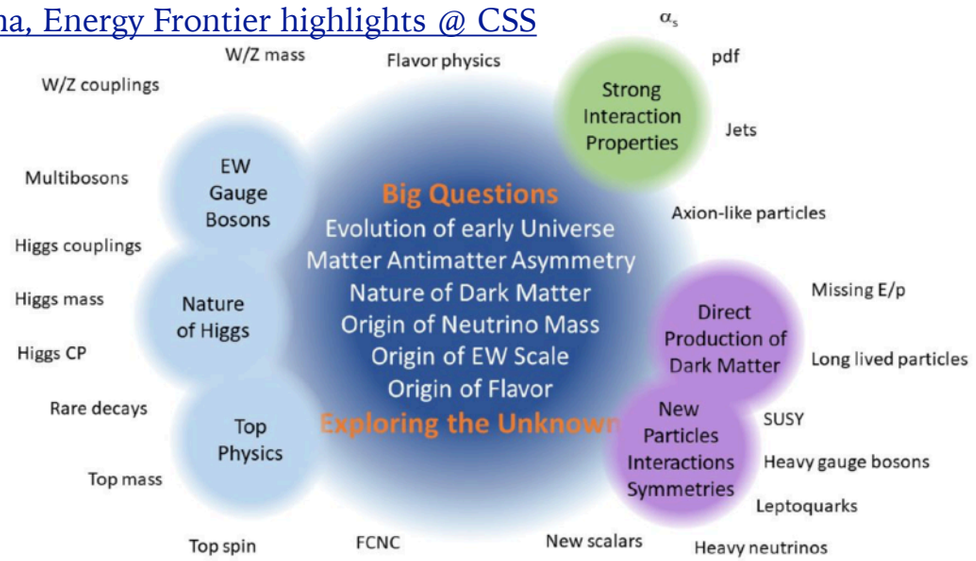


Very different situation with respect to LHC restart in 2010
when all eyes were on the Higgs and on early TeV scale (SUSY?) discoveries

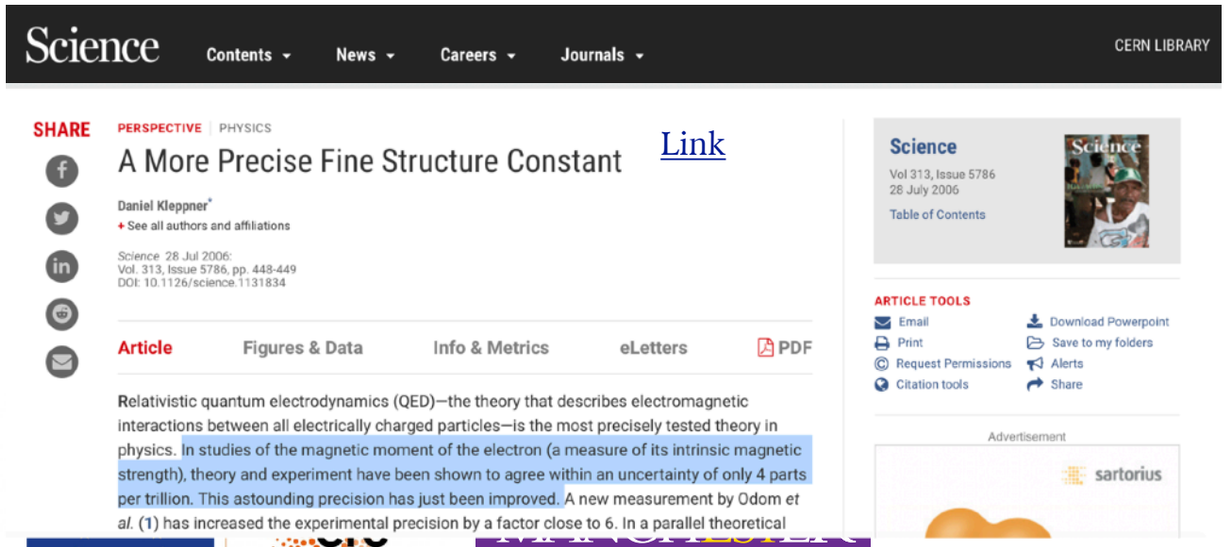
So, why keep measuring & looking for new physics?

Reason #1: to answer open questions in our universe

L. Reina, Energy Frontier highlights @ CSS



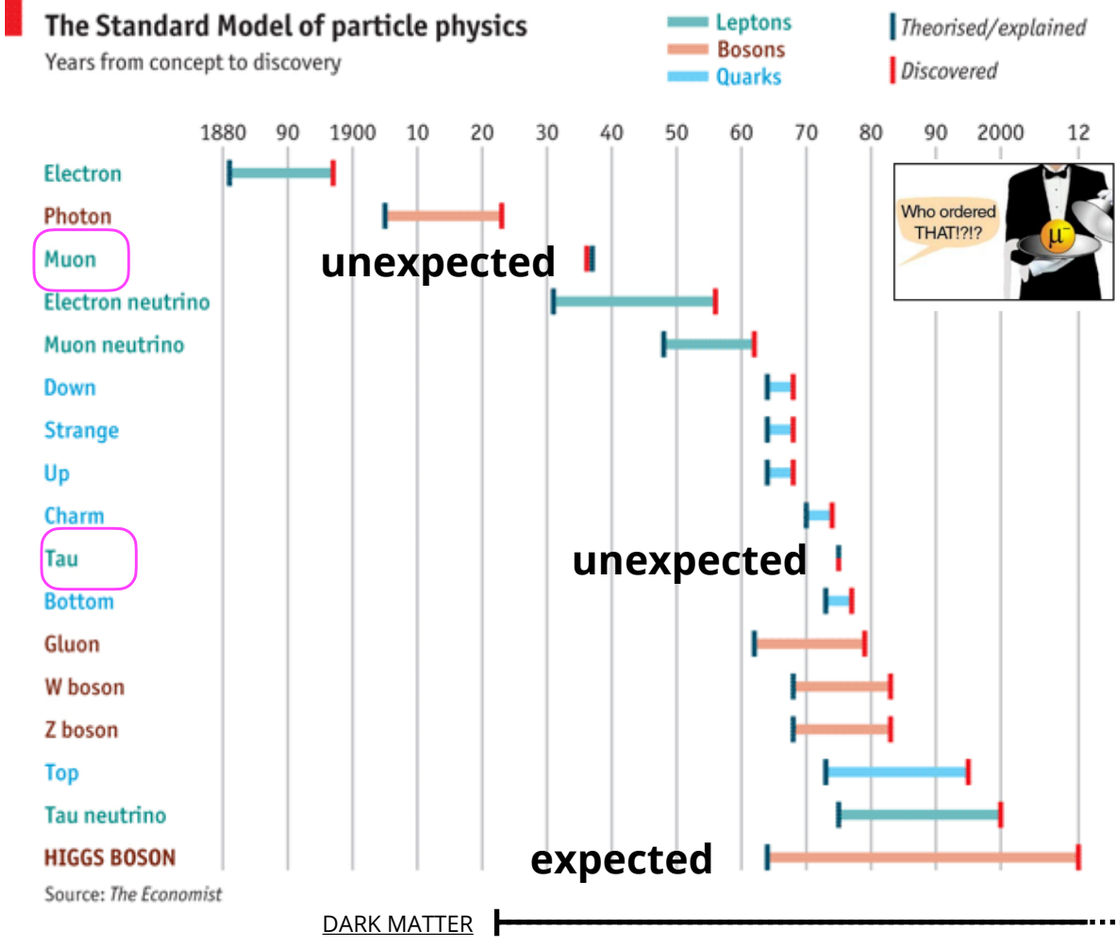
Reason #2: extending our understanding



Link

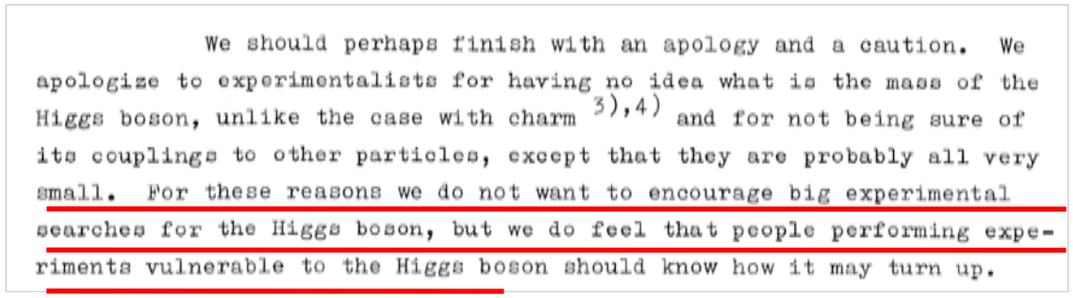
Reason #3: unexpected discoveries

The Economist



[Historical] reason #4: stubbornness

https://cds.cern.ch/record/874049



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Do we need any problems of the SM to look for BSM?

The SM has no problems (according to LHC measurements so far)!

- Measurements so far agree with theory

✅Energy frontier => direct exploration of the unknown

"Generic" ***direct search strategies***:

look for (sizeable) deviations signalling the presence of new particles

Example of bread-and-butter (is this really true?) search:

look for "BSM portal particles" decaying into SM particles

❌Energy frontier => it'll be a while before a big increase in center of mass energy

Indirect search strategies:

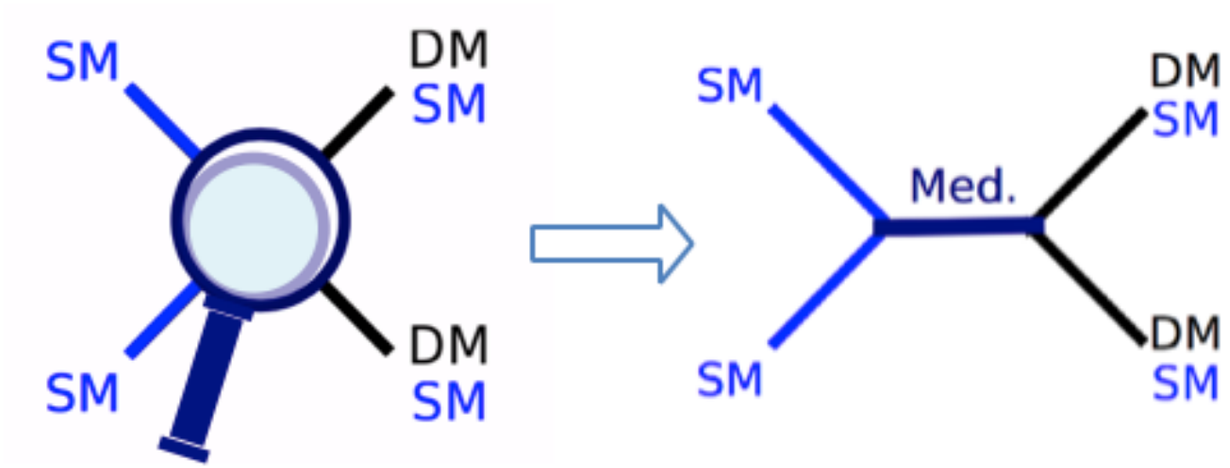
look for (small) deviations from the presence of new particles in loops

Examples: flavour physics at present/future colliders & B-factories

(leaving this to later talks, e.g. D. Redigolo's talk, today's Belle-II talks…)

So, why are *portals* interesting as generic benchmarks?

If there's a new force, there's a **mediator/portal** particle,



Examples: *Simplified dark matter models* (see Phys. Dark Univ. 26 (2019) 100371 & references within) and *dark sector portals* (see e.g. this talk by B. Batell) are popular LHC benchmarks

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If there's a new force, there's a **mediator/portal** particle,
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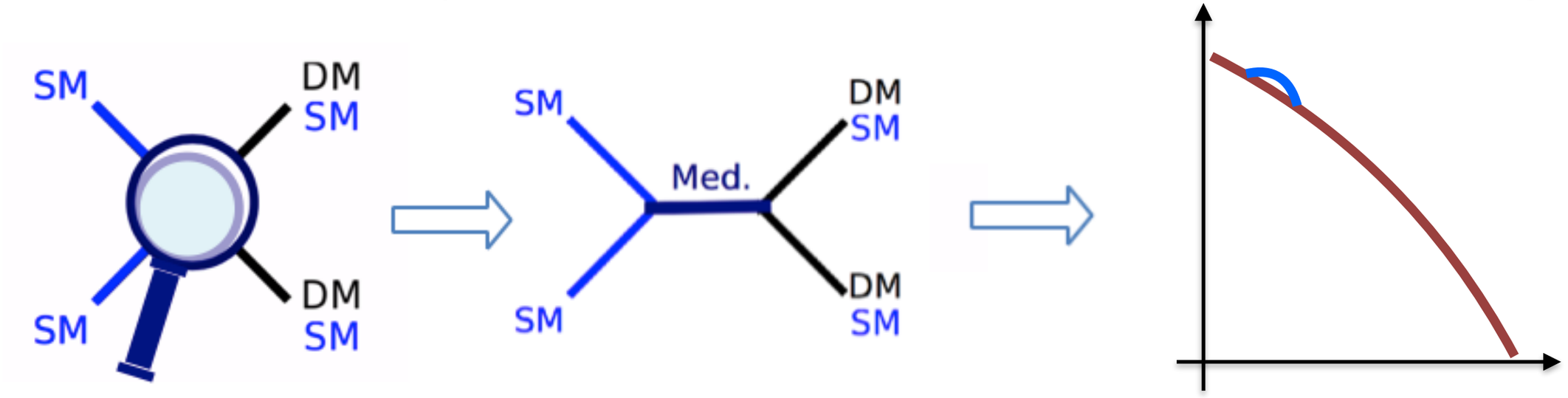

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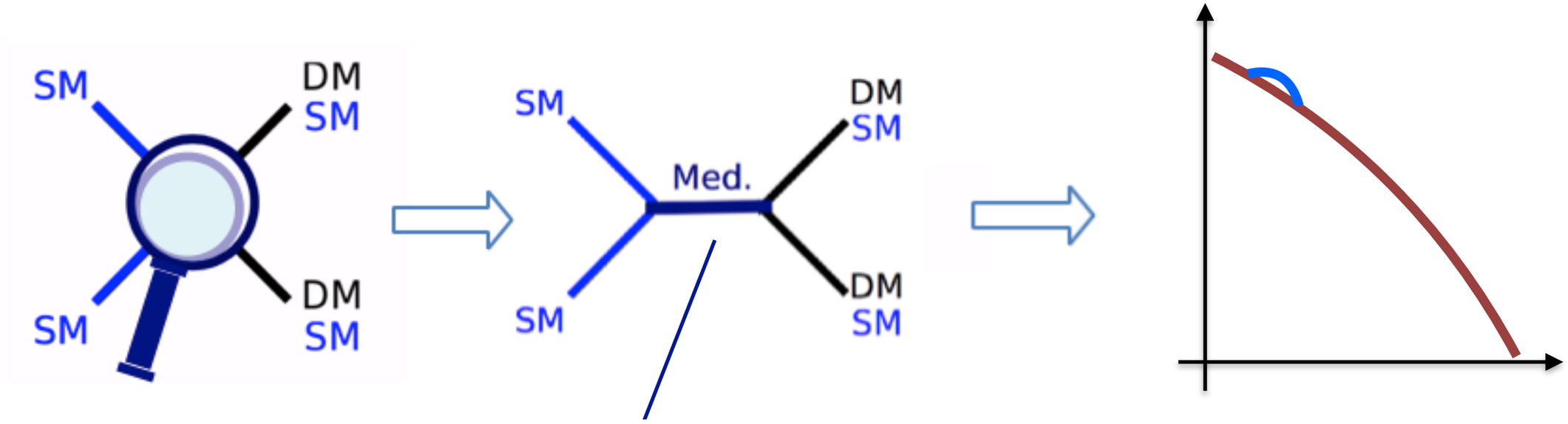

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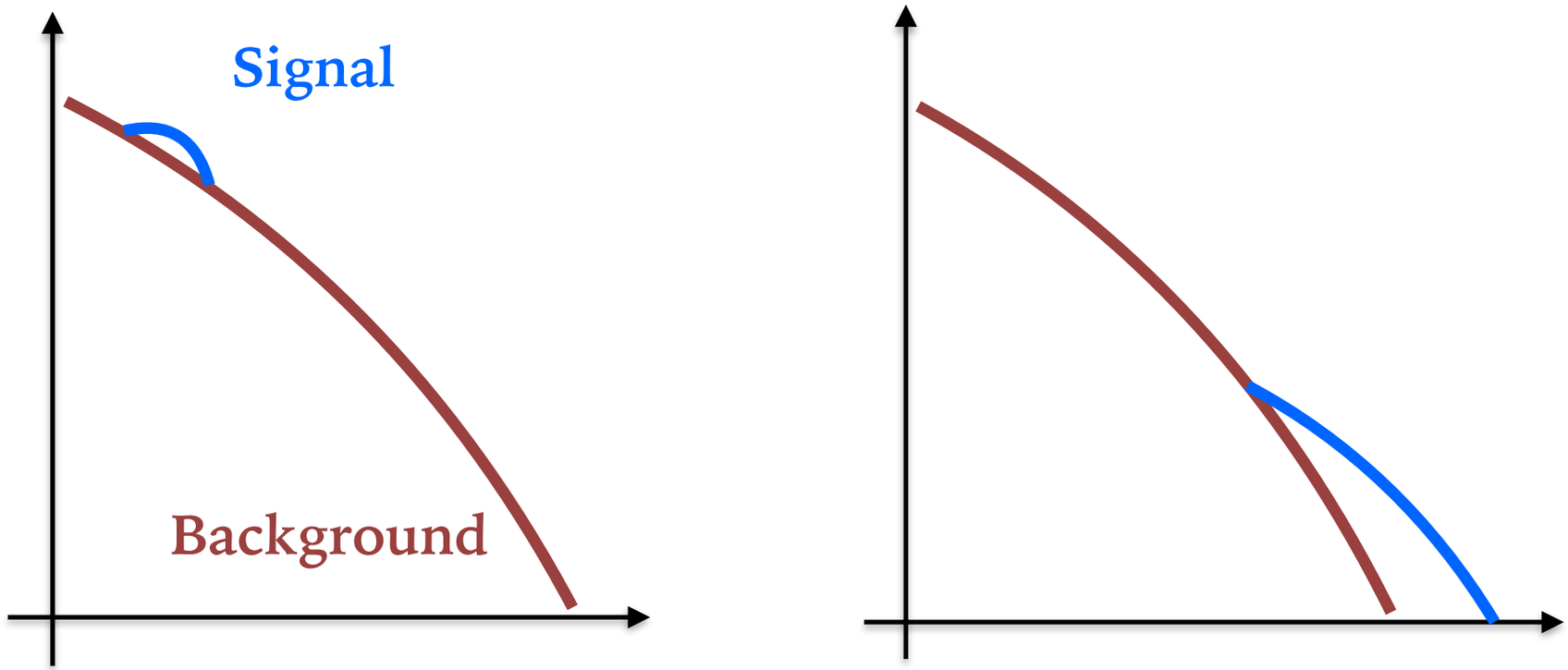
Searches for resonances can be used to **find hints of dark sectors**

