Dark matter searches in ATLAS
and complementarity with other experiments

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MANCHESTER 1824 The University of Manchester

Lunds Universitet

European Research Council
Established by the European Commission

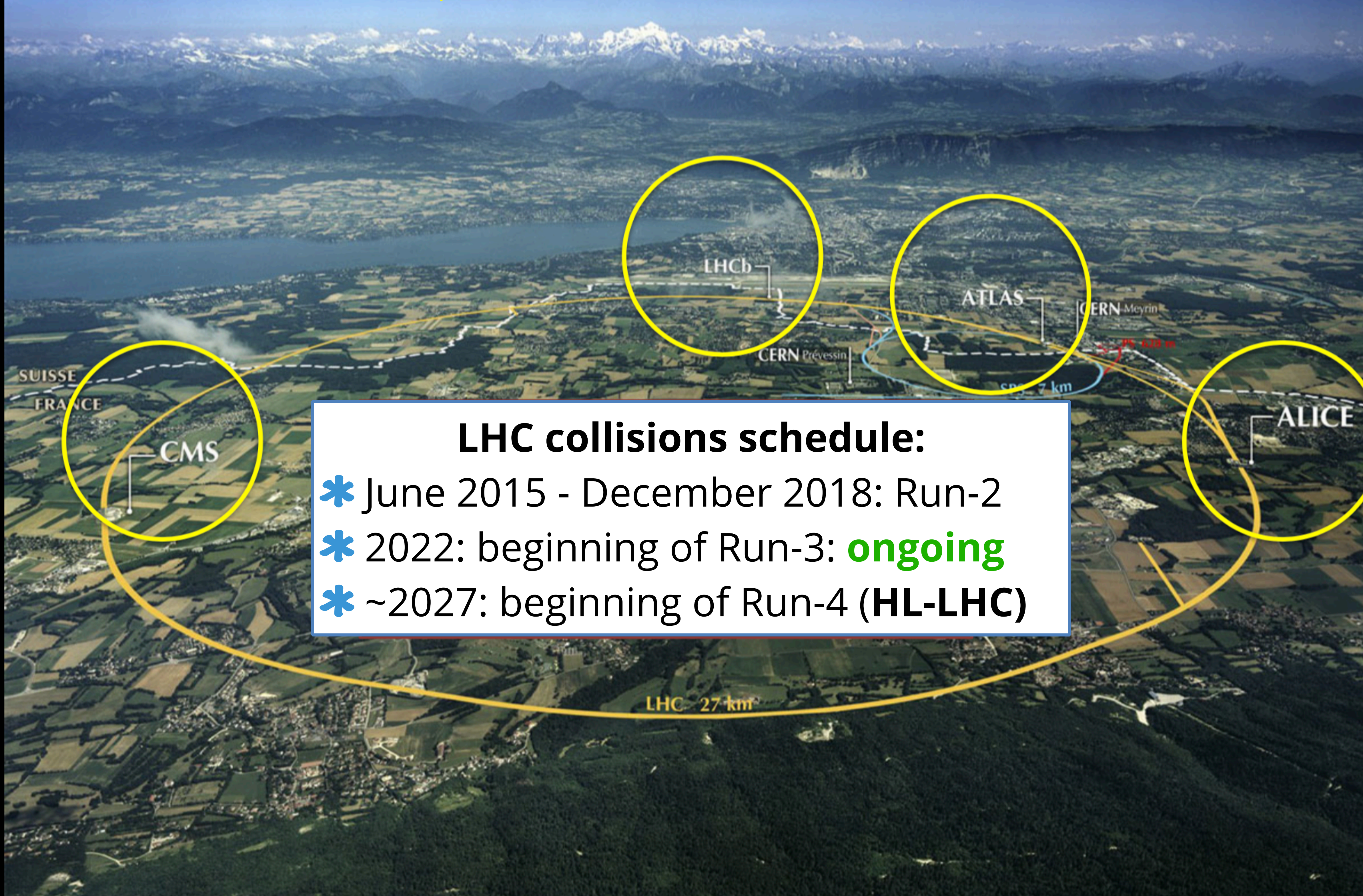
Outline

- Finding ~~dark matter~~ invisible particles at the LHC
- LHC data taking and real-time analysis (or: making the most of the data for DM searches)
- [Hopefully] confirming dark matter discoveries, across complementary experiments
- Synergistic activities (ideas for collaborations?)

Finding ~~dark matter~~ invisible (& visible) particles at the LHC

We can't see dark matter, hear dark matter (or talk about dark matter?)

Current discovery machine: the Large Hadron Collider

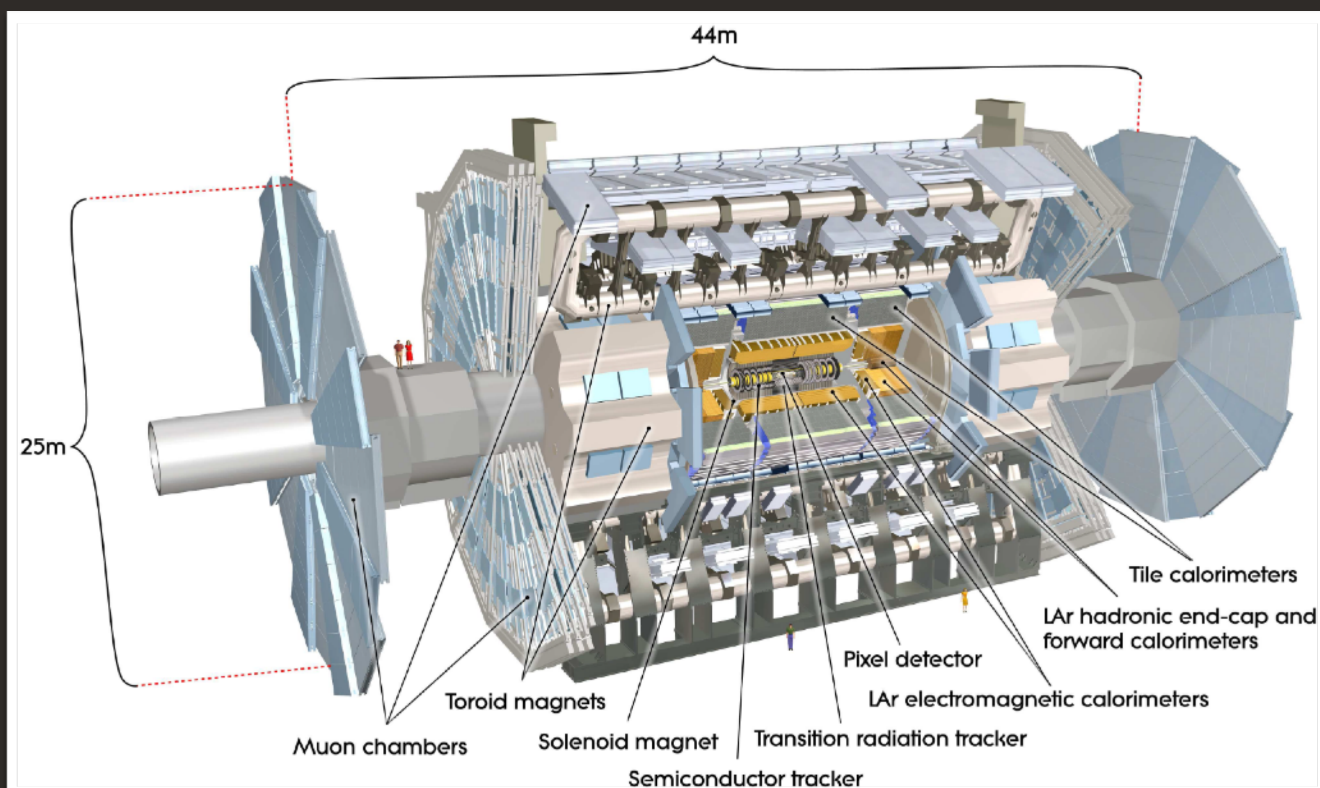


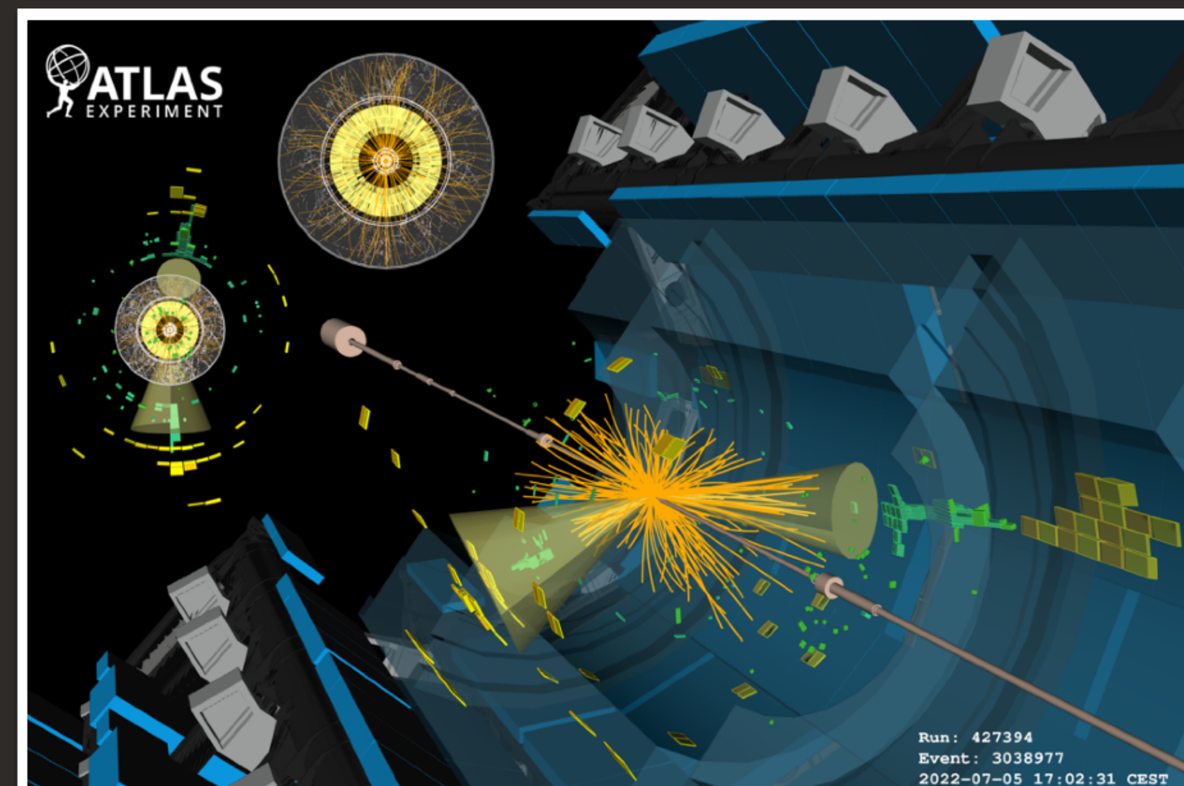
LHC collisions schedule:

- June 2015 - December 2018: Run-2
- 2022: beginning of Run-3: **ongoing**
- ~2027: beginning of Run-4 (**HL-LHC**)

Our current experiment: ATLAS detector

First Run-3 collisions in ATLAS: July 2022



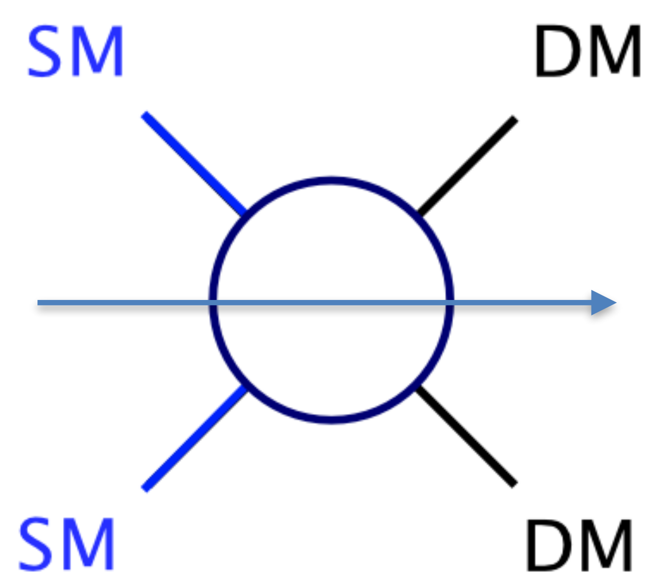


Motivation for DM@colliders

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



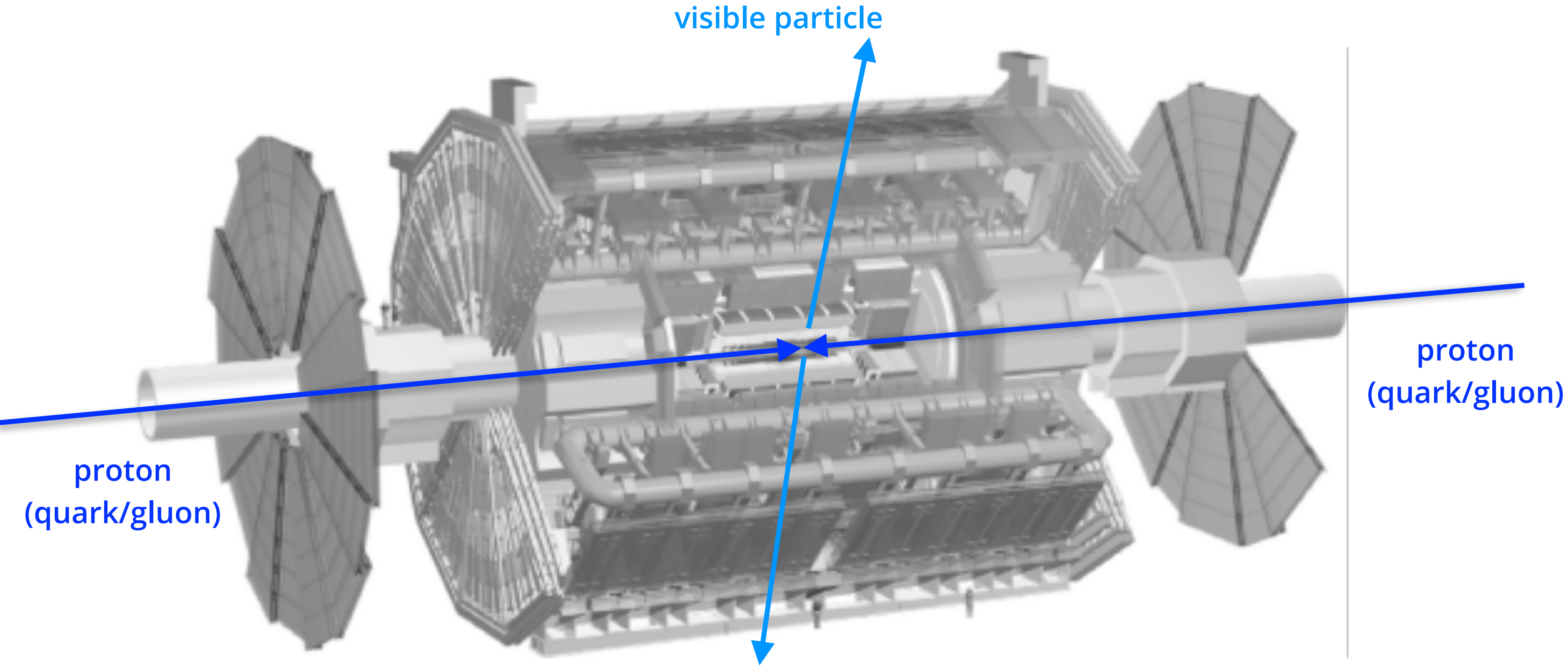
production of DM particles

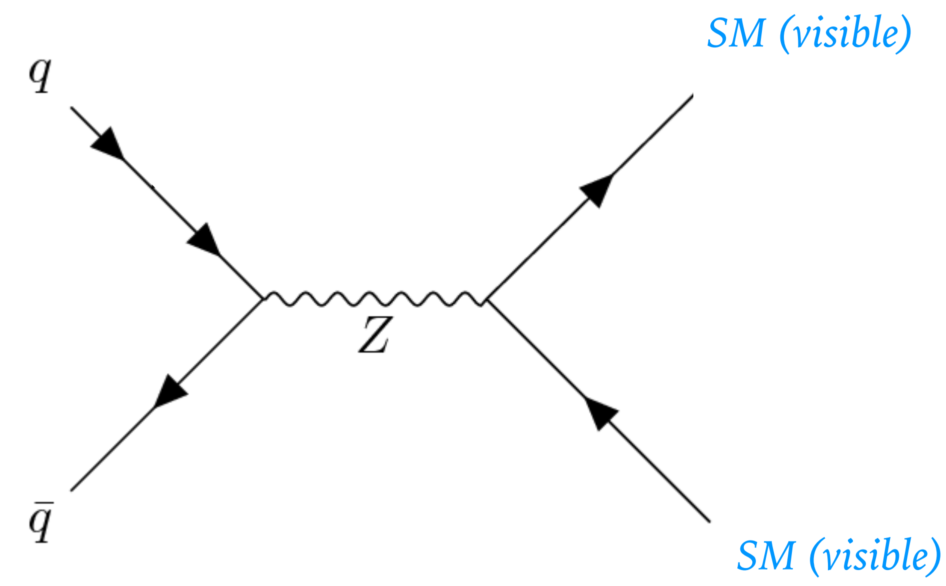
Caveat: very simplified diagram

- dark, stable → **invisible to detectors**

Searches for ~~DM~~ invisible particles at colliders

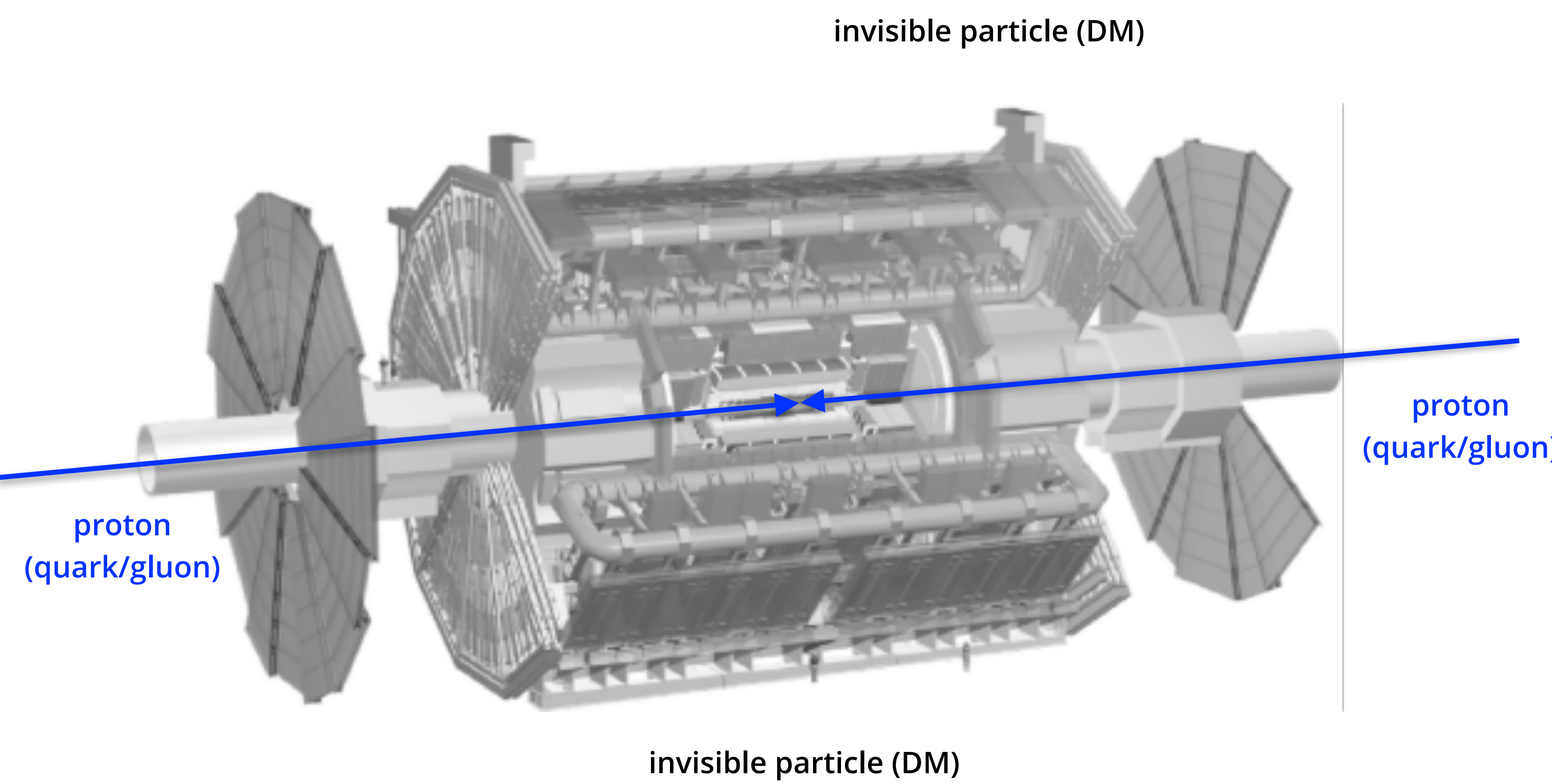
Detector covers all the solid angle and catches ~all visible particles

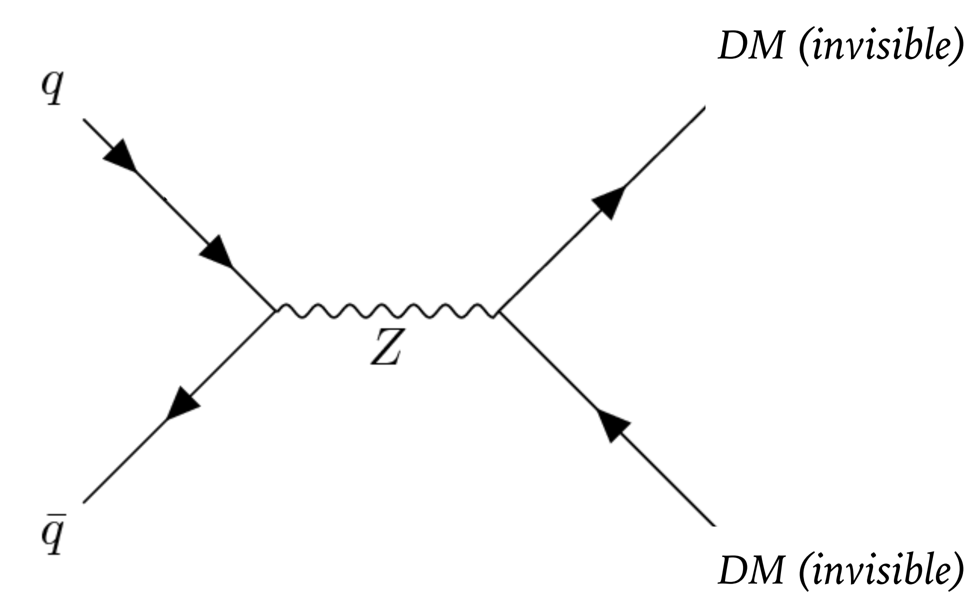


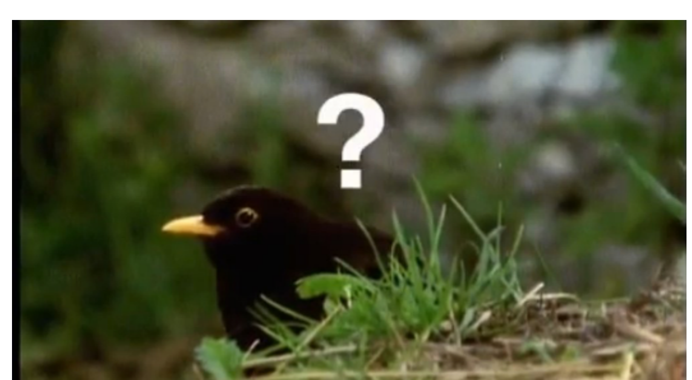


Searches for ~~DM~~ invisible particles at colliders

Dark matter doesn't interact significantly with our detectors → invisible







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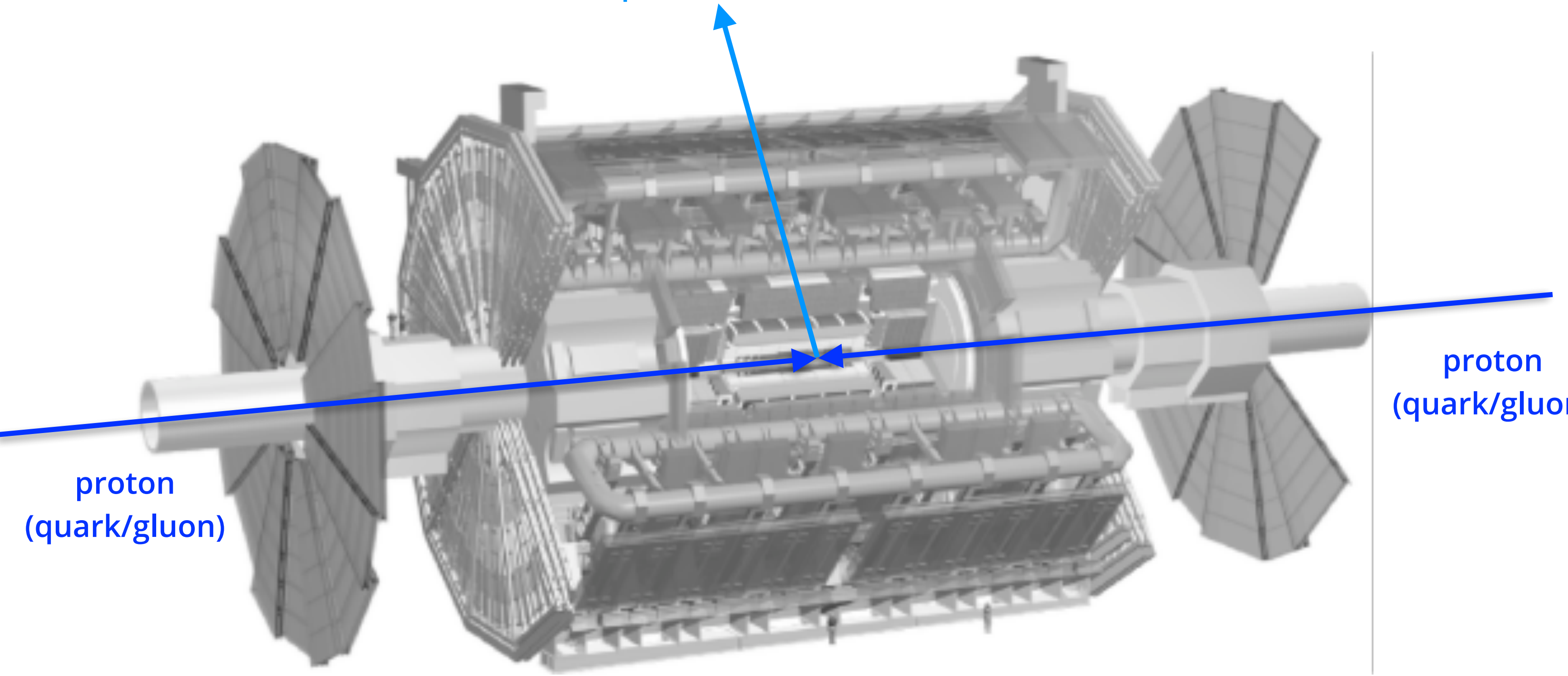
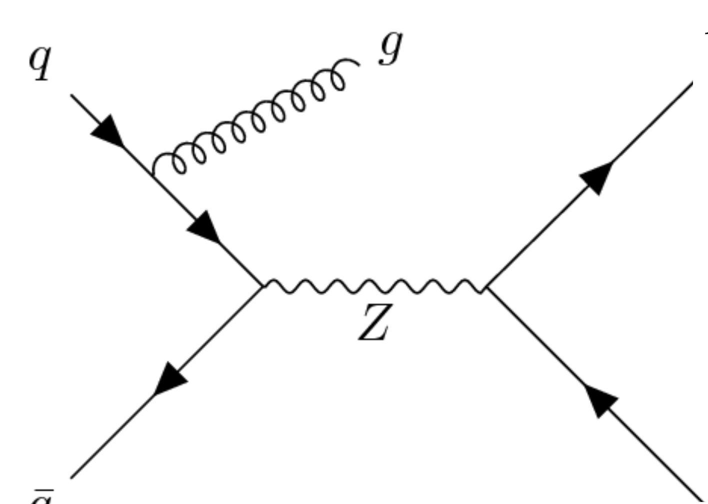
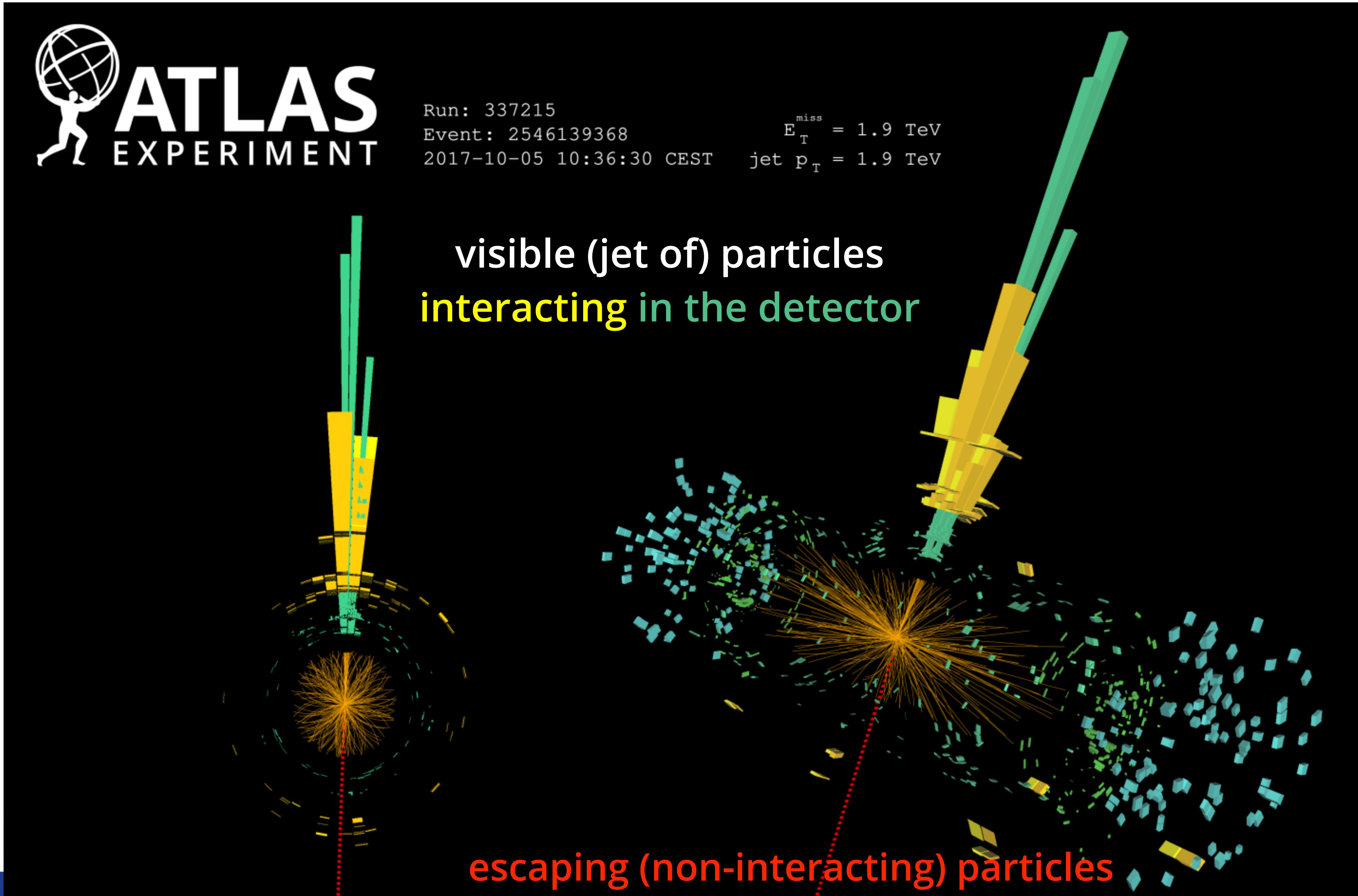




Signature of invisible particles
(like Dark Matter):
missing (transverse) momentum (E_T^{miss})

A "monojet event" at ATLAS

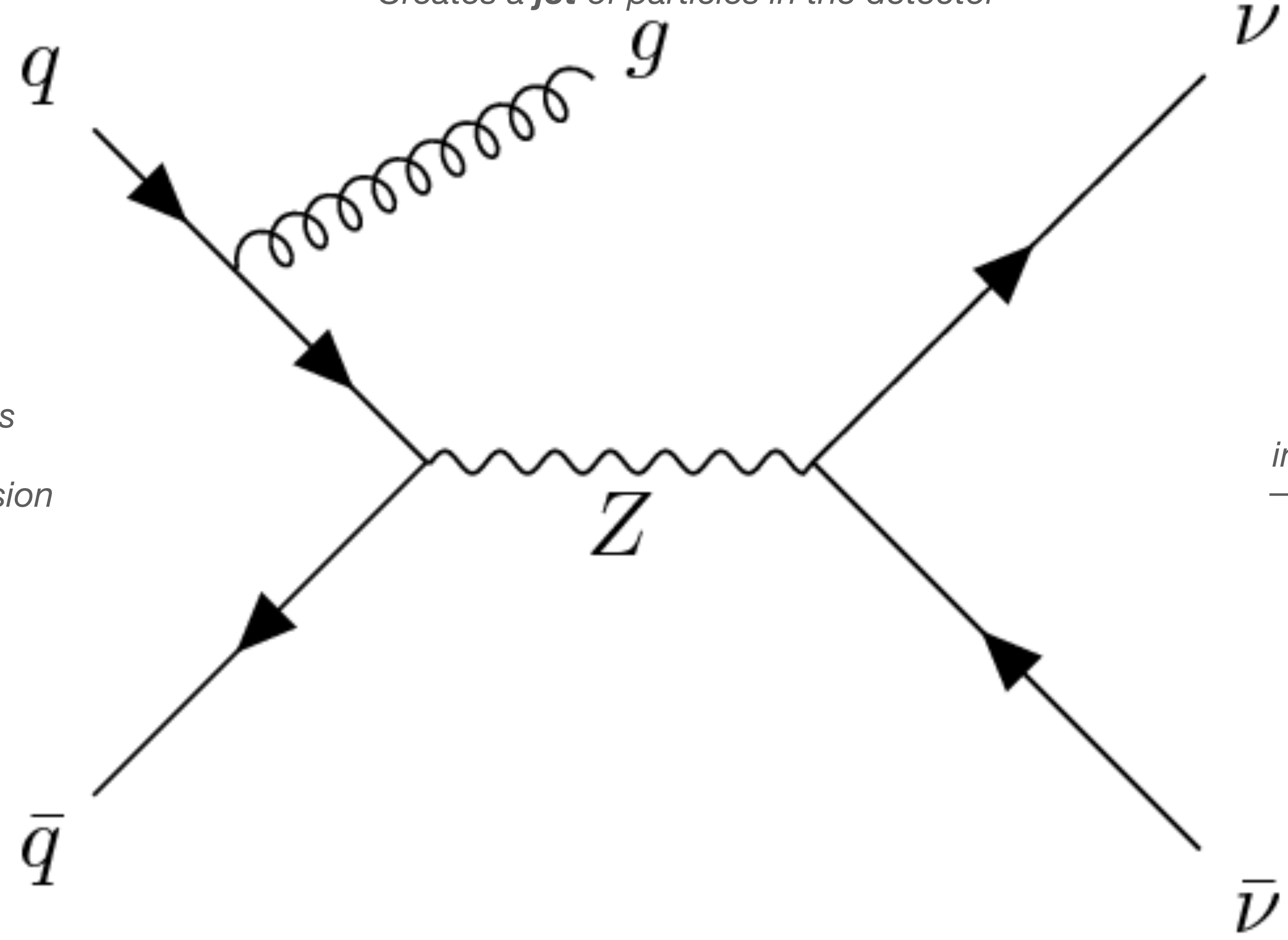


Generic production of invisible particles

Production of invisible particles is common in the Standard Model…

Initial State Radiation (ISR)
*Creates a **jet** of particles in the detector*

initial state quarks from the LHC proton-proton collision



final state neutrinos, interacting only weakly → invisible to detectors

[Eur. Phys. J. C 77 (2017) 765]

Generic production of dark matter?

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

Initial State Radiation (ISR)
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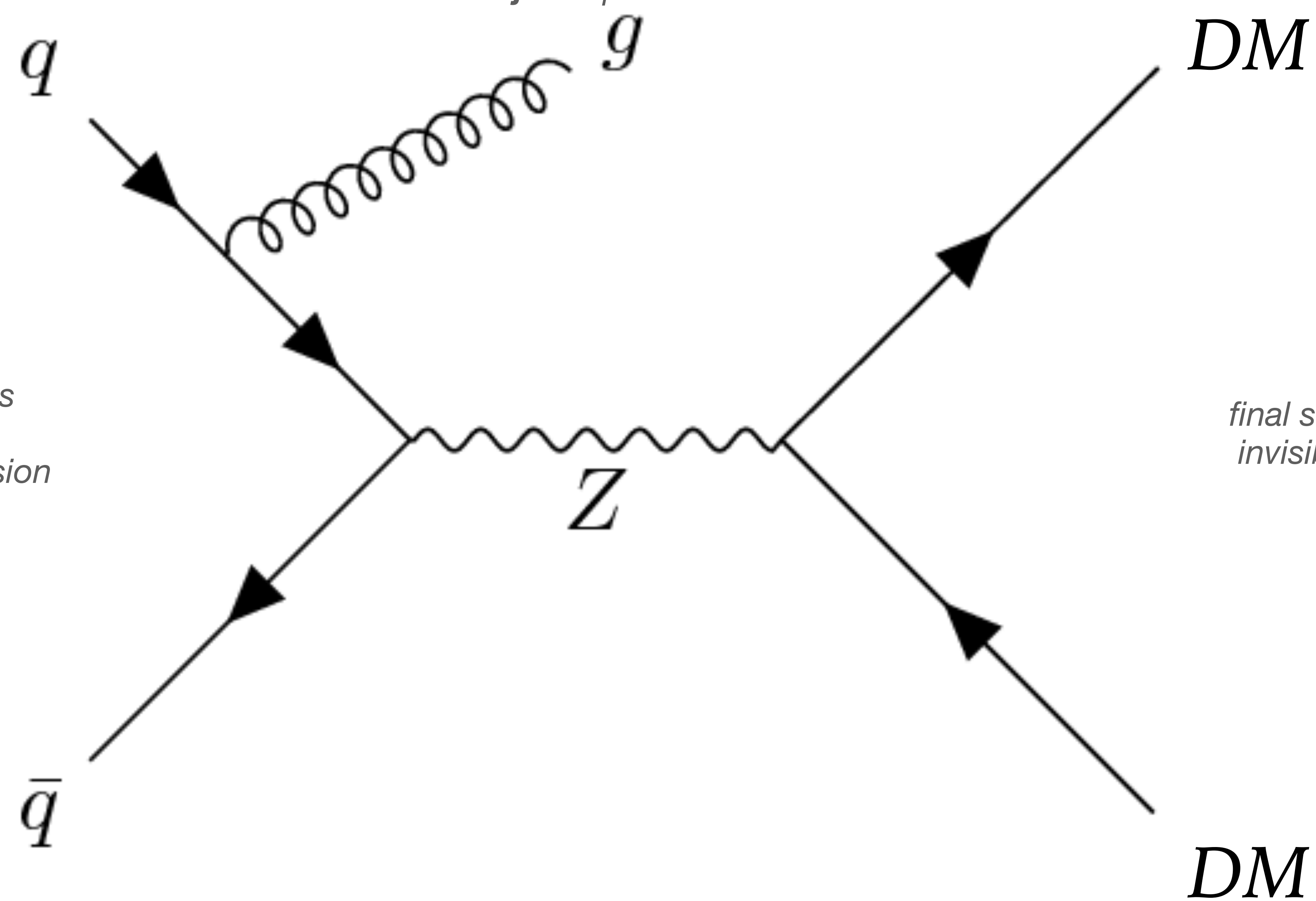


final state Dark Matter invisible to detectors

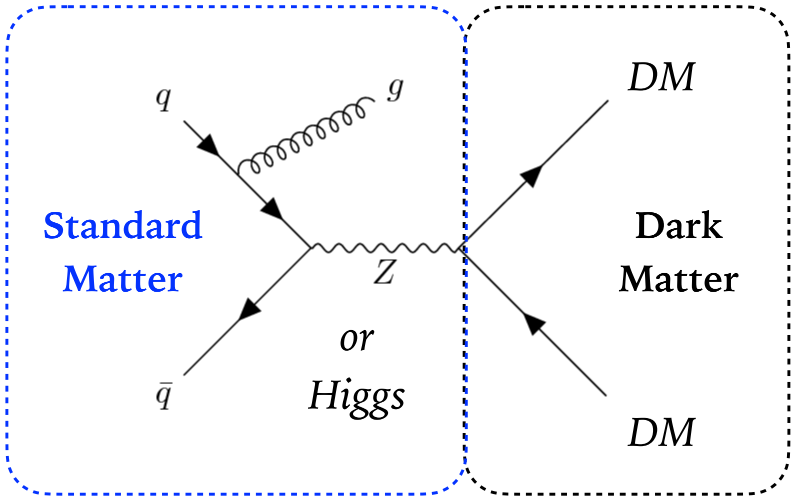
Eur. Phys. J. C 77 (2017) 765

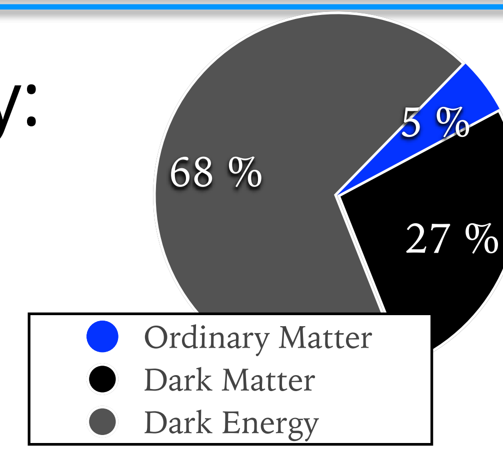
Note: this is only one of the many DM *signatures* we look for in ATLAS…

Weakly Interacting Massive Particles

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

- only add one particle to the Standard Model





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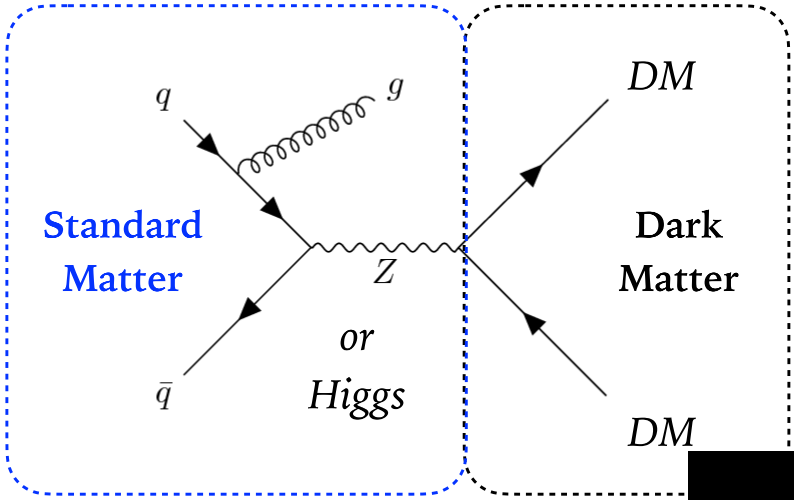

- stable **TeV-scale** particle with **weak-force-sized** interactions
  - Weakly Interacting Massive Particle (**WIMP**)…
  - …conveniently appearing in models that also solve other problems in particle physics (e.g. supersymmetry)
  - Beautiful and simple, almost *miraculous!*

More about non-WIMP DM & dark sectors in Sukanya's slides

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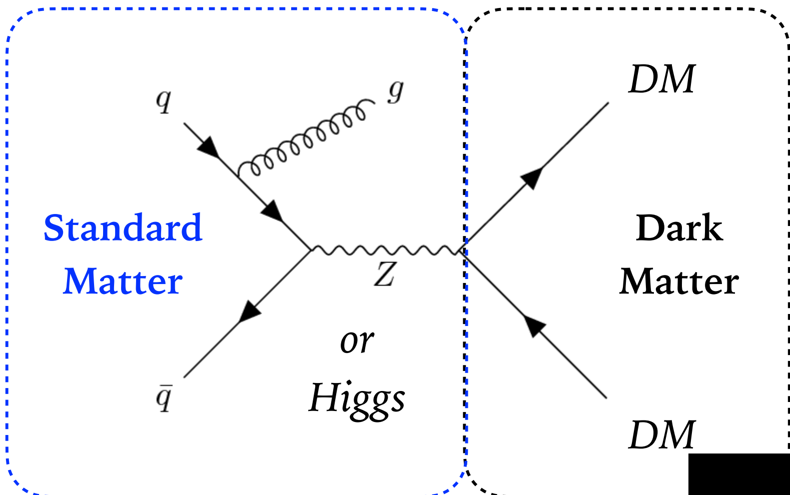

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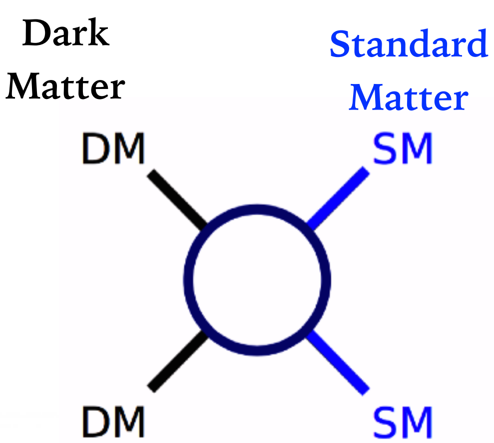
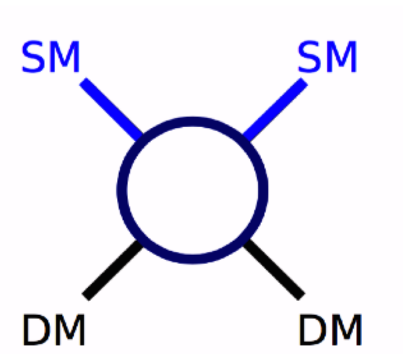
Experimental advantage: many experiments can detect it in different ways

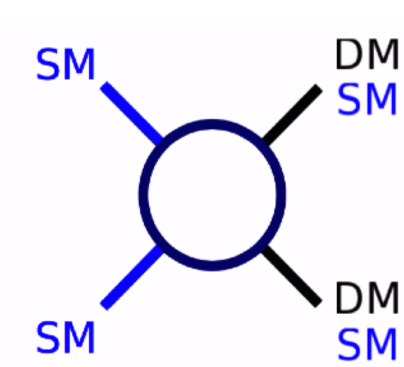
complementary discoveries



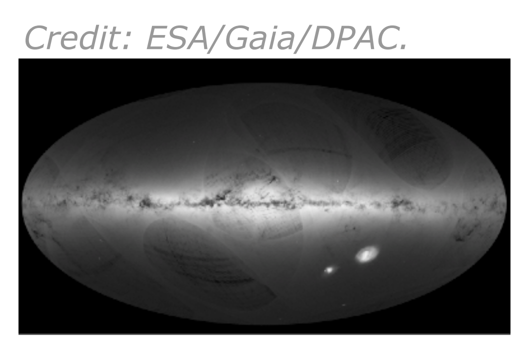
Indirect Detection



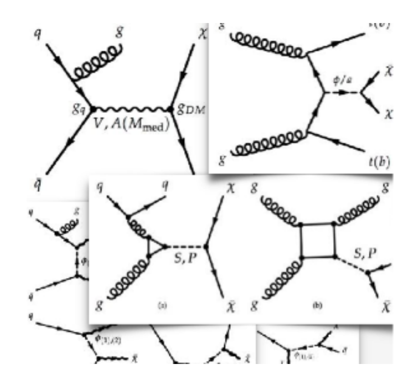
Direct Detection



Colliders/ Accelerators



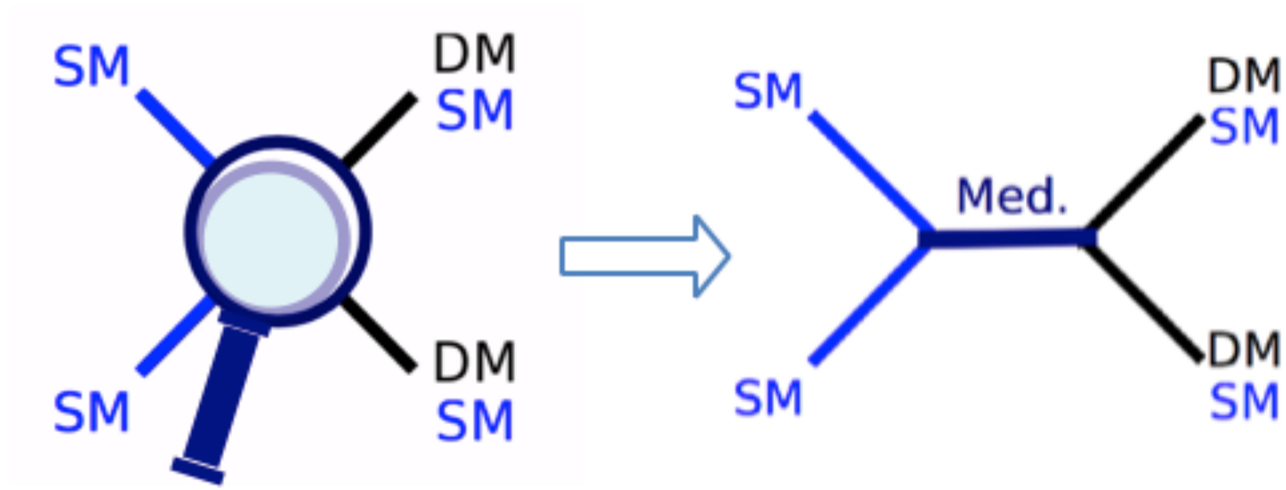
Astrophysics

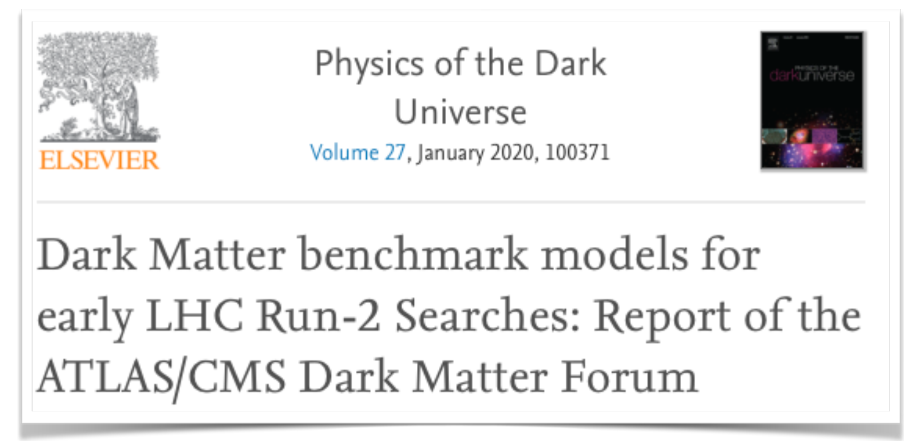


Theory input always necessary to contextualize

Dark Matter mediators at the LHC

If there's a force other than gravity, there's a **mediator**,
and the LHC could **detect** it via its **visible decays**:
(WIMP) *simplified models* are popular 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

