LUNDS UNIVERSITET

Real-time analysis at the LHC

HOW TO MAKE THE MOST OF LHC DATA

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http://www.hep.lu.se/staff/doglioni/

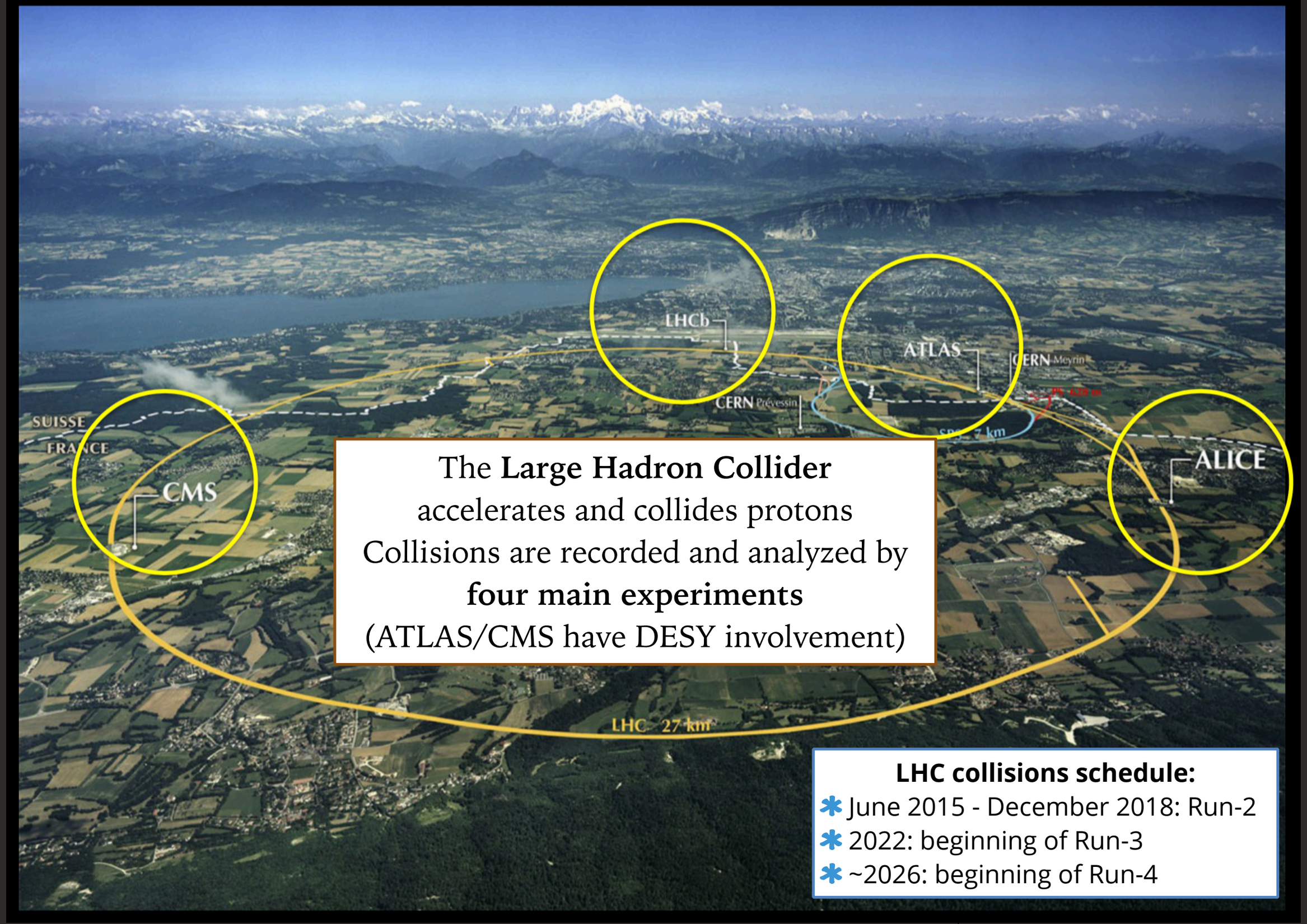
European Research Council
Established by the European Commission

ATLAS EXPERIMENT

Outline

- The Large Hadron Collider and its experiments
- How/why making the most of the data
- Dark matter searches with real-time analysis
- Real-time analysis beyond LHC/high energy physics

Introduction

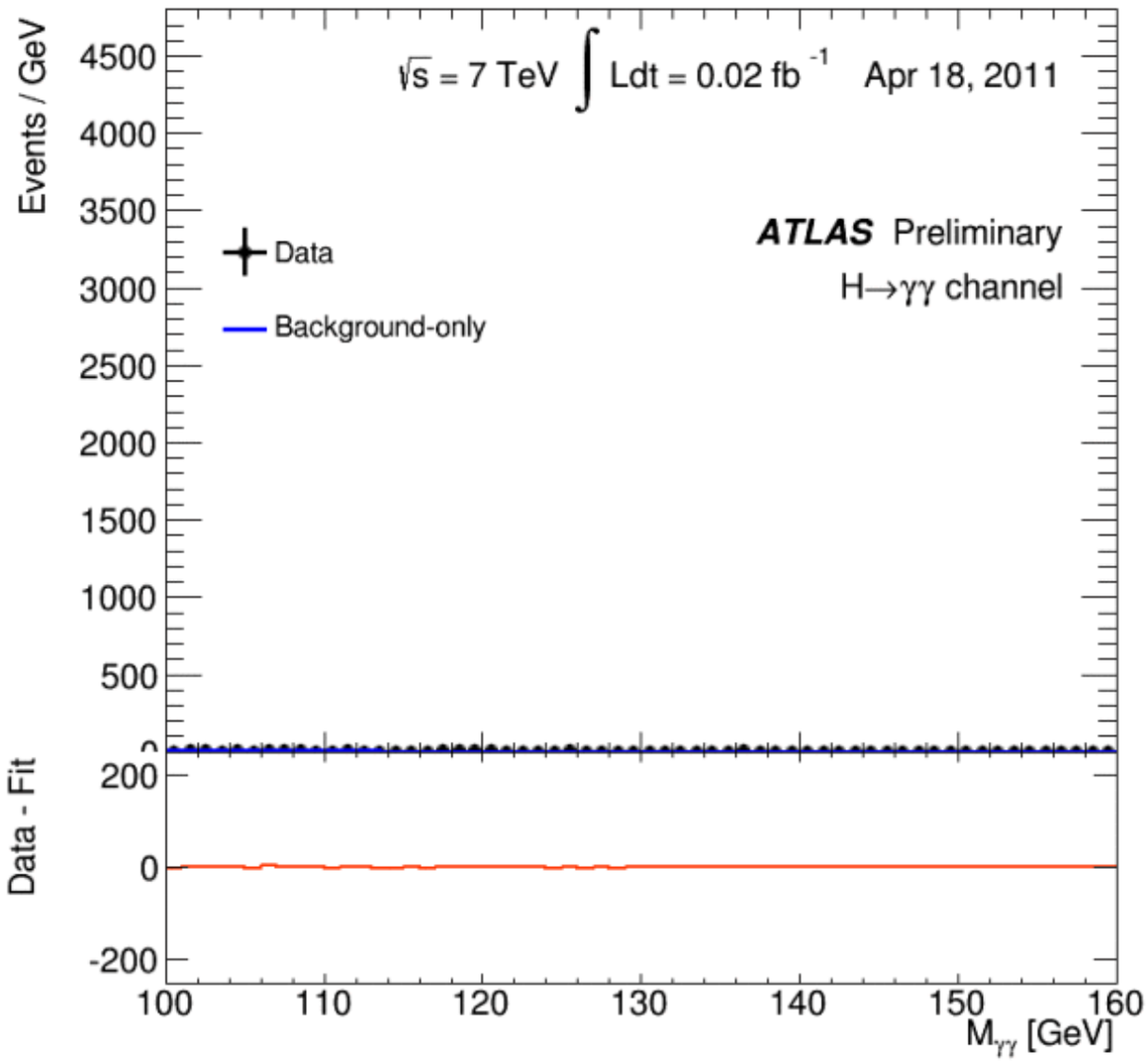


The **Large Hadron Collider**
accelerates and collides protons
Collisions are recorded and analyzed by
four main experiments
(ATLAS/CMS have DESY involvement)

LHC collisions schedule:

- June 2015 - December 2018: Run-2
- 2022: beginning of Run-3
- ~2026: beginning of Run-4

What does it take for a discovery?



https://cds.cern.ch/record/2230893

- A particle **collider** (LHC)
  - 600000 collisions/second
  - Only one in 10^{13} may contain a Higgs boson
- **Detectors** able to select and precisely measure particles (photons)
  - ATLAS, CMS
  - Millions of read-out channels
- Many **teams** that:
  - Operate the detector
  - Reconstruct and calibrate particles
  - Do the data analysis

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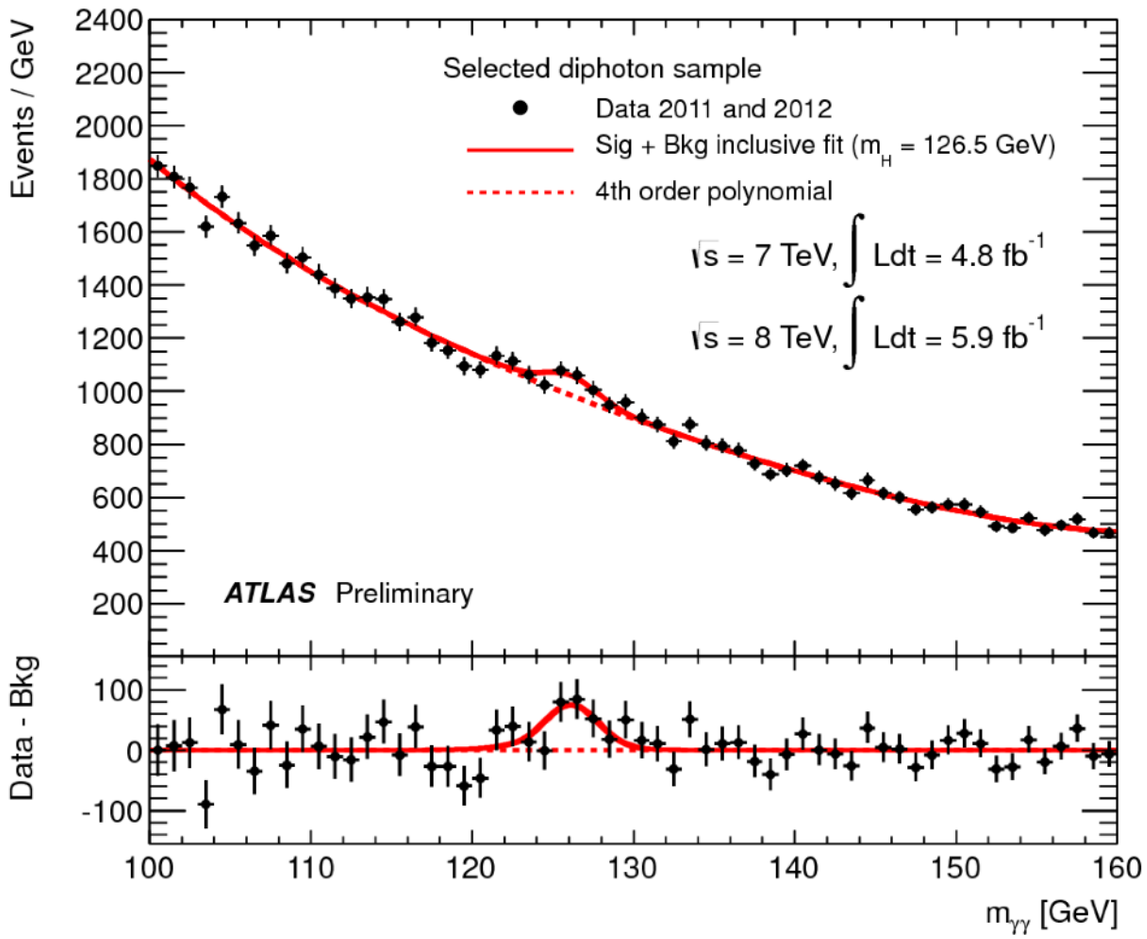

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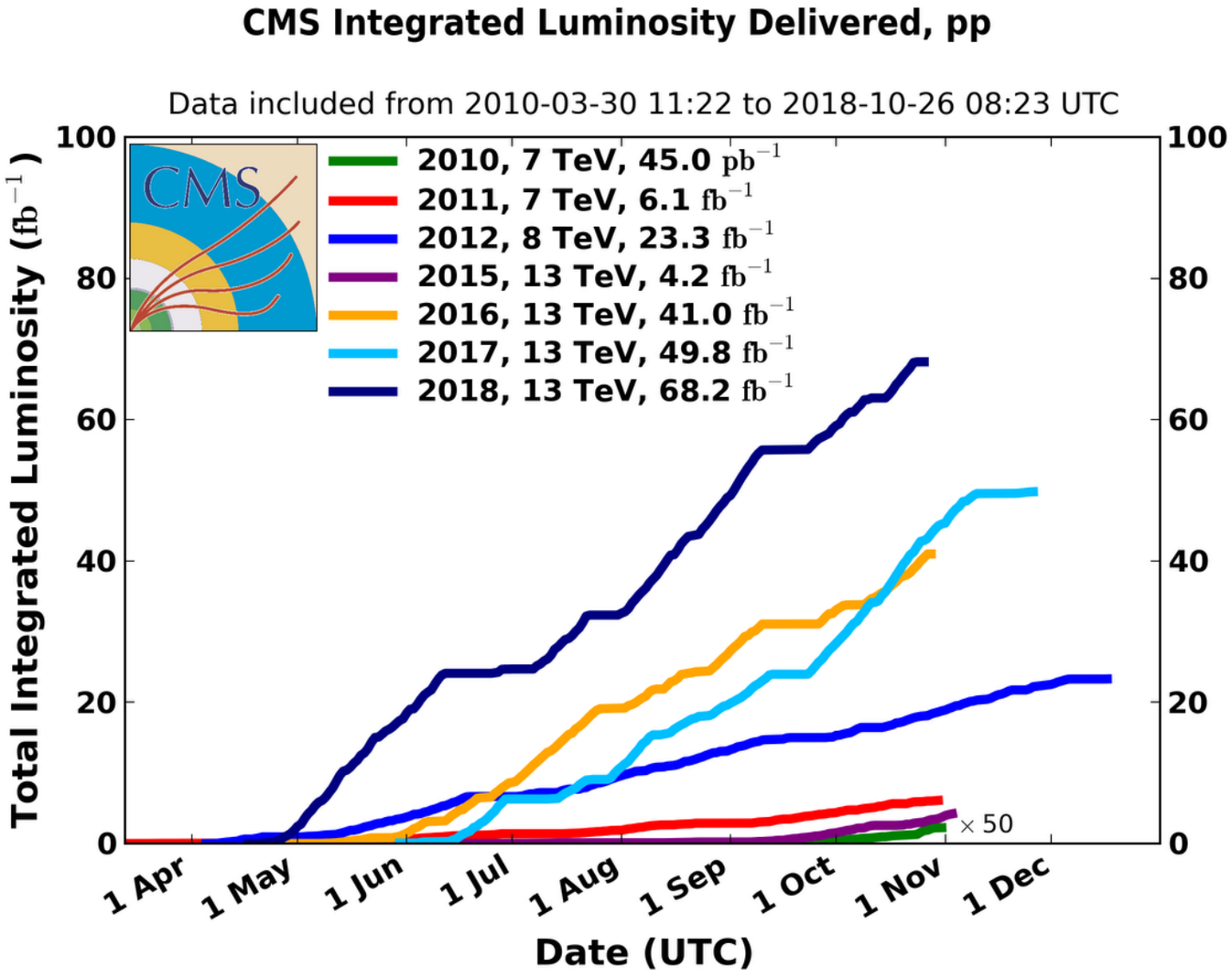
What does it take for a discovery? LHC data



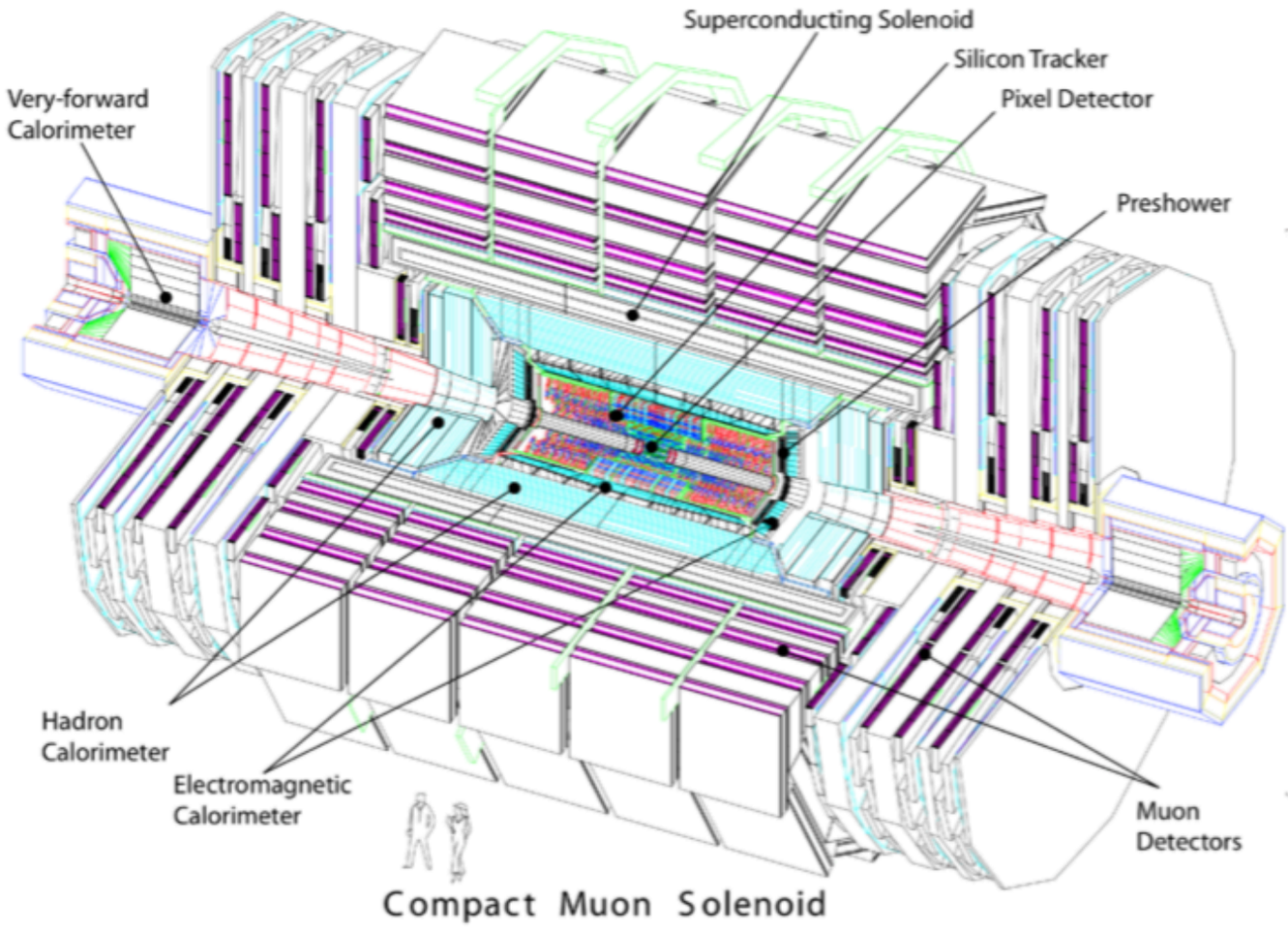
√s = Centre of mass energy

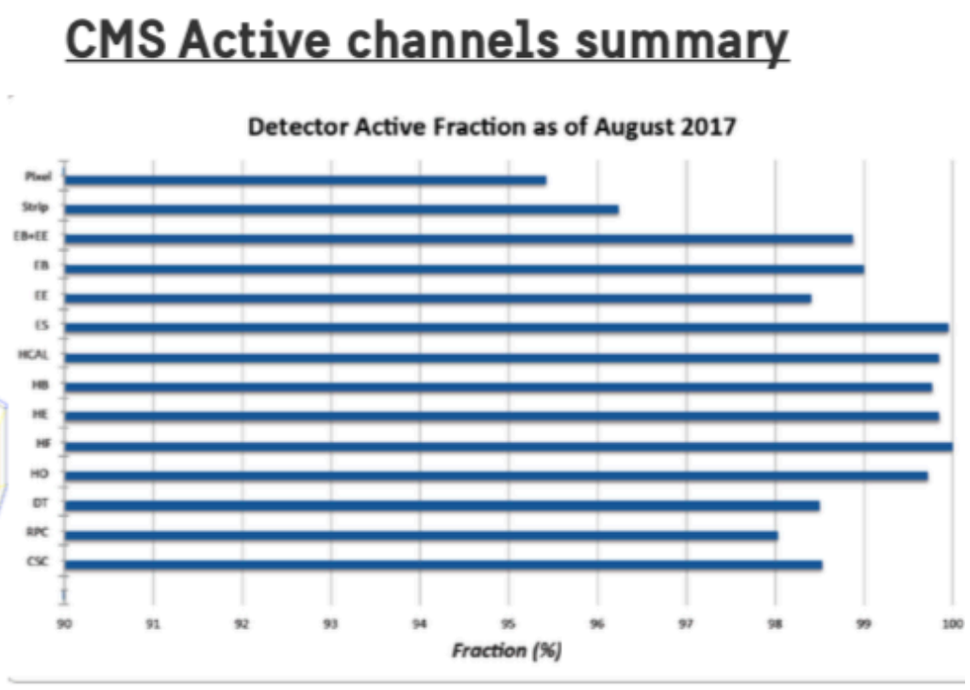
More energy ⇔ can discover more massive particles ($E=mc^2$)

Luminosity = how much data is collected (proportional to # of collisions)

More data ⇔ more chances to see rare processes

What does it take for a discovery? Detectors





Many **sub-detectors** used to measure different particle properties
Information from sub-detectors combined in **reconstruction**
Physicists analyze the collections of **events recorded**

What does it take for a discovery? Collaborations

ATLAS

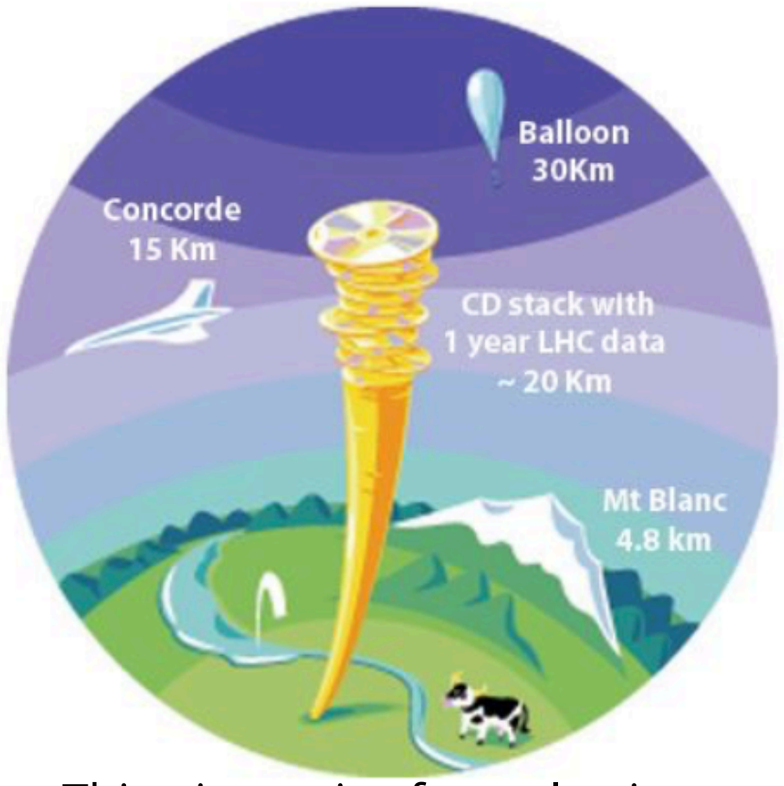
CMS

LHCb

ALICE

Selecting interesting data at the LHC

- If everything was recorded at the LHC:
  - up to 30 million collisions/second (MHz)
  - 1-1.5 MB/data per collision
  - 30 MHz * 1 MB = 30 TB/s
  - 30 TB/s * 10e+6 s/year (day & night) ~ 0.05 ZB/year
- facebook
  - 600 TB/day ~ 200 PB/year [Facebook 2014]
    - **"There's always a bigger fish"**
      [C. Tully's talk @ siRTDM18]
- But bigger fish also have bigger money…
  cost-effectiveness important for scientific instruments!



