Dark Matter at Colliders - Lecture 1
(including complementarity considerations)

HEP Graduate Workshop, Batna, 24-26/05/22

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European Research Council
Established by the European Commission

Outline

- Quick recap on dark matter
- Collider searches for invisible & visible particles
  - 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 at colliders ever discussed
Inclusions (and omissions) are a matter of personal taste and expertise

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Quick dark matter recap

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Empirical problems of the SM

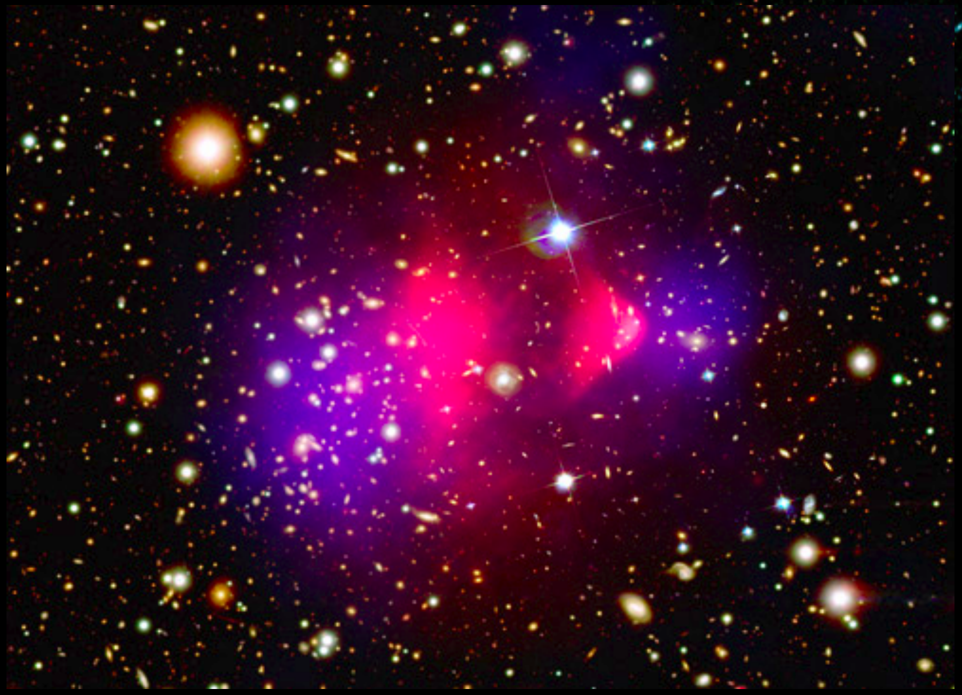
- **Dark matter (DM)**
- Dark energy
- Matter vs antimatter
- Weakness of gravity
- Neutrino masses

Dark Matter, what do we know about it?

it is dark

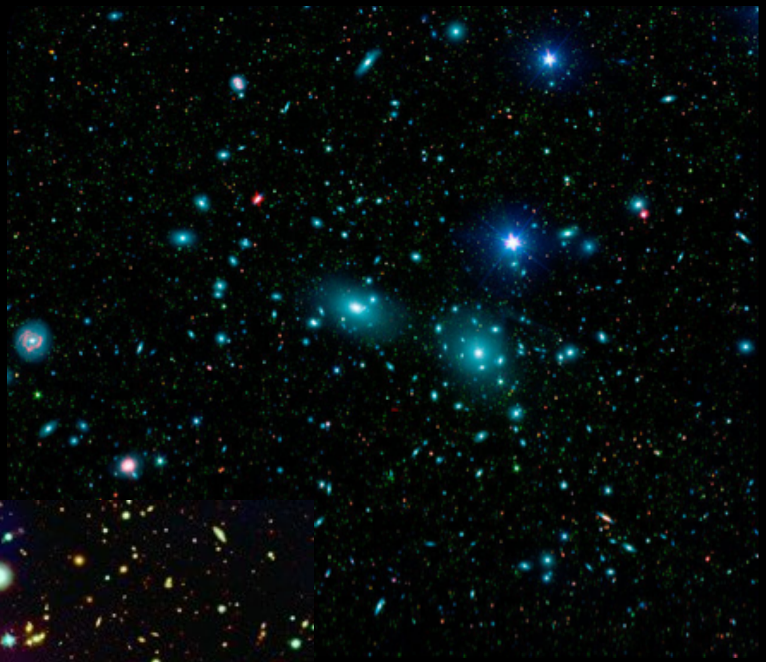
it is dark

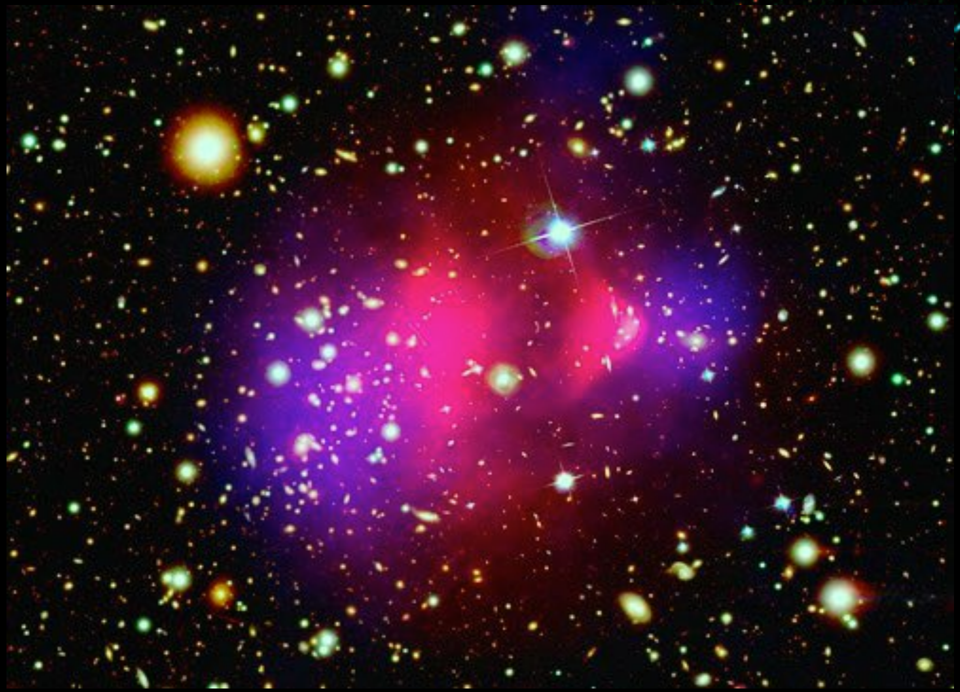
it has mass

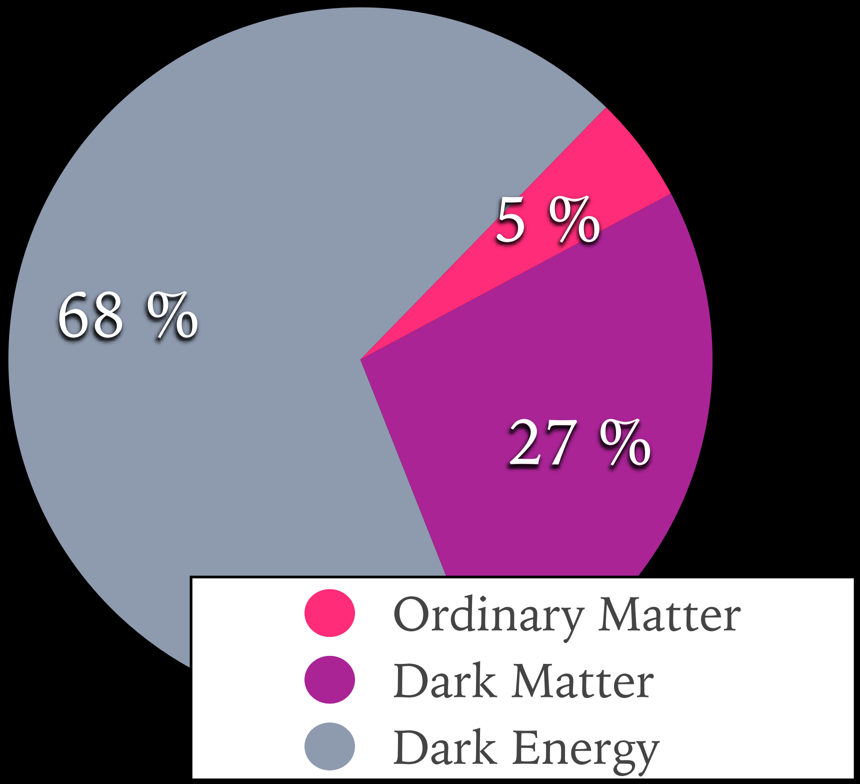


it is dark

it has mass

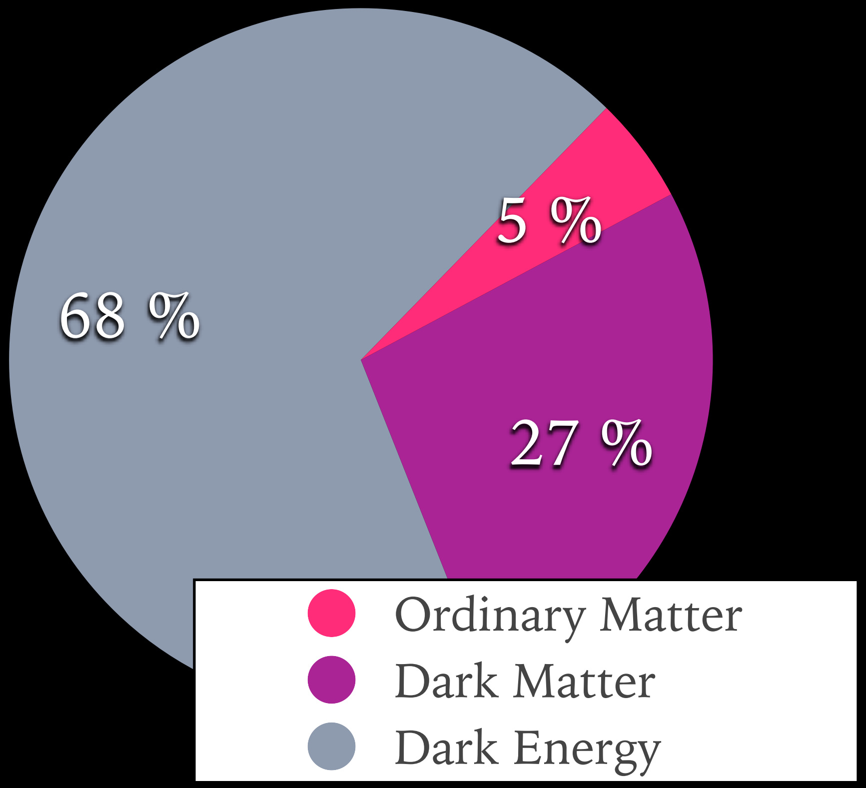






it constitutes
most of the matter
in the universe

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…

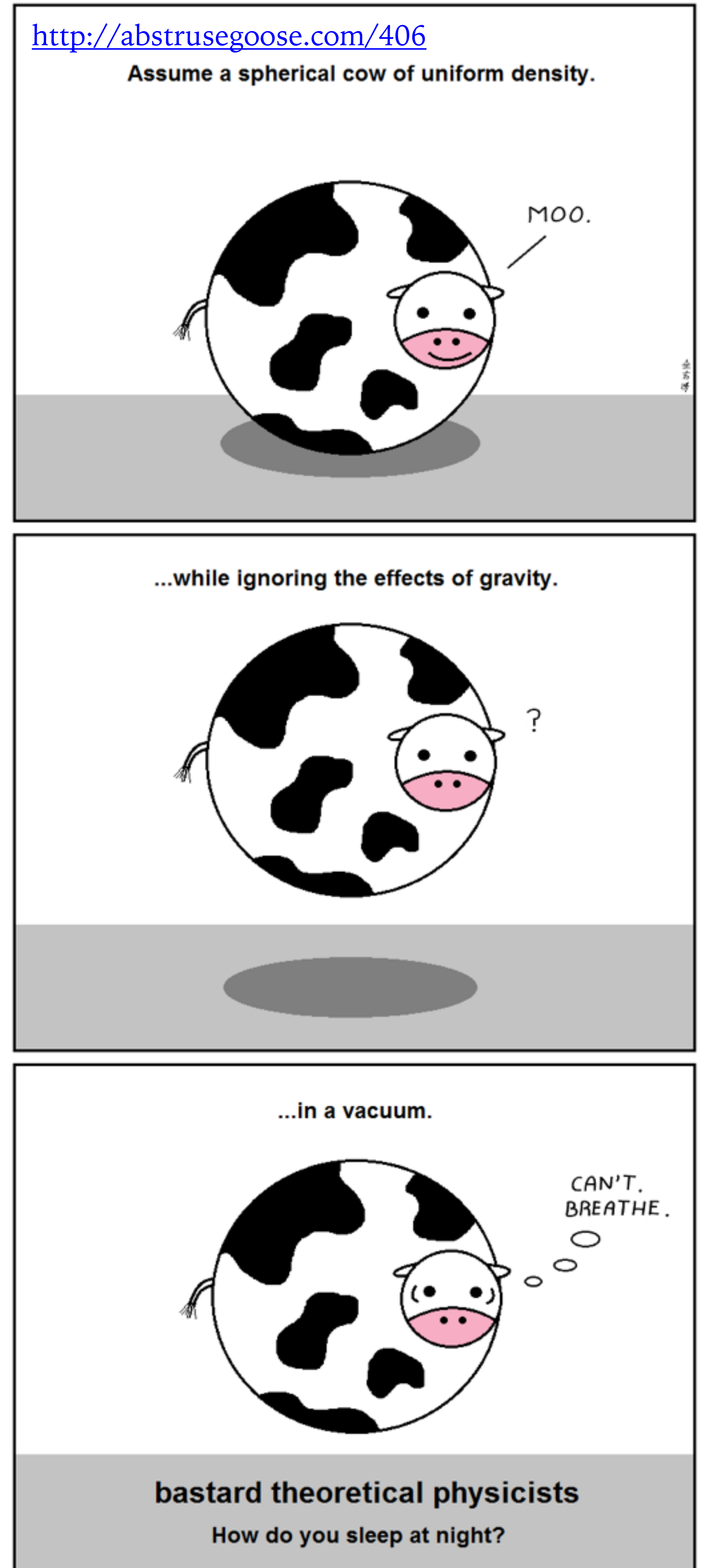
This relic density can be explained with

a new particle

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

(a possible candidate: WIMP)

Under these assumptions…

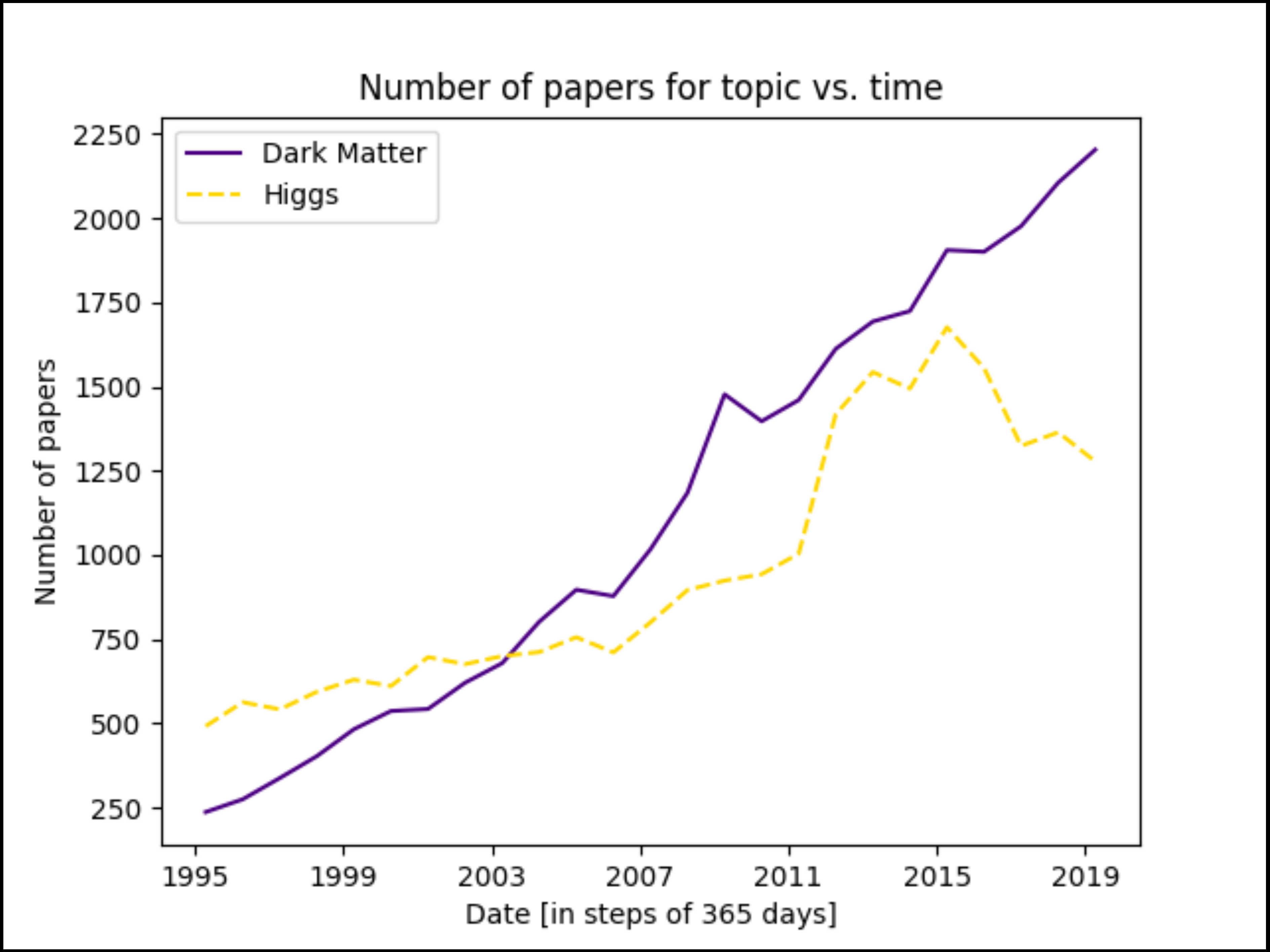


…we could discover Dark Matter in the next decade!

Unless…

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

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

Why should dark matter be a particle?

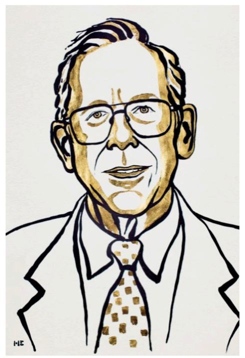
Why not?

us & our experiments, made of particles

In this talk I will <u>assume</u> Einstein's gravity does not need modifications…

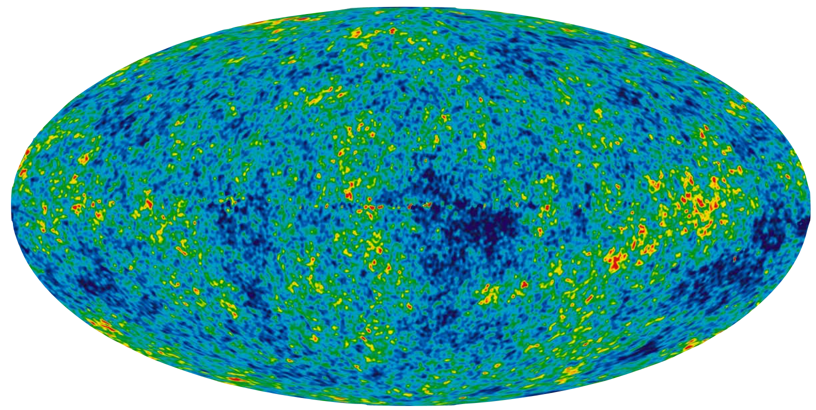
More seriously: the *relic density*

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

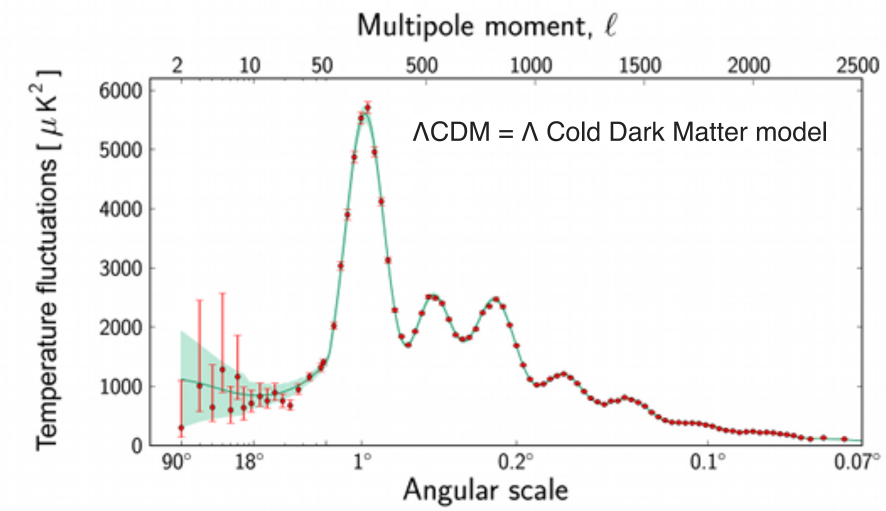
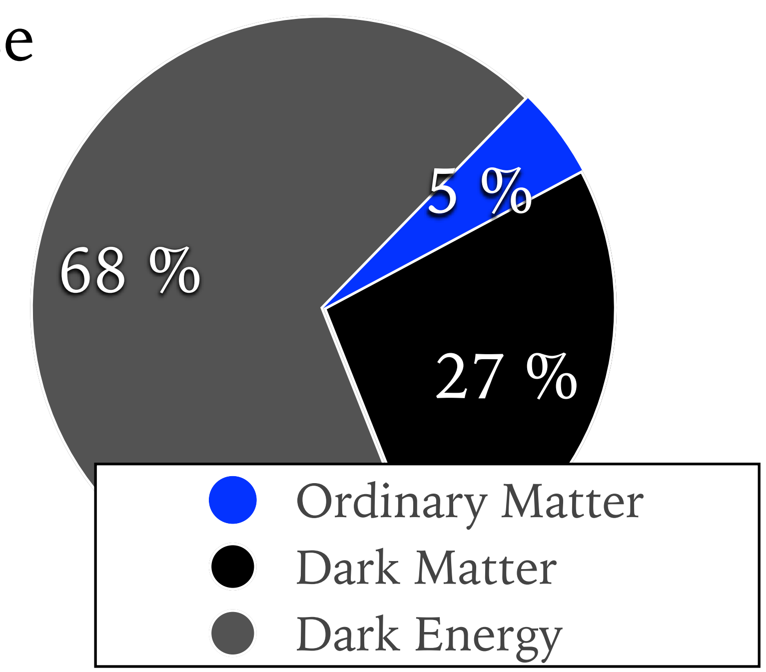


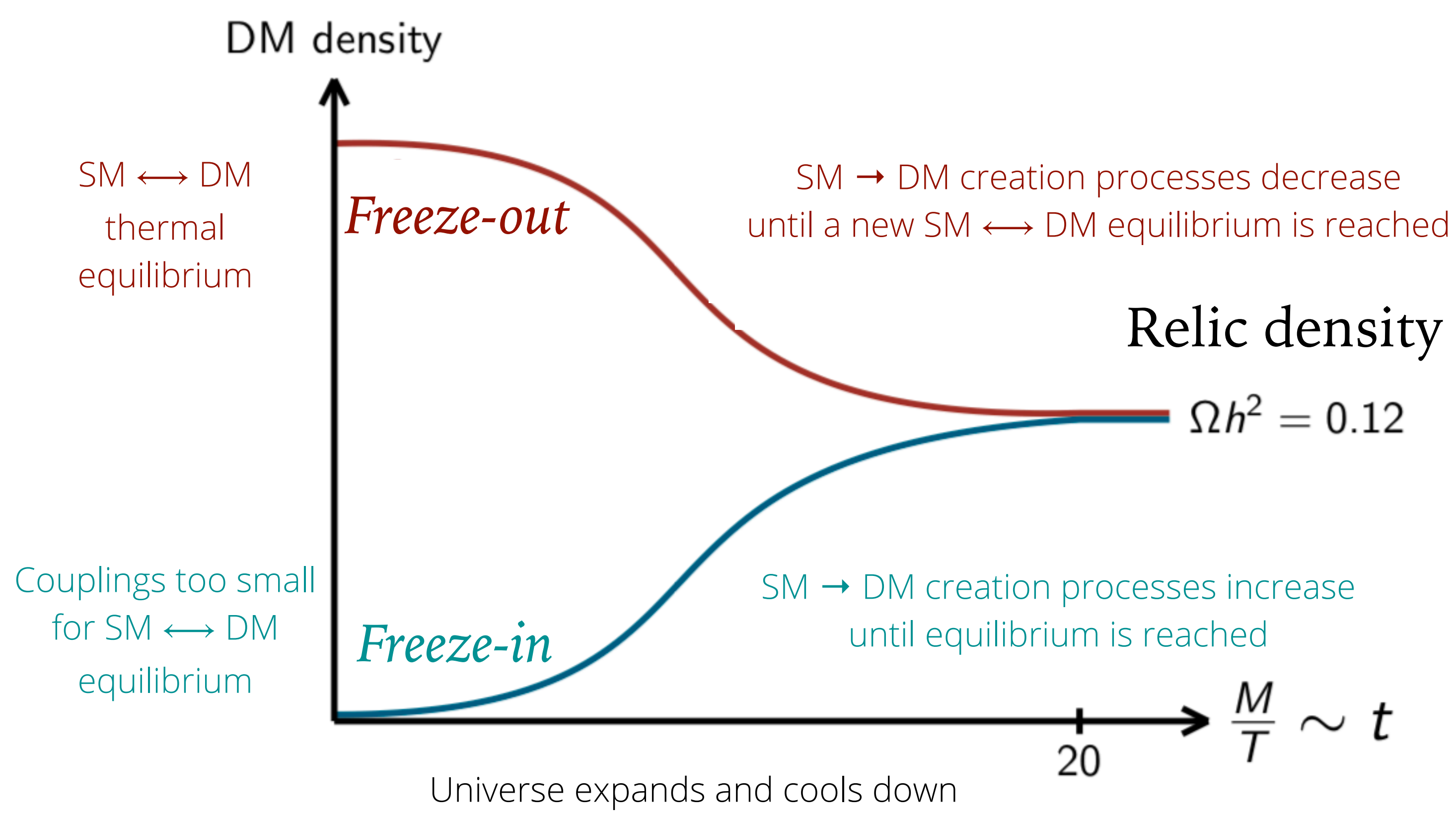
Image: Planck/NASA/ESA

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



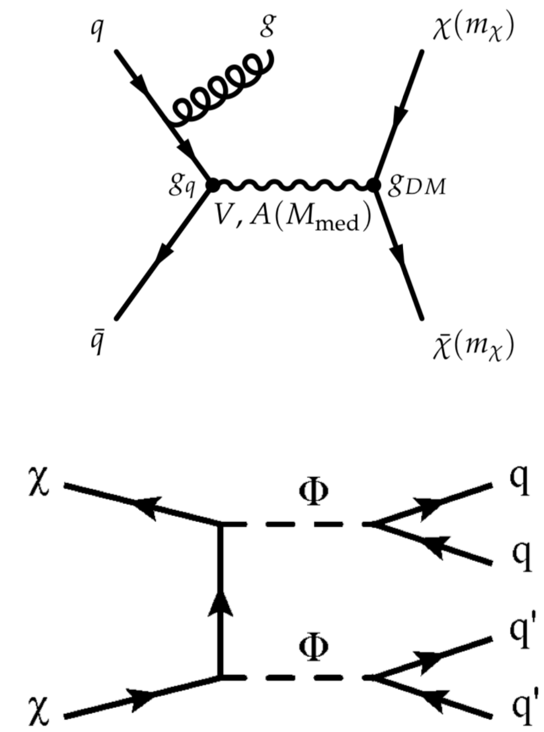
The DM we measure today **[relic DM density]**
already points at some properties of DM candidates
(e.g. dark, stable)
can it **guide us further**?

How did the relic density come to be?



Isabelle John's thesis

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



Examples of DM ⟷ SM processes

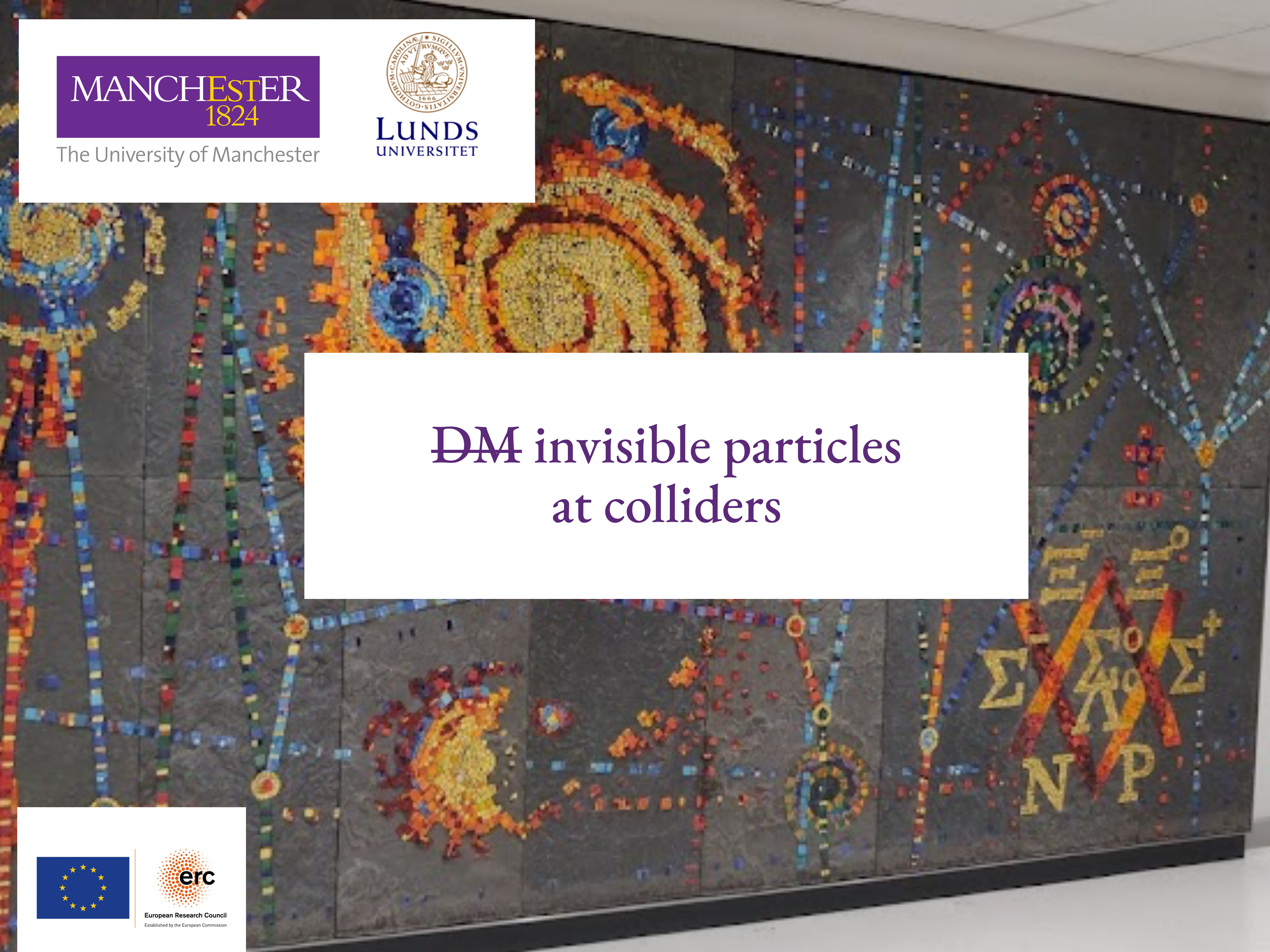
Commonality of many of these models: they require **some form of interaction** (it can be more or less significant) between ordinary matter and dark matter

interaction ⇔ particles & forces

Take-home point #1:

we don't know very much about DM beyond its gravitational interactions and astrophysics abundance

any ~~LHC~~ search will necessarily contain some assumptions (e.g. about interactions/model) so that DM can be observed experimentally



~~DM~~ invisible particles at colliders

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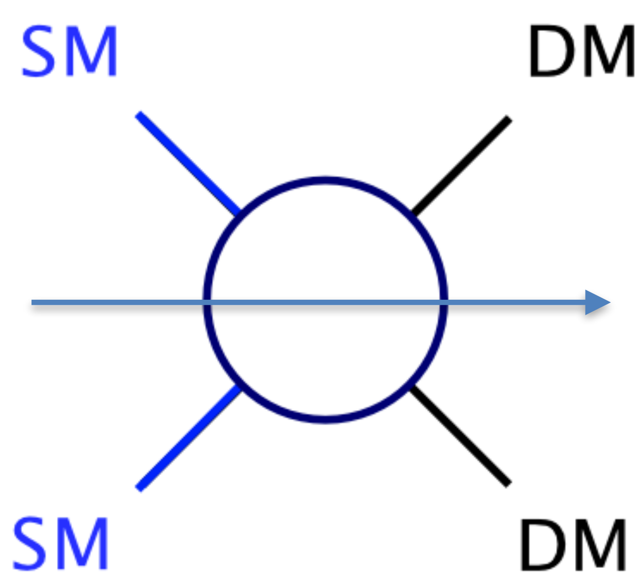
Motivation for DM@colliders

How do we search for DM at colliders, depending on its properties?

- Generally assume some properties for the DM particle, our assumptions:
  - interacts with SM particles → we can **produce it at colliders**

known particle collision



production of DM particles

Caveat: very simplified diagram

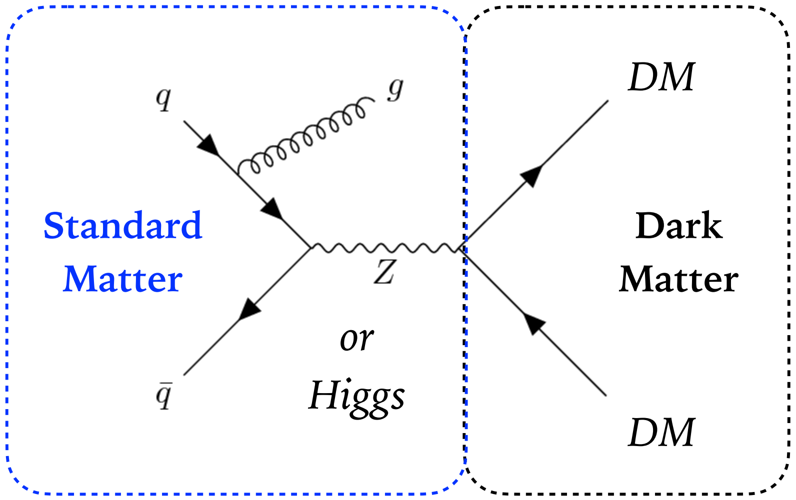
- [a matter of preference] is a thermal relic → **WIMP**
- dark, stable → **invisible to detectors**

a **SUSY LSP** is a good candidate!

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!*

22

Weakly Interacting Massive Particles

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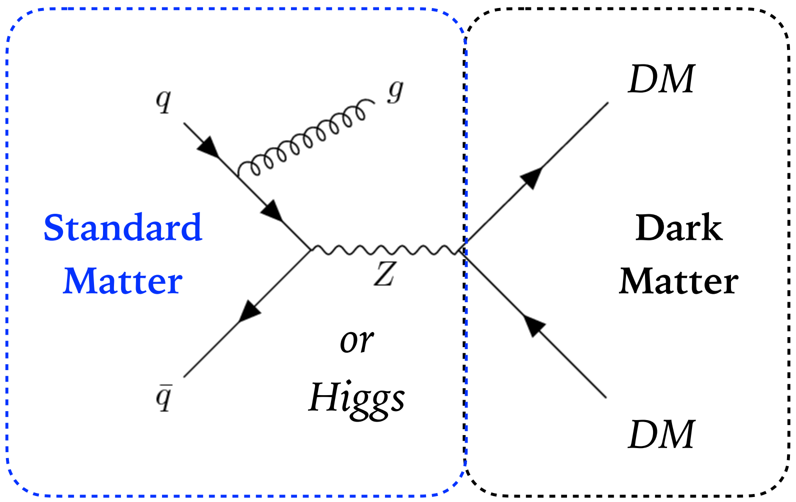

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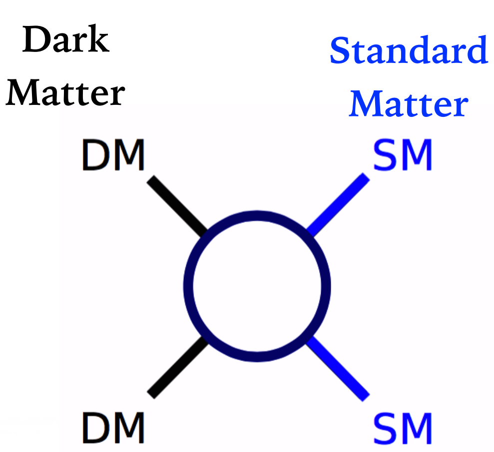
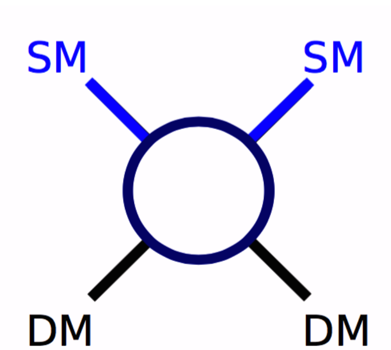
Experimental advantage: many experiments can detect it in different ways

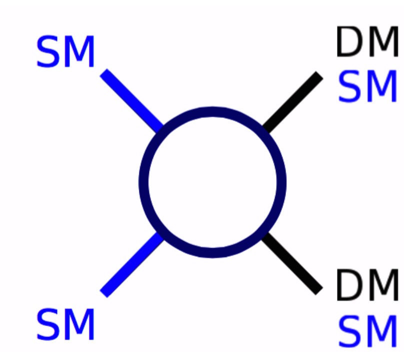
complementary discoveries (main topic of the second part of this talk)



Indirect Detection

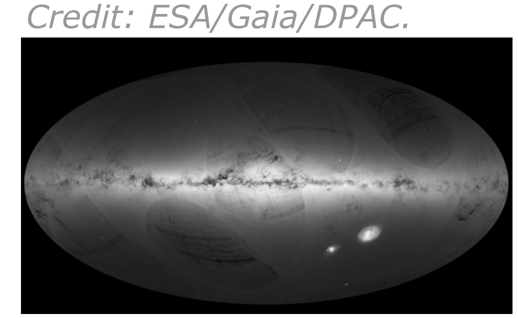


Direct Detection

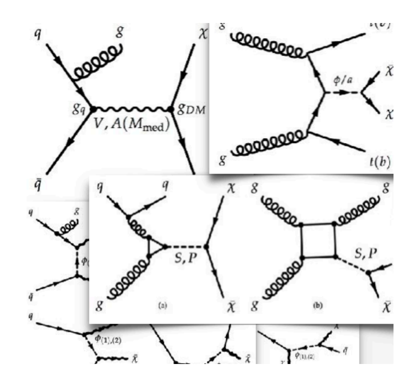


Colliders/ Accelerators

Credit: ESA/Gaia/DPAC.



Astrophysics



Theory input always necessary to contextualize

23

Dark matter needs to be a global scientific problem…

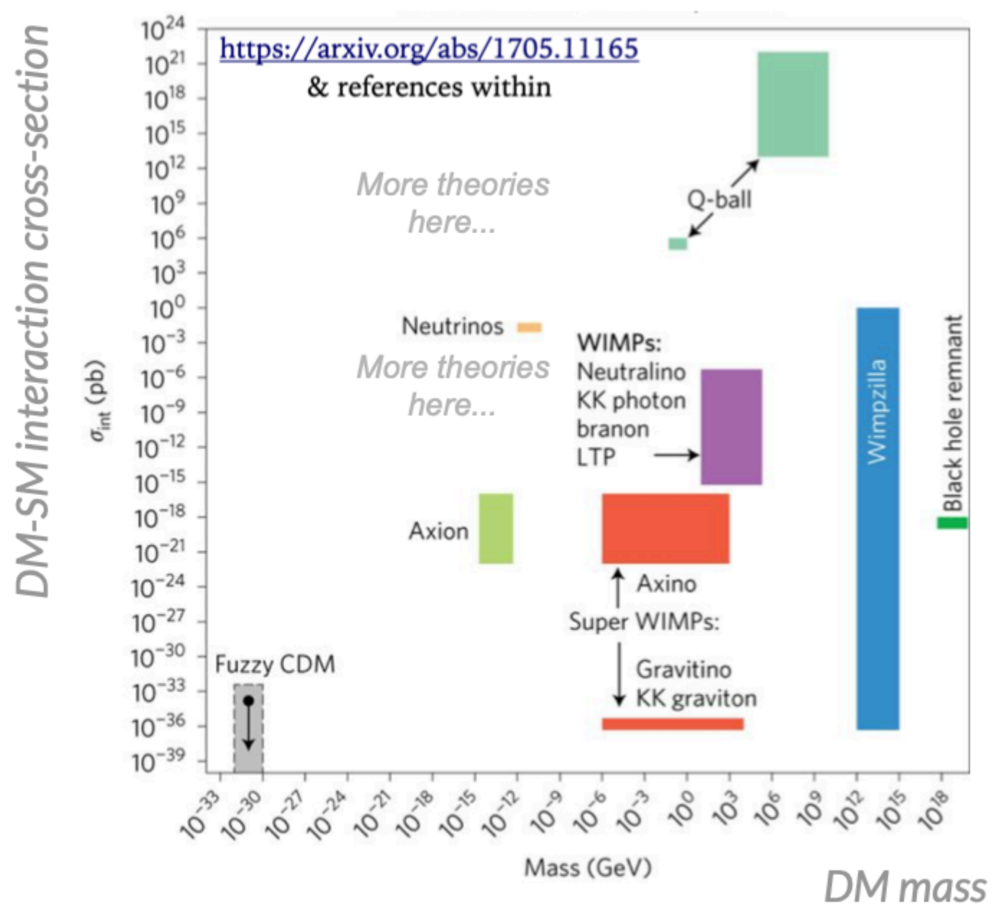
Not just a WIMP! (even though I'll mostly talk about WIMP-like particles)

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



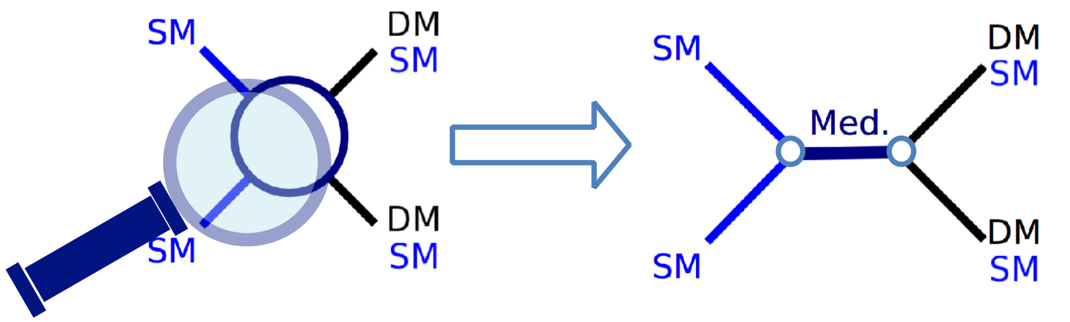
Looking right:
more massive DM objects

Looking down: feebler interactions

Some of the benchmarks for collider WIMP searches

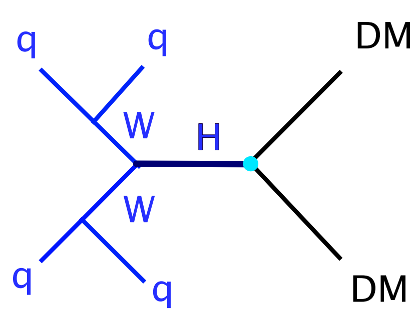
Simple models ⟷ More complex/complete models

Simple DM mediation



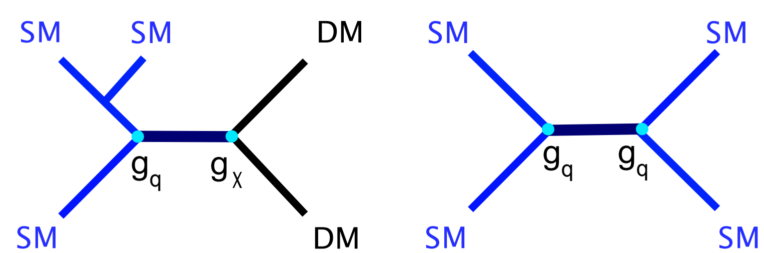
SM mediator

- **Z/Higgs** portals



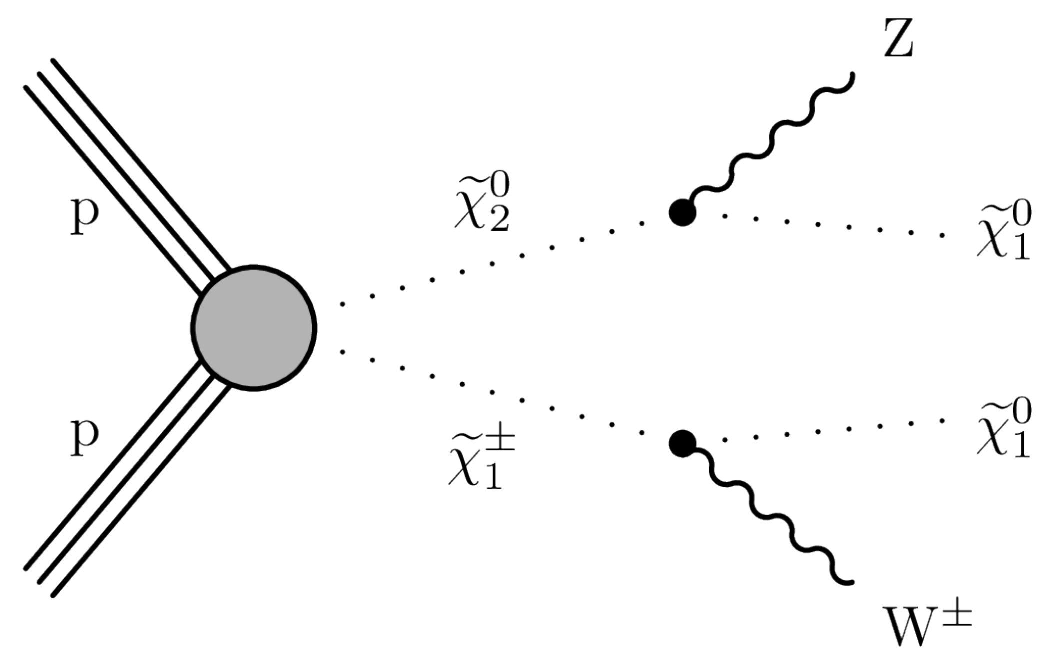
Beyond-SM mediator

- **Vector-like** mediator



- **Scalar-like** mediator and Two Higgs Doublet Models

Supersymmetry



(*Simplified model* diagram)

