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Dark Matter Complementarity (including general BSM considerations)

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European Research Council
Established by the European Commission

Outline

- Quick recap on dark matter
- Complementarity of collider searches
  - Interlude: the importance of data selection for DM @ colliders
- Complementarity in the global DM context
- Community activities
- Conclusions

Disclaimer: This is not an exhaustive talk on all DM complementarity ever discussed
Inclusions (and omissions) are a matter of personal taste and expertise

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Quick dark matter recap

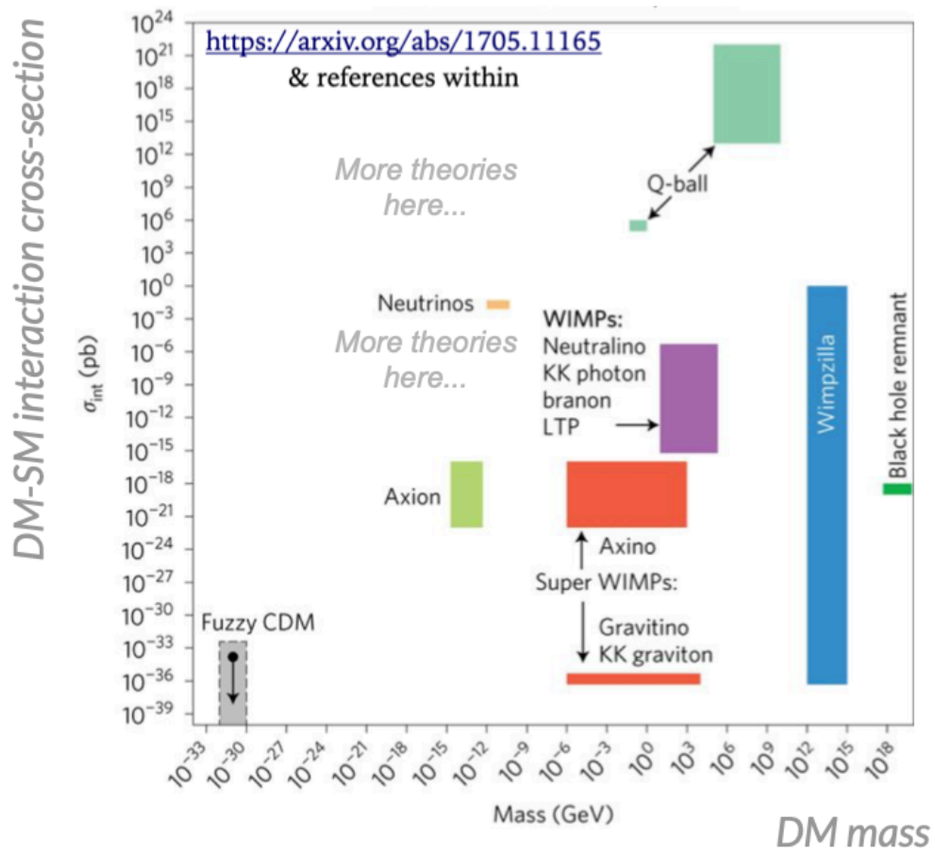
European Research Council
Established by the European Commission

Dark matter needs to be a global scientific problem...

Wide range of **mass scales / interaction strenghts** for DM candidates
→ wide range of **theories** and **experiments** to discover DM

Looking up: stronger interactions

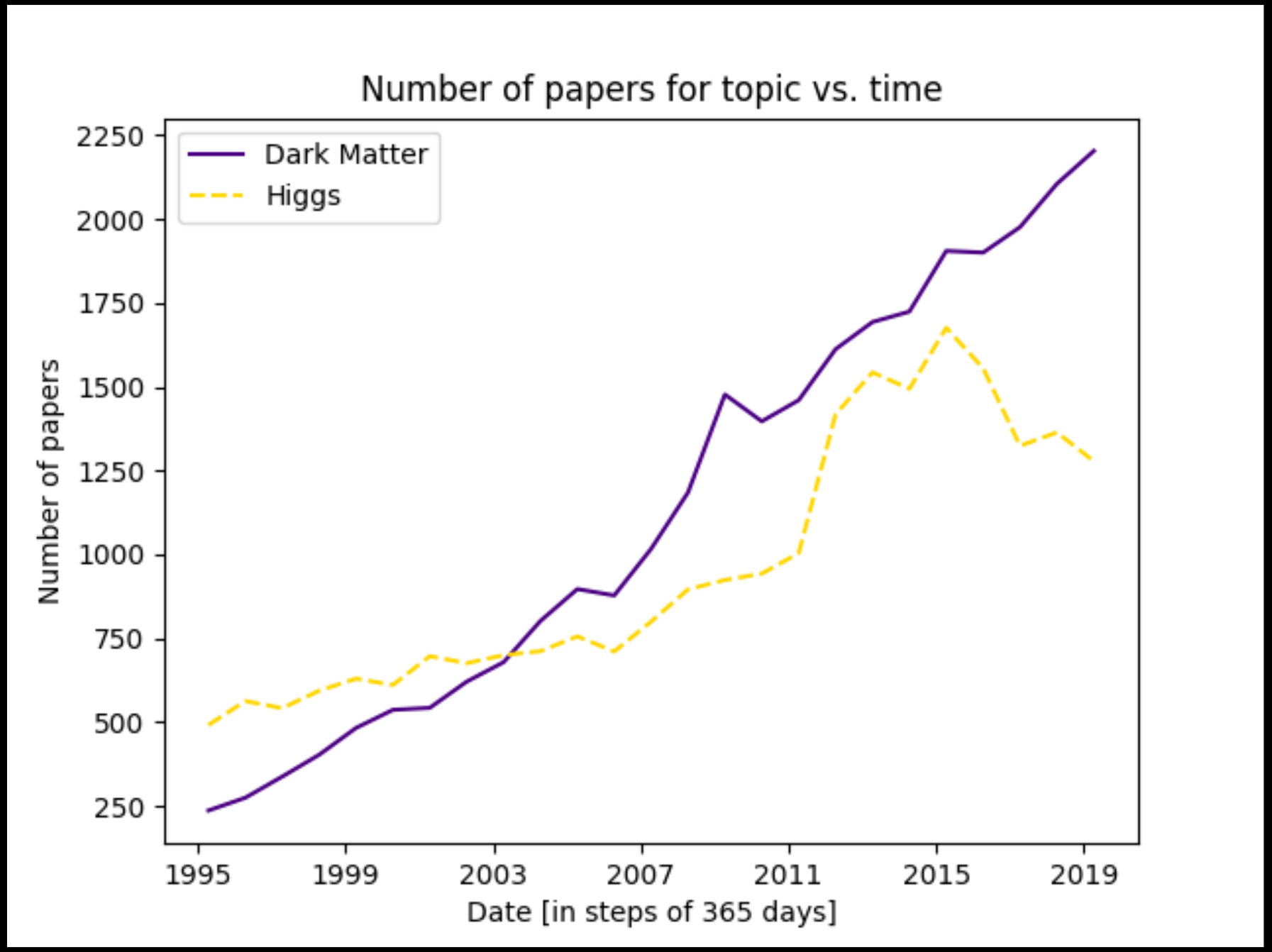
Looking left:
(ultra)light dark matter



Looking right:
more massive DM objects

Looking down: feebler interactions

DM is a much-sought particle



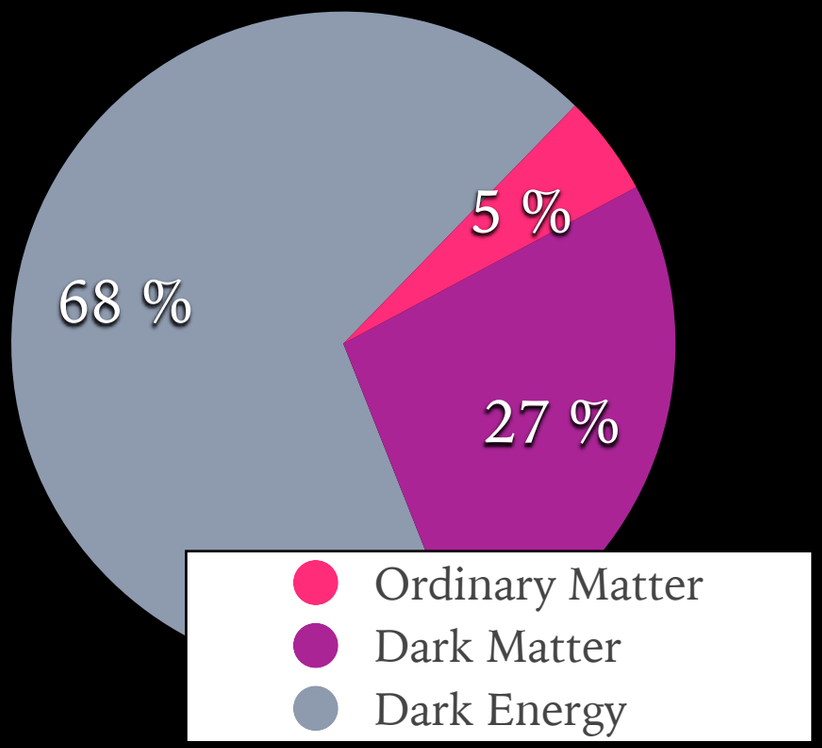
https://benty-fields.com/trending

Papers on the arXiv with the words in the title or abstract

Credits for finding it: Xenon1T, Twitter

Disclaimer: website not to be used as input by funding agencies

You may all have already heard of the WIMP miracle (in Monica D'Onofrio's lectures yesterday)...



Dark Matter constitutes most of the matter in the universe

↓

relic density

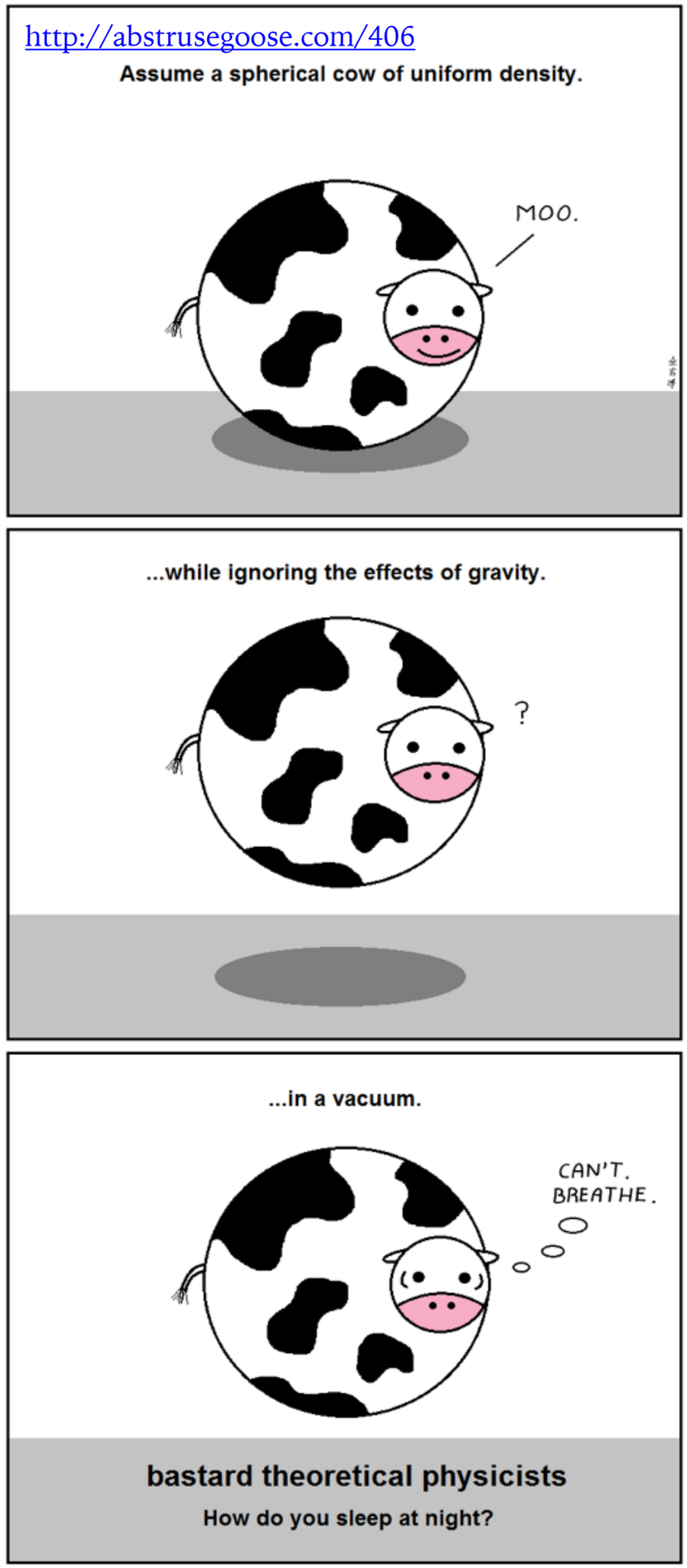
many caveats and options on how to get it…

This relic density can be explained with

a new particle

- that interacts only weakly with known matter
- with mass in the range of current experiments (WIMP)

Under these assumptions…



…we could discover Dark Matter in the next decade!

Unless…

(this is here just to avoid singling out theorists in jokes)

More seriously: the *relic density*

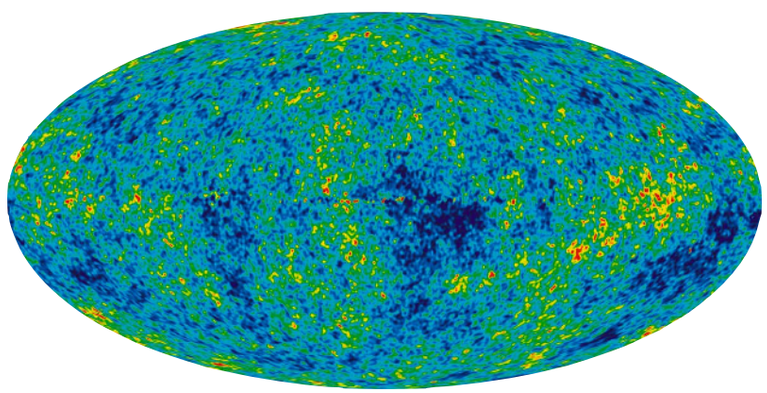
The Nobel Prize in Physics 2019

Ill. Niklas Elmehed. © Nobel Media.

James Peebles

Prize share: 1/2

"for theoretical discoveries in physical cosmology"



https://sci.esa.int/s/Wnqq4bw

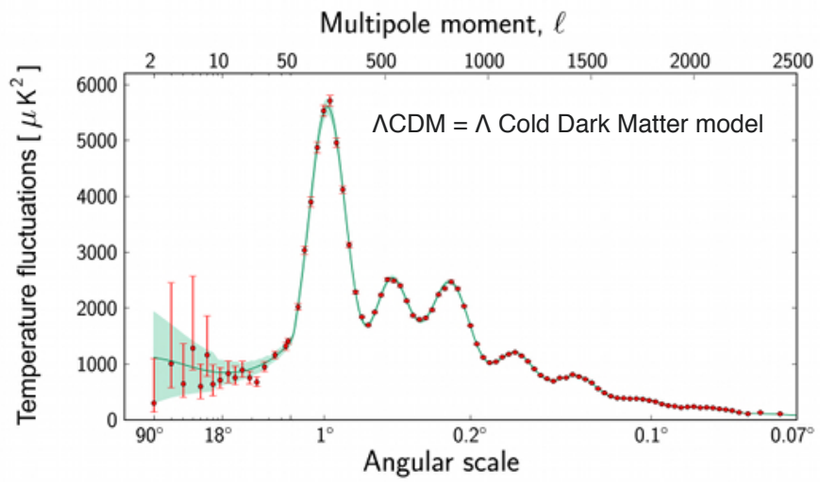
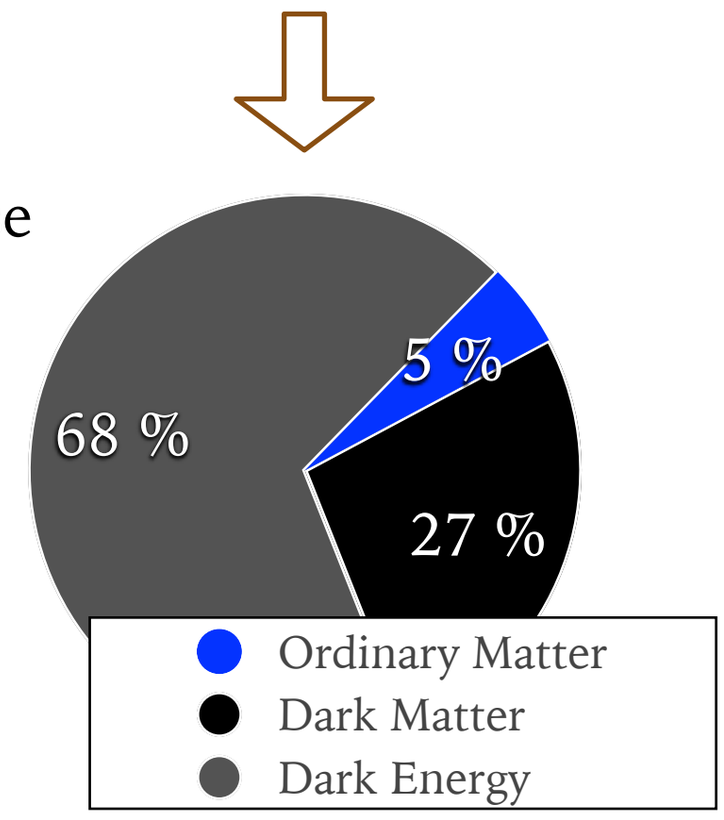


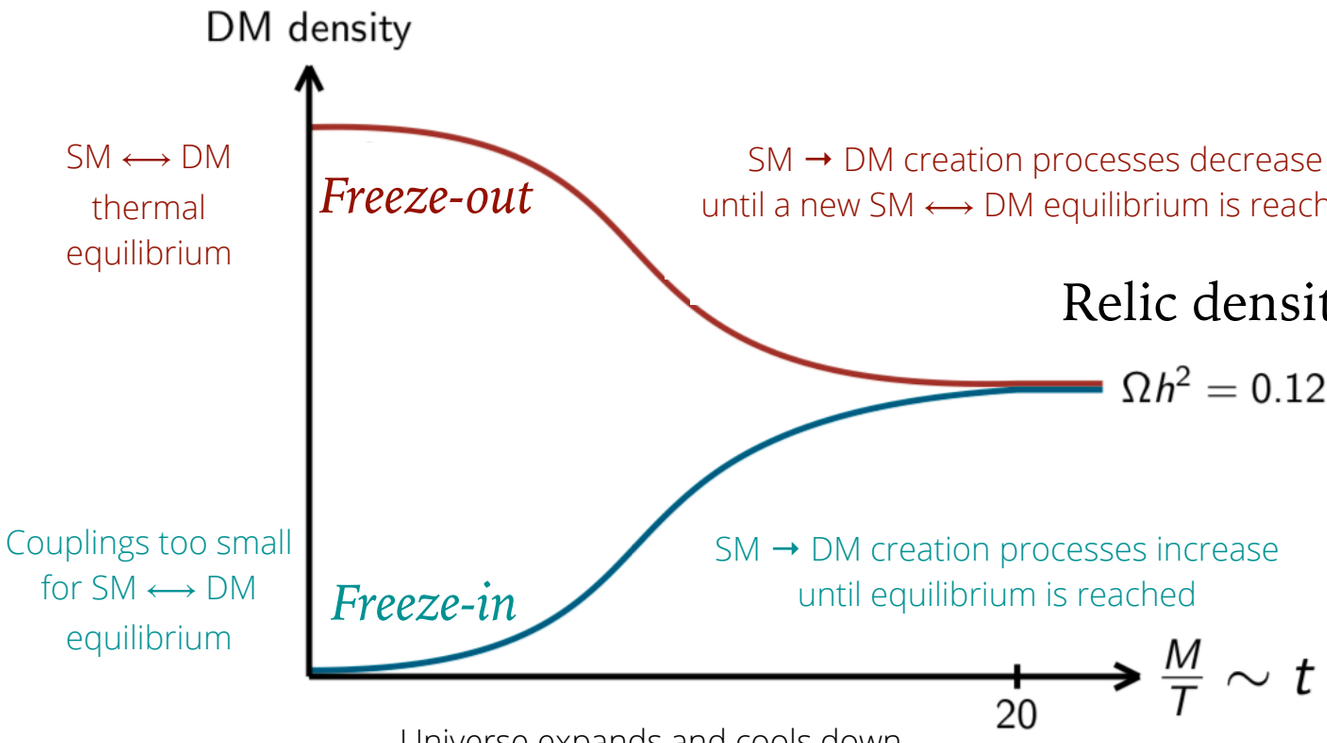
Image: Planck/NASA/ESA

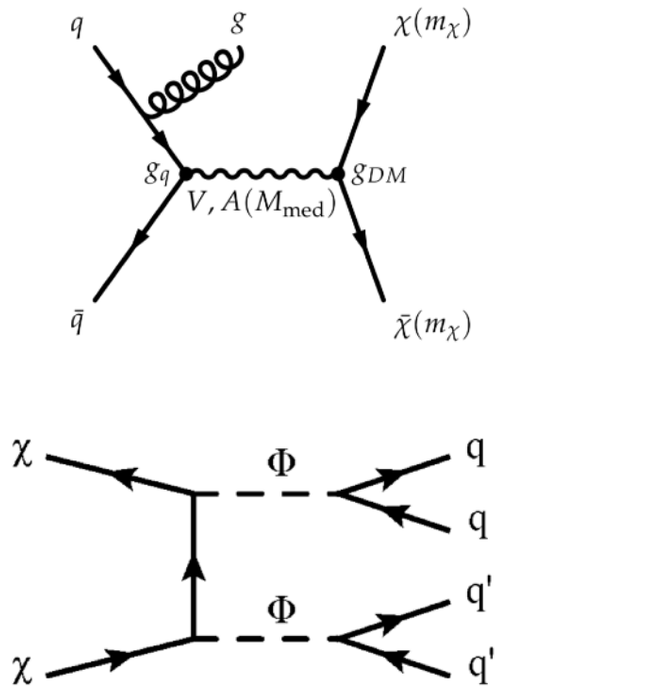
Dark matter constitutes **most of the matter** in the universe

The DM we measure today **[relic DM density]**
already points at some properties of DM candidates
(e.g. dark, stable)
can it **guide us further**?



How did the relic density come to be?





Examples of DM ⟷ SM processes

[Isabelle John's thesis]

Note: simplified picture, for a more complete one see https://arxiv.org/abs/1706.07442

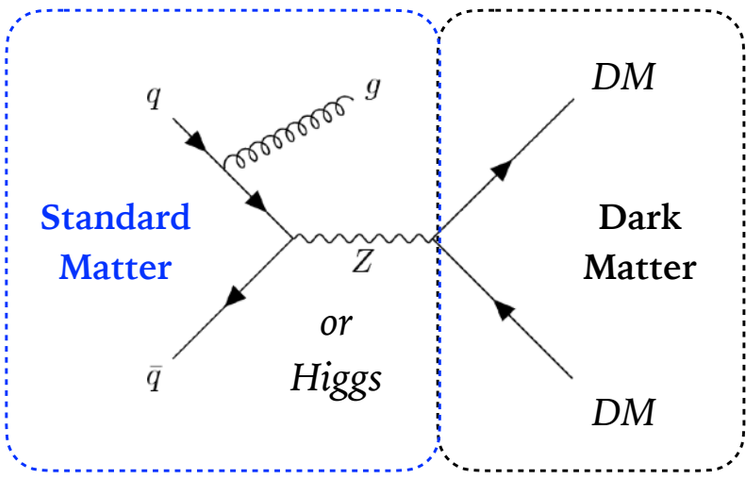
Commonality of many of these models: they require **some form of interaction** (it can be more or less significant) between ordinary matter and dark matter

interaction ⇔ particles & forces

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!*

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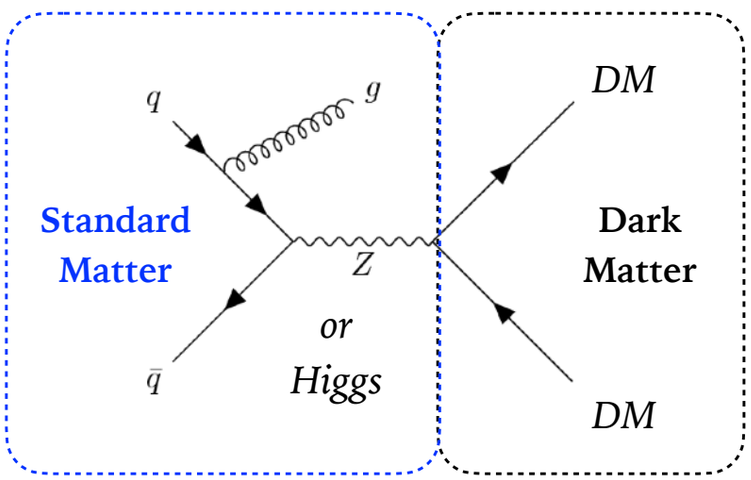

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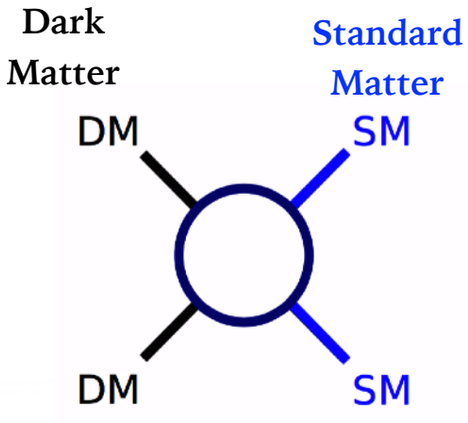
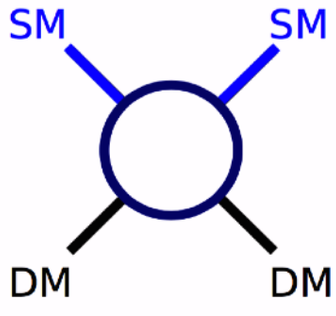
Experimental advantage: many experiments can detect it in different ways

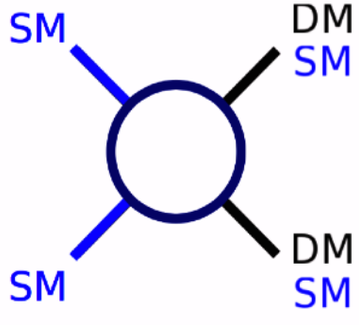
complementary discoveries (main topic of the second part of this talk)



Indirect Detection

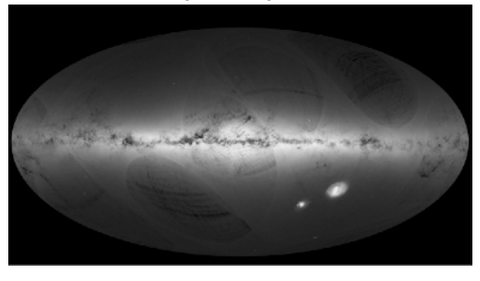


Direct Detection

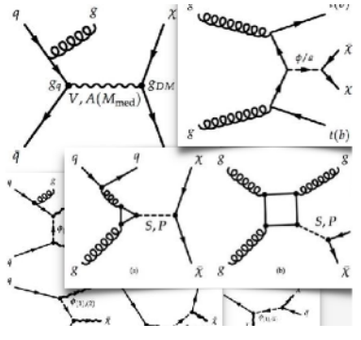


Colliders/ Accelerators

Credit: ESA/Gaia/DPAC.



Astrophysics



Theory input always necessary to contextualize

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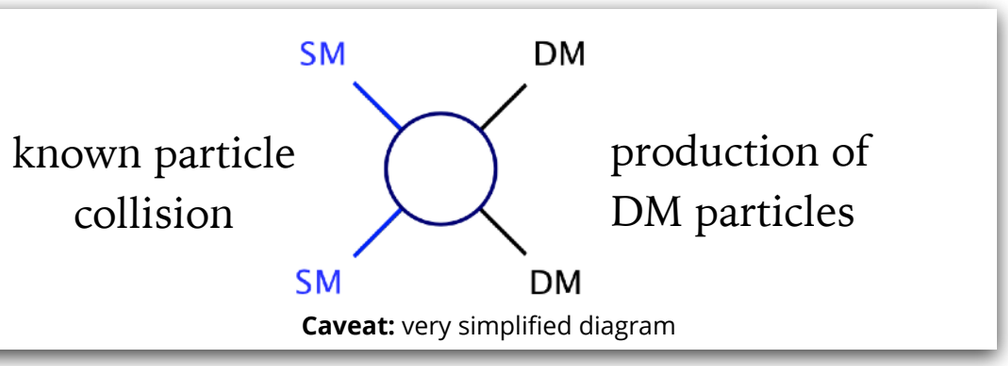
Complementarity within collider searches

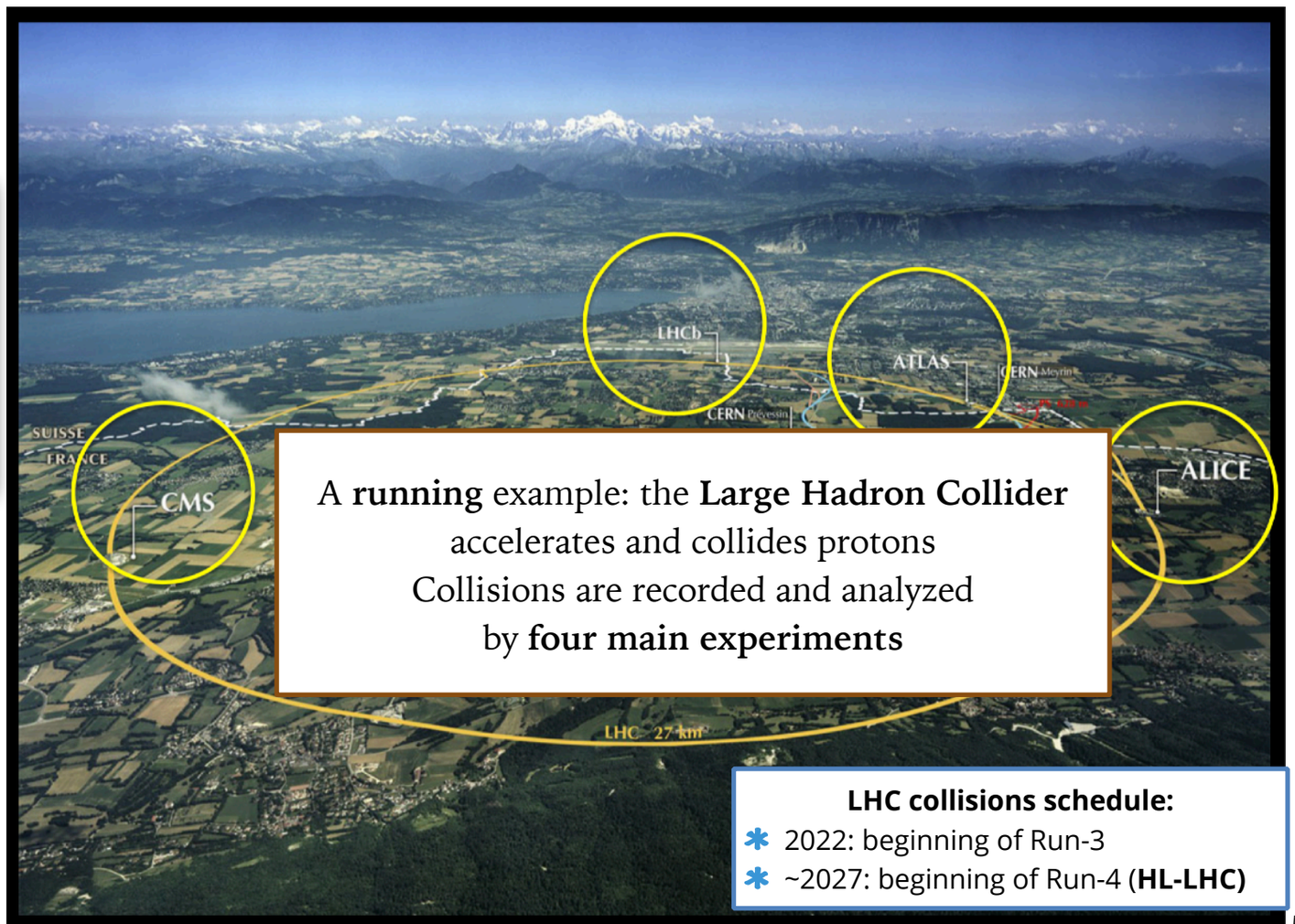
~~Dark matter~~ Invisible particles at colliders

- Starting from our baseline assumption: WIMP DM
  - **interacts with SM** particles → we can **produce and detect it** at

Particle colliders { **LHC** (ATLAS, CMS, LHCb); KEK (Belle-2); ILC, CLIC, CEPC, FCC, muon … (Future) } Collider experiments



Caveat: very simplified diagram



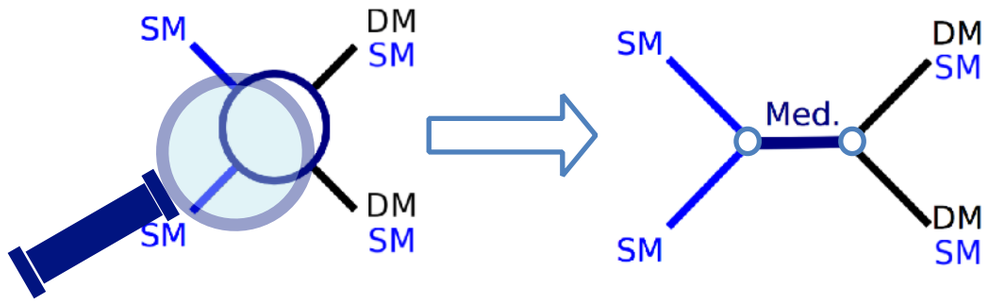
A **running** example: the **Large Hadron Collider** accelerates and collides protons
Collisions are recorded and analyzed by **four main experiments**

LHC collisions schedule:
- 2022: beginning of Run-3
- ~2027: beginning of Run-4 (**HL-LHC)**

Some of the benchmarks for collider WIMP searches

Simple models ⟵ More complex/complete models

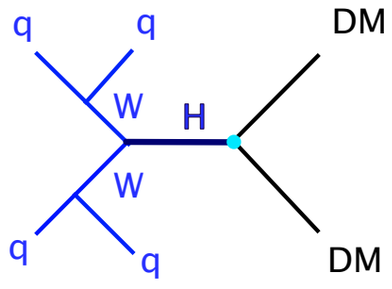
Simple DM mediation



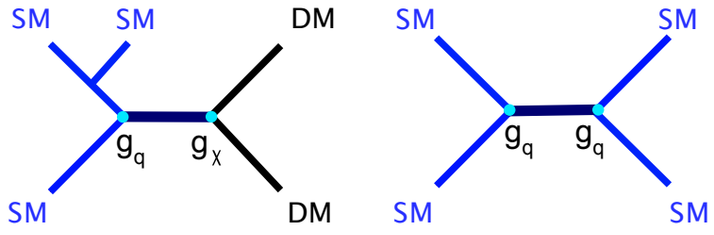
SM mediator

Beyond-SM mediator

Z/Higgs portals

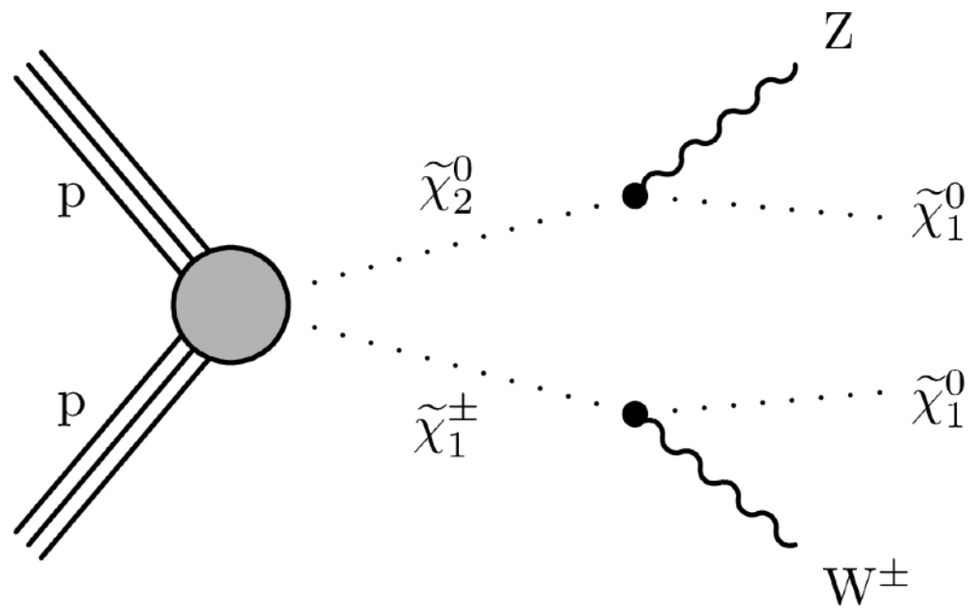


Vector-like mediator



Scalar-like mediator
and Two Higgs Doublet Models

Supersymmetry



(*Simplified model* diagram)

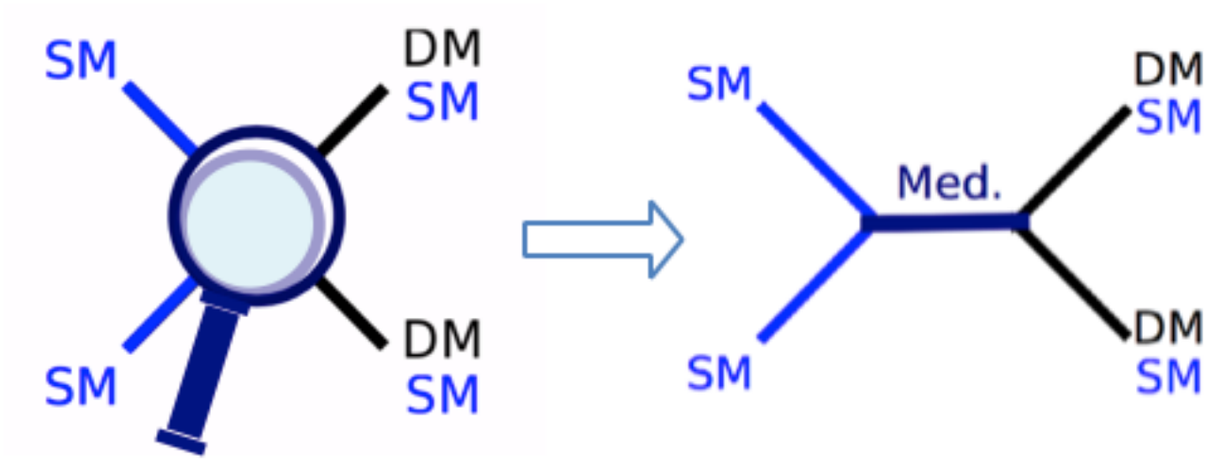
JHEP 03 (2018) 160

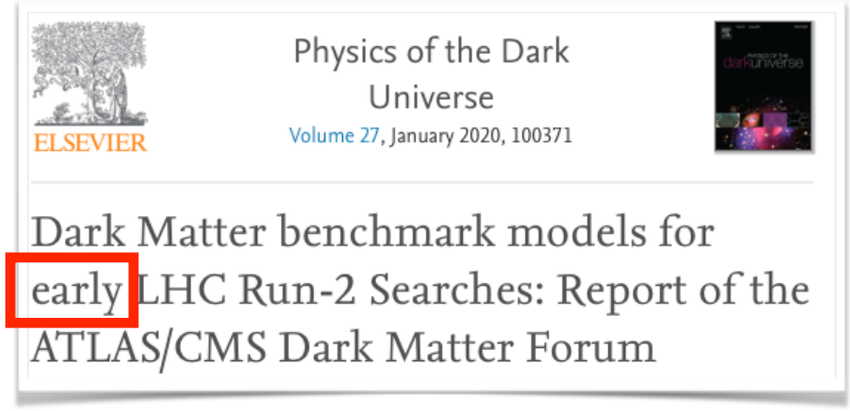
See Monica D'Onofrio's lecture

Also: *DM models with long-lived particles (see Rebeca Gonzalez Suarez's lecture)*