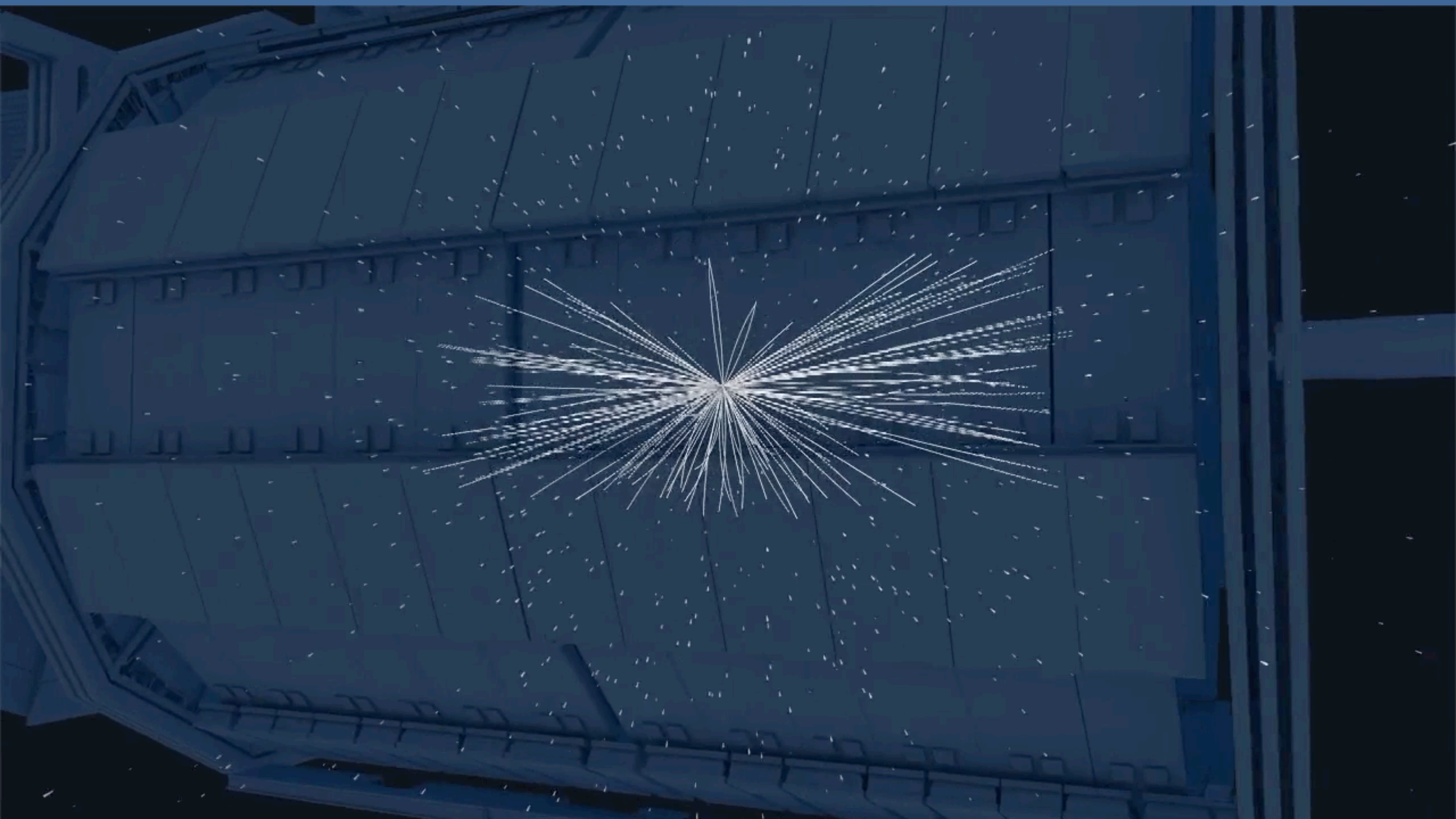
This picture is after selection of "interesting" data:
with all data, the stack of CDs reaches to the moon

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

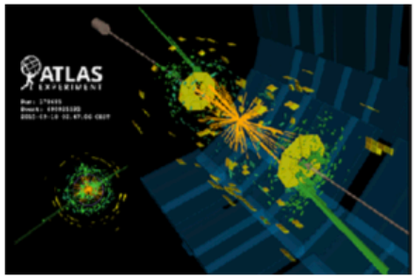
The LHC trigger systems

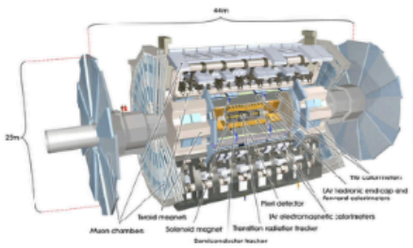
Video: selecting collisions of interest

CERN-MOVIE-2013-041-001



Trigger and data acquisition chain





Online | Offline

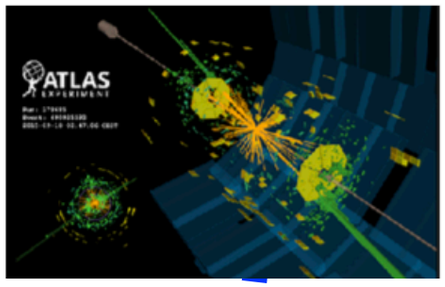
Event selection (trigger) → Object reconstruction and calibration → Data analysis

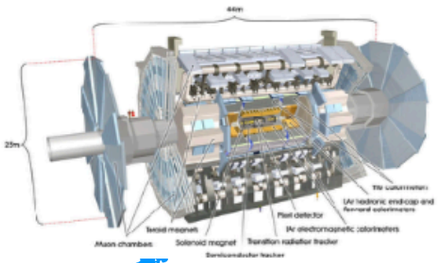
Computing resources are essential for the full data taking chain

Trigger and data acquisition: select interesting events

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

Online | Offline





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

Data produced by the LHC
(multiplied by large number)

Data I like

...maybe discoveries?

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

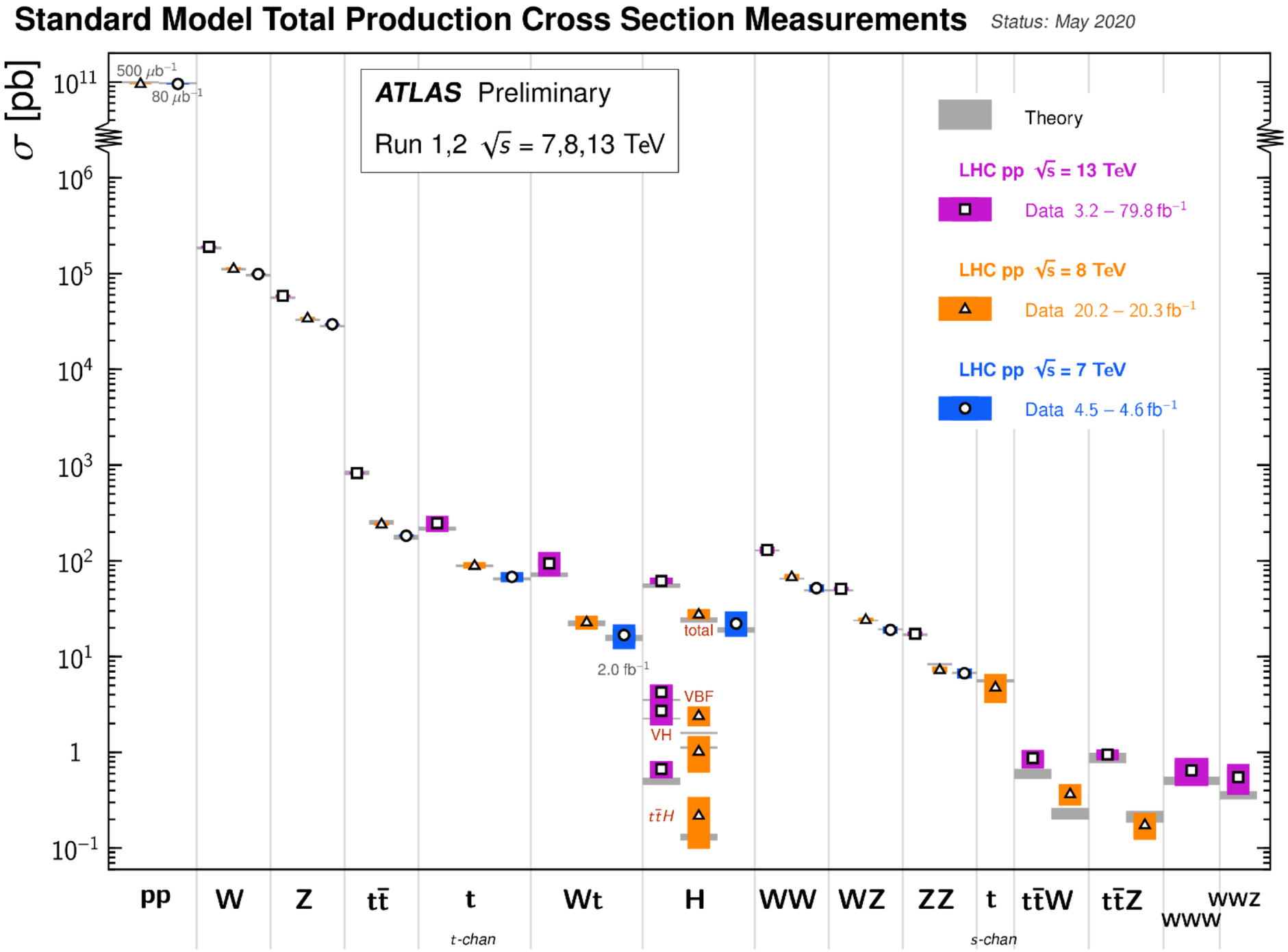
Data you like

What we can record in full after the trigger

Data ~nobody likes

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

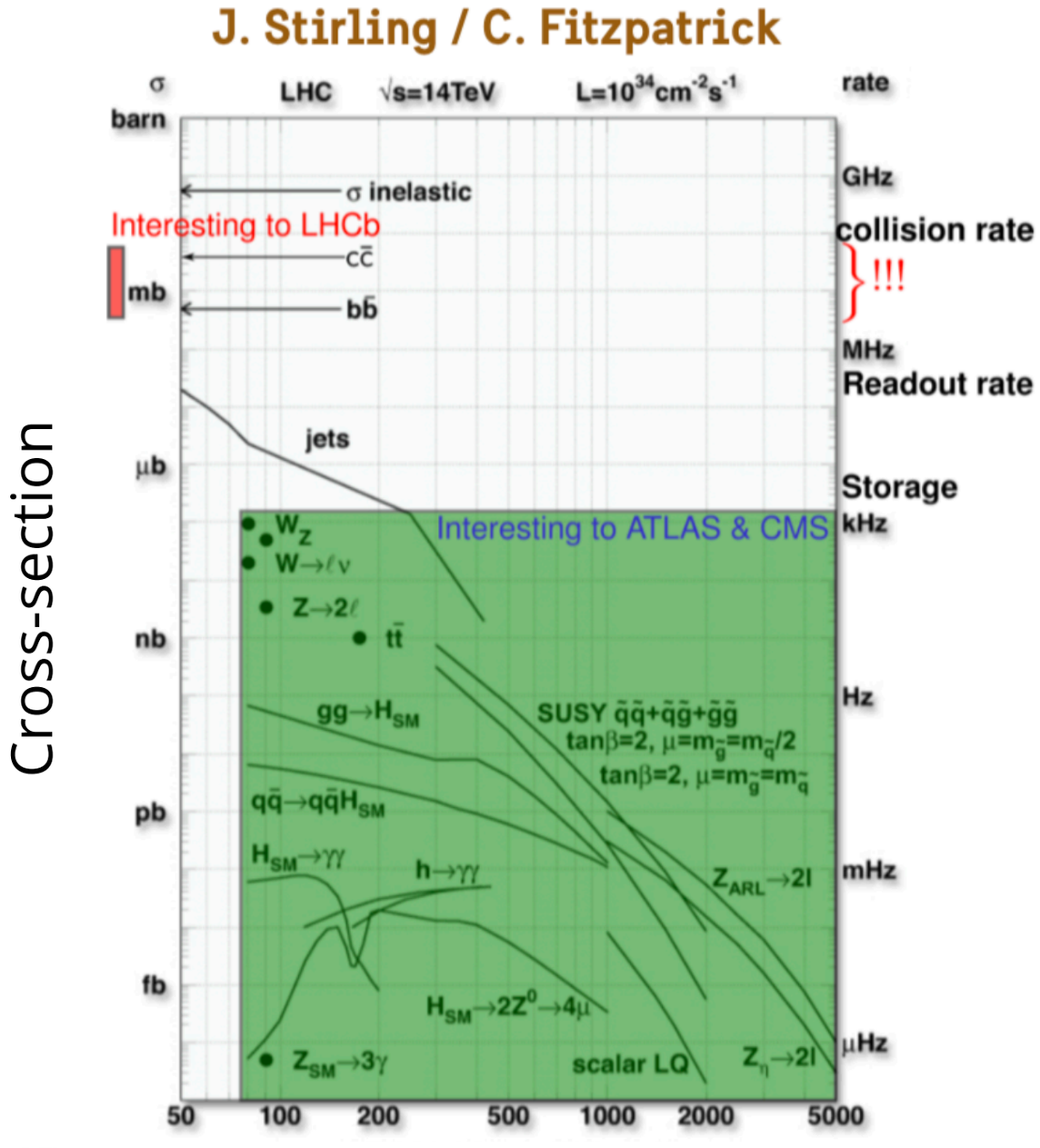
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2020-010/



...but are we missing something?

What we can trigger on

What is interesting at the LHC?



Cross-section * Luminosity
= number of events produced

Challenges:

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

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

Deciding what to record: trigger menu

Trigger menu decided in advance of data taking period

Example for **ATLAS**:

Year	2012		2015		
$\sqrt{s}$	8 TeV		13 TeV		
Peak luminosity	7.7×10^{33} cm^{-2} s^{-1}		5.0×10^{33} cm^{-2} s^{-1}		
	p_{T} threshold [GeV], criteria				
Category	L1	HLT	L1	HLT	Offline
Single electron	18	24i	20	24	25
Single muon	15	24i	15	20i	21
Single photon	20	120	22i	120	125
Single tau	40	115	60	80	90
Single jet	75	360	100	360	400
Single b-jet	n/a	n/a	100	225	235
$E_{\mathrm{T}}^{\mathrm{miss}}$	40	80	50	70	180

- More or less flexible to adjustments (changes need very good reasons!)
  - Follows priorities dictated by experiment's physics strategy
  - **LHCb**: using MVA to optimize selections and rates

Risks: **not recording** enough events, **missing** whole classes of events

Where are the limitations?

Detector readout to L1

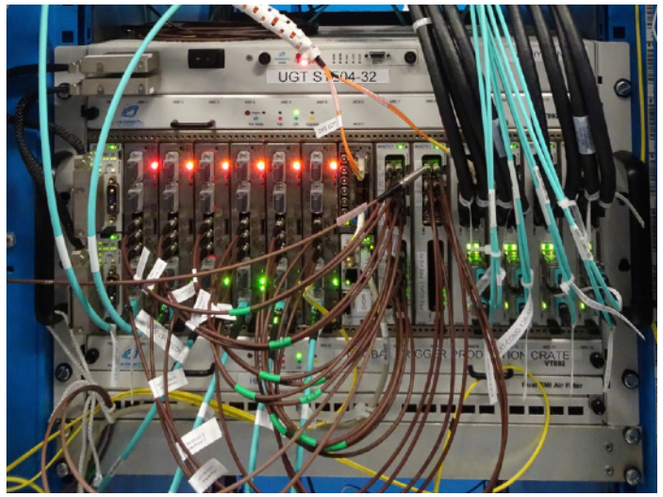


Image from CMS HEPHY

Disk/tape to store events

Image from CERN

CPU for processing events (within the HLT, and in the offline farm)

Image from C. Bernius's talk

How to overcome them?

How LHC collaborations can make the most of the data

Interesting time for high energy collider physics:
we don't know what to expect from DM/new physics
(but we have a prior: it should be *somewhere*)
we have the **LHC running now**,
and the data we discard is **gone forever**

1. **Readout**: Build detectors (+services) that can read-out more
   - LHCb/ALICE aiming for 40 MHz readout, CMS/ATLAS going for HL-LHC
2. **CPU:** Save data for **further reconstruction, later**
   - HL-LHC long shutdowns can be long…
3. **CPU:** Make trigger & algorithms faster (in software/with heterogeneous architectures)
4. **Storage:** Analyze as much data as possible, **as fast as possible**
   - This requires making **hard choices** on what to keep for further analysis
5. Implement more refined algorithms to **look for the unexpected**
   - Including unsupervised searches / novelty detection

How LHC collaborations can make the most of the data

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data parking / selective persistency

real-time analysis

Real-Time Analysis (RTA)

Not to scale

Using high-level trigger data for physics analysis

Continuous readout

Triggerless analysis
(histogramming @ L1…)

Trigger systems

note that

Real-time analysis

can have many meanings, even when only talking about HEP

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A paradigm change

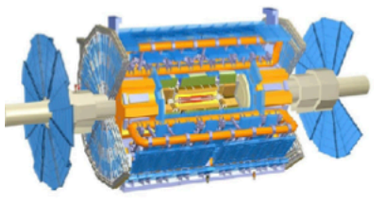
Asynchronous data analysis

First record data, then reconstruct/analyze it

Real-time data analysis

Reconstruct/analyze data as soon as it is read out
so that only (**smaller**) final-state objects
or histograms need to be stored

Regular trigger & data analysis path



Trigger event reconstruction

Decision

only if trigger passed

Full event reconstruction

Main stream

Standard data analysis

Turbo/Data Scouting/TLA path

Turbo stream (LHCb),
Data Scouting (CMS),
Trigger-level Analysis (ATLAS),

Trigger event reconstruction

Decision

only if trigger passed

Full event reconstruction

Main stream

Standard data analysis

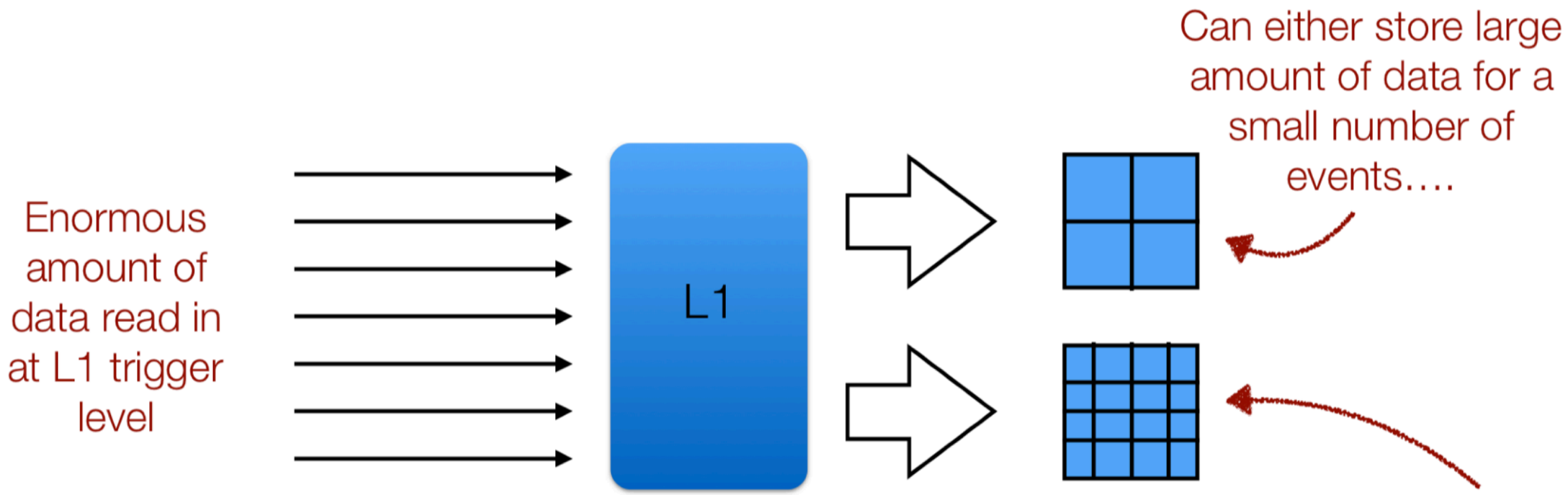
In any case

Partial (HLT-only) event reconstruction

Special trigger analysis stream

Analysis with trigger objects

(Near-)real-time analysis of LHC data



Perform as much "analysis" as possible @ HLT

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

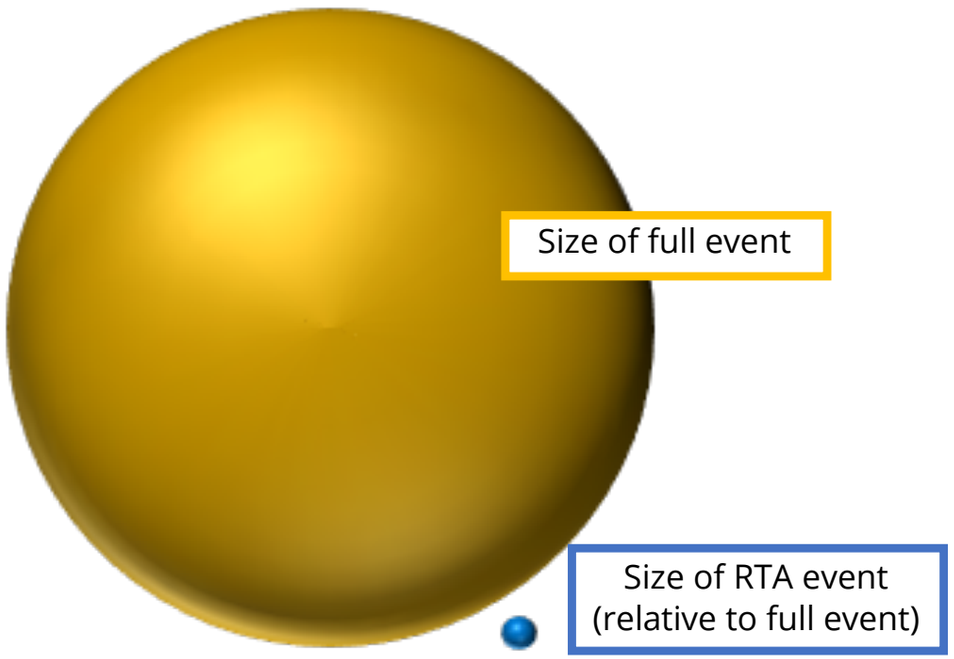
Reduced data formats:

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

real-time analysis

Overcoming storage (and CPU) bottlenecks

Save many more smaller events



- Allows to record and store much higher event rates

Overcoming storage (and CPU) bottlenecks

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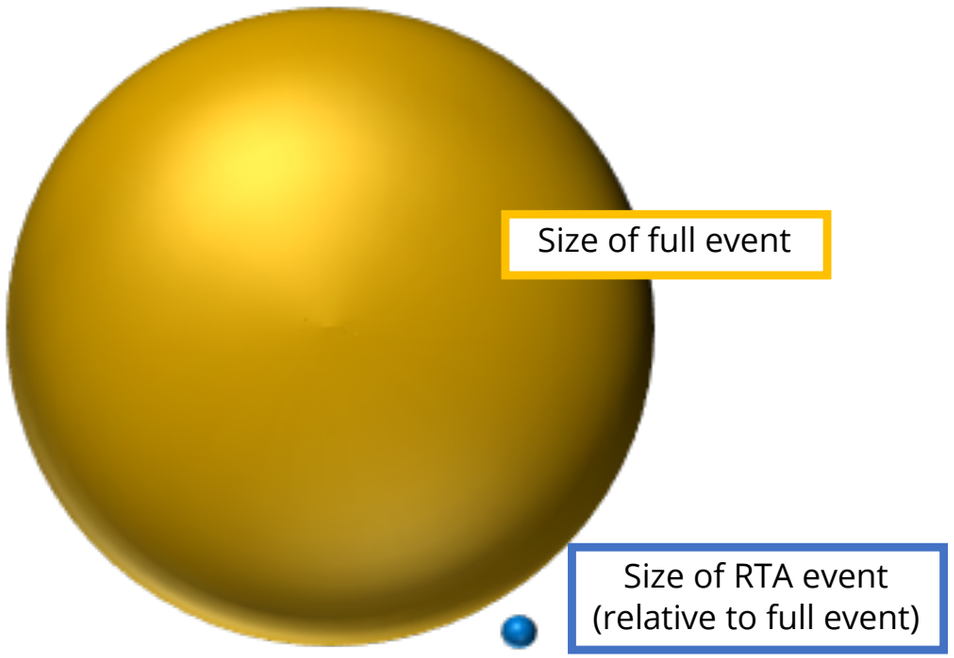