JHEP 03 (2018) 160

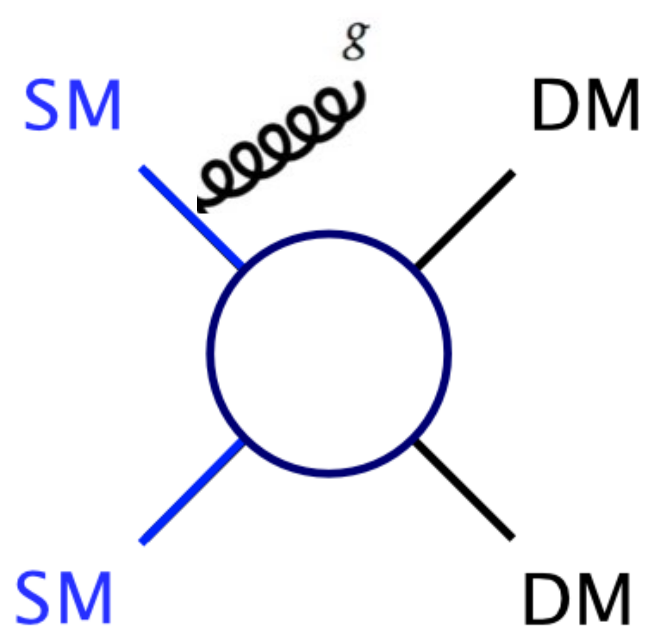
***Also:** DM models with long-lived particles (see Katharine Leney's lecture)*

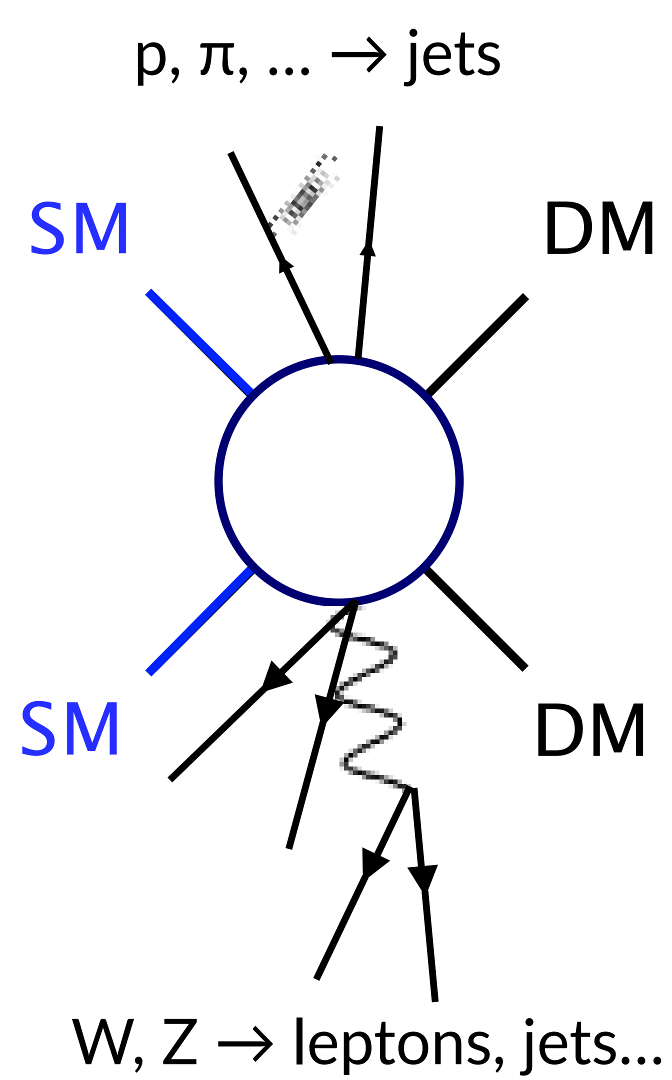
Broad categories of searches for DM@colliders

Generic searches → More specific searches

- Good for **simple models** with **sizable cross-sections**
- **Fewer assumptions** on specific model characteristics

- More sensitive to **specific models**
- More reliant on **model assumptions**





→ the way we think of benchmark models **influences searches**

26

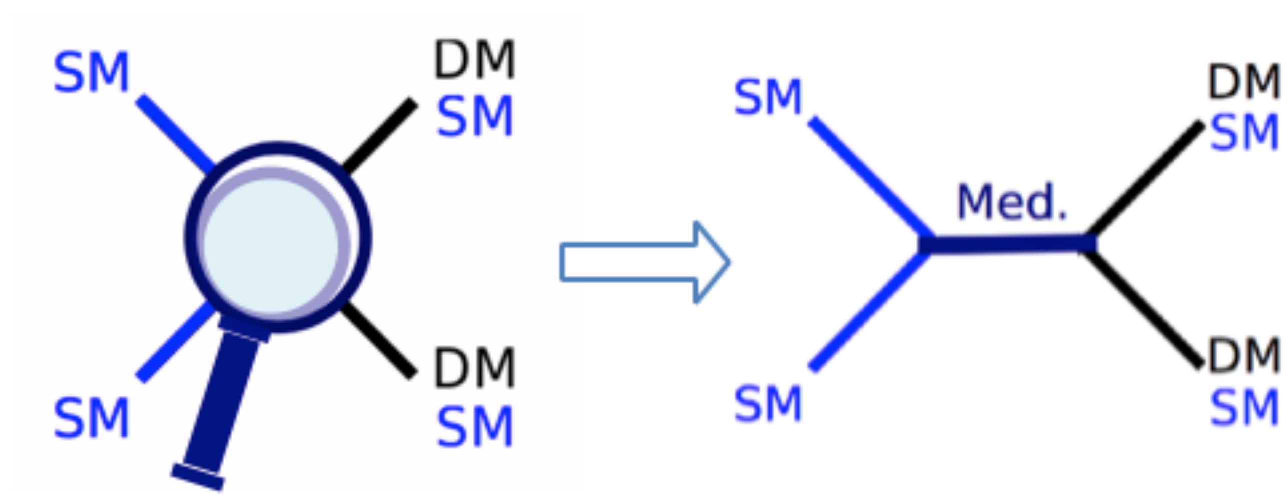
Take-home point #2:

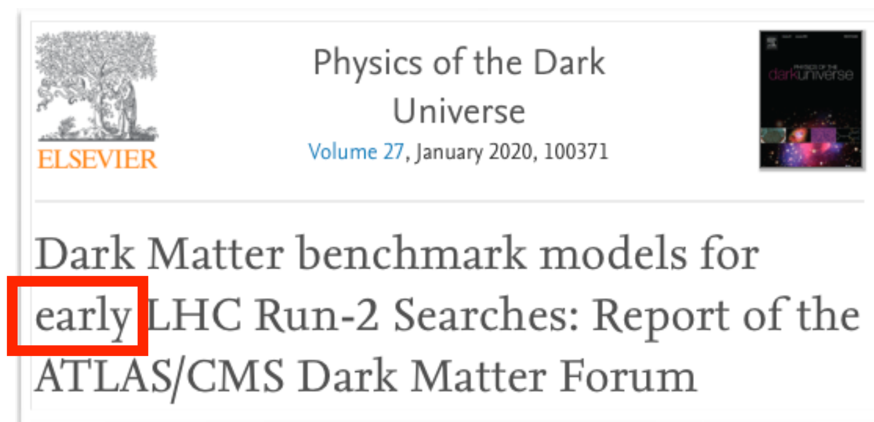
The assumptions we make on DM candidates influence searches. To avoid limiting our "field of view" to one candidate only, it's **important to think about the big picture / all kinds of DM (not just WIMPs)**

Simplified models of DM-SM interactions

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



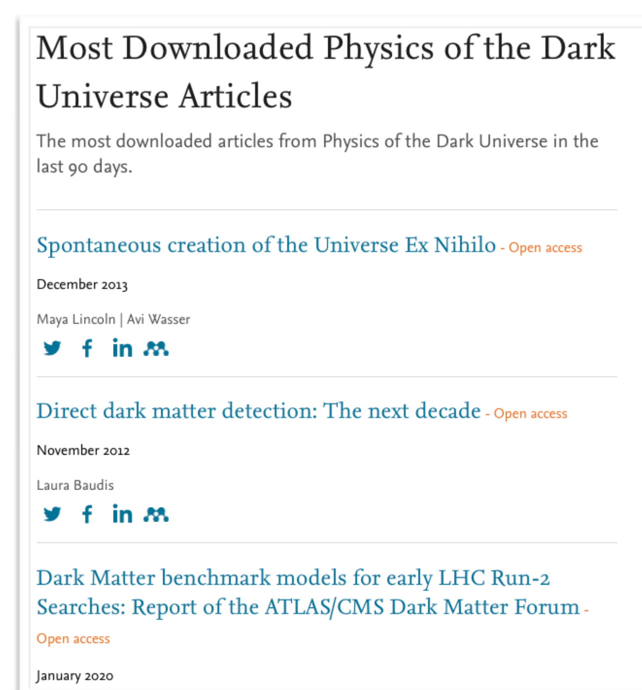

ELSEVIER

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

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

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


Most Downloaded Physics of the Dark Universe Articles

The most downloaded articles from Physics of the Dark Universe in the last 90 days.

Spontaneous creation of the Universe Ex Nihilo - Open access
December 2013
Maya Lincoln | Avi Wasser

Direct dark matter detection: The next decade - Open access
November 2012
Laura Baudis

Dark Matter benchmark models for early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum - Open access
January 2020

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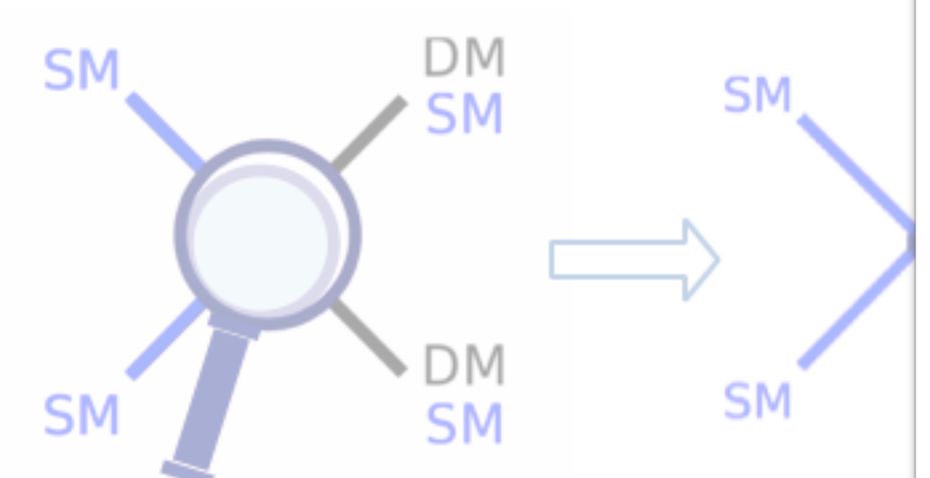
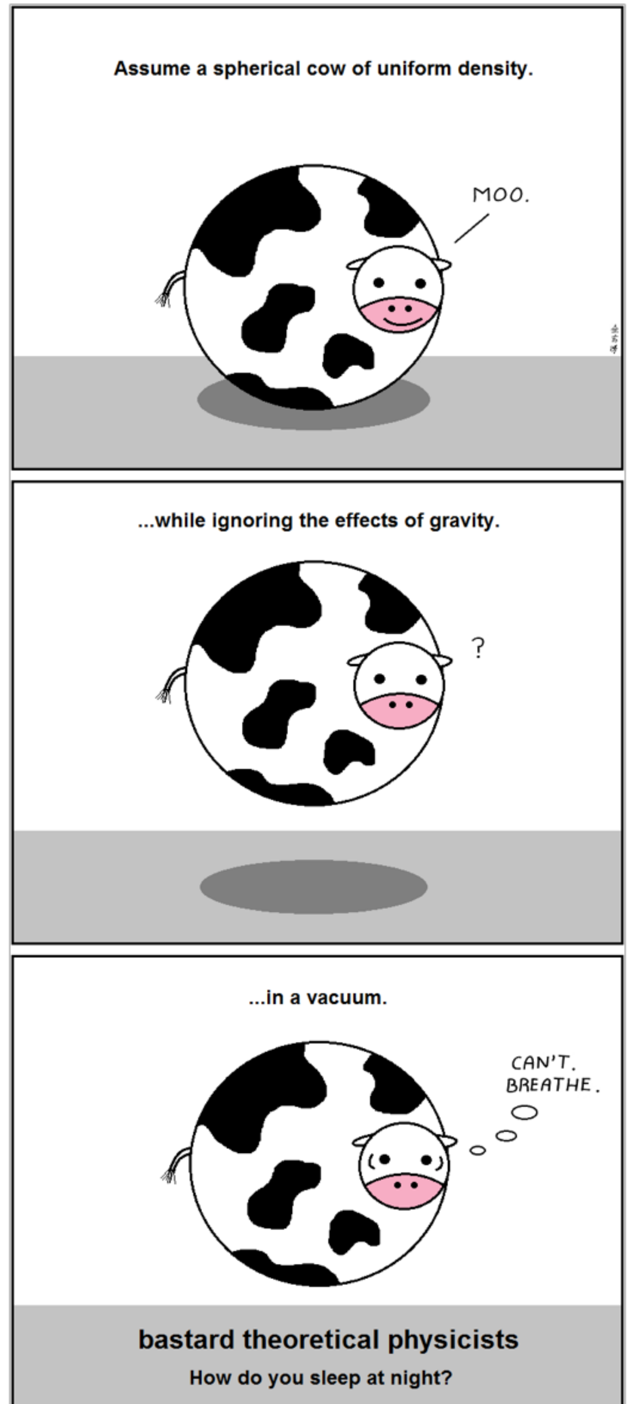
Beware of simple models…

https://abstrusegoose.com/406

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





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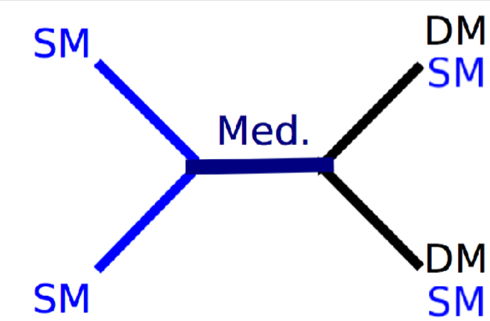
…Matter benchmark models for …LHC Run-2 Searches: Report of the …S/CMS Dark Matter Forum

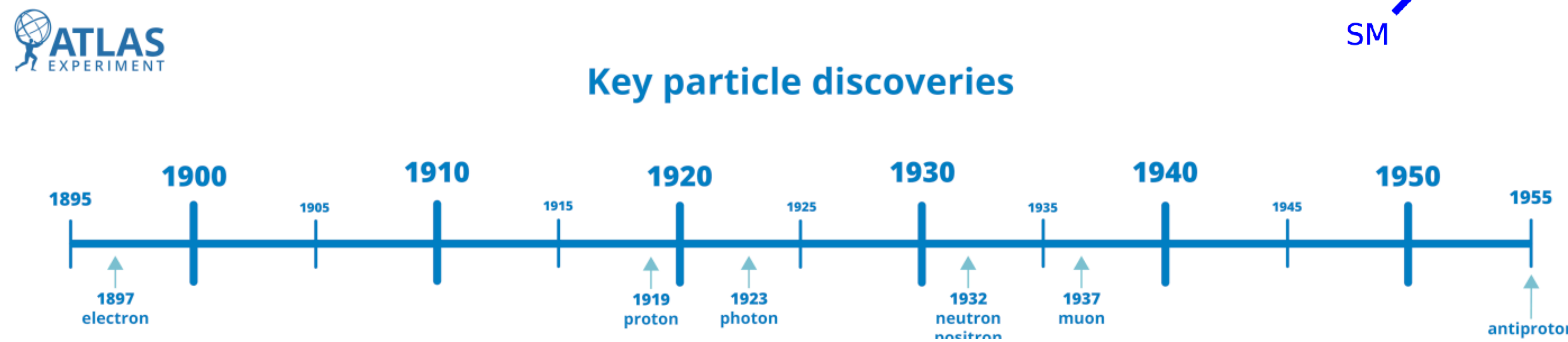
LHC Dark M… …rking Group

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

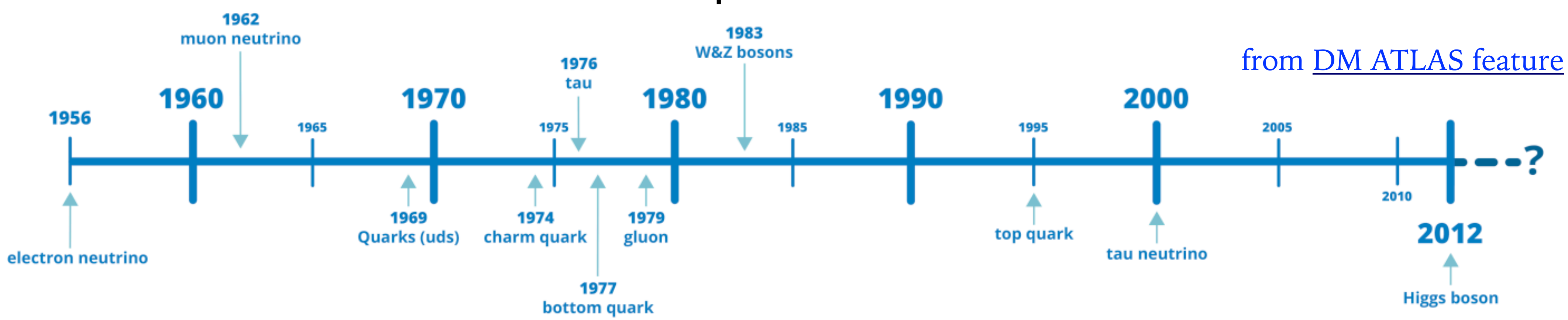
...but not all hope is lost!

"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

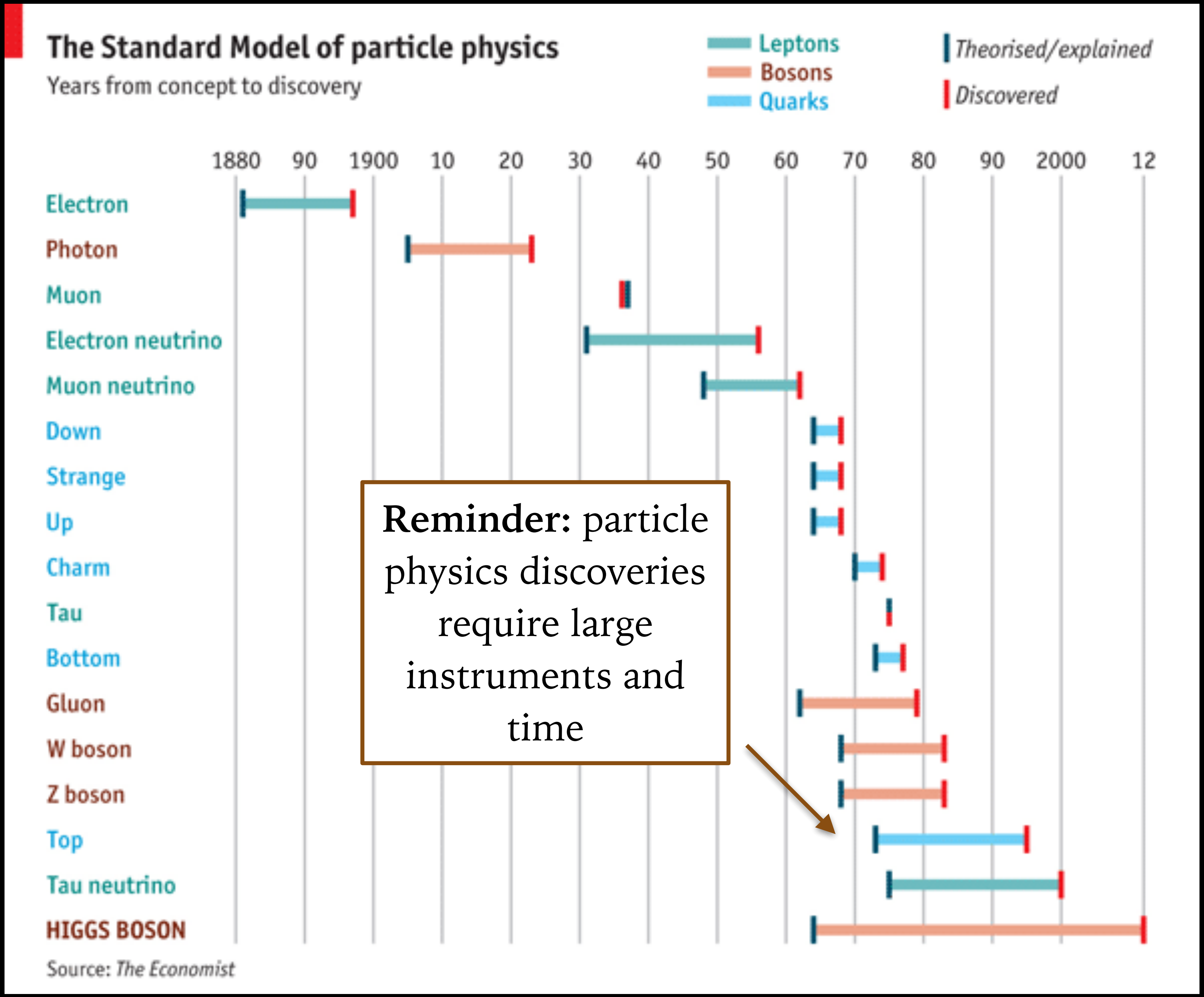


from DM ATLAS feature

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

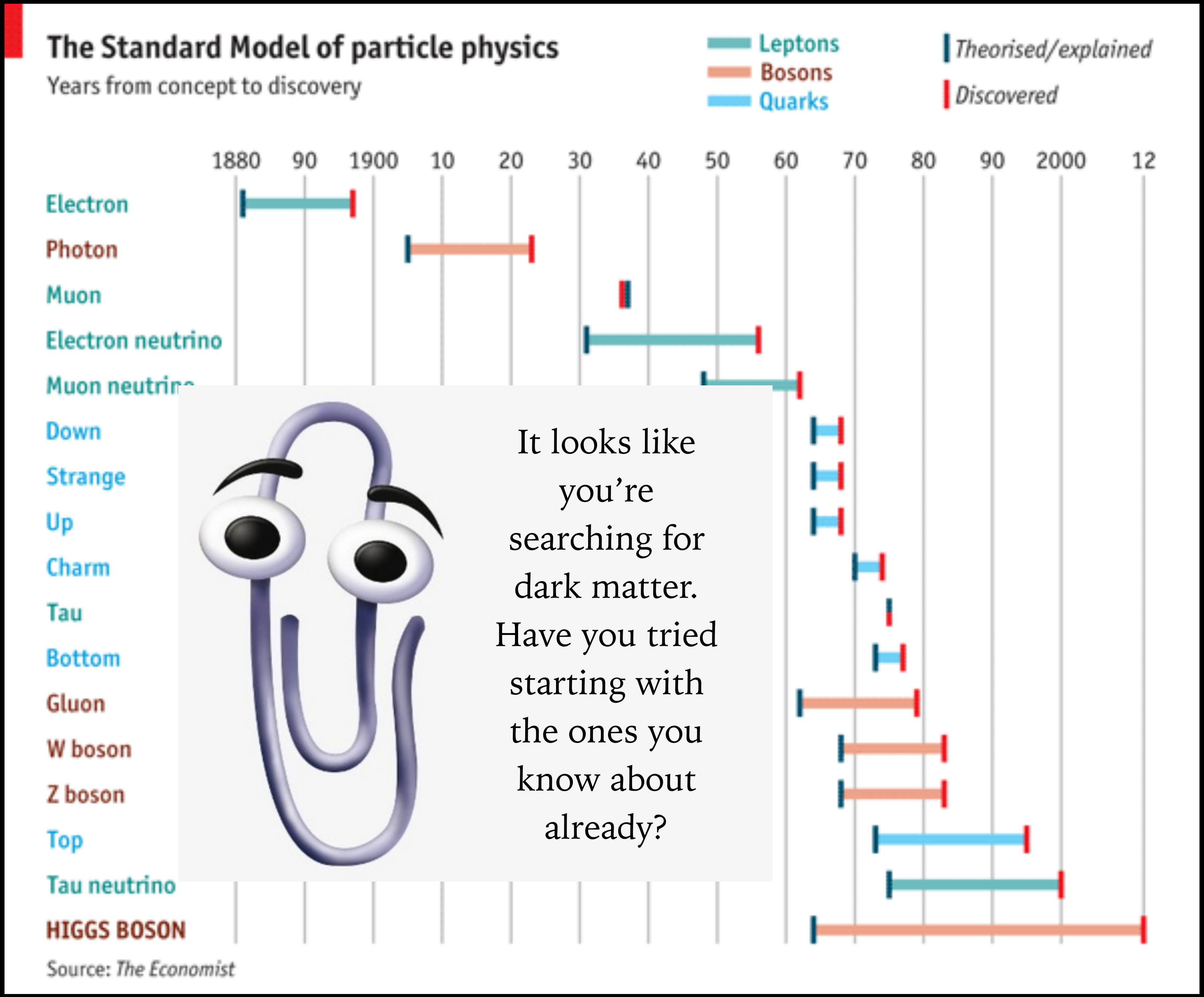
as long as we are aware that they can be more rare than what we choose as example

Finding new particles takes time



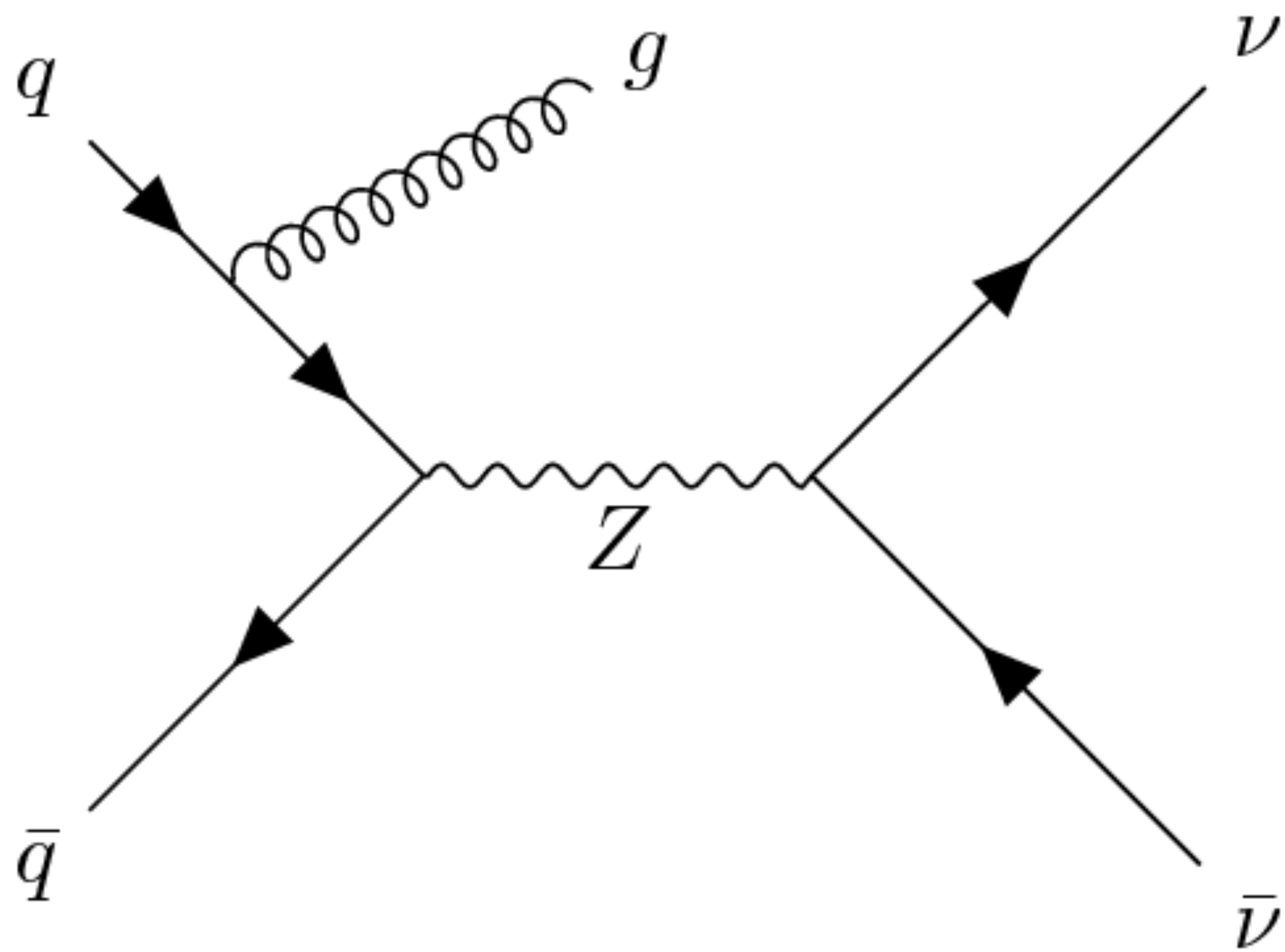
Reminder: particle physics discoveries require large instruments and time

Finding new particles takes time



Generic production of invisible particles

Production of invisible particles is common in the Standard Model…



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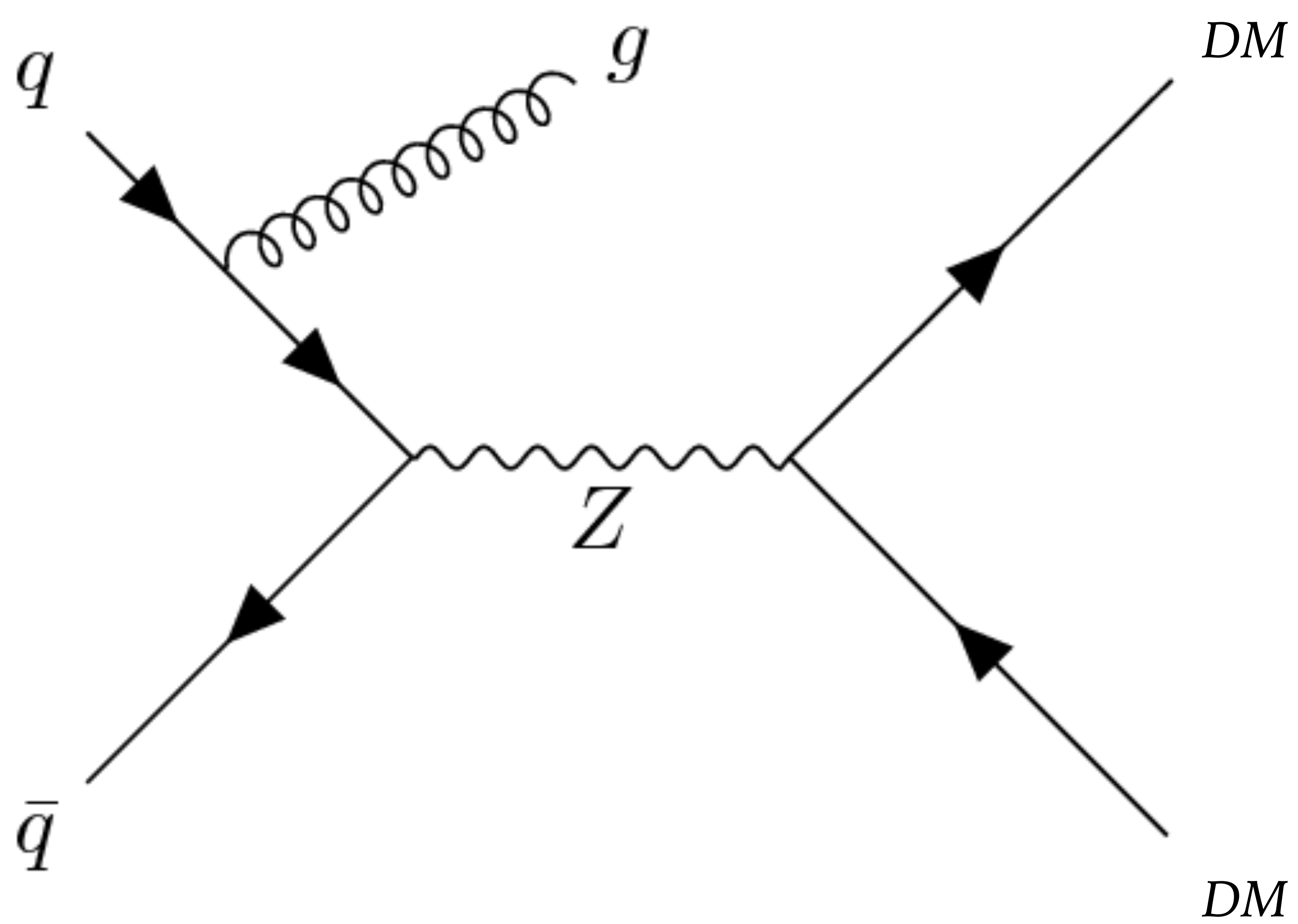
Generic production of dark matter?

What other invisible particles (that are suitable thermal relics) could we produce?



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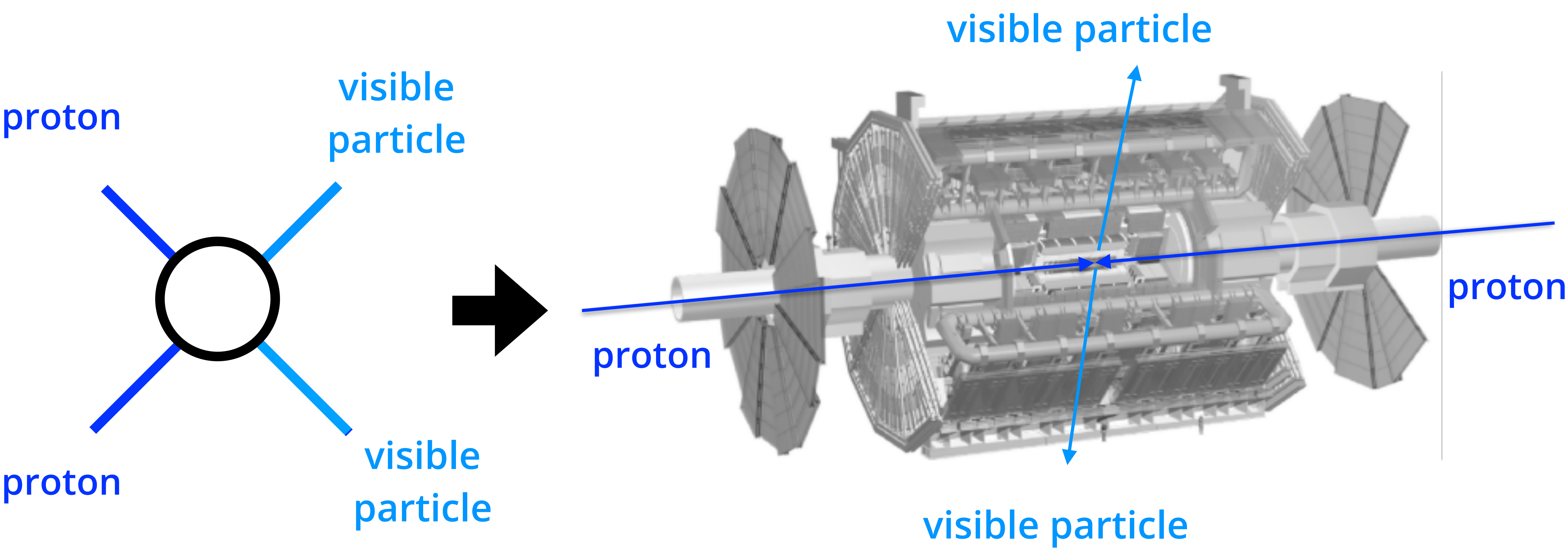
35

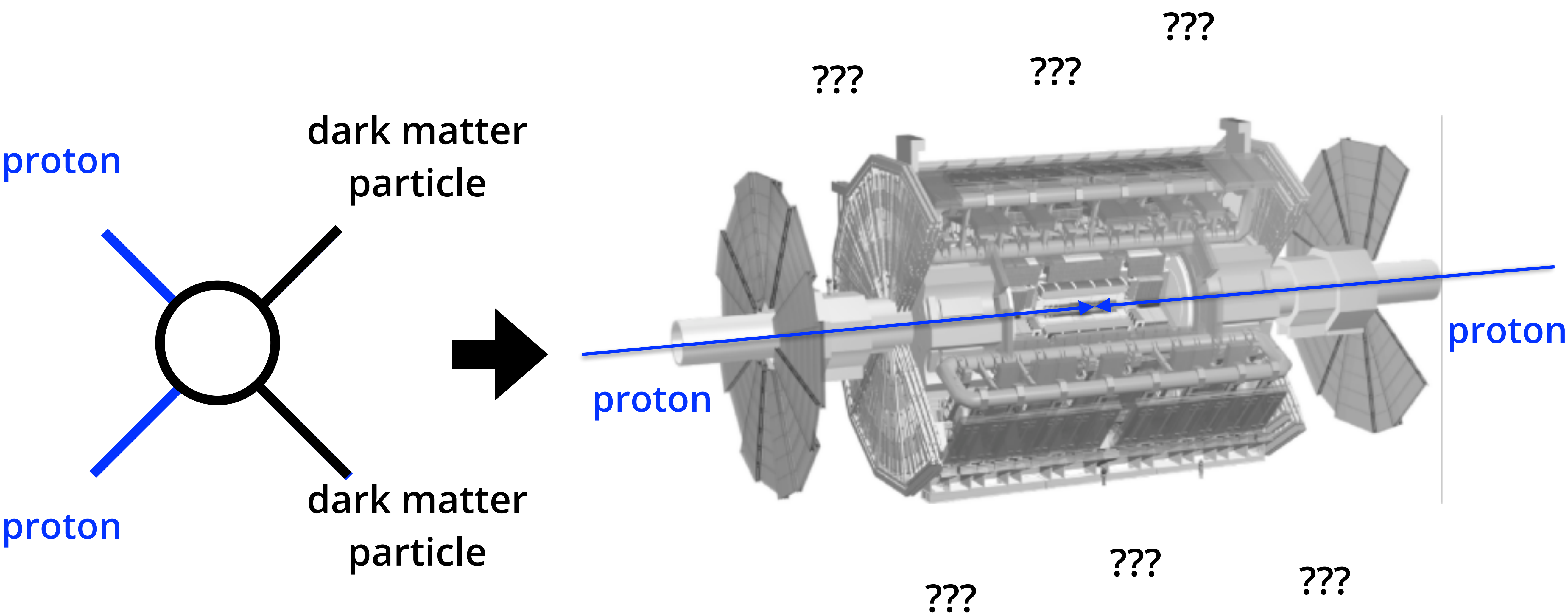
But how can we *see* these particles, given that they're invisible?

Detector catches ~all visible particles
produced by the collision



But how can we *see* these particles, given that they're invisible?

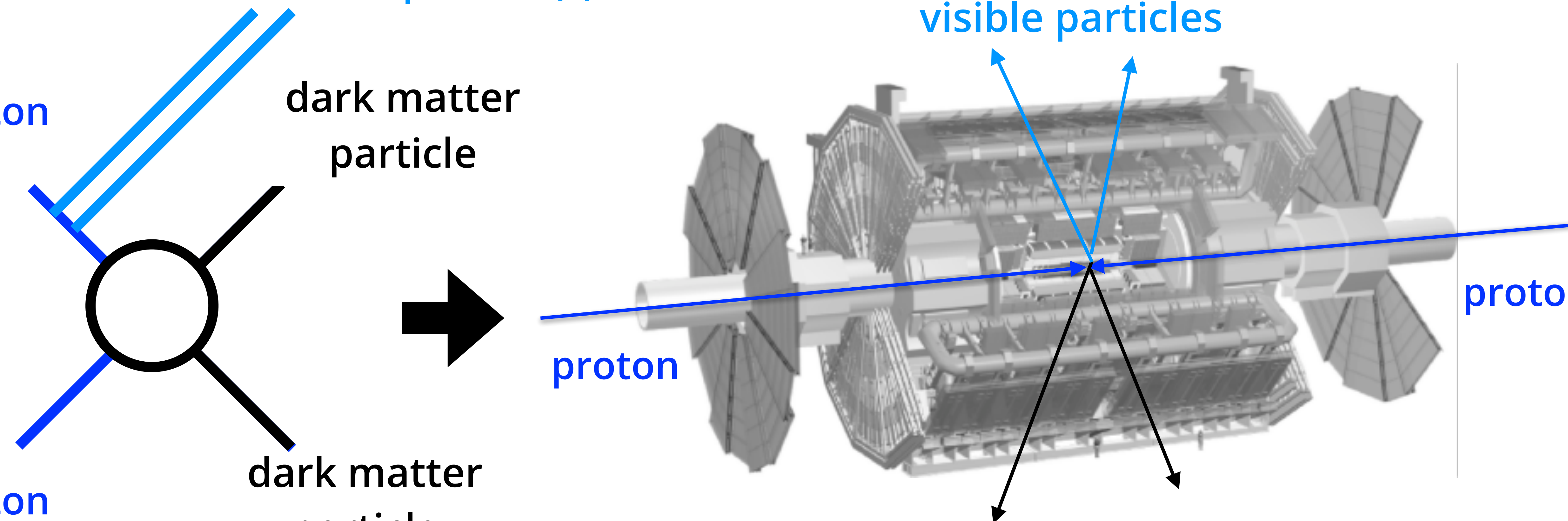
...but since neutrinos (and dark matter particles) do not interact much, they are effectively invisible to the detector!



But how can we *see* these particles, given that they're invisible?

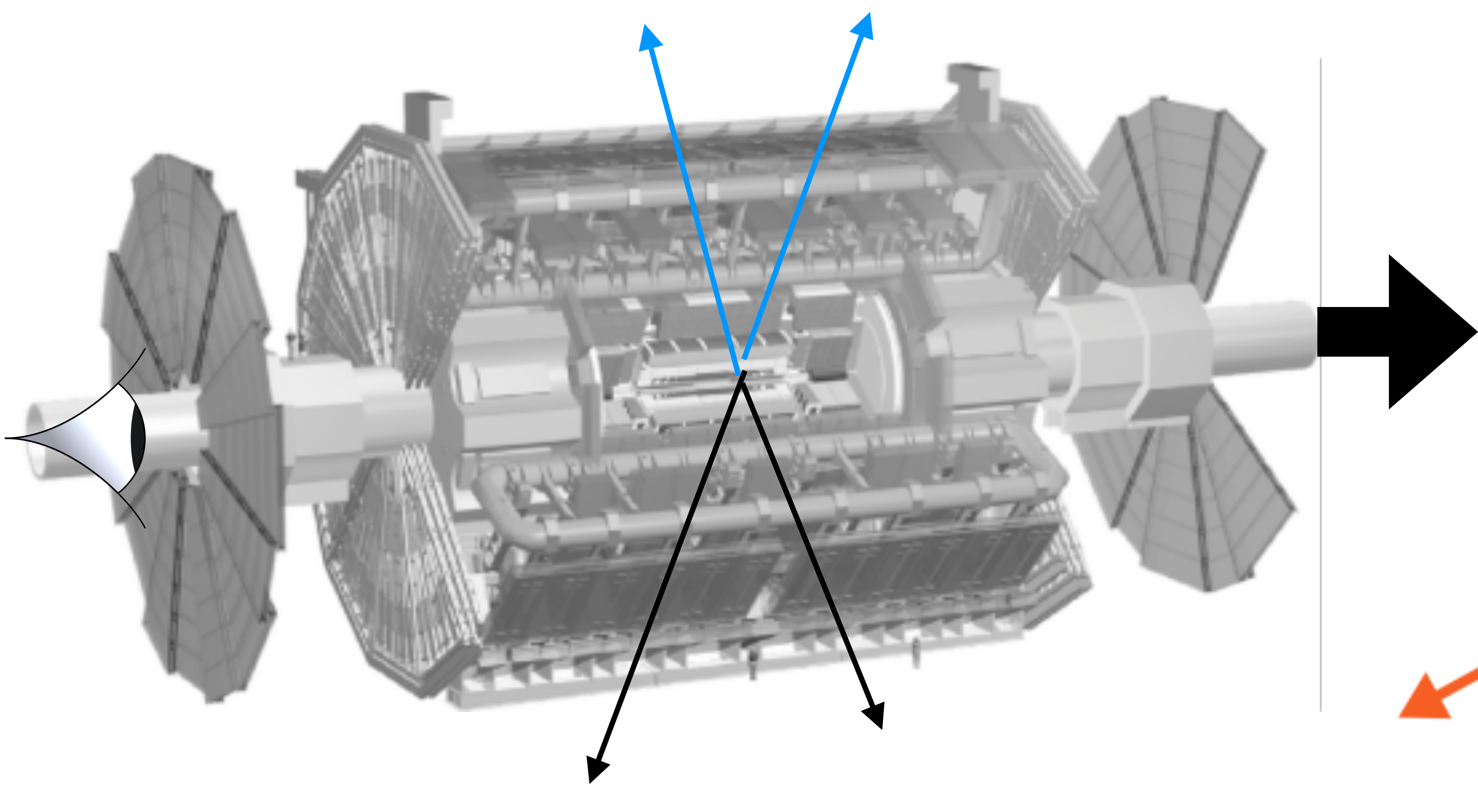
Solution: use another visible particle from the collision, and look for what is missing (*conservation of energy*)

More correctly: conservation of transverse momentum

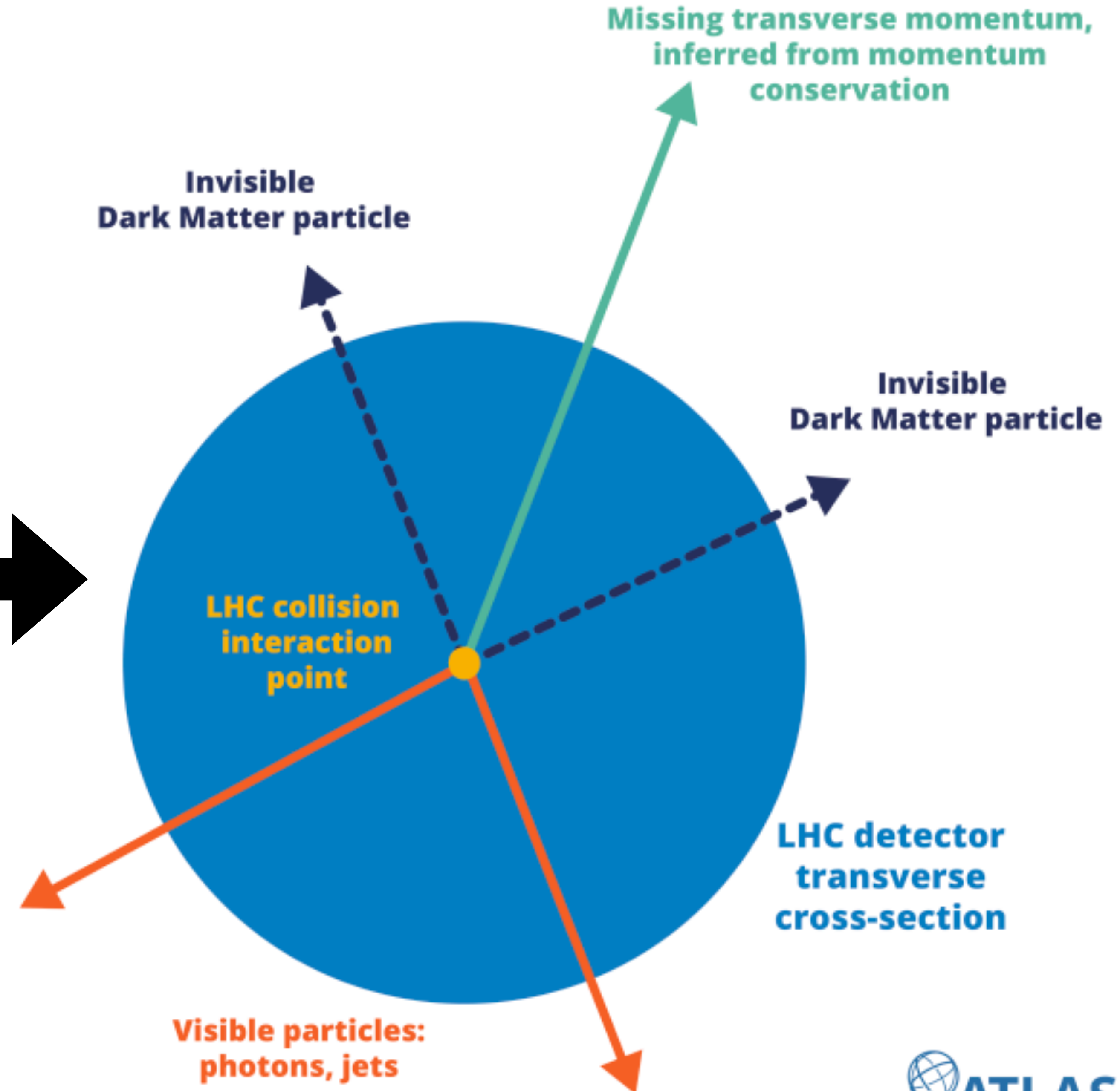


But how can we *see* these particles, given that they're invisible?