Dark Matter mediators at the LHC

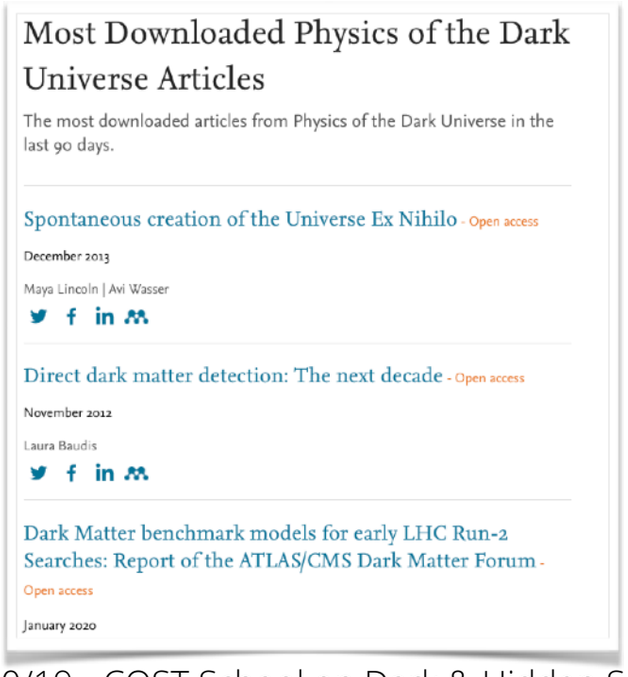
If there's a force other than gravity, there's a **mediator**,
and colliders could **detect** it via its **visible decays**:
(WIMP) *simplified models* have been popular Run-2 LHC search benchmarks





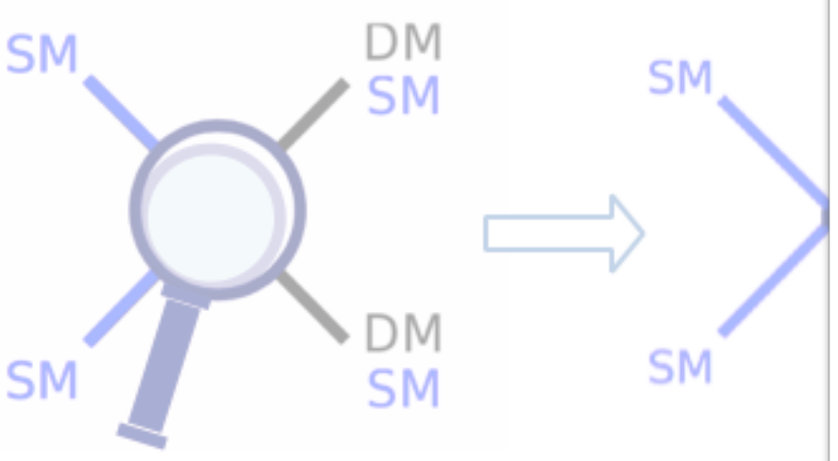
Dark Matter Forum & Working Group

https://lpcc.web.cern.ch/content/lhc-dm-wg-dark-matter-searches-lhc
Phys. Dark Univ. 26 (2019) 100371 & references within
Ann Rev Nucl Part Sci Vol. 68:429-459, 2018 for a LHC review

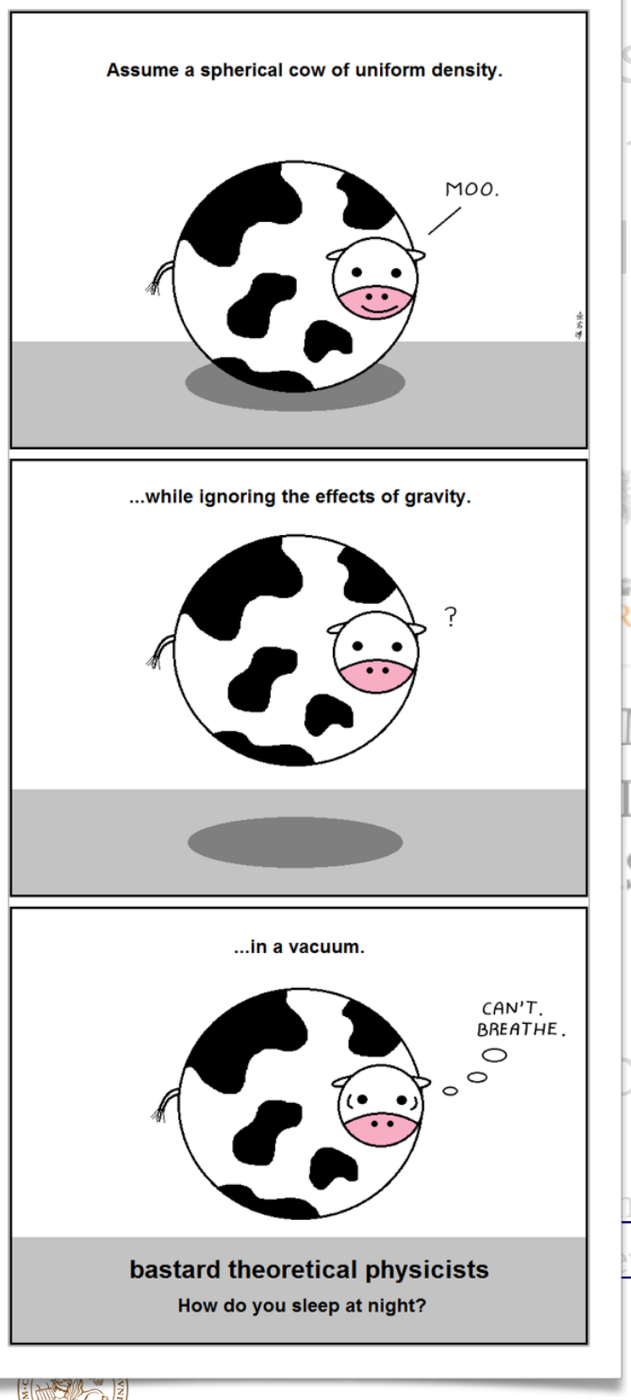


Beware of simple models...

If there's a force other
s a **mediator (/portal)**,
and the LHC could
to **visible particles**:
simplified/portal mode
ler search benchmarks



https://abstrusegoose.com/406



Physics of the Dark Universe
Volume 27, January 2020, 100371

Matter benchmark models for
LHC Run-2 Searches: Report of the
S/CMS Dark Matter Forum

LHC Dark M
orking Group

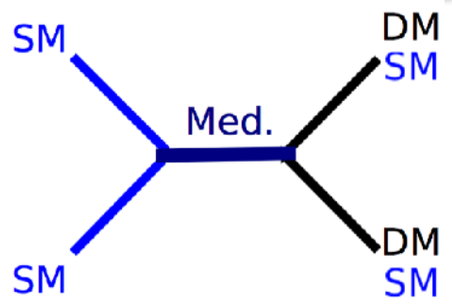
https://lpcc.web
atter-searches-lhc
Phys. Dark Univ. 26 (2019) 1
ev. Nucl. Part. 68:429-459, 2018

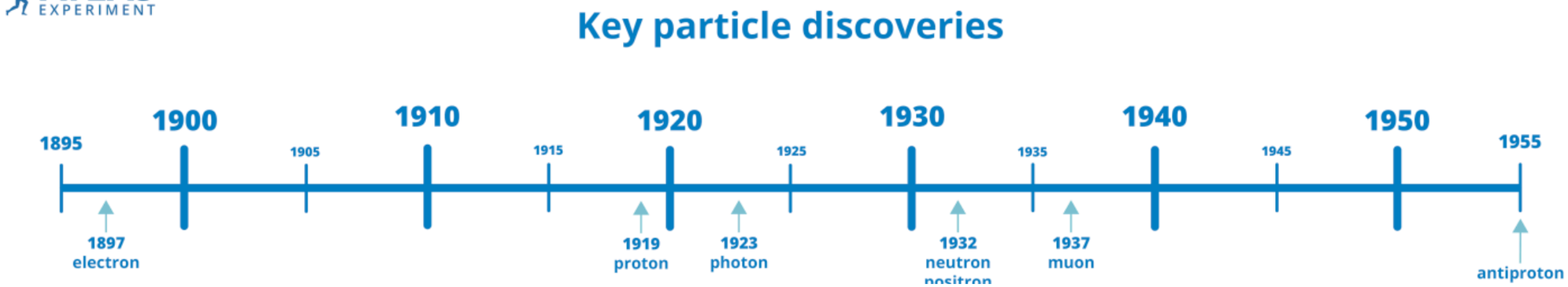
...but not all hope is lost!

"Why should we choose/believe the simplest models?"

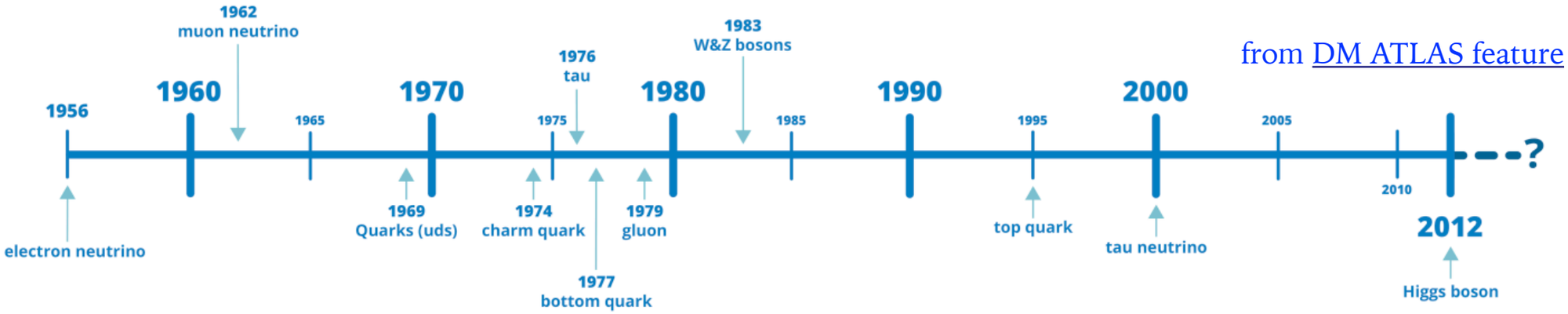
"Do we think DM is all made of a single (WIMP) model?"

(not really…see dark sectors later!)





- **Lesson from SM:** most common particles discovered first



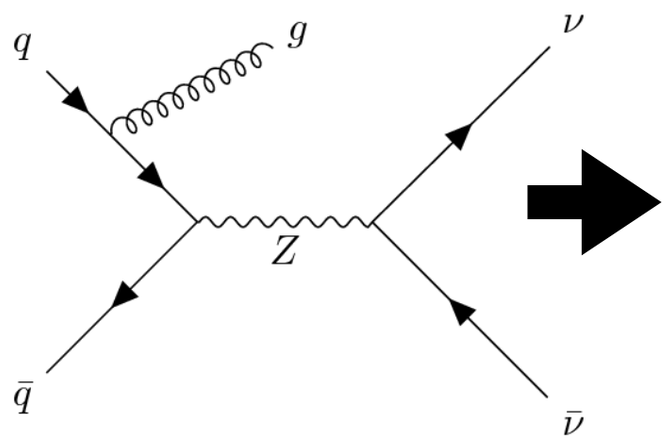
from DM ATLAS feature

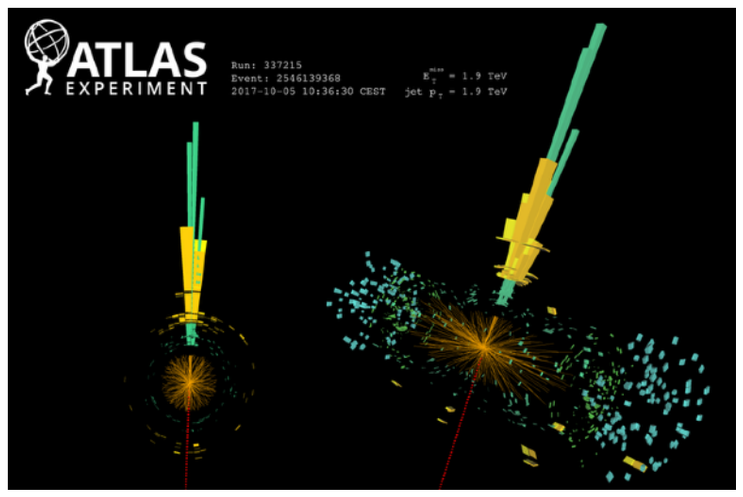
- Even simple models can encapsulate **relevant experimental characteristics** representing wider classes of theories

as long as we are aware that they can be more rare than what we choose as example

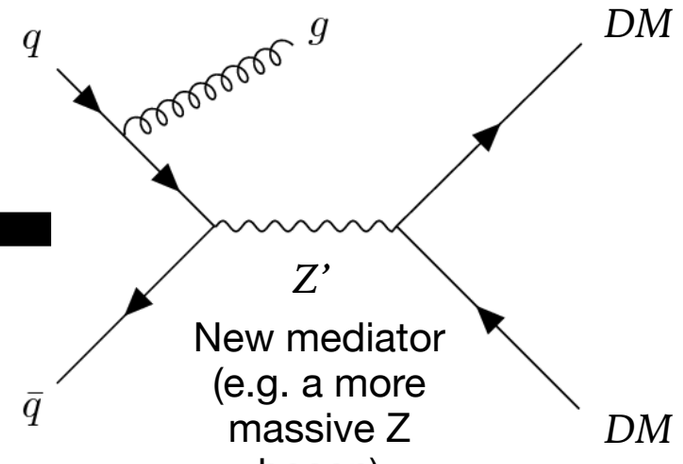
A generic search for WIMP DM: "*X+MET*"

Background (frequent)

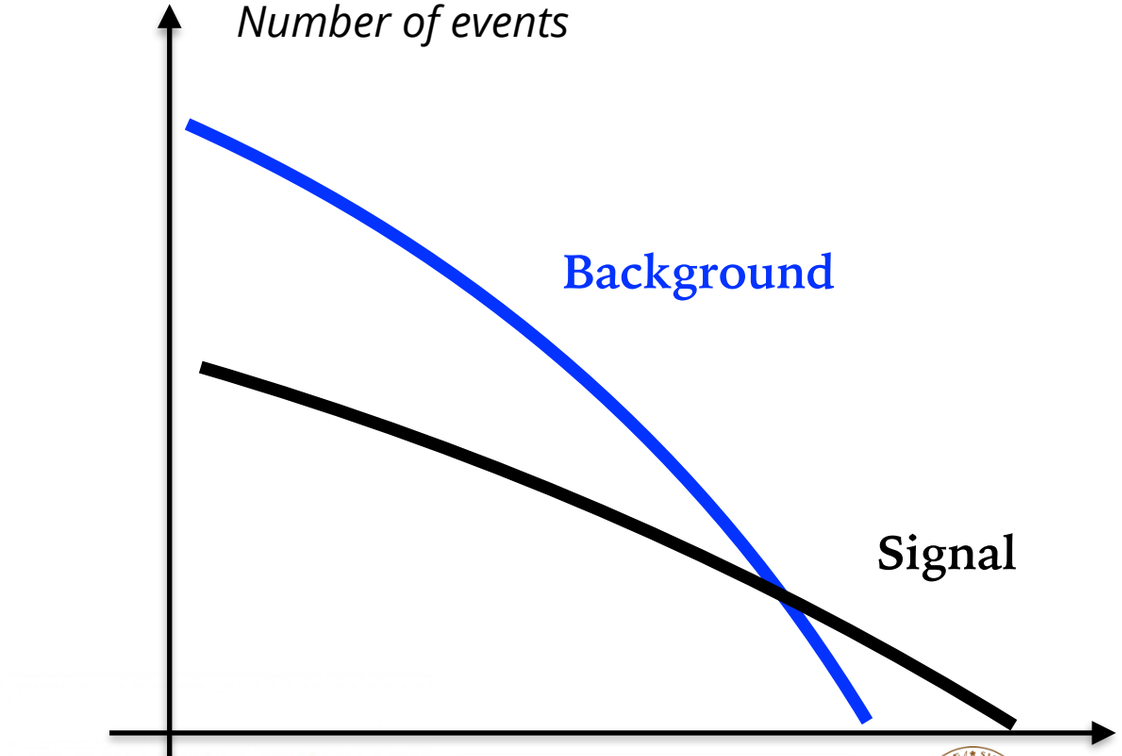




Signal (rare)



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



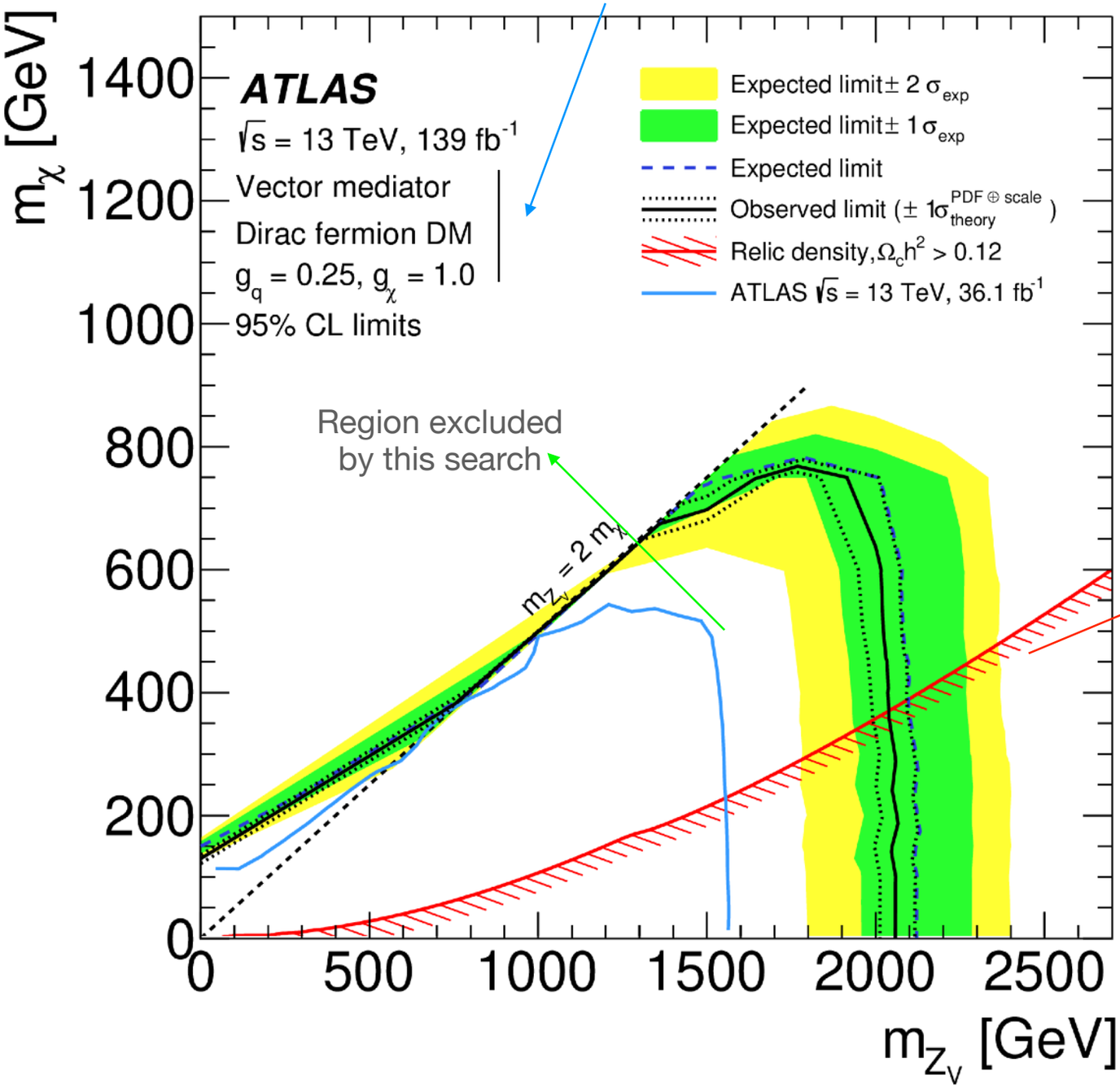
X = (jet, photon, W/Z boson…) + MET search

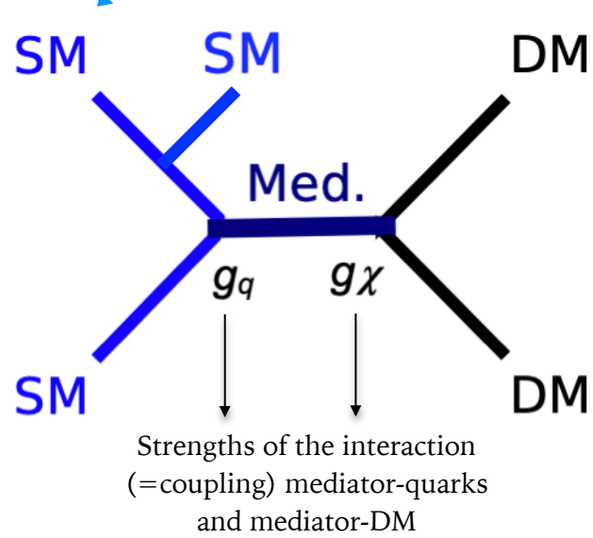
- Look for an excess of events with high MET over the SM background
- Background shapes need precise EPJC 2017 77:829 theory predictions (*precision search*)

See Monica D'Onofrio's lecture

A DM interpretation of LHC jet+MET search

arXiv:2102.10874 Model assumptions - more models can be/are tested





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

Model produces too much DM

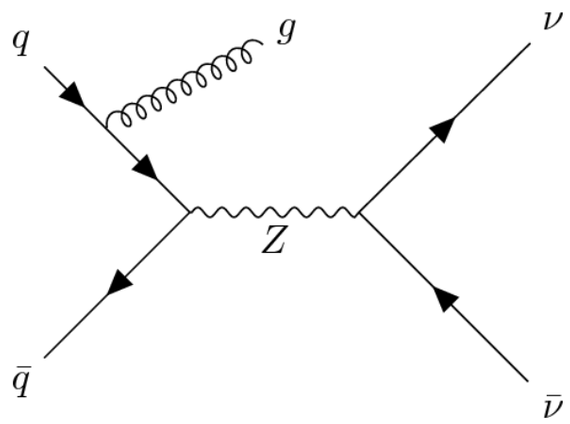
Other interpretations:

- Different kinds of mediators
- Supersymmetric models
- Extra dimensions
- Axion-like particles

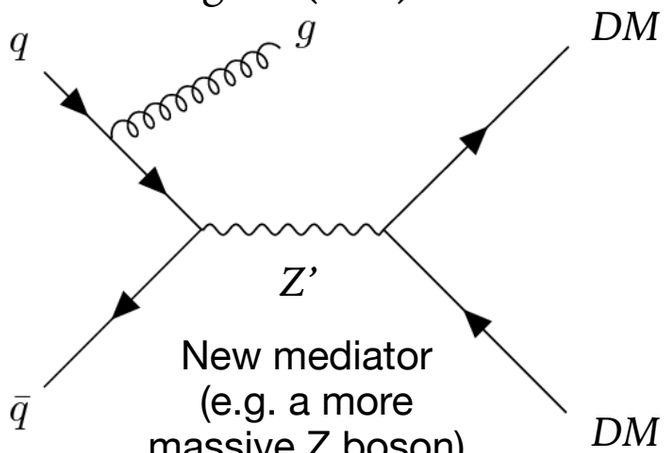
Parallels: visible and invisible mediator-based searches

Detection of **DM** (invisible particles) **from a mediator**

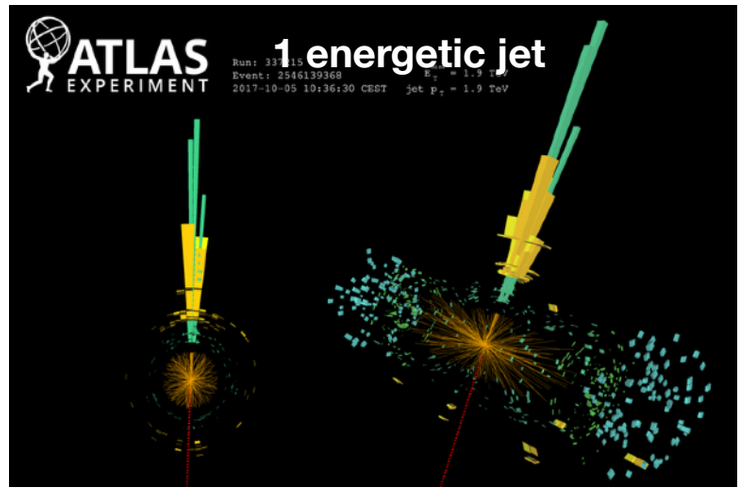
Background (frequent)



Signal (rare)



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



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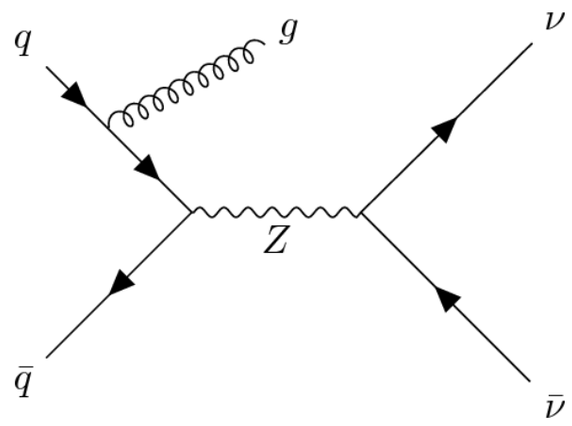
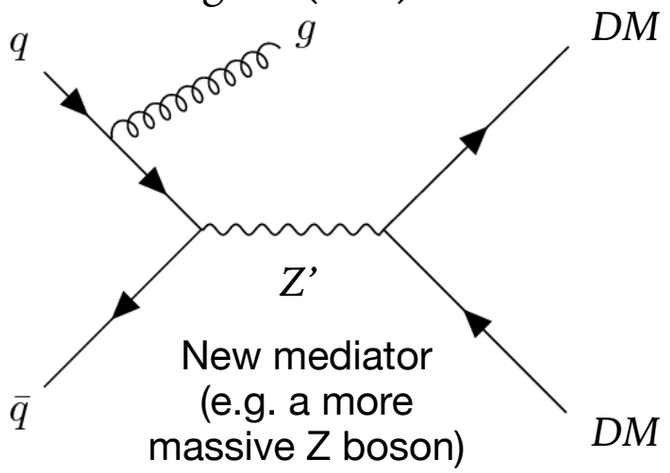


Signal (rare)



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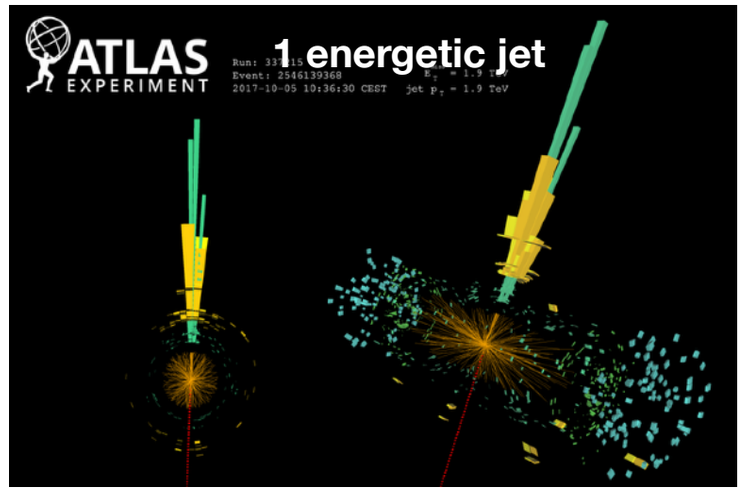
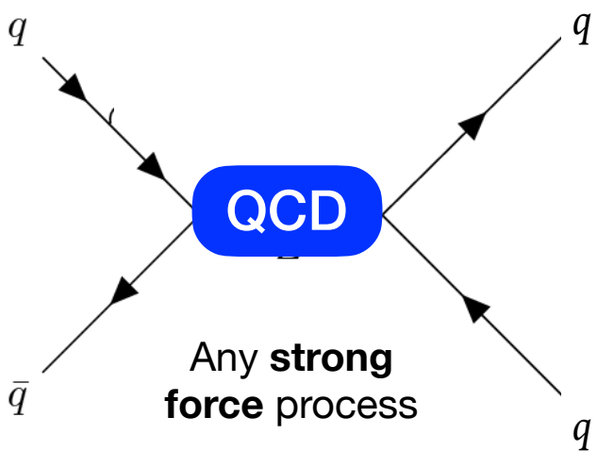


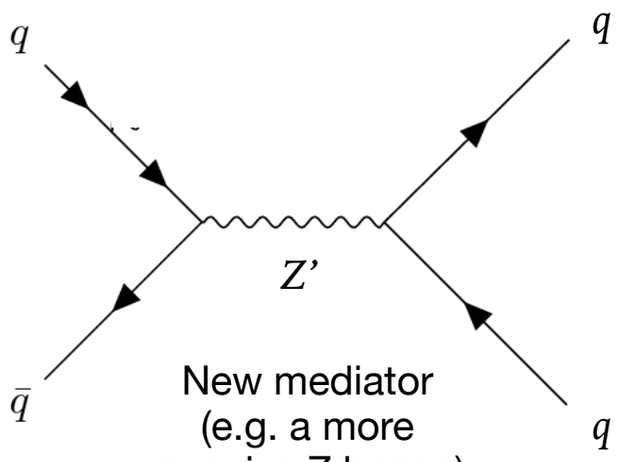
Detection of the DM **mediator**, via its **visible** (hadronic) **decays**:

Background (very frequent)



Any **strong force** process

Signal (rare)



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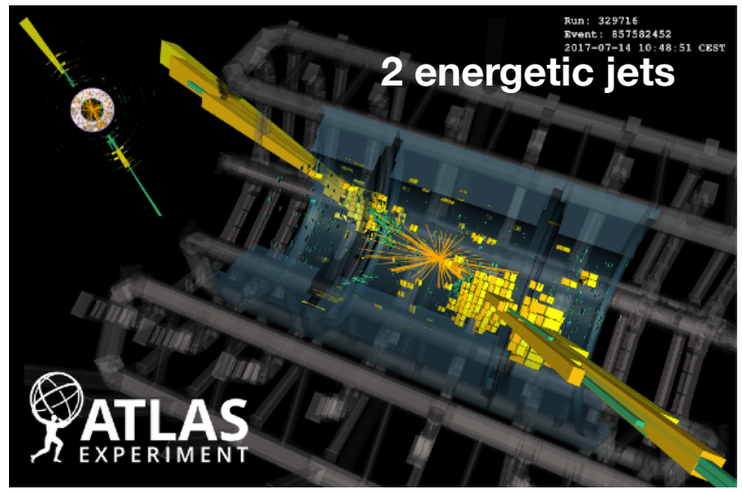
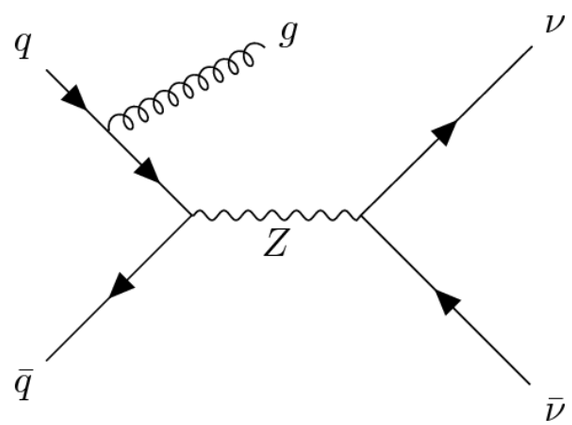


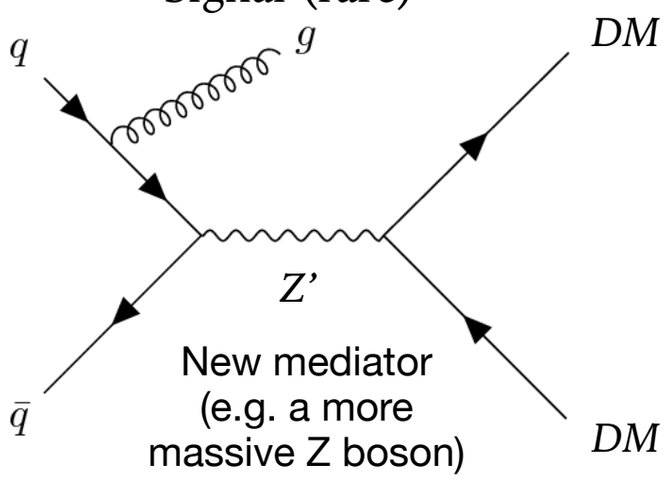
Parallels: visible and invisible mediator-based searches

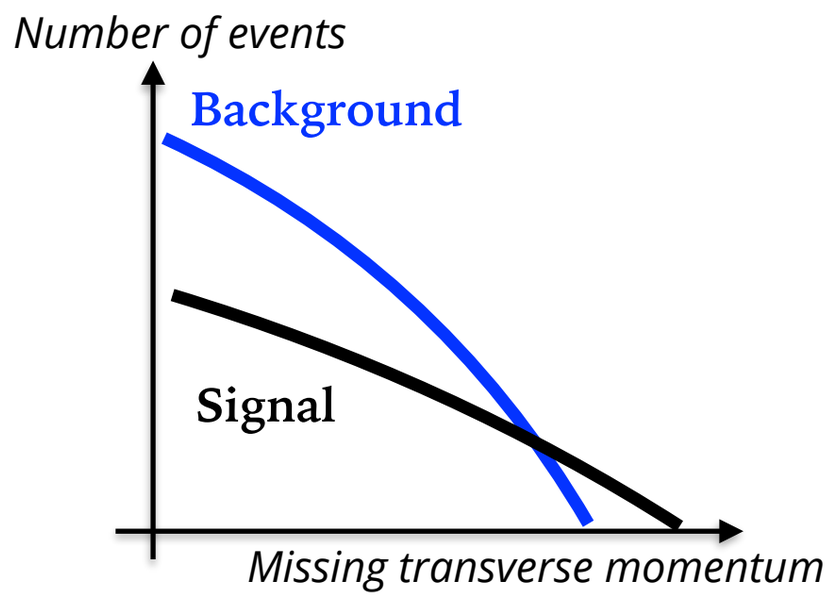
Detection of **DM** (invisible particles) **from a mediator**

Background (frequent)



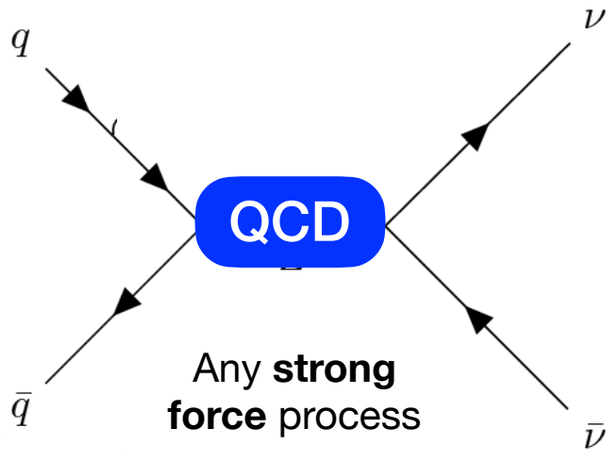
Signal (rare)



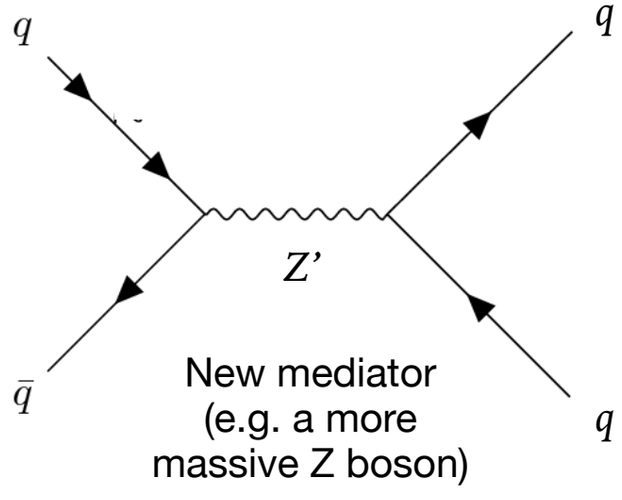


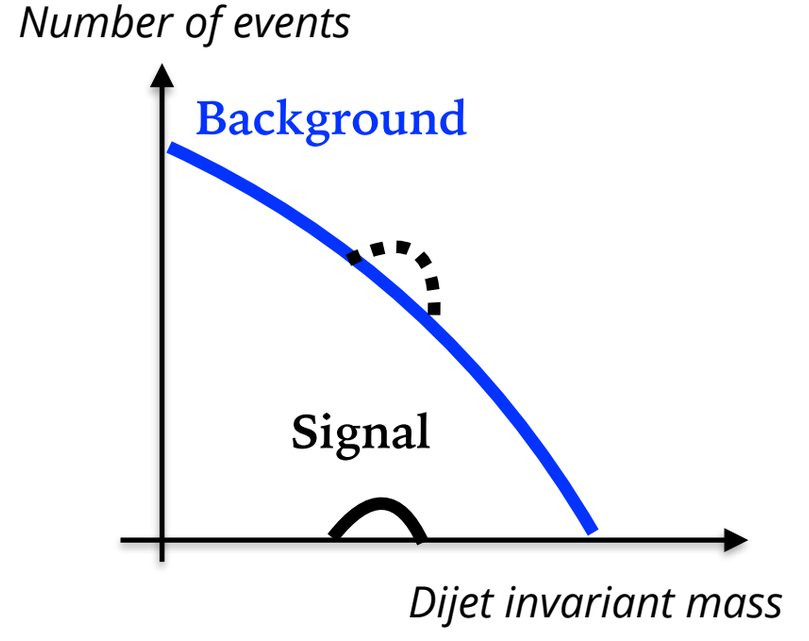
Detection of the DM **mediator**, via its **visible** (hadronic) **decays**:

Background (very frequent)



Signal (rare)