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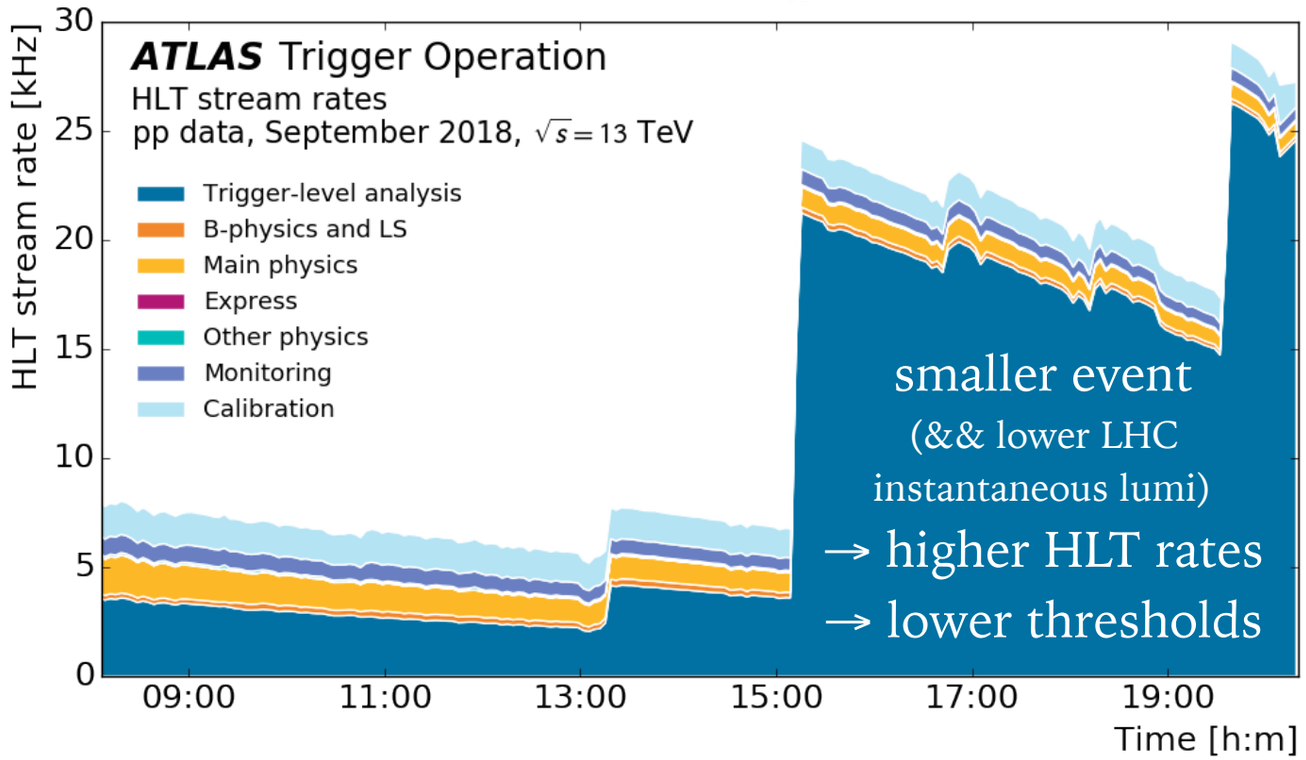
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults



Use all the CPU, all the time

- LHC end-of-fill → unused HLT farm nodes
- Can lower the HLT thresholds to record more RTA(-like) events
- Note: this does not work with lumi-leveling (but GPD could think of getting closer to LHCb buffers for HL-LHC)

More with less: Selective persistency/Partial Event Building

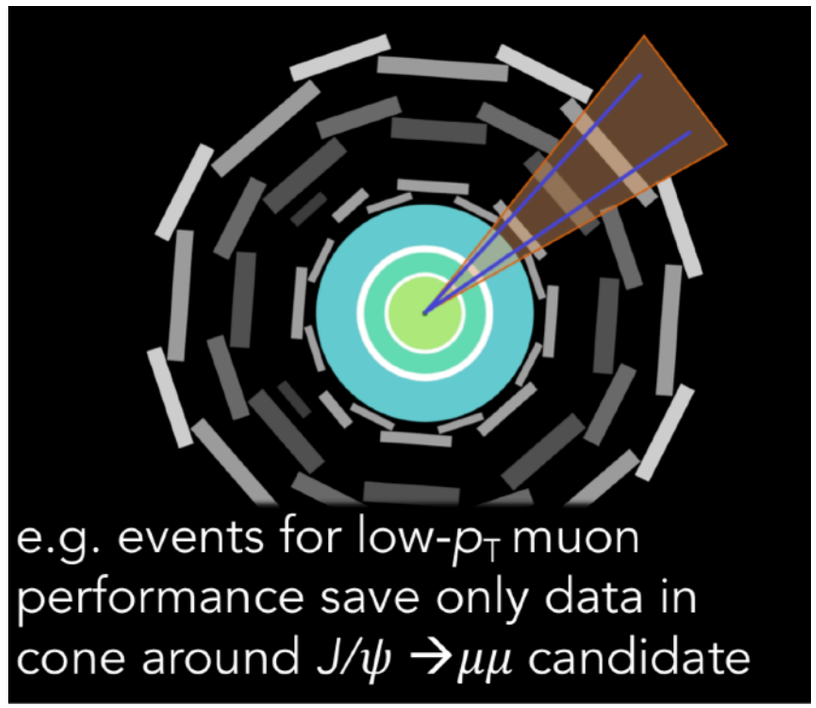
Real-time analysis is necessary for searches
that would otherwise have been impossible due to trigger constraints

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

H. Russell, EPS-HEP 2019,

Customizable output data @ 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/

data parking / **selective persistency**

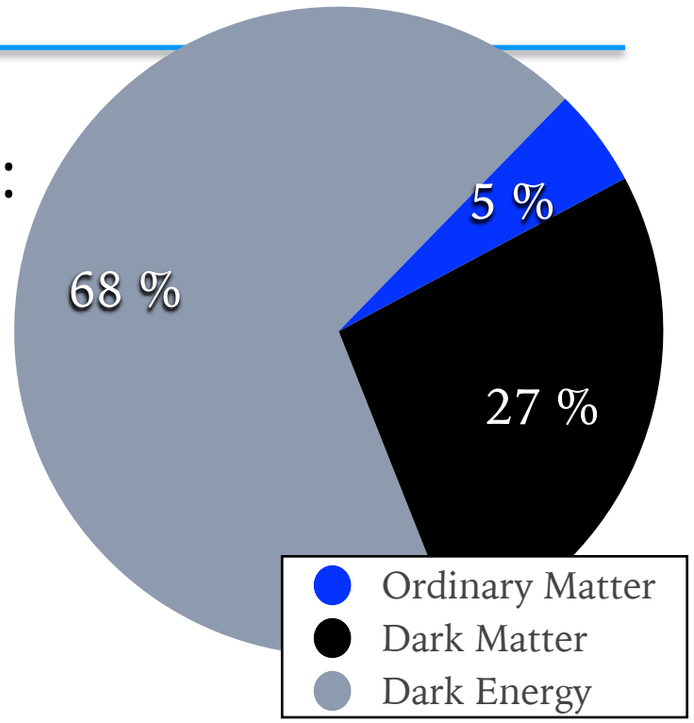
Physics use cases for real time analysis

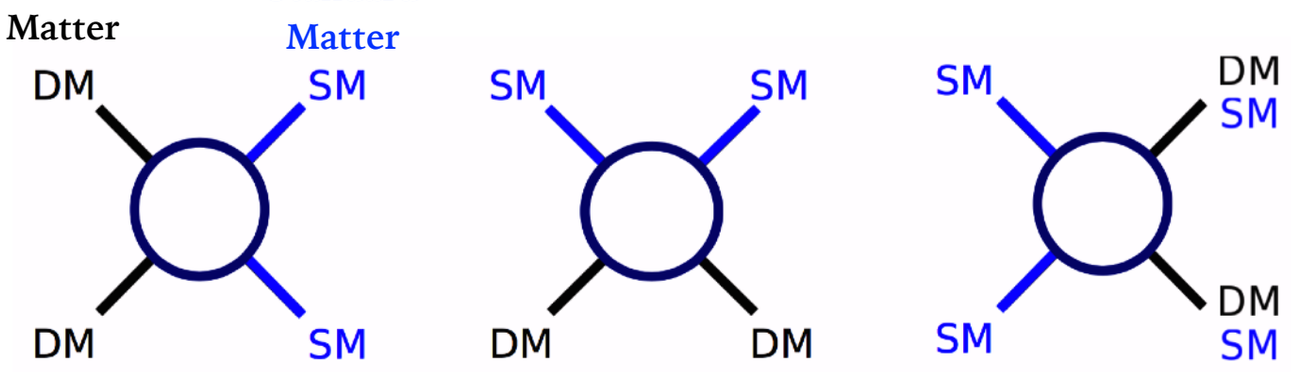
The need for dark matter

Empirical **problem** in the Standard Model of Particle Physics:
no explanation for **Dark Matter**

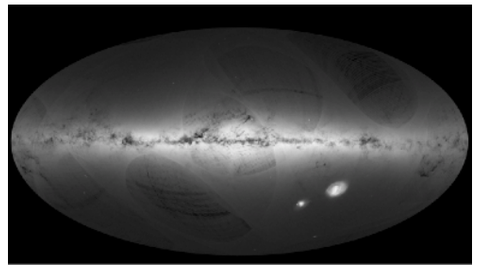
[arXIv:0704.2276v1]

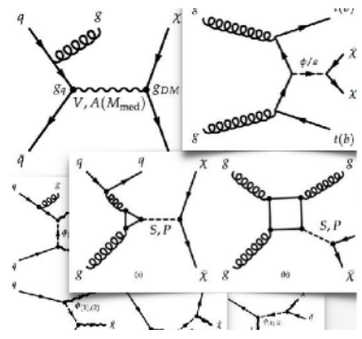
A possible **solution,** guided by **relic density**:
invisible **Dark Matter particles** at the **TeV scale**
(*Weakly Interacting Massive Particles*)





Credit: ESA/Gaia/DPAC.



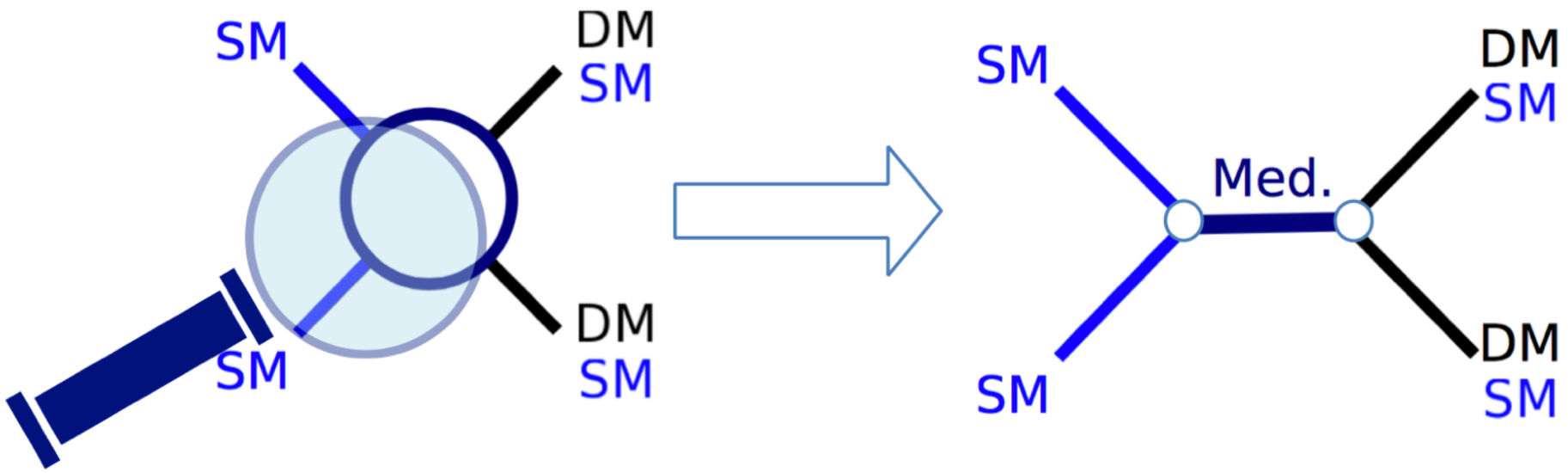


Indirect Detection | Direct Detection | Colliders & accelerators | Astrophysics | Theory

Complementary experimental strategies & inputs

Dark matter mediators at the LHC

If there's a force there's a mediator:
(in this case, with axial vector couplings)

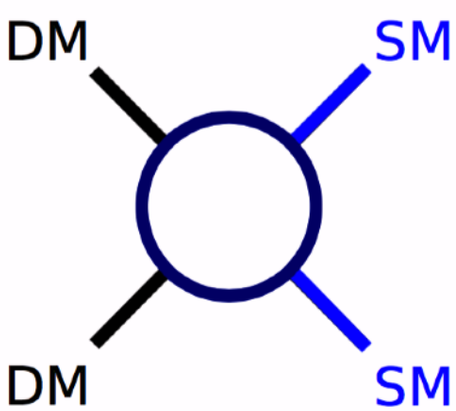


For this kind of models to be consistent with relic density: mediators should have low masses

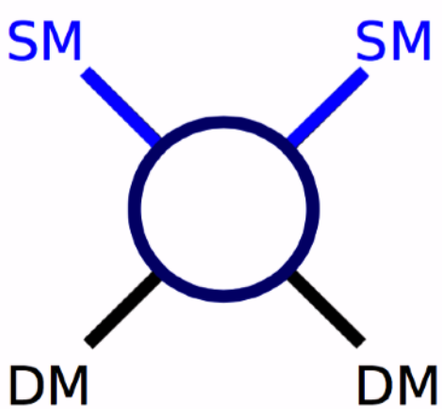
Caveat: very simple picture
See DESY's "Puzzle of Dark Matter" workshop talks for more

Colliders, direct and indirect detection

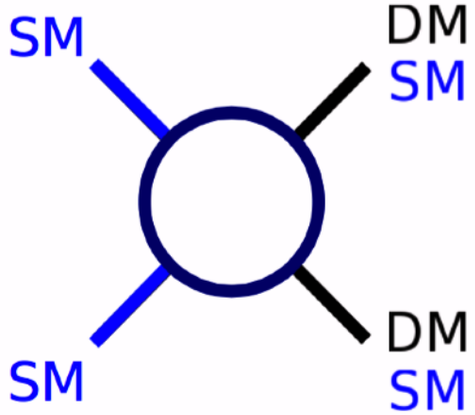
- Why DM discoveries need complementary experiments:
  - DD/ID can discover DM with **cosmological origin**



Indirect Detection



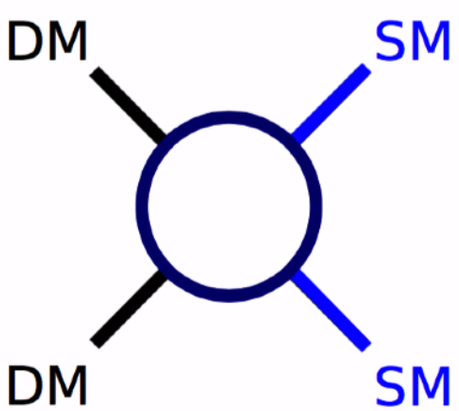
Direct Detection



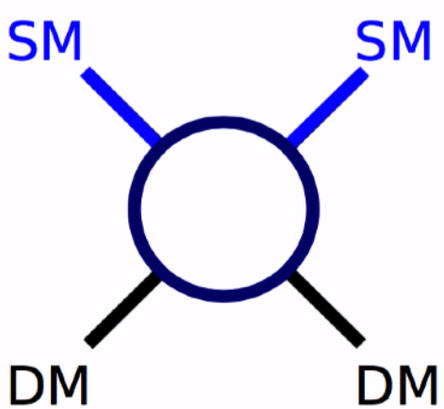
Particle Colliders

Colliders, direct and indirect detection

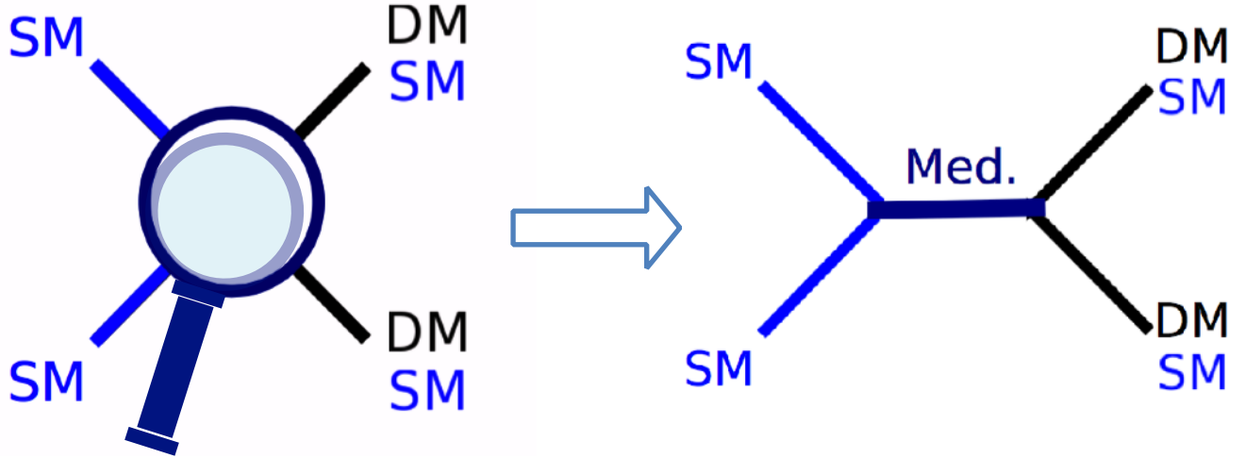
- Why DM discoveries need complementary experiments:
  - DD/ID can discover DM with **cosmological origin**
  - Colliders can produce DM and **probe the dark interaction**



Indirect Detection

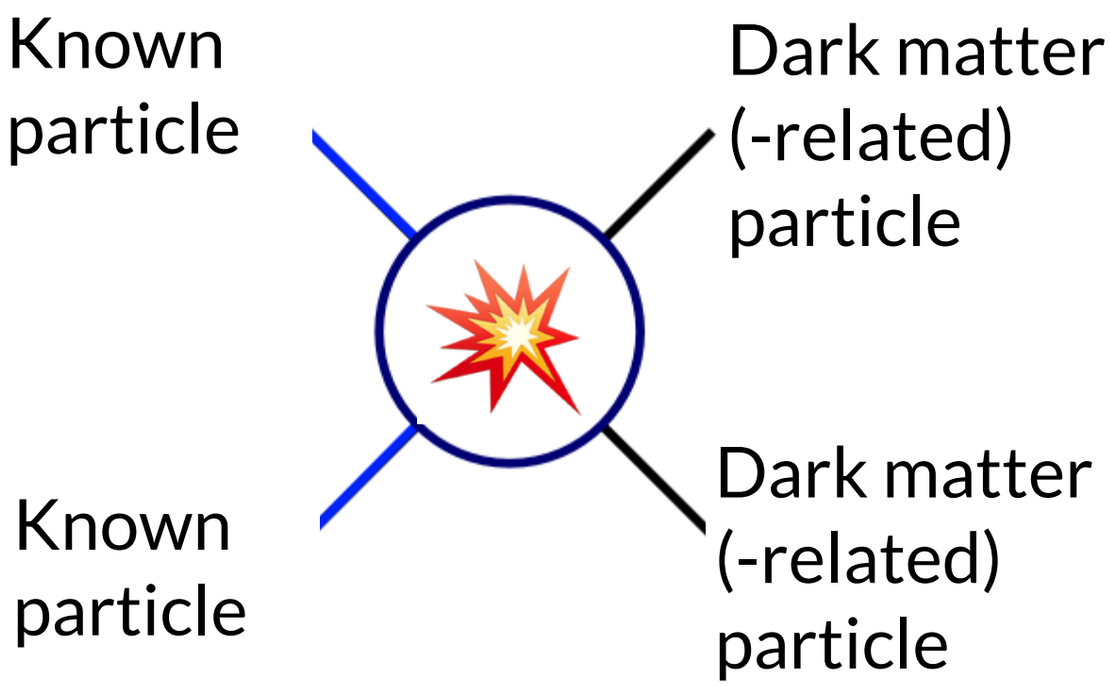


Direct Detection



Particle Colliders

Recreating dark matter in the lab: challenges

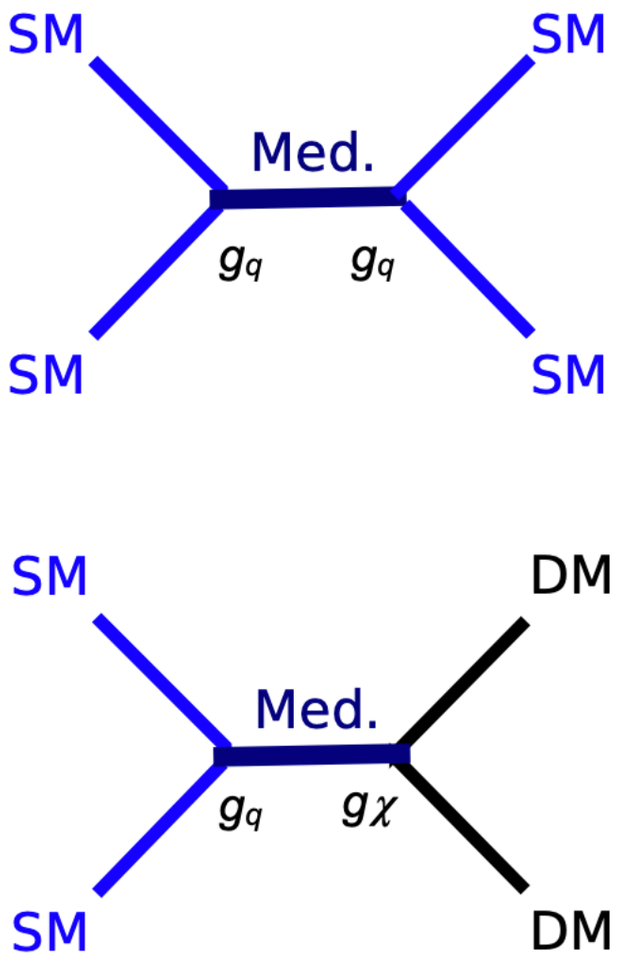


Challenges:

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

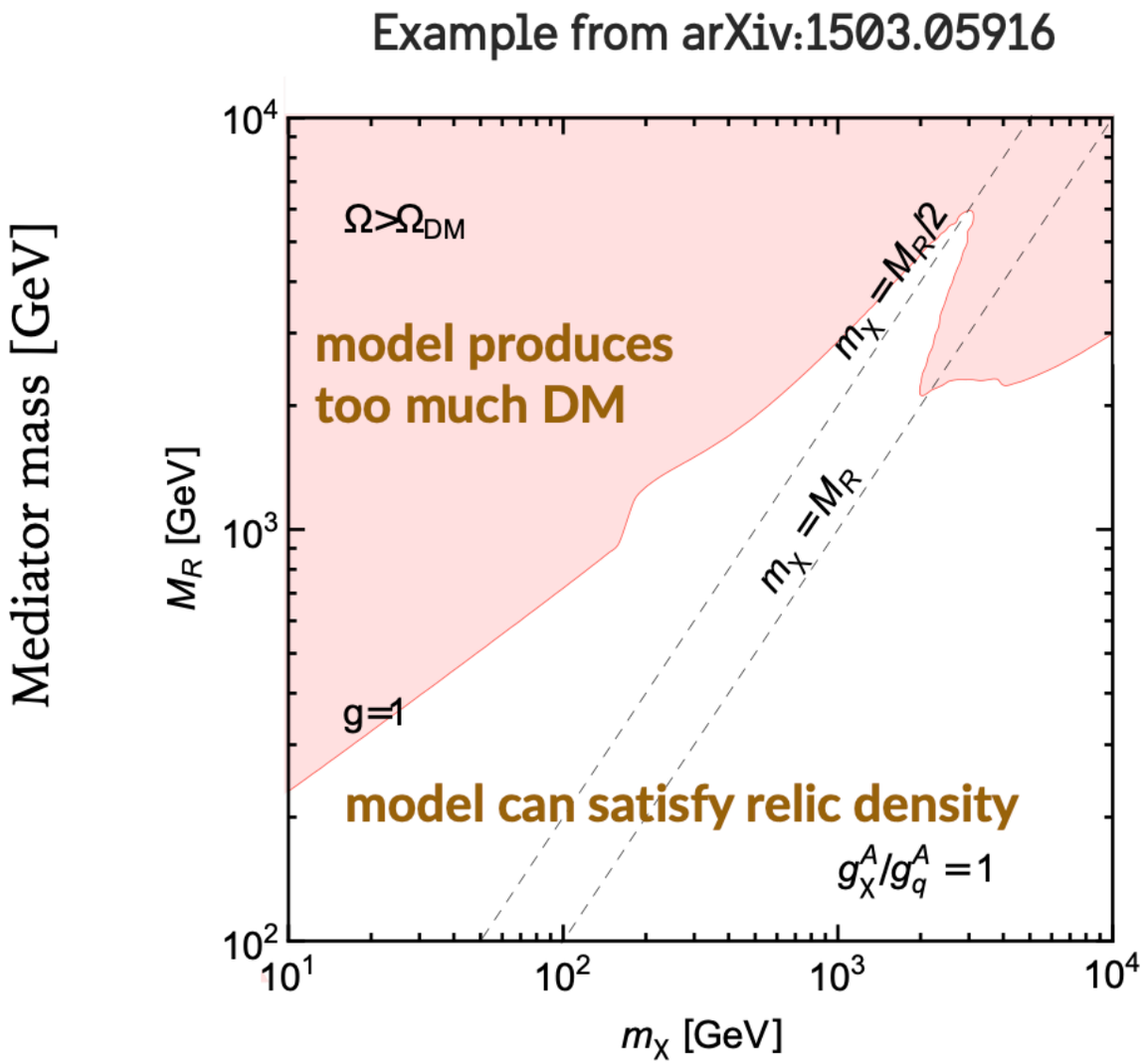
These challenges can be met with real-time analysis!

