CATERINA DOGLIONI
LUND UNIVERSITY

Search for Dark Matter at the Large Hadron Collider and beyond

(with a focus on the ATLAS experiment)

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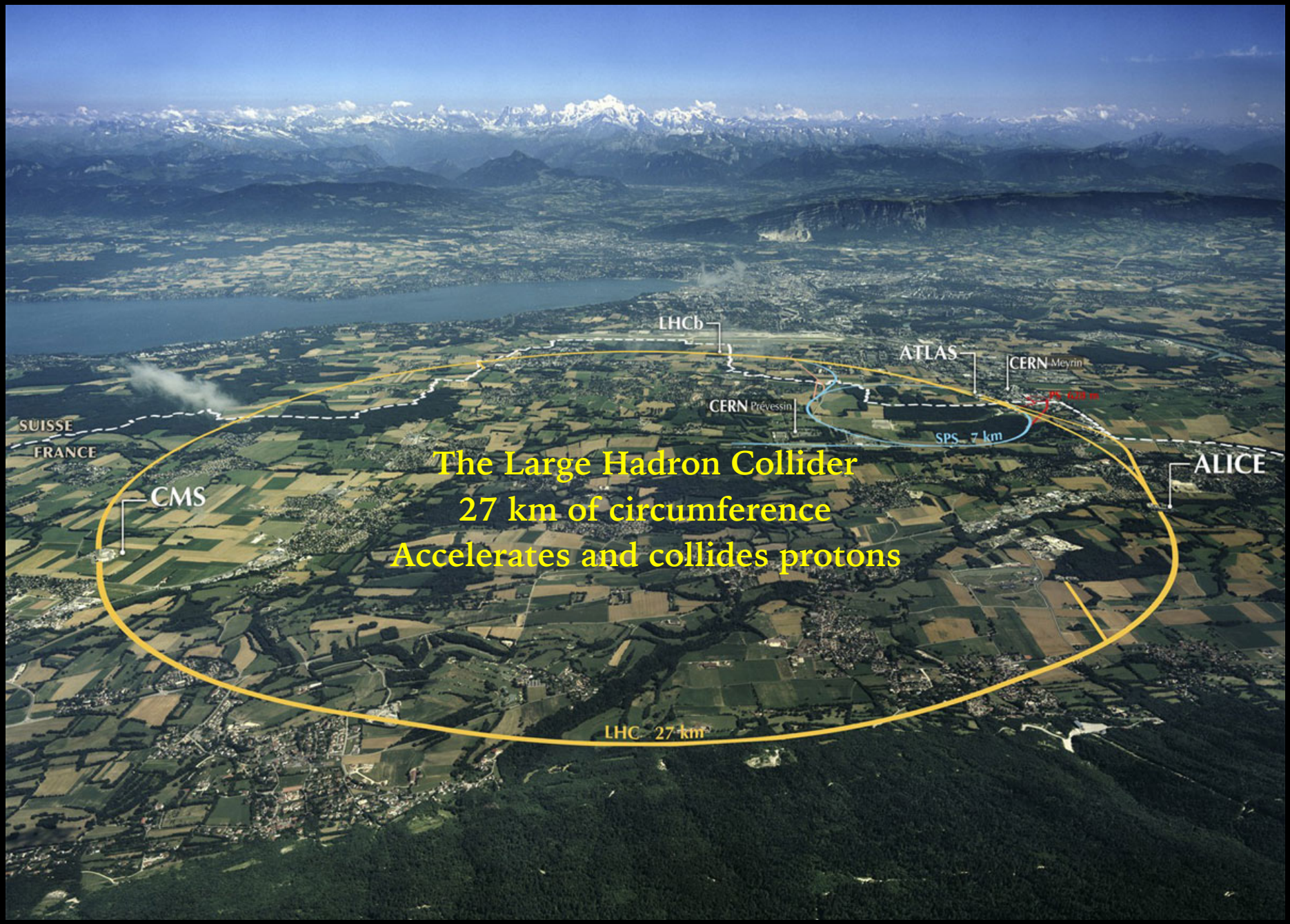
Horizon 2020
European Union funding for Research & Innovation

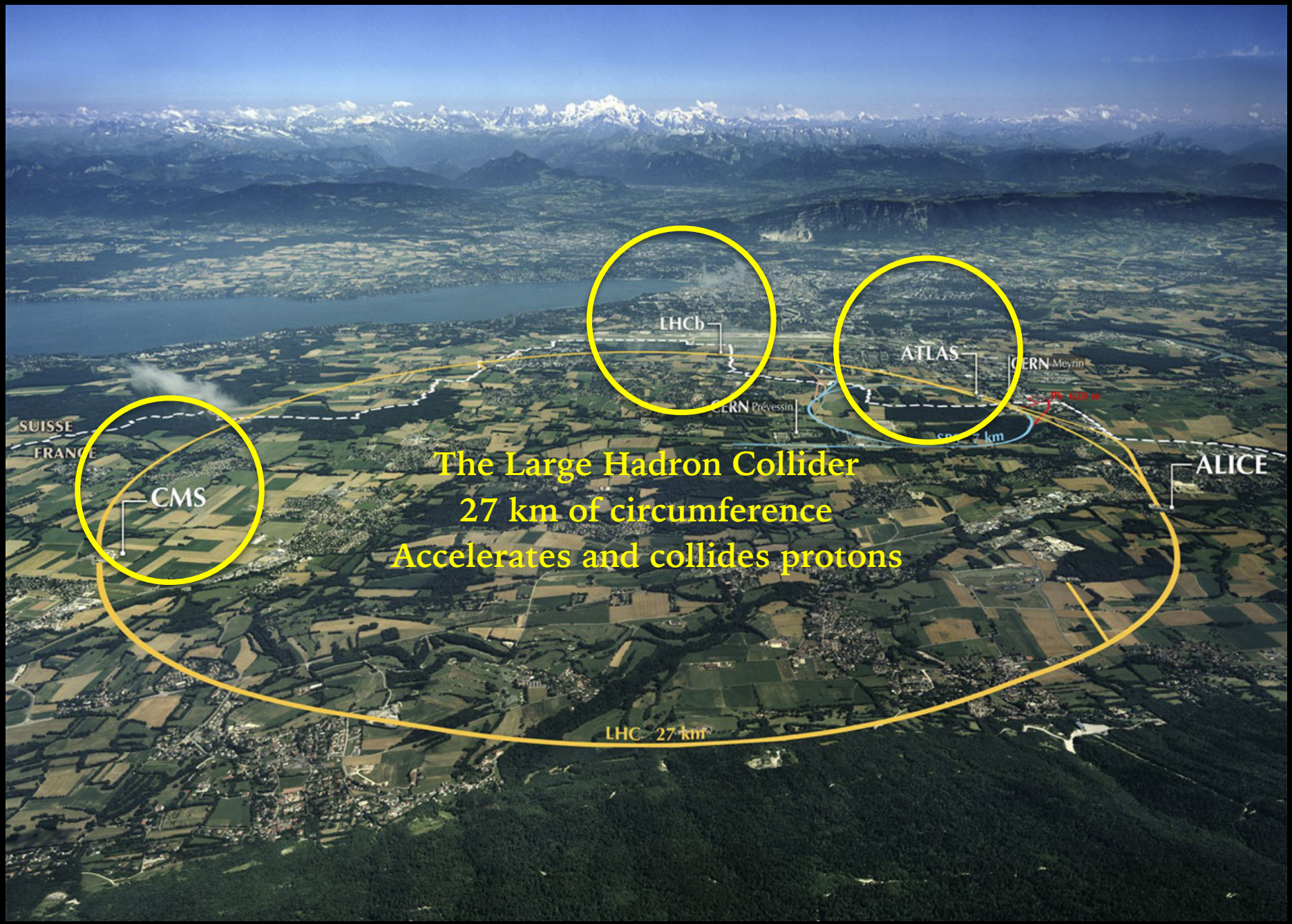
Outline

1. The Large Hadron Collider and ATLAS
2. Why, and how to search for new physics
3. Dark Matter at colliders & other experiments
4. Looking for Dark Matter (mediators)
5. Highlighting complementarity

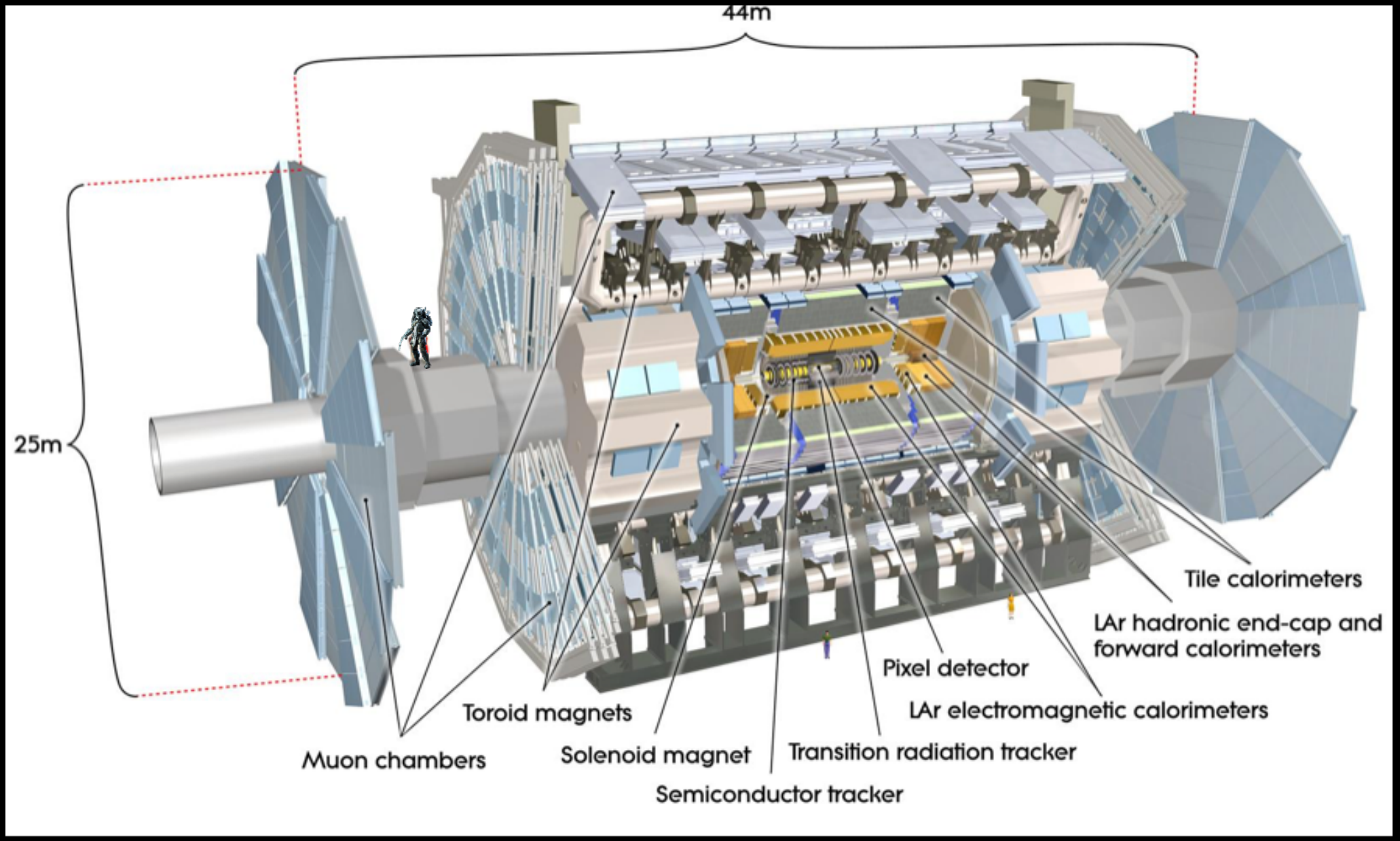
Introduction: the Large Hadron Collider and the ATLAS experiment



The Large Hadron Collider
27 km of circumference
Accelerates and collides protons


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
CMS
ALICE
The Large Hadron Collider
27 km of circumference
Accelerates and collides protons
LHC 27 km

The ATLAS detector
Records the products of the collision
We analyse them in search of new phenomena



Who are we? The ATLAS Collaboration

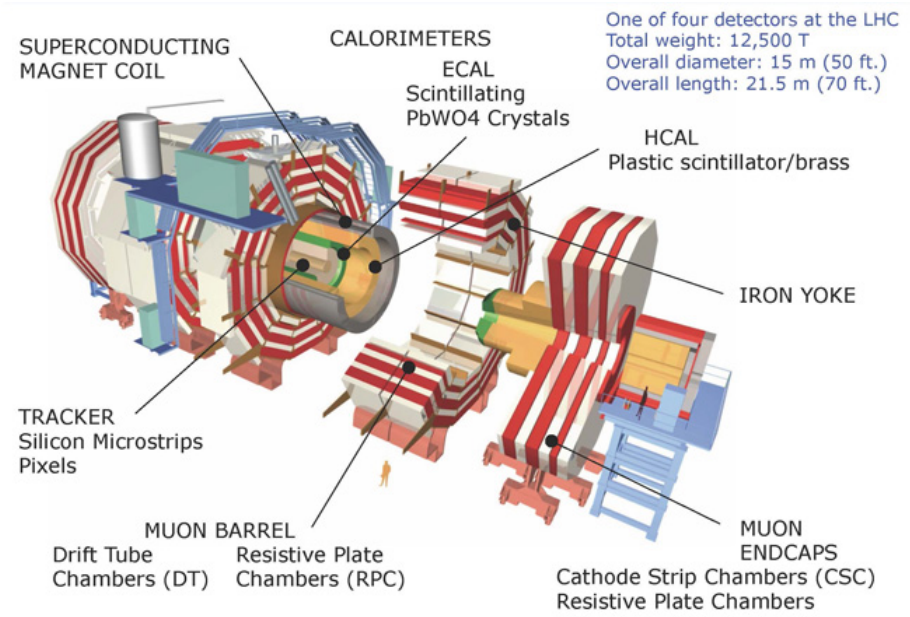
Only < 1/10 of the ATLAS collaboration shown here

38 countries, ~180 universities,
>1000 students

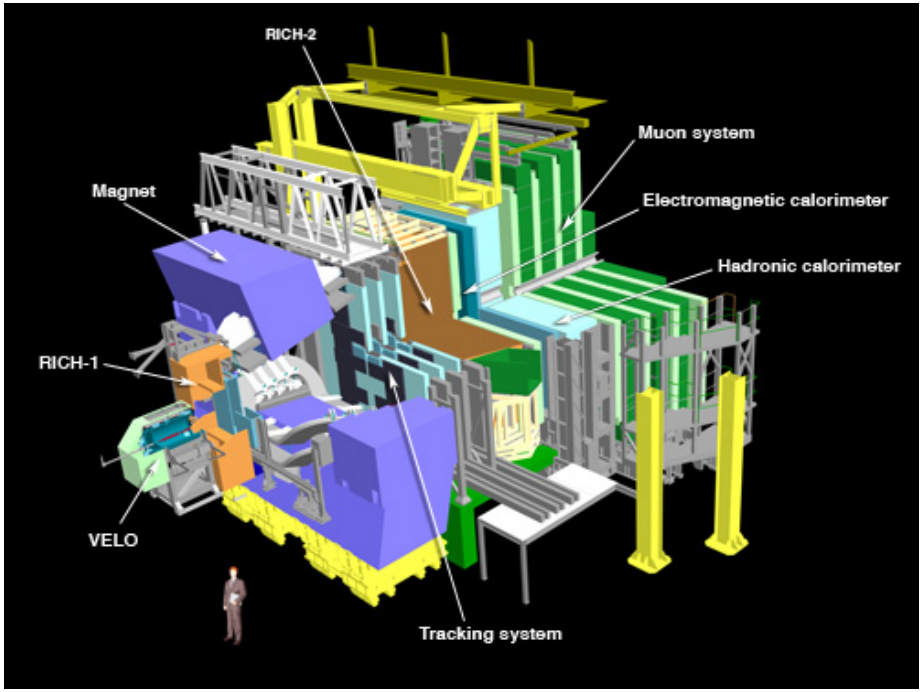
> **600 peer-reviewed papers as of today**

Other LHC experiments in this talk

Compact Muon Solenoid



LHC beauty apparatus



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What are the interesting events?
How to search for new physics at the LHC

The main question for the LHC Run-1

Among the outstanding questions of the Standard Model:

- How do particles get mass?
  - Higgs mechanism?

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

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

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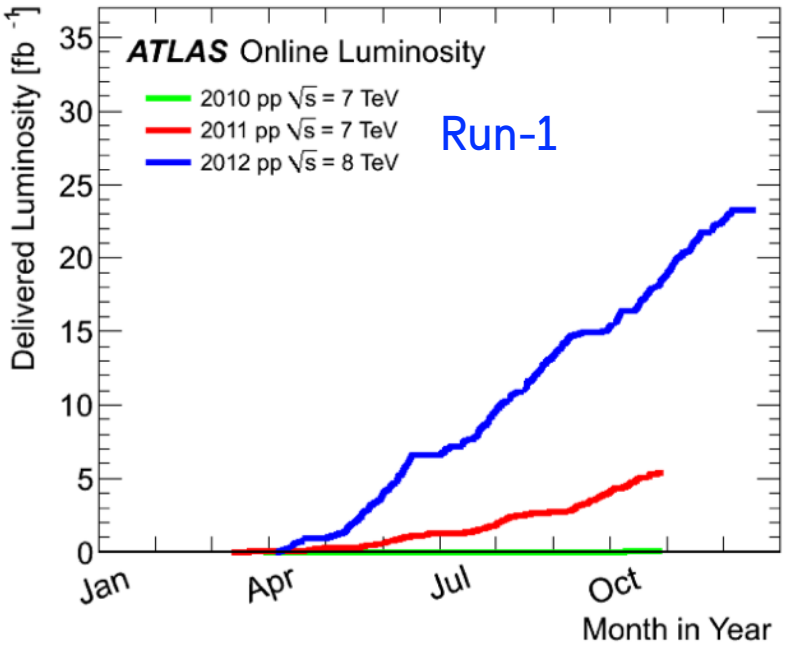
LuminosityPublicResults



√s = Centre of mass energy

More energy ⇔ more new massive particles **($E=mc^2$)**

Luminosity = how much data is collected

More data ⇔ more chances to see rare processes

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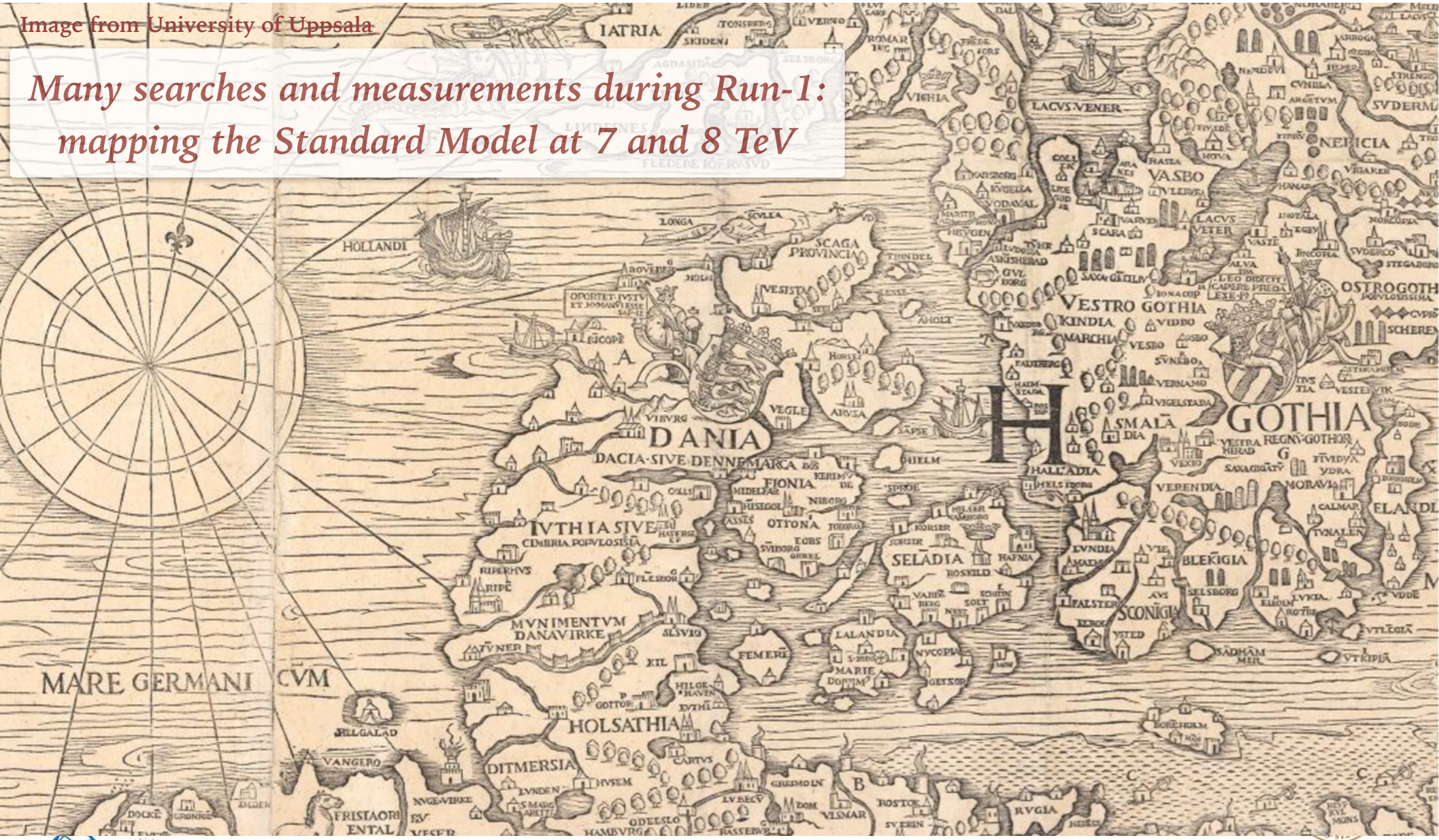
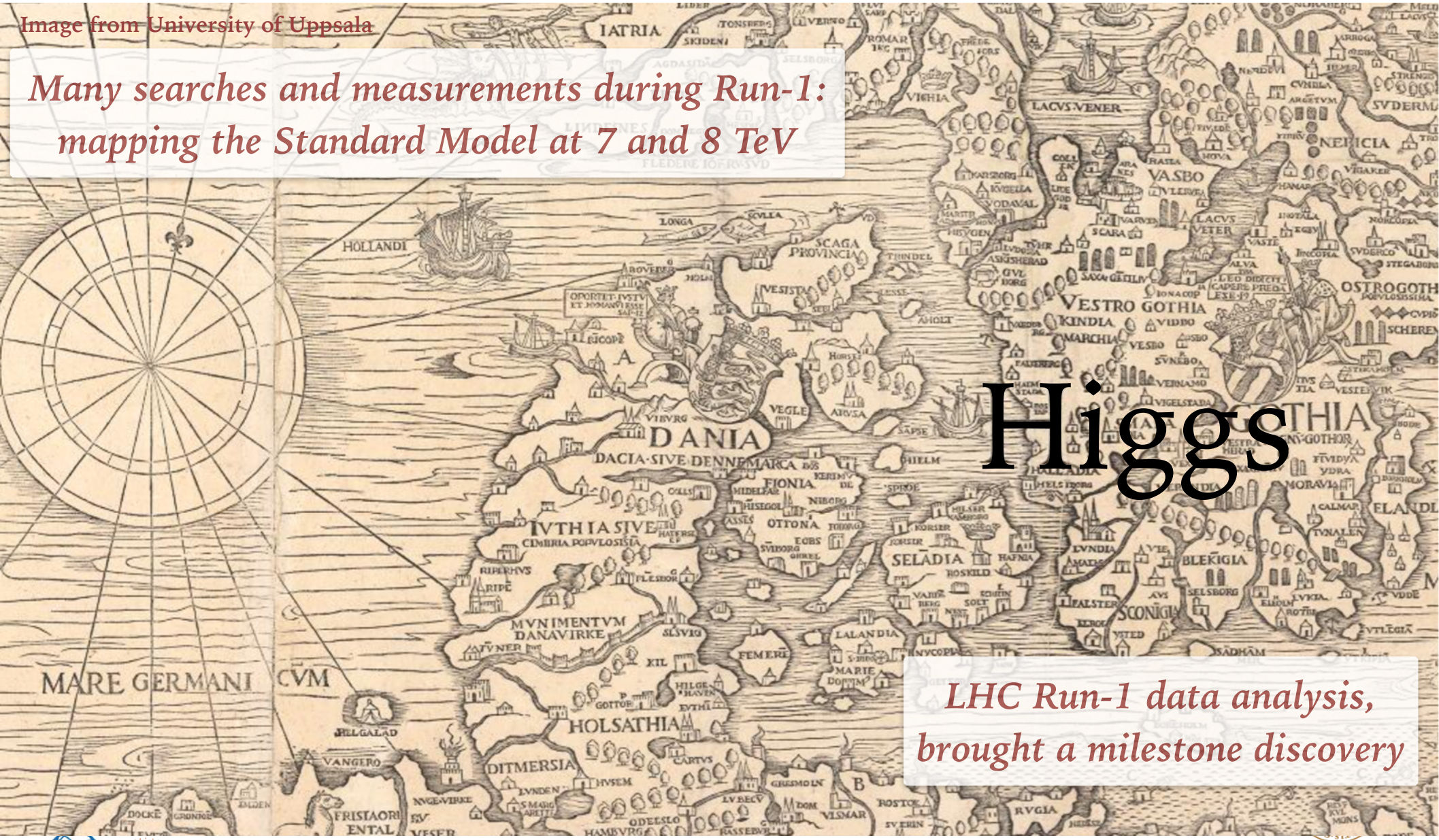
A chart of searches (and discoveries)



A chart of searches (and discoveries)

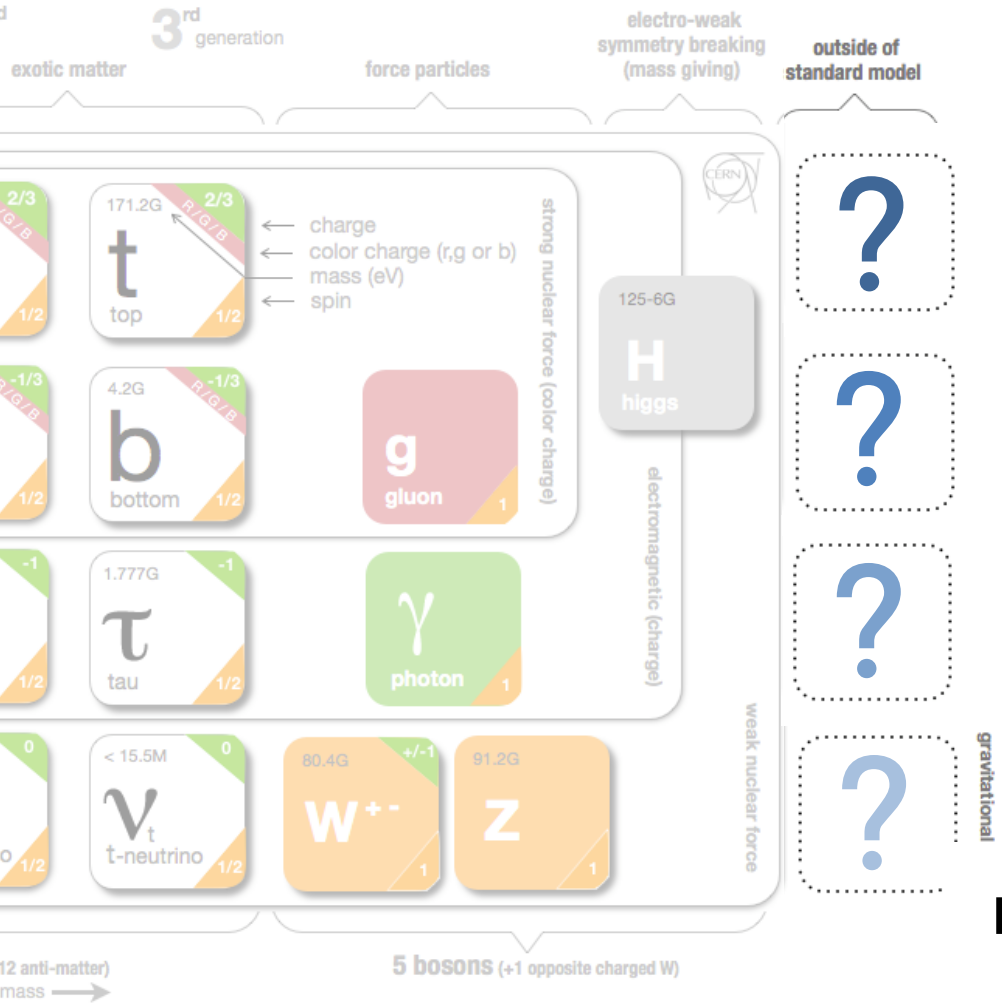


A chart of searches (and discoveries)

Discovery of the Higgs boson:

guided by **clues** from the **Standard Model** of particle physics

Uncharted discoveries in Run 2

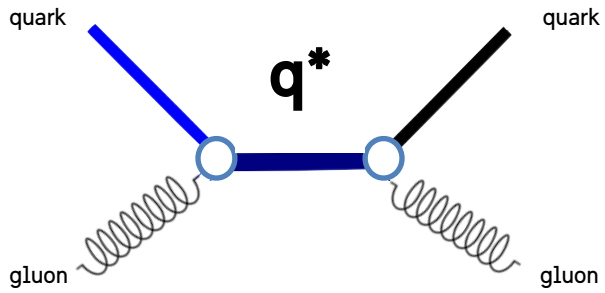


Where to look for new physics?

Everywhere, starting with high masses

Increase of LHC energy

Increase of reach for new phenomena



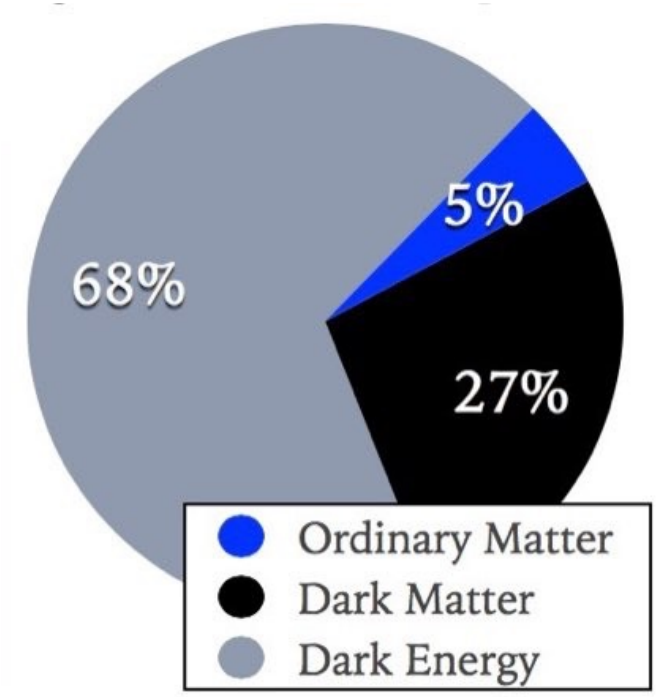
Example: production rate of excited quarks (q*) with mass of 4 TeV would **increase** by **56 times** from Run 1 to **Run 2**

Where ~~do~~ did we go from ~~here~~ the LHC Run-1?

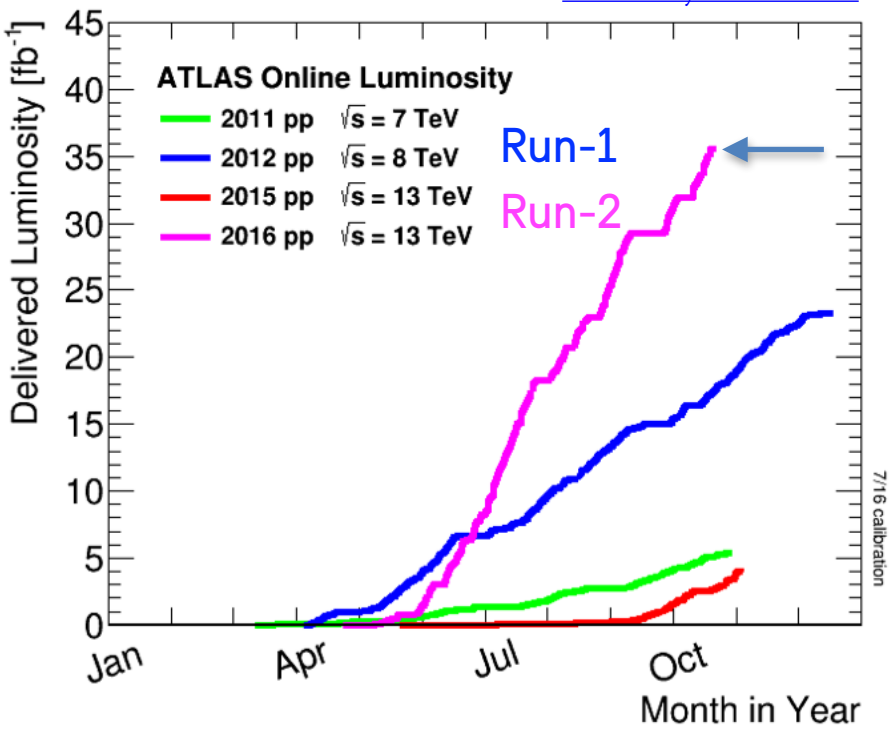
(Some) outstanding questions of the Standard Model:

- How do particles get mass?
  - Higgs mechanism ✓
- Why is the Higgs boson mass so light?

- What is the nature of dark matter?