Need other experiments to confirm the rest of the content of the dark sector
(e.g. DM candidates, see later)

"Direct" collider manifestation of new phenomena



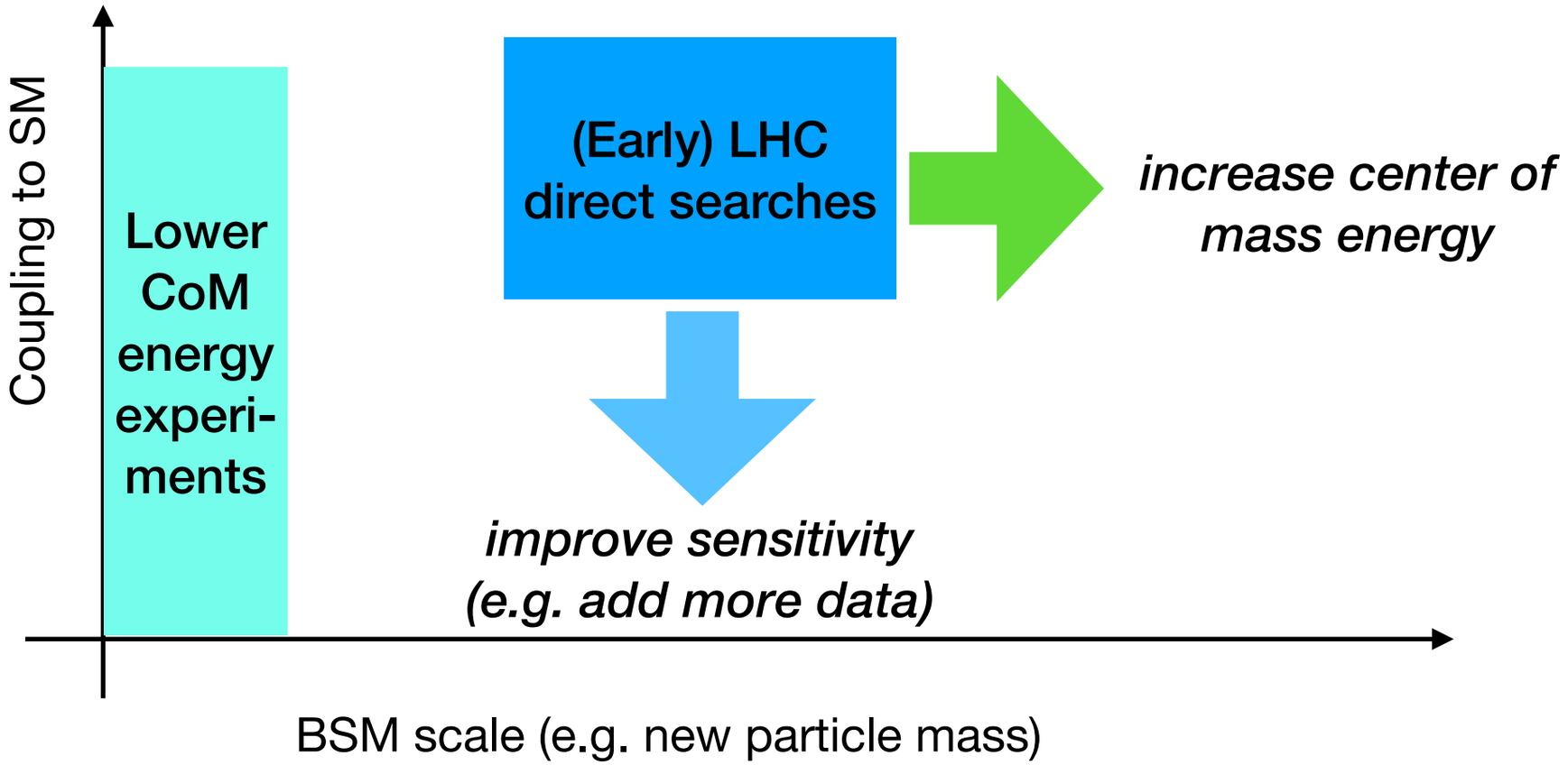
These are just **examples** of distributions
analysed in searches at ATLAS and CMS (LHC and HL-LHC)

Ingredients: data, background prediction, statistical analysis

...will focus on the first two for HL-LHC searches,
but the third one is not trivial either:

How can the HL-LHC help with portal searches?

Caution: very simplified sketch, somewhat restricted to direct searches & hadronic final states



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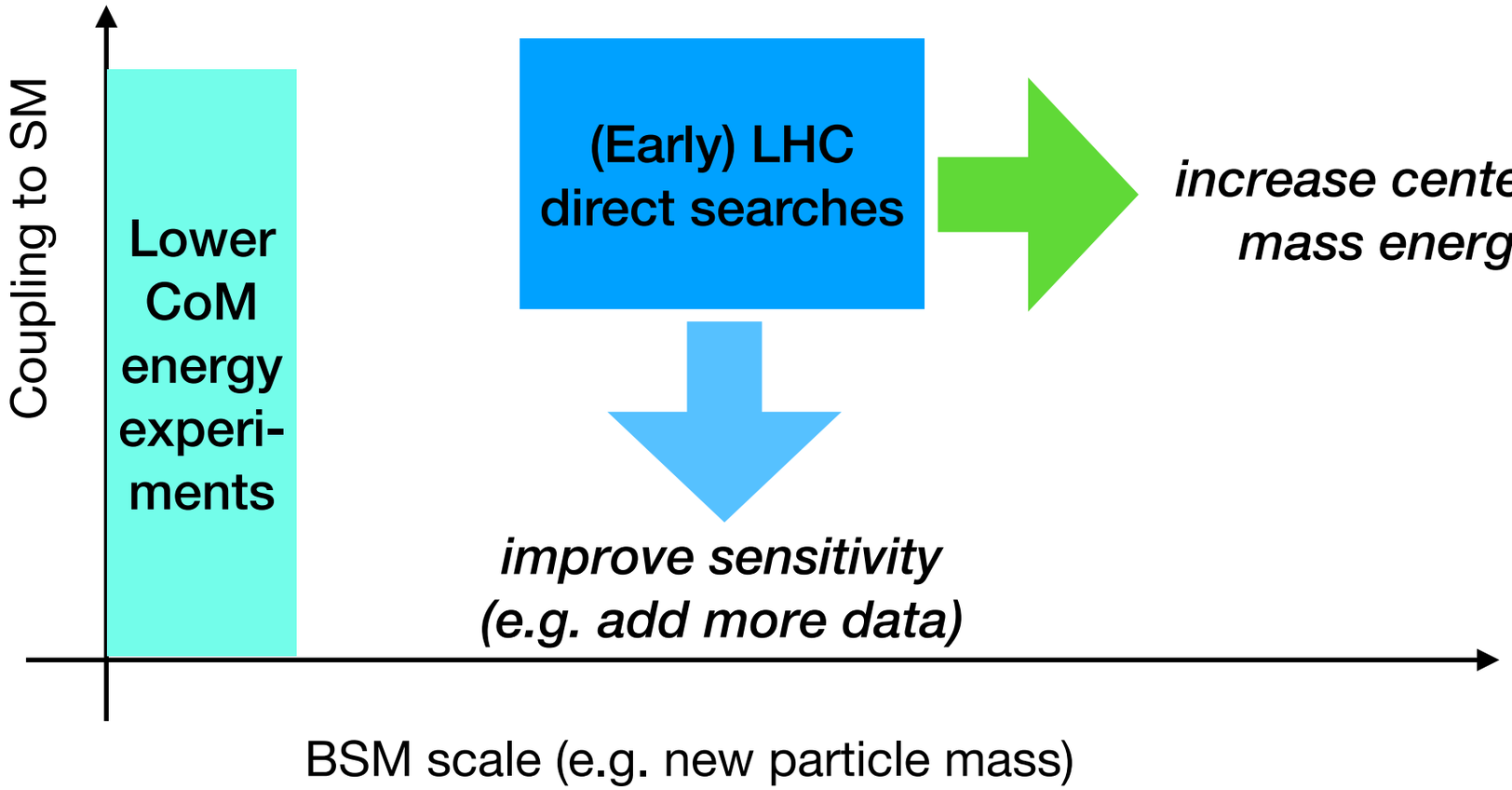

Without changing the state of the art,
we can upgrade to **more powerful** colliders
and let them **run for longer**

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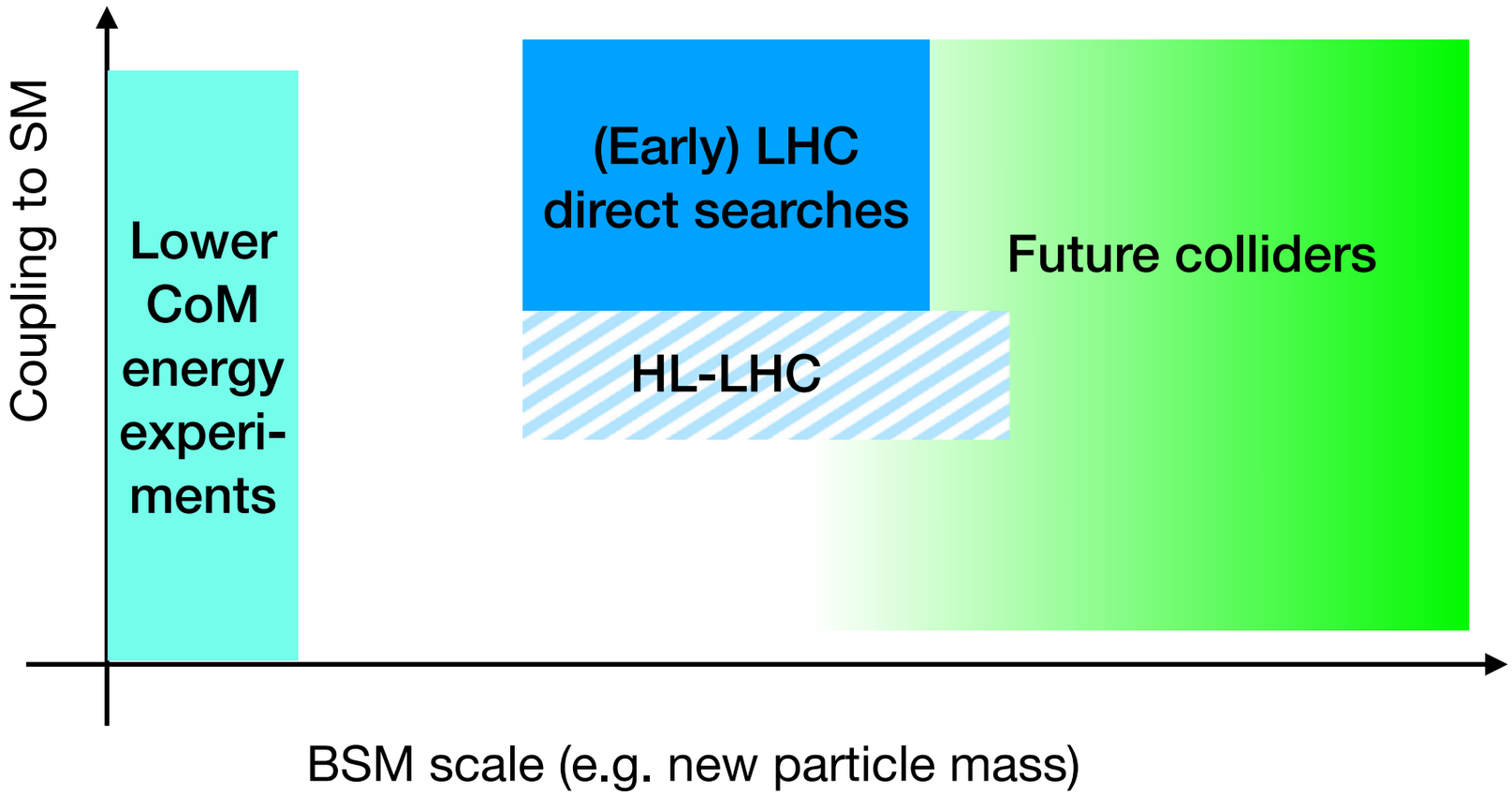

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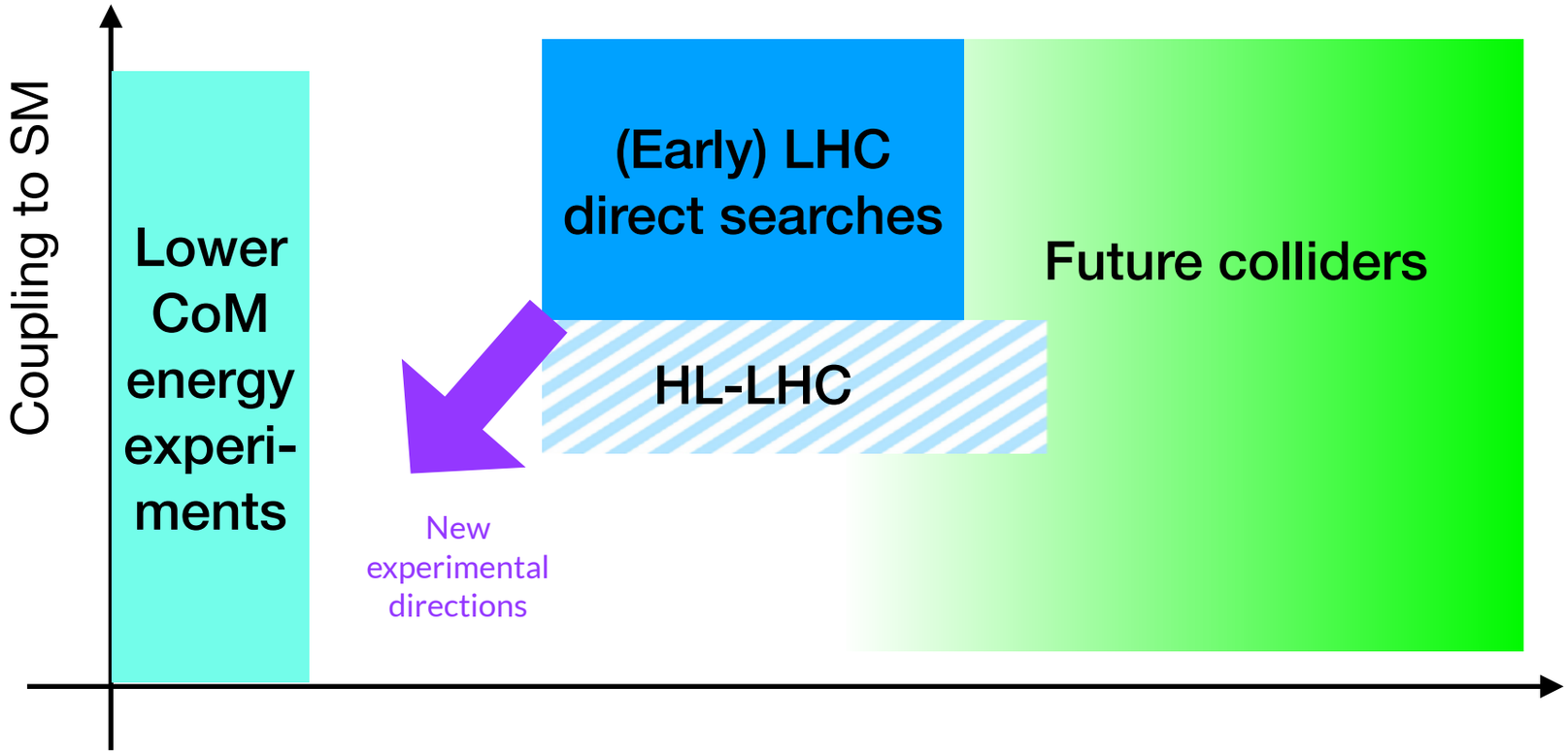
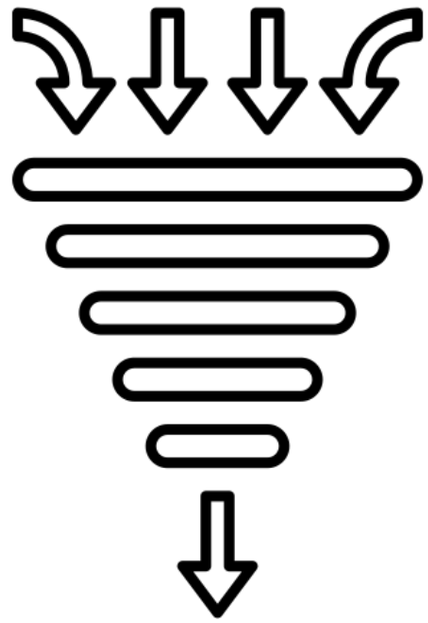


New experimental directions needed to reach lower couplings

In particular, much unexplored parameter space at lower energy scales creating "gap" between LEP + lower-energy experiments and LHC

Where can we gain in HL-LHC portal particle searches (& more)?