…rotating the detector to look into it (as if we were a proton):

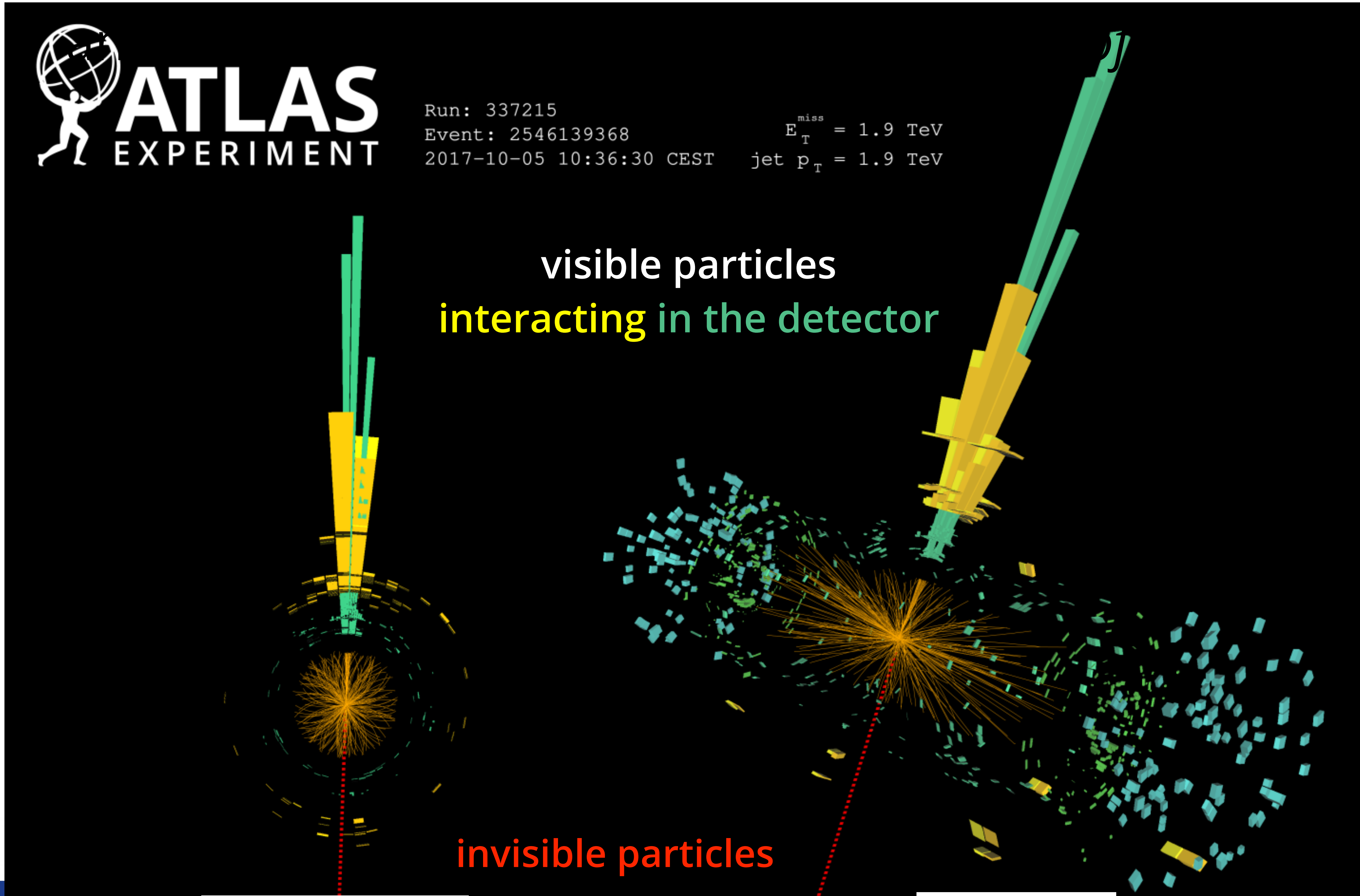


what we observe



But how can we *see* dark matter, given that it’s dark?

How dark matter could look like in the ATLAS detector:



transverse view

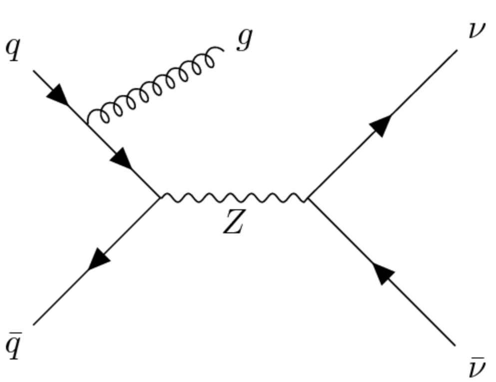
lateral view

Take-home point #3:

LHC searches for invisible particles look for **missing transverse momentum** (which means we need to reconstruct everything else very well!)

LHC production of new invisible particles

Production of invisible particles can be common in the SM
use **standard candles** (Z boson) to search for non-SM production



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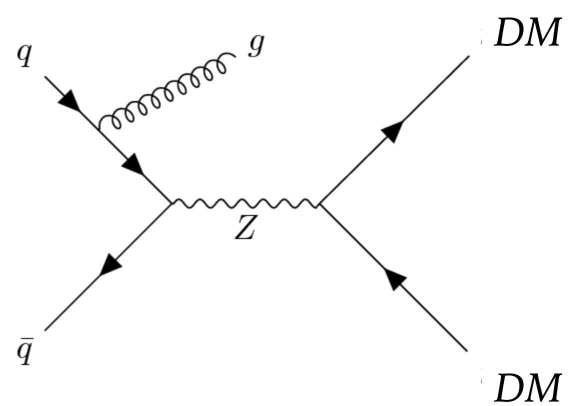
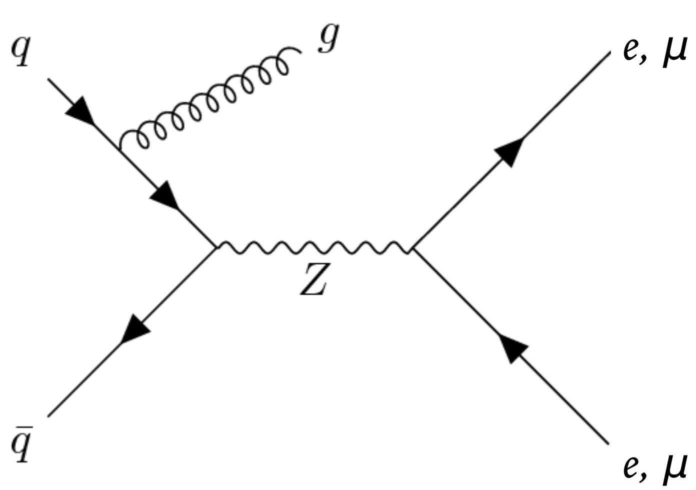
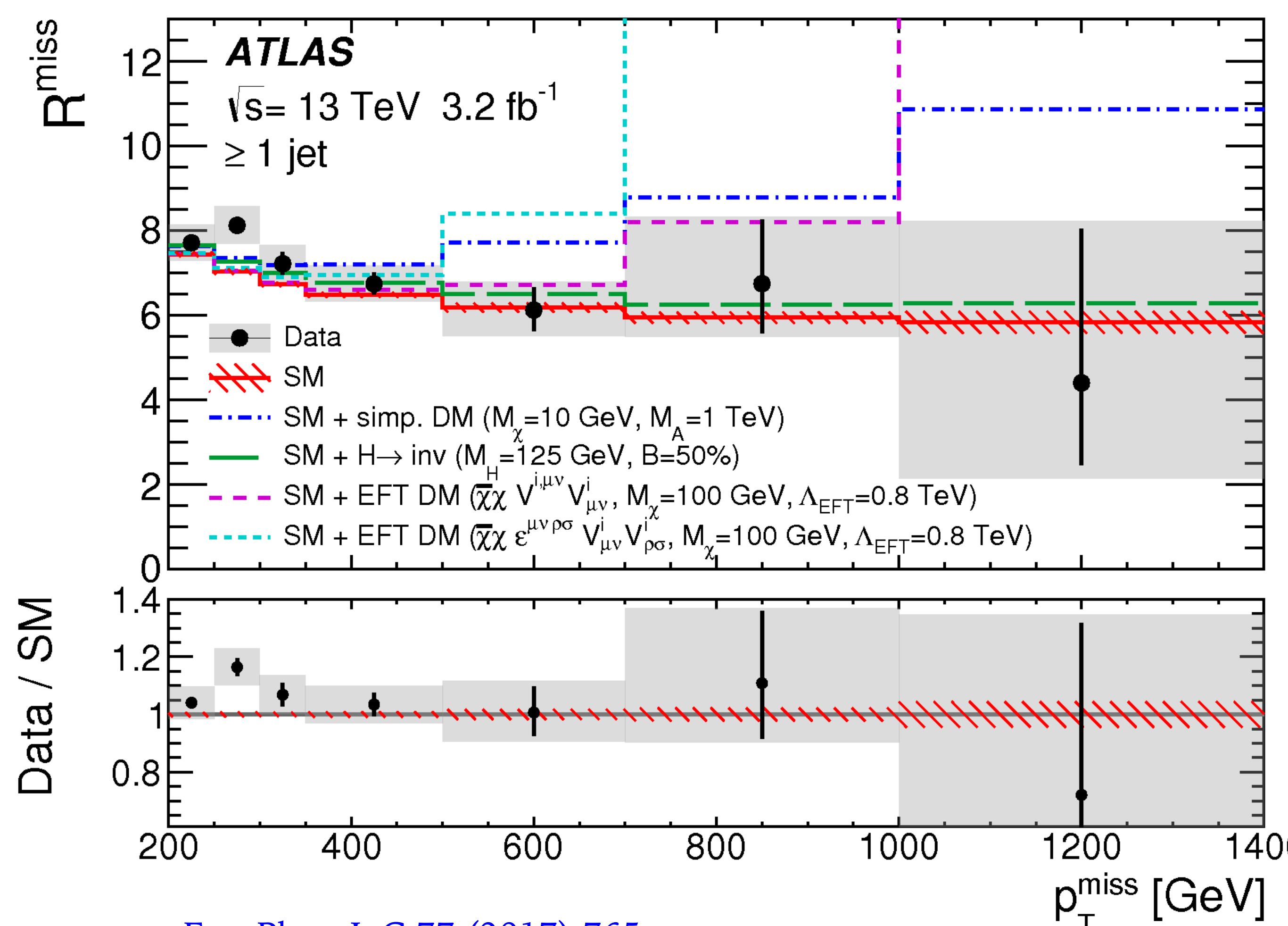




$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}\left(p_{\text{T}}^{\text{miss}} + \text{jets}\right)}{\sigma_{\text{fid}}\left(\ell^{+}\ell^{-} + \text{jets}\right)}$$



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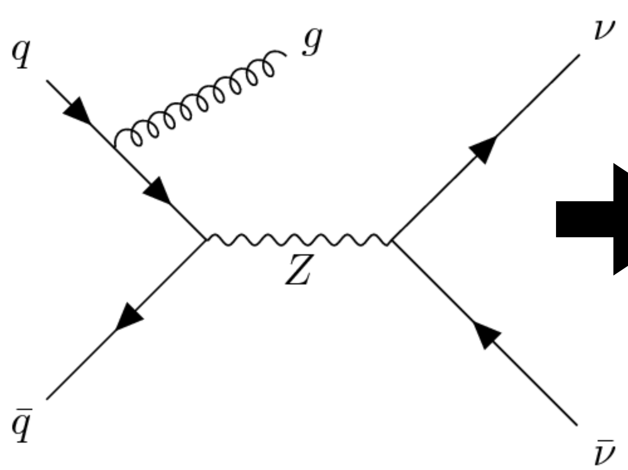
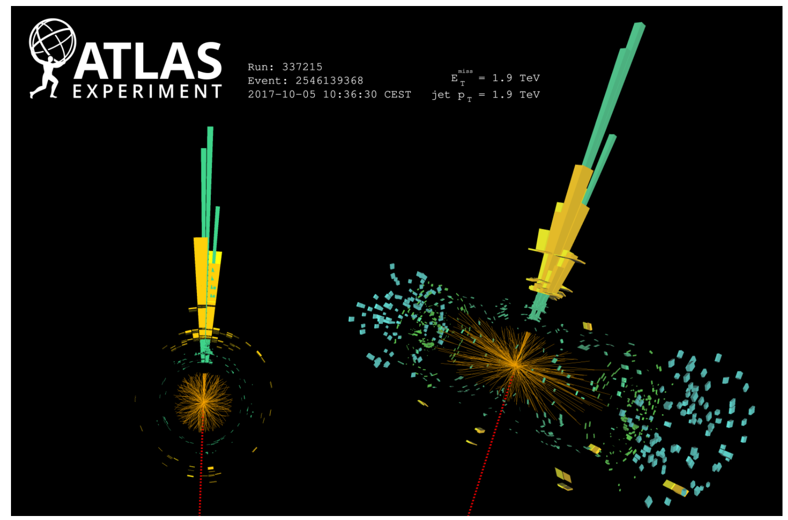
42

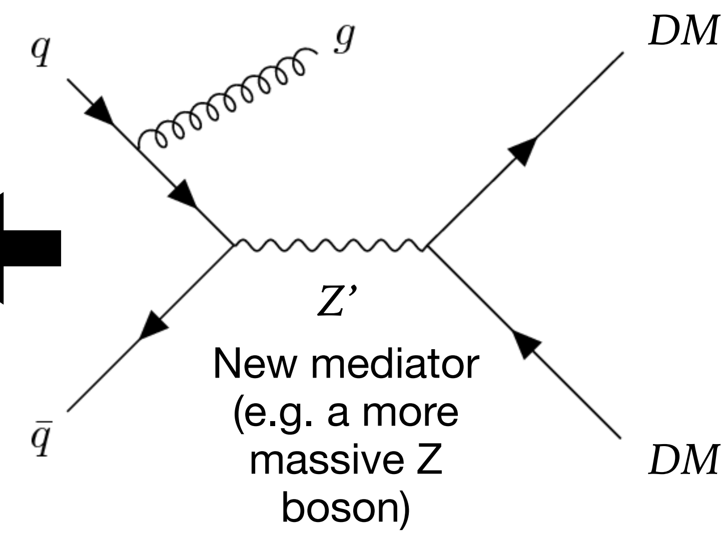
A generic search for WIMP DM: "*X+MET*"

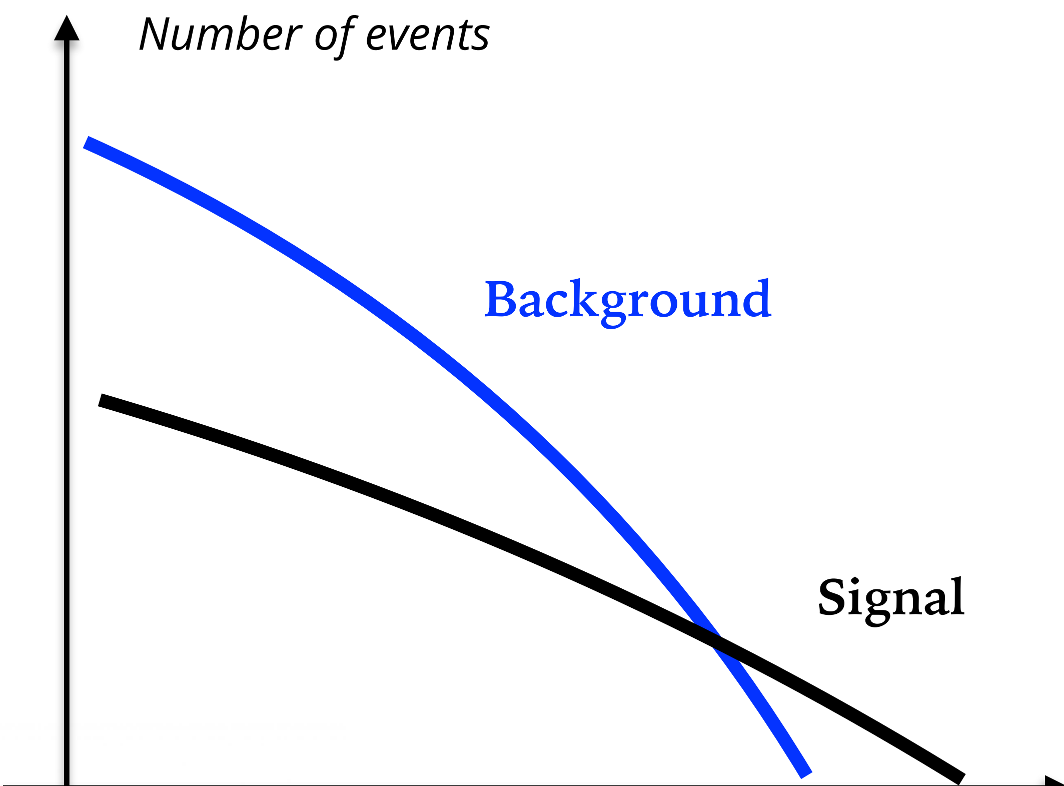
Background (frequent)





Signal (rare)





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

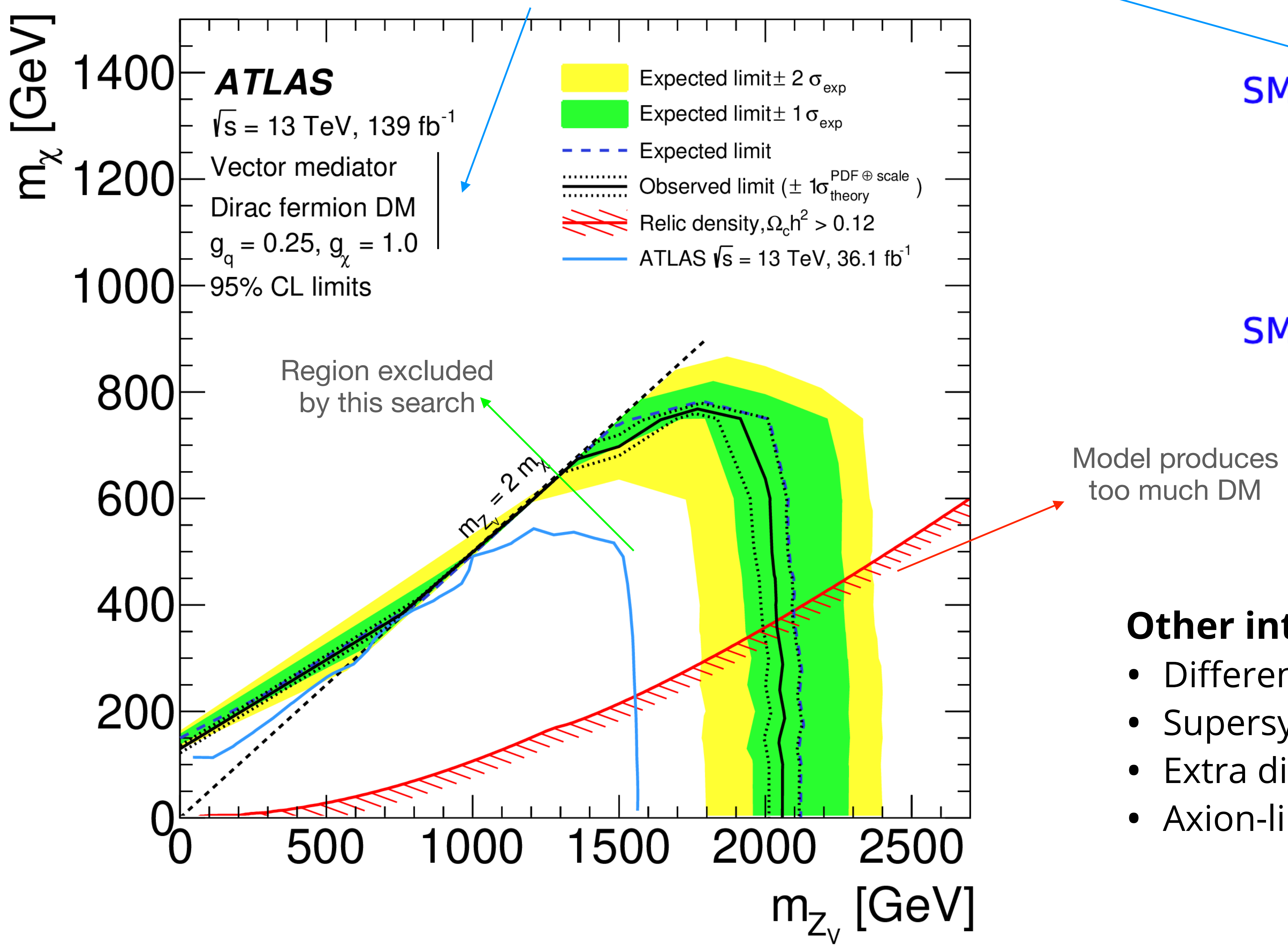
- Look for an excess of events with high MET over the SM background
- Background shapes need precise [EPJC 2017 77:829] theory predictions (*precision search*)

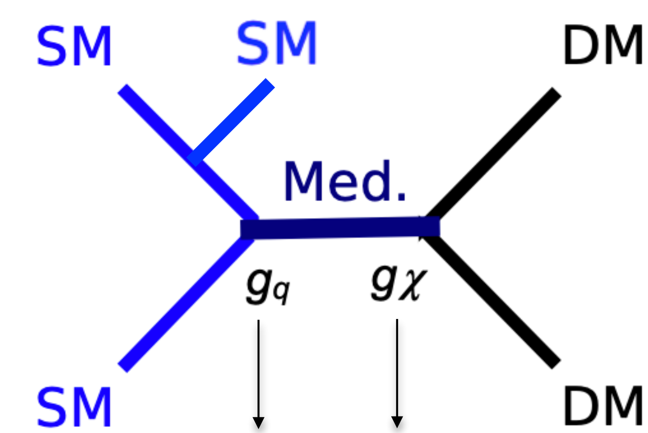
See Monica D'Onofrio's lecture

43

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

Other interpretations:

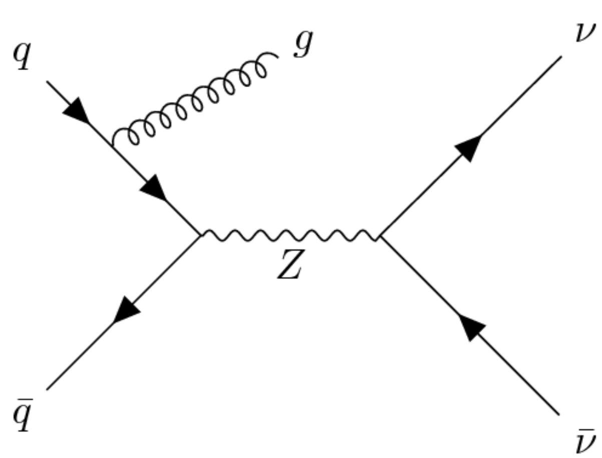
- Different kinds of mediators
- Supersymmetric models
- Extra dimensions
- Axion-like particles

44

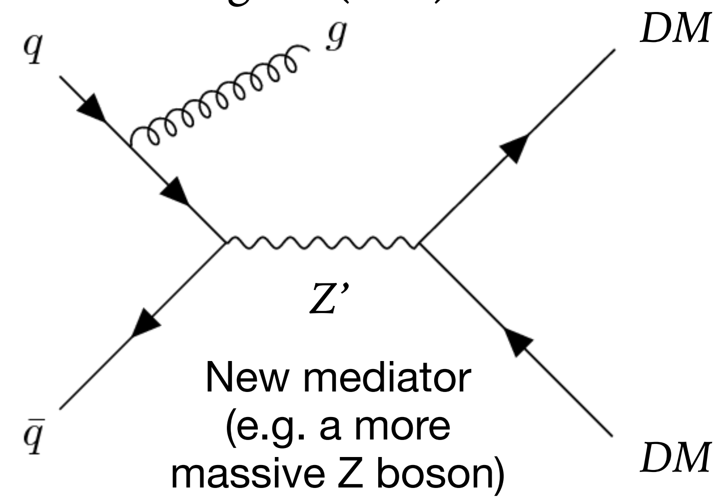
Parallels: visible and invisible mediator-based searches

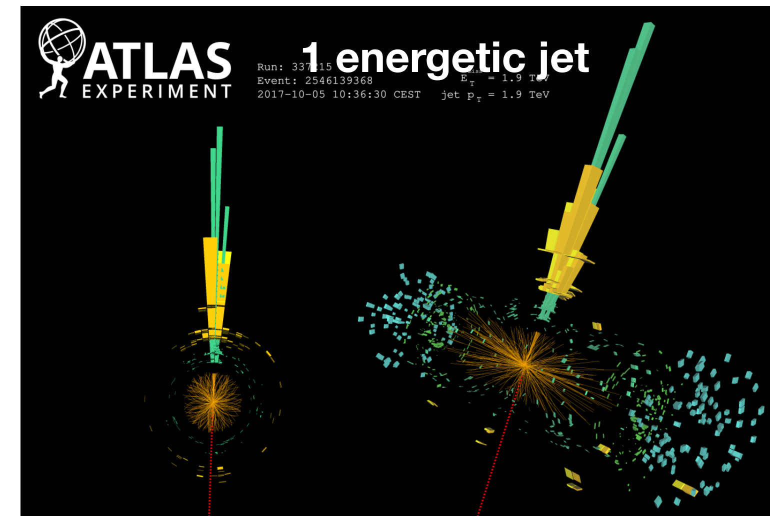
Detection of **DM** (invisible particles) **from a mediator**

Background (frequent)



Signal (rare)





45

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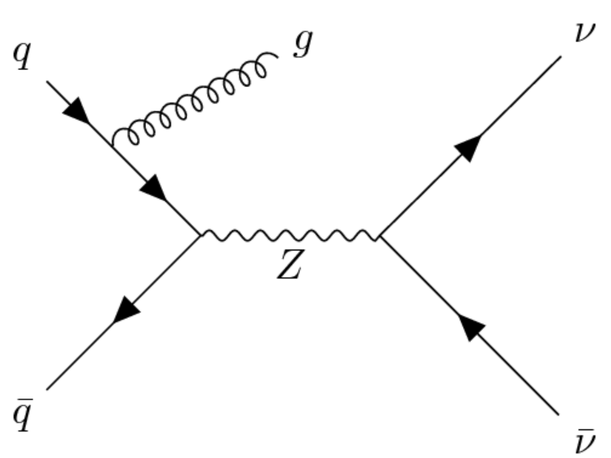
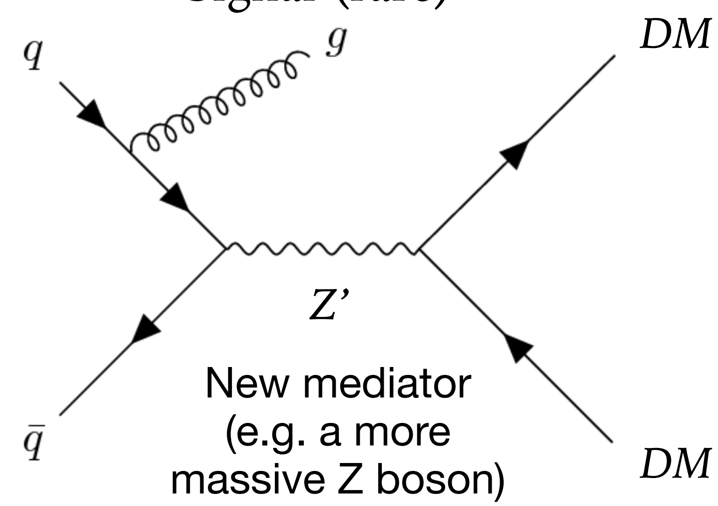
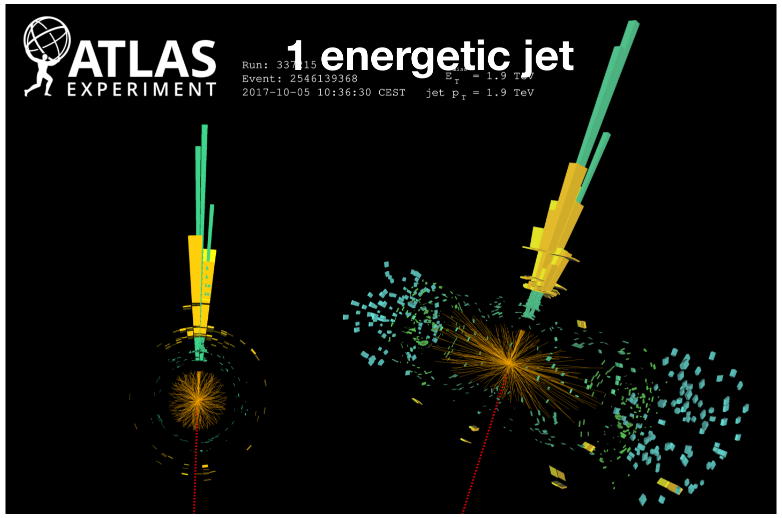


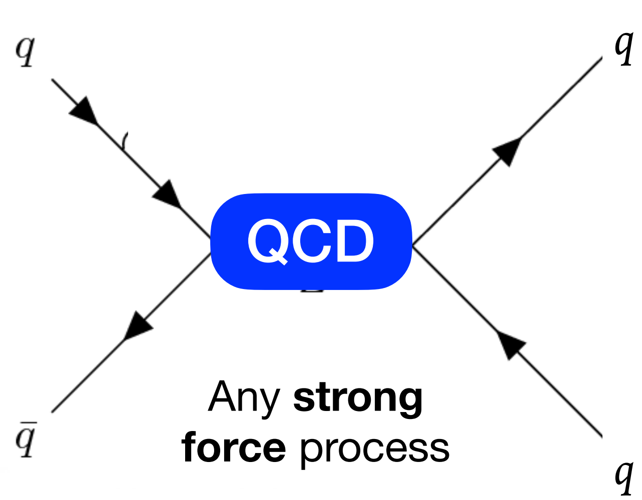
Signal (rare)





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

Background (very frequent)



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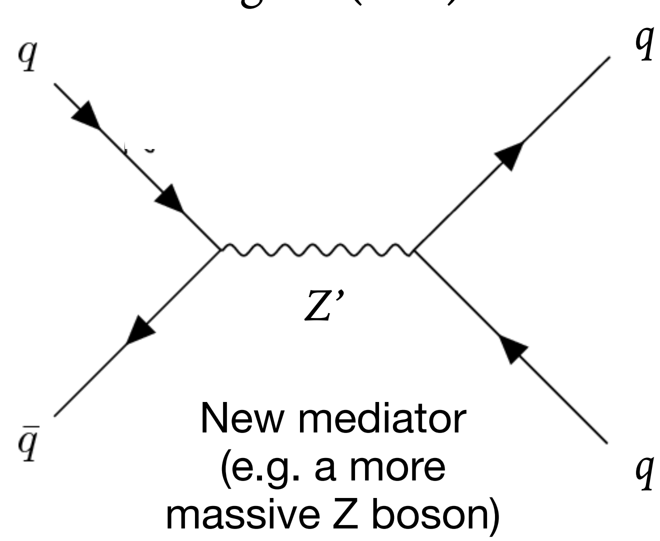

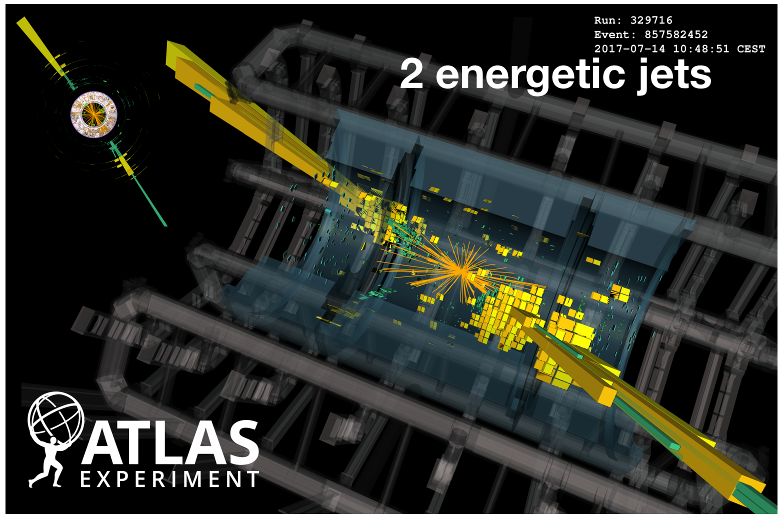

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Parallels: visible and invisible mediator-based searches

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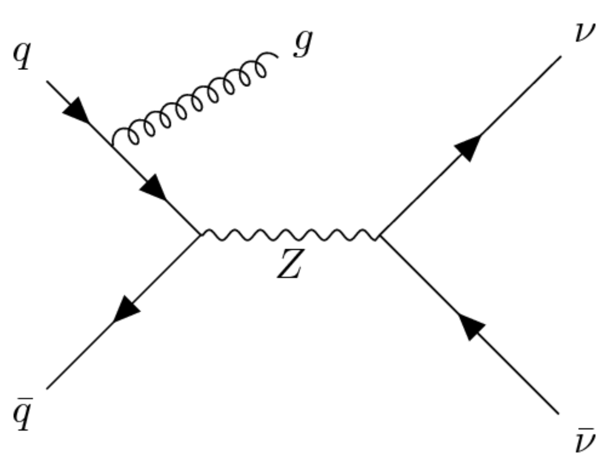

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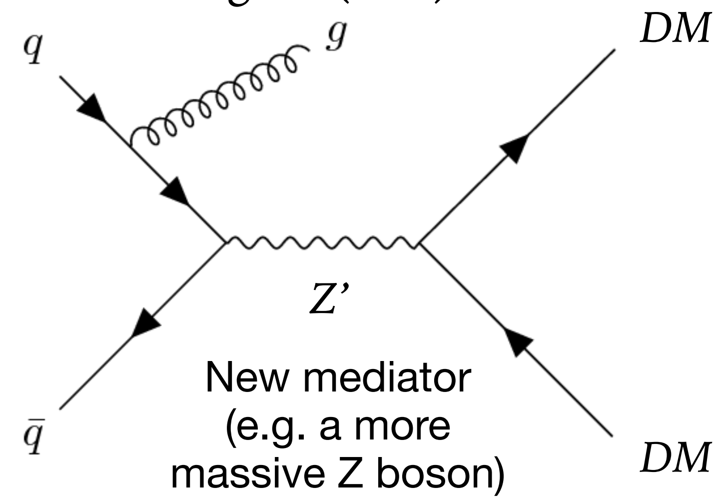

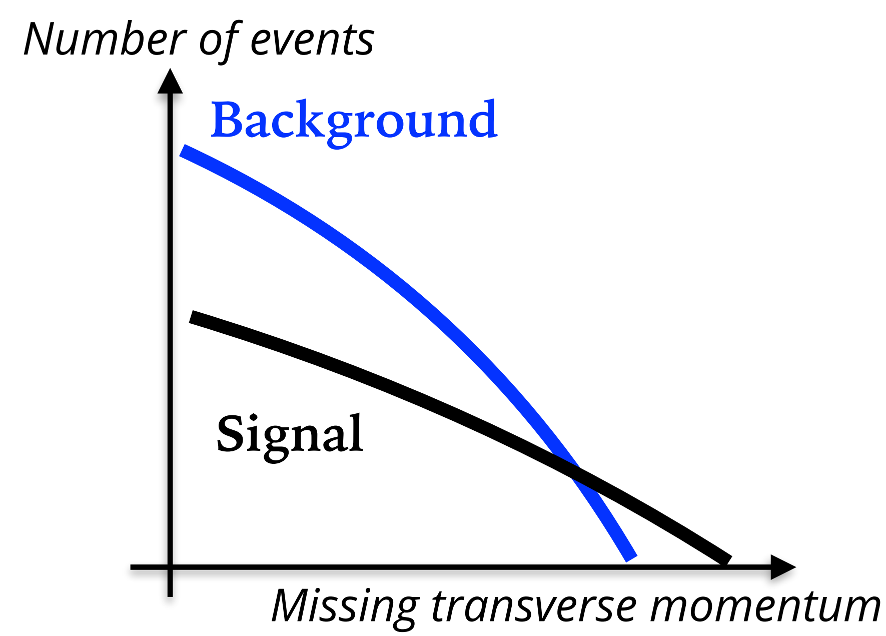

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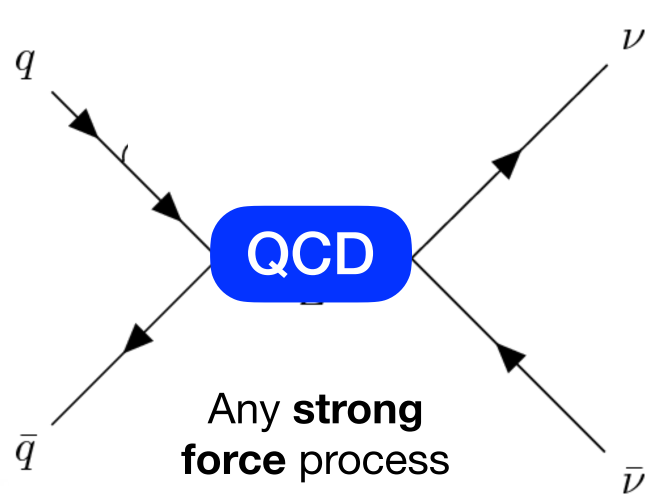
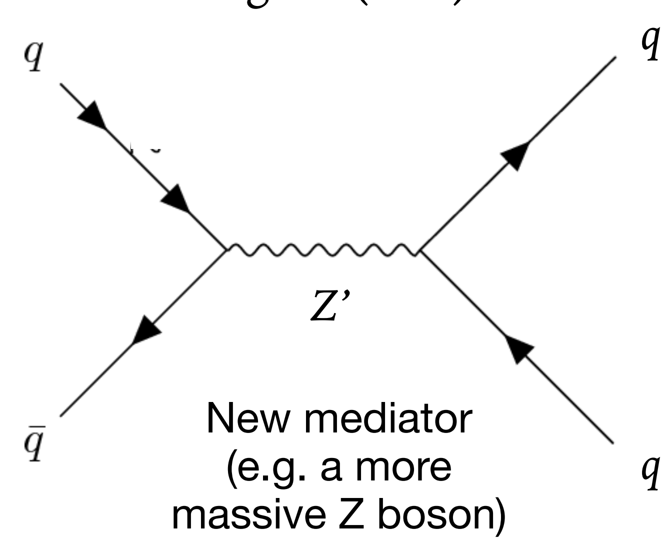
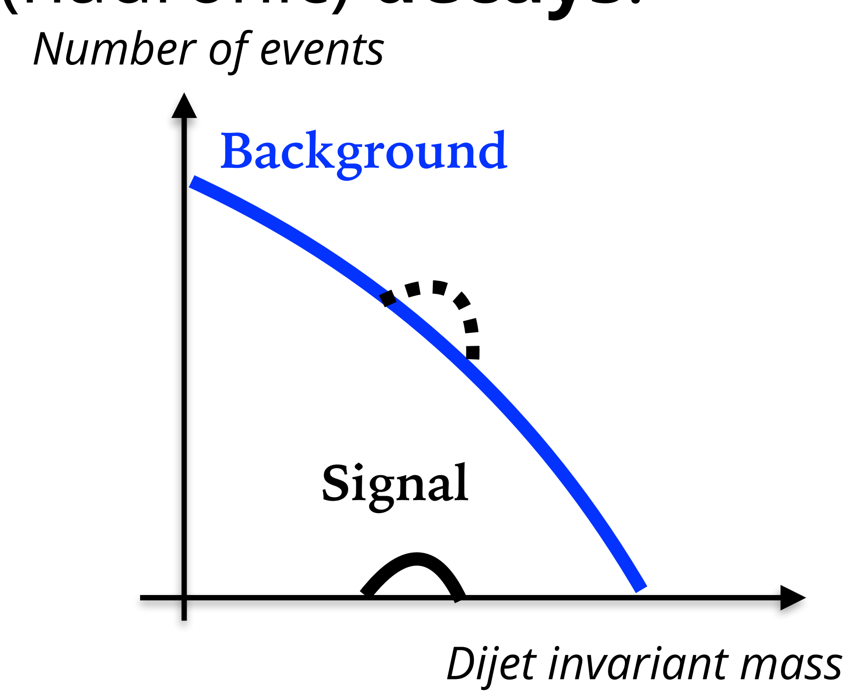


Signal (rare)





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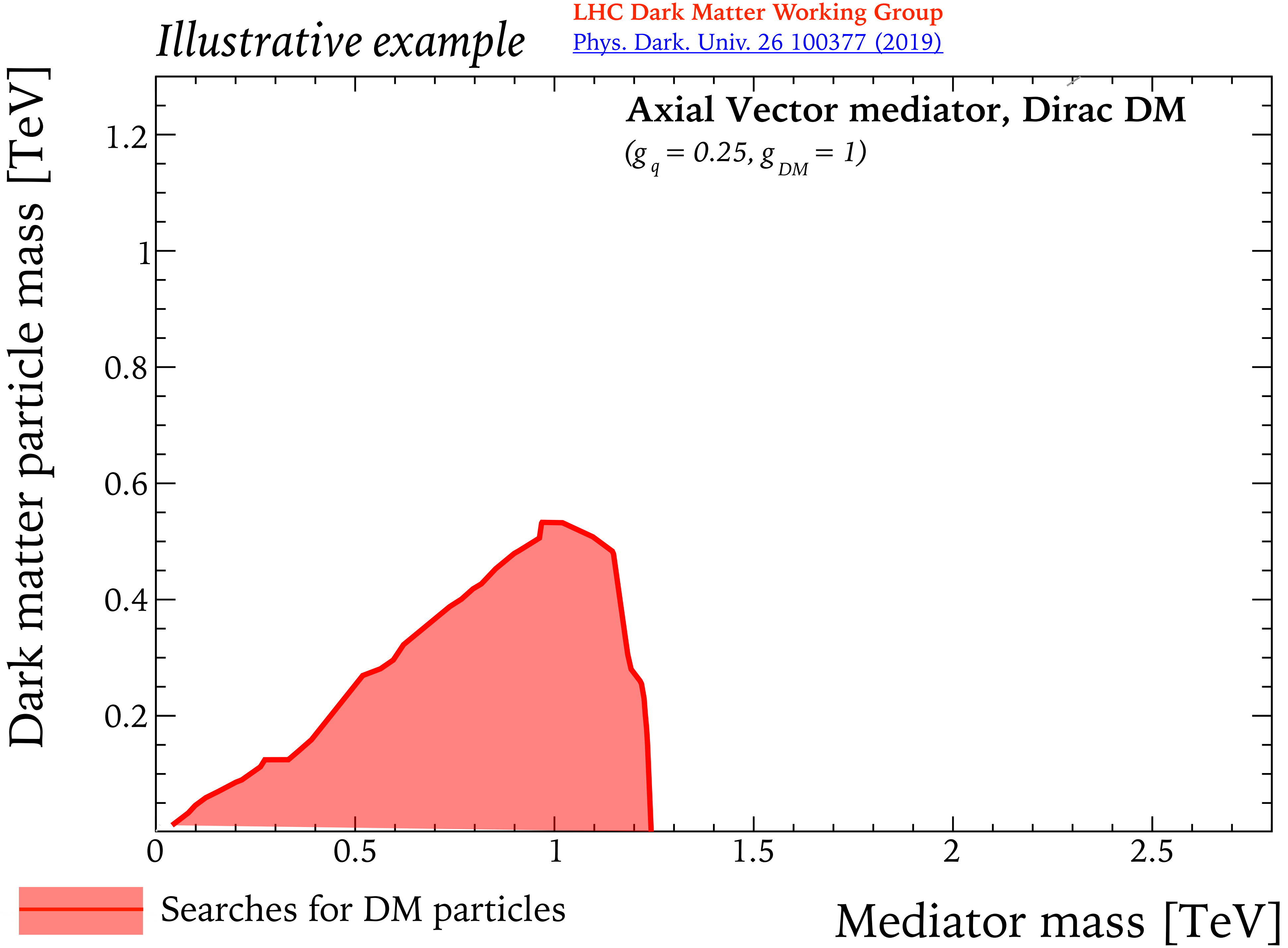
Complementarity of visible/invisible searches