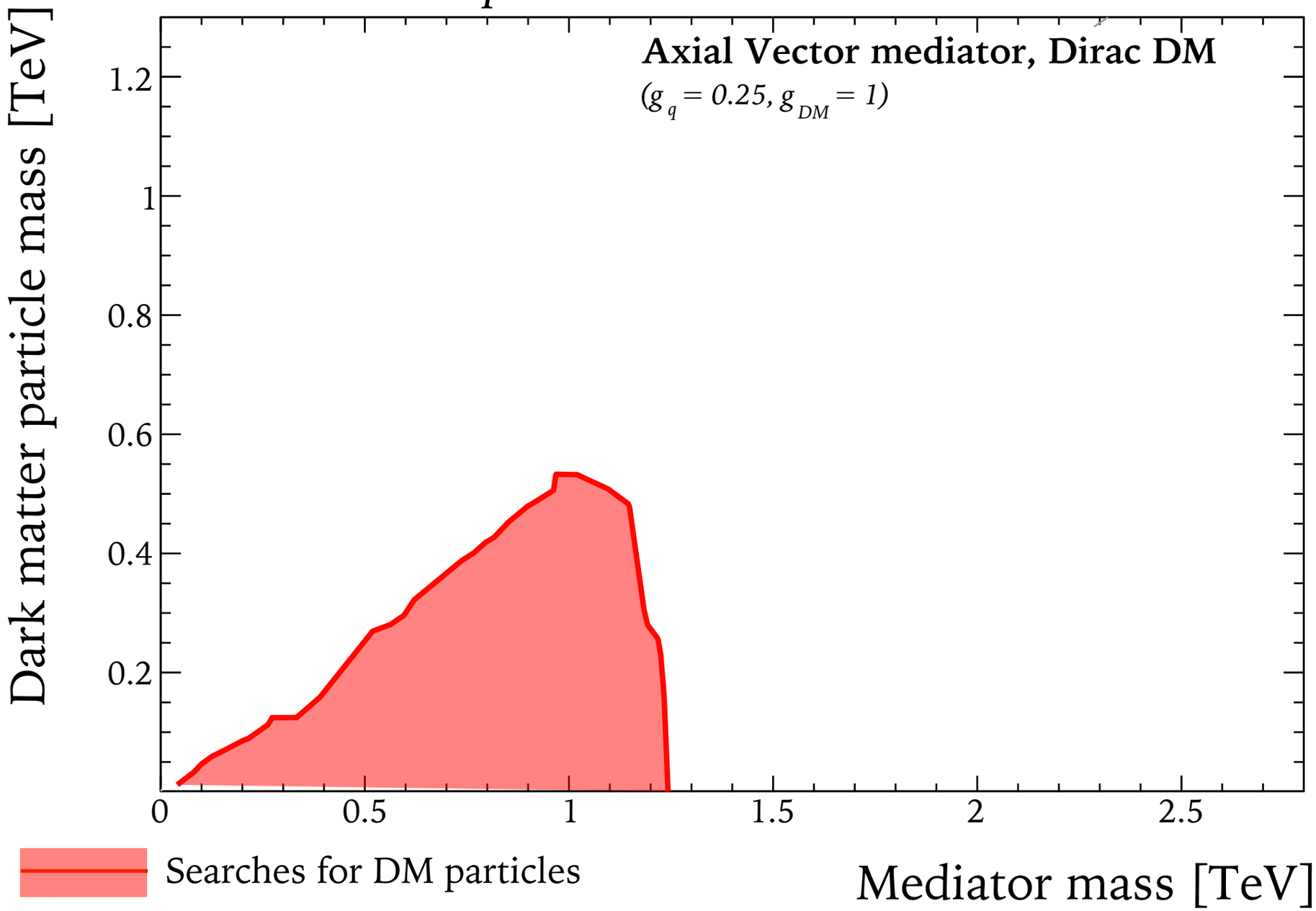




Complementarity of visible/invisible searches

Illustrative example

LHC Dark Matter Working Group
Phys. Dark. Univ. 26 100377 (2019)



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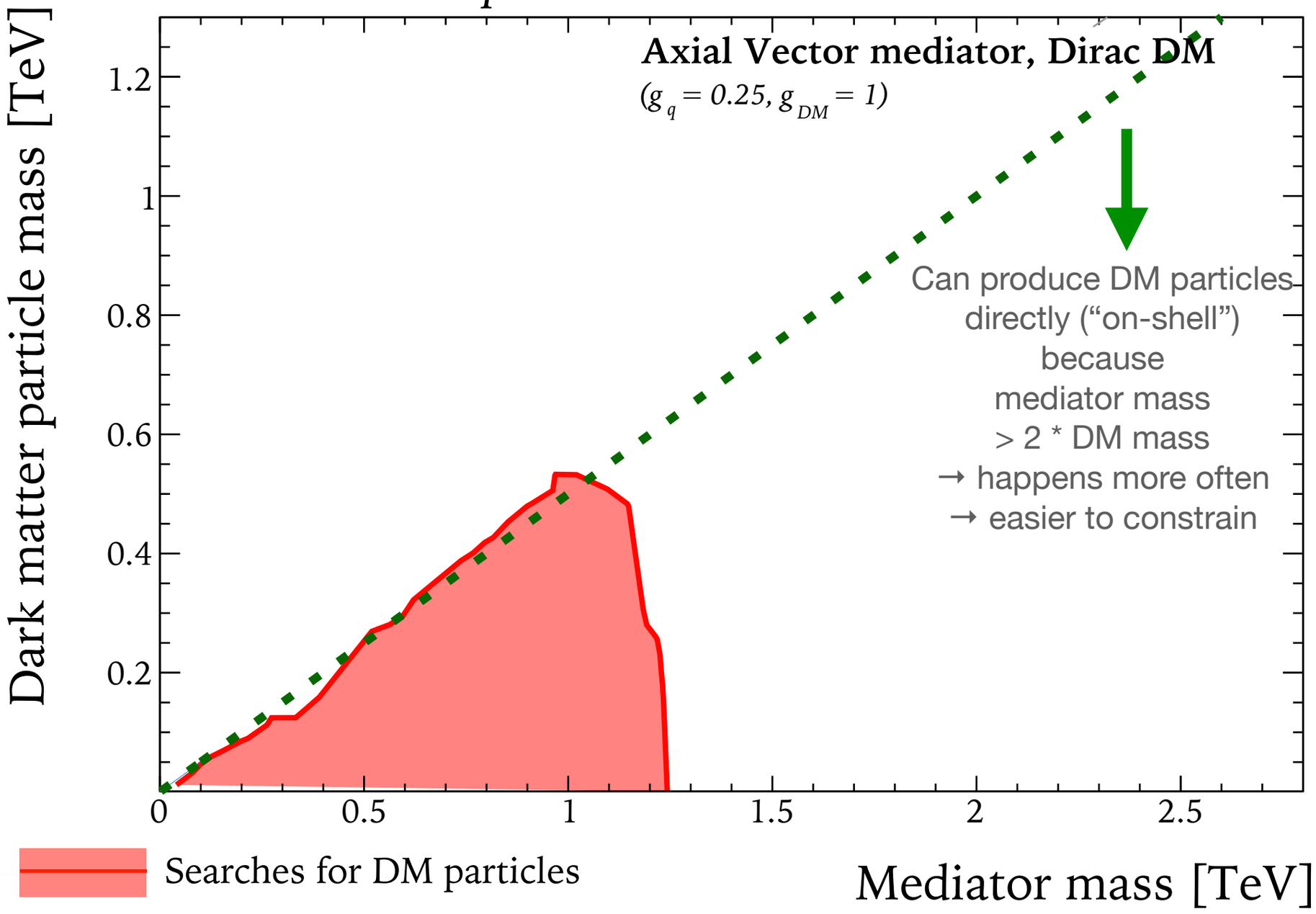

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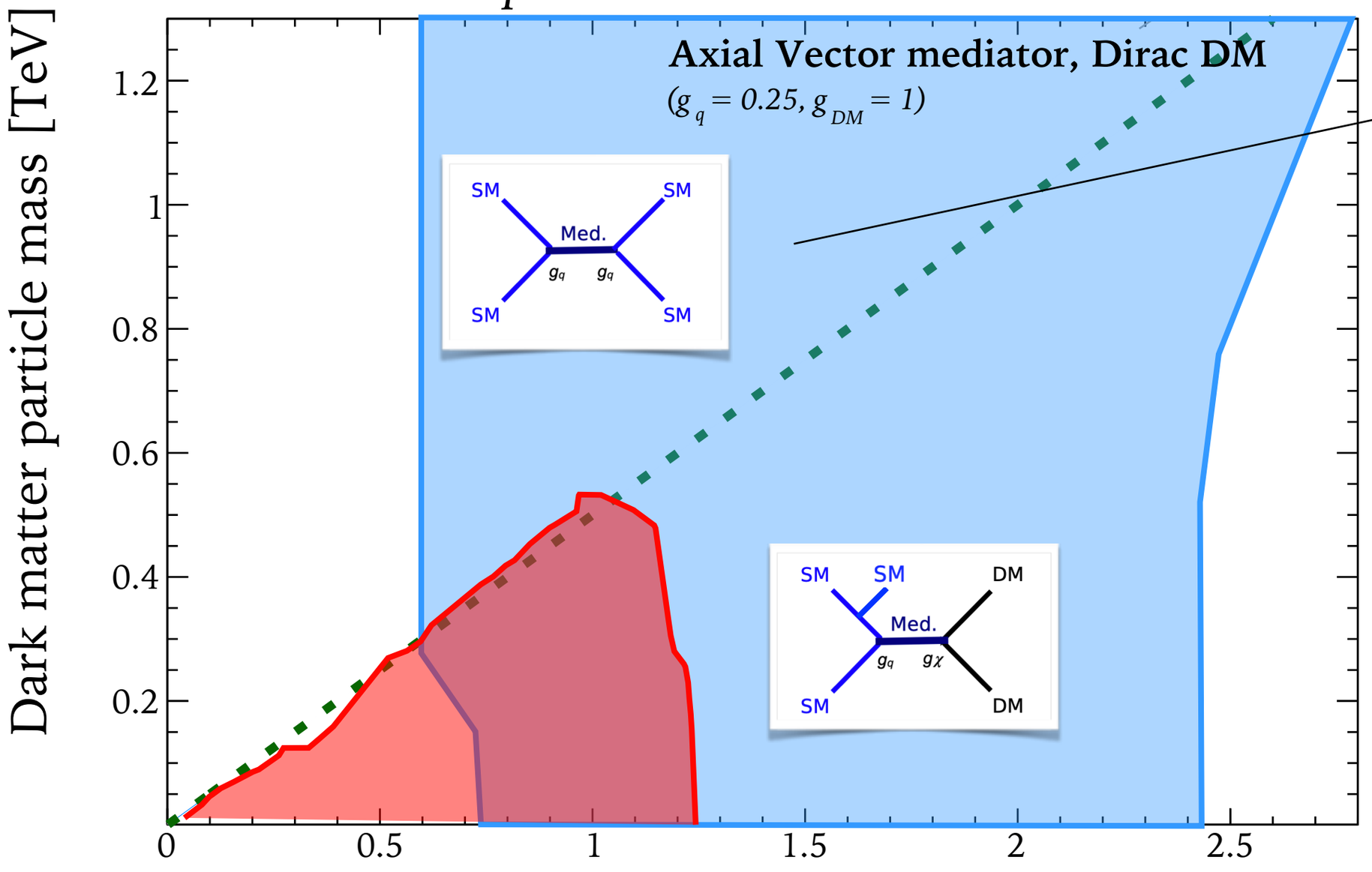


For mediator decays into quarks, the DM mass isn't too relevant (especially when they dominate)

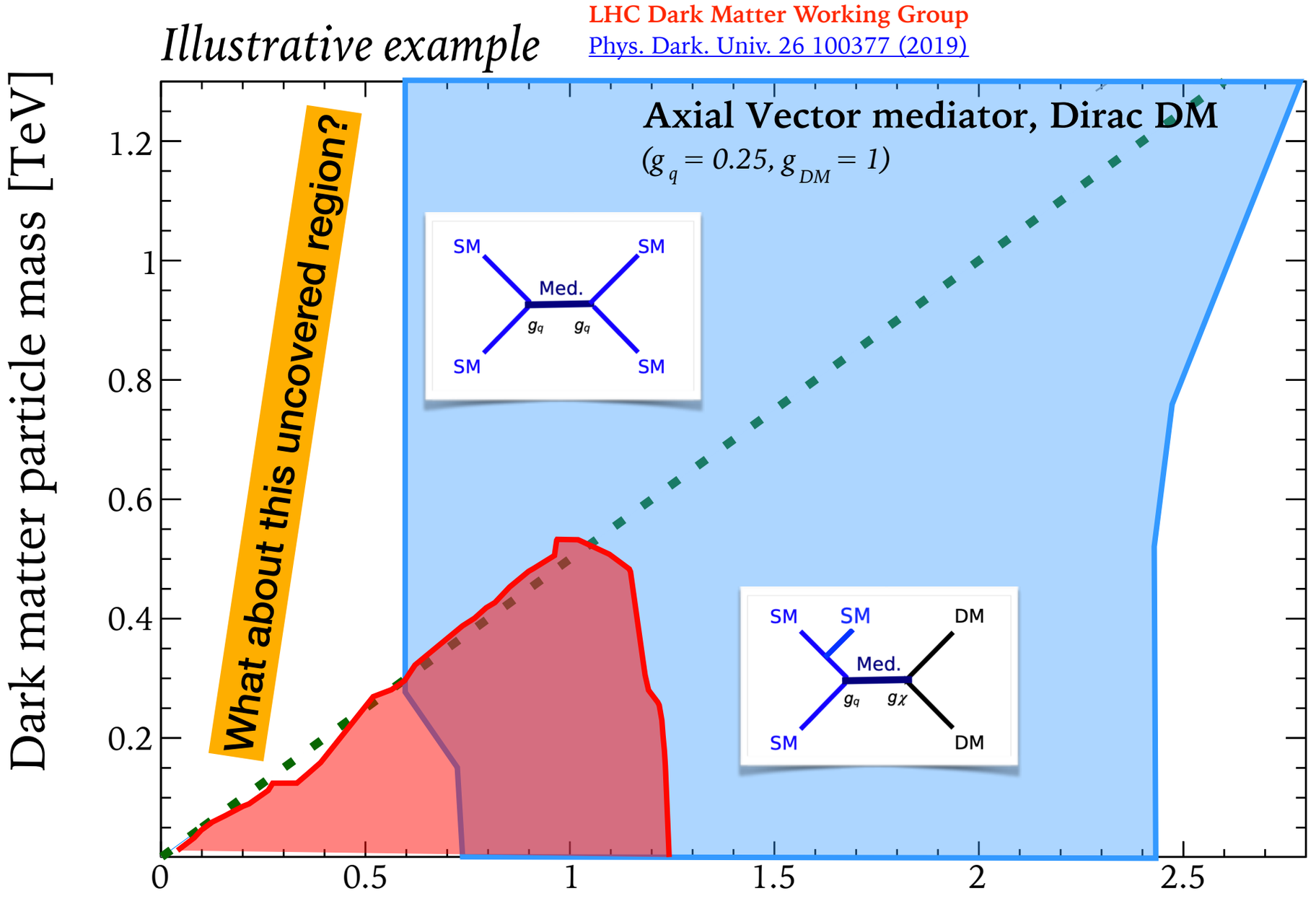
Possible to constrain the parameter space even if DM is too heavy to be produced at the LHC

However, we need a connection between a dijet discovery and a DM discovery… *more later!*

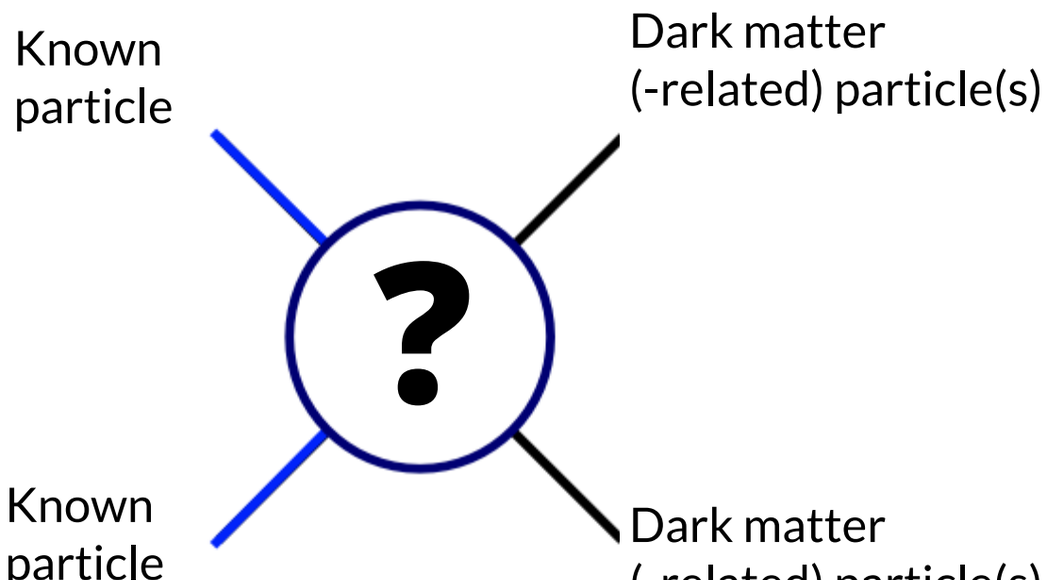
Searches for DM particles

Dijet searches for DM mediators

Complementarity of visible/invisible searches



Recreating dark matter/dark sectors in the lab: challenges



Trying to stay
as **model-agnostic** as possible,
while exploiting what the **LHC** is good at:
focus on the presence of a **resonance**
(alongside EFTs/more complete theories)

added bonus: resonance searches are bread&butter at colliders → robust analysis toolkit available

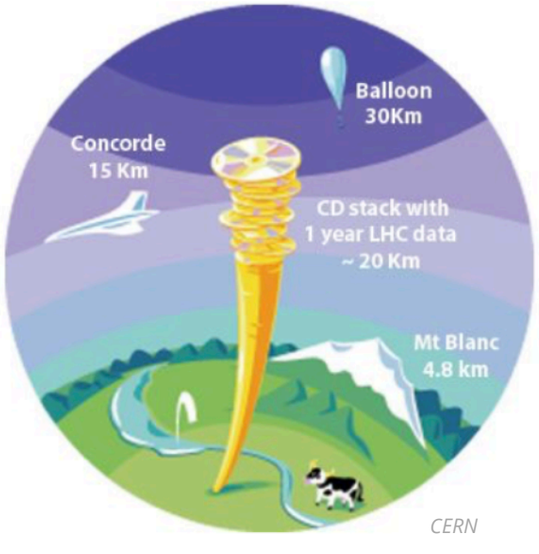
Challenges:

1. This kinds of processes are very **rare**
2. Many other processes may look the same (→large **backgrounds**)
3. Often **we don't know** how the resonance decays look like

These challenges can be met with non-standard analysis workflows!

A "Big Science" problem to solve: *too much data*

- The **dark matter signals** we are looking for are **rare**
  → need enormous amount of collisions to produce them
- Their **backgrounds** look the same and are **much larger**
- **Problem:** recording all LHC data takes 400000 PB/year [Ref]
  - up to 30 million proton-proton collisions/second (MHz)
  - ~ 1-1.5 MB/data per collision event, including raw data
- FCC-hh plans to collide beams up to every 5 ns (now: 25 ns)
  - and Moore's law / storage costs don't scale as fast as that yet



CERN

after selection of "interesting" data

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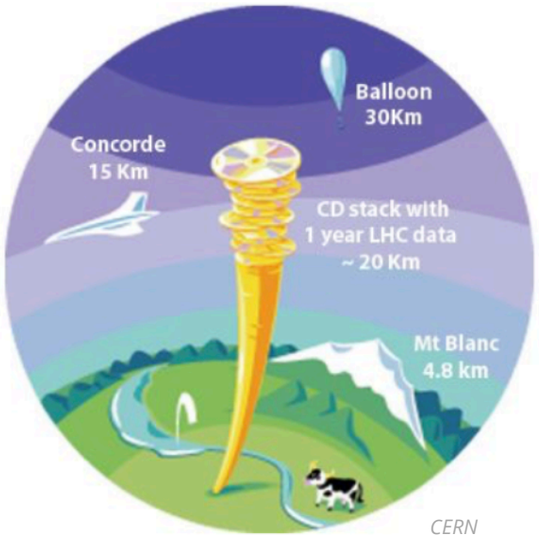


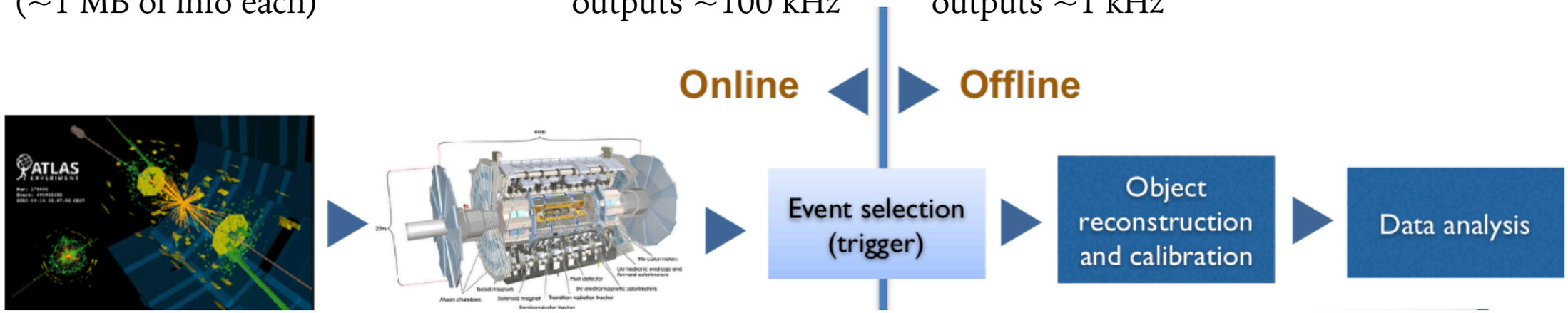
LHC & future hadron collider experiments need to select "interesting" events (=*trigger*) **in real-time** (milli/microseconds)

after selection of "interesting" data

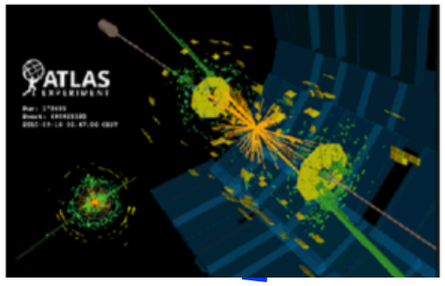
Collisions at ~30 MHz
(~1 MB of info each)

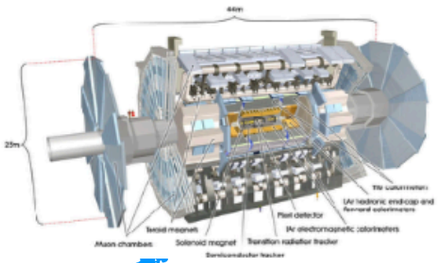
Hardware trigger
outputs ~100 kHz

Software trigger
outputs ~1 kHz



Online | Offline





Event selection (trigger) → Object reconstruction and calibration → Data analysis

Data produced by the LHC
(multiplied by large number)

Data I like

...maybe discoveries?

Data I would have used to like if I had been a data hipster

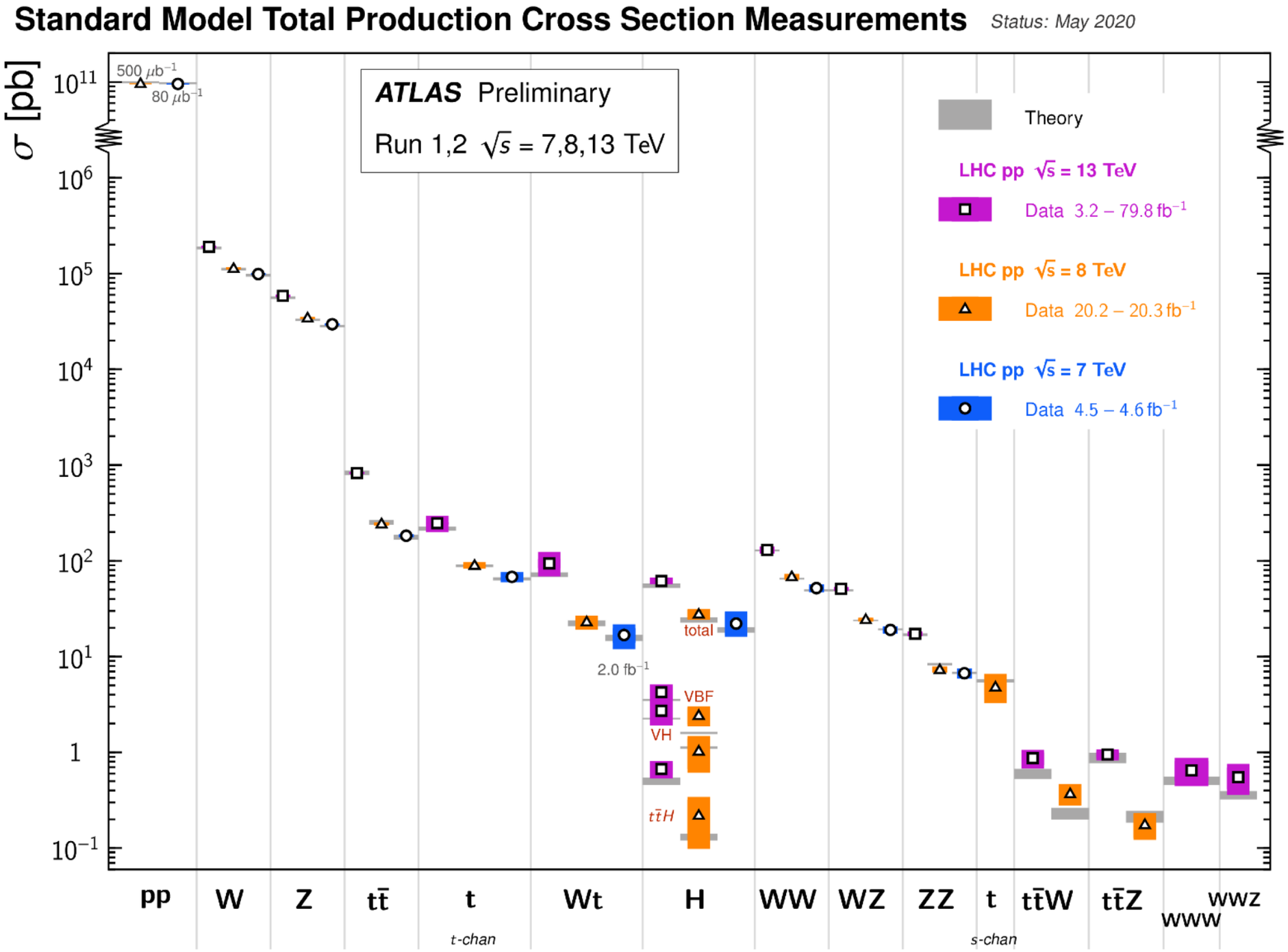
Data you like

What we can record in full after the trigger

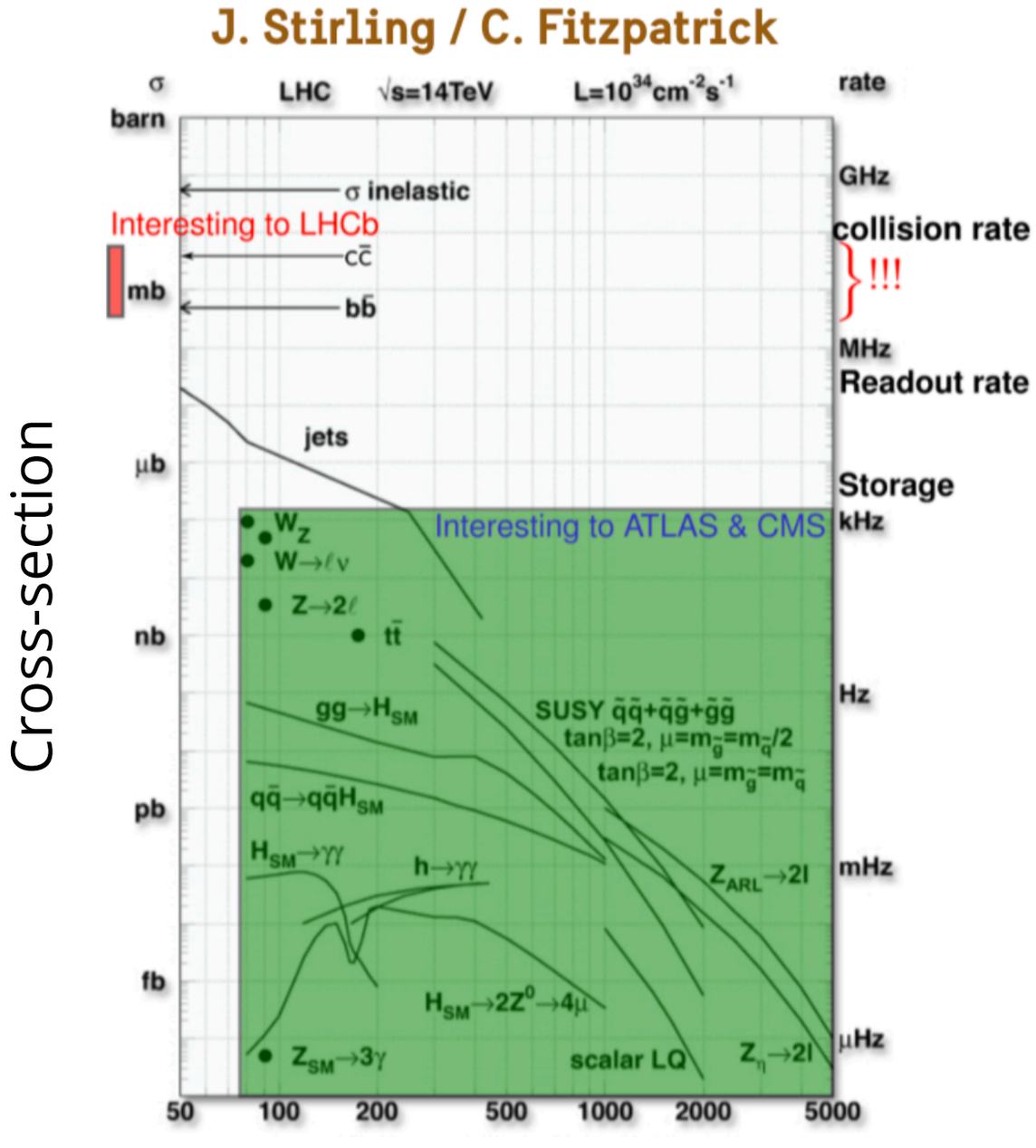
Data ~nobody likes

This works for a number of LHC measurements (& searches…)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2020-010/



What is interesting at the LHC/at hadron colliders?



Cross-section * Luminosity
= number of events produced

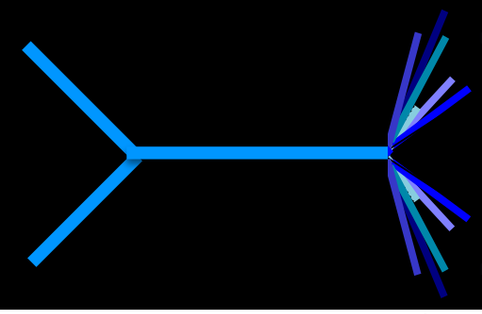
Challenges:

The **definition of "interesting"** changes experiment by experiment

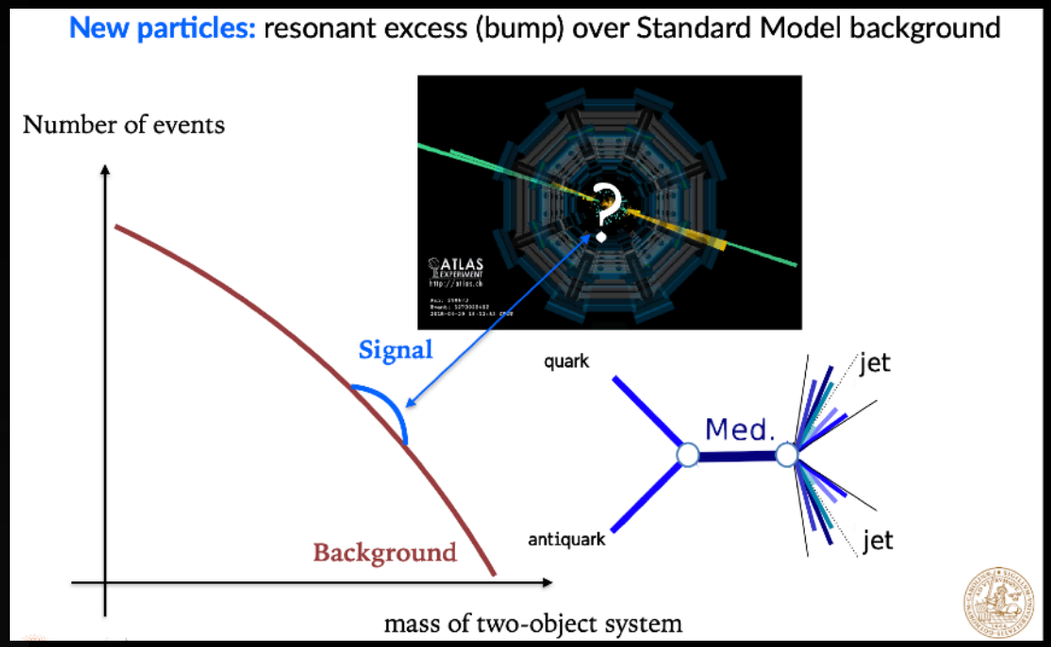
Rare signal processes that are buried in **high-rate backgrounds** have to be discarded

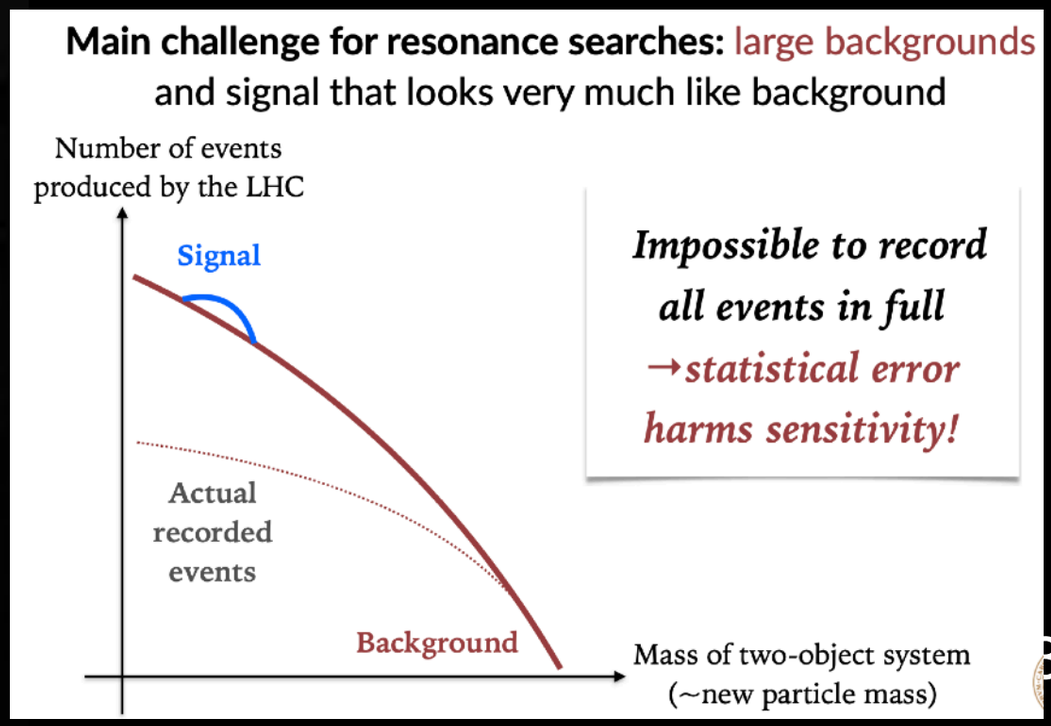
Are we missing rare hadronic processes?