LuminosityPublicResults

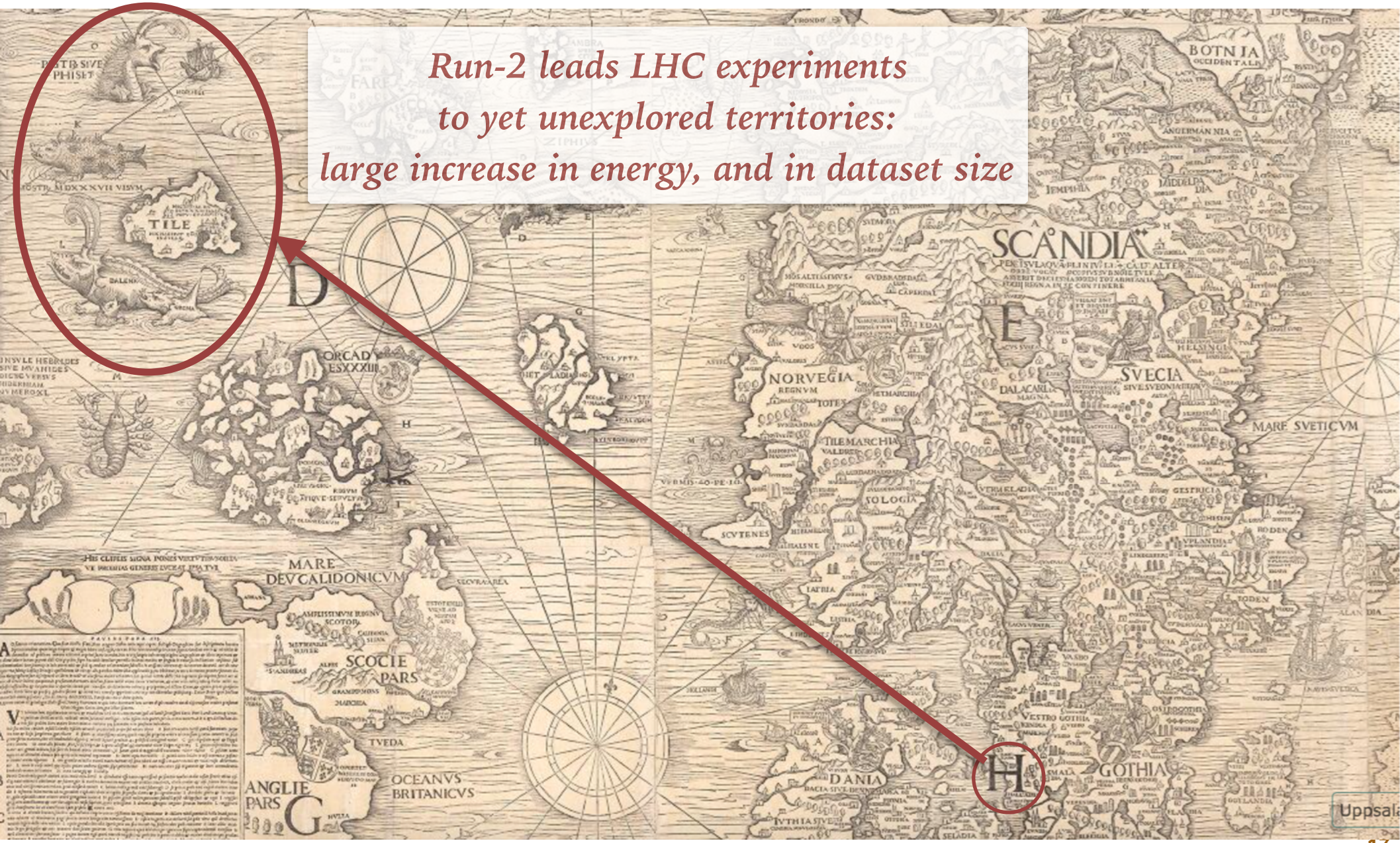


LHC operating beyond its design luminosity!

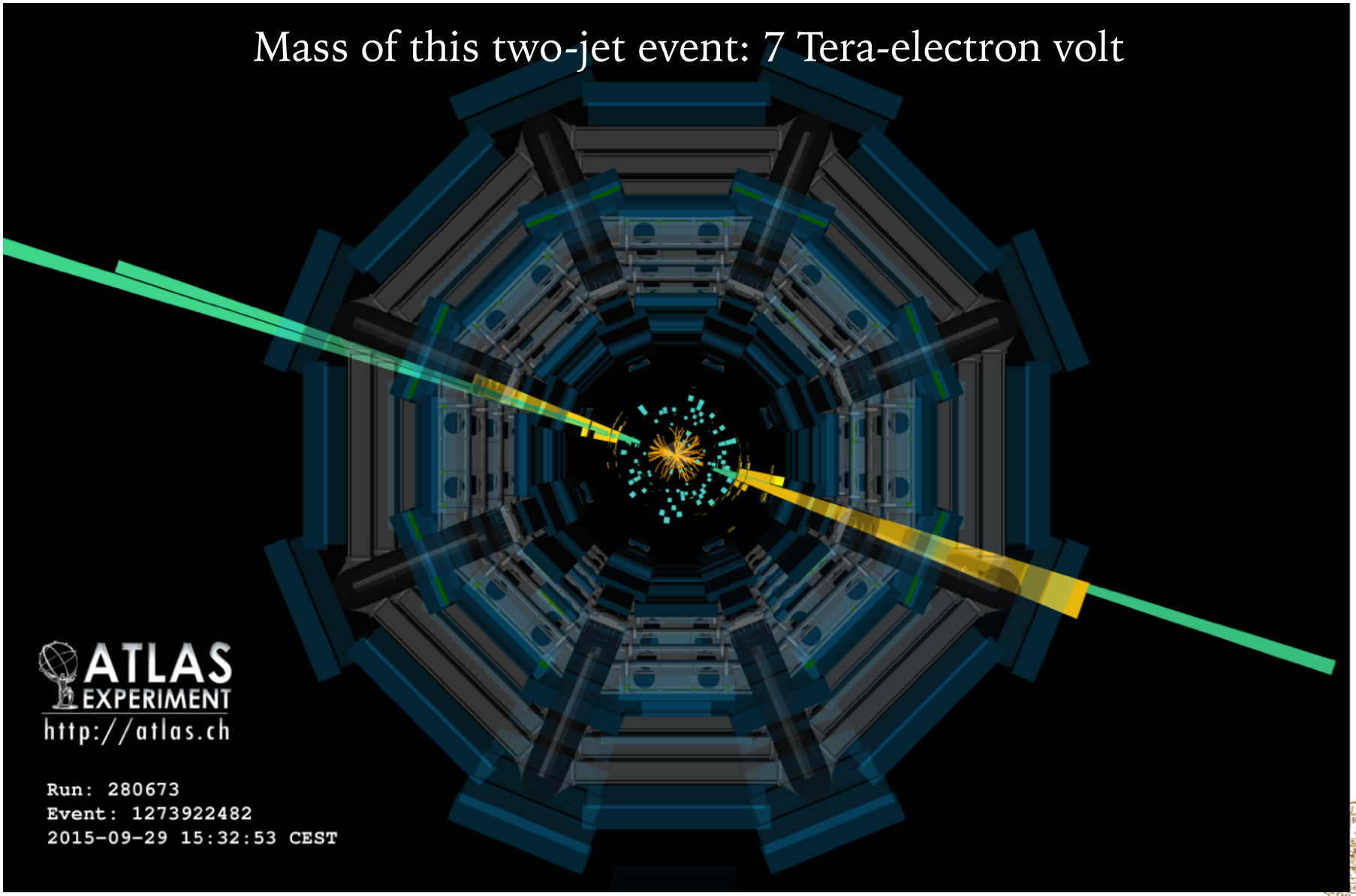
We have the chance to answer these questions with LHC Run-2 data

Uncharted energies at the LHC Run 2

Image from University of Uppsala



Uncharted energies in (ATLAS) Tile (calorimeter)



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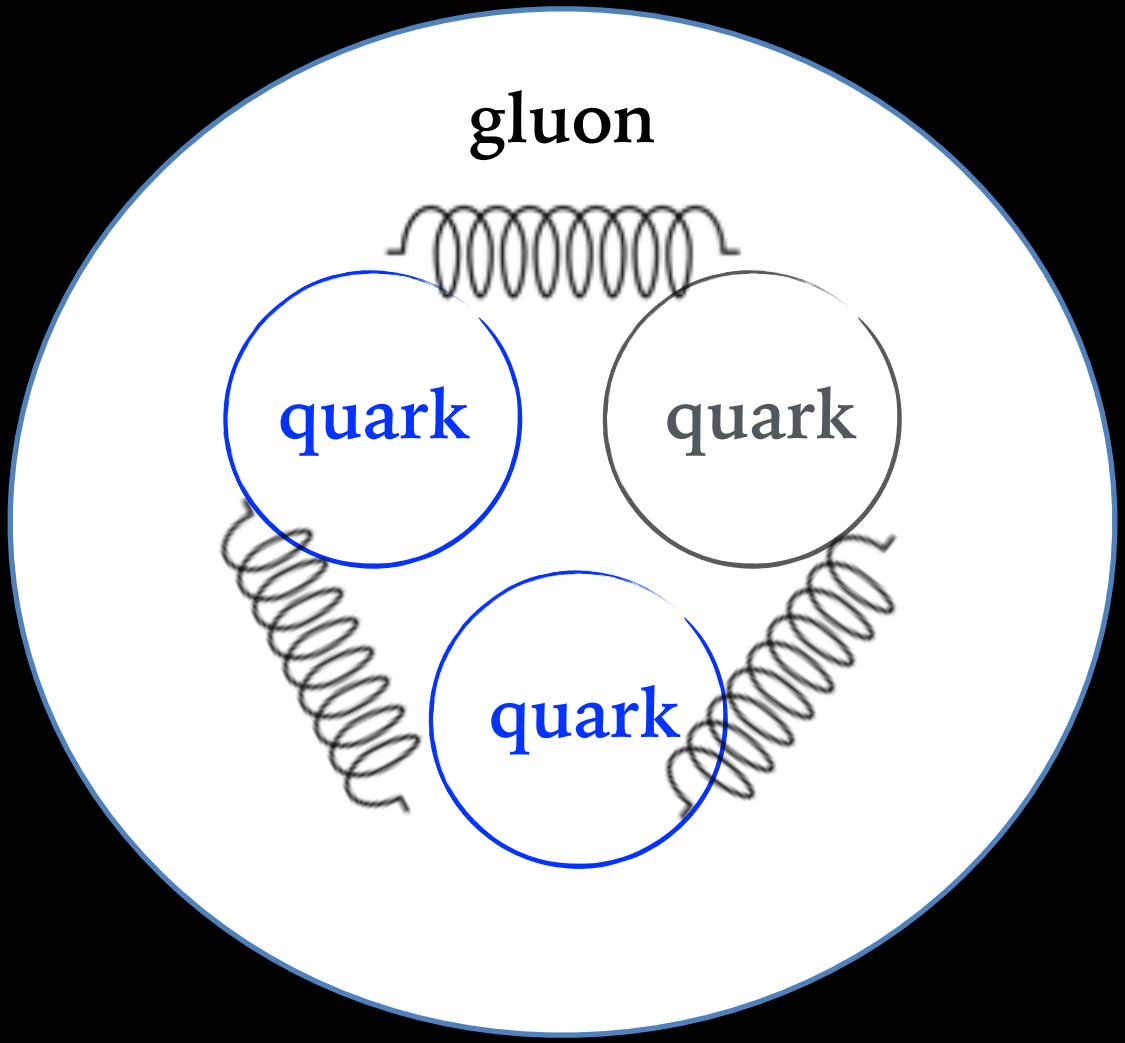
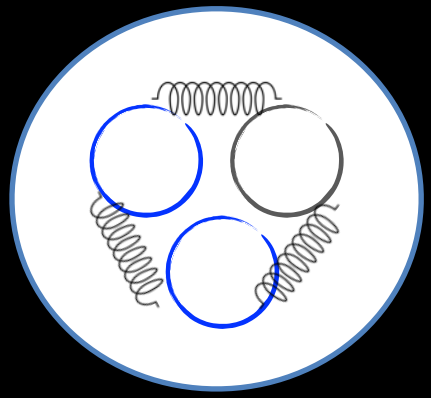
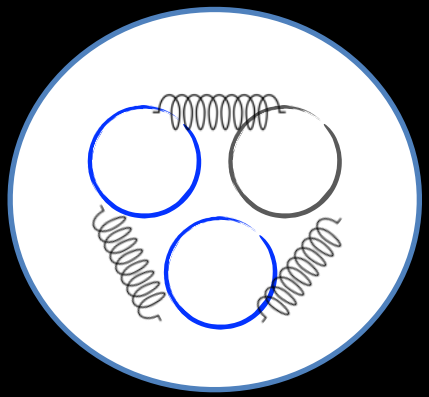
Back to basics: proton

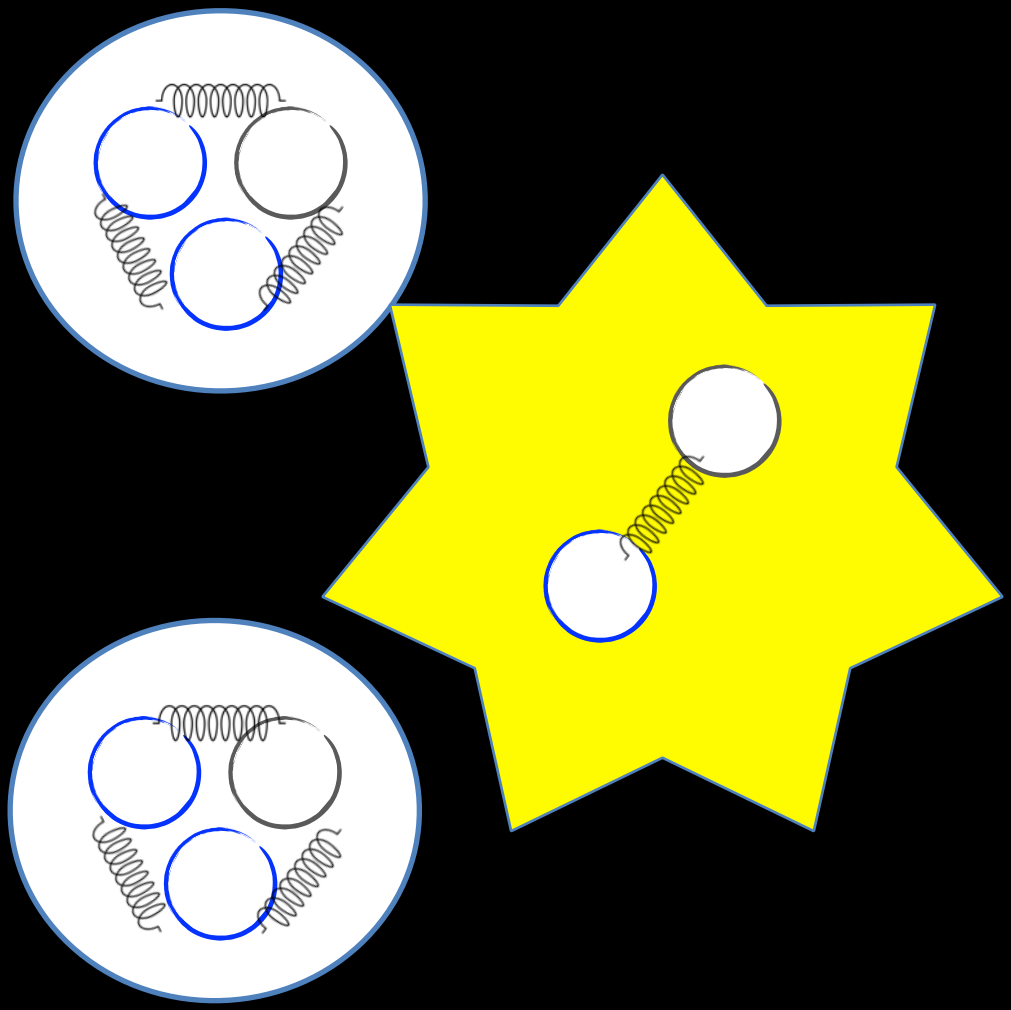


Protons are made of quarks and gluons

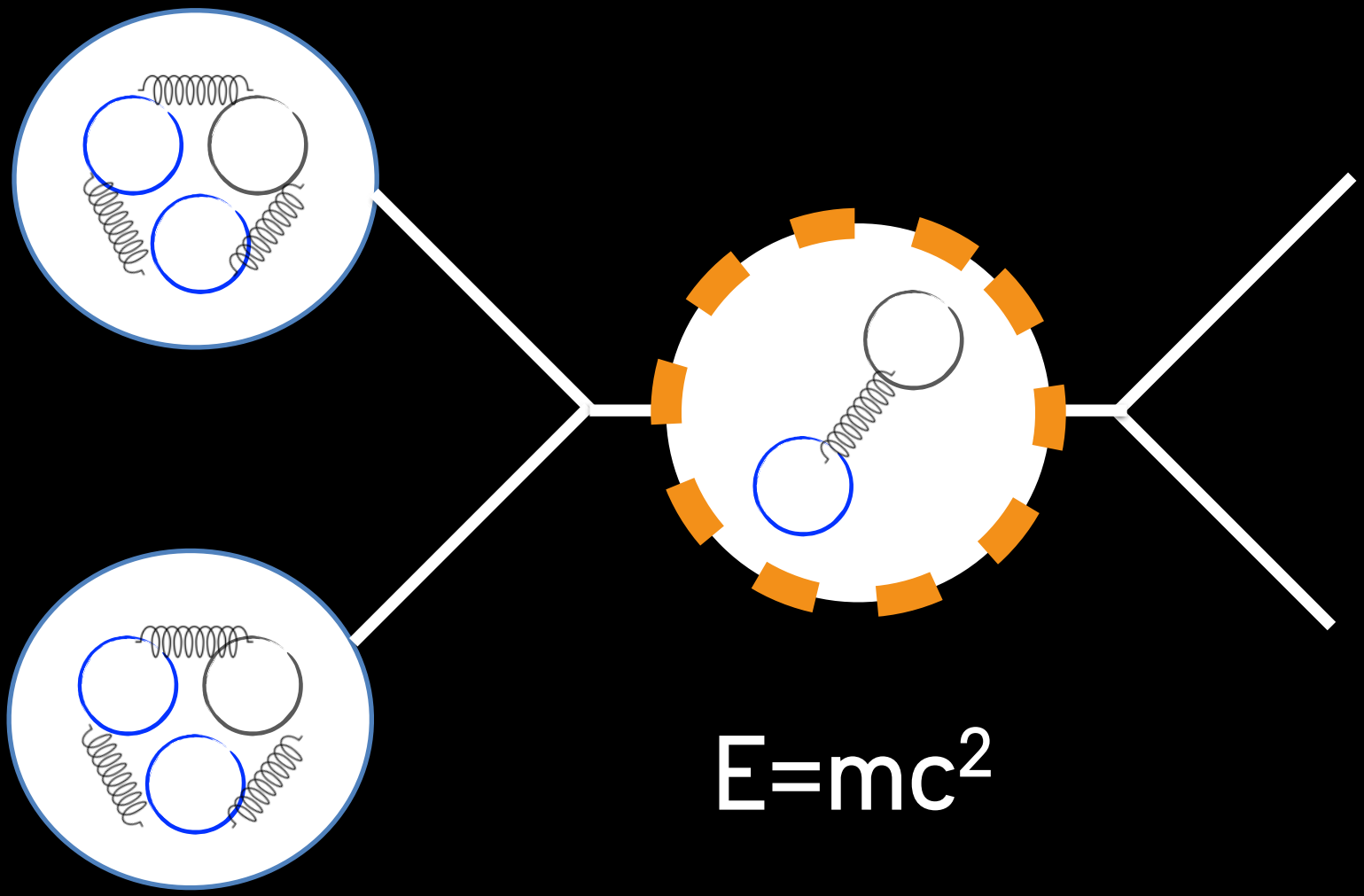




quarks and gluons collide at the LHC

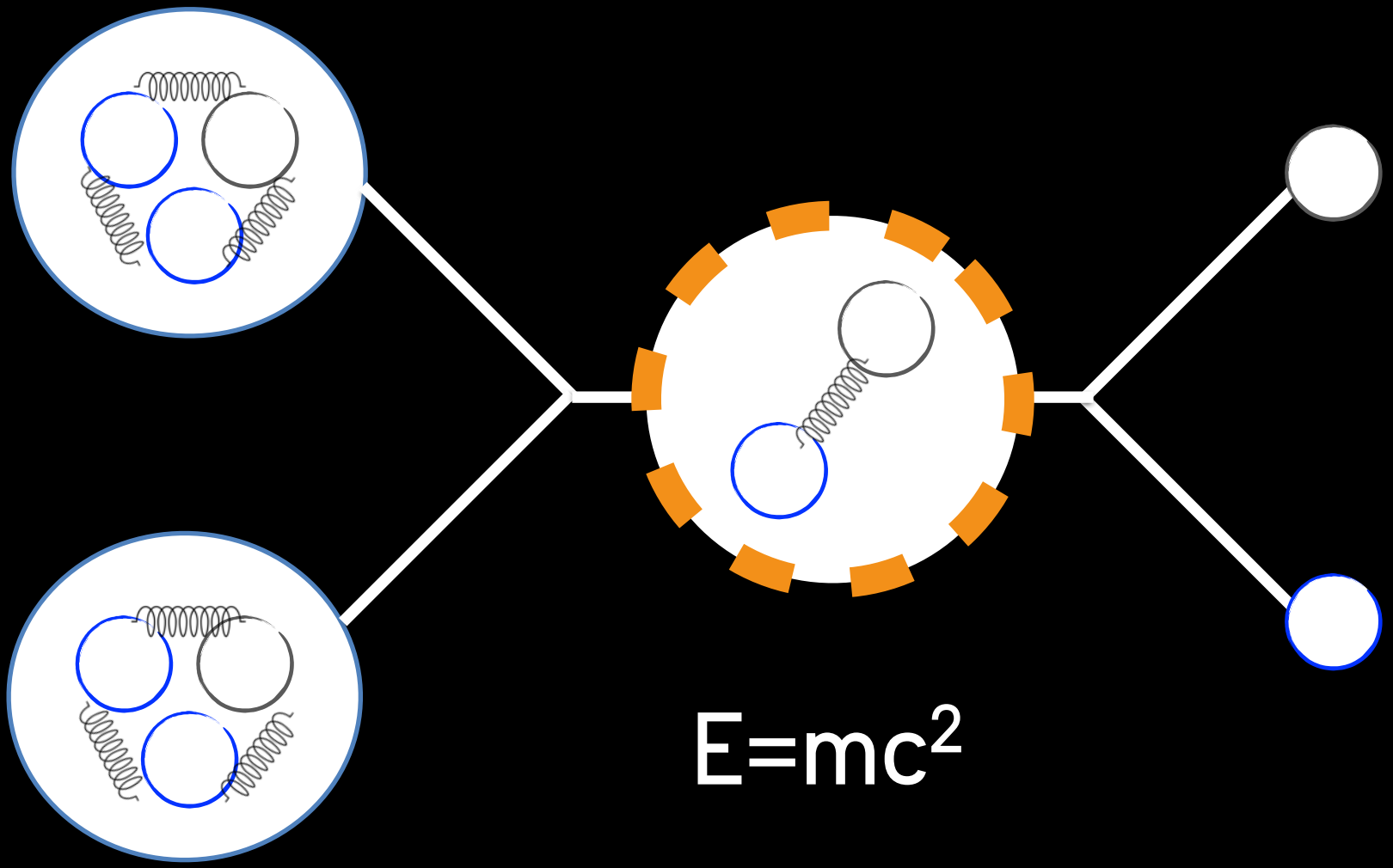


in the collision, new particles can be created

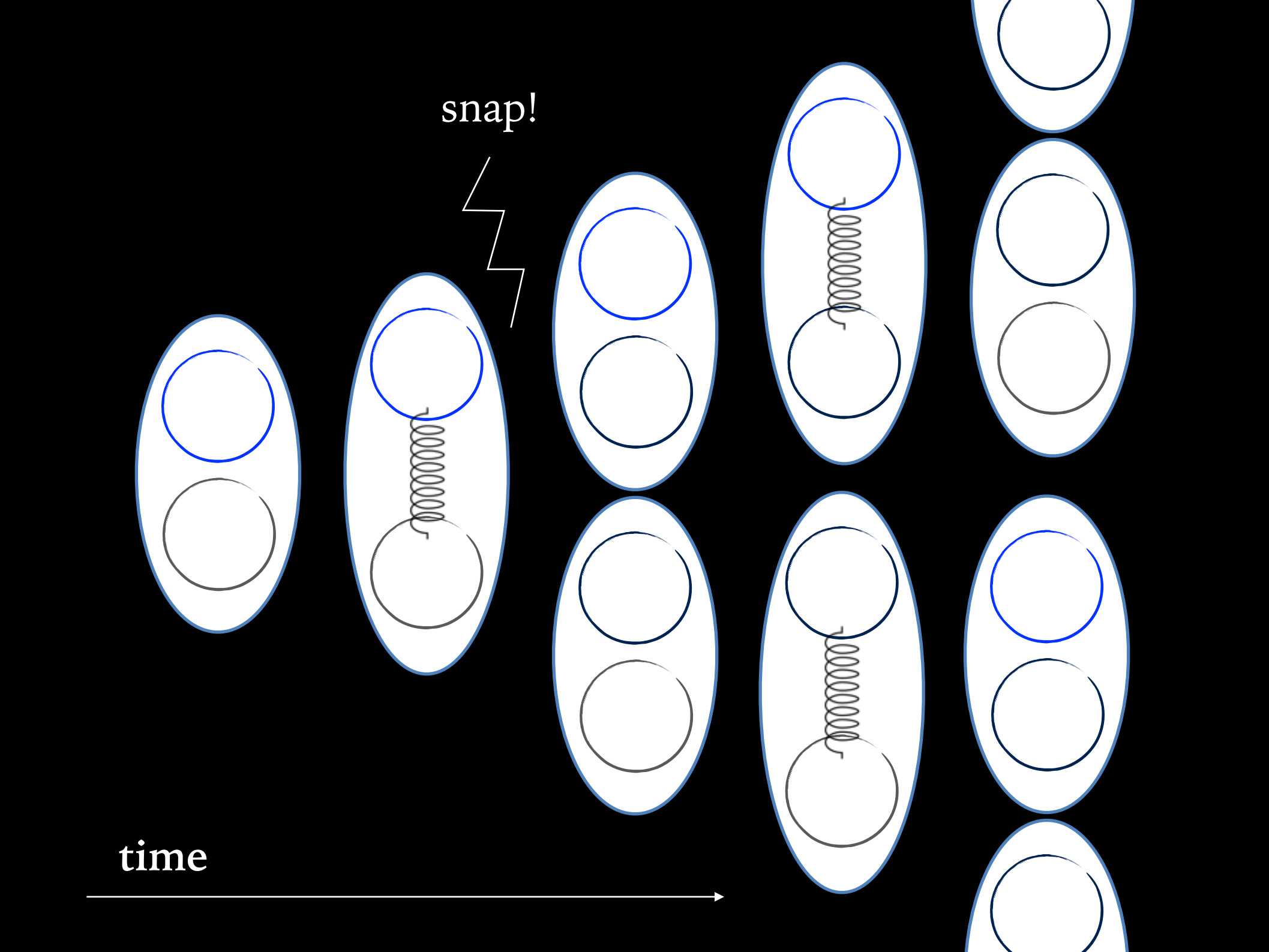


$E=mc^2$

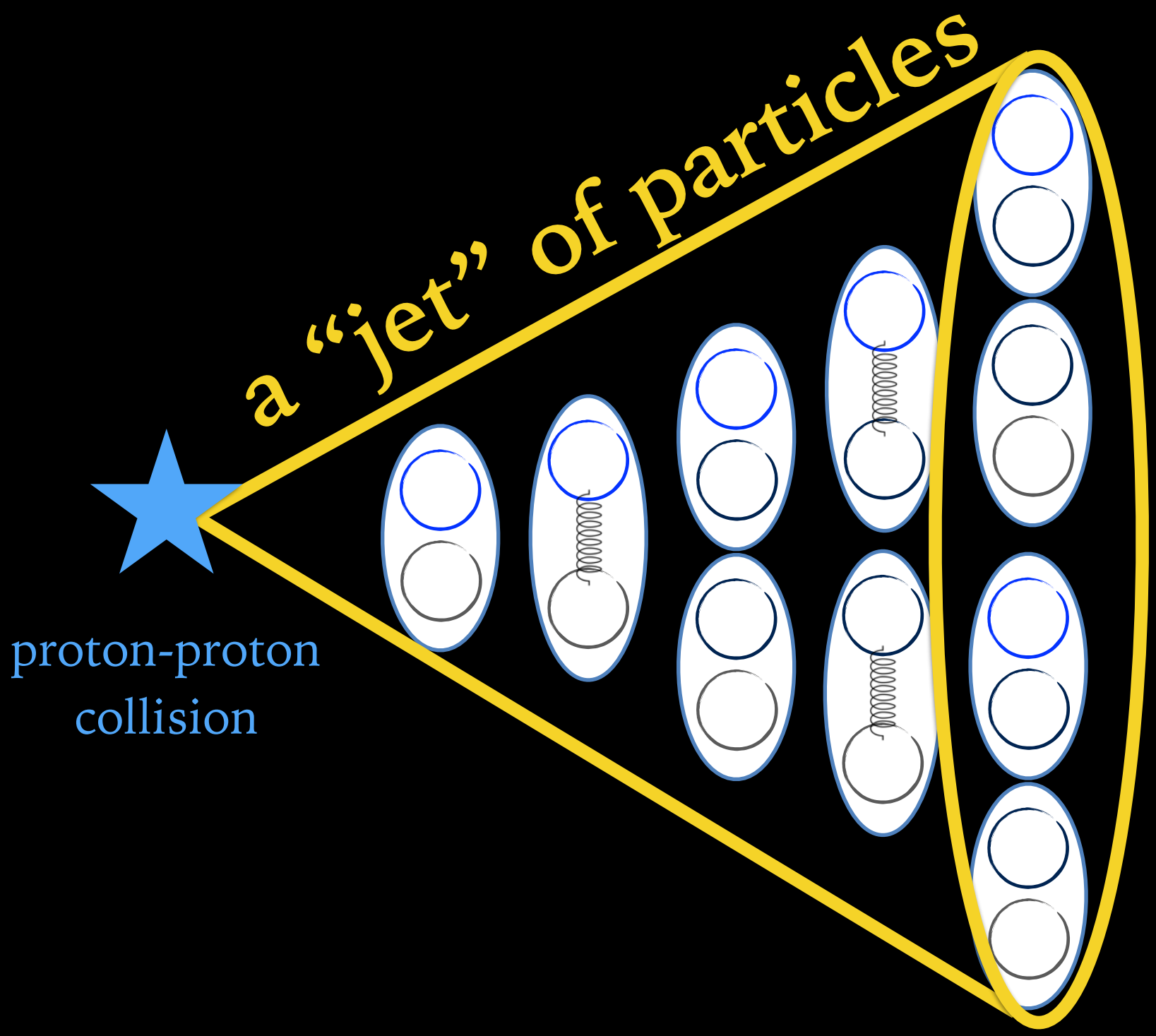
these new particles are unstable
and decay back into quarks



$E=mc^2$

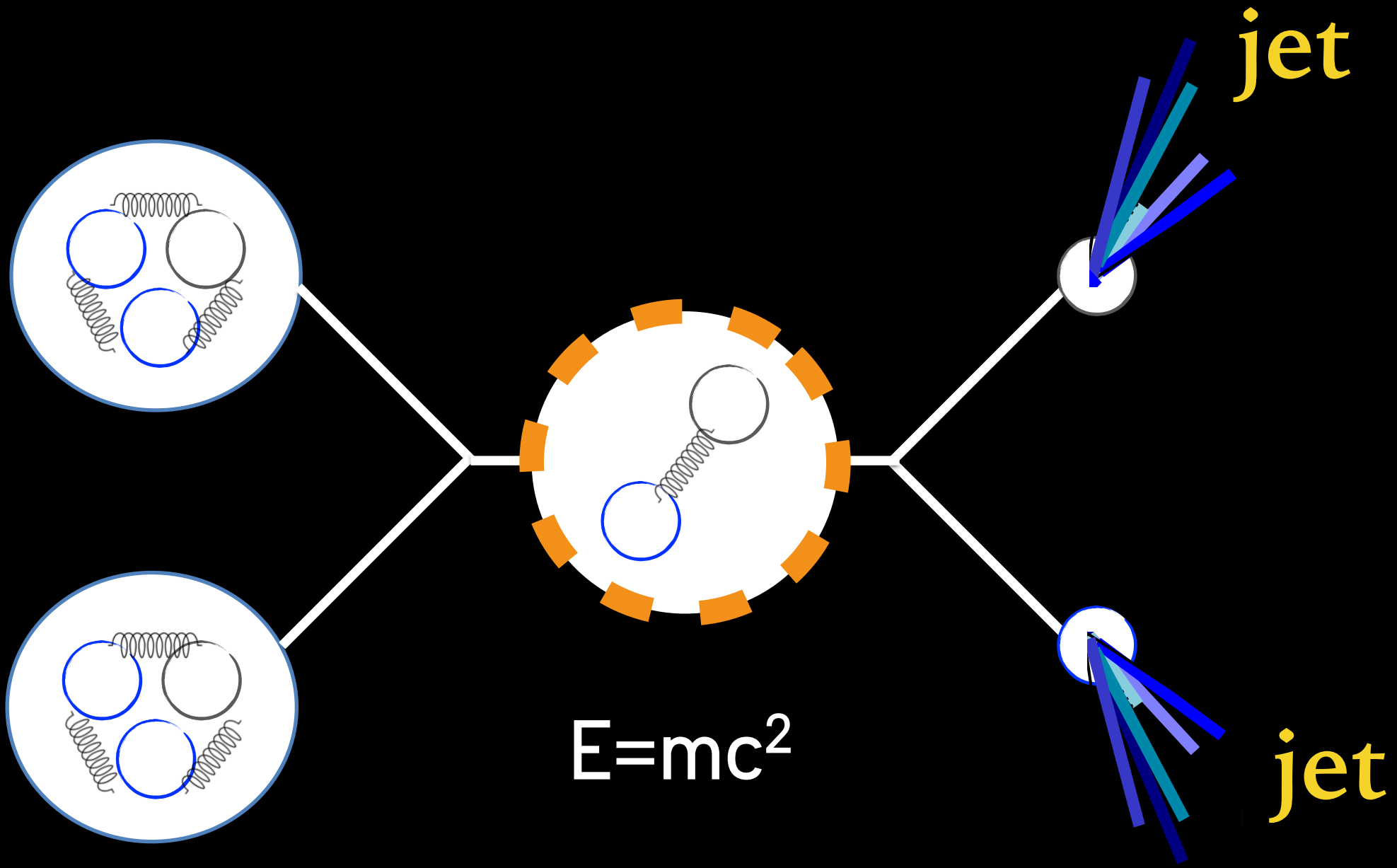

snap!
time


Scandinavian
Airlines
SAS
OY-KBD


a "jet" of particles
proton-proton
collision

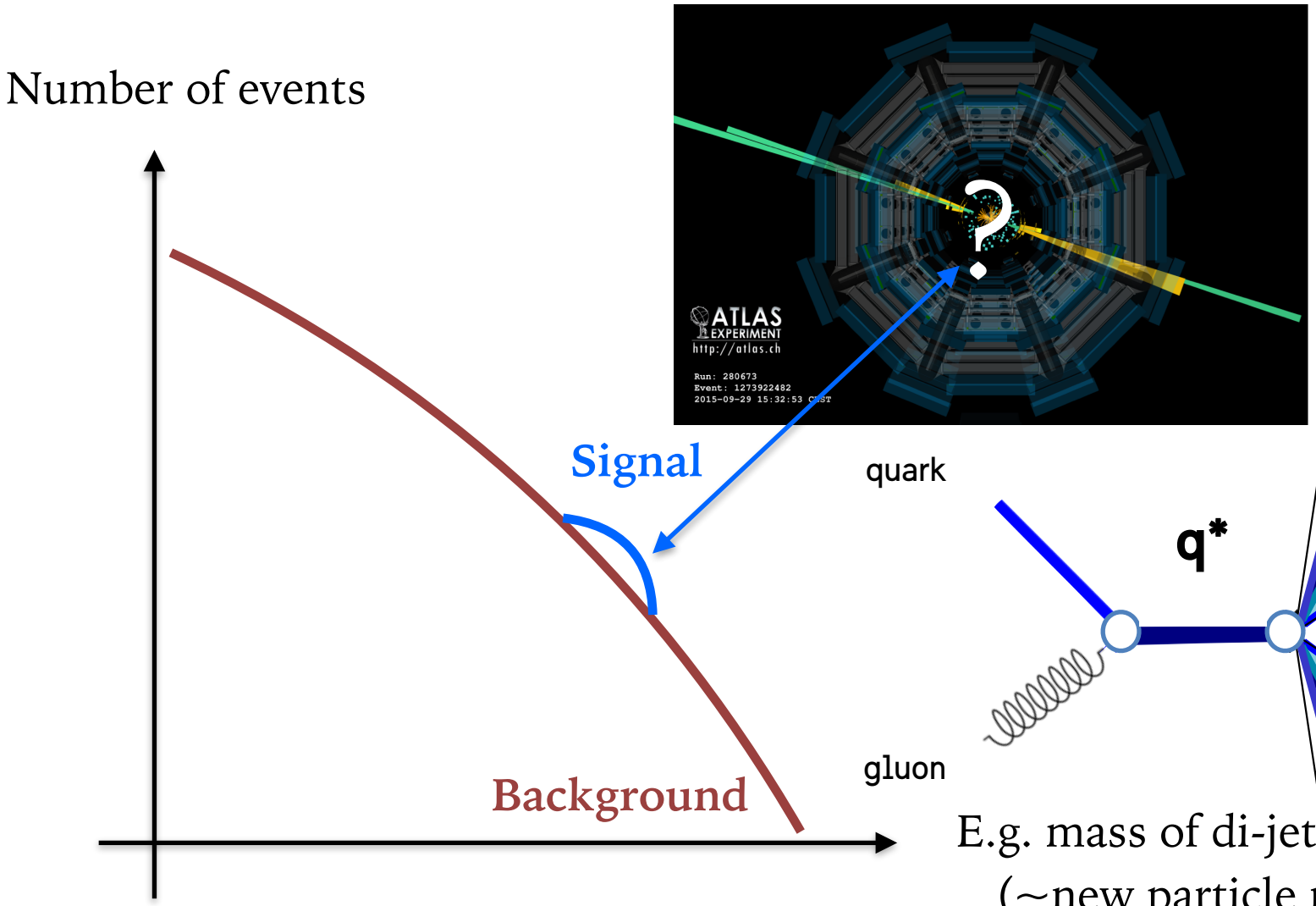
quarks then turn into jets

jets are observed at LHC experiments



How would new phenomena manifest?