By using ways that **preserve signal**
in presence of **high-rate backgrounds**



- Take advantage of **upgrades** of the real-time selection (**trigger**) systems, e.g. by:
  - Applying *more targeted selections*, earlier on
  - Use *non-standard data-taking techniques*,
    e.g. saving less information but more collision events

images: Flaticon.com

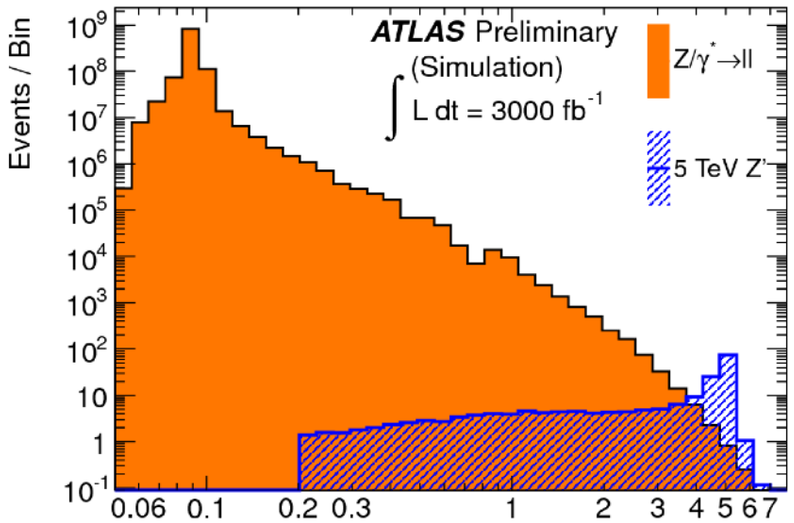
By targeting **unexplored signatures** with upgraded detectors

- Example: **long-lived particles** from portal particle decays
  - Long lifetime due to a variety of dark/secluded reasons (e.g. small couplings, virtual intermediate states, small mass splitting…)

By using **anomaly detection**, see J. Curran's talk today

New gauge boson (Z') direct searches

Example spectrum from: ATL-PHYS-PUB-2013-003

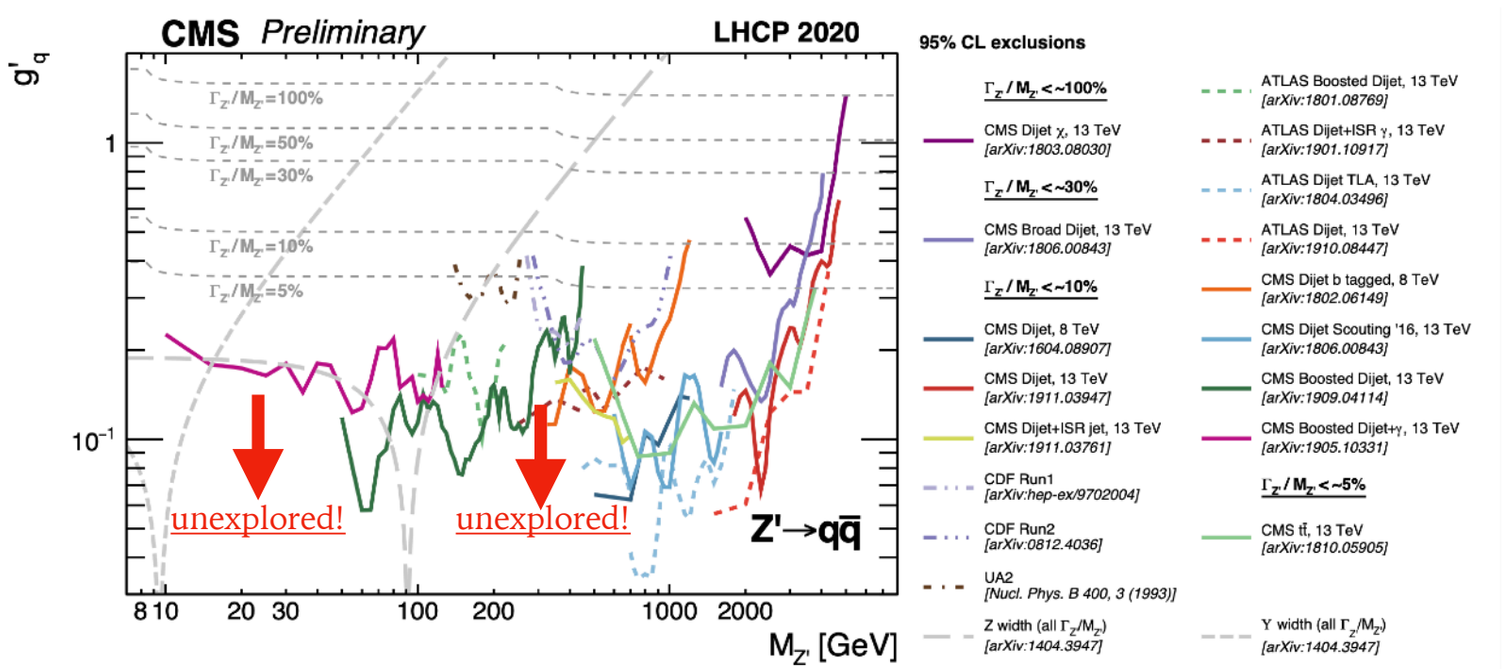


Current LHC constraints: ~3.5 TeV

arXiv: 2202.03389 [R. H.]
Snowmass BSM report

Machine	Type	√s (TeV)	∫L dt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \to l^+ l^-$	6.3	6.8
				EPPSU*	$Z'_{Univ}(g_Z'=0.2)$	--	6

Z' decaying to quarks: much unexplored phase space at the electroweak scale



Backgrounds are too high to be saved on disk, discard them + signal → sensitivity lost!

Solution: perform the analysis **in real-time** as close as possible to the detector (and avoid saving raw data)

Real-time analysis in place for all experiments, developments for Run-3 and HL-LHC expected

Displaced dark boson (*dark photon*) decays

Physics case for an LHCb Upgrade II, arXiv:1808.08865

A′: dark photon

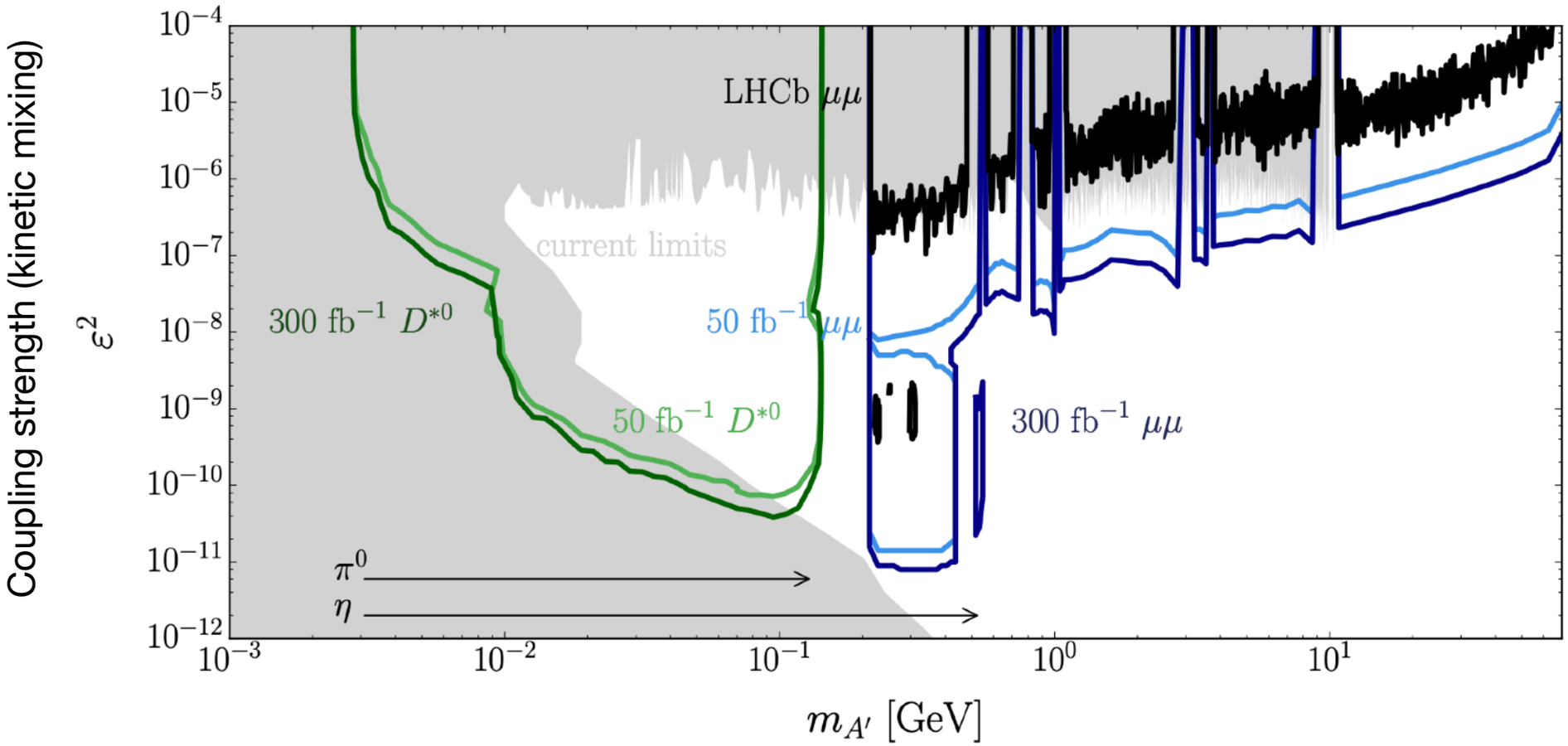
$$A' \to \mu^+\mu^-$$

$$D^{*0} \to D^0 A', \quad A' \to e^+e^-$$

$$\pi^0 \to e^+e^-\gamma \text{ and } \eta \to e^+e^-\gamma \text{ (arrows)}$$

LHCb search combines two "new directions" from S16:

- **real-time analysis** on *triggerless readout* (take data at LHC rates), already in Run-3 / Upgrade 1
- **new functionalities of tracking detectors** to detect and identify displaced leptons

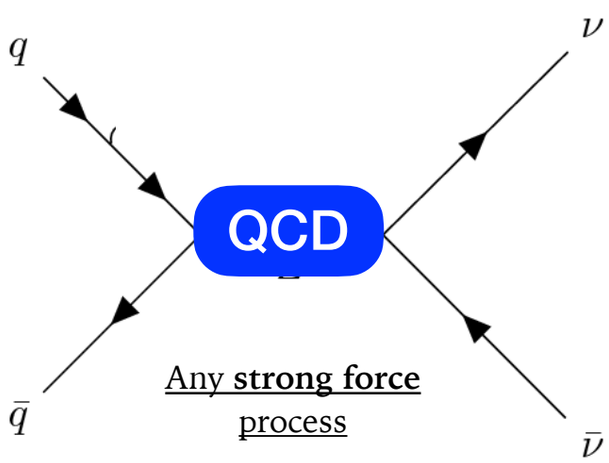


Dark photon mass

Back to portals: visible and invisible searches

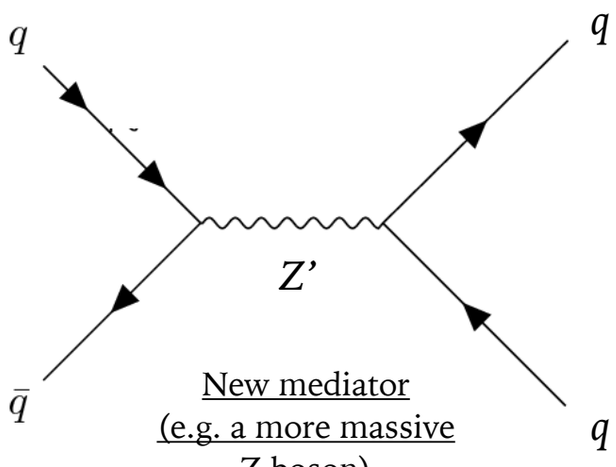
Detection of the dark sector/matter **portal**, via its **visible** (hadronic) **decays**:

Background (very frequent)

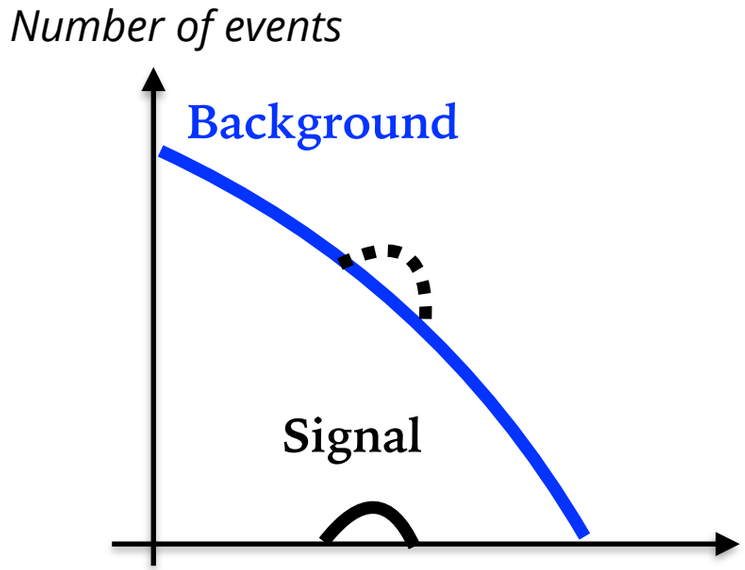


Any **strong force** process

Signal (rare)

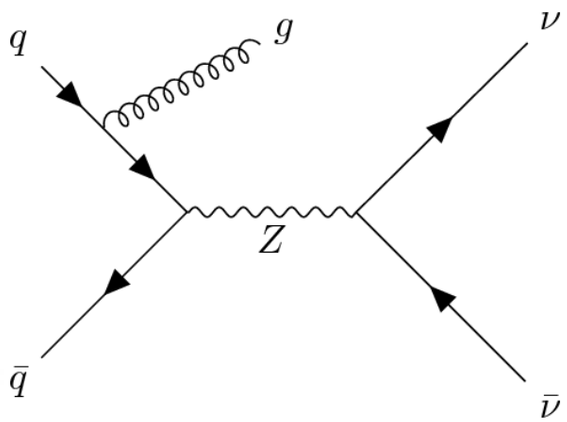


New mediator (e.g. a more massive Z boson)

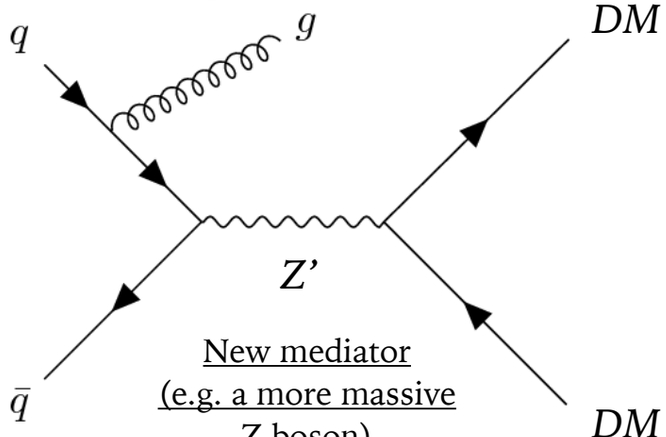


Detection of **DM** candidates (invisible particles) **from a portal particle**

Background (frequent)



Signal (rare)



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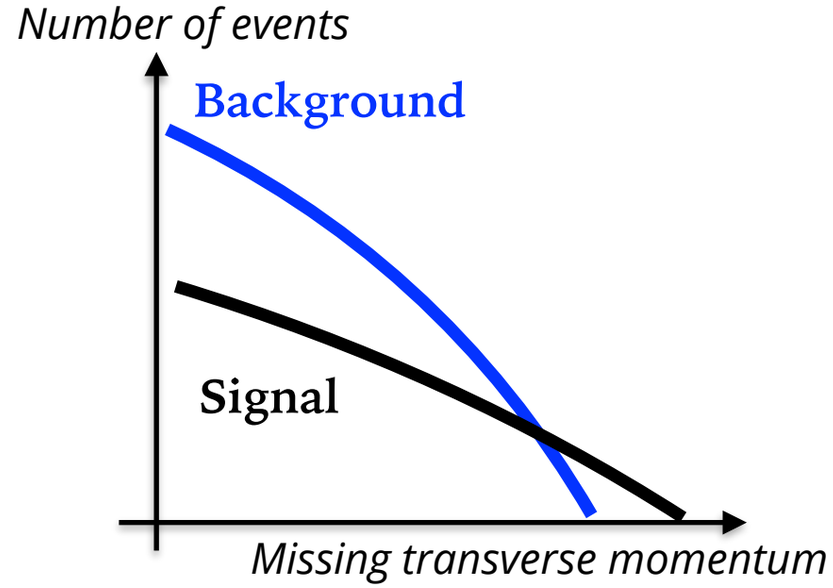
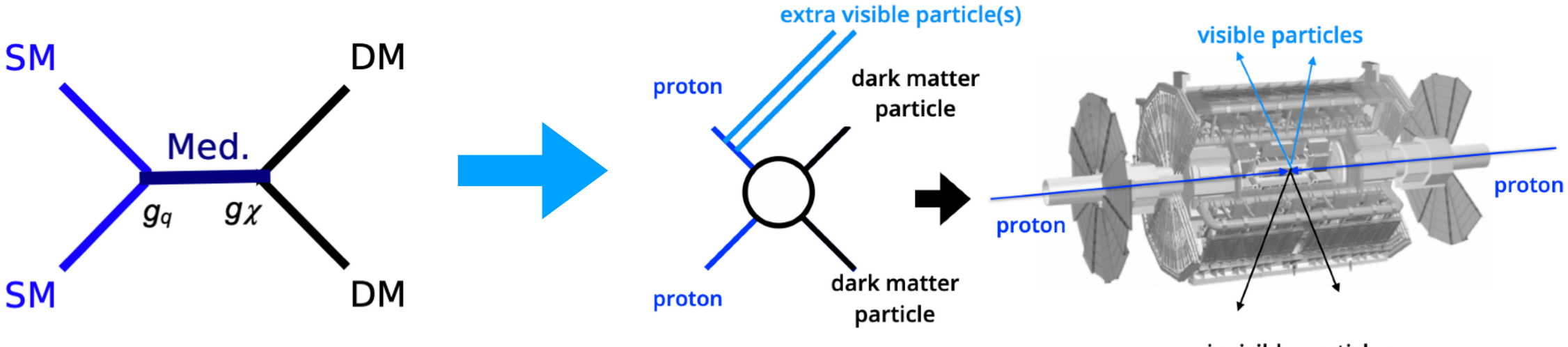