Events selected by the trigger



DM mediators

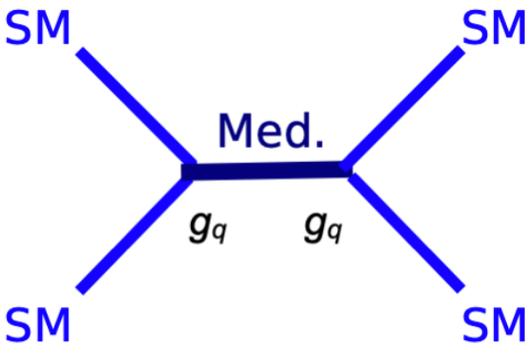




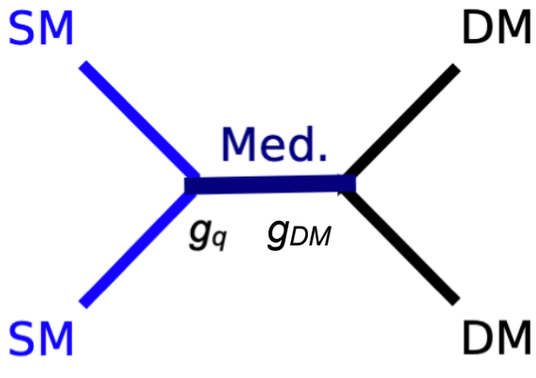
Example: dijet decays of DM mediators, ca 2013

Selecting interesting events works for most of the LHC physics program...
...but it is not optimal for rare processes with high-rate backgrounds:
we cannot record and store all data, and trigger discards both background and signal

This prevented us from being sensitive to low-mass DM mediators decaying into jets

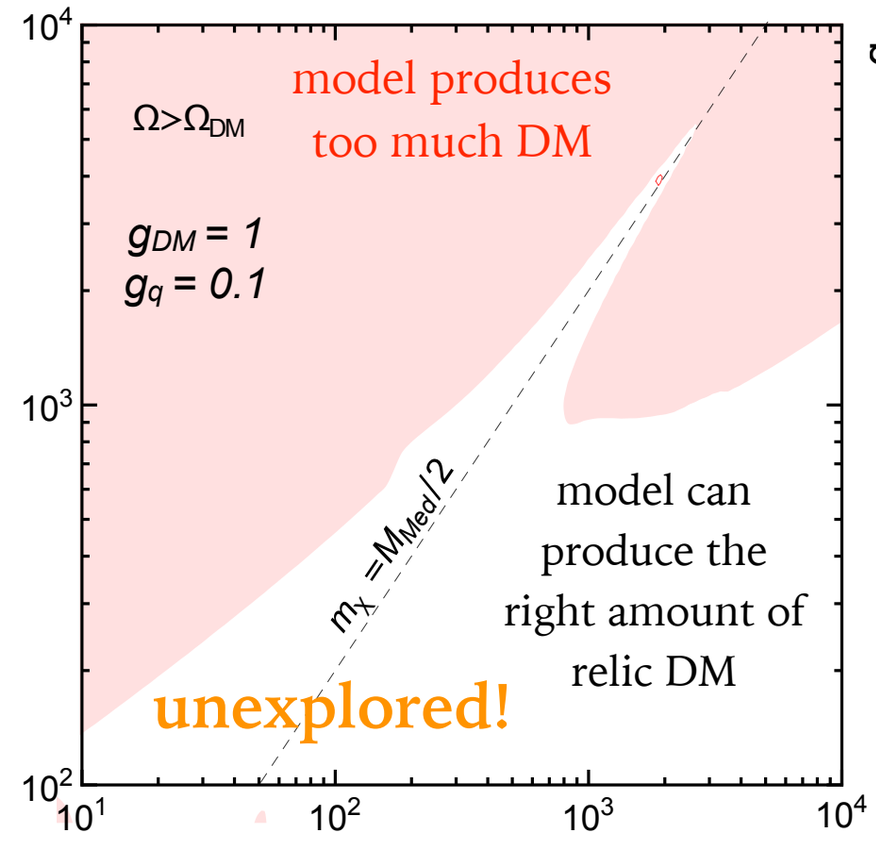


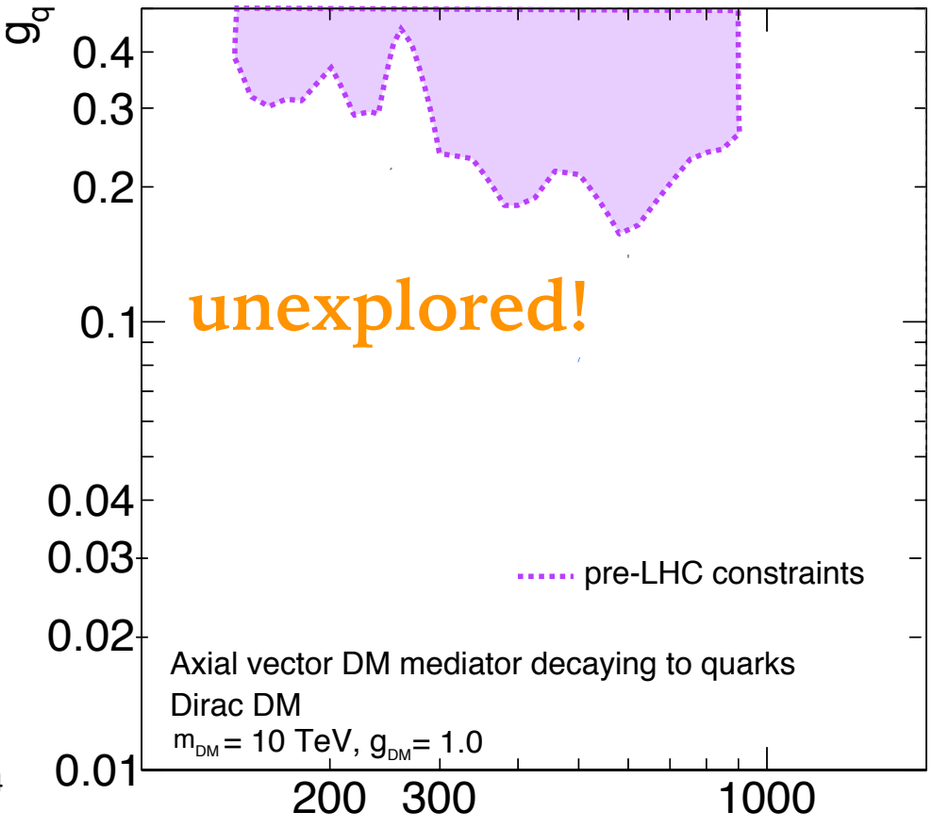
Visible mediator decays



Invisible mediator decays

Adapted from JHEP 1507 (2015) 089





A paradigm change for collider experiments

Asynchronous data analysis

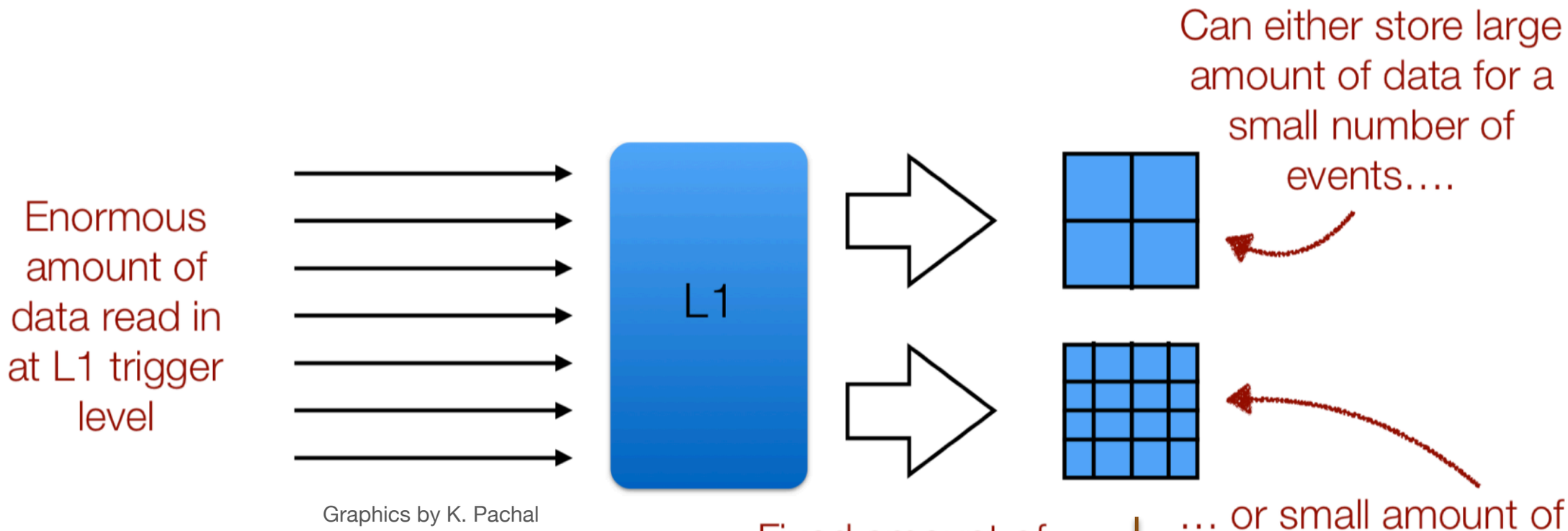
First record and store data, then reconstruct/analyze it

Real-time data analysis

Reconstruct/analyse data as soon as it is read out so that only (**smaller**) final-state information needs to be stored

ATLAS: Trigger Level Analysis **CMS**: Data Scouting, **LHCb**: Turbo stream

(Near-)real-time analysis of LHC data



Graphics by K. Pachal

Perform as much "analysis" as possible in real time

- Reconstruction & calibration
- First preselection to skim "backgrounds"

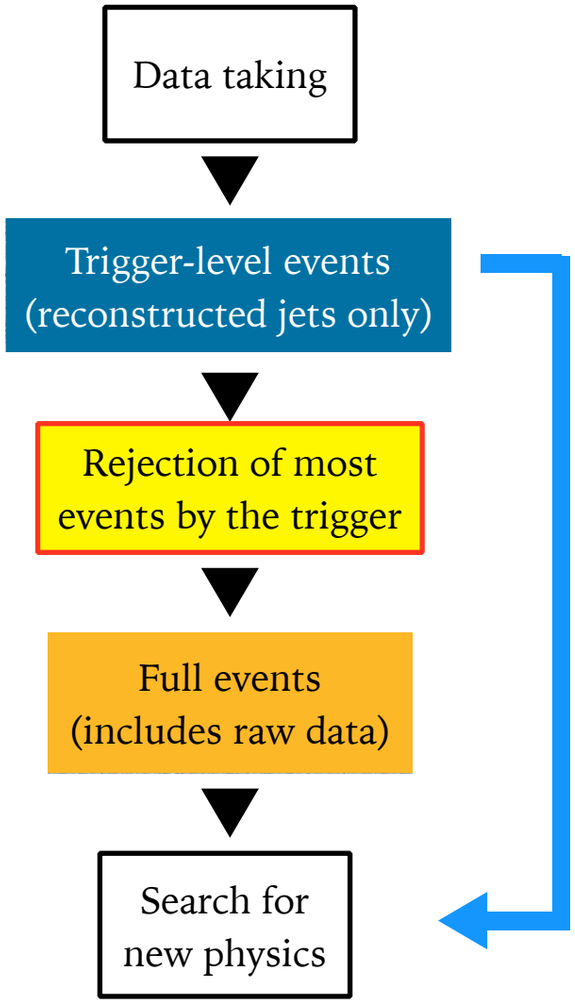
Reduced data formats:

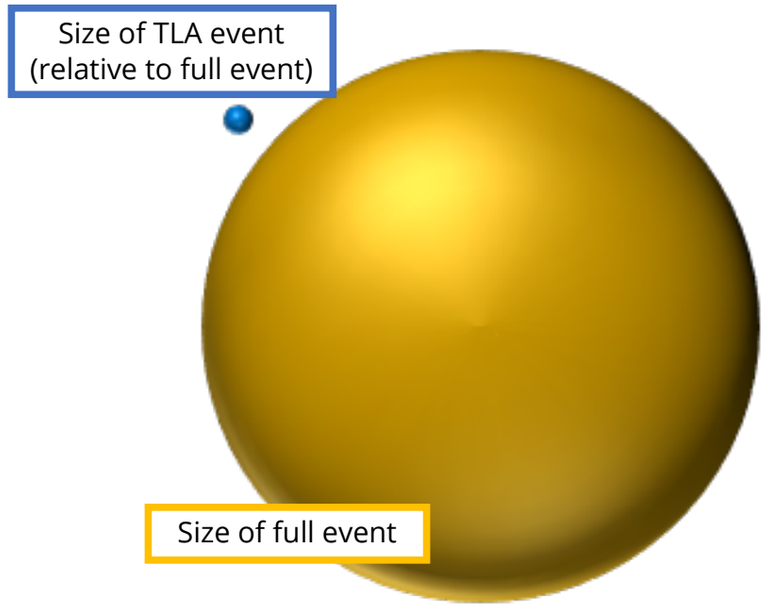
- Only keep final trigger objects (drop raw data)
- Save only "interesting" parts of the detector
- Run-3 / LHCb: A combination of the two

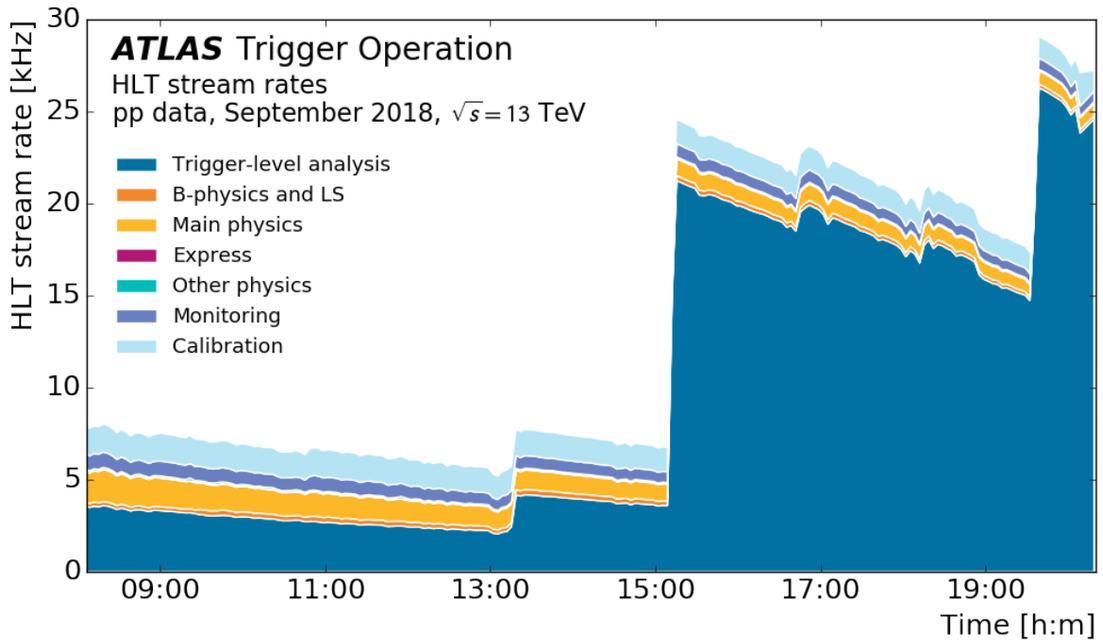
ERC Consolidator Grant REALDARK (2021-2026)

ATLAS implementation: Trigger Level Analysis (TLA) *

Much smaller event size → orders of magnitude more data can be recorded





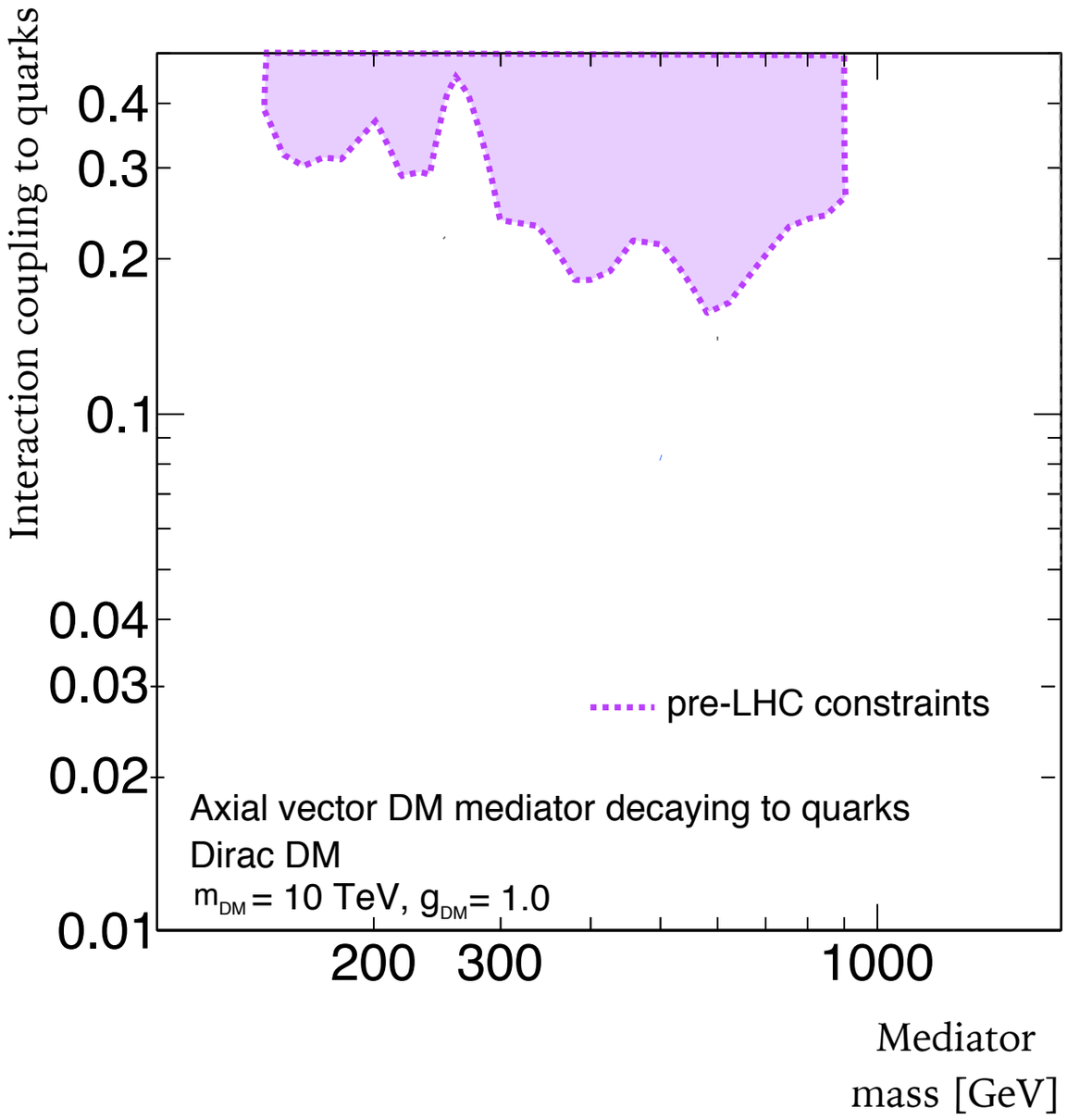


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults

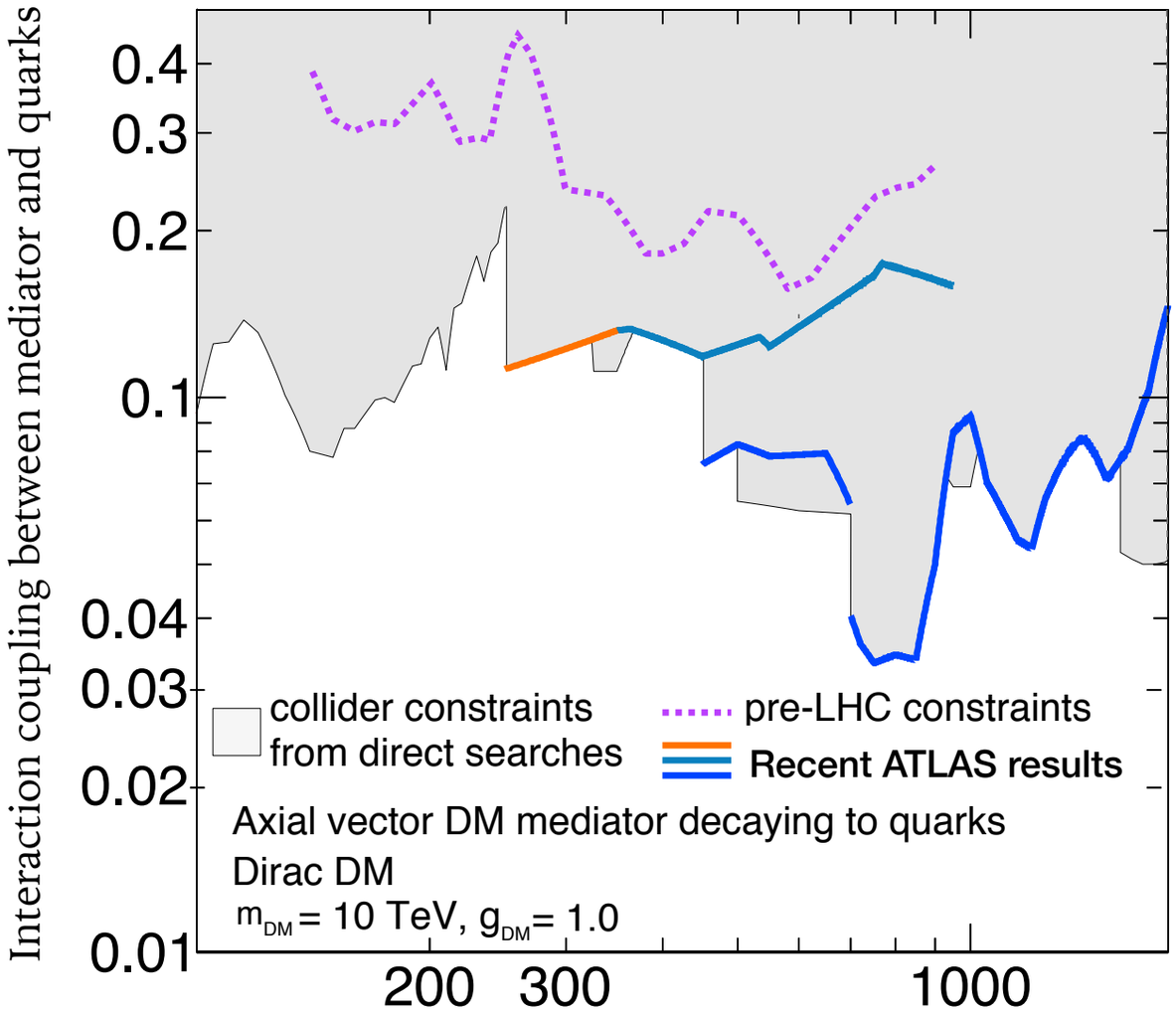
More data → increased sensitivity to rarer processes at lower masses

* Trigger Level Analysis is a Three Letter Algorithm (TLA)

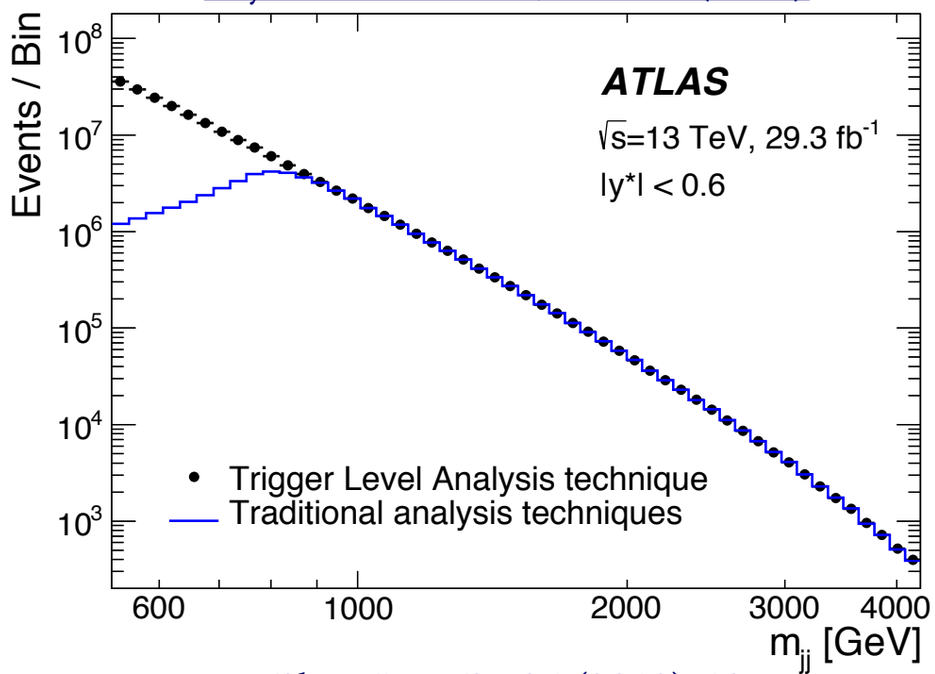
Filling the uncovered parameter space of low-mass



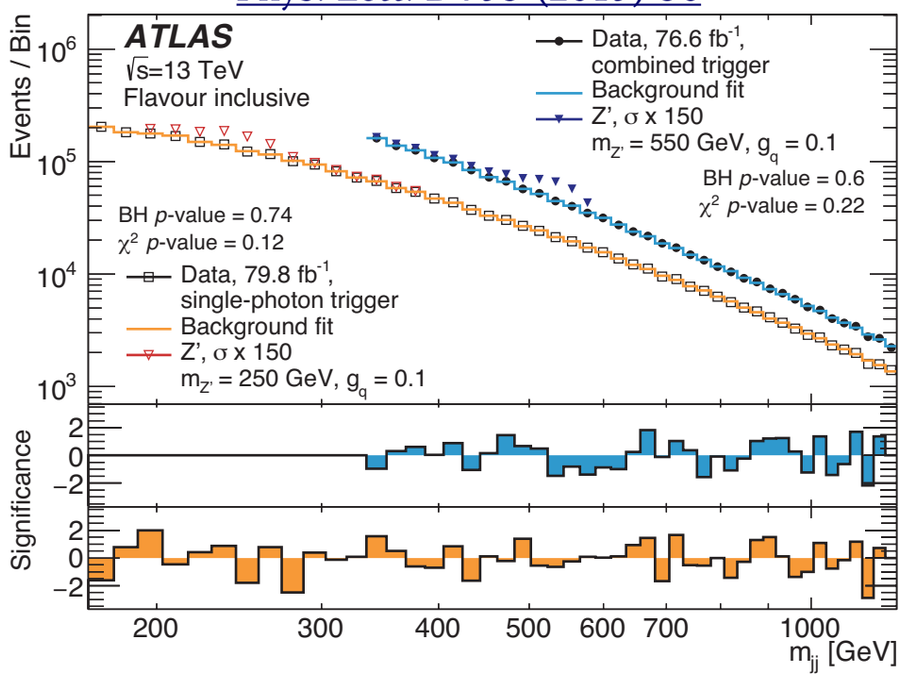
Filling the uncovered parameter space of low-mass



Phys. Rev. Lett. 121, 081801 (2018)

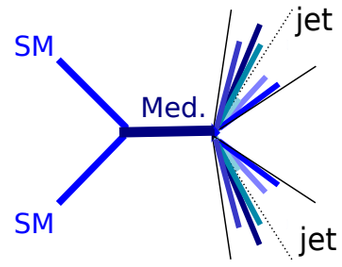


Phys. Lett. B 795 (2019) 56

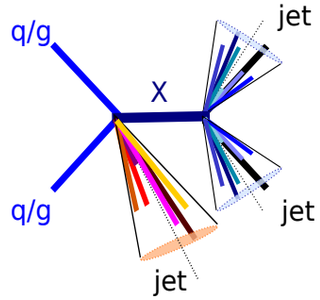


UChicago-inspired: Phys.Dark Univ. 2 (2013) 50-57

TLA technique:
Make the event size smaller



Dijet+ISR signature:
Reduce the background



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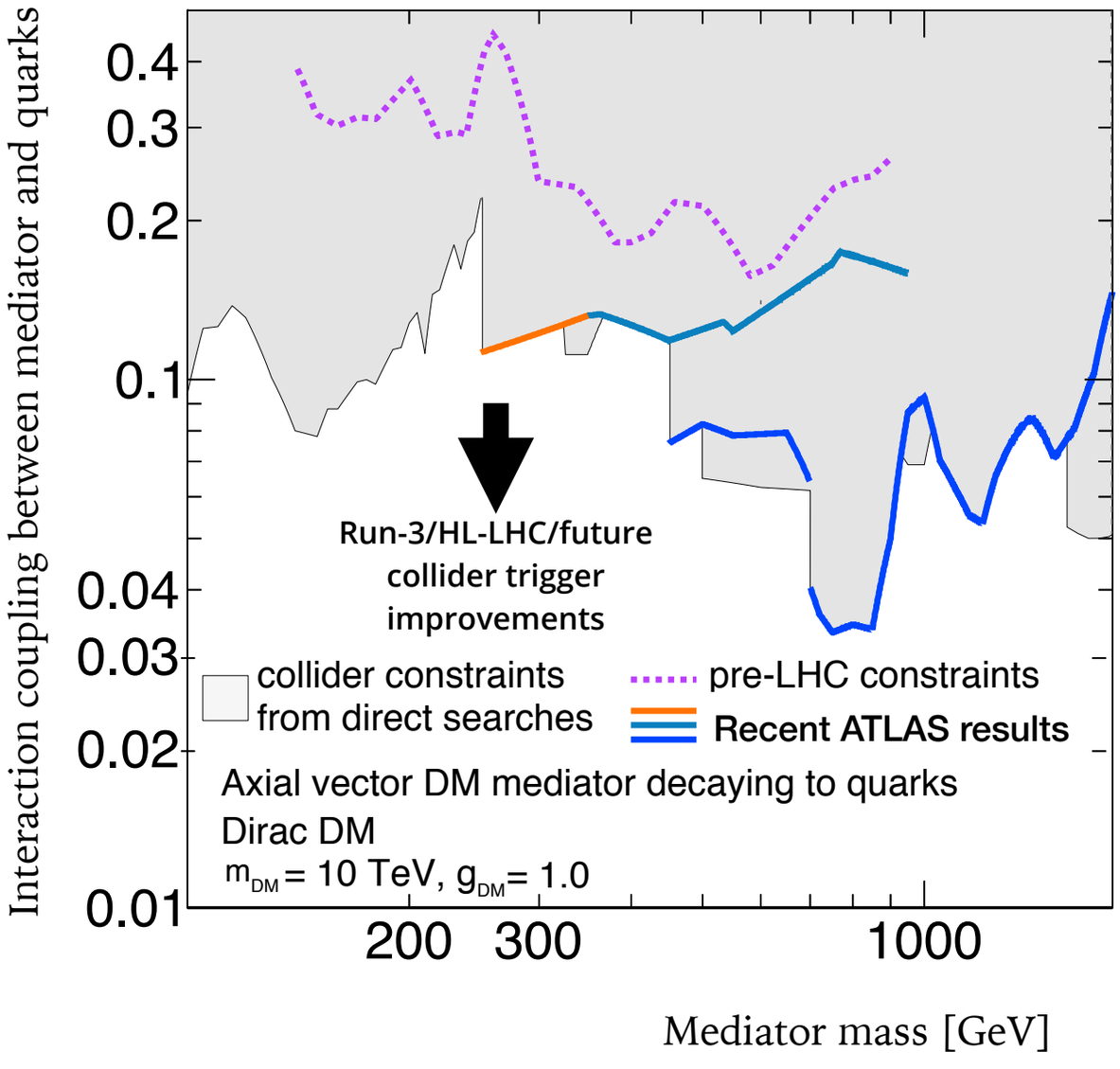

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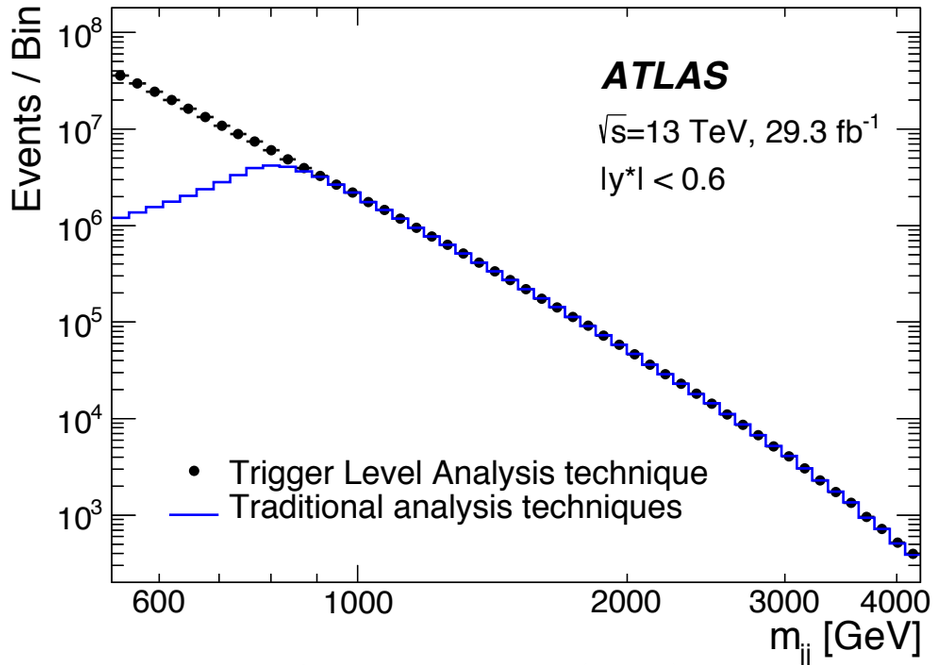

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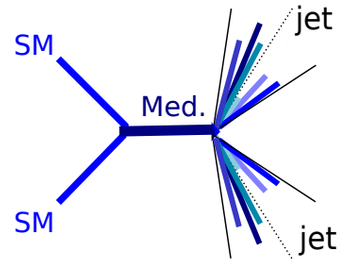
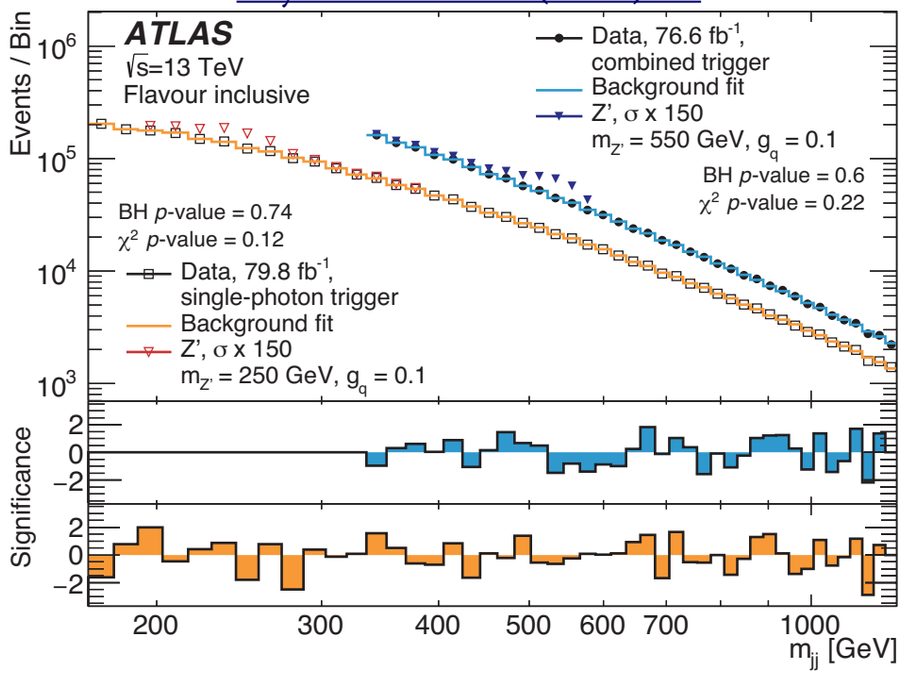


Phys. Lett. B 795 (2019) 56



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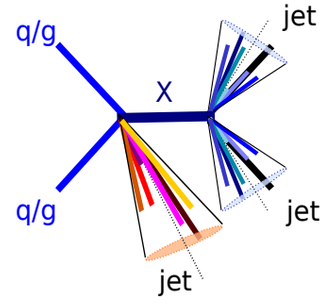
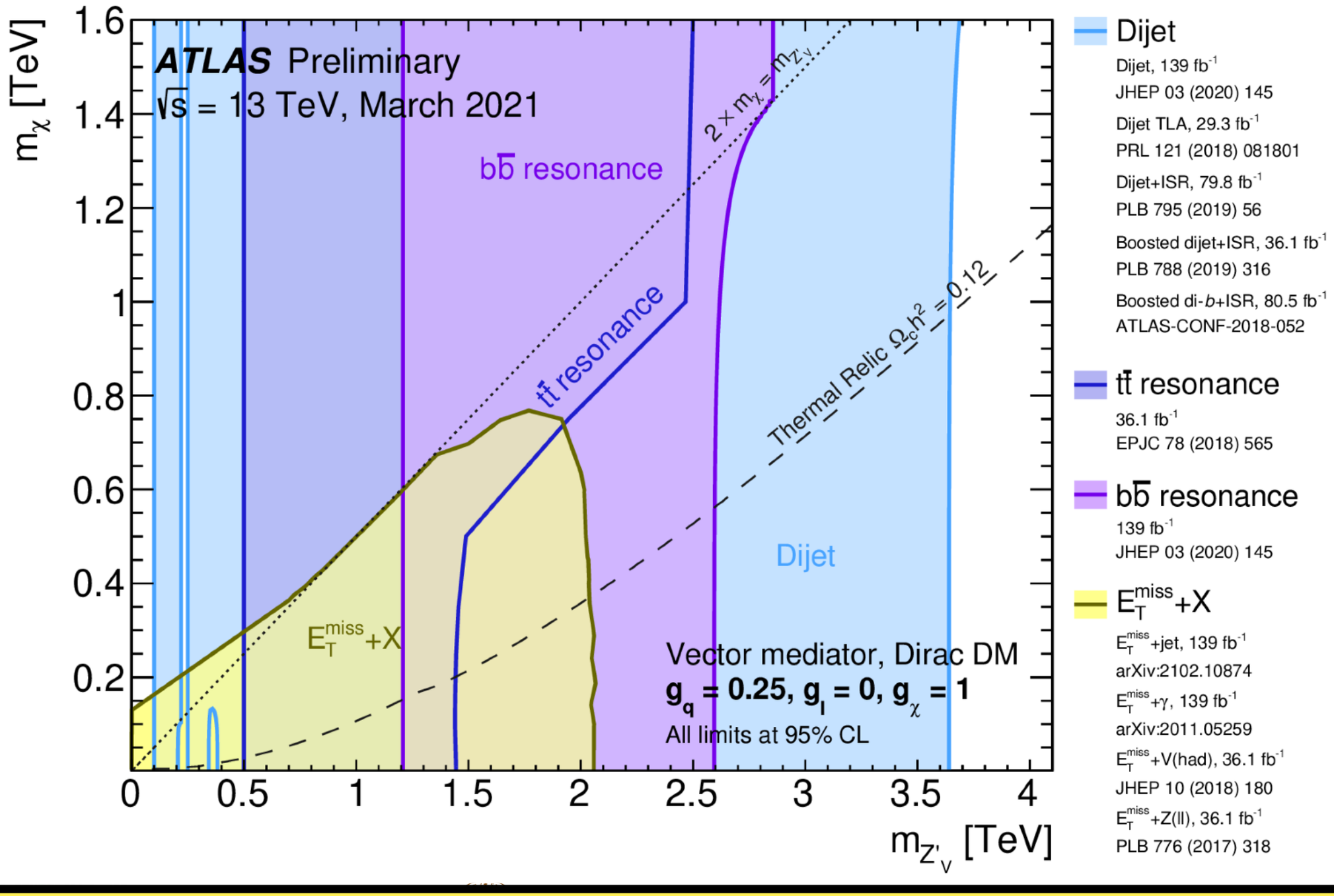


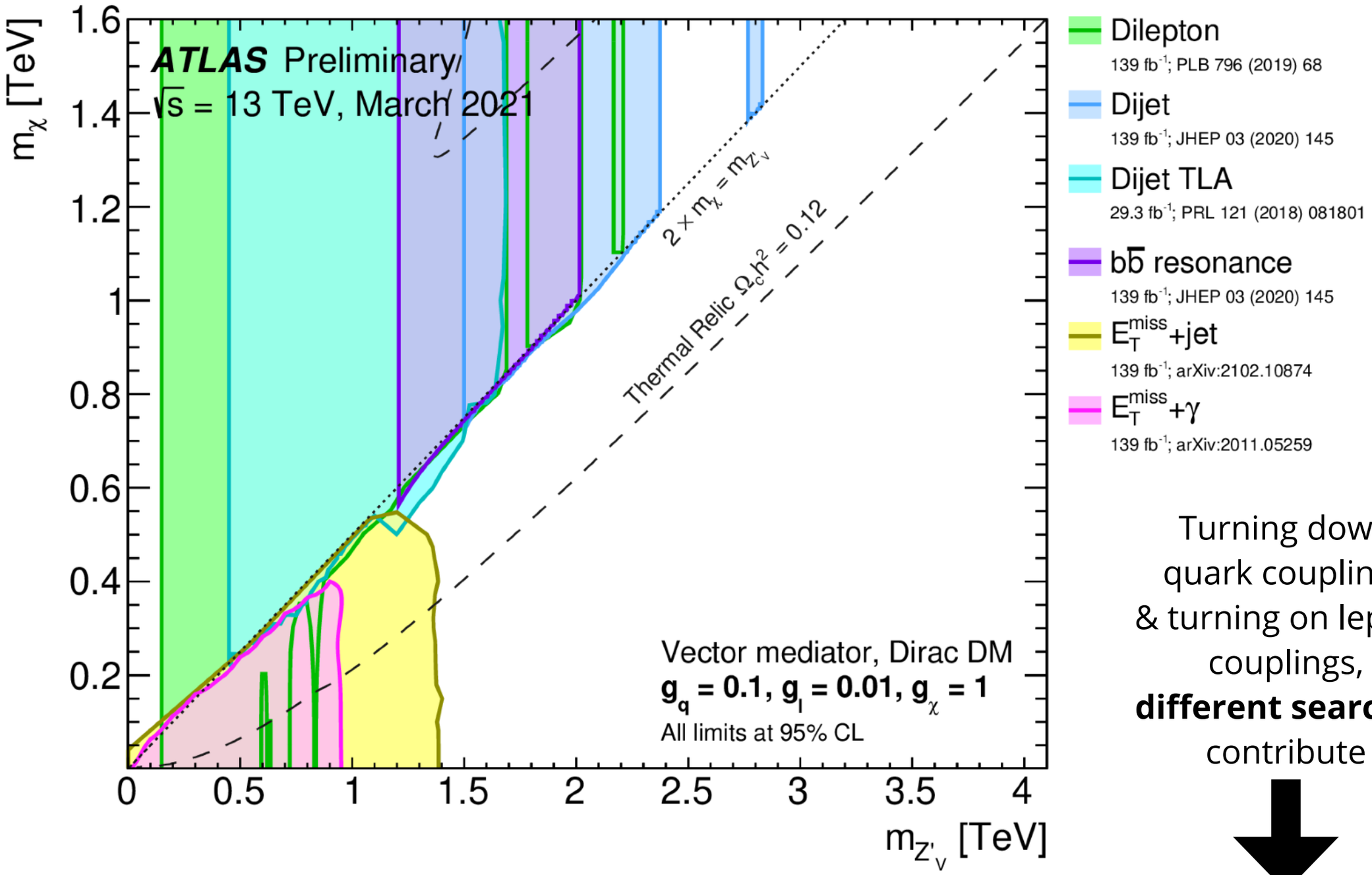
Searching for even rarer dijet resonances: **EW-scale couplings still unexplored** and probably not something we want to give up at any future colliders *(to discuss!)*

Complementarity of visible/invisible searches, 2021



Does it mean we're done with these searches & everything is excluded? No! Results depends on couplings…

Complementarity of visible/invisible searches, 2021



Turning down quark couplings & turning on lepton couplings, **different searches** contribute

Need to keep looking && think of ways to show this dependence

You may have noticed:
definitions of *low-mass*/*light* varies...