New particles: resonant excess (bump) over Standard Model background



E.g. mass of di-jet system
(~new particle mass)

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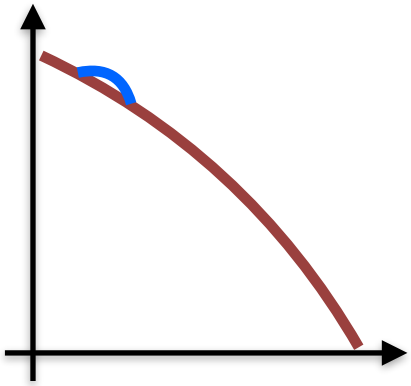
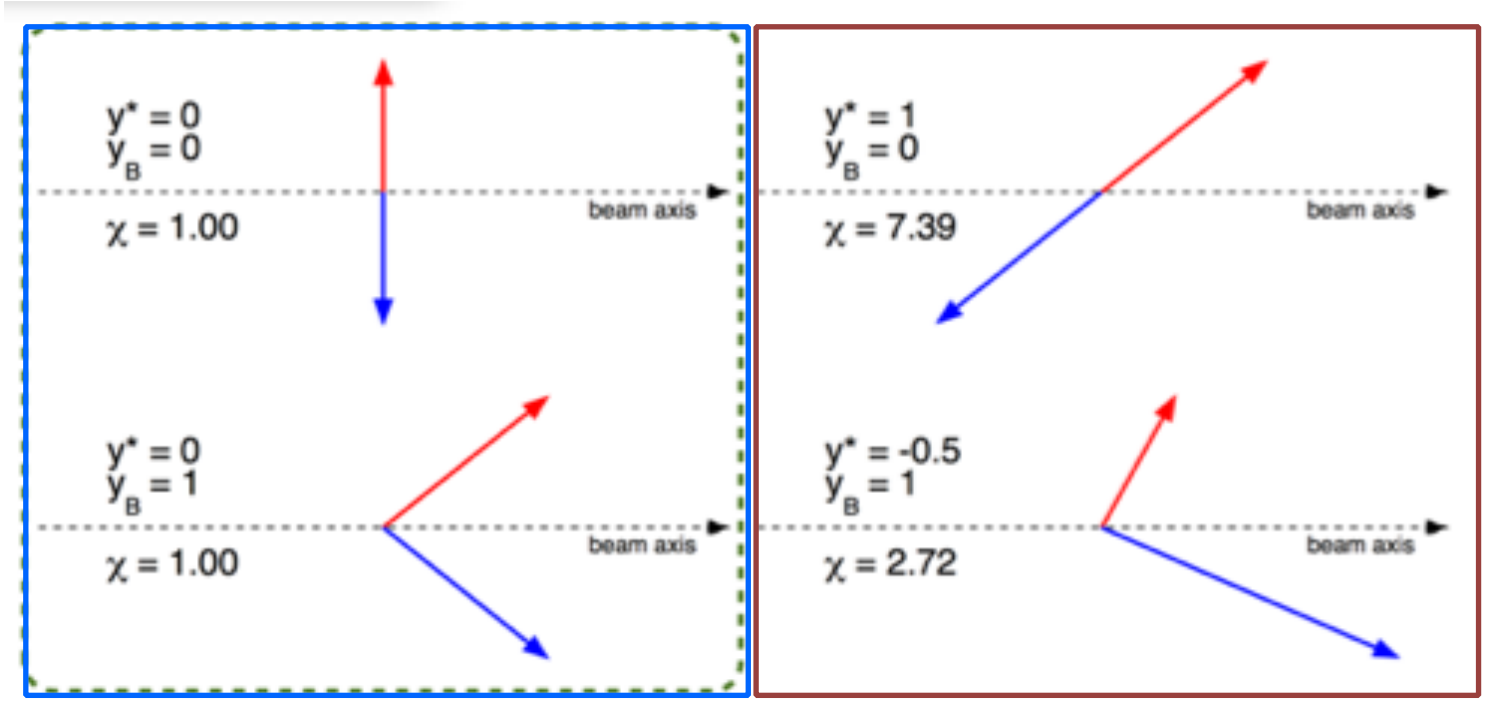
How would new phenomena manifest?

New interactions: more central production with respect to backgrounds

Dag Gillberg, ICHEP 2012



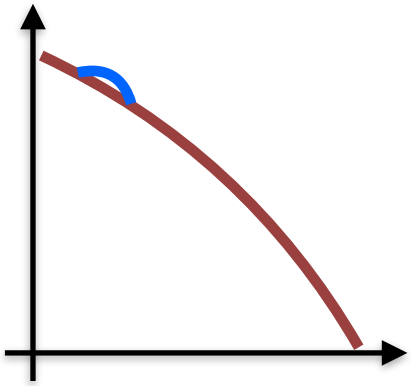


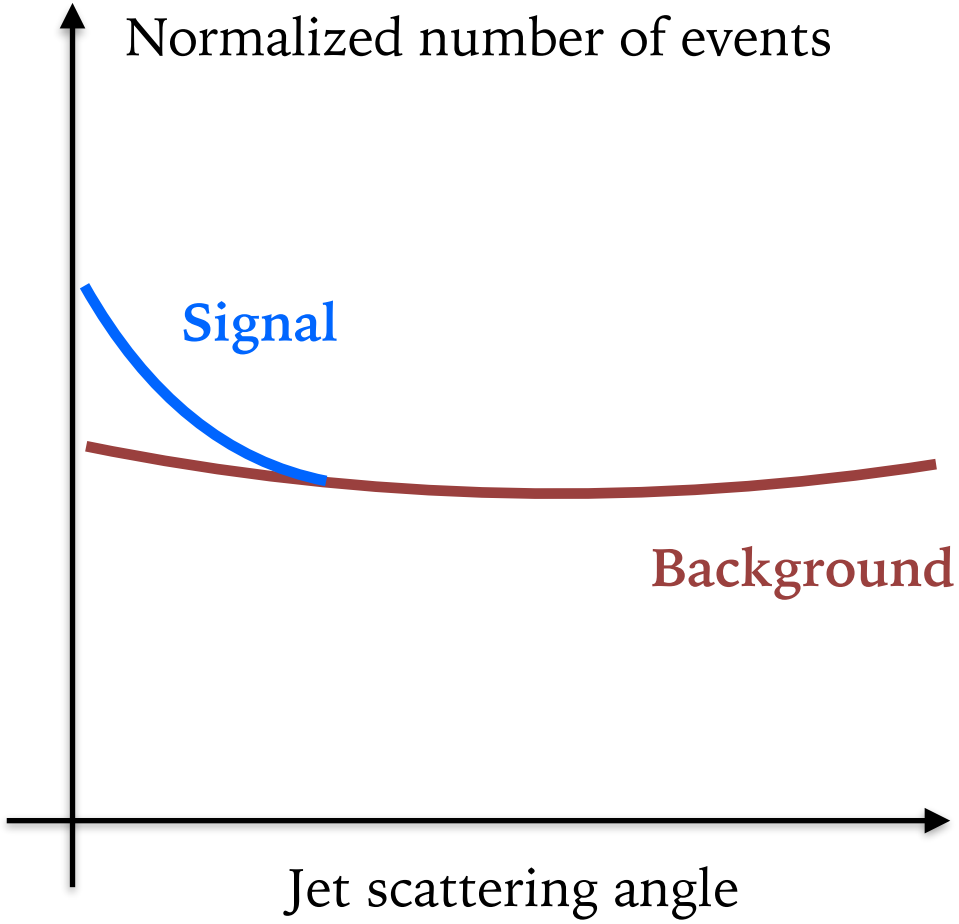
signal:
more central events

background:
more forward events

How would new phenomena manifest?

New interactions: more central production with respect to backgrounds



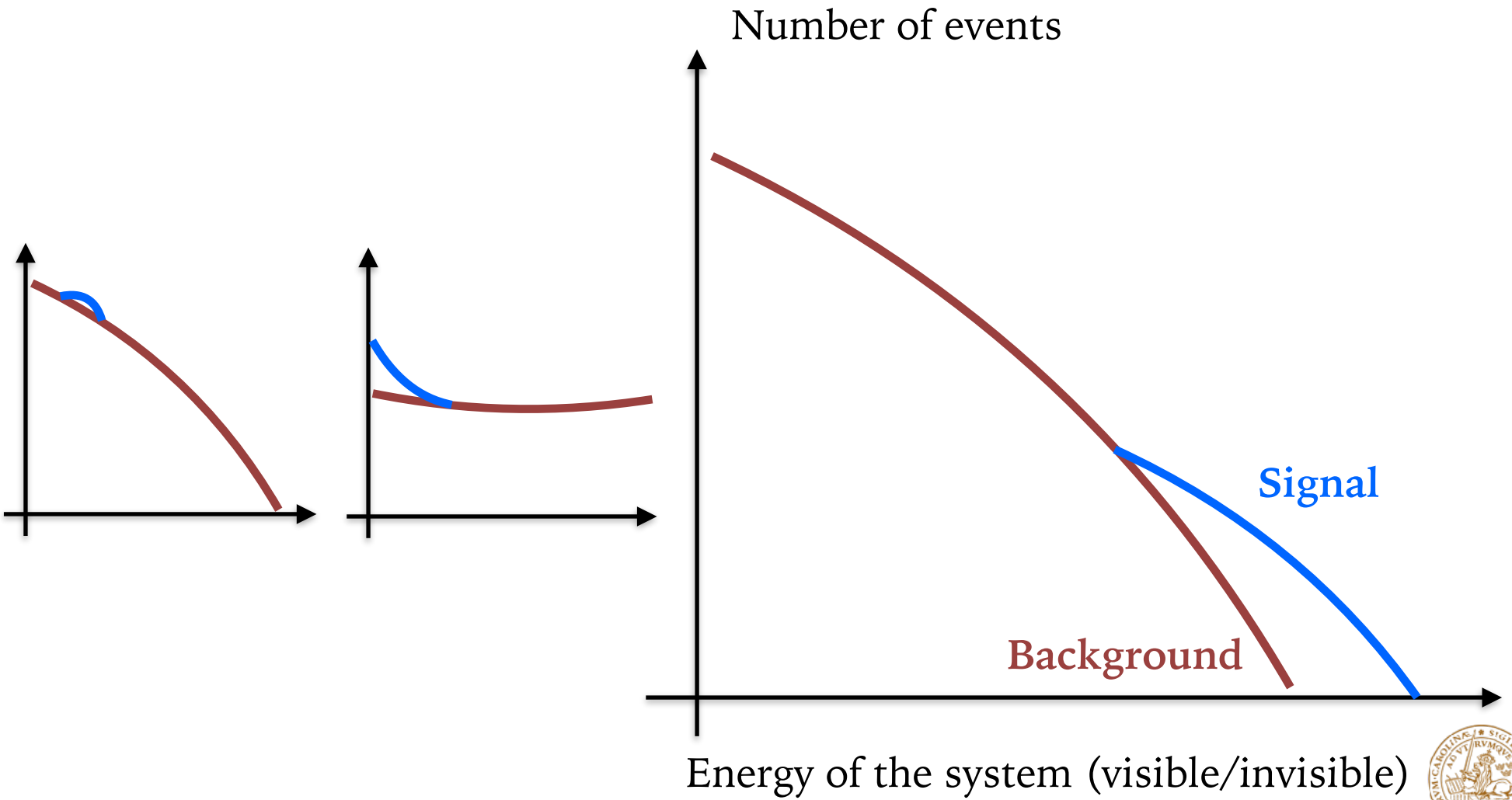


more central events

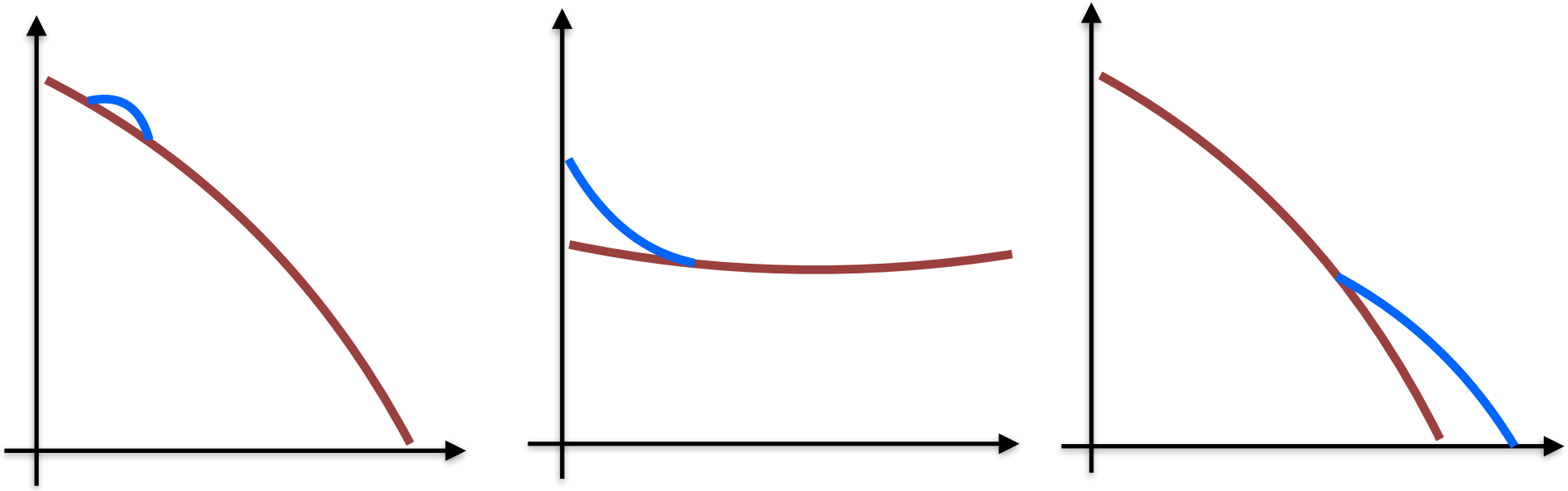
more forward events

How would new phenomena manifest?

New particles and states: larger multiplicity of objects at high masses



How would new phenomena manifest?



These are just **examples** of distributions analysed in ATLAS searches

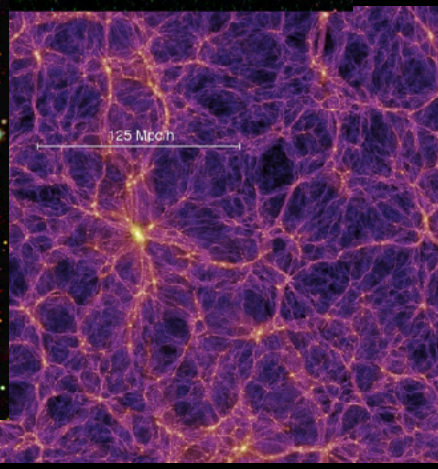
Now we are equipped with the tools to discover…

Dark Matter at the Large Hadron Collider and at other experiments

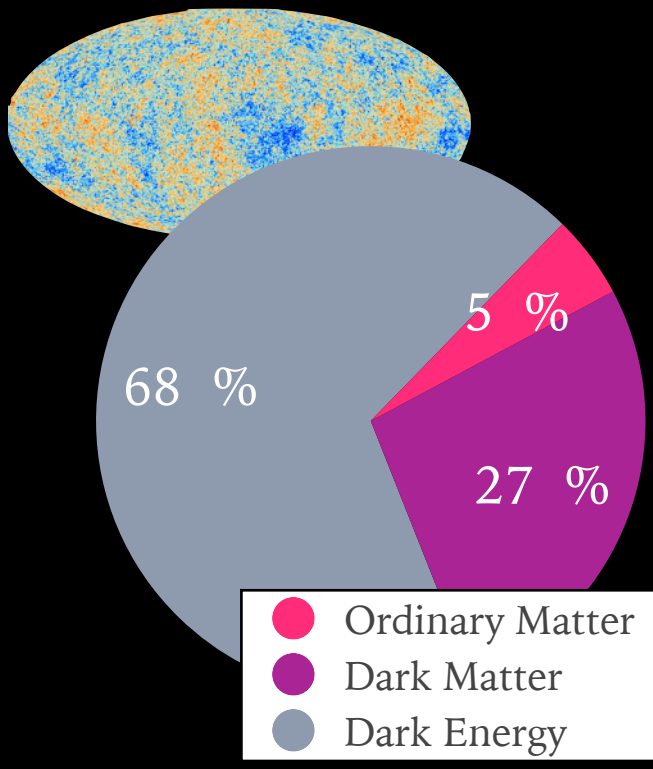
it is dark

it is dark

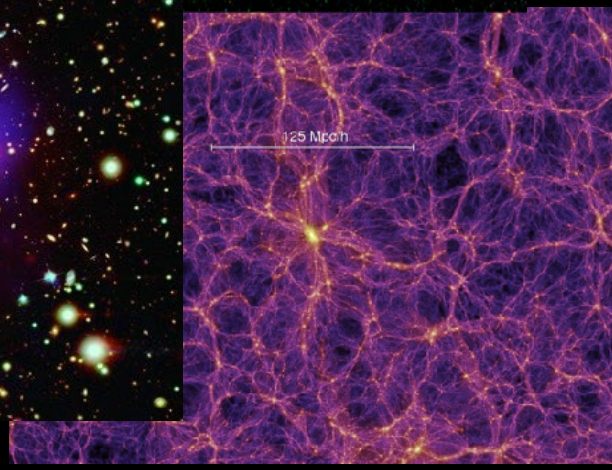
it has mass



it is dark



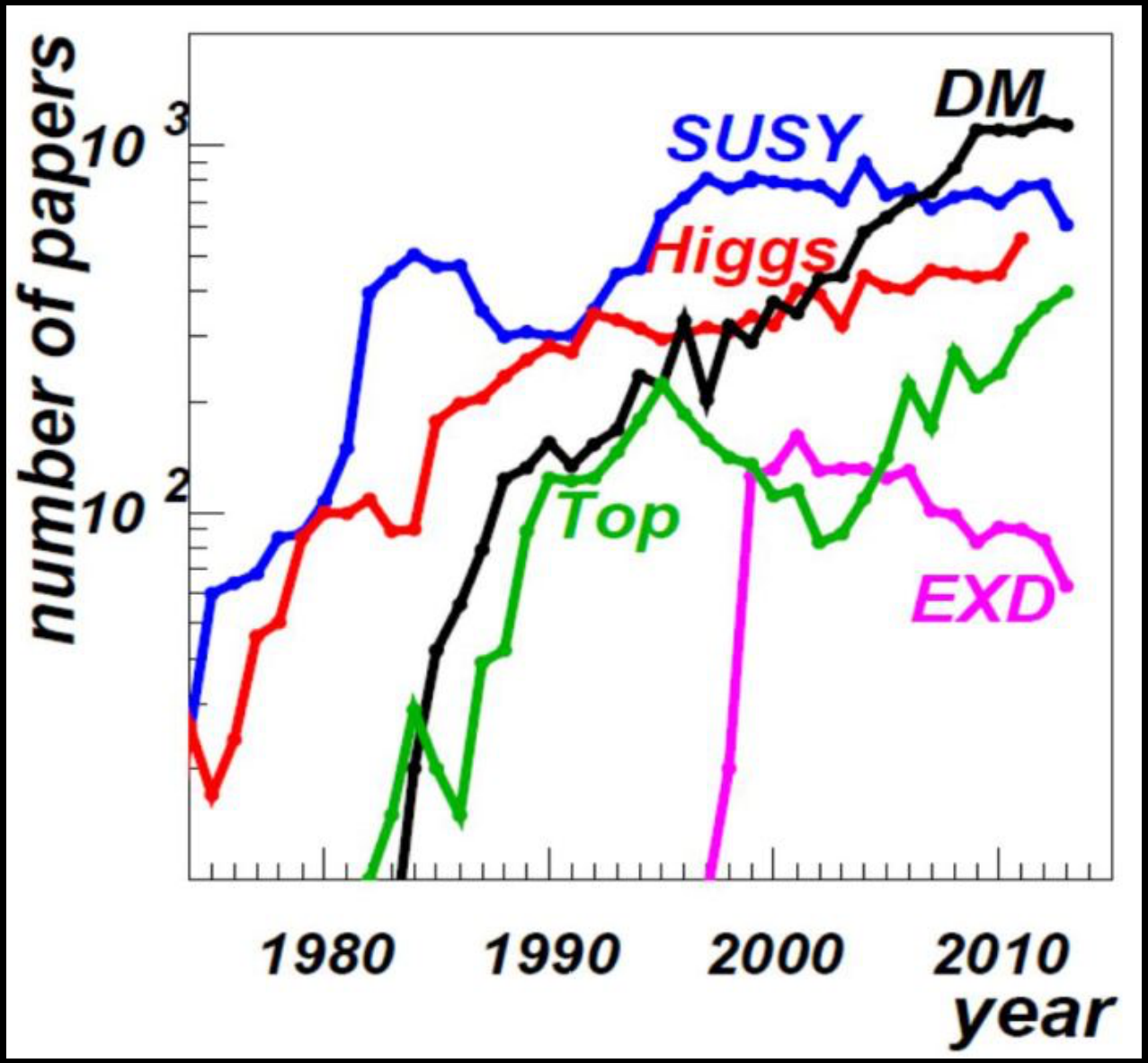
it has mass



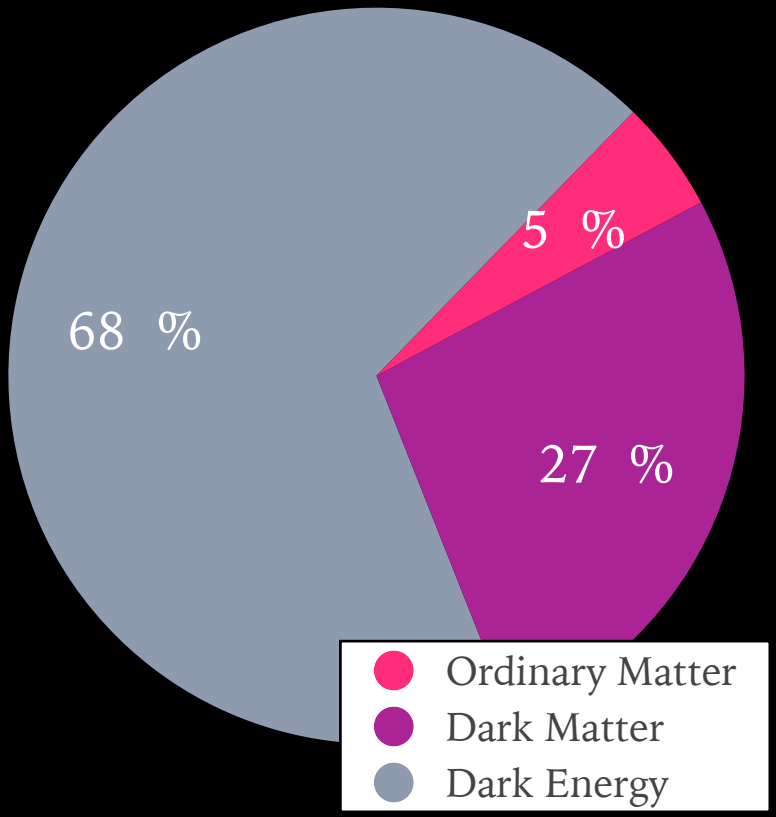
it constitutes
most of the matter
in the universe

(either that, or we need to rethink gravity)

many physicists are talking about it



A. Belyaev



it constitutes
most of the matter
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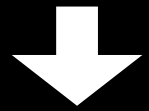


relic density

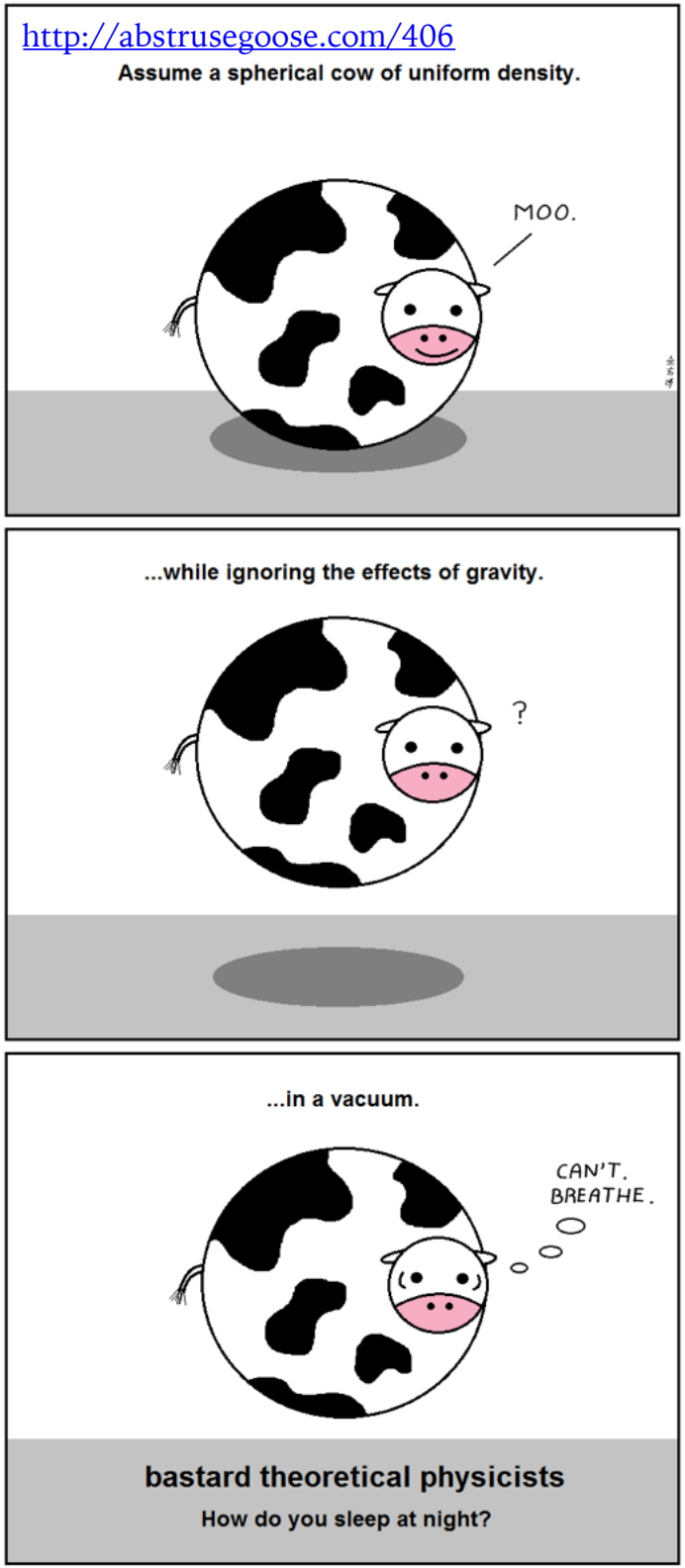
This relic density can be explained with

a new particle

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

(Weakly Interacting Massive Particle)

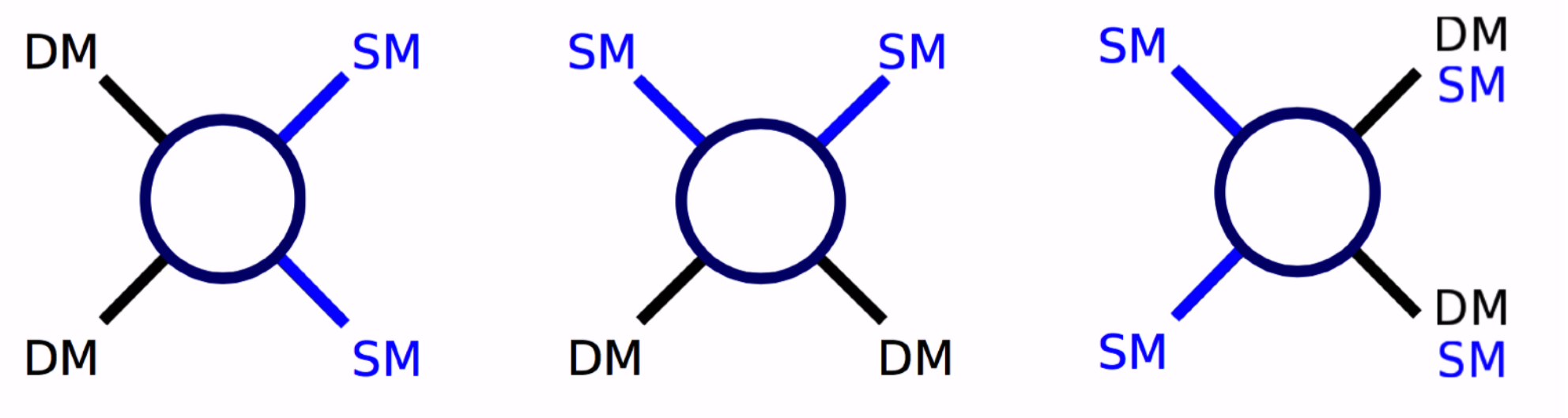
Under these assumptions…



...we could discover Dark Matter!

Dark Matter in different experiments

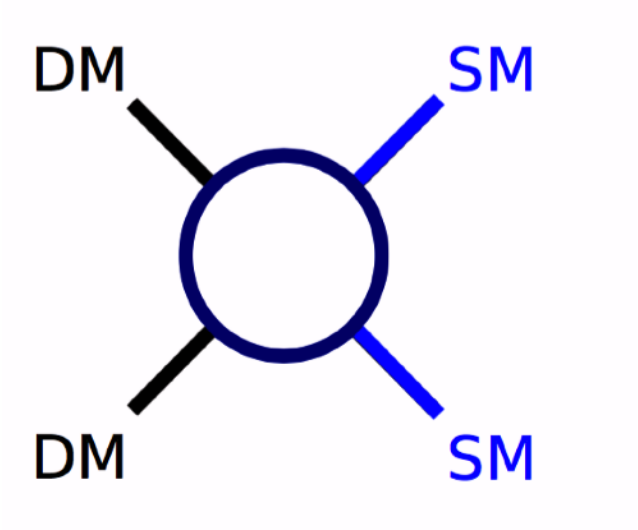
Dark Matter — **Ordinary particles**



Indirect Detection | Direct Detection | Particle Colliders

Complementary experimental strategies
All looking for **small signals**
over **large, complex backgrounds**

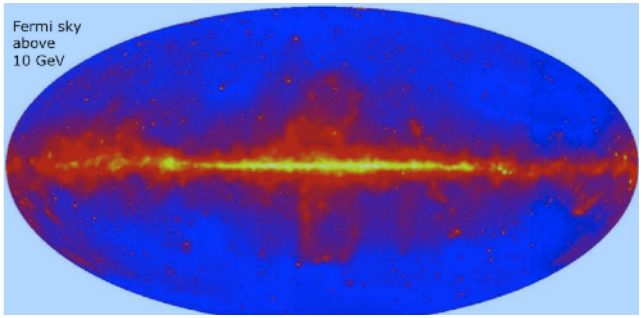
Indirect Detection: example



Indirect Detection

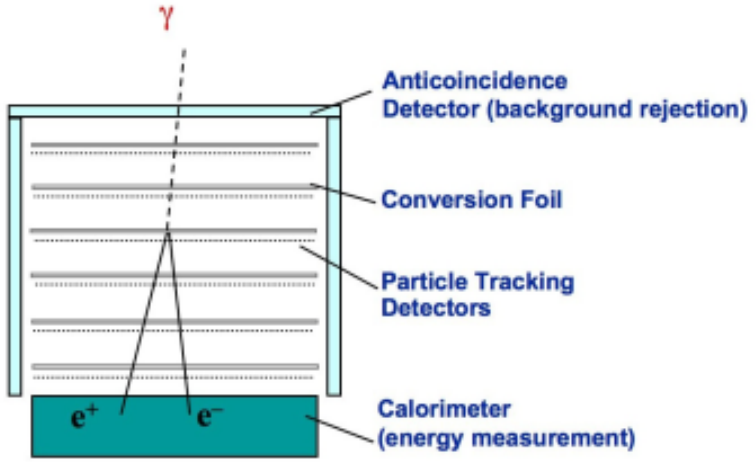
Dark Matter annihilates in the GC / dwarf galaxies (a place) to photons (some particles), which are detected by Fermi, HESS, … (an experiment).