Dark matter mediators at the LHC



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

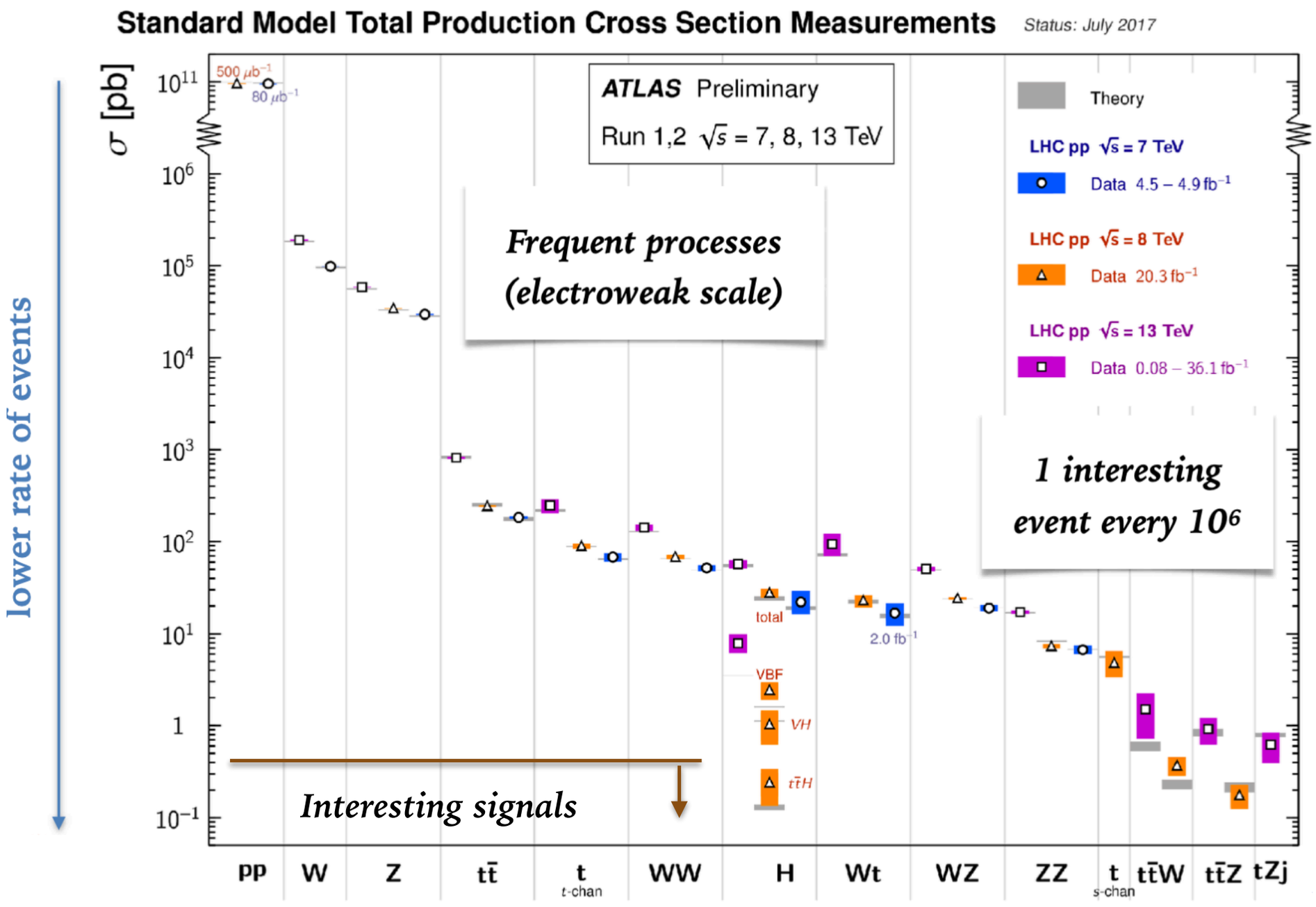
Example from arXiv:1503.05916



Caveat: very simple picture

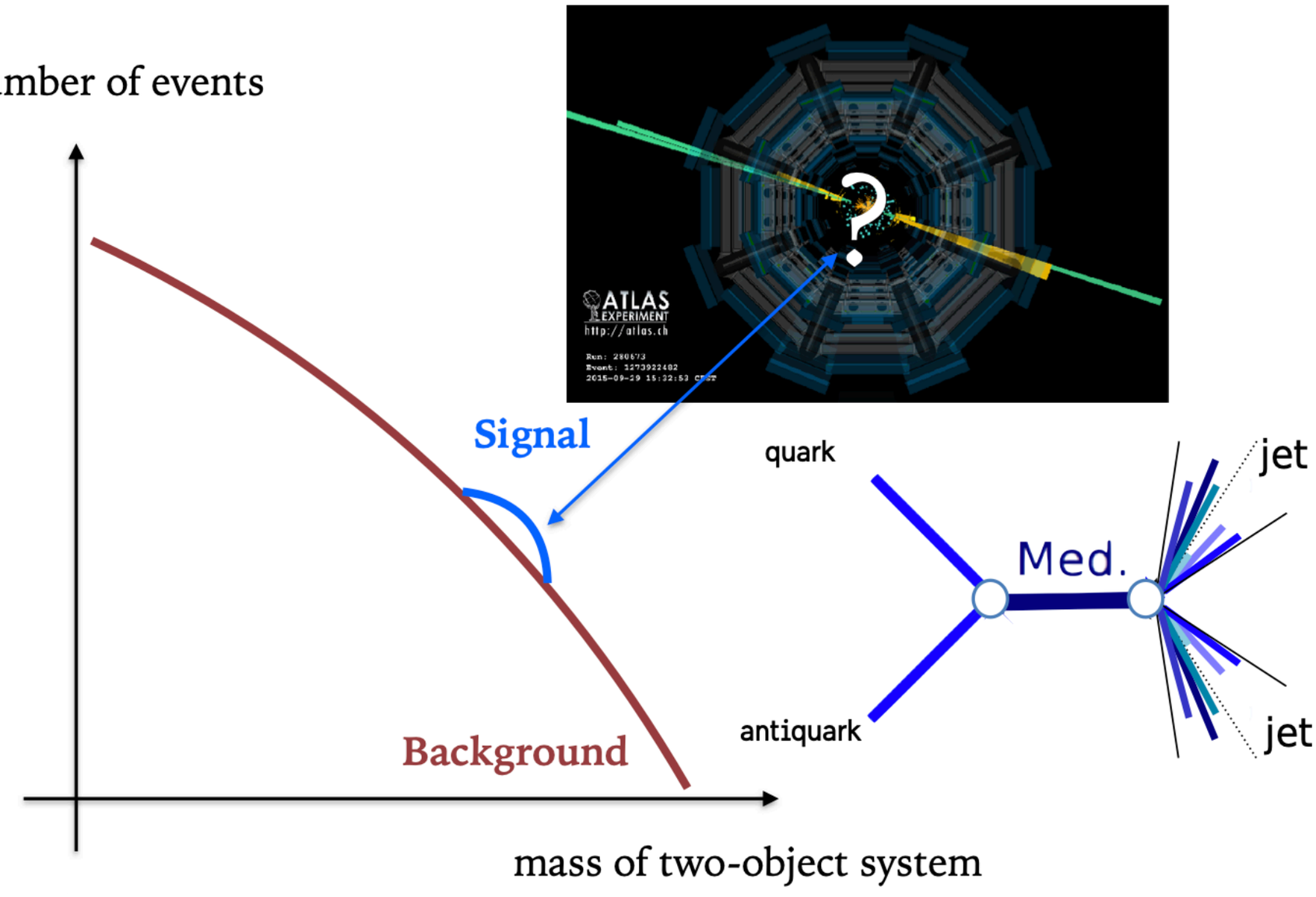
See DESY's "Puzzle of Dark Matter" workshop talks for more

Another look at the Standard Model



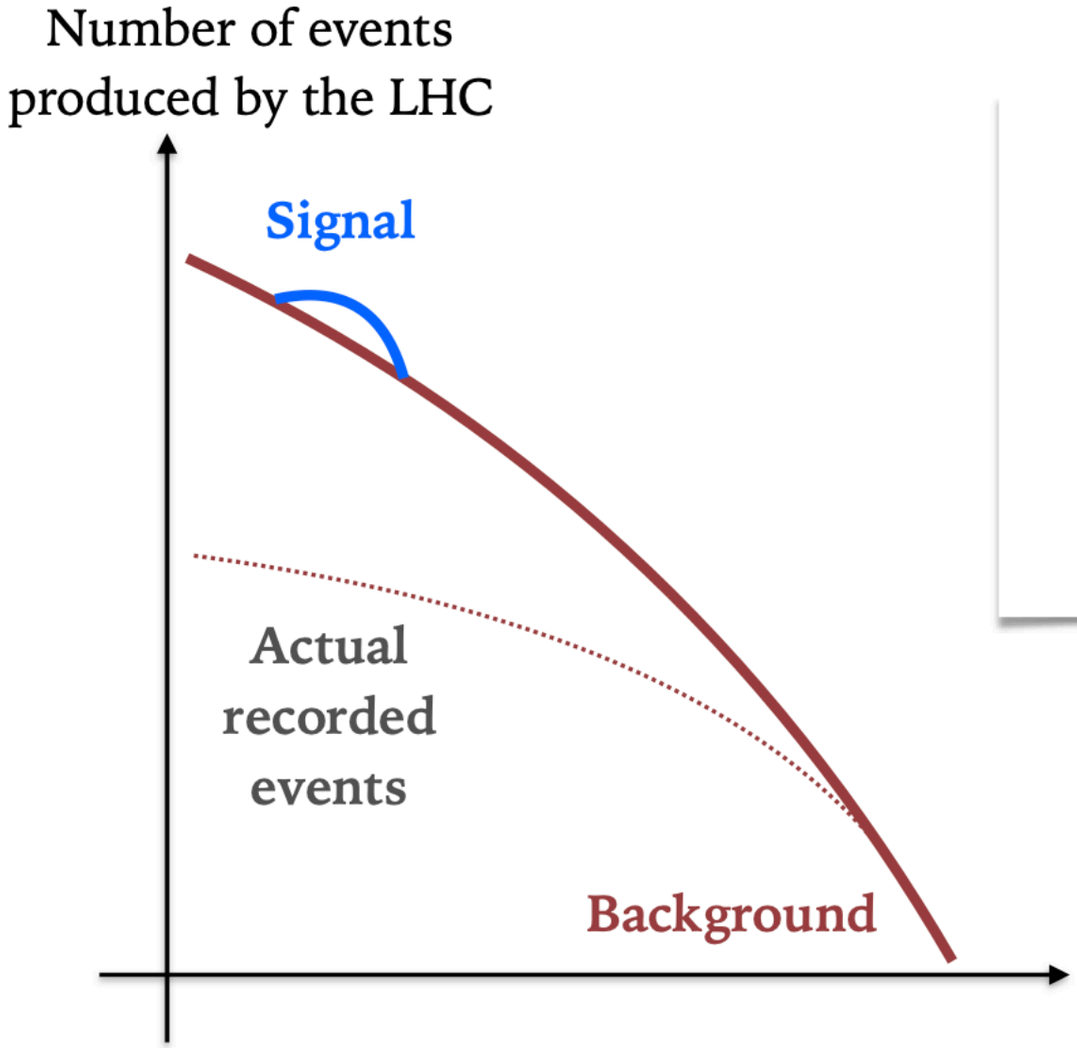
How would new particles manifest?

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



Challenges for new particle searches

Main challenge for resonance searches: large backgrounds and signal that looks very much like background



Impossible to record all events in full

→statistical error harms sensitivity!

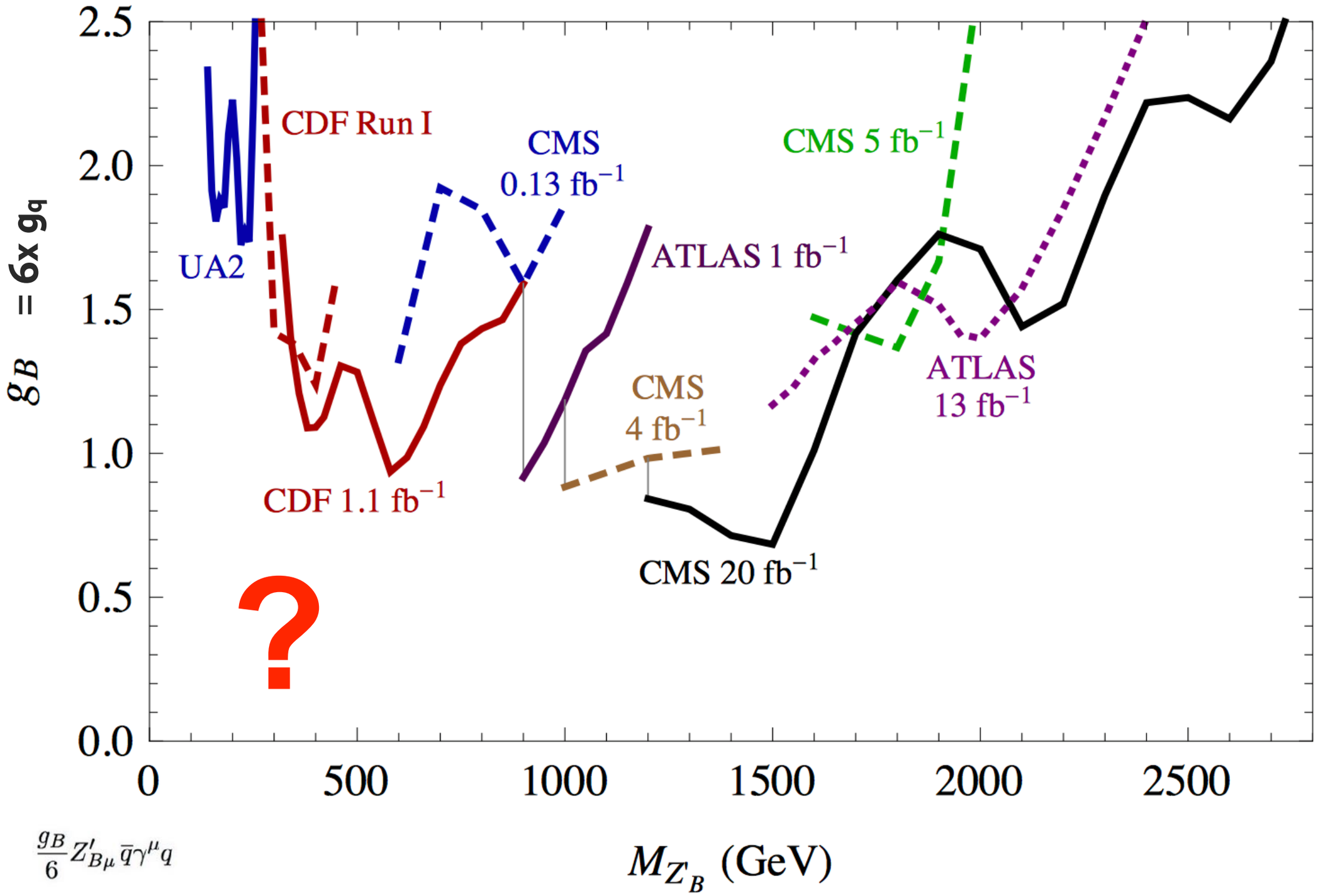
Dijet Resonances: Constraints on Coupling Values vs. Mass, 2013

A. Boveia, LBL workshop

Dobrescu, Yu Phys Rev D 88 035021 (**2013**)

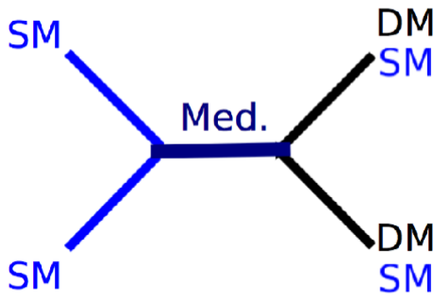
lower rate of events

Coupling of new particle to quarks

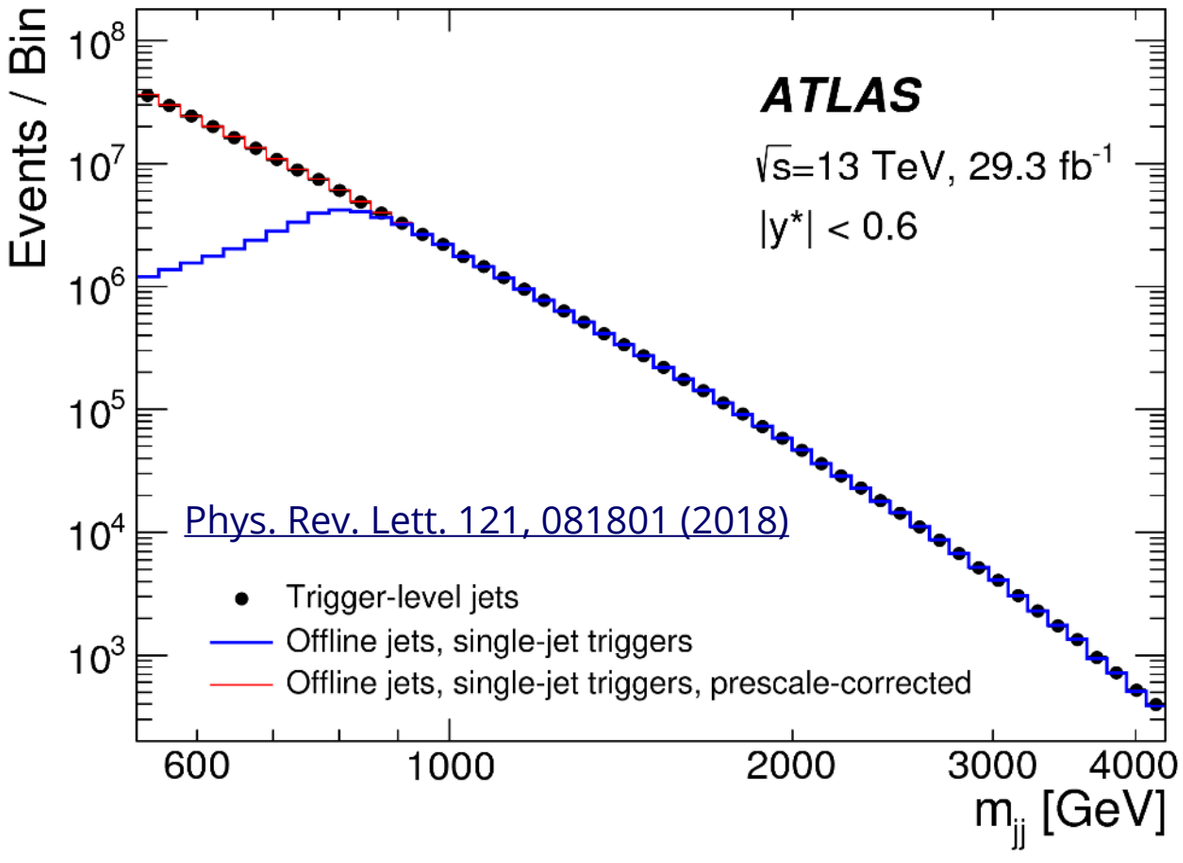


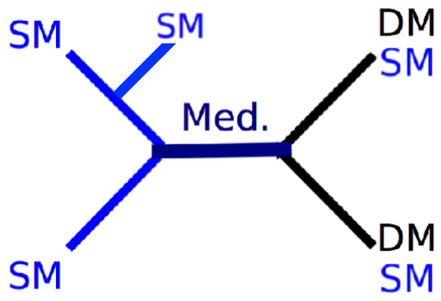
the LHC was not probing for di-jet resonances at the EW scale

ATLAS/CMS results on DM mediator searches

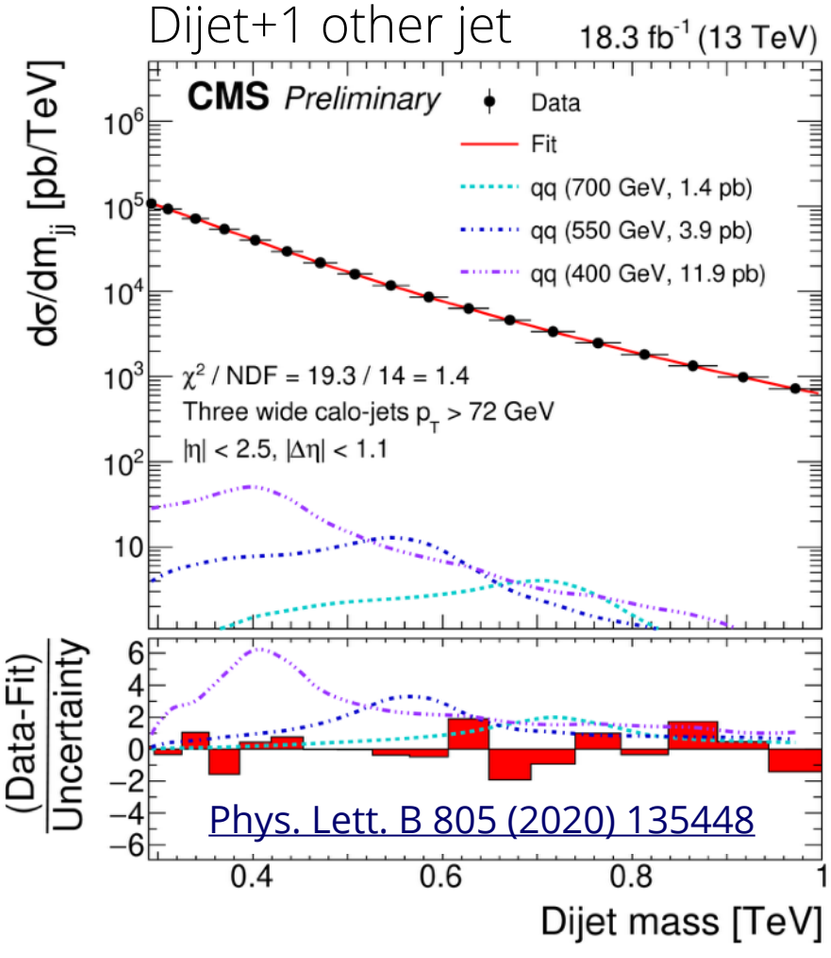


Dijet+anything





Dijet+1 other jet

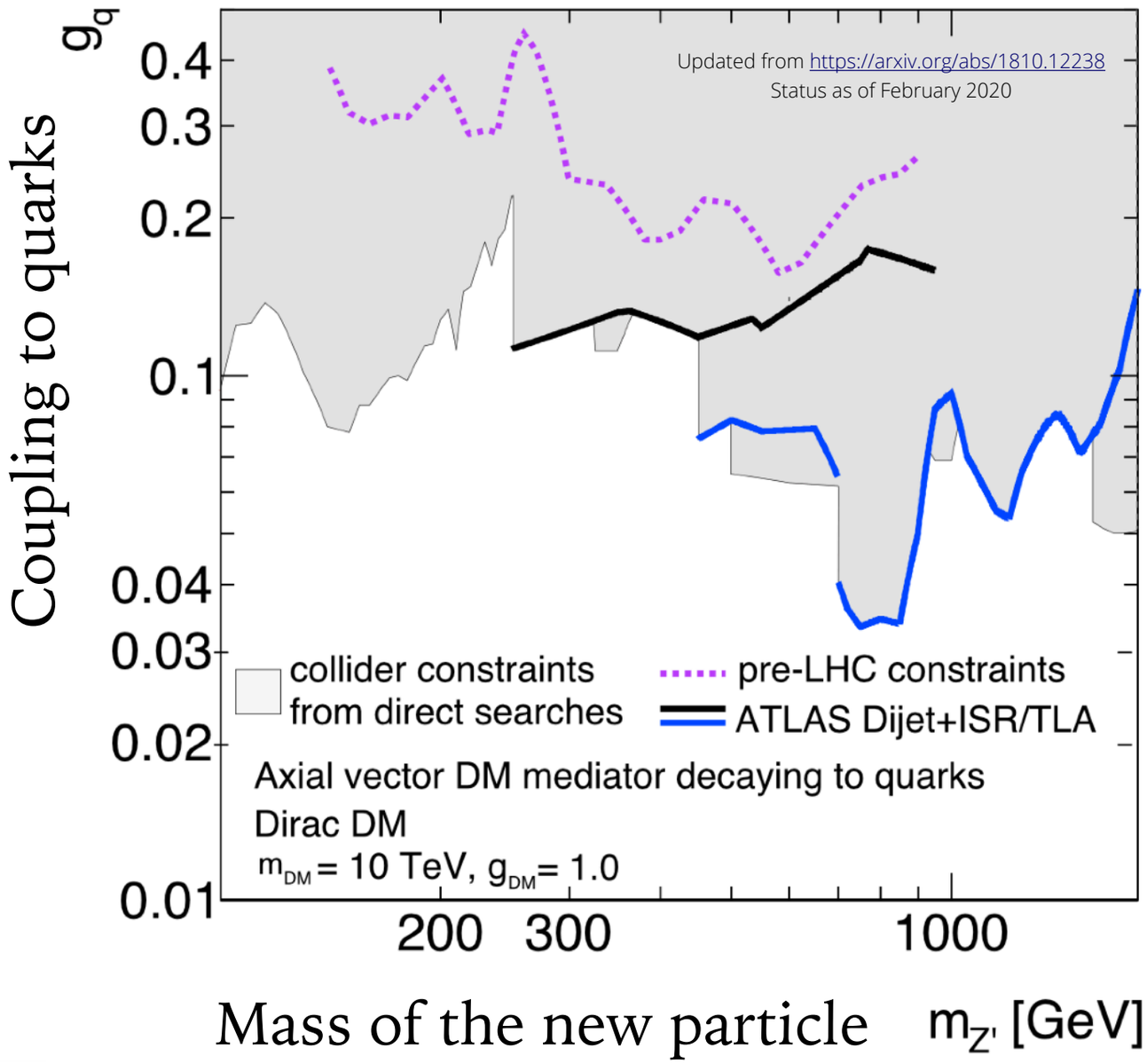


Mass reach limitation by hardware trigger…

…can also be overcome by choosing other signatures!