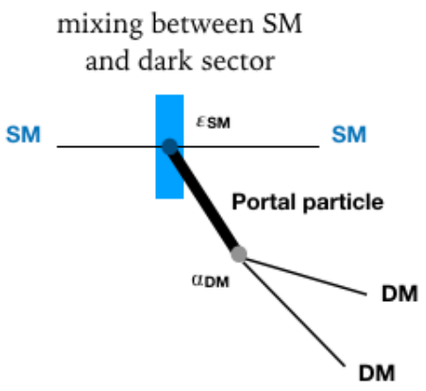
Low-mass mediators to a collider physicist in dijet searches: EW scale [o(100) GeV]

But this mediator can easily *(?)* be connected to less-explored lighter [o(GeV)] mediators

Note: see this summary talk / this review / Rebeca's lecture
for searches where the mediator is feebly coupled and therefore displaced

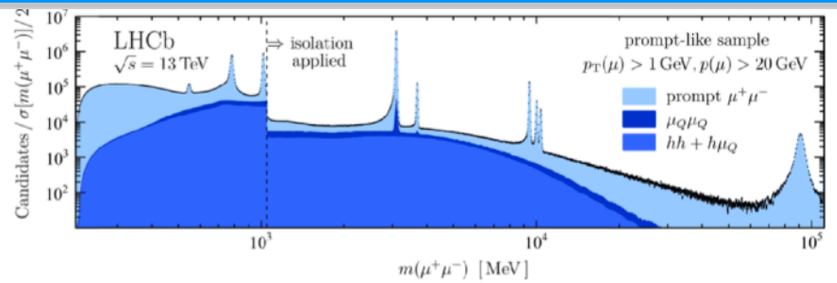
The obligatory dark photon slide

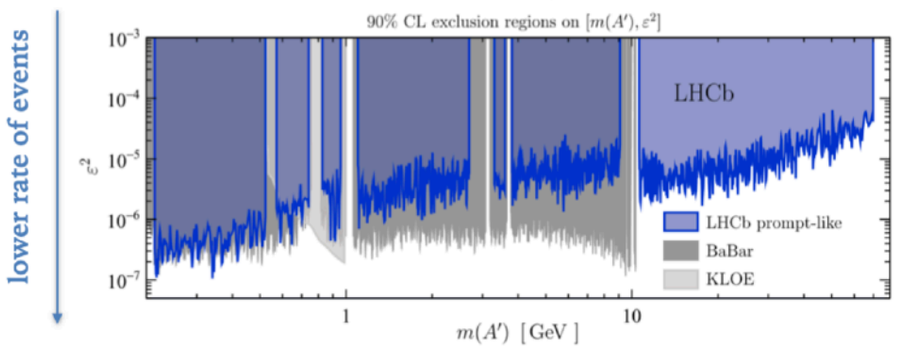
European Strategy Update Briefing Book



Dark photon → *dimuon* searches face the same problem as dijet searches at masses below the Z

→ large benefits from real-time analysis (or untriggered colliders)

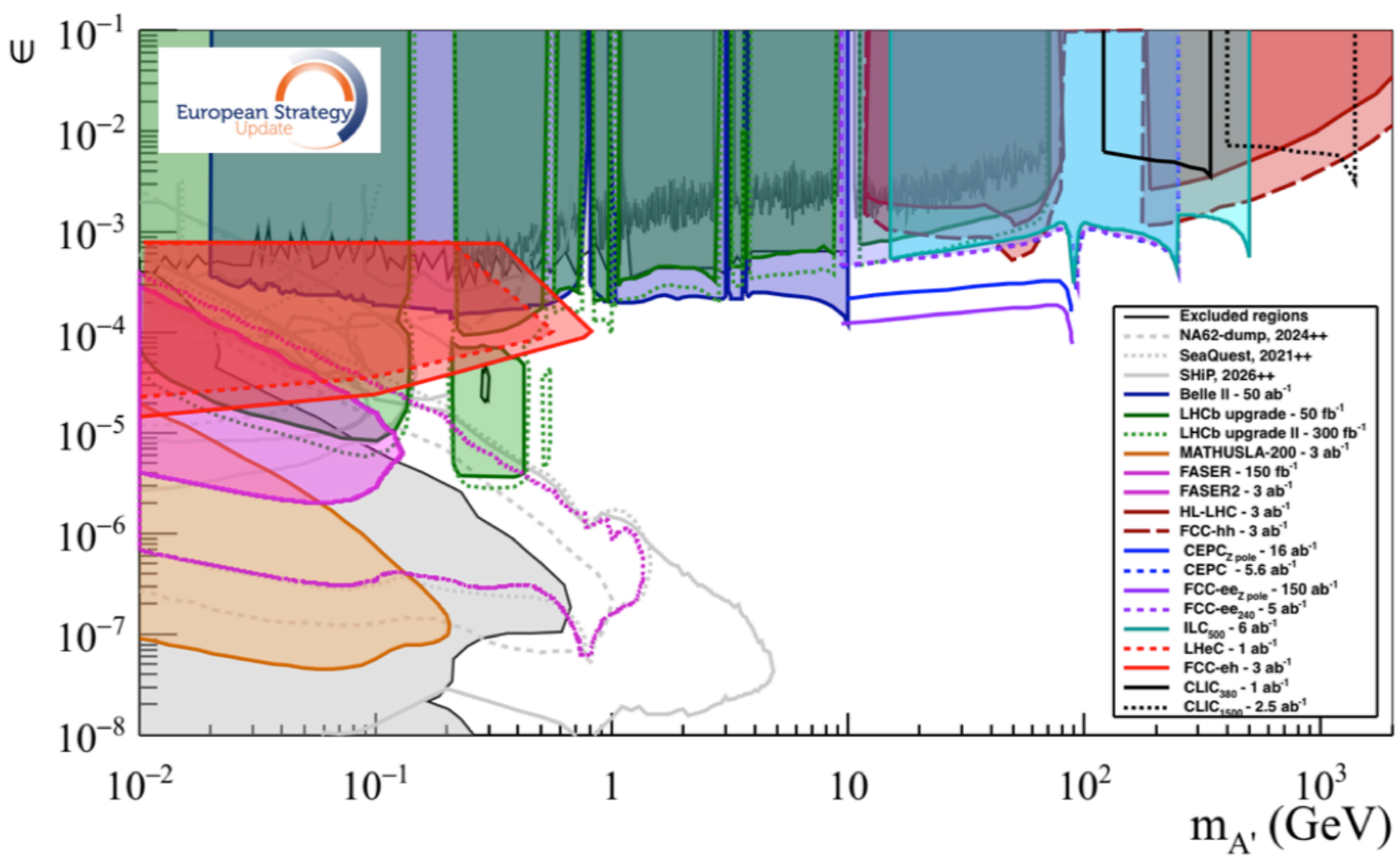




Phys. Rev. Lett. 120, 061801 (2018)

See also CMS's Phys. Rev. Lett. 124 (2020) 131802

(A little) more about accelerator experiments coming soon

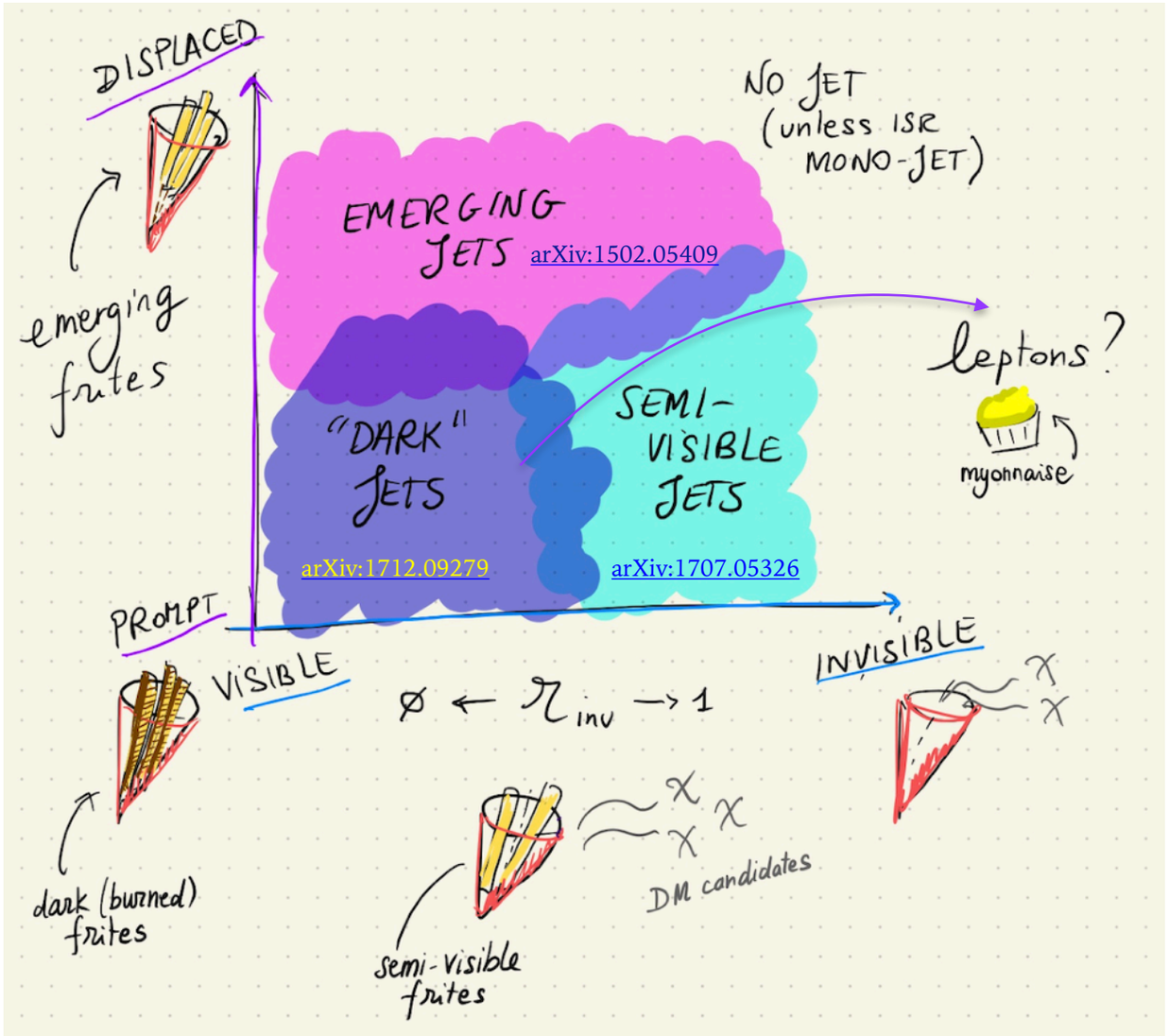


Projections from HL-LHC (and some future colliders) assume trigger thresholds like LHC Run-1

⇩

Important to keep in mind non-standard analysis workflows (& work on improving trigger systems) to make the most of future collider data

Stronger dark interactions ⇒ non-standard collider jets



Inspired by K. Pedro & C. Fallon's talk @ DMLHC2019 and by this twitter thread

Searches for dijet resonances. ⇒ Nature making our jets weirder than QCD

Going beyond the "low-hanging fruit":

- **Dark sector** models (some including DM candidates) with much uncovered territory
  Class of models including ***dark quarks*** that fragment in a QCD-like way (***dark QCD***):
  - **Dark dijets** → prompt dark sector jet constituents
  - **Emerging jets** → long-lived jet constituents
  - **Semi-visible jets** → invisible jet constituents
- Current searches searching for signals >~ TeV (limited by trigger rates)

A family of signatures, with DM particles (& more) in the dark shower
⇒ need more than simple real-time analysis!

Can be searched for in LHCb, ATLAS and CMS [arXiv:1810.10069]

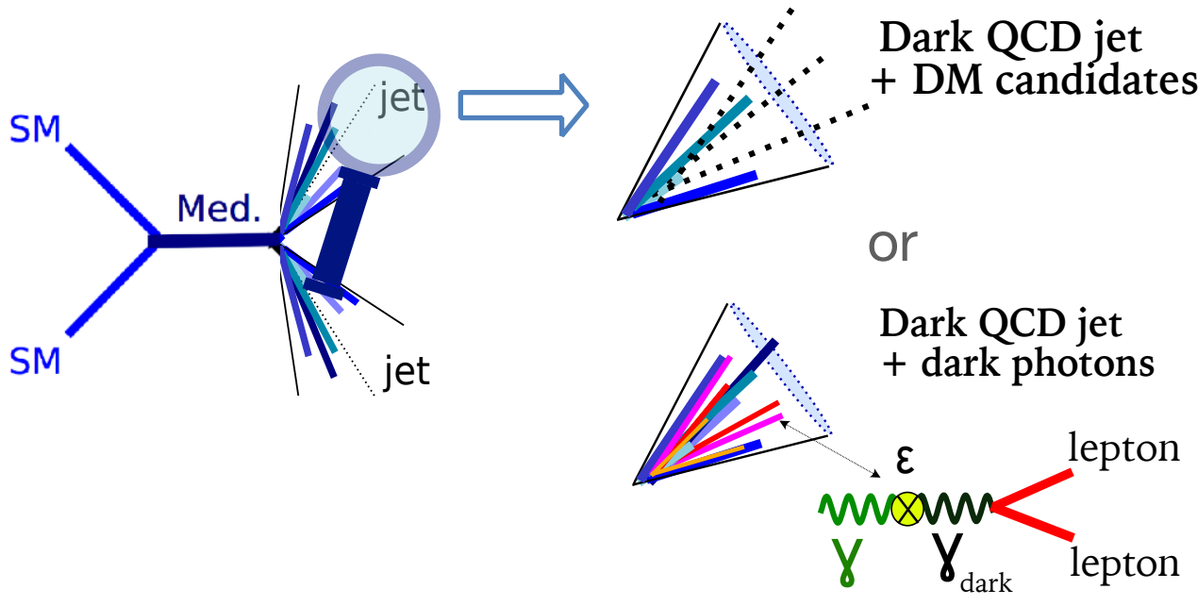
SnowMass2021

Discussions every ~3 weeks at this indico, hosted by Suchita Kulkarni Marie-Helene Genest

Dark sectors in jets: collaborative efforts @ LU

Non-WIMP searches
with non-standard jet signatures

What if dark matter is part of a whole new particle sector (*dark sector*) and its forces mirror the SM?
Dark Quantum Chromo/Electrodynamics



How do we make sure we don't miss these processes?

1. The model space is complex and has many more parameters with respect to WIMP searches shown earlier
→ organize workshops to **discuss with theorists** (LU expertise)

Dark Jets workshop organized by J. Geisen and E. Hansen, Lund 2019

STINT
Stiftelsen för internationalisering av högre utbildning och forskning
The Swedish Foundation for International Cooperation in Research and Higher Education

+ STINT Internationalisation grant
with the University of Witwatersrand

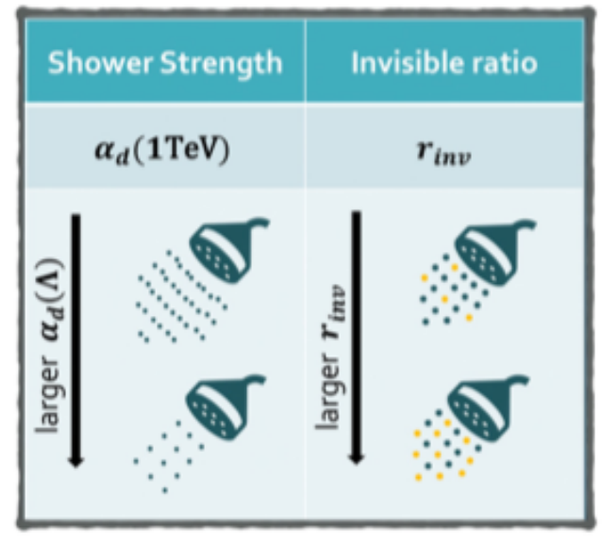
2. Current real-time analysis techniques are blind to these processes because there isn't enough information in the reduced data format
→ upgrade the trigger system to **retain the needed information**

Link to data selection: exotic dark jets & other signatures

Tim Cohen, Snowmass 2021

Mapping of "exotic" signatures to big picture of theoretical models not easy
→ difficult to prioritize on theory grounds
→ difficult to decide what exactly to save and select, in advance

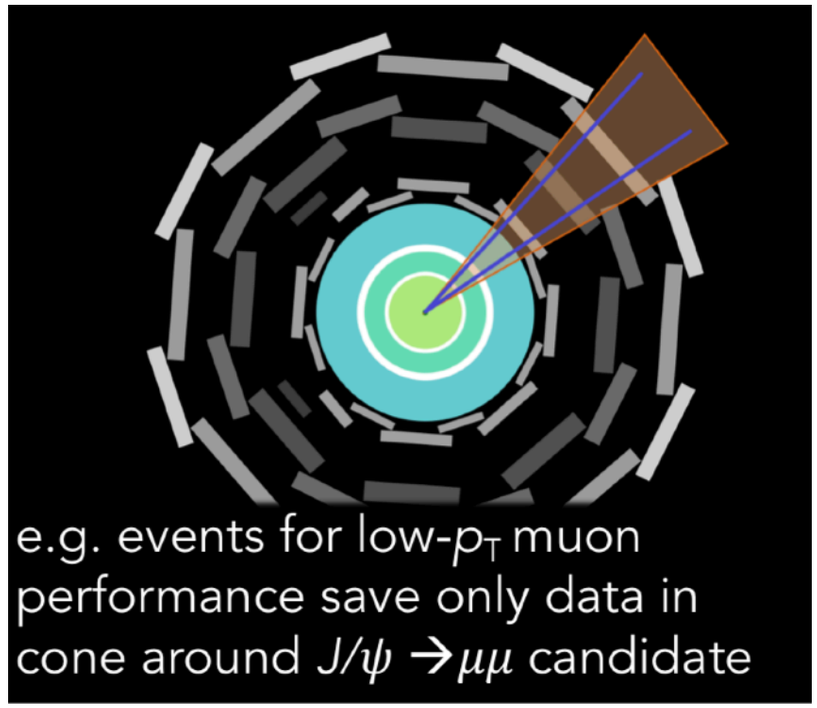
Example: group of signatures with a **common denominator**:
unusual tracks/energy distributions,
more or less localized in the detector, e.g. **dark QCD** jets



H. Russell, EPS-HEP 2019

How do we make sure we don't miss these events?

1. write dedicated trigger algorithms
2. save (custom-reconstructed) trigger-level objects only
3. save a mixture of trigger-level objects and raw data in interesting regions
4. save any of the above and reconstruct data later
5. [outlier detection…in the very far future]



Partial event building

ATLAS/CMS starting a research program, interesting benchmarks for a variety of reasons:

- forces us to understand QCD better
  - Note role of measurements, e.g. CONTUR
- plenty of phase space to be explored
- requires connection between theory, generators, and different experiments (dark sector particles in jets vs 'weird jets' as a whole)

See Andy Buckley's lecture

Complementarity between collider searches and other experiments

A look to the future: the landscape of future colliders

We have the LHC now, but what are we expecting in the future?

e+e- colliders

Collider	Geometry	$\sqrt{s}$ [GeV]	$\mathcal{L}_{inst}$/Det. [10^{34}cm^{-2}s^{-1}]	Time [years]	$\mathcal{L}$ [ab^{-1}]
FCC-ee	Circular	91	100–200	4	150
		161	25	1–2	10
		240	7	3	5
		365	0.8–1.4	5	1.5
CEPC	Circular	91	17–32	2	16
		161	10	1	2.6
		240	3	7	5.6
ILC	Linear	250	1.35–2.7	11.5	2
		350	1.6	1	0.2
		500	1.8–3.6	8.5	4
CLIC	Linear	380	1.5	8	1
		1500	3.7	7	2.5
		3000	6	8	5

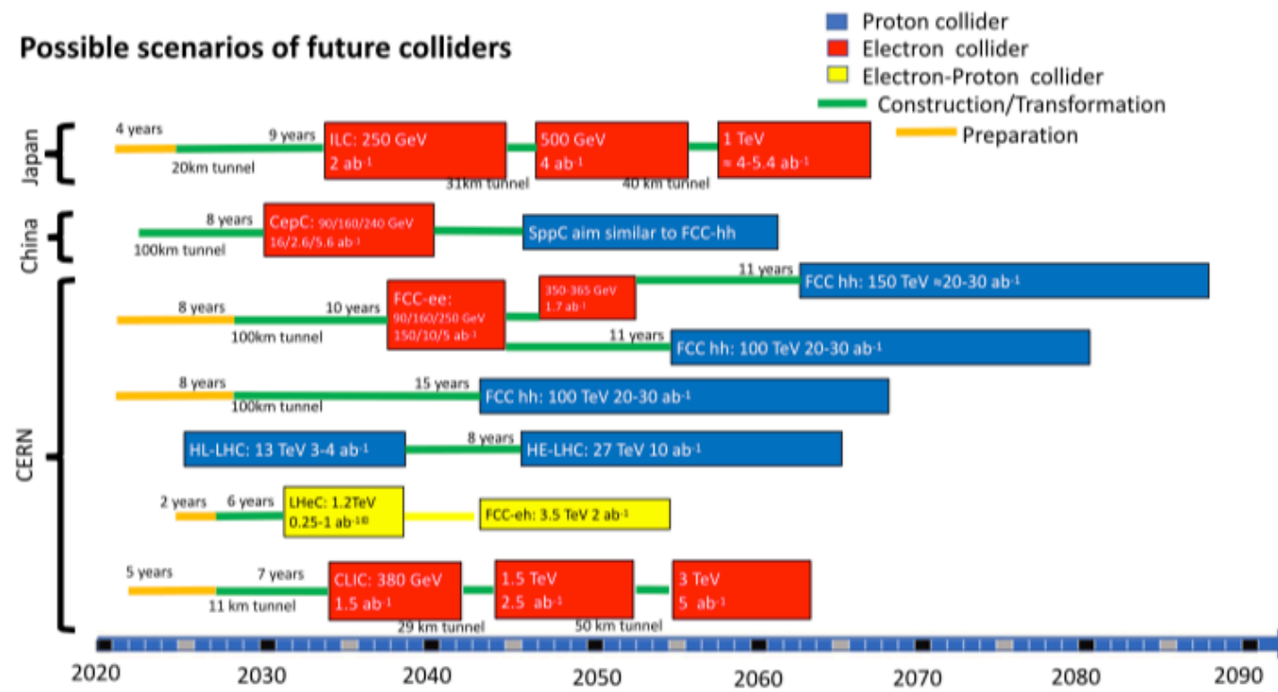
muon colliders

Collider: muon collider
Geometry: circular
CoM energy: 3-30 TeV
Instantaneous luminosity:
Time [years]: ??
Integrated luminosity: up to 2/ab

pp colliders

Collider	$\sqrt{s}$ [TeV]	$\mathcal{L}_{inst}$/Det. [10^{34} cm^{-2}s^{-1}]	Time [years]	$\mathcal{L}$ [ab^{-1}]
HL-LHC	14	5	12	3
HE-LHC	27	16	20	15
FCC-hh	100	20–30	25	20
LE-FCC	37.5	–	–	10

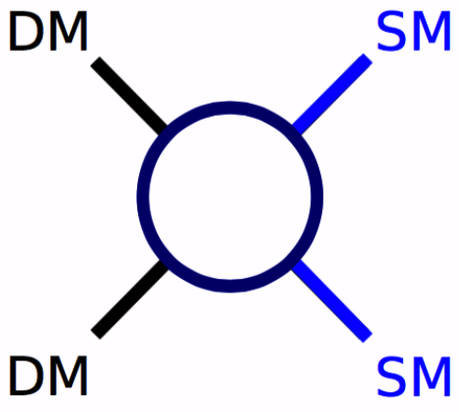
H. Gray, Reviews in Physics 6 (2021) 100053



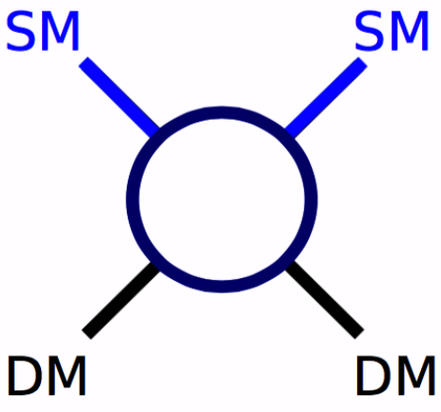
Controversial: why colliders can't discover every/any kind of DM

- **Reason #1**: there are DM models that are not accessible at accelerator energies / intensities
- **Reason #2:** DM discoveries need complementary experiments that involve DM with **cosmological origin**
  - Direct detection can **discover DM that interacts** inside the detector
  - Indirect detection can see **annihilating/decaying DM** through its decays

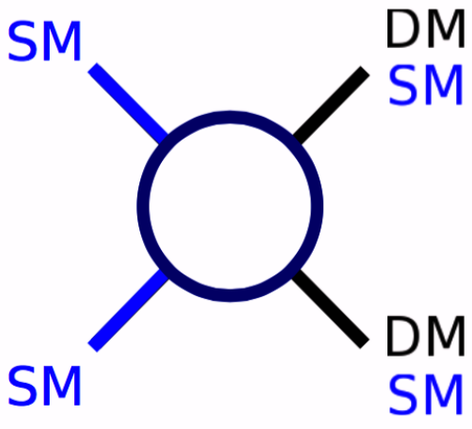
We need complementary experiments!



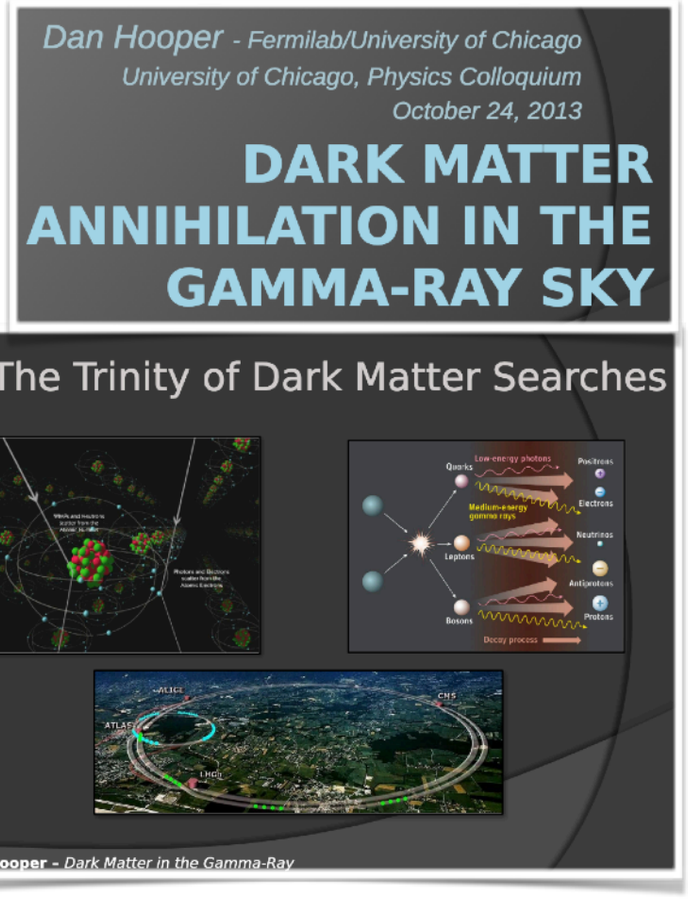
Indirect Detection



Direct Detection

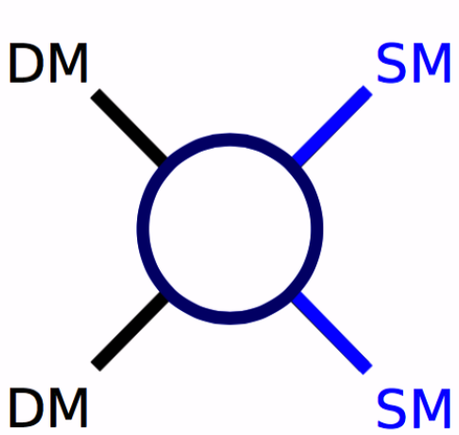


Colliders

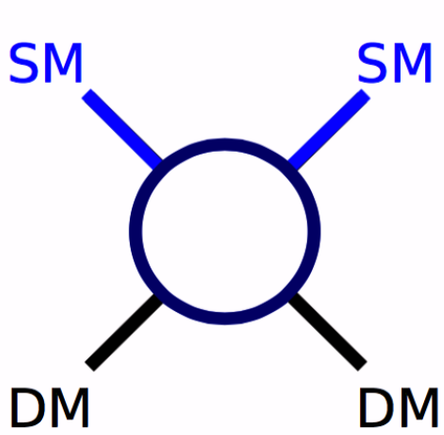


Controversial: why colliders can't discover every/any kind of DM

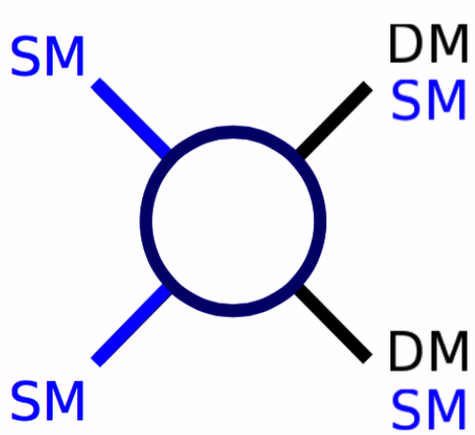
- **Reason #1**: there are DM models that are not accessible at accelerator energies / intensities
- **Reason #2:** DM discoveries need complementary experiments that involve DM with **cosmological origin** / can **produce DM**
  - Direct detection can **discover DM that interacts** inside the detector
  - Indirect detection can see **annihilating/decaying DM** through its decays
  - Accelerators/colliders can produce DM and **probe the dark interaction**

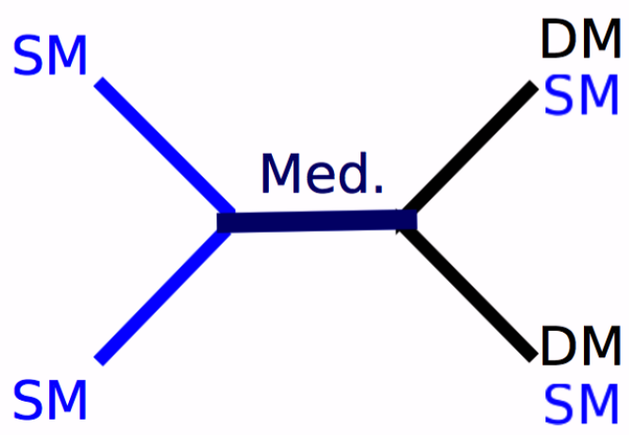


Indirect Detection



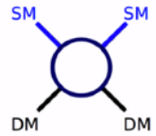
Direct Detection





Particle Accelerators (colliders & extracted beam lines)

Direct detection experiments: examples



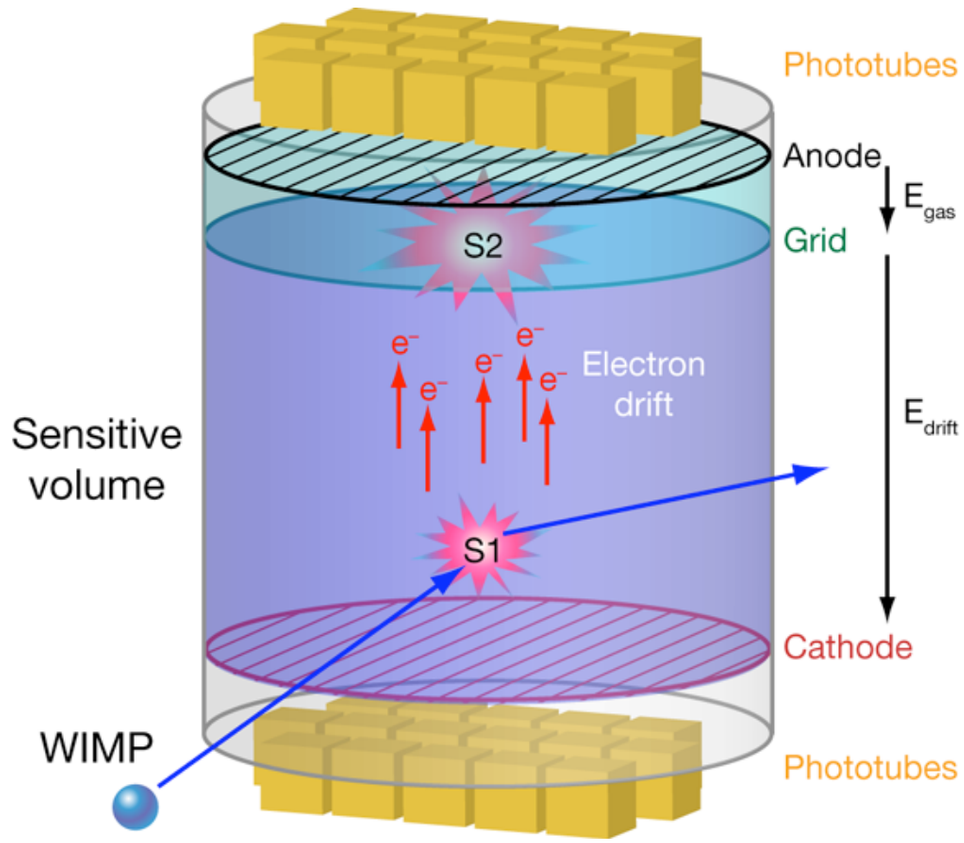
XENON/LZ

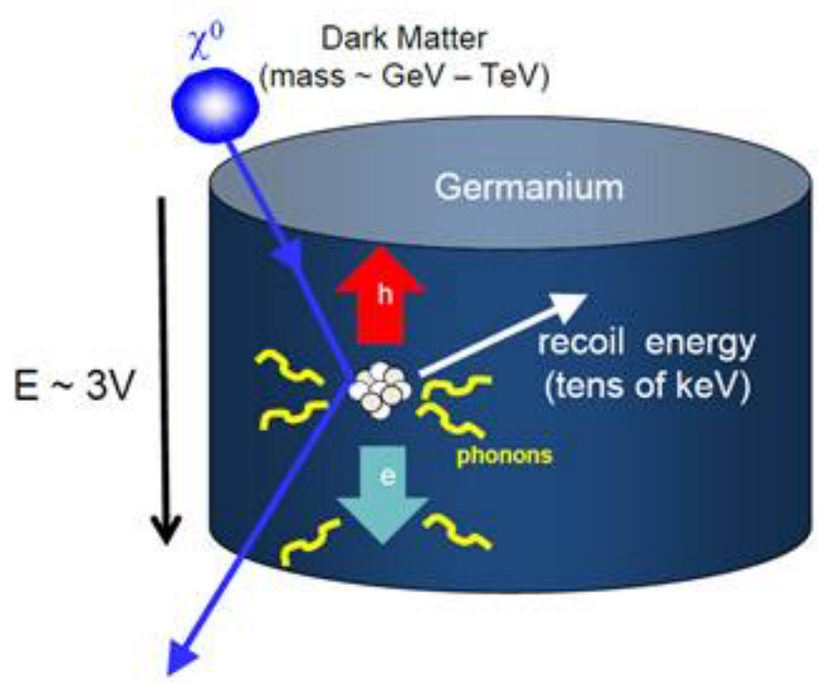
See Sergei Burdin's lecture

CDMS

Large volumes (order: meters)

Smaller volumes, lower threshold
(order: centimeter-meter)



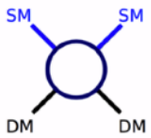


http://www.xenon1t.org
https://lz.lbl.gov

https://www.slac.stanford.edu/exp/cdms/

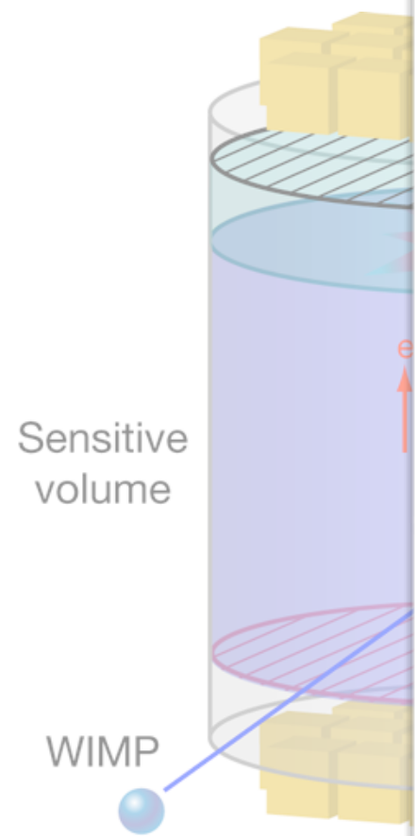
Many more experiments operational/planned for this decade:
from Generation-2 to Generation-3

Direct detection experiments: examples



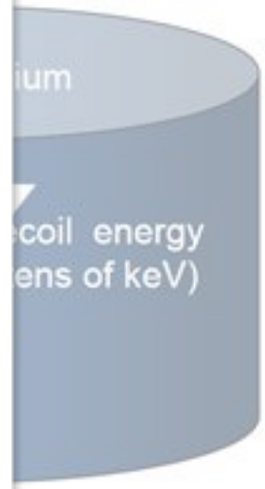
XENON/LZ

Large vol



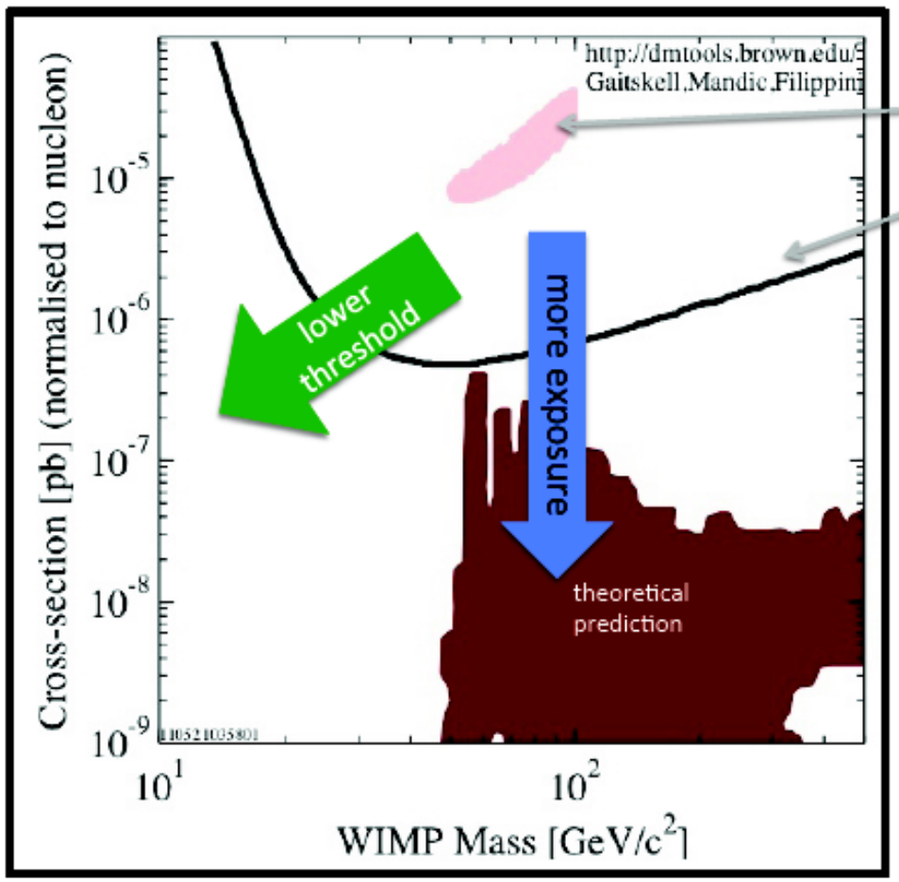
CDMS

wer threshold
r-meter)



d.edu/exp/cdms/

Exclusion Plot – Comparison of Results



Raimund Strauss, MPI Munich 8

Many more experiments operational/planned for this decade:
from Generation-2 to Generation-3

SnowMass2021 CF1

Looking for rarer DM (examples from direct detection)

- Major updates to direct/indirect detection experiments planned:
  - in terms of **detectors**
  - in terms of **reduction of challenging backgrounds**