Jet+missing transverse momentum searches at HL-LHC

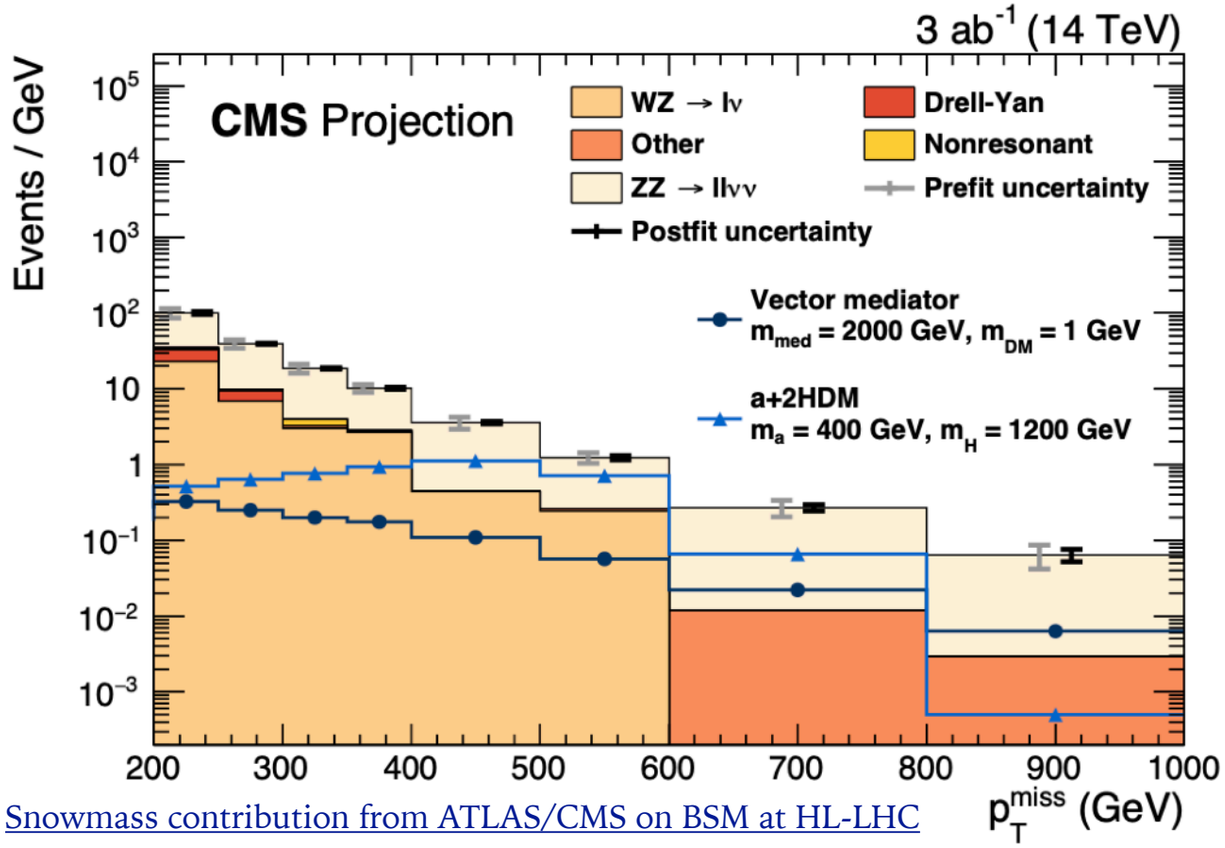
Basic idea for detection of invisible particles at collider experiments like ATLAS and CMS



Could also be neutrinos from Z decays!

Key points to **enhance sensitivity of searches** with much **larger datasets**, entering a *precision search* regime:

- minimise **systematic uncertainties**
- rely on **precise theory predictions**

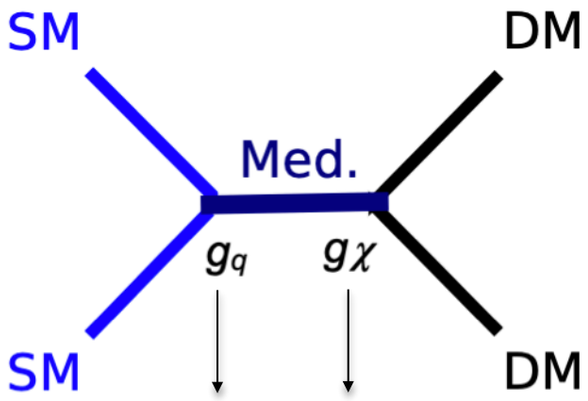


Snowmass contribution from ATLAS/CMS on BSM at HL-LHC

European Research Council
Established by the European Commission
The University of Manchester

Jet+missing transverse momentum searches at HL-LHC

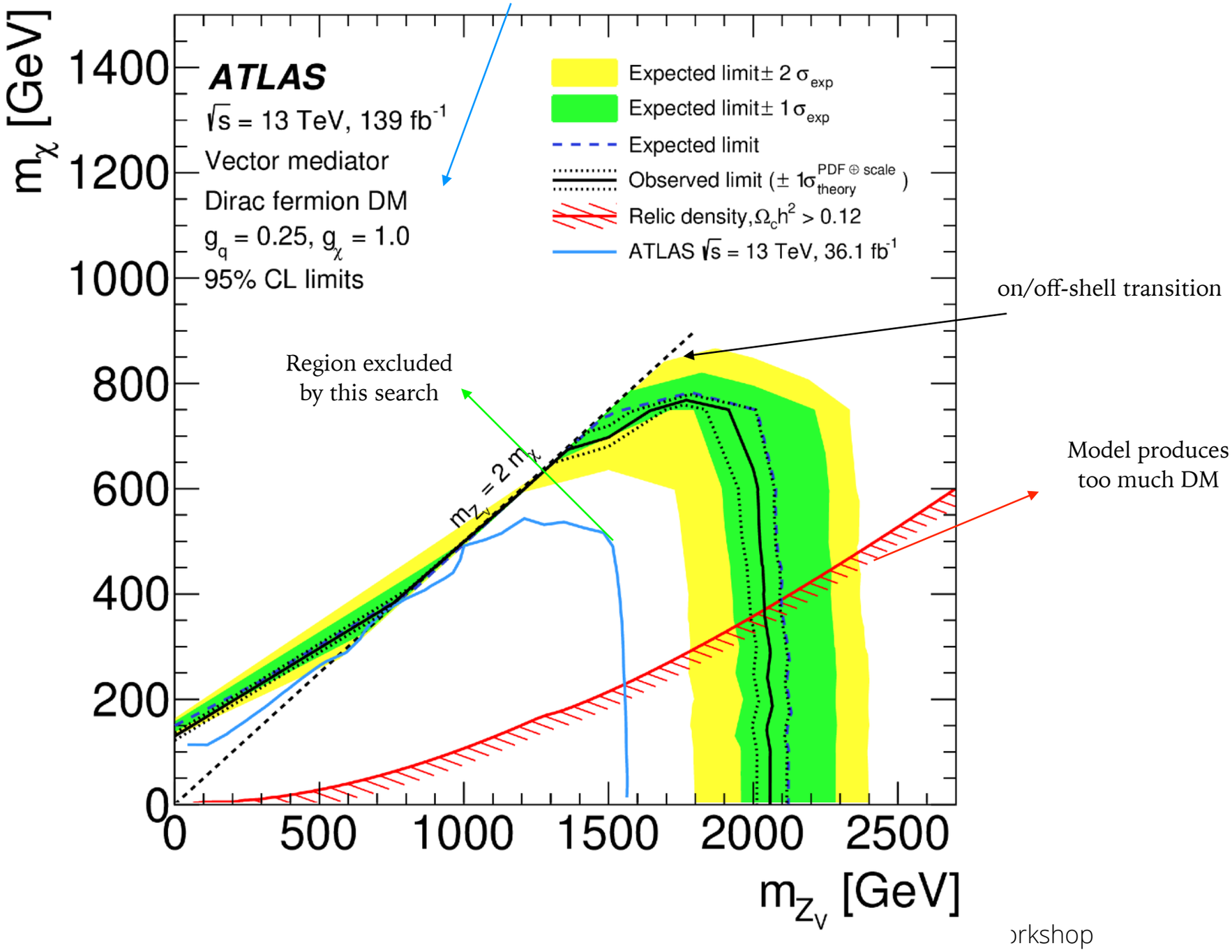
DM interpretation of searches with jets + missing transverse momentum



Strengths of the interaction (=coupling) mediator-quarks and mediator-DM

arXiv:2102.10874

Model assumptions - more models can be/are tested



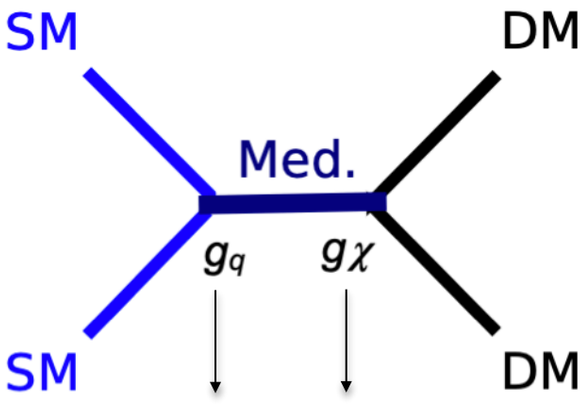
on/off-shell transition

Region excluded by this search

Model produces too much DM

Jet+missing transverse momentum searches at HL-LHC

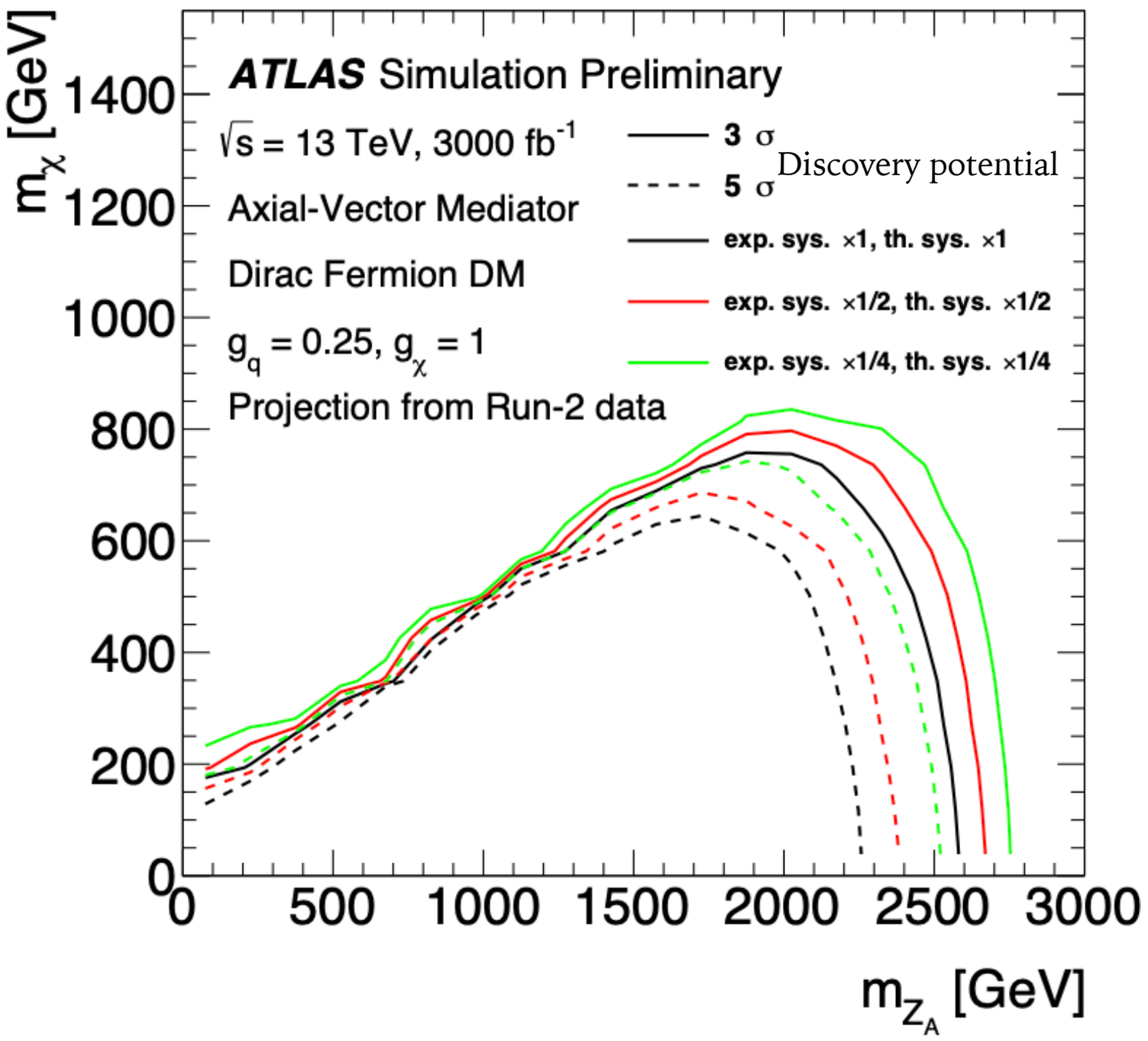
DM interpretation of searches with jets + missing transverse momentum



Strengths of the interaction (=coupling) mediator-quarks and mediator-DM

Impact of theory and experiment **systematics** on discovery potential will be **sizeable**!

Snowmass contribution from ATLAS/CMS on BSM at HL-LHC



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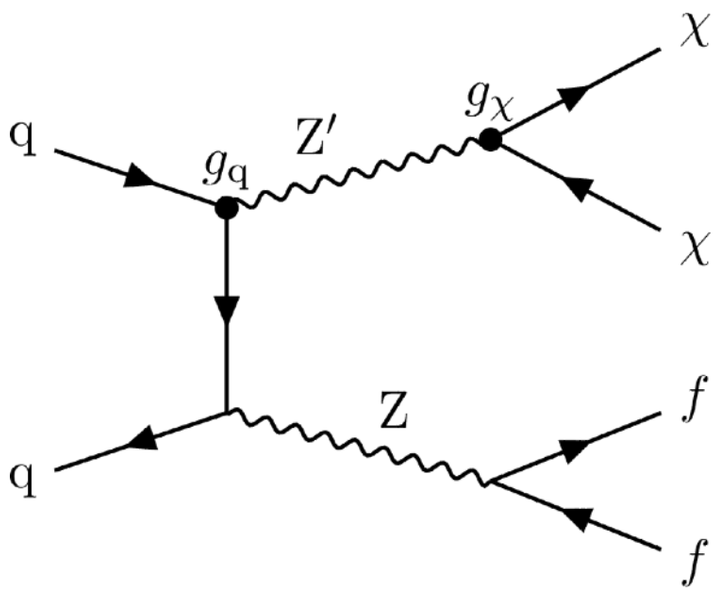

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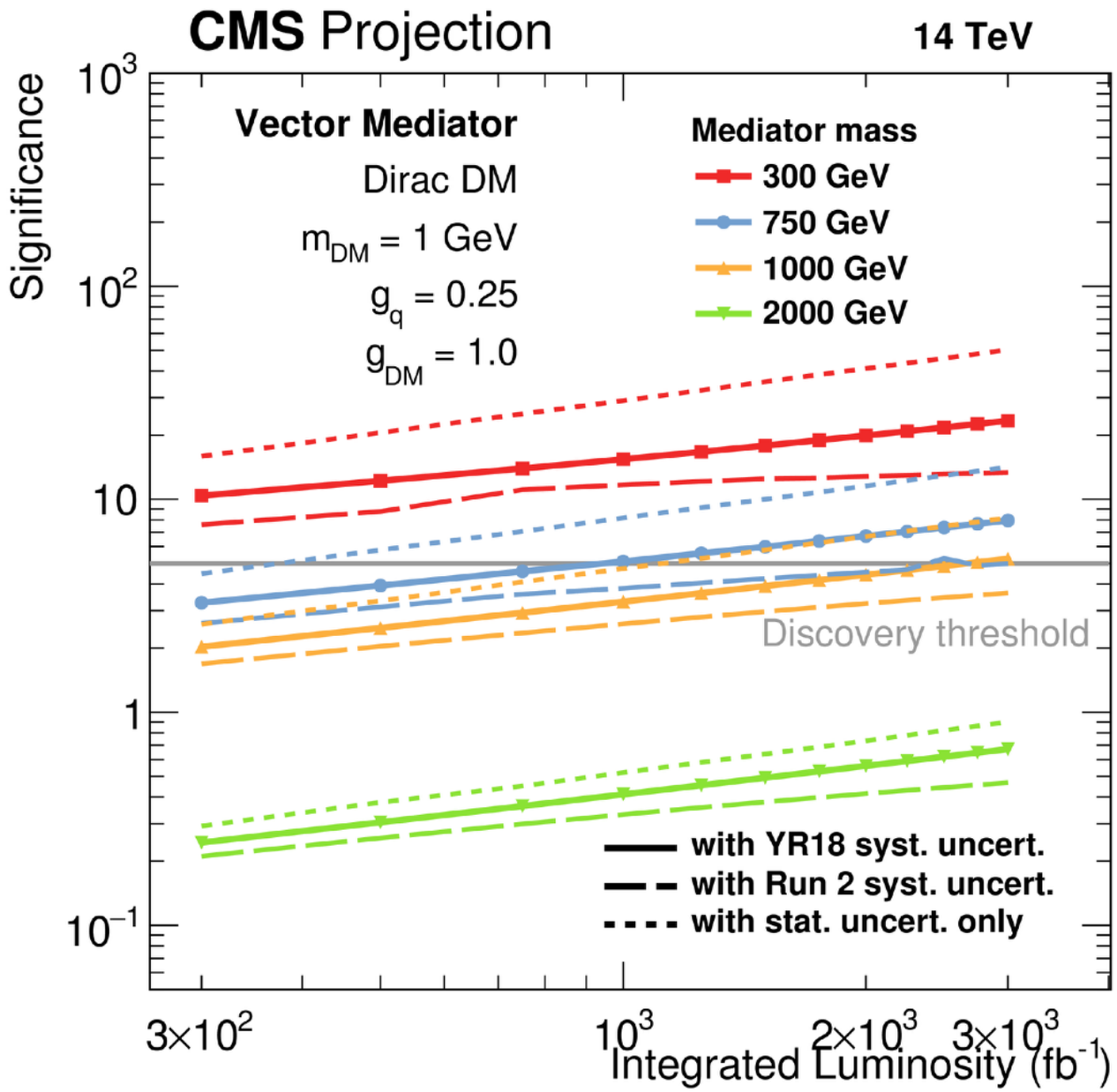
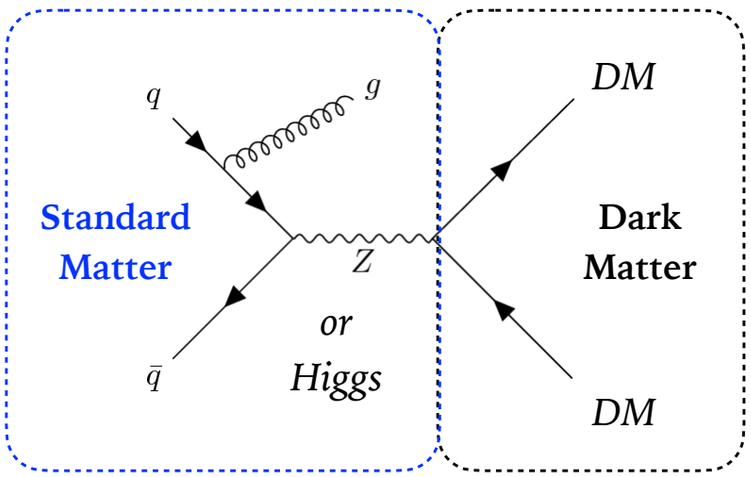