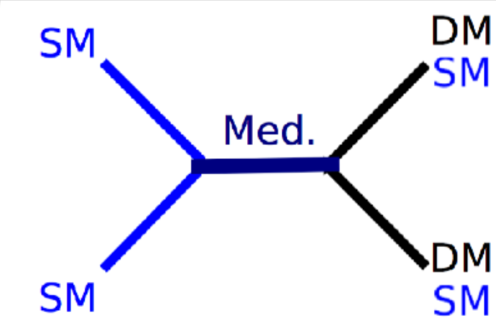
Dark Matter Forum & Working Group

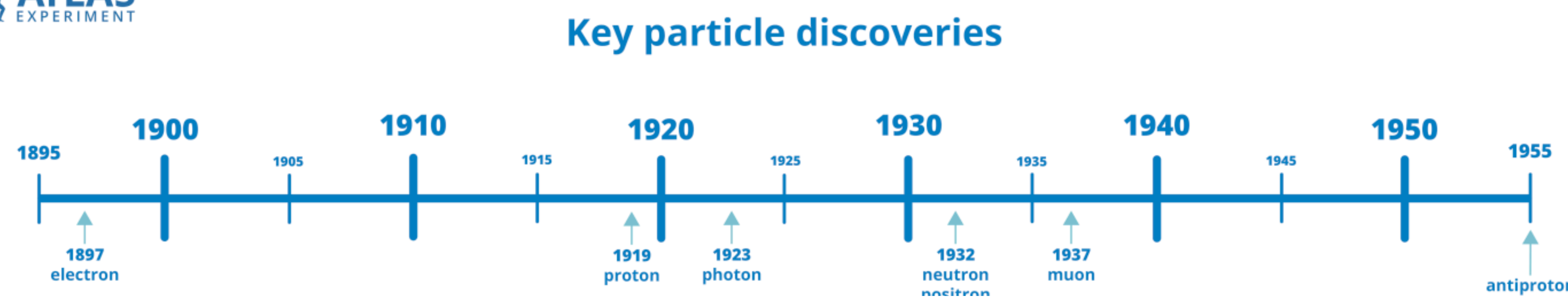
https://lpcc.web.cern.ch/content/lhc-dm-wg-dark-matter-searches-lhc
Phys. Dark Univ. 26 (2019) 100371 & references within

Choice of WIMP benchmarks

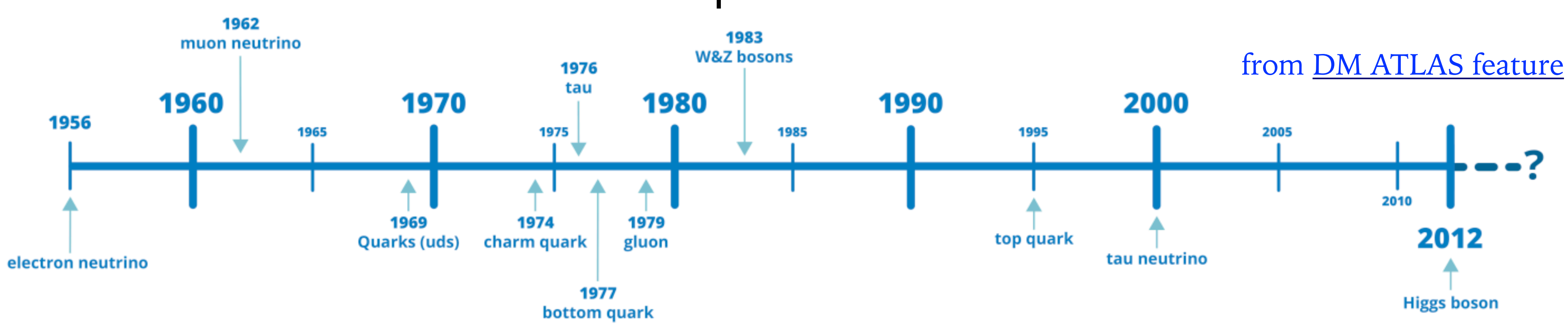
https://abstrusegoose.com/406

"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!**)





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



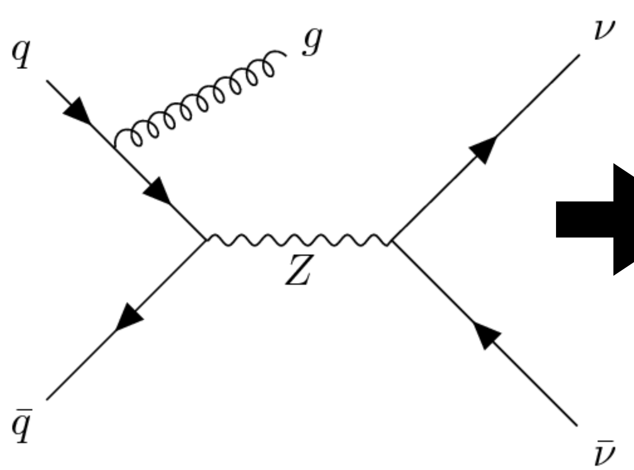
from DM ATLAS feature

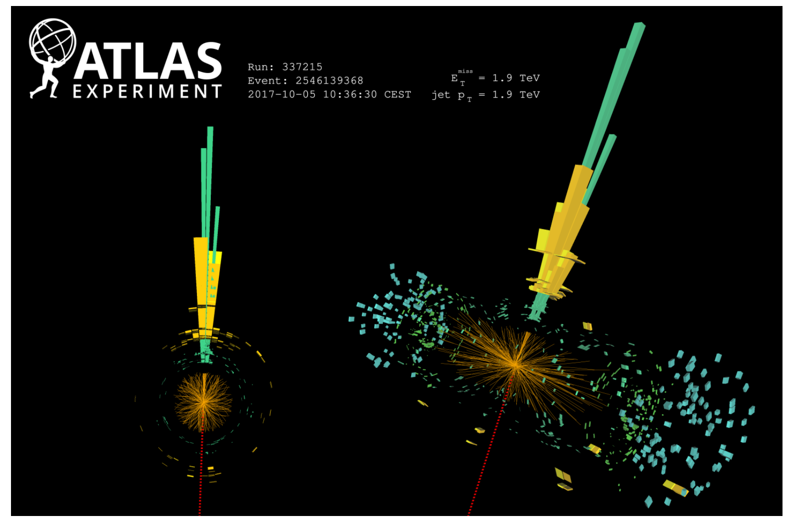
- Even simple models can encapsulate **relevant experimental characteristics** representing wider classes of theories as long as we are **aware of their limitations…more on this later**

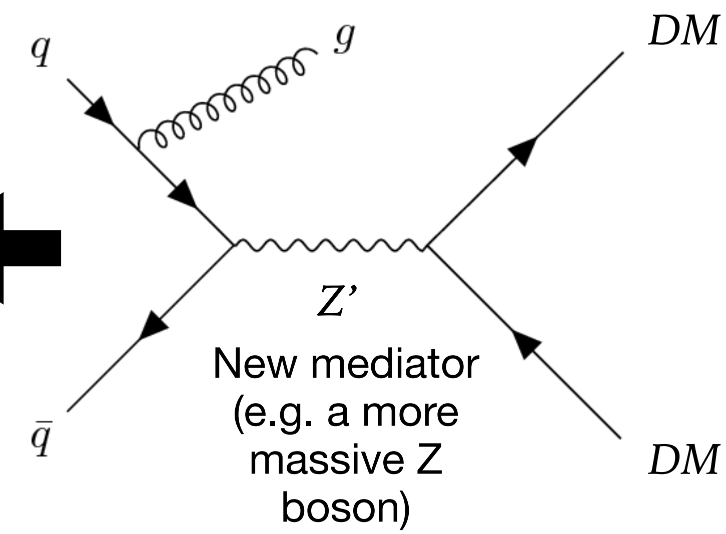
A generic search for WIMP DM: "*X+MET*"

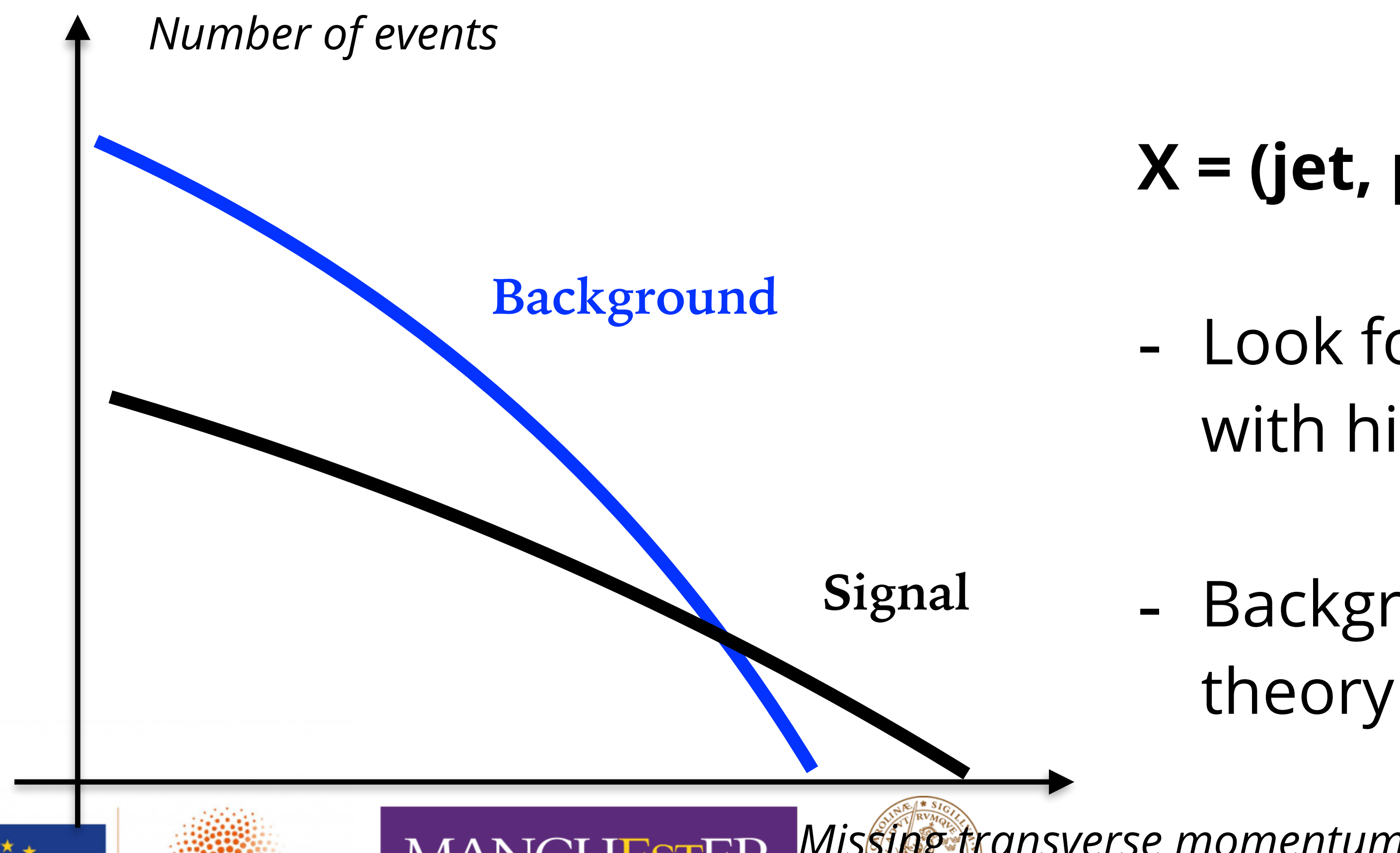
Background (frequent)

Signal (rare)









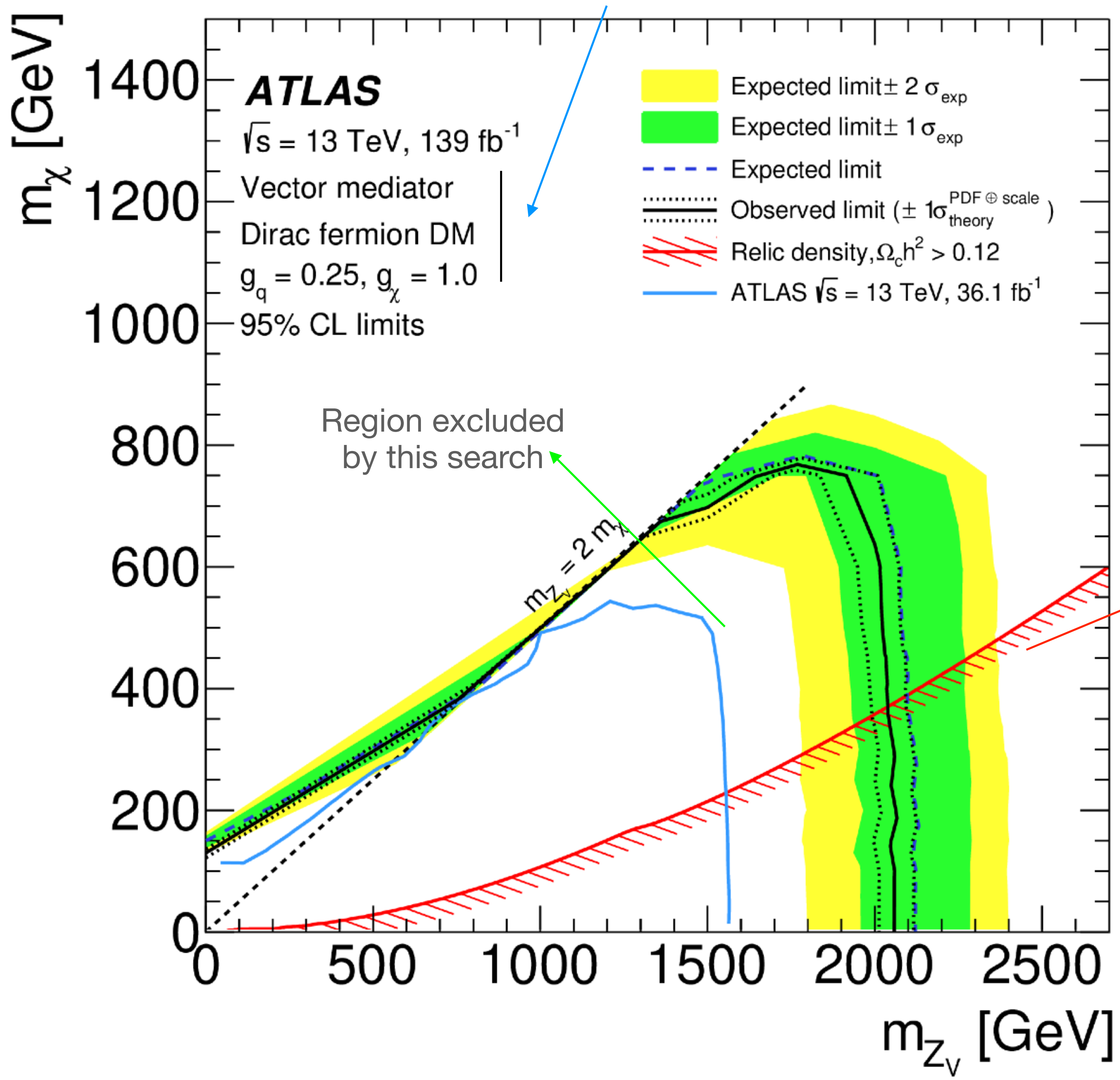
X = (jet, photon, W/Z boson…) + MET search

- 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*)

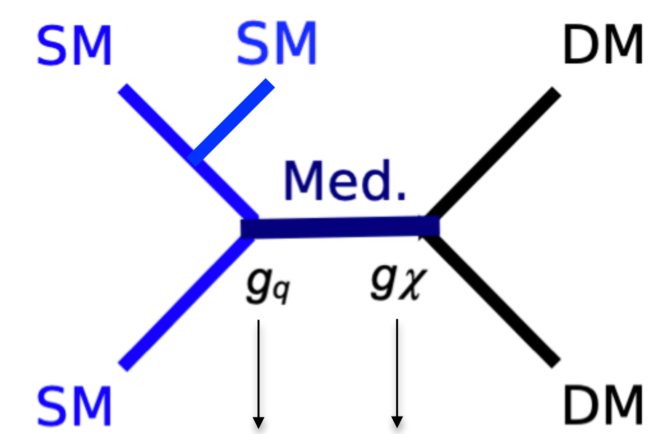
More about search techniques in Sukanya's slides

DM interpretation of ATLAS jet+MET search

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



Model produces too much DM



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

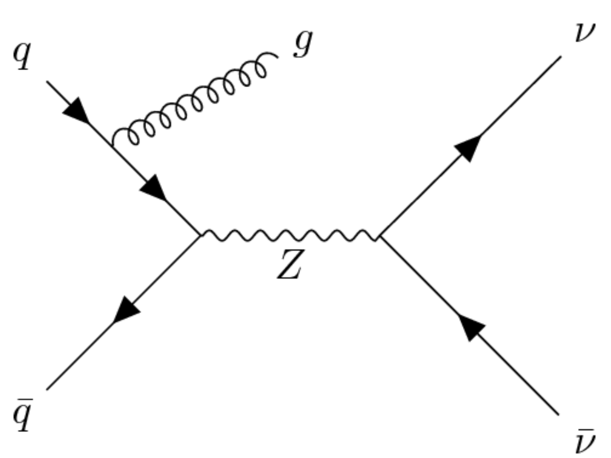
Other interpretations:

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

Parallels: visible and invisible mediator-based searches

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

Background (frequent)



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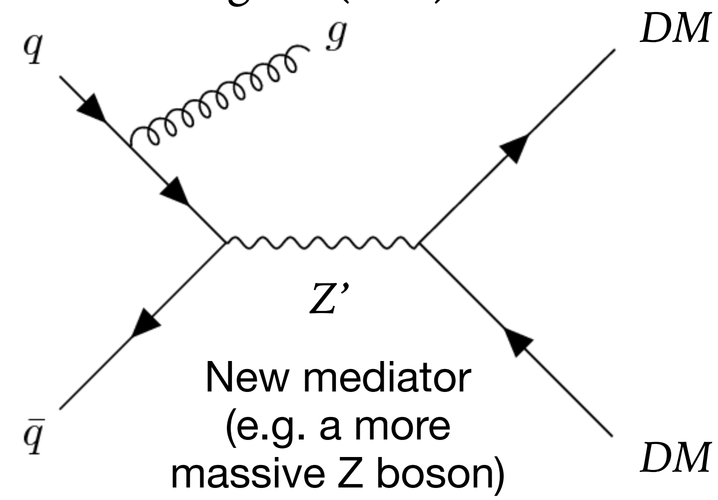

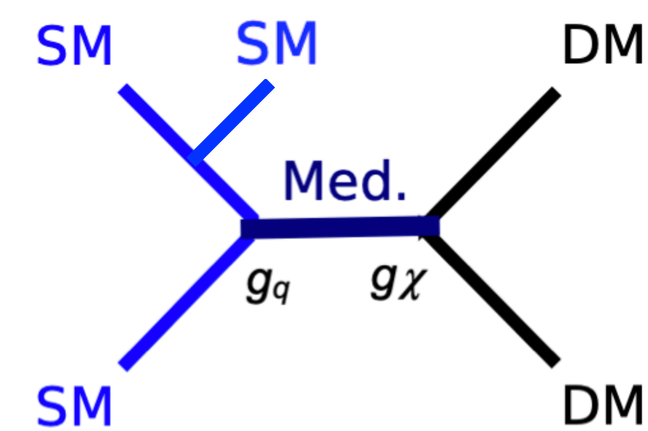

Detection of the DM **mediator**, via its **visible decays**:

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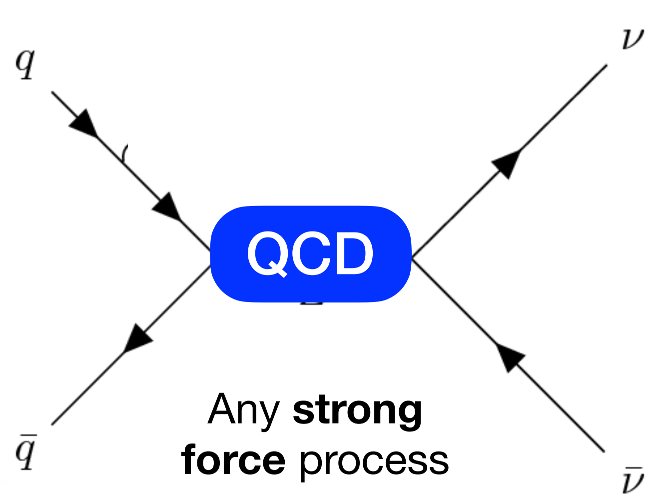

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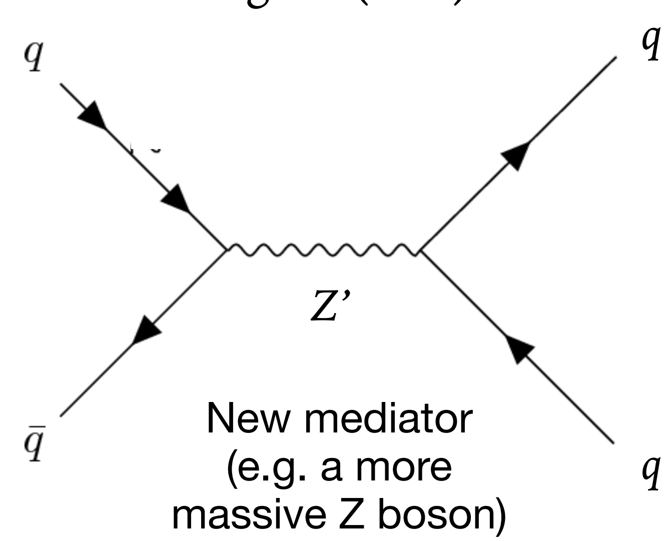

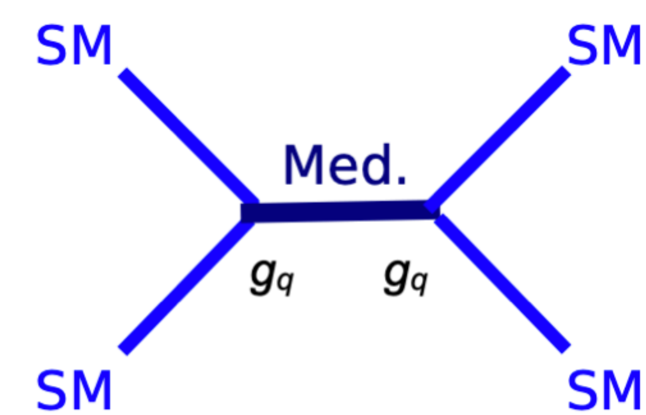

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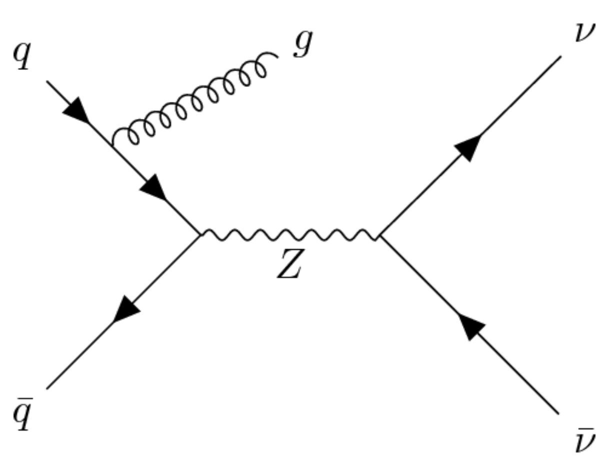

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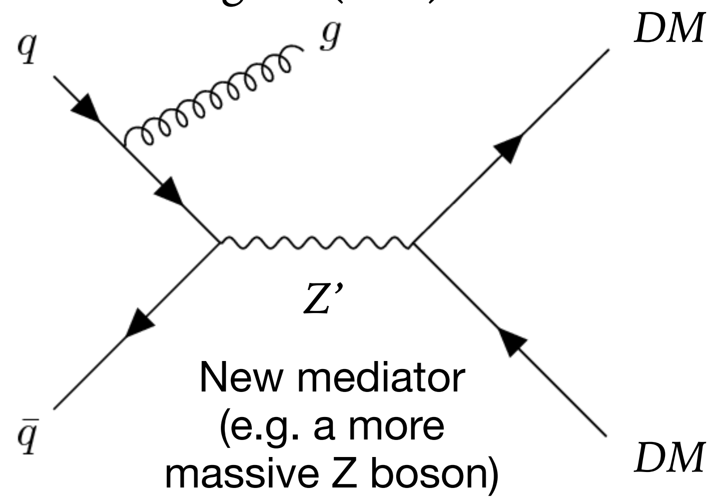

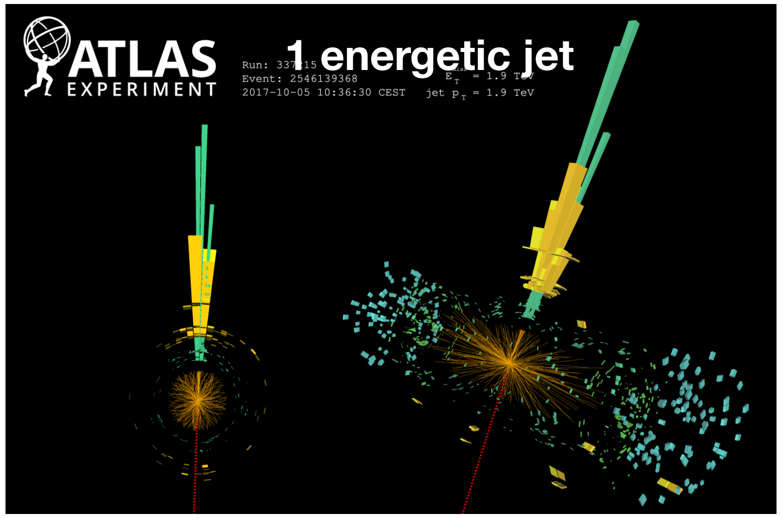

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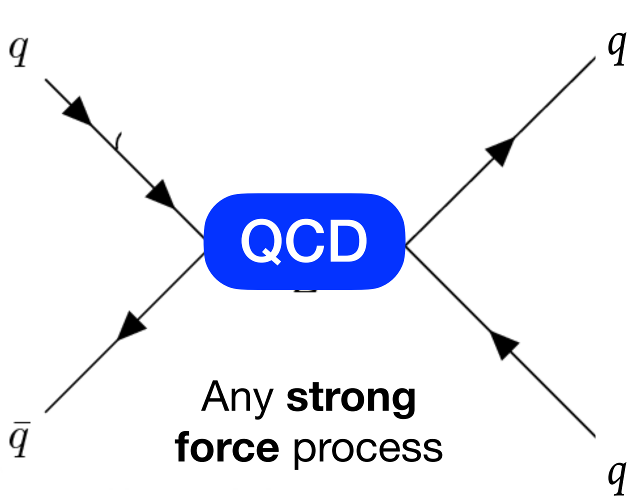

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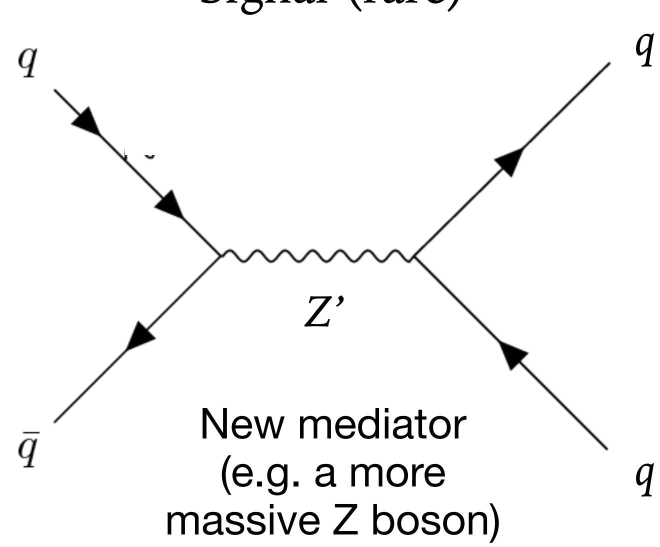

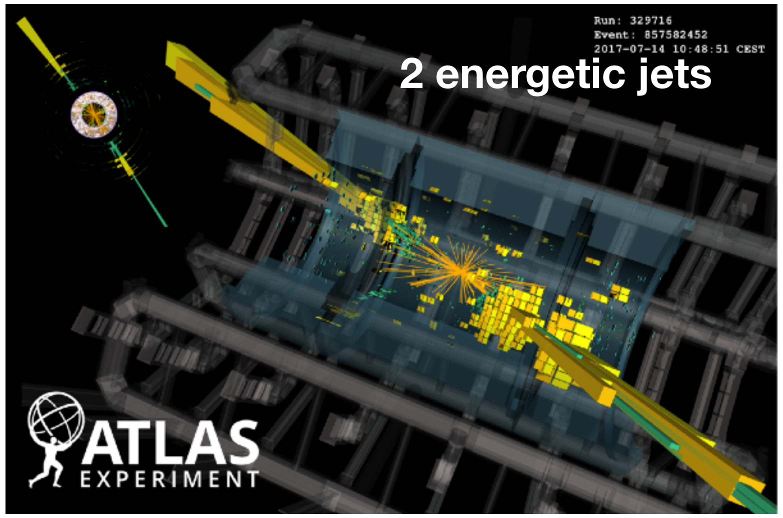

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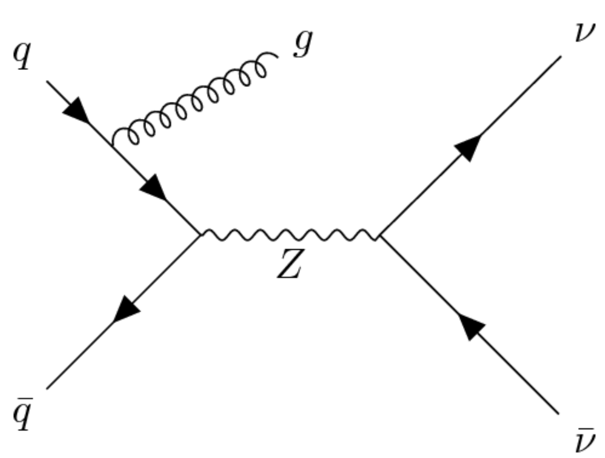

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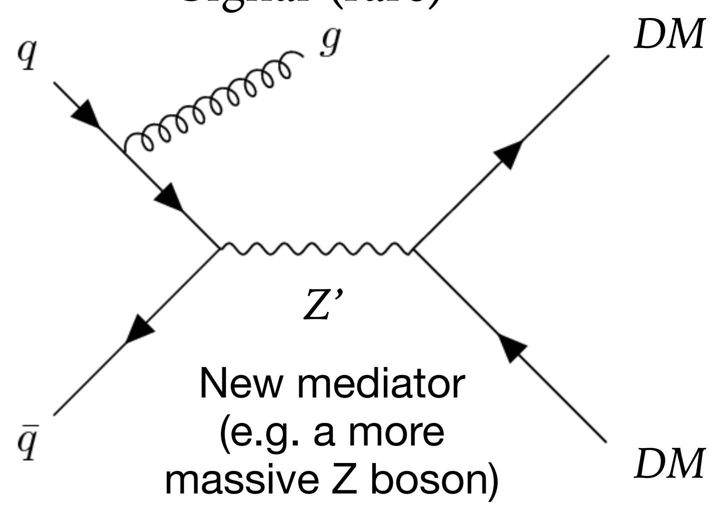

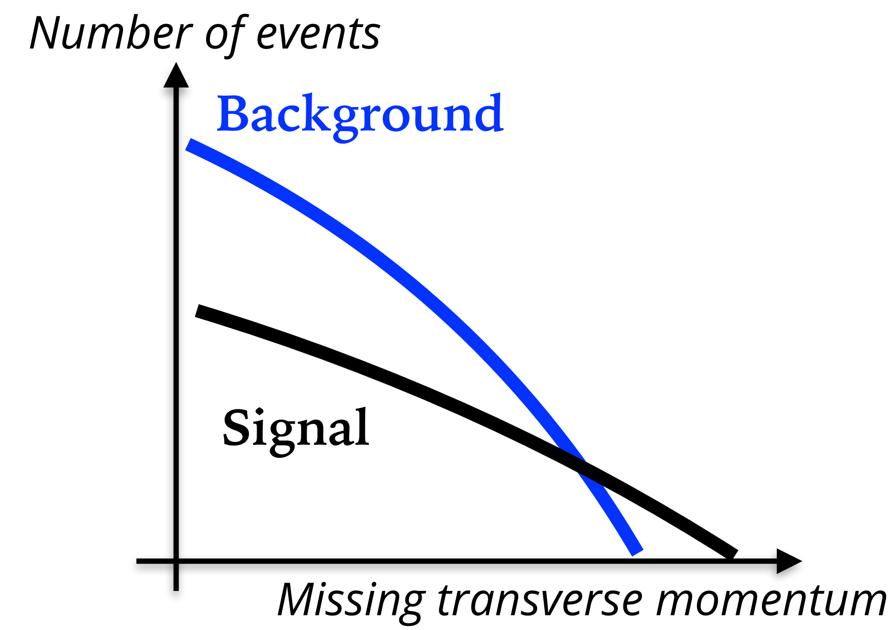

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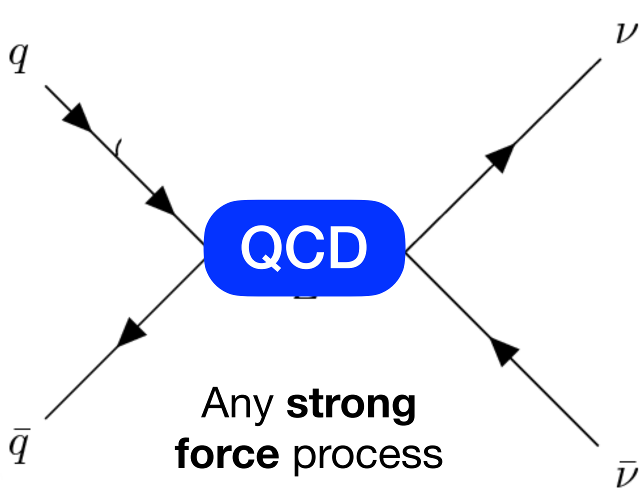

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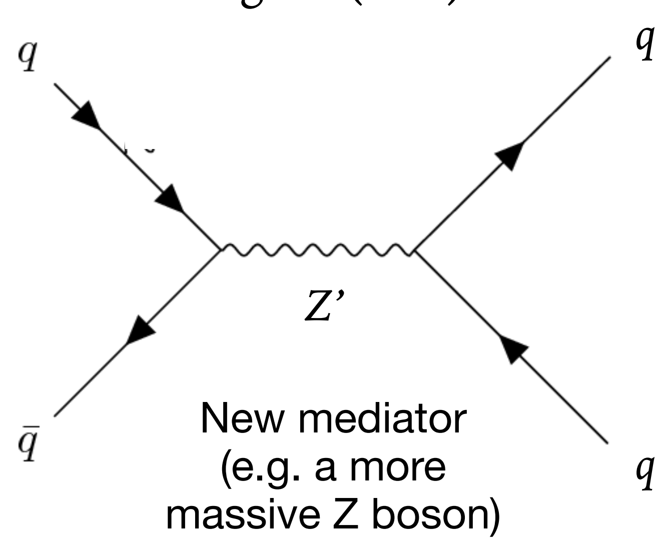
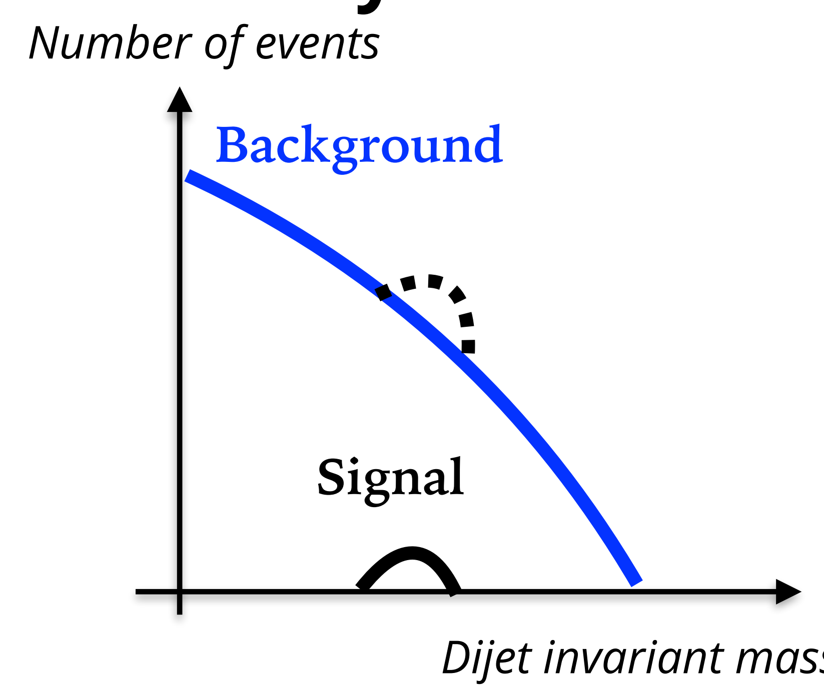
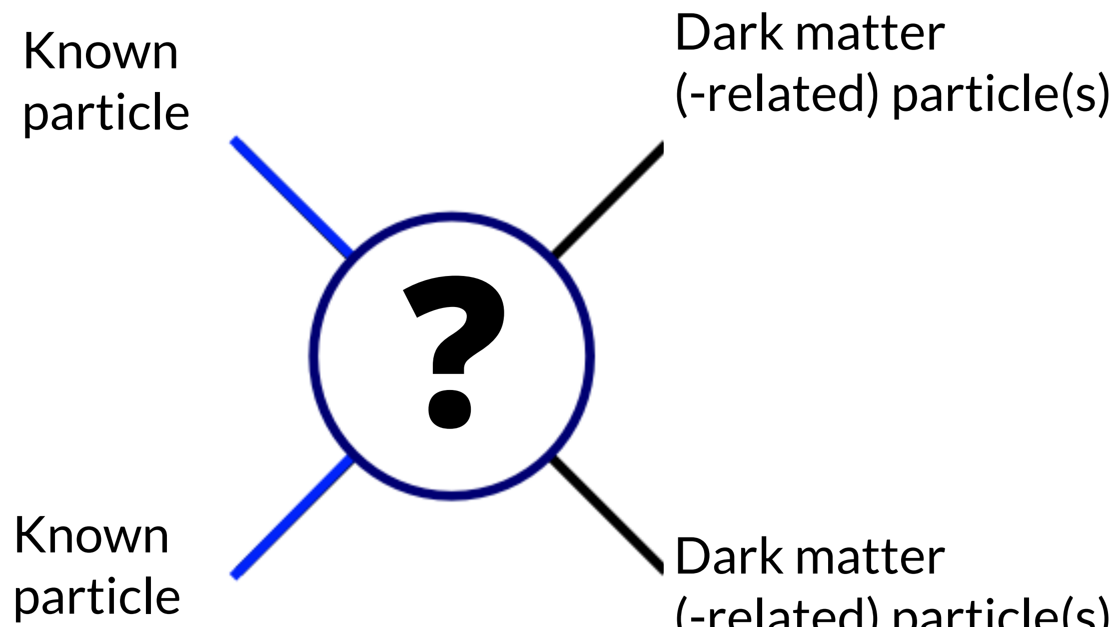




Digression: LHC data taking and dark matter mediators

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:

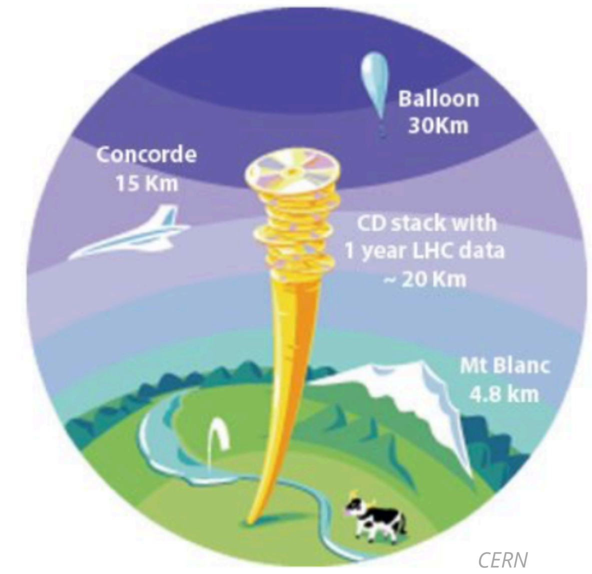
1. This kinds of processes are very **rare**
2. Many other processes may look the same (→large **backgrounds**)
3. Often **we don't know** how the resonance decays look like

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

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

- The **new physics signals** we are looking for are **rare**
  → need enormous amount of collisions to produce them
- Their **backgrounds** look similar 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



after selection of "interesting" data

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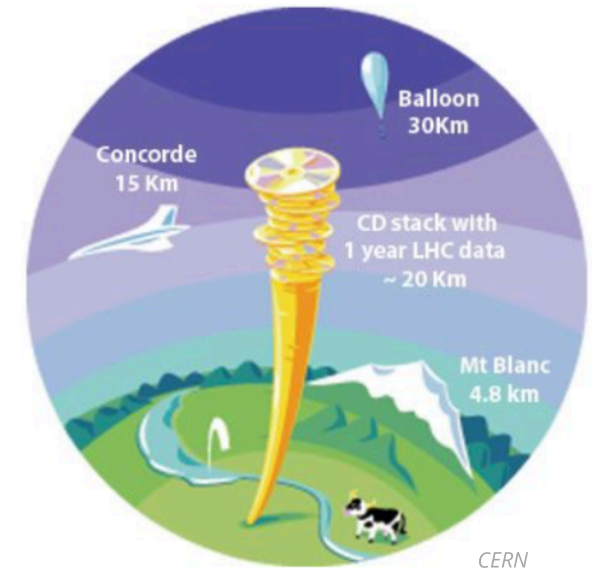

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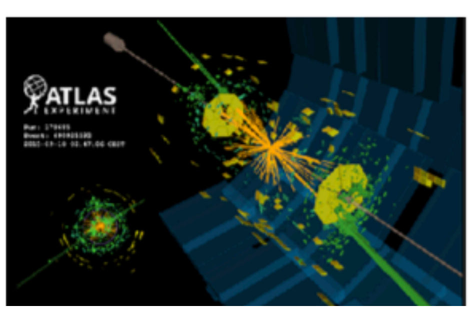
> LHC experiments need to select "interesting" events (=*trigger*)
> **in real-time** (milli/microseconds)

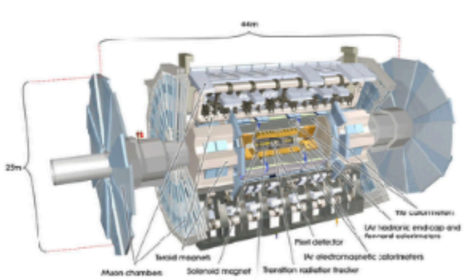
Collisions at ~30 MHz (~1 MB of info each)

Hardware trigger outputs ~100 kHz

Software trigger outputs ~1 kHz

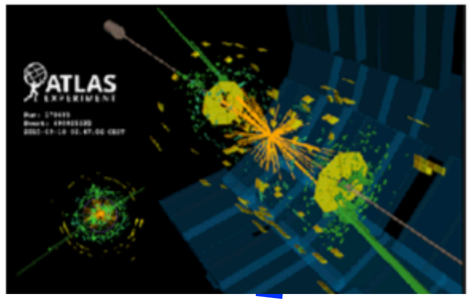
Online ◀ ▶ Offline

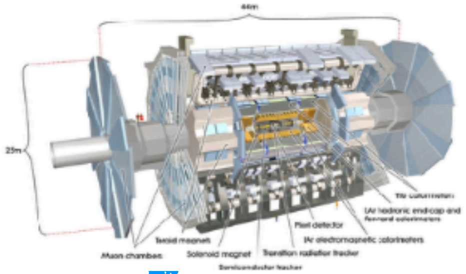




Event selection (trigger) → Object reconstruction and calibration → Data analysis

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

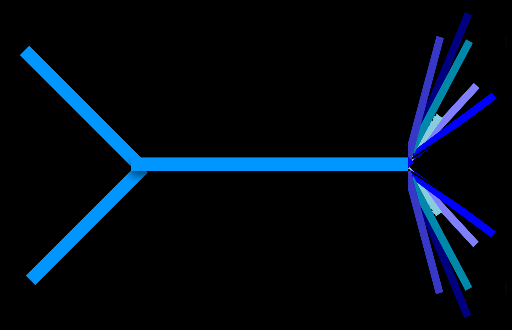
What we can record in full after the trigger

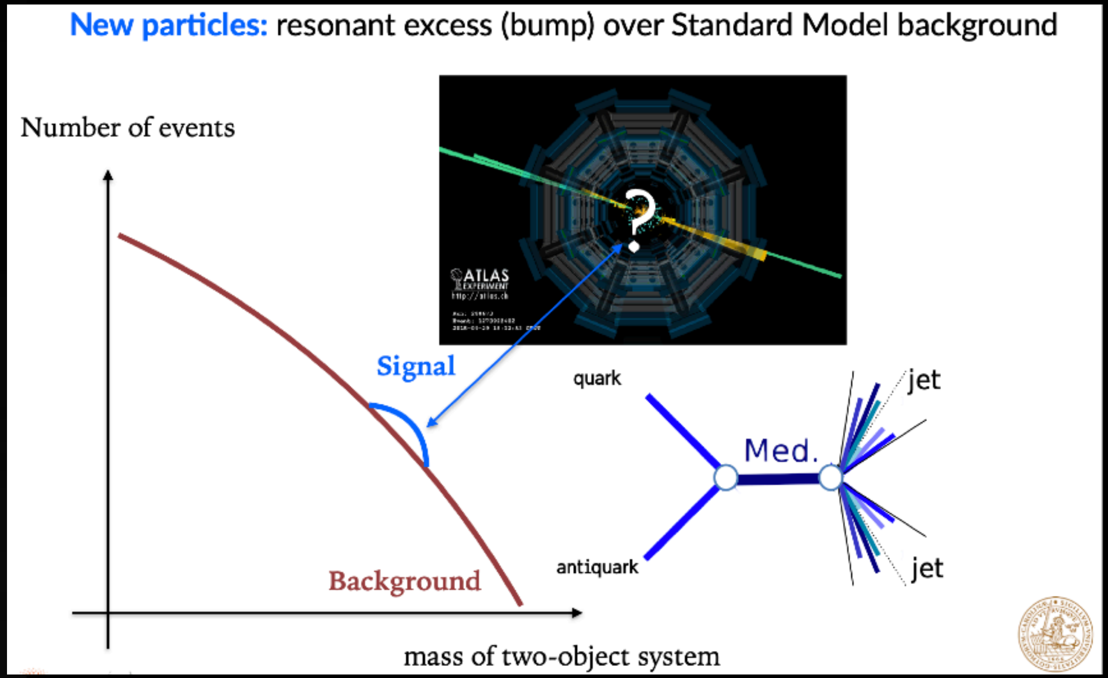
Data ~nobody likes

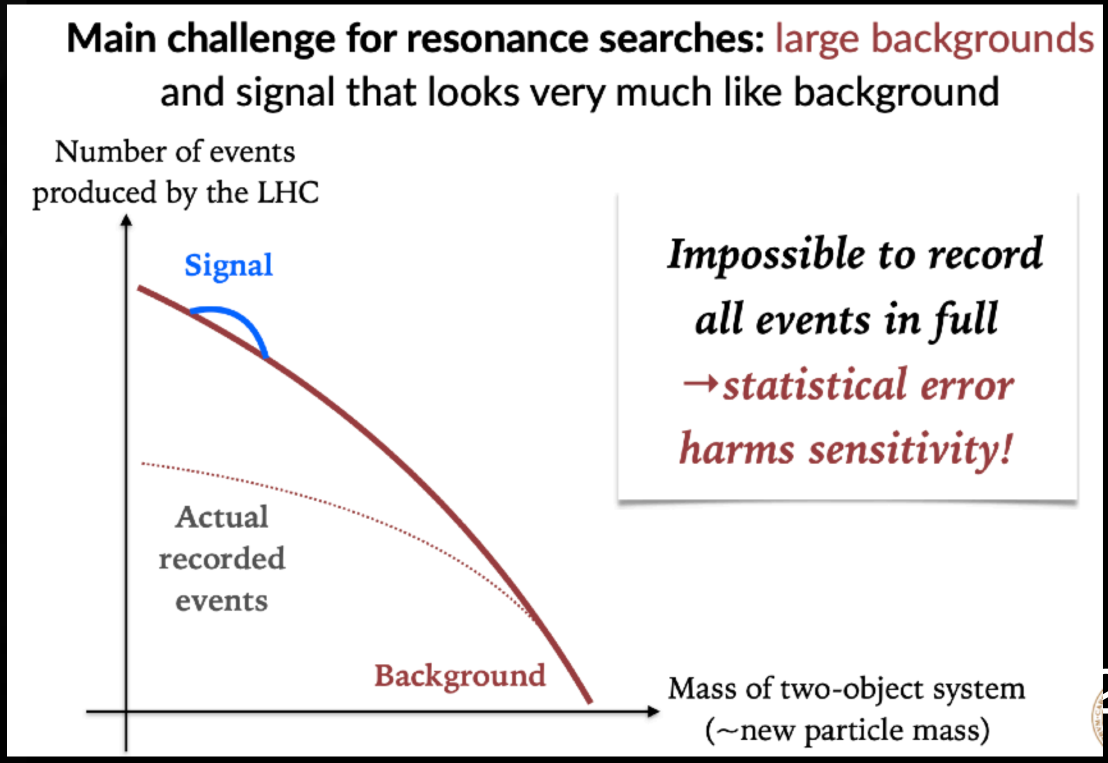
Data produced by the LHC (multiplied by large number)

Are we missing rare dark matter processes?