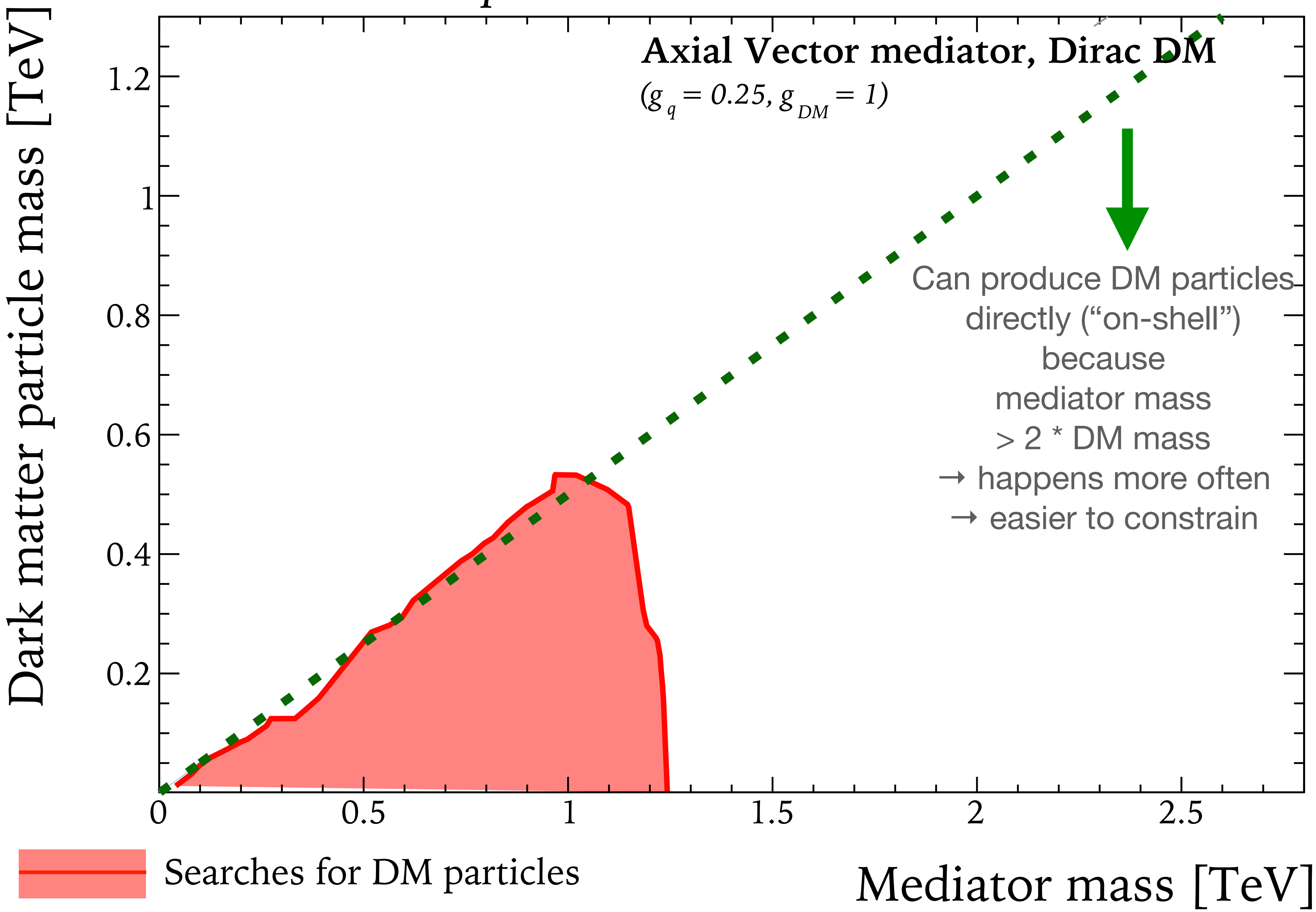
LHC Dark Matter Working Group
Phys. Dark. Univ. 26 100377 (2019)



Complementarity of visible/invisible searches

Illustrative example

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



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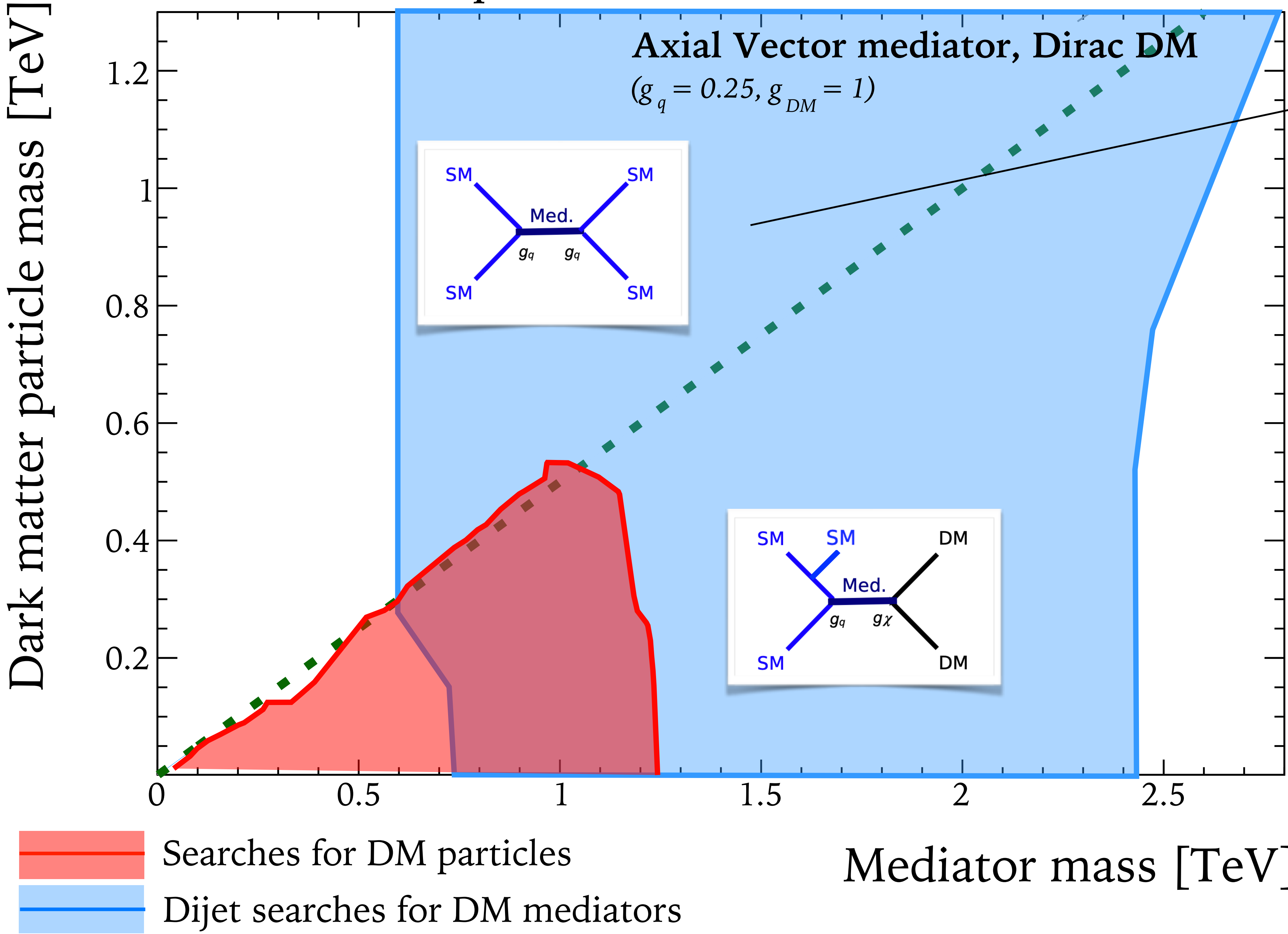

For mediator decays into quarks, the DM mass isn't too relevant (especially when they dominate)

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!*

Complementarity of visible/invisible searches

Illustrative example

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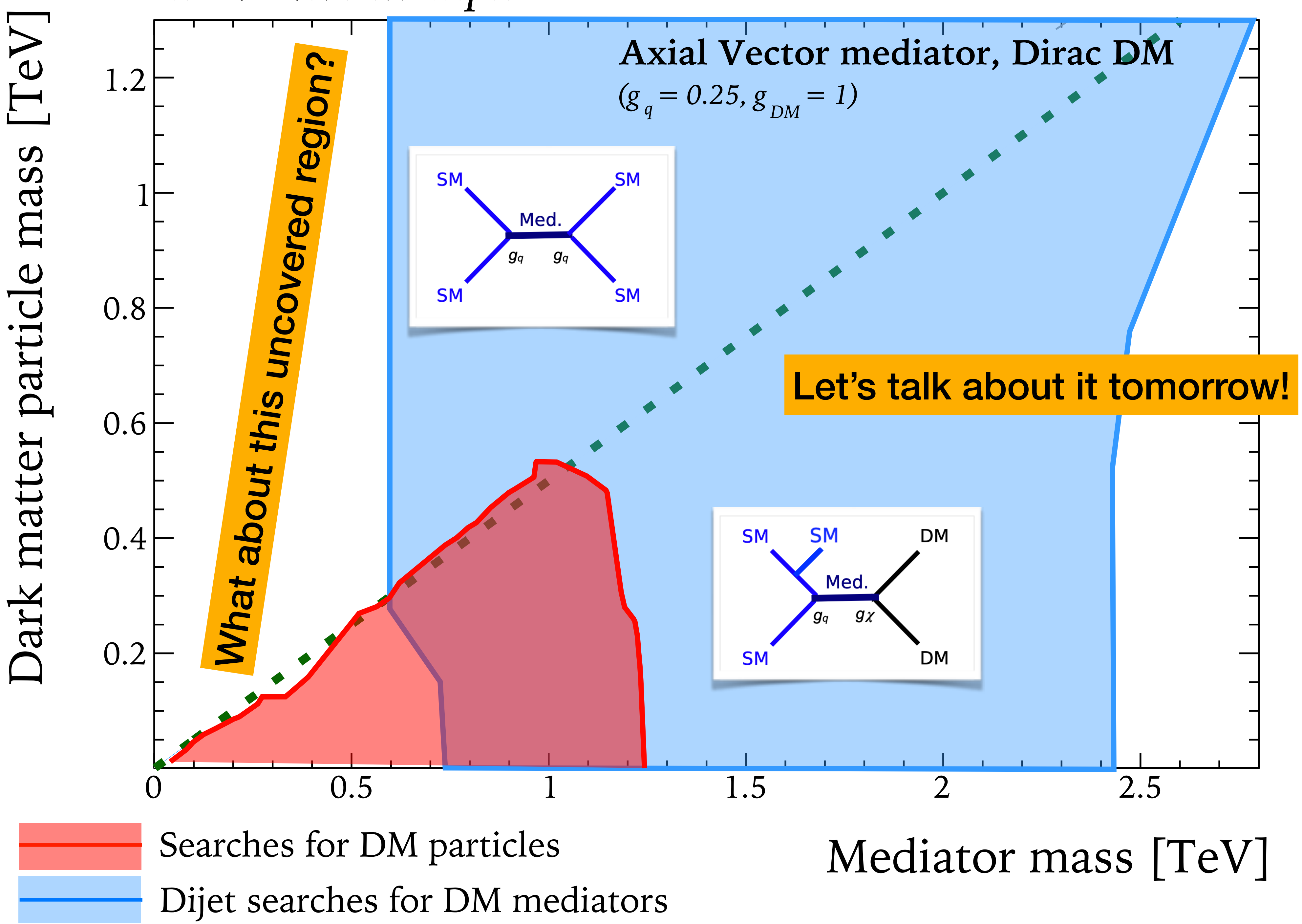

Take-home point #3:

When there is a **mediator** particle between the SM and the DM particle sector, LHC **searches for invisible particles are complementary to searches for visible particles**

Dark Matter at Colliders - Lecture 1
(including complementarity considerations)

HEP Graduate Workshop, Batna, 24-26/05/22

Caterina Doglioni - University of Manchester & Lund University
@catdoglund, she/her http://www.hep.lu.se/staff/doglioni/

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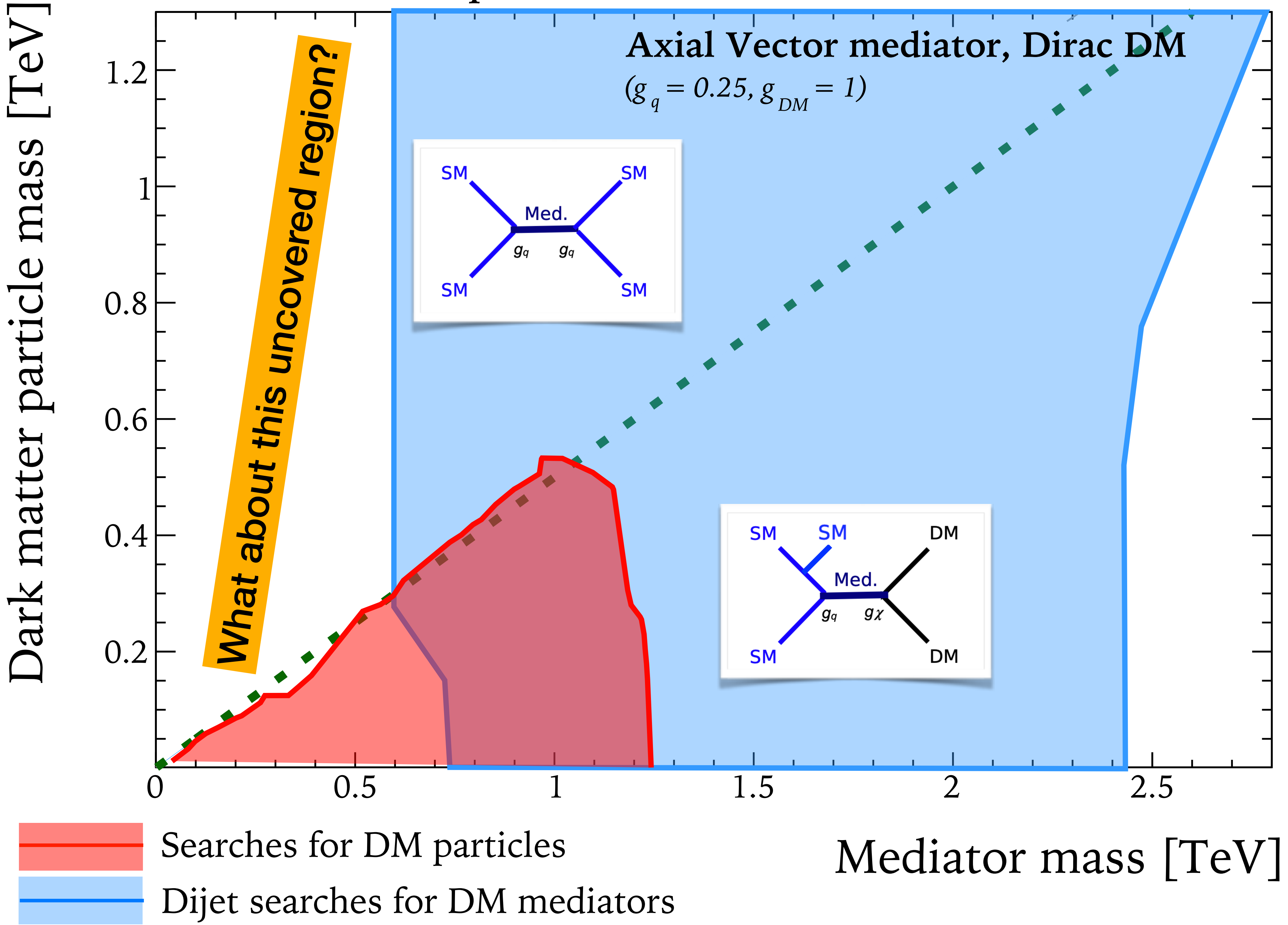
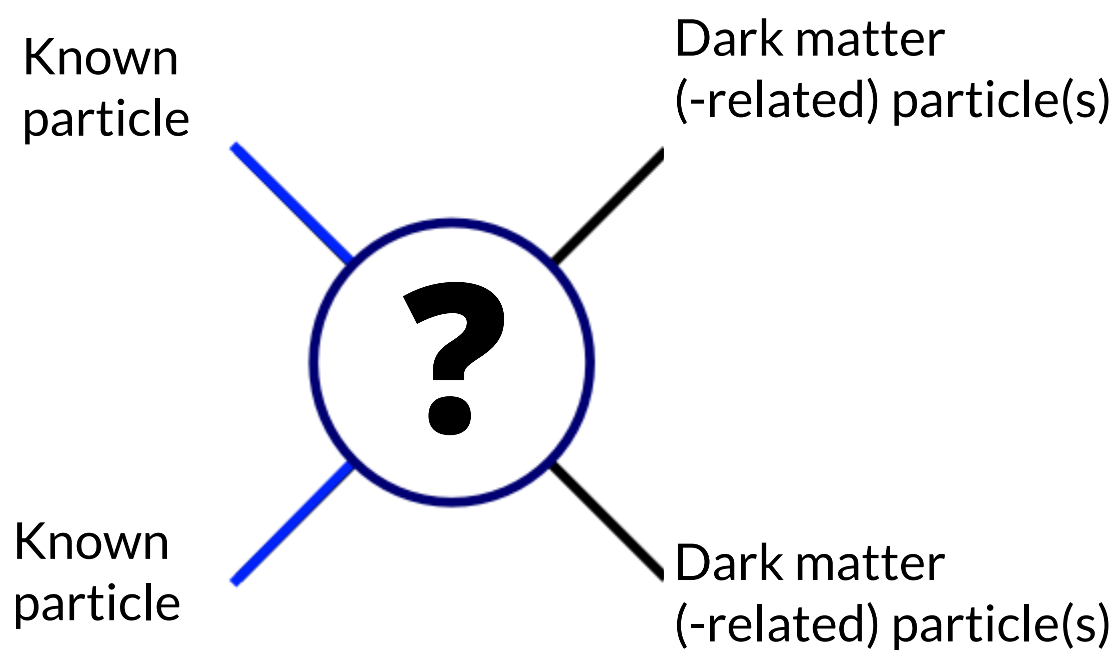
Complementarity of visible/invisible searches

Illustrative example

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



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

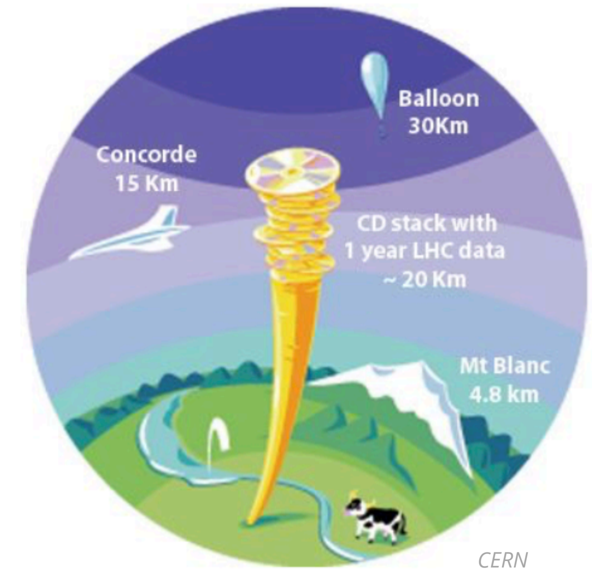
Challenges:

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



after selection of "interesting" data

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

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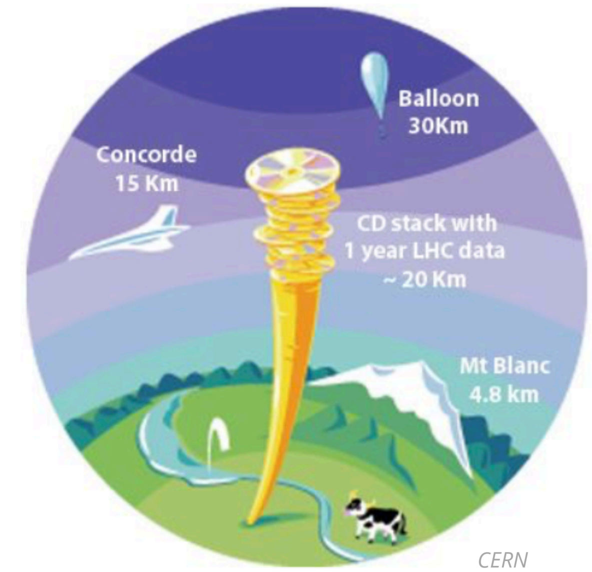


after selection of "interesting" data

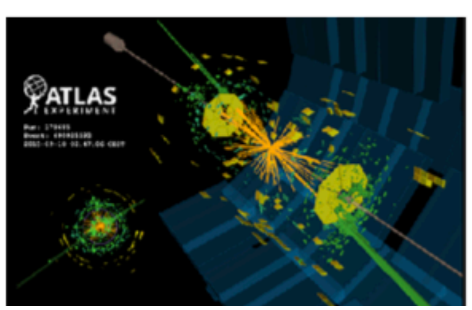
LHC & future hadron collider experiments need to select "interesting" events (=*trigger*) **in real-time** (milli/microseconds)

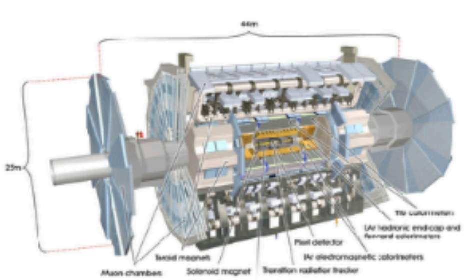
Collisions at ~30 MHz (~1 MB of info each)

Hardware trigger outputs ~100 kHz

Software trigger outputs ~1 kHz

Online ◀ ▶ Offline





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

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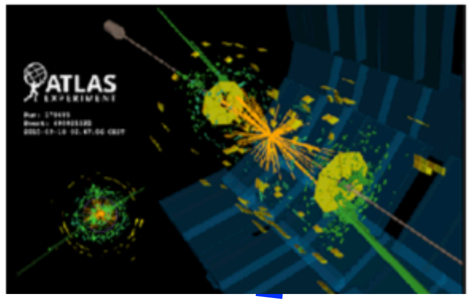
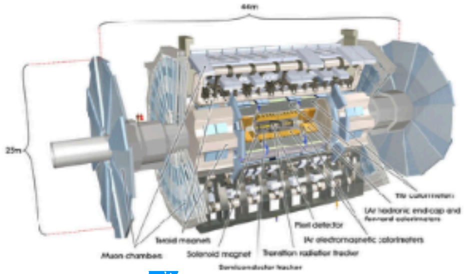
Online ◀ ▶ Offline





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

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

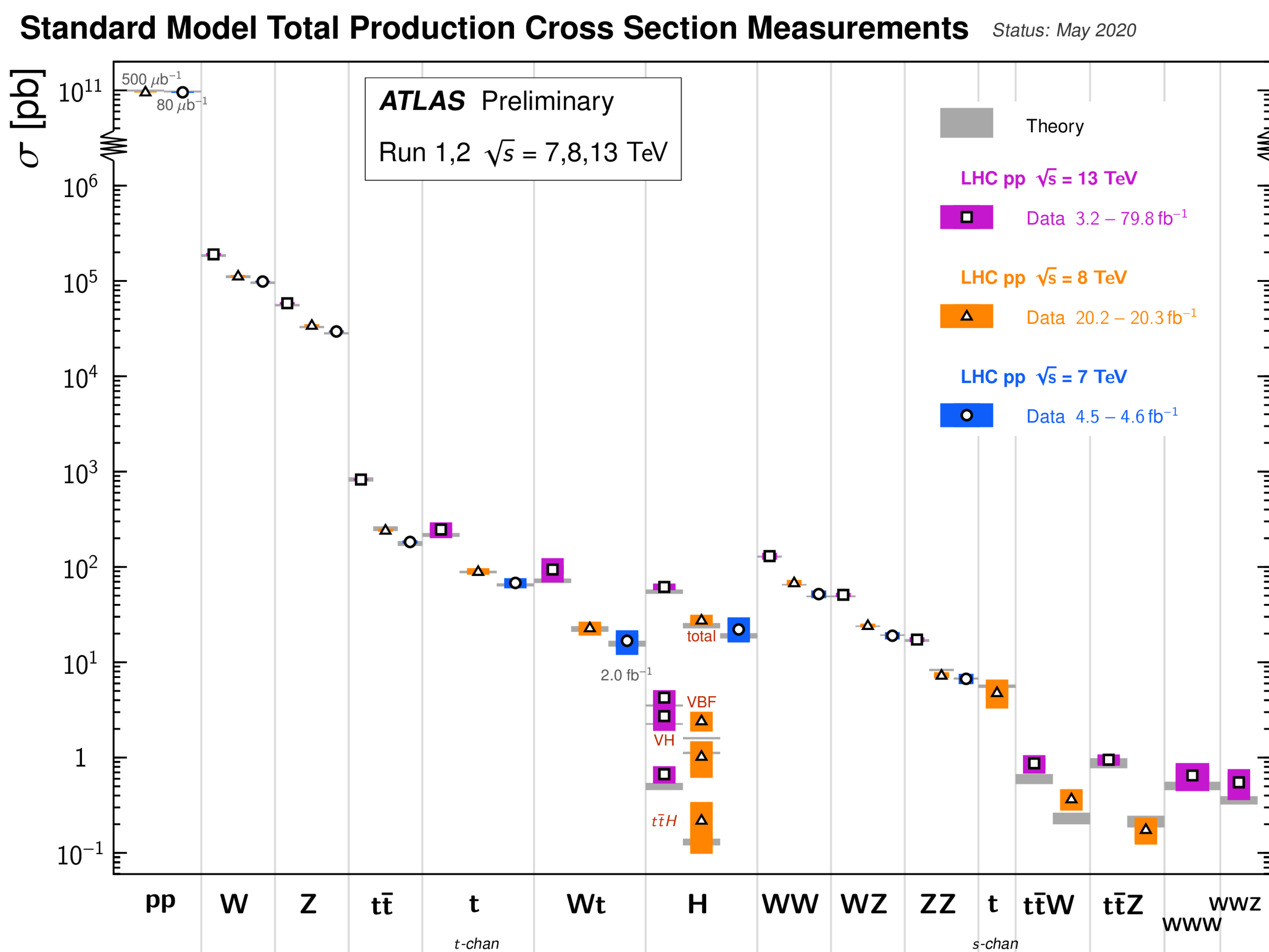
Data ~nobody likes

Data produced by the LHC

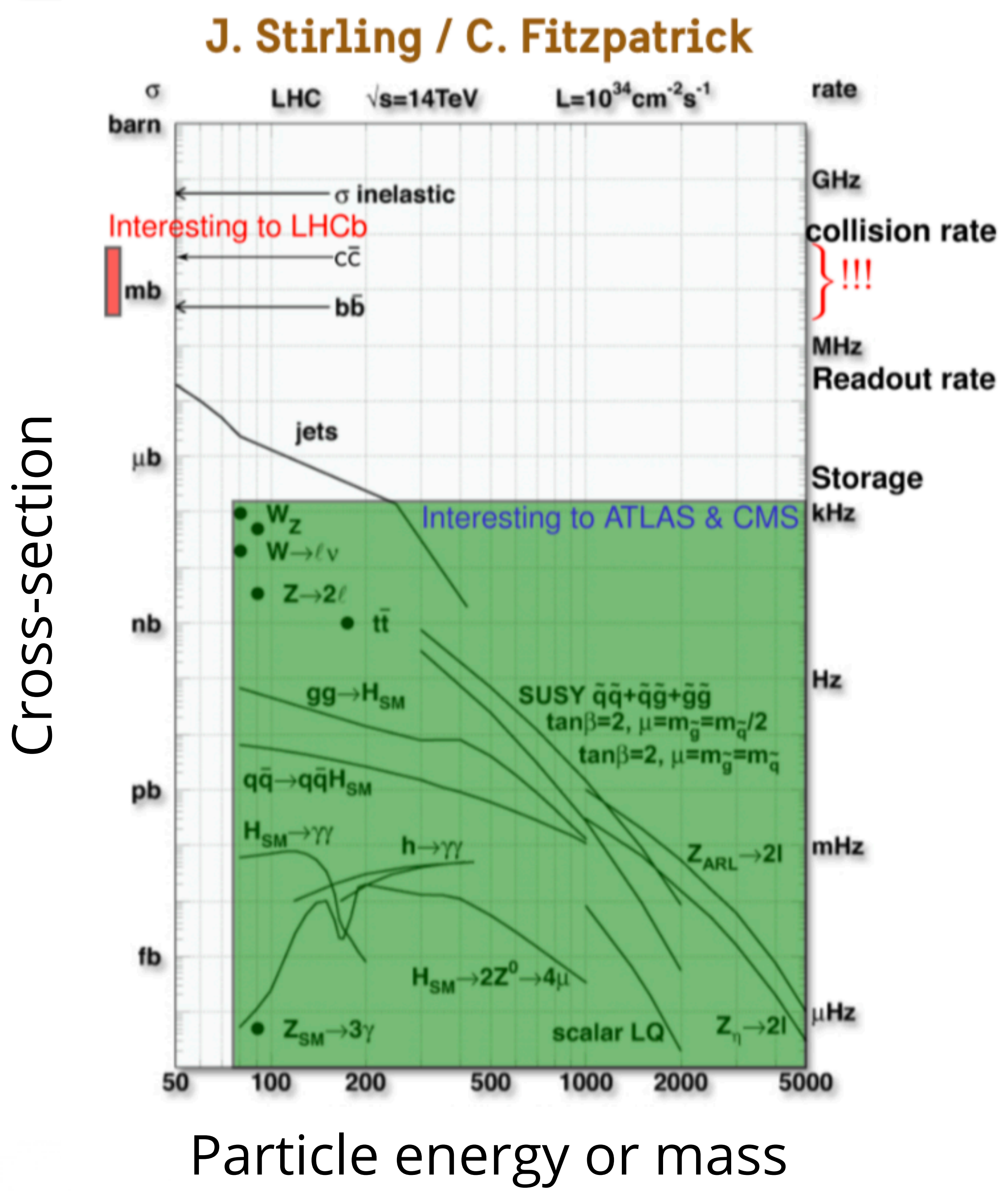
(multiplied by large number)

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?



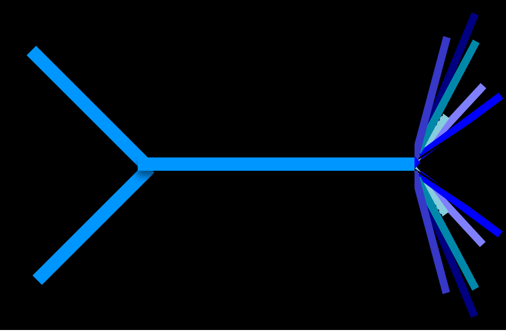
Cross-section * Luminosity
= number of events produced

Challenges:

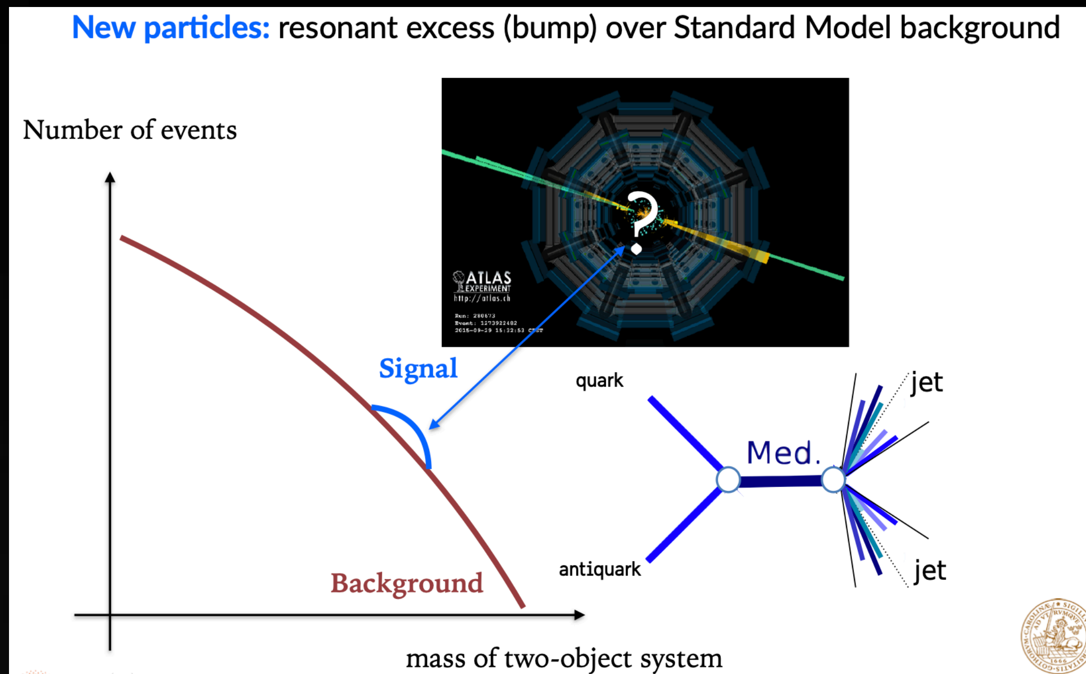
The **definition of ”interesting”** changes experiment by experiment

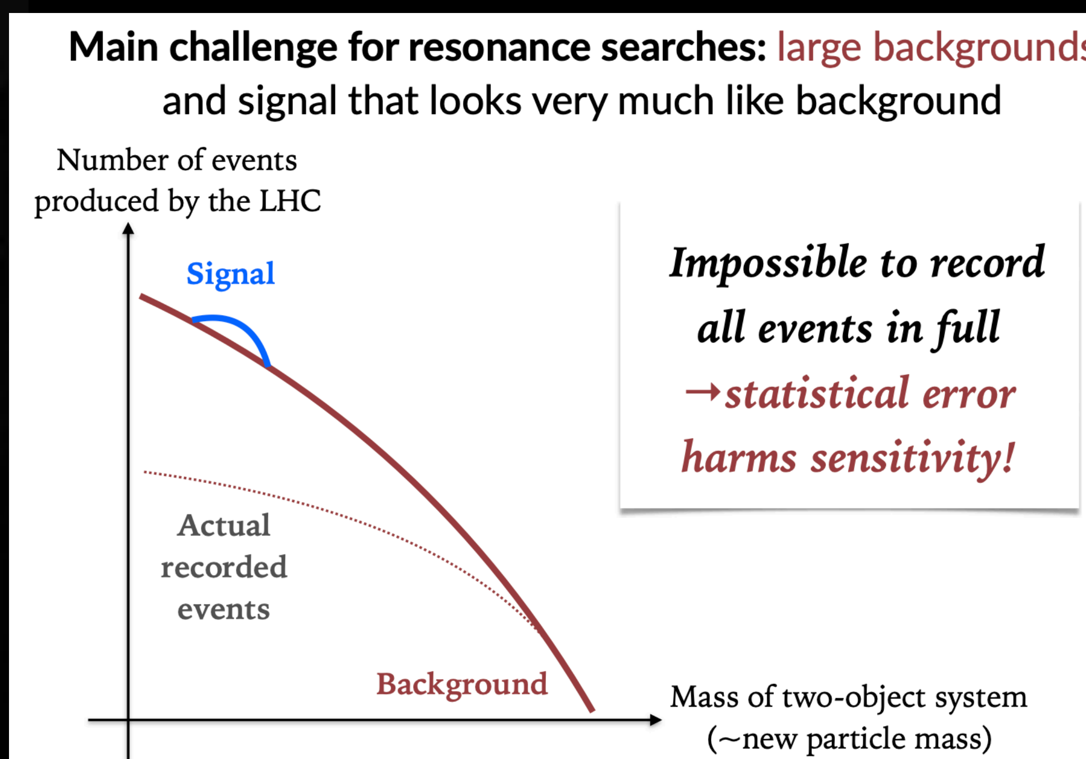
Rare signal processes that are buried in **high-rate backgrounds** have to be discarded

Are we missing rare hadronic processes?



DM mediators



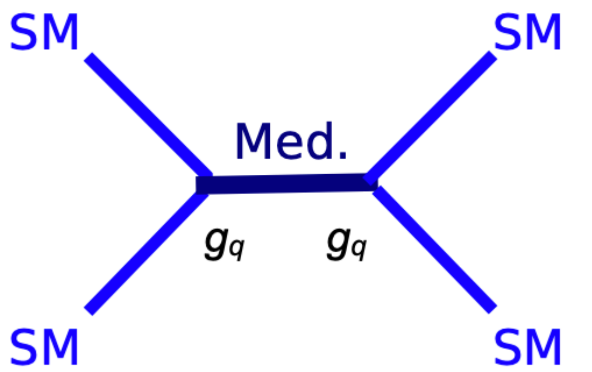


Events selected by the trigger

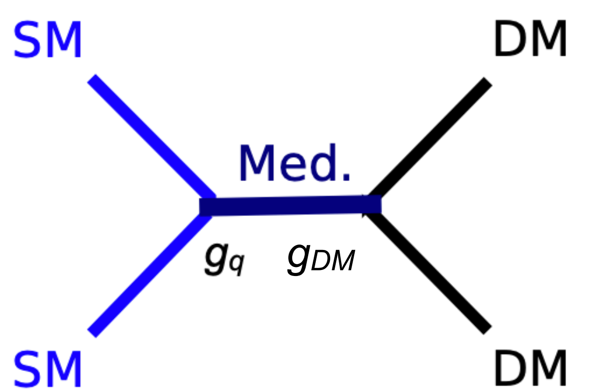
Example: dijet decays of DM mediators, ca 2013

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

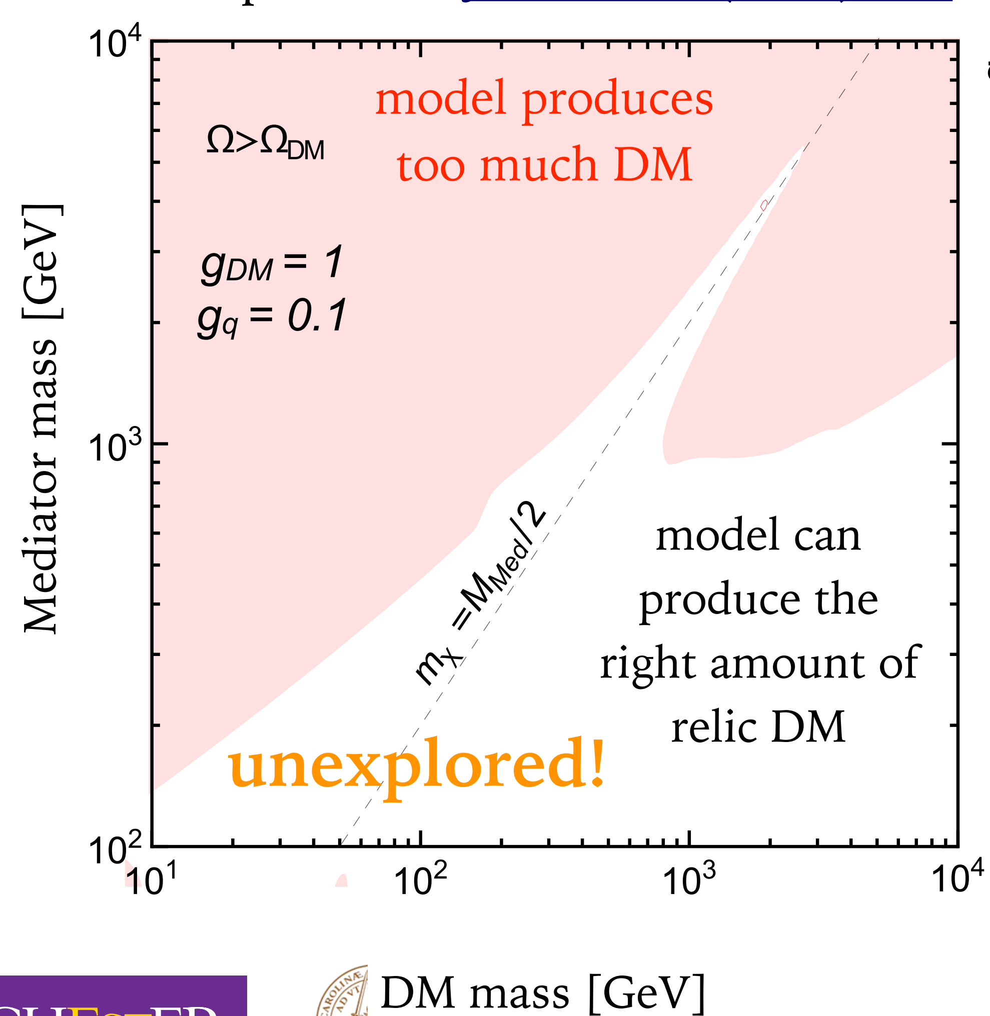


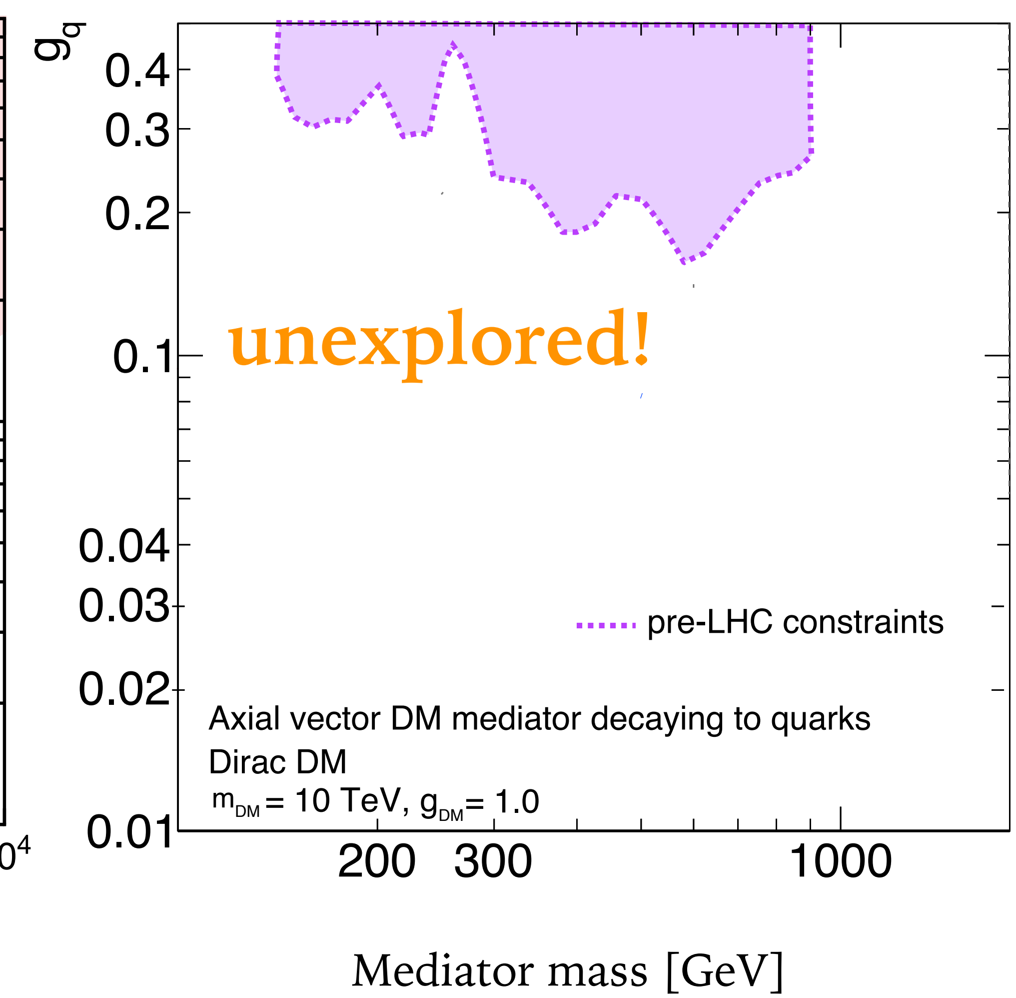
Visible mediator decays



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

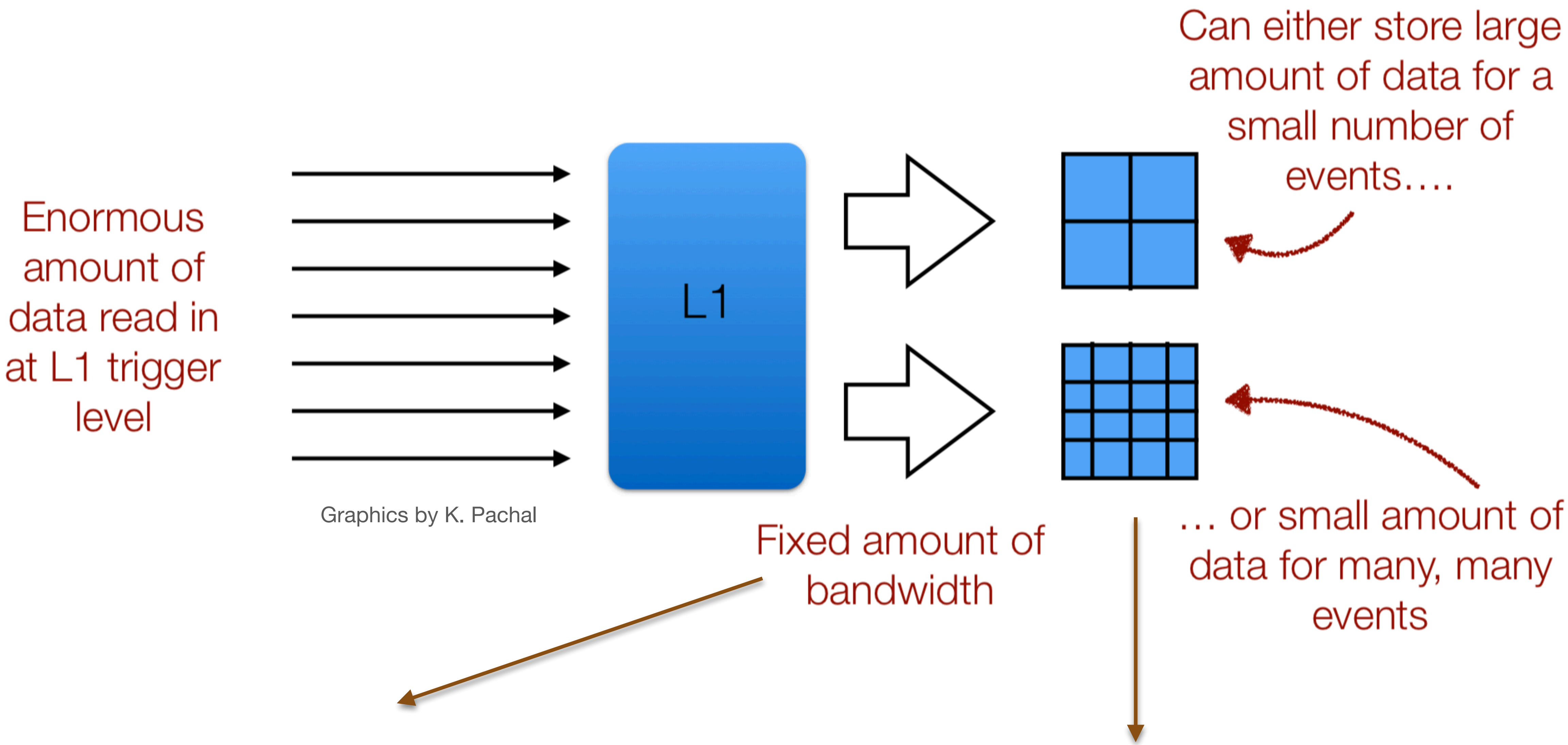
⇩

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



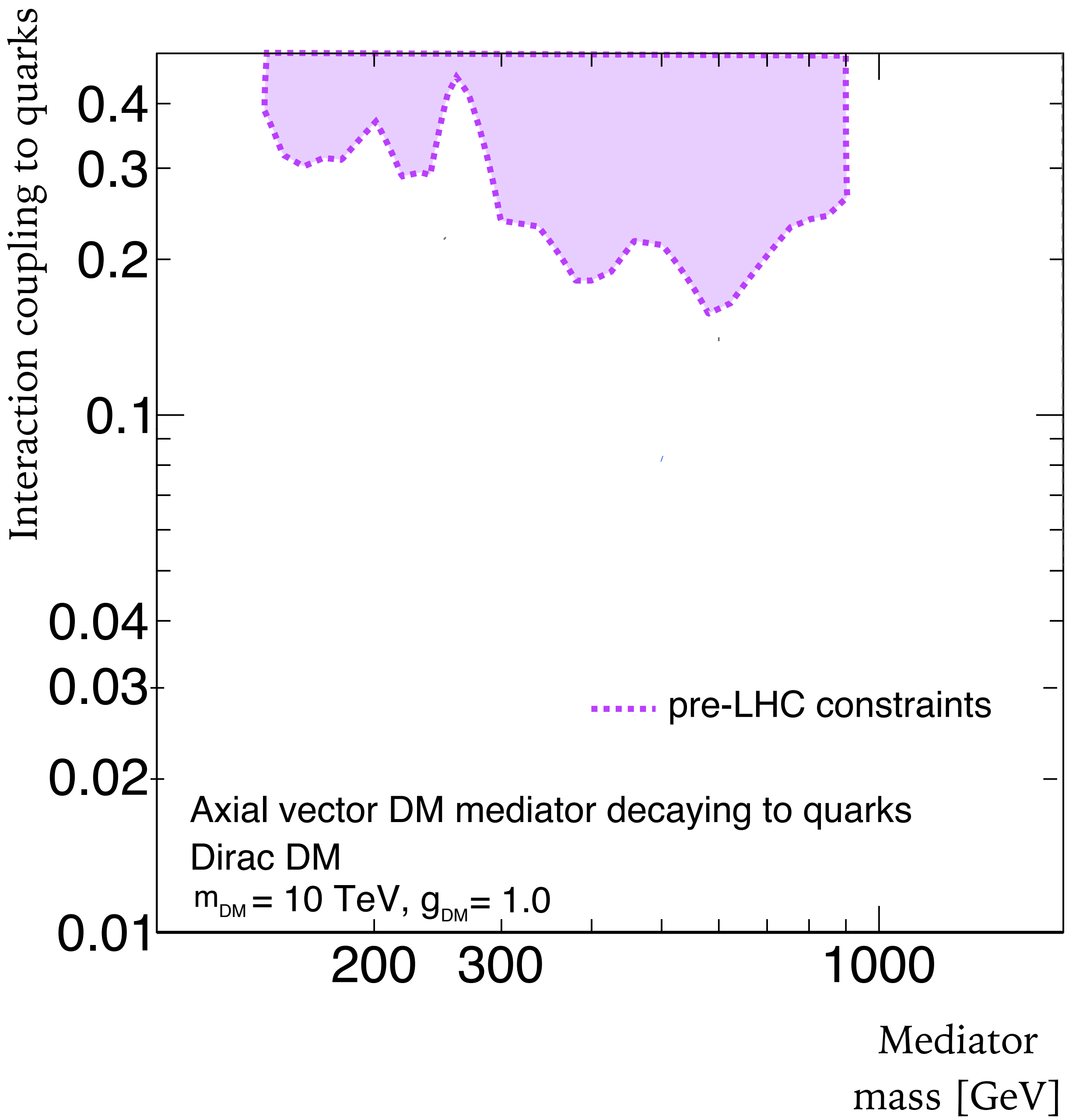
Perform as much "analysis" as possible in real time