Portals and Weakly Interacting Massive Particles

A **minimal** option to make up 100% of the relic density:

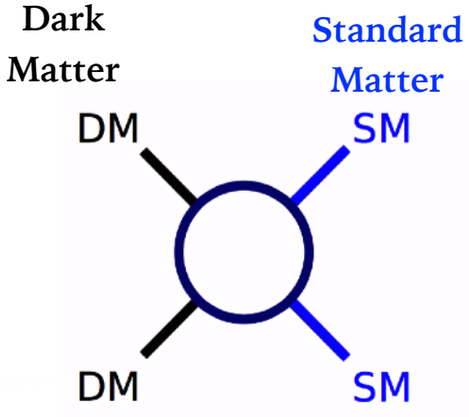
- only add one particle to the Standard Model



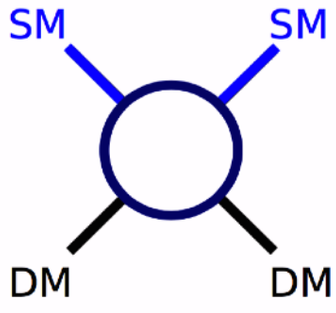
- stable **TeV-scale** particle with **weak-force-sized** interactions
  - Weakly Interacting Massive Particle (**WIMP**)…
  - …conveniently appearing in models that also solve other problems in particle physics (e.g. **supersymmetry**)
  - Beautiful and simple, almost *miraculous!*

Experimental advantage: many experiments can detect it in different ways

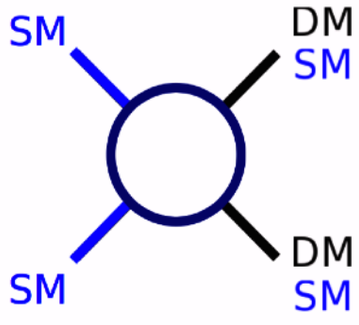
complementary discoveries



Indirect Detection

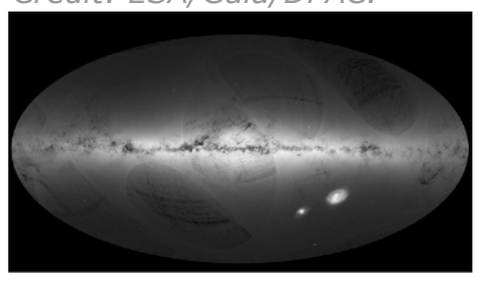


Direct Detection

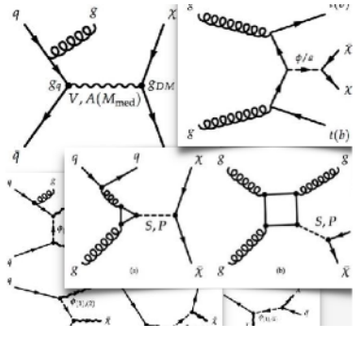


Colliders/ Accelerators

Credit: ESA/Gaia/DPAC.



Astrophysics

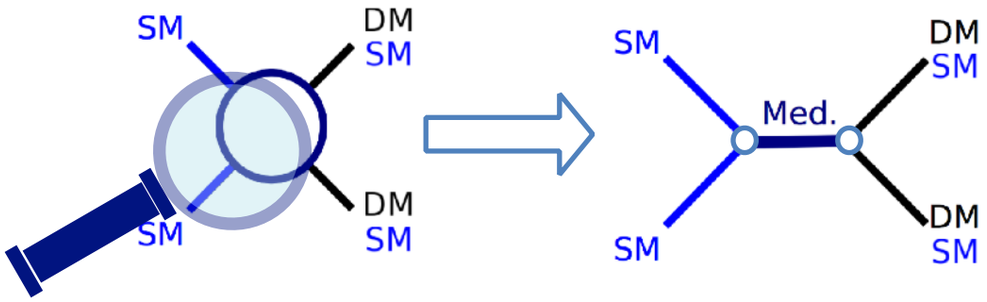


Theory input always necessary to contextualize

Many benchmarks for collider WIMP searches...

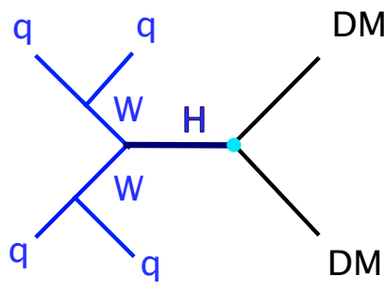
Simple models ⟵ More complex/complete models

Simple DM mediation



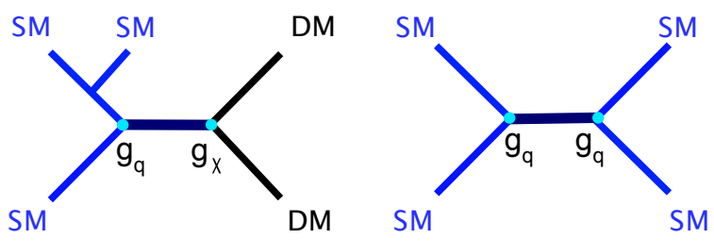
SM mediator

Z/Higgs portals



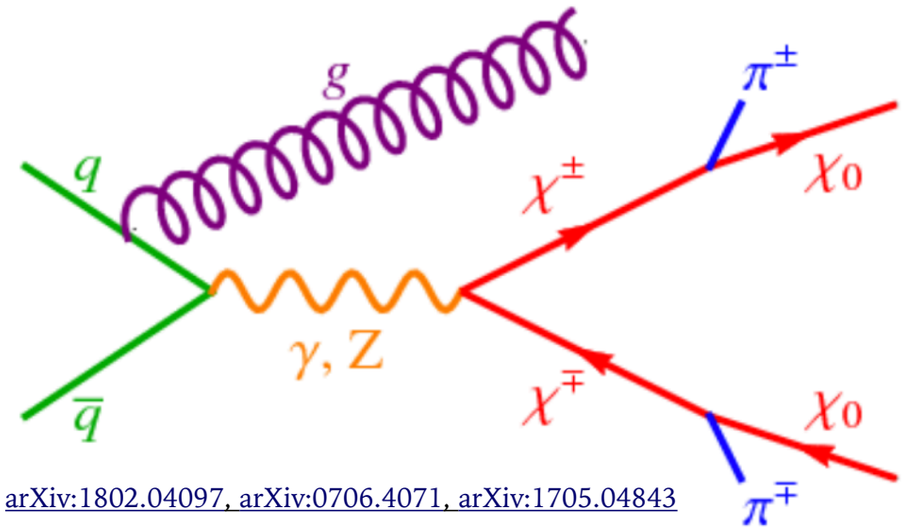
Beyond-SM mediator

Vector-like mediator



Scalar-like mediator
and Two Higgs Doublet Models

Supersymmetry



arXiv:1802.04097, arXiv:0706.4071, arXiv:1705.04843

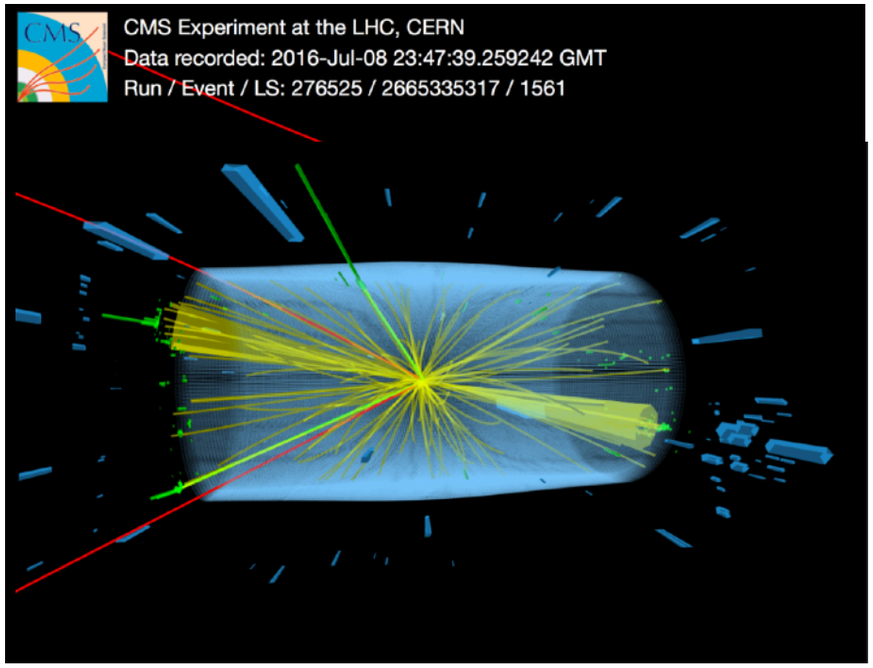
Example: **Wino/Higgsino DM**
See S. Shirai's talk yesterday
for more information and HL-LHC
results, 's poster

Much exists beyond WIMP: DM models with long-lived particles, unusual dark sector signatures...

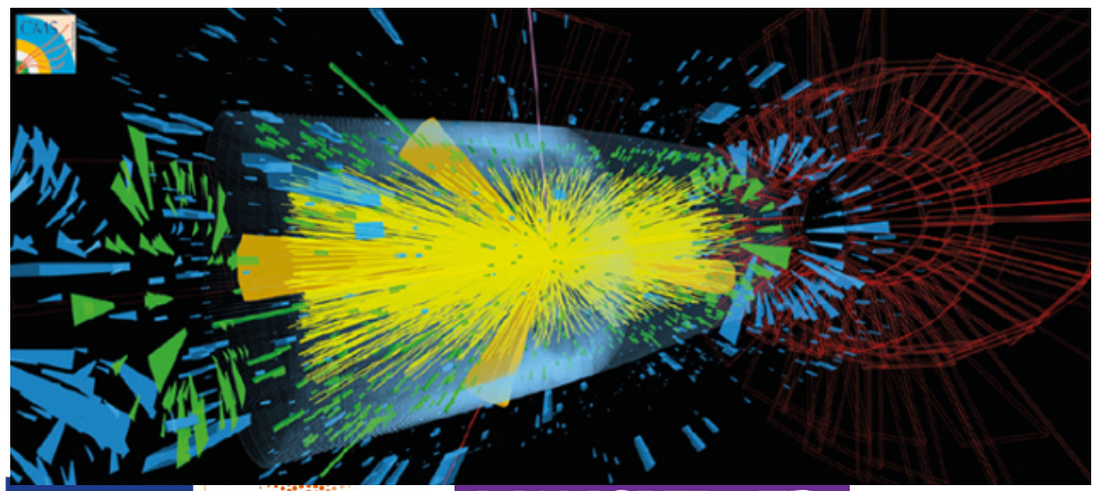
Systematics aren't everything: pile-up at HL-LHC

Example: Higgs boson produced in the VBF process on top of:

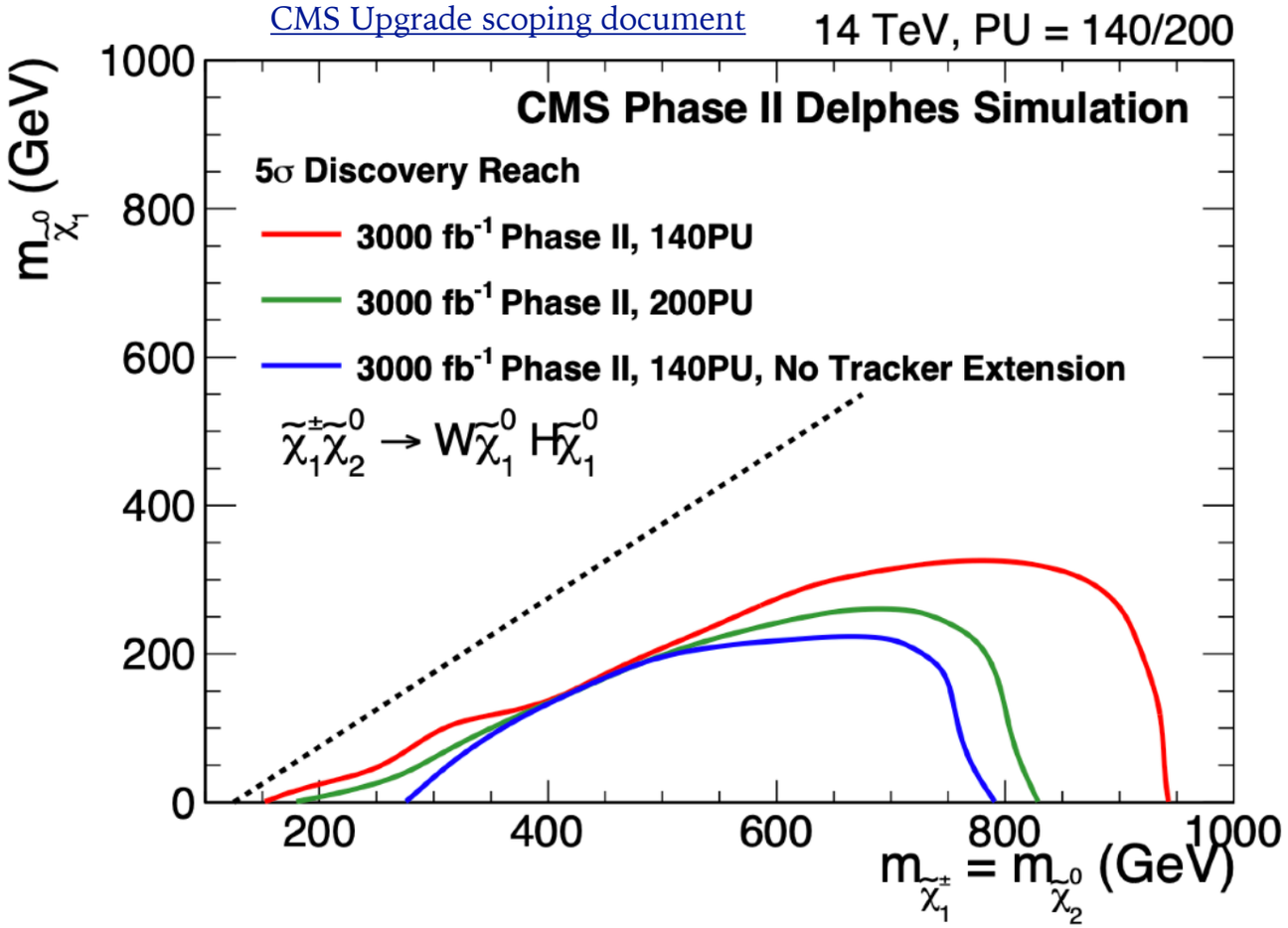
o(20) simultaneous (pile-up) collisions



200 pile-up collisions



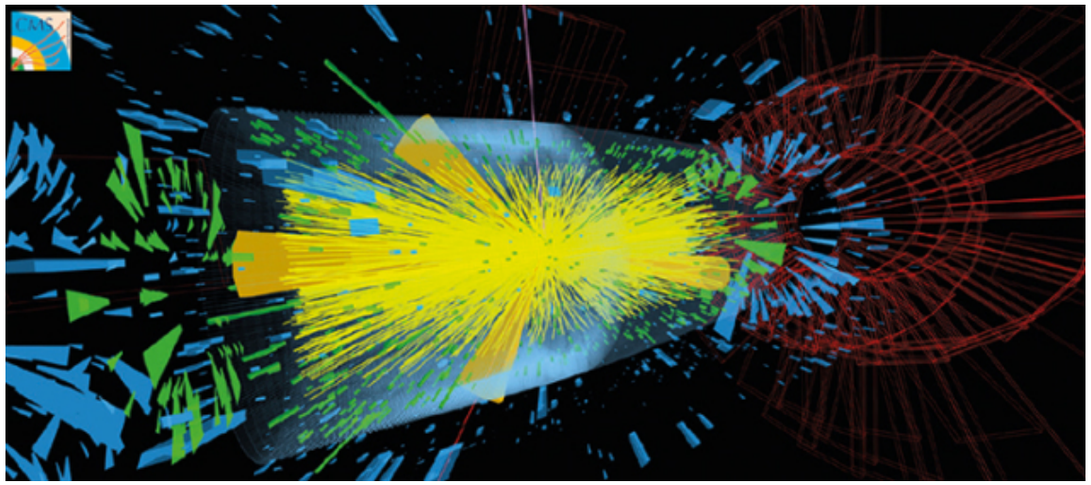
CMS Upgrade scoping document

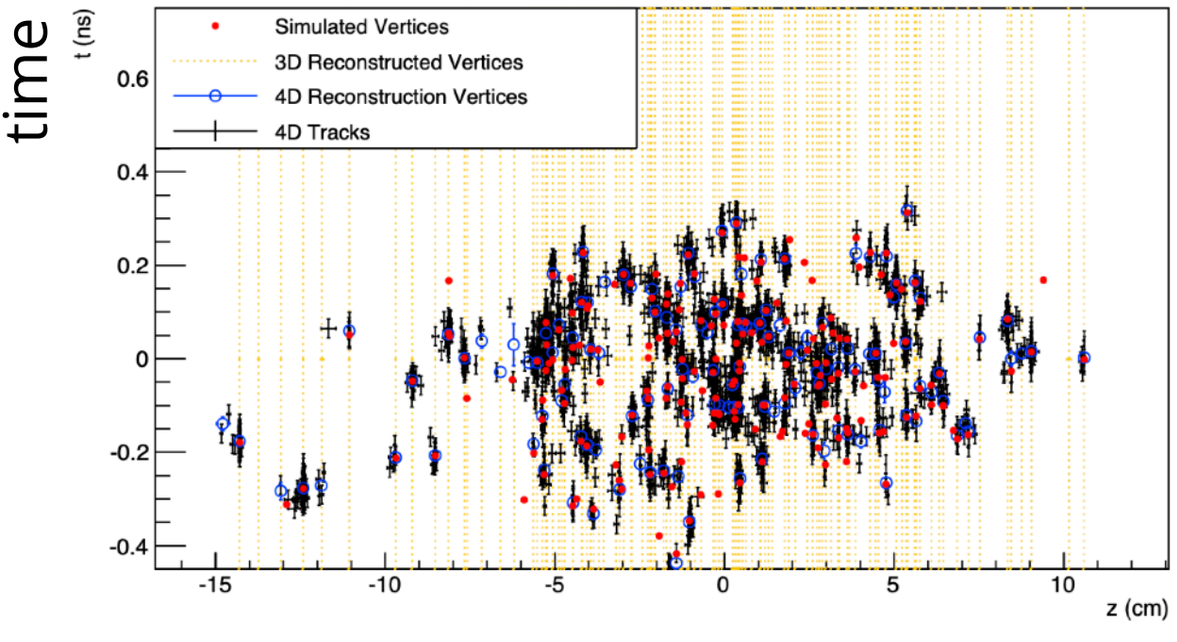


- Example: **SUSY search** with missing transverse momentum
- **Sensitivity degradation** in going from pile-up of 140 to 200 (design)
  - Mainly due to **decrease in resolution**: more difficult to accurately identify/reconstruct objects in busy environments