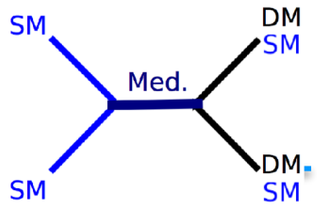
CMS and ATLAS are closing the gap at low masses

Summary of public material from ATLAS and CMS, plot by C. Doglioni / W. Kalderon
Apologies for ATLAS-centricity! CMS results are equally sensitive

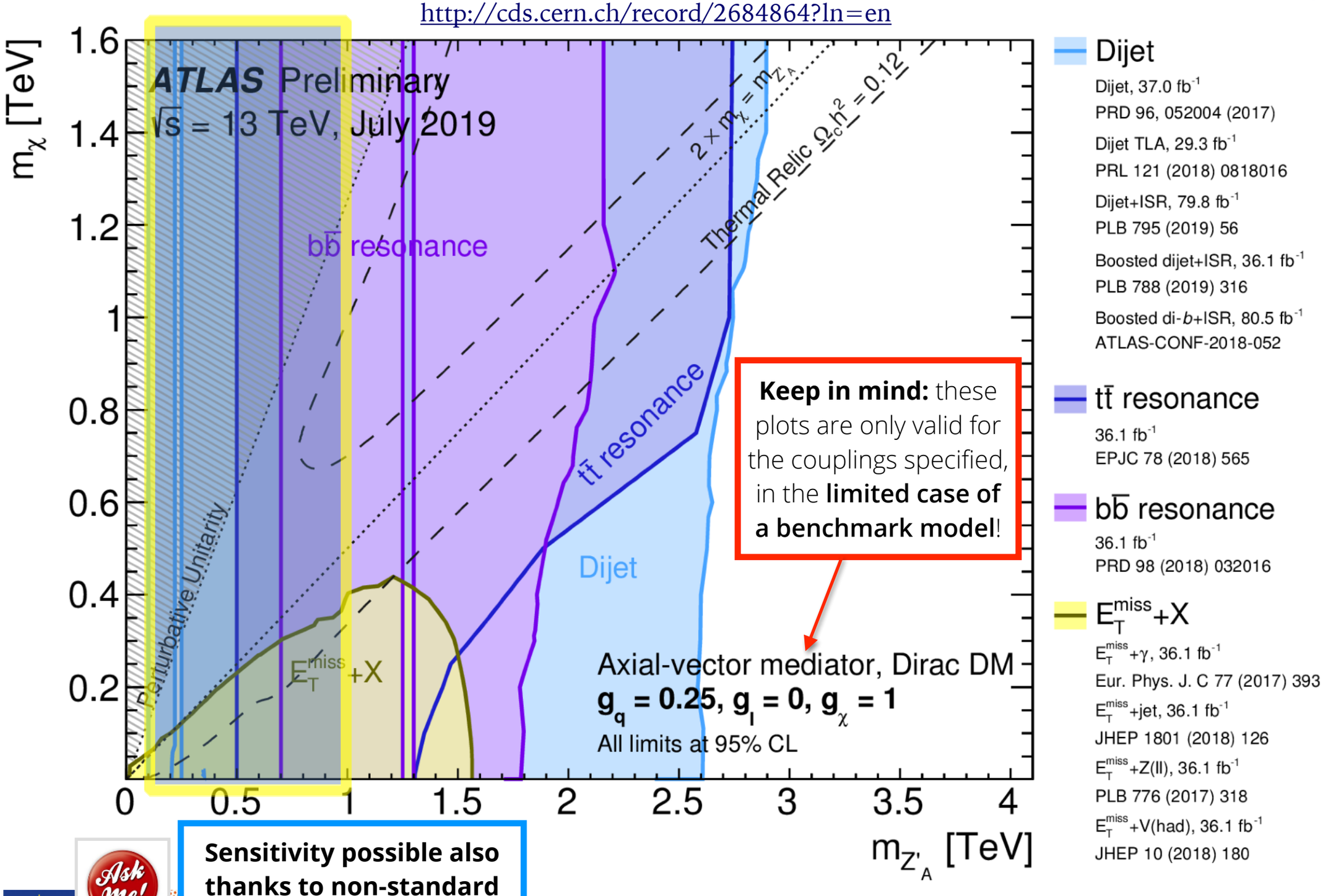


real-time analysis

Visible/invisible searches for DM (mediators)



http://cds.cern.ch/record/2684864?ln=en

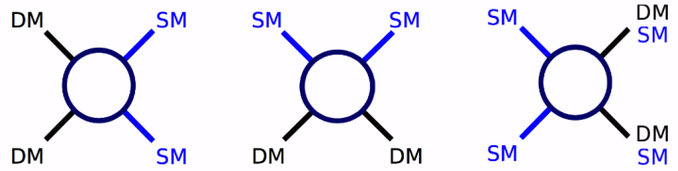


Keep in mind: these plots are only valid for the couplings specified, in the **limited case of a benchmark model**!

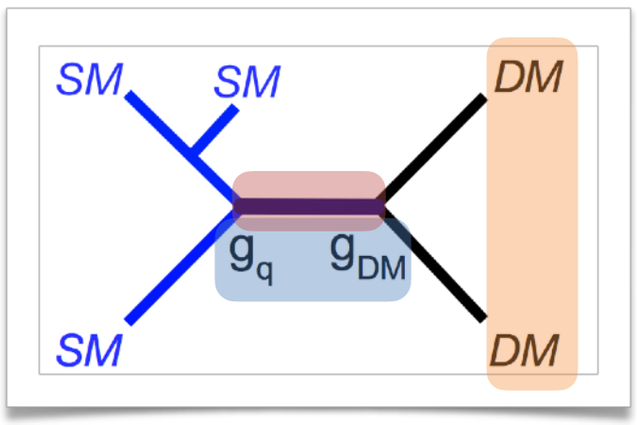
Sensitivity possible also thanks to non-standard analysis workflows

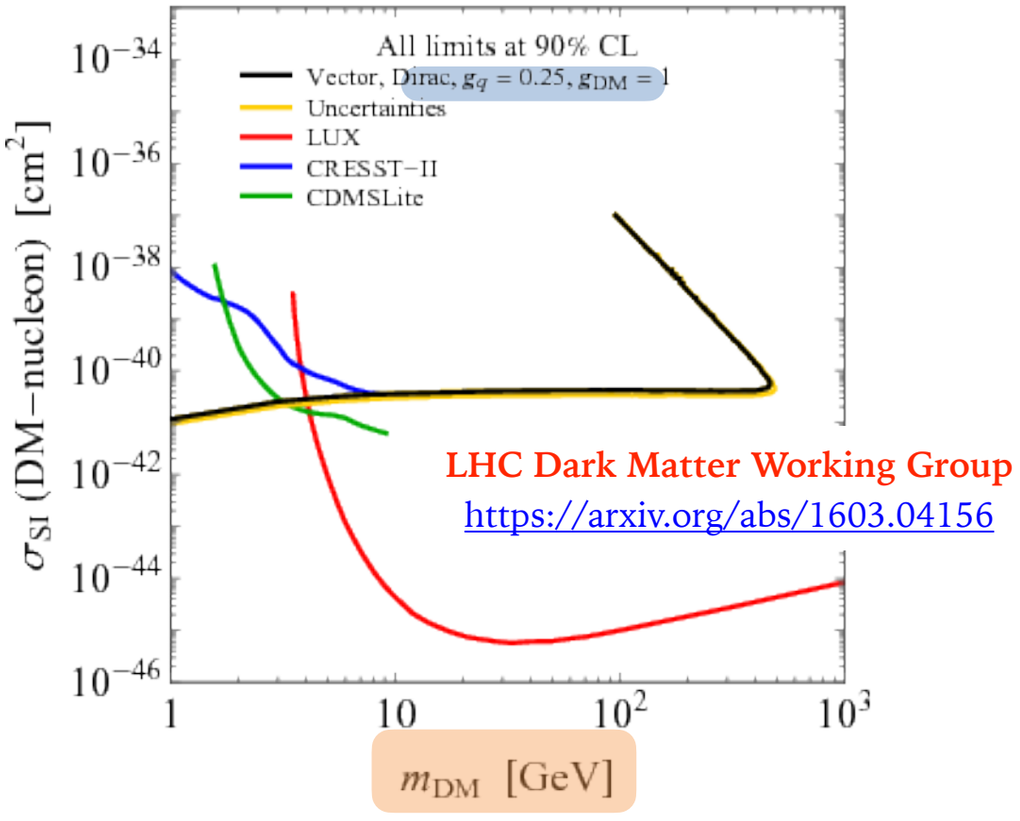
Complementarity of DM experiments

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



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
https://arxiv.org/abs/1603.04156

For more thoughts on upper bounds to collider sensitivity:
arXiv:1810.07705 and DMWG meeting June 2017

Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**
(work started in ATLAS together with Manchester colleagues: how to visualize different assumptions?)

Complementarity of DM experiments

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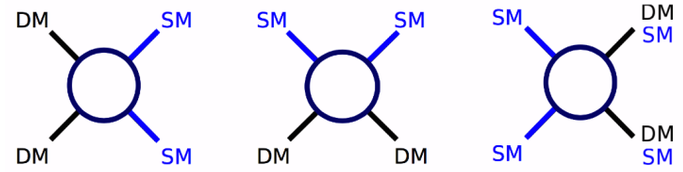

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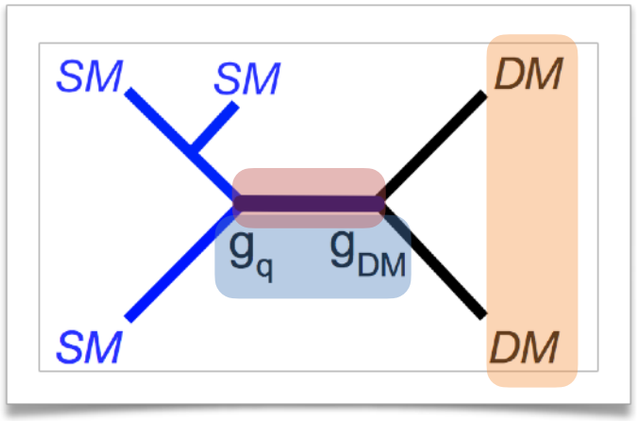

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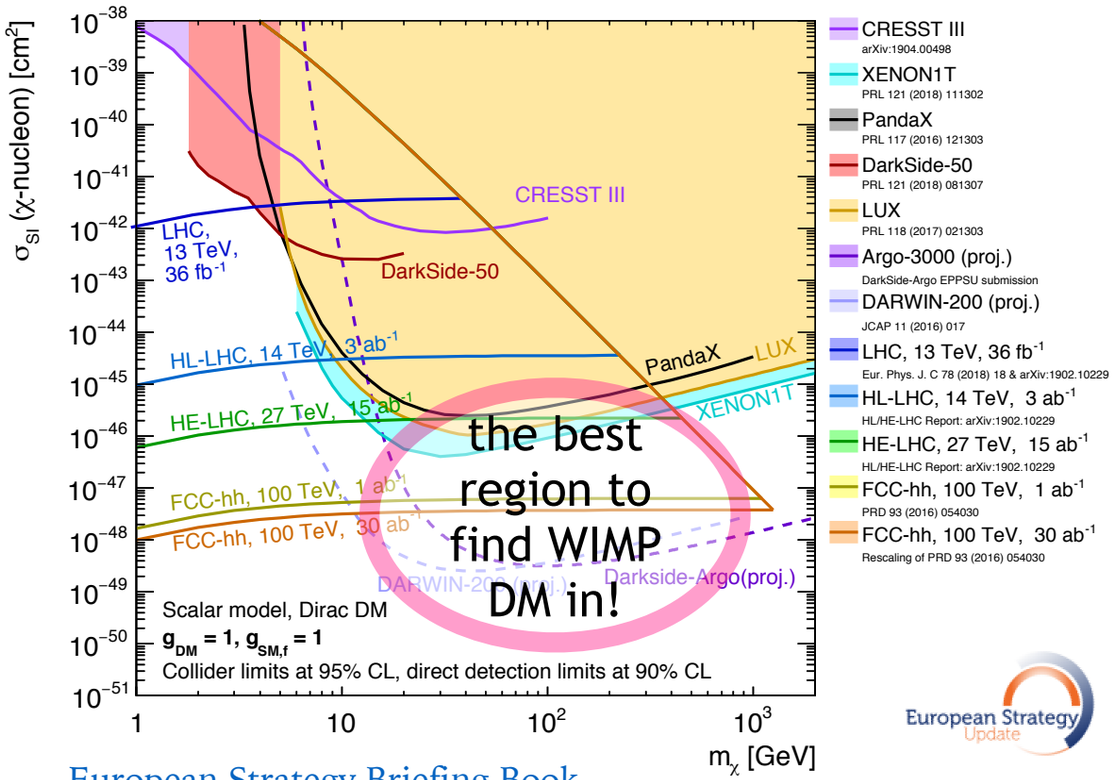
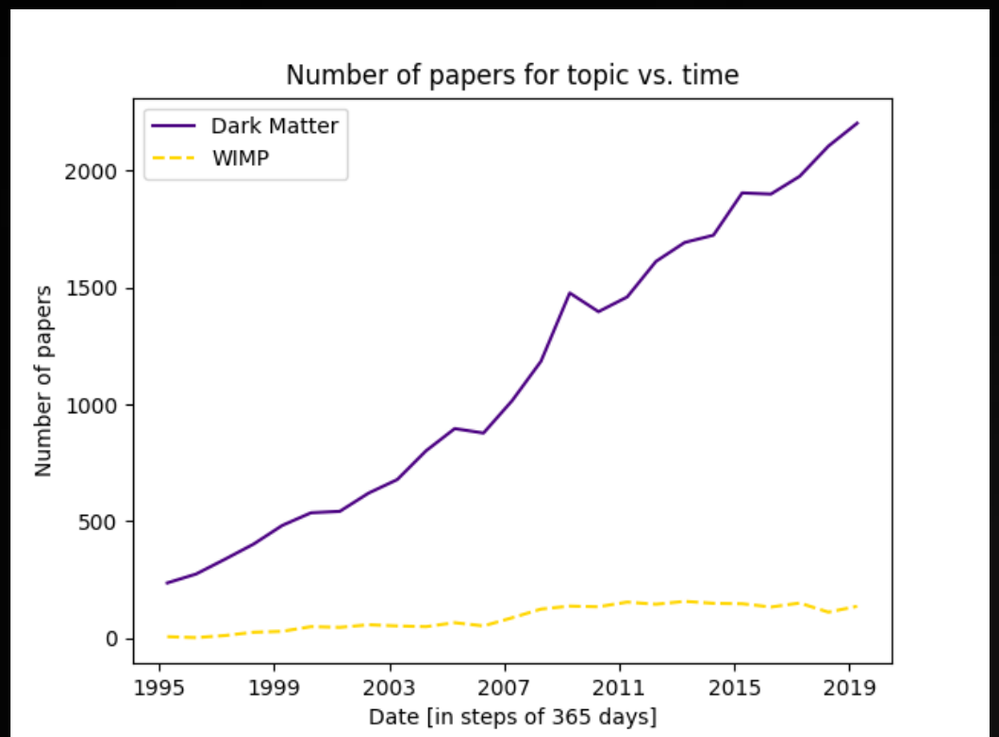


European Strategy Briefing Book

Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**
(work ongoing in ATLAS together with UK/US colleagues: how to visualize different assumptions?)

Are we looking everywhere?

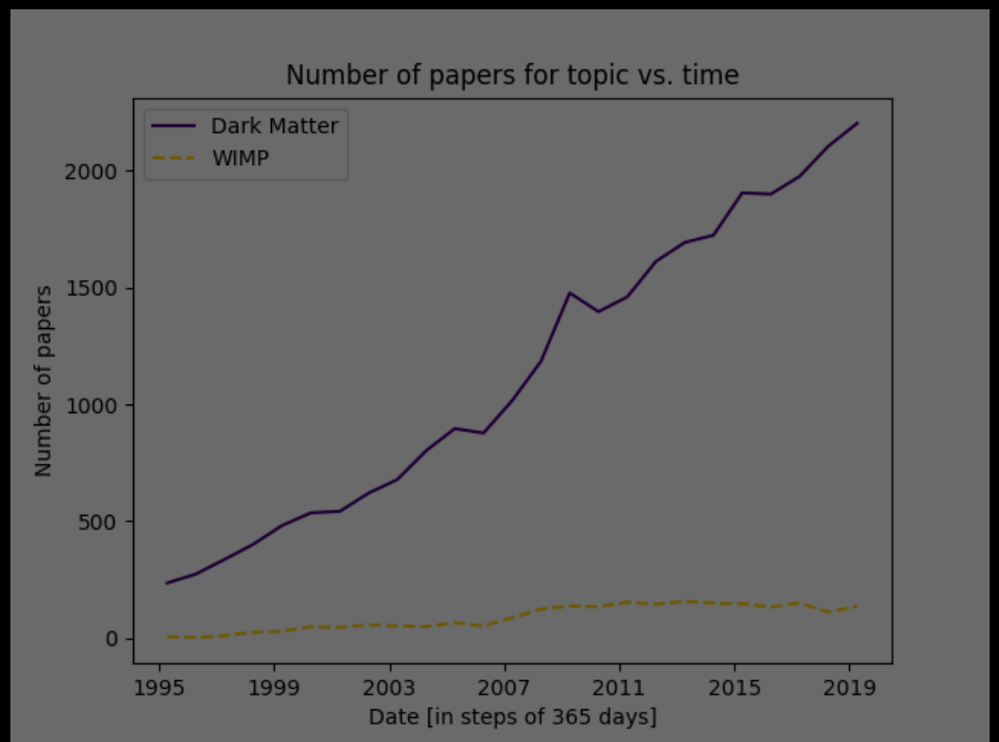


What might we learn from lines of research that are off the beaten track? They check accepted ideas, always a Good Thing, and there is the chance Nature has prepared yet another surprise for us.

J. Peebles

WIMP

Are we looking everywhere?