Events selected by the trigger



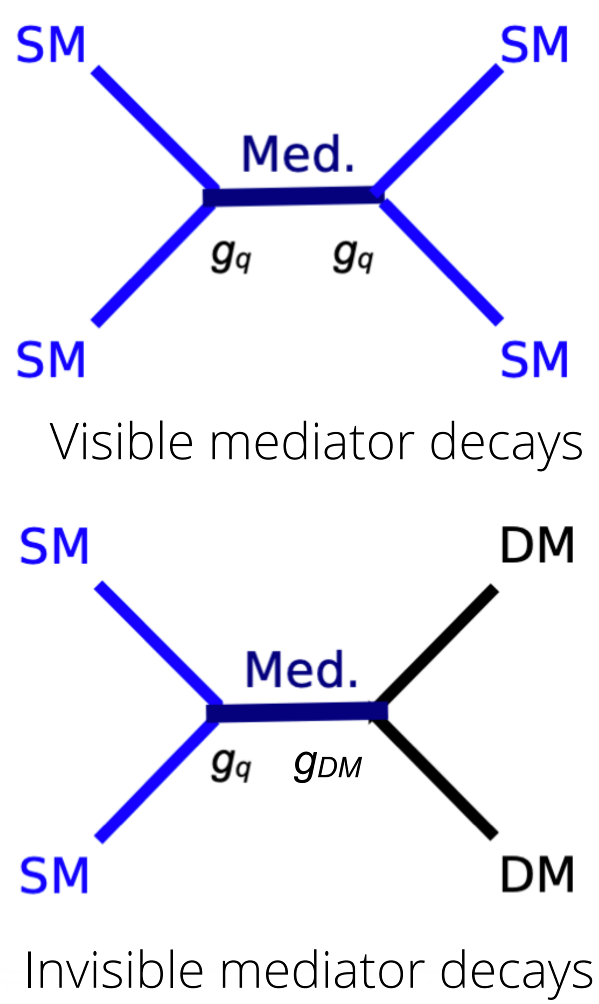




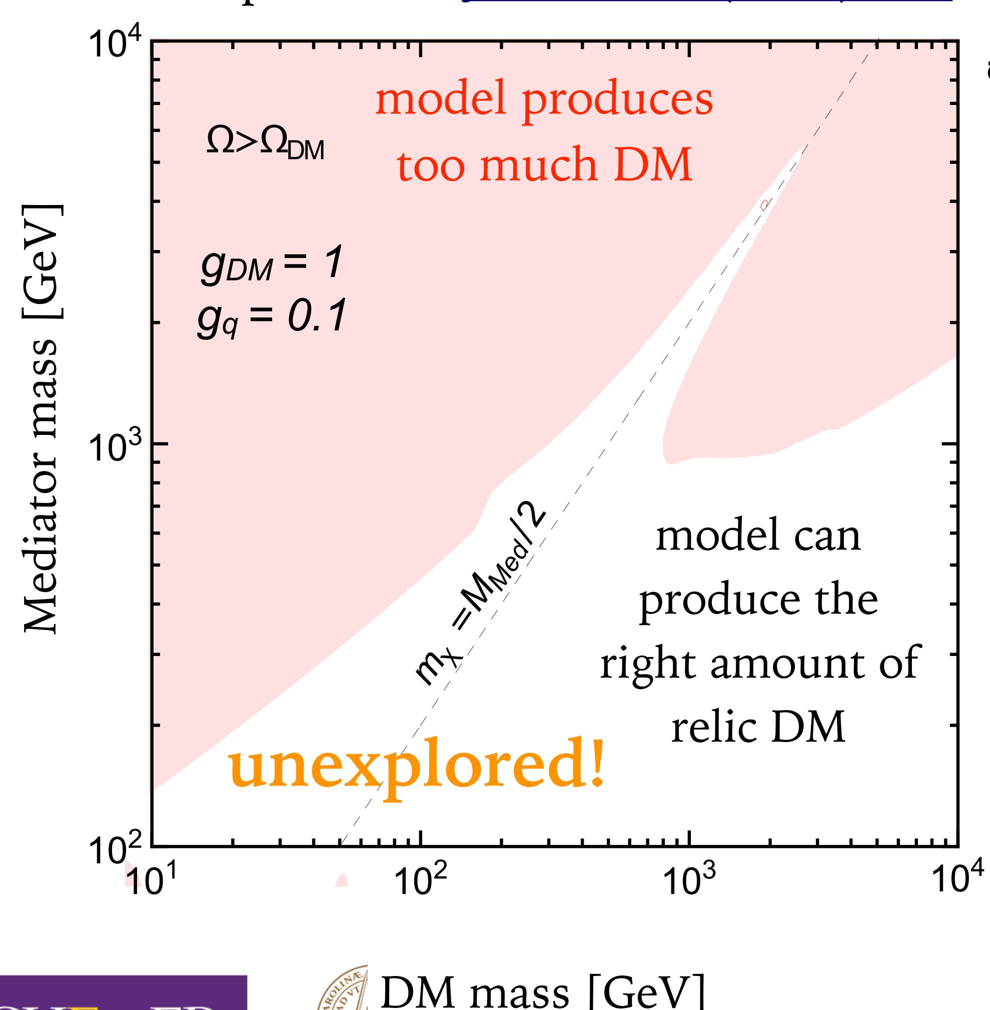
Example: dijet decays of DM mediators

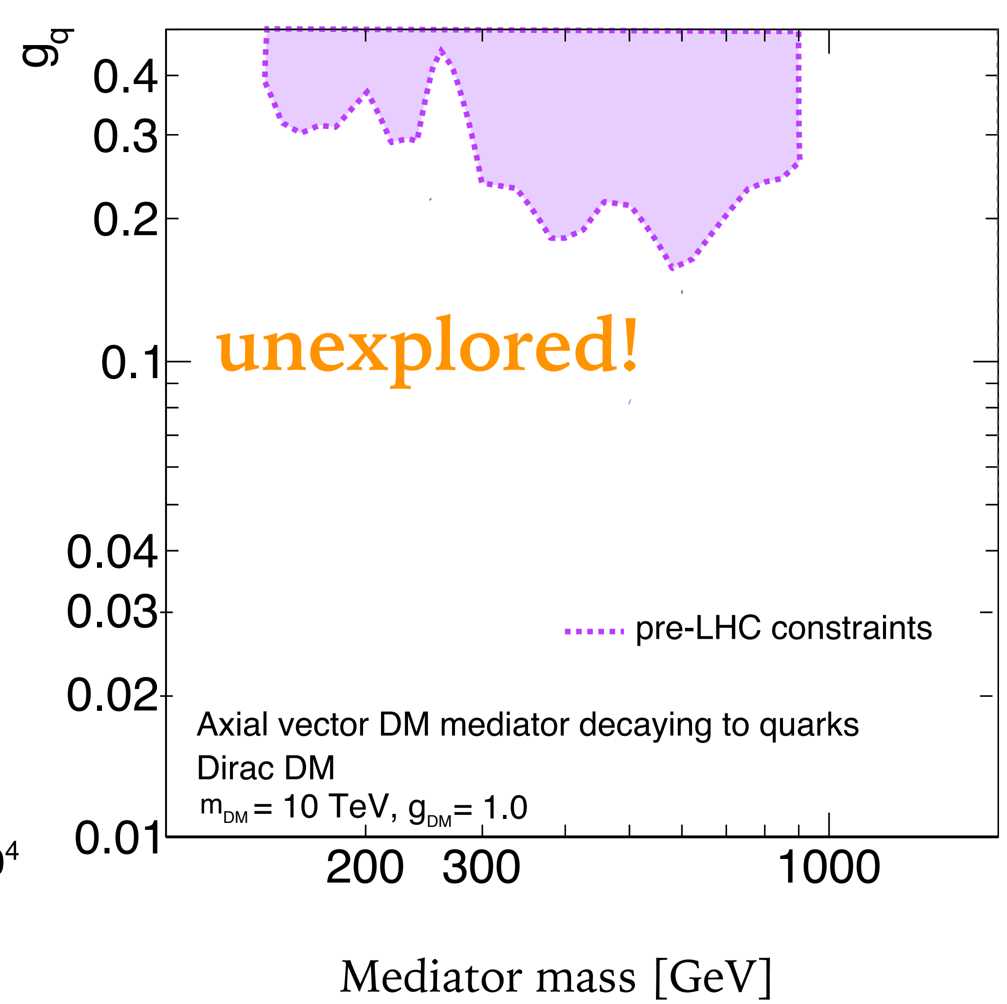
Selecting interesting events works for most of the LHC physics program...
...but it is not optimal for rare processes with high-rate backgrounds:
we cannot record and store all data, and trigger discards both background and signal

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

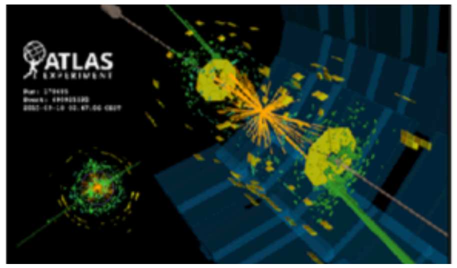


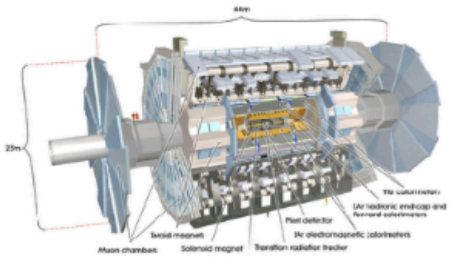
Adapted from JHEP 1507 (2015) 089





Limitations to record (more) data from trigger & DAQ





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

Detector readout | **L1** hardware trigger

limited detector readout rate to hardware trigger

CPU for processing events

large farm, but limited processing power

limited **Disk/tape** to store events

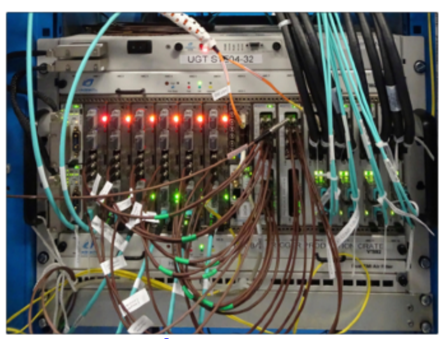


Image from CMS HEPHY

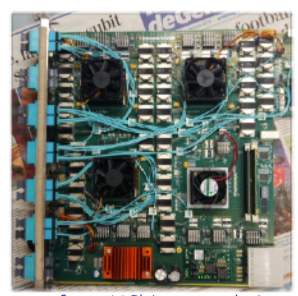


Image from UChicago website

Image from C. Bernius's talk

Image from CERN

What we do at UofM and in ATLAS:

we want to overcome data-taking limitations
so we can make the most of the Run-3 data (ongoing now!)

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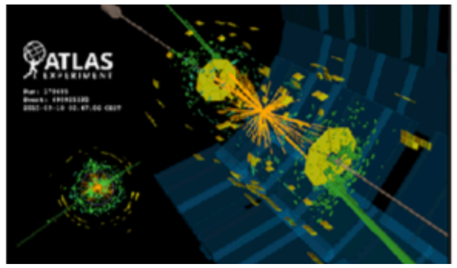
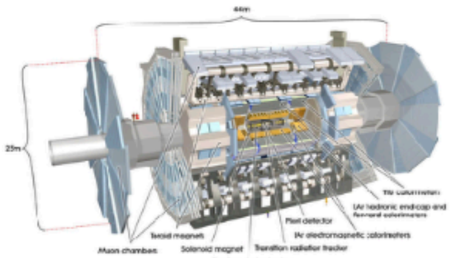
Limitations to record (more) data from trigger & DAQ





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

Detector readout

L1 hardware trigger

limited detector readout rate to hardware trigger

CPU for processing events

large farm, but limited processing power

limited **Disk/tape** to store events

to overcome these limitations:

Optimise code for efficiency (and sustainability)

Use **hybrid computing architectures**
e.g. that can reconstruct particles from detector signals more efficiently

Use **non-standard analysis workflows**
that reduce (immediate) CPU use and storage needs

Refine **trigger algorithms and selections** to get more of the data we need for our searches

Compress the data

A paradigm change for LHC experiments

Asynchronous data analysis

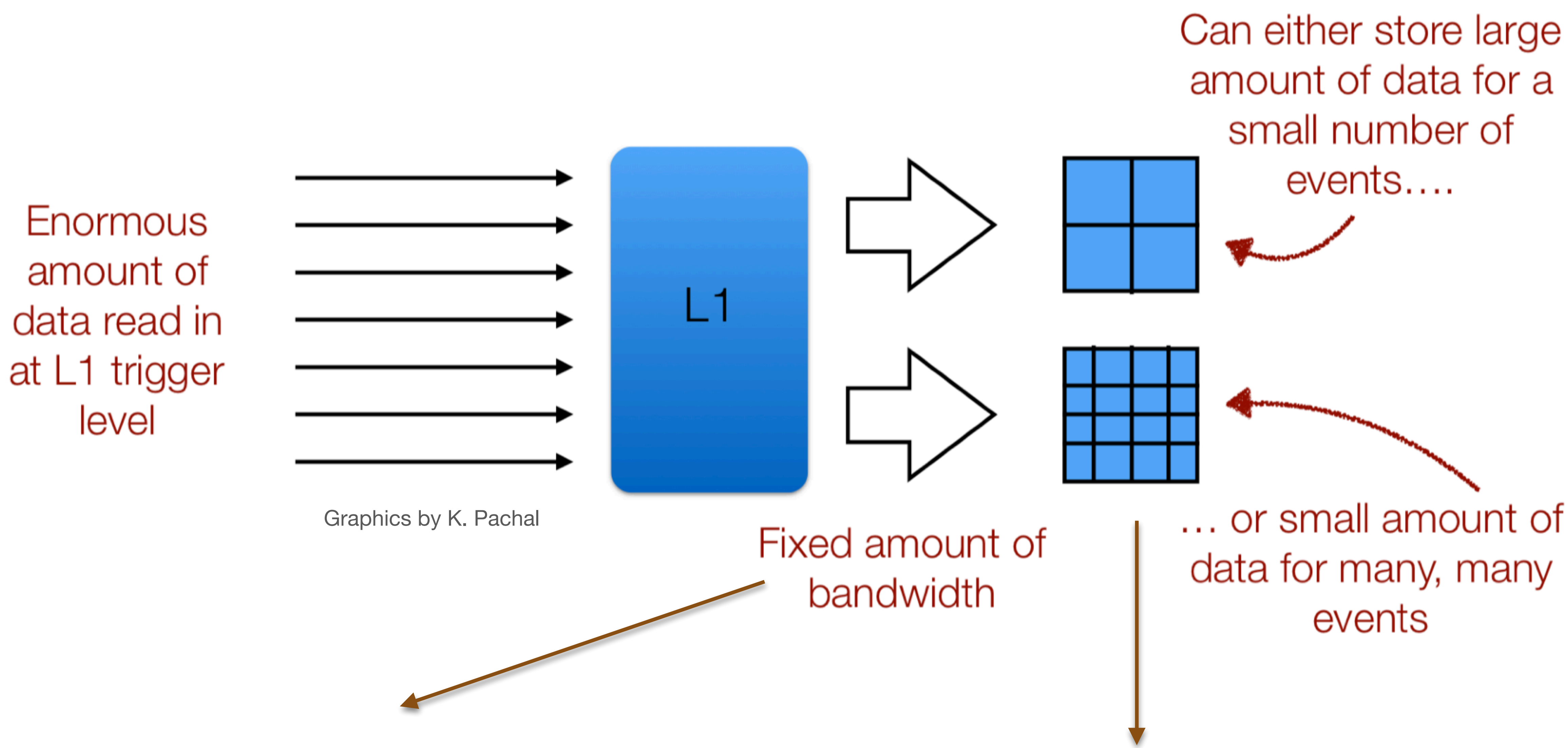
First record and store data, then reconstruct/analyze it

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"

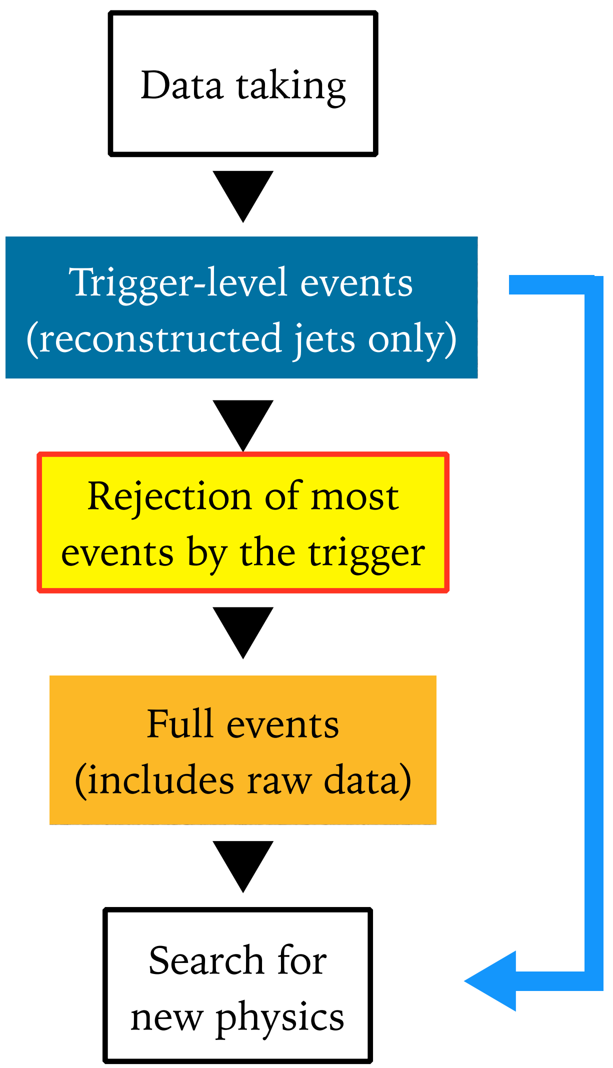
Reduced data formats:

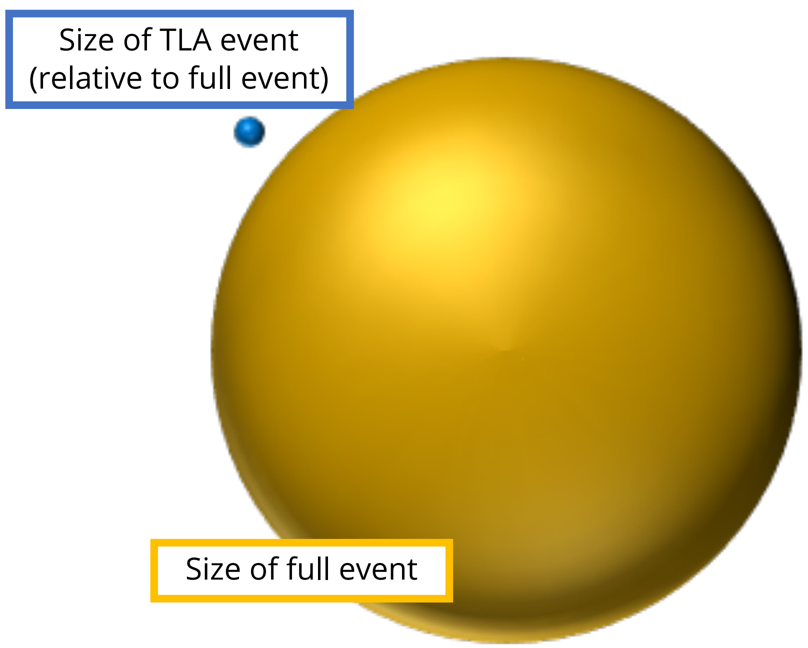
- Only keep final trigger objects (drop raw data)
- Save only "interesting" parts of the detector
- <u>Run-3, in progress:</u> A combination of the two

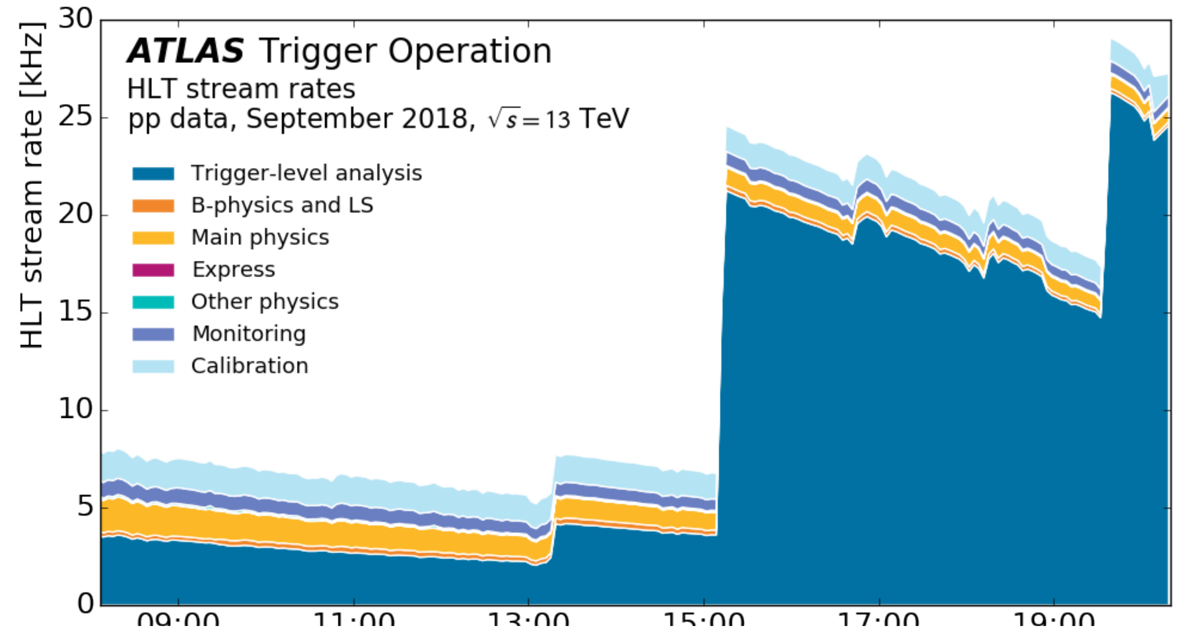
ERC Starting Grant DARKJETS (2015-2021)
ERC Consolidator Grant REALDARK (2021-2026)

ATLAS implementation: Trigger Level Analysis (TLA) *

Much smaller event size → **orders of magnitude more data** can be recorded
More data → **more sensitivity** to new physics at lower masses



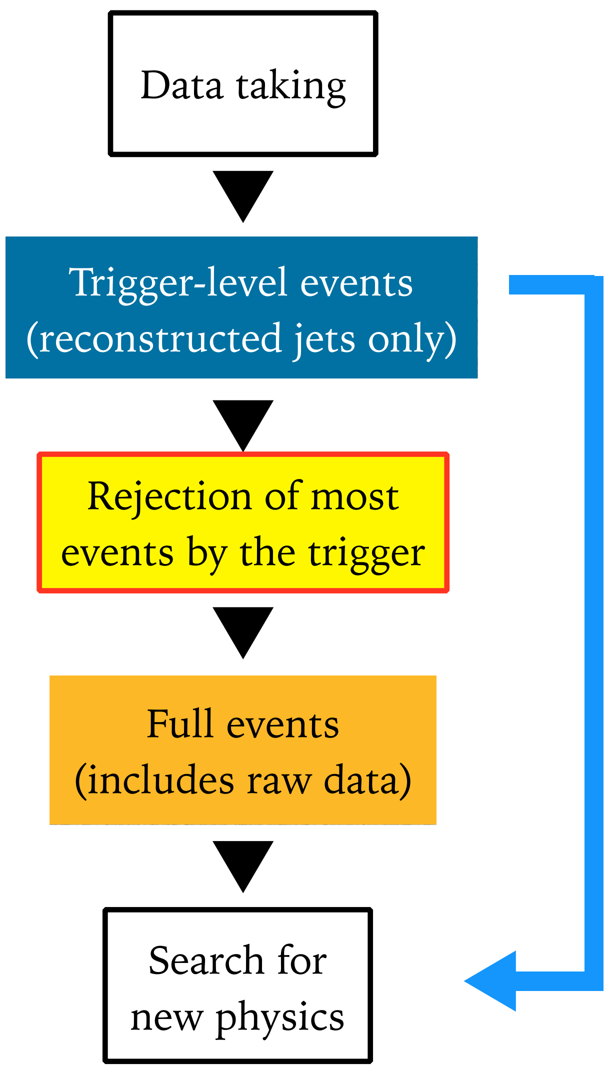




https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults

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

ATLAS implementation: Trigger Level Analysis (TLA) *



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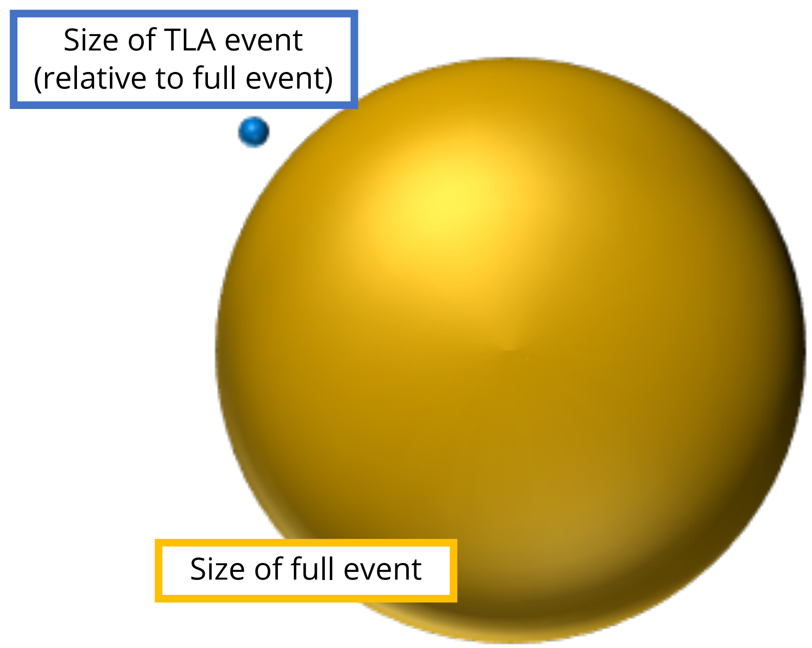

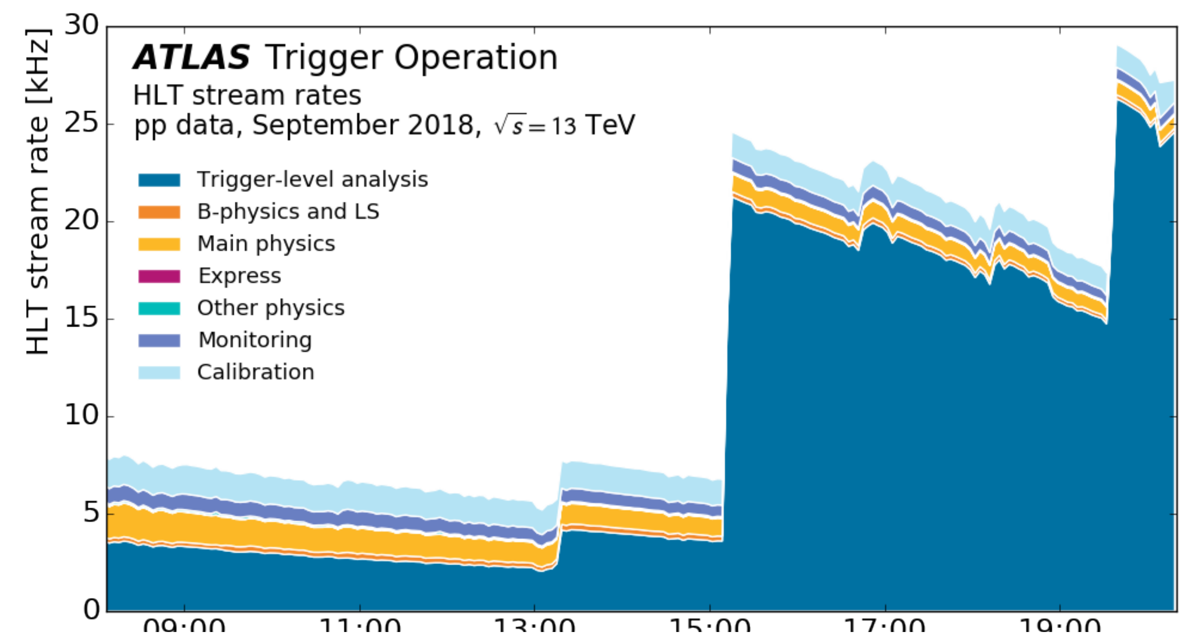

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults

- Challenges solved by **ATLAS TLA team**
  - **software**: technical implementation and large-scale deployment
  - **performance**: is a reduced data format "good enough" for a discovery"?
  - **statistical analysis**: how to deal with unprecedented amounts of data?

Ohio State, Lund, Heidelberg. Manchester, Geneva, Buenos Aires, but also Tel Aviv for the very first iteration of this!

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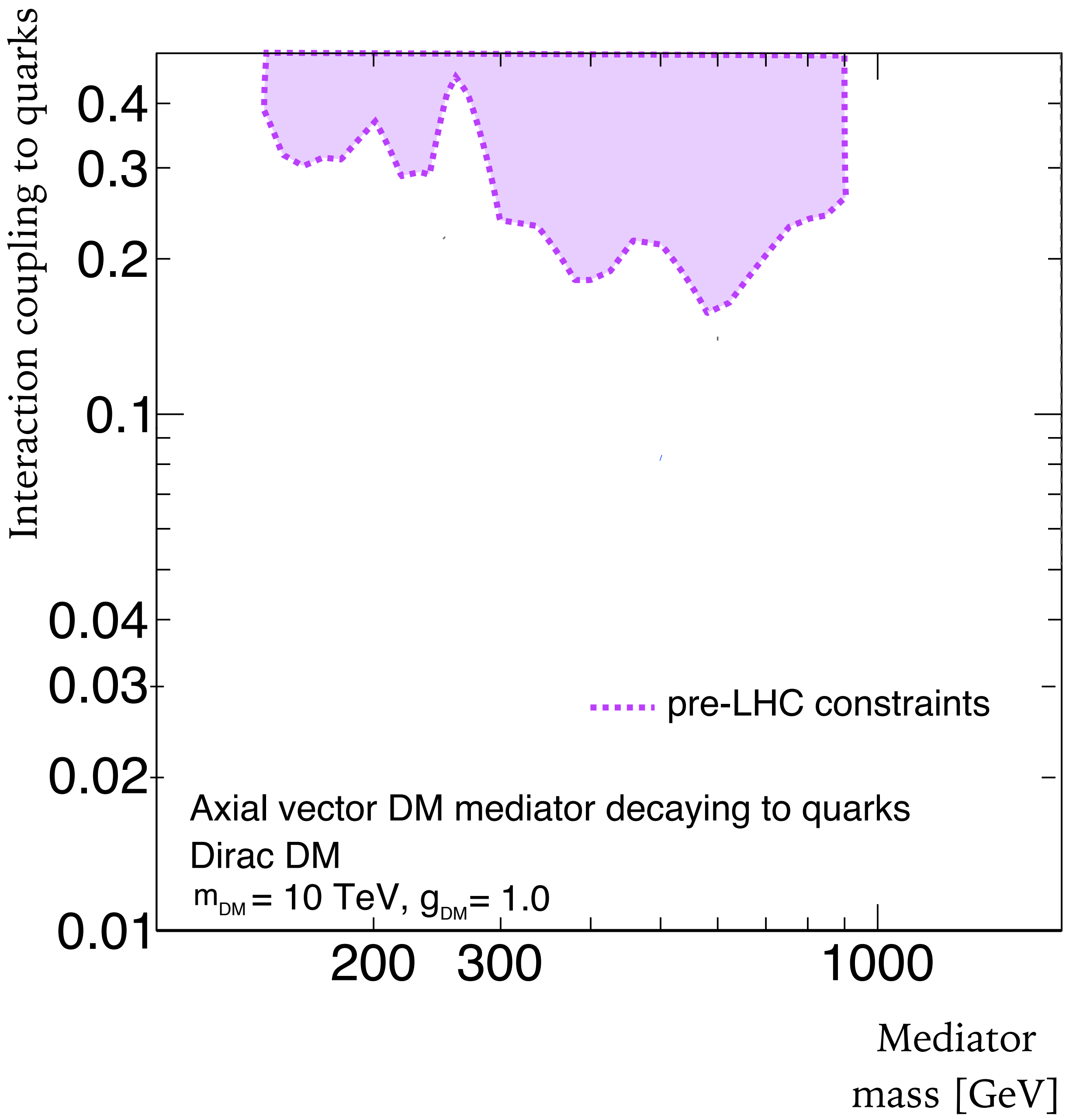
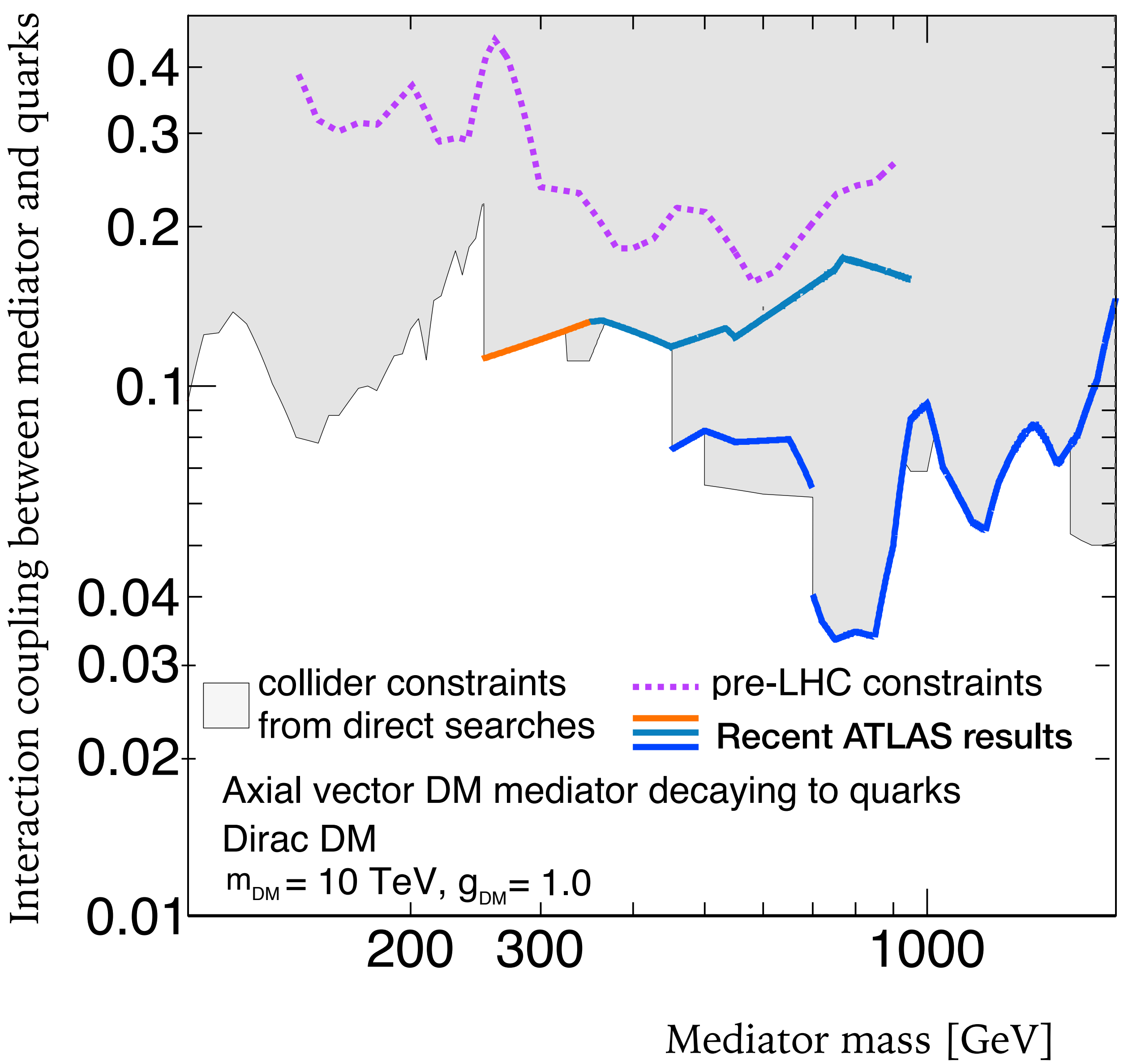
* Trigger Level Analysis is a Three Letter Algorithm (TLA)

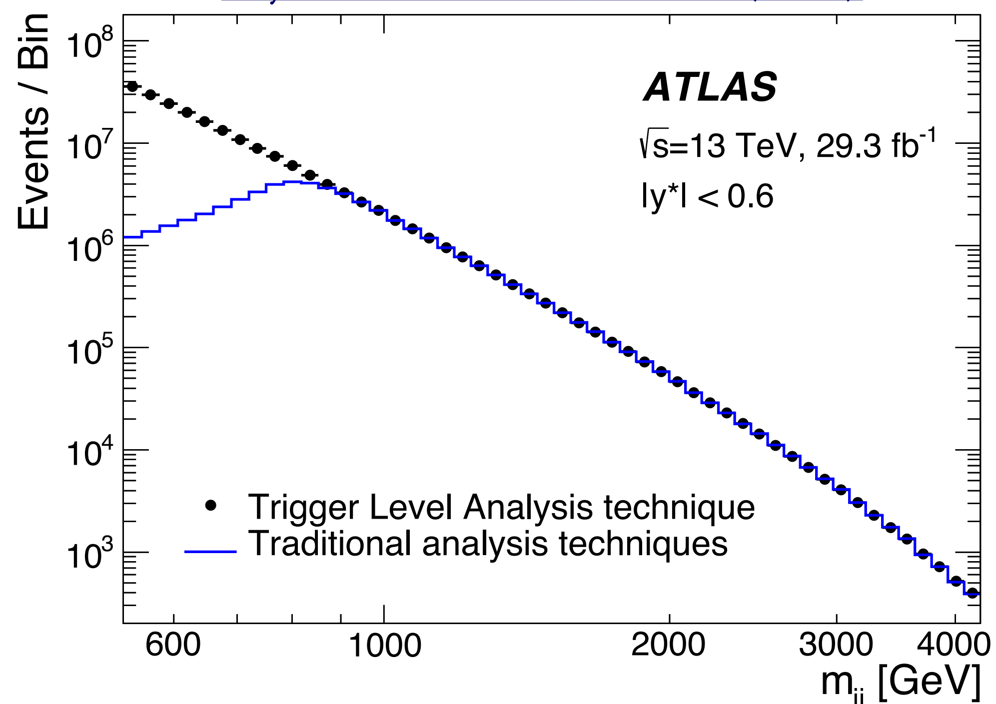
Filling the uncovered parameter space of low-mass resonances



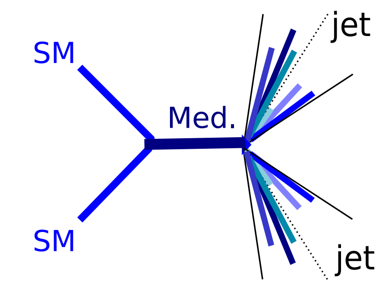
Filling the uncovered parameter space of low-mass resonances



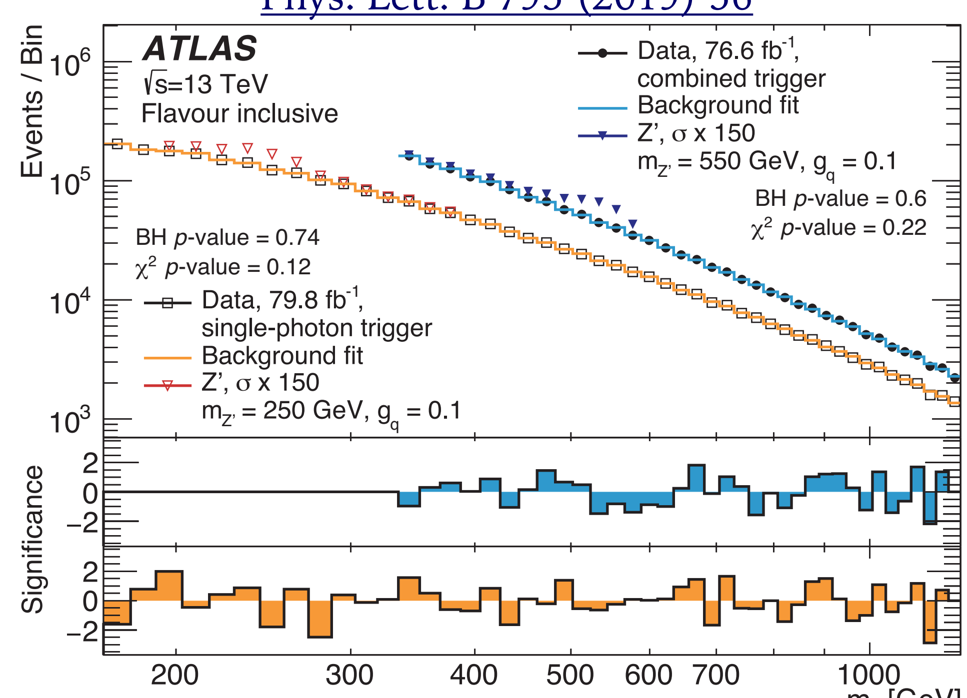
Phys. Rev. Lett. 121, 081801 (2018)



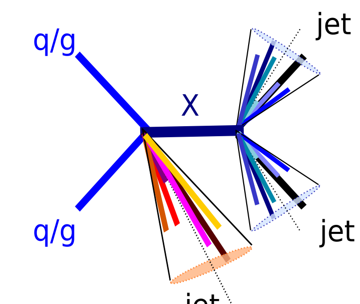
TLA technique: Make the event size smaller



Phys. Lett. B 795 (2019) 56



Dijet+ISR signature: Reduce the background



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

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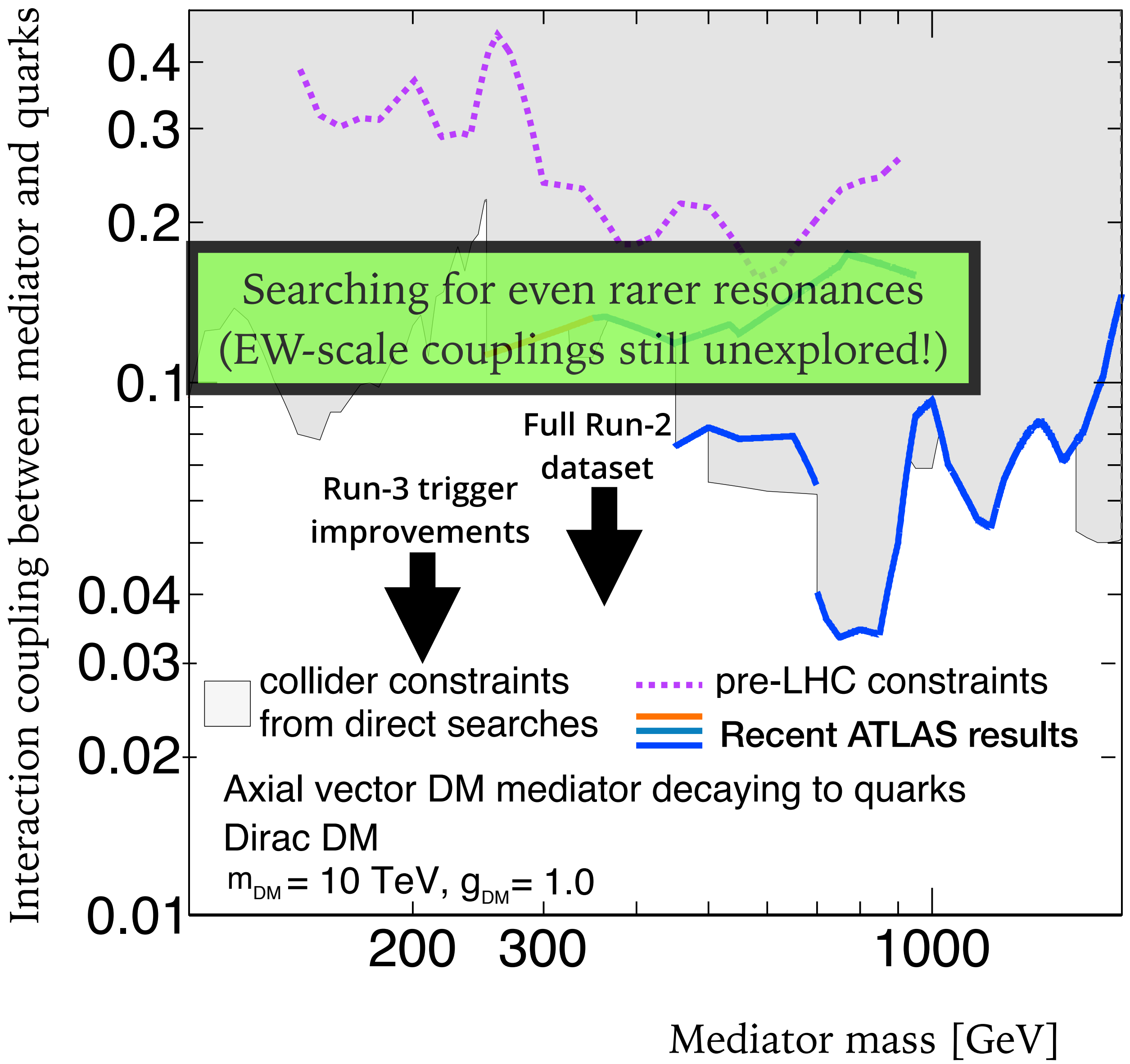
Filling the uncovered parameter space of low-mass resonances



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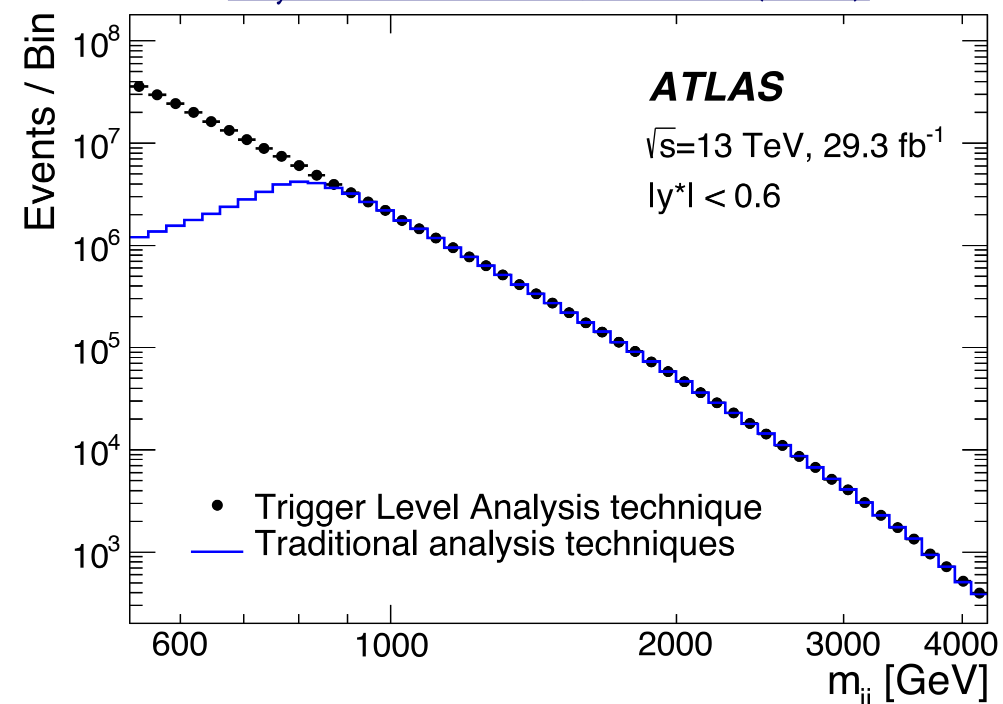

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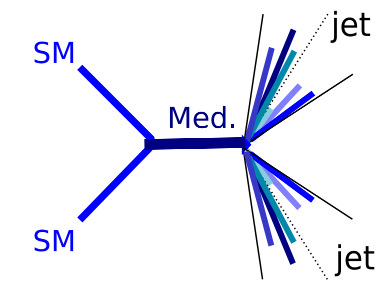
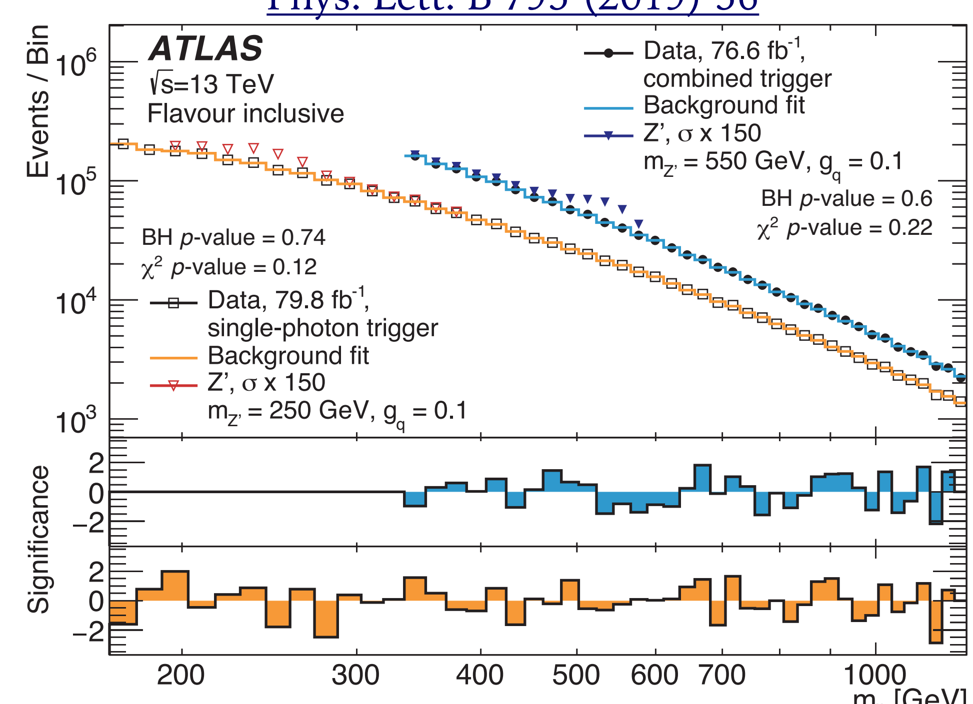


Phys. Lett. B 795 (2019) 56



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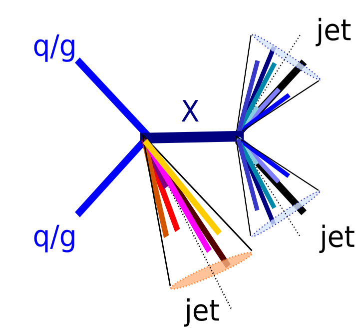

UChicago-inspired: https://arxiv.org/abs/1212.2221

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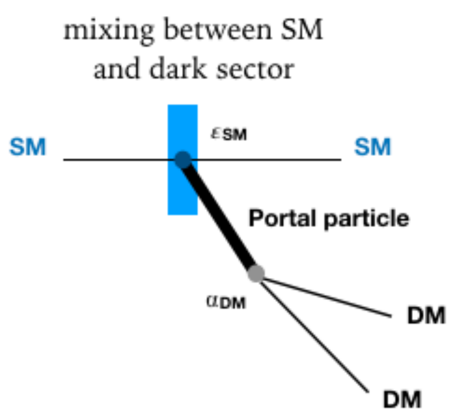
You may have noticed:
definitions of *low-mass*/*light* varies...