Systematics aren't everything: pile-up at HL-LHC

Precision timing detectors add a 4th dimension to spatial vertex information





Systematics aren't everything: pile-up at HL-LHC

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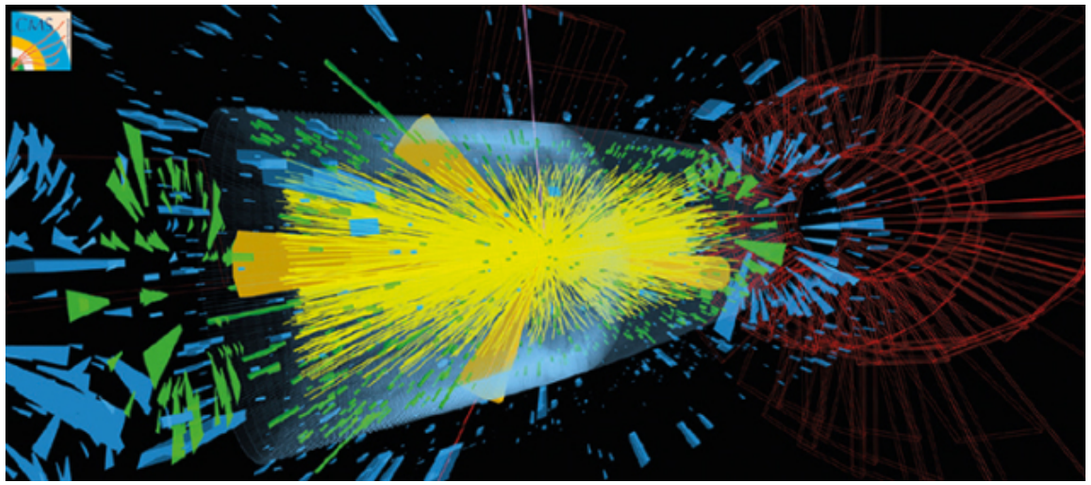

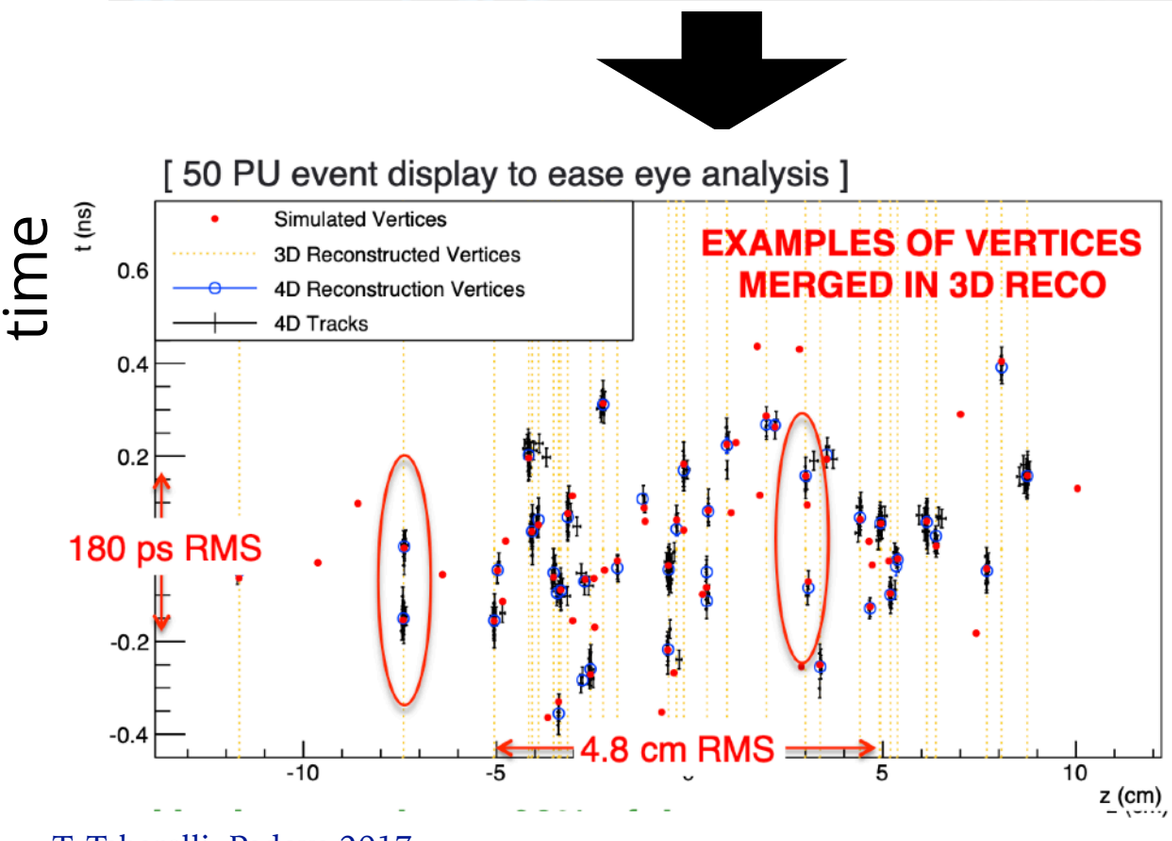

T. Tabarelli, Padova 2017

Systematics aren't everything: pile-up at HL-LHC

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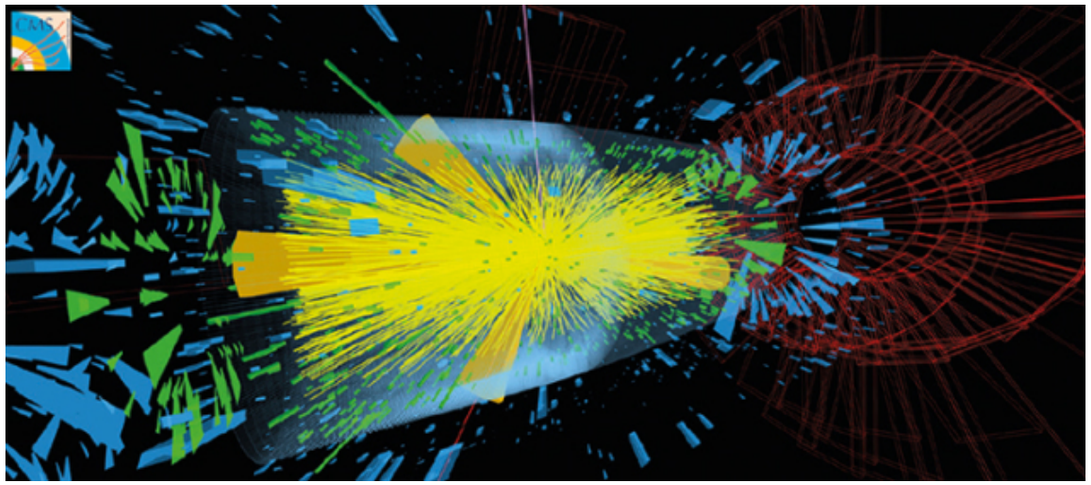
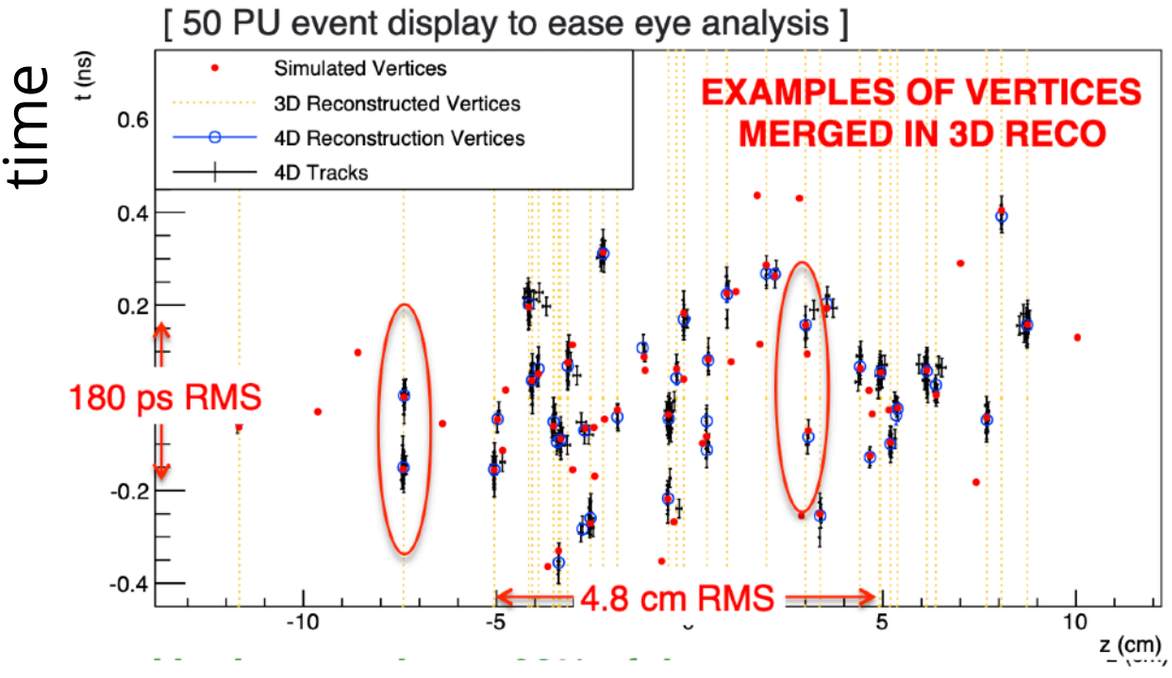


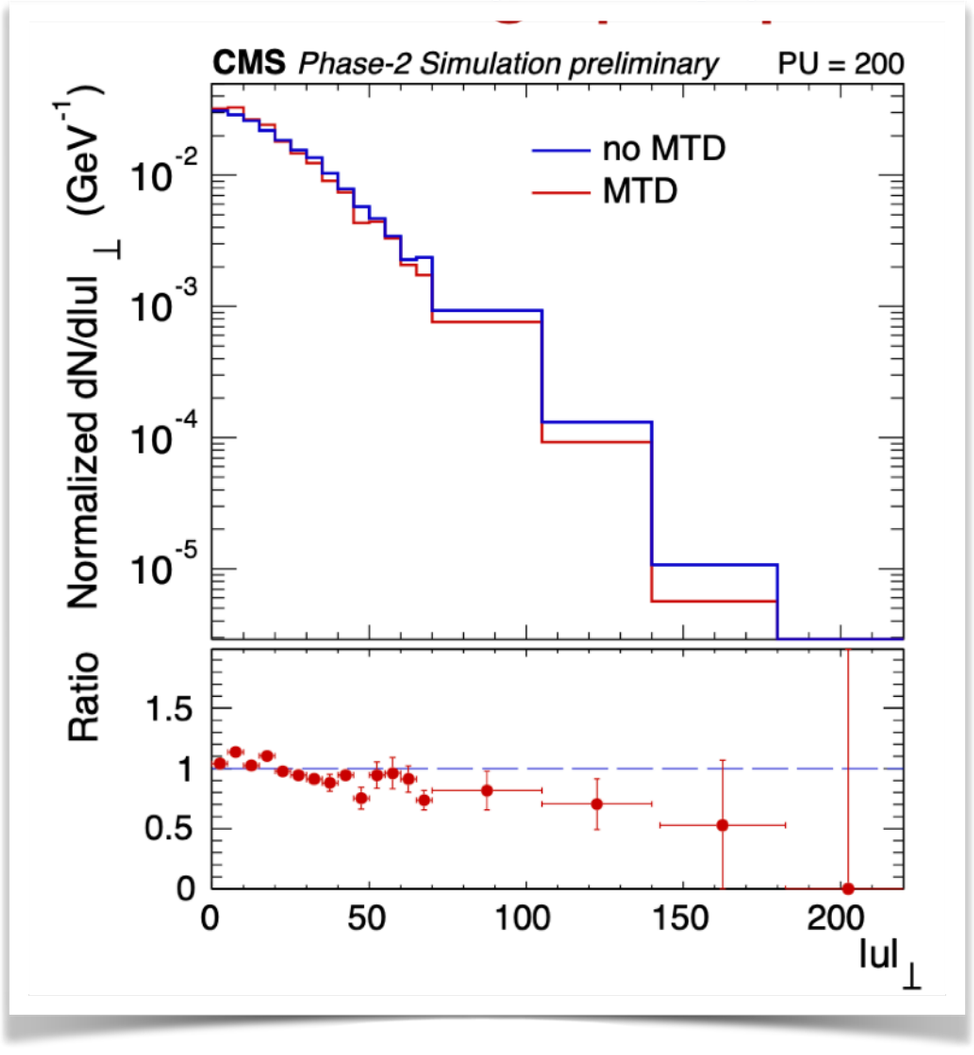
time



space (along beam axis)

T. Tabarelli, Padova 2017

CMS MIP Timing Detector scoping document



Reduction in missing transverse momentum (hadronic recoil) tails

So, why can't we discover DM with HL-LHC alone?

- **Reason #1**: *(clear from this workshop!)* there are DM models that are not accessible at accelerator energies / intensities

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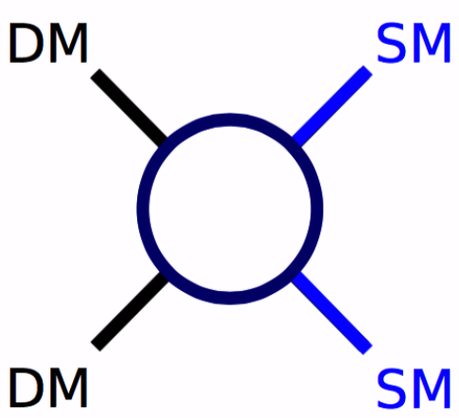
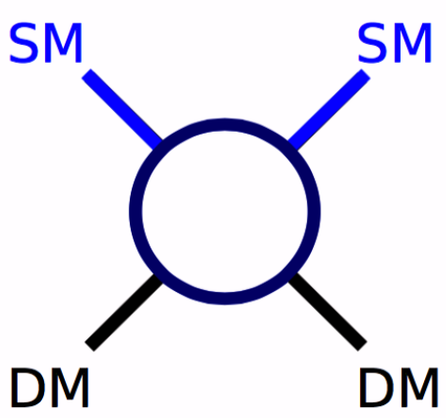
  - Direct detection can **discover DM that interacts** inside the detector
  - Indirect detection can see **annihilating/decaying DM** through its decays



Indirect Detection



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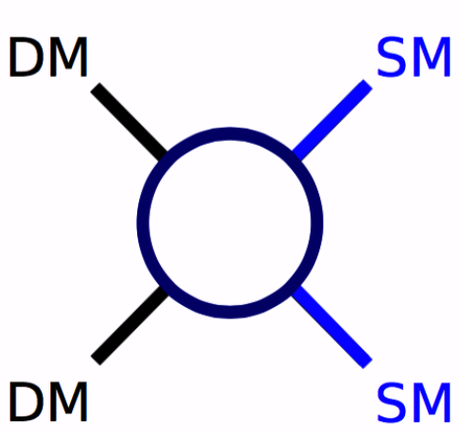
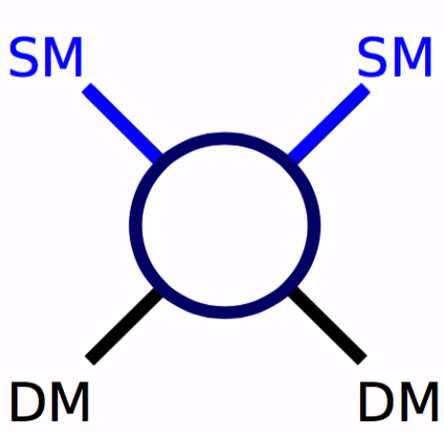
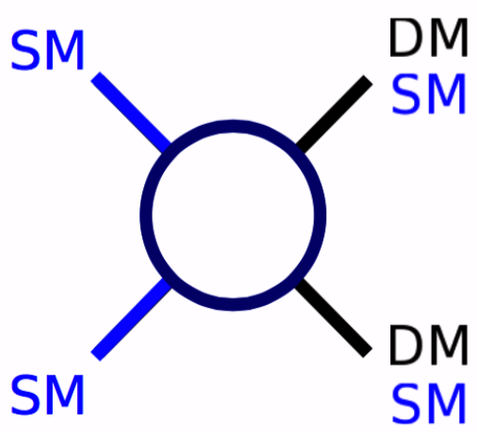
  - Indirect detection can see **annihilating/decaying DM** through its decays
  - Accelerators/colliders can produce DM and **probe the dark interaction**