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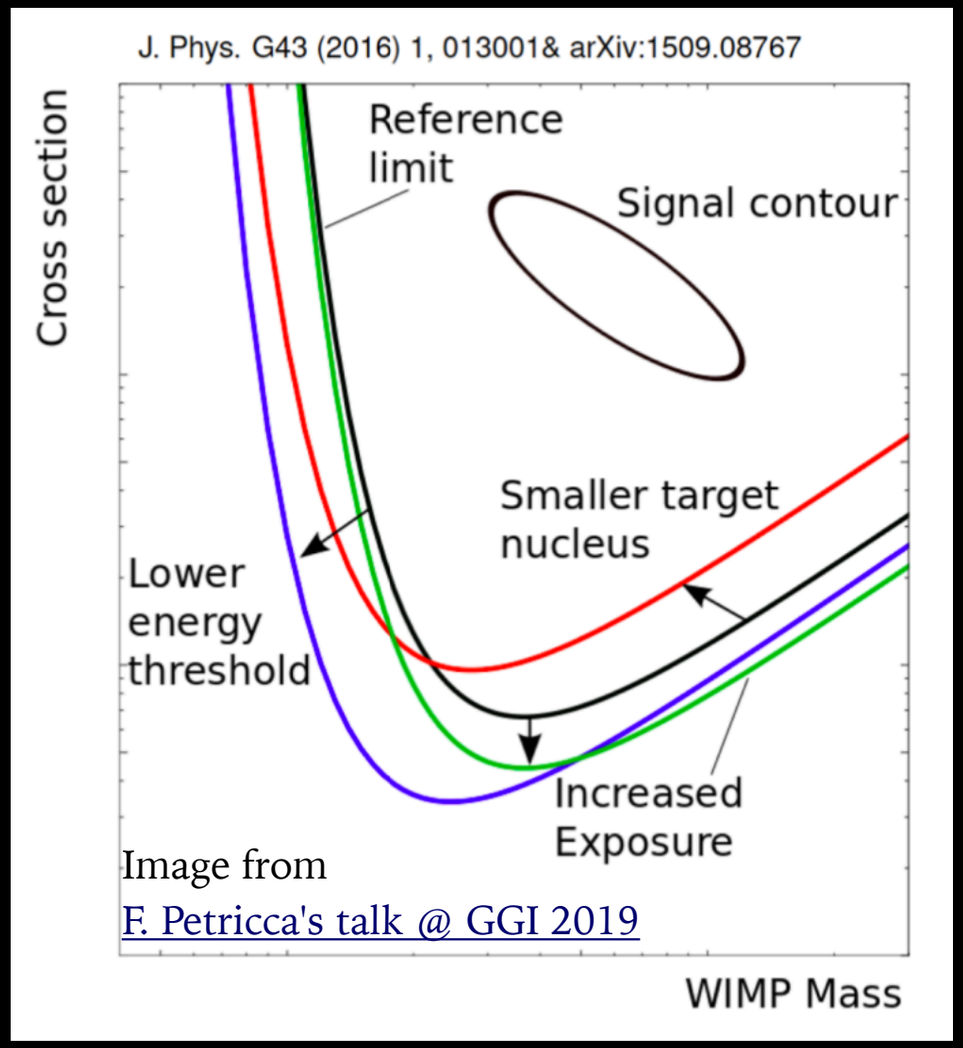
J. Peebles

left: lower masses

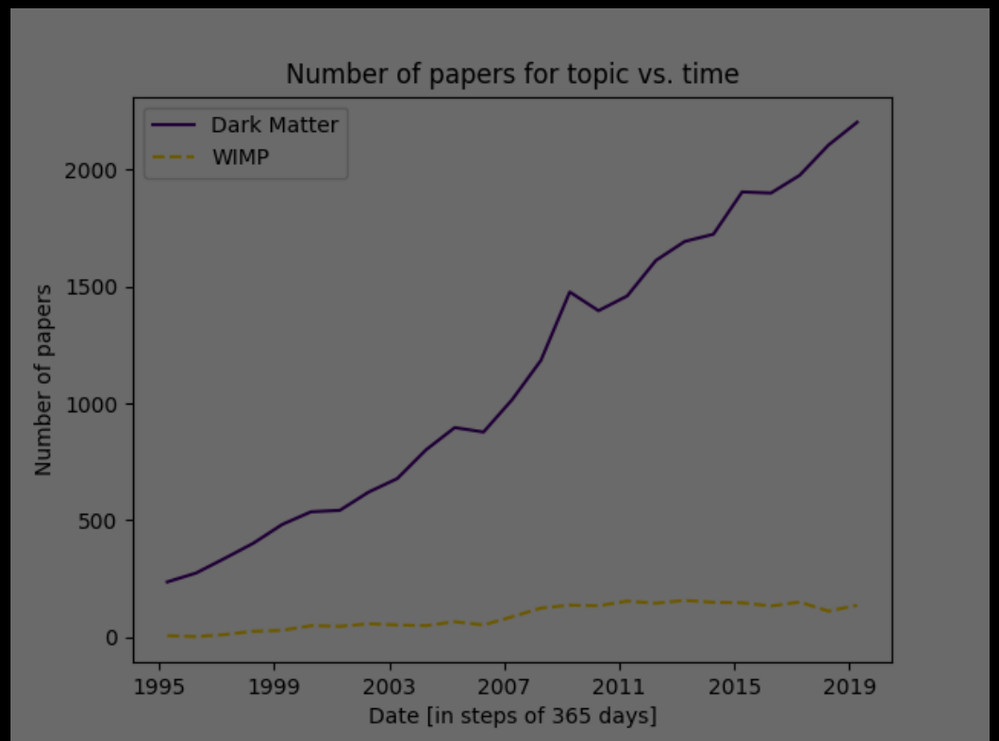
up: stronger interactions



right: more massive objects

Are we looking everywhere?

up: stronger interactions



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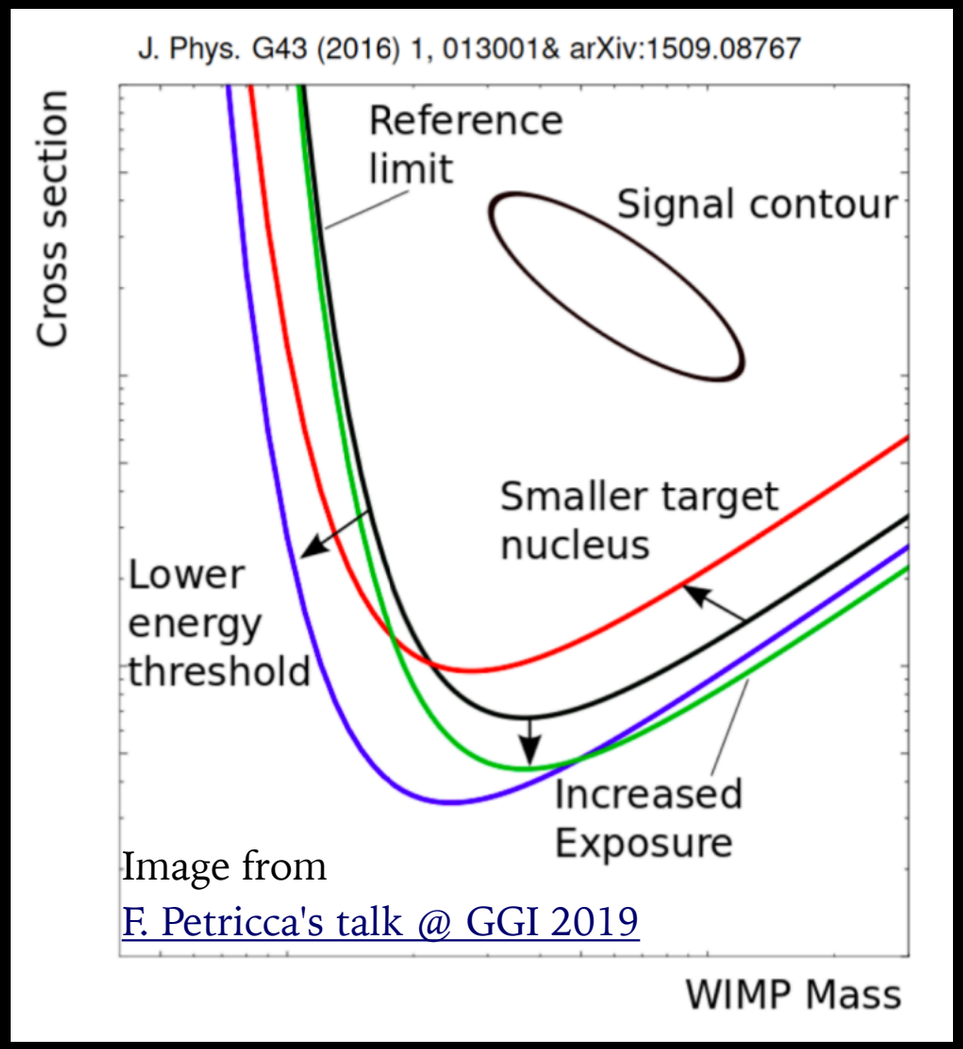
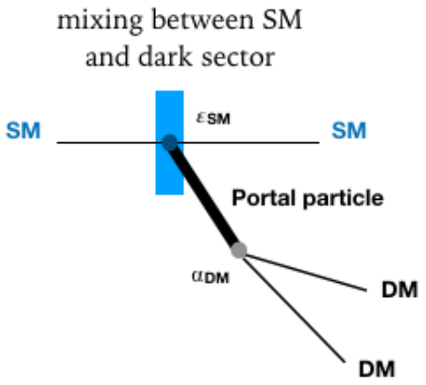


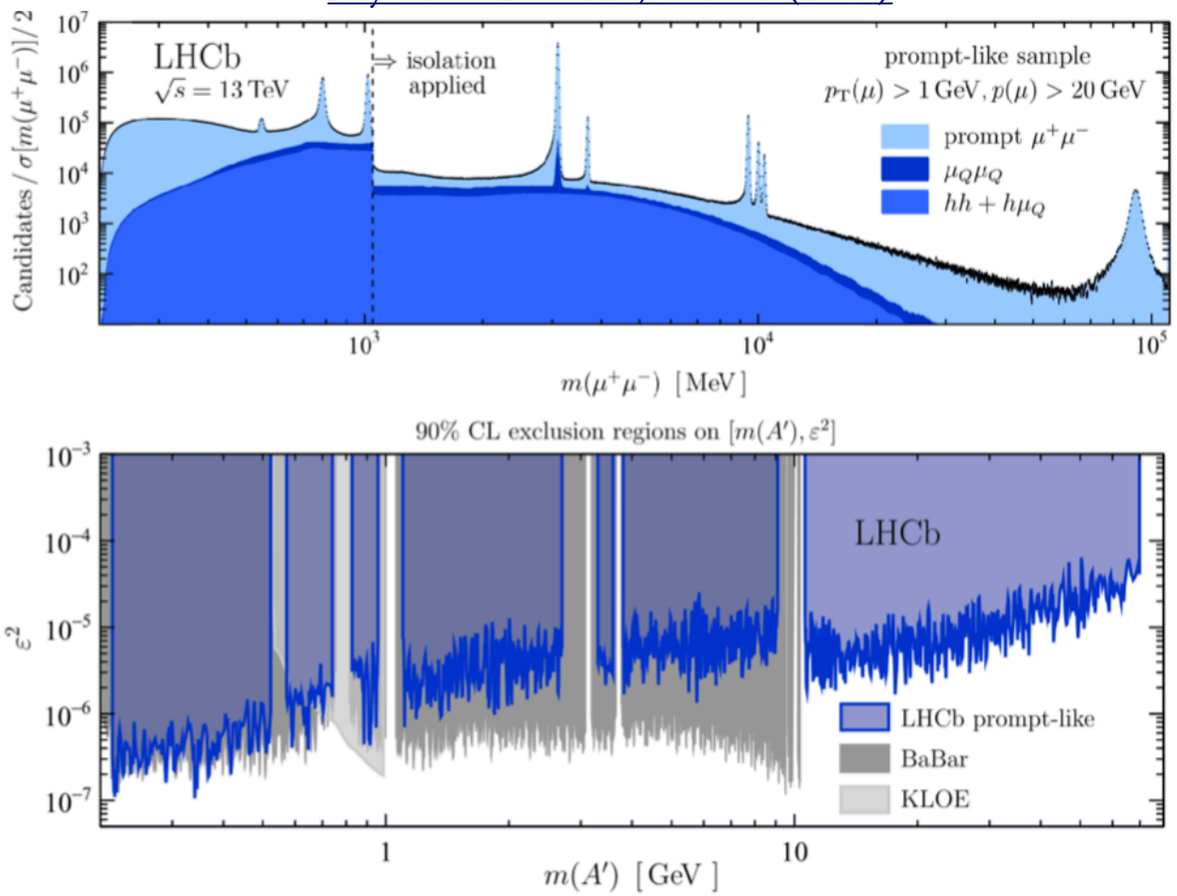
right: more massive objects

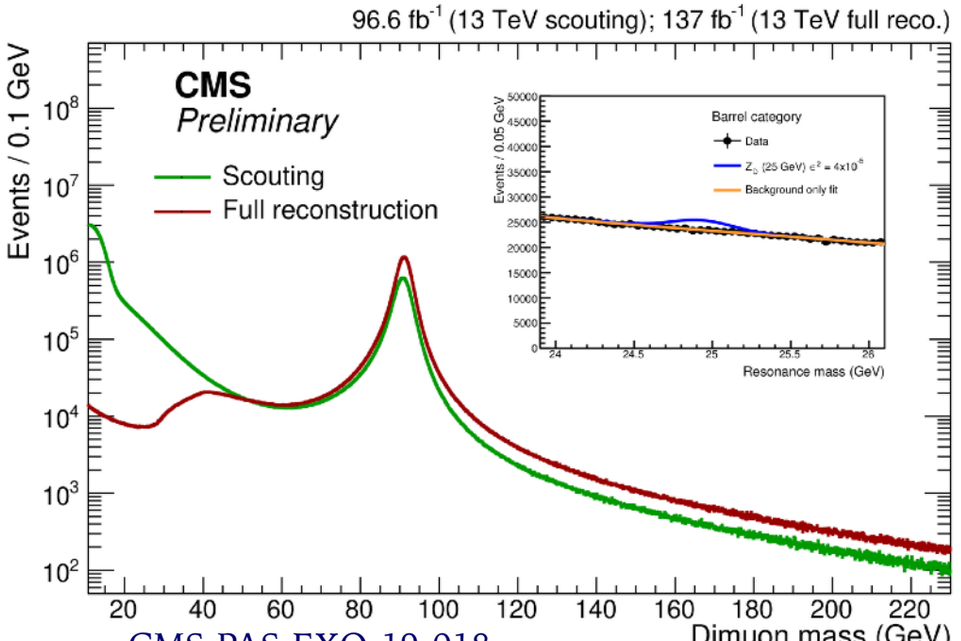
Visible decays of dark photon: LHCb and CMS



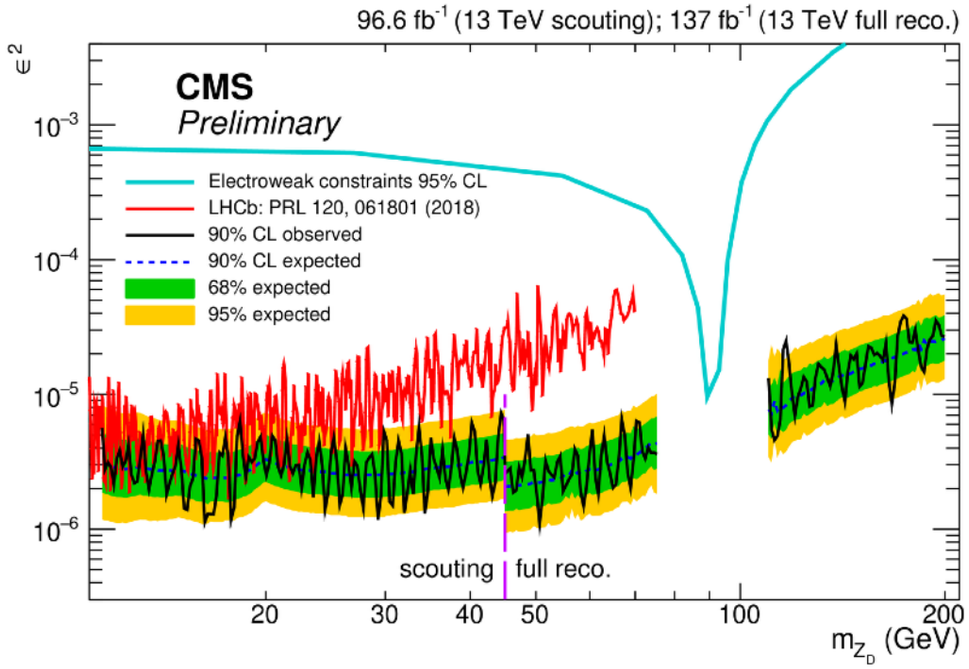
Dark photon → *dimuon* searches face the same problem as dijet searches at masses below the Z
→ **large benefits from RTA**

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





CMS-PAS-EXO-19-018



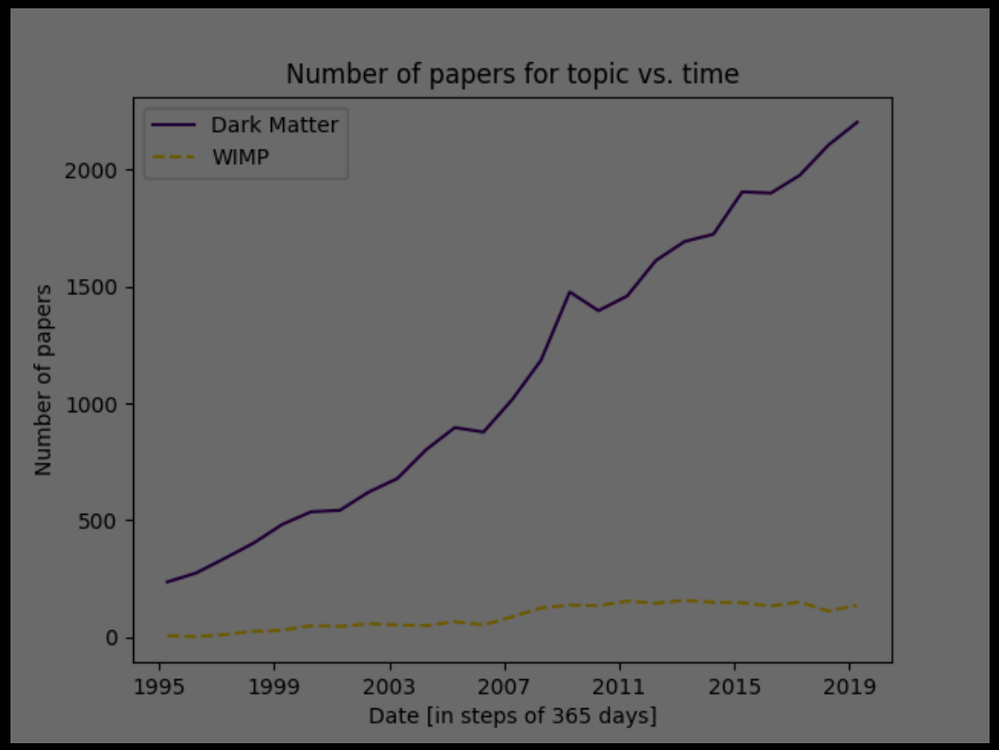
Run-3 prospects in arXiv:1509.06765

Are we looking everywhere?

up: stronger interactions

left: lower masses

right: more massive objects



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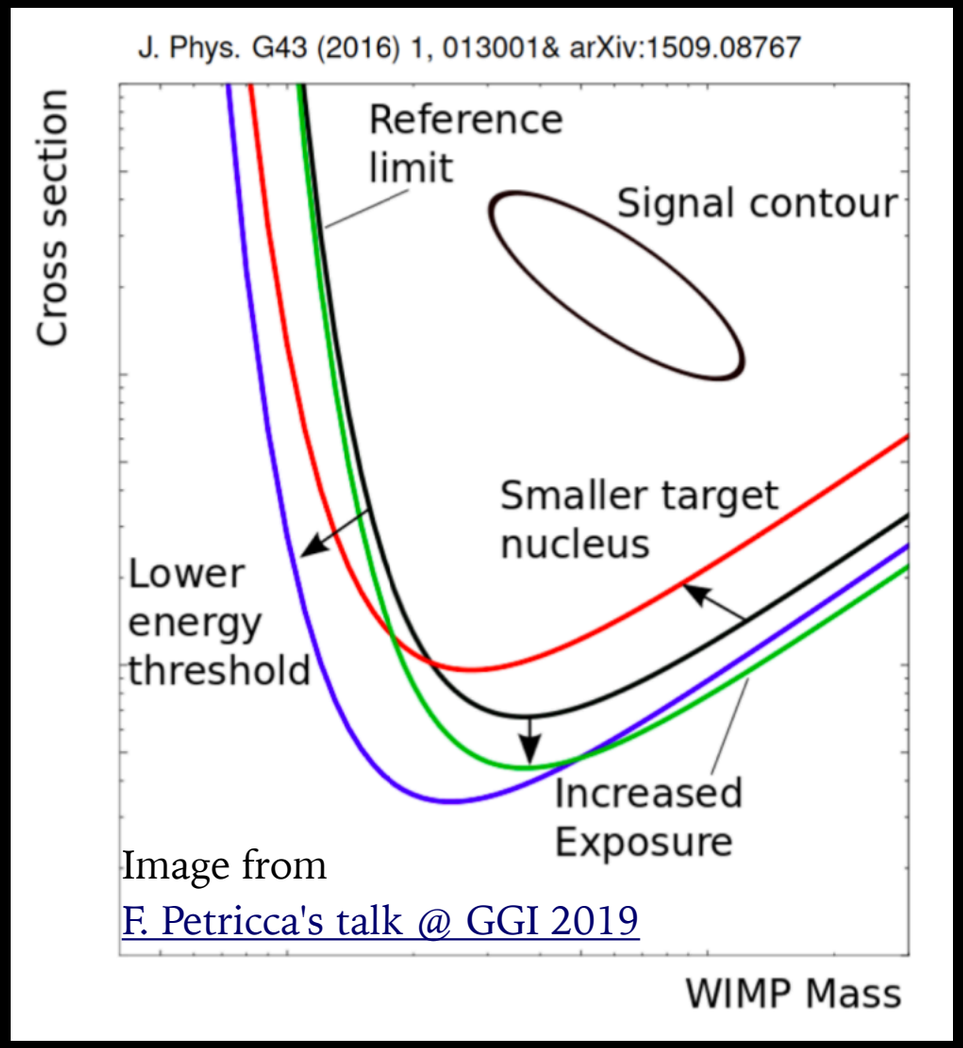
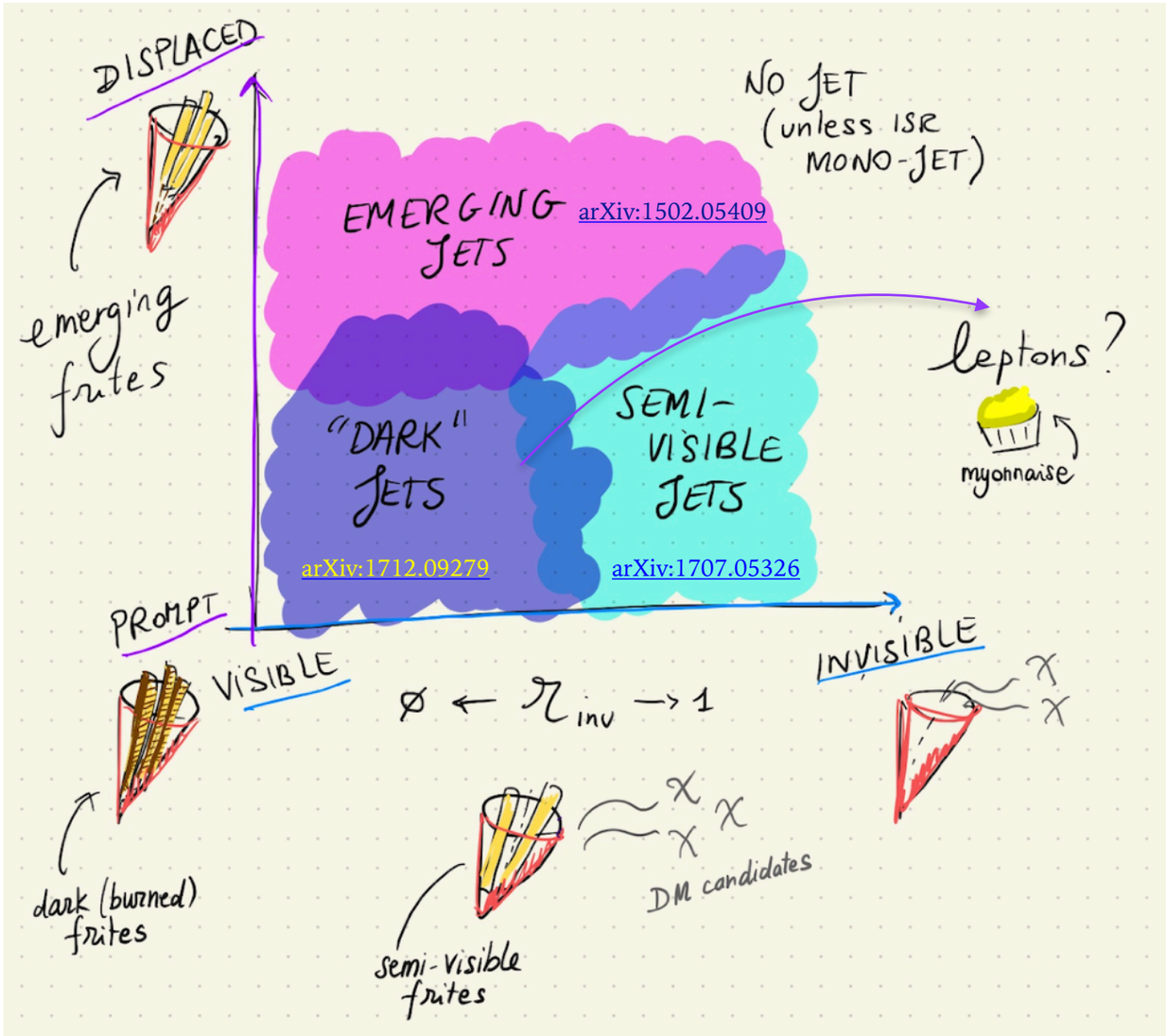


Dark sectors ⇒ non-standard jets



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

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

Going beyond the "low-hanging fruit":

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

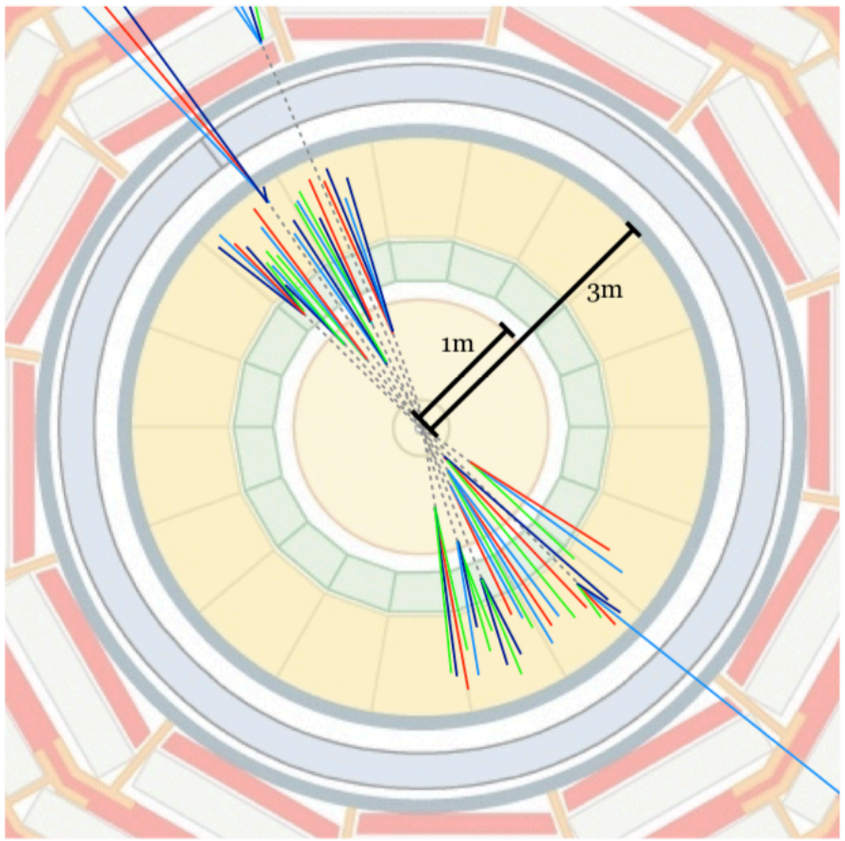
A family of signatures, with DM particles (& more) in the dark shower
⇒ need more than simple RTA!