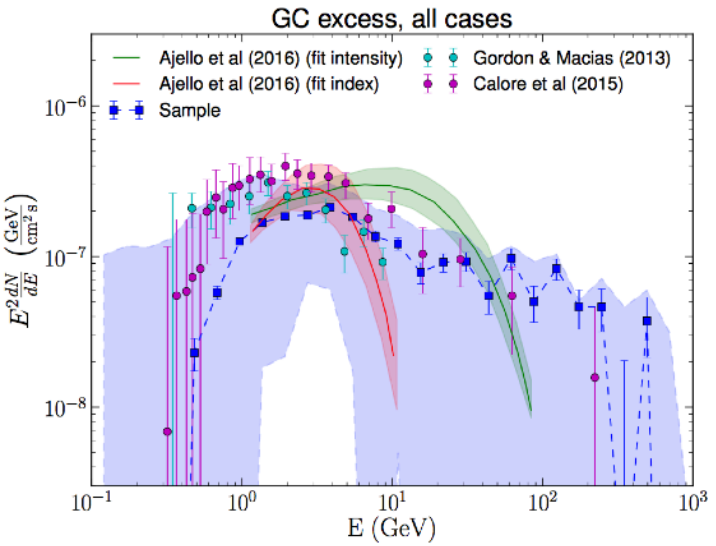
J. Feng



Fermi Large Area Telescope

https://www-glast.stanford.edu/





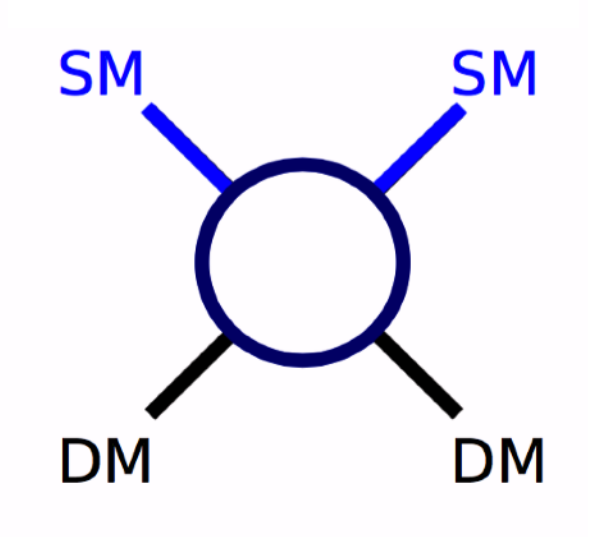
https://arxiv.org/abs/1704.03910

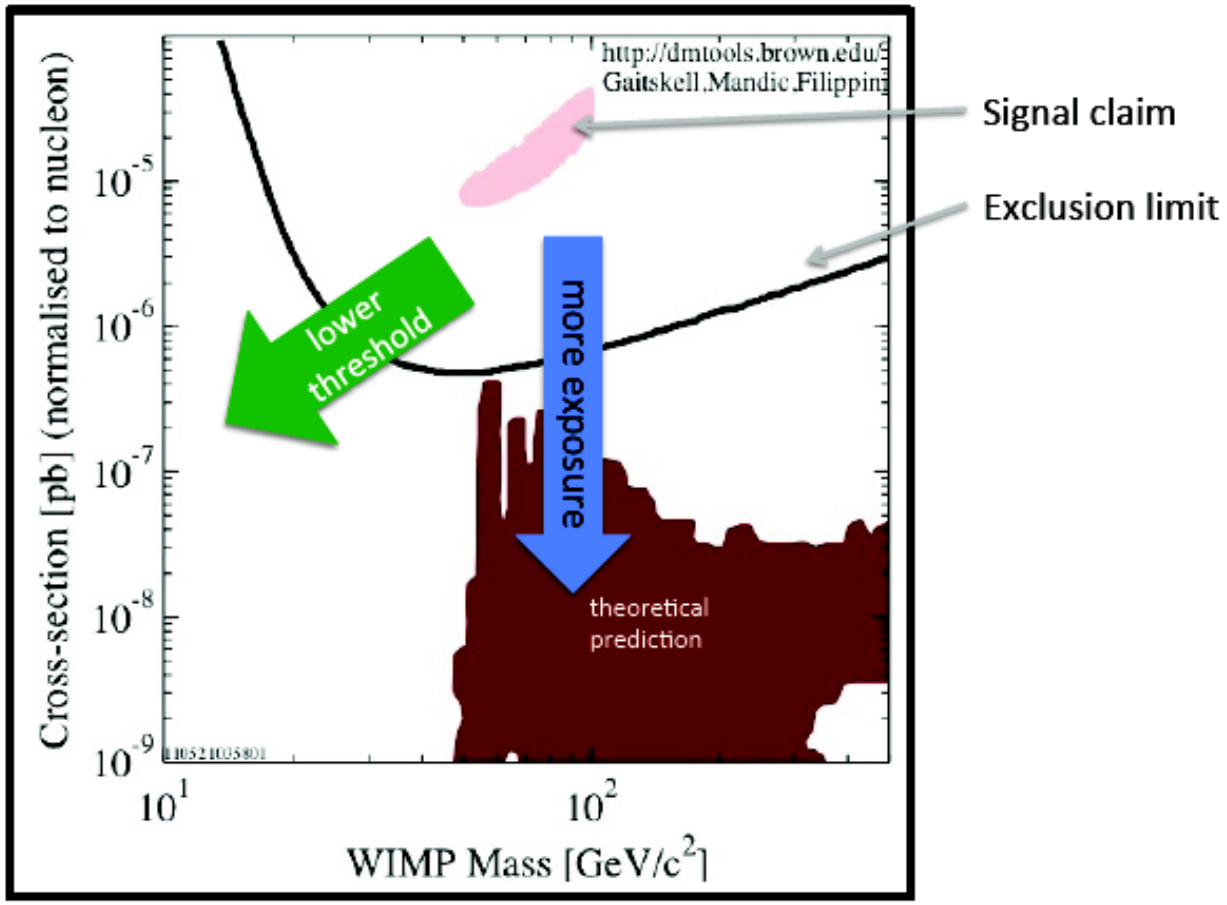
Also: *interesting* results from DAMA, AMS

Direct Detection: examples

We don't know Dark Matter interaction frequency or mass!

Direct Detection



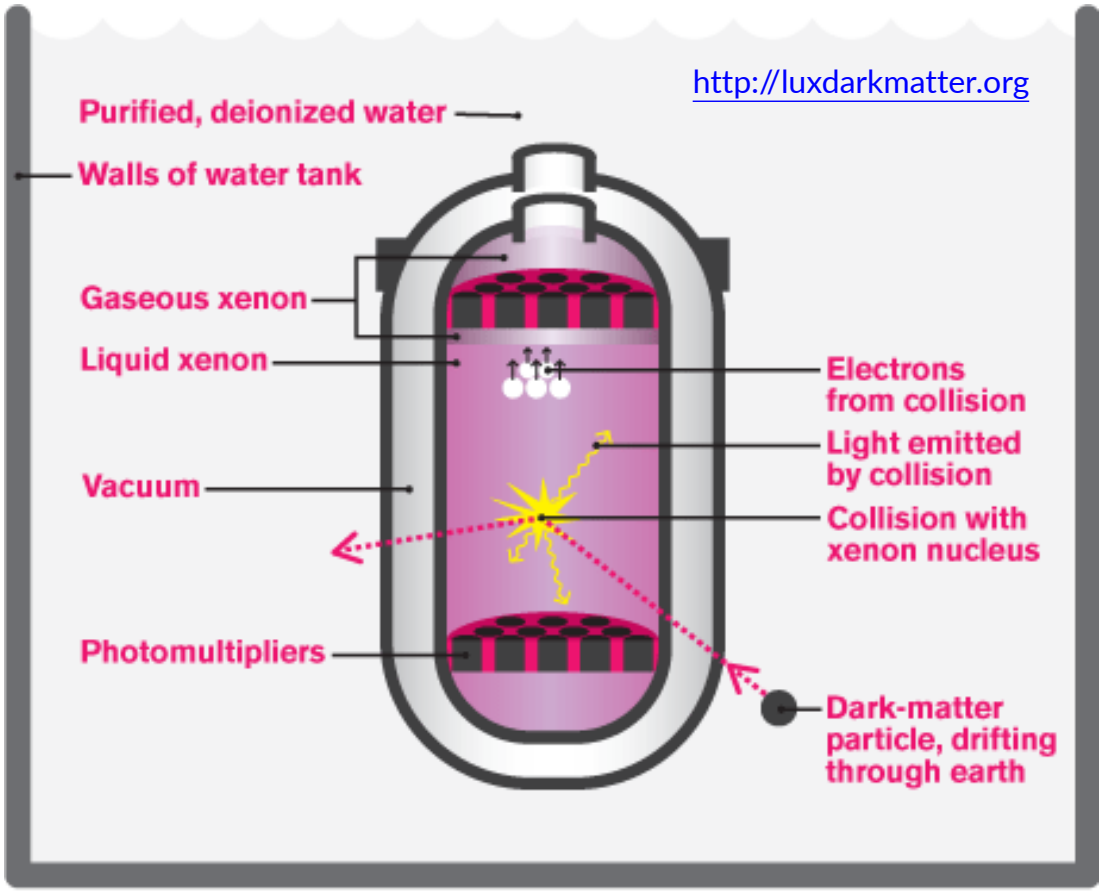


Raimund Strauss, MPI Munich 8

R. Strauss

Direct Detection: examples

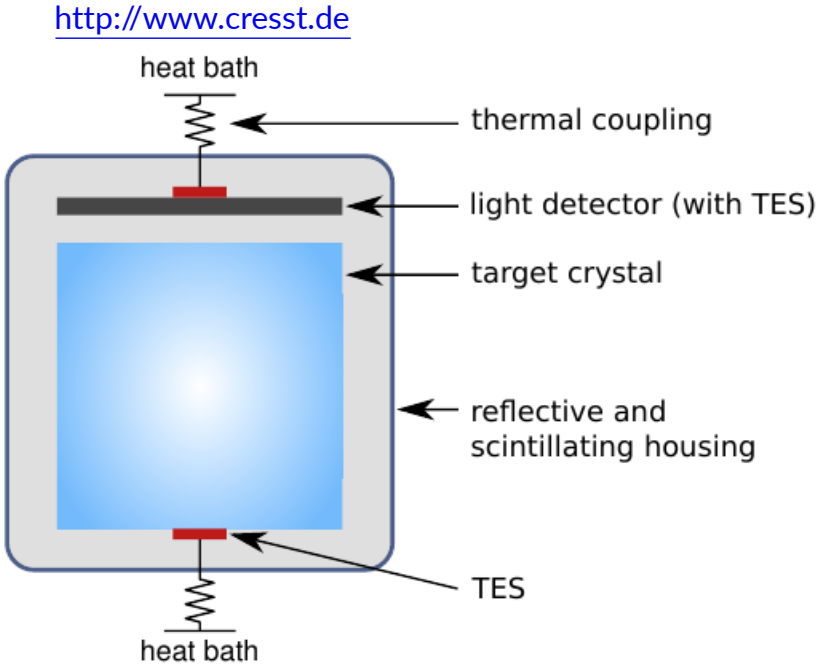
High Dark Matter mass: **LUX**



LUX detector

Large volume
(order: 10s of meters)

Low Dark Matter mass: **CRESST**



Very sensitive, smaller volume
(order: 10s of centimeters)

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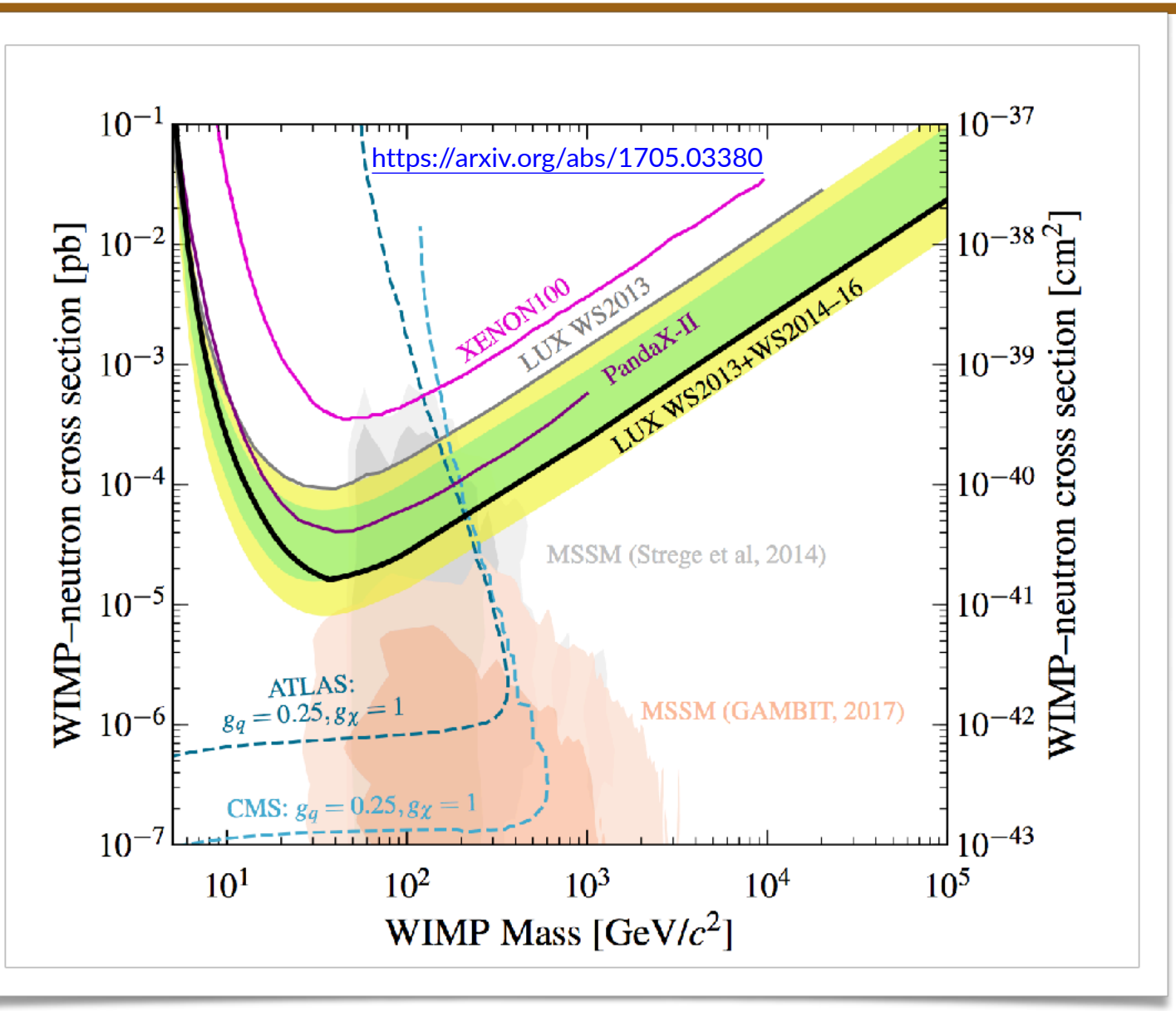
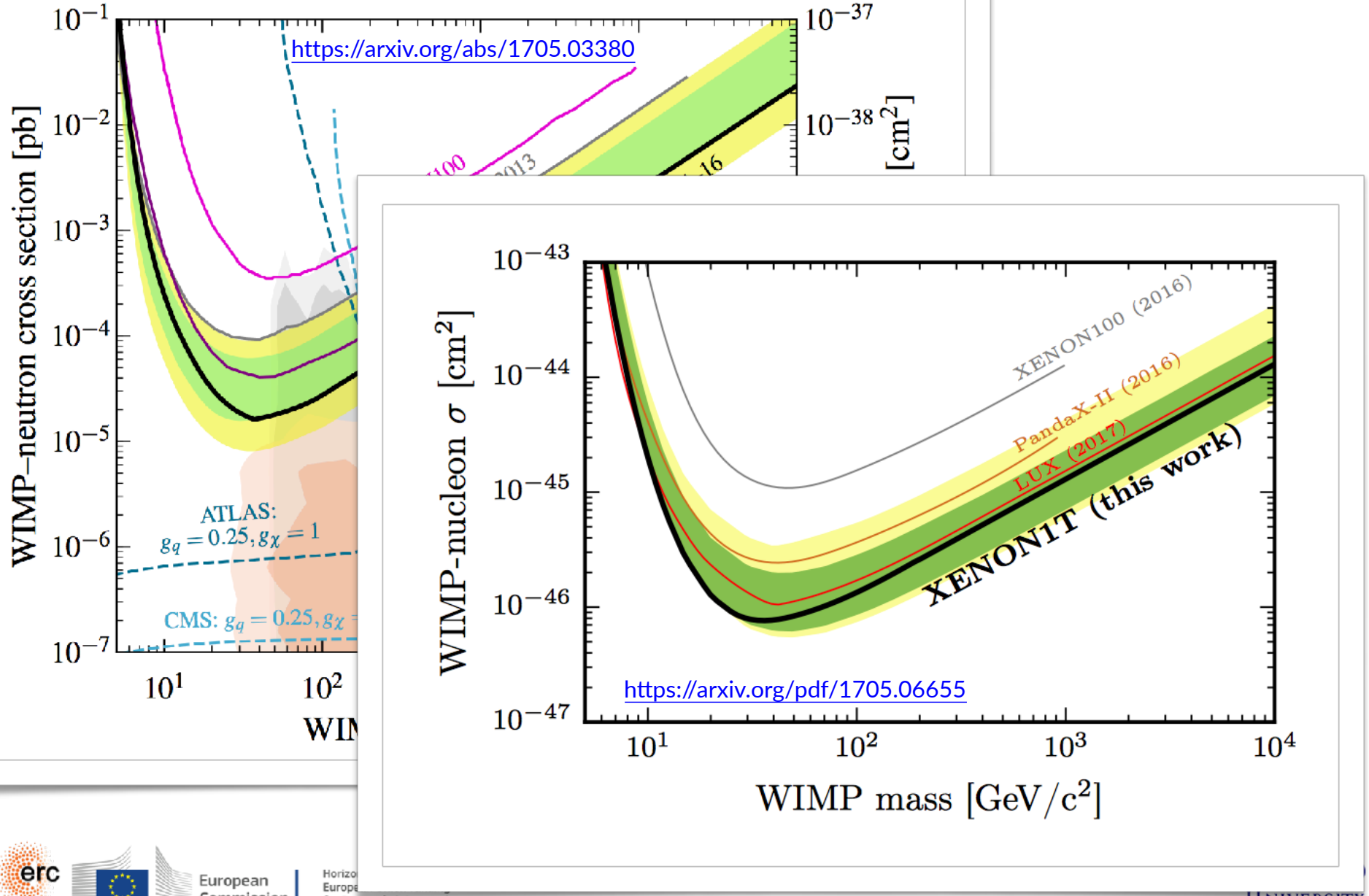
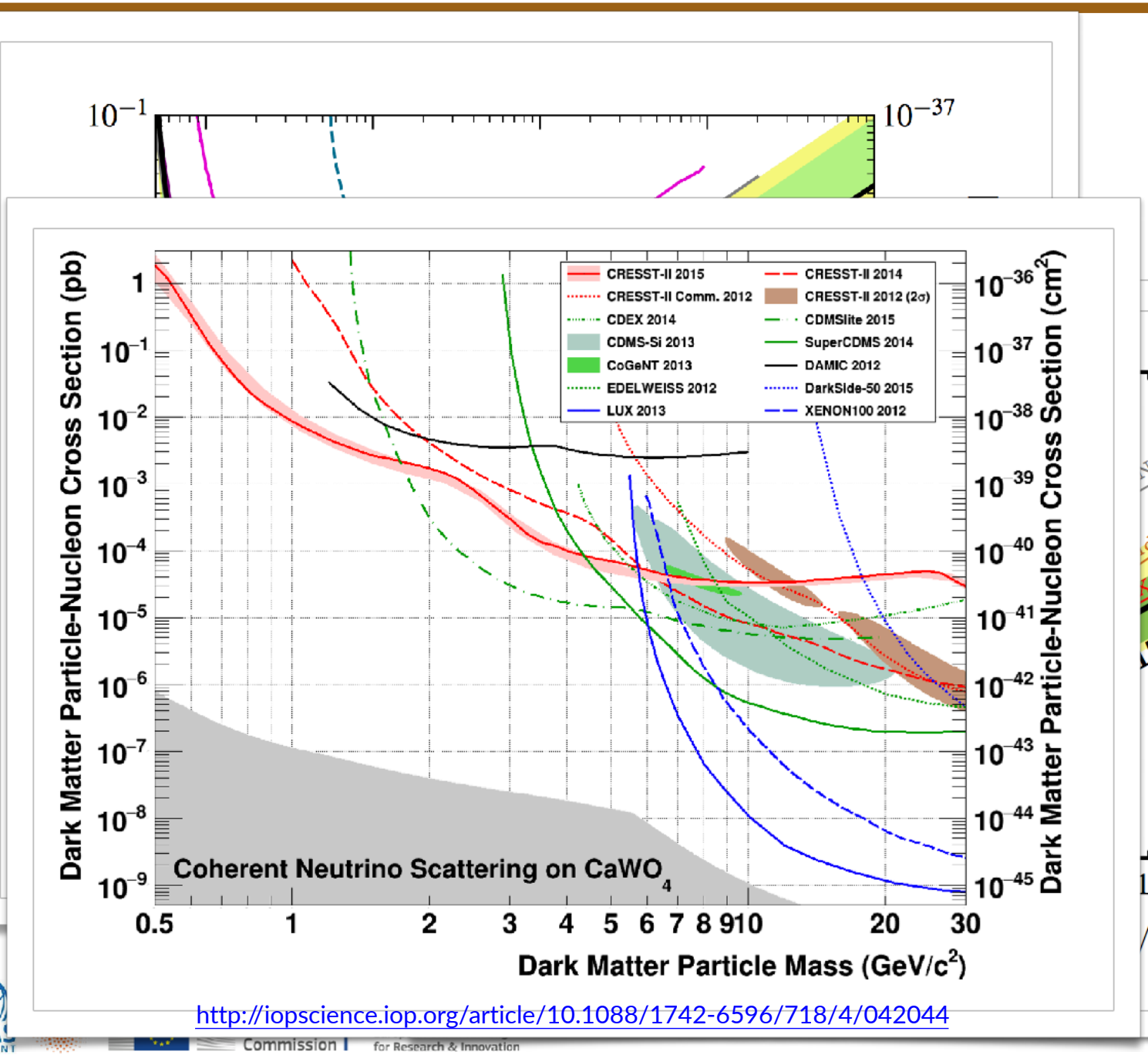
Direct Detection: example results



Direct Detection: example results

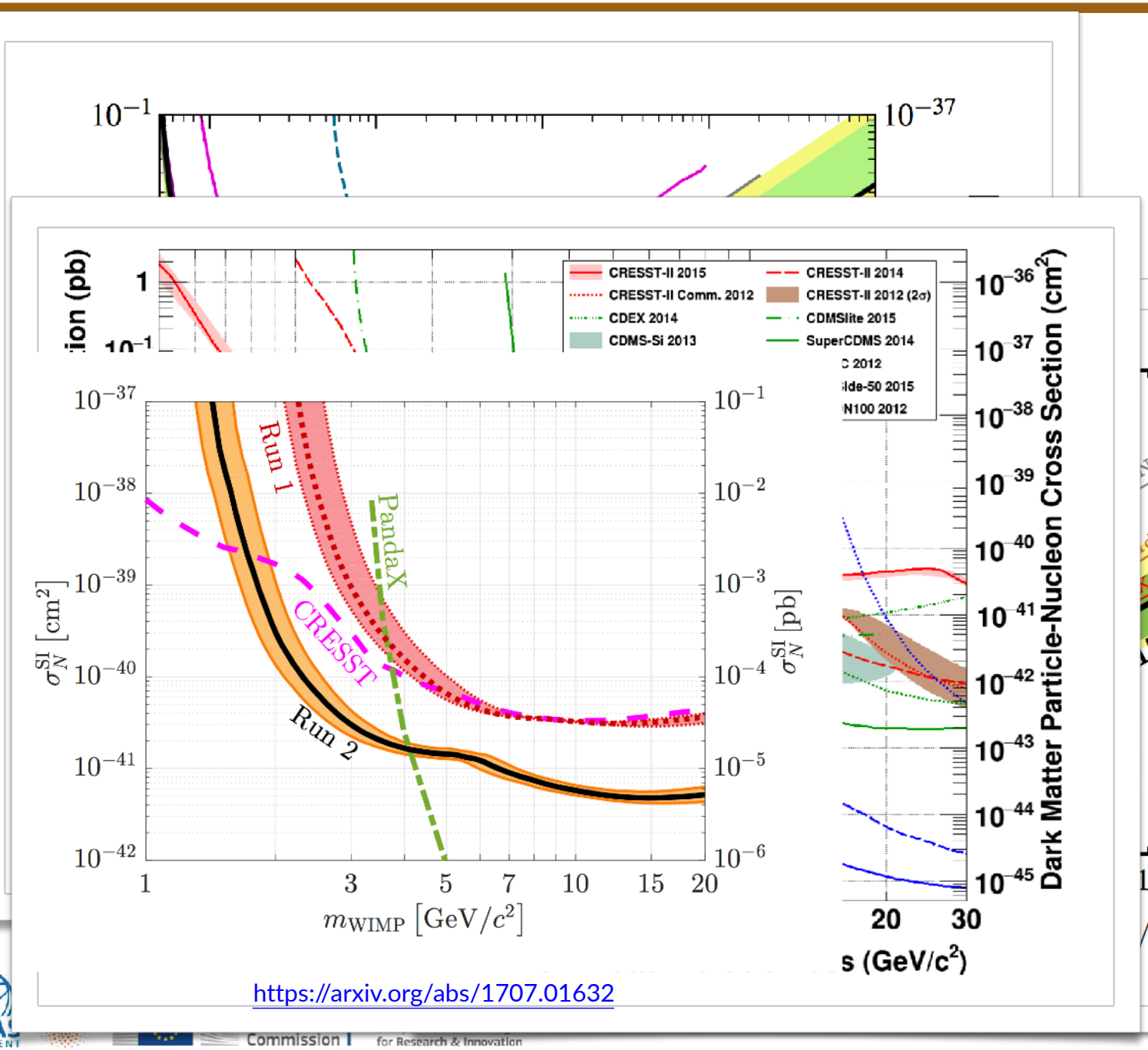


Direct Detection: example results



http://iopscience.iop.org/article/10.1088/1742-6596/718/4/042044

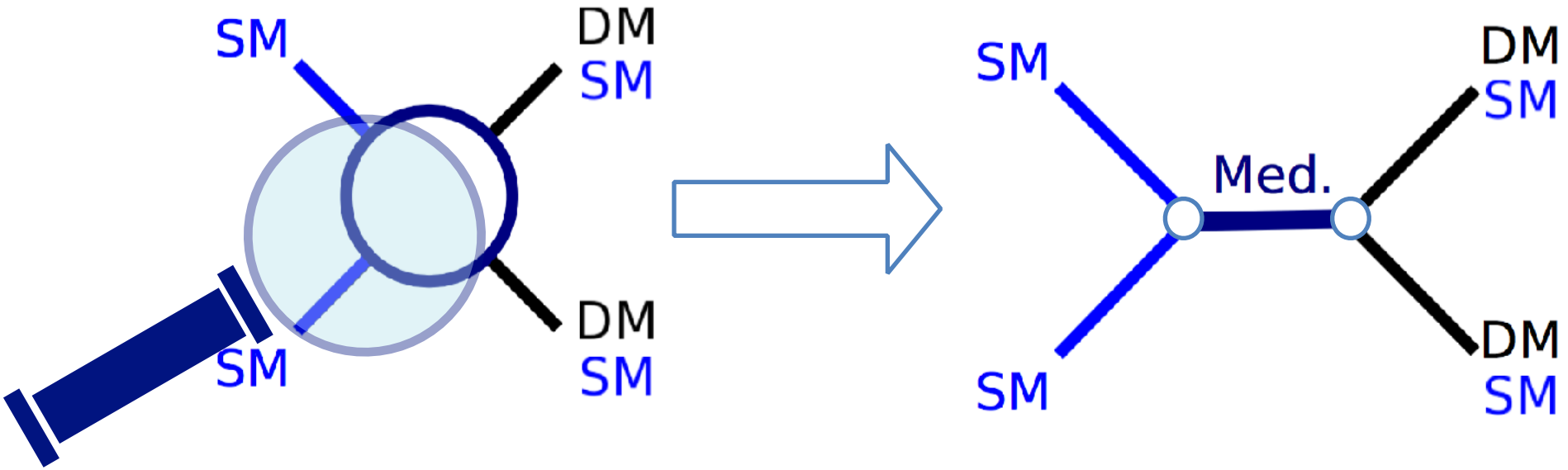
Direct Detection: example results



https://arxiv.org/abs/1707.01632

Dark Matter mediators at the LHC

If there's a force there's a mediator:



Particle Colliders

Can look for both invisible and visible decays of the mediator

(this talk: case in which the mediator is a new particle, but it can also be a known particle)

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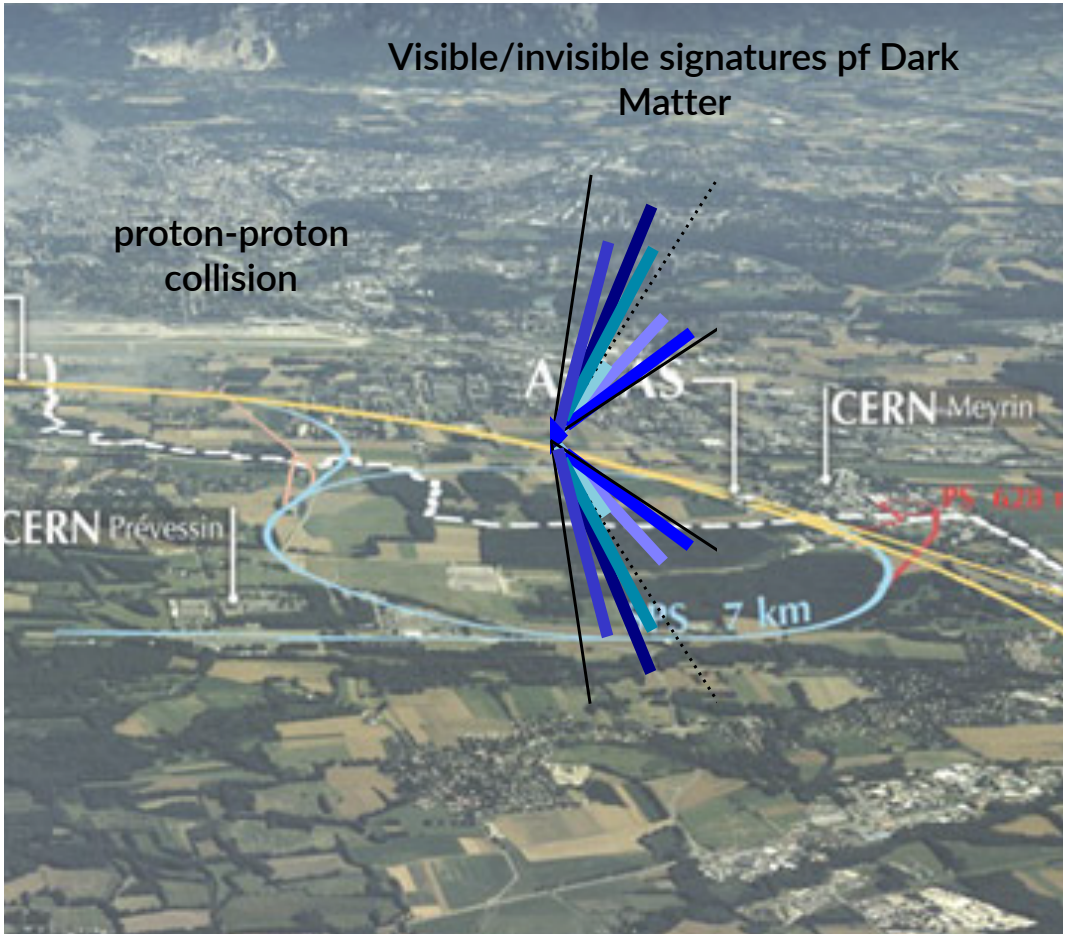
Where to start? Dark Matter Working Group

ATLAS, CMS and theory, within LHC Physics Centre (LPCC)

- Mandate:
  - Define guidelines and recommendations for the benchmark models, interpretation and characterisation for broad and systematic DM searches at the LHC
    - Example: agree on **classes of benchmark models** used for experimental searches
    - Example: **improve tools** available to the experiments, such as higher-precision calculations of signals/backgrounds
  - Connect with broader DM community towards comprehensive understanding of viable dark matter models



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Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum

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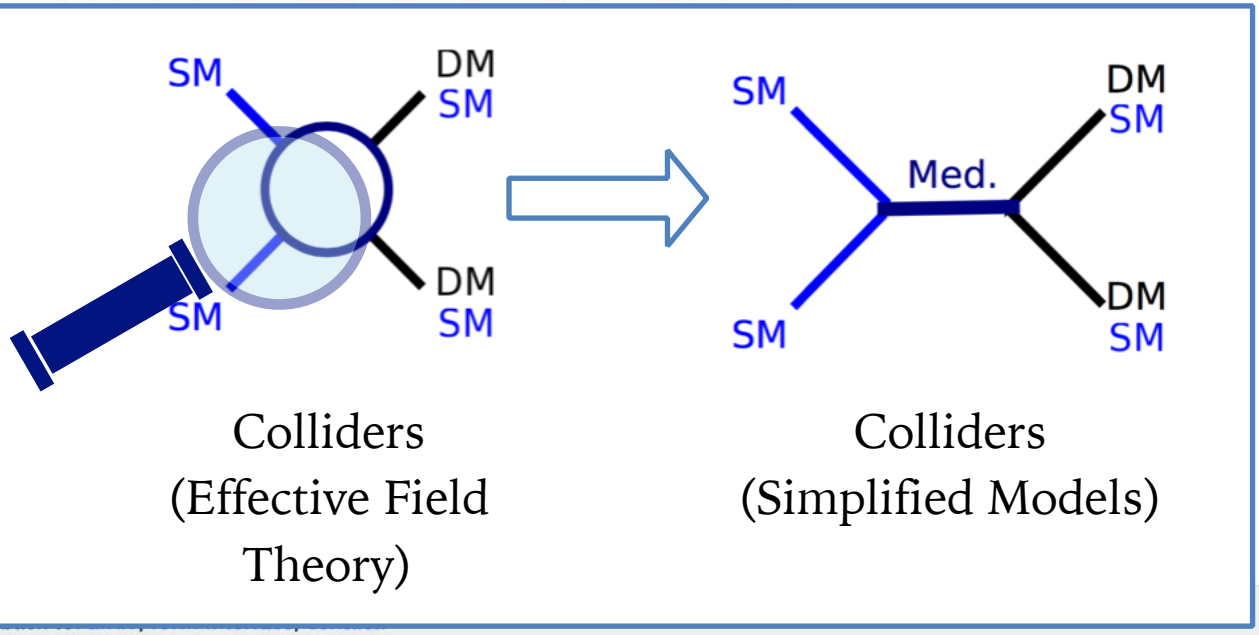