- 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

Filling the uncovered parameter space of low-mass



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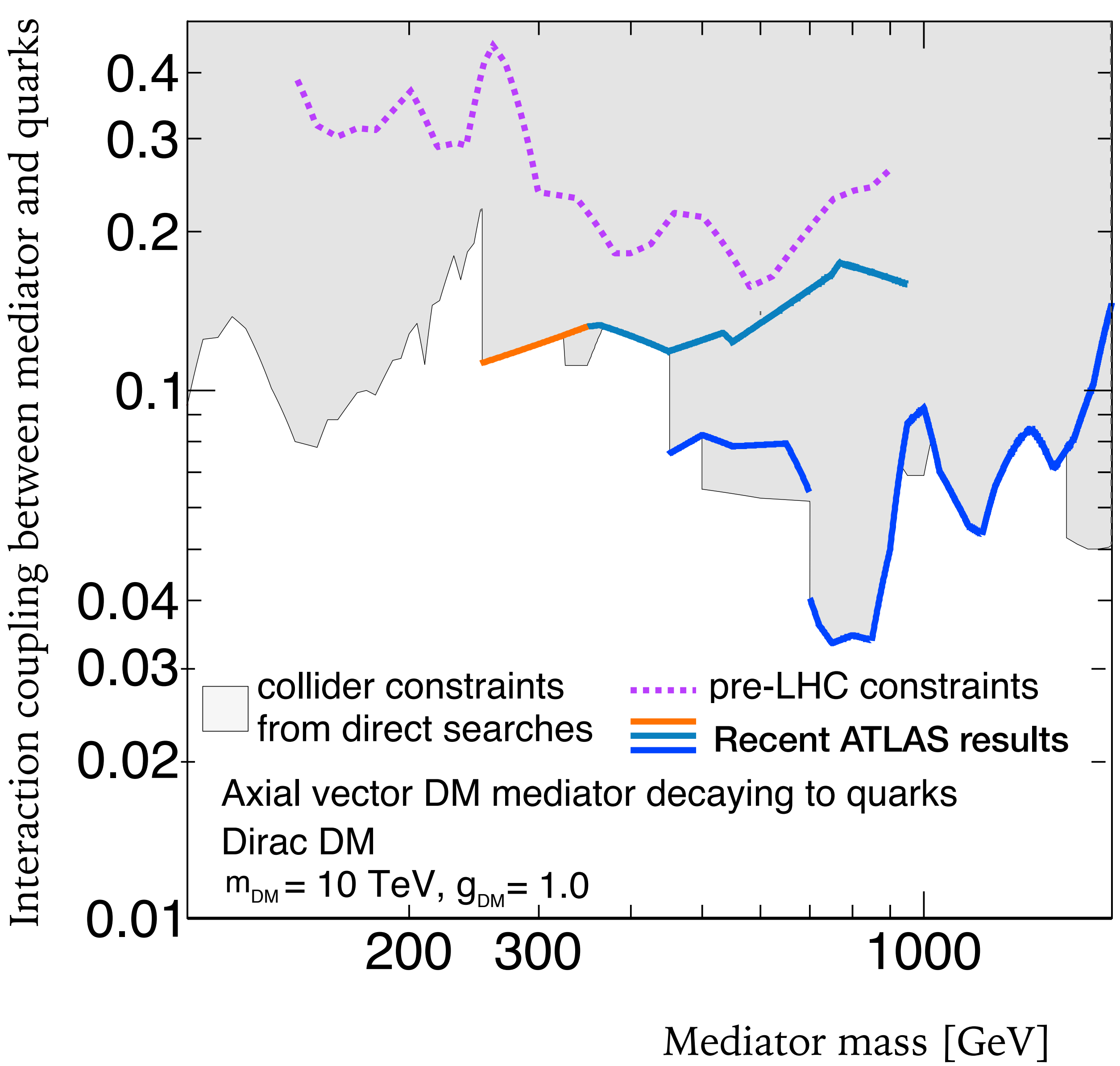
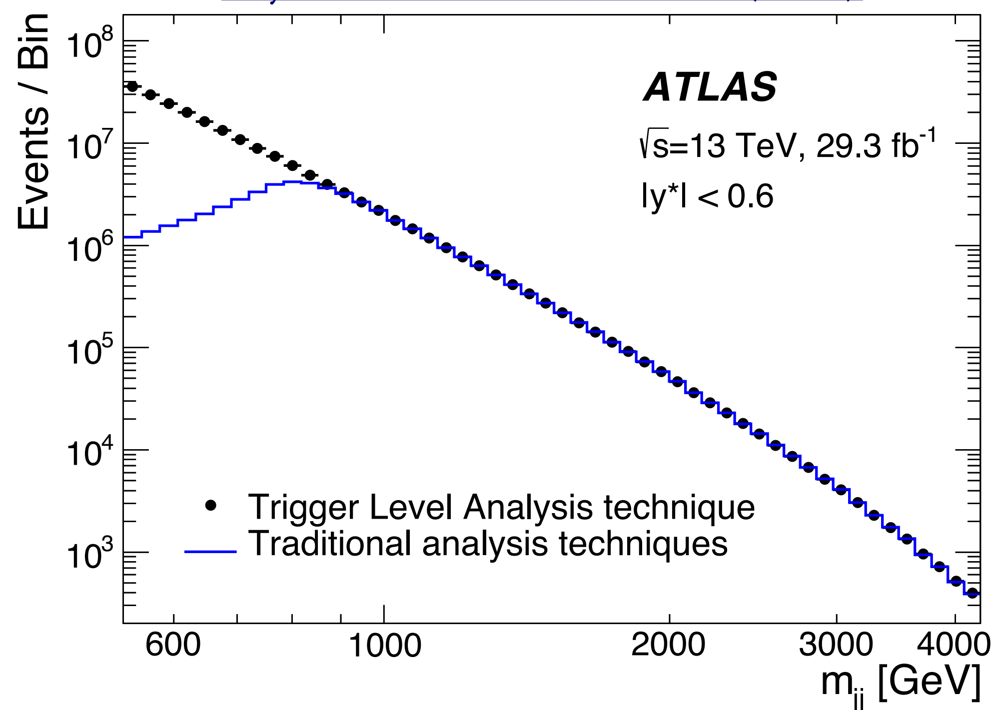
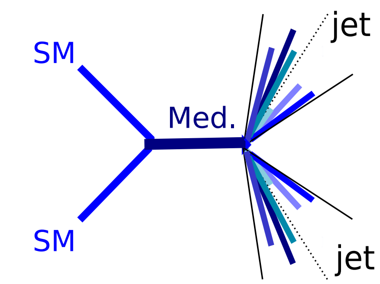


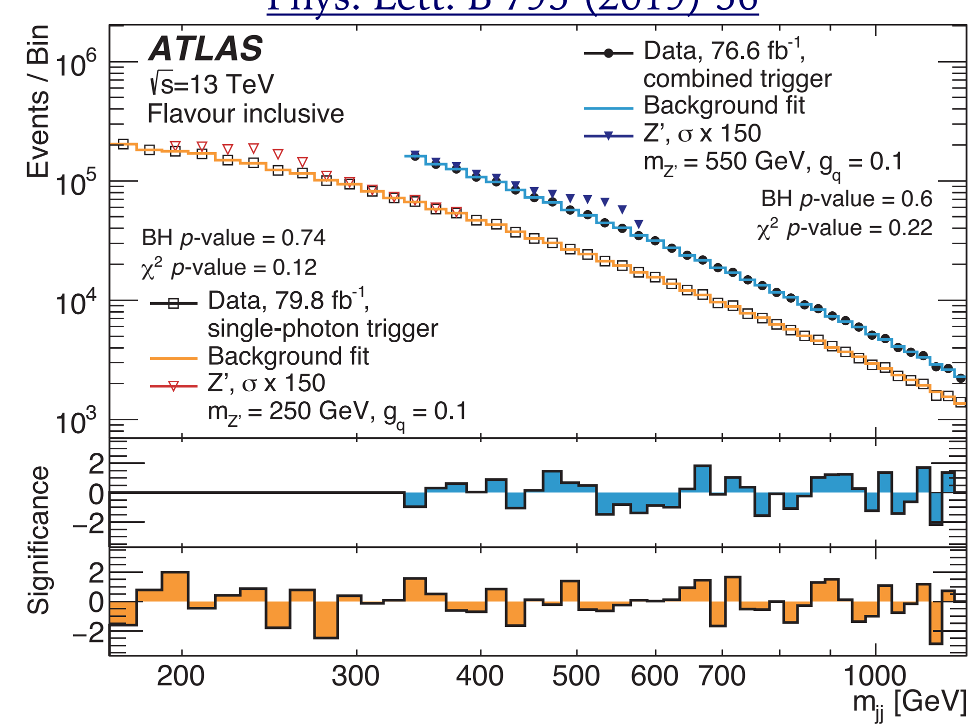
Phys. Rev. Lett. 121, 081801 (2018)



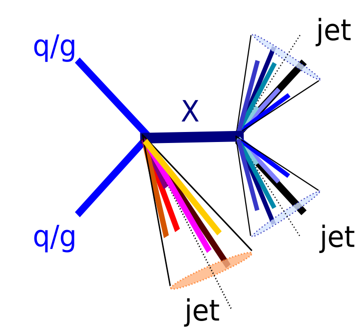
TLA technique: Make the event size smaller



Phys. Lett. B 795 (2019) 56

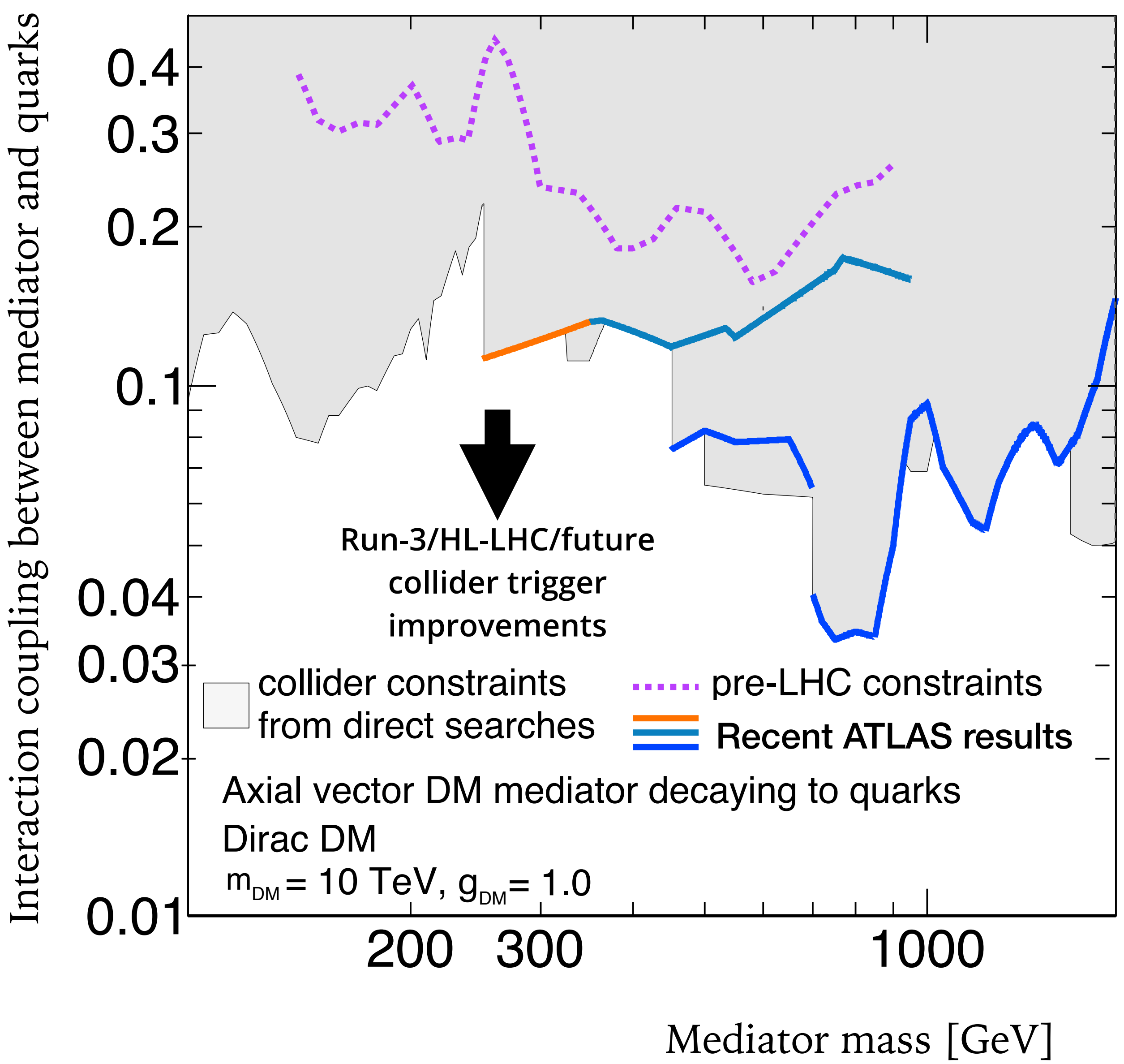


Dijet+ISR signature: Reduce the background



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

Filling the uncovered parameter space of low-mass



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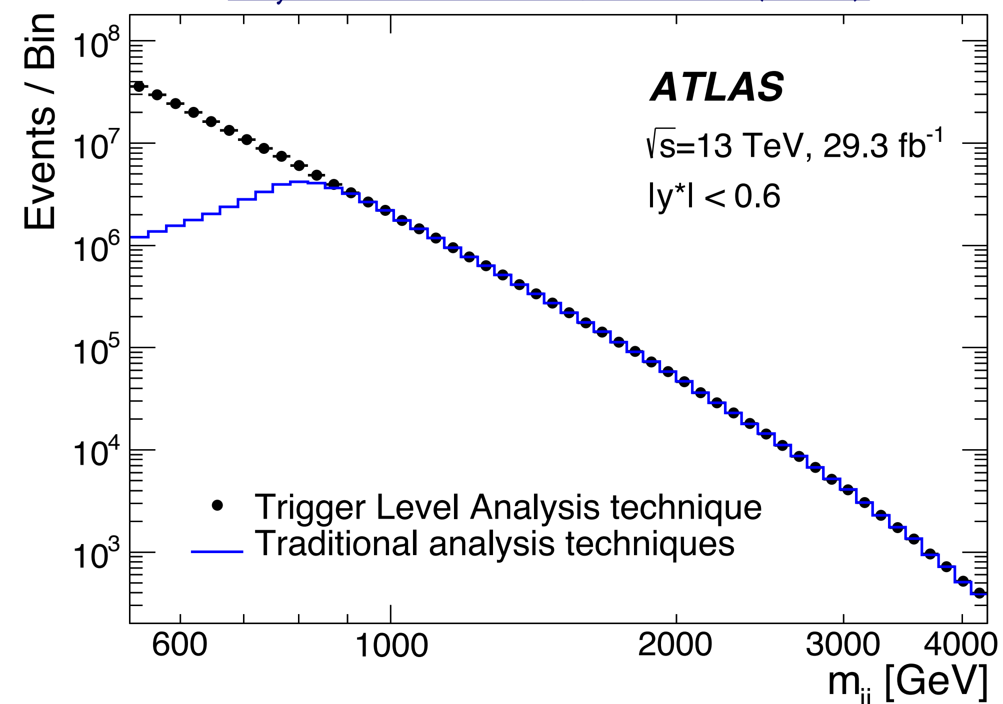

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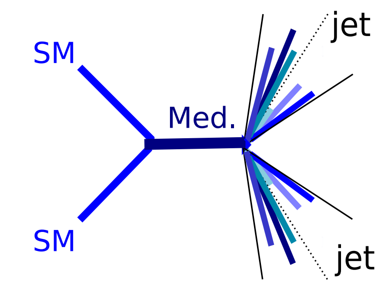
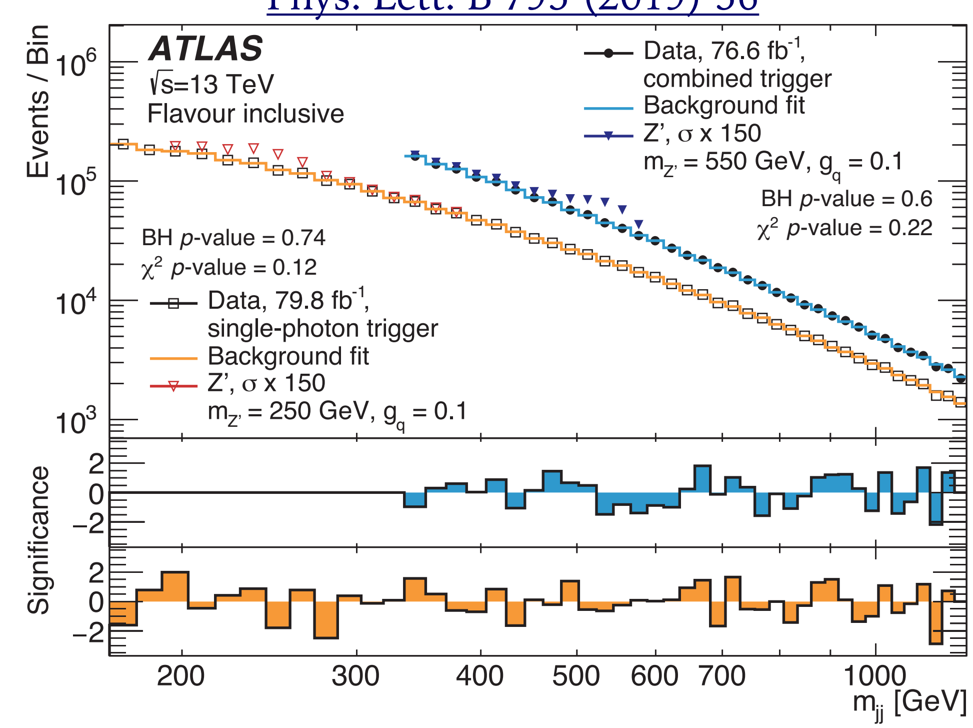


Phys. Lett. B 795 (2019) 56



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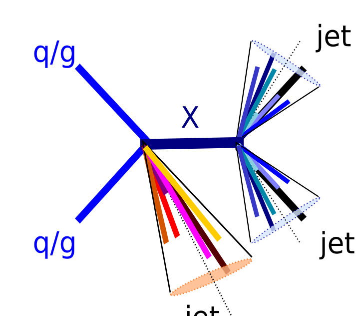
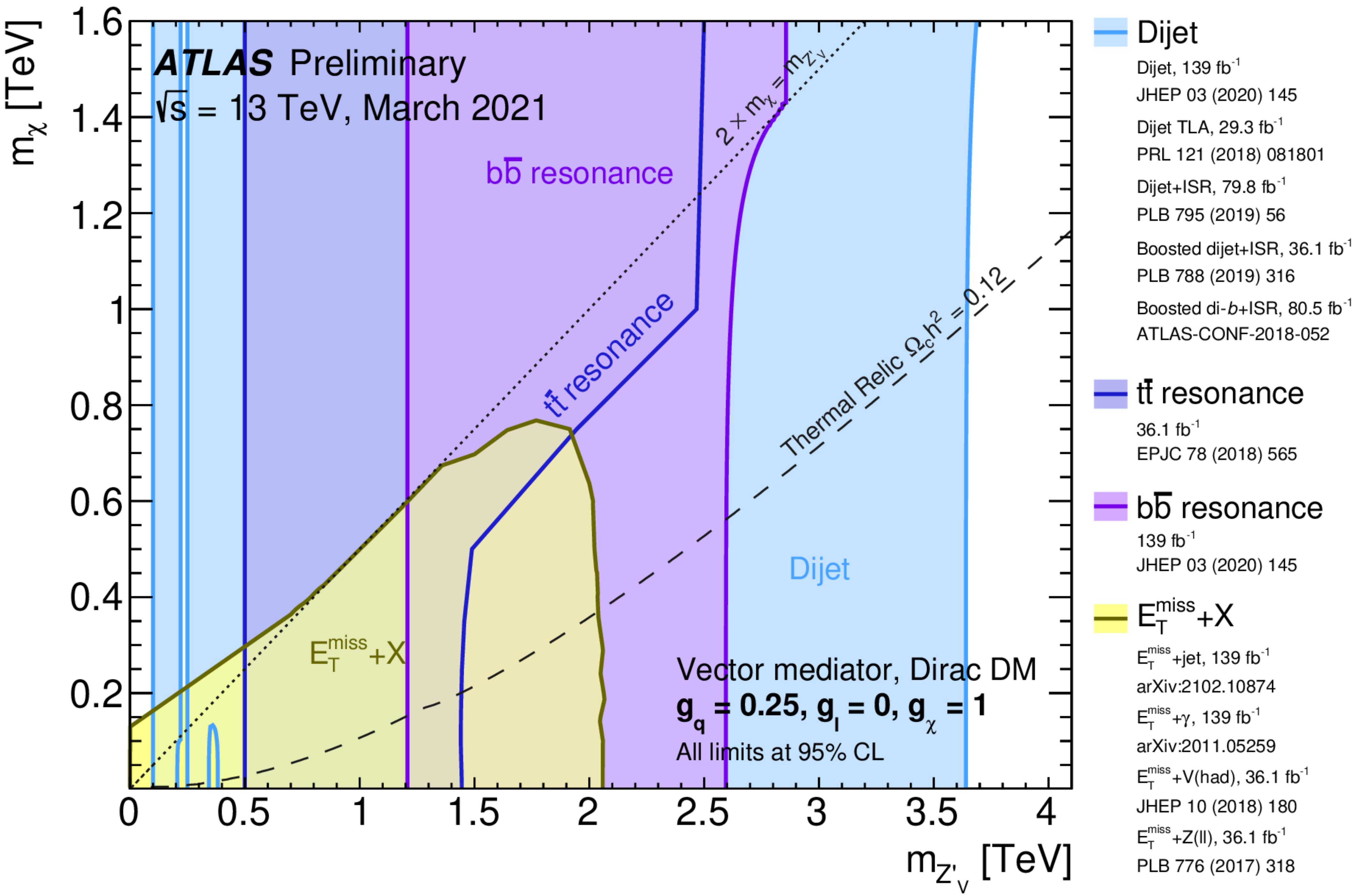


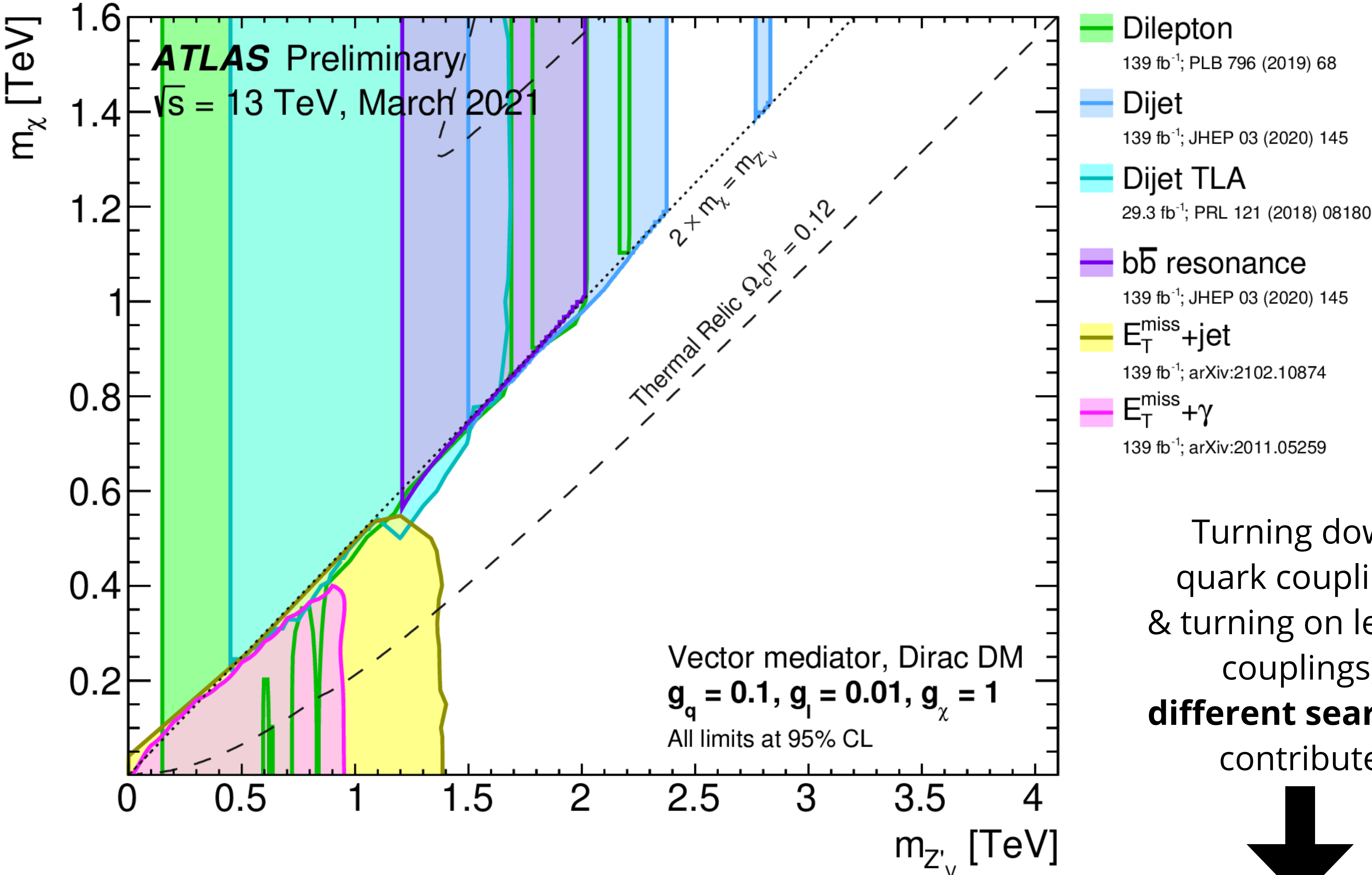
Searching for even rarer dijet resonances: **EW-scale couplings still unexplored** and probably not something we want to give up at any future colliders *(to discuss!)*

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

Take-home point #4:

Generic searches for DM particles targeting simple (simplified) models show the **unique LHC ability to look into the SM-DM interactions,** but they are only a **starting point**

An example of Supersymmetric DM

The University of Manchester

Lunds Universitet

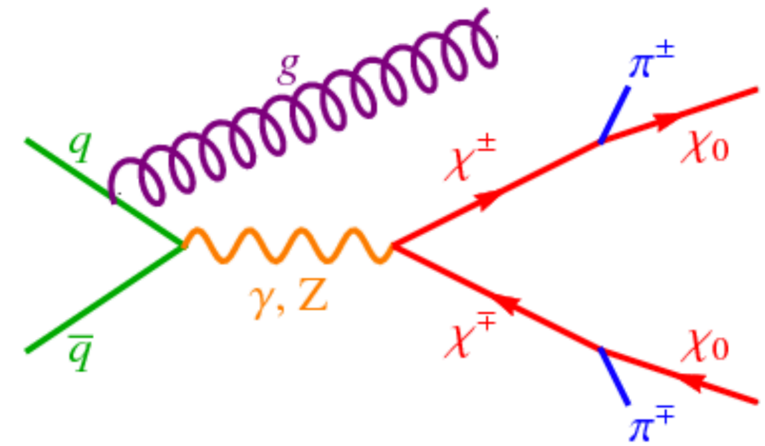
European Research Council
Established by the European Commission

DM in SUSY: Pure Wino and Higgsino DM

European Strategy Update Briefing Book

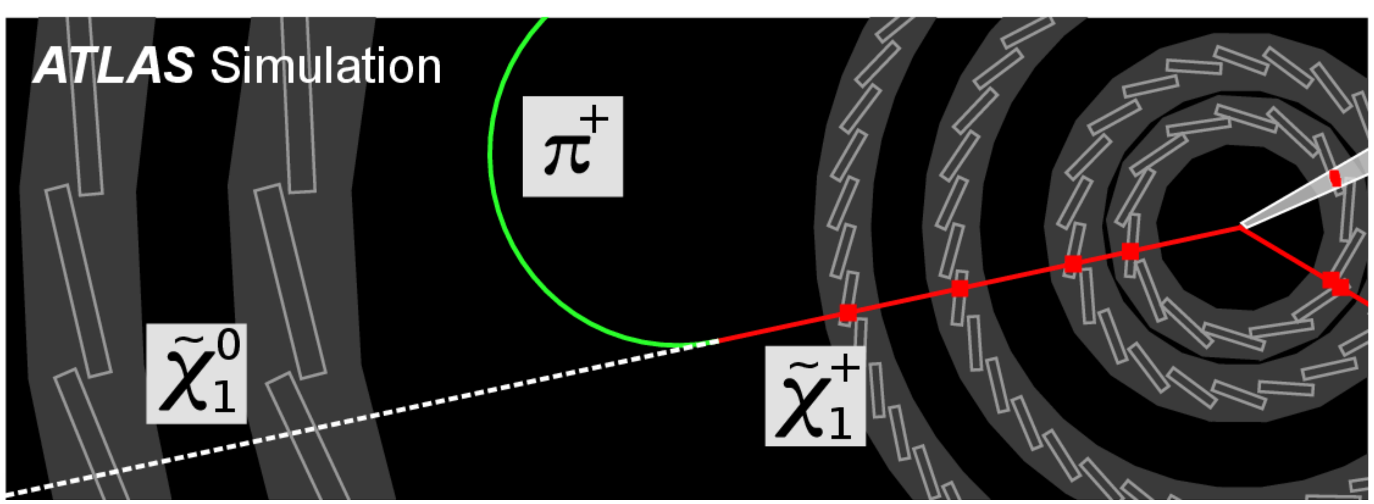
arXiv:1802.04097, arXiv:0706.4071, arXiv:1705.04843

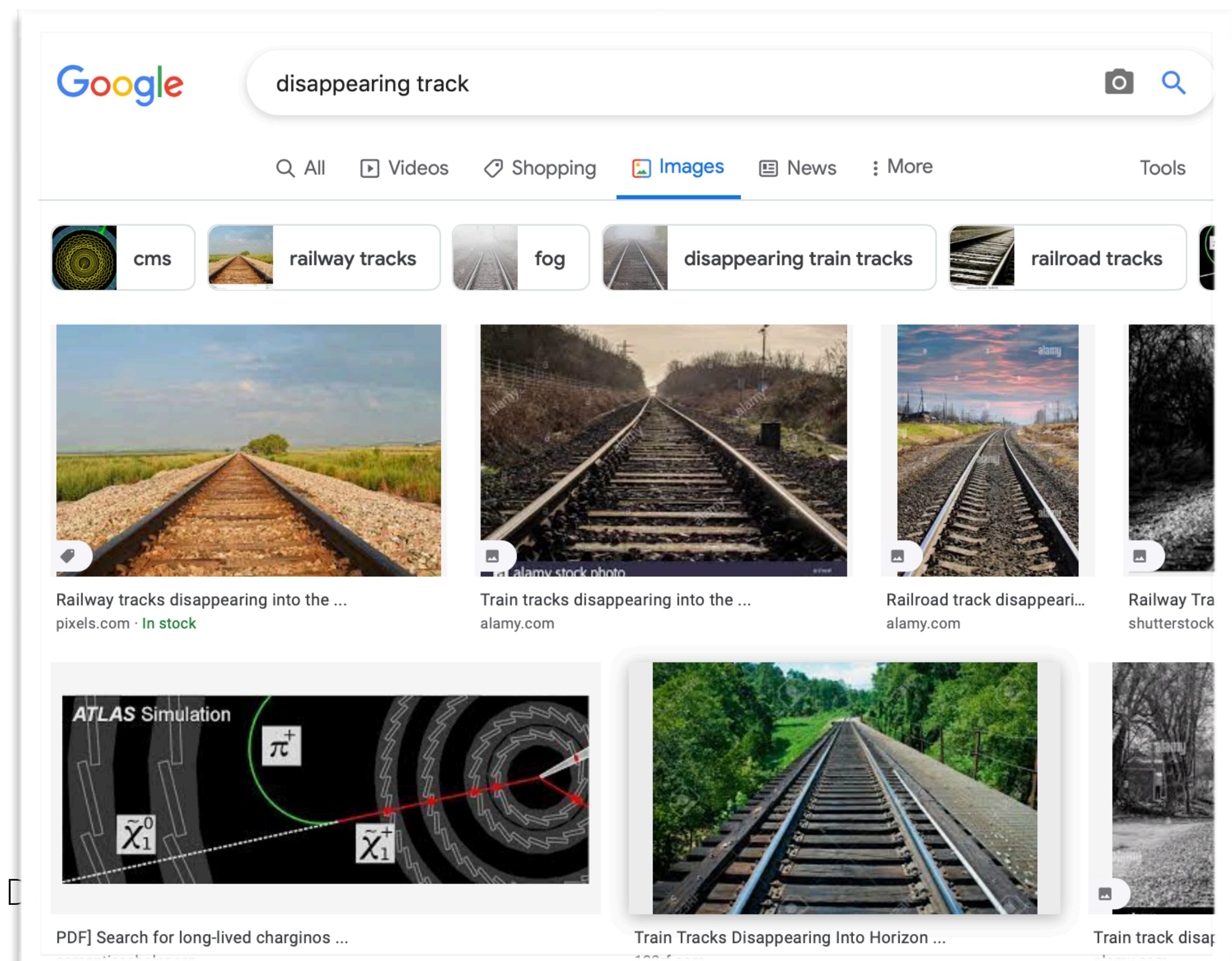
- R-parity conservation → Lightest SUSY particle is stable → **DM candidate** with WIMP characteristics



- Viable thermal relic WIMP candidate in SUSY terms: lightest neutralino = pure Wino/Higgsino
  - Also standalone model of "minimal DM"

- A possible signature: **disappearing track**

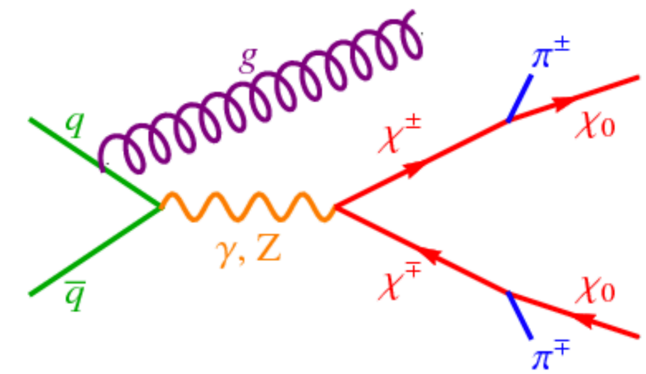




Wino and Higgsino DM: prospects

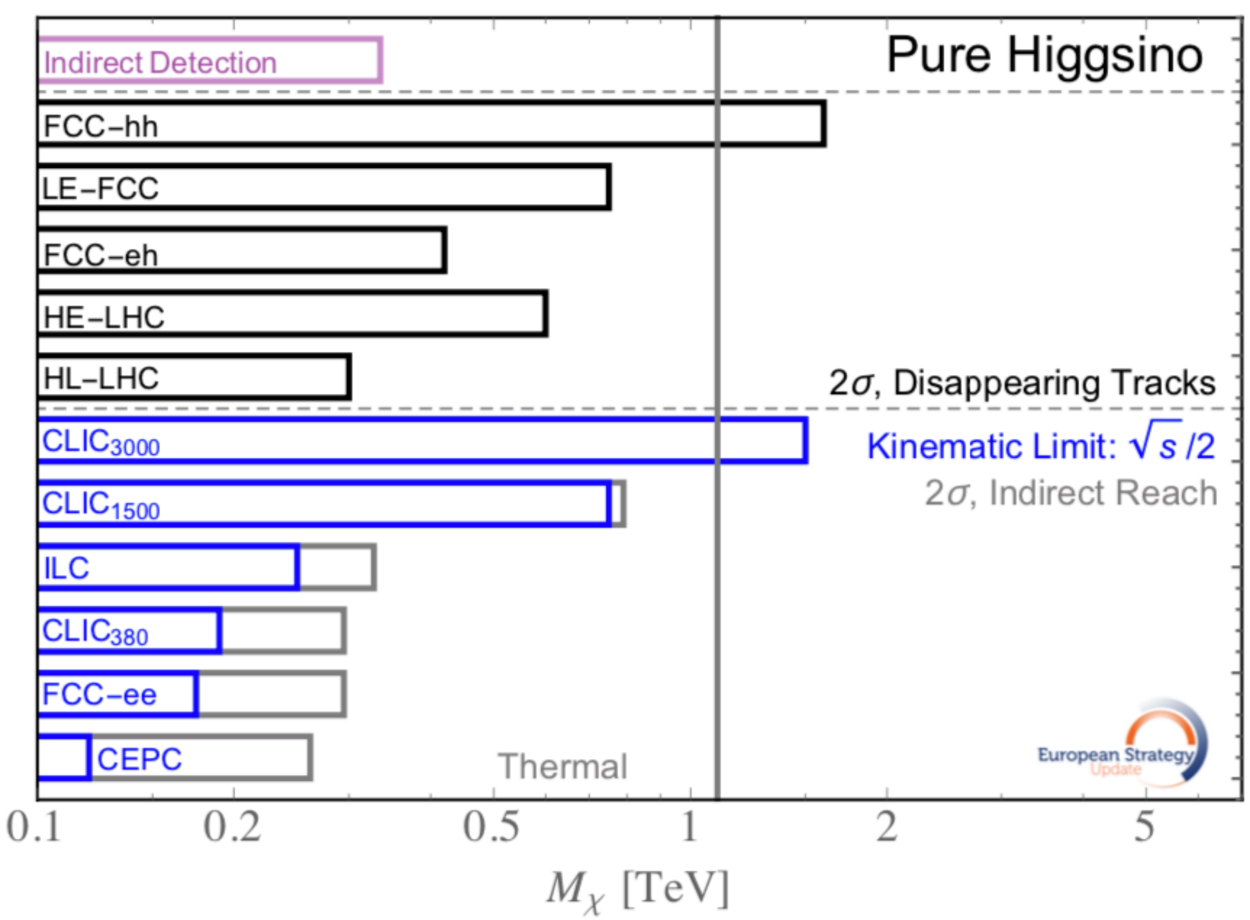
arXiv:1802.04097, arXiv:0706.4071, arXiv:1705.04843

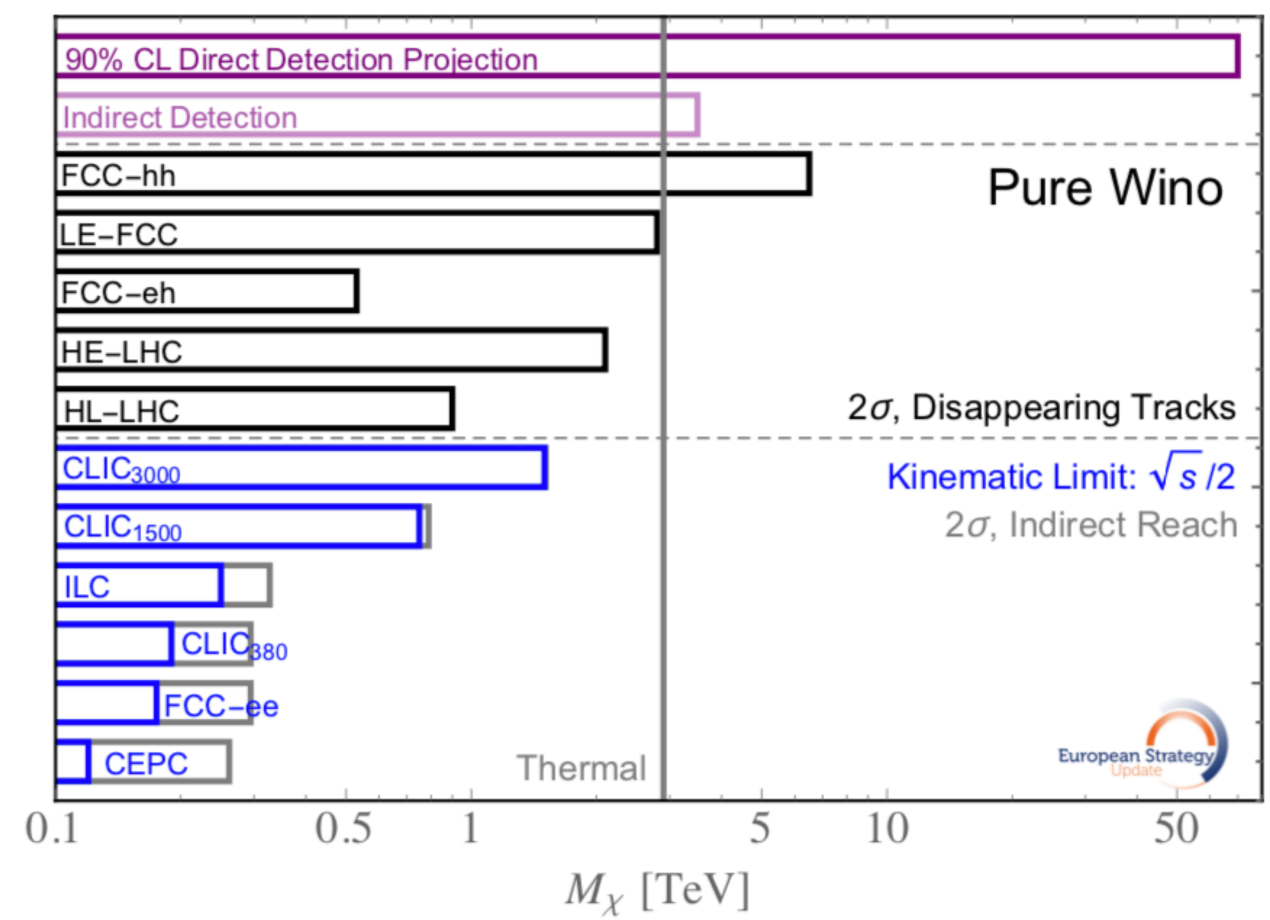
- Electroweakinos that can make up the relic density are heavy & rare: need **future colliders**