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

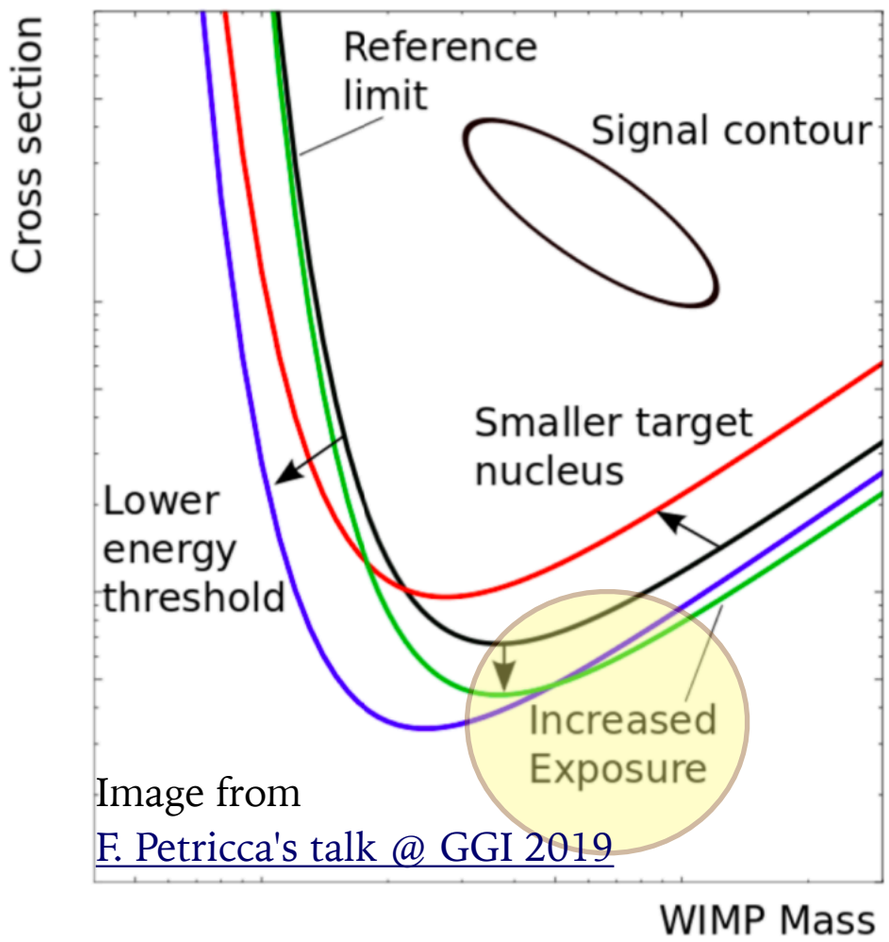
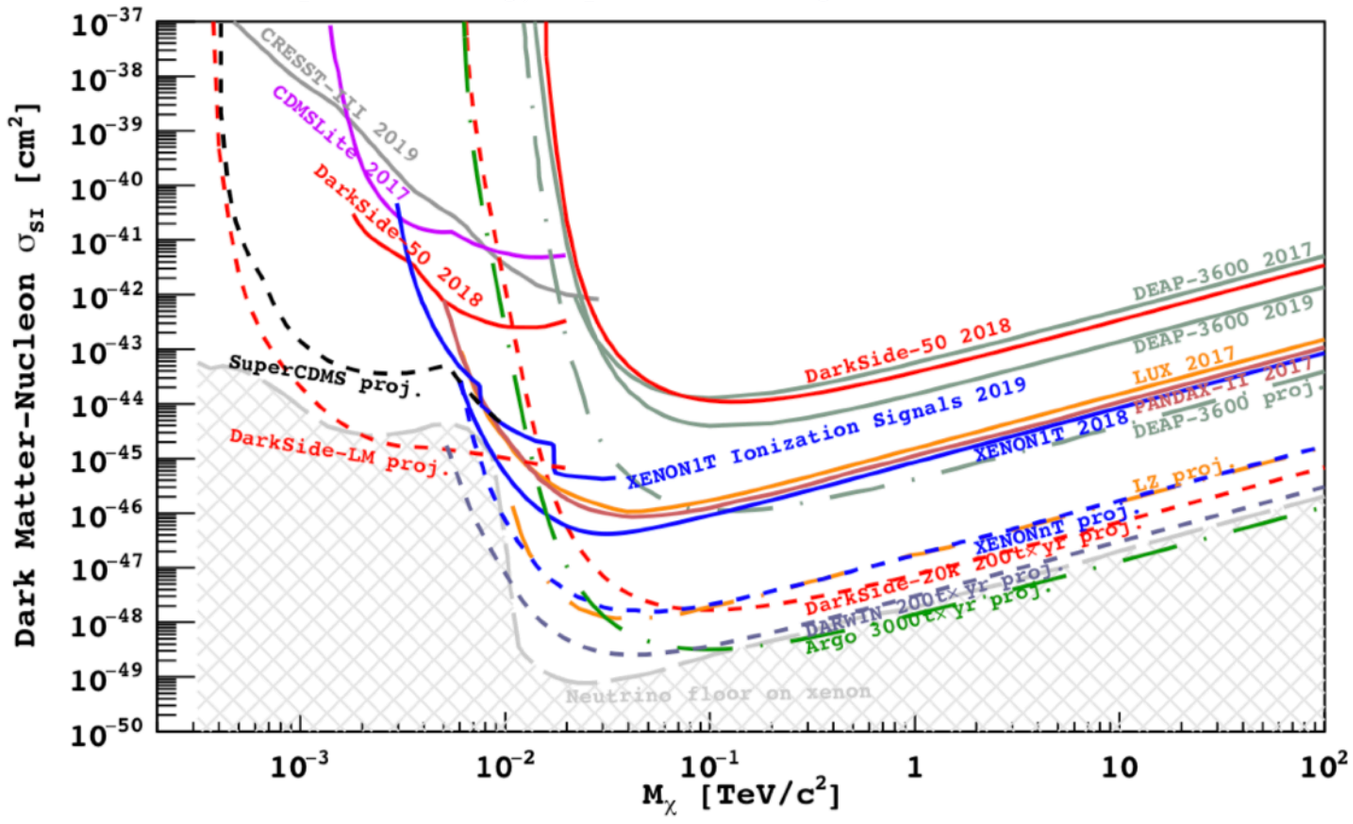


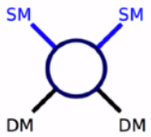
Image from
F. Petricca's talk @ GGI 2019

European Strategy Update Briefing Book



solar/cosmic neutrino scattering xsec may become larger than DM xsec
(but **irreducible backgrounds** haven't stopped anyone so far)

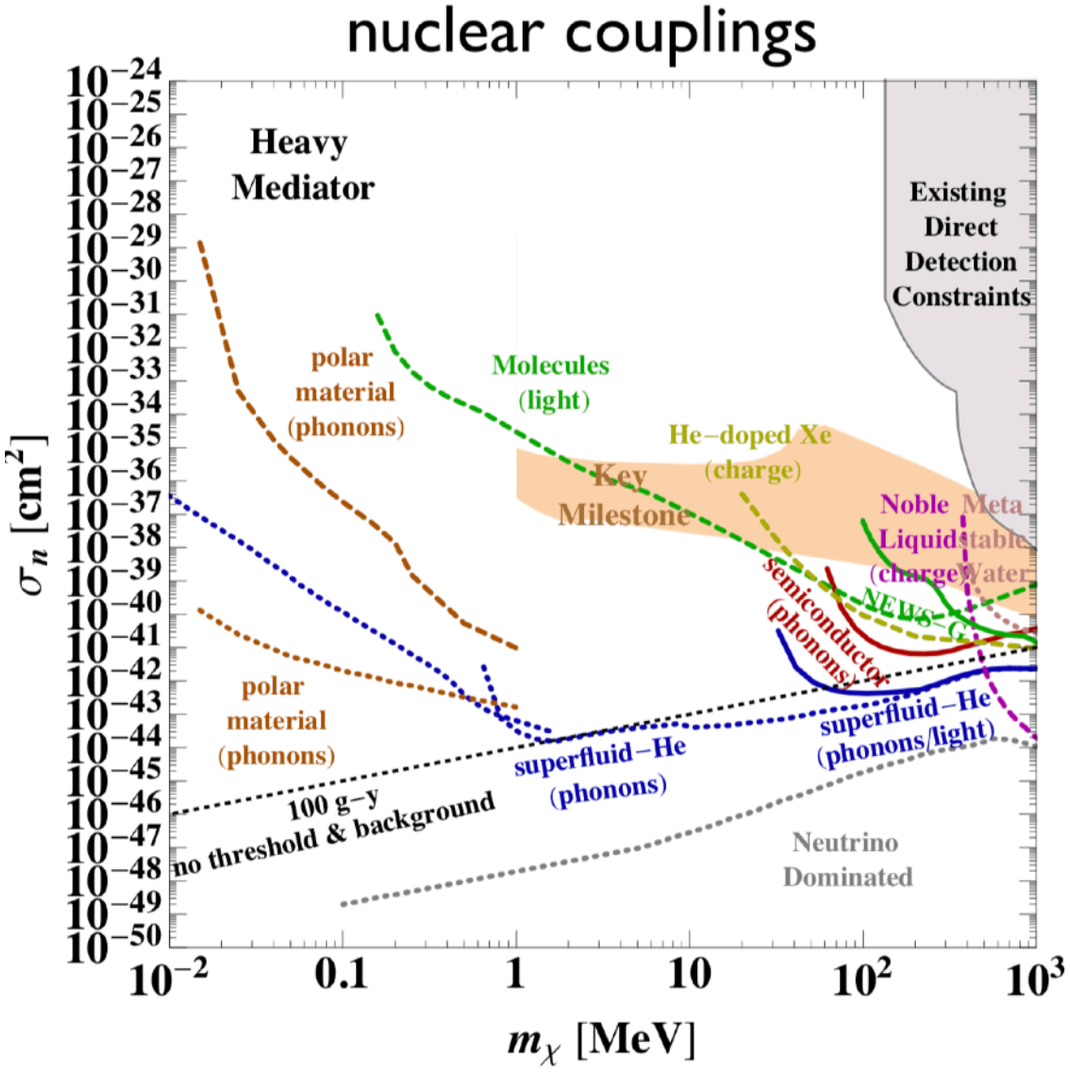
Direct detection for very light DM



"Traditional" DM-SM recoil direct detection searches lose sensitivity to low-DM masses, but...

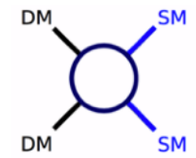
- detectors can be made **more sensitive** to lower thresholds (e.g. phonon-based calorimeters) F. Petricca's talk @ GGI 2019
- **subdominant effects** can enhance "kick" from DM E.g. arXiv:1702.04730, 1707.07258, 1905.00046, 1810.07705, 1810.10543...
- can explore **new materials & detectors** → collaboration of **astro/ particle physics** & **solid state physics**
  - Including **quantum sensors**

E.g. arXiv:1709.07882, CPM Session #77



BRN Report

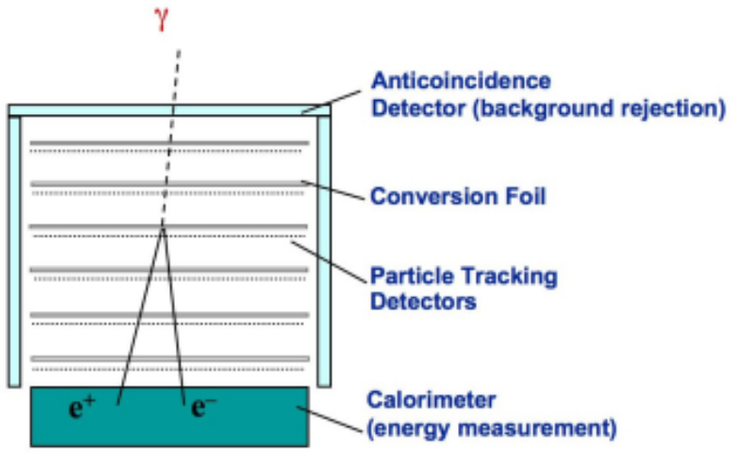
Indirect Detection experiments: examples



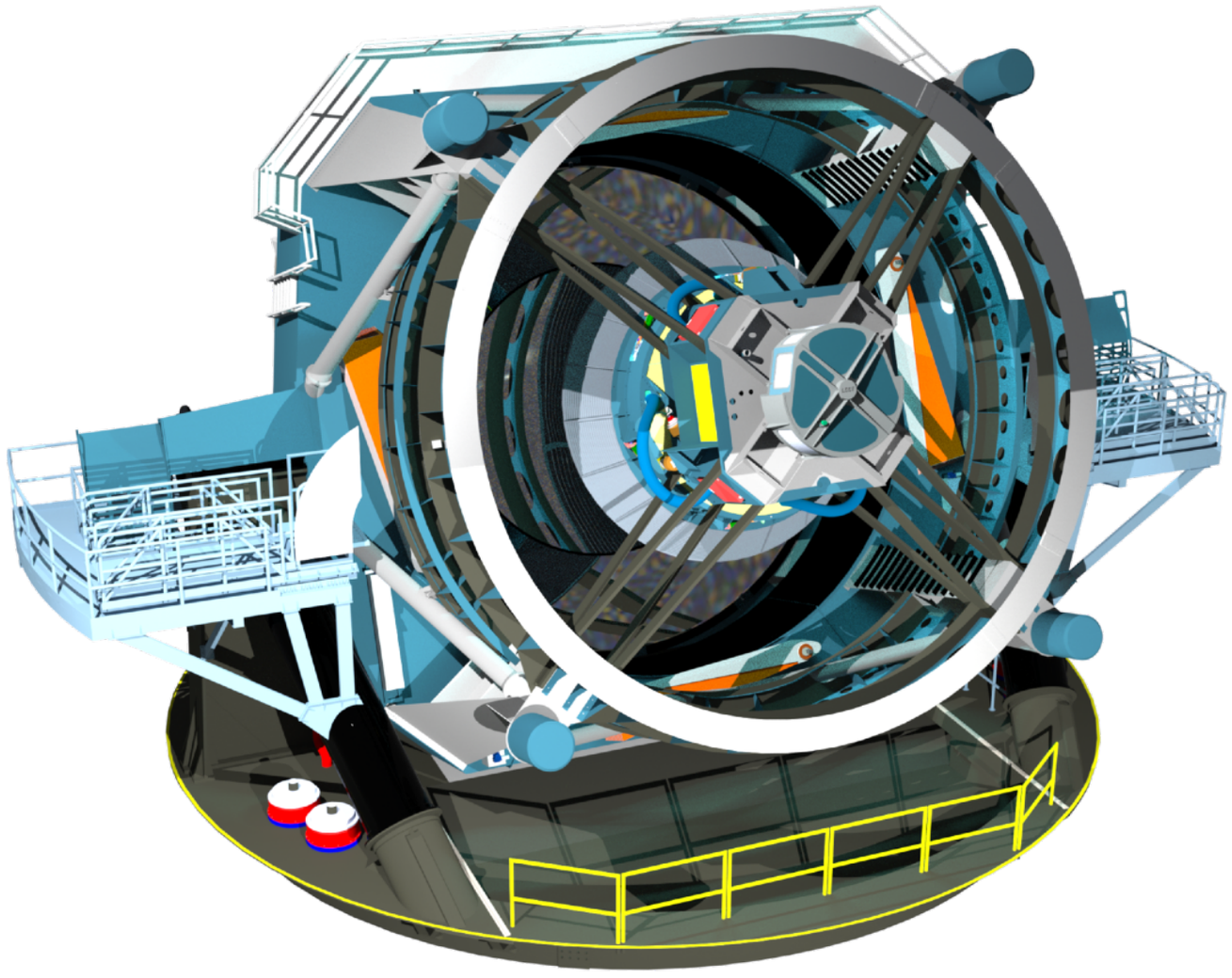
Dark Matter annihilates in the GC / dwarf galaxies (a place) to photons (some particles), which are detected by Fermi, HESS, … (an experiment).

how to detect DM decays:
indirect detection experiments
(e.g. Fermi-LAT, CTA,…)

Fermi Large Area Telescope
https://www-glast.stanford.edu/

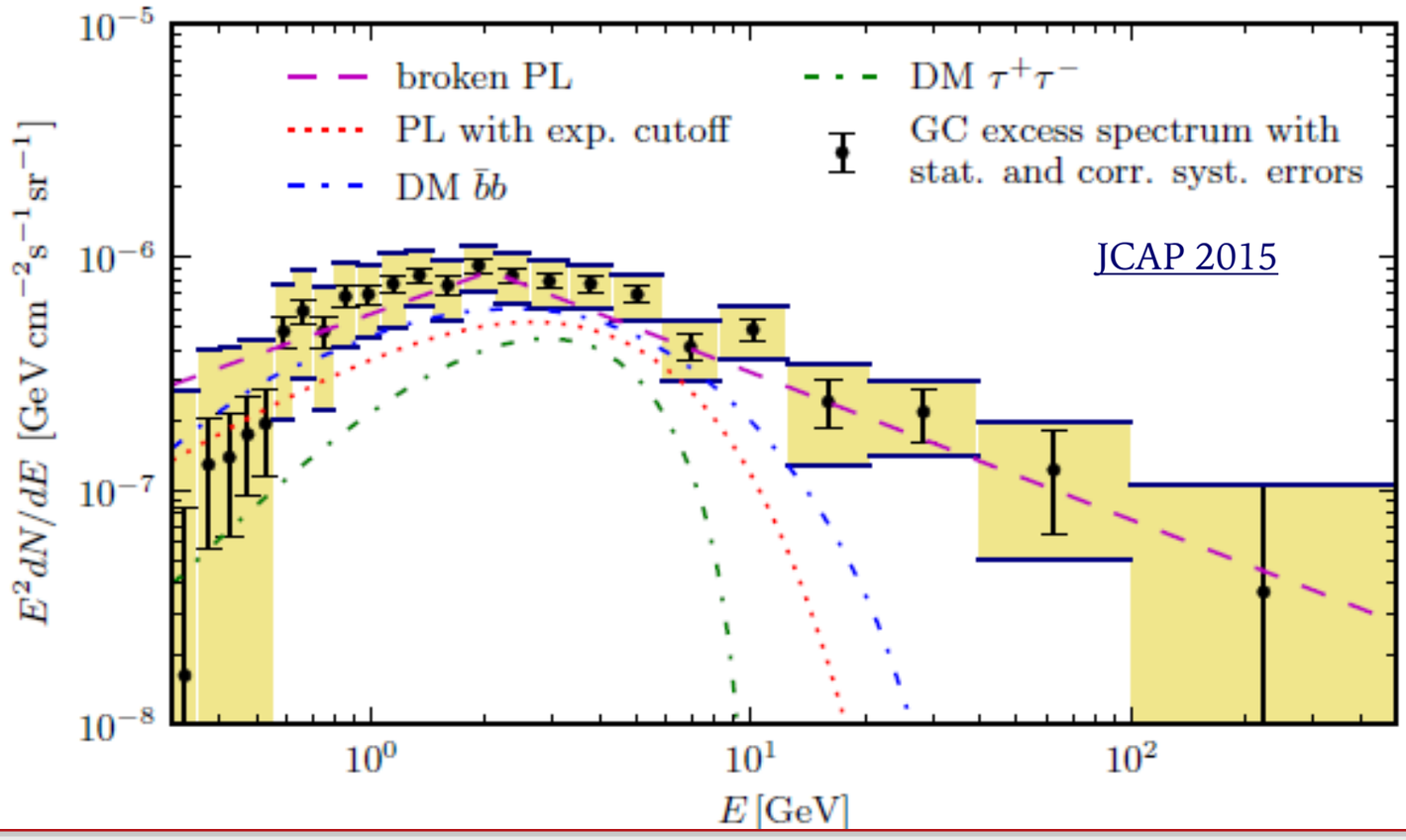


where to find DM:
galaxy surveys SnowMass2021 CF3
(e.g. LSST, SKA,…)
(also able to probe properties of DM & test DM models)



SnowMass2021 CF1

Indirect Detection example/excess: Fermi-LAT



Astrophysics > High Energy Astrophysical Phenomena

Dark Matter Strikes Back at the Galactic Center

Rebecca K. Leane, Tracy R. Slatyer

Phys. Rev. Lett. 123, 241101 (2019)

Many possibilities for interpretation, floor still open!

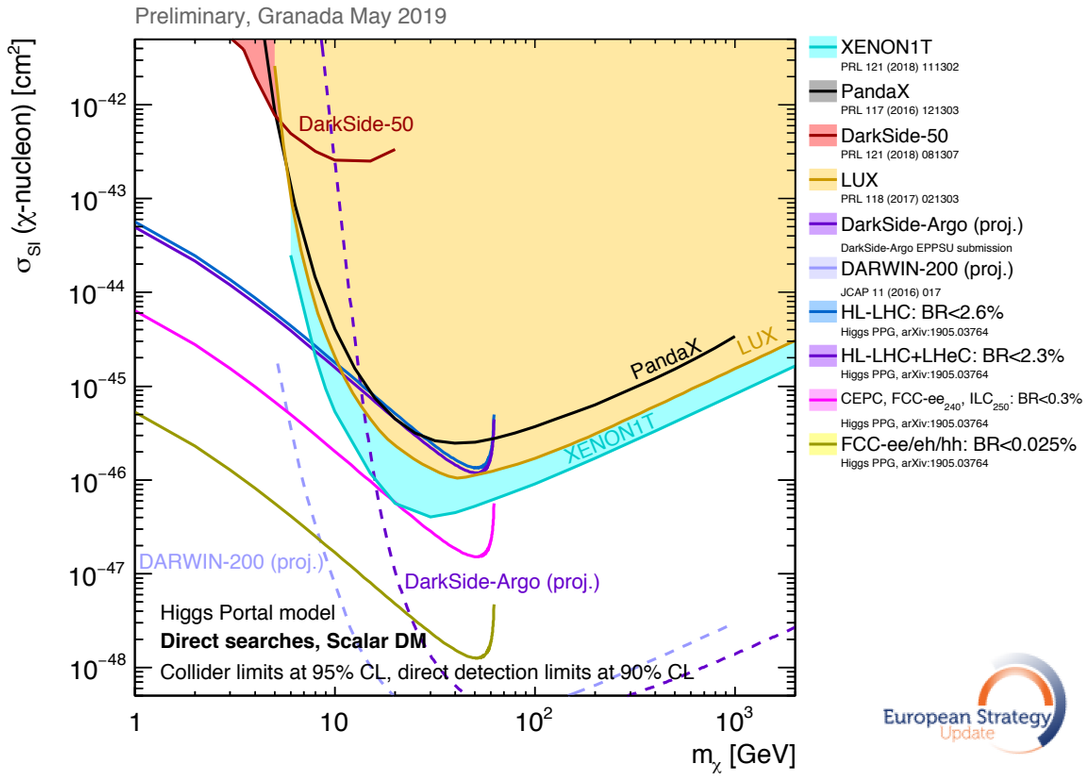
Something we all wish for...

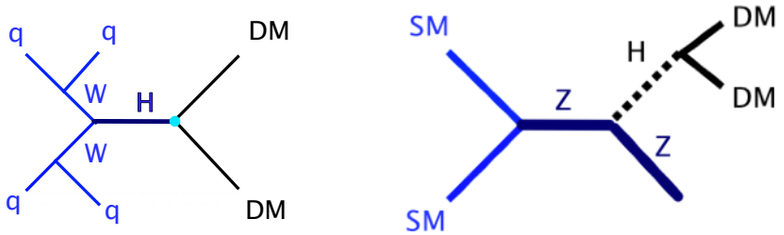
What if we **discover** something?
Need **complementary experiments!**

Complementarity so far: within WIMP frameworks

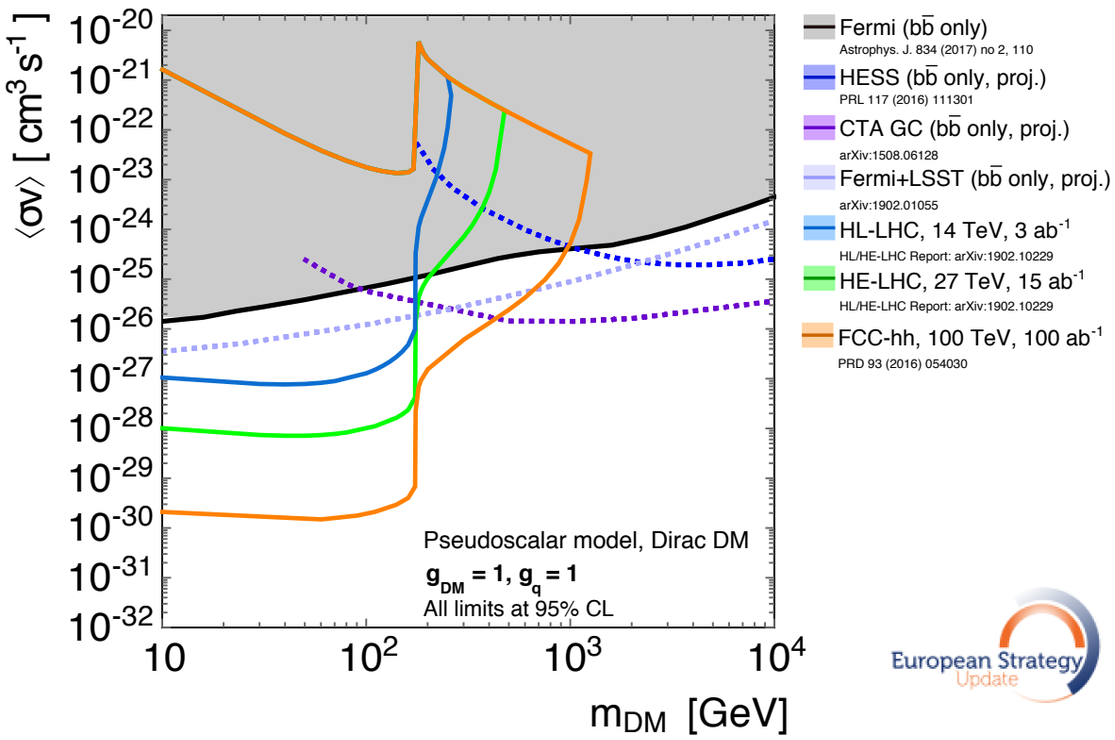
LHC DM Working Group, European Strategy Update Briefing Book, for non-WIMP examples, see Physics Beyond Colliders report

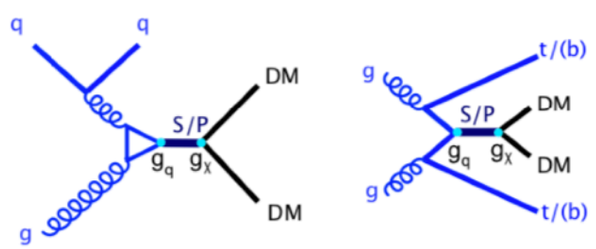
Invisible Higgs @ colliders and direct detection





Scalar mediators and indirect detection





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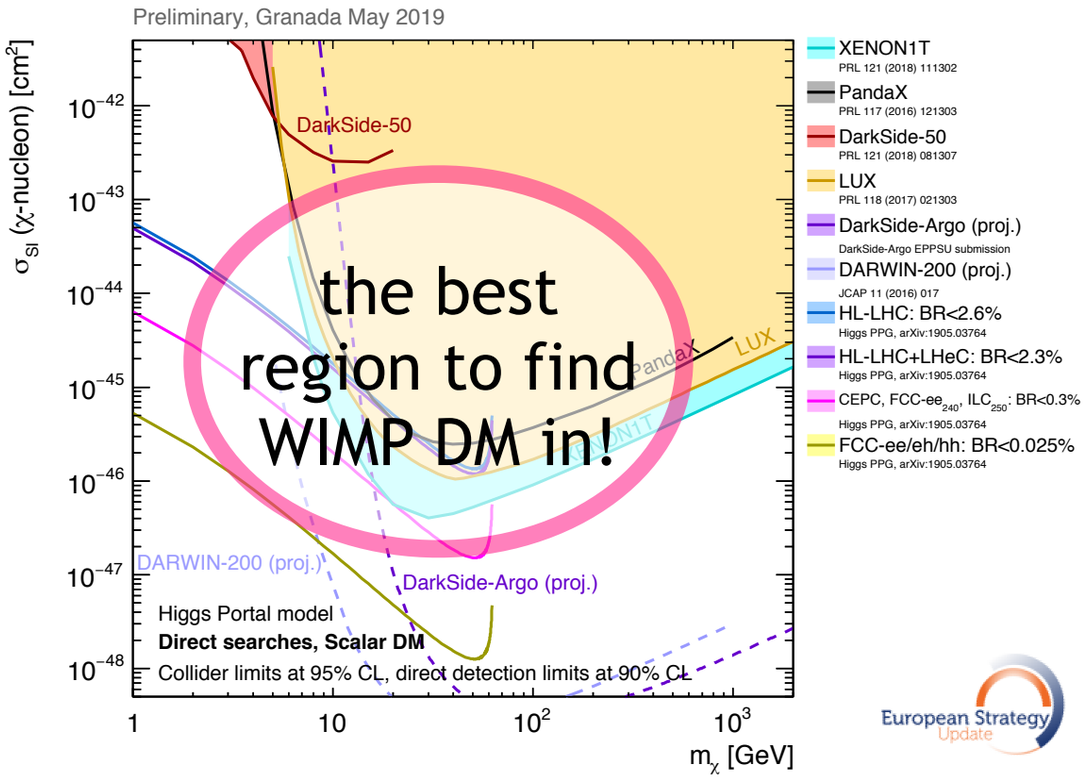
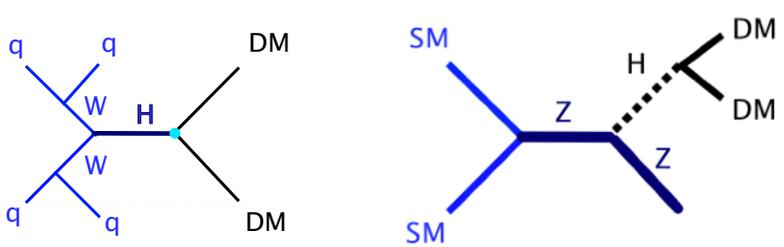
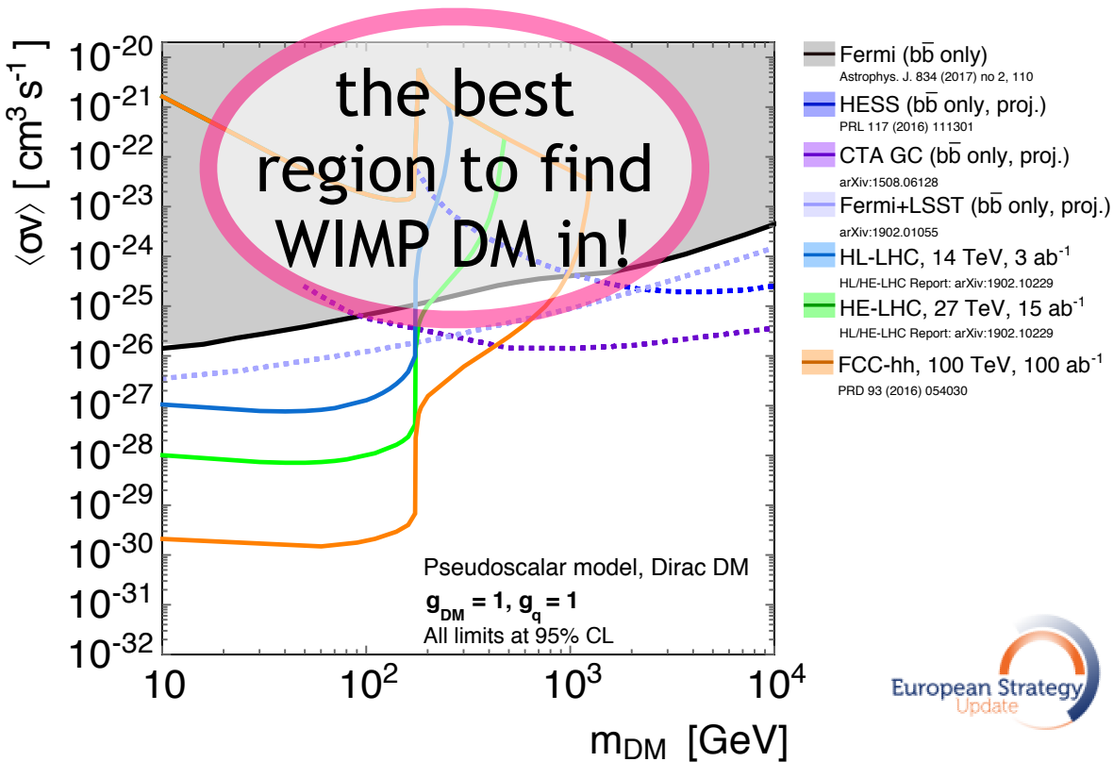




Scalar mediators and indirect detection



Health hazard : these plots are only valid for the couplings specified, in the **limited space of a benchmark model**!

Not to be used to deduce general things like:

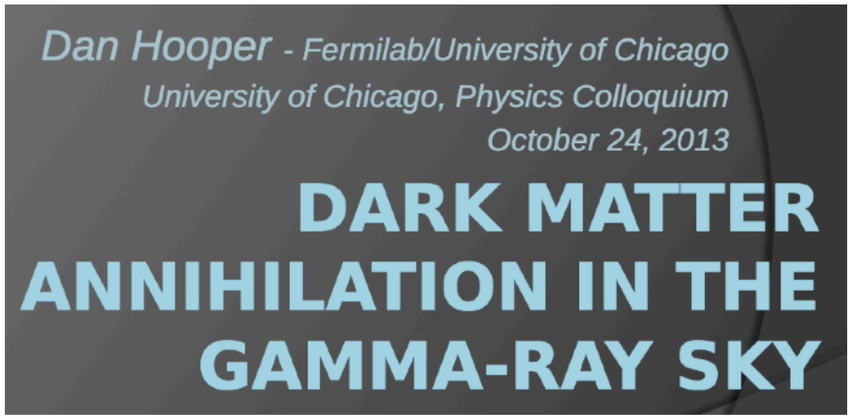
"In the next 50 years we will exclude WIMP DM"

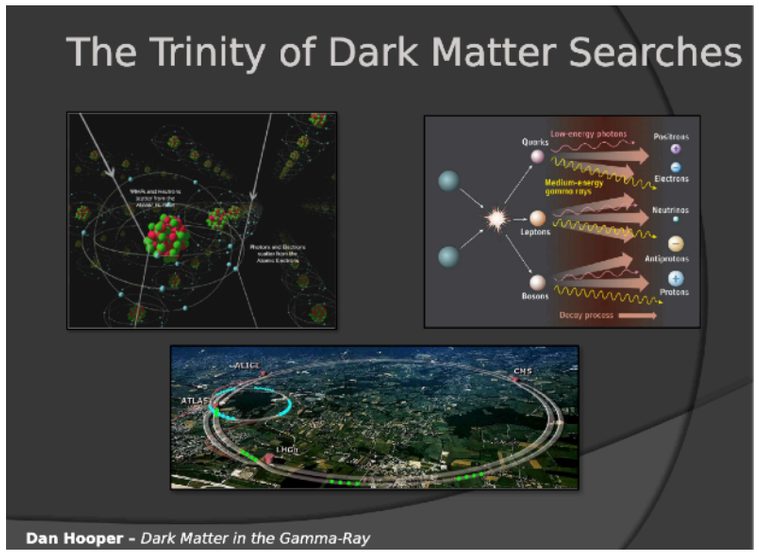
"Technique A is better than technique B to find DM"

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

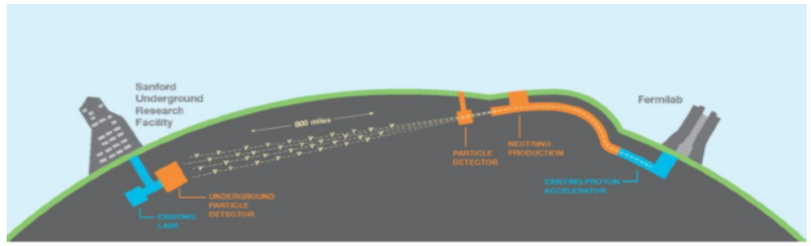
The evolution of dark matter searches in the last decade

Note: not an exhaustive list



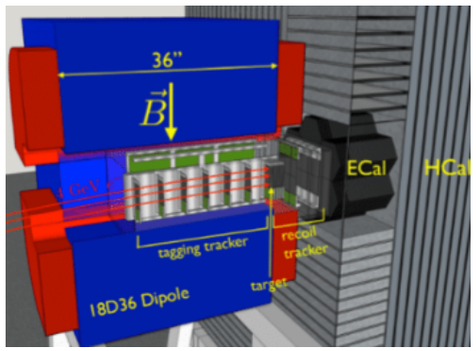


Neutrino experiments



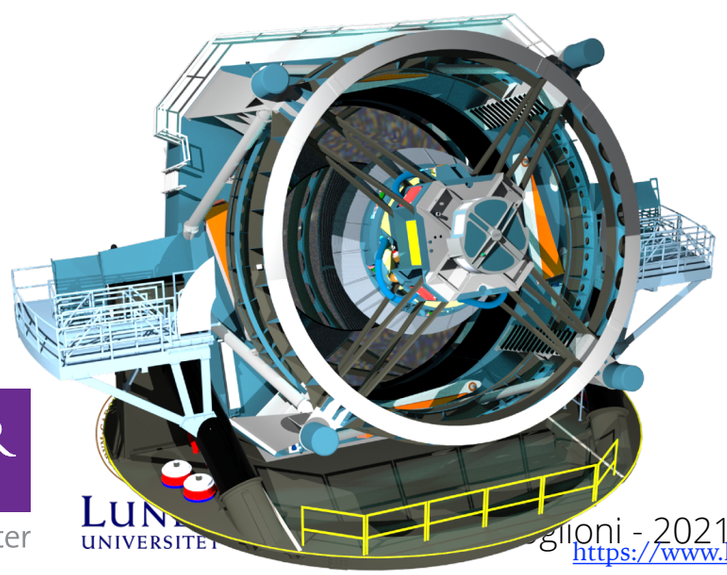
https://www.dunescience.org

Accelerator experiments



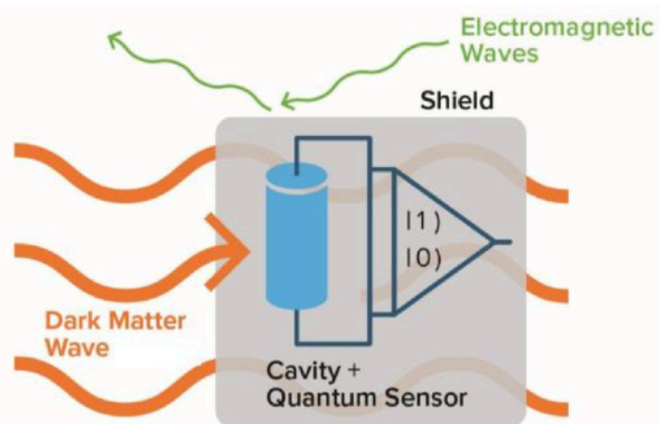
arXiv:1808.05219

Astrophysical probes



https://www.lsst.org

(quantum) sensors for light/ultralight DM



BRN report for new initiatives in DM

Gravitational wave experiments

arXiv:1907.10610

Beyond WIMP DM → beyond high-energy colliders

DM models with **light** particles && **very feeble interactions** w/SM benefit from high intensities, not only high energies

- Starting from our baseline assumption: DM
  - **interacts with SM** particles → we can **produce and detect it** at

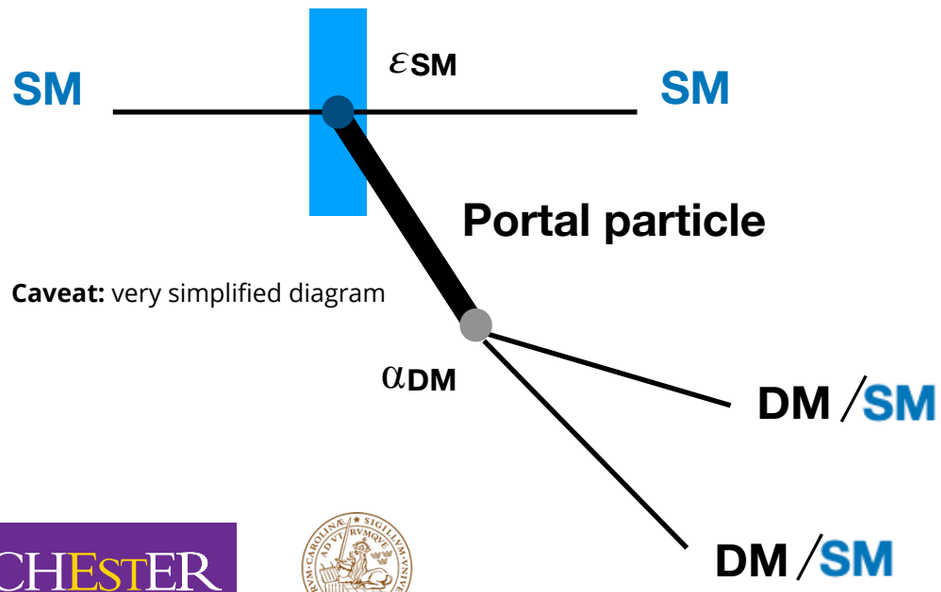
(Intense) beams from particle accelerators