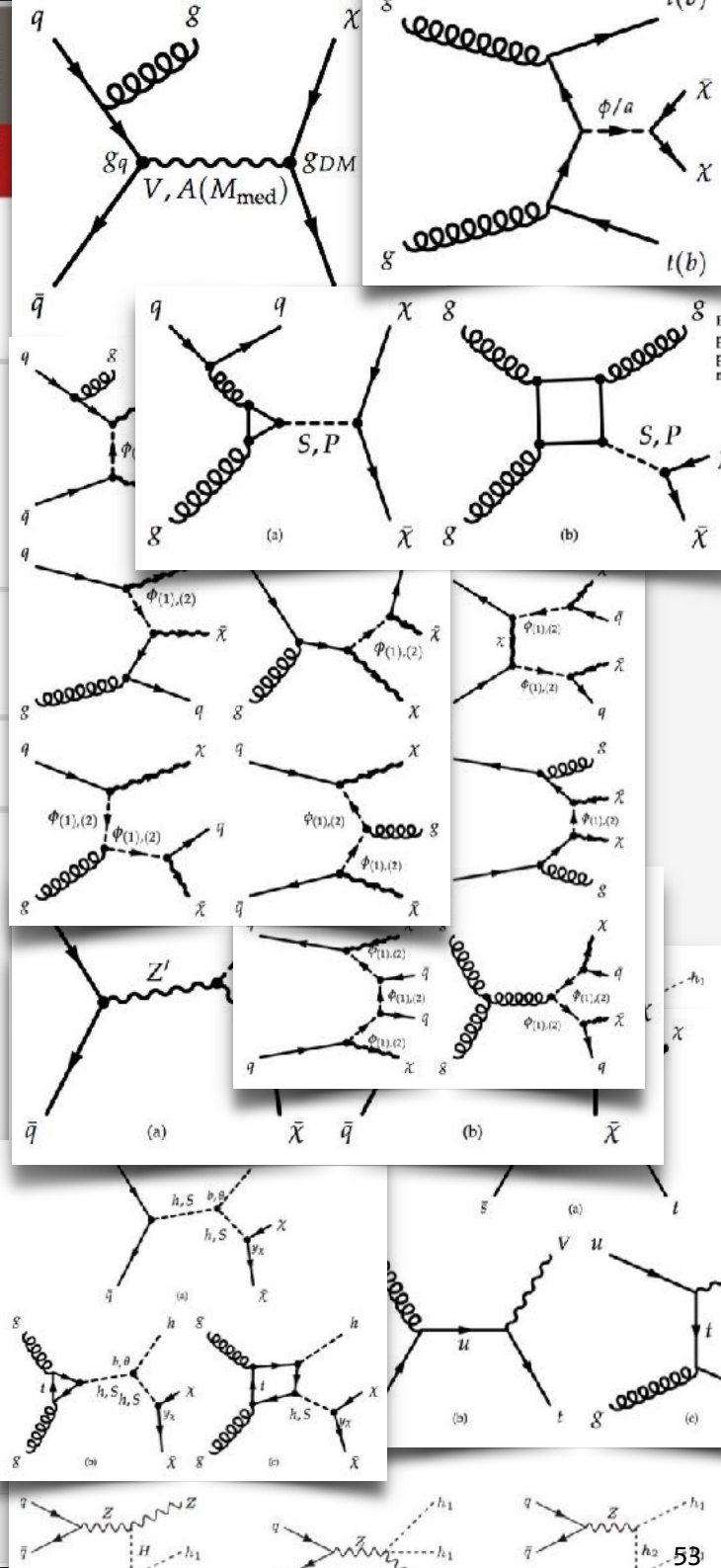

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Simplified models as building blocks for **experimentalists** (designing and performing searches) and **theorists** (building new theories, reinterpreting searches) and as common framework for reinterpretation together with **complementary experiments**

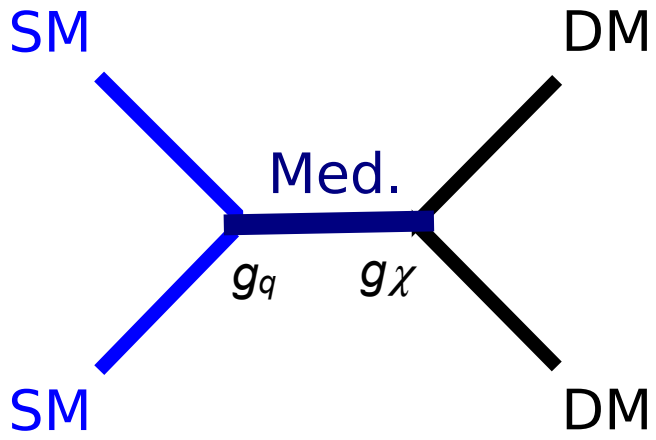
Colliders (Effective Field Theory)

Colliders (Simplified Models)

Searching for Dark Matter (mediators) at the Large Hadron Collider

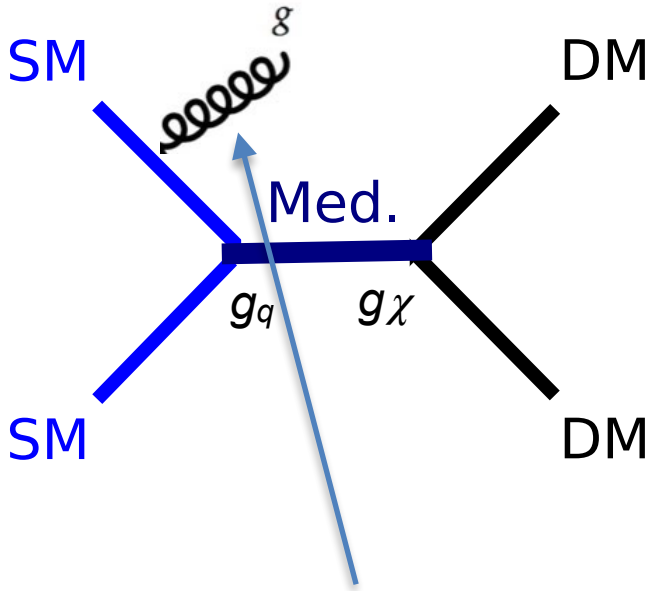
Looking for Dark Matter at the LHC

WIMPs are invisible to detectors

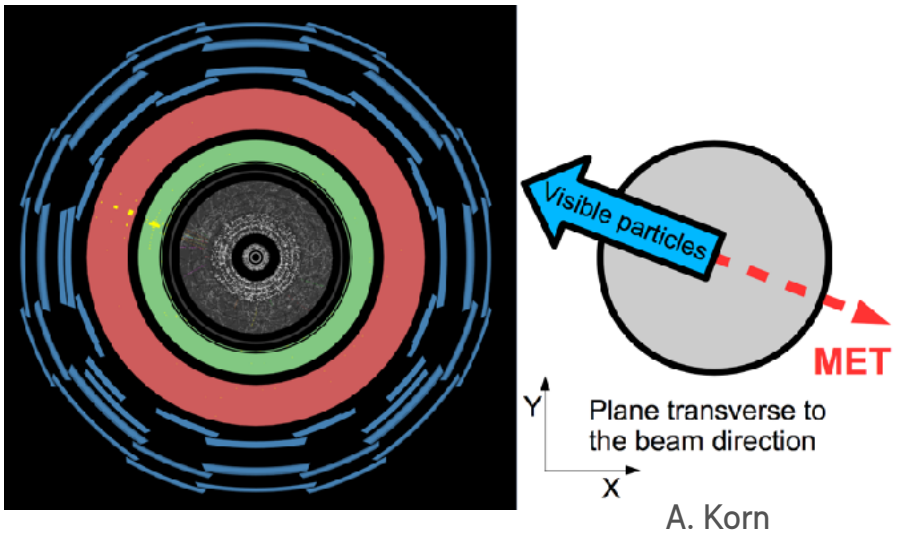


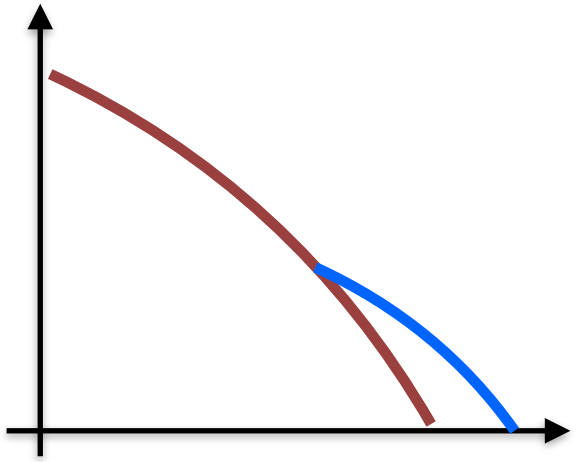
Looking for invisible Dark Matter at the LHC

Signature of Dark Matter:
missing transverse momentum



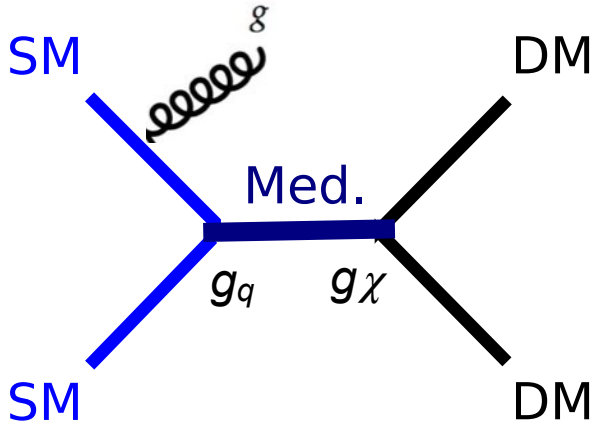
Invisible WIMPs:
Initial state radiation
makes them visible



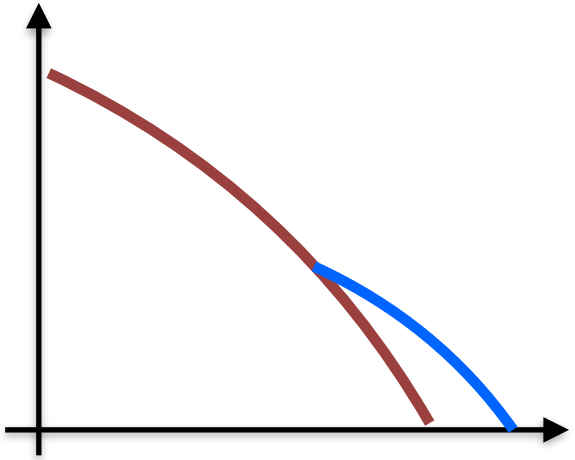


Excess of missing transverse momentum

Latest "monojet" result from ATLAS



Signature of Dark Matter: **missing transverse momentum**



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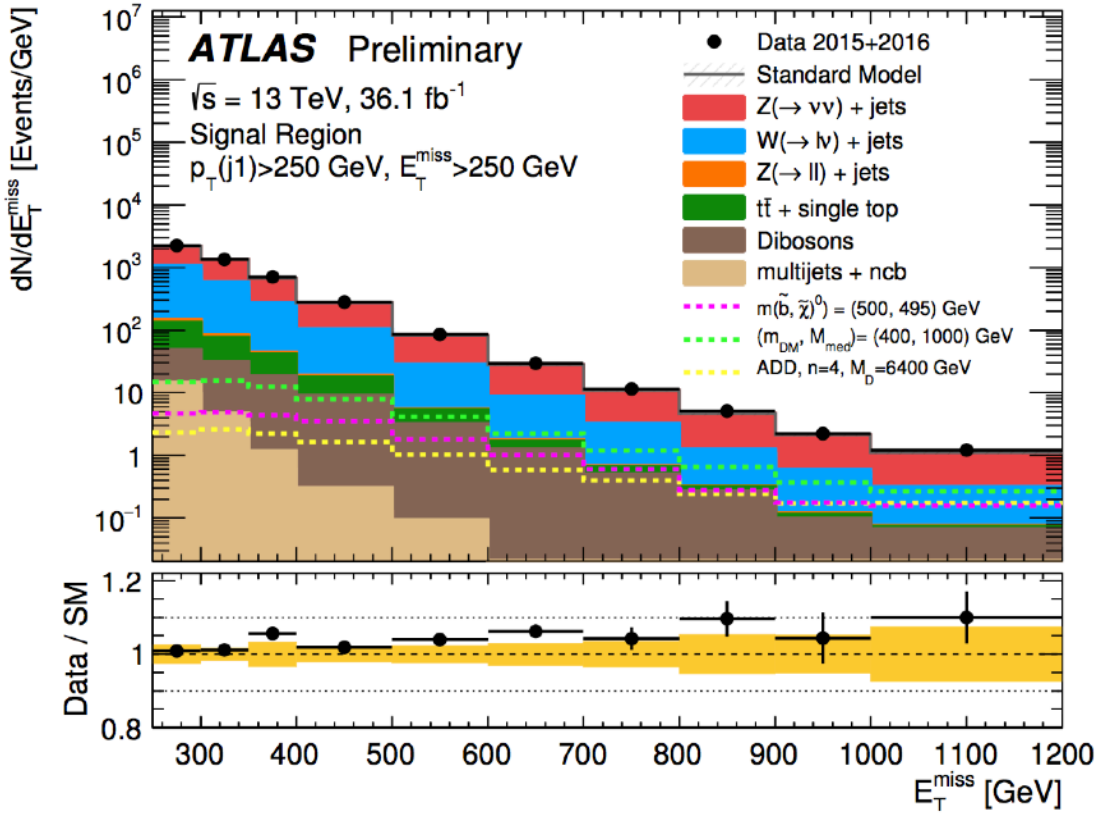

No signals of Dark Matter

Can also use other radiated objects: photon, W, Z, Higgs

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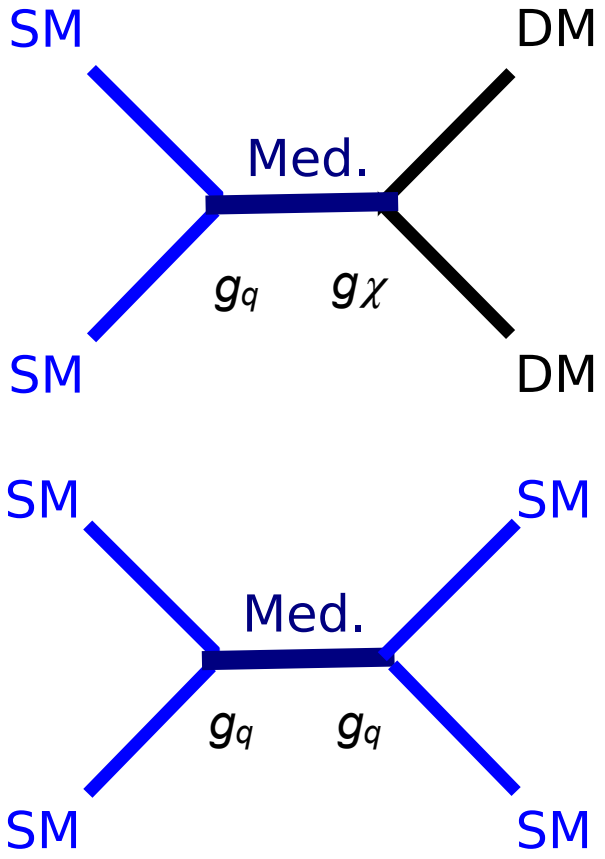
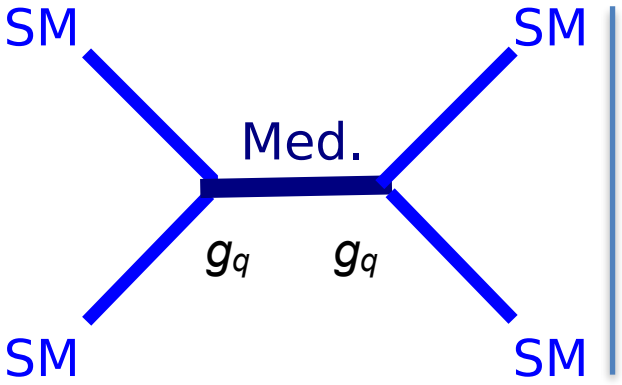
Searches for DM mediators



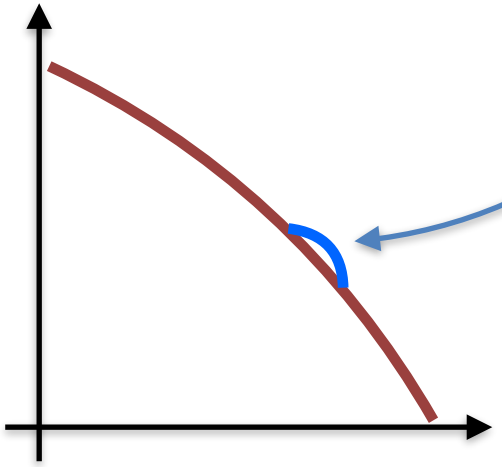
Look for an inevitable LHC physics process: **di-jet resonances**

Anatomy of a *bump-hunt*



invariant mass

number of events

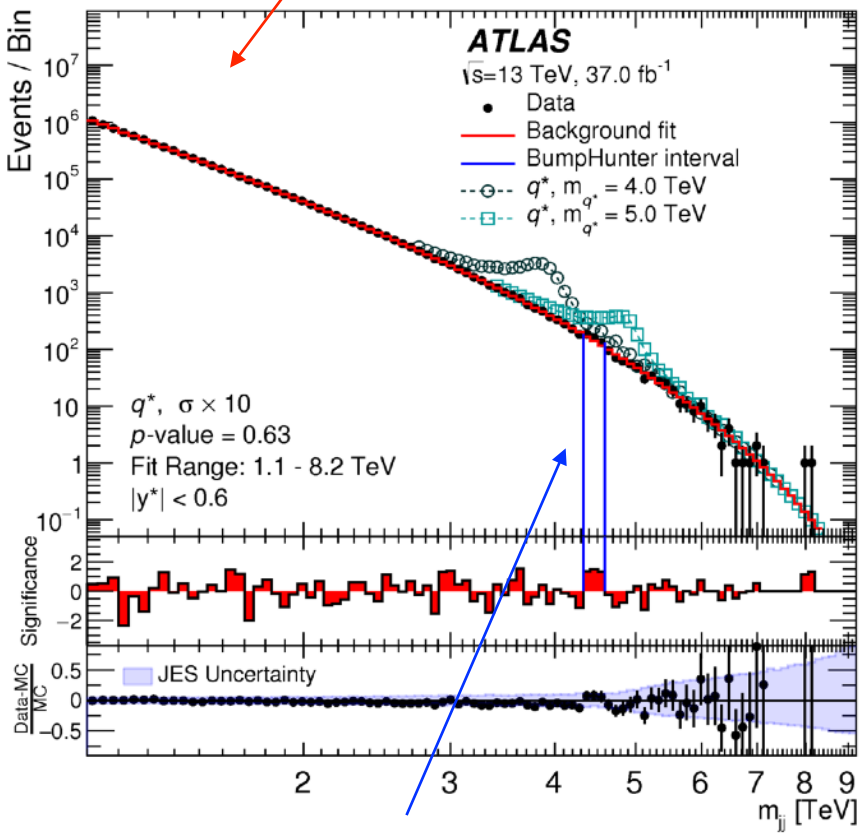


invariant mass

Data-driven background fit

$$f(z) = p_1(1-z)^{p_2} z^{p_3+p_4 \log z}$$

arXiv: highmassdijets



Most discrepant region

No signals of Dark Matter mediators (or other resonances)

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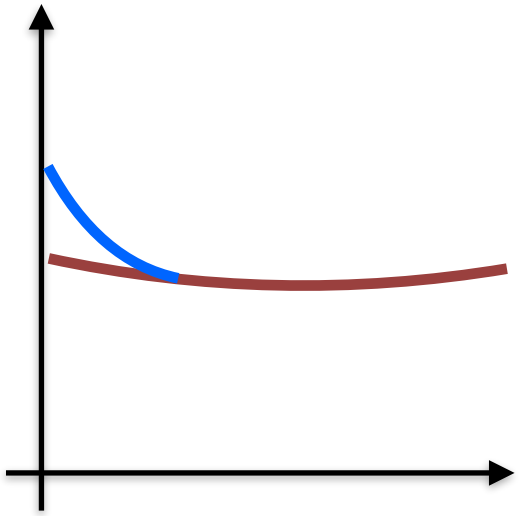
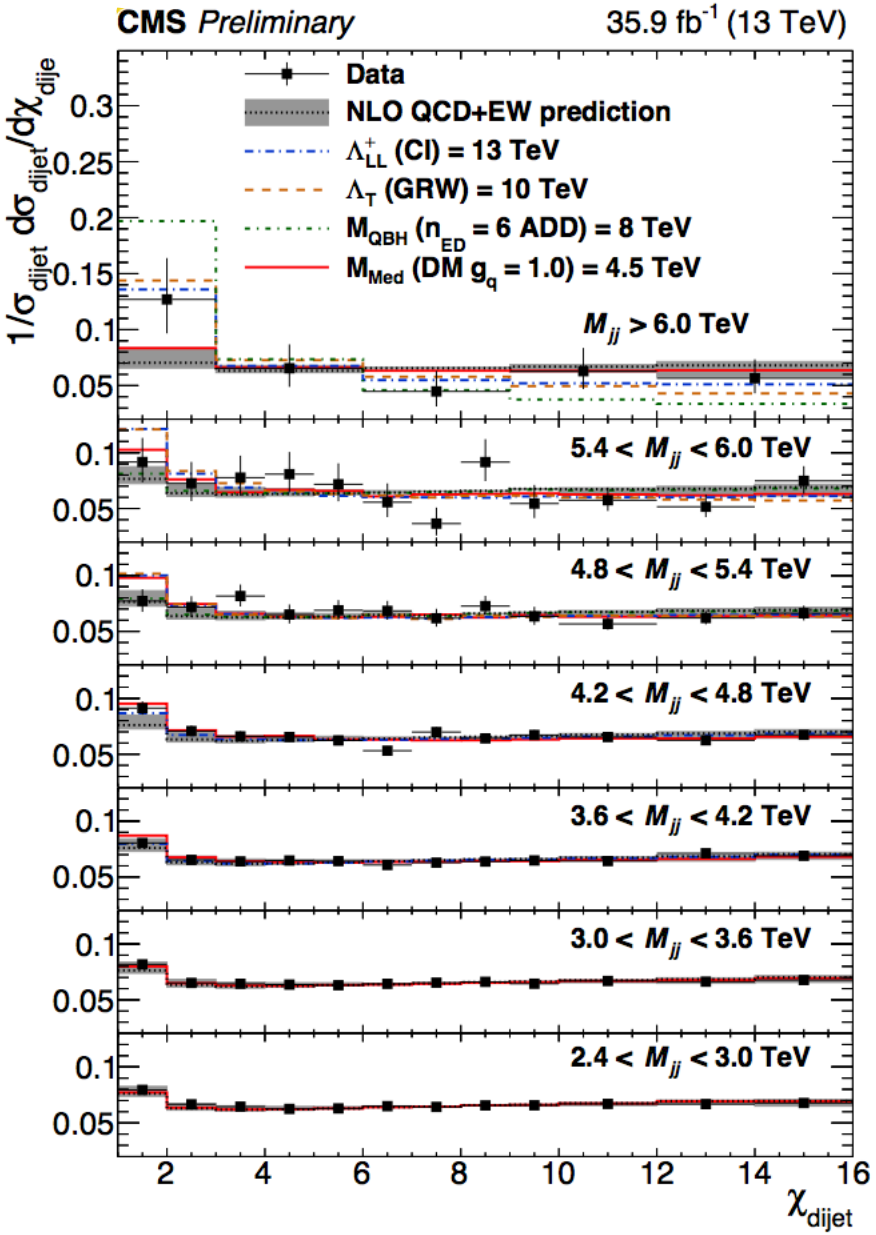
Wide mediators: angular distributions

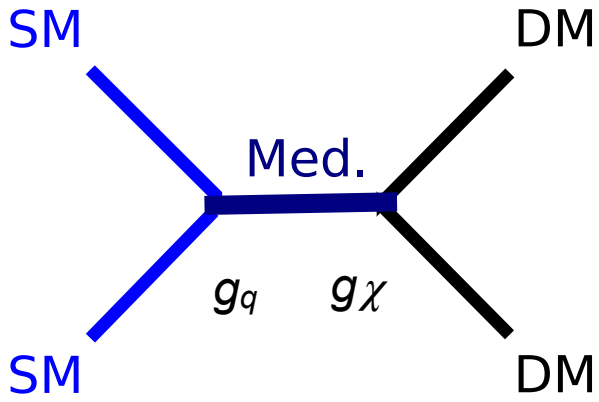
If the **mediator is wide**,
a fit is not effective
→ use dijet scattering angle
to discriminate signal/background

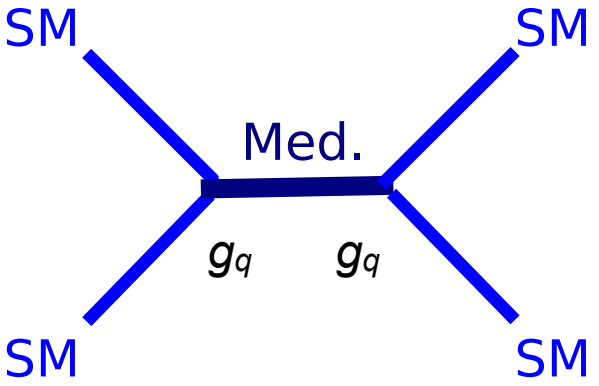




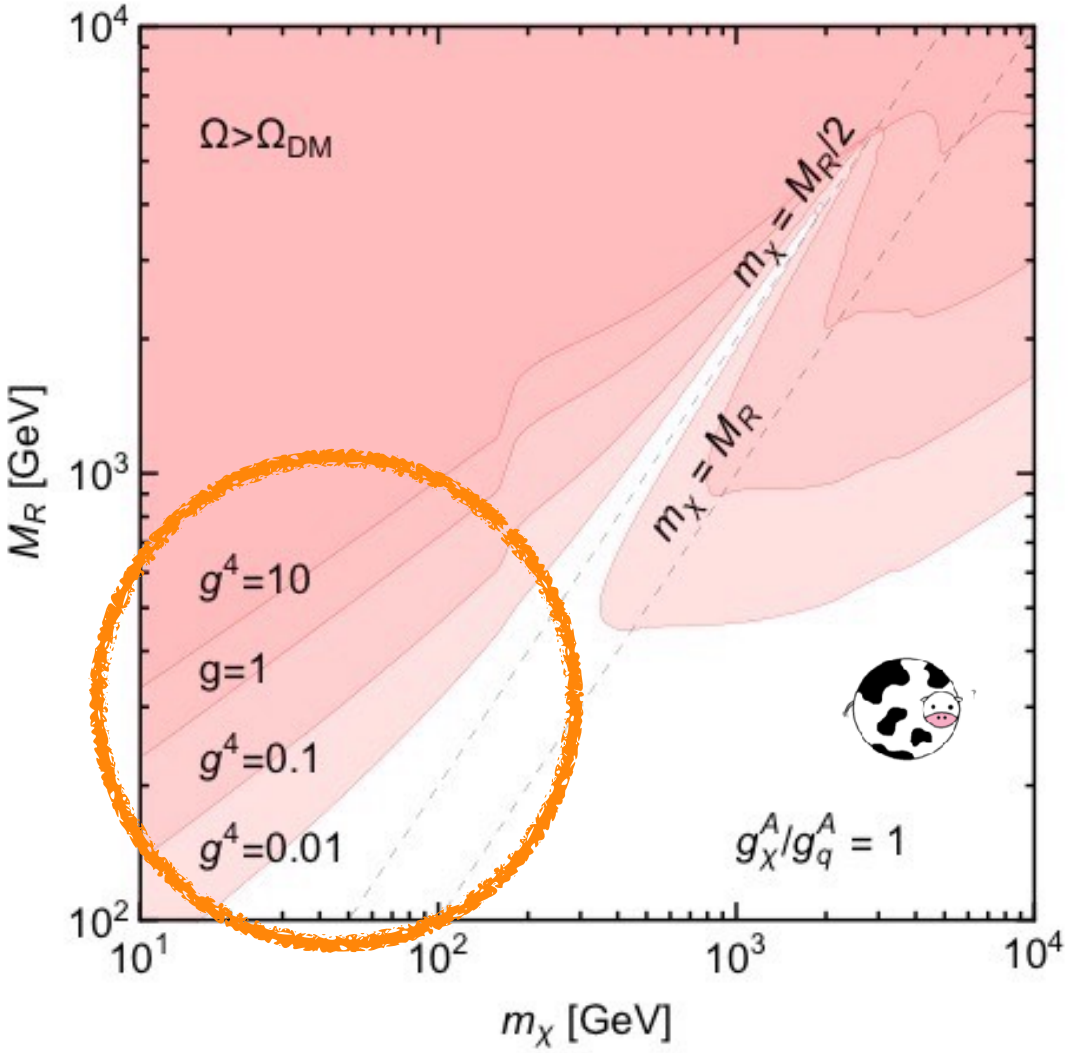
No signals of Dark Matter mediators

Visible low mass DM mediators: interesting!





$$g \equiv (g_q^A \, g_\chi^A)^{1/2}$$



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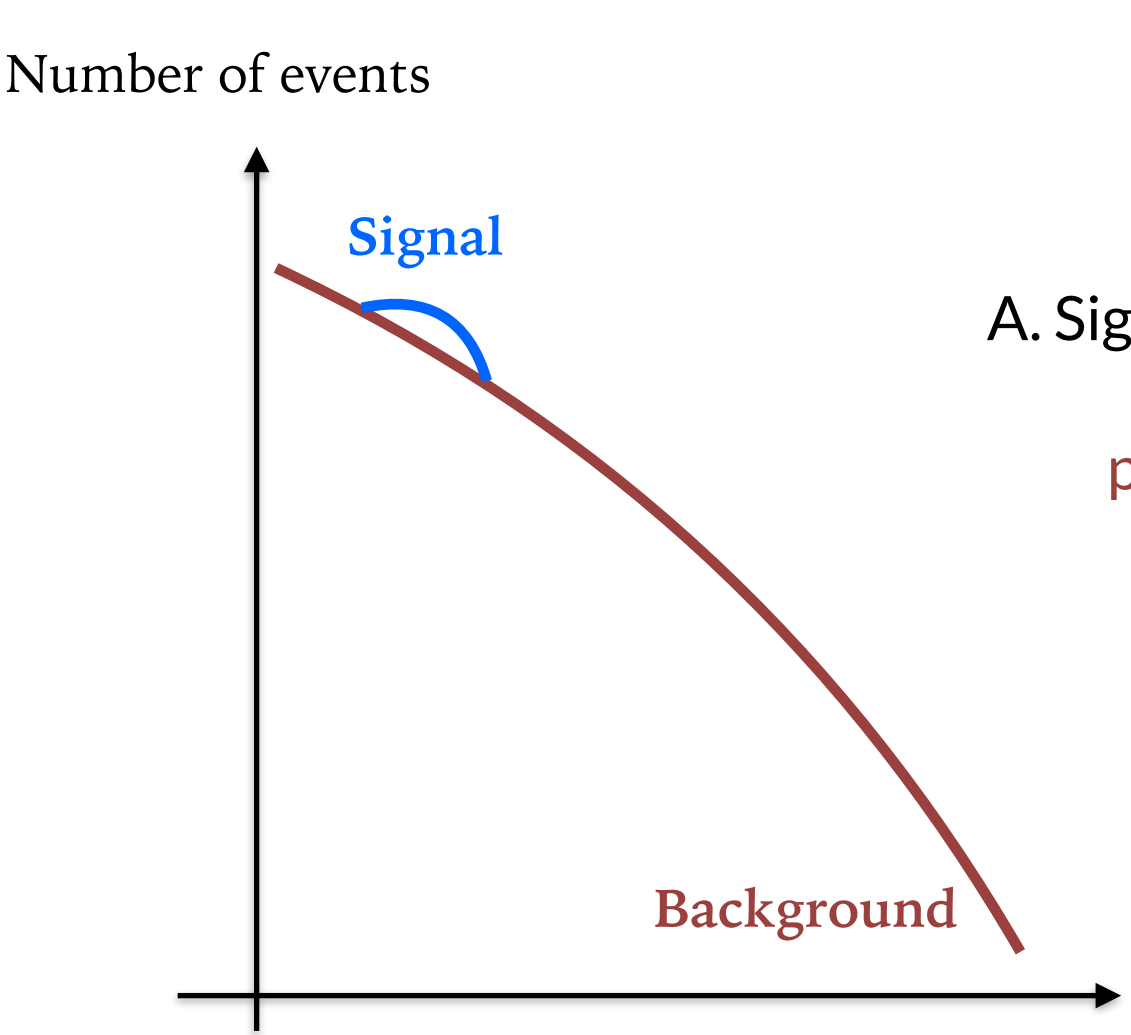
Signals and backgrounds with jets

Main challenge for jet searches: large backgrounds, impossible to store all data



A. Signal overwhelmed by background if no discriminating power
poor sensitivity to new physics!

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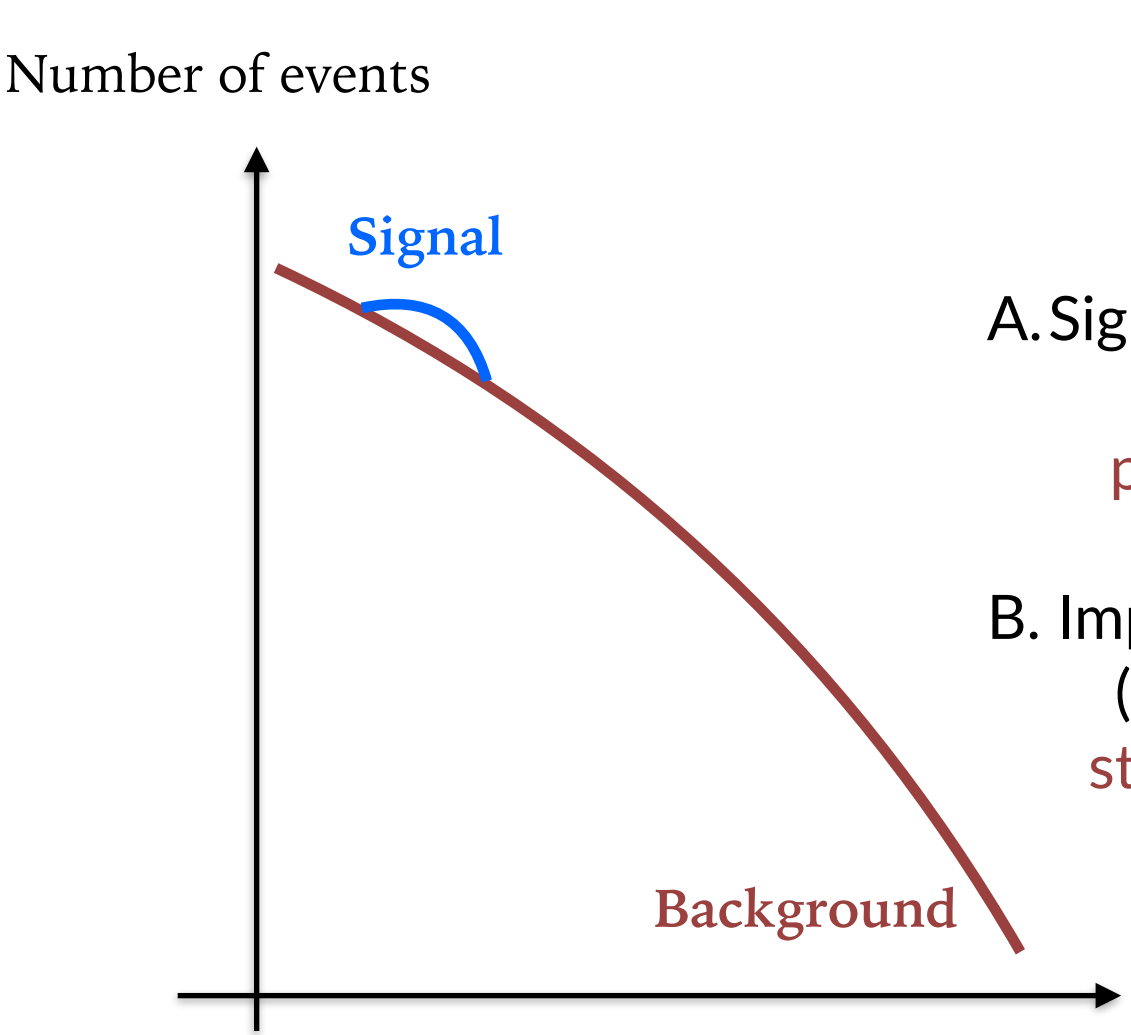
Signals and backgrounds with jets