- 2019: Update of the European Strategy of Particle Physics, inputs from different future colliders

European Strategy Update Briefing Book





Recent (future?) news on Wino and Higgsino

SnowMass2021

Wino & Higgsino at muon colliders

EF10 Focus Topic #1: **WIMPs**

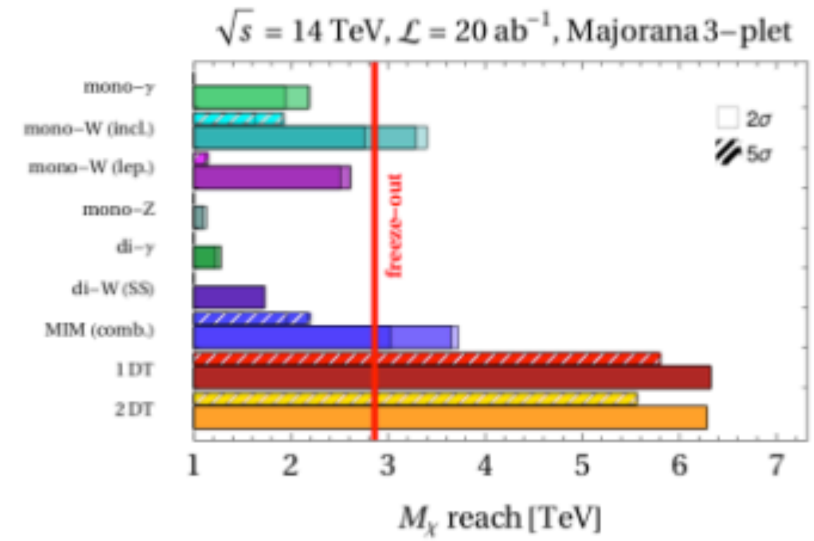
https://arxiv.org/abs/2107.09688

Speakers at EF10 Parallel Session H: Marco Costa, Jose Francisco Zurita talk link

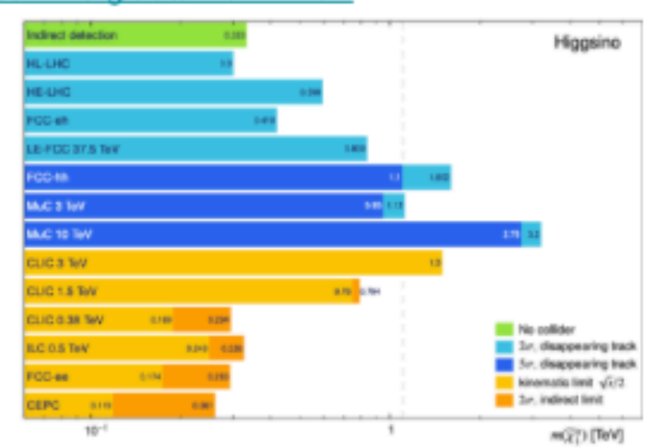
Considering **pure WIMP scenarios** where the EW interaction sets the relic (mass as a free parameter) and DM is the neutral component of a multiplet

Many different signatures for WIMPs @ muon colliders in new literature / recent workshops:

- Recoil against visible objects
- Resonances from the DM particle bound states, which can be excited as a resonance and decay into visible particles
- Disappearing tracks (DT)



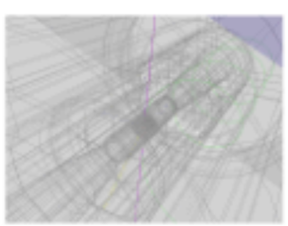
https://arxiv.org/abs/2102.11292



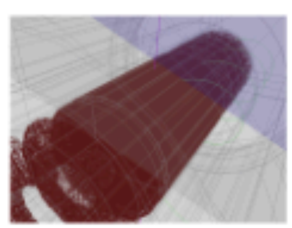
Results can be put into context of direct and indirect detection (esp. CTA projections)

"Lessons learned" from studies that can be brought back to AF:

- Beam background is significant at muon colliders



BIB off



BIB on

Credit: F. Meloni

Message for EF10 whitepaper: a muon collider is competitive with FCC-hh for thermal WIMP scenarios

Complementarity message: muon collider results can lead to joint WIMP discoveries with DD and ID

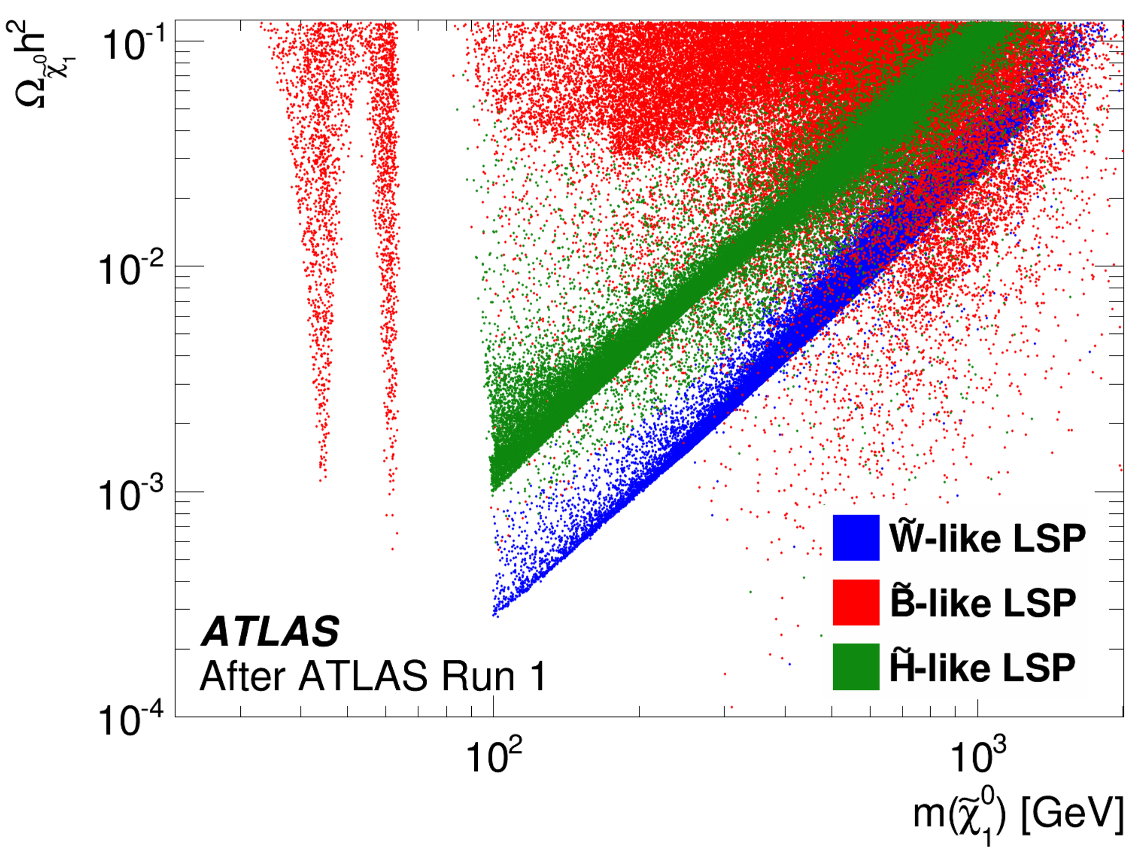
11

Caterina Doglioni & Liantao Wang - EF10 - 2021/03/09 Snowmass EF Restart Workshop

SUSY examples in DM context: scans & fits

Parameter scan of a SUSY model (point = set of SUSY parameters) plotted as a function of relic density and neutralino mass

JHEP09 (2016) 175

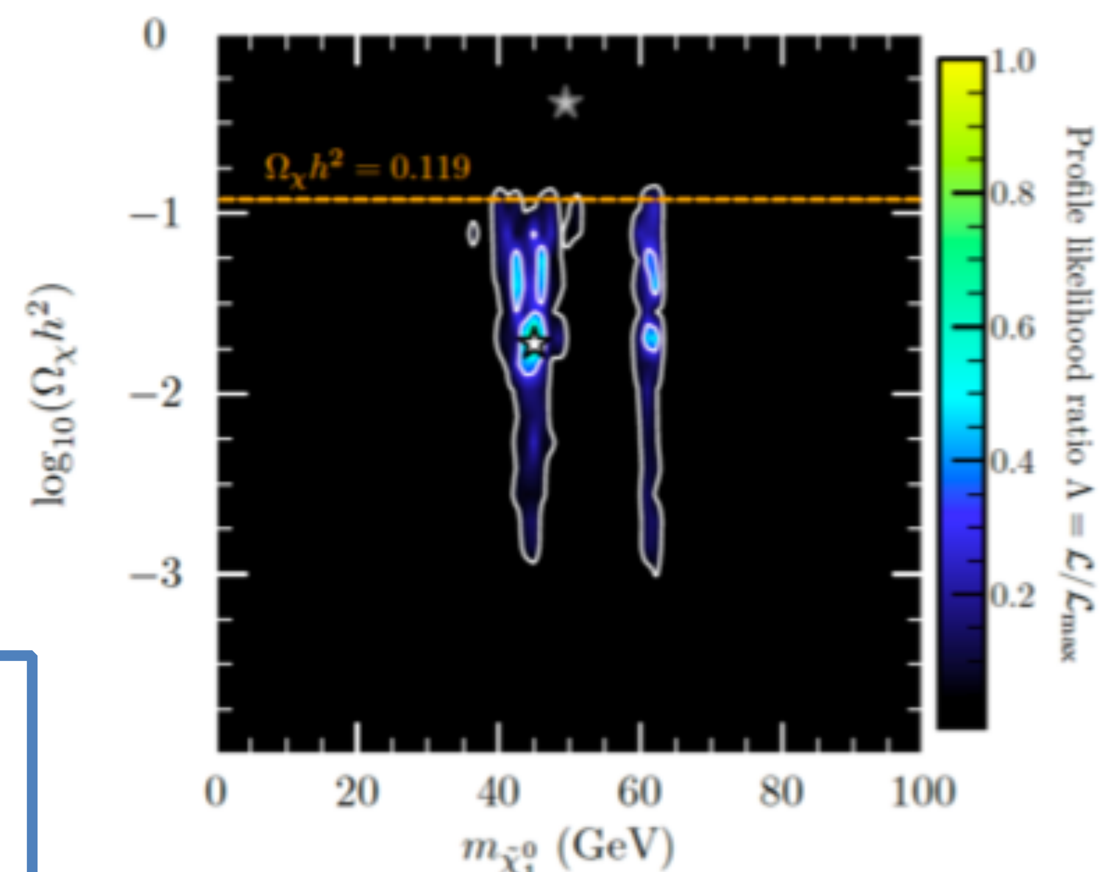


Global fits including a variety of constraints (e.g. GAMBIT)

$$\mathcal{L} = \mathcal{L}_{\text{collider}} \mathcal{L}_{\text{DM}} \mathcal{L}_{\text{flavor}} \mathcal{L}_{\text{EWPO}} \ldots$$

https://gambit.hepforge.org + Eur. Phys. J. C (2019) 79:395

Example: combined collider constraints on neutralinos and charginos



Many other SUSY DM searches @ LHC!

ATLAS SUSY results CMS SUSY results

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Higgs and Dark Matter

erc
European Research Council
Established by the European Commission

Back to basics: Higgs portal models

arXiv:1903.03616

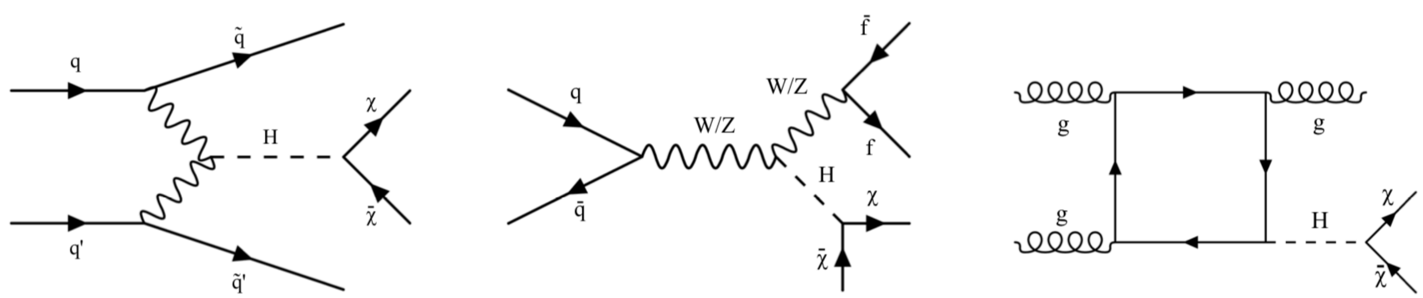
$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi\bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi\,.$$

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2\,,$$

Lambda for fermion EFT: assumed 1 TeV

- Only add the DM particle to SM
- One can test different kinds of dark matter (vector, scalar, fermion)

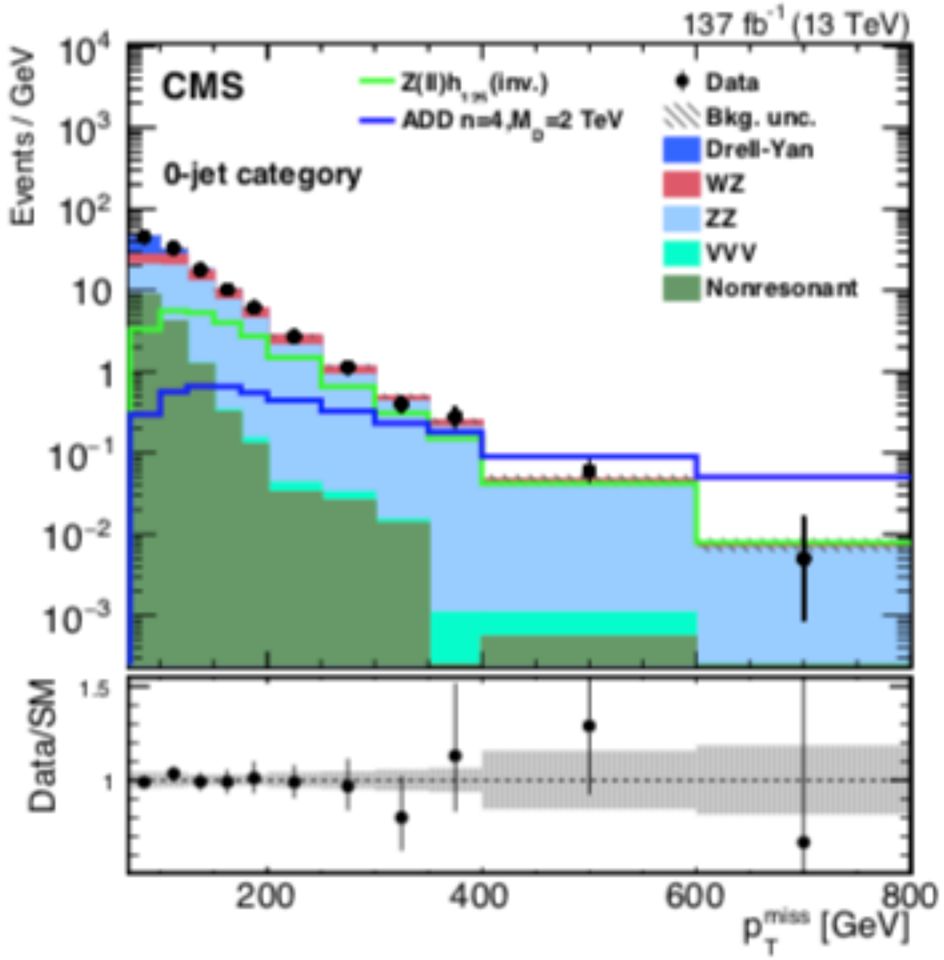
- How to detect invisibly decaying Higgs:
  - **directly** (Higgs decays to invisible particles, we see an excess)



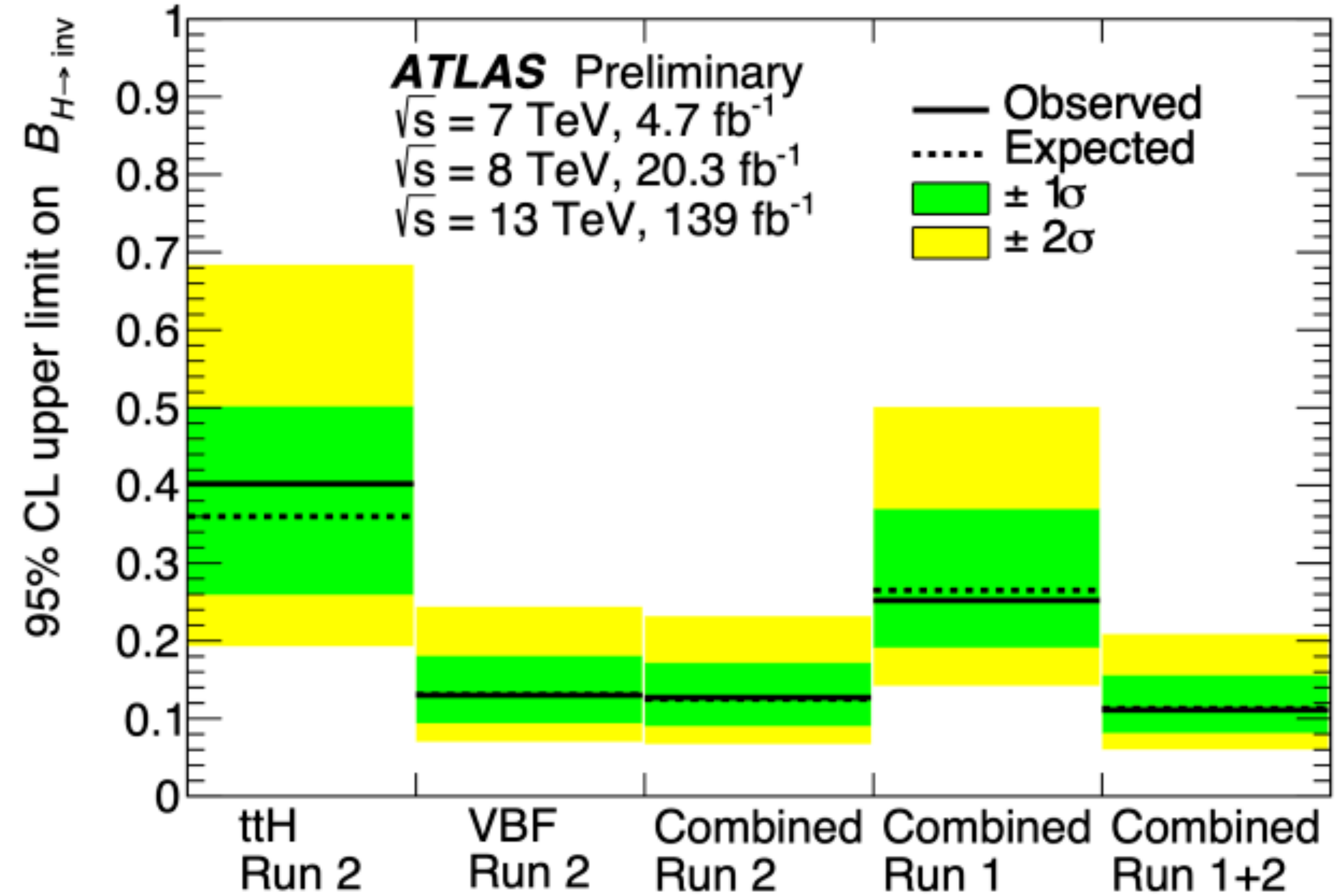
  - **indirectly** (deviation of SM coupling through fits, using κ-framework)
    - including only σ x Branching Ratio (BR) measurements/ratios, no high-pT Higgs keeping SM BR fixed, only allow invisible BR to float in the fit (subtracting SM)

Higgs portal DM results with LHC data

EPJC 81 (2021) 13



ATLAS-CONF-2020-052



LHC sensitive to a Higgs to invisible BR of ~0.1

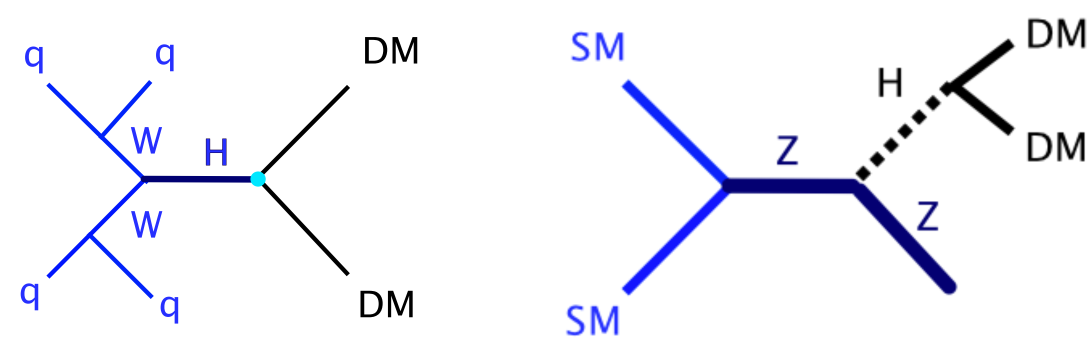
(SM value: invisible BR ~ 10^{-3}, reachable by future colliders)

https://atlas.cern/updates/briefing/higgs-boson-search-dark-matter

European Research Council
The University of Manchester

Higgs portal: future constraints

Higgs to invisible constraints
interpreted as **Higgs Portal** models

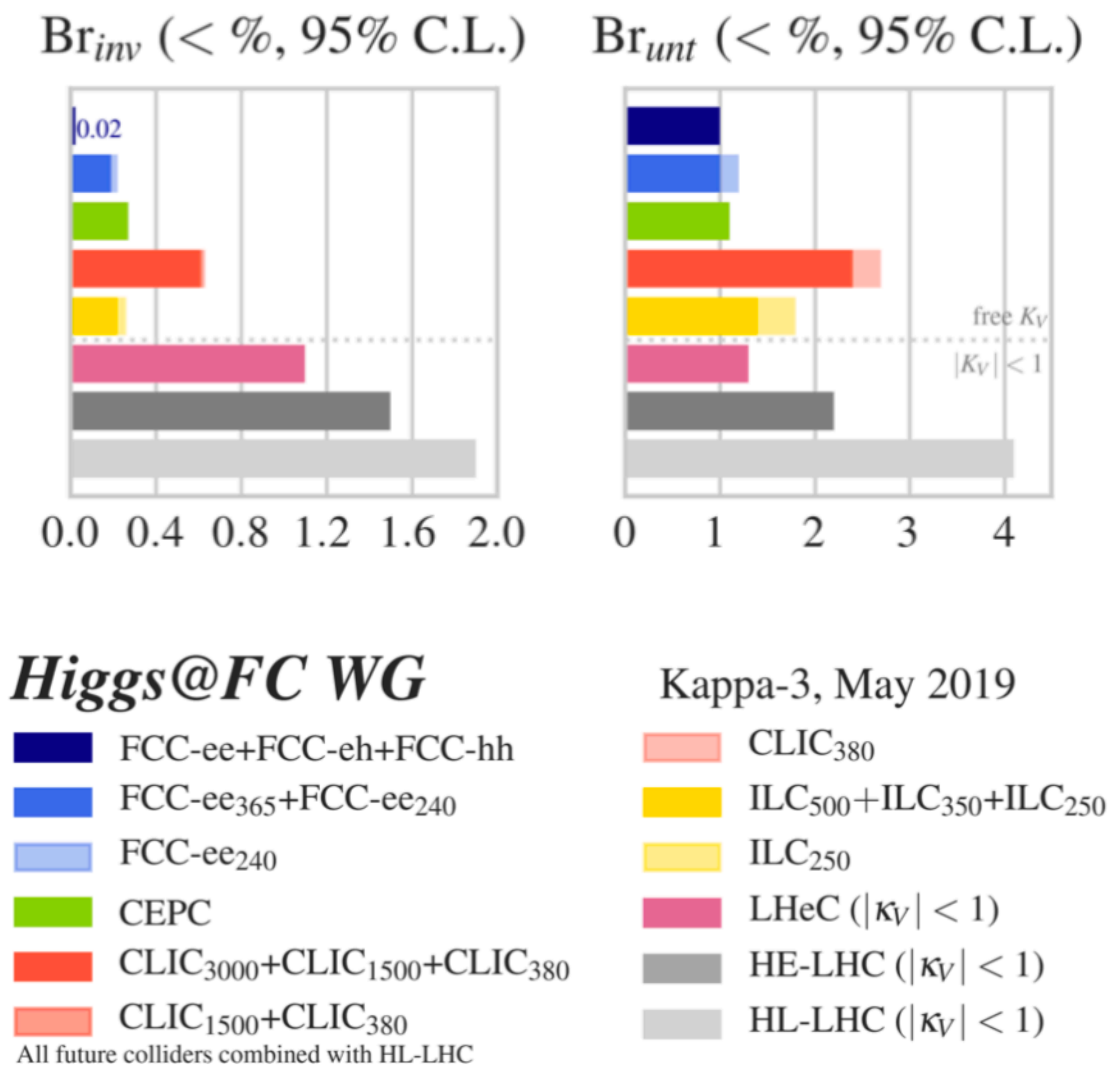


arXiv:1905.03764

Collider	95% CL upper bound on BR_{inv} [%]		
	Direct searches	kappa-3 fit	Fit to BR_{inv} only
HL-LHC	2.6	1.9	1.9
HL-LHC & HE-LHC		1.5	1.5
FCC-hh	0.025	0.024	0.024
HL-LHC & LHeC	2.3	1.1	1.1
CEPC	0.3	0.27	0.26
$FCC\text{-}ee_{240}$	0.3	0.22	0.22
$FCC\text{-}ee_{365}$		0.19	0.19
ILC_{250}	0.3	0.26	0.25
ILC_{500}		0.22	0.22
$CLIC_{380}$	0.69	0.63	0.60
$CLIC_{1500}$		0.62	0.41
$CLIC_{3000}$		0.61	0.30

LHeC	5.5 (2-sigma, no syst.)
HE-LHeC	3.4 (2-sigma, no syst.)
FCC-eh	1.7 (2-sigma, no syst.)

arXiv:1903.03616



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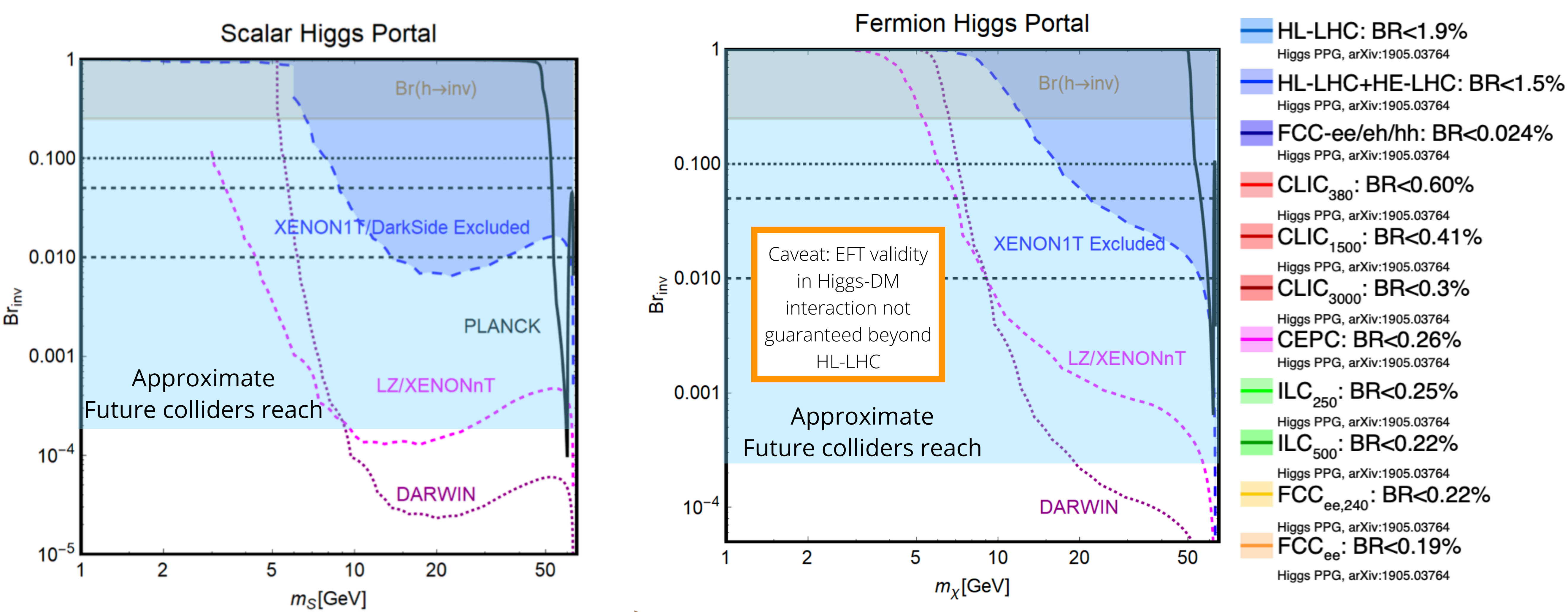
Higgs portal in DM context: relic density

- Very simple model, so careful with taking relic density at face value
- If Higgs portal is to make up 100% of DM, can exclude using colliders + other experiments (see tomorrow's lecture on complementarity)

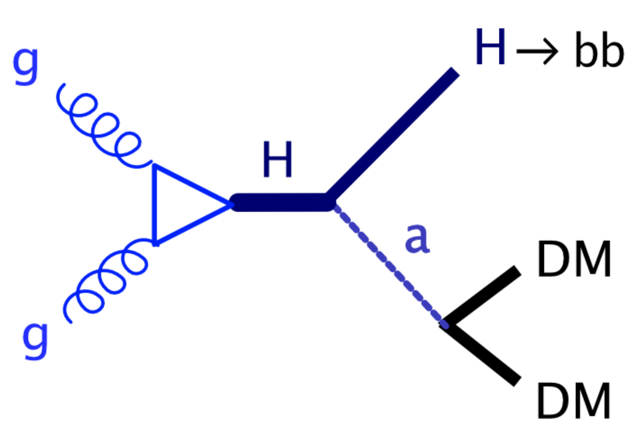


arXiv:1903.03616

More complex models: pseudo/scalars in 2HDM

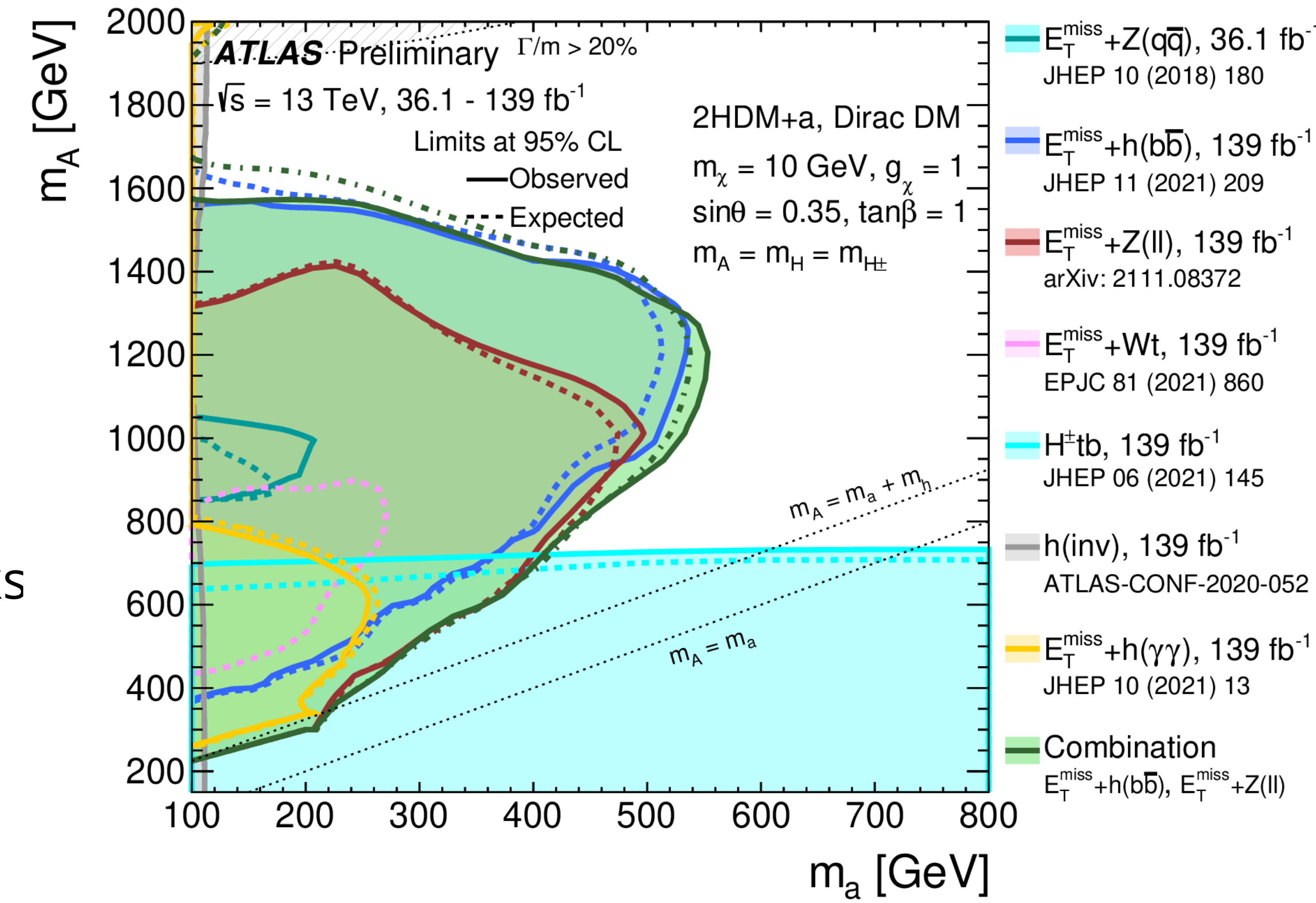
Compelling searches with increase of LHC dataset involve **new particles interacting with DM**, alongside **Higgs boson**

Example: pseudoscalar interacting with DM in a Two (2)-Higgs Doublet Model (H & A bosons)



LHC Dark Matter Working Group
https://arxiv.org/abs/1810.09420

ATL-PHYS-PUB-2021-045/



E.g. above search for MET + two b-quarks
ATLAS / CMS
No excess observed yet

LHC dataset sufficient to start being sensitive to this kind of processes, **Run-3 dataset needed** for more

81

Take-home points #5 and #6:

The Higgs is a very good (known) mediator between the SM and the DM particle sector

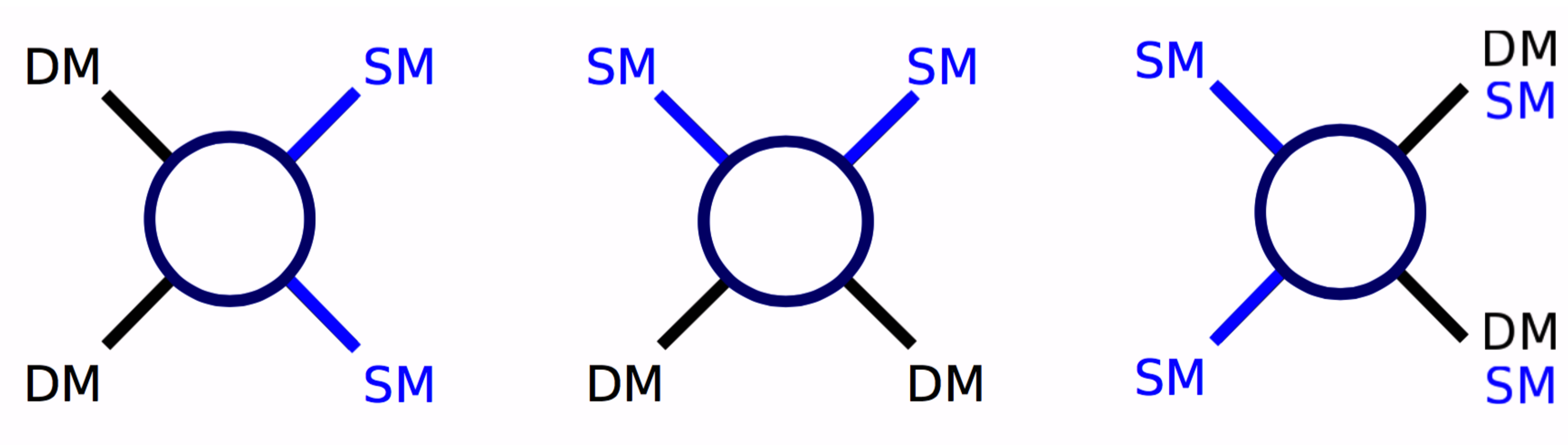
SUSY provides a very good DM candidate in the form of the Lightest Supersymmetric Particle (LSP)

Complementarity between collider searches and other experiments

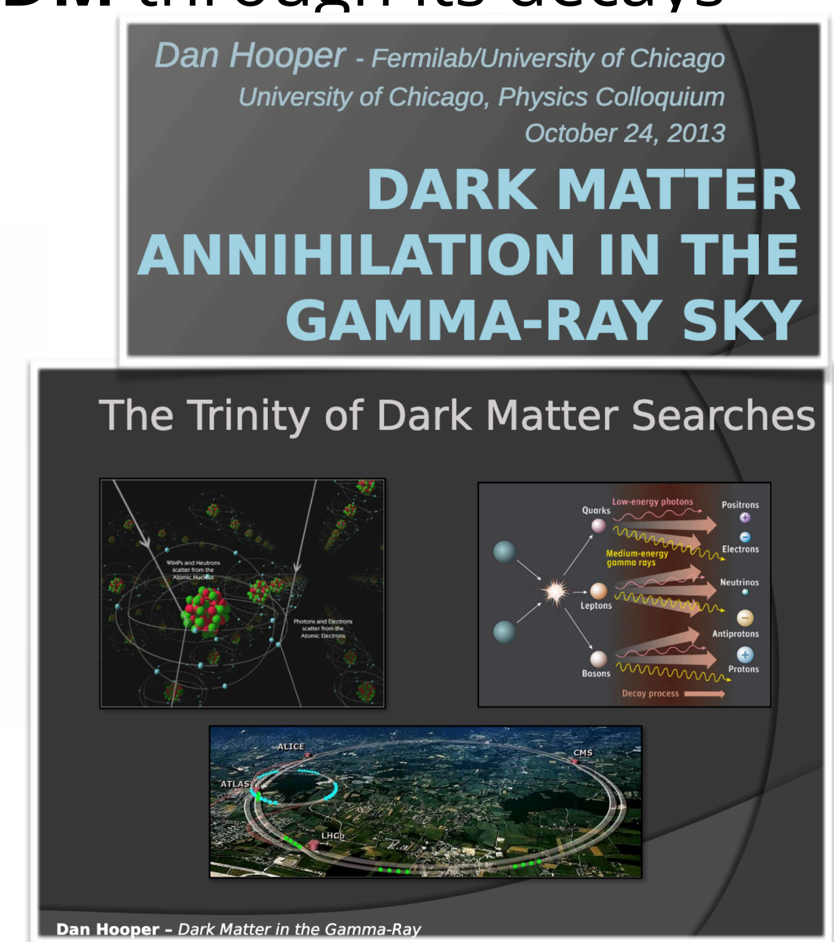
Controversial: why colliders can't discover every/any kind of DM alone

- **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!