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

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

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

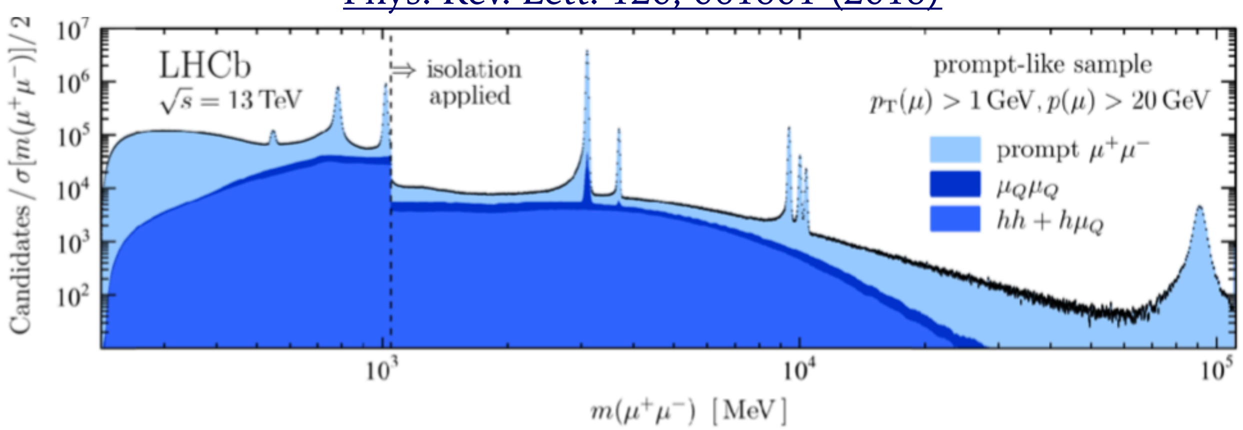
CMS / LHCb real-time analysis dark photons



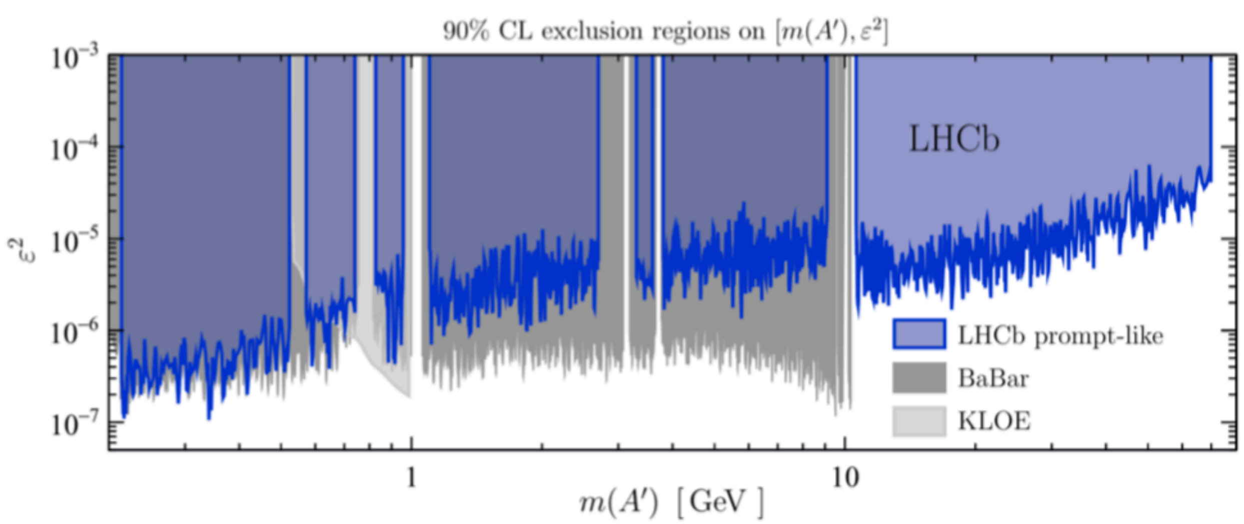
Dark photon → dimuon searches face the same problem as dijet searches at masses below the Z

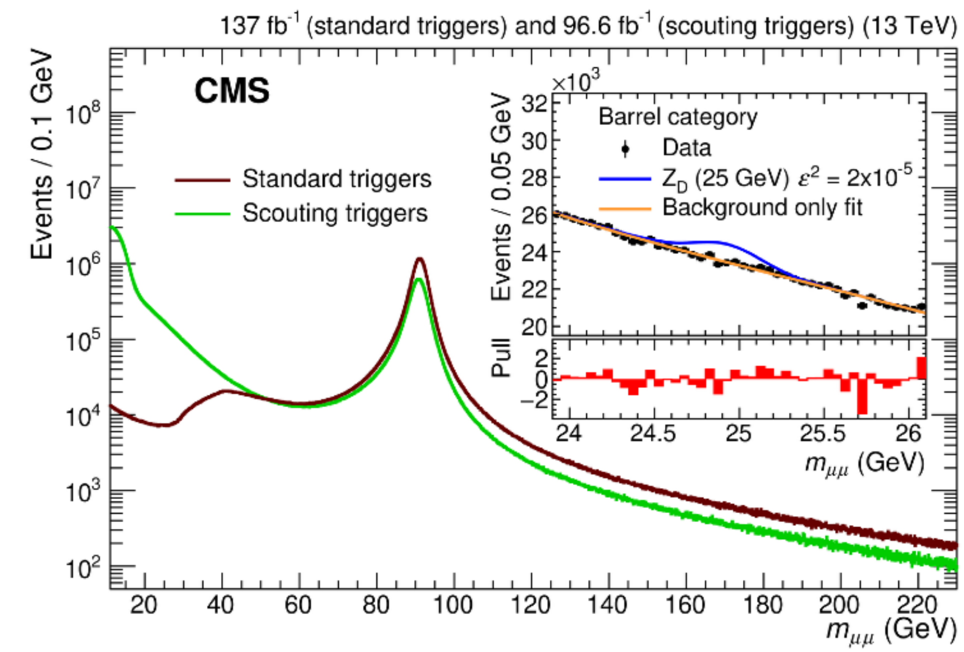
→ large benefits from real-time analysis

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

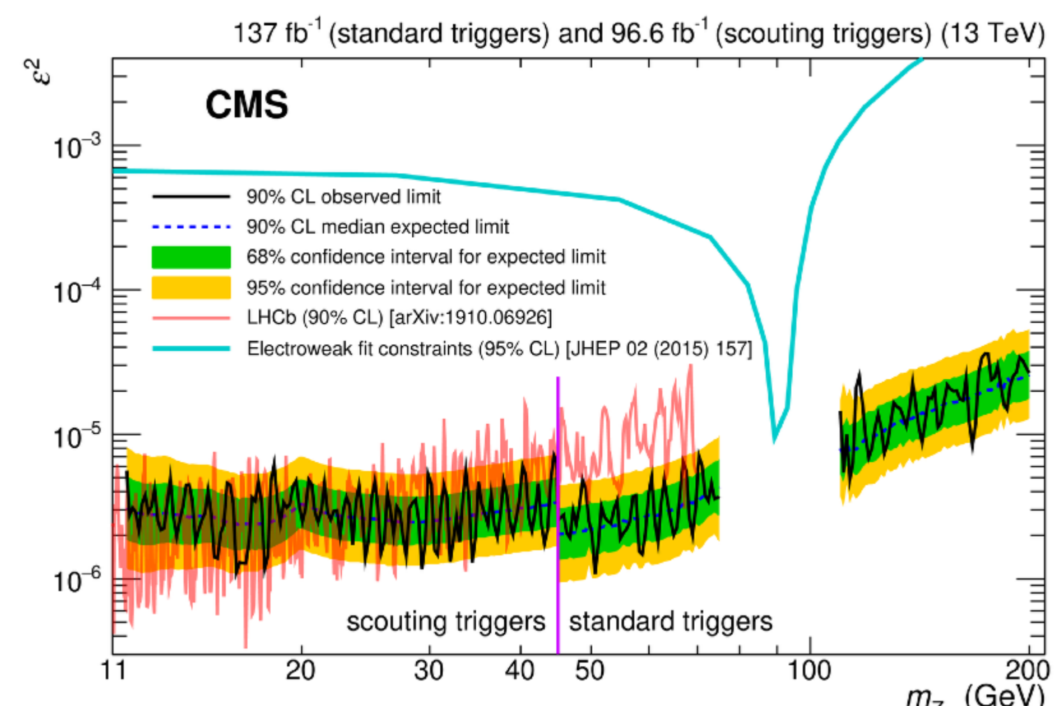


lower rate of events





Phys. Rev. Lett. 124 (2020) 131802



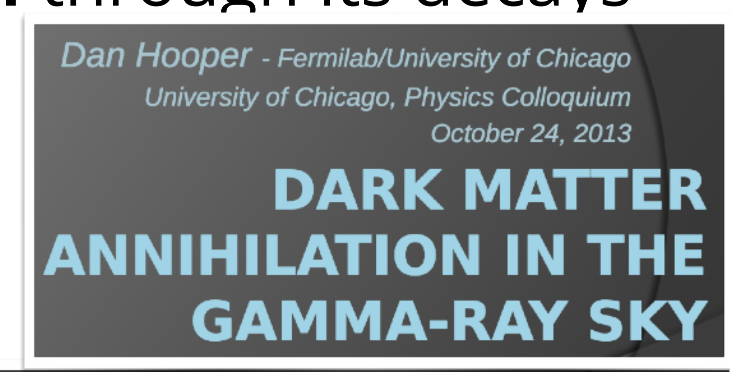
Run-3 prospects in arXiv:1509.06765

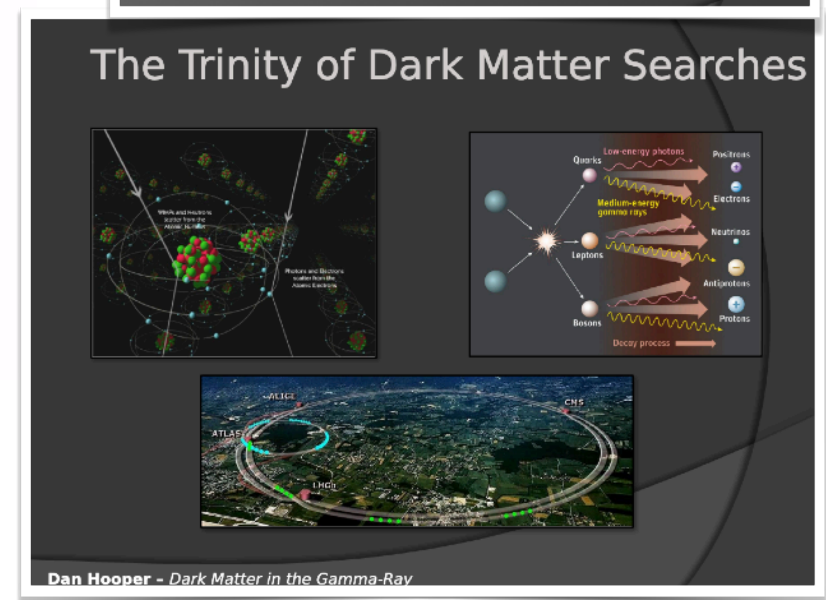
More non-minimal dark photons in Sukanya's talk

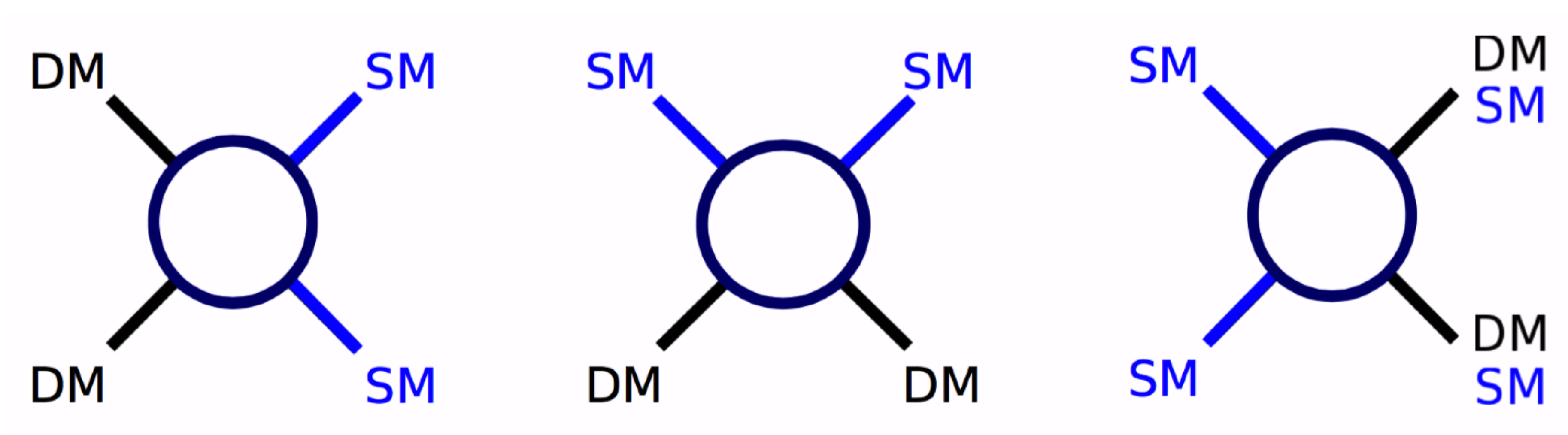
What's needed for dark matter discoveries: complementary experiments

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



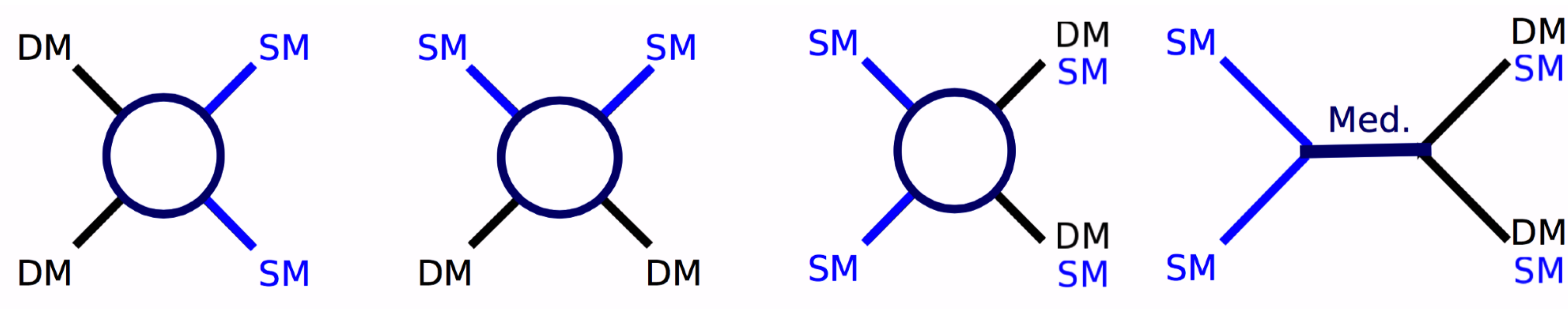




Indirect Detection | Direct Detection | Colliders

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)

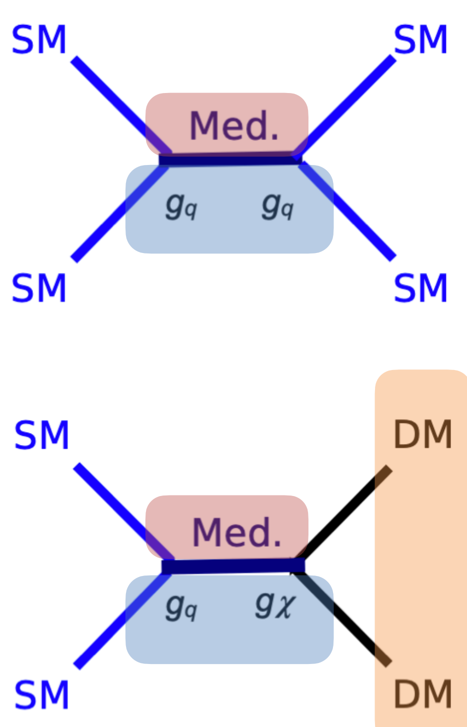
A “global” view of WIMP dark matter

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

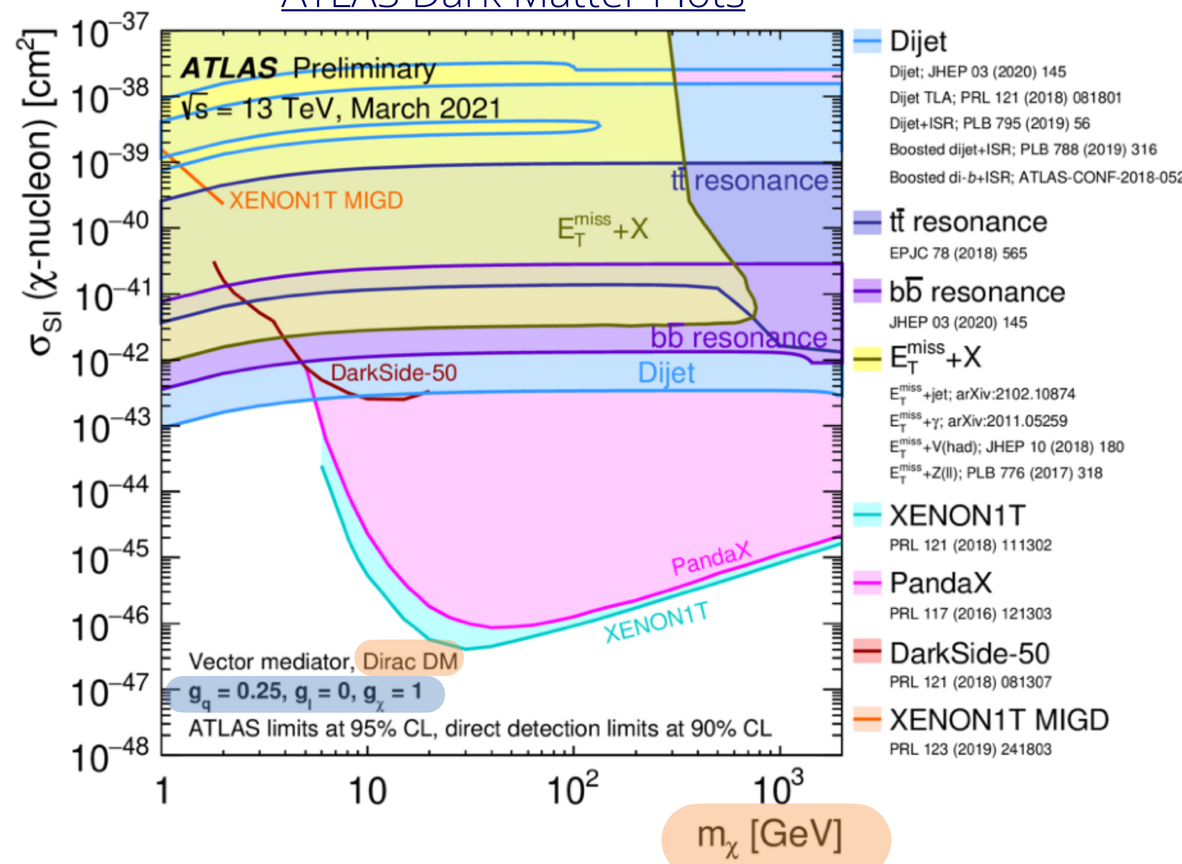
European Strategy Update
“Big Question”

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



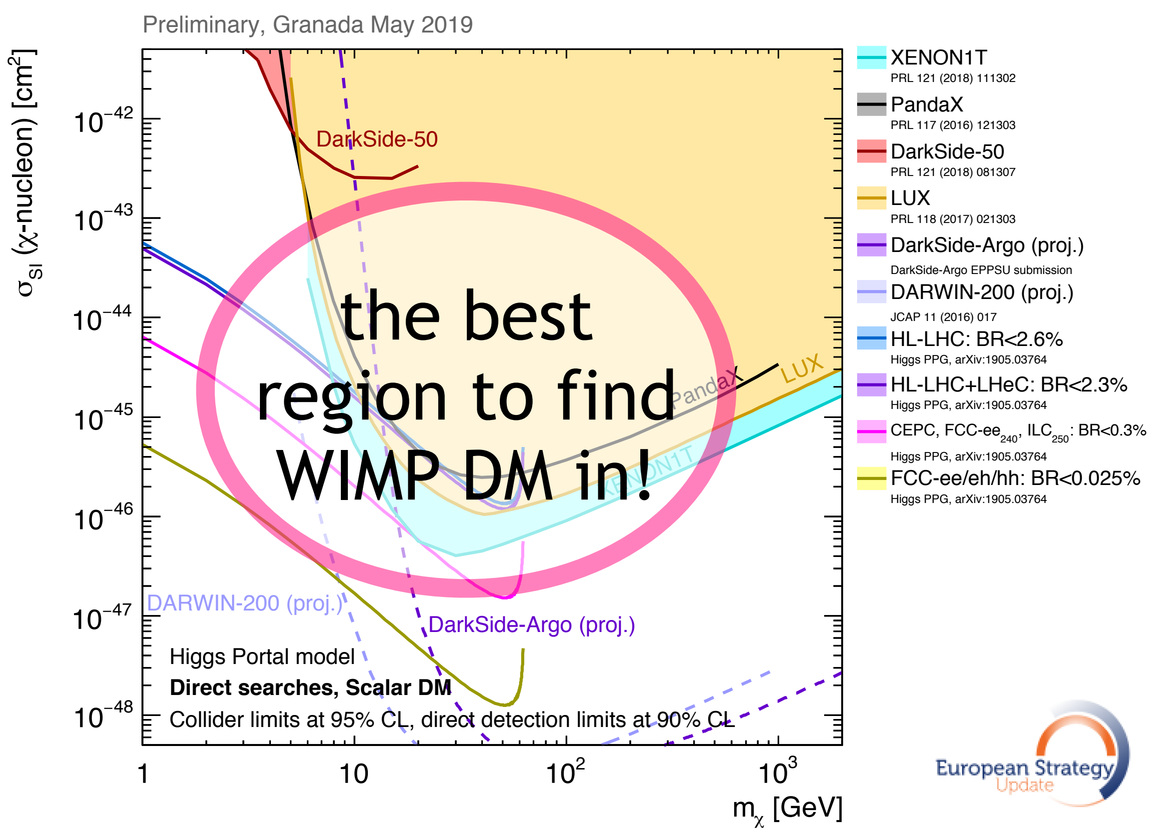
Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**

…more discussions with direct/indirect detection needed, see last part of the talk…

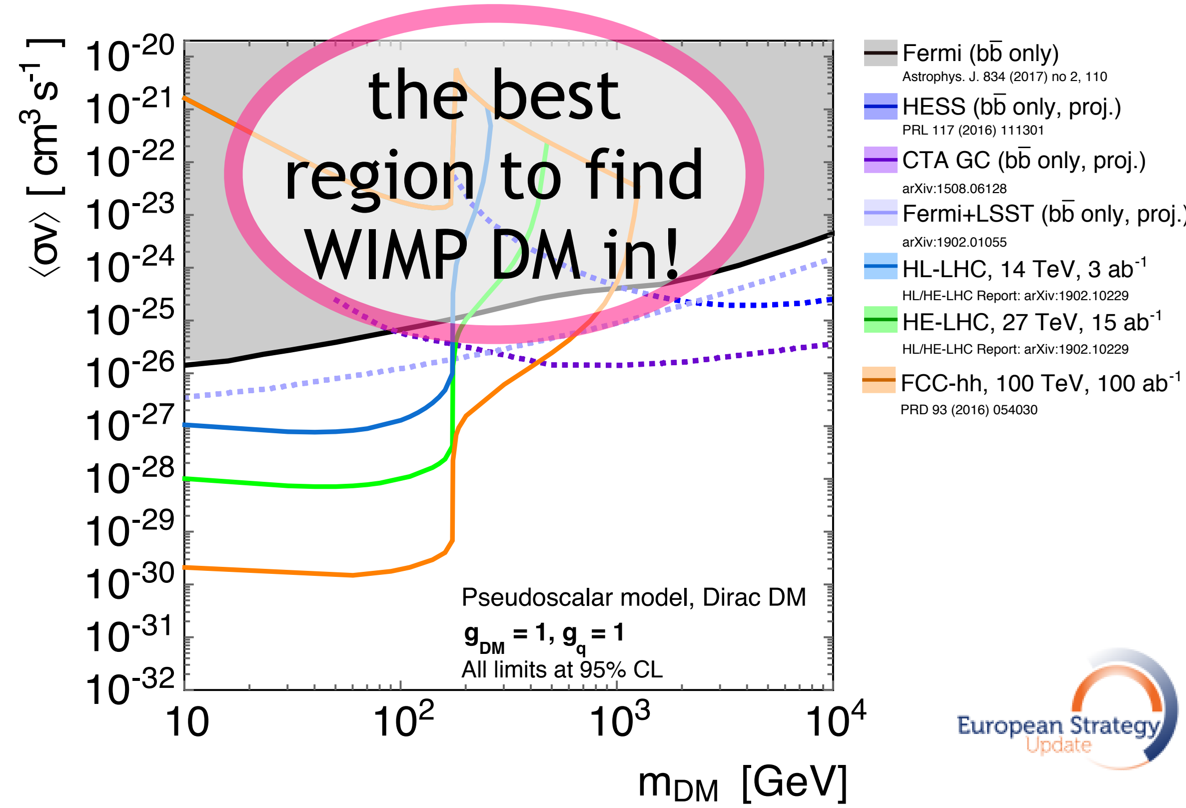
Complementarity within simplified models

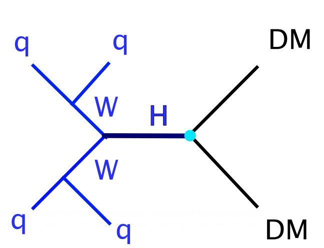
LHC DM Working Group, European Strategy Update Briefing Book, for non-WIMP examples, see Physics Beyond Colliders report

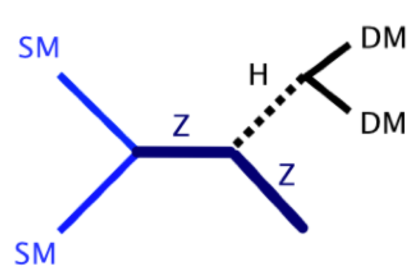
Higgs boson as mediator: colliders & direct detection



Generic scalar mediator: colliders & indirect detection







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"
For work on smaller masses and couplings, see

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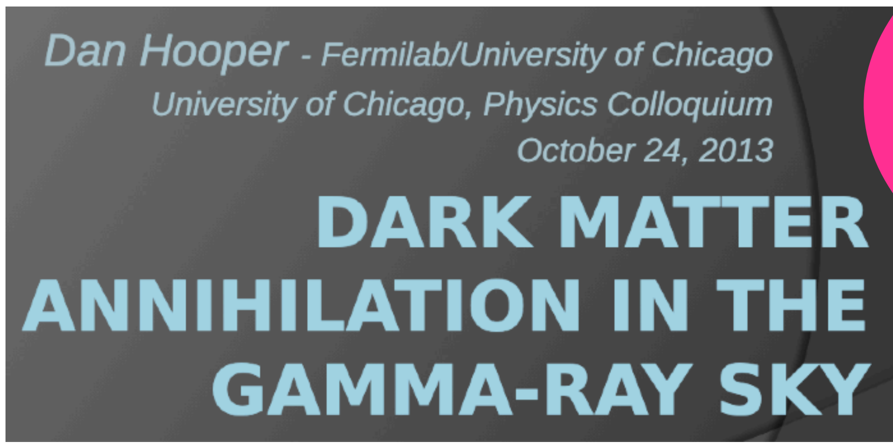
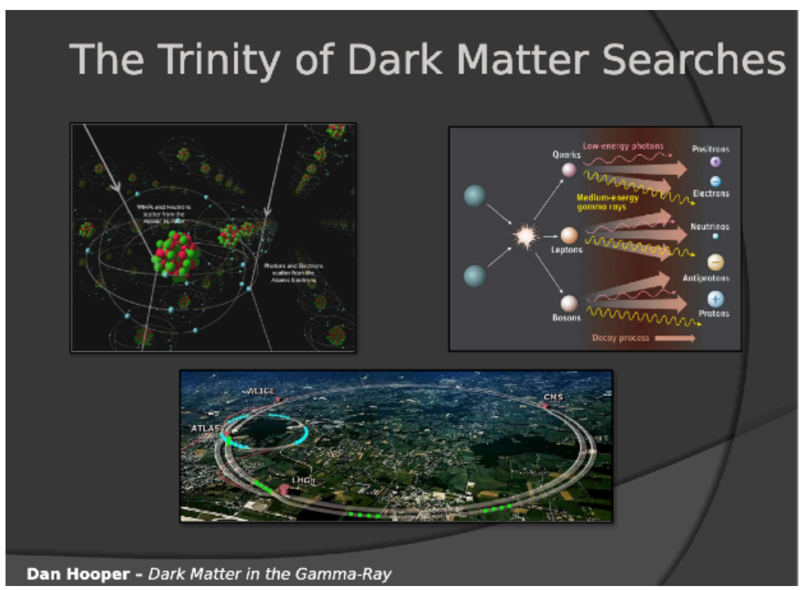
What's needed for dark matter discoveries: new ideas, new tools, new collaborations

The evolution of dark matter searches in the last decade

Note: not an exhaustive list



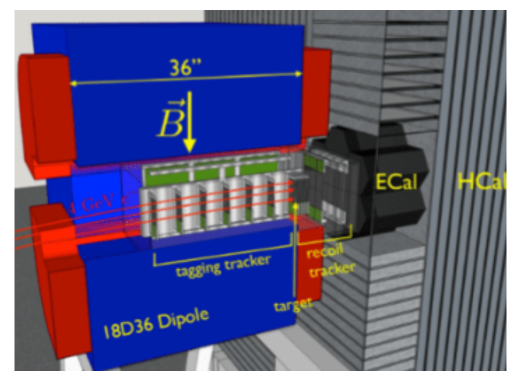


+

Neutrino experiments

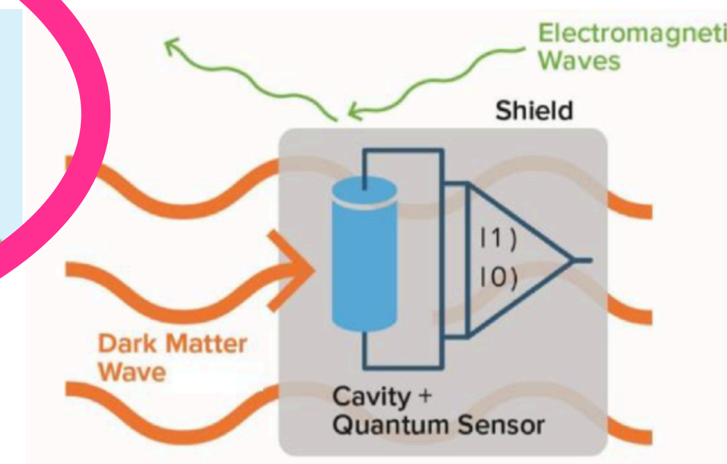
https://www.dunescience.org

Accelerator experiments



arXiv:1808.05219

(quantum) sensors for light/ultralight DM

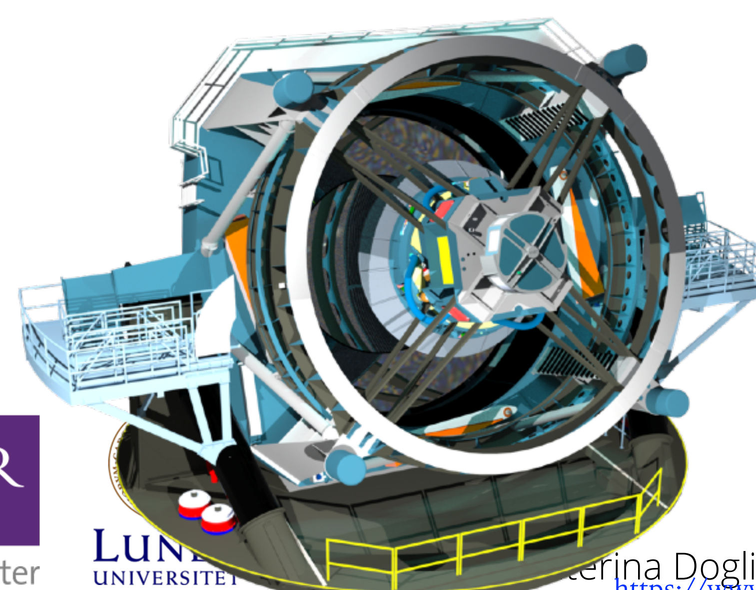


BRN report for new initiatives in DM

Gravitational wave experiments

arXiv:1907.10610

Astrophysical probes



https://www.lsst.org

DM complementarity at SnowMass2021

- Since the last Snowmass process (2013), there has been a fundamental shift in how we think about searches for dark matter
- We are in an **exciting exploratory phase** where new ideas can be implemented on short timescales
- Dark matter crosses **every** frontier
- In order to get a full picture of the "elephant", we need to combine information from different experiments
- **How do we portray this complementarity?**

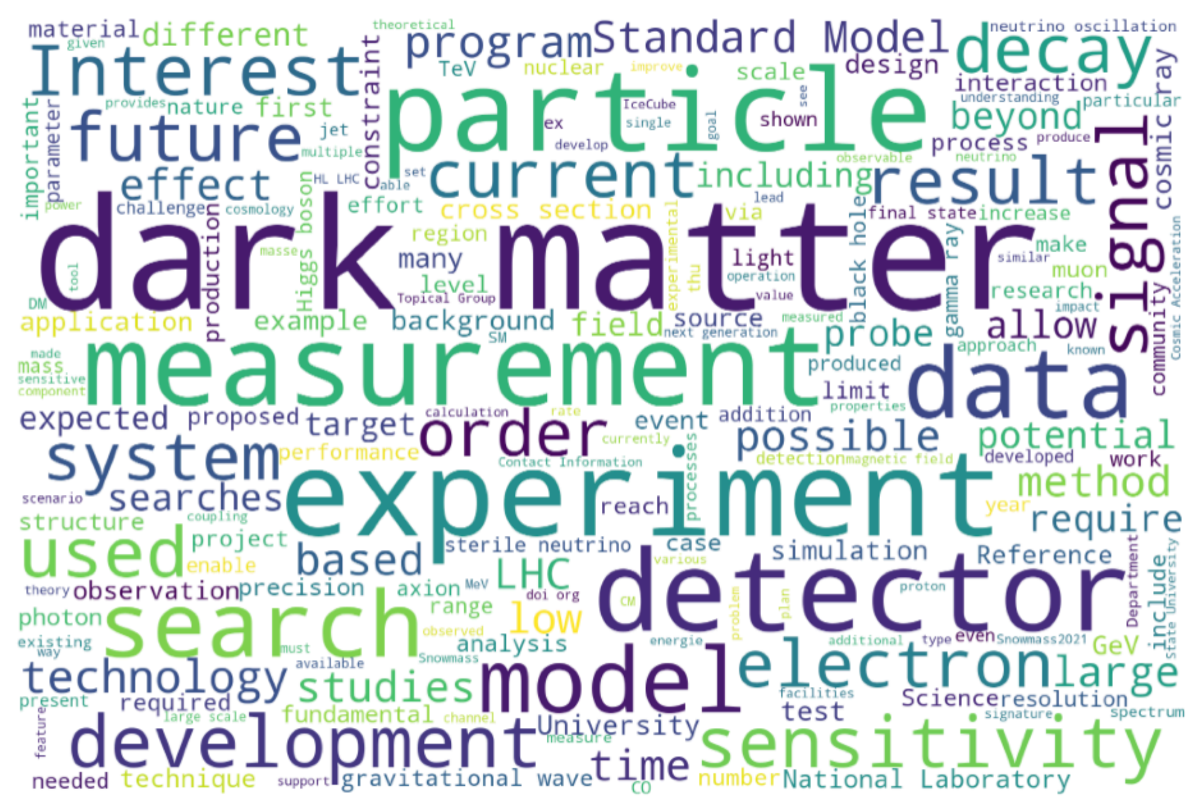
[Link to Community Planning Meeting session #150 - DM complementarity]

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

Word Clouds

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

All LOI's



Led to a cross-frontier whitepaper from Cosmic, Energy and Neutrino Frontiers
https://arxiv.org/abs/2210.01770

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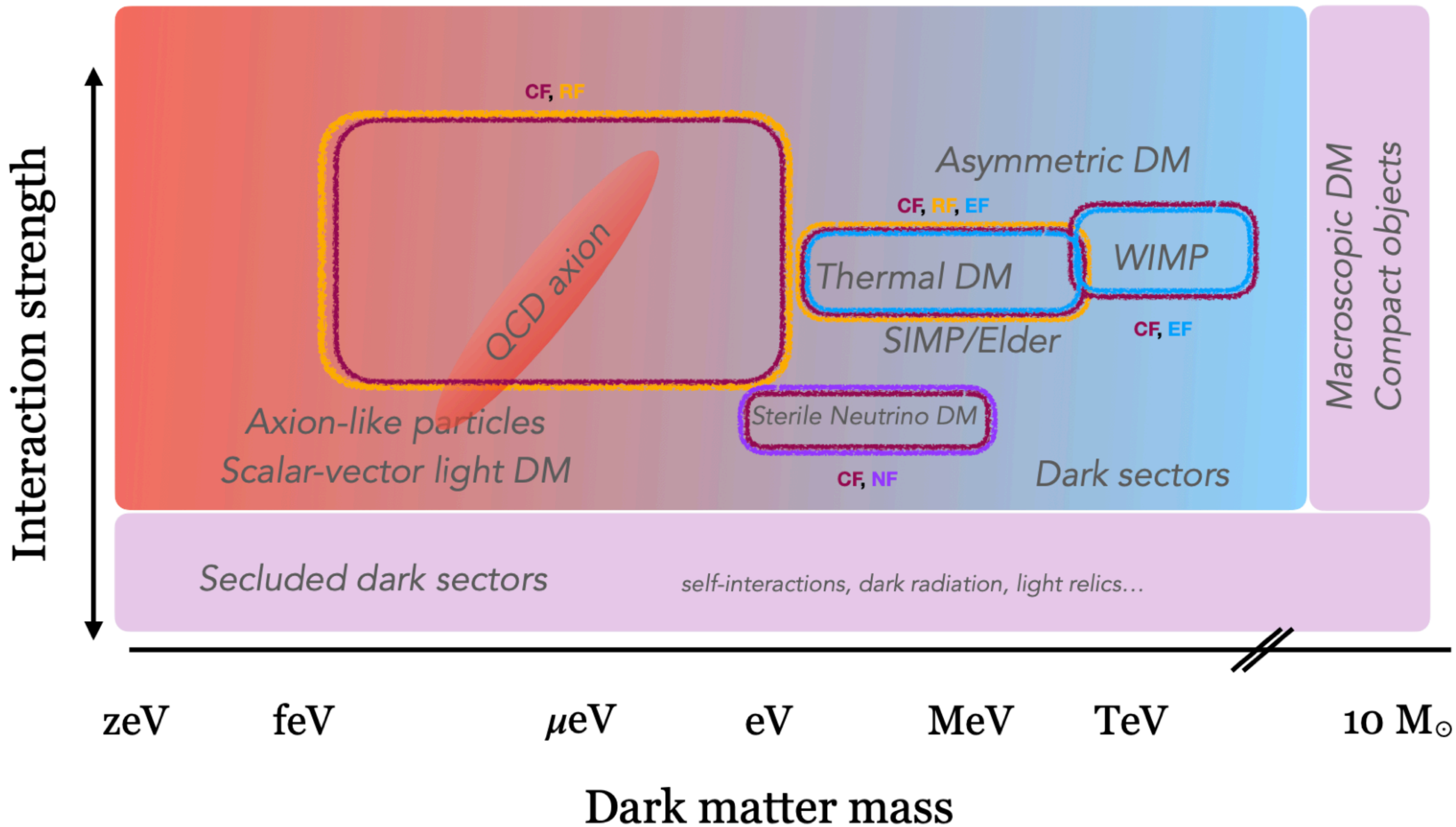
Snowmass complementarity: some examples of DM models



EF = Energy Frontier (e.g. ATLAS & future colliders)

CF = Cosmic Frontier (e.g. DarkSide, Sensei…)

RF = Rare & Precision Frontier (e.g. FASER, Mathusla. LDMX…)

NF = Neutrino Frontier (e.g. DUNE, MicroBoone)

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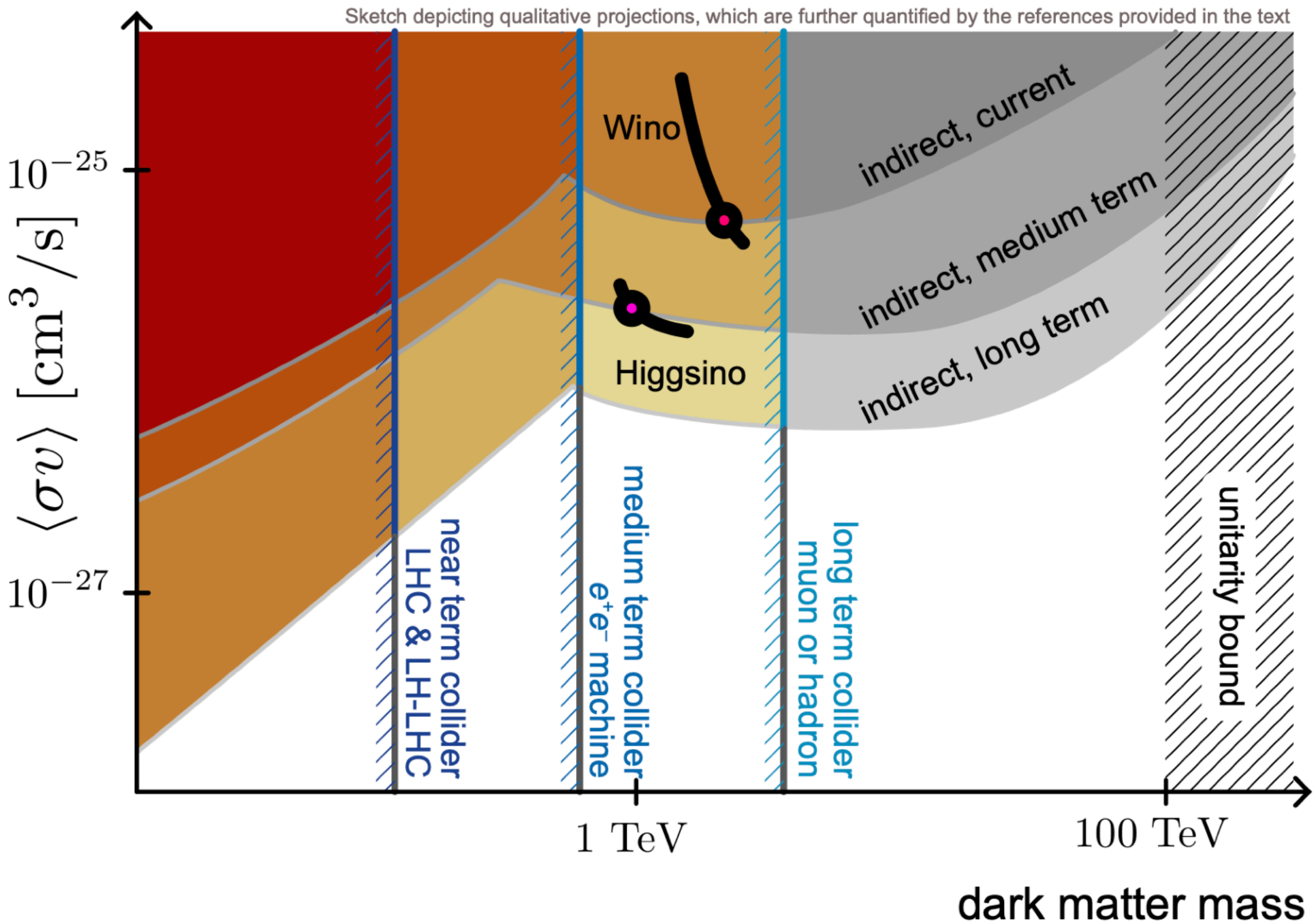
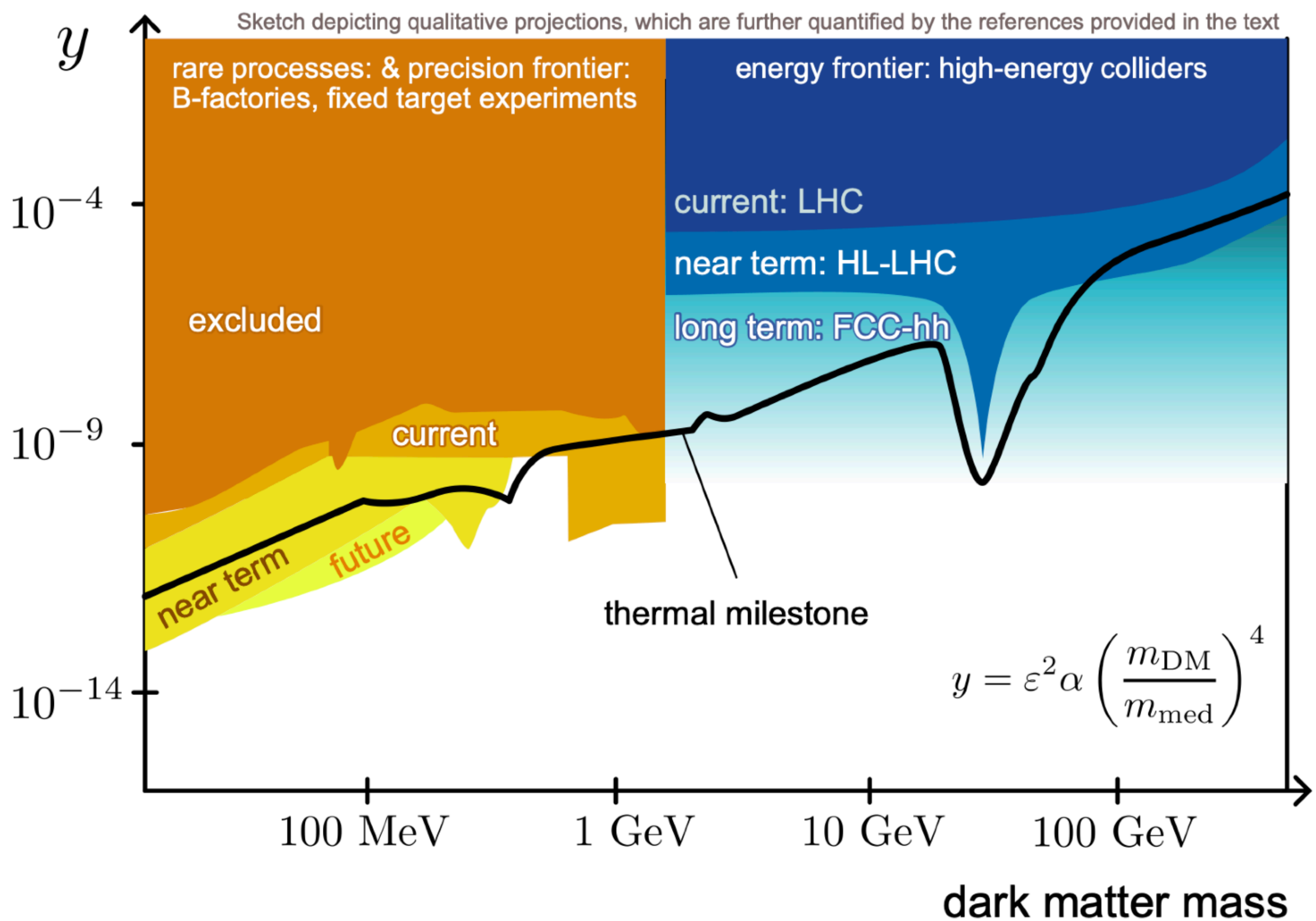
Snowmass complementarity: WIMP



EF = Energy Frontier (e.g. ATLAS & future colliders)

CF = Cosmic Frontier (e.g. CTA…)

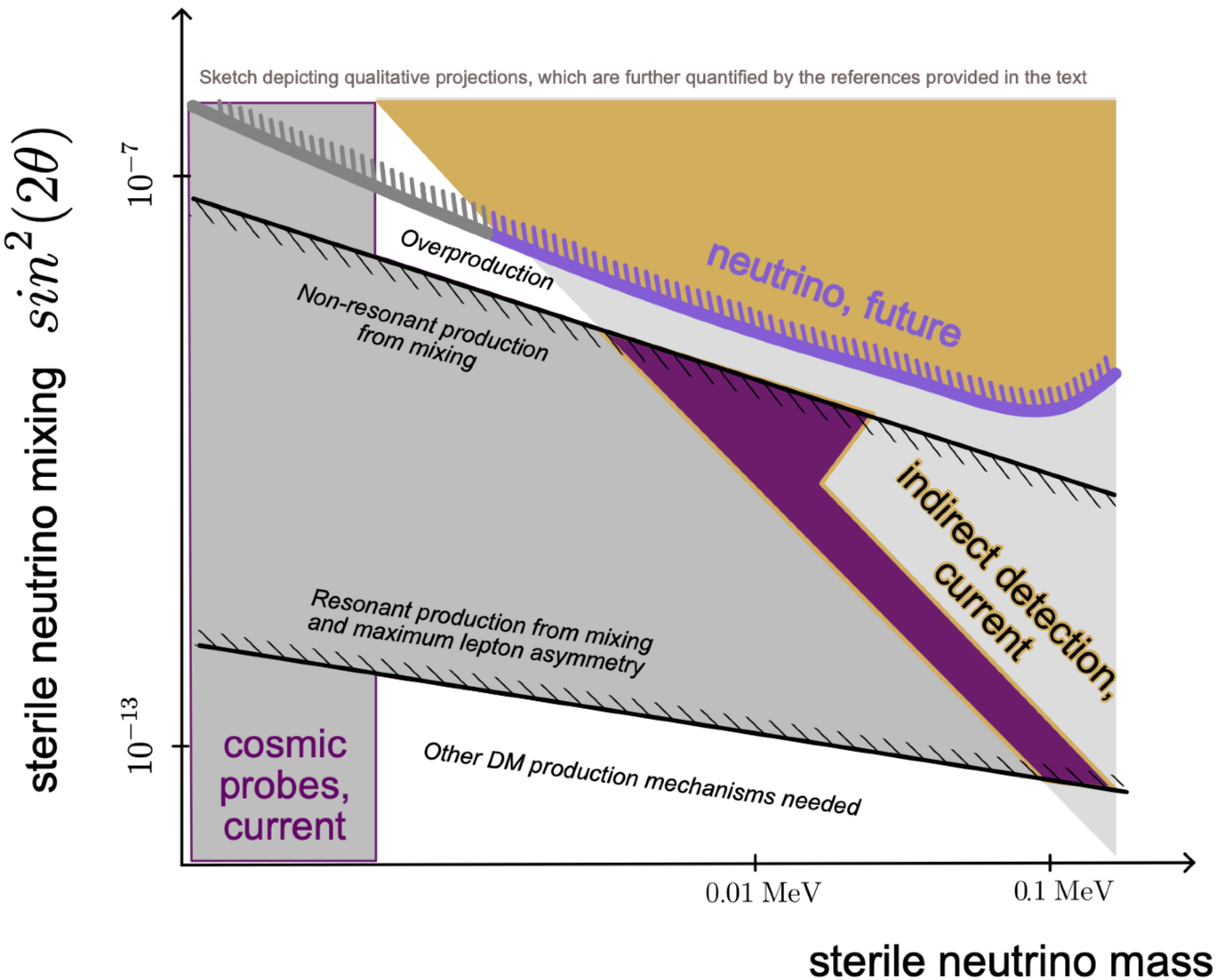
Snowmass complementarity: “dark photon”



EF = Energy Frontier

RF = Rare & Precision Frontier

Snowmass complementarity: sterile neutrino



CF = Cosmic Frontier

NF = Neutrino Frontier

(European) initiatives for DM complementarity

scientific outcome:
searches & interpretation

Astroparticle | Particle | Nuclear

Common theory ground

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

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

foundations:
(open) data & software tools

More software&tools to make the most of the data in Danielle's talk

JENAA Joint ECFA-NuPECC-APPEC Activities

Initiative for Dark Matter in Europe and Beyond (iDMEu)

Online platform / series of meetings to discuss dark matter synergies across all experiment & theory fields, endorsed by European particle / astroparticle and nuclear physics communities

+ Snowmass 2021 (submitted input to P5)

Link to kick-off meeting: https://indico.cern.ch/event/1016060/

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

Dark Matter Test Science Project Link

5 postdocs working in European institutes on reproducible and sustainable dark matter analysis (colliders, DD, ID) in the European Open Science Cloud

European Research Council · The University of Manchester 1824 · Lunds Universitet

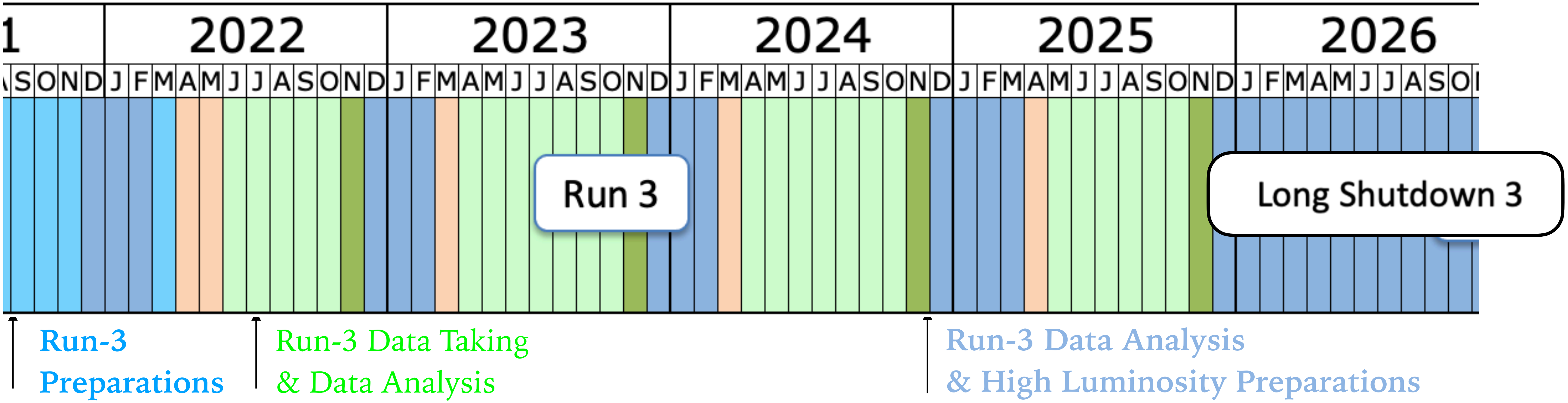
Passing the microphone to Sukanya and Danielle…

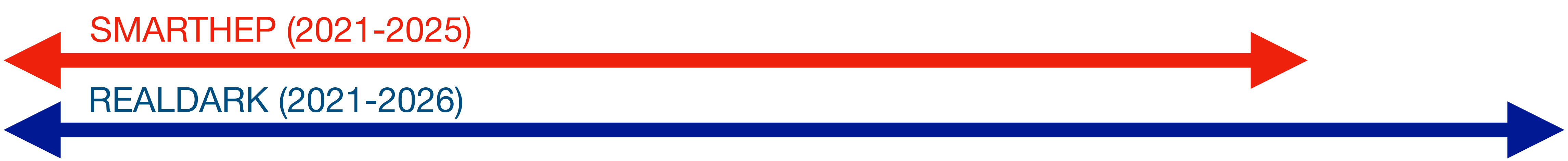
In the next few days: looking forward to
talking to more trigger / machine learning / dark matter enthusiasts
(but also learning more about neutrinos,
catching up with old friends and meeting new friends!)

What are we
(Caterina, Sukanya, Danielle & closest collaborators in Manchester)
going to do in the next 5 years?