Main challenge for jet searches: large backgrounds, impossible to store all data



A. Signal overwhelmed by background: if no discriminating power poor sensitivity to new physics!

B. Impossible to record all events fully: (ATLAS **trigger system** needed) statistical error harms sensitivity!

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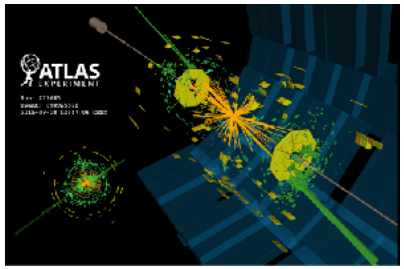
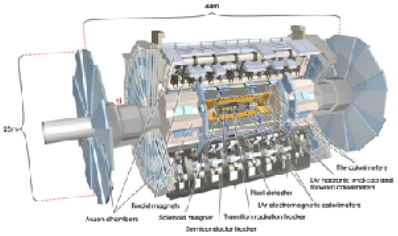
Data taking in ATLAS





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

Computing resources are essential for the full data taking chain

Trigger and data acquisition: select interesting events

First step: **fast hardware selection (Level 1)**
data taking rate: 100 kHz
Second step: **computer farm (High-Level Trigger)**
data taking rate: 1000 Hz

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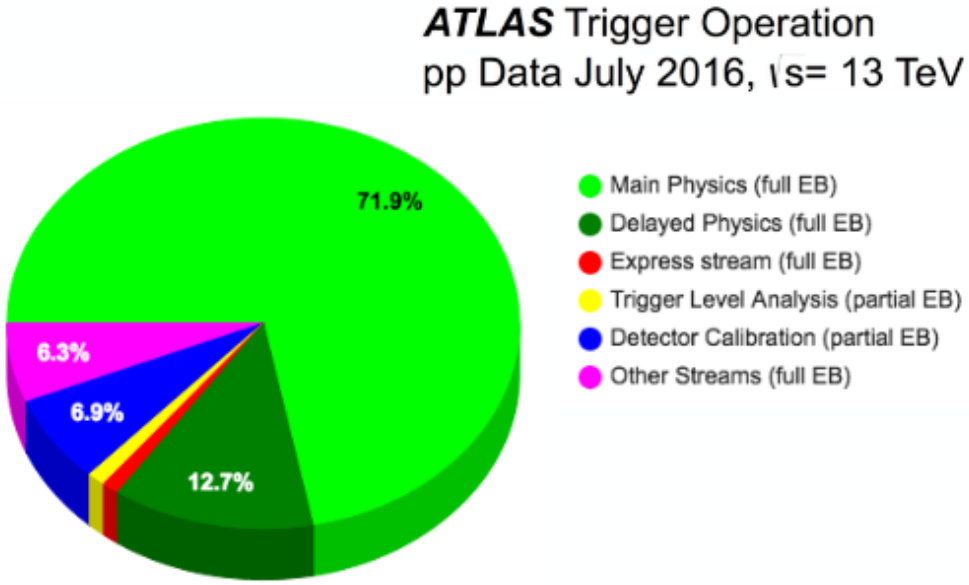
Trigger Level Analysis technique (TLA)

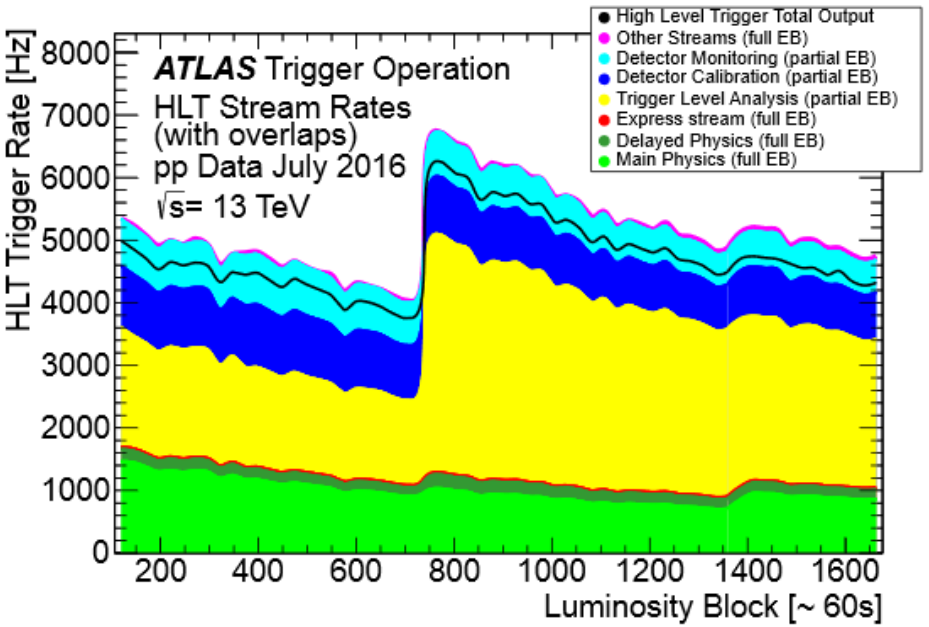
(CMS: Data Scouting, LHCb: Turbo Stream)

Record only necessary information for jet search: **jets**
Use information already available to make the decision: **trigger jets**

Event size reduced to 5%
of fully recorded event

Reduced size -> increase number
of events that can be recorded





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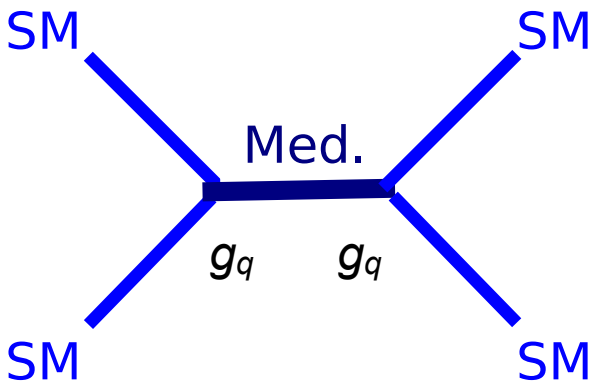
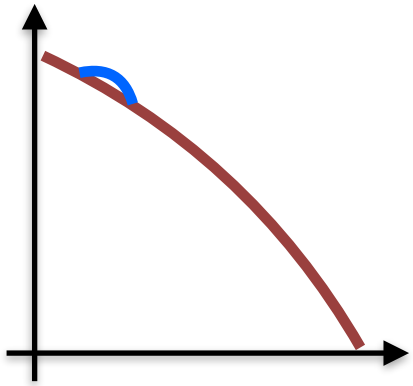
ATLAS Trigger Level Analysis results





Most discrepant region (p-value 0.44)

Data-driven background fit

$$f(z) = p_1(1-z)^{p_2} z^{p_3+p_4 \log z}$$

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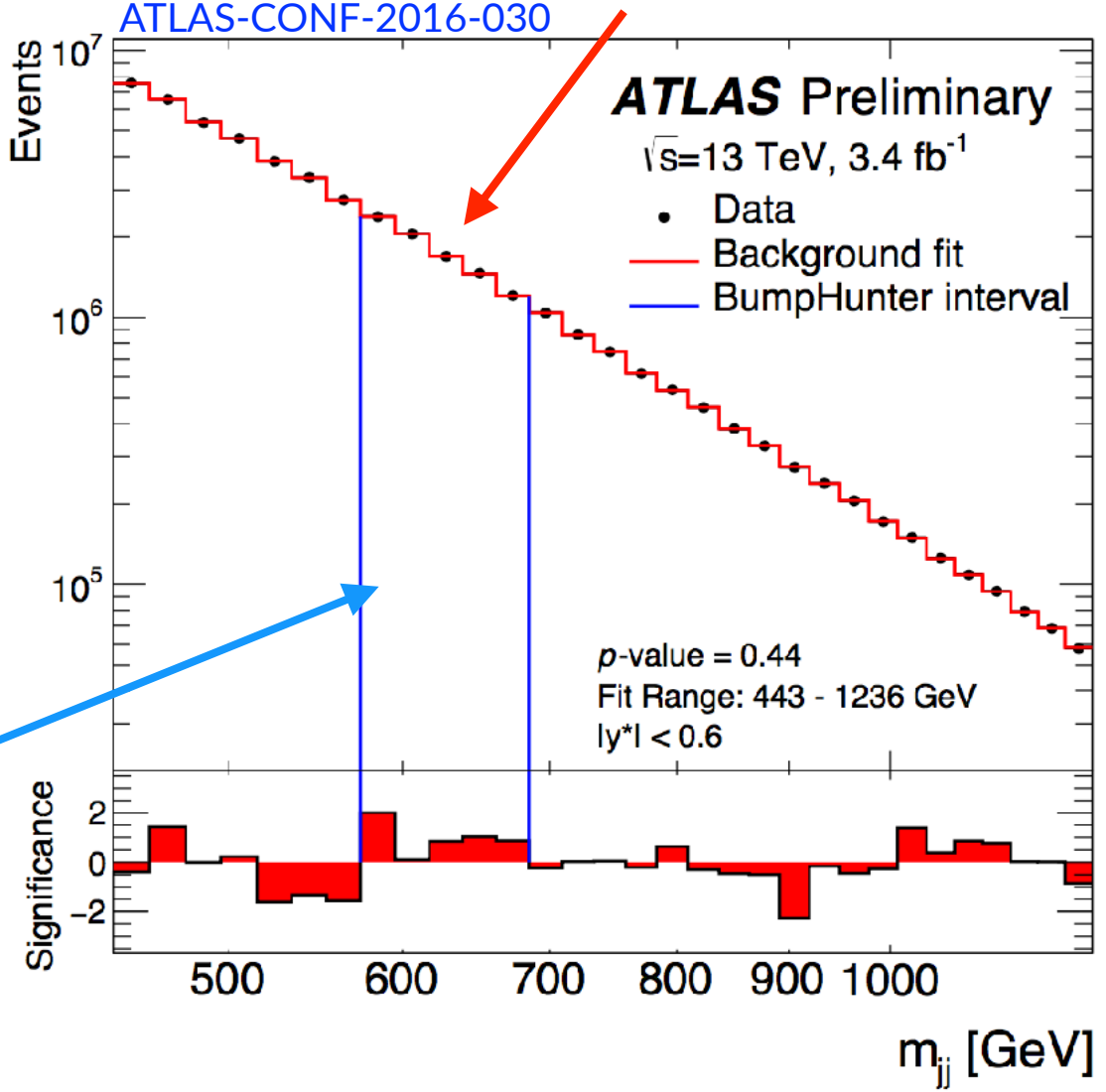

No signals of Dark Matter mediators

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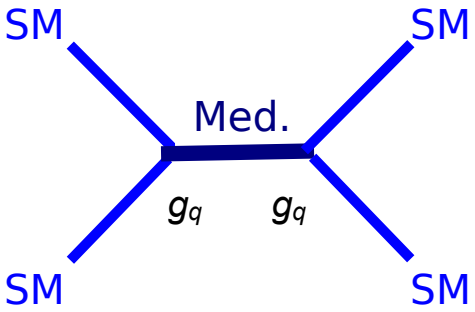
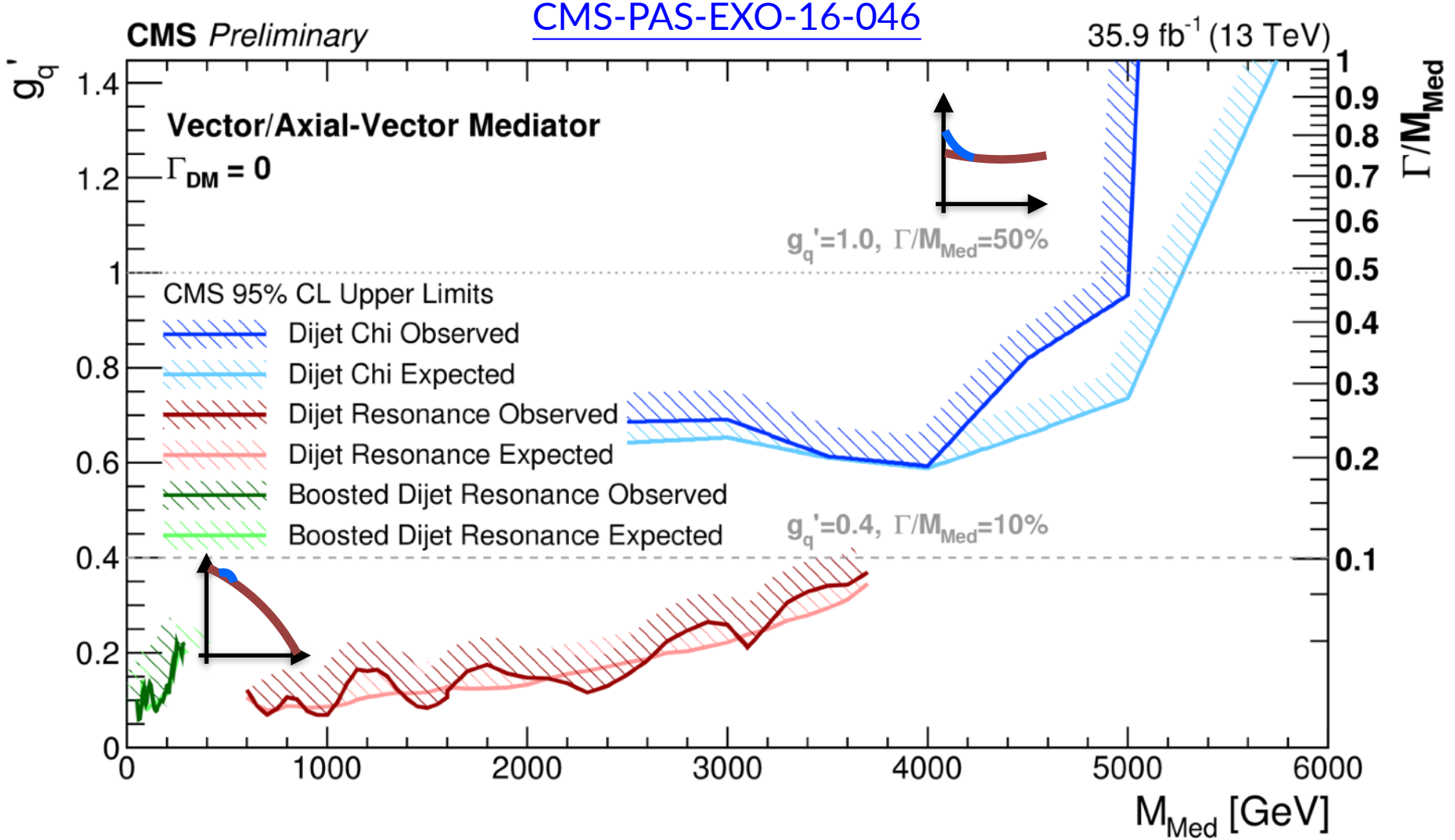
The full (CMS) picture of mediator searches



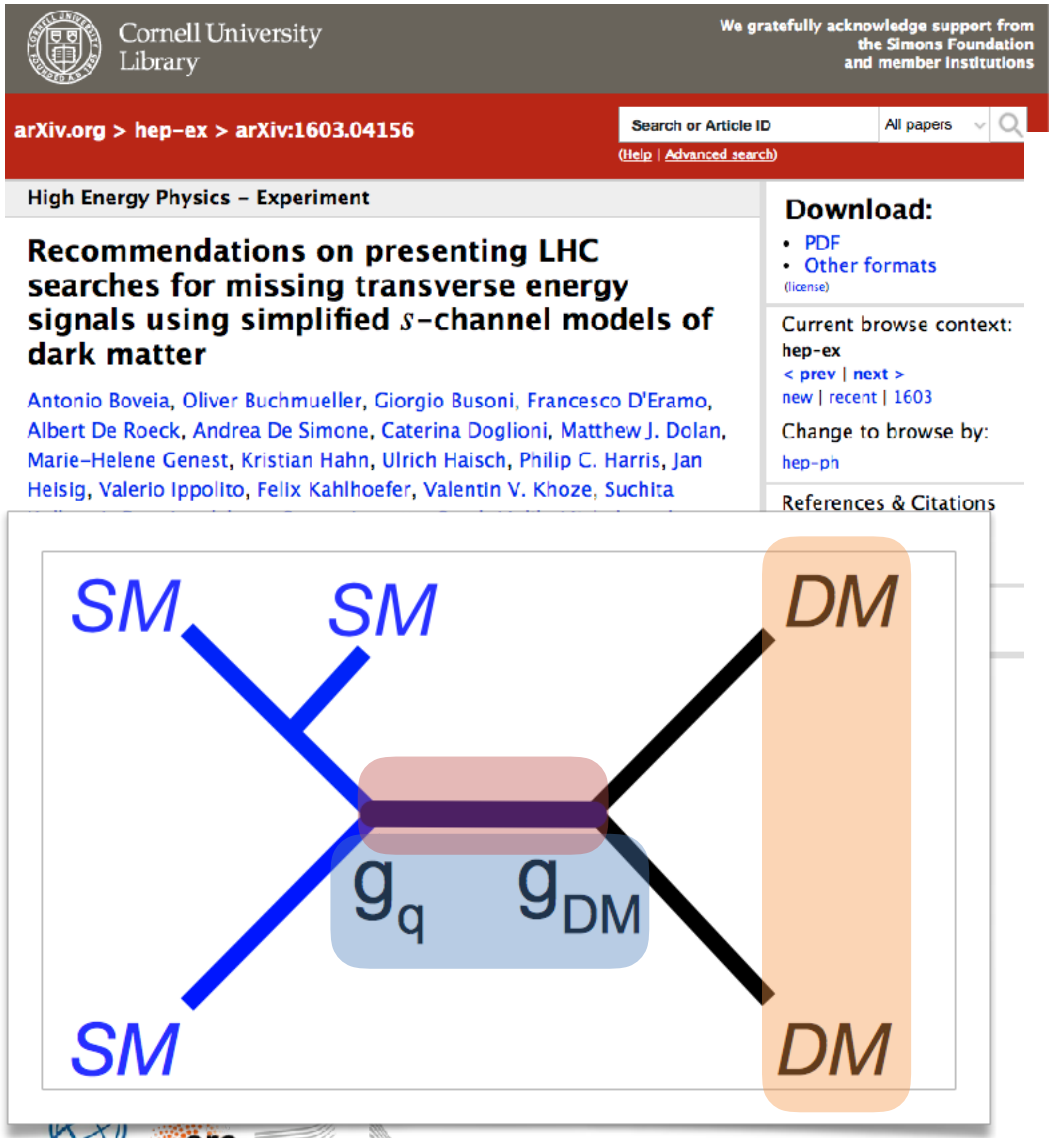
CMS-PAS-EXO-16-046



Highlighting complementarity of Dark Matter searches

Visible/invisible DM LHC searches

How to display interpretation of collider search using simplified models



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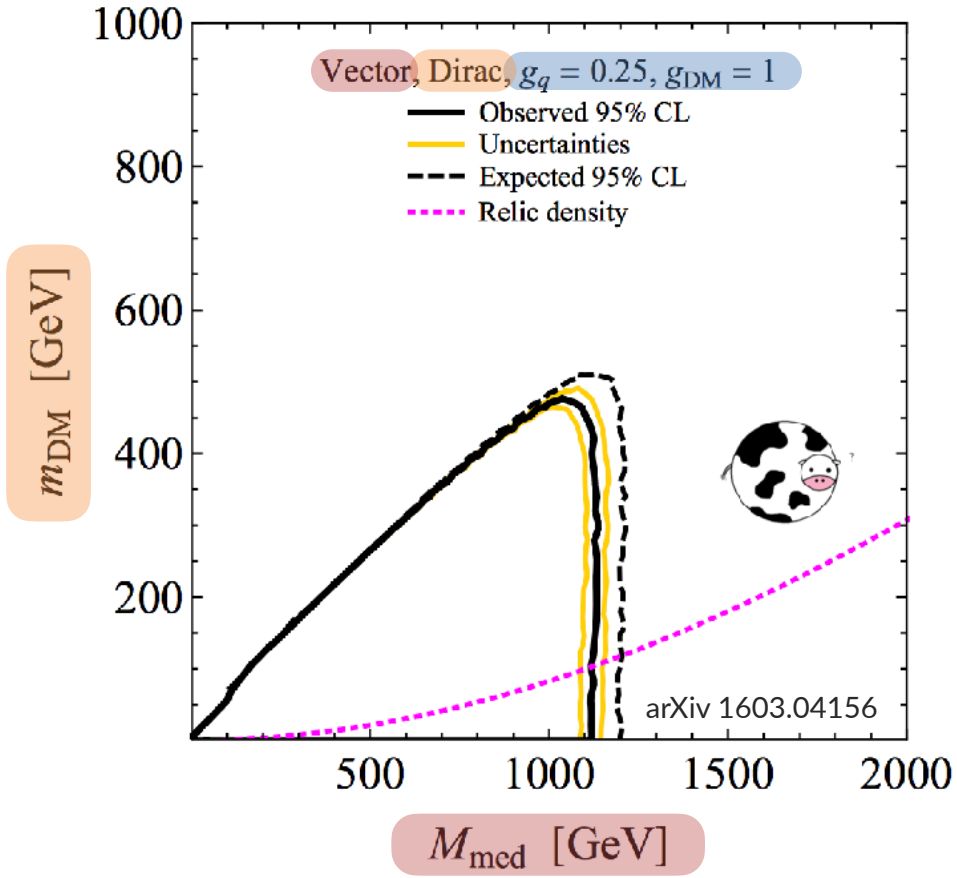

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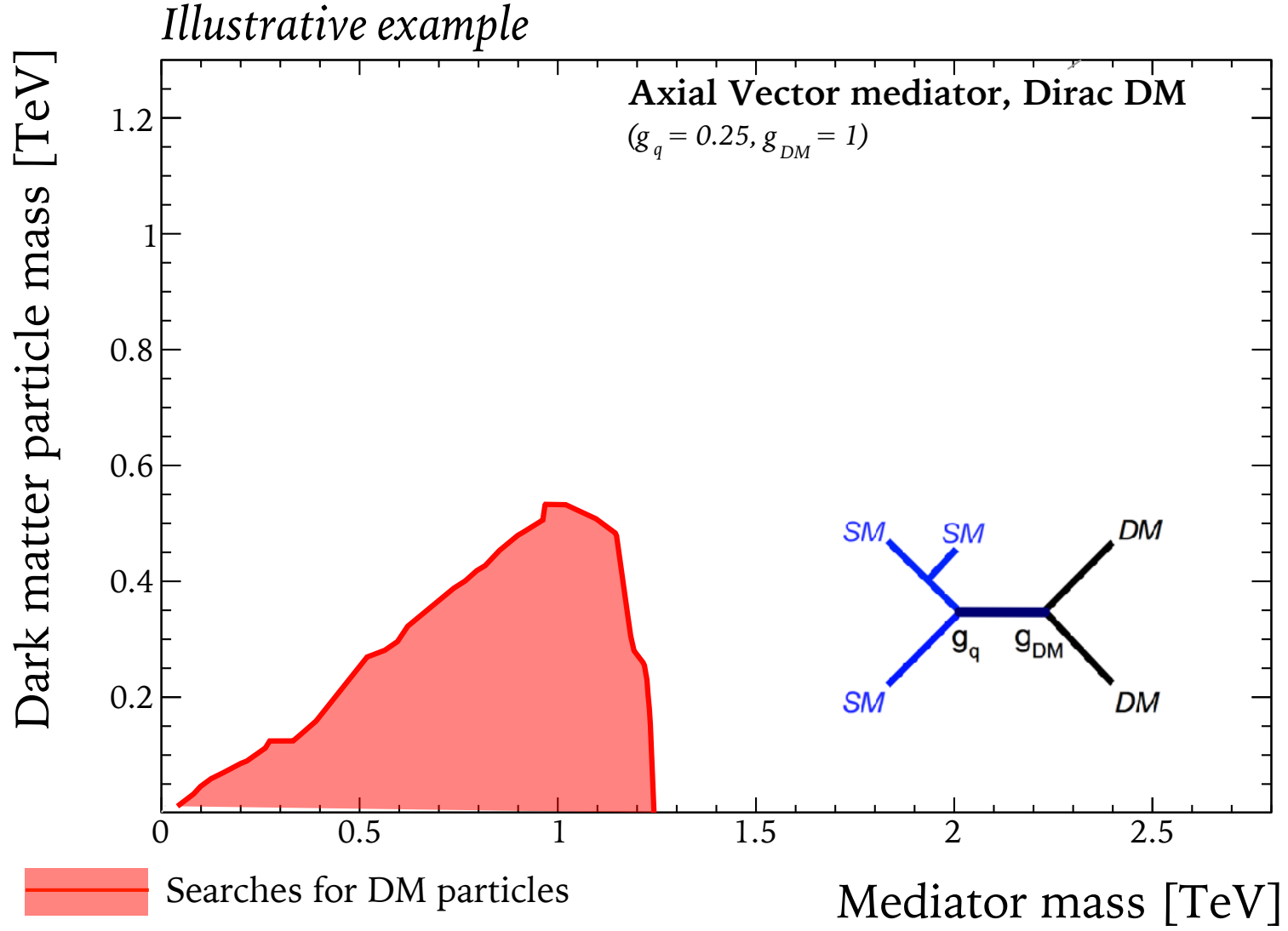
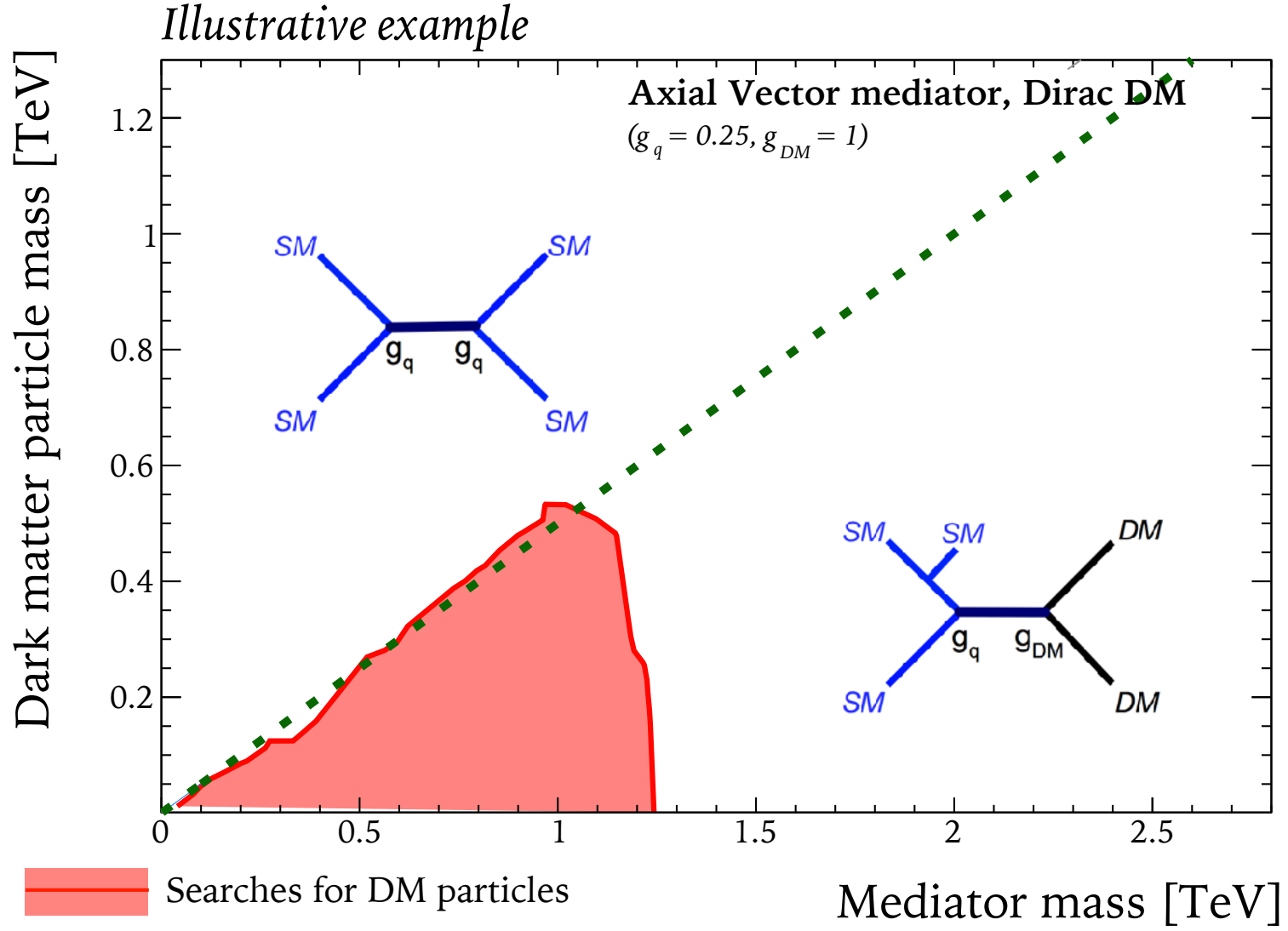
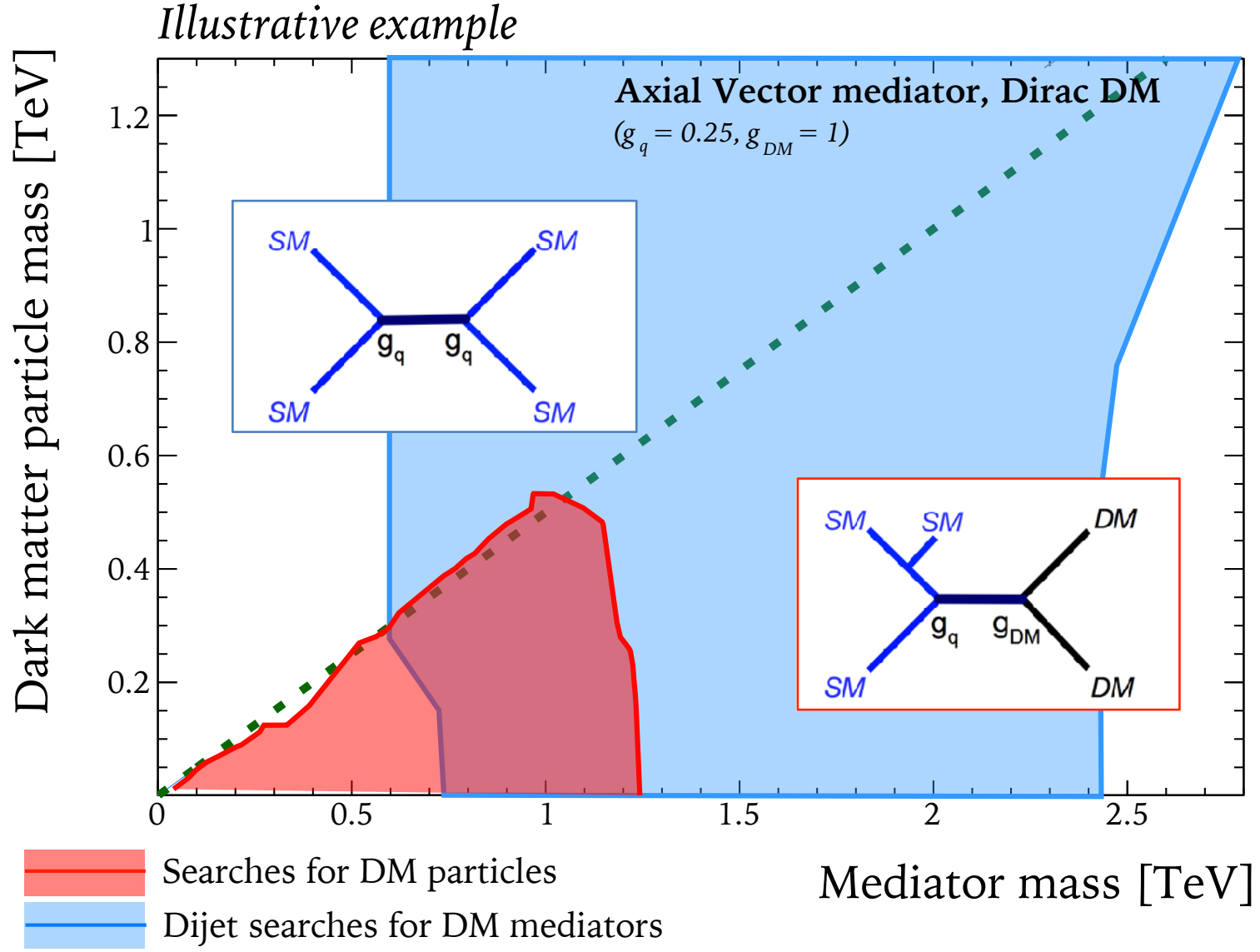
Visible/invisible DM LHC searches