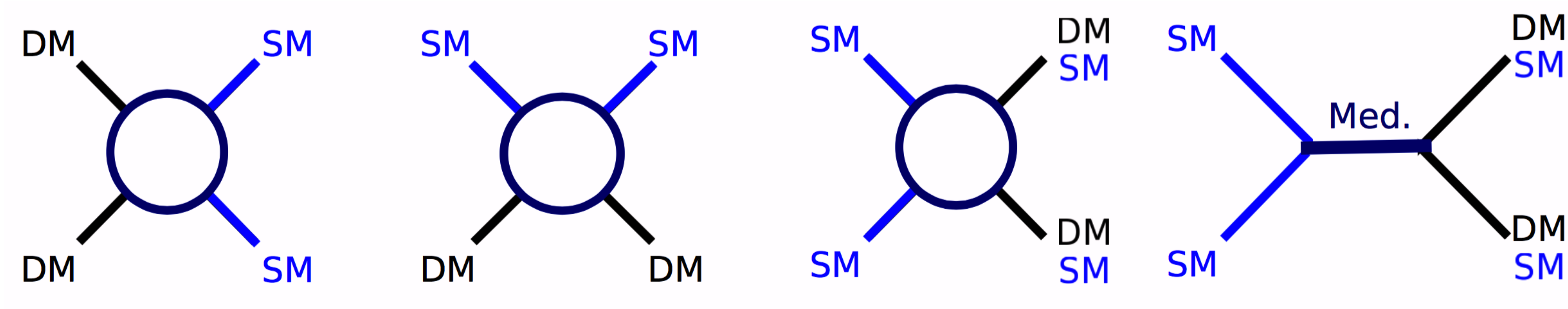


Indirect Detection Direct Detection Colliders



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

- **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**

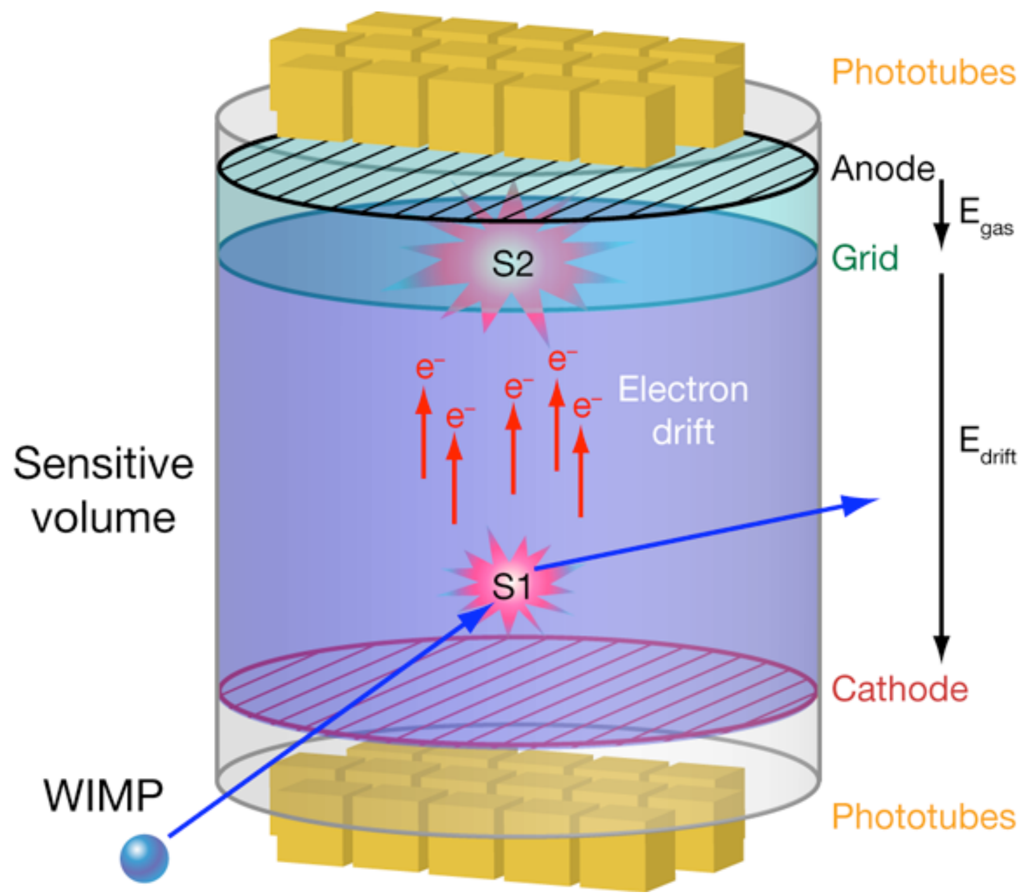


Indirect Detection Direct Detection Particle Accelerators (colliders & extracted beam lines)

Direct detection experiments: examples

XENON/LZ

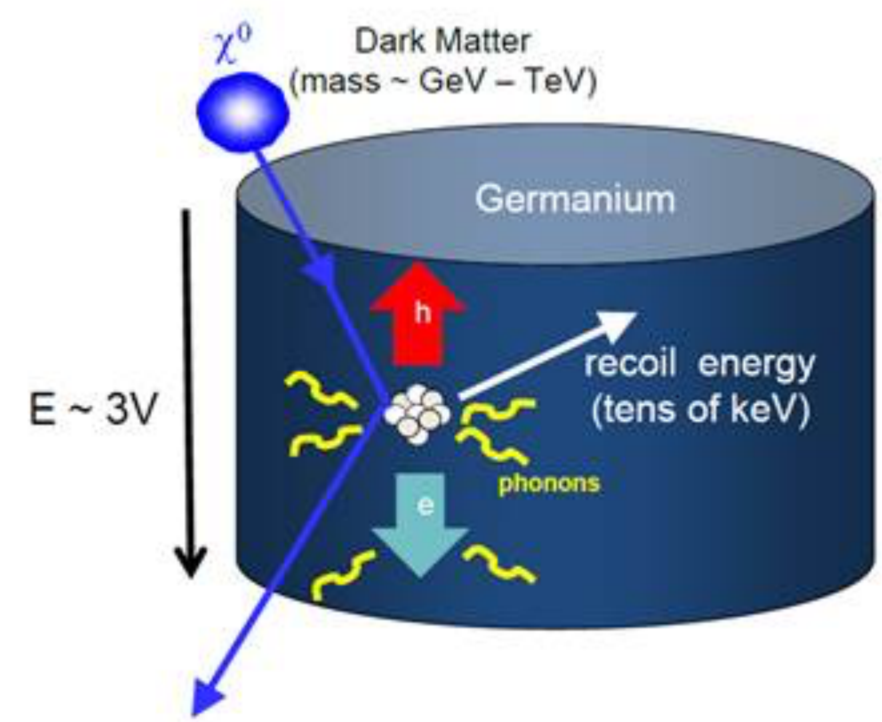
Large volumes (order: meters)



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

CDMS

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



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

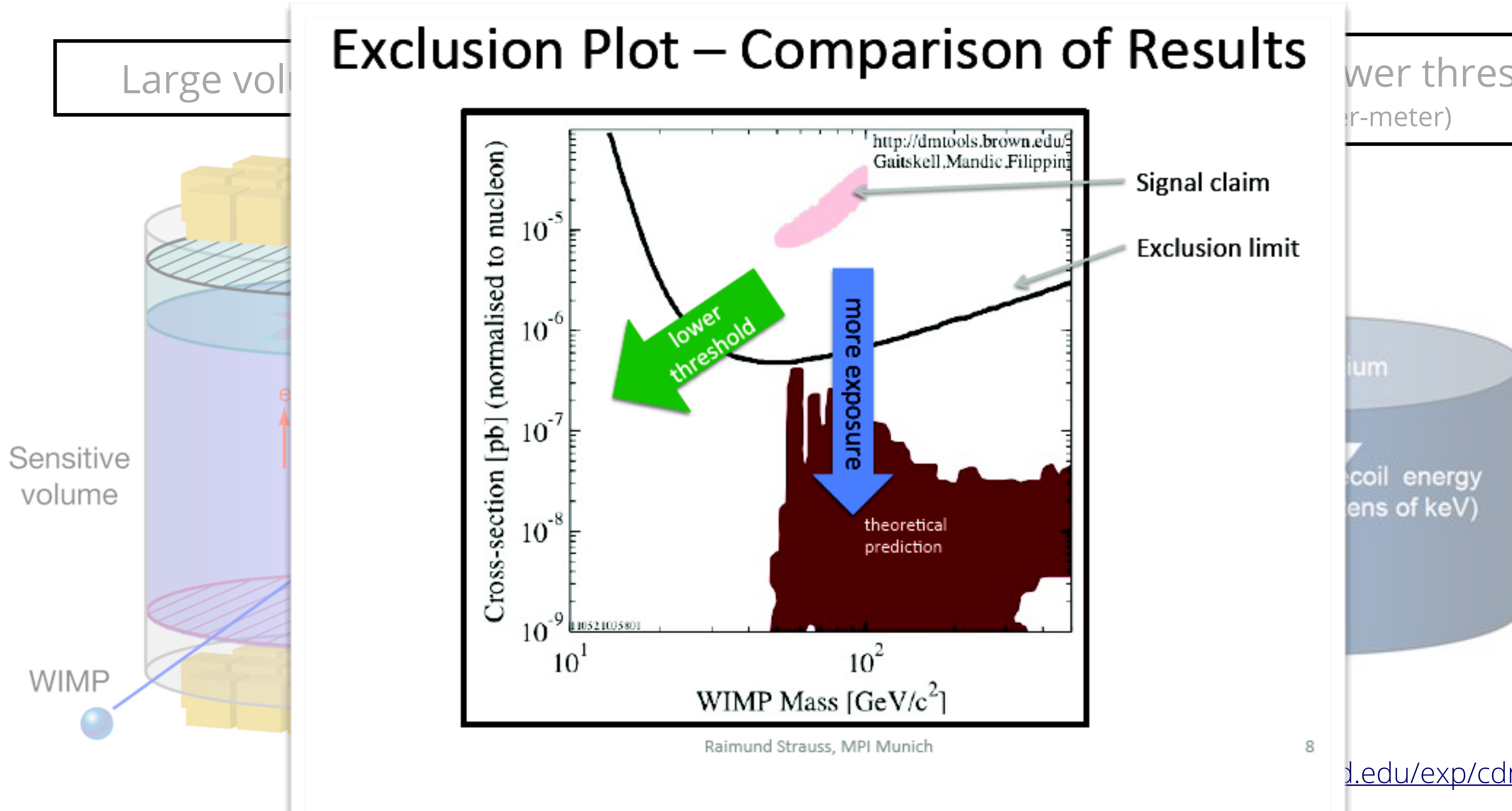
XENON/LZ

CDMS

Large vol

wer threshold

r-meter)



l.edu/exp/cdms/

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

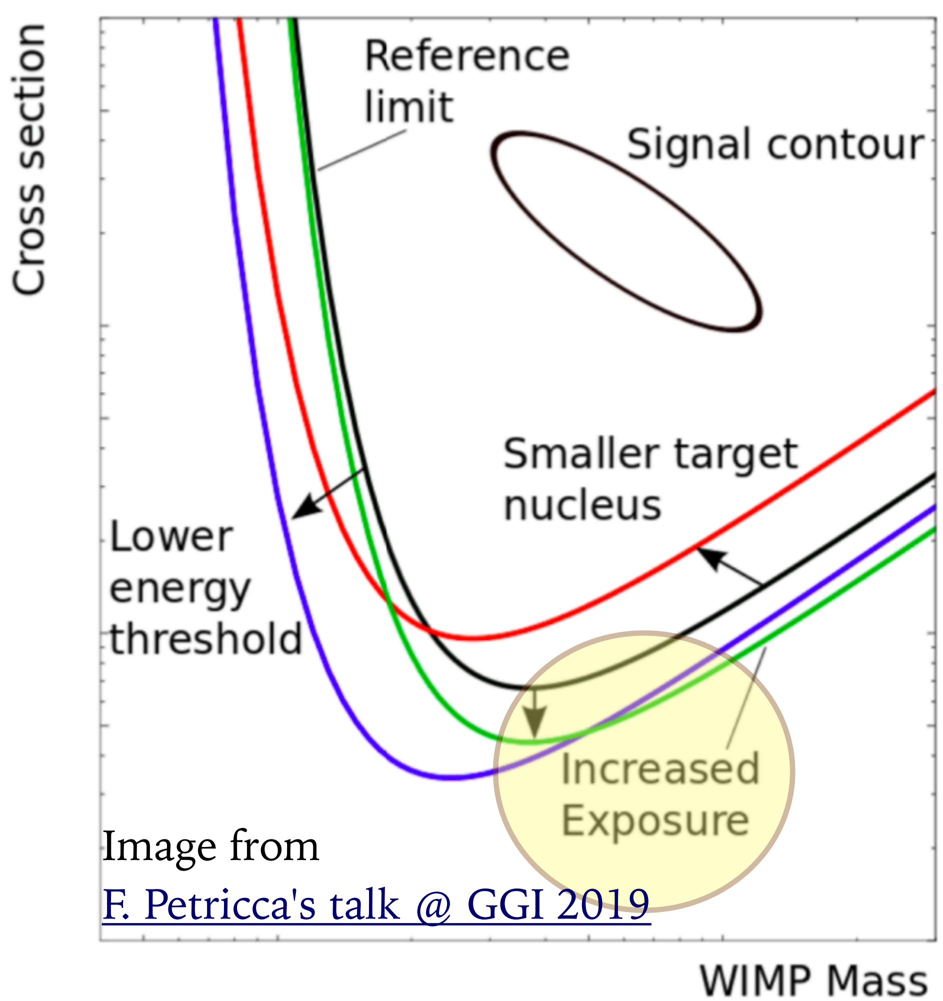
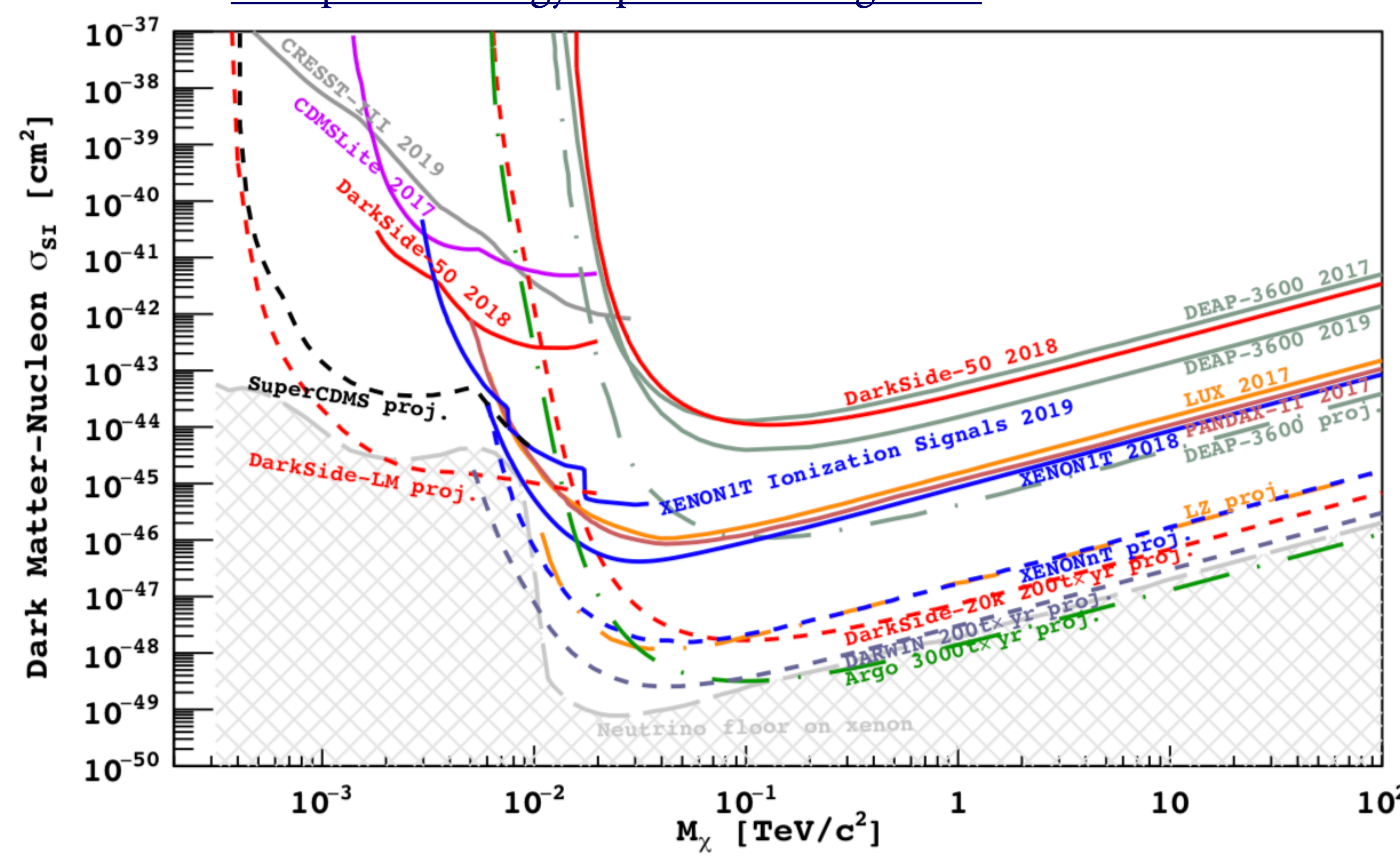


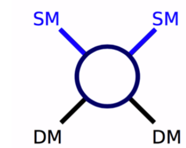
Image from
F. Petricca's talk @ GGI 2019

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

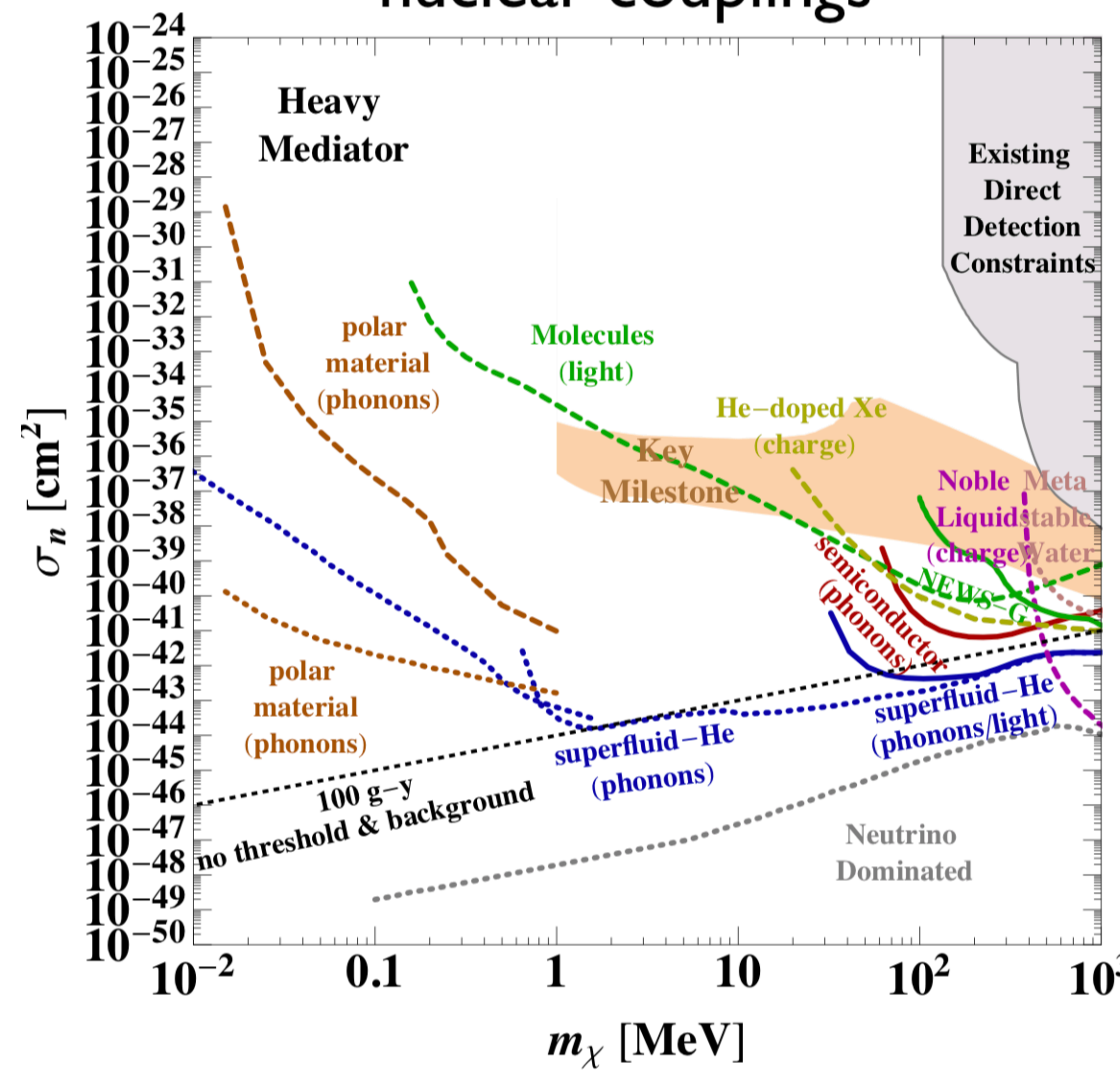


"Traditional" DM-SM recoil direct detection searches lose sensitivity to low-DM masses, but…

- 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**

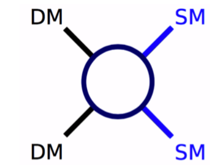
E.g. arXiv:1709.07882, CPM Session #77

nuclear couplings



BRN Report

Indirect Detection experiments: examples



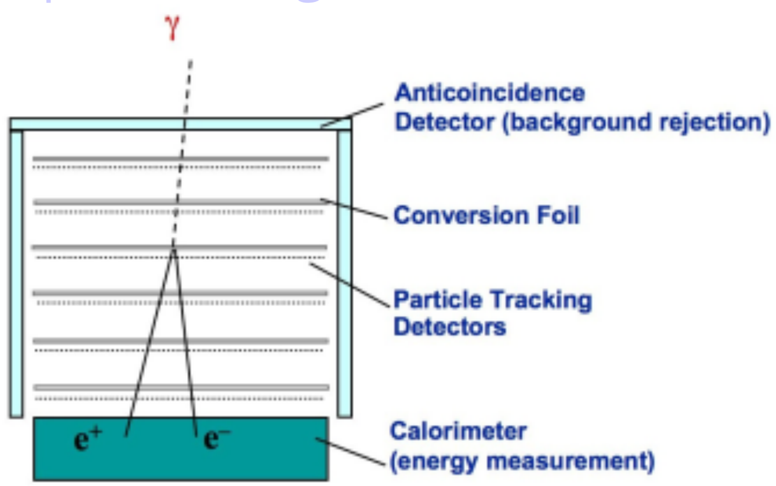
Dark Matter annihilates in the GC / dwarf galaxies (a place) to photons (some particles), which are detected by Fermi, HESS, ... (an experiment).

where to find DM:
galaxy surveys SnowMass2021 CF3
(e.g. LSST, SKA,...)

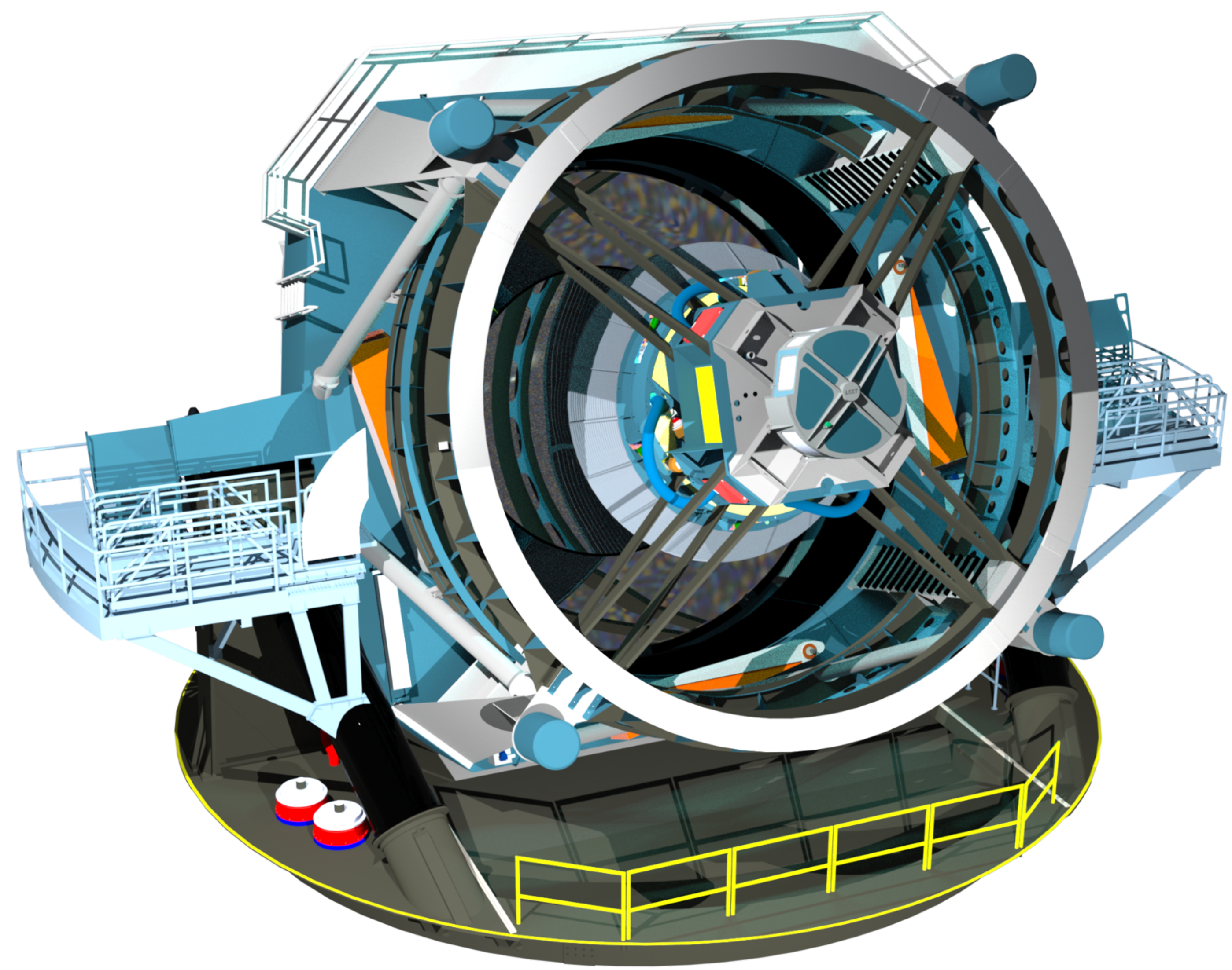
(also able to probe properties of DM & test DM models)

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

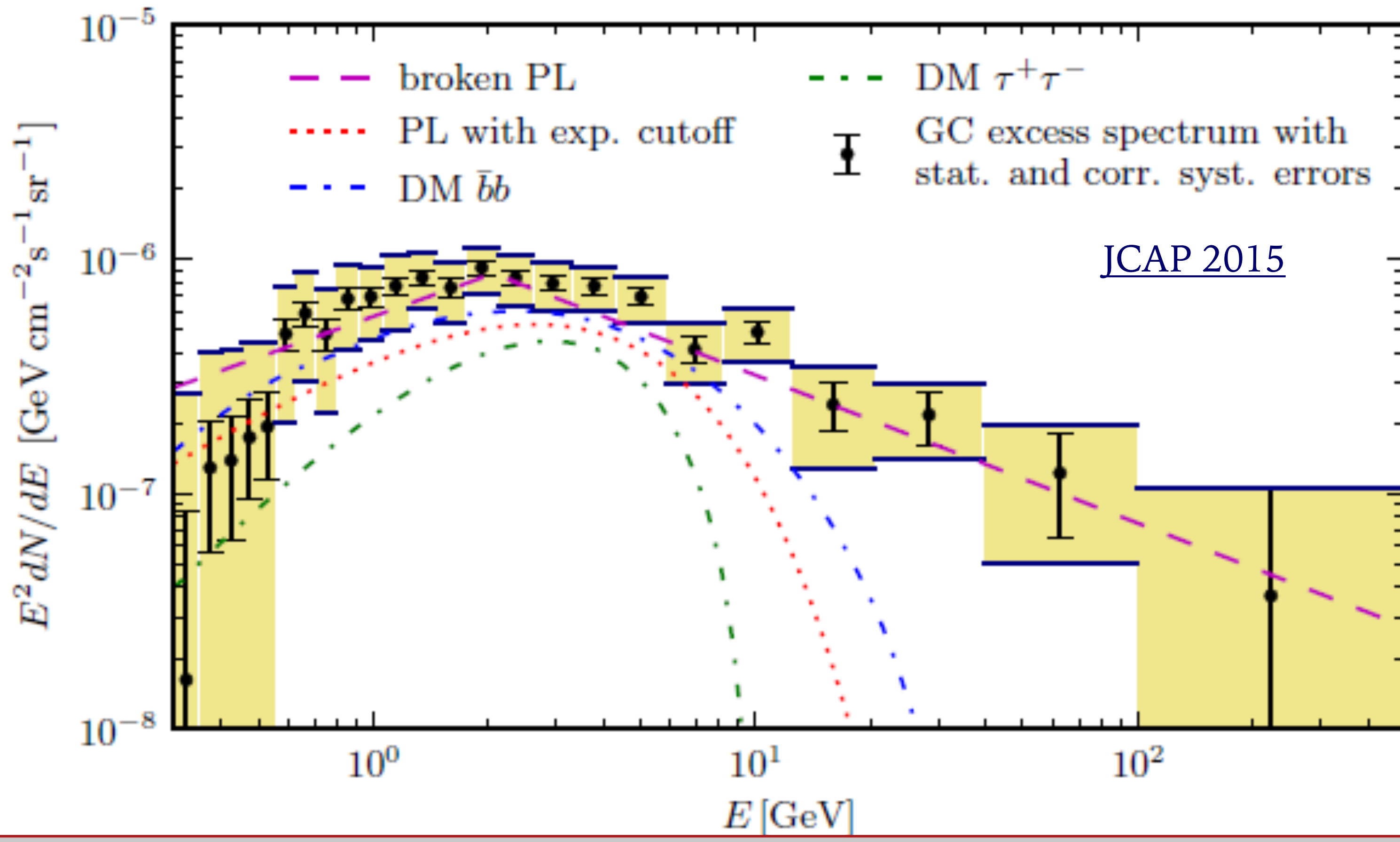
Fermi Large Area Telescope
https://www-glast.stanford.edu/



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!**

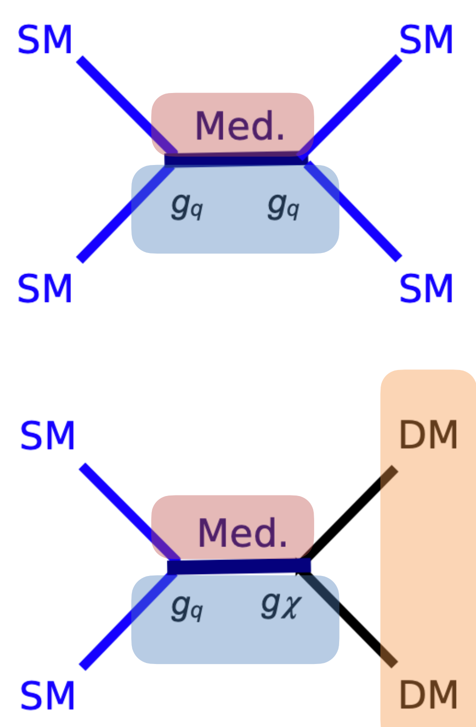
A "global" view of WIMP dark matter

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

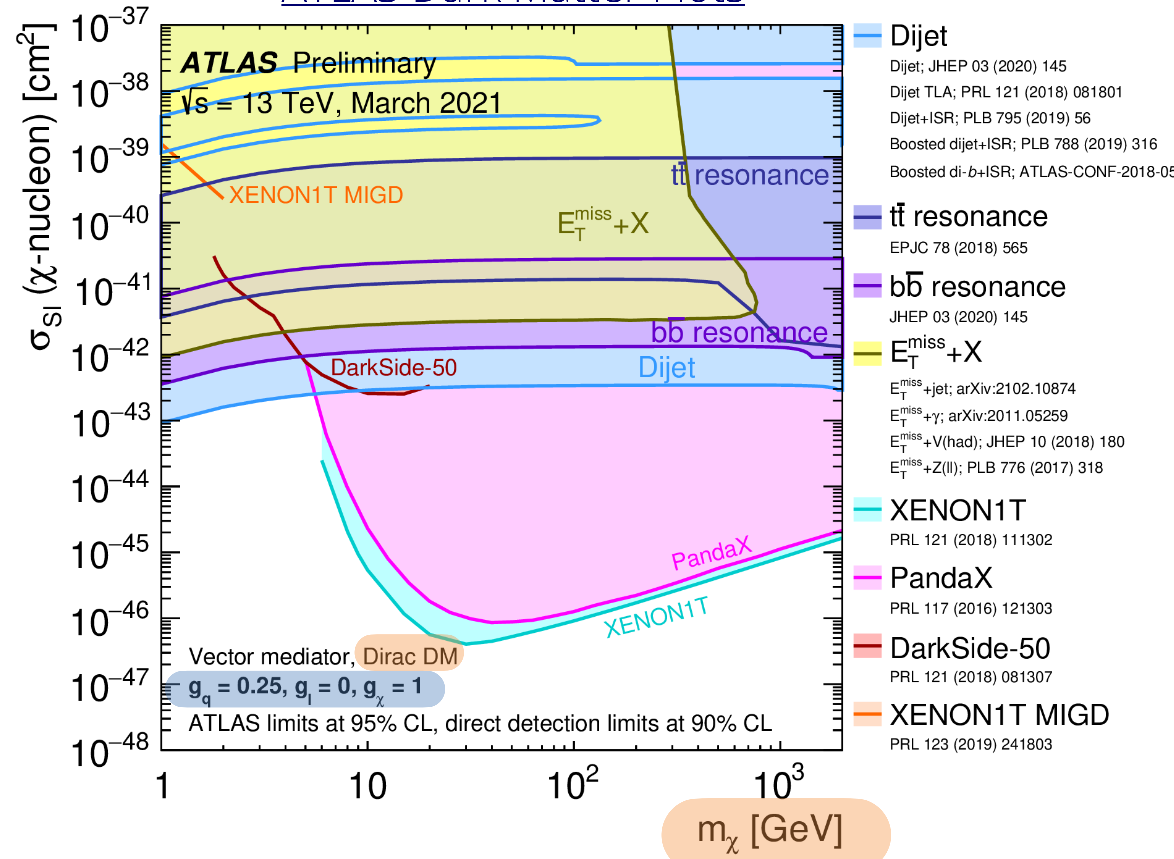
European Strategy Update "Big Question"

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

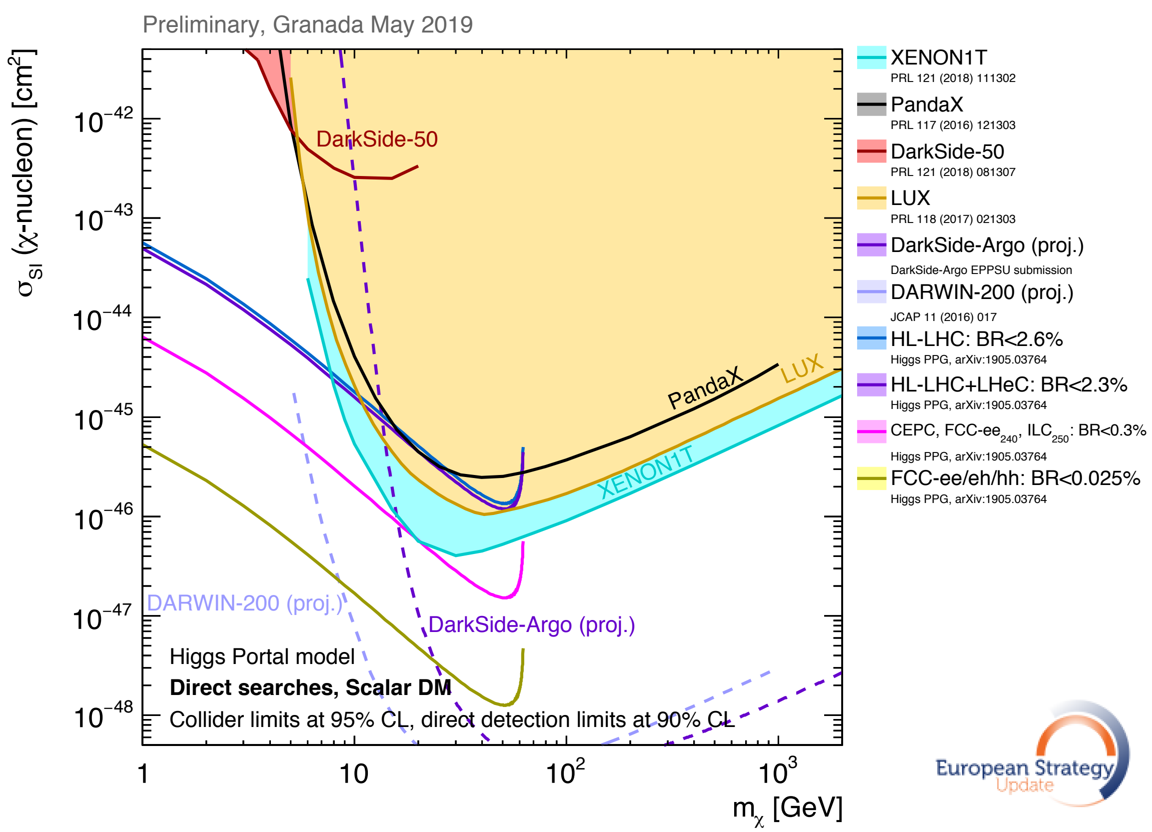


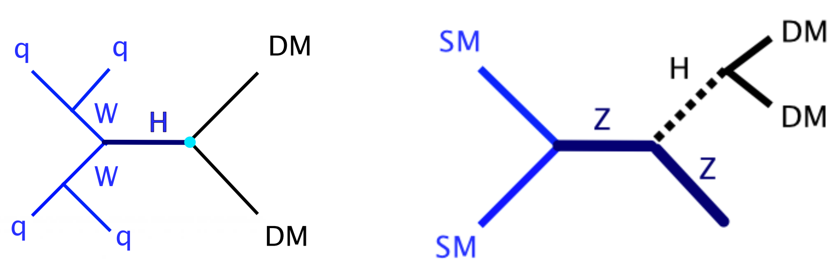
Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**

Complementarity so far: within WIMP frameworks

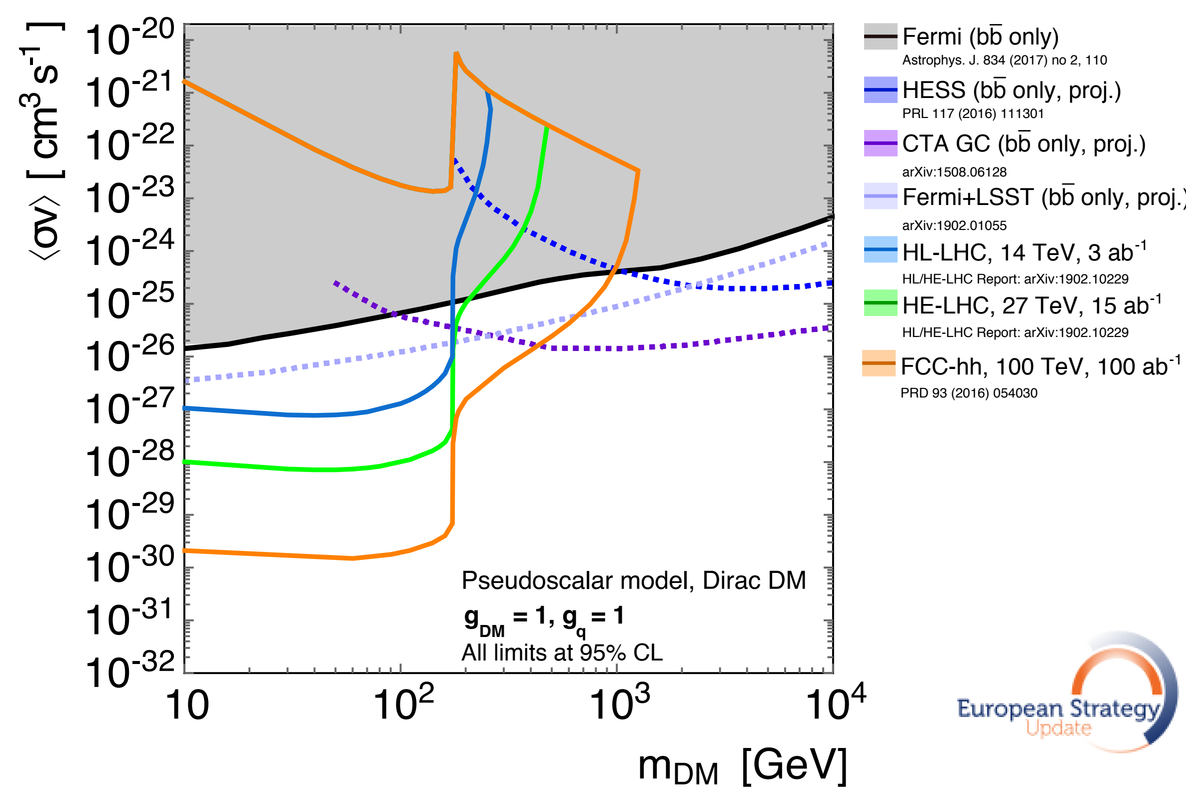
LHC DM Working Group, European Strategy Update Briefing Book, for non-WIMP examples, see Physics Beyond Colliders report

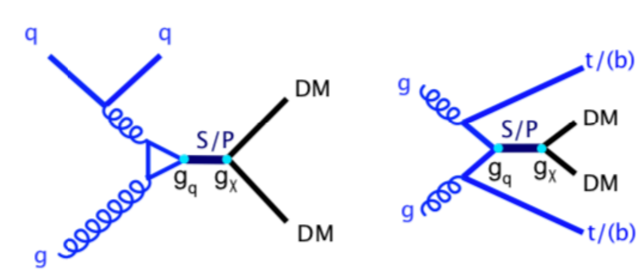
Higgs portal @ colliders and direct detection





Scalar mediators and indirect detection





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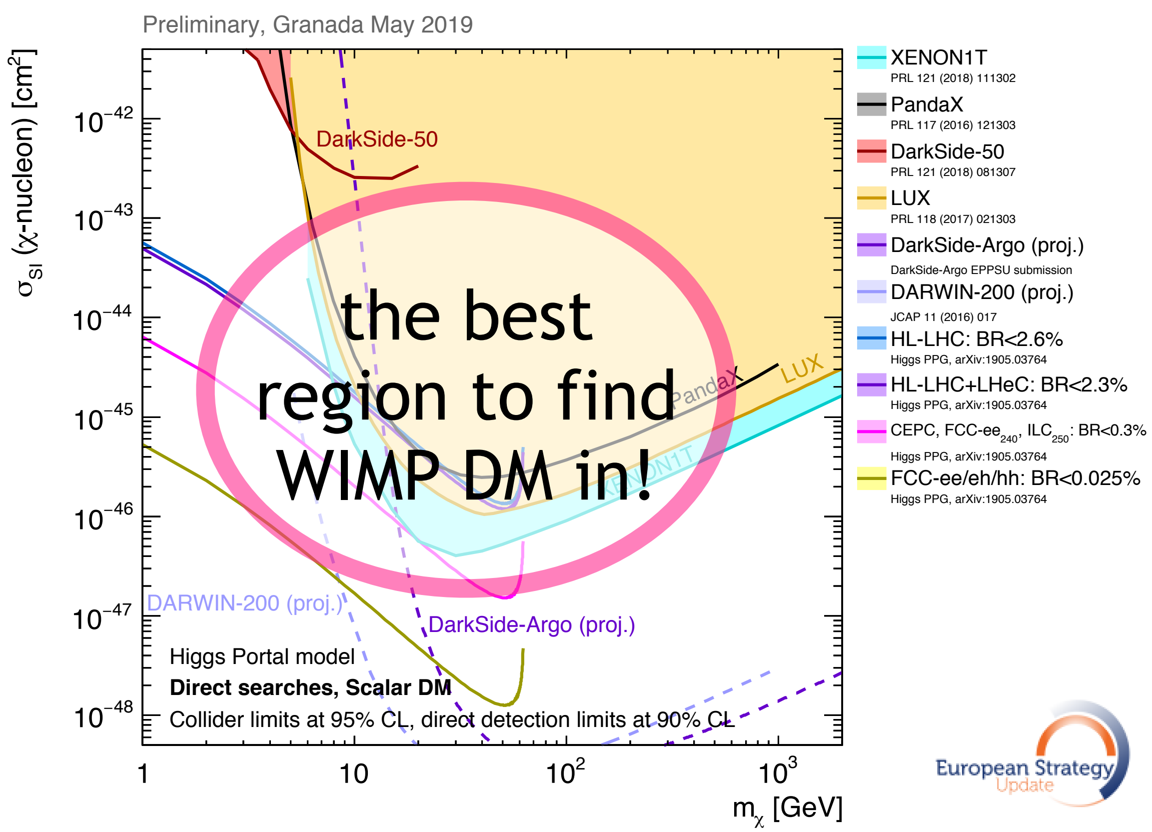
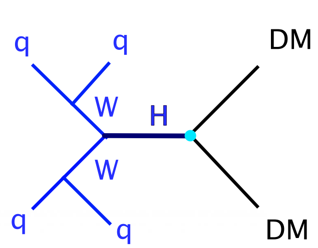
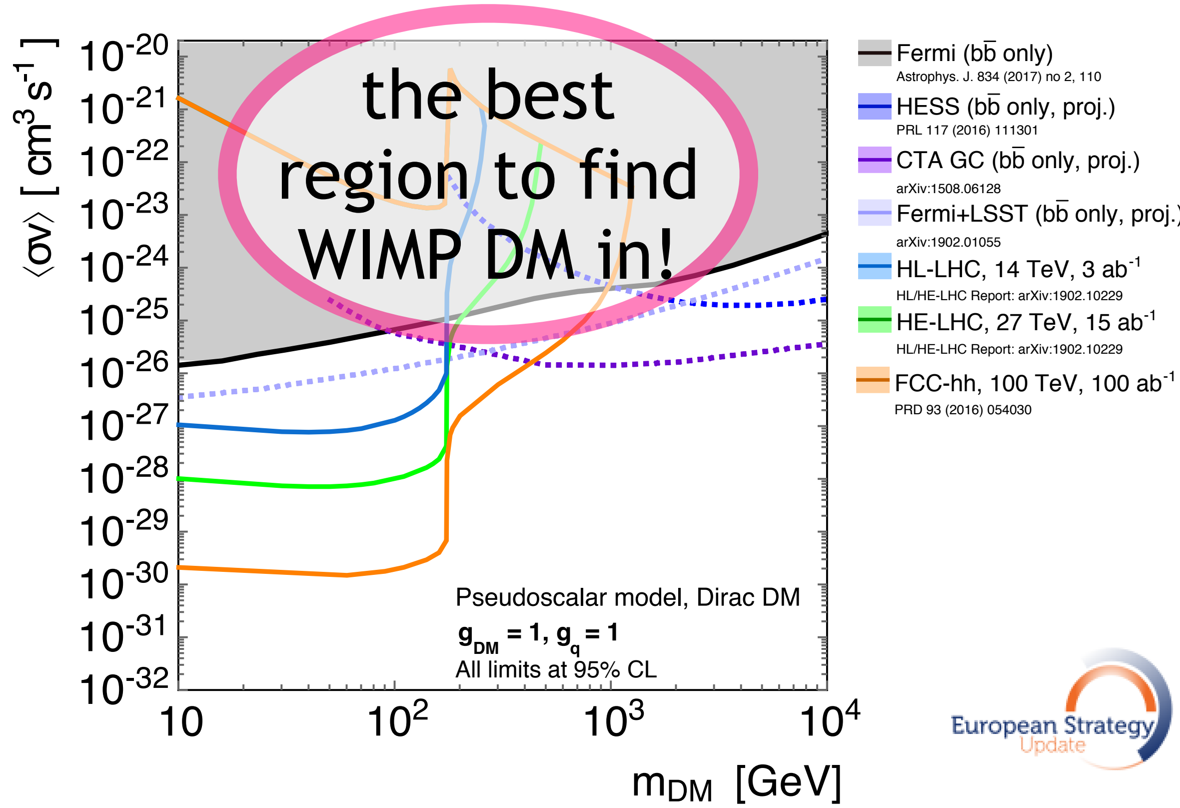
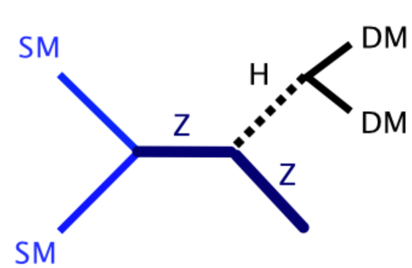




Scalar mediators and indirect detection





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"

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Take-home point #7:

The ideal WIMP DM discovery includes simultaneous observations in

Direct and Indirect Detection

(detection from astrophysical phenomena: cosmological connection)

+ invisible particle found @ collider

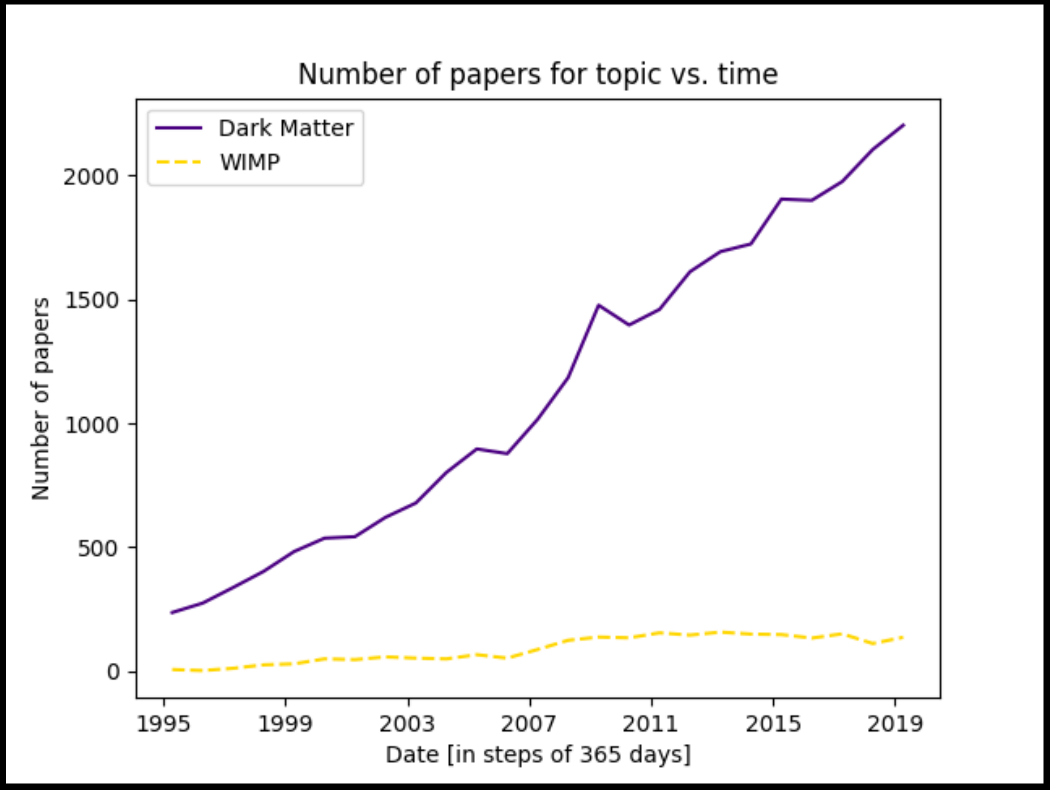
(creation in controlled condition: understanding nature of interaction)

…are we looking everywhere?

up: stronger interactions

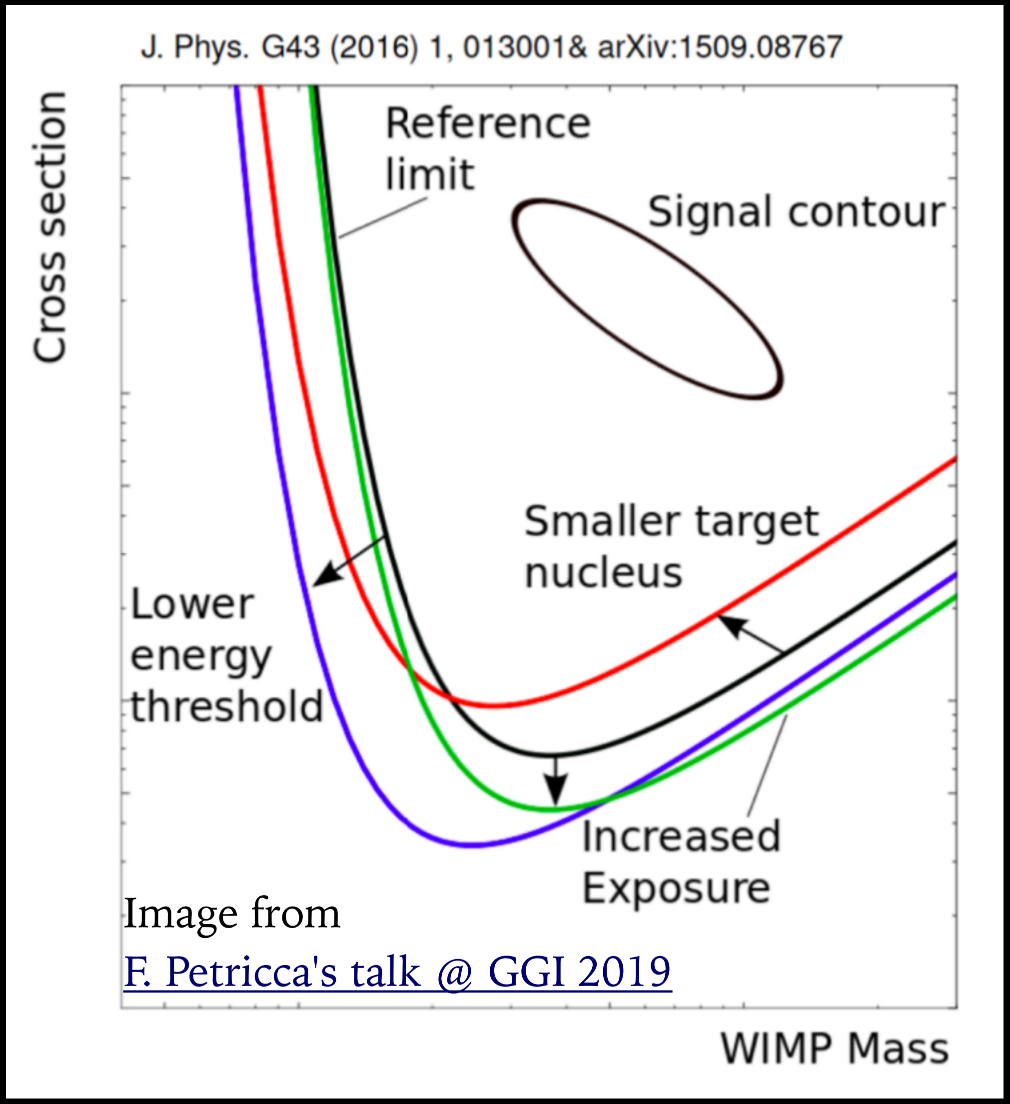
left: much lighter DM

right: more massive objects



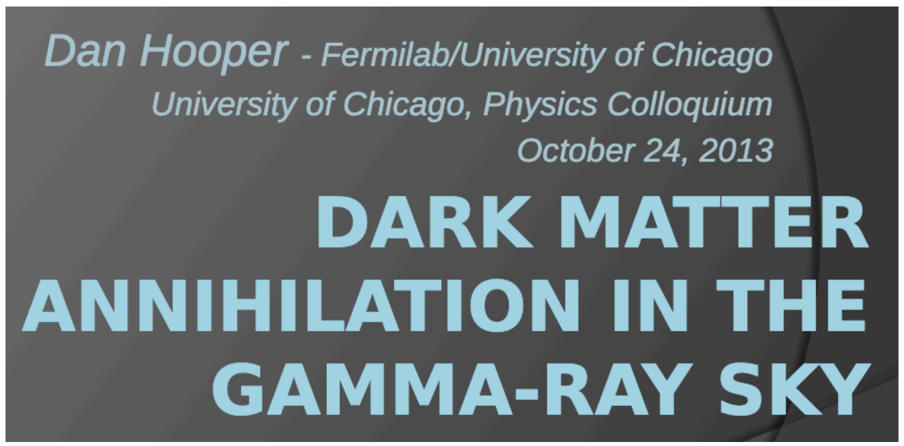
What might we learn from lines of research that are off the beaten track? They check accepted ideas, always a Good Thing, and there is the chance Nature has prepared yet another surprise for us.