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

Example of "dark shower" search @ LHC

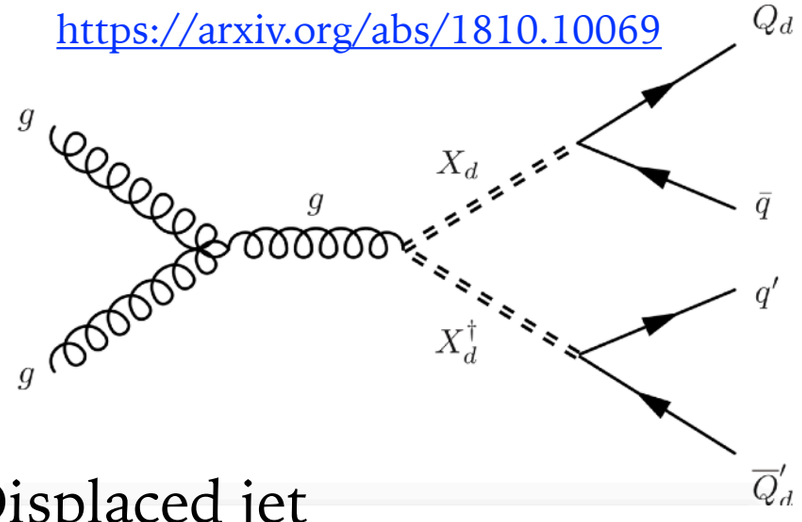
Theory:
a variety of models for "*dark QCD*"
stable *dark hadron* = DM candidate
example: emerging jets

https://arxiv.org/pdf/1502.05409.pdf



Experiment: select events
with regular & displaced jets

https://arxiv.org/abs/1810.10069

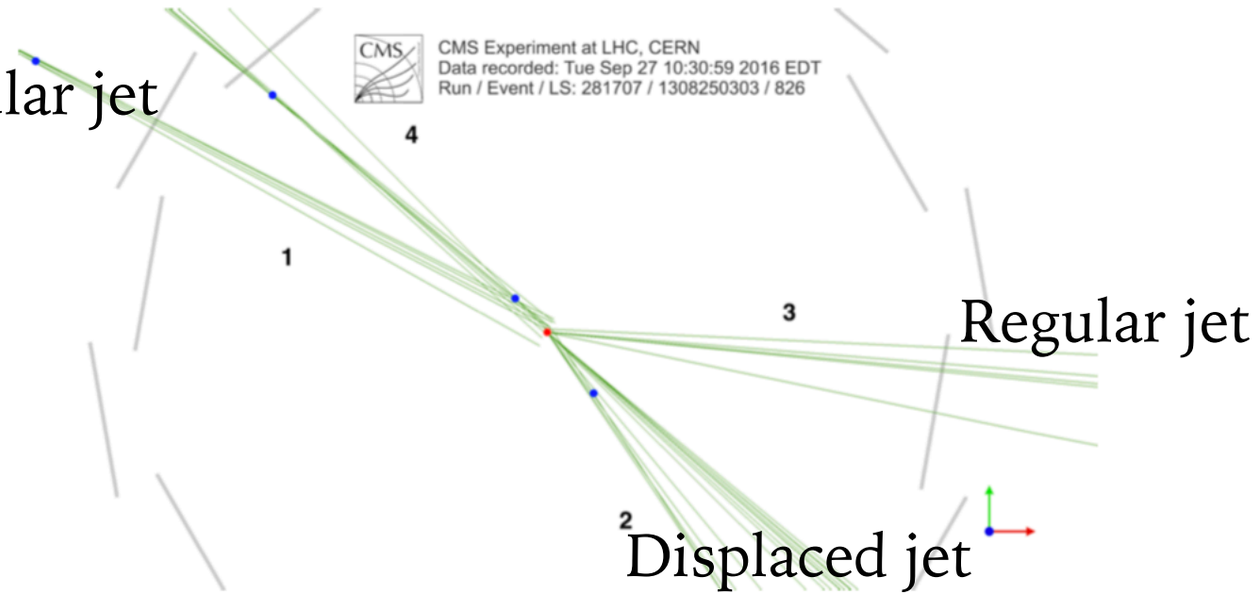


Regular jets

Emerging jets

Displaced jet

Regular jet



Regular jet

Displaced jet

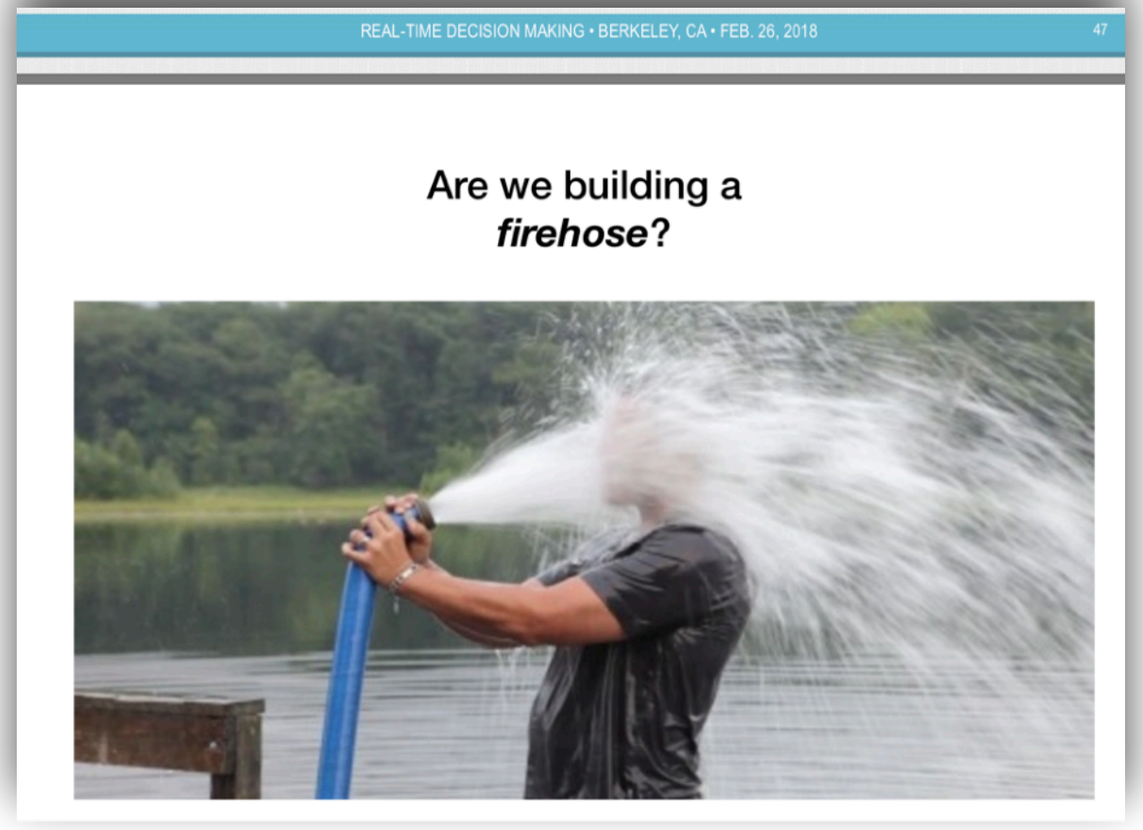
(no evidence for new phenomena)

Real-time analysis beyond HEP

Parallels with astrophysics?

C. Fitzpatrick, LHCb

E. Bellm, LSST



The LHC and modern surveys are **data firehoses**

Possible common challenges

LSST [data broker, or other alert] spots interesting event
Triggers a follow-up with other instruments
Limited resource: follow-up instrument time
Cost of not following up: missing information for interesting transient

LHC experiment: spots interesting event
Triggers the recording of the event for further analysis
Limited resource: data-taking bandwidth
(among many others, e.g. computing resources...)
Cost of not recording: event (or category of events) is lost and costs $$$$ to recreate

Real-time analysis (well) beyond HEP

Welcome to our REALTIME ASG blog! We're a group of researchers interested in real-time data acquisition and decision making as well as open data working as an Advanced Study Group 2019-2020 at the Pufendorf Institute for Advanced Studies.

- **Connections to astrophysics**
  - Real-time alerts for interesting events
- **Connections to accelerator beams / physics / engineering**
  - Beam steering, "triggering" for synchrotron and laser experiments
  - Sharing of technology, hybrid architectures (FPGA/GPU)
- **Connections to social sciences & law**
  - Real-time data deposition promotes open data and credibility of science
    - Implications for treatment and ownership of data treatment
    - Sharing of tools (versioning / data persistency)

- Ask Me! about the REALTIME Advanced Study Group

open to discuss further collaborations!

Real-time analysis in HEP and industry

- **Big data analysis / real-time analysis**
  - Shared tools: machine learning, hybrid computing architectures
  - Connections: IT, industry (e.g. Internet-of-Things)
    - data is mostly cheap to record
    - time-to-insight is the key metric
  - 

about the SMARTHEP and HELIOS networks

open to discuss further collaborations!

(proposal currently in “reserve list”)

HELIOS
Helmholz-Lund International Graduate School

(proposal funded as Helmholtz International Graduate School)

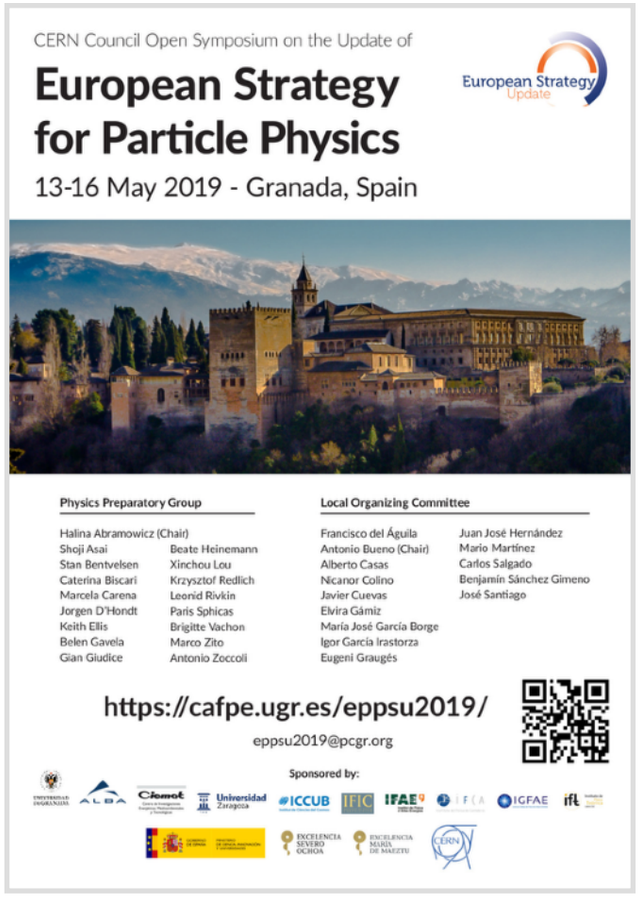
Possibilities for cross-talk in collaborative environments

- **High Energy Physics Software Foundation**
  - Not only LHC experiments
  - Forum for physicists with interest in software for HEP
  - Instrumental for creation of IRIS-HEP NSF effort
  - Working groups including trigger & reconstruction
    - Website
    - Mailing list: hsf-forum@googlegroups.com (google group)
- **DarkMachines**
  - Collective of astro/particle physicists interested in machine learning tools for dark matter
  - Various (self-organized) efforts, including unsupervised searches
    - Website
    - Subscribe to main mailing list

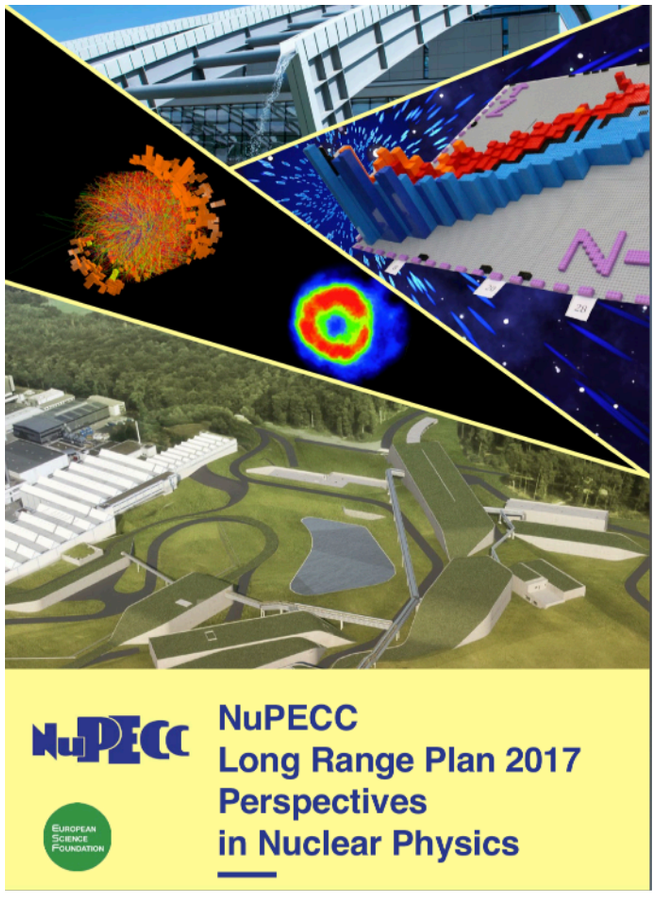
Finding synergies

Astroparticle (APPEC)

Particle (ECFA)



Nuclear physics (NuPECC)



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

US: ***Snowmass*** effort has started, (for *DM at Colliders* WG:

Foundations needed to exploit synergies

Common theory ground

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

data acquisition, computing, data sharing & open science

HSF HEP Software Foundation

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

iris hep

& more…

EuCAPT

[Talk at EPS-HEP / ECFA session 2019](), [CERN EP Newsletter]()

[Slides from European Strategy Update release, 19/06/2020]()

European Strategy Update

2020 Strategy Statements

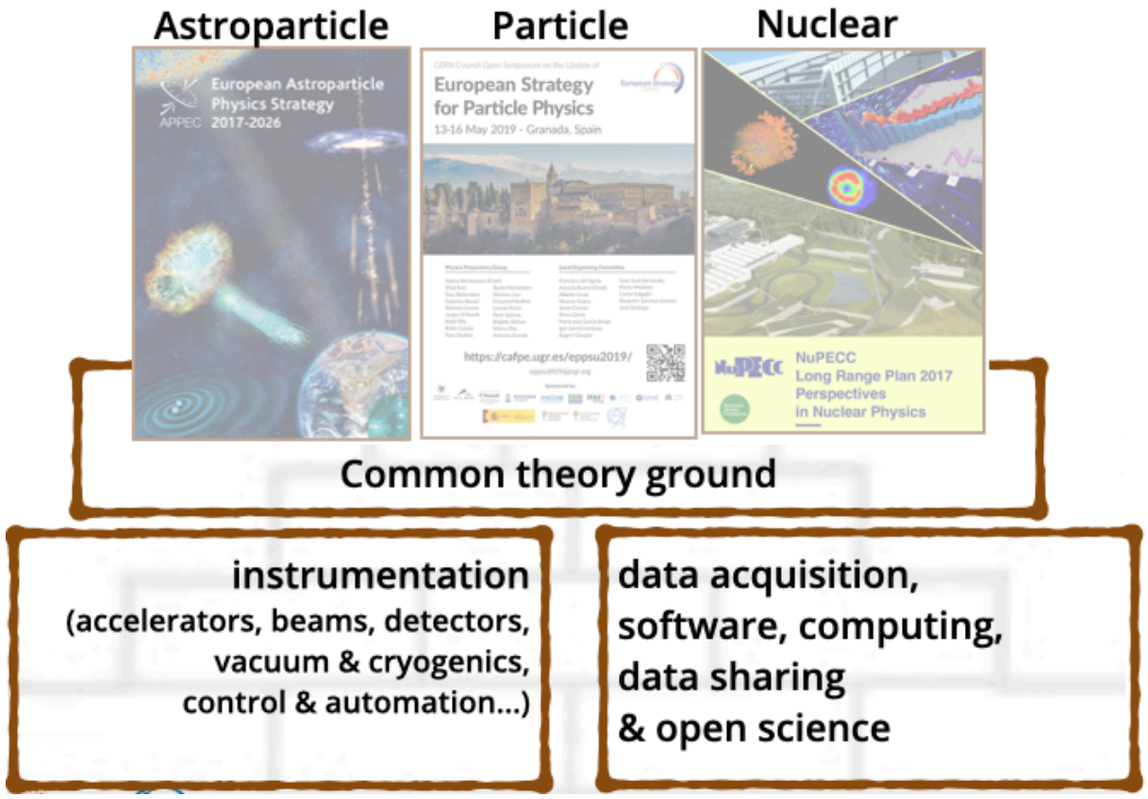
5. Synergies with neighbouring fields

Particle and Astroparticle Physics

- Synergies exist at the level of infrastructure, detectors, computing, interaction models and physics goals (ex.: neutrinos, dark matter, cosmic rays and gravitational waves)
- The need to foster these synergies has been clearly identified in the national inputs

Two ongoing projects focused on Dark Matter

searches & interpretation



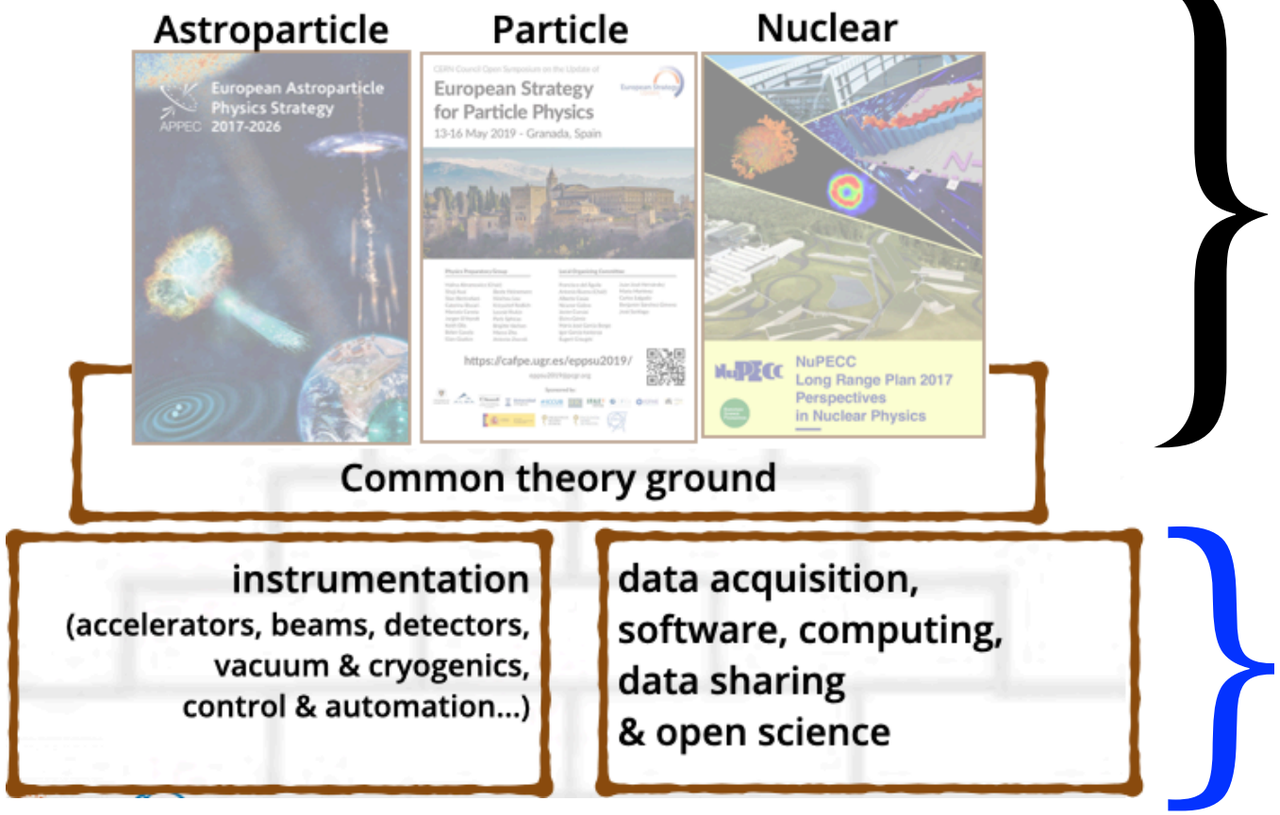
JENAS EoI: Initiative for Dark Matter in Europe and beyond: Towards facilitating communication and result sharing in the Dark Matter community (iDMEu)

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 **interpretation**

Two ongoing projects focused on Dark Matter

searches & interpretation



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ESCAPE newsletter APPEC newsletter

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

software & data

Towards a Dark Matter Test Science Project

ESCAPE Progress Meeting, 2020

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 initiatives and links in backup slides

Conclusions

The Standard Model is not enough

Example of **aesthetical problem:**

- Measured Higgs boson mass is “fine-tuned”

Example of **empirical problem:**

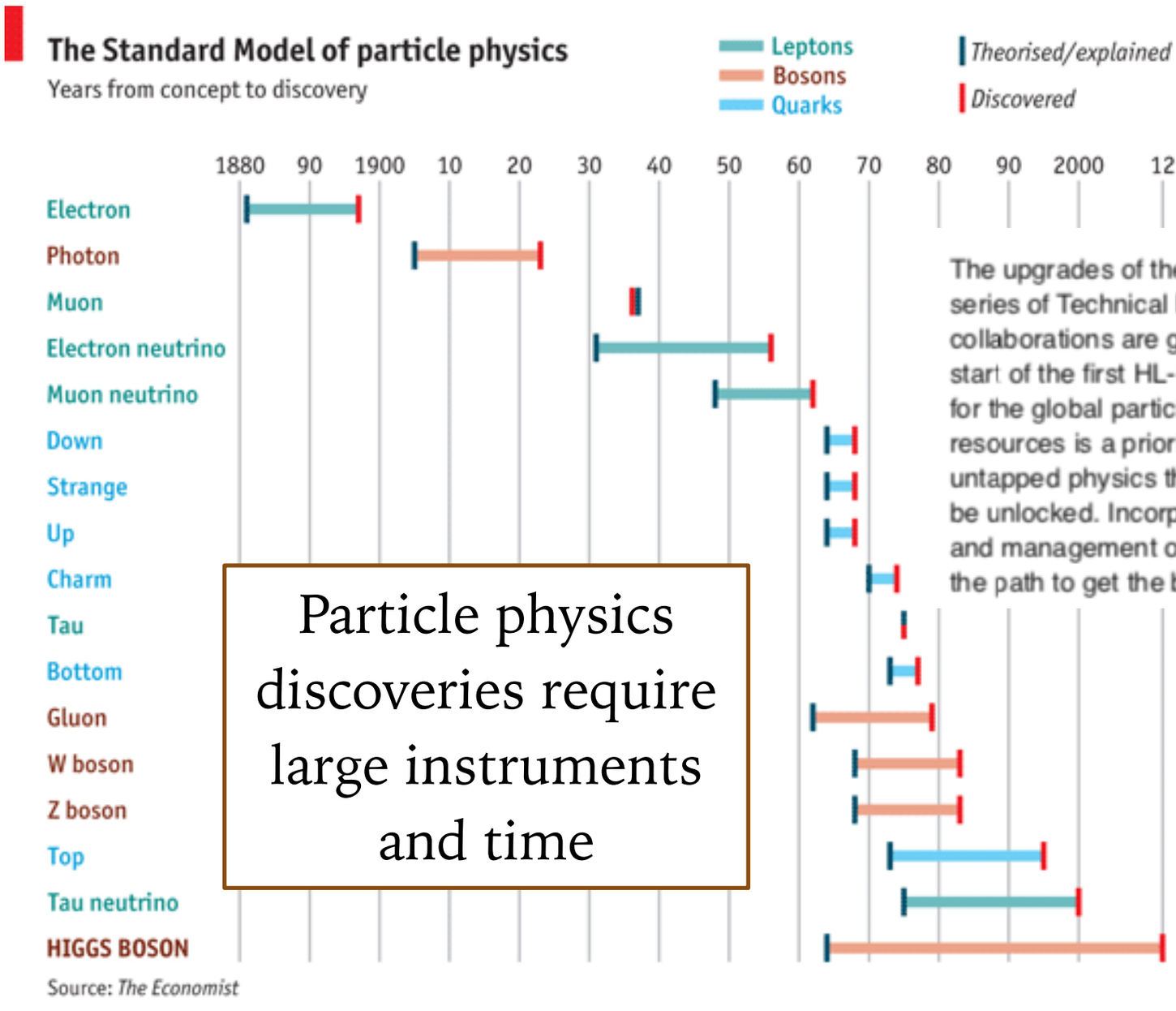
- Dark Matter not described in the Standard Model

The **Standard Model** may be only a **low-energy approximation** of a more complete theory

- **Many different theories** can explain those shortcomings
  - None of these theories is yet favored by data
  - Very different detector signatures
    - Some of them buried in **high-rate backgrounds**
    - Some of them **rare but very unusual**

Making the most of the data: **enabling discoveries** ensuring these events are recorded and analyzed

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



Particle physics discoveries require large instruments and time

[European Strategy Update, deliberation document](#)

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

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

[The Economist](#)

Outlook

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

- **Probing for new physics below/at the electroweak scale** where many (rare) SM particles are located requires **efficient trigger systems** and **novel data taking** techniques

- **Real-time analysis and decision making** crosses fields: let's think together and collaborate on tools & infrastructure

Thanks for your attention from the DARKJETS team

Photo: Lena Björk Blixt.