Visible/invisible DM LHC searches

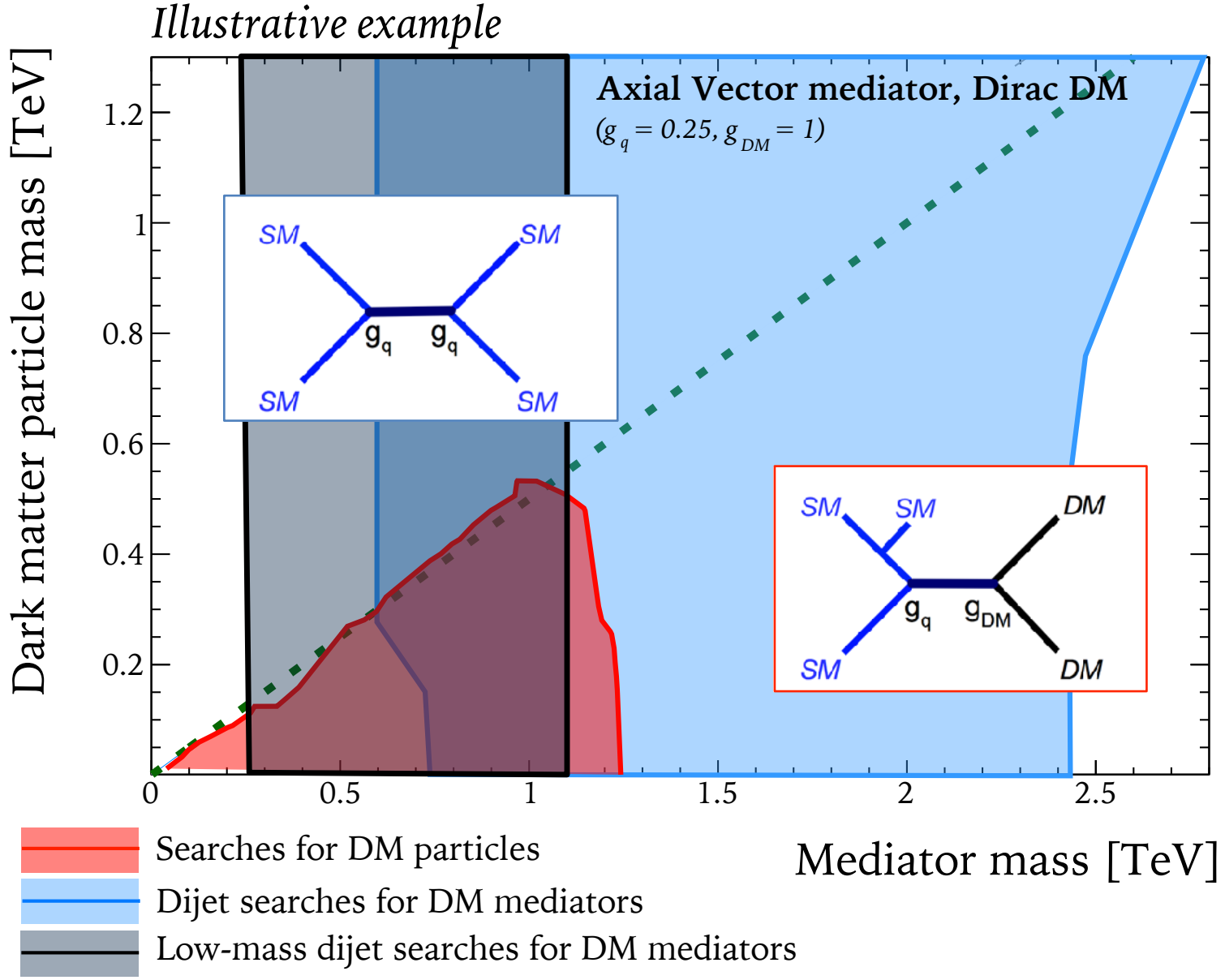


Visible/invisible DM LHC searches



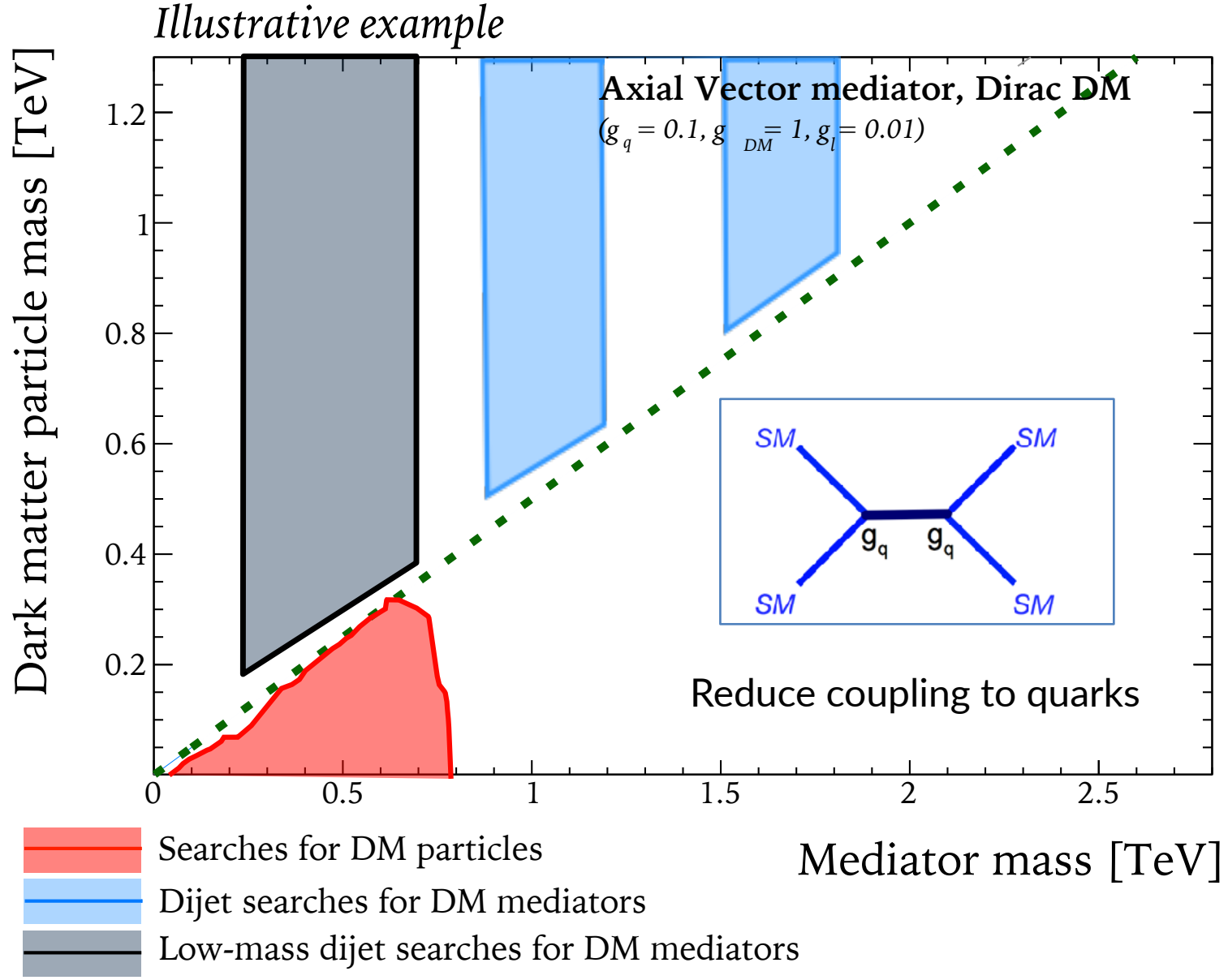
Collider strength: searches for visible mediator decays

Visible/invisible DM LHC searches



Motivating new searches for visible mediator decays

Visible/invisible DM LHC searches



However, sensitivity is a coupling-dependent statement

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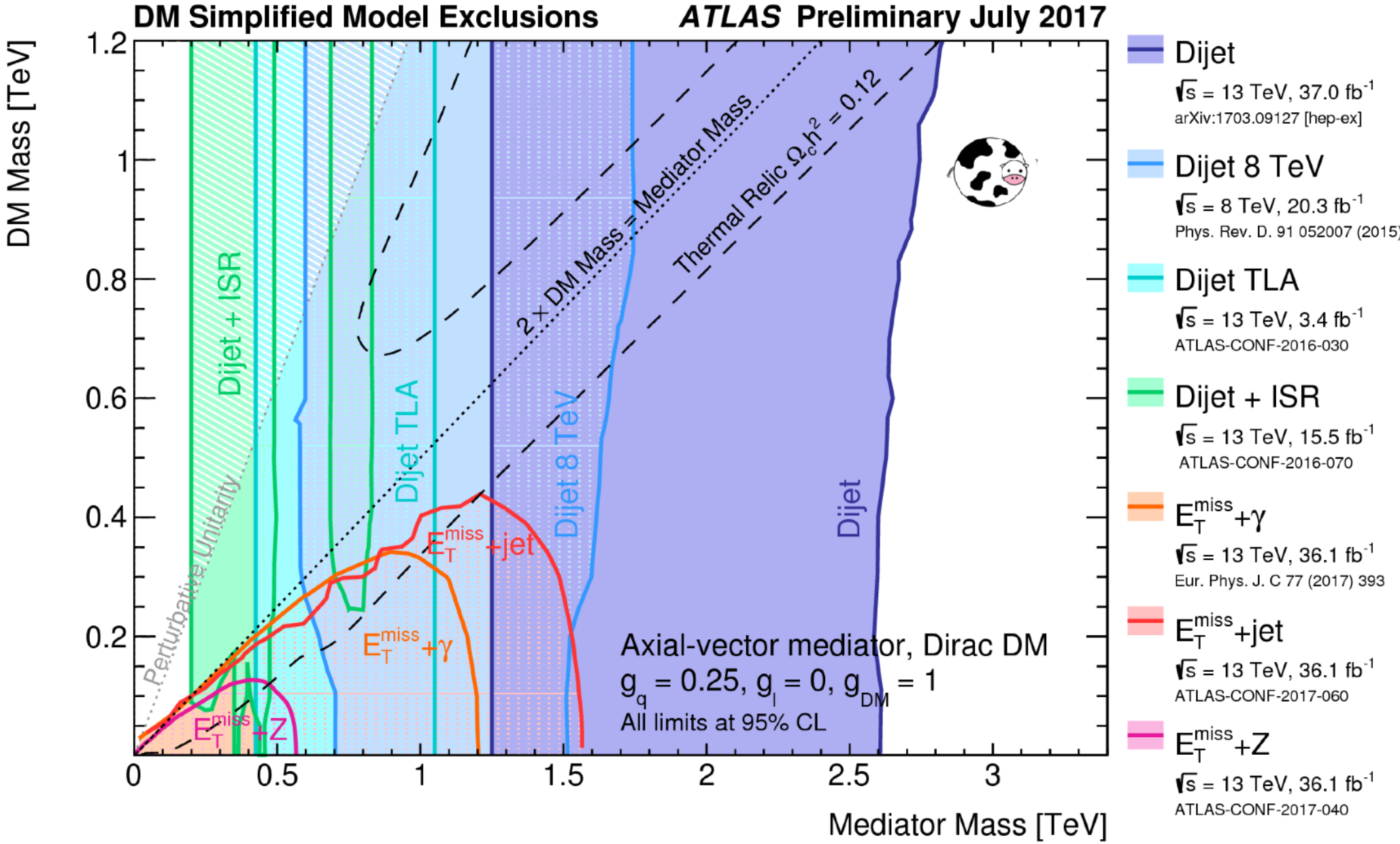
ATLAS results on visible/invisible DM searches



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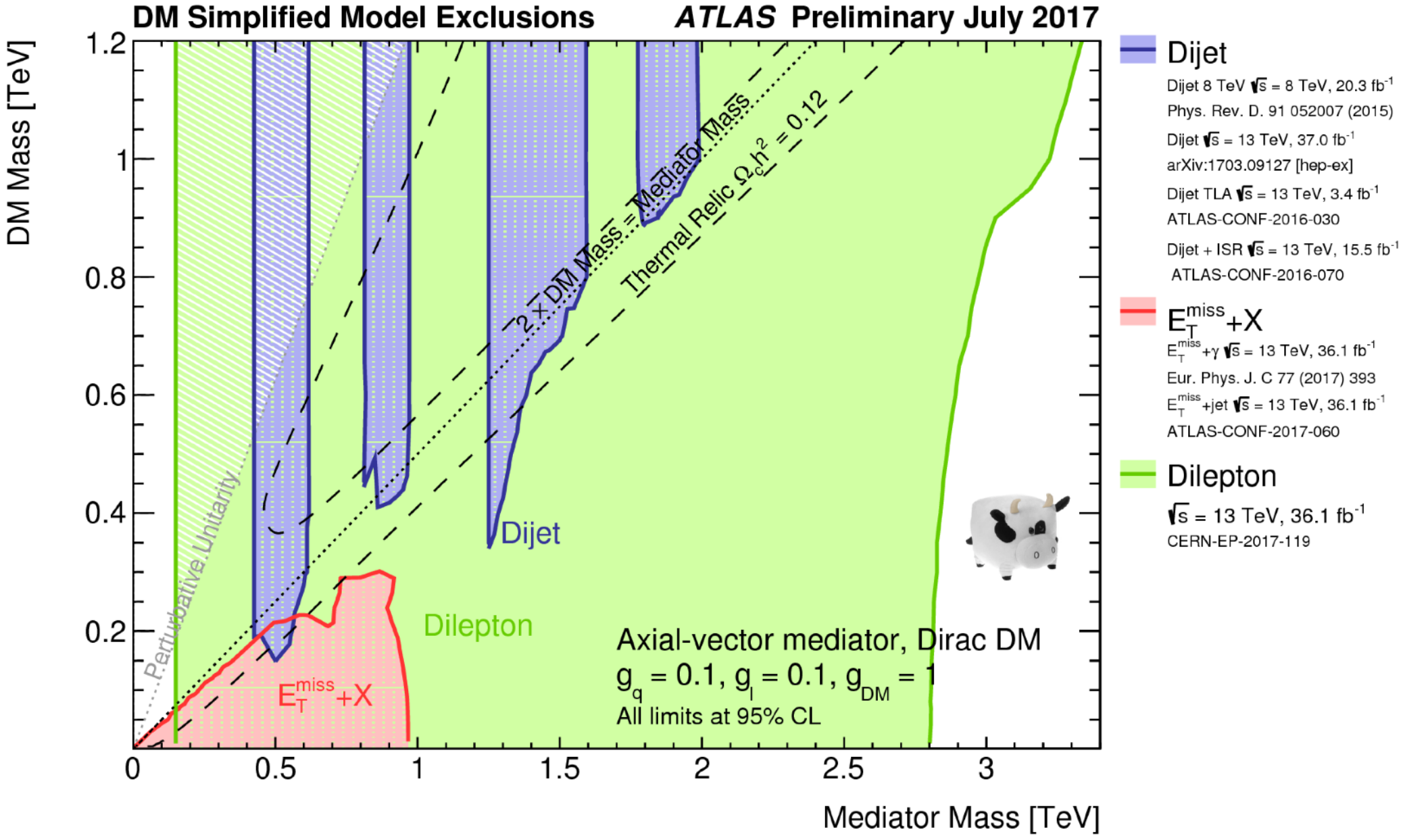
ATLAS results on visible/invisible DM searches



A (simplified) global picture of DM

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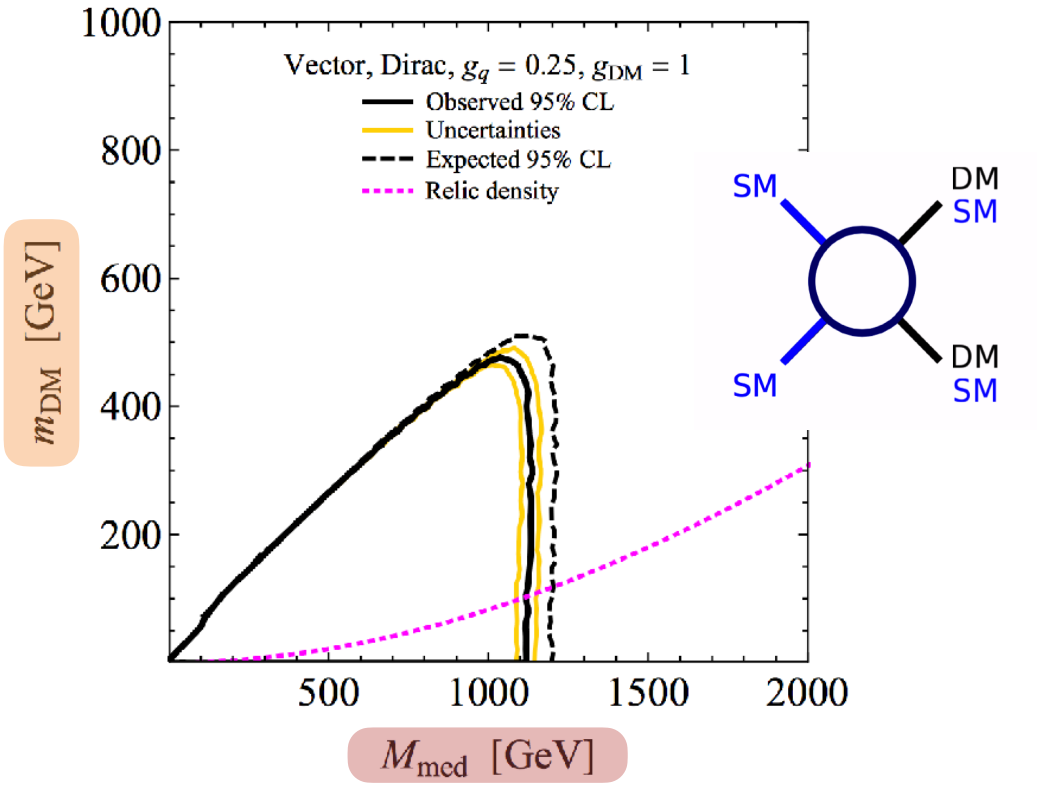
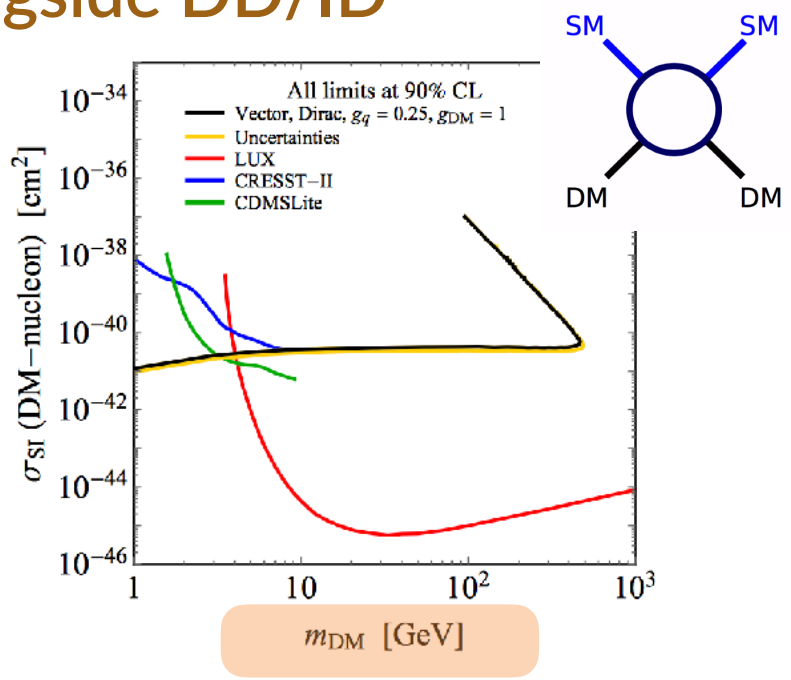
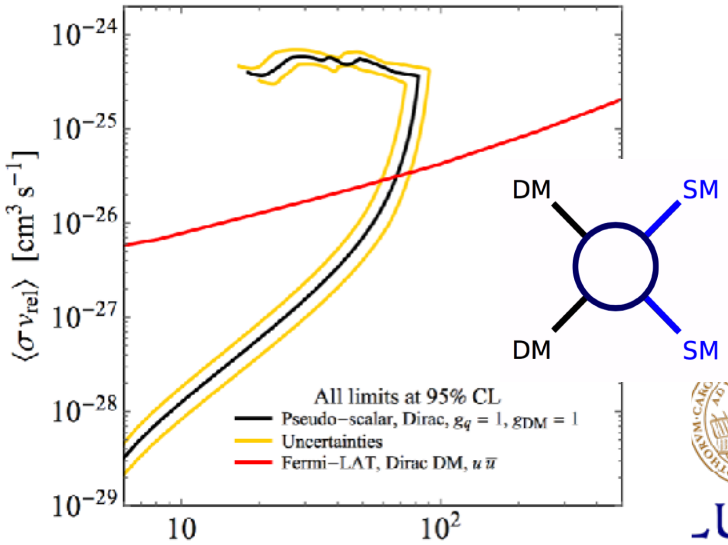
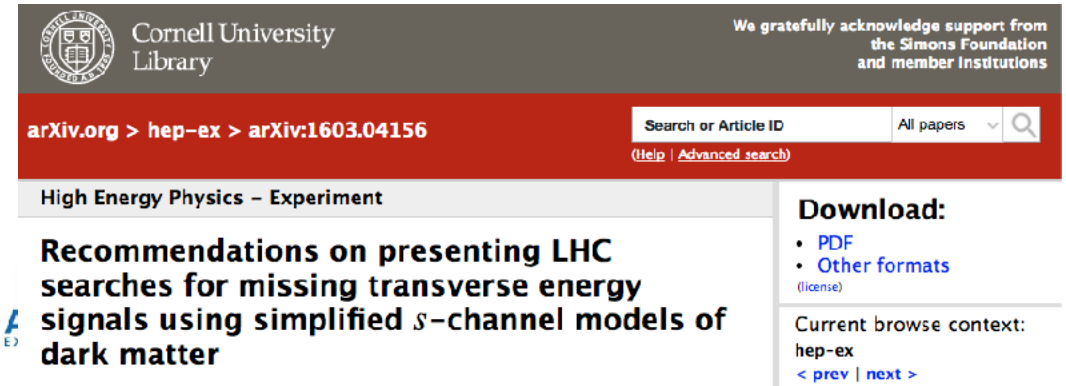
How to display collider searches alongside DD/ID



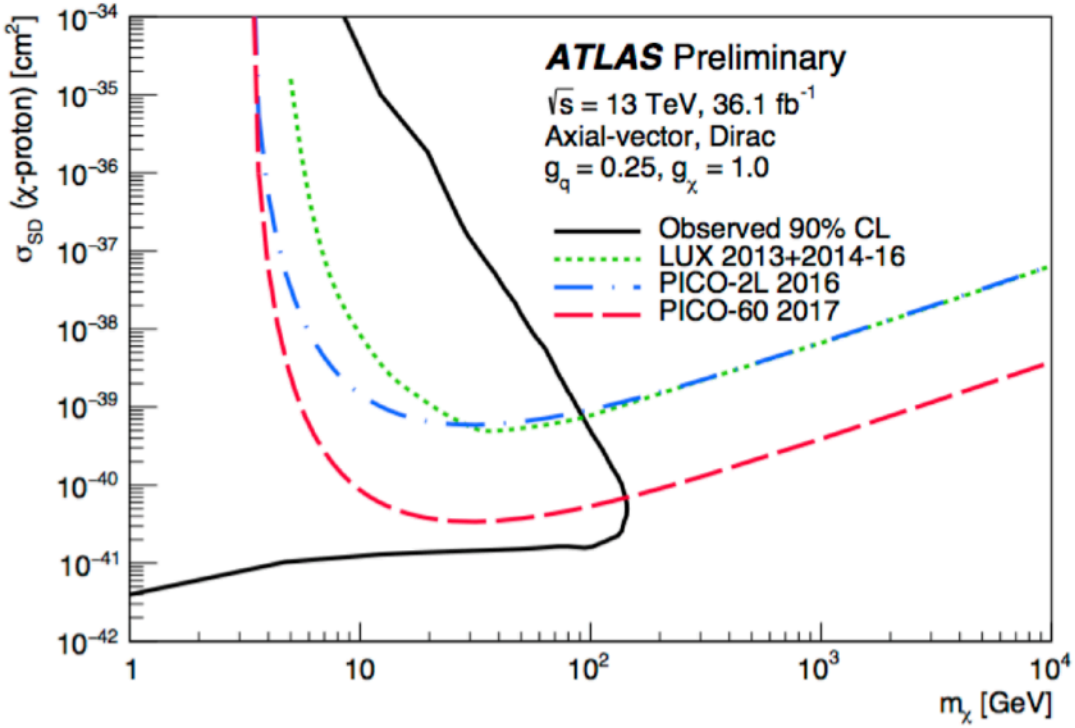






ATLAS/CMS results, in context

ATLAS-CONF-2017-060



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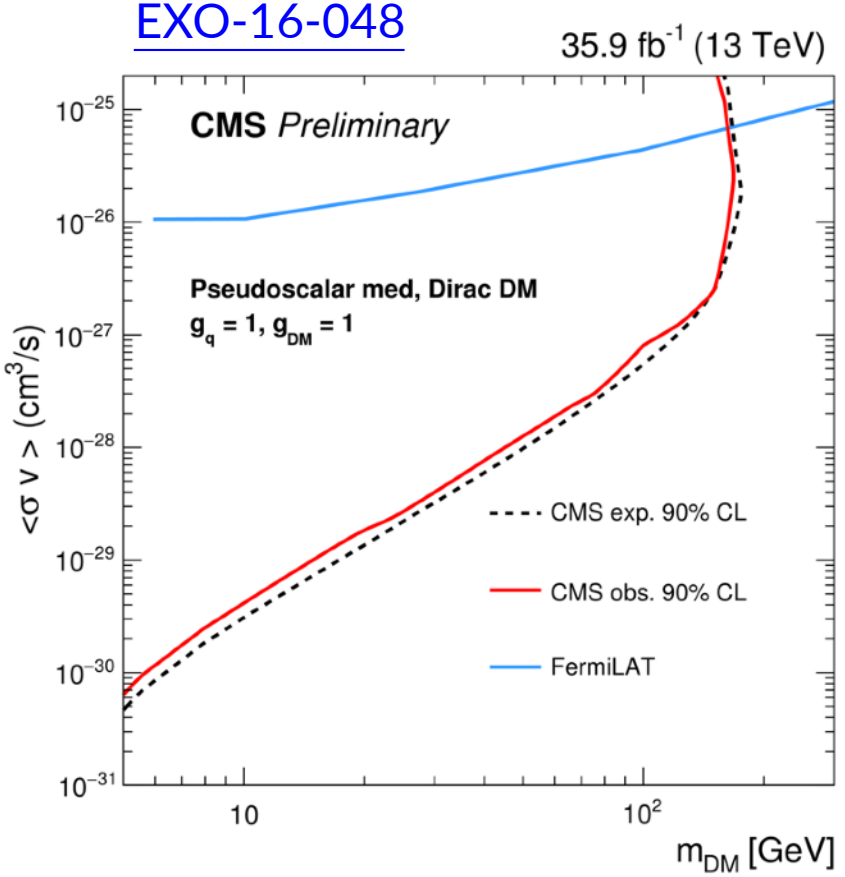

Note: complementarity between DD/ID and colliders, requires a model

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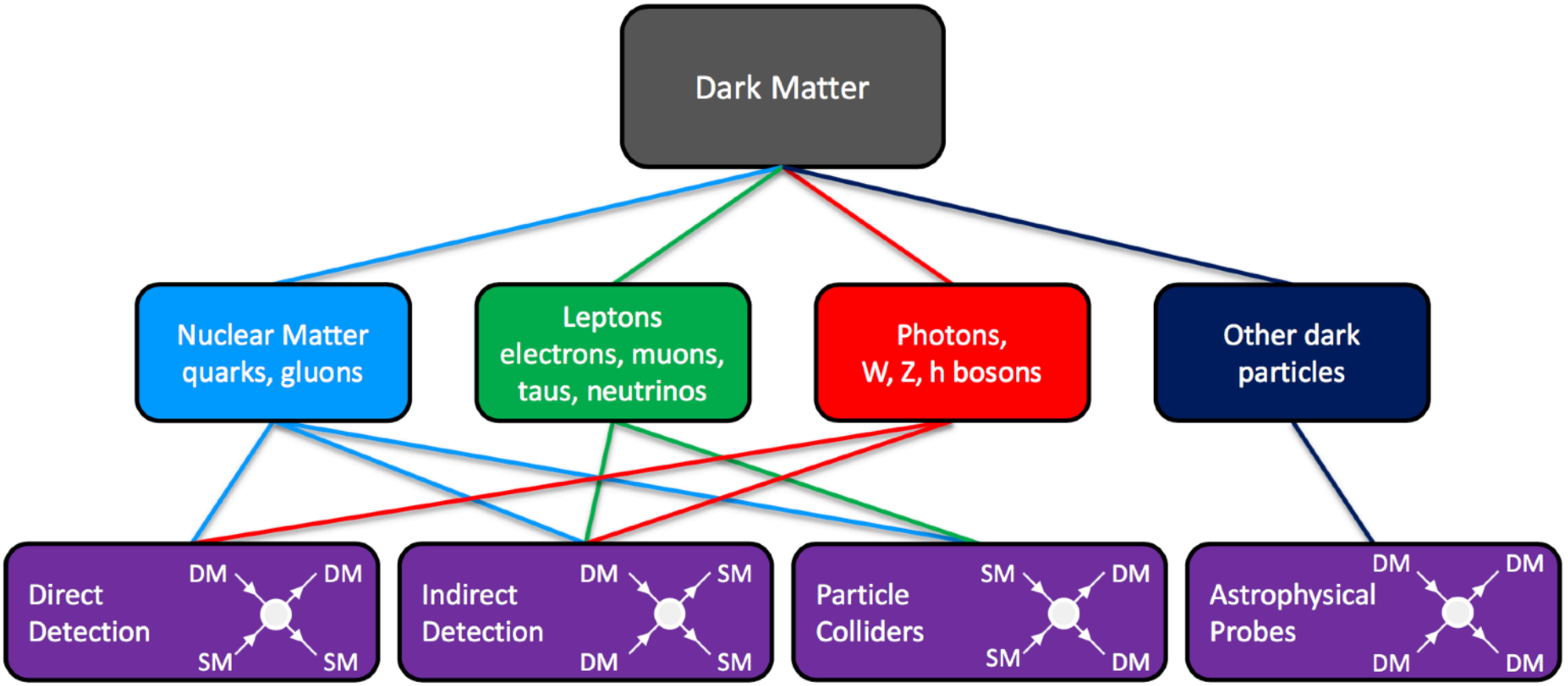
Astrophysical probes: complementarity

arXiv:1305.1605



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Further complementarity?

Relic density

Is the relic density a "guide for the eye" in the WIMP paradigm, or more? How should its (precise) measurement influence DM searches?

Galaxy formation

Is it possible to introduce different models and assumptions in simulations, or are those too fine-grained to make a difference?

Nature of DM

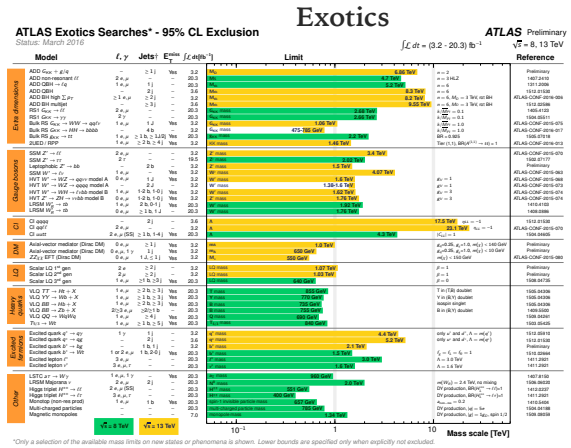
Could astrophysics help shedding light on the nature of DM? Growing interest (also in the direction of black holes) -> anything colliders can do?

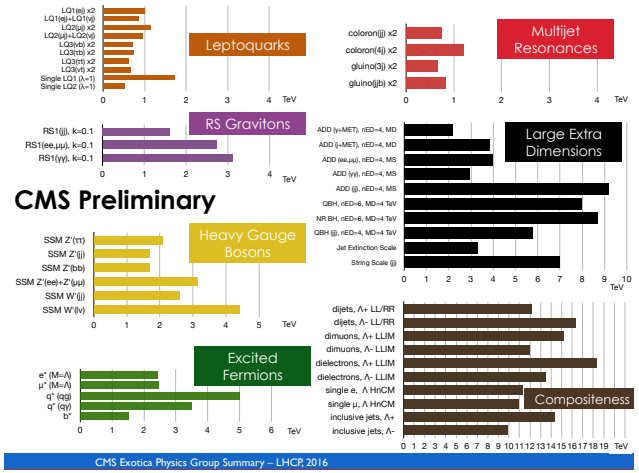
Role of the Higgs

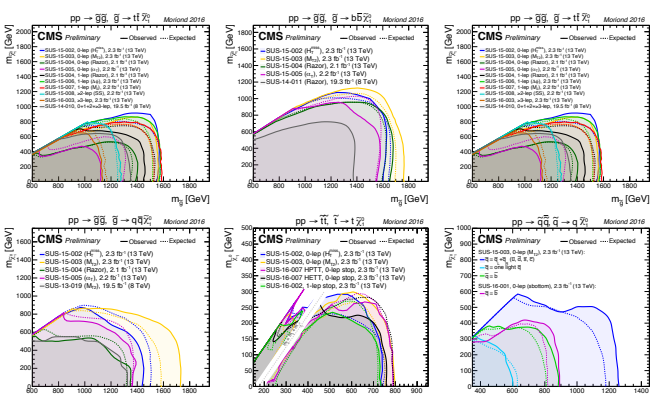
We discovered a new particle: what is the role it played in the early universe?

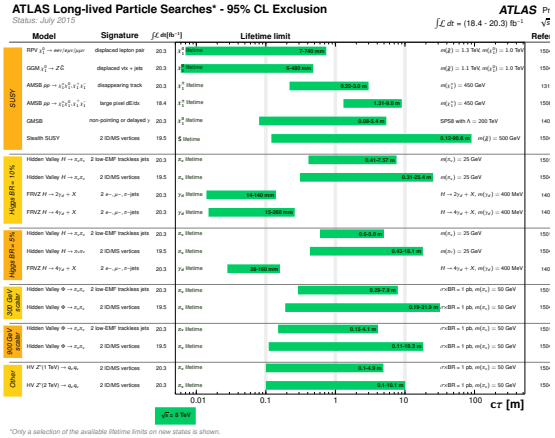
Conclusions and outlook

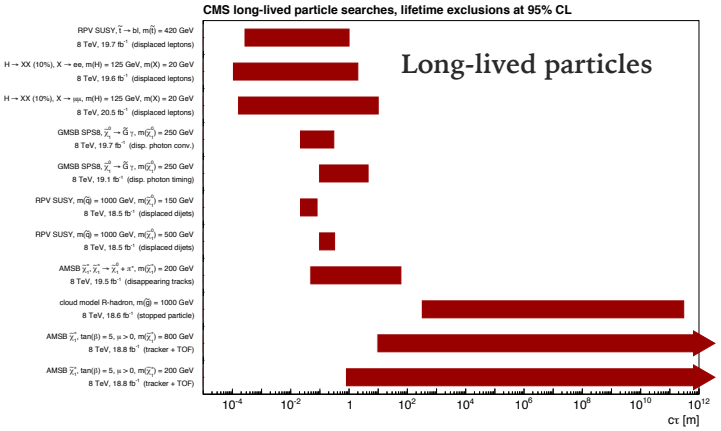
A wealth of results…we keep searching!

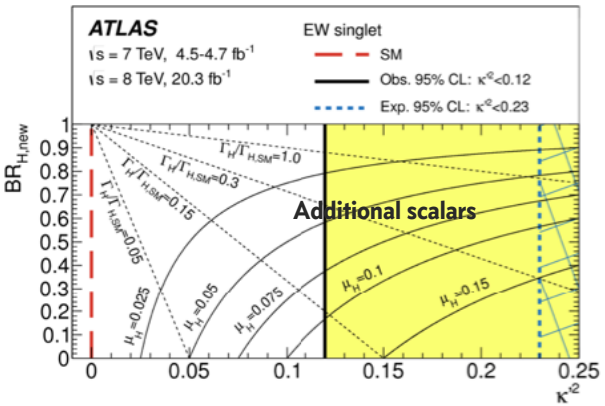












[ATLAS Summary Plots]

[CMS Summary Plots]

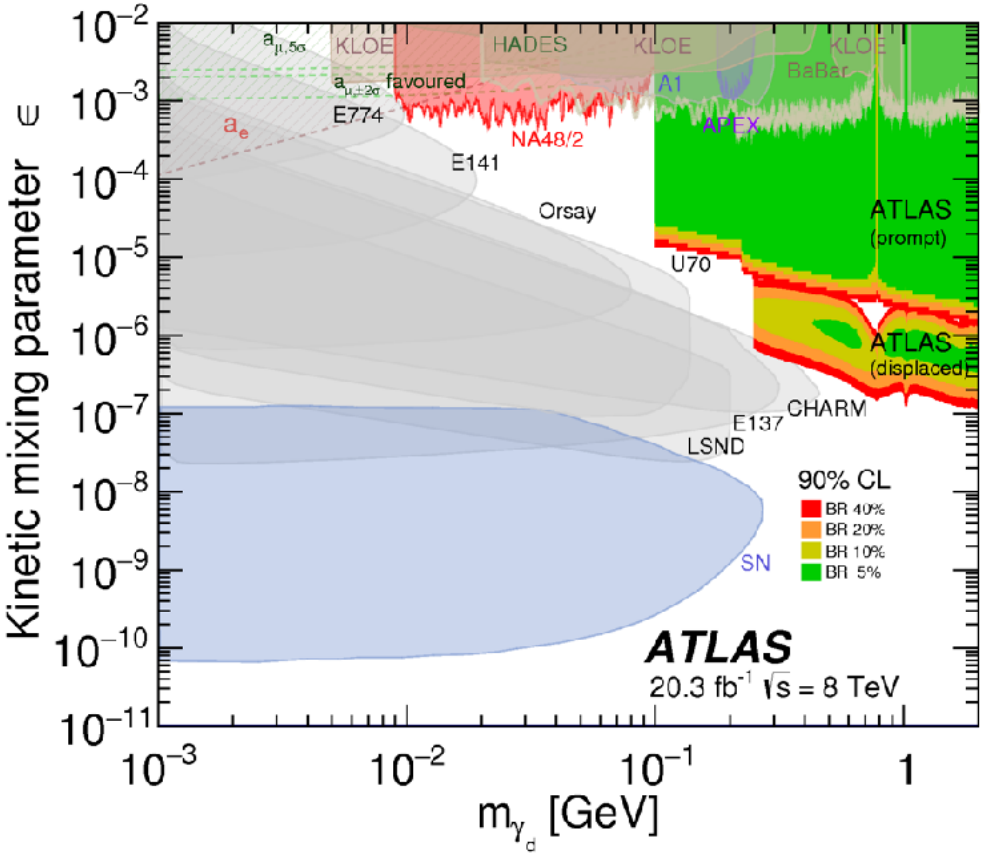
Experiments analysed **only 1%** of the planned LHC dataset so far

…rich program of measurements and searches up to 2035!