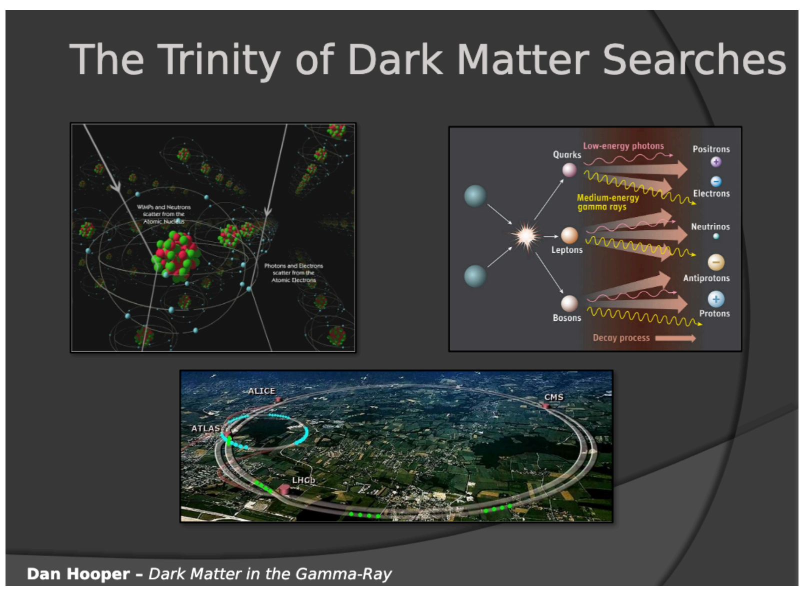
J. Peebles



The evolution of dark matter searches in the last decade

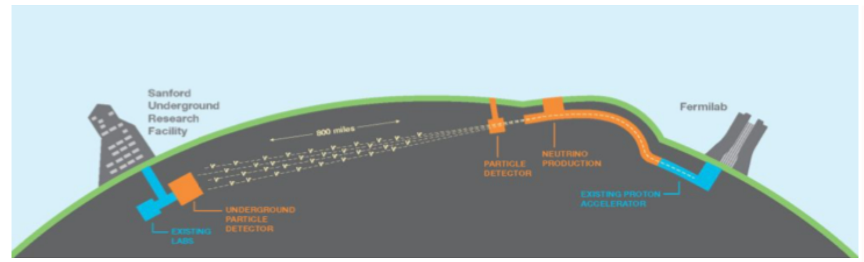
Note: not an exhaustive list





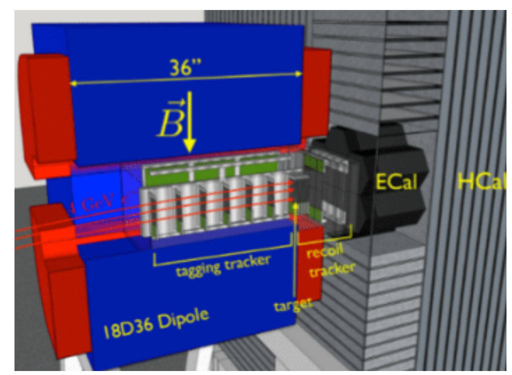
+

Neutrino experiments



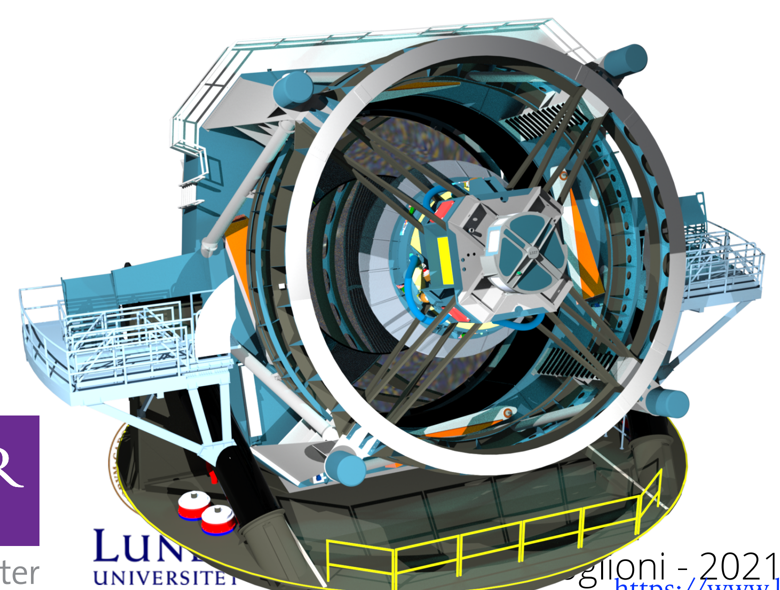
https://www.dunescience.org

Accelerator experiments



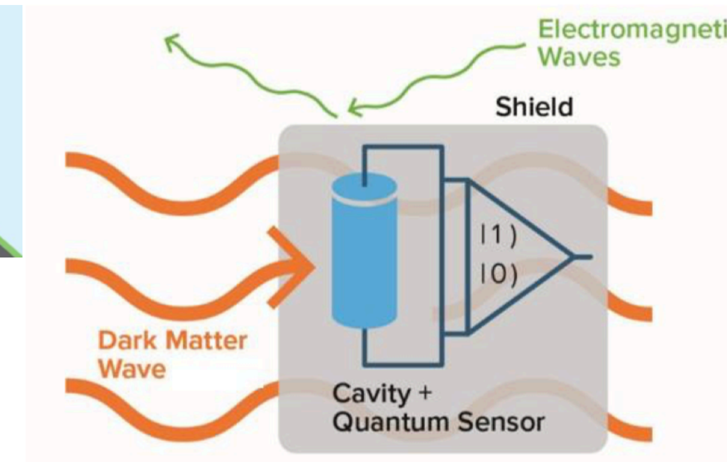
arXiv:1808.05219

Astrophysical probes



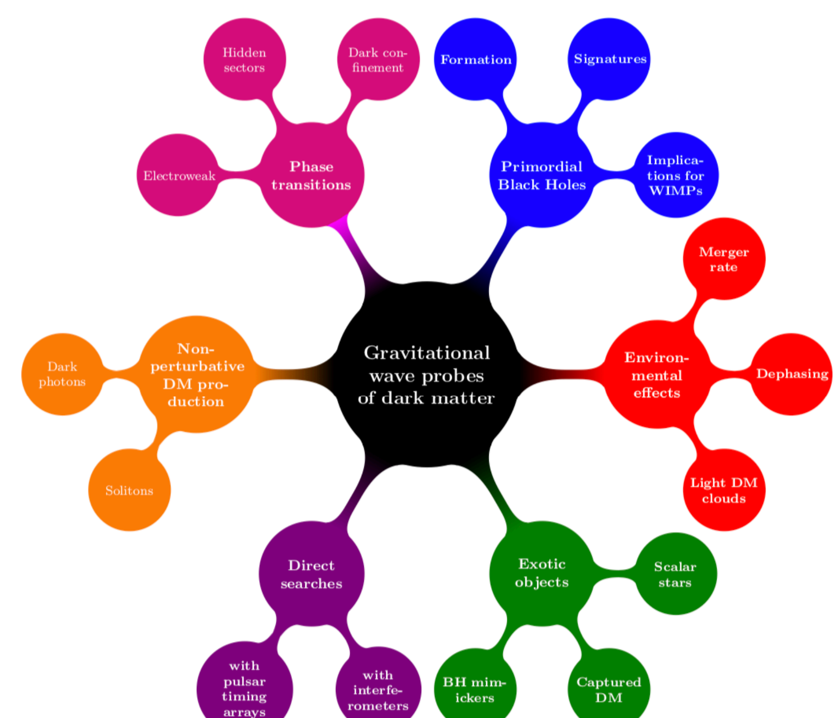
https://www.lsst.org

(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

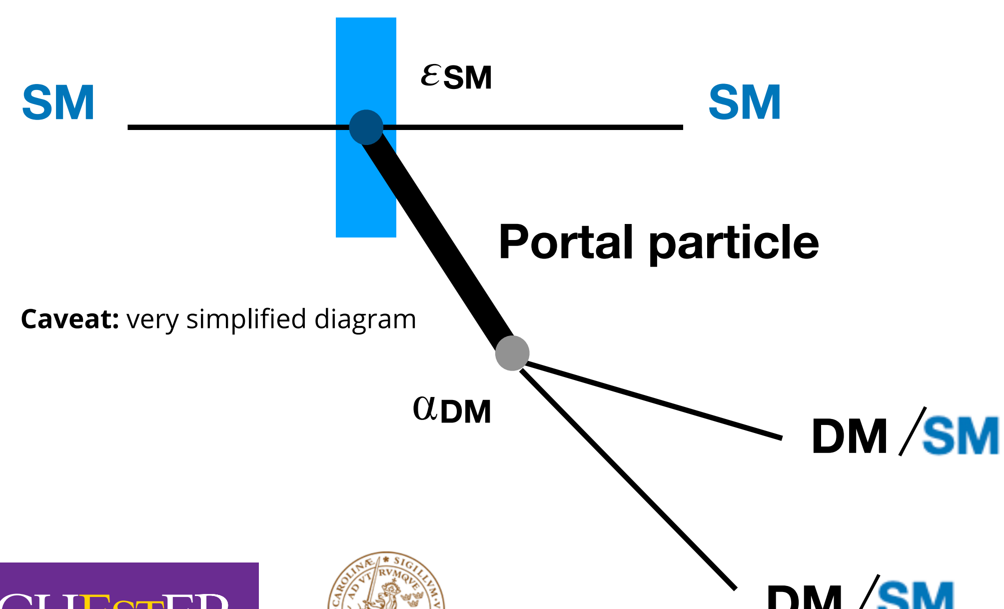
DM models with **light** particles && **very feeble interactions** w/SM benefit from <u>high intensities,</u> not only <u>high energies</u>

- 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

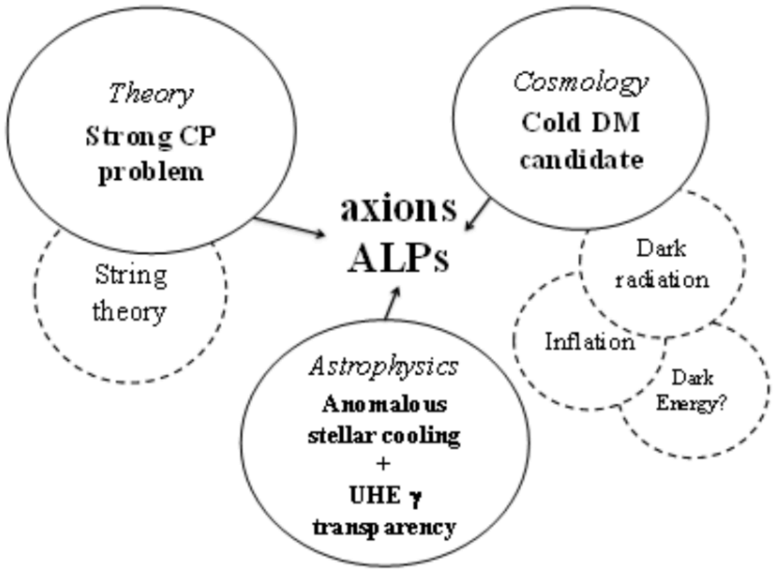


→ production of DM/SM particles

Even lighter DM: axions

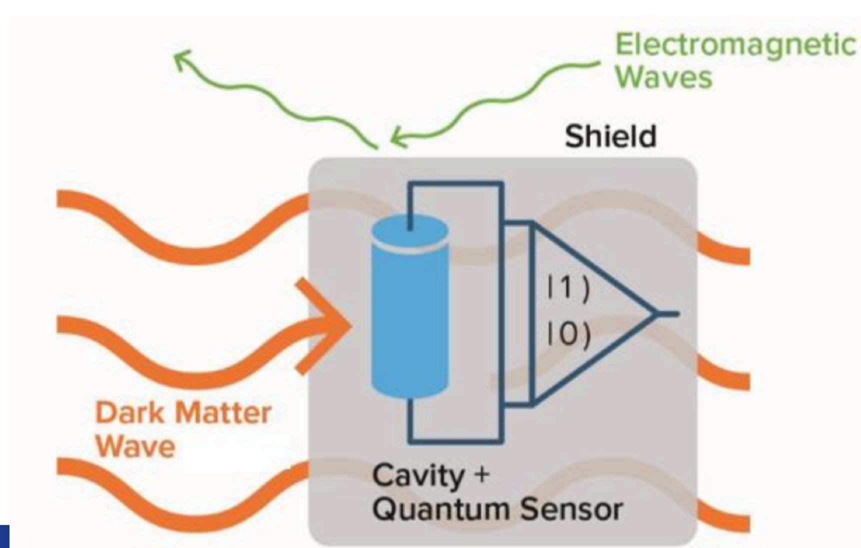
Axions/Axion-Like Particles (ALPs):

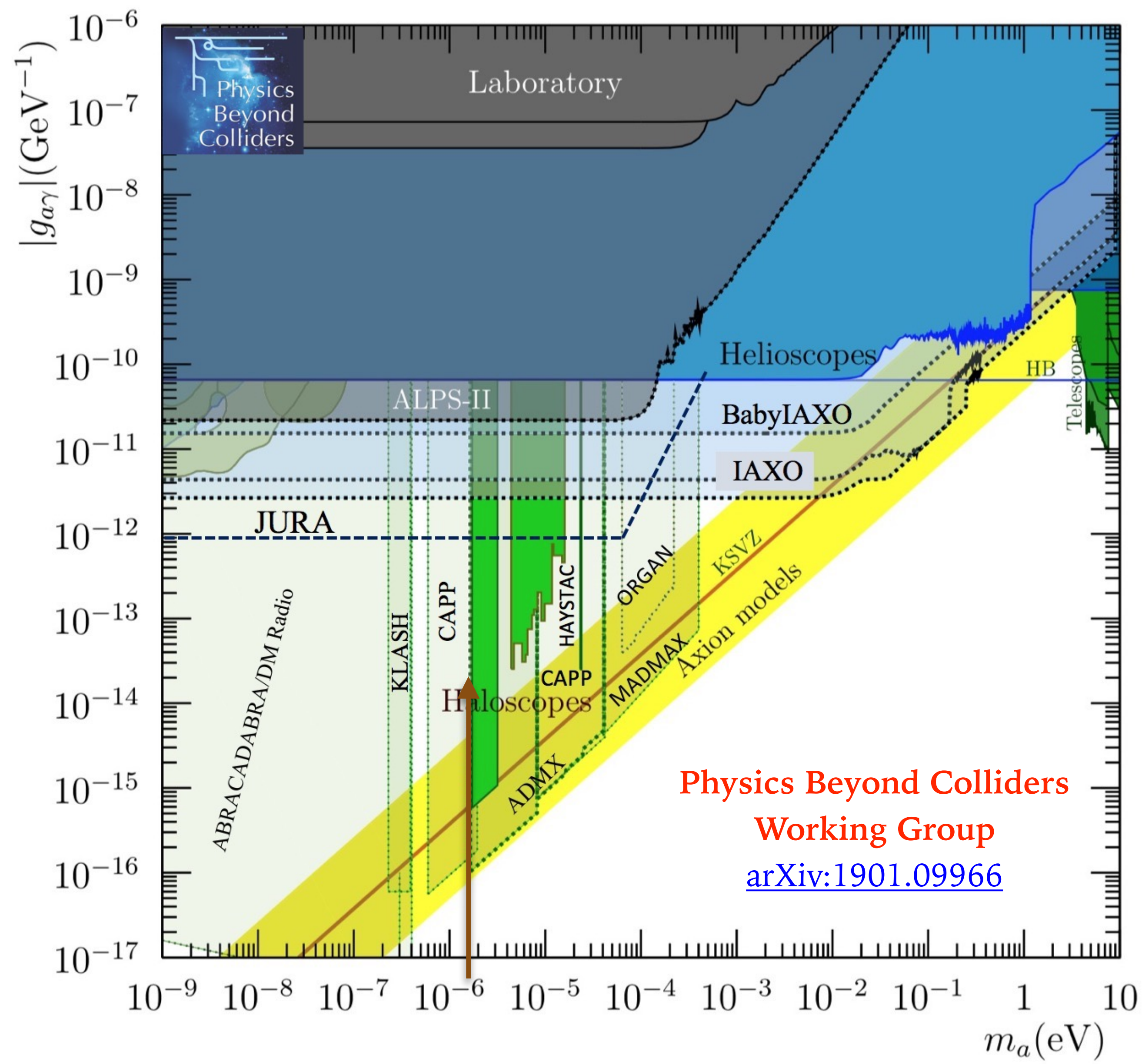
example of new particle with inter-field connections, solving more than the DM problem



[I. Irastorza's talk @ EPS-HEP 2019]

New technologies (small experiments) now available





New: **sensitivity of haloscopes to "dark matter" axions**

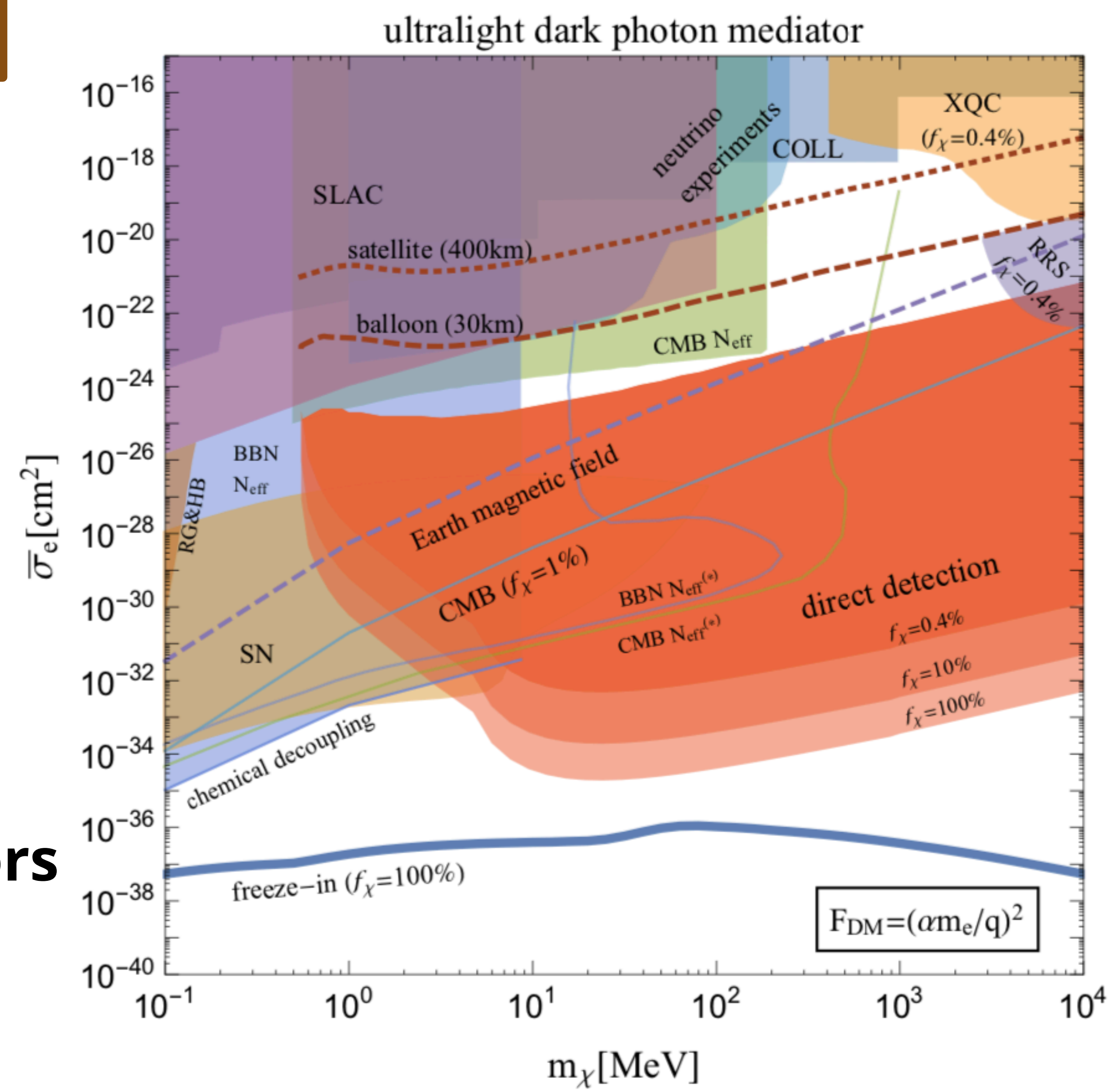
Looking *up* (to hints from astrophysics & more)

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

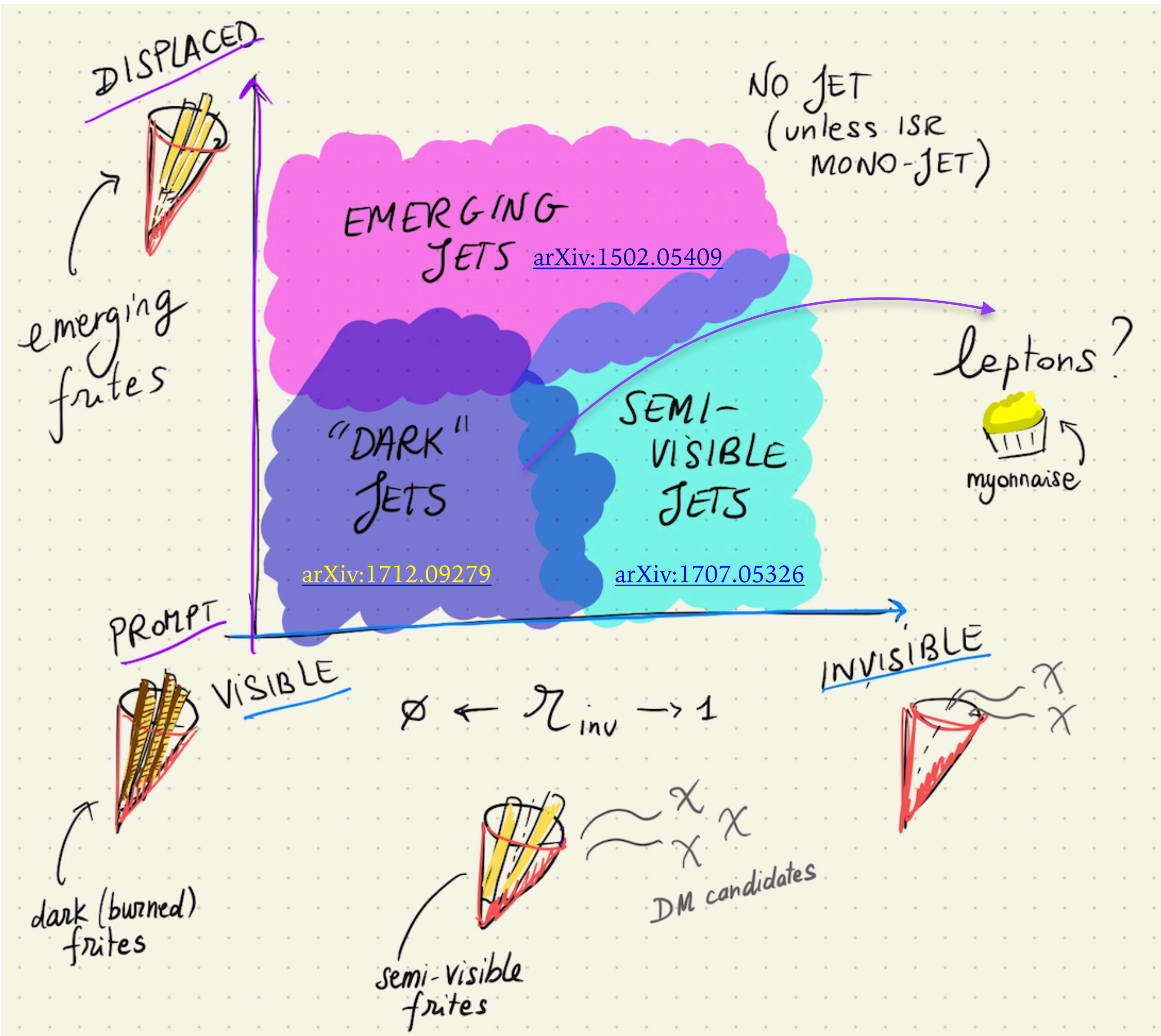
(potentially low-mass) & ”strongly interacting” DM particles will

- 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



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)

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

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]

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More about community initiatives & efforts

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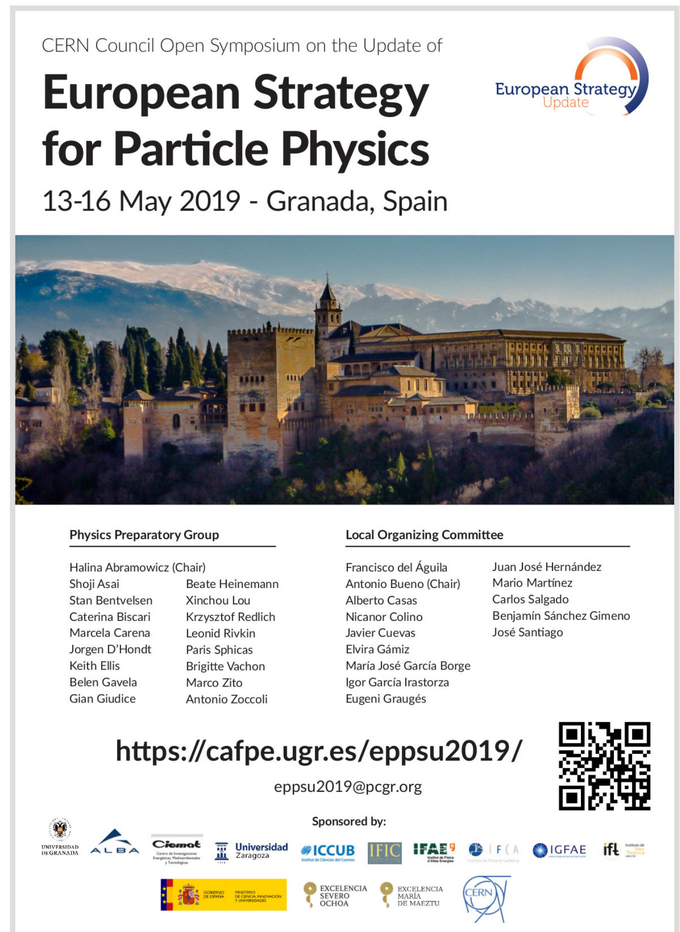
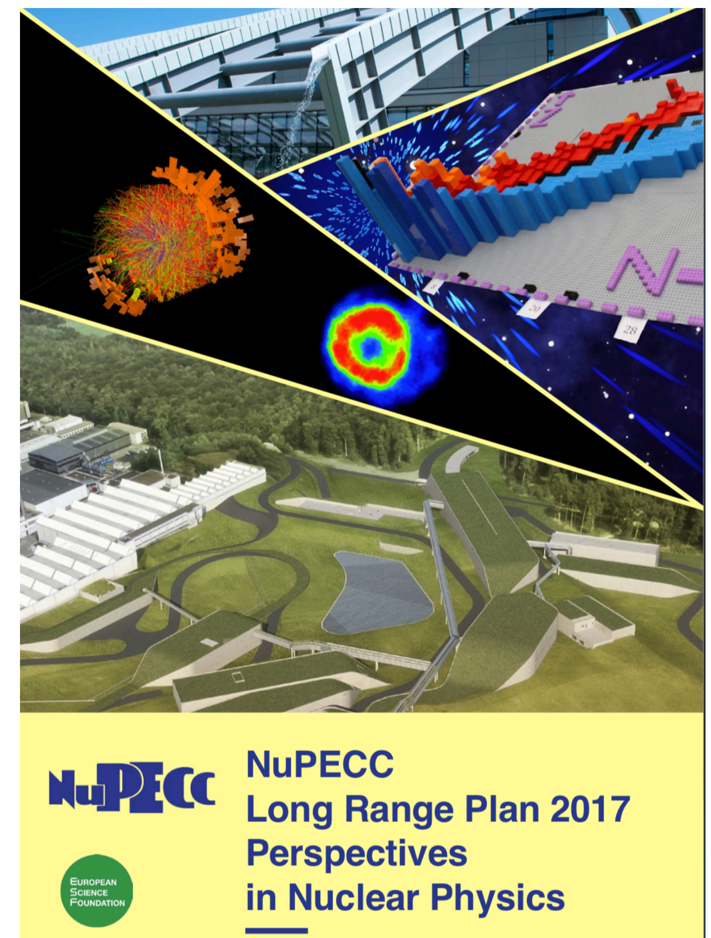
European visions for particle, astroparticle and nuclear physics

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:

Nature of dark matter and dark energy

Fundamental forces & symmetries

Properties of neutrinos at all energy scales

Origin of elements

Extreme states of matter

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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

Astroparticle Particle Nuclear

Common theory ground

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

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

data acquisition, software, computing, data sharing & open science

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!

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The Initiative for DM in Europe and Beyond

The JENAA iDMEu LOI organizers:
Marco Cirelli
Caterina Doglioni
Federica Petricca
(+ more will join)

iDMEu

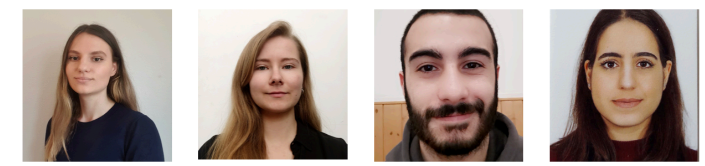
initiative for Dark Matter in Europe and beyond

[iDMEu kick-off - 2021/05/10-12](https://indico.cern.ch/e/iDMEu)
https://indico.cern.ch/e/iDMEu
idmeu.org (preliminary)

If you're interested in becoming a curator, email me :)

iDMEu Curators

The contents of this site are made possible by the work of the following people.



Gabriella Szabó (Bachelor student, Lund University, Sweden)
Romane Kulesza (Bachelor student, PSL University, Paris, France)
Tom Laclavère (Bachelor student, Université de Paris, France)
Sarah Ayoub (Master student, Sorbonne University, Paris, France)

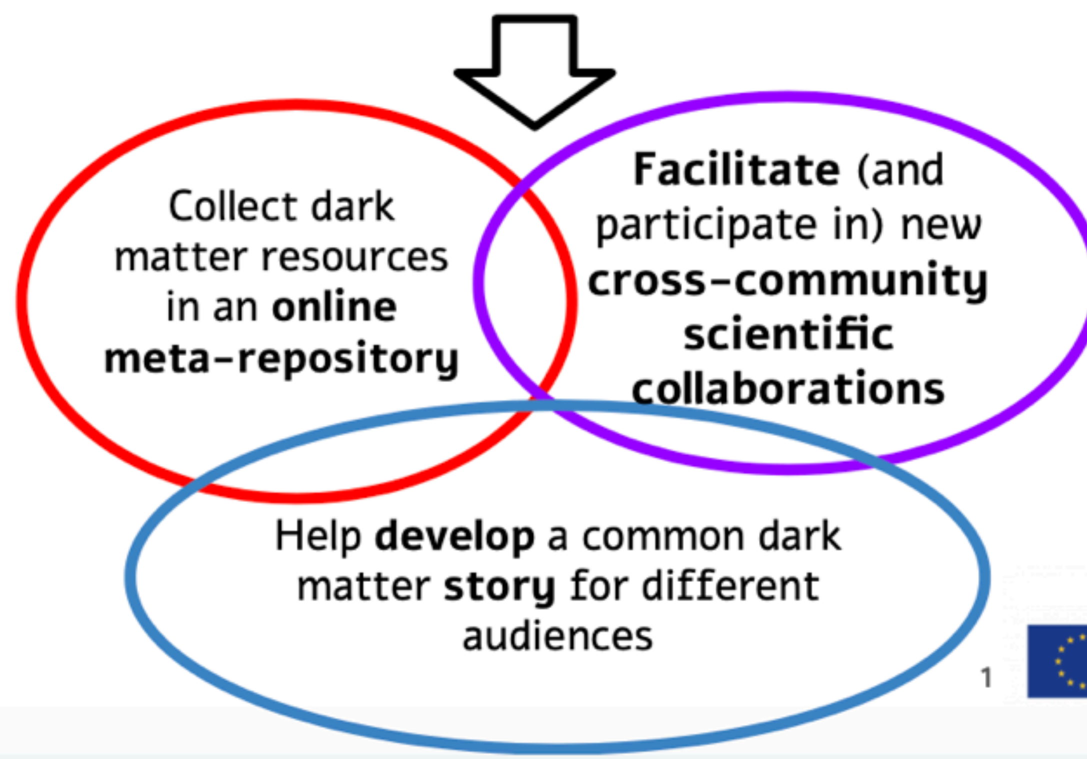
The best region to find dark matter is the one where more techniques and ideas can **discover** and **explore** DM!

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?"

More info on ECFA Newsletter

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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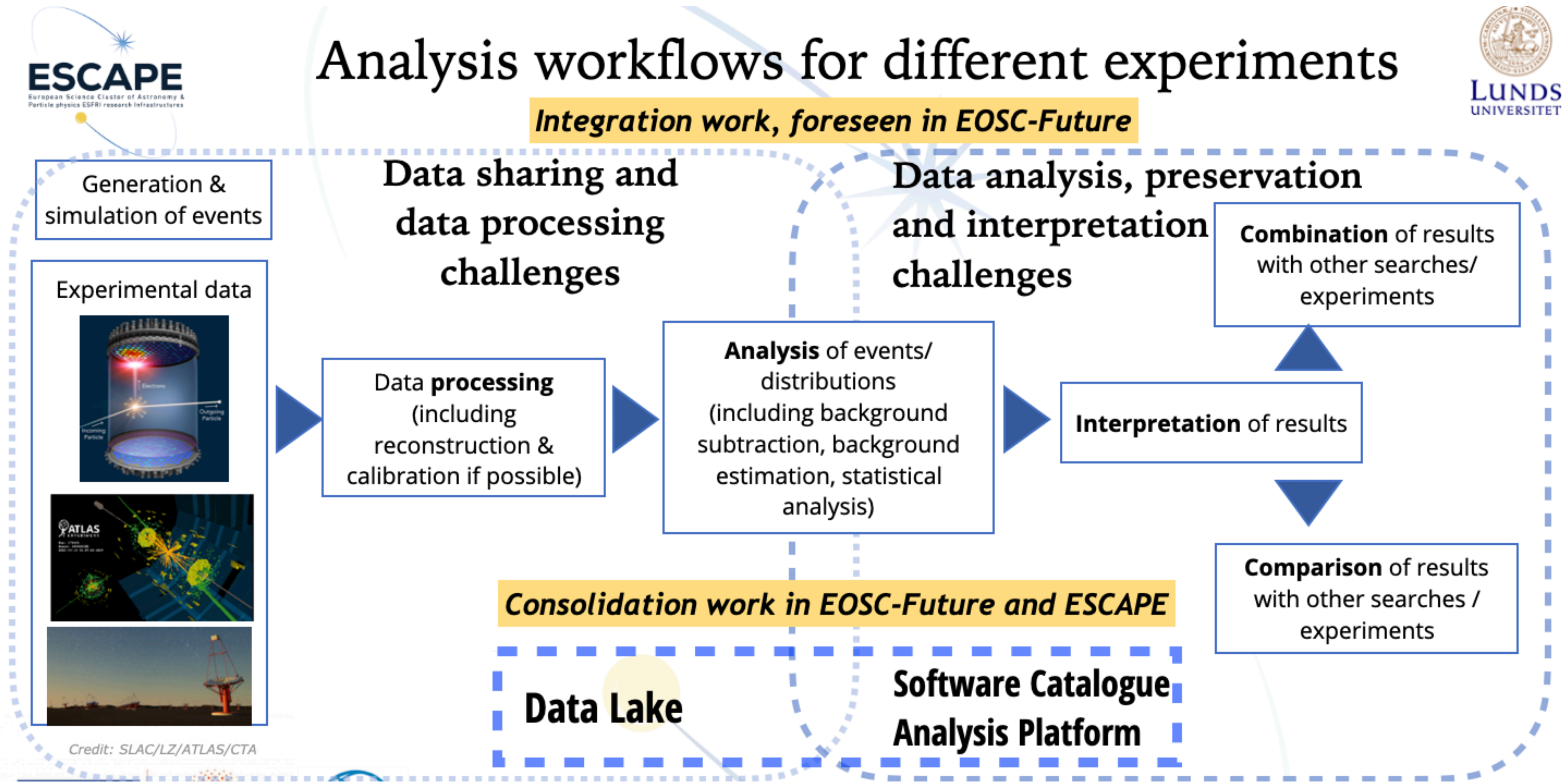
The ESCAPE Test Science Project

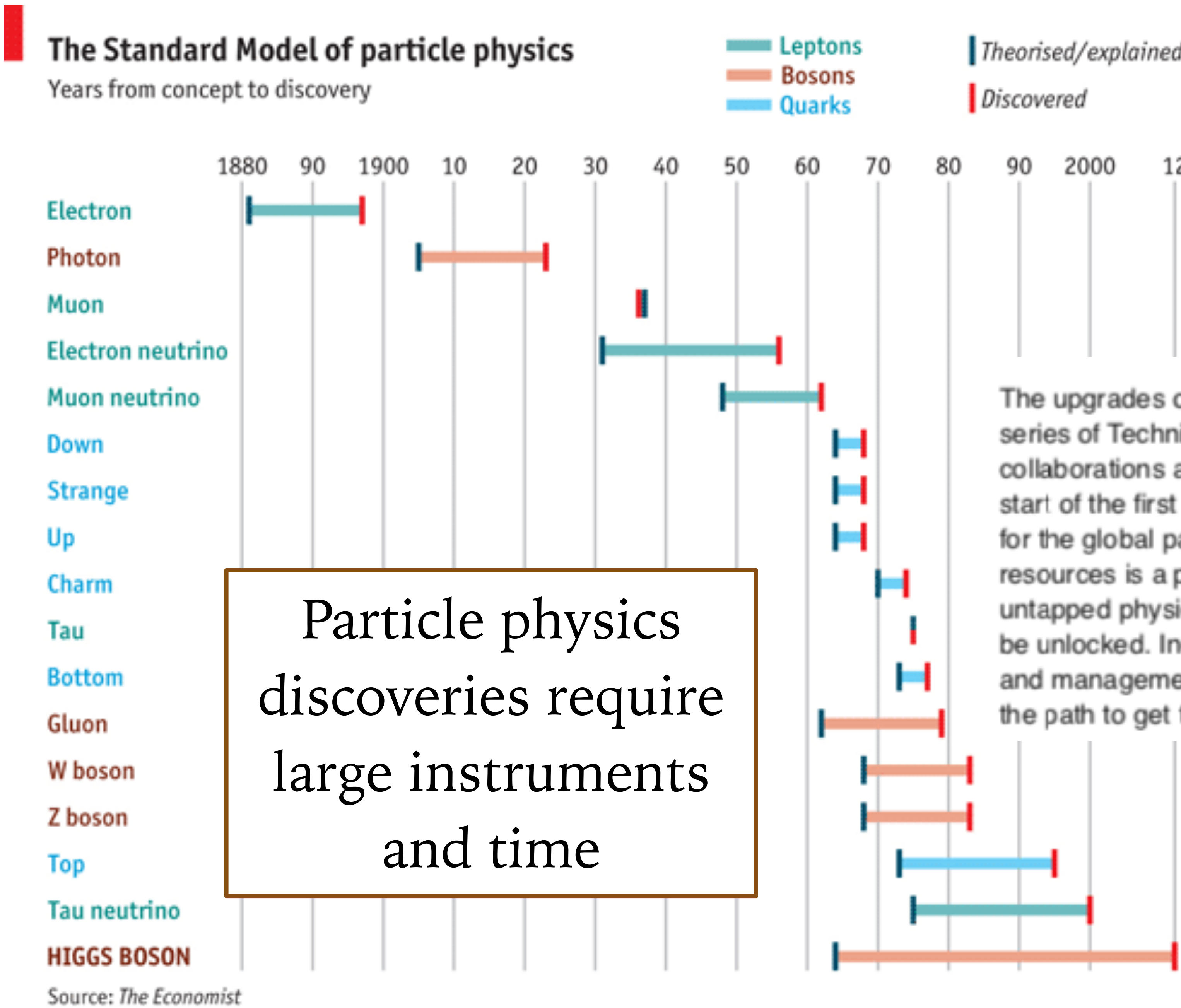
5 postdocs all over Europe working on this (funded by EOSC-Future)



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

Conclusions

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



Particle physics discoveries require large instruments and time

[The Economist]

- **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...

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

What does it take for a discovery? Collaborations

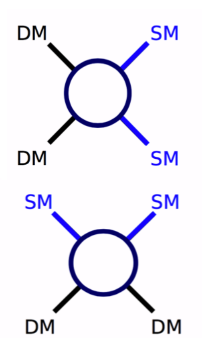
The search for BSM/Dark Matter has a long way to go at future colliders**...**

...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

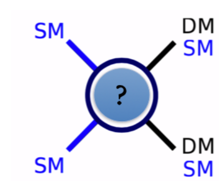
Now and future: essential **complementarity between colliders and other experiments**, *e.g. for dark matter*



cosmological origin
DD/ID/astrophysics

and

nature of the DM-SM interaction
accelerators / colliders



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

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Towards a Dark Matter Test Science Project

iDMEu
initiative for Dark Matter in Europe and beyond

Discussion / work together ongoing, you're welcome to join in!

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Thanks for your attention!

Photo credits: C Fitzpatrick

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