Timelines

LHC Schedule for the next 5 years





New team & network with expertise in real-time analysis + industry connections

ATLAS-Manchester expertise and leadership in trigger & data acquisition, connections to dark matter experiments (FASER, DarkSide)

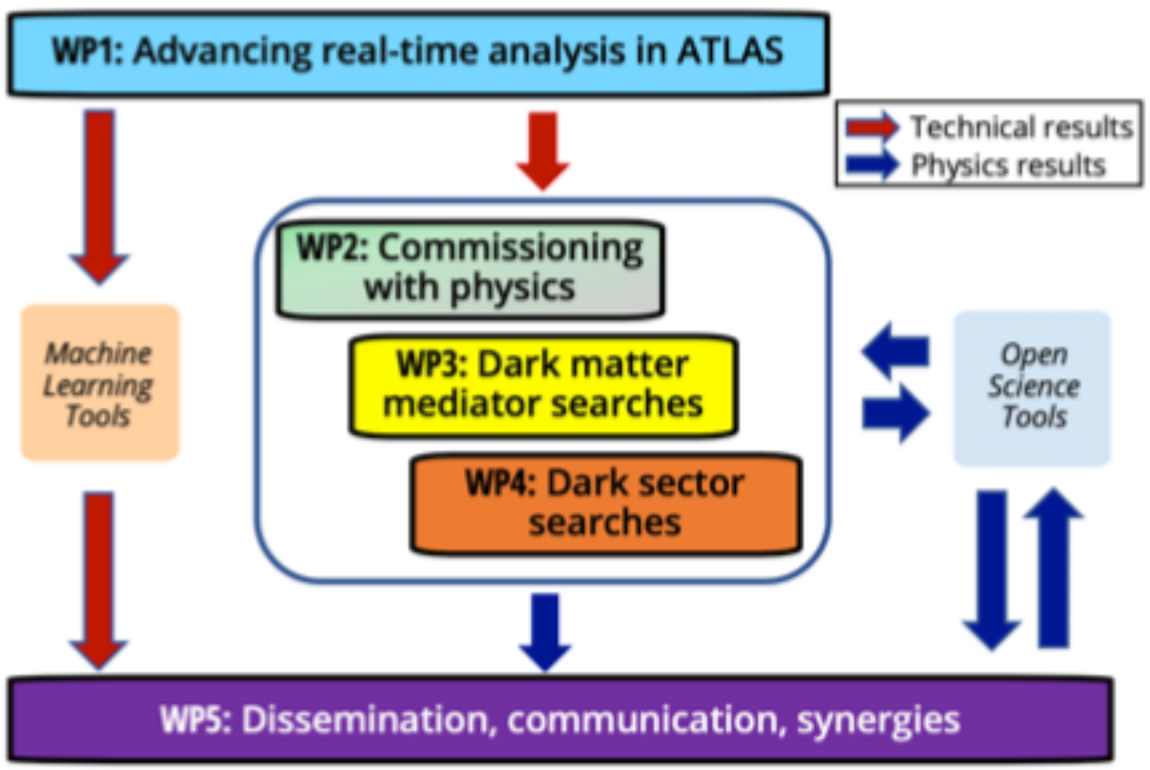
High Luminosity LHC and Future Colliders

The REALDARK Project (ERC Consolidator)

Team: Tobias Fitschen, **Sukanya Sinha** (PDRAs), Max Amerl, **Danielle Wilson** (PhD), 1 RSE

Upgrade ATLAS trigger for next LHC run with new data-taking workflows (Partial Event Building)

Make **real-time analysis** widely usable for searches and measurements in ATLAS (and at the LHC)



Further exploration of the electroweak scale @ LHC($\sim$100 GeV)

Sustainability and reusability of LHC/DM analyses, in terms of data and pipelines

Machine learning for data compression

DM @ colliders complementarity with accelerator experiments & astrophysics

Non-WIMP dark matter searches with non-standard jet signatures

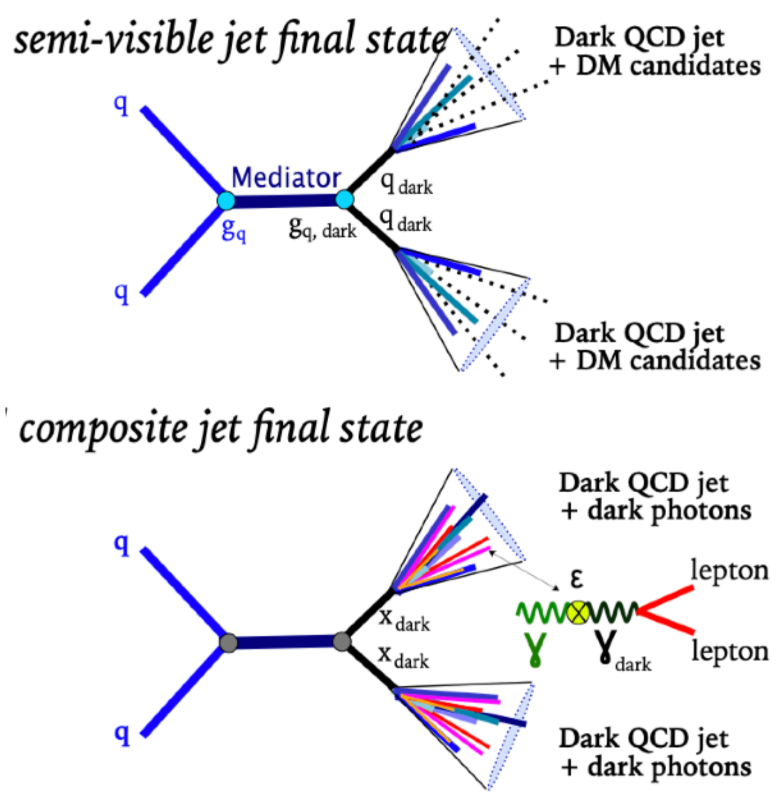
erc European Research Council Established by the European Commission

ATLAS EXPERIMENT

Possibilities for collaboration with TAU / neutrino:

- Real-time analysis / ML techniques for searches and measurements
- Dark matter: theory and experimental synergies

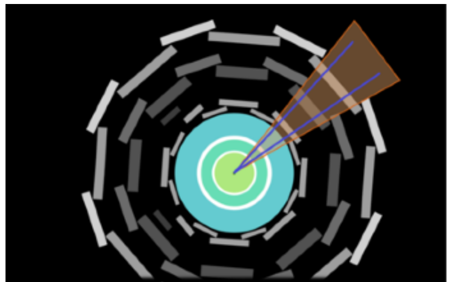
Danielle Wilson:
Searches for dark jets with novel data-taking techniques and ML in ATLAS



- But ***what if DM is not that simple?***
  → look into more complex dark sectors, where DM could be embedded into the jets: *dark QCD/dark showers*

H. Russell, EPS-HEP 2019,

We will need more information than "just the jets" in TLA:
partial event building
(still smaller than full event)



e.g. events for low-p_T muon performance save only data in cone around $J/\psi \rightarrow \mu\mu$ candidate

With this information, investigate different **ML techniques** to distinguish dark QCD/ordinary QCD based on jet content

Danielle's PhD project *(co-supervisor: Mike Seymour)*:

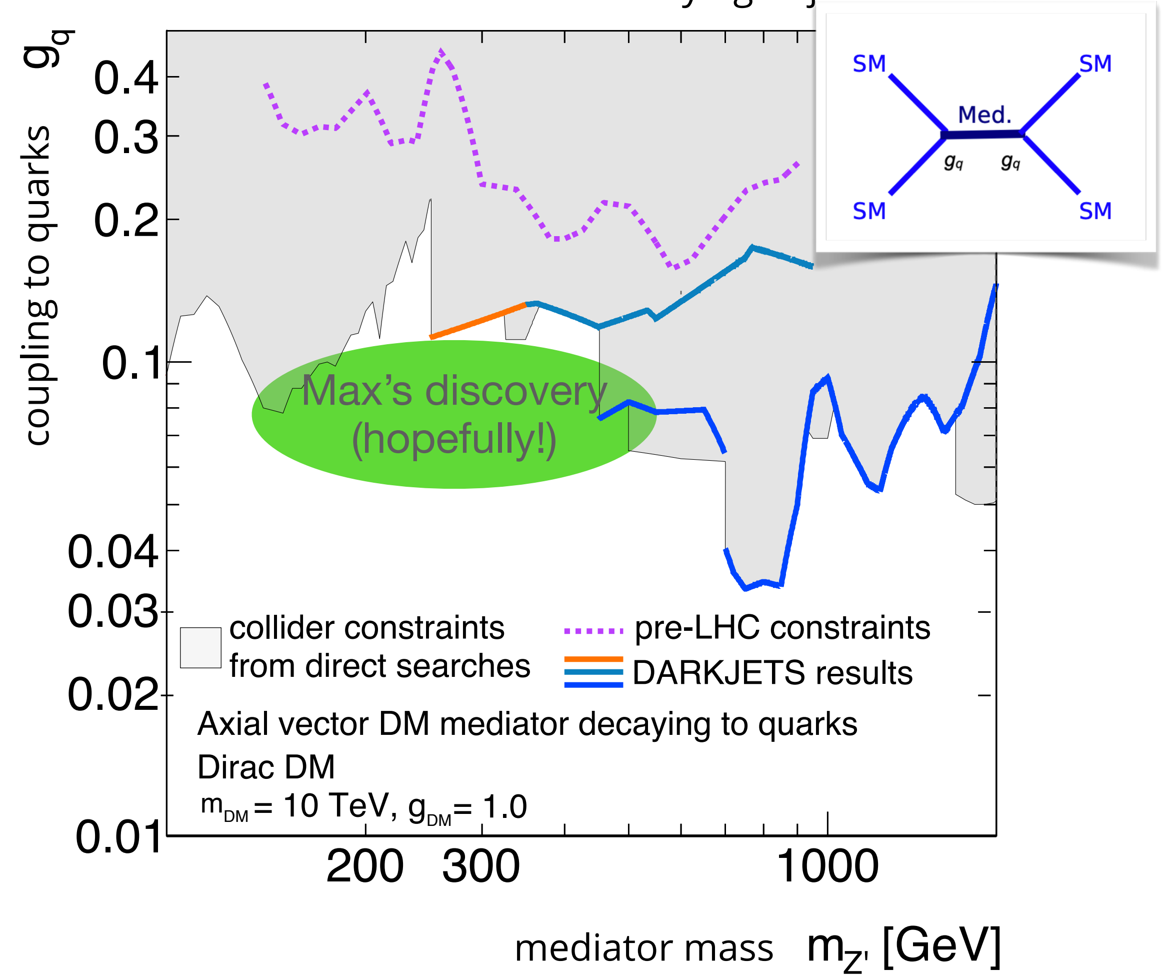
- Make use of existing measurements && input from theory to define models of *dark QCD*
- Use PEB/ML to search for *dark jets* == hadronic-like jets with DM particles

Max Amerl: *Searching for dark matter with real-time analysis techniques at ATLAS*

- Trigger leads ATLAS to save only *interesting* events (<< 1% of total events produced by LHC)
  - This works for most ATLAS physics…
  - …but not for **rare processes with large backgrounds**, e.g. DM mediators

- **Solution:** do as much analysis as possible in the trigger system, and only save **smaller** final-state objects (e.g. jets, photons)
  → **Trigger Level Analysis (TLA)**

dark matter mediators decaying to jets



Max's PhD project *(co-supervisors: Darren Price (currently doing masterclasses))*:

- Commission Run-3 jet trigger and Trigger Level Analysis stream with early data
- Search for dark matter mediators with the TLA technique in unexplored regions
- Share ATLAS searches data, results, and tools with the entire community searching for DM

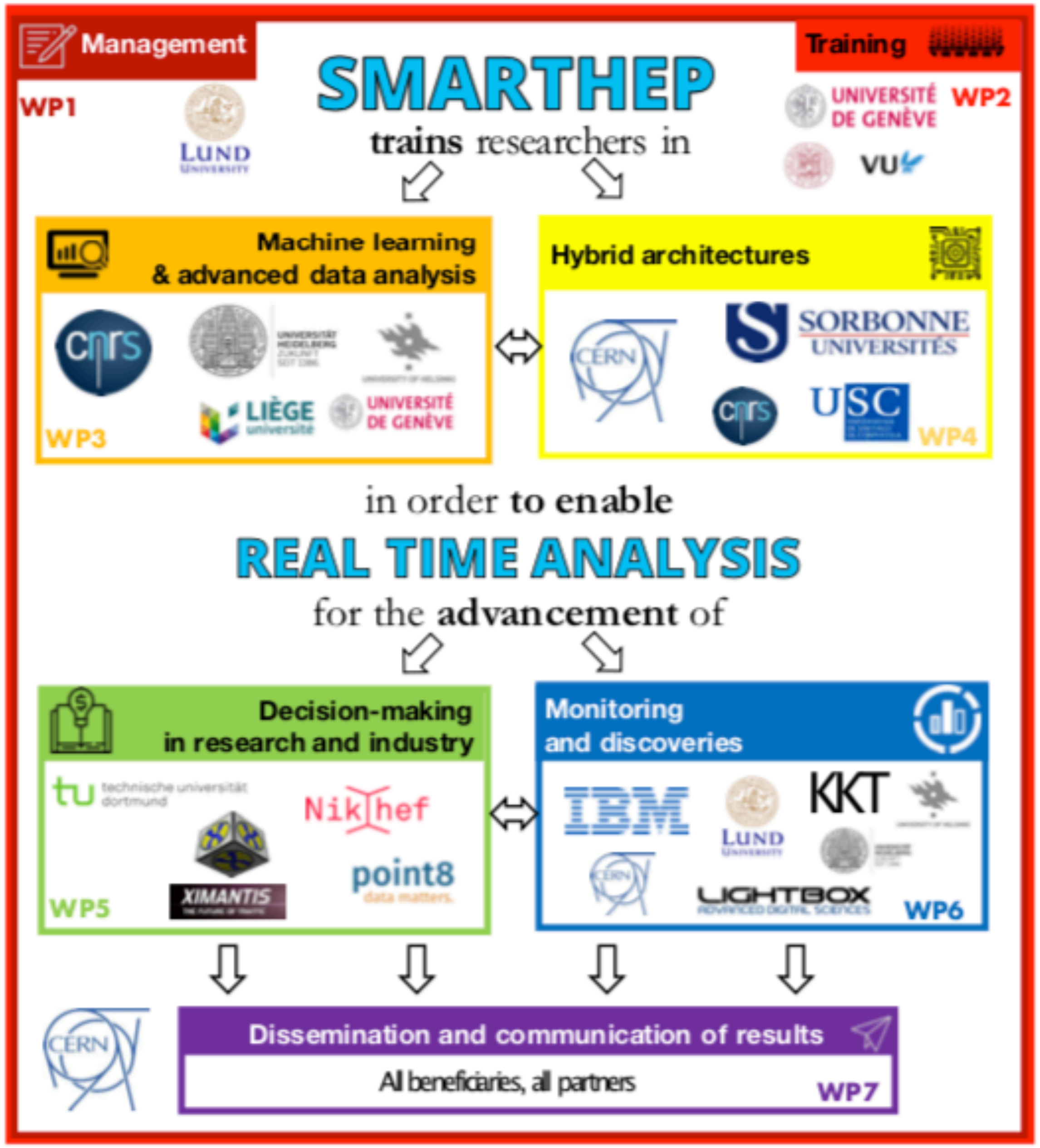
Pratik Jawahar: *accelerated anomaly detection*
in the SMARTHEP European Training Network

- **“Too much data”** problem by no means unique to LHC physics
- Data is abundant in industry, so need fast decision-making (short **time-to-insight**)
- **Solution:** real-time analysis (RTA)
  - Tools to accelerate **RTA in industry & research**: machine learning, hybrid computing architectures (GPU, FPGA)

Pratik’s PhD project *(co-supervisors: Alex Oh, Jiri Masik)*:

- Commission Run-3 tracking trigger algorithms
- Employ machine learning solutions, especially unsupervised learning (anomaly detection), for new physics discoveries in dark sectors
- Use accelerators (GPU/FPGA) for particle tracking at the HL-LHC

SMARTHEP trains
12 (+N) **PhD students**
20 participants: industries, labs and academic institutions

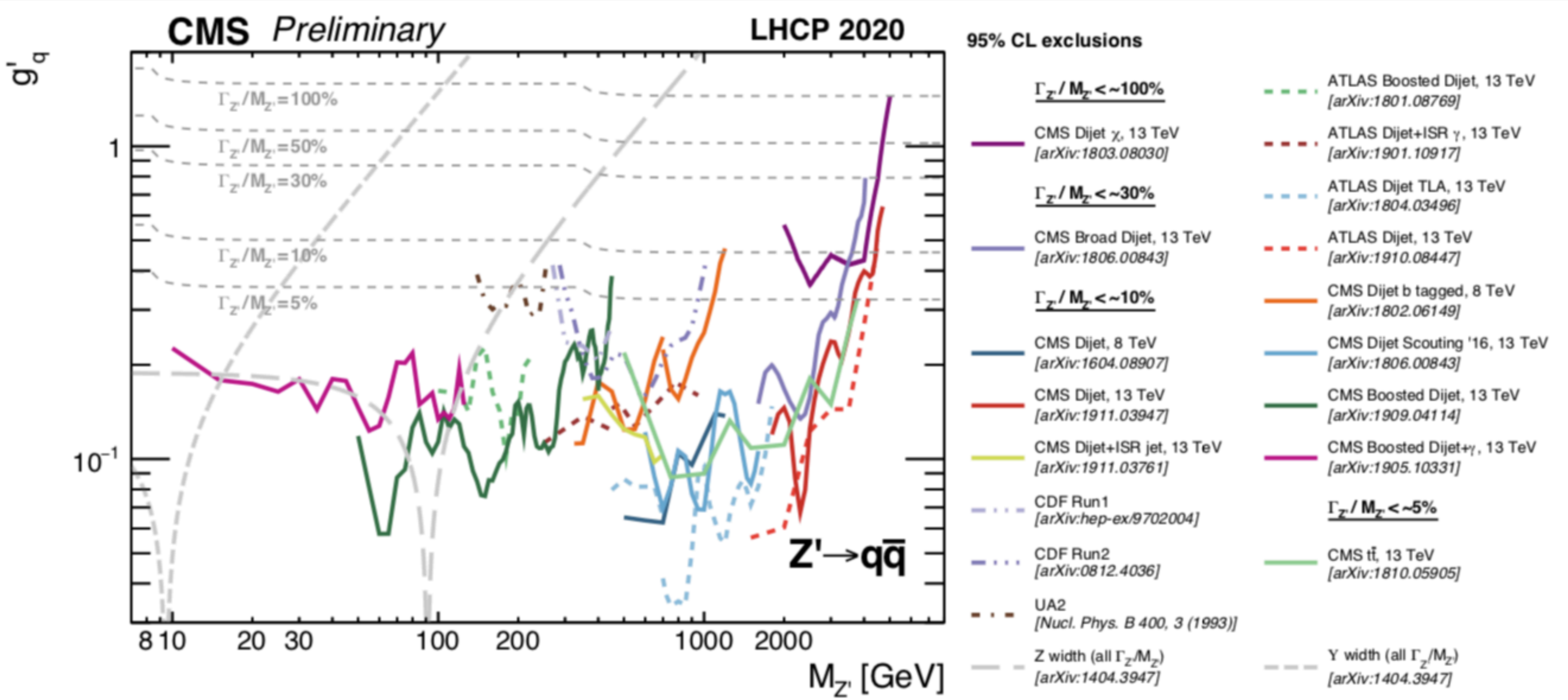


Backup slides

CATERINA DOGLIONI - LUND UNIVERSITY
@CATDOGLUND, SHE/HER
http://www.hep.lu.se/staff/doglioni/

Dark matter and dark matter mediators

Mediator mass-coupling summary plot



An example: some very exotic signatures

Mapping of exotic signatures to big picture of benchmark models not always easy → difficult to prioritize → may be difficult to decide what exactly to include in trigger menu

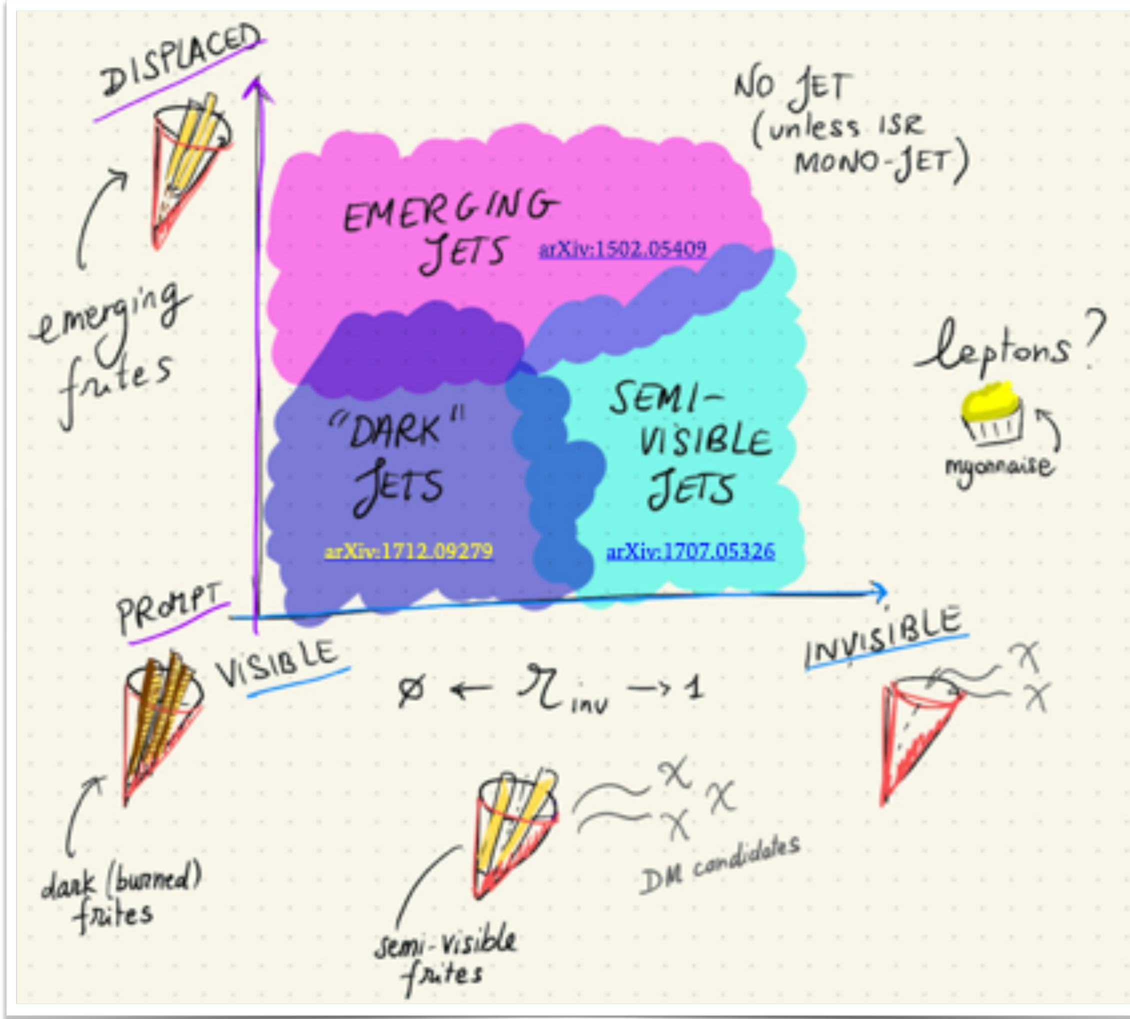
Signatures with a **common denominator**: unusual tracks/energy distributions, more or less localized in the detector

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

increasing event rate ↓

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

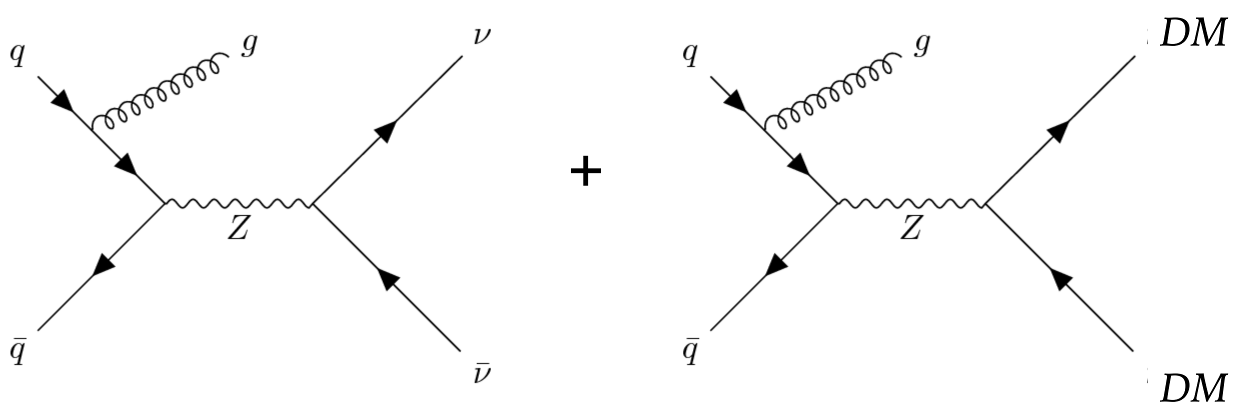
↑ *increasing event size*

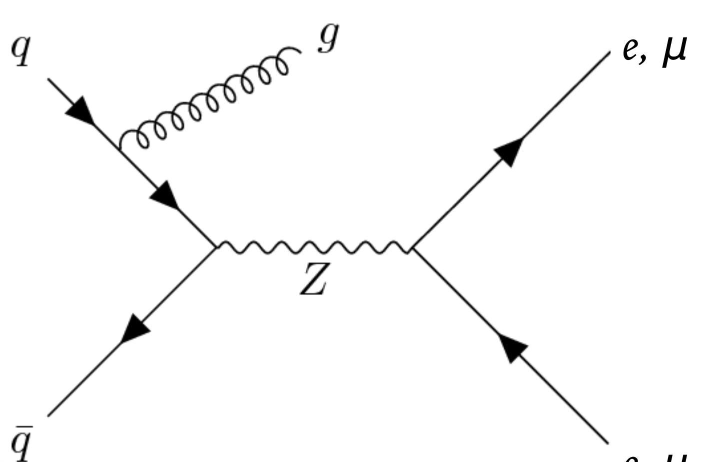


Inspired by K. Pedro & C. Fallon's talk @ DMLHC2019 and by this twitter thread

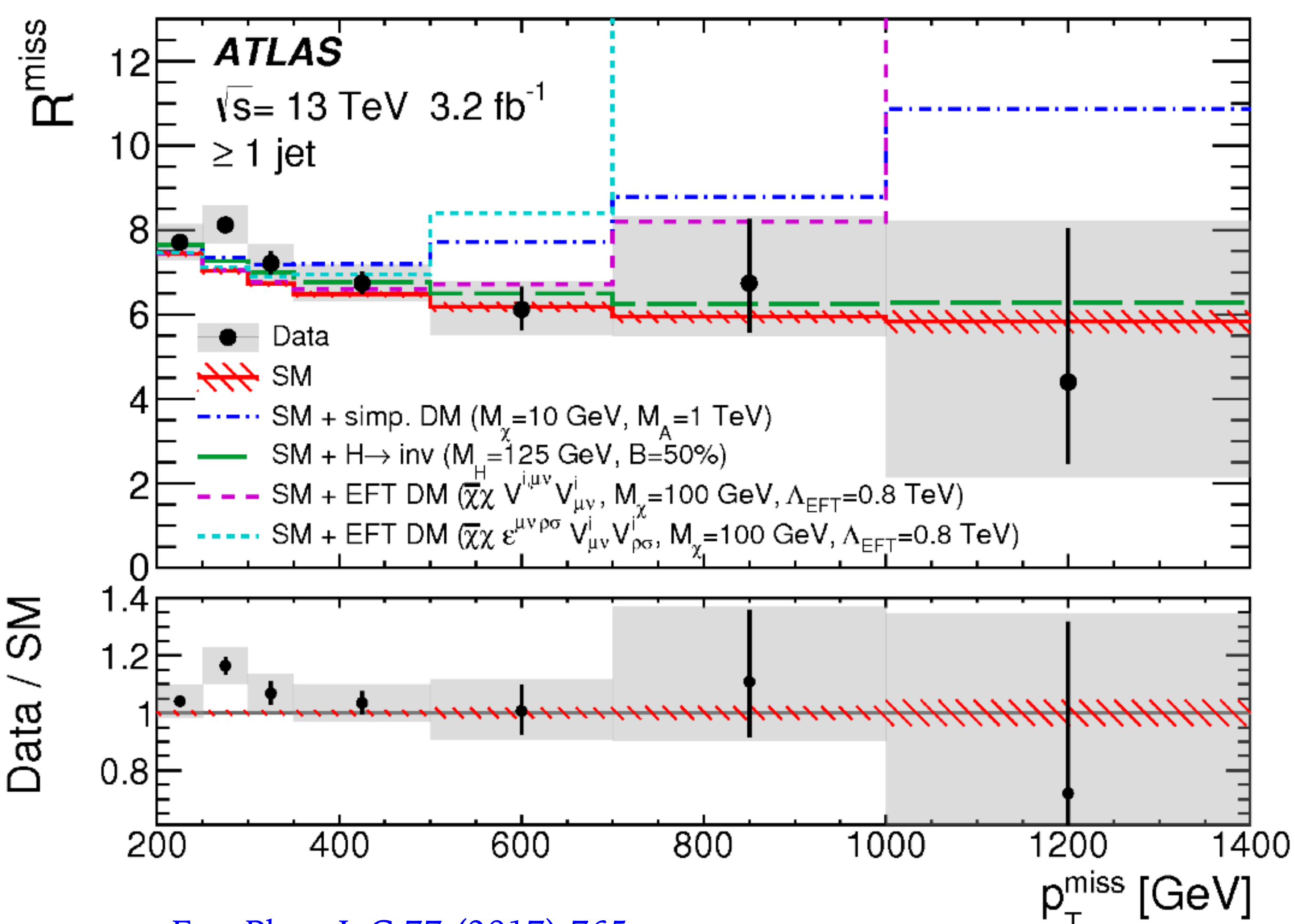
LHC production of new invisible particles

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





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



[Eur. Phys. J. C 77 (2017) 765]

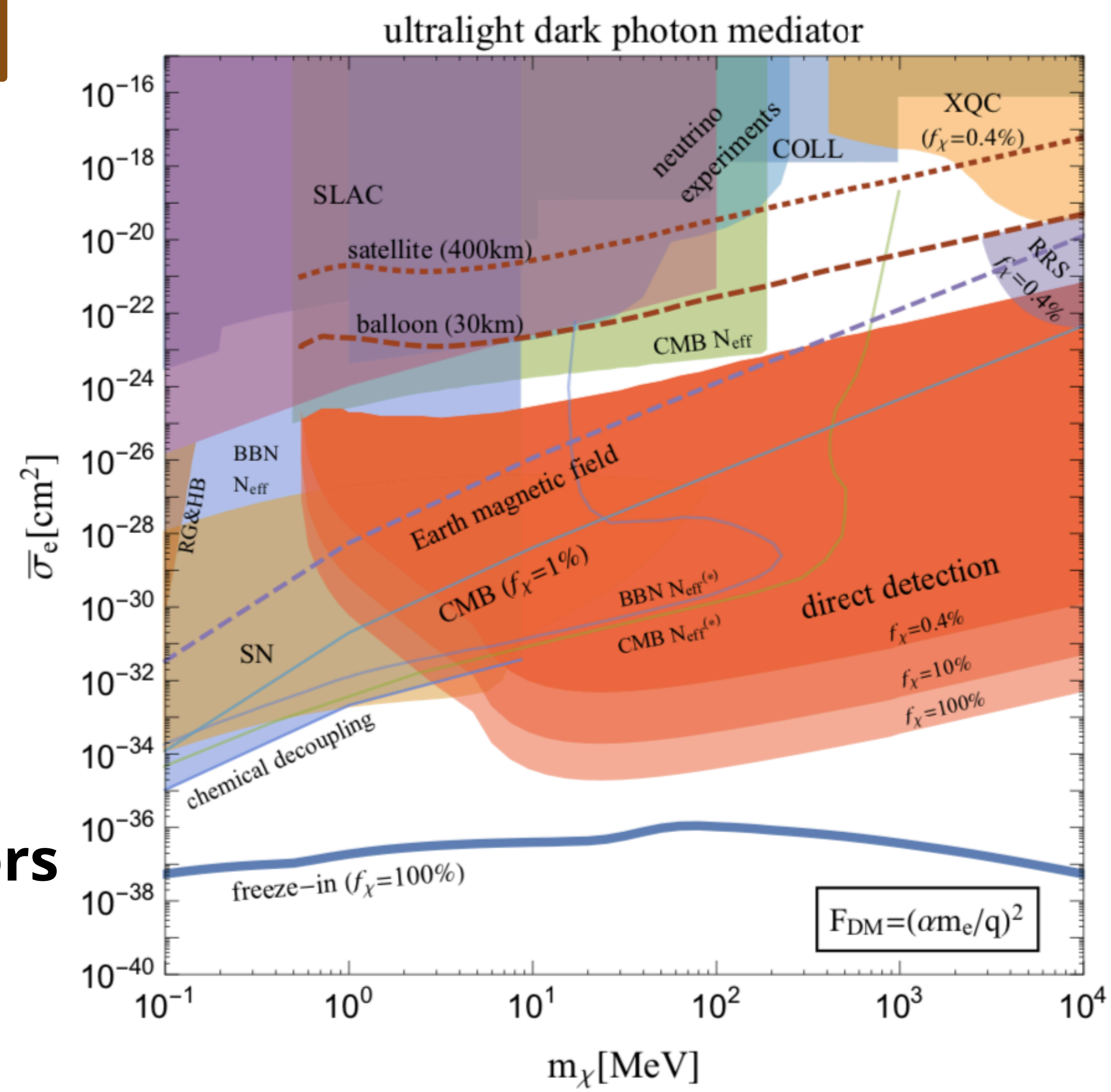
Example: looking *up* (to hints from astrophysics & more)

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

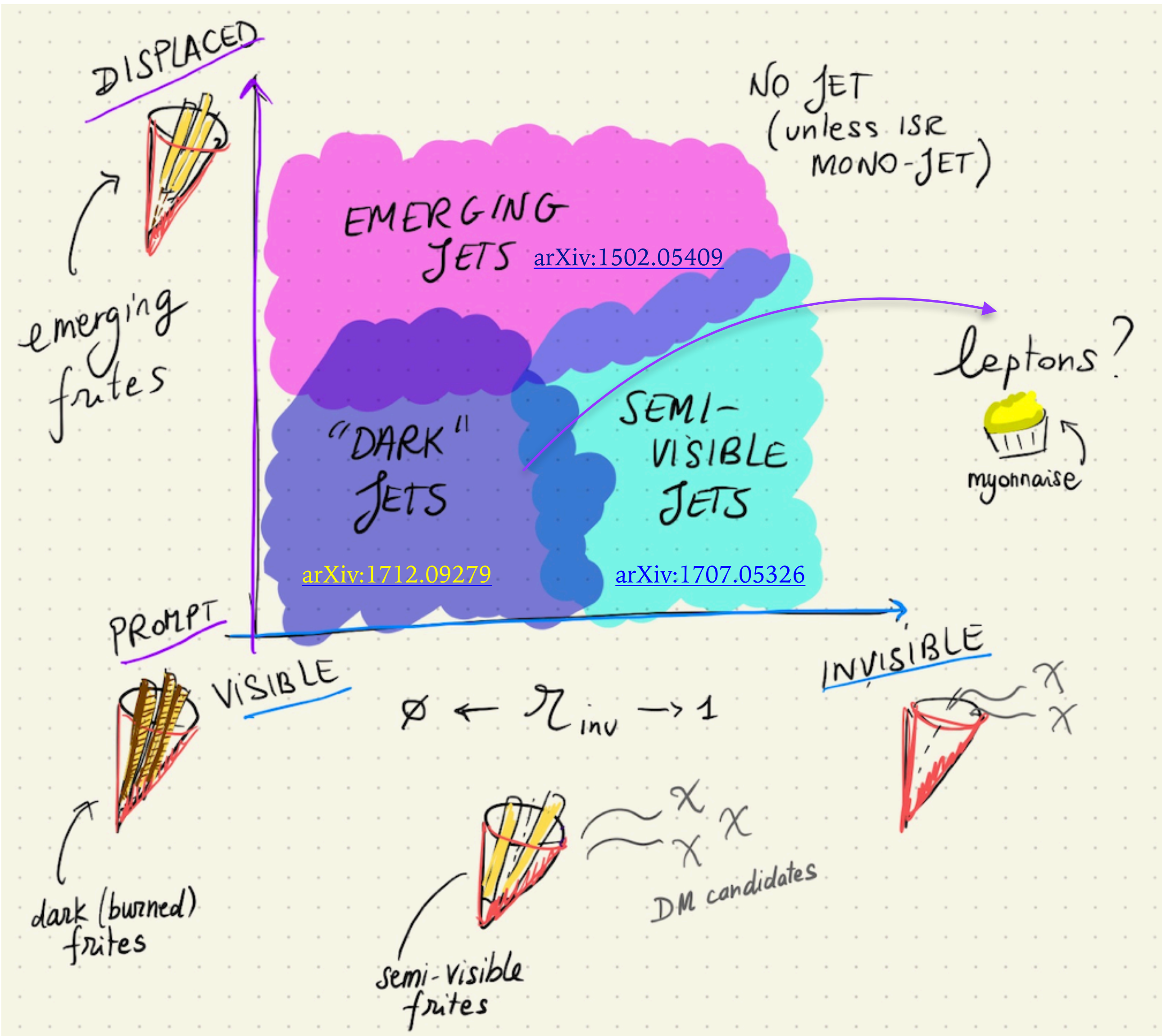
(potentially low-mass) & "strongly interacting" DM particles will

- 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



Strong 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)

SnowMass2021

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

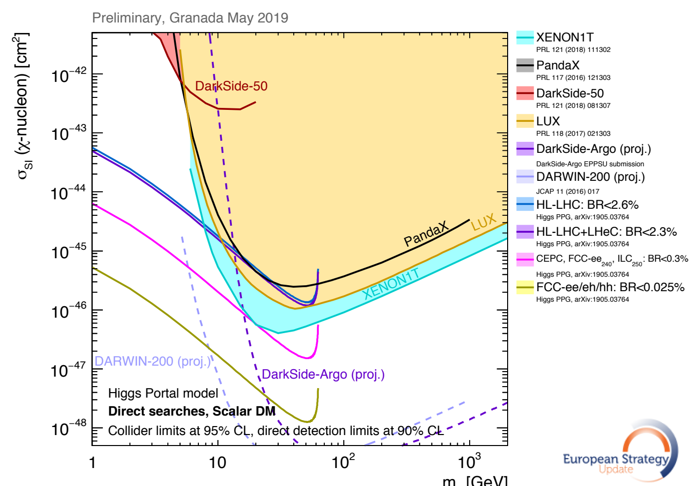
A family of signatures, with DM particles (& more) in the dark shower ⇒ need more than simple real-time analysis!

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

Extending DMWG models to lower masses / couplings

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

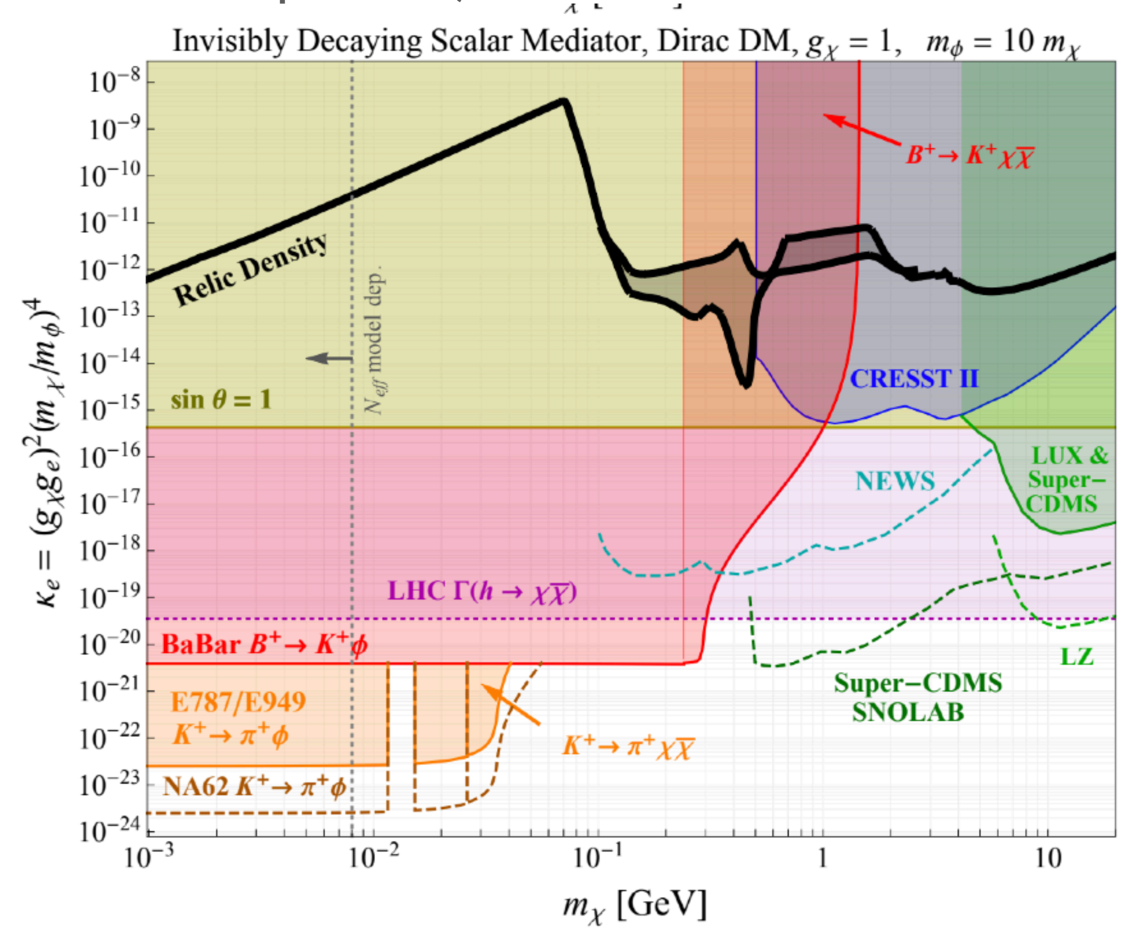
- In principle one ***could*** extend those plots to **m_{DM} < 1 GeV**



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

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

- Wherever this is done, it's not easy to understand how to (re)interpret the y axis & understand full model details for non-theorists (see yesterday's dark photon discussion during Maurik Holtrop's talk)



Discussion needed!

Extending DMWG models to lower masses / couplings

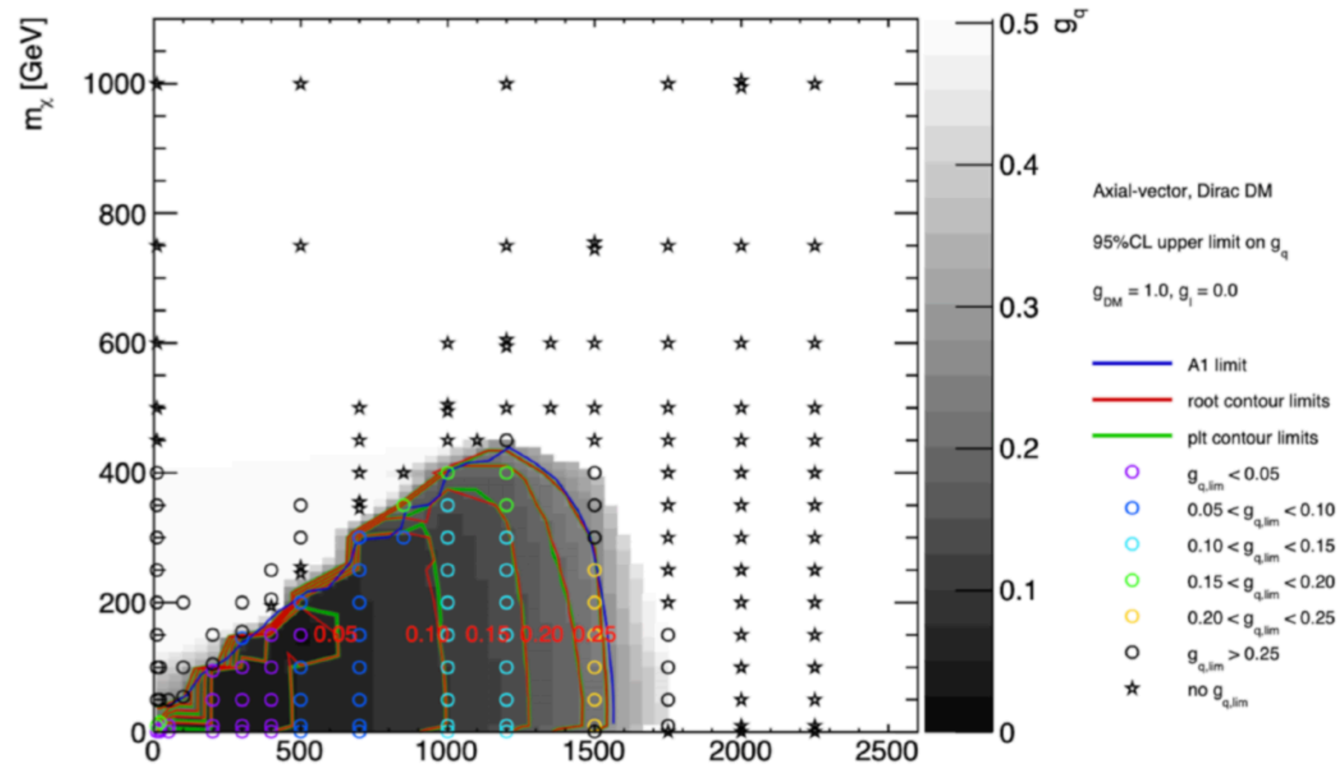
How do generic LHC searches "move on" from benchmarks with couplings of order 1?

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

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

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

B. Gao's thesis



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

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

SnowMass2021

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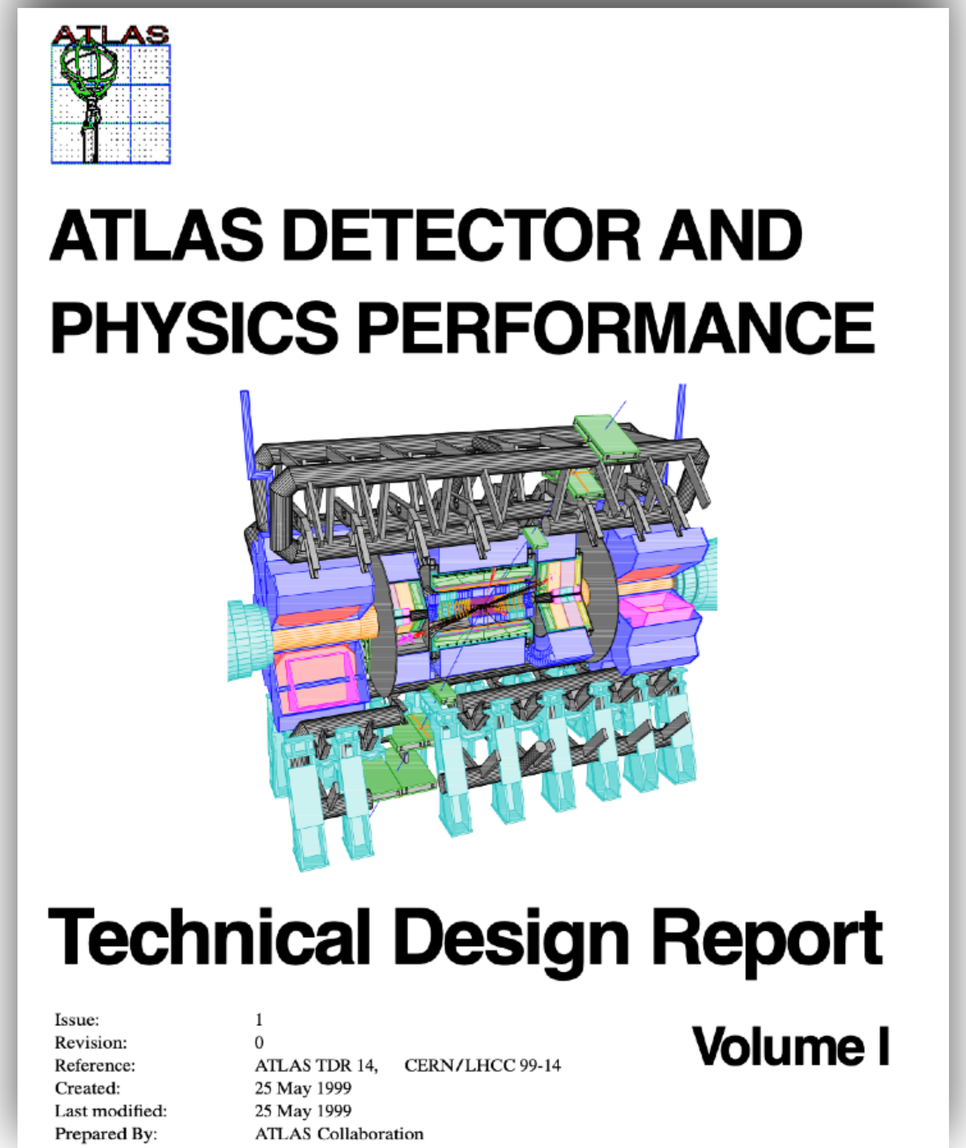
Data compression

As ATLAS physicists, we also like *high accuracy*...


ATLAS

ATLAS DETECTOR AND PHYSICS PERFORMANCE

Technical Design Report

Volume I

Issue: 1
Revision: 0
Reference: ATLAS TDR 14, CERN/LHCC 99-14
Created: 25 May 1999
Last modified: 25 May 1999
Prepared By: ATLAS Collaboration

ATLAS detector and physics performance *Volume I*
Technical Design Report *25 May 1999*

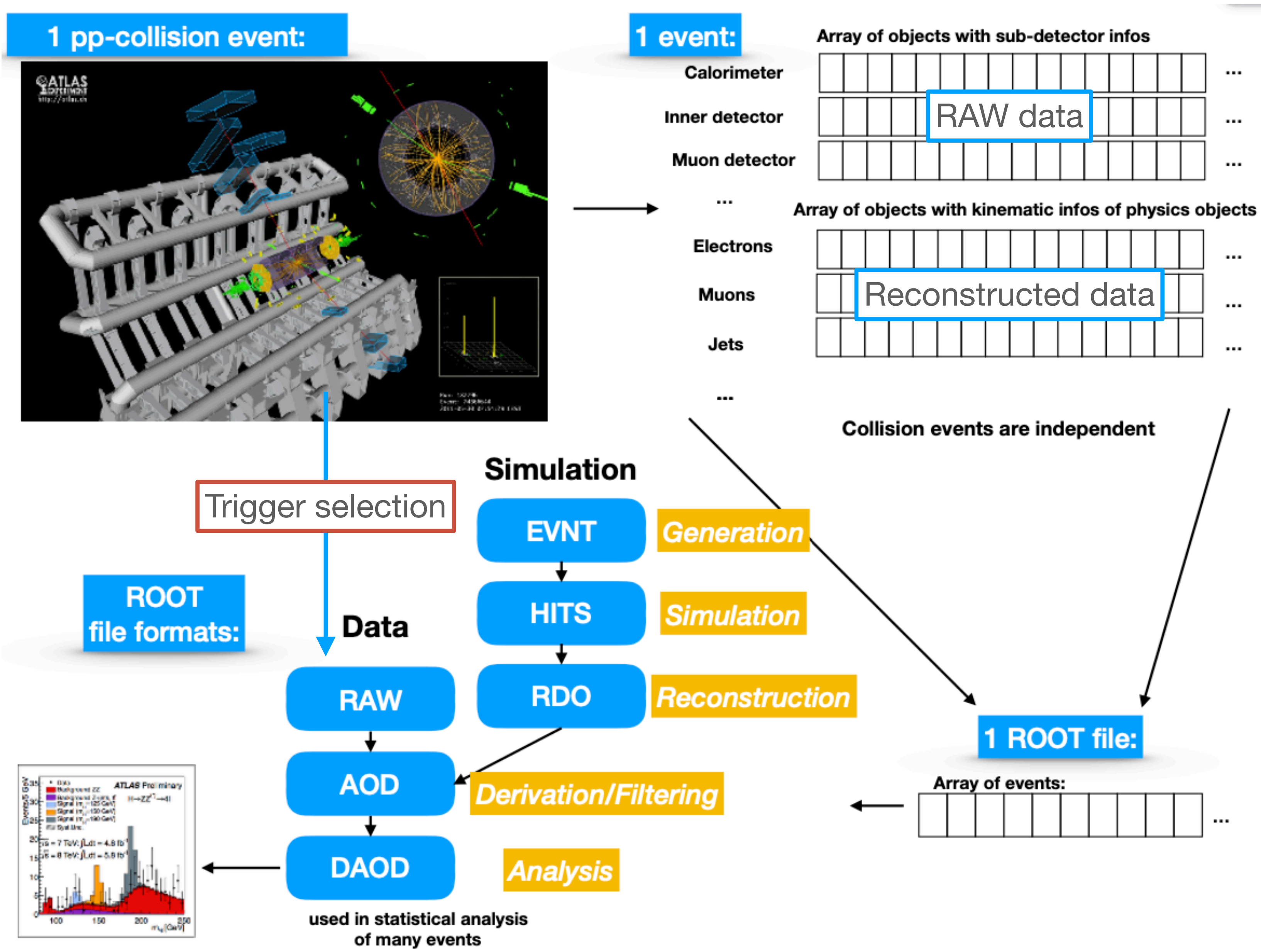
Preface

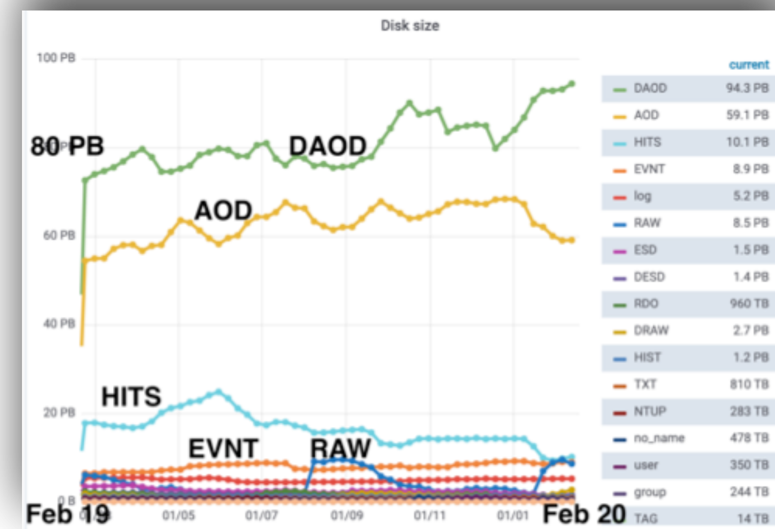
The Large Hadron Collider opens a new frontier in particle physics due to its higher collision energy and luminosity compared to the existing accelerators. The guiding principle in optimising the ATLAS experiment has been maximising the discovery potential for new physics such as Higgs bosons and supersymmetric particles, while keeping the capability of high-accuracy measurements of known objects such as heavy quarks and gauge bosons.