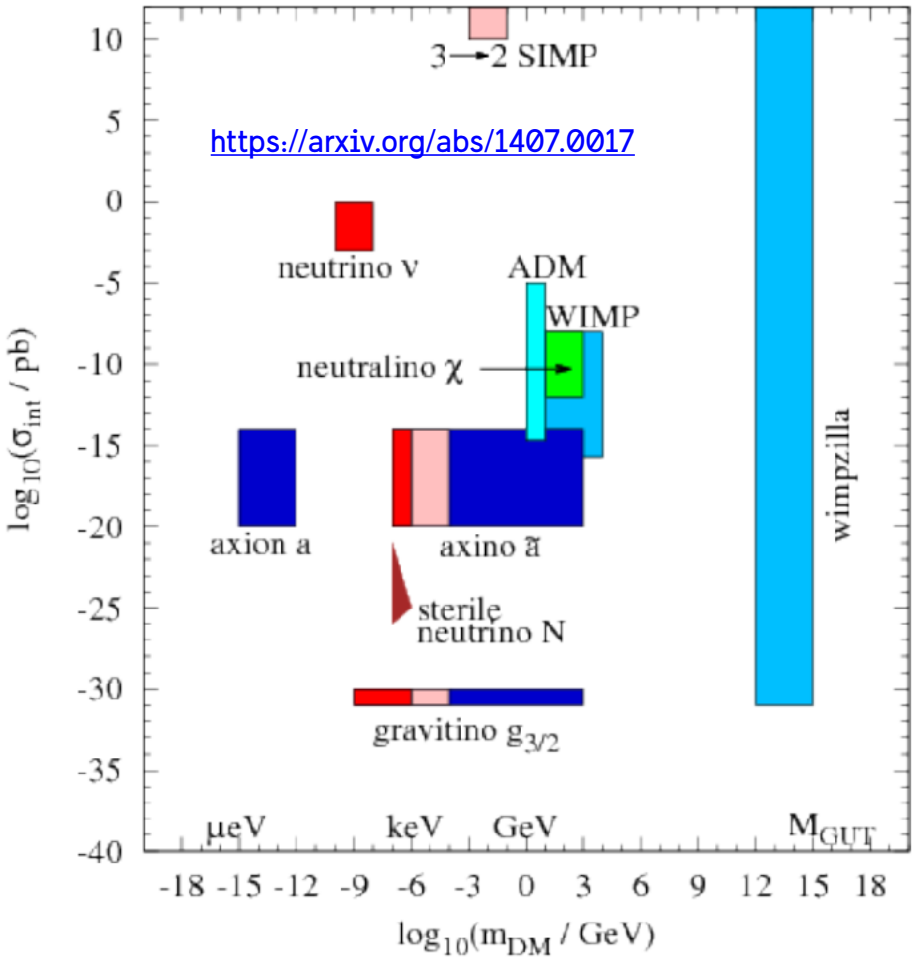
Everything we don't want to miss

by thinking of WIMPs only

Searches for Dark Sector particles
(no direct DM/SM interaction)

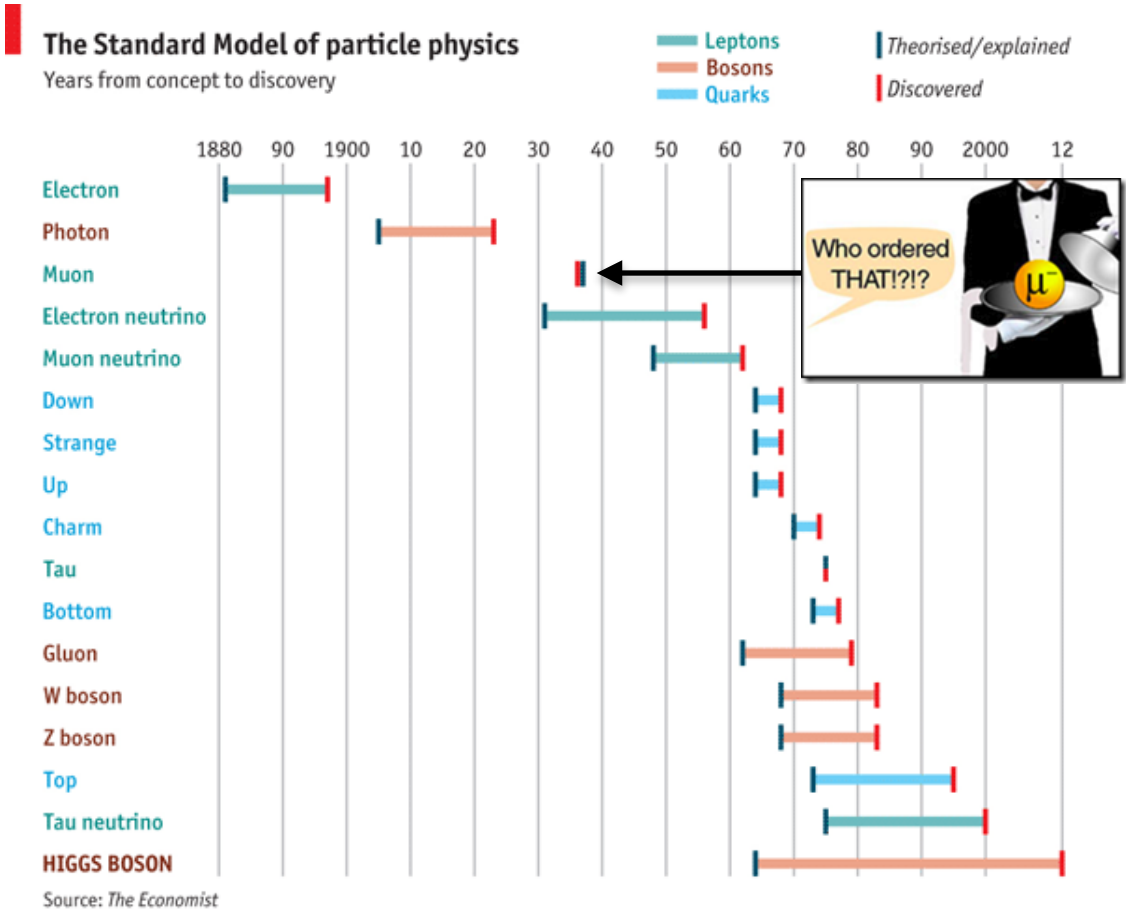


http://en.wikipedia.org/wiki/Streetlight_effect



No details in this talk, but **many** other interesting and compelling DM candidates at colliders and beyond

Where to look for DM and new particles?



Everywhere!

design **model-independent searches** for new phenomena

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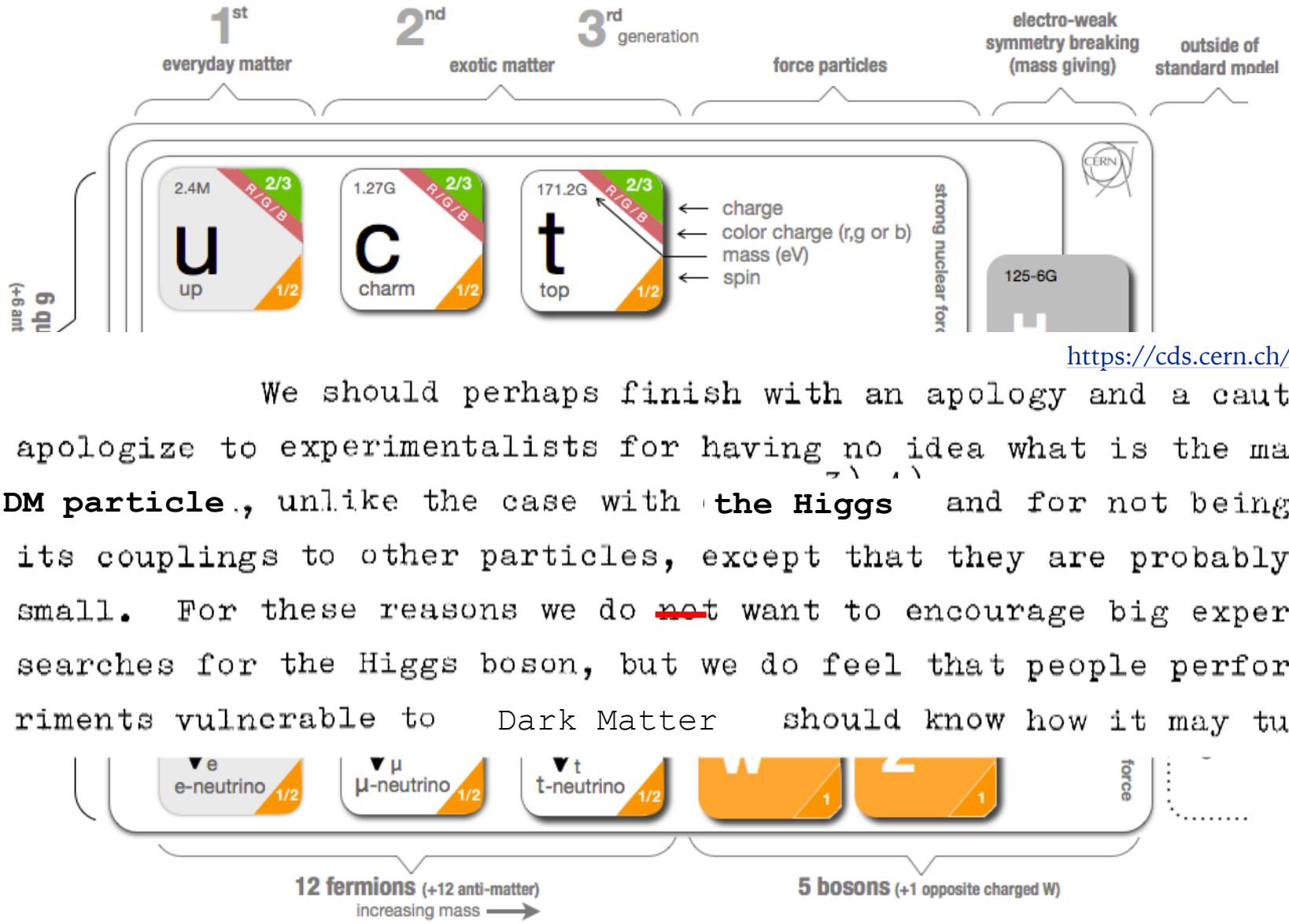
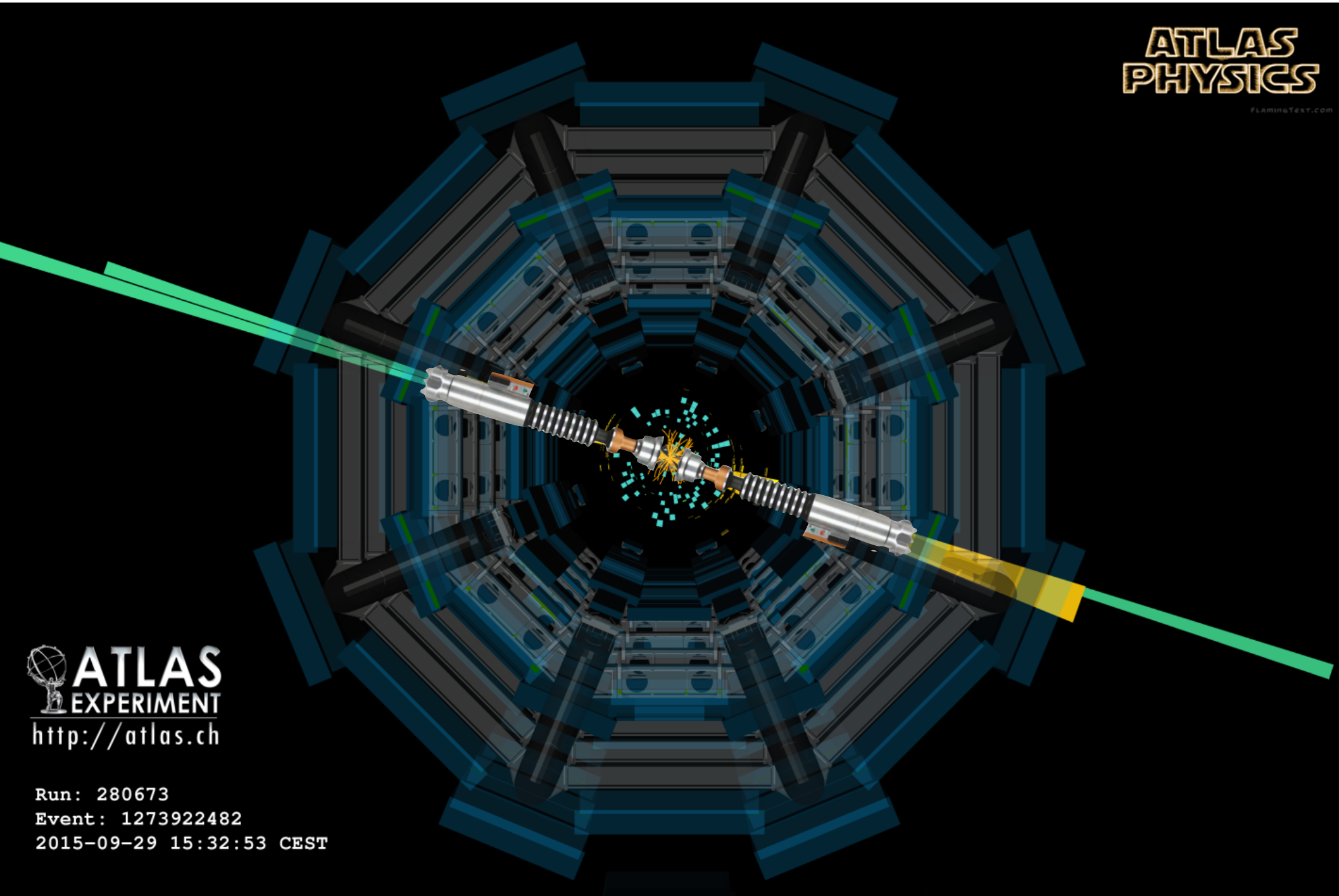
Looking forward to more searches



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

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

Thanks for your attention!



List of DMWG topics covered so far

http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg

Summer 2015

[Dark Matter Forum] Reach consensus on a common set of benchmark models for ATLAS and CMS early Run-2 searches

Winter 2015

Within the framework of the DMF simplified models, present results and compare Direct Detection (DD) / Indirect Detection (ID) / collider searches

Winter 2016

Agree on how to present searches for mediators of DM interactions in visible decays together with searches to DM particles, add lepton couplings to DMF benchmark models

Spring 2017 (ongoing)

Develop scalar sector and t-channel benchmark models

Spring 2017 (ongoing)

Arrive at a joint estimation of theory uncertainties for *precision DM searches* at colliders (e.g. mono-jet)

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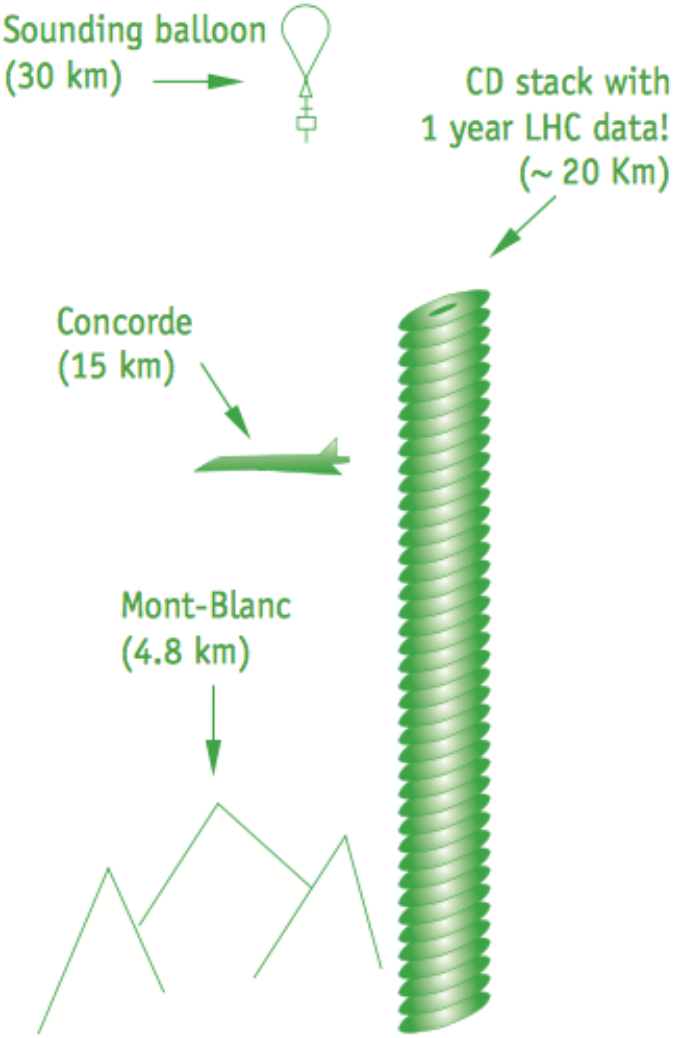
Data volumes at the LHC

- LHC: if everything was recorded…
  - up to 40 million collisions/second (MHz)
  - 1-1.5 MB/data per collision
  - 40 MHz * 1 MB = 40 TB/s
  - 40 TB/s * 10e+6 s/year = 0.05 ZB/year

- Facebook:
  - 600 TB/day ~ 200 PB/year [Facebook]

LHC experiments need to:

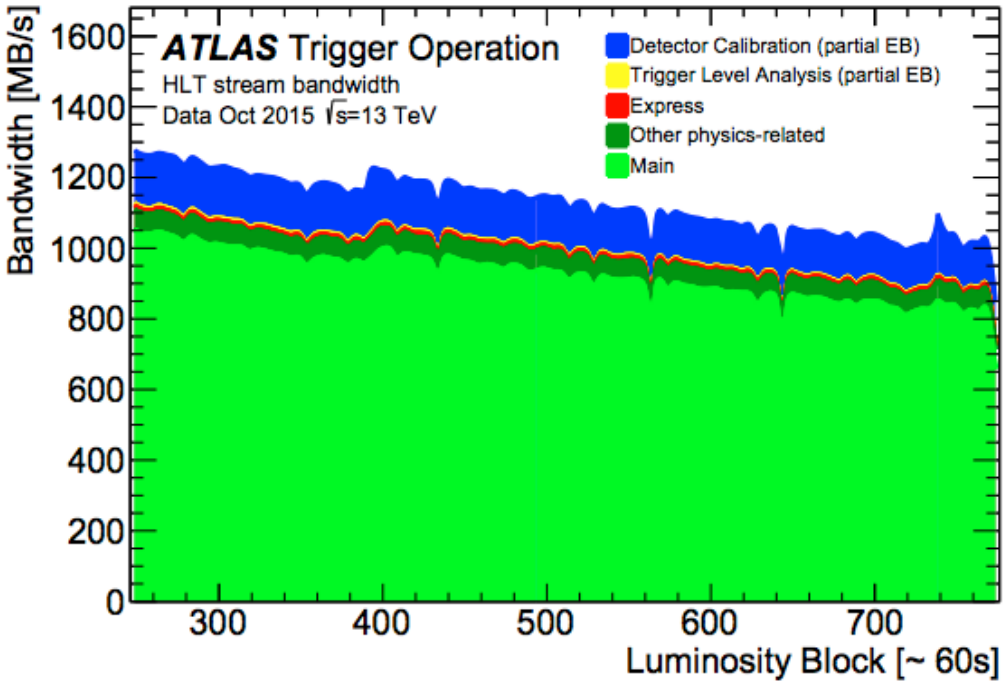
1. **process** all data, fast
2. **select** only interesting events

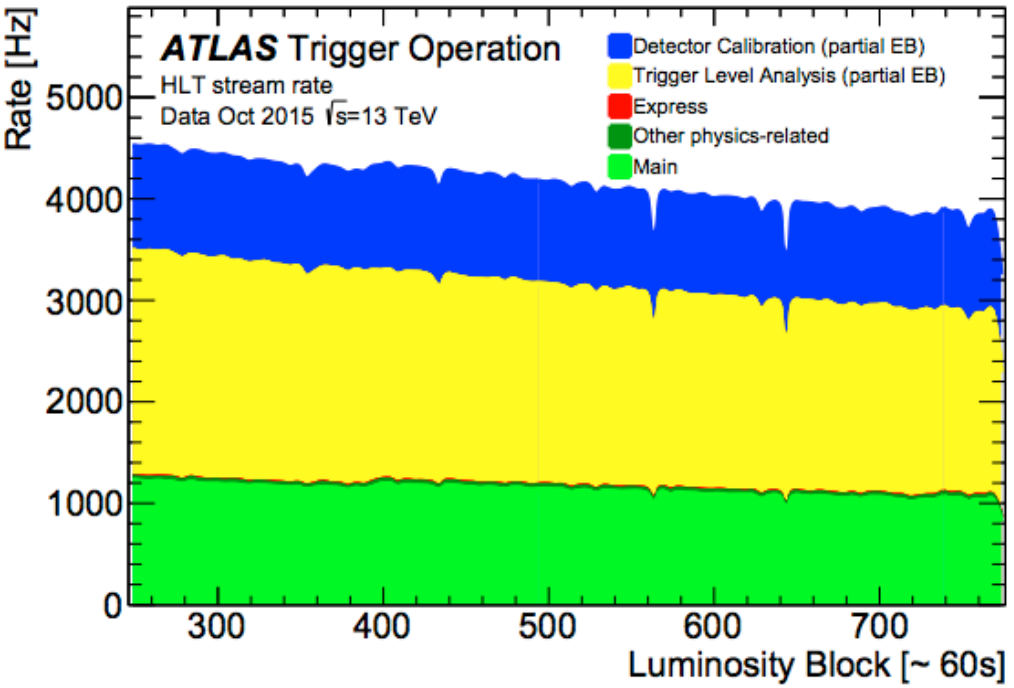


(**after** selecting interesting events)

Overcoming data taking limitations

Bandwidth = **Event rate** x Event size





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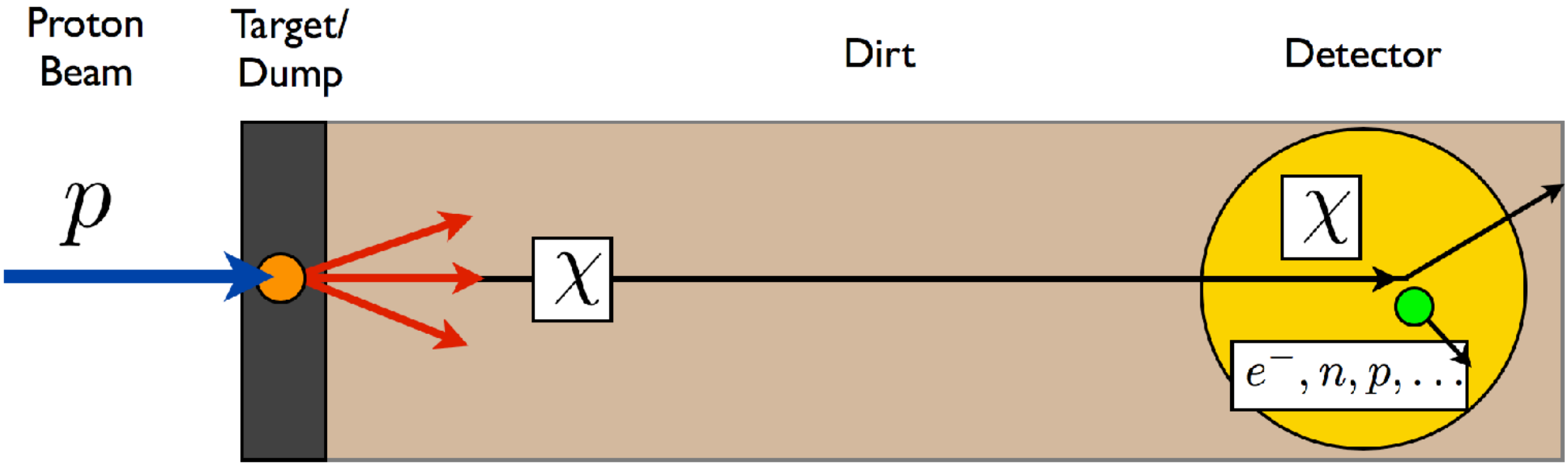
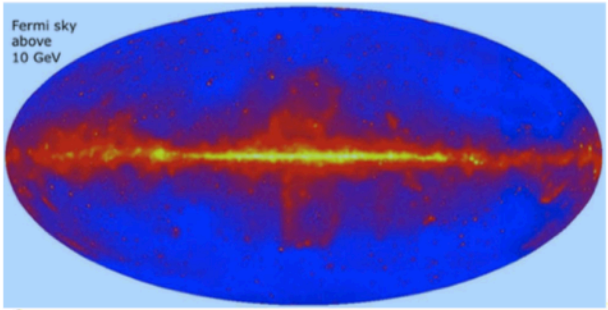
Beam Dump Search for Light Dark Matter

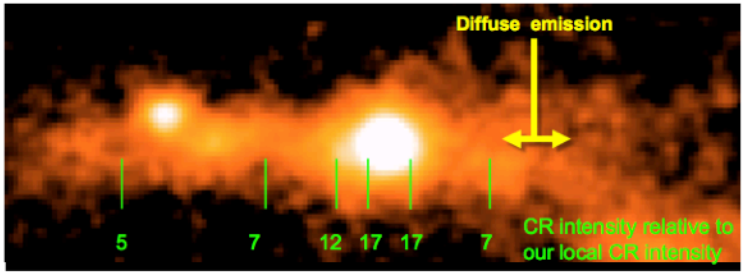


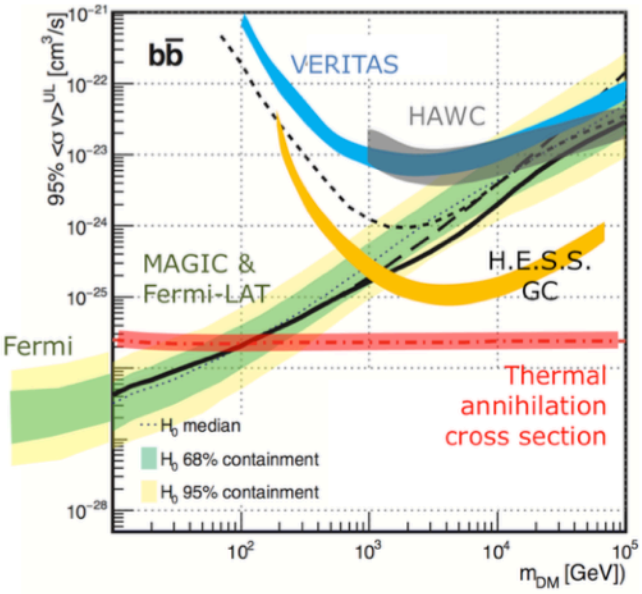
[BB, Pospelov Ritz, '09]
[deNiverville, Pospelov Ritz, '11]
[McKeen, deNiverville, Ritz, '12]

- Superior sensitivity for many models with light dark matter + light mediator
- Can be done with existing neutrino experiments
  - MiniBooNE, NOvA, MicroBooNE, T2K, DUNE…
- Provides a strong motivation for intense proton sources (FNAL, CERN, JPARC,…)
- Electron beam dump searches are also promising and complementary

DM indirect searches: γ–ray expts

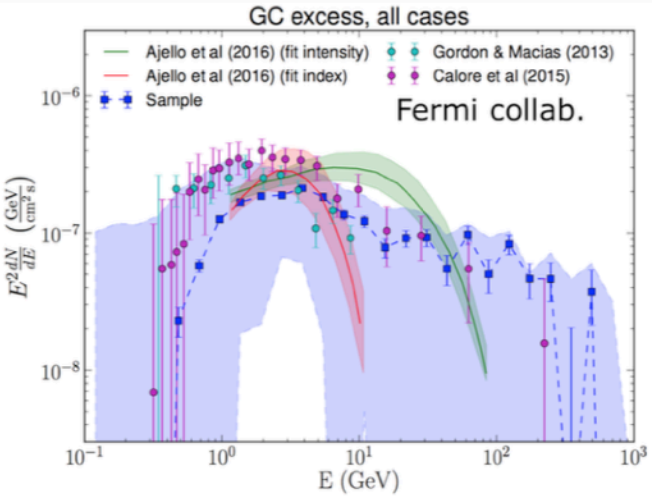




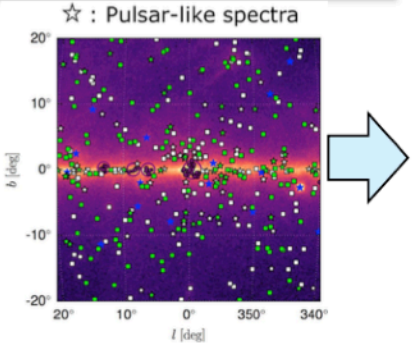


Clearly, experiments have evolved significantly;
Caveats: not in control of the beam; not in control of the space between the source and the experiment; "limits are easy; signal very hard!"

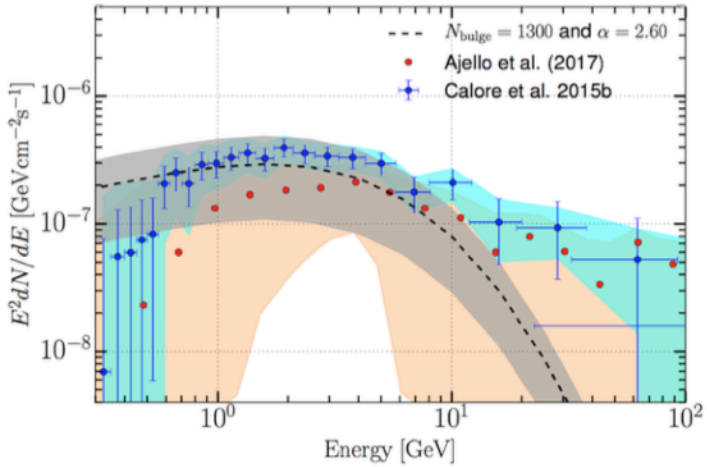
Excess – significant? DM???



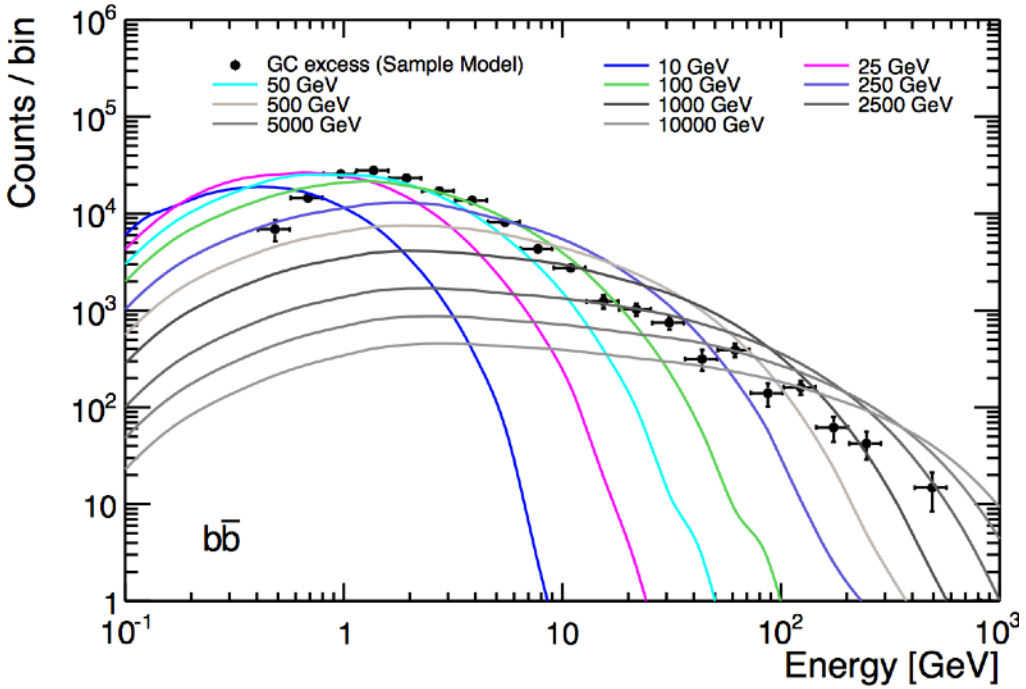
Add pulsars…

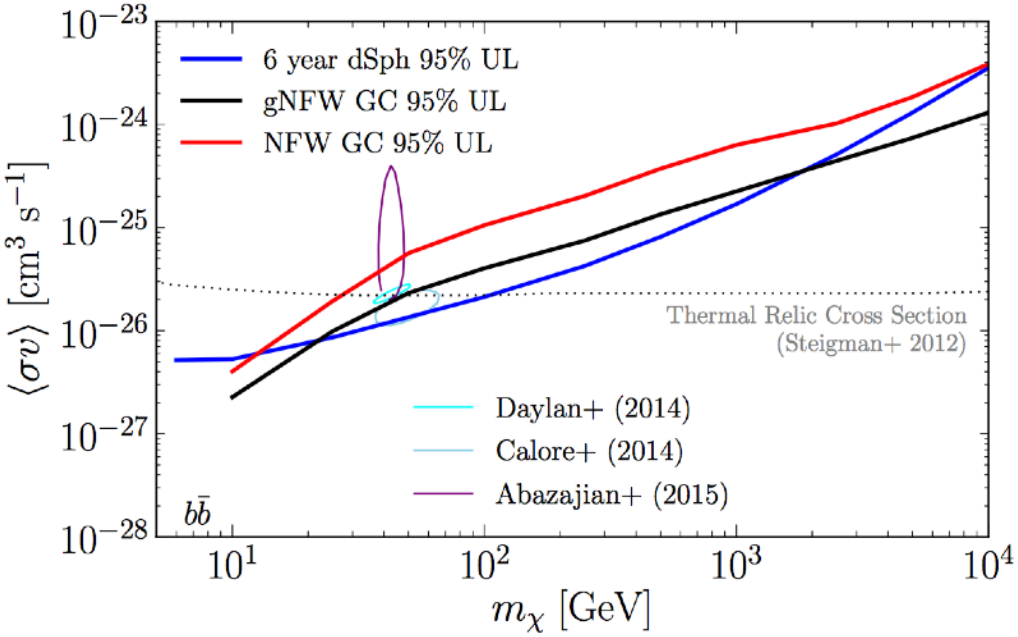


Accounts for much of the effect?



Fermi LAT Galactic center DM interpretation





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