- SPS
- LHC
- Fermilab Booster
- Future

NA62/4, LDMX, SHIP…
FASER, CODEX-b…
MiniBoone, …
MANY more ideas…

Planned/proposed experiments

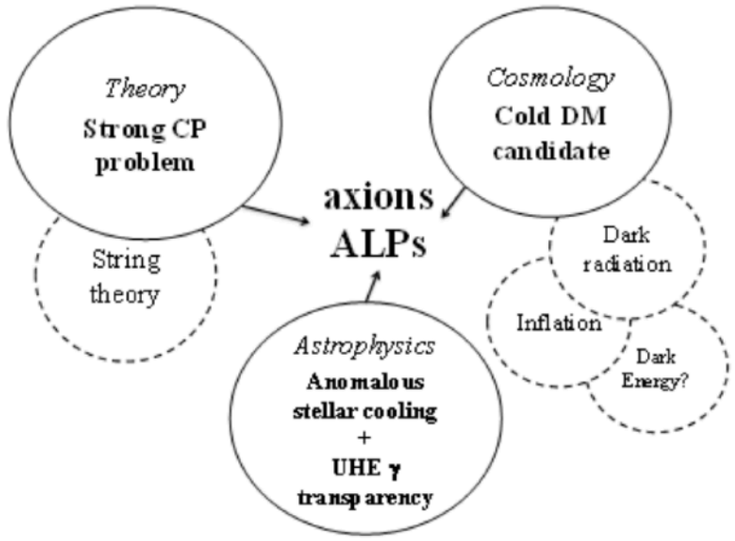
SnowMass2021 RF06
SnowMass2021 NF



→ production of DM/SM particles

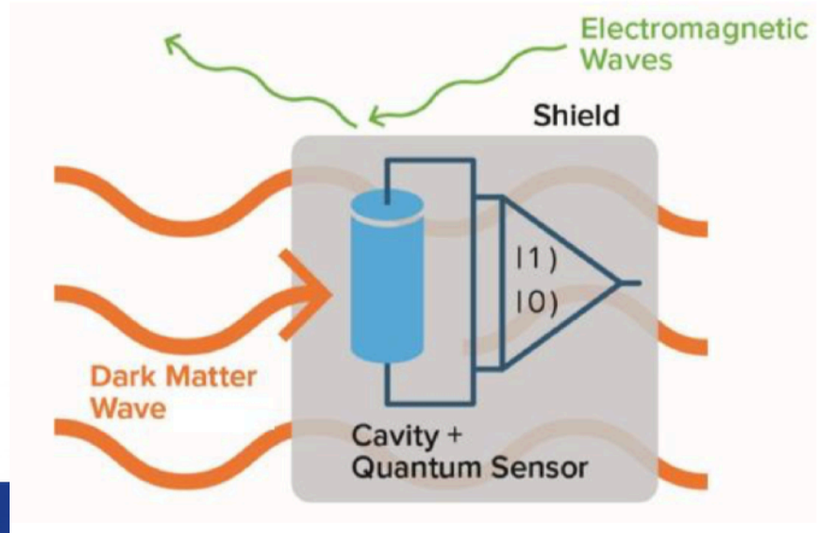
Even lighter DM: axions

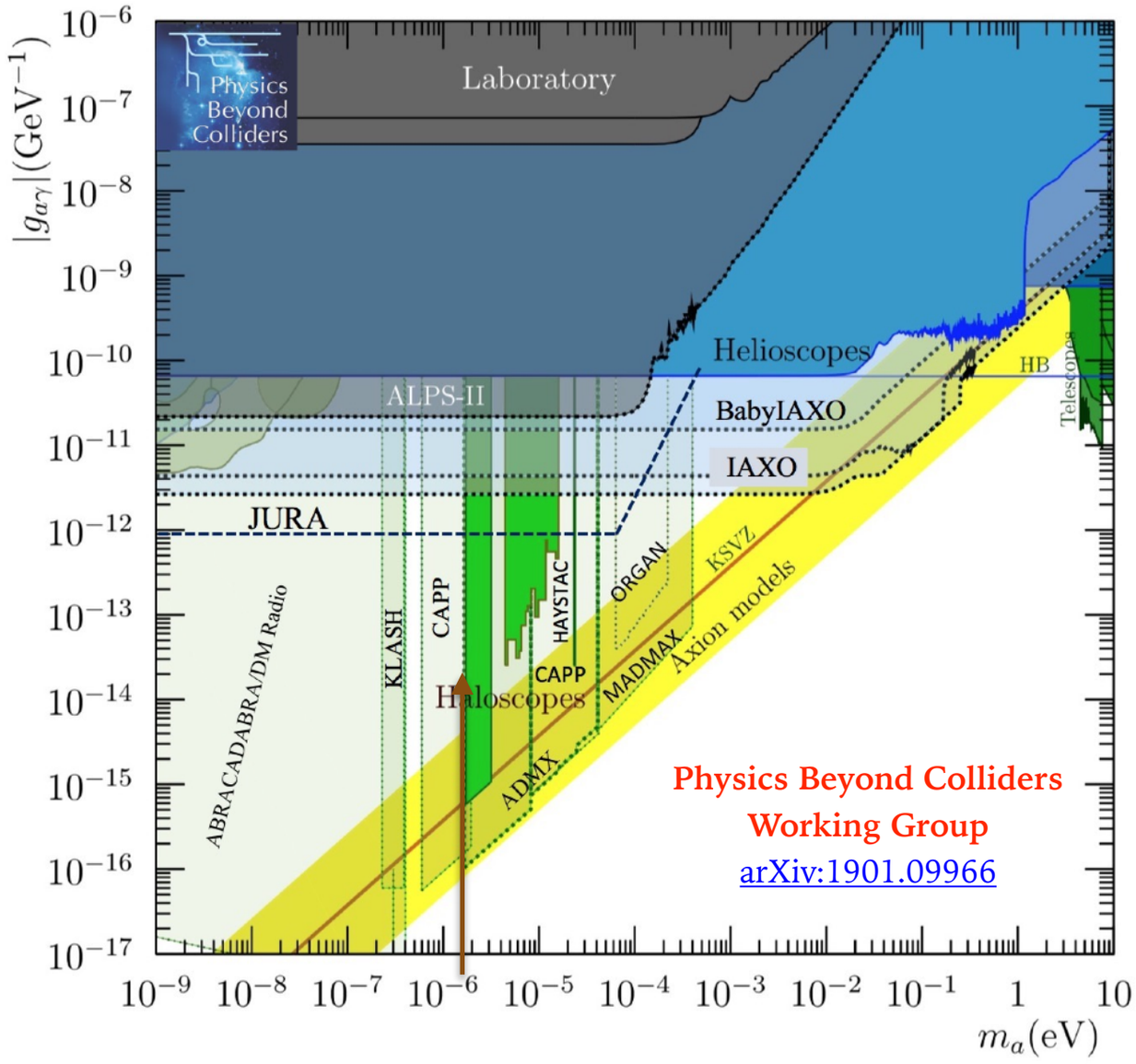
Axions/Axion-Like Particles (ALPs):
example of new particle with inter-field connections, solving more than the DM problem



I. Irastorza's talk @ EPS-HEP 2019

New technologies (small experiments) now available





Physics Beyond Colliders Working Group
arXiv:1901.09966

New: sensitivity of haloscopes to "dark matter" axions

Complementarity thoughts from Snowmass

Link to CPM session #150 - DM complementarity

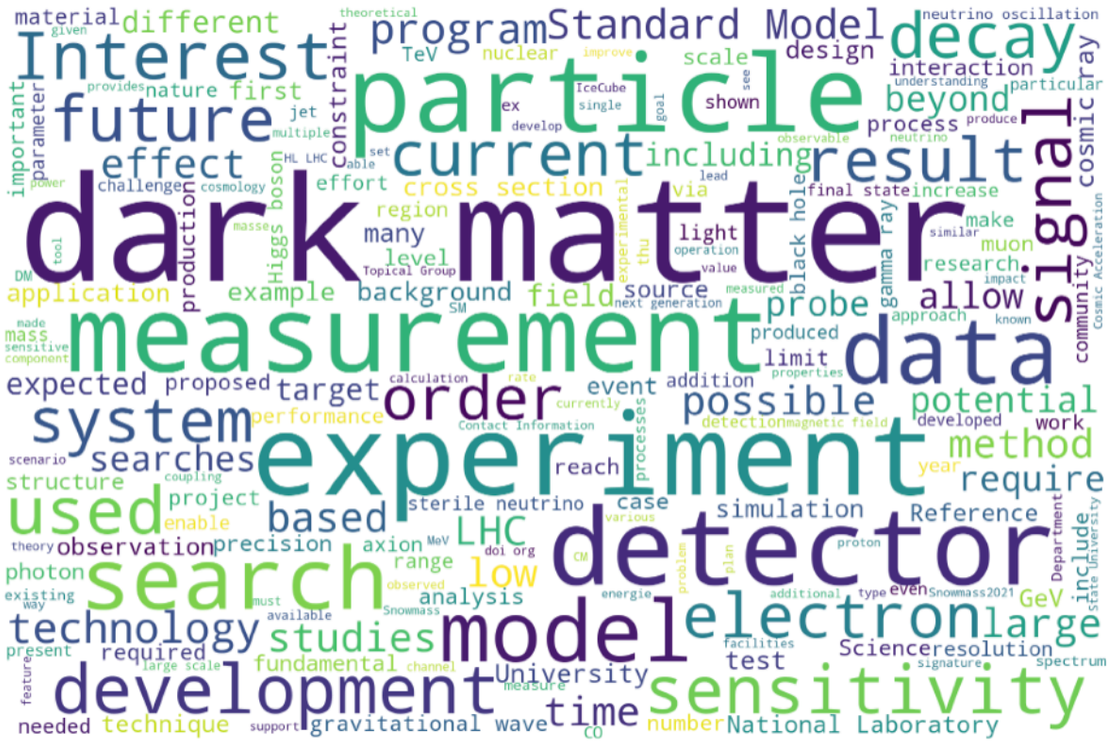
- Since the last Snowmass, there has been a fundamental shift in how we think about searches for dark matter.
- We are in an exciting exploratory phase where new ideas can be implemented on short timescales.
- Dark matter crosses **every** frontier.
- In order to get a full picture of the "elephant", we need to combine information (more about this later)
- CF Conversation Starter: Dark matter could be *the* focal topic of this Snowmass Report.
- **How do we portray this complementarity?**
  - You can join us in thinking (e-mail me for a new mailing list!)

https://gordonwatts.github.io/snowmass-loi-words

Word Clouds

Word clouds are made by looking at the word frequency in the LOI's. The more frequent the word, the larger the font-size in the word cloud.

All LOI's



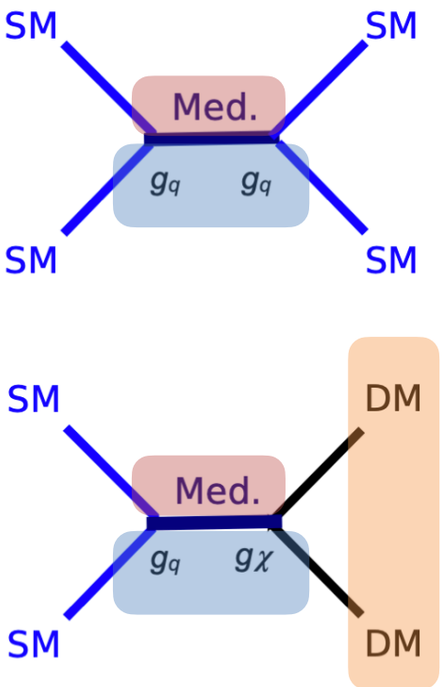
A "global" view of WIMP dark matter

How do we compare results of different experiments ~~in the most model independent way possible?~~

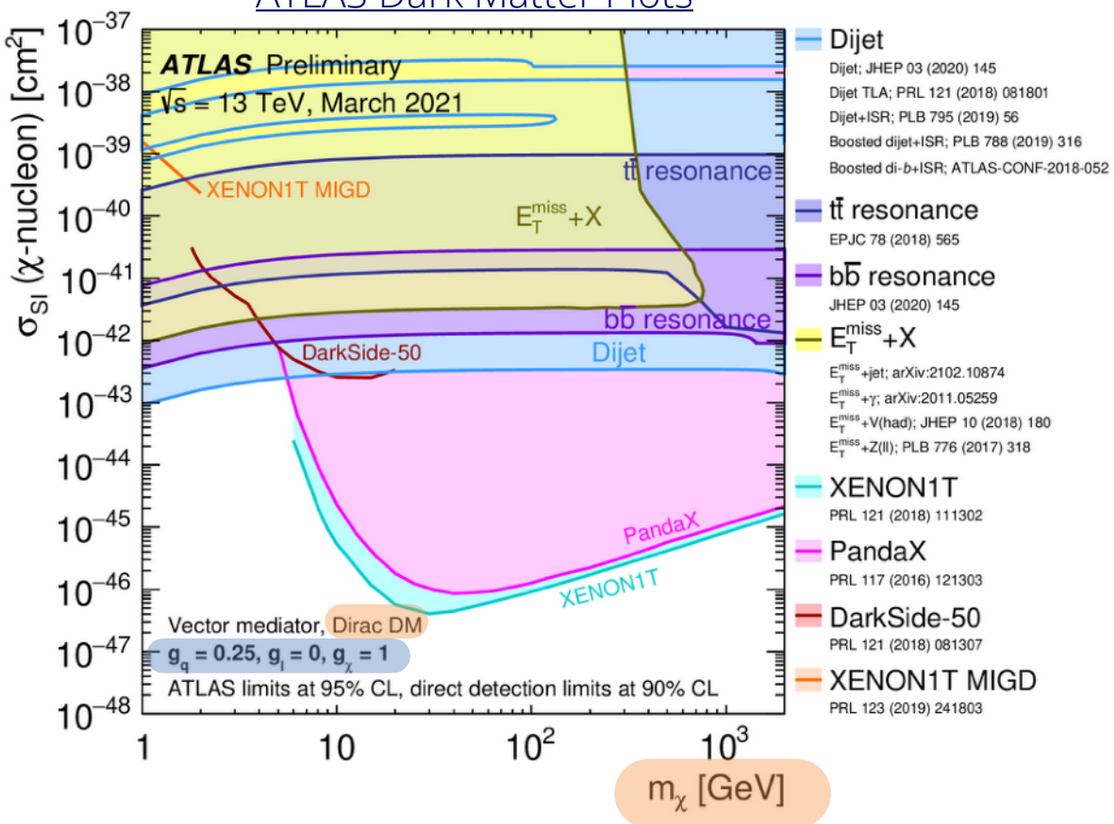
European Strategy Update
"Big Question"

Comparisons are possible only in the context of a model
Essential to **fully specify model/parameters** and **be aware of limitations**

LHC Dark Matter Working Group
Phys. Dark Univ. 27, 100365 (2020)



ATLAS Dark Matter Plots

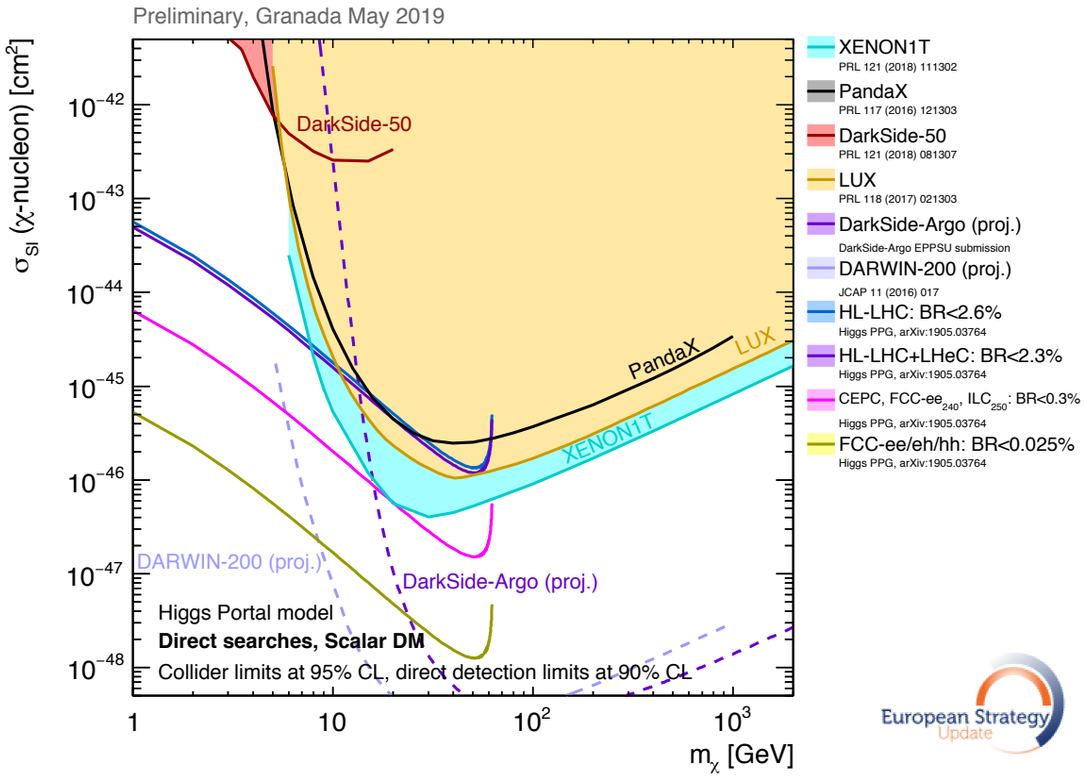


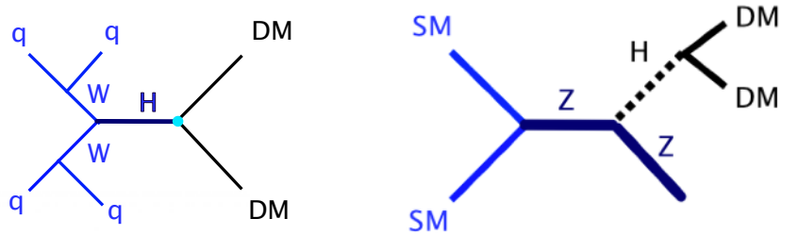
Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**

Complementarity so far: within WIMP frameworks

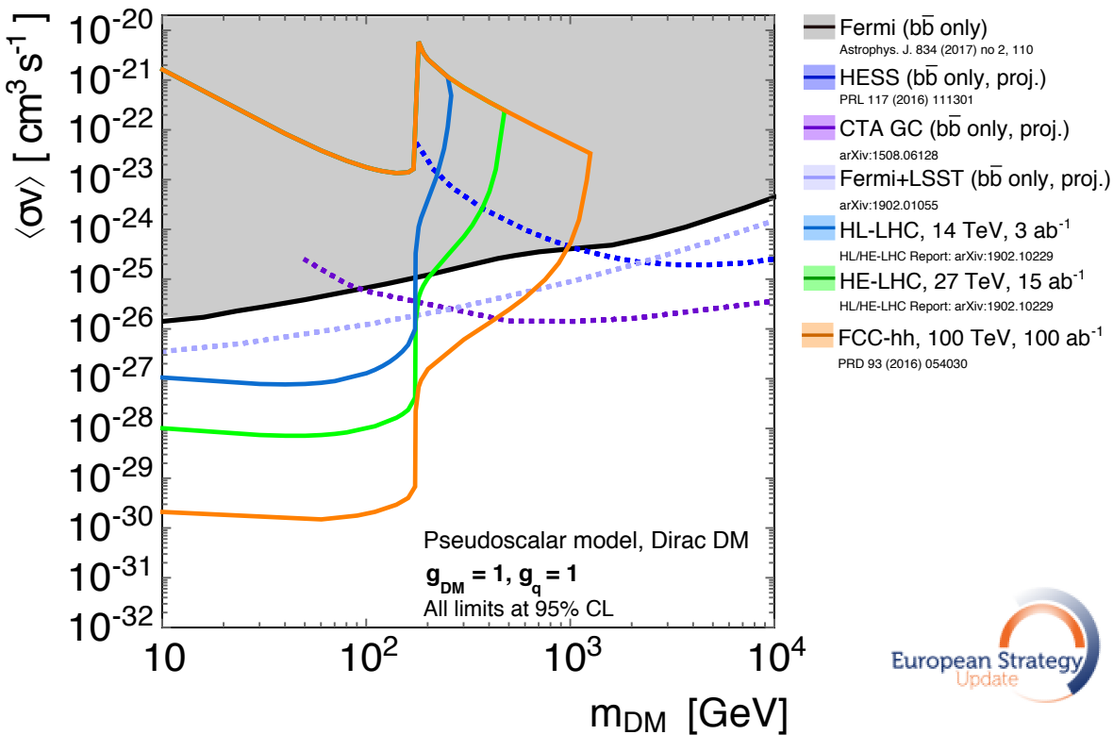
LHC DM Working Group, European Strategy Update Briefing Book, for non-WIMP examples, see Physics Beyond Colliders report

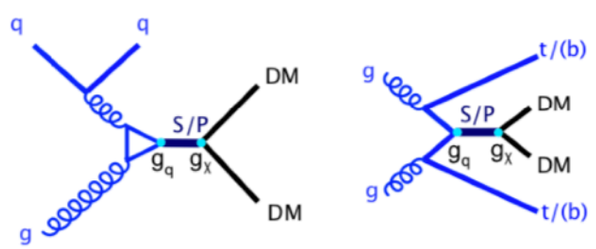
Higgs boson as mediator: colliders & direct detection





Generic scalar mediator: colliders & indirect detection





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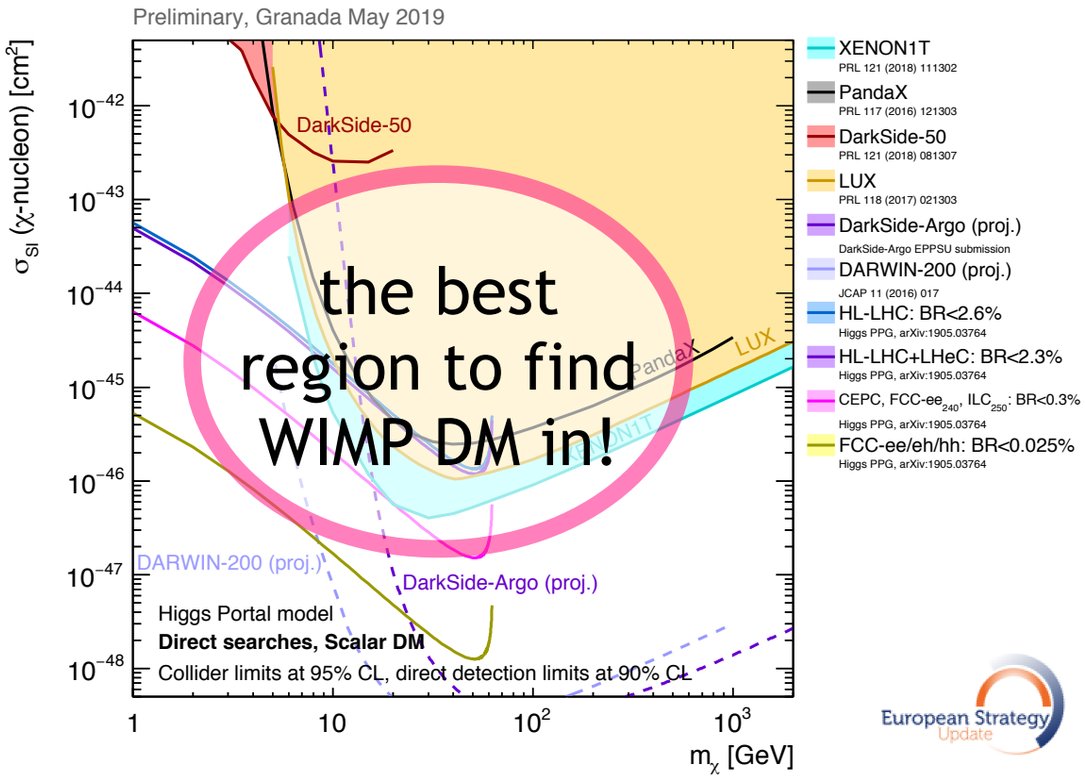
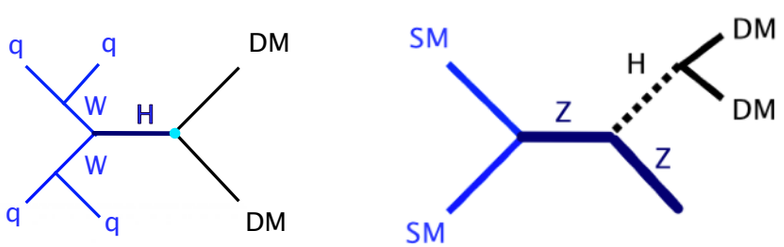
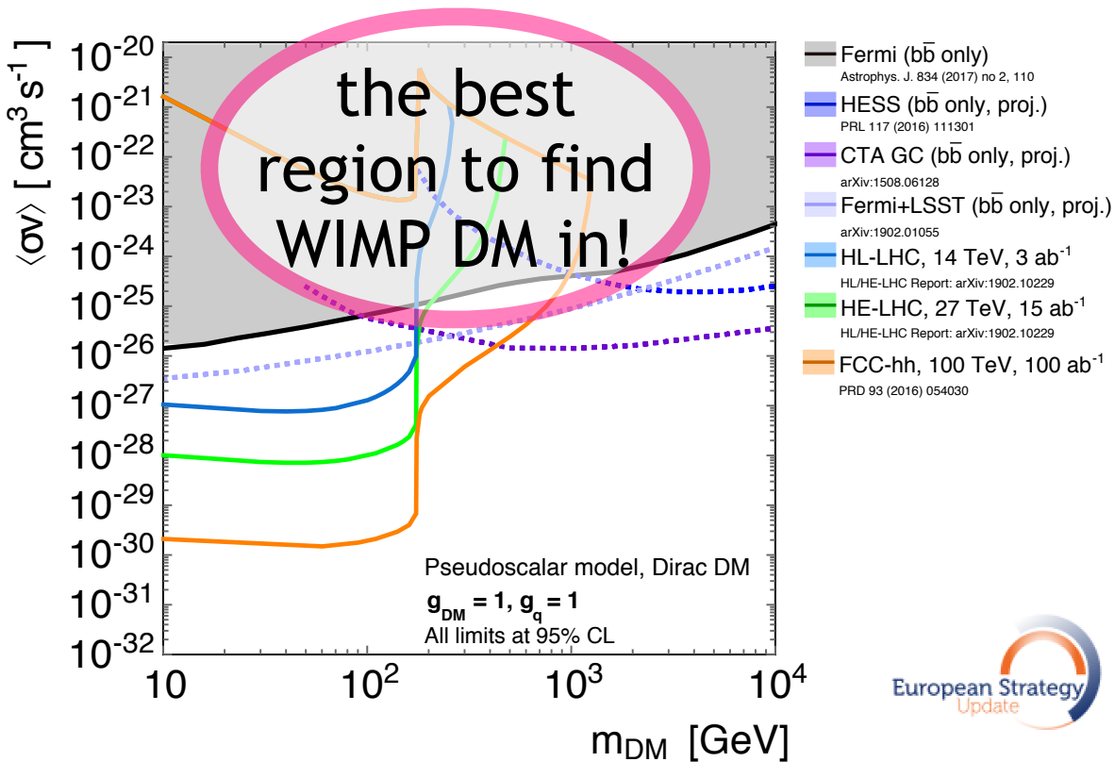




Generic scalar mediator: colliders & indirect detection



Health hazard : these plots are only valid for the couplings specified, in the **limited space of a benchmark model**!

Not to be used to deduce general things like:

"In the next 50 years we will exclude WIMP DM"

"Technique A is better than technique B to find DM"

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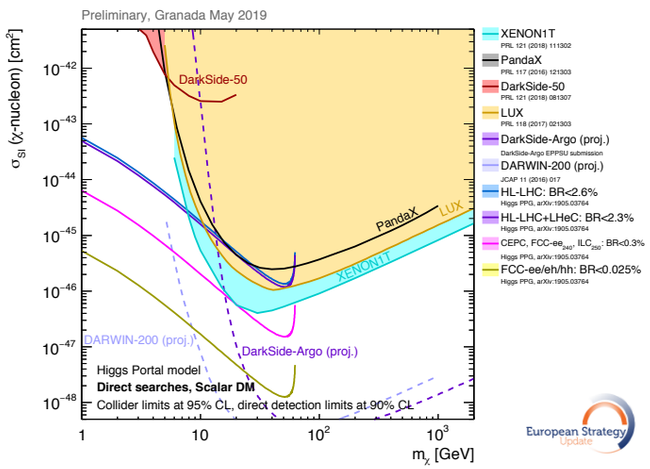
Ongoing work: extending early LHC benchmarks to lower masses /

Can LHC invisible particle searches be interpreted in terms of arbitrarily low DM masses (/couplings)?

- In principle one ***could*** extend those plots to $m_{DM} < 1$ GeV

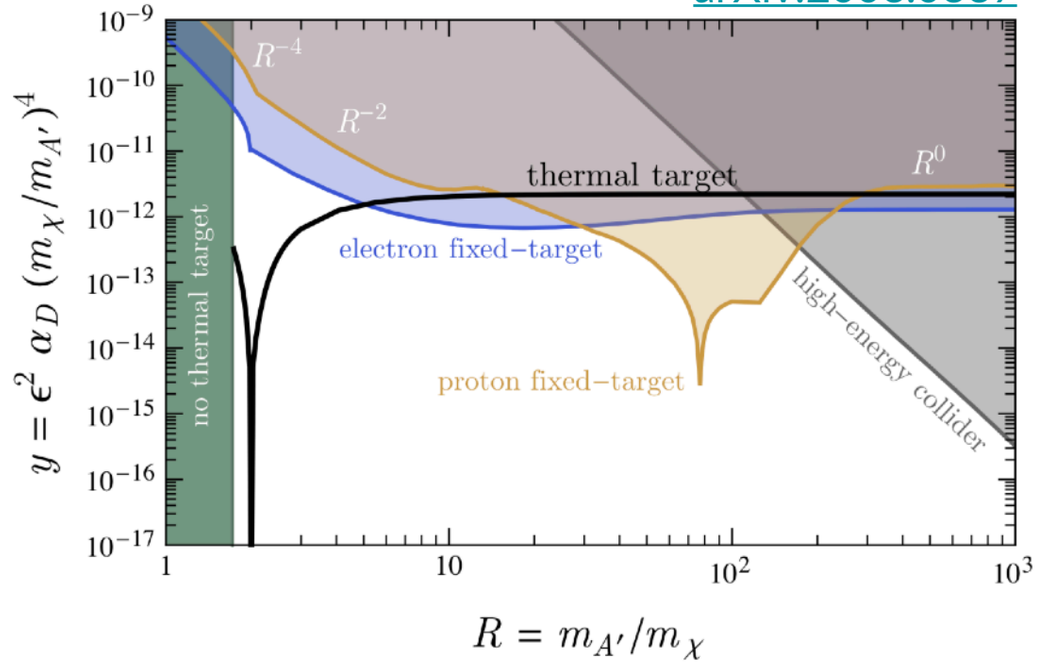


- Are there **theory/nuclear physics issues** in the translation of results?

- Personal feeling (from a collider person!) is that **couplings of order 1 may paint a misleading picture** if we do so, even if we have all caveats specified on the plot → lower coupling models needed

- (Natalia Toro's) Idea for a complementarity plots to be made in Snowmass, linking lower and higher energy scales

arXiv:2003.0337



Discussion welcome!

Ongoing work: extending DMWG models to lower masses / couplings

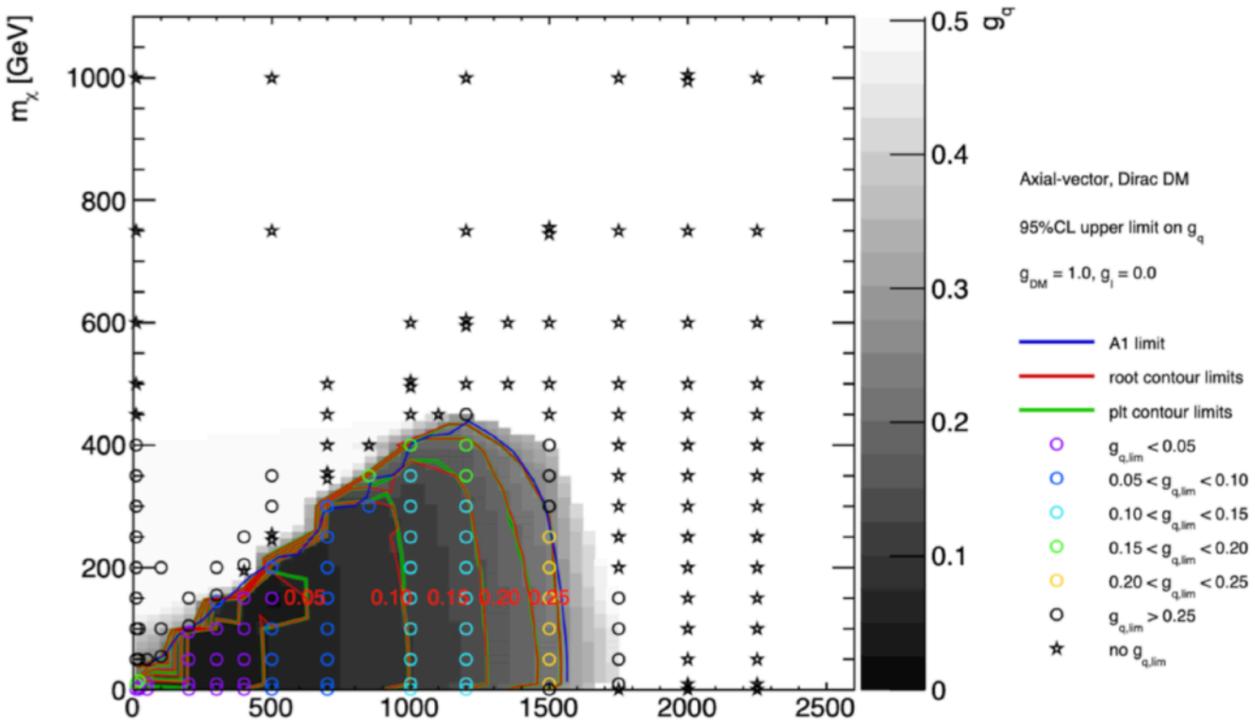
How do generic LHC searches "move on" from benchmarks with couplings of order 1?

(which still have a lot of merit as collider benchmarks)

- Technical "issue": production of new simulated signal samples is a big overhead for "small" LHC analyses → inertia from moving on from previous recommendations

- Solution: analytical methods being developed within ATLAS/CMS/ Snowmass (K. Pachal, A. Albert, B. Gao, E. Corrigan) - Letter of Intent

B. Gao's thesis

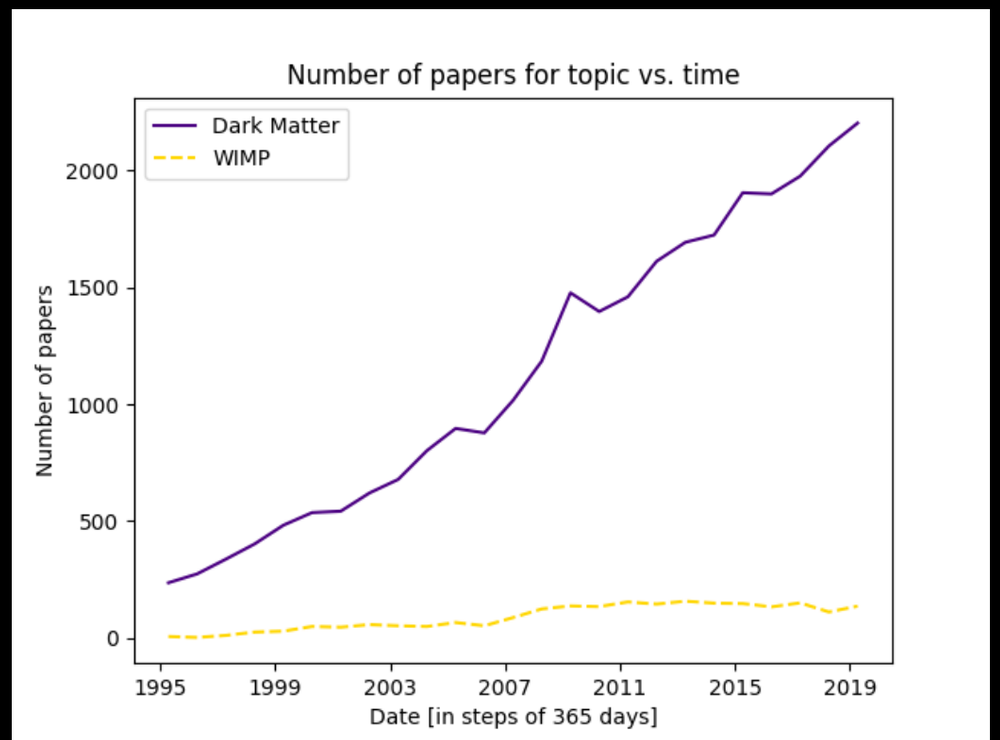


- Even with analytical methods, filling the low-mDM parameter space requires more samples

- Aim to extend vector/axial vector mediator plots for future colliders with more points at lower mediator/DM masses

...are we looking everywhere?

Example of non-WIMP searches
with non-standard jet signatures



What might we learn from lines of research that are off the beaten track? They check accepted ideas, always a Good Thing, and there is the chance Nature has prepared yet another surprise for us.