- *Lossless compression* is a much easier choice to make with respect to *lossy compression*
- However there are use cases where **trade-off between more data and less information/precision** is worth it
  - Example: searches where not enough collision events containing signal can be recorded because background exhausts storage resources
- We also have to take into account the **time and resources needed to compress/decompress**, especially within a resource-constrained trigger system

Data tiers and needs in ATLAS

J. Elmsheuser's talk at CERN/Google TIM (2020)





- Total ATLAS available disk: **o(300) PB** (similar amounts of tape)
  - Distributed on the Worldwide LHC Computing Grid
  - Also limiting factor to recording more data: disk on CERN site
- Assuming we can't just "buy more disk"…
- Lossless compression already used so far in ROOT formats
  - Overview from 2019: arXiv:1906.04624
  - For future perspectives, see e.g. this ACAT 2021 talk
  - Lossy compression (e.g. float truncation) could also help!

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Compression in the ATLAS trigger, now

Thanks to Wainer Vandelli, Werner Wiedenmann and Oxana Smirnova for discussions

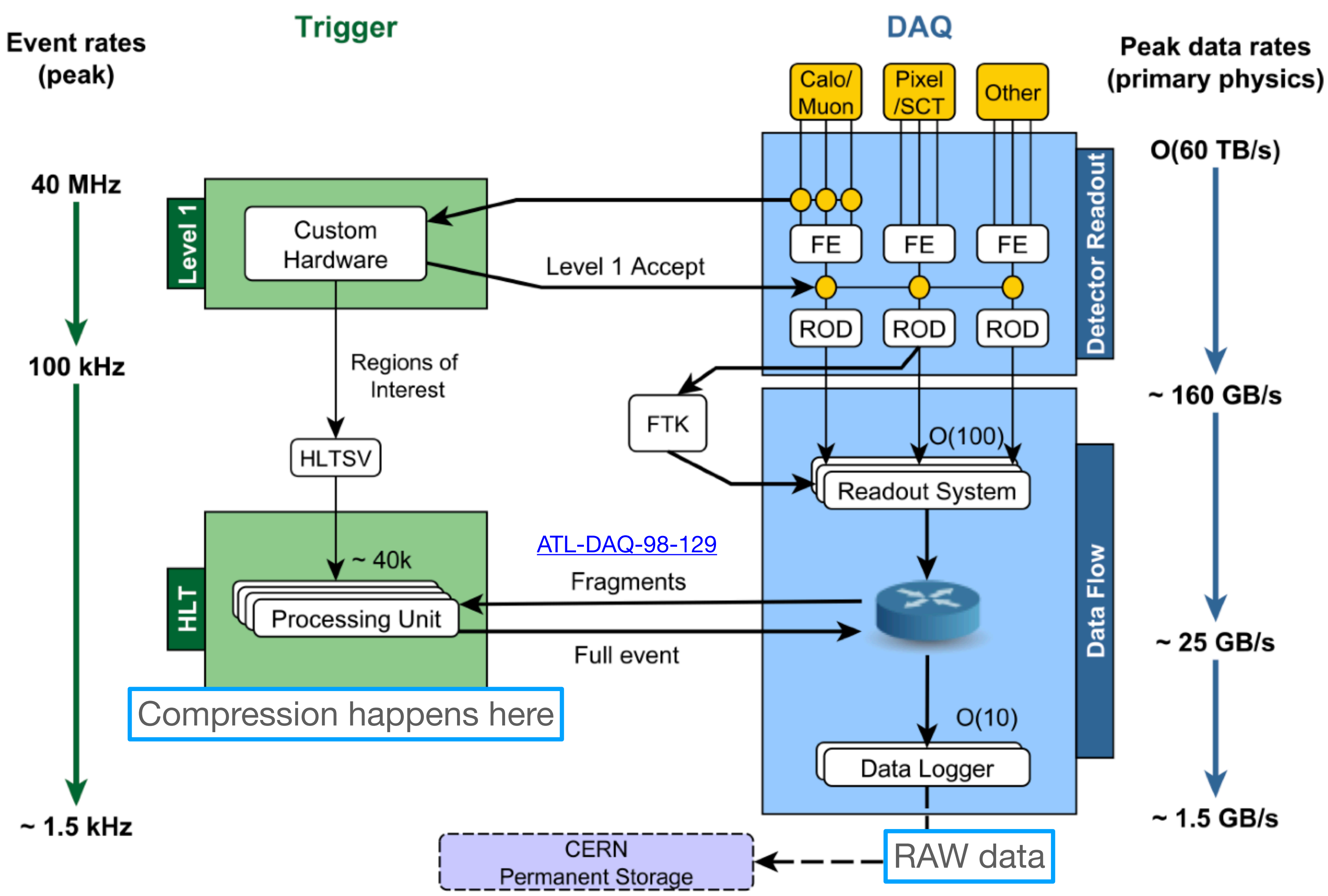
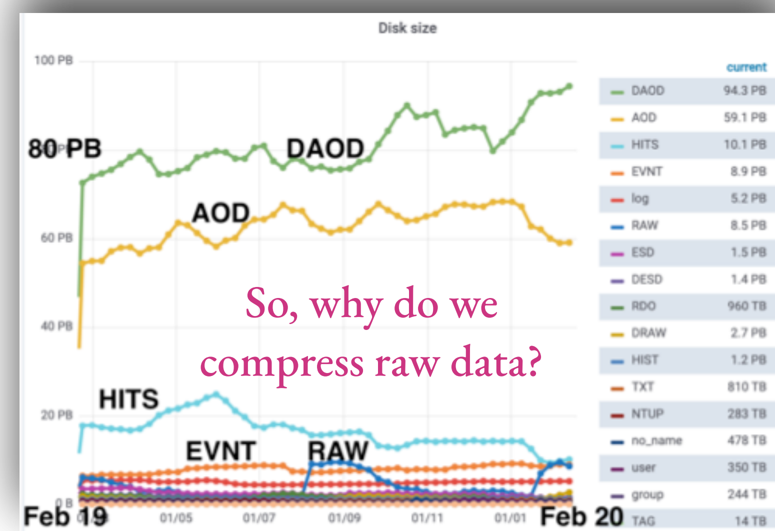


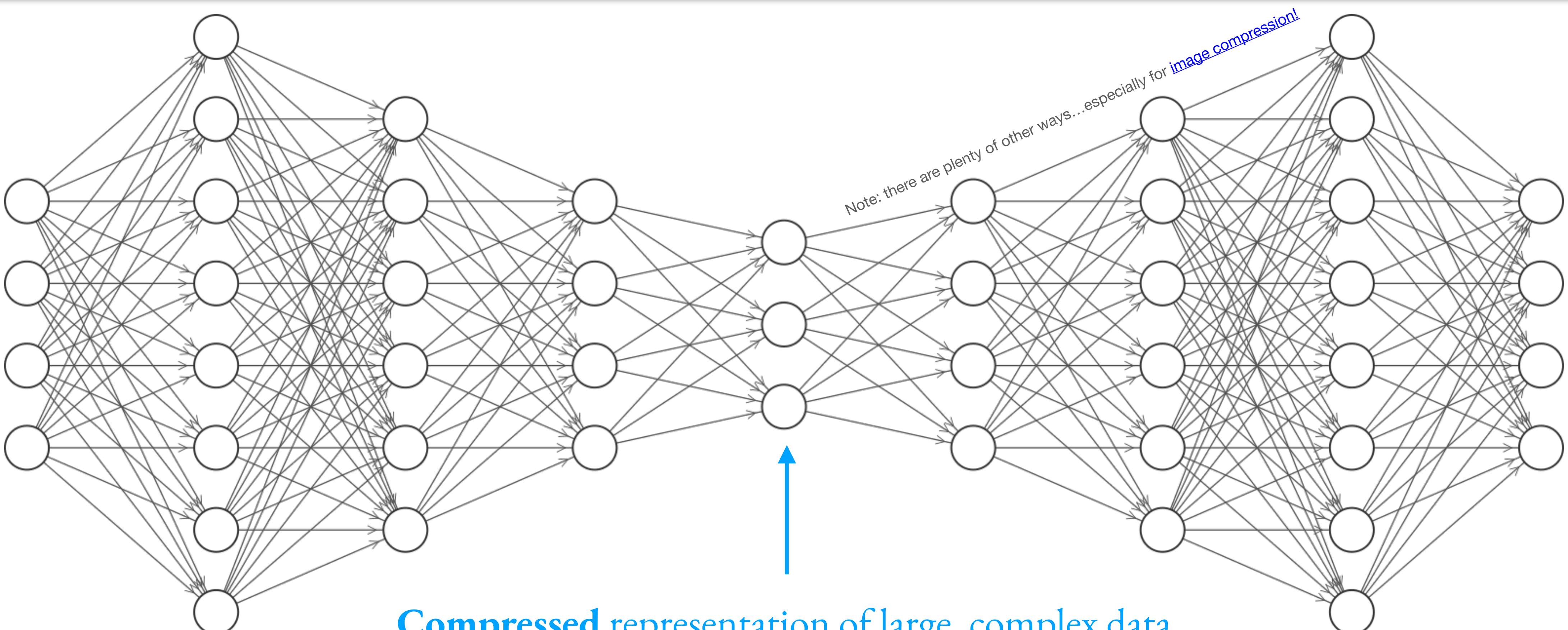
Figure from ATLAS TDAQ Twiki



J. Elmsheuser's talk at CERN/Google TIM (2020)

- RAW data ⟺ "Fragments" of information from each sub-detector are compressed in trigger CPU nodes using fast, lossless compression (*zlib* level 1)
- Not necessarily for final storage…but because data needs to be *sent to* storage at high rate with **limited network bandwidth**!
  - This also contributes to limitations on recording more data

Compression with ML: deep autoencoders



Compressed representation of large, complex data

Network **minimises reconstruction error** → accuracy targets

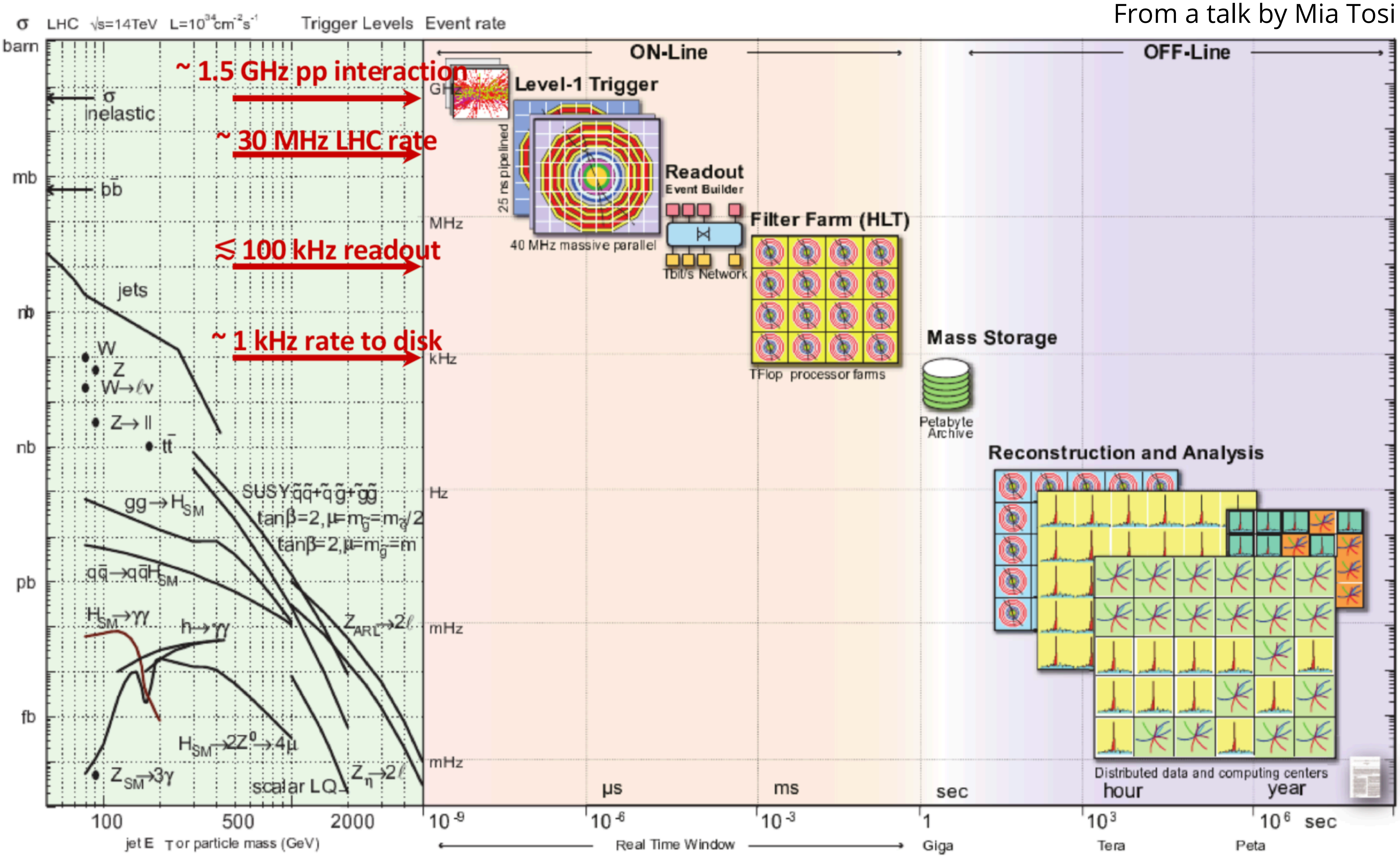
Lukas will be speaking tomorrow

- Effort started in 2019 from a chat with Lukas Heinrich at the HEP Software Foundation Workshop
  - Also some discussion in LHCb (see this GitHub repo and talk)
- 5 undergraduate theses [1][2][3][4], 2 Google Summer of Code studentships [5][6] and 1 IRIS-HEP fellowship later [7]…this looks promising for data from colliders and other fields
  - getting everything ready for demonstrator + publication
    → *see Alexander Ekman's talk in the next slot*

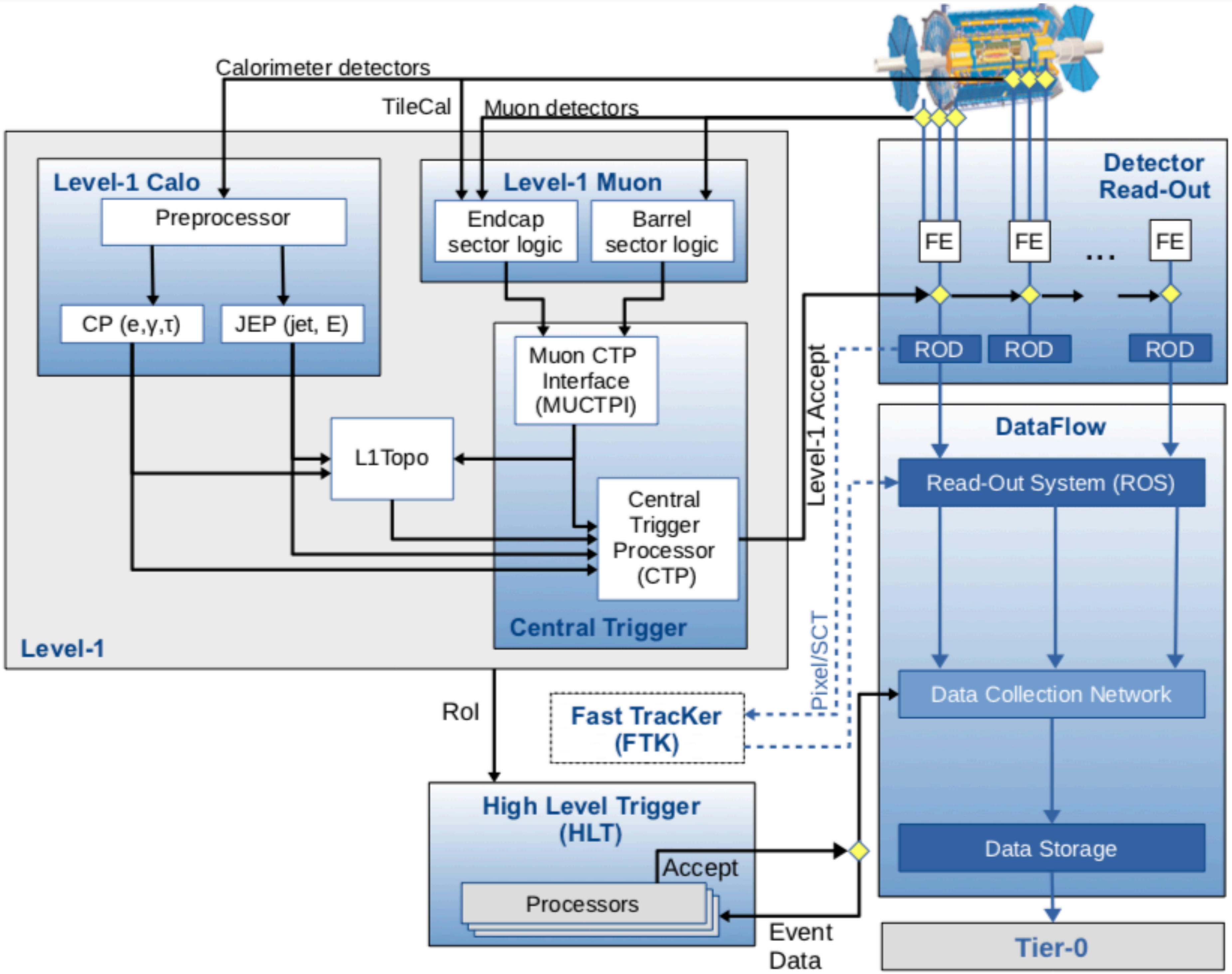
Triggers

Real-time analysis, in the CMS trigger

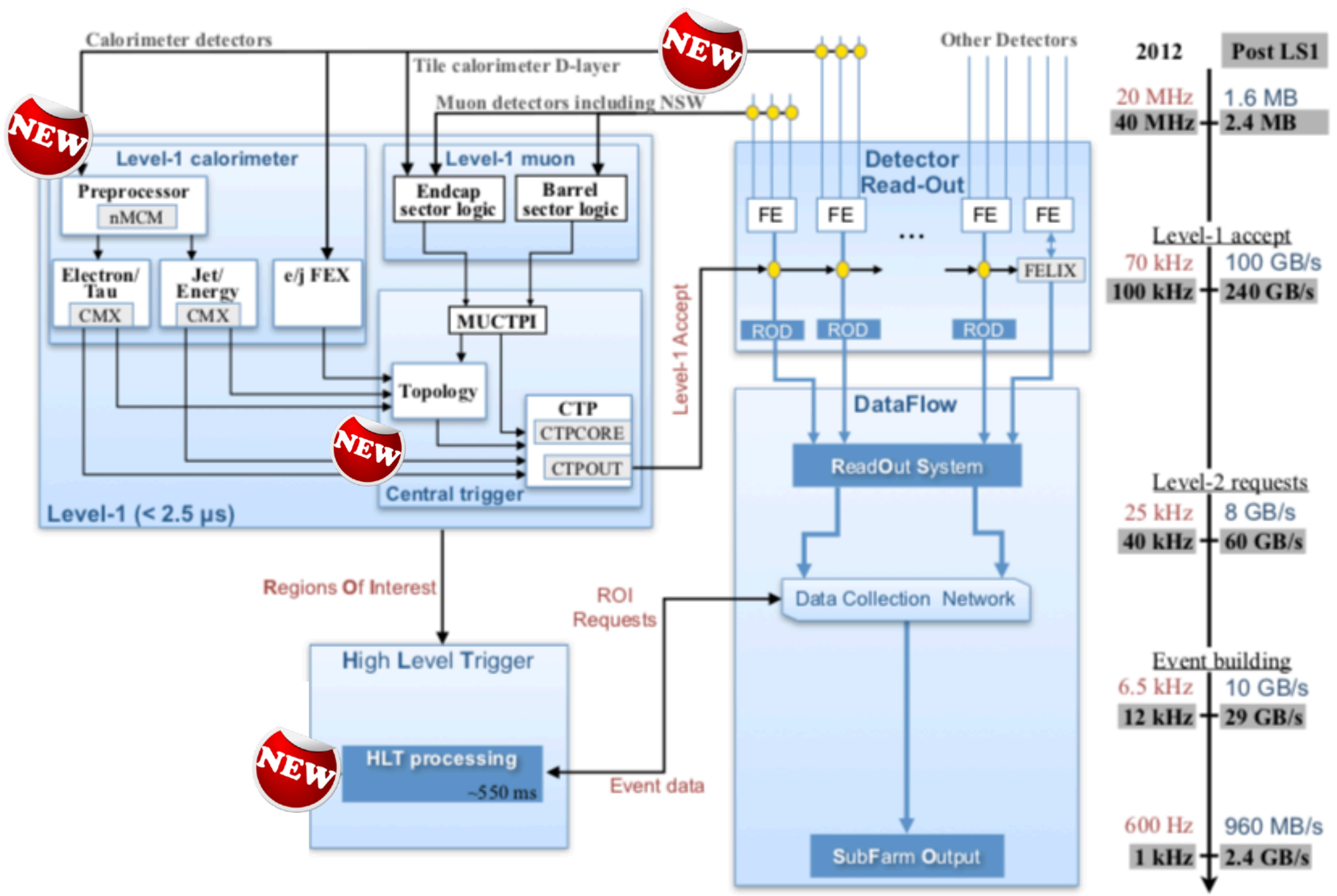
From a talk by Mia Tosi



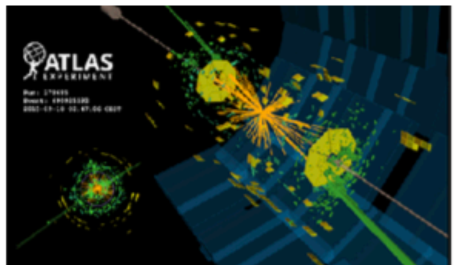
The ATLAS Run-2 trigger system

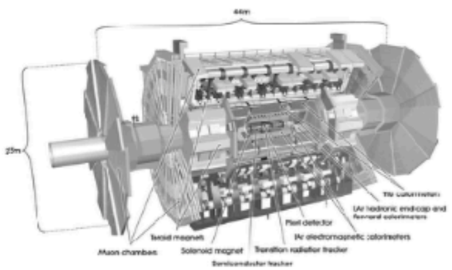


The ATLAS Run-3 trigger system



Where are the limitations to record (more) data?





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

Detector readout to hardware trigger

L1 hardware trigger

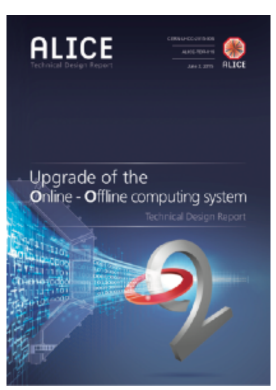
CPU for processing events

Disk/tape to store events

Generally triggering on what we know about / what we expect

For Run-3, see e.g. LHCb and ALICE

For ideas, see e.g. this talk by M. Pierini



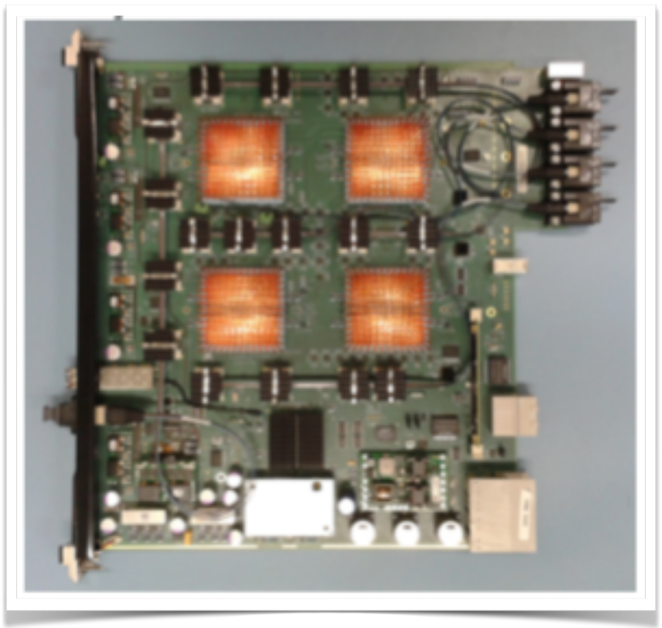
LHCB-TDR-016 ALICE-TDR-019

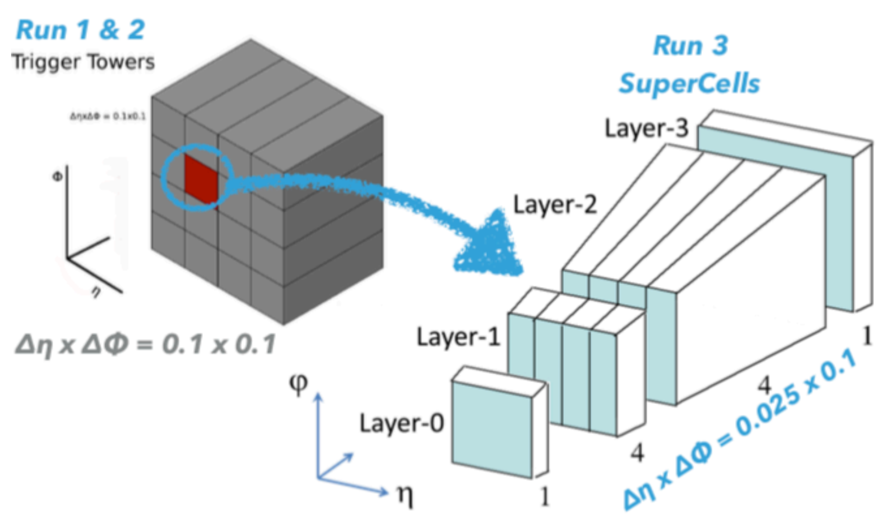
Topics deferred to HL-LHC and future experiments…

[some ideas from the Snowmass Instrumentation Frontier]

L1Calo for electrons and photons: *eFEX*

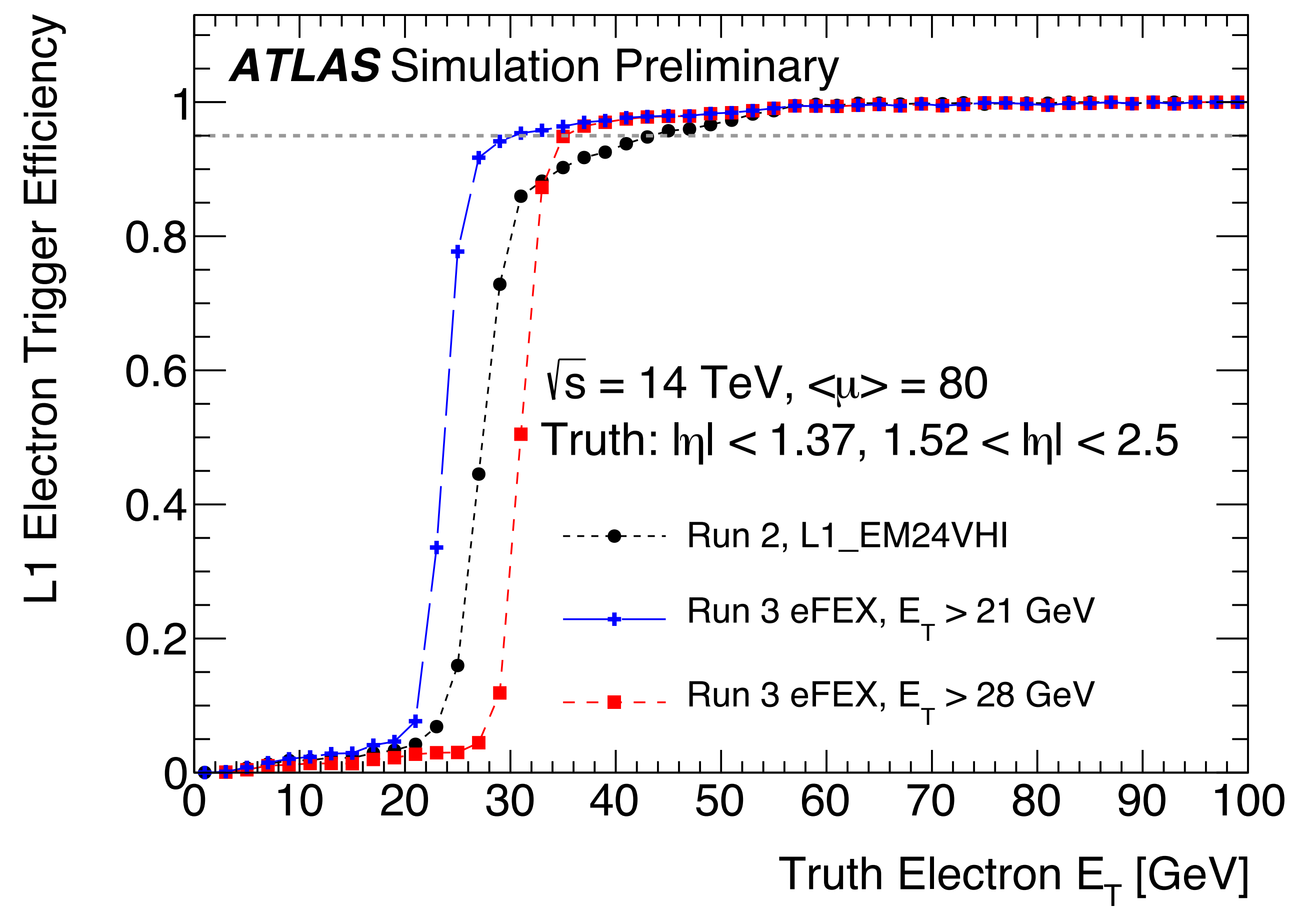
ATL-DAQ-SLIDE-2020-310





- More granular input for electron and photon identification in Run-3
  - Can be used for more sophisticated algorithms

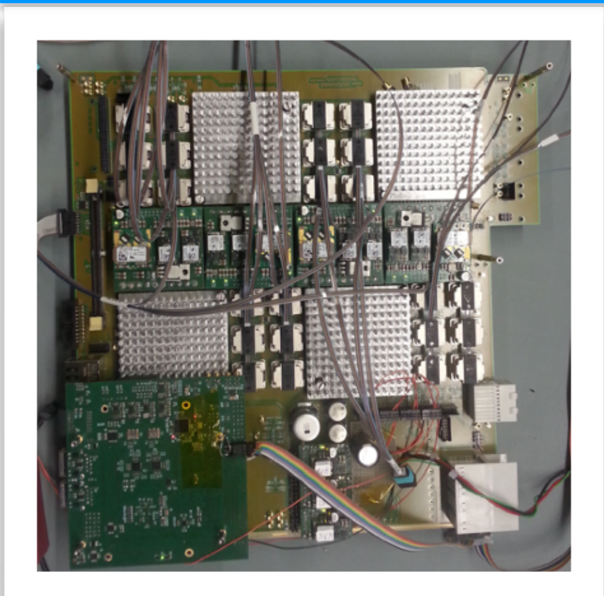
ATL-COM-DAQ-2018-019

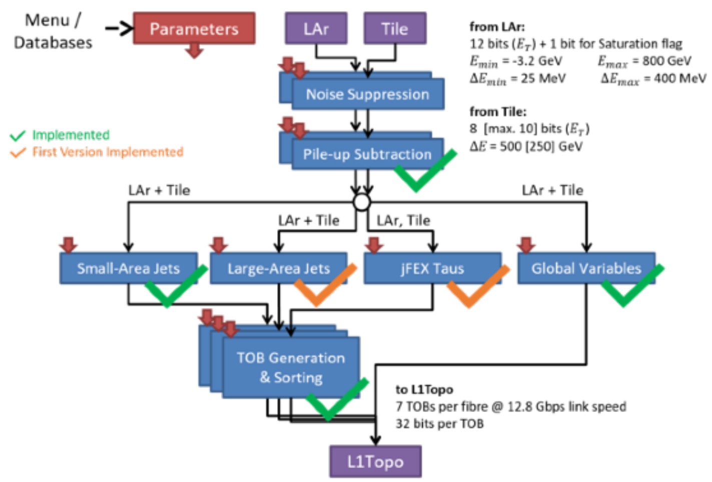


- Much "steeper" turn-ons for Run-3
  - Improves the rate of useful events
- Trigger rate depends on threshold
  - Run-3 L1 21 GeV threshold leads to same event rate as 24 GeV Run-2 L1 threshold
  - ET>28 GeV has half the rate as ET>28 GeV

L1Calo for jets, MET and taus: *jFEX*

ATL-DAQ-SLIDE-2020-135

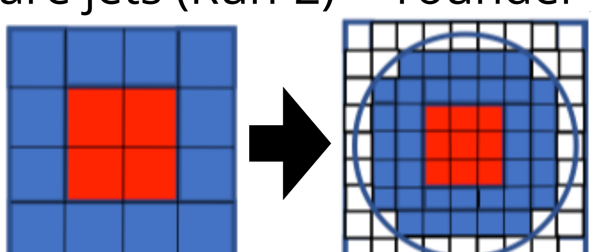




Board prototype, from arXiv:1806.09207

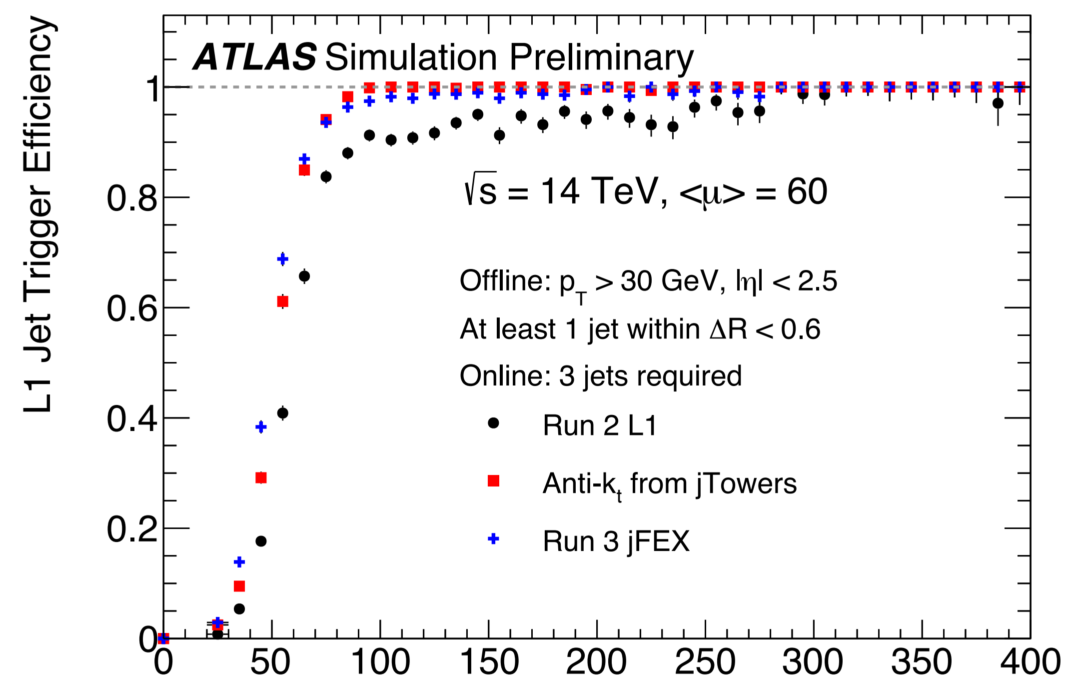
- Used to trigger on jets, MET and hadronic taus
  - Inputs: calorimeter towers

- Improvements with respect to Run-2: more refined algorithms, e.g.
  - square jets (Run-2) →rounder jets (Run-3)

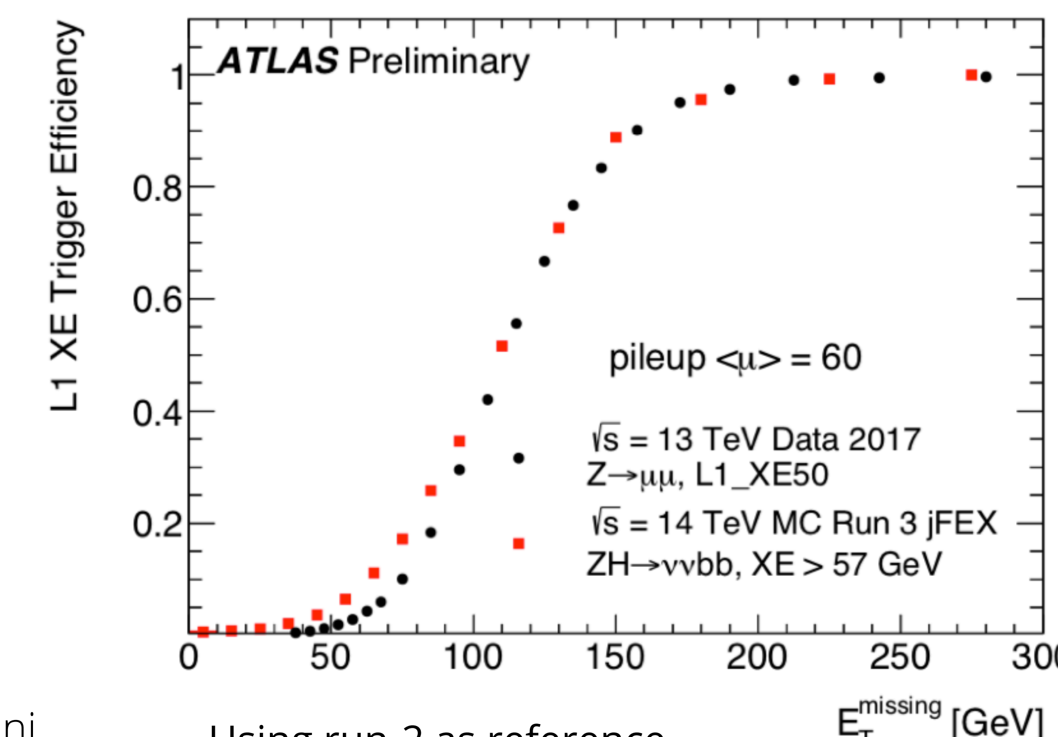


  - improved pile-up mitigation
    - use custom noise thresholds on inputs
    - MET calculated after average energy subtraction

HH → 4b, with close-by jets

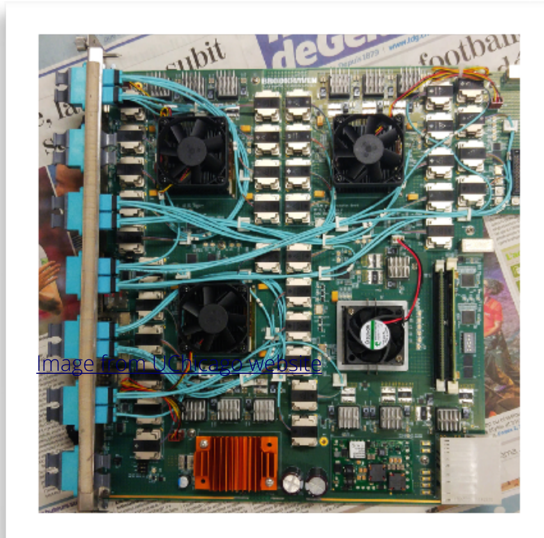


ATL-COM-DAQ-2018-019

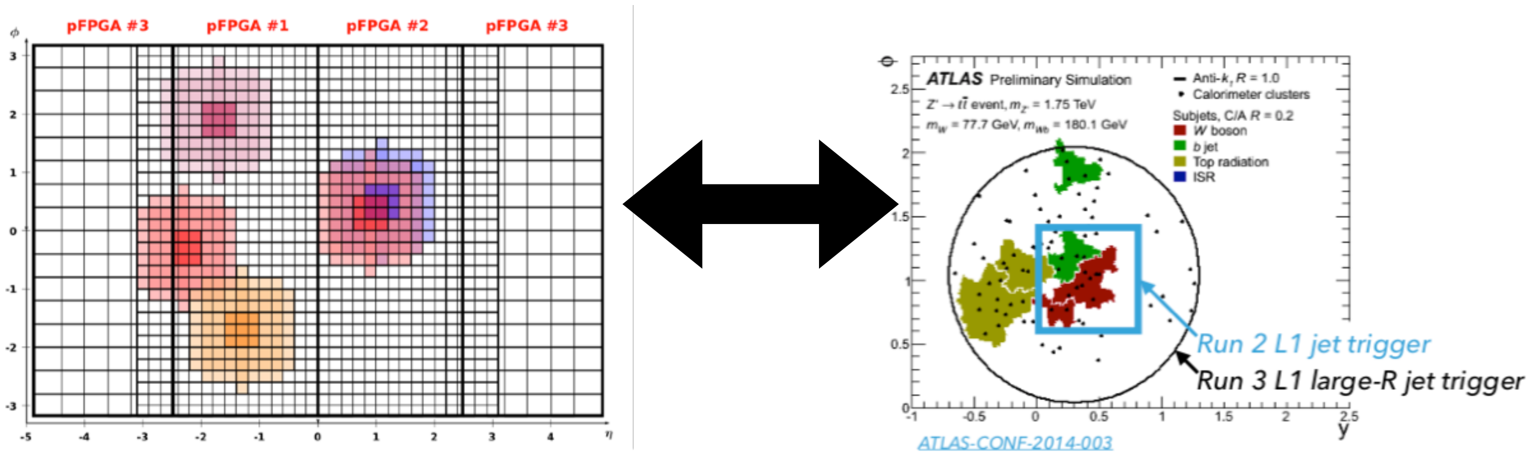


Using run-2 as reference

L1Calo for large-R jets and MET: *gFEX*

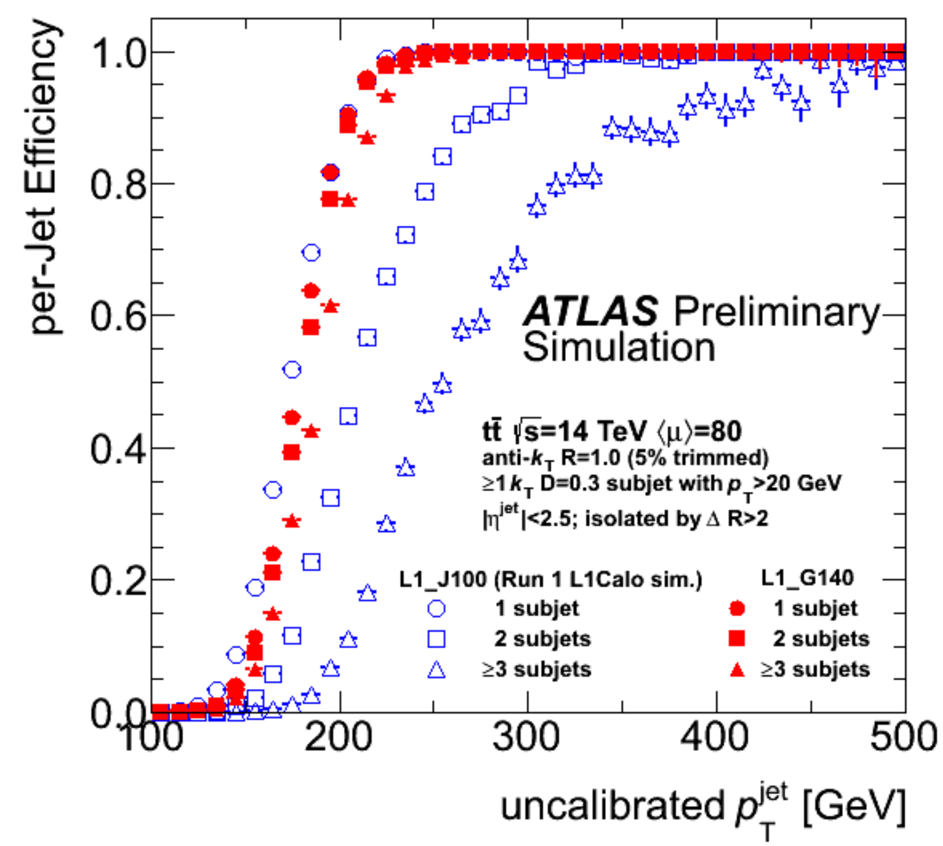


- Inputs to the board: coarse towers from **entire calorimeter**
  - Ideal for large-R jet identification



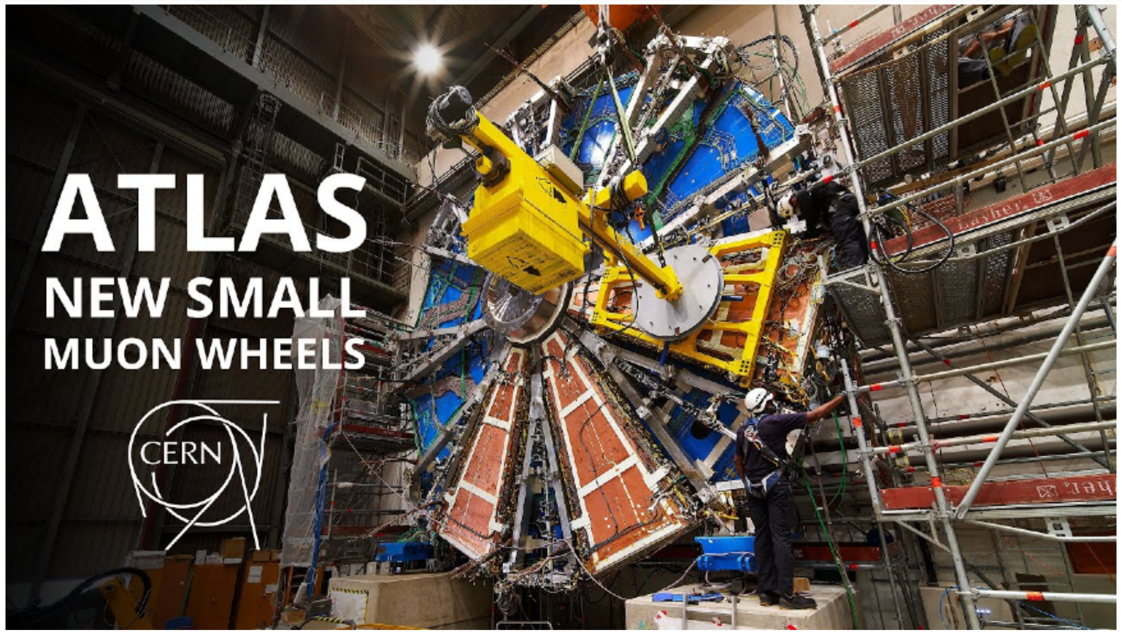
  - Full-scan algorithms can be used for event-level quantities (e.g. pile-up density)

Boosted top simulation



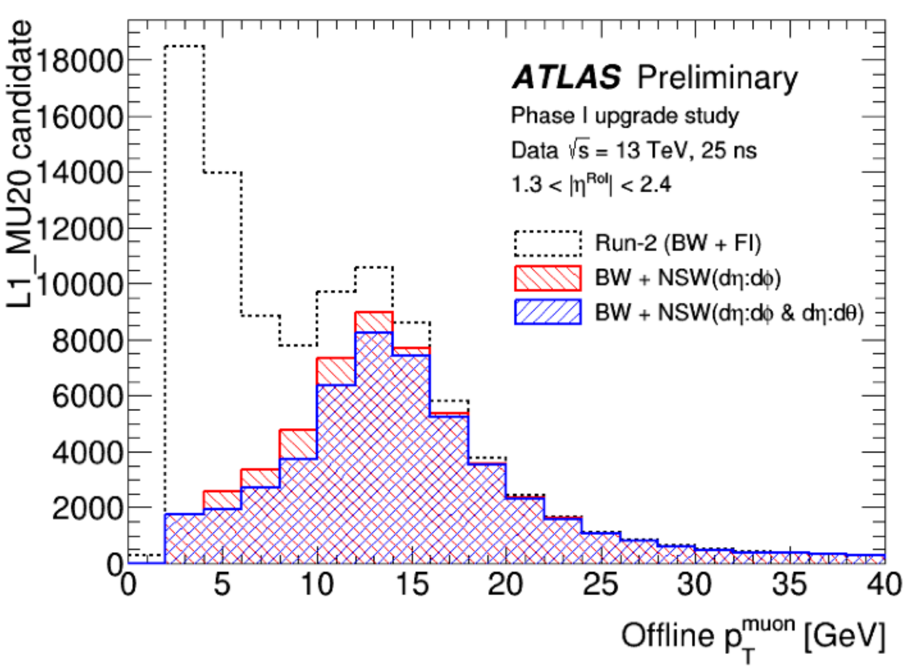
More efficient triggering on large-R jets-with-subjets (with gFEX) than Run-2 (standard square jets)

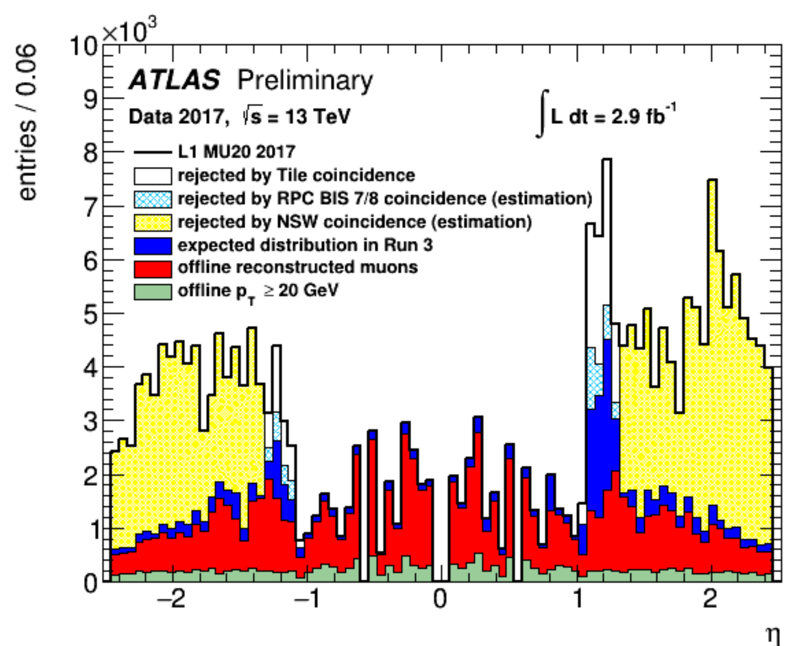
Muon triggers and the New Small Wheels (NSW)