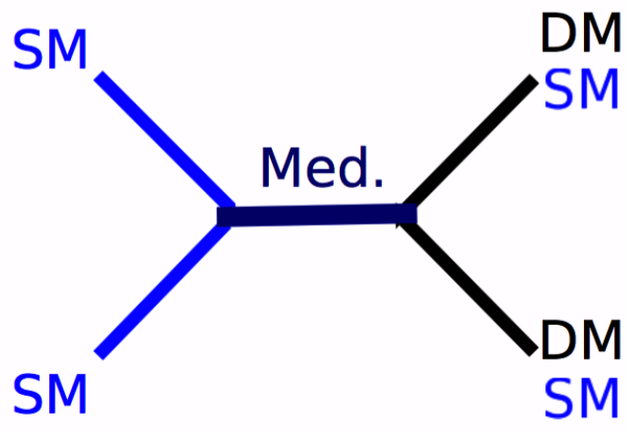


Indirect Detection



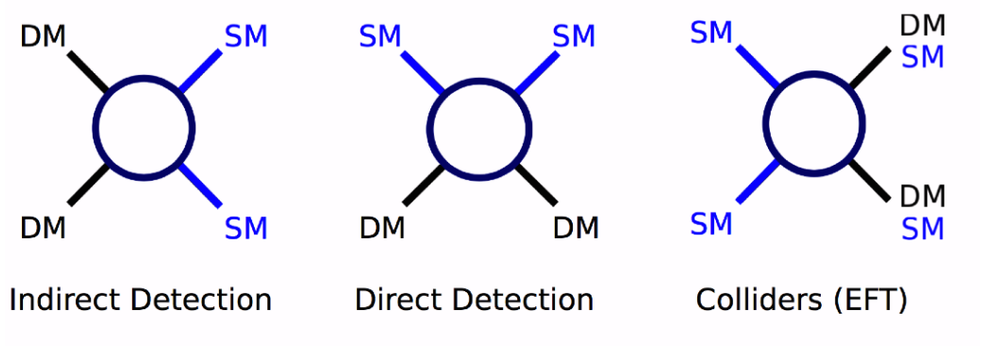
Direct Detection





Particle Accelerators (colliders & extracted beam lines)

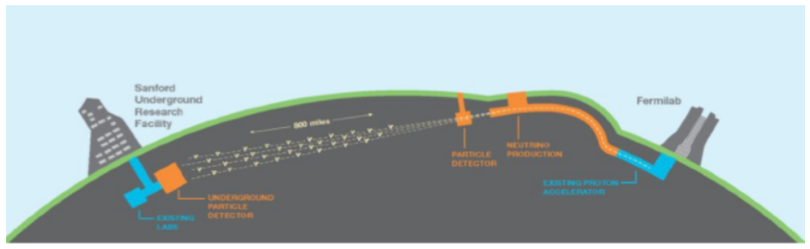
The evolution of dark matter searches in the last decade



HL-LHC DM and dark sector searches will take place in a very interesting context!

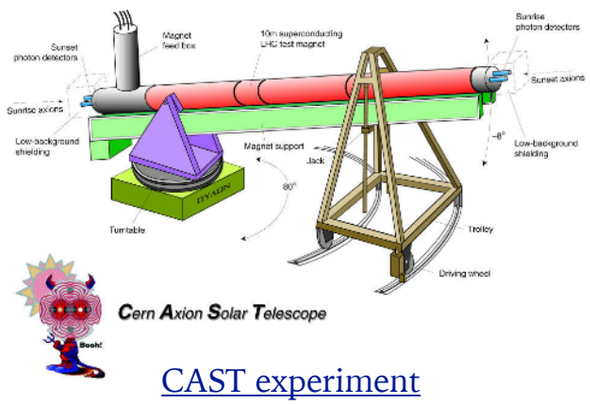
are complementary to:

Neutrino experiments



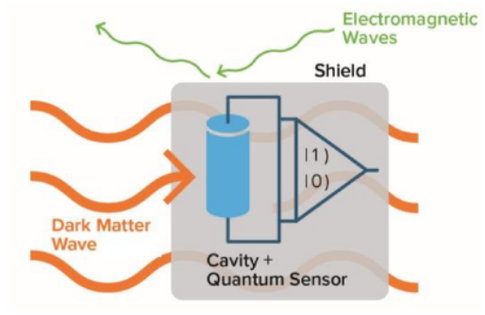
https://www.dunescience.org

Axion experiments



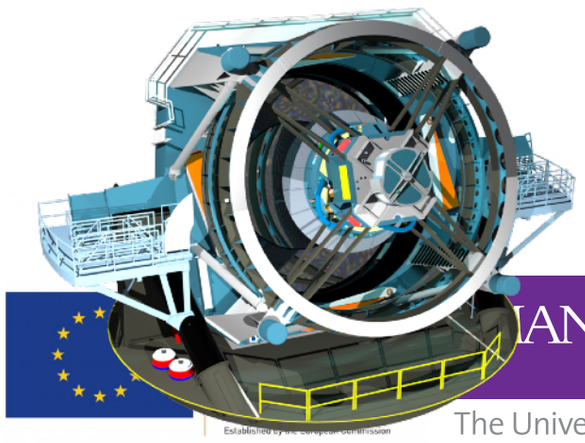
CAST experiment

(quantum) sensors for light/ultralight DM



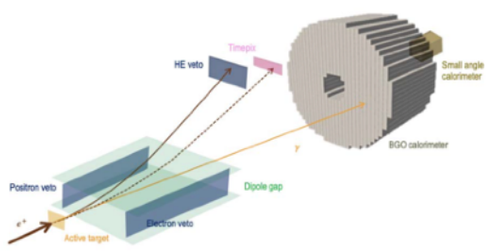
BRN report for new initiatives in DM

Astrophysical & cosmology probes



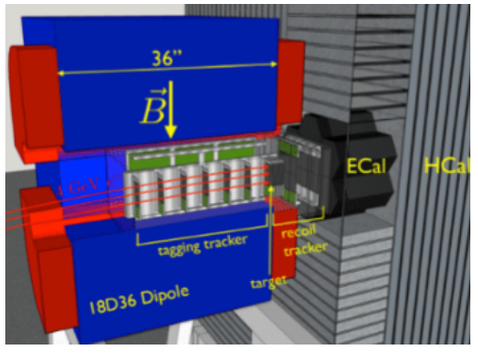
https://www.lsst.org

Kaon & flavour experiments



https://padme.lnf.infn.it/

Light DM accelerator experiments



arXiv:1808.05219

Gravitational wave experiments

arXiv:1907.10610

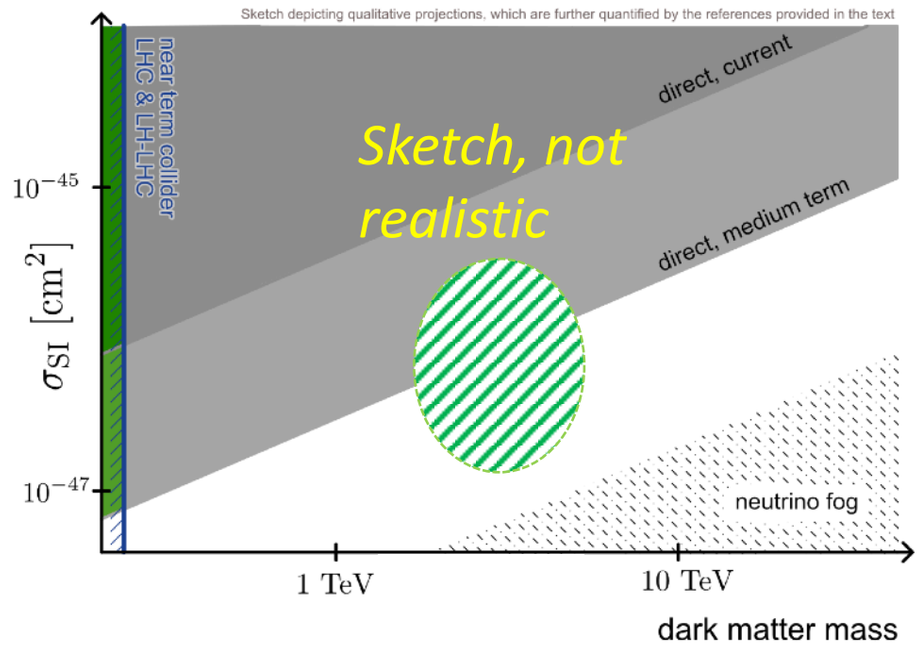
Note: not an exhaustive list

Complementarity: a Wino/Higgsino story

The HL-LHC is just the start of a possible discovery story!

Late 2020s

Direct detection experiment sees a hint of a signal, with characteristics compatible with WIMP DM



Mid 2030s

2040s

Inspired by:
Dark Matter Complementarity (Snowmass report), arXiv:2210.01770
T. Slatyer's "Paths to discovery" talk at Snowmass 2022

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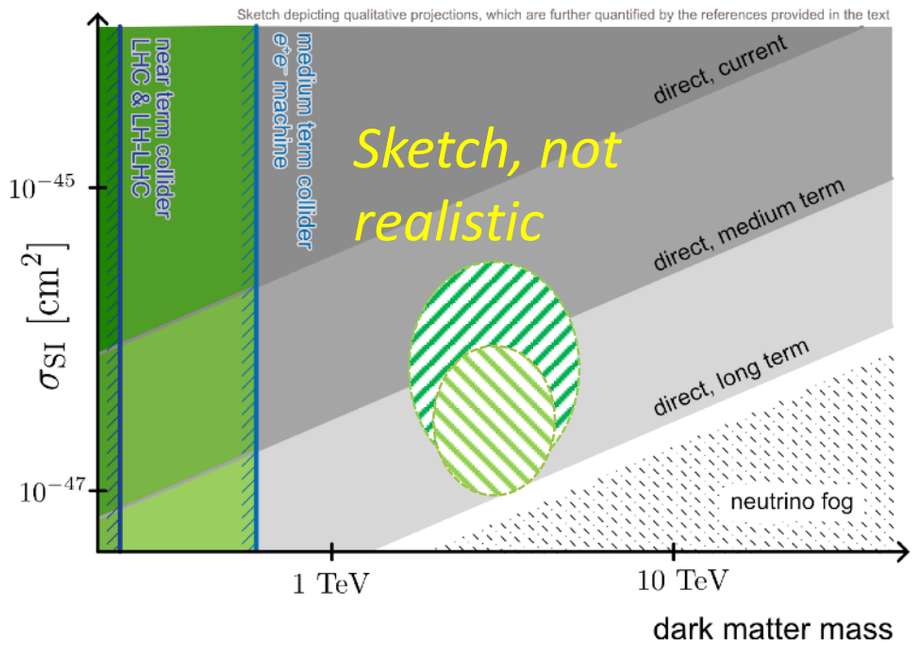

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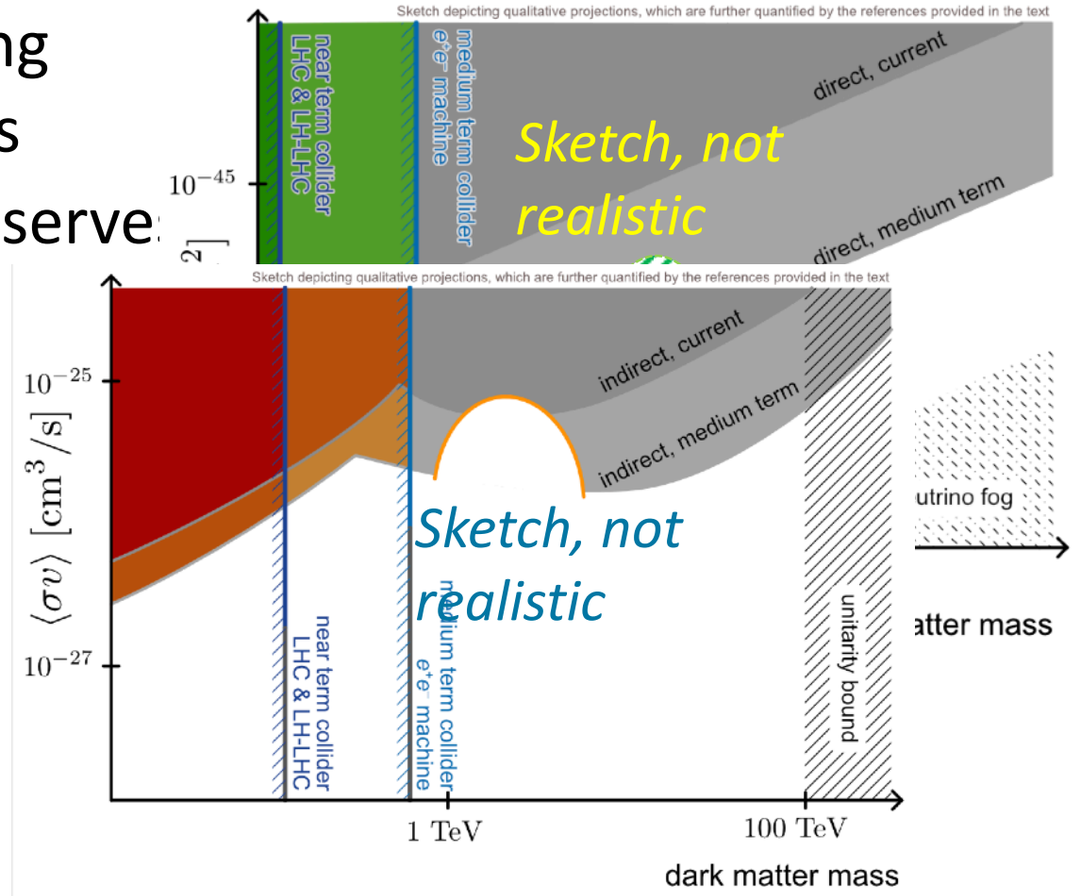
Mid 2030s

Direct detection experiment (using another technique) confirms hints

Indirect detection experiment observes signals of DM annihilation

2040s



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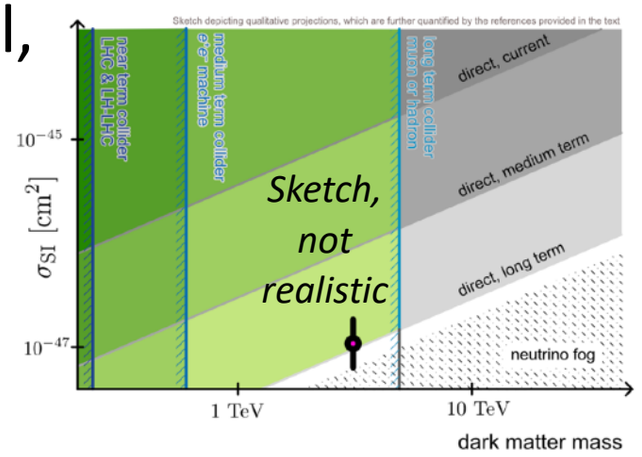
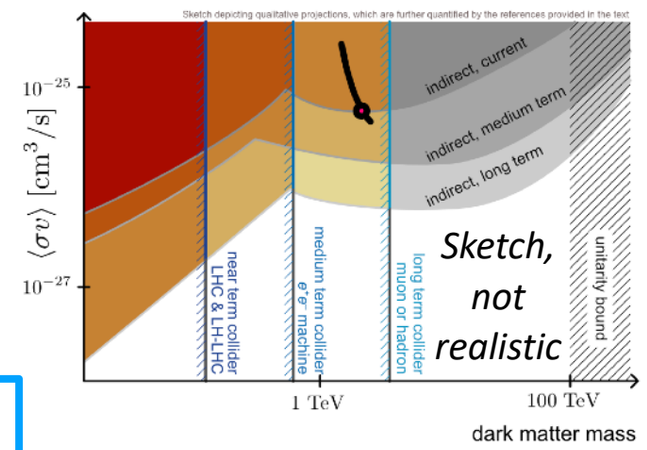
2040s

Future collider, built to target particles with the mass of the putative DM candidate, sheds light on interactions between DM and ordinary matter





Inspired by:
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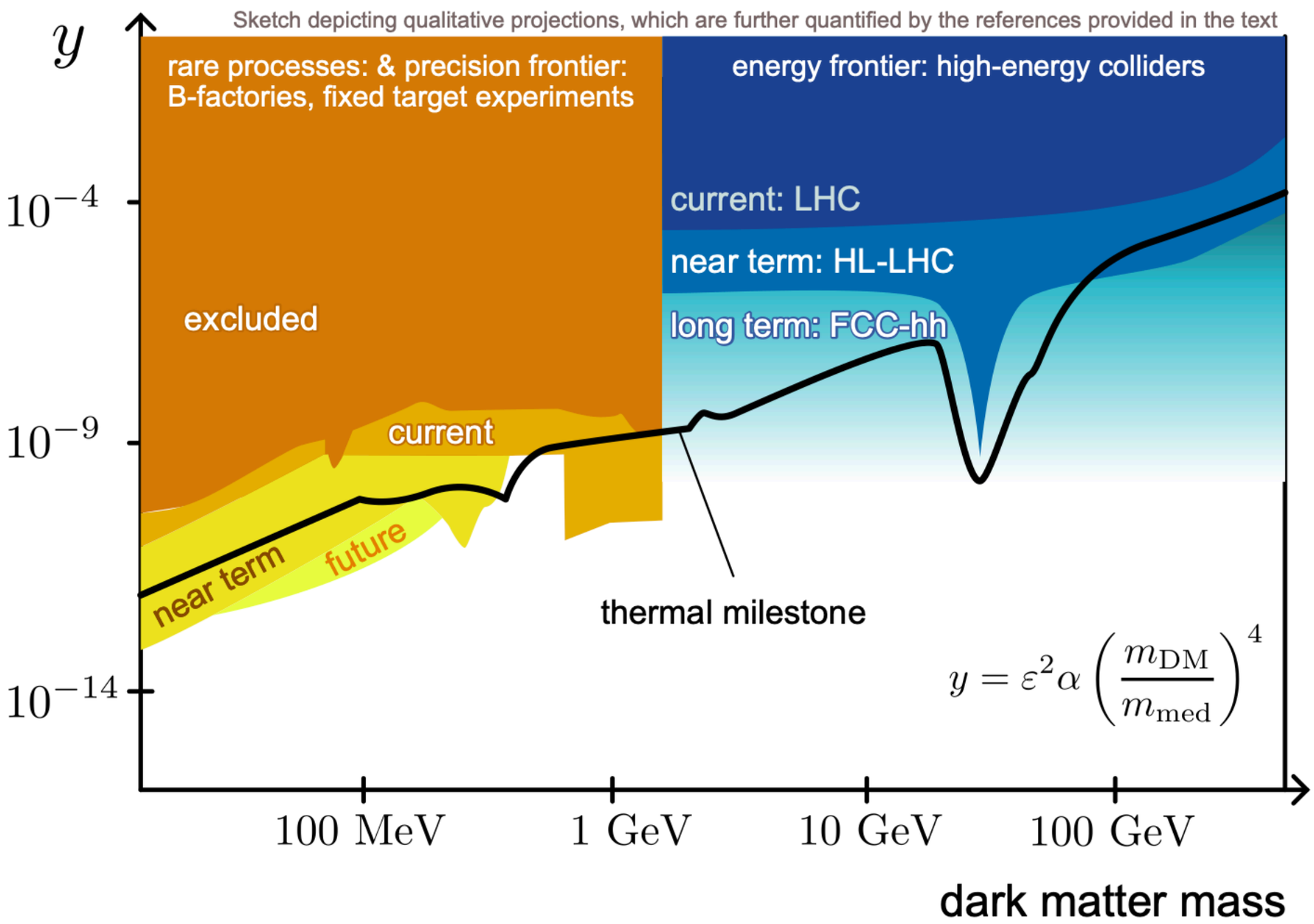
T. Slatyer's "Paths to discovery" talk at Snowmass 2022