J. Peebles

left: much lighter DM

up: stronger interactions

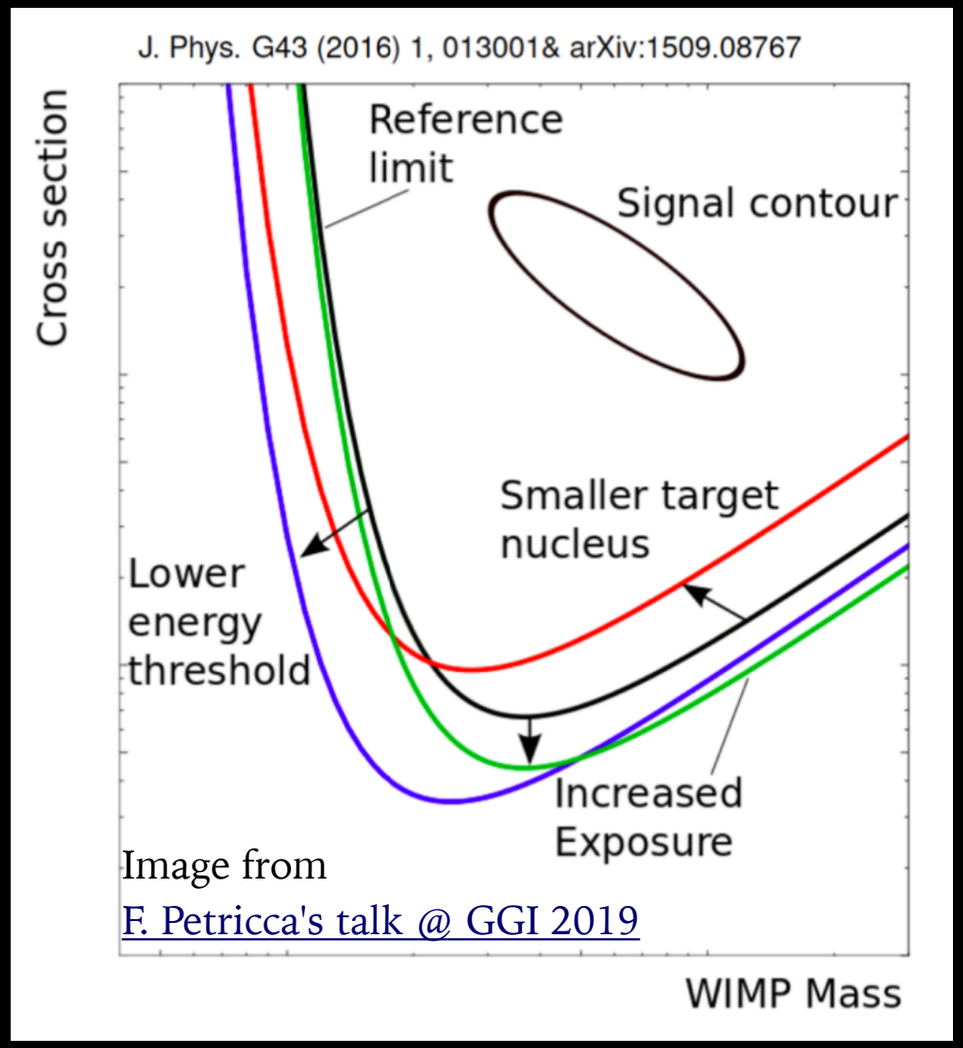


Image from
F. Petricca's talk @ GGI 2019

right: more massive objects

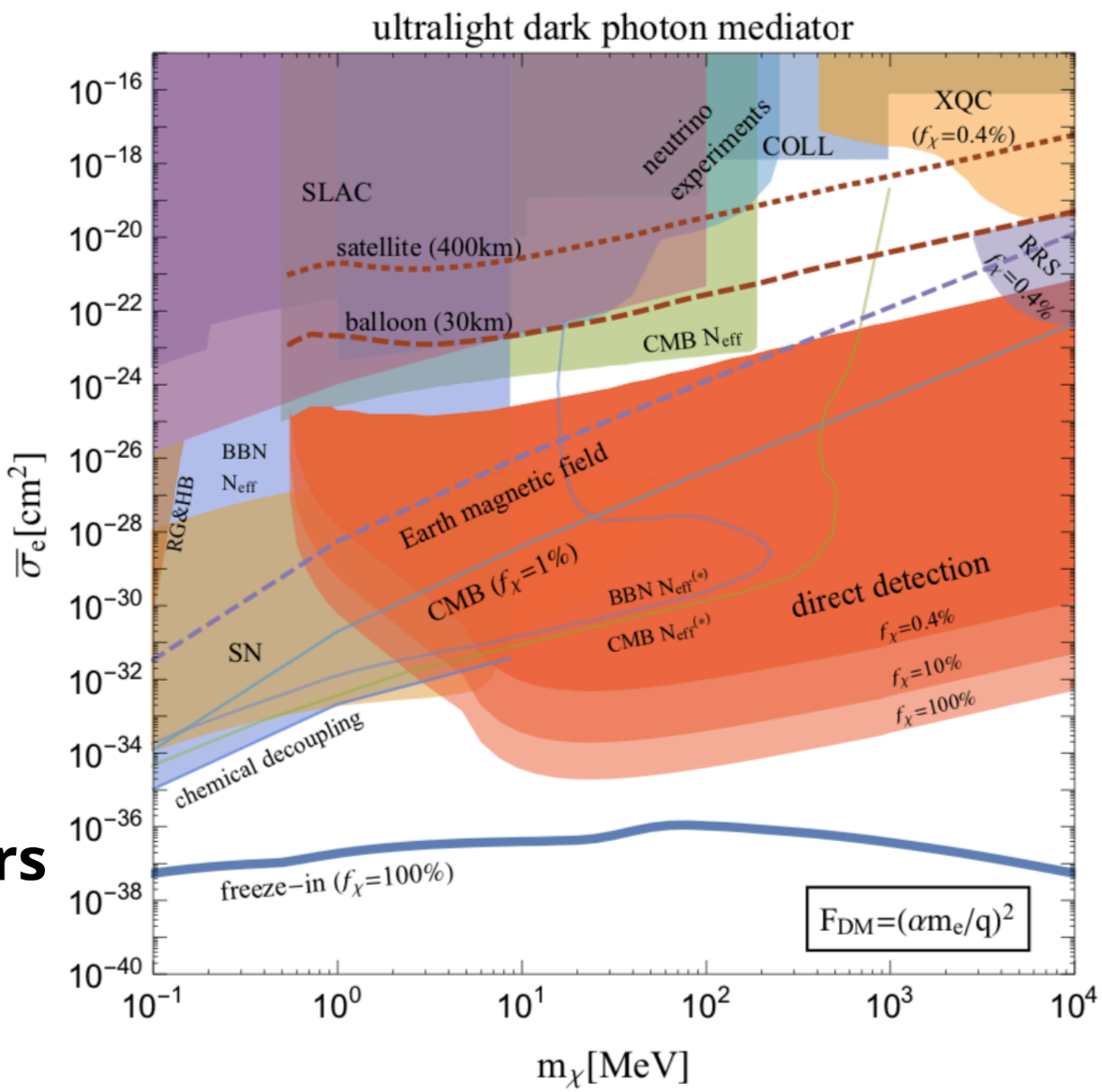
Looking *up* (to hints from astrophysics & more)

A change of paradigm from "DM == invisible particles"

(potentially low-mass) & "strongly interacting" DM particles will

- interact with **detectors**
  - need to take this into account for collider searches!
- interact with **atmosphere & earth**
  - use/send detectors higher up!
- leave **astrophysical signals**
  - Supernova (SN), BBN, CMB...
- be part of more **complex dark sectors**
  - with interesting collider / cosmological signatures, as dark sector particles could be produced as part of particle jets!

https://arxiv.org/abs/1905.06348



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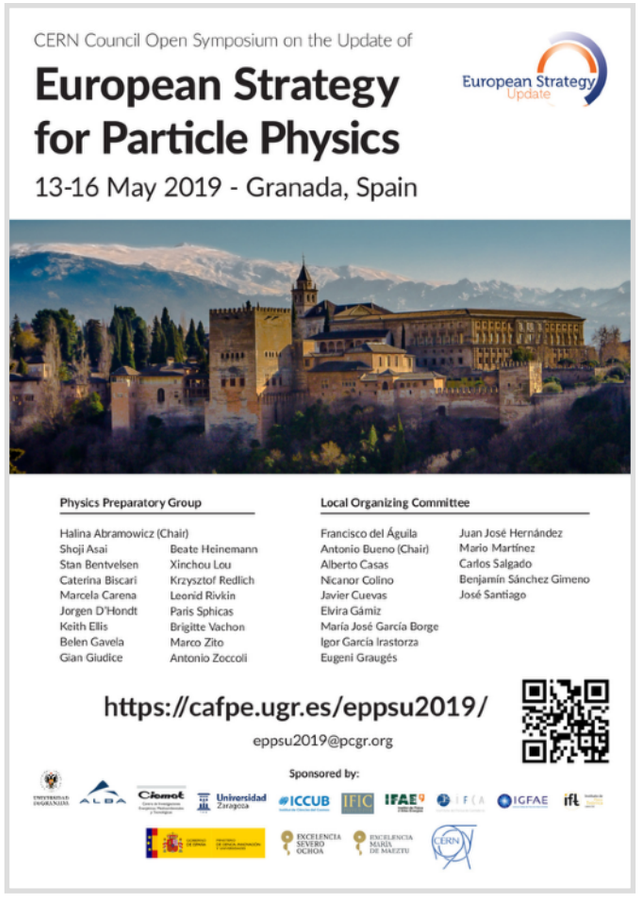
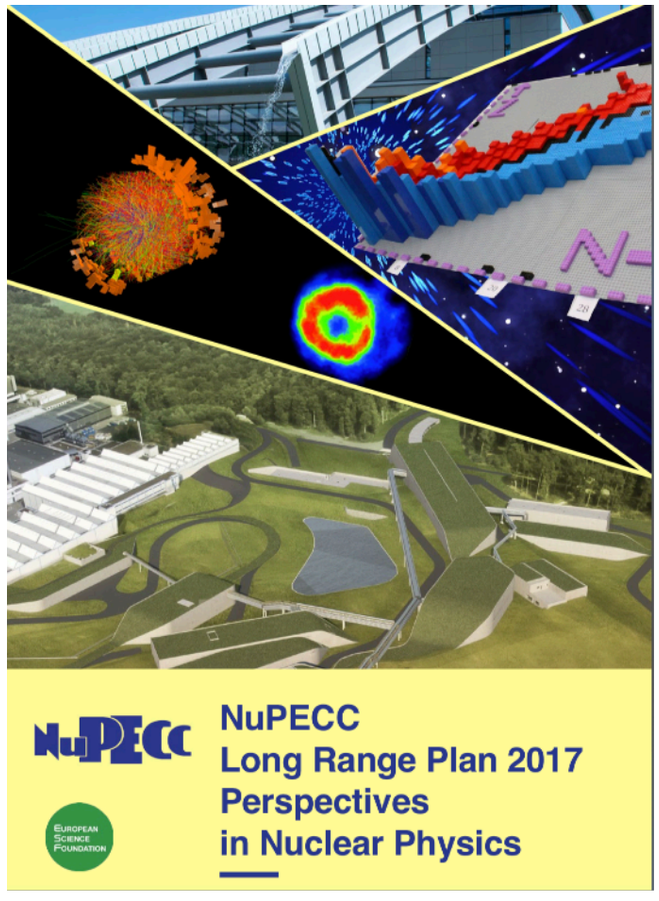
More about community initiatives & efforts

European visions for particle, astroparticle and nuclear physics

https://www.appec.org https://ecfa.web.cern.ch http://nupecc.org

Astroparticle (APPEC) Particle (ECFA) Nuclear physics (NuPECC)

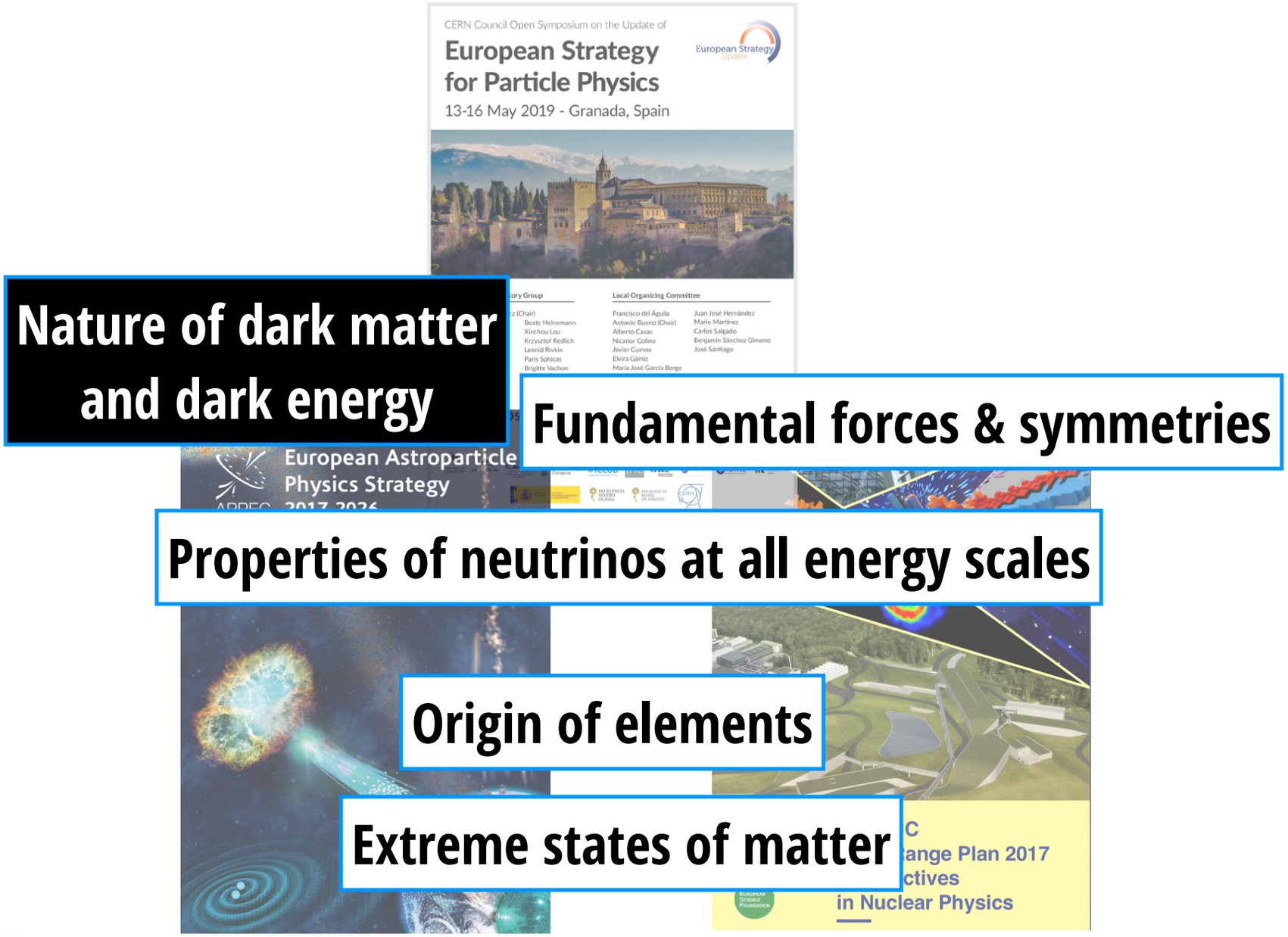




Astroparticle, particle and nuclear physics in Europe have **strategies and plans** that **recognize the importance of synergies** between the different fields

Visions: APPEC, ECFA, NuPECC

Some of the **common scientific goals** in the strategy documents:

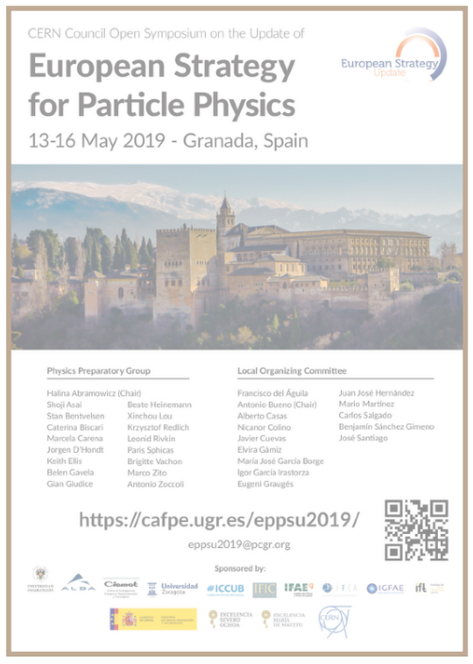


More synergies: ”foundations” for common challenges

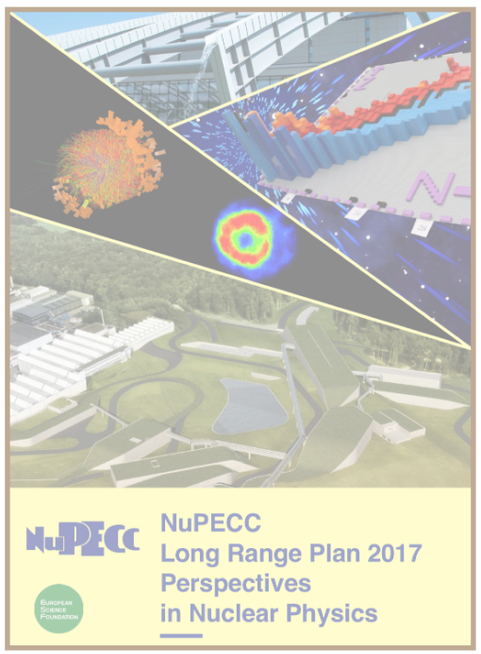
To reach common goals, one needs to work together on tools as well...

Astroparticle

Particle



Nuclear



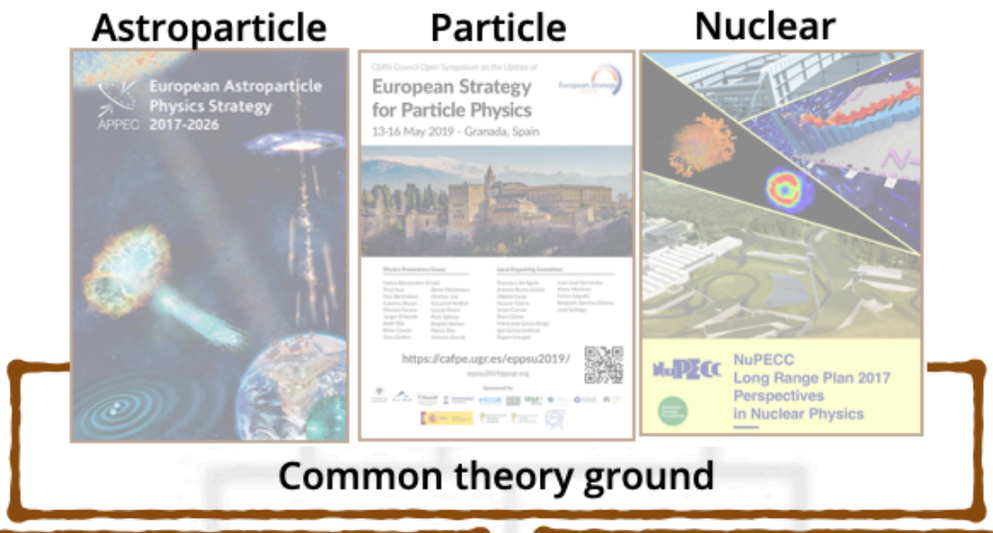
Common theory ground

instrumentation
(accelerators, beams, detectors, vacuum & cryogenics, control & automation...)

data acquisition, computing, data sharing & open science

Two complementary projects (everyone is welcome!)

searches & interpretation



JENAS EoI: Initiative for Dark Matter in Europe and beyond: Towards facilitating communication and result sharing in the Dark Matter community (iDMEu)

https://indico.cern.ch/event/869195/
ESCAPE newsletter APPEC newsletter

build a discussion platform and tools to facilitate collaboration of existing groups/ efforts on **dark matter searches** and their **interpretation**

kick-off meeting 9-12/05/2020

software & data

ESCAPE
European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

HSF
HEP Software Foundation

Towards a Dark Matter Test Science Project

ESCAPE Progress Meeting, 2020
TOOLS conference contribution

compare **end-to-end analysis workflows** for WIMP searches, towards their implementation in a common **Software Catalogue** and as input to the design of the **European Open Science Cloud**

Now hiring!

European Research Council
Established by the European Commission

The University of Manchester

Lunds Universitet

The Initiative for DM in Europe and Beyond

iDMEu

initiative for Dark Matter in Europe and beyond

iDMEu kick-off - 2021/05/10-12
https://indico.cern.ch/e/iDMEu

The JENAA iDMEu LOI organizers:

Marco Cirelli
Caterina Doglioni
Federica Petricca
(+ more will join)

The best region to find dark matter is the one where more techniques and ideas can **discover** and **explore** DM!

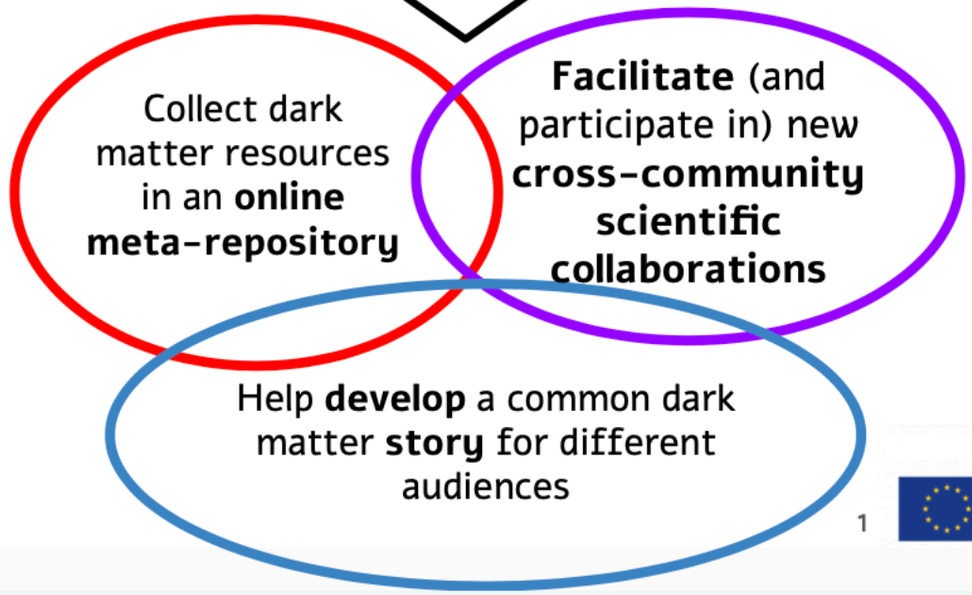
⇩

After the European Strategy Update process and during a joint ECFA/APPEC/NuPECC (JENAA) meeting, a number of DM researchers met with similar questions:

E.g. "what are your assumptions?" "why do you use this technique?" "how will findings in your DM research impact my DM research?" "where can we meet and discuss this topic in depth after this meeting?"

We realized that there was **no common platform** for these discussions or for resource sharing
→ we decided to start developing it, with three interconnected objectives

⇩



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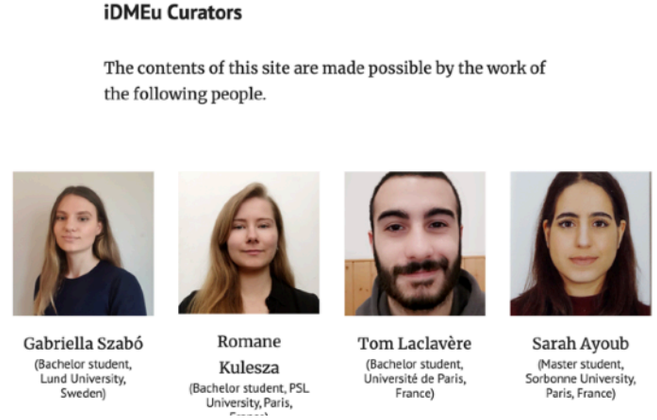
https://indico.cern.ch/e/iDMEu
idmeu.org (preliminary)



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More info on ECFA Newsletter

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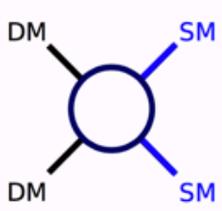
with three interconnected objectives

The ESCAPE Test Science Project

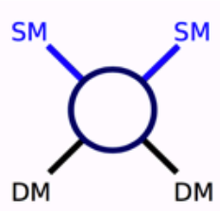
Scientific question: dark matter

Many hypotheses for dark matter
→ many ways to detect it
→ many different experiments
→ many different data / workflow needs
→ many different data / result sharing policies

one of many models predicting **Weakly Interacting Massive Particles (WIMP) - could also use others...**



Indirect Detection



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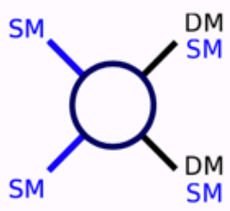
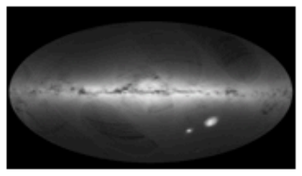
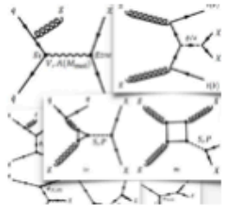


Colliders

Credit: ESA/Gaia/DPAC.

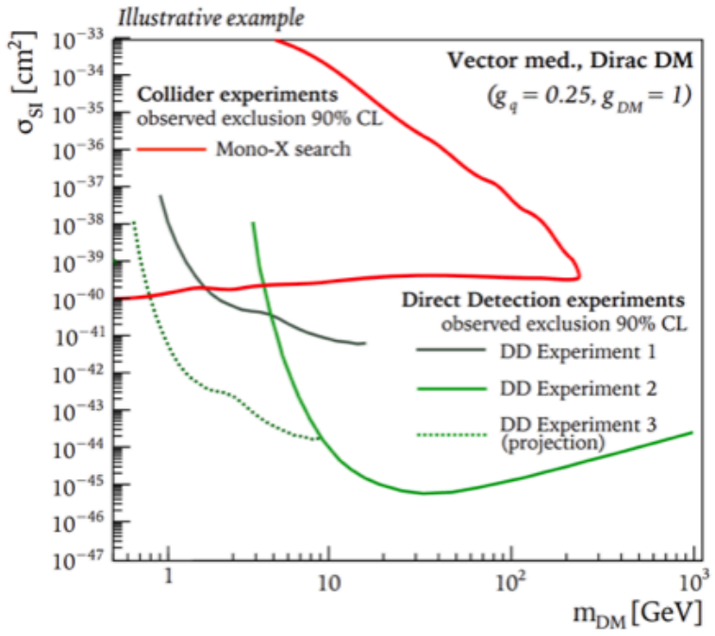


Astrophysics



Theory

Scientific content of DM-TSP:
New plots of dark matter discoveries / constraints



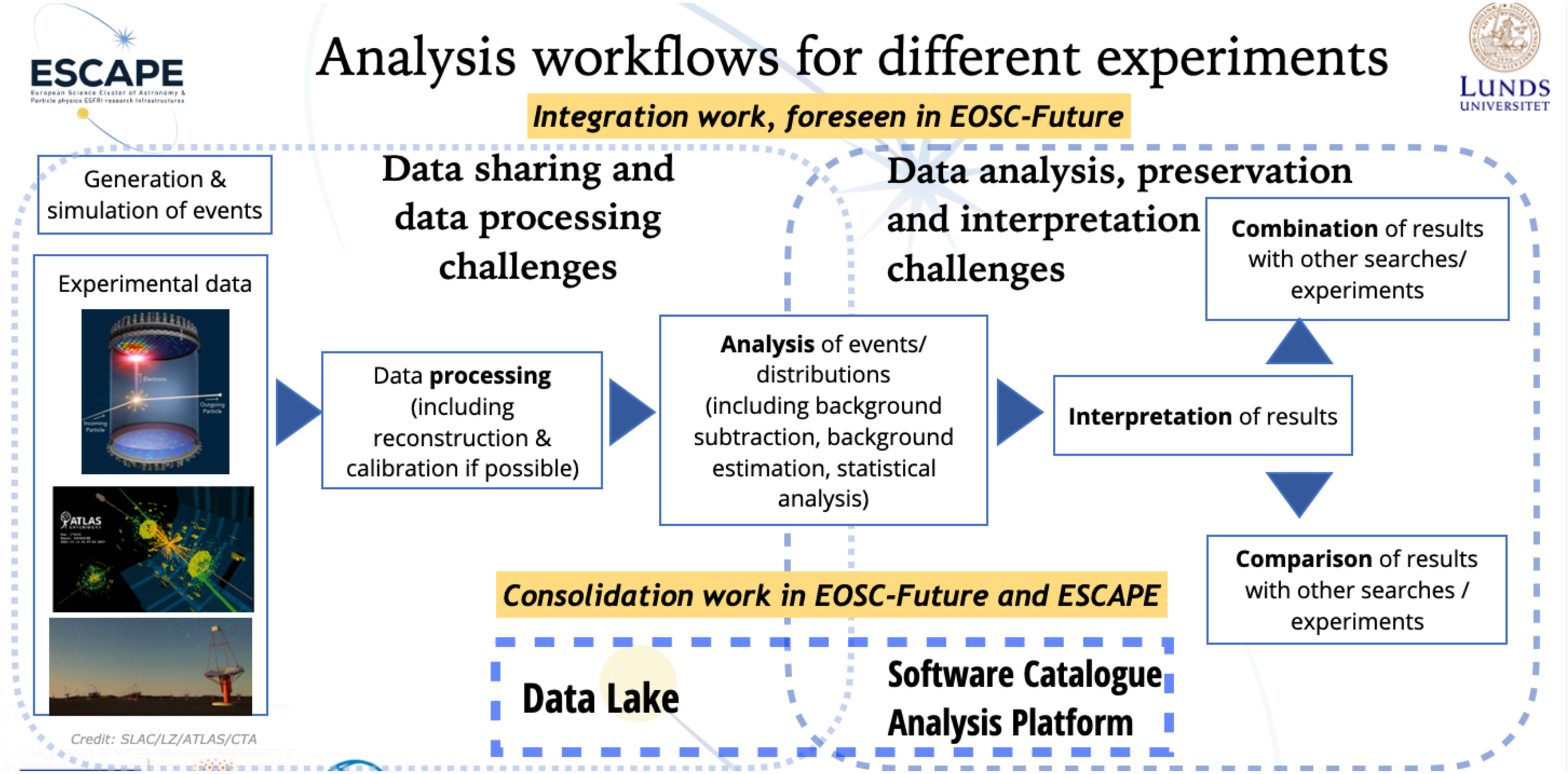
arXiv:1912.12739 & refs therein

There are many combinations/comparisons of results on the market...
but none that sees them all work together with FAIR data & end-to-end workflows!

This is where this Test Science Project comes in!

The ESCAPE Test Science Project

5 postdocs all over Europe working on this (funded by EOSC-Future)



Take-home point: we need open data and sustainable analysis software for complementary experiments

To discuss DM complementarity in SnowMass2021

Link to Community Planning Meeting session #150 - DM complementarity

- Since the last Snowmass process as input to prioritization of particle physics in the US (2013), there has been a fundamental shift in how we think about searches for dark matter
- We are in an **exciting exploratory phase** where new ideas can be implemented on short timescales
- Dark matter crosses **every** frontier
- In order to get a full picture of the "elephant", we need to combine information from different experiments
- **How do we portray this complementarity?**
  - You can join us in thinking and making plots (mailing list for when Snowmass restarts: SNOWMASS-DM-COMPLEMENTARITY@FNAL.GOV, instructions on how to join are on snowmass21.org)

https://gordonwatts.github.io/snowmass-loi-words

Word Clouds

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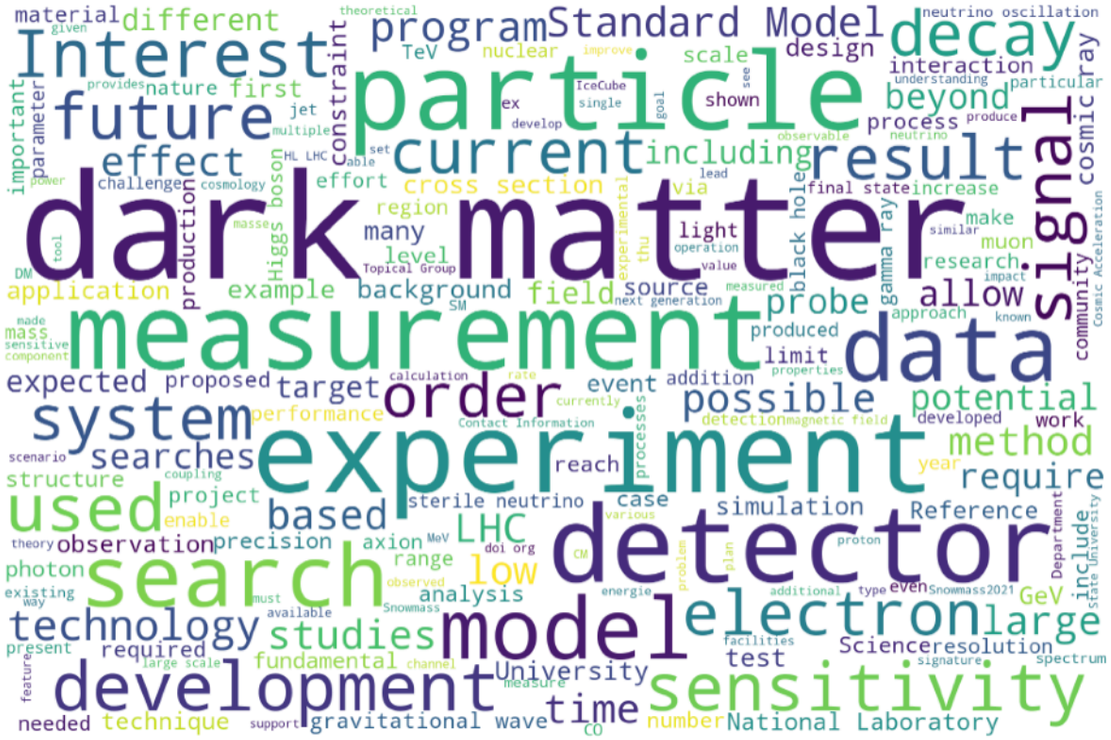
All LOI's



Slide written jointly by Cosmic, Energy and Neutrino Frontier Topical Group Conveners

The University of Manchester

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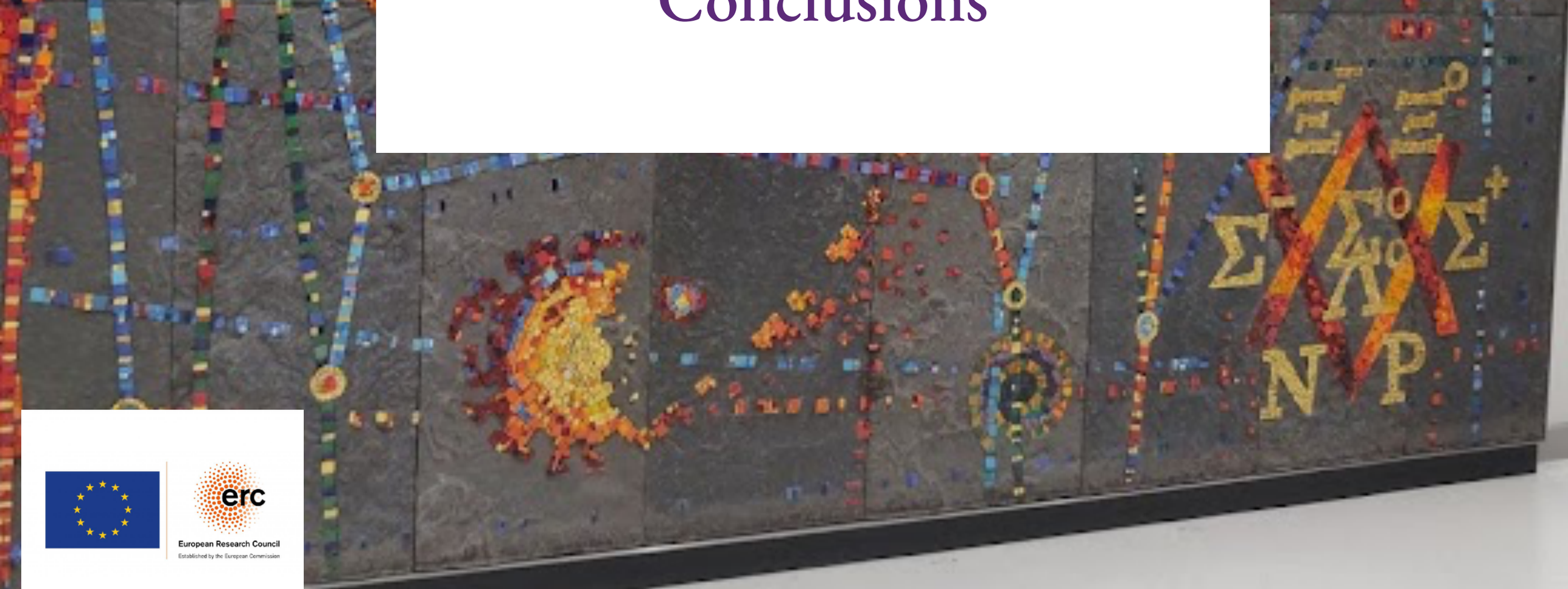
Conclusions



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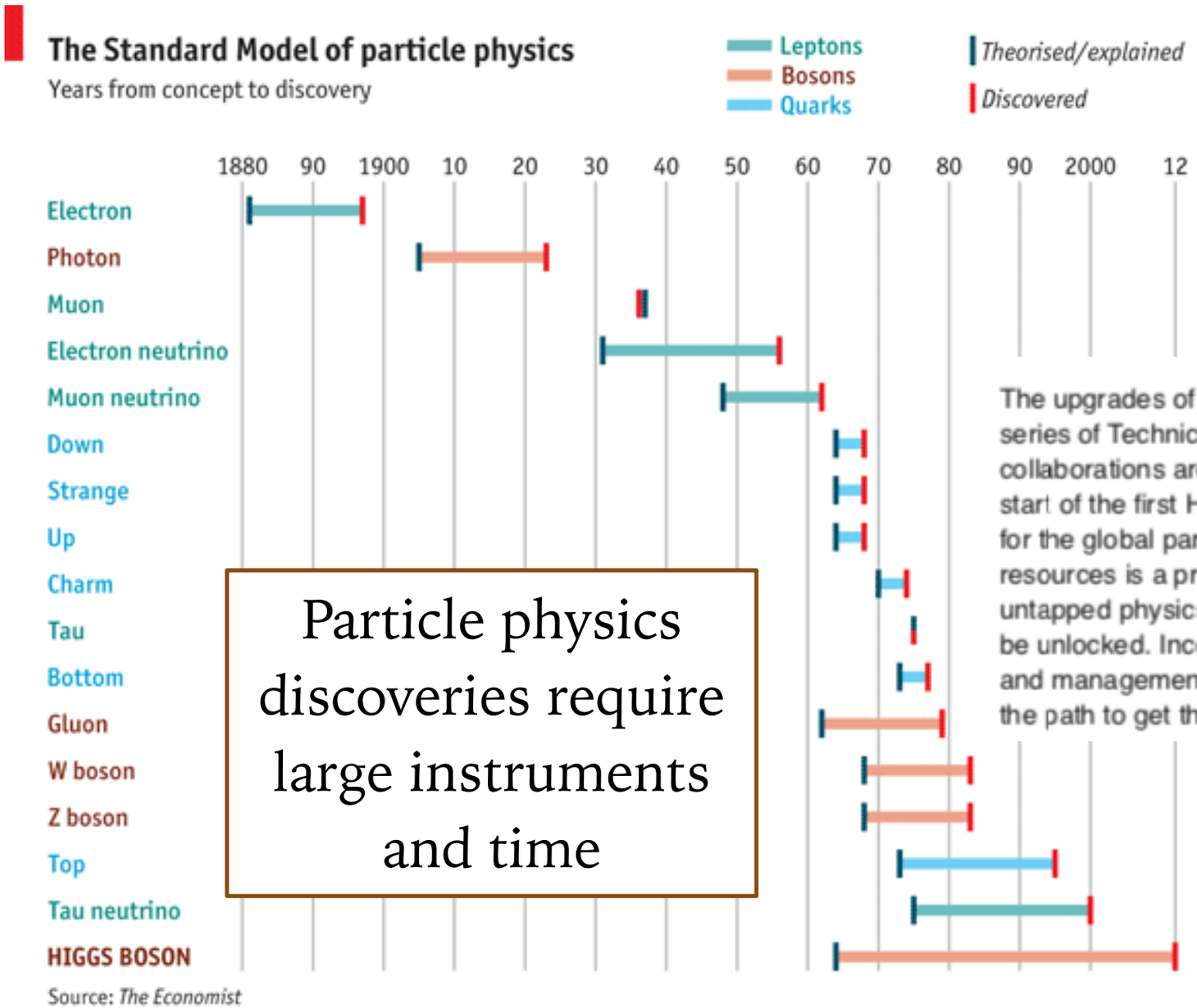
What does it take for a discovery? ~~Real~~ Time



Particle physics discoveries require large instruments and time

- **We aren't done taking LHC data (10x more expected)**
  "low-hanging fruit" checked first, expect surprises

European Strategy Update, deliberation document

The upgrades of the ATLAS and CMS experiments have been documented in a series of Technical Design Reports and have been approved, and the international collaborations are gearing up to commission these detectors by 2027, the scheduled start of the first HL-LHC run. The timely delivery of these upgrades is a milestone for the global particle physics community, and the continued allocation of adequate resources is a priority. Based on continued innovations in experimental techniques, the untapped physics that is surely awaiting in the third LHC run and the HL-LHC era can be unlocked. Incorporating emerging new technologies into trigger systems, computing and management of big data, reconstruction algorithms and analysis methods is the path to get the best out of these upcoming dataset...

The Economist

Many interesting upgrades planned for HL-LHC (and beyond)!

What does it take for a discovery? Collaborations

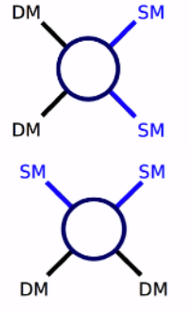
The search for BSM/Dark Matter has a long way to go at future colliders…

…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

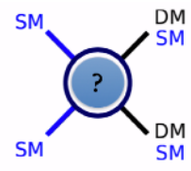
Now and future: essential **complementarity between colliders and other experiments,** *e.g. for dark matter*



cosmological origin
DD/ID/astrophysics

and

nature of the DM-SM interaction
accelerators / colliders



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

SnowMass2021

Towards a Dark Matter Test Science Project

iDMEu
initiative for Dark Matter in Europe and beyond

Discussion / work together ongoing!

European Research Council
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Thanks for your attention!

Photo credits: C Fitzpatrick

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