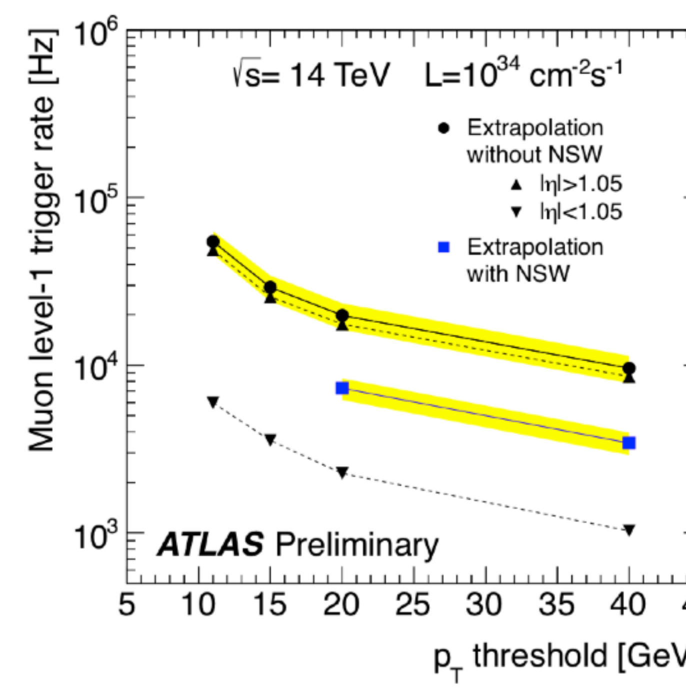
- Significant trigger rate from endcap muon detector
- Replace forward muon detectors with improved New Small Wheels
- NSW playing significant role in Run-3 triggers

Better identification of "real" low-pT muons using coincidences
L1MuonTriggerPublicResults





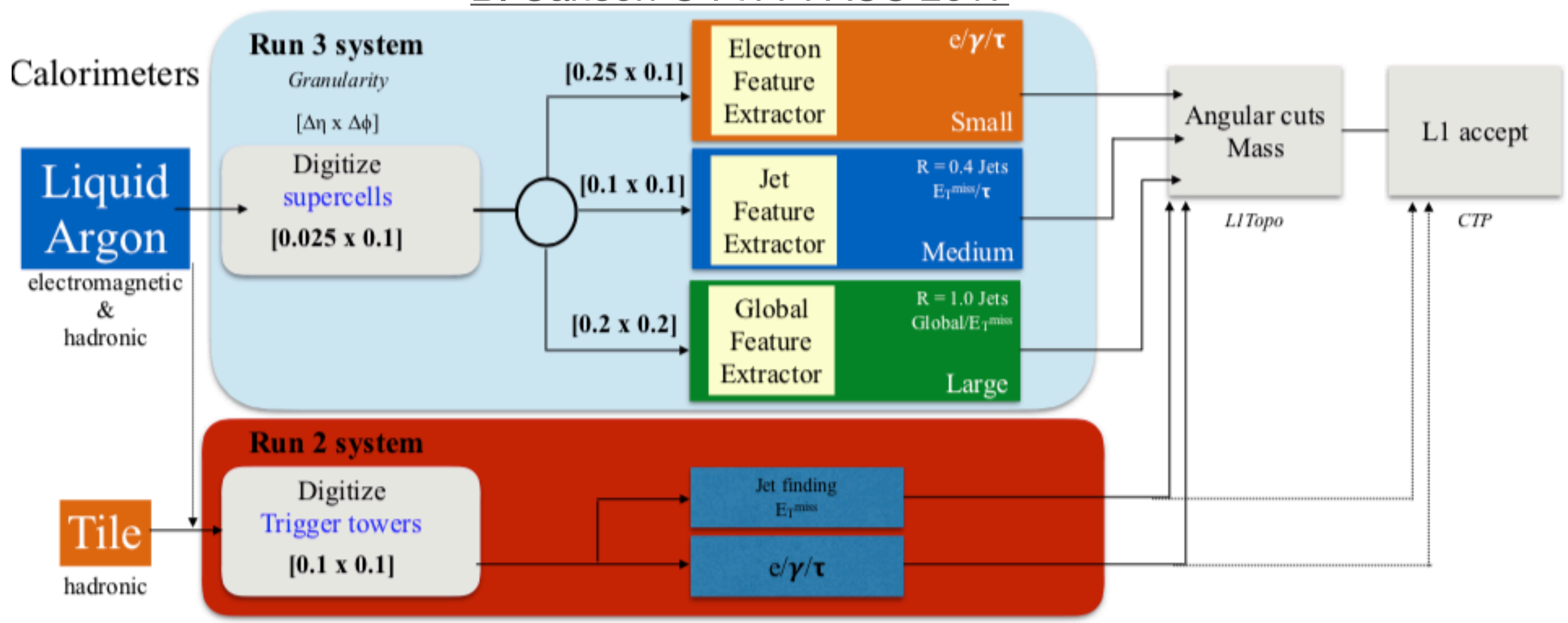
Lower rate → lower thresholds
MuonTriggerPublicResults



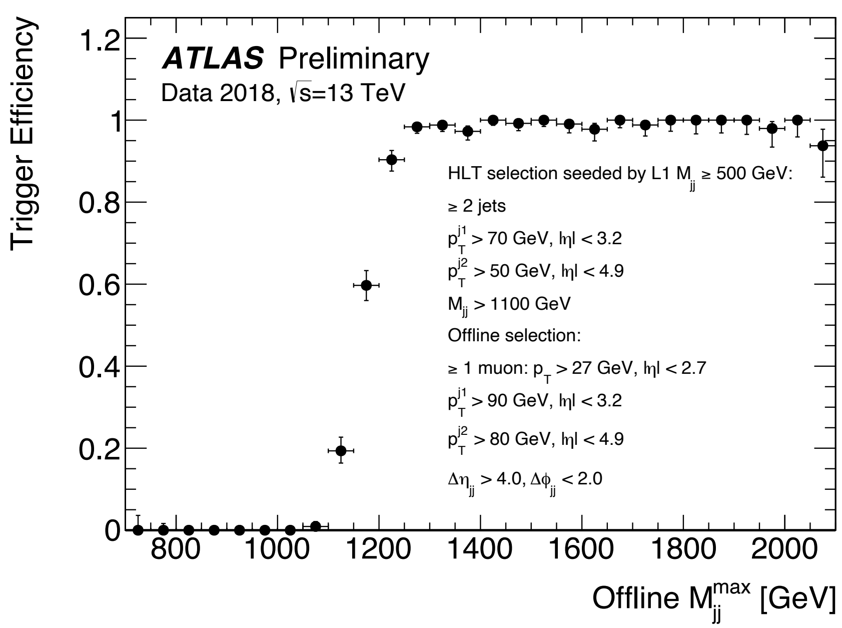
L1 trigger combinations: L1Topo

L1Topo: trigger board to combine L1 objects in multi-object and topological algorithms

B. Carlson @ PITT-PACC 2017



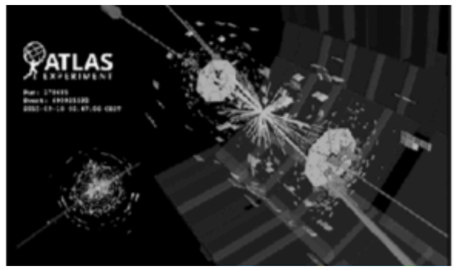
*muons not shown

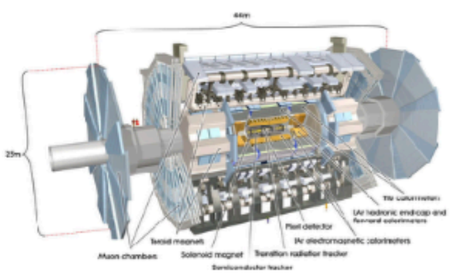


- Case of **VBF topologies**: can select large-dijet- mass events already at the hardware level
- Can also be tailored towards e.g. measurements / searches in the forward region

TriggerOperationPublicResults

Where are the limitations to record (more) data?





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

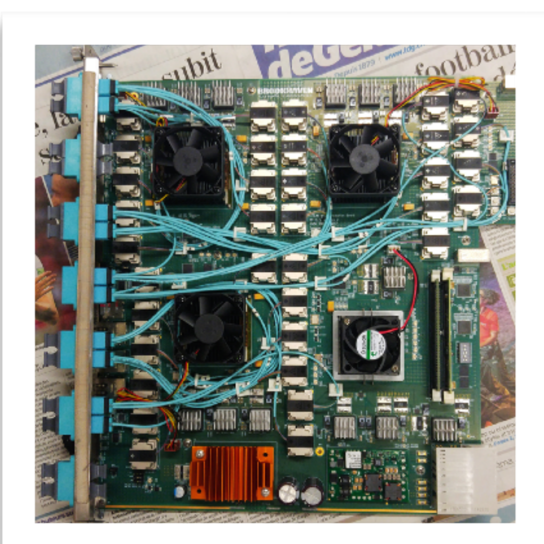
Detector readout to hardware trigger

L1 hardware trigger
reconstruction & identification of physics object in hardware → rates

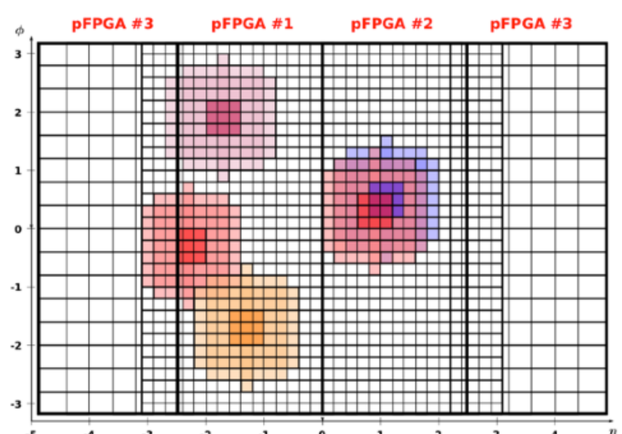
CPU for processing events

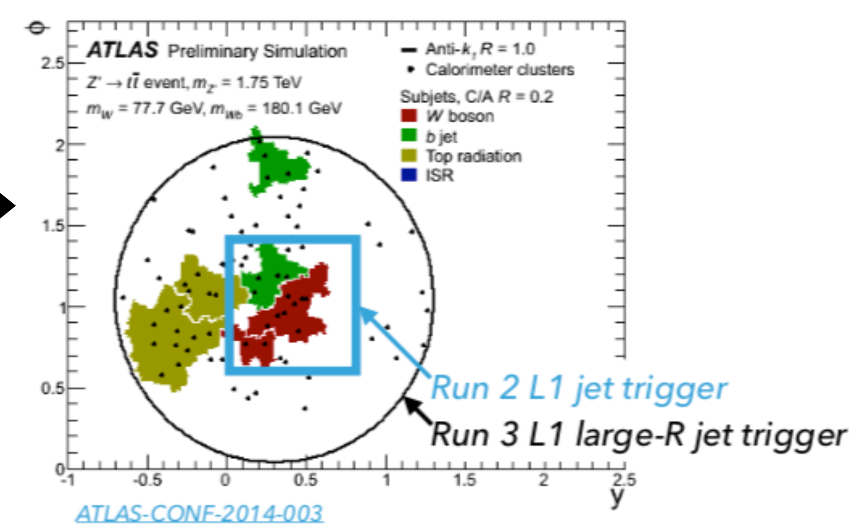
Disk/tape to store events

Example of Run-3 improvement:
UChicago-led **gFEX board**



- Inputs to the board: coarse towers from **entire calorimeter**
  - Ideal for large-R jet identification





ATLAS-CONF-2014-003

- Full-scan algorithms can be used for event-level quantities (e.g. pile-up density)

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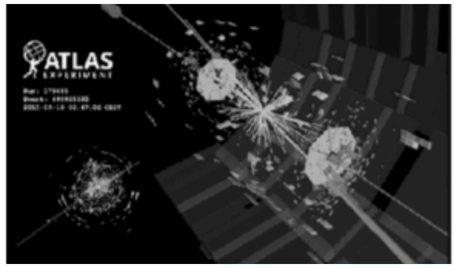
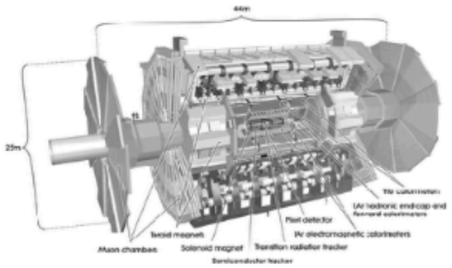
Where are the limitations to record (more) data?



Detector readout to hardware trigger



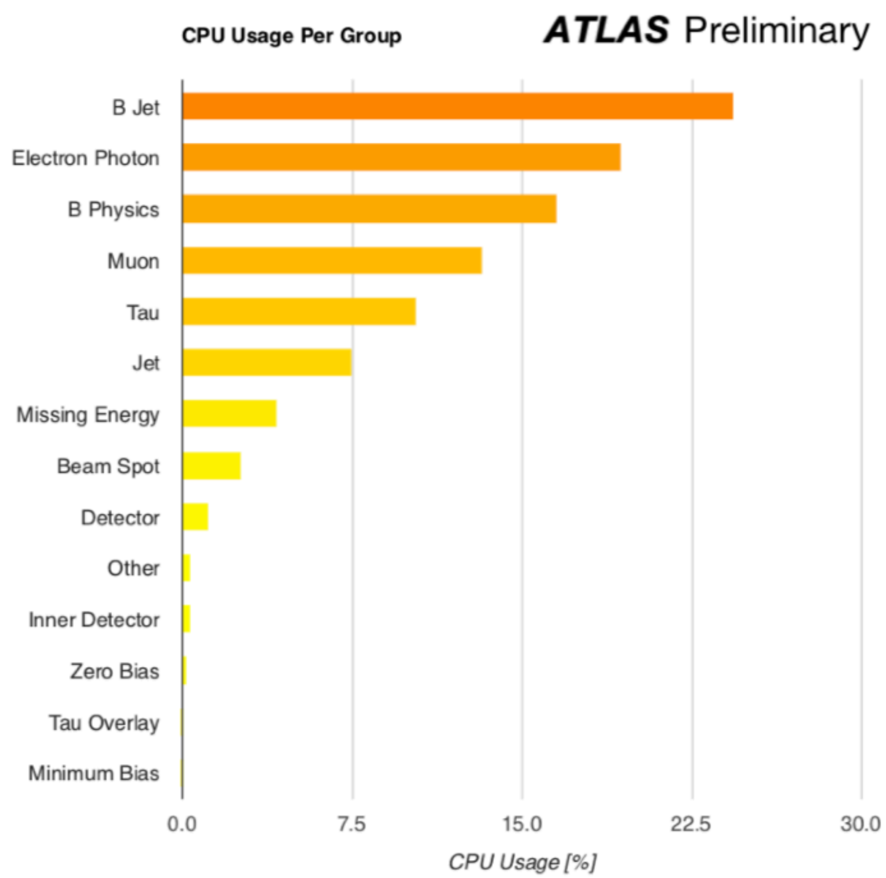
L1 hardware trigger

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

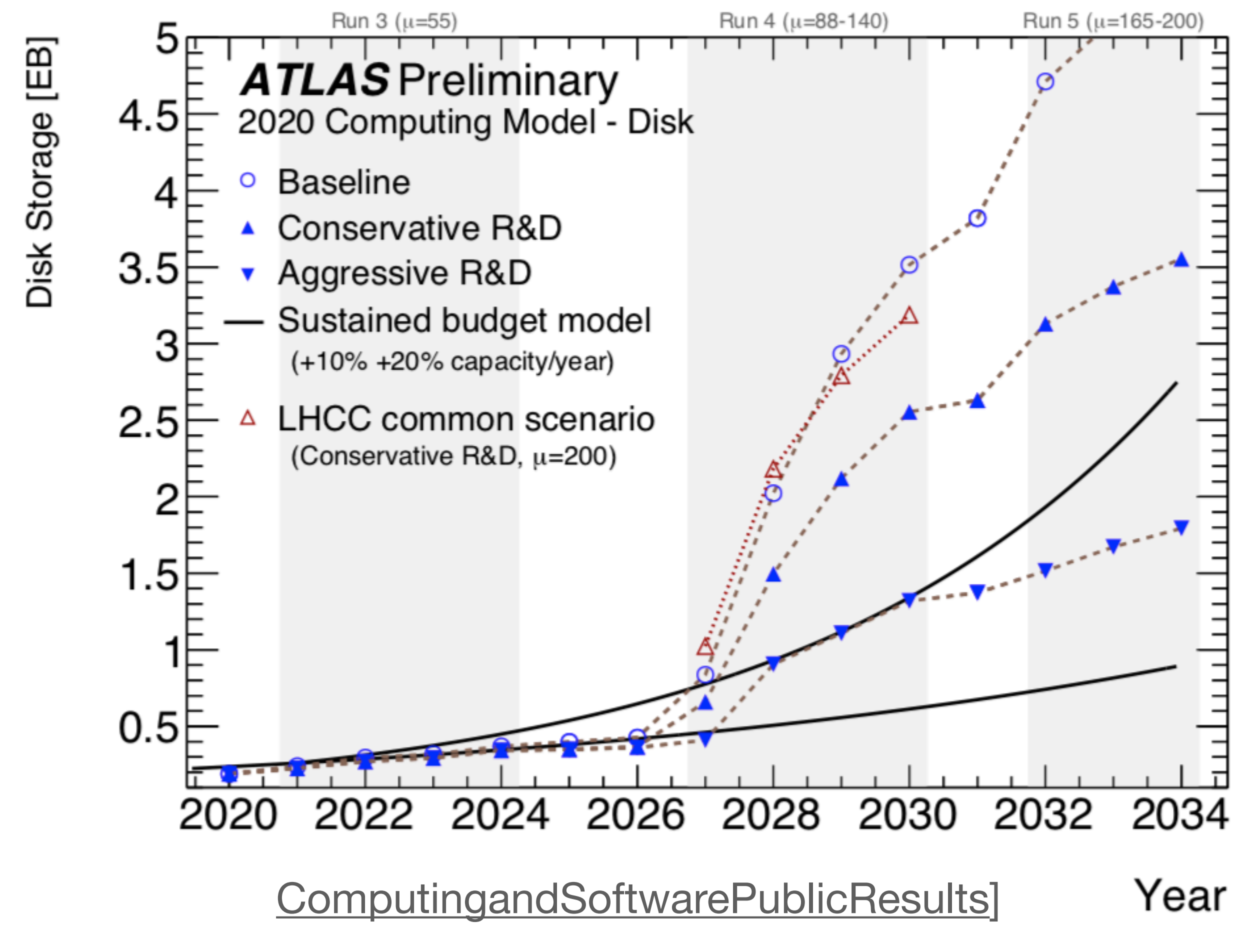
CPU for processing events
large but limited processing power

Disk/tape to store events

Example of CPU consumers in current trigger system

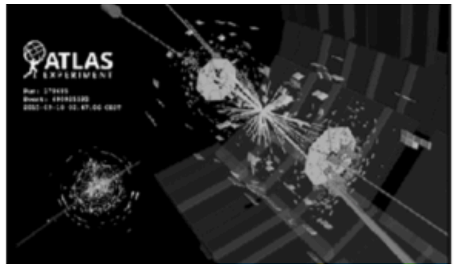


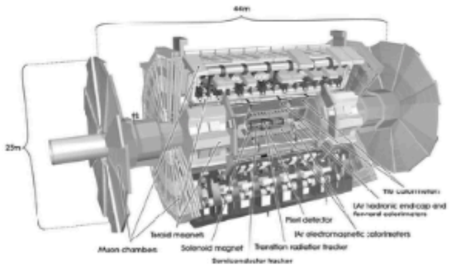
Data storage estimate
(dominated by simulation, but everything helps)



ComputingandSoftwarePublicResults]

Where are the limitations to record (more) data?





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

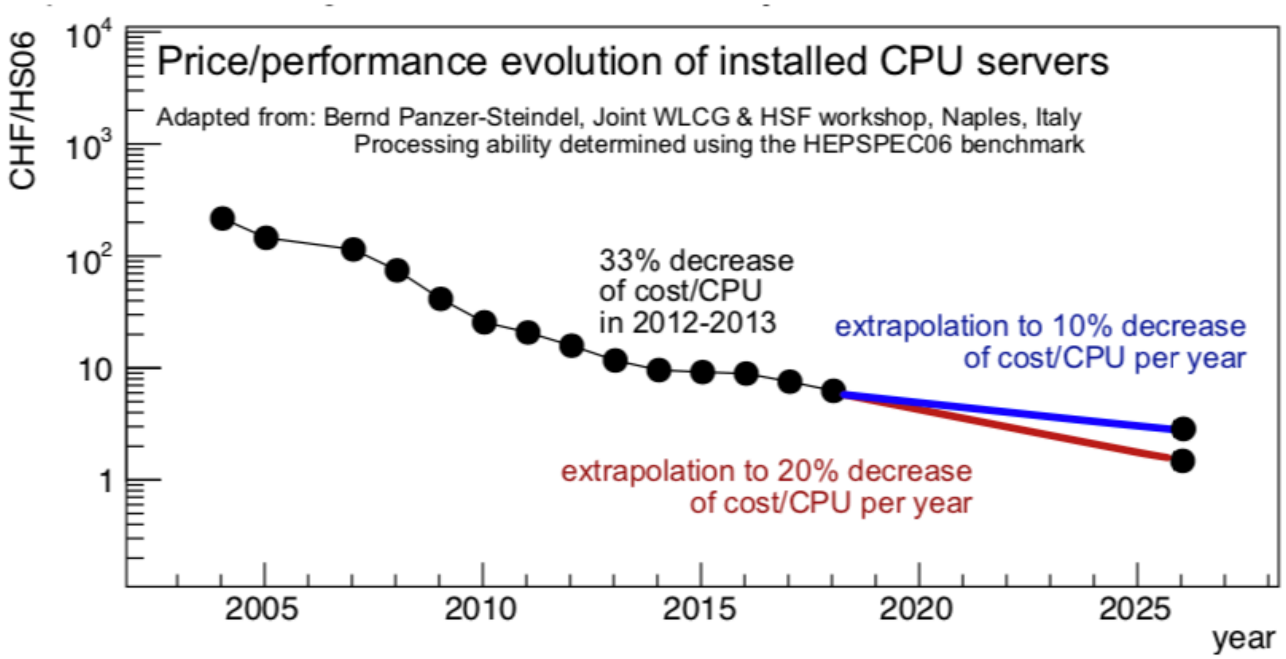
Detector readout to hardware trigger

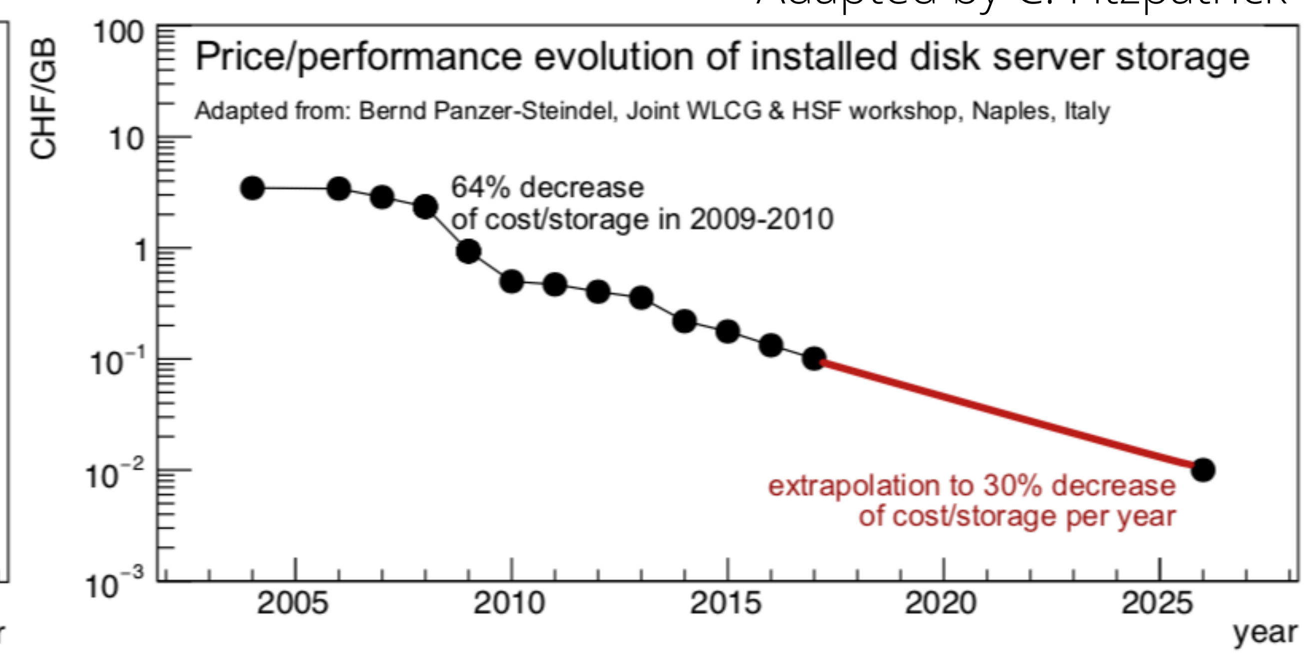
L1 hardware trigger

CPU for processing events
large but limited processing power

Disk/tape to store events

Adapted by C. Fitzpatrick





Only **moderate improvement** in price/performance evolution of CPU and disk servers

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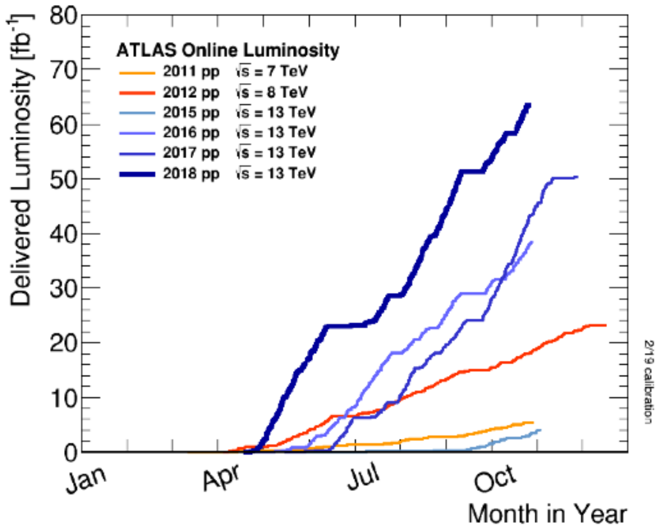
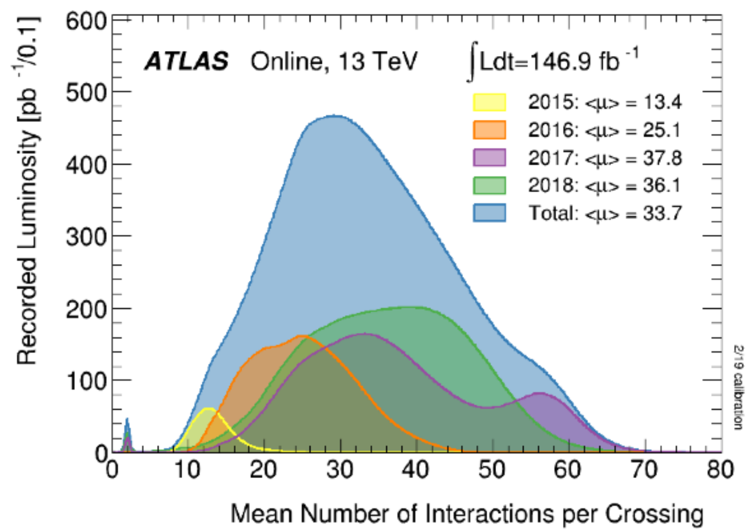
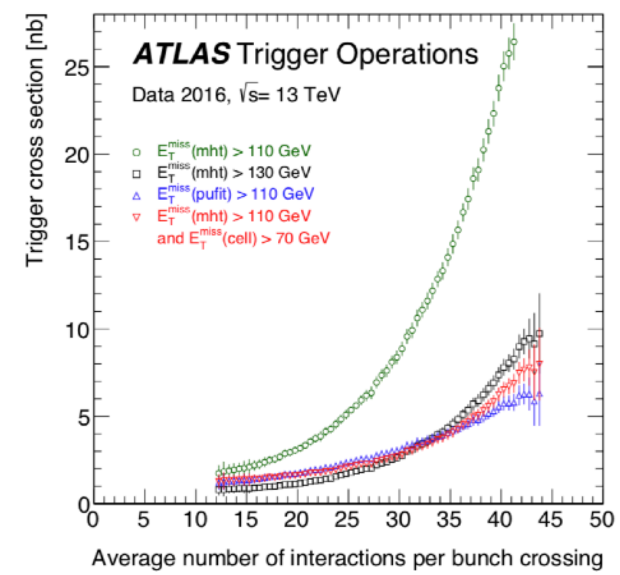
Pile-up (and tracking)

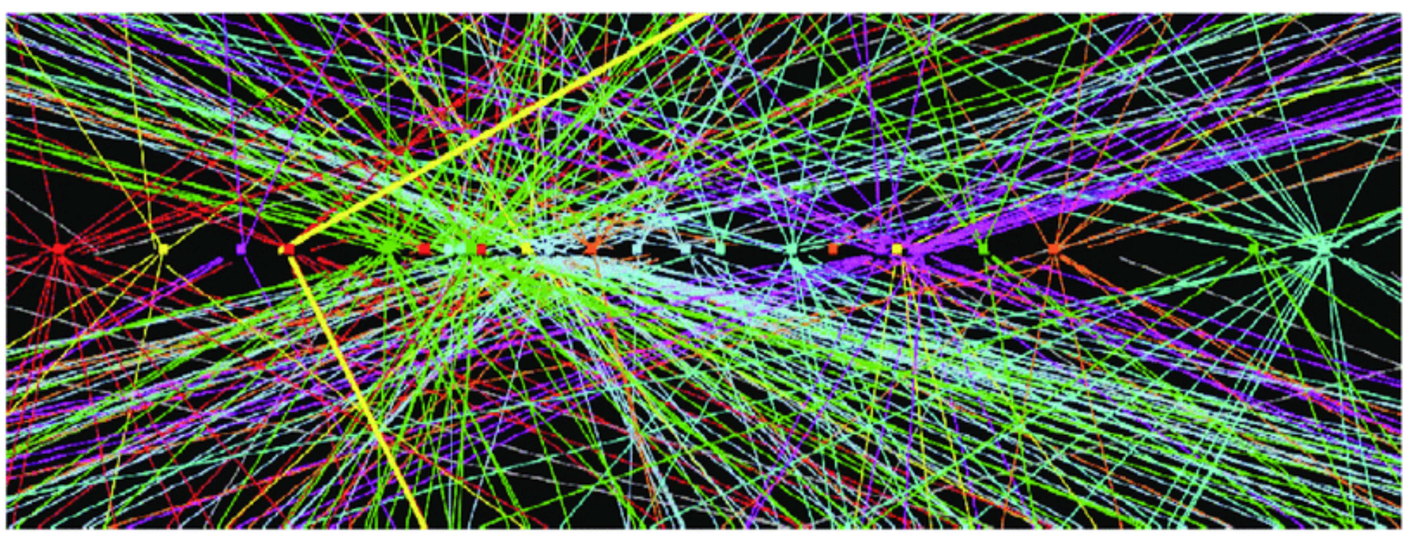
Increase in dataset size means increase in instantaneous luminosity
→ increased number of simultaneous interactions / beam crossing → pile-up → higher trigger rates







Trigger and data acquisition systems are designed to be as robust as possible to increased pile-up



How to meet the pile-up challenge:

- **Software tracking**
  - Challenge: computationally expensive
    FTK paper: arXiv:2101.05078 accepted by JINST
- **Detector timing**
  - Challenge: precision / simulation
  - (Not covered in this talk)

Design and optimization of software tracking

ATL-COM-DAQ-2020-104

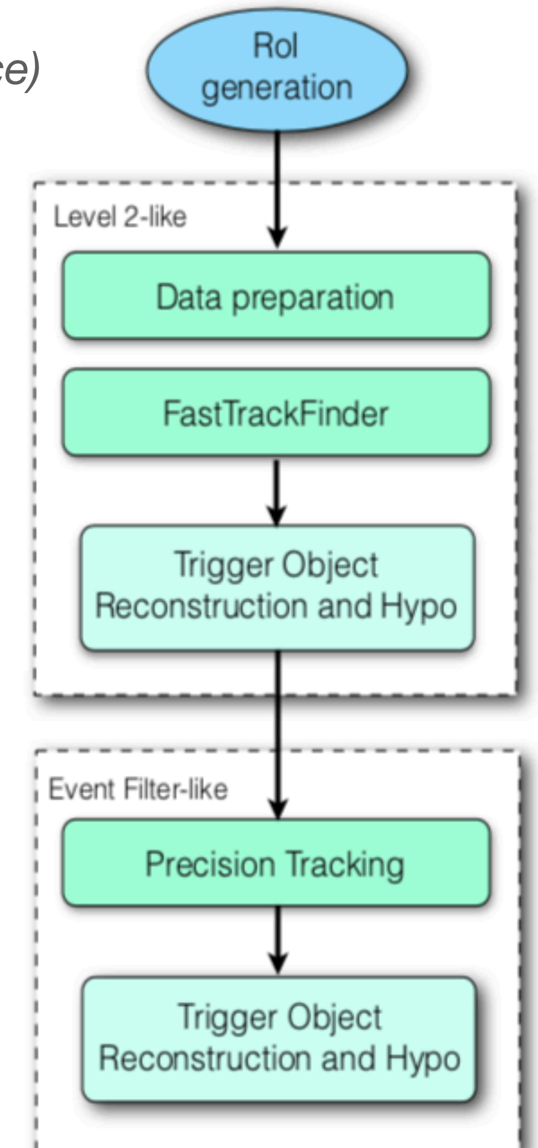
(only prepare data once)

Fast tracking step

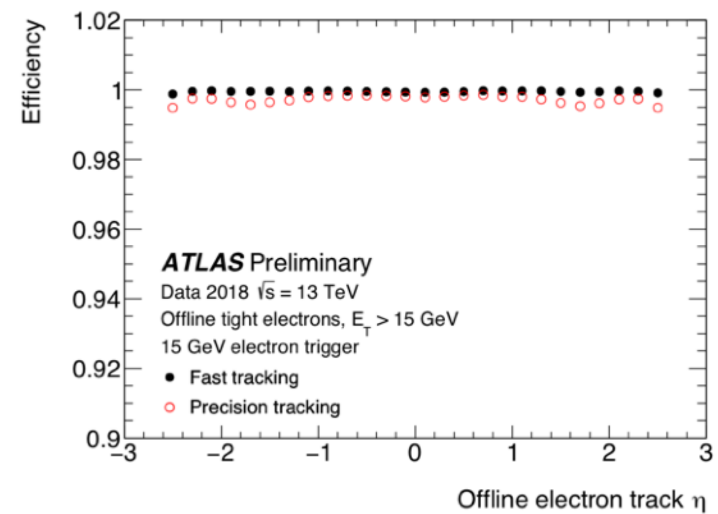
can reject early

input to

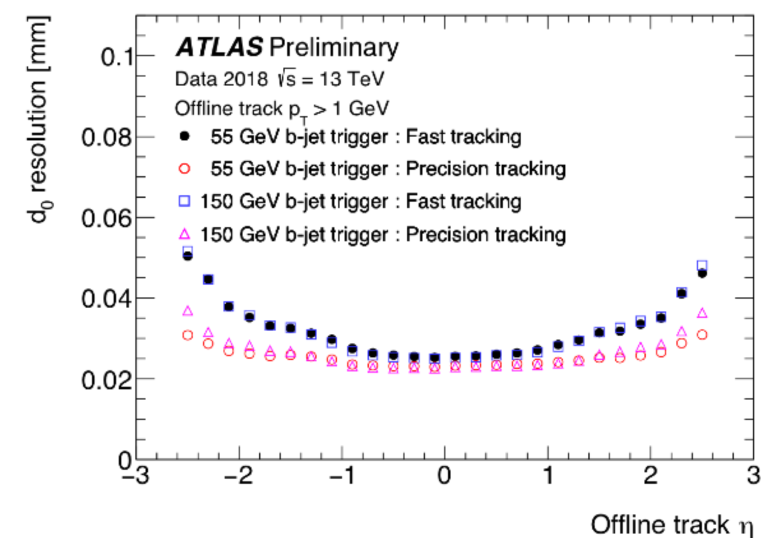
Precision tracking step



Fast tracking sufficient for e.g. object identification



Precision tracking needed for e.g. *b*-jet tagging



ATL-COM-DAQ-2020-059

- Rewriting of software tracking for Run-3 currently ongoing *[no public results yet]*
  - Improvements to offline tracking also included
  - Machine learning-based improvements: see next slide

On track to have **high-rate *full-scan tracking*** to be used in reconstruction of HLT objects (including long-lived signatures) & non-standard workflows

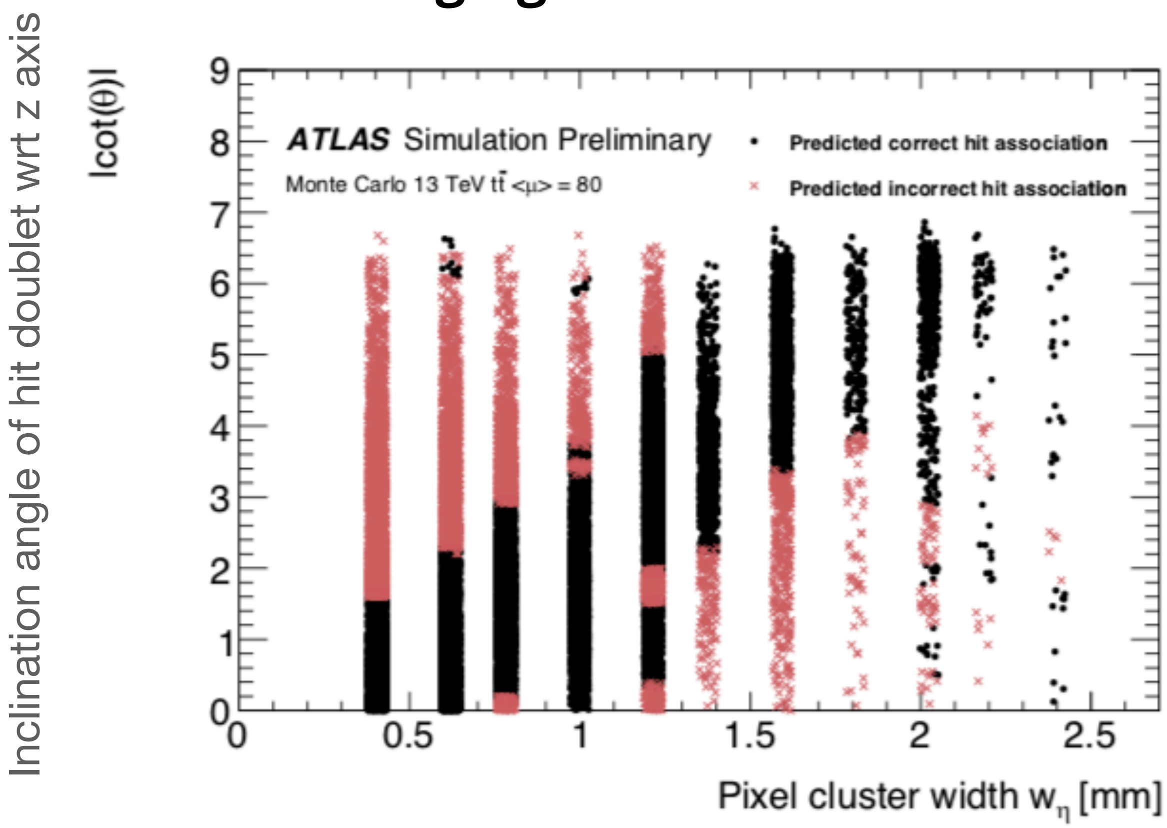
European Research Council
Established by the European Commission

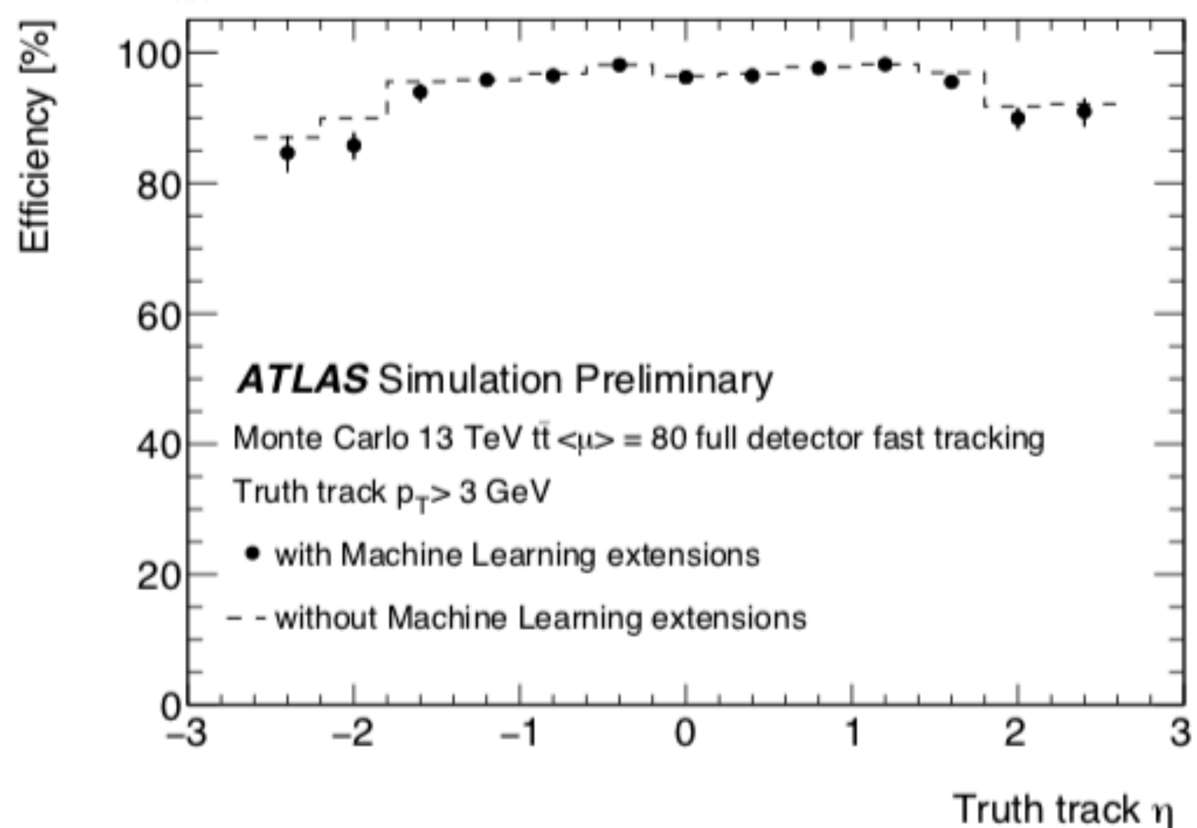
Further improvements: machine learning

ATL-COM-DAQ-2021-003

CPU time grows linearly with the number of tracking seeds (due to combinatorics)
→ reduce the number of fake seeds as soon as possible

ML algorithm
(Classifier based on Kernel Density Estimator)
can predict **probability of pair of hits belonging to the same track**



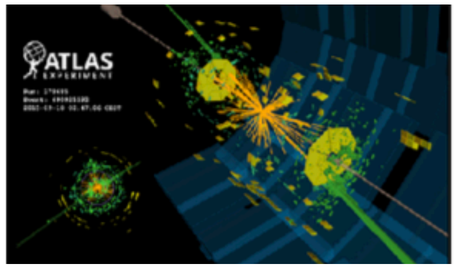


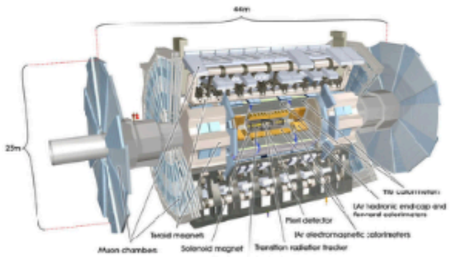
Total Speed-up Factor	Seed Generation	Seed Processing	Track Fitting
2.3×	1.3×	3.3×	1.5×

$<\mu>$	Efficiency Loss (%)	Total Speed-up Factor
40	0.7	1.6×
60	0.7	2.1×
80	1.1	2.3×

For use in the trigger: trained predictor implemented in Look Up Tables (LUT)

Where are the limitations to record (more) data?





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

Detector readout — **L1** hardware trigger

limited detector readout rate to hardware trigger

CPU for processing events

large farm, but limited processing power

limited **Disk/tape** to store events

Intuitively,

a smaller data size (e.g. compressed)

could help reducing storage constraints

but the data flow in the trigger/readout system is constrained,

especially in the **hardware trigger (L1)**

⟹ data and ML model compression can also be useful at earlier stages!

*In this talk I'll focus on **data compression from the HLT onwards***

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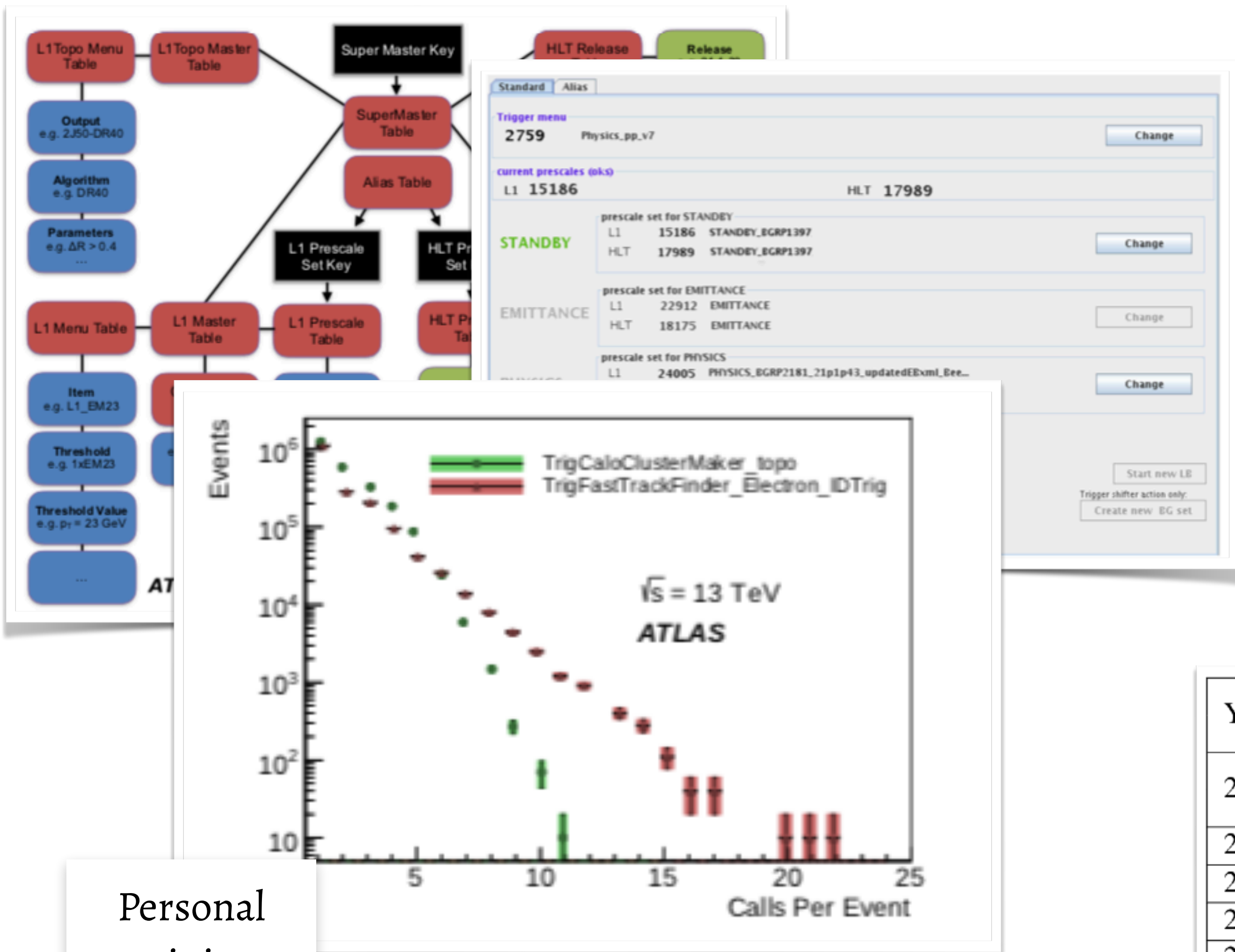
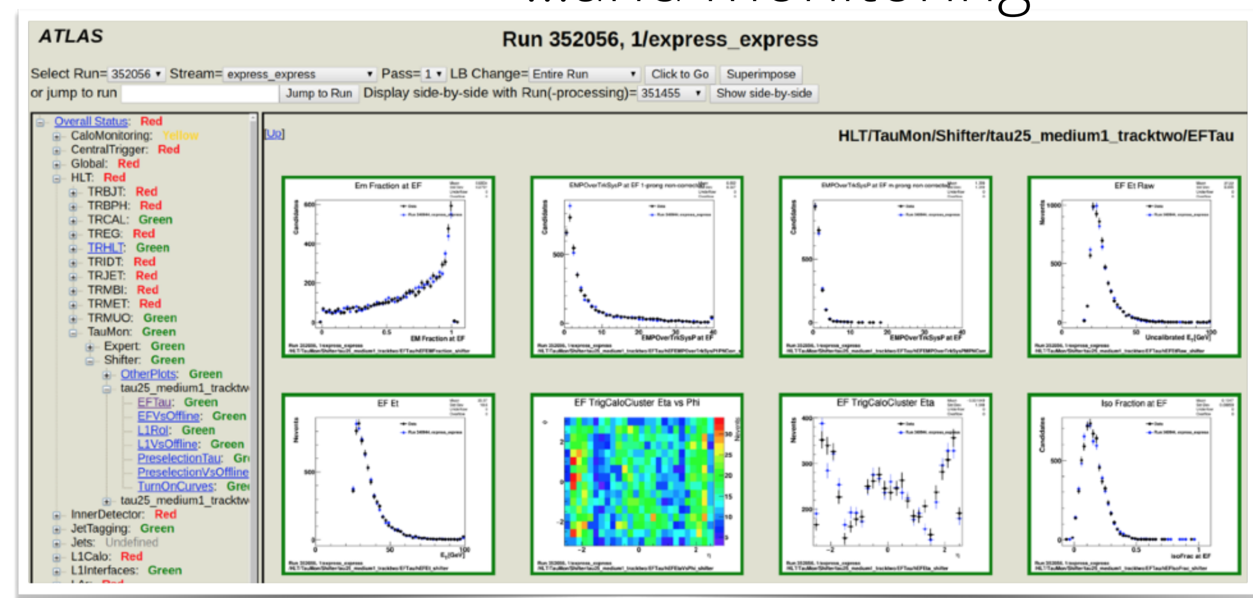
What is needed to operate the Run-3 trigger

Designing, implementing, operating…



…and monitoring



Year	Dataset	Trigger DQ Eff. L1 [%]	Trigger DQ Eff. HLT [%]	ATLAS DQ Eff. [%]	Integrated Luminosity of good quality data
2015	*pp* @ 13 TeV (50 ns)	100.00	99.94	88.77	84 pb^{-1}
	pp @ 13 TeV	99.97	99.76	88.79	3.2 fb^{-1}
2016	*pp* @ 13 TeV	98.33	100.00	93.07	33 fb^{-1}
2017	*pp* @ 13 TeV	99.95	99.96	95.67	44 fb^{-1}
2018	*pp* @ 13 TeV	99.99	99.99	97.46	59 fb^{-1}
2015–2018	*pp* @ 13 TeV	99.57	99.94	95.60	139 fb^{-1}

arXiv:2007.12539, submitted to JINST

Personal opinion

Run-3 temptation: *"I'll get a hobby until we collect the entire dataset"*

In order to make the most of the Run-3 data, we need to make sure we dedicate enough experimentalist's time & funding & career prospects to technical / performance work

The ATLAS trigger menu in Run-2

Trigger menu decided in advance of data taking period: example for 2018

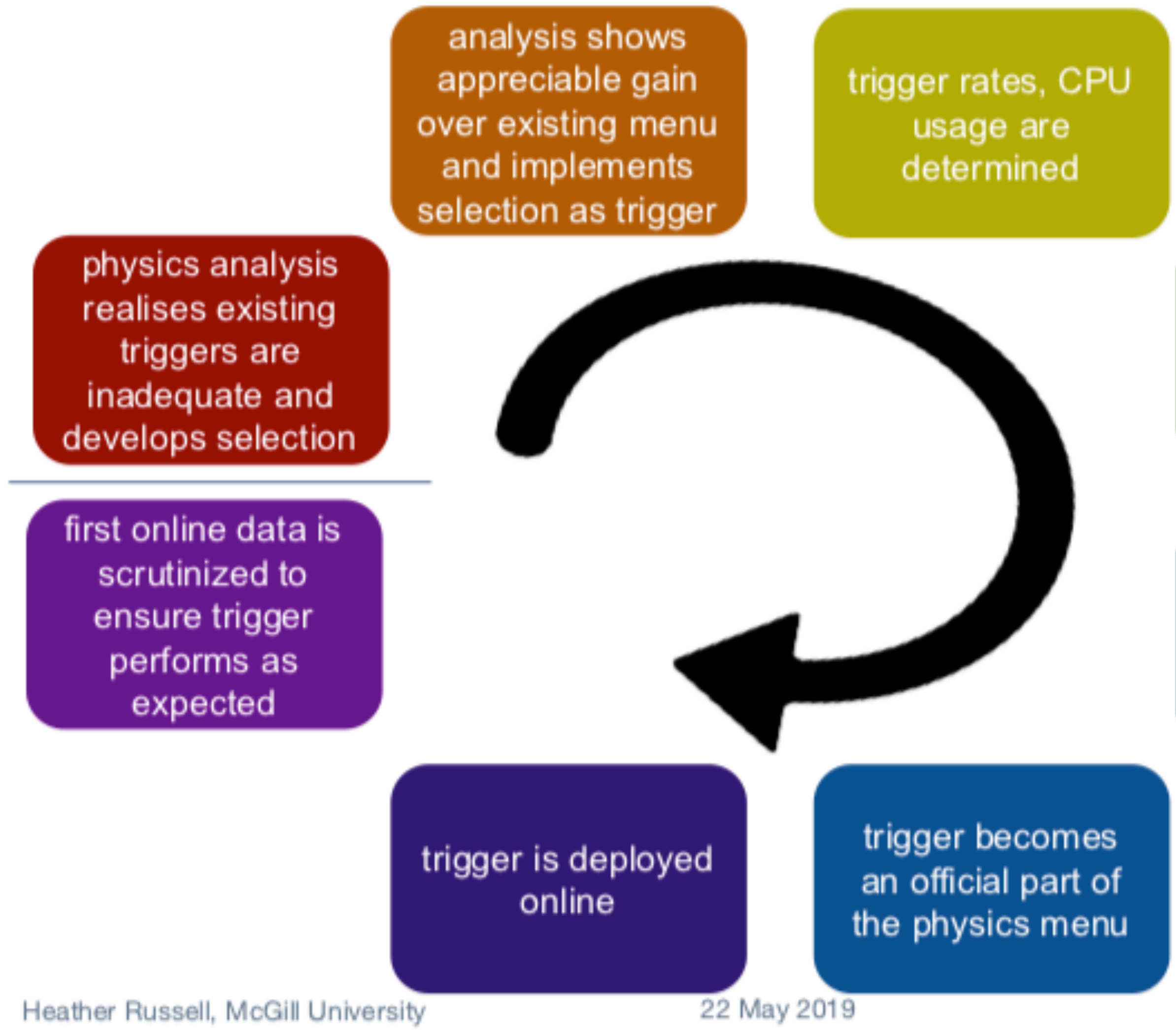
Trigger	Typical offline selection	Trigger Selection		L1 Peak Rate [kHz]	HLT Peak Rate [Hz]
		L1 [GeV]	HLT [GeV]	$L=2.0\times10^{34}$ $cm^{-2}s^{-1}$	
Single leptons	Single isolated μ, $p_T > 27$ GeV	20	26 (i)	16	218
	Single isolated tight e, $p_T > 27$ GeV	22 (i)	26 (i)	31	195
	Single μ, $p_T > 52$ GeV	20	50	16	70
	Single e, $p_T > 61$ GeV	22 (i)	60	28	20
	Single τ, $p_T > 170$ GeV	100	160	1.4	42
Single photon	One loose γ, $p_T > 145$ GeV	24 (i)	140	24	47
Single jet	Jet ($R = 0.4$), $p_T > 435$ GeV	100	420	3.7	35
	Jet ($R = 1.0$), $p_T > 480$ GeV	111 (topo: $R = 1.0$)	460	2.6	42
	Jet ($R = 1.0$), $p_T > 450$ GeV, $m_{jet} > 45$ GeV	111 (topo: $R = 1.0$)	420, $m_{jet} > 35$	2.6	36

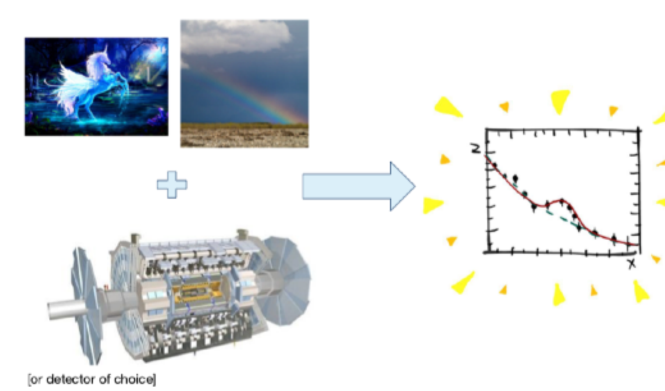
TRIG-2019-04, ATL-DAQ-PUB-2019-001

- More or less flexible to adjustments (changes need very good reasons!)
  - Follows priorities dictated by experiment's physics strategy
  - Algorithms for object identification/selection also make use of machine learning

There will be new triggers...