Crucial to be able to reproduce & share results, data, workflows…

ask me about the ESCAPE Dark Matter Science Project

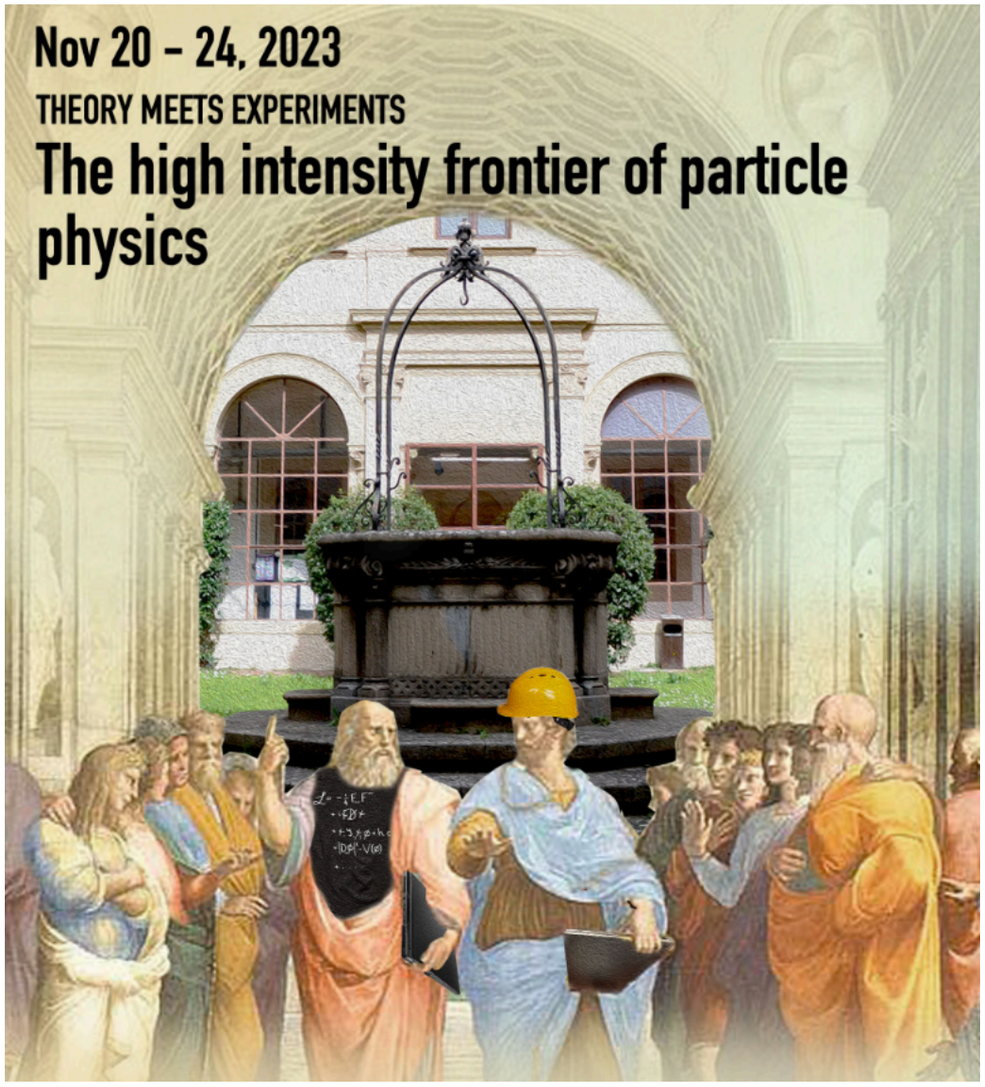
Complementarity: invisibly decaying dark bosons

Dark photon mediated DM: y axis is proportional to interaction strength



From Snowmass dark matter complementarity report: advocating for **support** for **theory** and **multiple experiments** (rather than competition on who has better sensitivity)

Complementarity: theory/experiment school @ GGI



Abstract

This school aims to prepare the next generation of physicists to leverage the opportunities provided by the upcoming high intensity accelerator programs. It will cover advanced topics in both experimental and theoretical physics as related to accelerators, and foster theory-experiment collaborations that they will need to design tomorrow's experiments and their physics program

Speakers and Topics:

- Matthew McCullough (CERN) — HL-LHC theory
- Luca Galli (INFN Pisa) — Low-E lepton experiments
- Simone Pagan Griso (LBNL) — HL-LHC experiments
- Maxim Pospelov (Minnesota Univ.) — Flavour theory
- Evelina Gersabeck (Manchester Univ.) — Low-E hadron beams

Supported by CSN1 and CSN4 INFN

Organizers:

Caterina Doglioni (Manchester University)
Roberto Franceschini (Roma3 Univ. and INFN)
Simon Knapen (Lawrence Berkeley National Laboratory)
Diego Redigolo (Firenze INFN and University)

Most students receive accommodation (and a meal?) from GGI

European Research Council
Established by the European Commission

The University of Manchester

Spatial synergies: the Forward Physics Facility

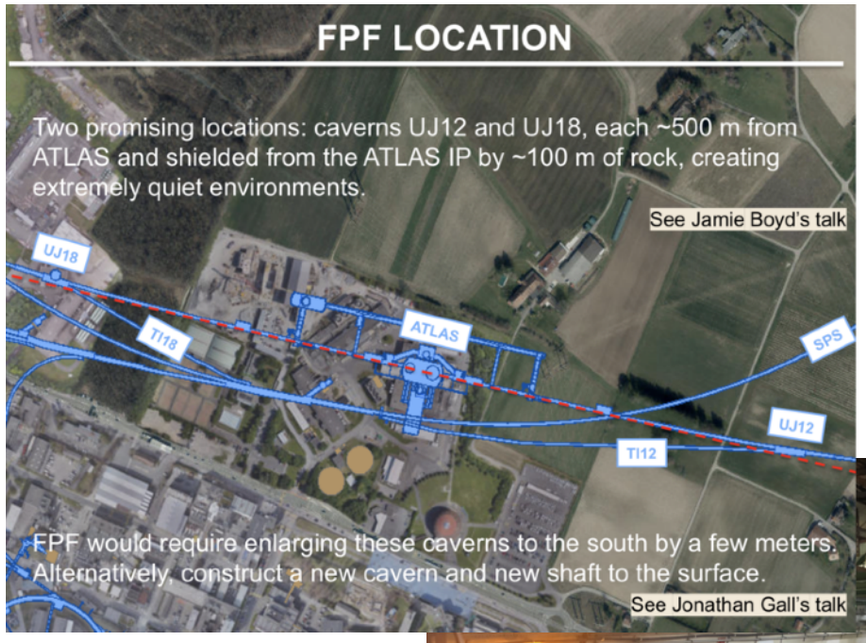
Snowmass Energy Frontier report

> The proposed plans in five year periods starting 2025 are given below.
>
> **For the five year period starting in 2025:**
>
> 1. Prioritize the HL-LHC physics program, including auxiliary experiments,

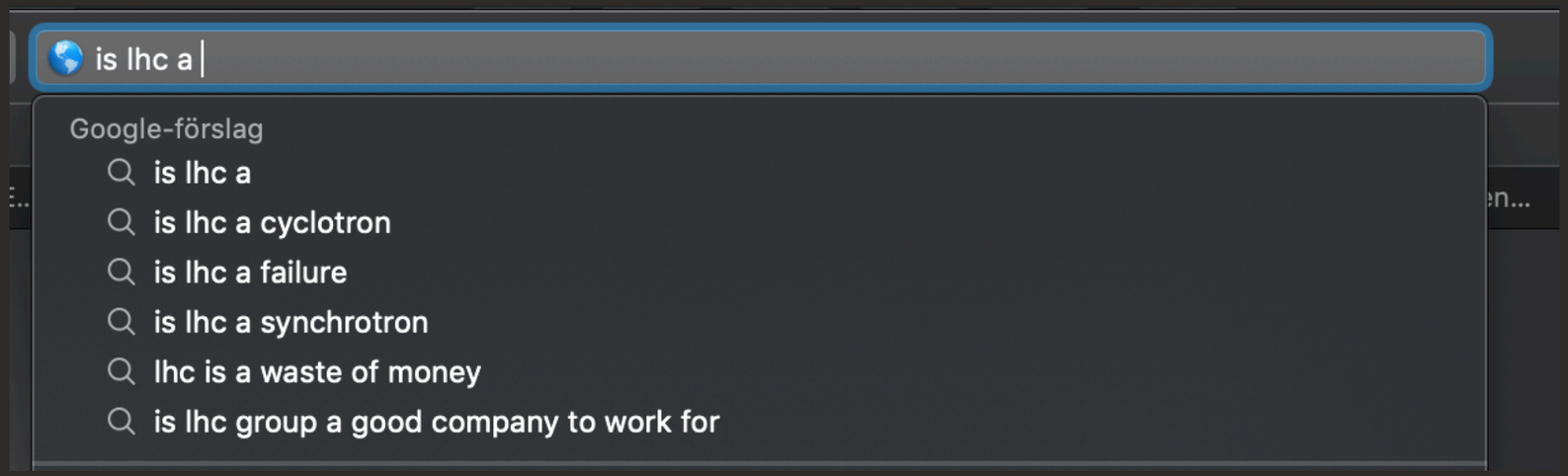
J. Feng's talk, Forward Physics Facility kick-off

Maximise the HL-LHC physics reach by **building experimental facility** where **multiple experiments** can **use the same beam**

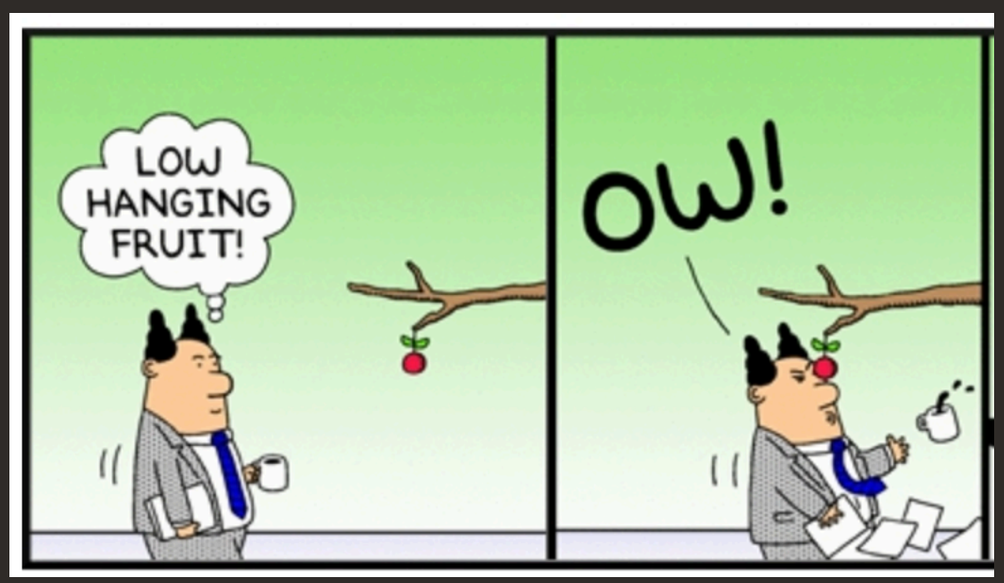
- See A. Ariga's talk on FASER/FPF
- Side note: **software** and **knowledge** can already be **shared** between larger and smaller experiments where appropriate, see the **HEP Software Foundation**



Closing words #1: HL-LHC for BSM physics



My feeling about HL-LHC (&beyond) BSM physics:



Dilbert comics

Let's keep looking!

New physics could still manifest in:

1. deviations through precision
2. rare, unusual processes

...and we have the detectors and datasets to find them!

Closing words #2: collaborations for discoveries

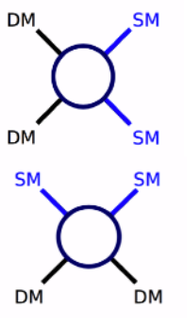
The search for BSM/Dark Matter has a long way to go starting with HL-LHC…

…it's the perfect time to **search everywhere, including for the rare & unusual**

much larger datasets,
"precision searches"
at colliders and accelerators

new / improved detectors & techniques,
backgrounds & analysis tools

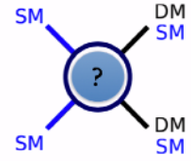
Now and future: essential **complementarity between colliders and other experiments,** *e.g. for dark matter*



cosmological origin
DD/ID/astrophysics/…

and

nature of the DM-SM interaction
accelerators / colliders



but also on **tools**, given **shared theory, experimental & computing challenges**

HEP Software Foundation

about

Initiative for DM in Europe and beyond

European Research Council
Established by the European Commission

The University of Manchester

We can continue the discussions / work together!

The University of Manchester

LUNDS UNIVERSITET

Thanks for your attention!
Backup slides

European Research Council
Established by the European Commission

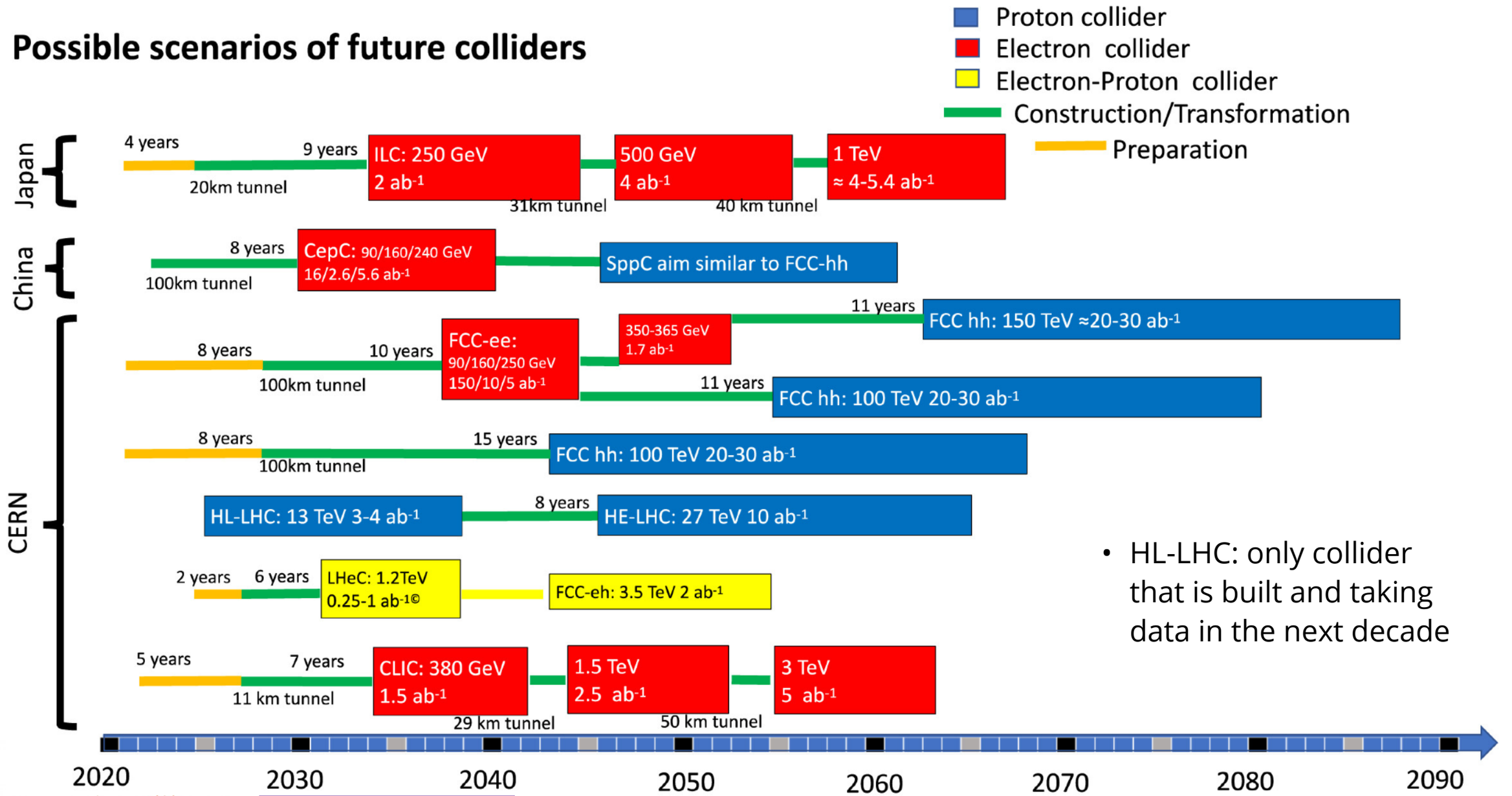
Photo credits: C Fitzpatrick

HL-LHC timeline

https://lhc-commissioning.web.cern.ch/schedule/images/2023/Complex-long-term-Apr23.png

HL-LHC, in context

H. Gray, Reviews in Physics 6 (2021) 100053



- HL-LHC: only collider that is built and taking data in the next decade