All graphics from H. Russell's slides, HEP Software Foundation Trigger & Reco WG, 2019

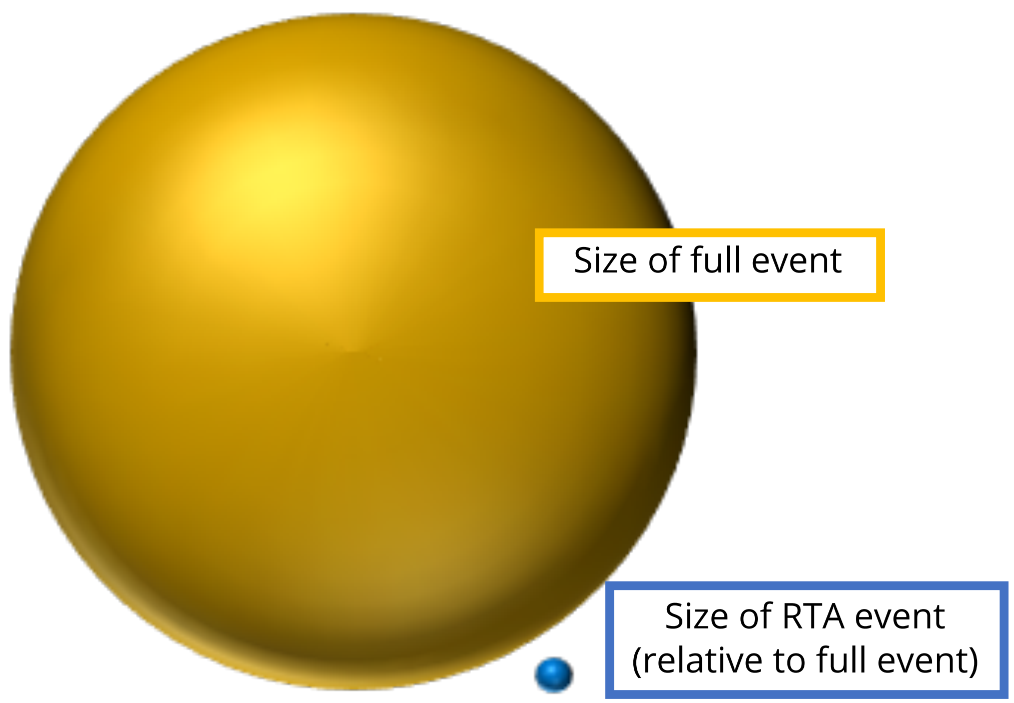




Now is the time to request trigger to record data in Run-3!
(good physics motivations & theory/experimental cross-talk always welcome)

Overcoming storage (and CPU) bottlenecks

Save many more smaller events

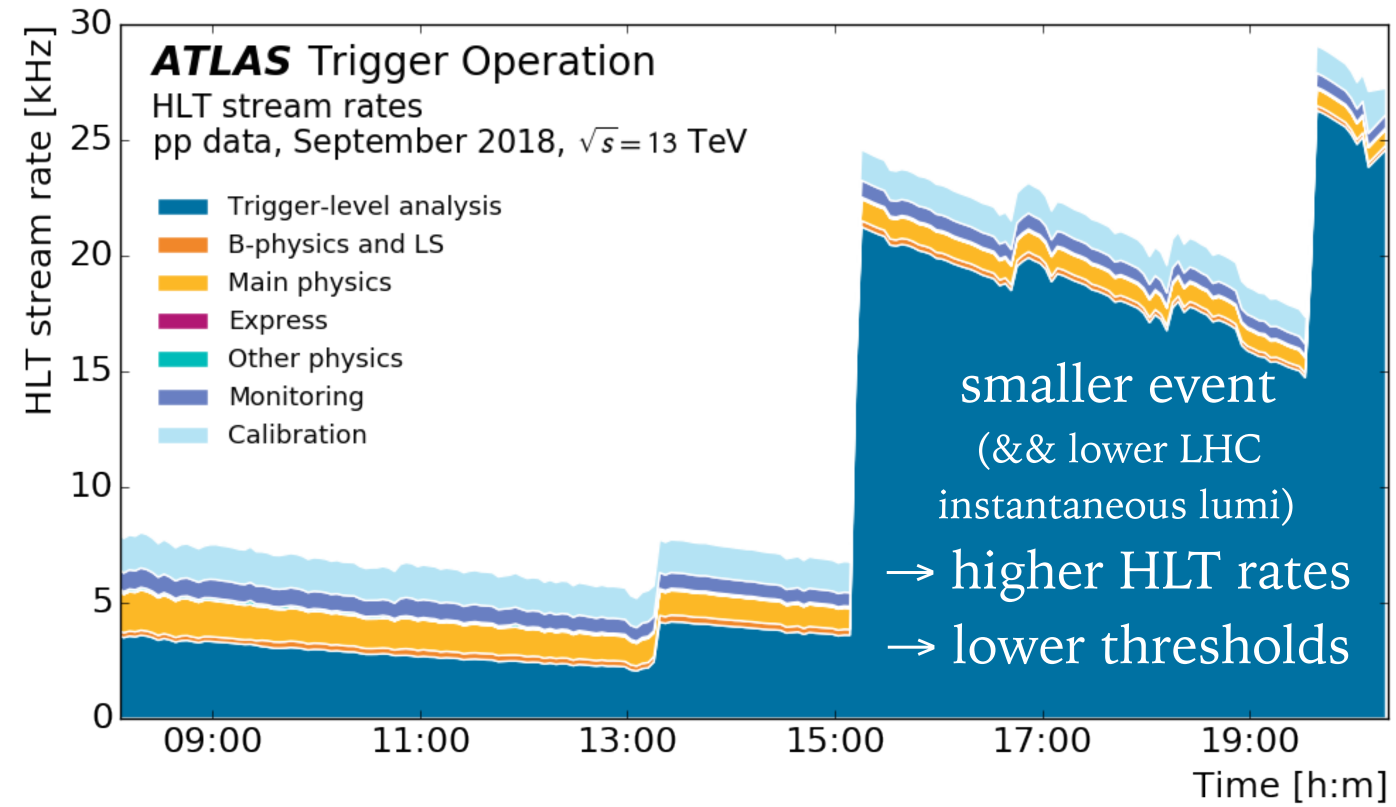


TRIG-2019-04

Stream	Average event size
Physics, express	1 MB
Trigger-level analysis	6.5 kB
Calibration	1.3 kB to 1 MB
B-physics and light states	1 MB

- Allows to record and store much higher event rates

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



Use all the CPU, all the time

- LHC end-of-fill ➞ unused HLT farm nodes
- Can lower the HLT thresholds to record more trigger-level events
- Note: this does not work with lumi-leveling, so not clear this will happen in Run-3

Run-3 plans: extend to physics objects beyond jets

More with less: Partial Event Building (=Selective persistency)

Real-time analysis is necessary for searches
that would otherwise have been impossible due to trigger constraints

Traditional offline analysis still required for a number of searches/final states
where all raw information is needed (but we could do better)

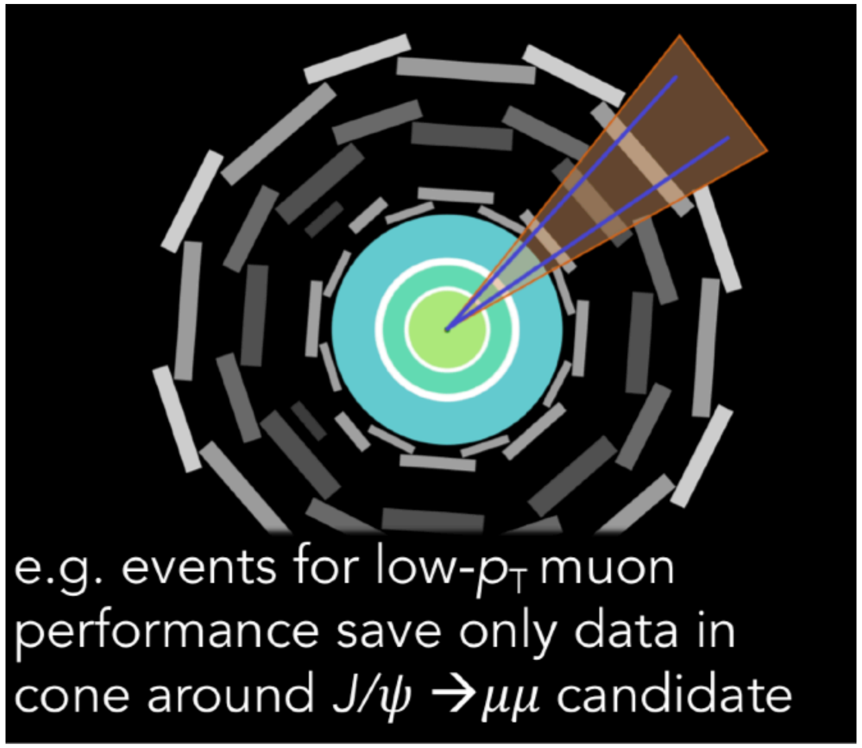
Partial Event Building / Selective Persistency as a middle way:
save raw data && trigger objects only in the regions of interest, re-reconstruct later

Example of customizable outputs @ LHCb:

- keep trigger objects only (7 kB)
- **keep trigger objects + "on-demand" raw and/or reco in selected regions (< 200 kB)**
- keep everything (200 kB)

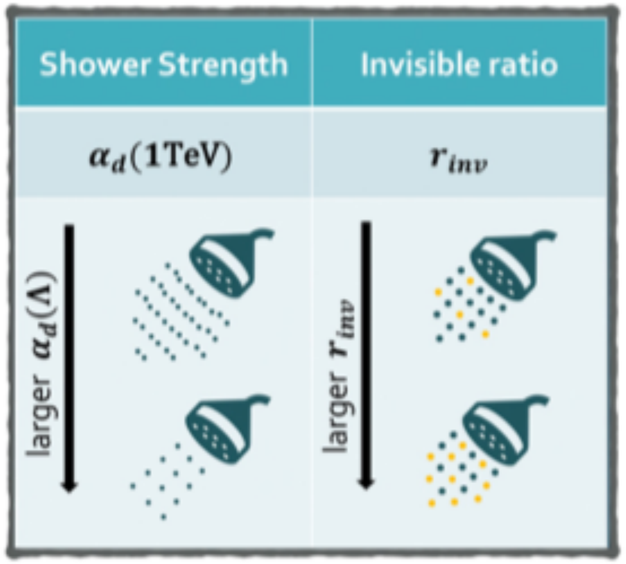
HSF Trigger & Reco / Institut Pascal discussion, July 2016:
https://indico.cern.ch/event/835074/

H. Russell, EPS-HEP 2019,



Link to data selection: exotic dark jets & other signatures

Tim Cohen, Snowmass 2021



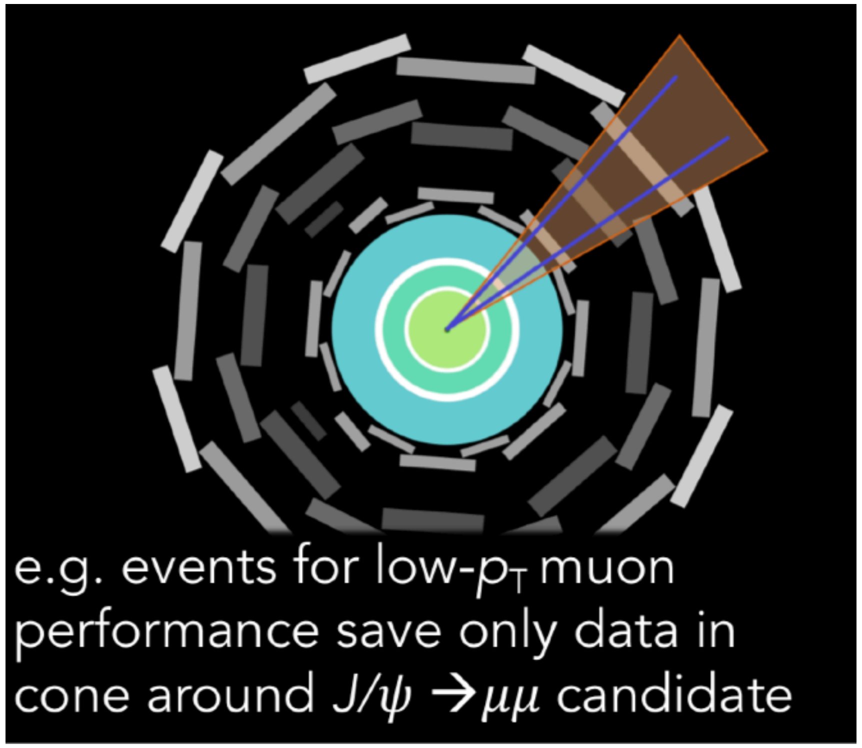
Mapping of "exotic" signatures to big picture of theoretical models not easy
→ difficult to prioritize on theory grounds
→ difficult to decide what exactly to save and select, in advance

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

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

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

H. Russell, EPS-HEP 2019



Partial event building

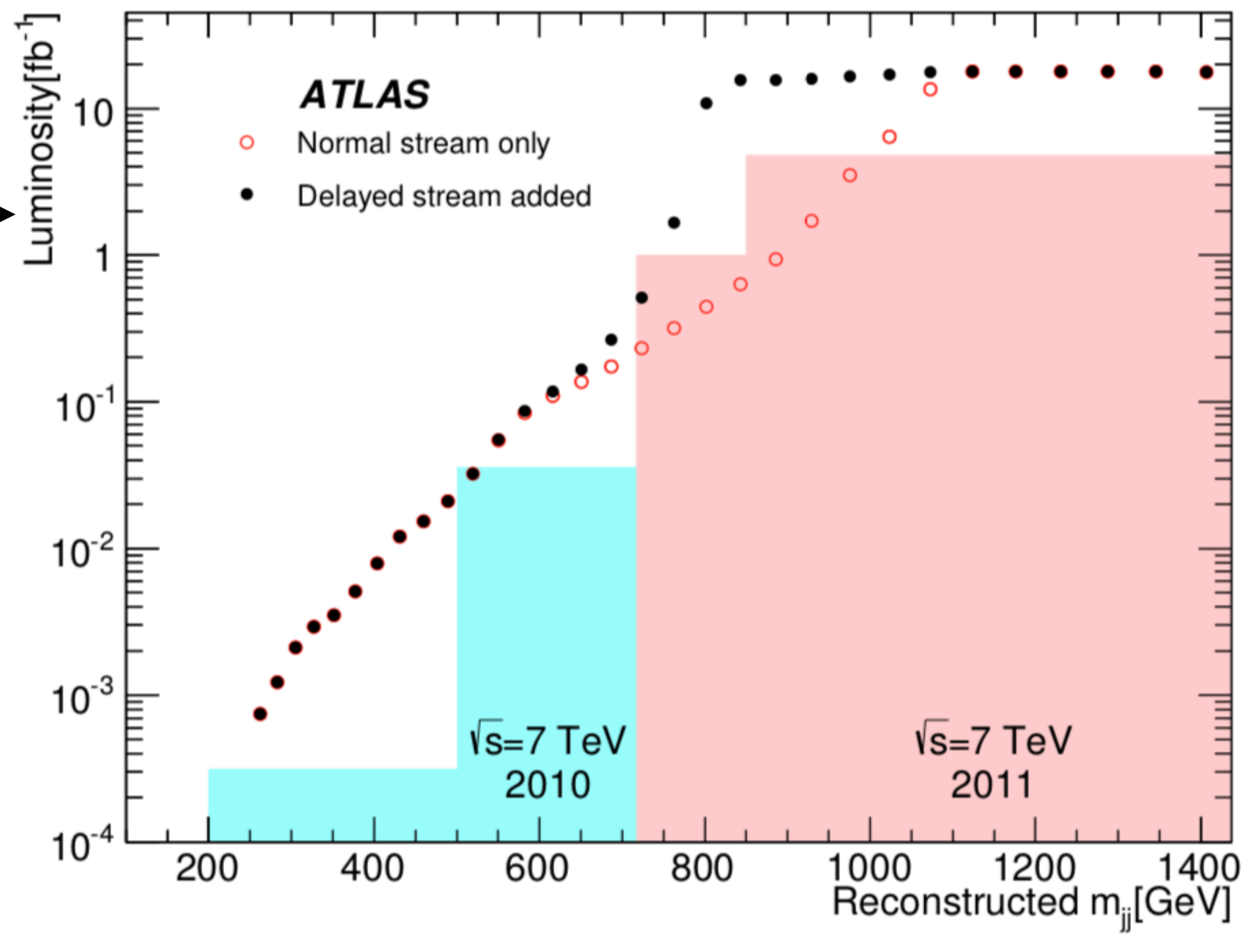
Stay tuned for ATLAS/CMS upcoming search results!

More, later: delayed streams (= data parking)

If **offline CPU availability** is the bottleneck to recording more data:
delay data reconstruction until LHC ends taking data and the (Tier-0) farm is free

Run-1: delayed stream (HT>500 GeV) brought large advantages for hadronic searches

- Dijet resonances (as a precursor to TLA): arXiv:1407.1376
- RPV stops (with b-tagging): arXiv:1601.07453
- Also used for 2012 jet energy scale derivation



Run-2: also available as “safety net” in case Trigger Level Analysis saw events

- A public answer to yesterday’s questions about RK is in the next slide

Run-3: plans to expand use of delayed stream

More, later: delayed streams (= data parking)

TRIG-2019-04, ATL-DAQ-PUB-2019-001

depending on their primary use case and their specific offline reconstruction needs. Figure 1 shows the average recording rate of the physics data stream of all ATLAS *pp* runs taken in 2018. Events for physics analyses are recorded at an average rate of ~ 1.2 kHz.[2] This comprises two streams, one dedicated to *B*-physics and light states (BLS) data, which averaged 200 Hz, and one for main physics data, which averaged 1 kHz. The BLS data are kept separate so the offline reconstruction can be delayed if available resources for offline processing are scarce due to high LHC uptime.

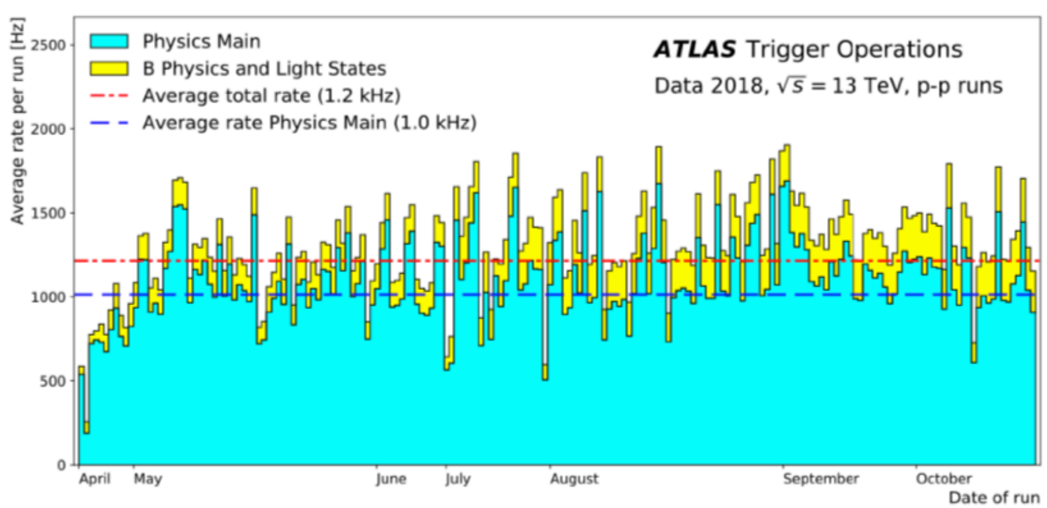
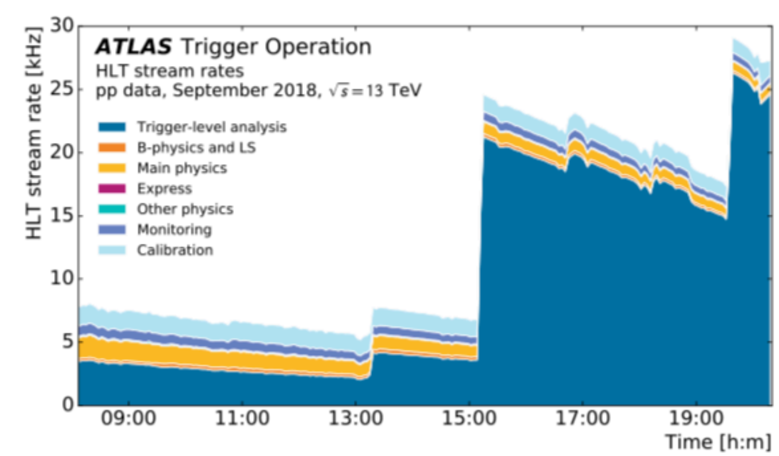
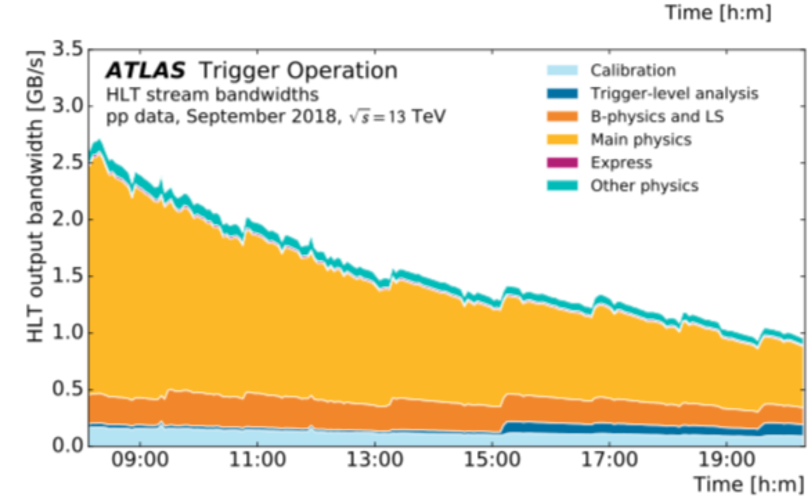


Figure 1: The average recording rate of the main physics data stream and the *B*-physics and light states data stream for each ATLAS *pp* physics run taken in 2018. The total average of all runs is indicated as a red dash-dotted line, and the total average of the main physics stream is indicated as a blue dashed line.

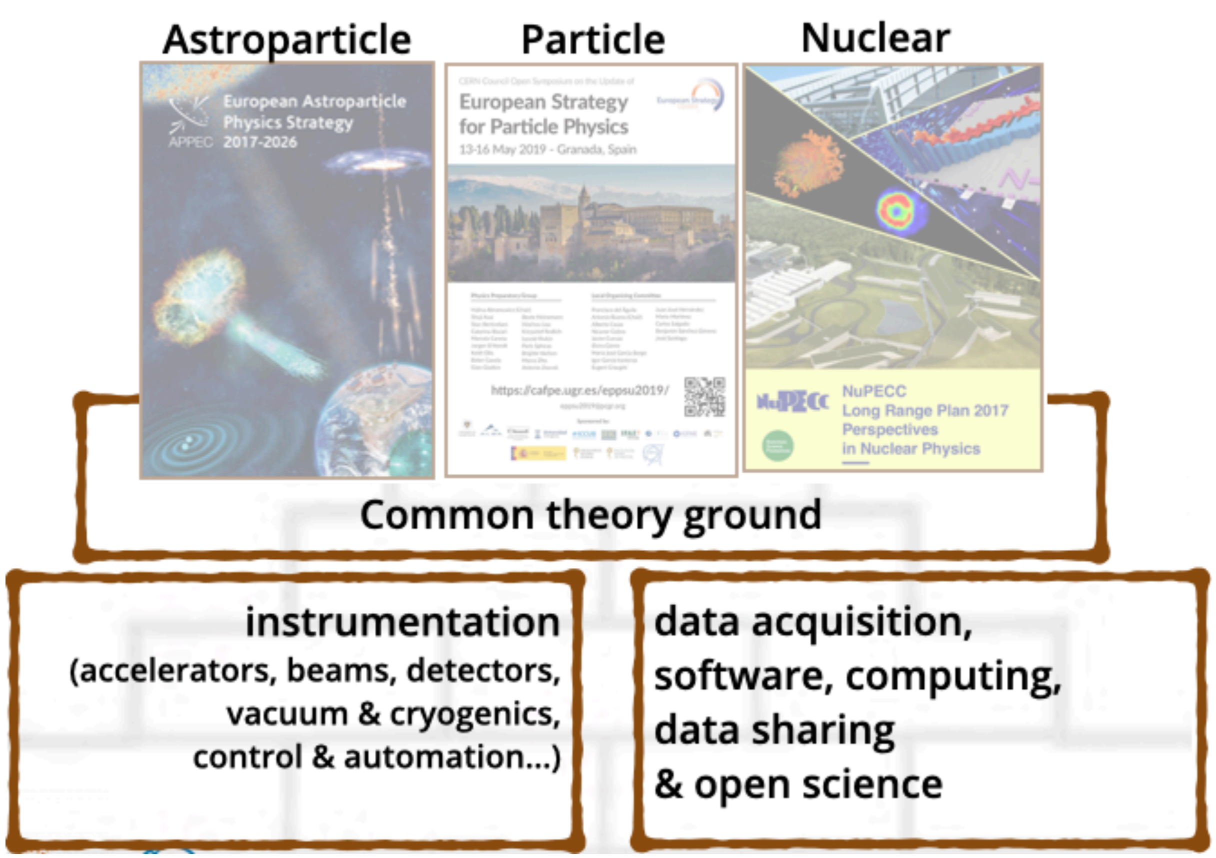




iDMEu,
the Dark Matter Test Science Project
and the HEP Software Foundation

Two complementary projects (everyone is welcome!)

searches & interpretation



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

https://indico.cern.ch/event/869195/

ESCAPE newsletter APPEC newsletter

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

kick-off meeting 9-12/05/2020

ESCAPE

HSF

Towards a Dark Matter Test Science Project

ESCAPE Progress Meeting, 2020

TOOLS conference contribution

software & data

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**

More about iDMEu (following yesterday's discussion)

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

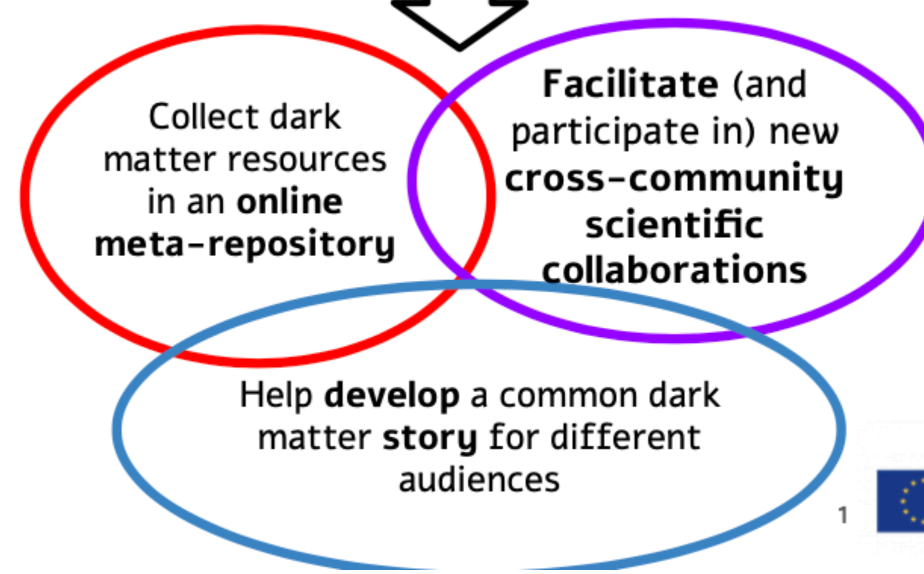
The JENAA iDMEu LOI proponents:
Elena Cuoco, Jocelyn Rebecca Monroe, Marco Cirelli, Silvia Pascoli, Caterina Doglioni, Federica Petricca, Gaia Lanfranchi, Florian Reindl

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

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

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

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



1

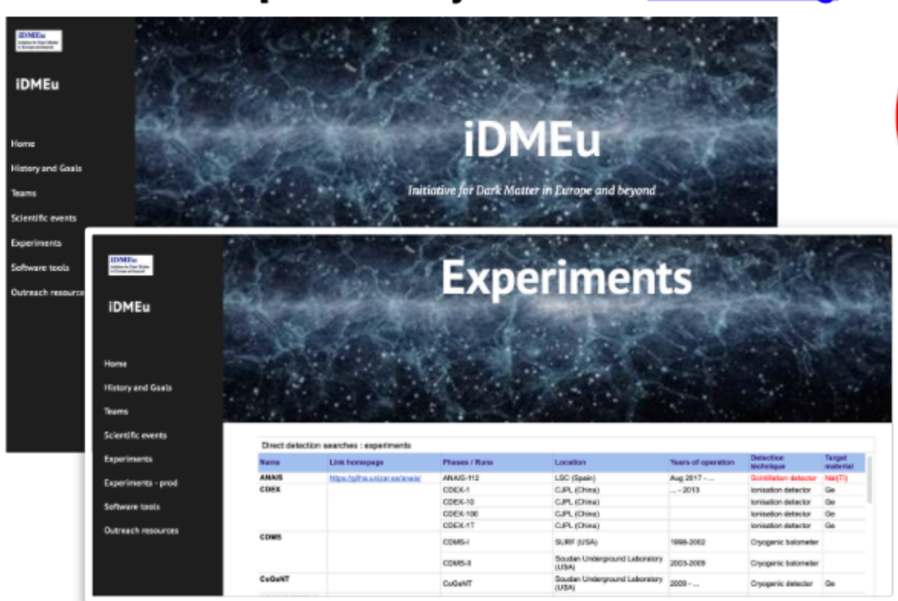
More about iDMEu (following yesterday's discussion)

Three connected **iDMEu objectives**

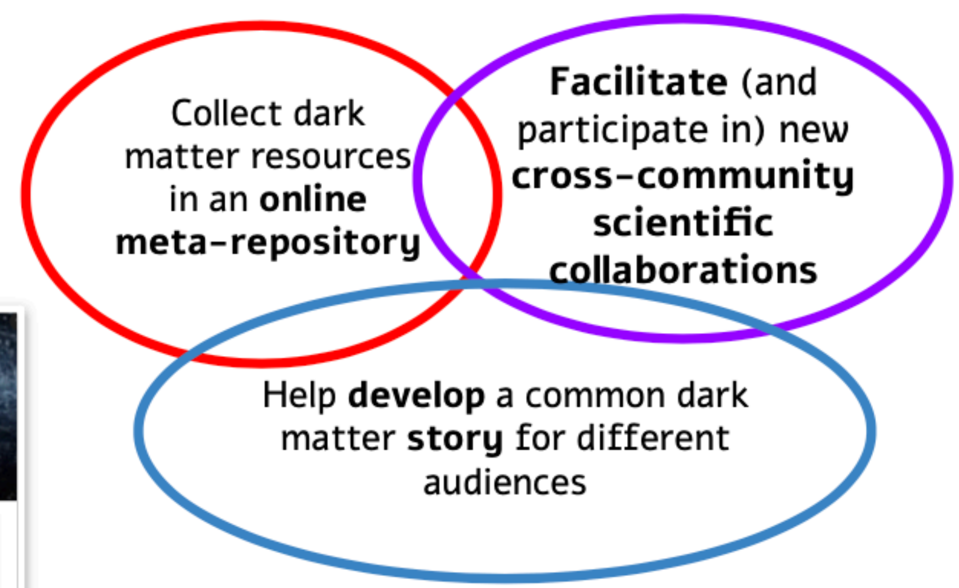
Note: iDMEu is intended as a platform that brings together **existing/future** community efforts

iDMEu enables finding **synergies** and highlighting the **complementarity** of different dark matter communities by developing a **common platform** to:

Domain and preliminary website: iDMEu.org



Work in progress: tables of past/present/future DM experiments



Today and tomorrow's **community talks** + Tomorrow's **breakout sessions** + Wednesday's **closing session**

Wednesday's **outreach session** (with a hands-on component)

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

Created by **curators:** students doing an internship on collecting info & learning about DM → contact us if interested!

2

Link to kick-off meeting (with recordings)

Mailing list: will be communicated to endorsers/kick-off meeting participants in the next few days —> if you'd like to stay informed, enter your details here

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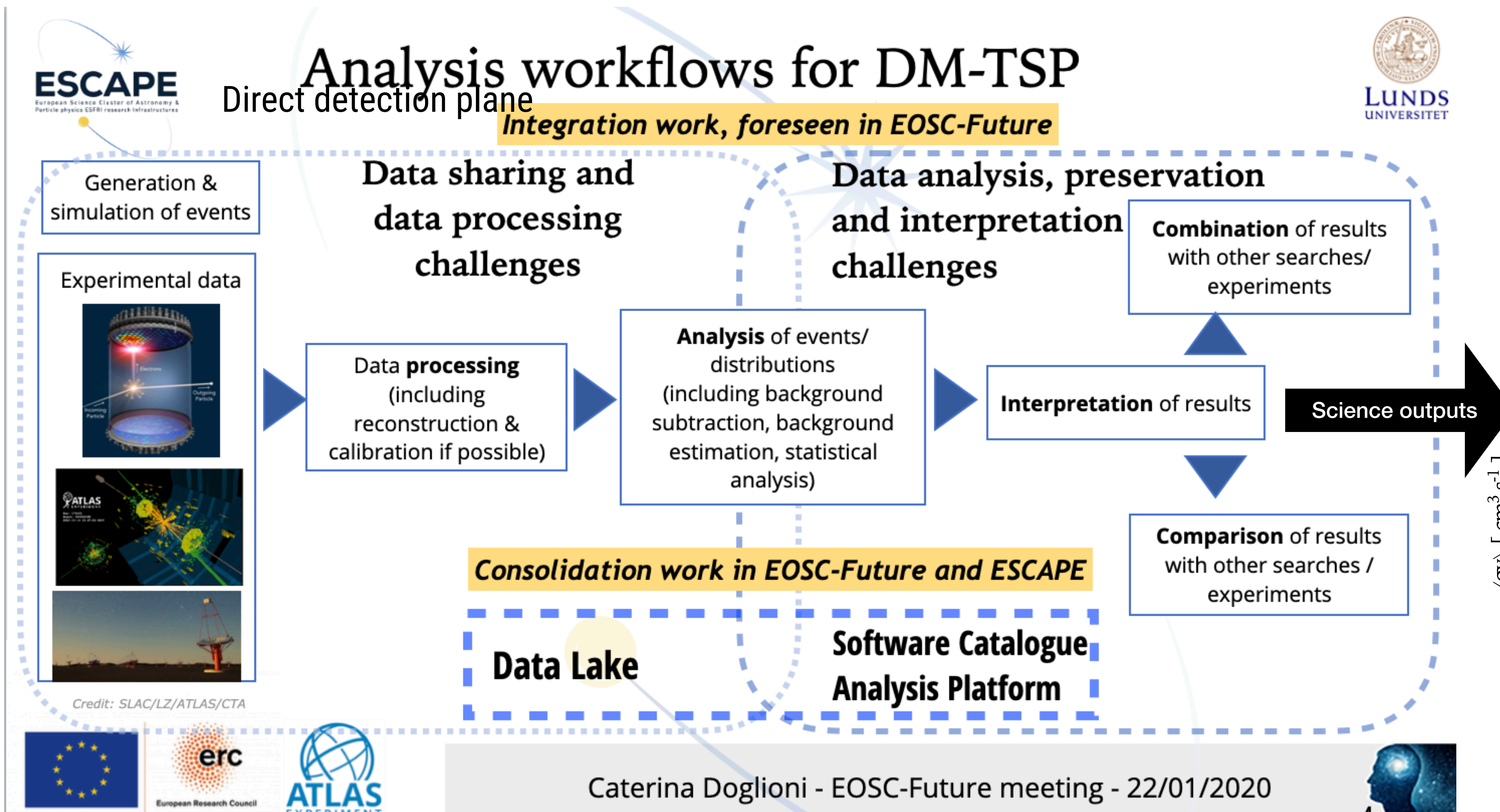
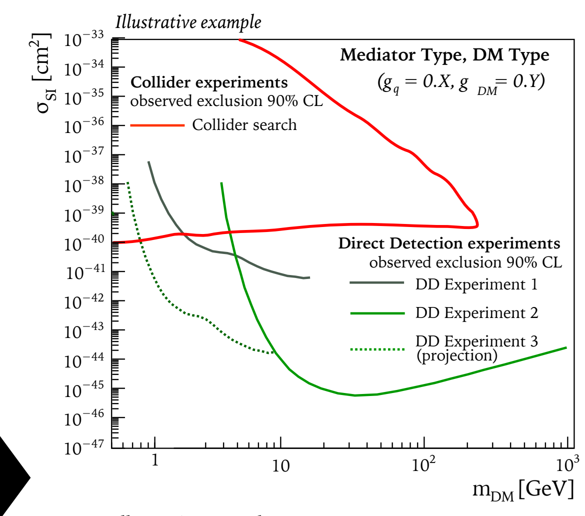
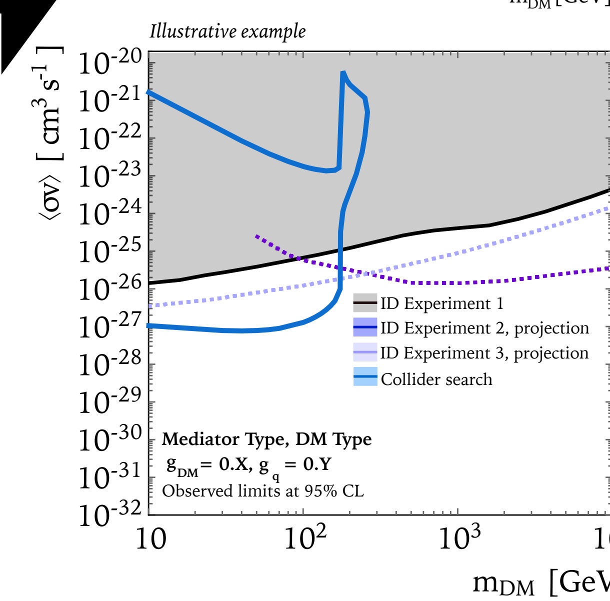
More about the Dark Matter Test Science Project in EOSC-Future

- Implement open and reproducible end-to-end analysis workflows on a common infrastructure
  - Using ESCAPE services, see https://projectescape.eu, to serve as stepping stone for European Open Science Cloud
- **DM Test Science Project (TSP):** take 5 use cases included in ESCAPE
  —> 5 postdoc positions funded by INFRAEOSC-03 open here
  - Another parallel TSP for Extreme Universe (focused around gravitational waves)

Indi







Meta-Workflow for DM sub-projects: Indirect detection

Discussions on improving interpretations/plots:
iDMEu (JENAA EoI), PhyStatDM, existing working groups

Data Lake

Open LHC data

Open Indirect Detection data

Discussions on standardized data formats for other experiments (iDMEu)

ATLAS/CMS [LAPP+Lund/INFN]

CERN

recast

reana

HSF

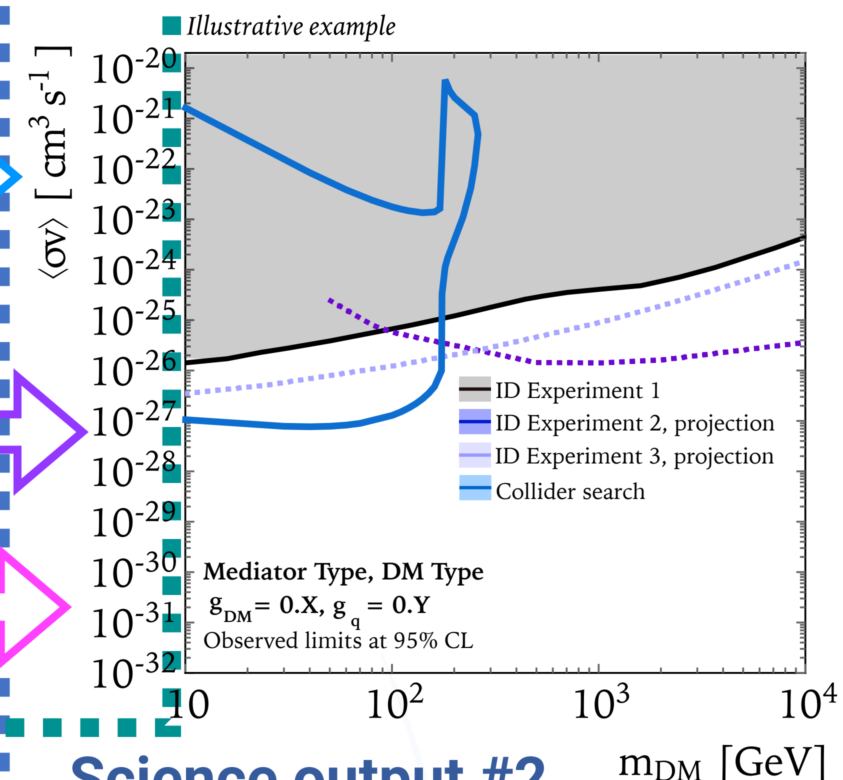
Discussions on using common steering (declarative?) analysis code

CTA [LAPP/LAPTH]

KM3NeT [FAU]

Theory input & automated codes for interpretation [LAPTH]

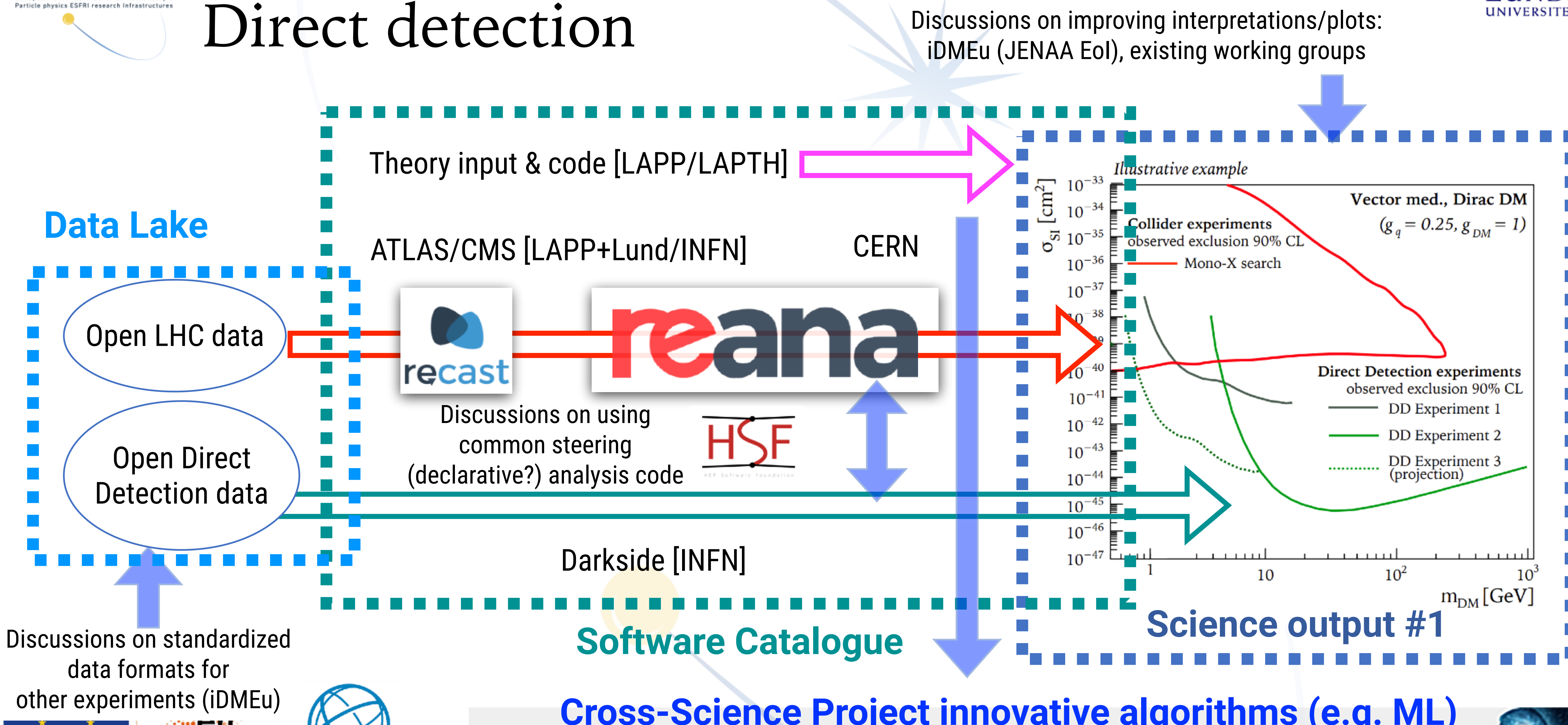
Software Catalogue



Science output #2

Cross-Science Project innovative algorithms (e.g. ML)

Meta-Workflow for DM sub-projects: Direct detection



Where to discuss trigger&reconstruction in HEP & beyond

HSF = High Energy Physics (HEP) Software Foundation

- Forum for physicists with interest in software for HEP
  - …and beyond: contacts and shared meetings with nuclear physics, accelerator, DM experiments
- Latest whitepaper on common software and techniques
  - Initial whitepapers helped shape IRIS-HEP US/NSF effort
- Working groups including trigger & reconstruction
  - Trigger & reconstruction plans for 2021 include ML for hardware triggers, heterogeneous architectures

HEP Software Foundation

Website
Discussion Forums

[Starting 10/21] **SMARTHEP = European Training Network on real-time analysis, machine learning and hybrid architectures**

- "Too much data" is not only a high energy physics problem
- Time-to-insight also the key metric for industry (= finance, self-driving cars, industrial maintenance…)
- Shared supervision: 12 students from LHC experiments + Computer Science + Industry, tackling the problem of efficient decision-making
- Shared Tools: Hardware (FPGA, GPU) & software, machine learning

Similar collaborations exist in the US, e.g. https://fastmachinelearning.org, https://clariphy.org

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