LU Press Release

In the picture from the left:

- Postdocs **William Kalderon (now BNL), Jannik Geisen** (not pictured)
- PhD students **Eric Corrigan, Eva Hansen** (remote on that day)
- Master's (now PhD) student **Alexander Ekman**

+ Lund Master's students:

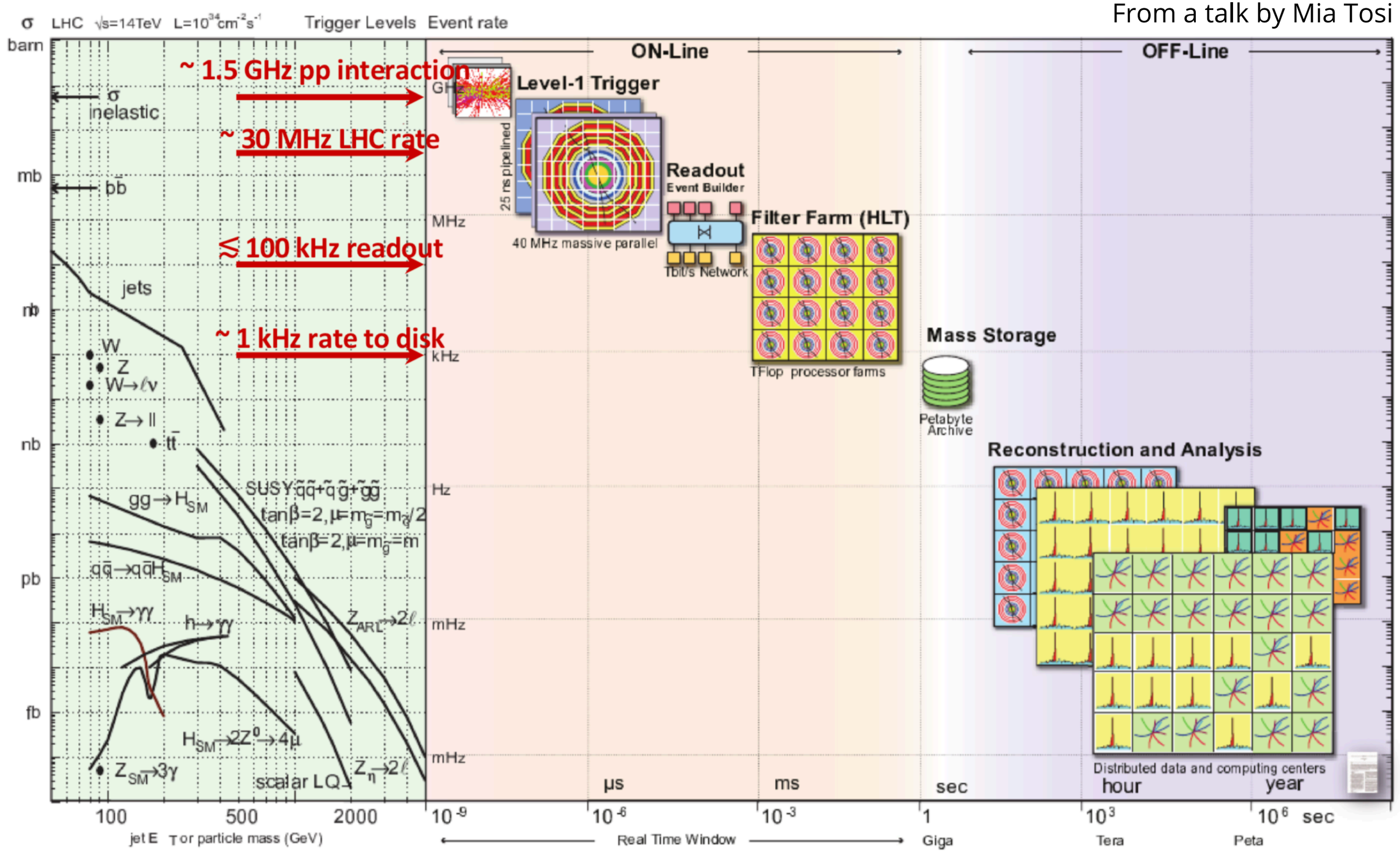
Herjuno Nindhito
now PhD student at the University of Geneva
Prim Pasuwan, Isabelle John
now PhD students at Stockholm University
Zhiying Li
now PhD student at the University of Oxford
Sebastian Murk
now PhD student at the University of Macquarie
Erik Wulff
now Deep Learning engineer at Axis communication
[+ many more Bachelor's students on the website]

Backup slides

LUNDS UNIVERSITET

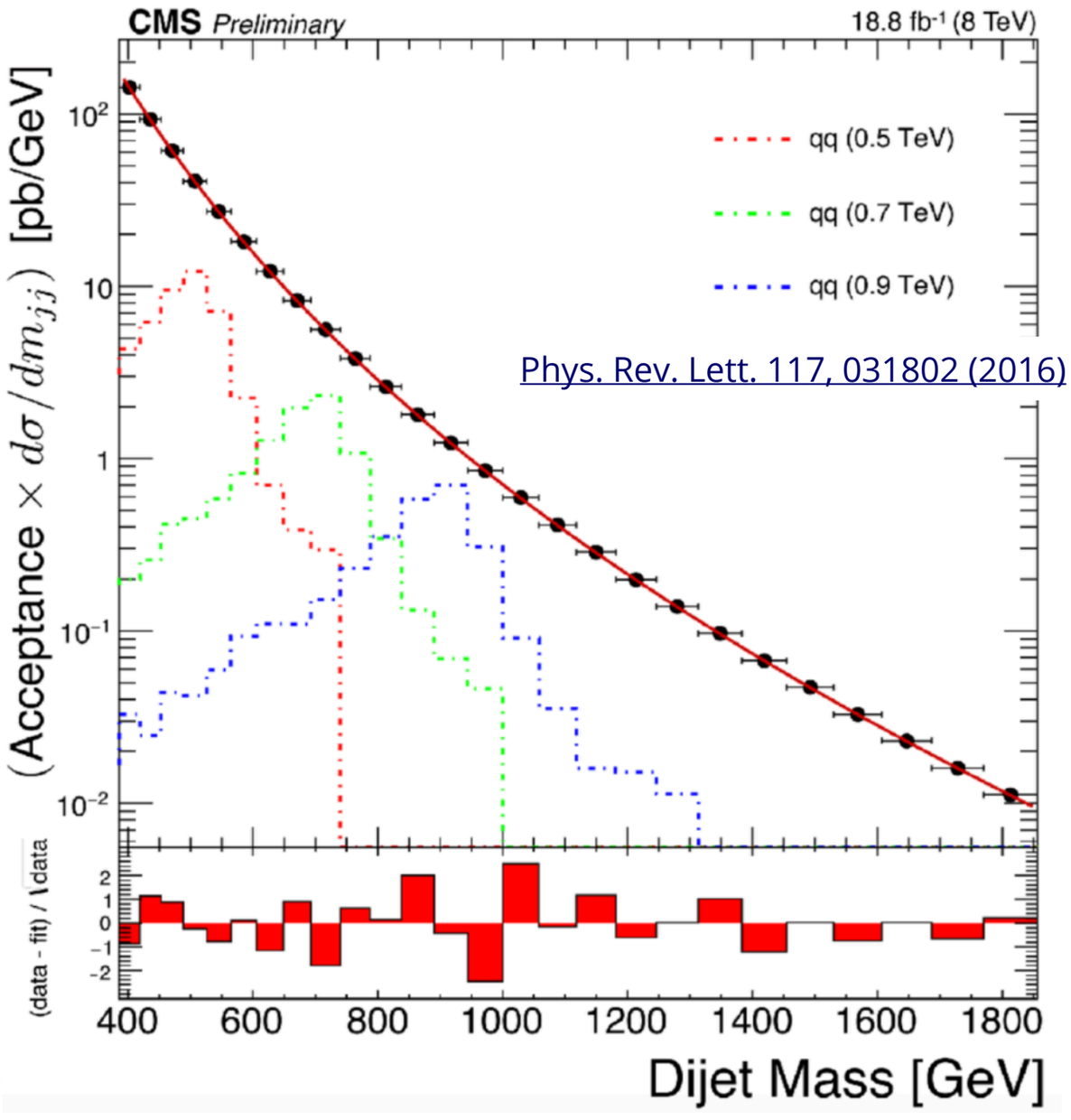
Real-time analysis, in the CMS trigger

From a talk by Mia Tosi



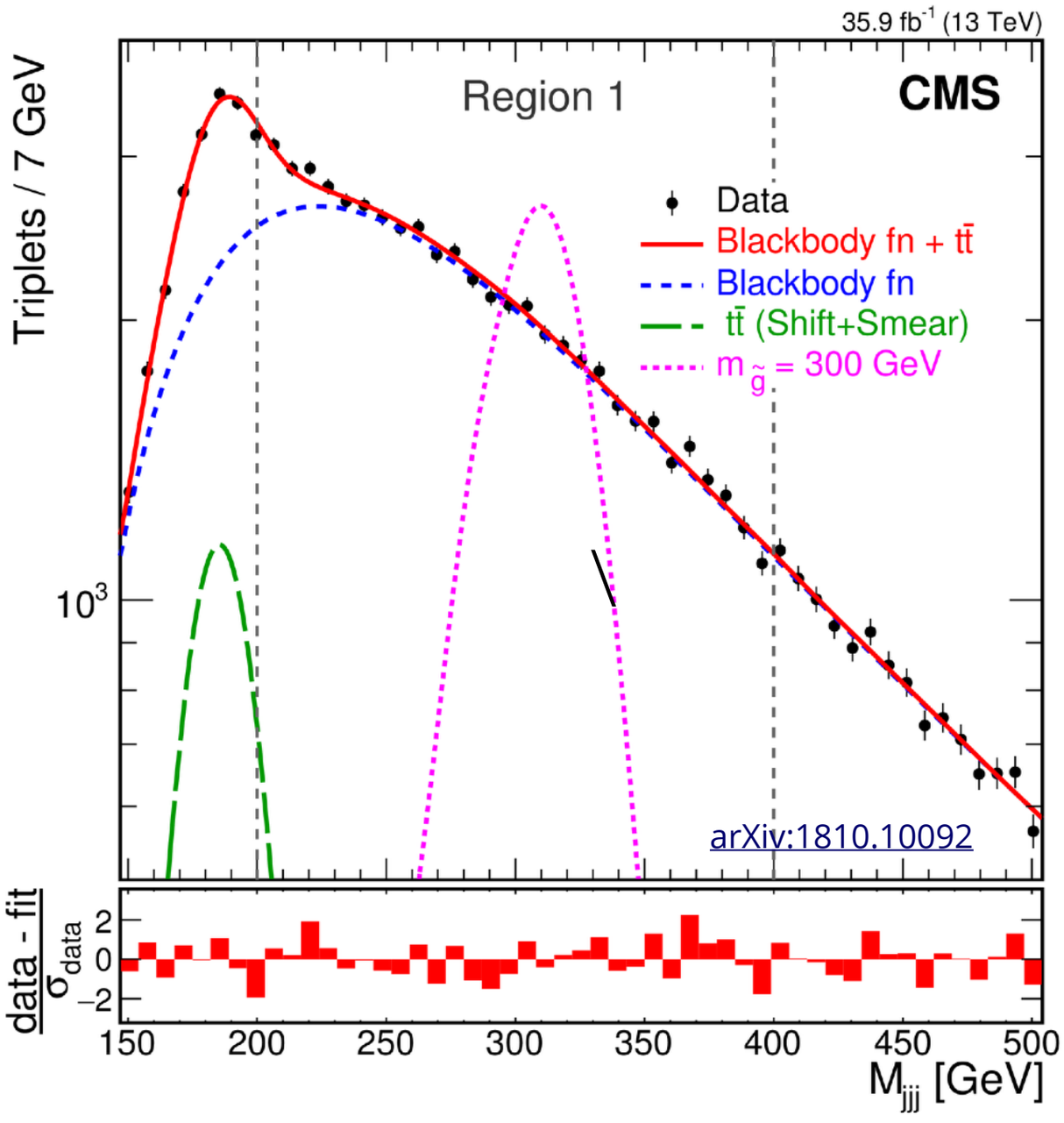
CMS results from jet searches

First results of this technique for dijets at 8 TeV...



Phys. Rev. Lett. 117, 031802 (2016)

...now also extended to three-jet searches



arXiv:1810.10092

Turbo/Data Scouting/TLA path

Turbo stream (LHCb),
Data Scouting (CMS),
Trigger-level Analysis (ATLAS),

Customizable output data @ LHCb:

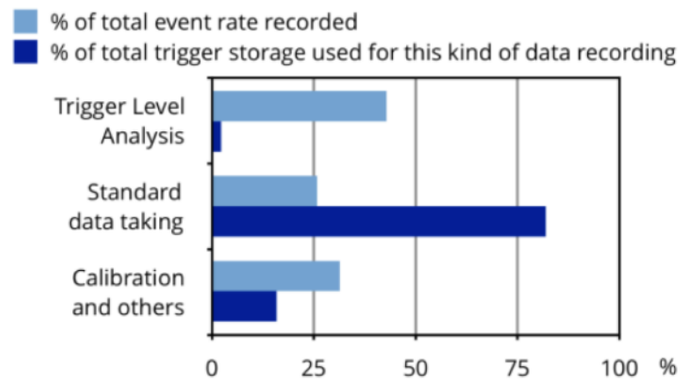
- keep trigger objects only (7 kB)
- keep trigger objects + ”on-demand” raw and/or reco in selected regions (< 200 kB)
- keep everything (200 kB)

Objects and data sizes @ CMS:

Stream	Rate (Hz)	Event Size	Bandwidth (MB/s)
PhysicsMuons	420	0.86 MB	360
PhysicsHadronsTaus	345	0.87 MB	300
ScoutingCaloMuon	4580	8.9 KB	40
ScoutingPF	1380	14.8 KB	20

Selected CMS stream rate, event size, and bandwidth at the beginning of LHC Fill 7334 (23 Oct. 2018, L≈1.5×10^{34}cm^{-2}s^{-1})

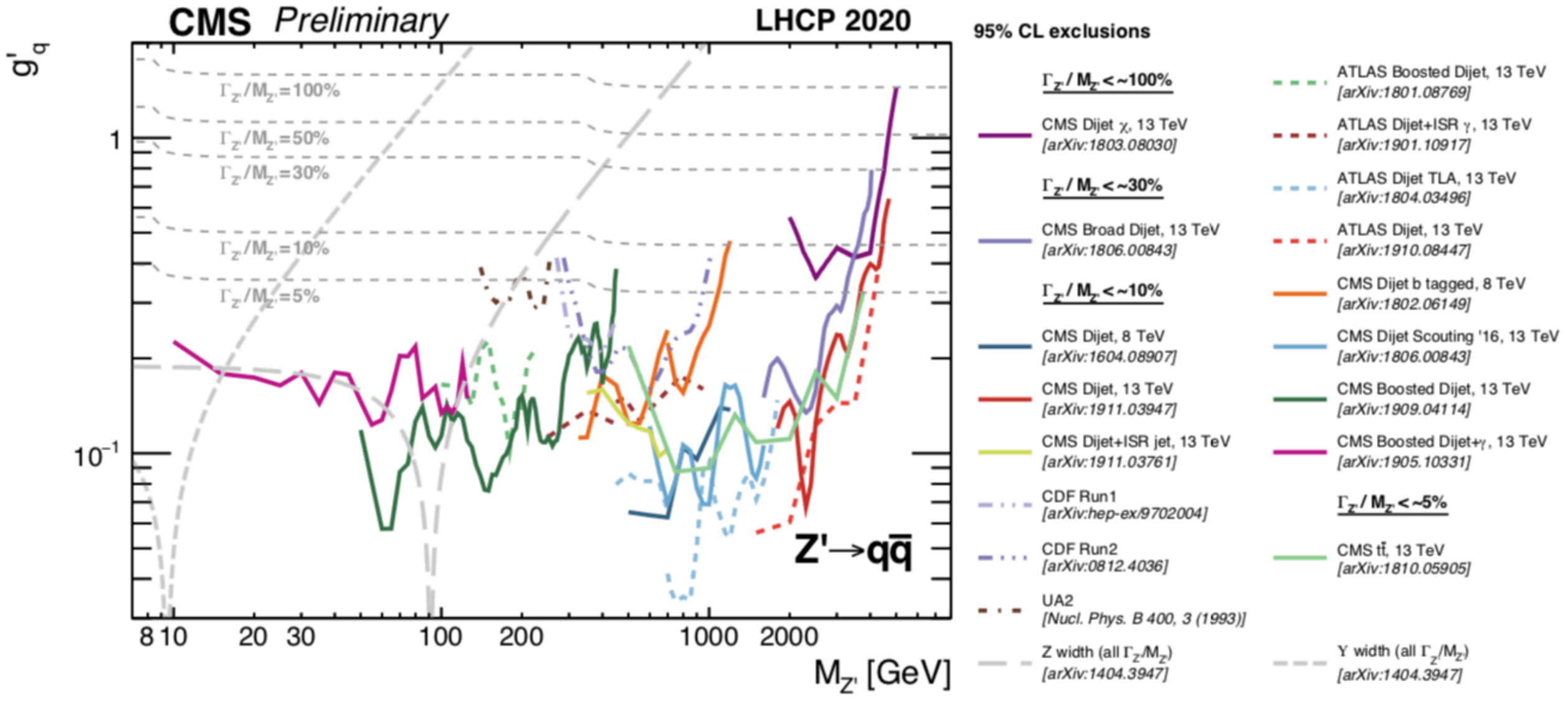
Data sizes @ ATLAS:



Information from ATLAS Trigger Operation plots, 2017

JLab HSF workshop session on RTA: LHCb, ALICE, ATLAS, CMS

Mediator mass-coupling summary plot



Mediator mass-coupling summary plot

Current set of dijet resonance searches don't yet reach **electroweak-scale couplings**

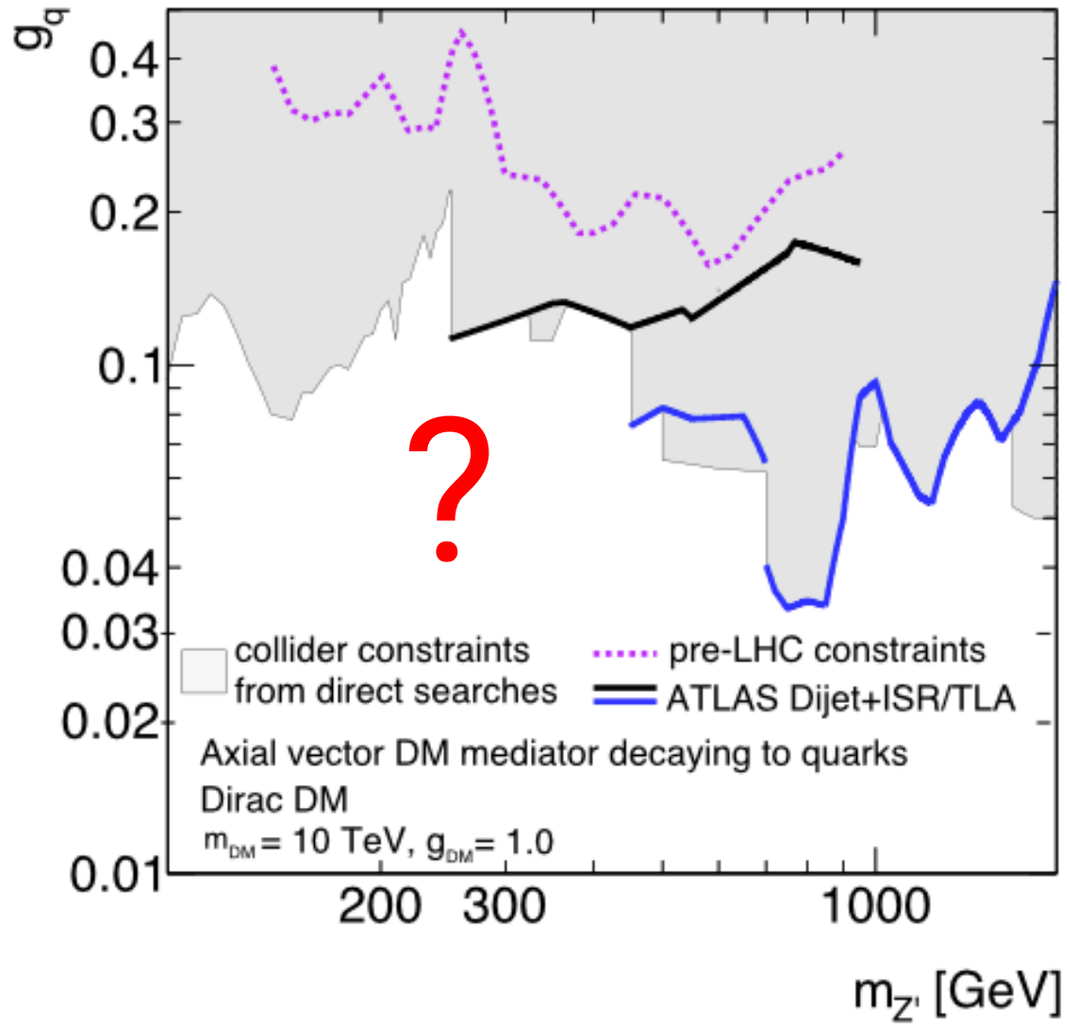
No reason to stop searching now:

- Many Z'-like models are still viable and motivated
  (see e.g. https://arxiv.org/abs/1807.02503 for "evolved DM simplified model Z's ")
- If a resonance is found, theories will appear
  (think of what happened for the 750 GeV diphoton excess)

TLA remains a flagship analysis for low-mass Z's:

- Extremely high statistics → great to test robust solutions
- But luminosity scaling is not fast, and we're still L1-limited…

  → **we need to be more creative with triggers!**



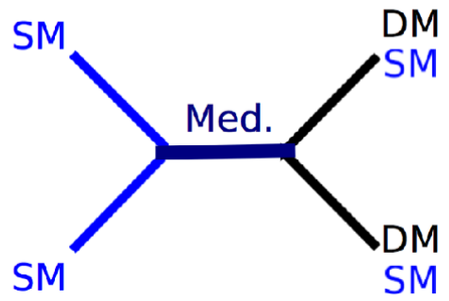
Choice of benchmarks

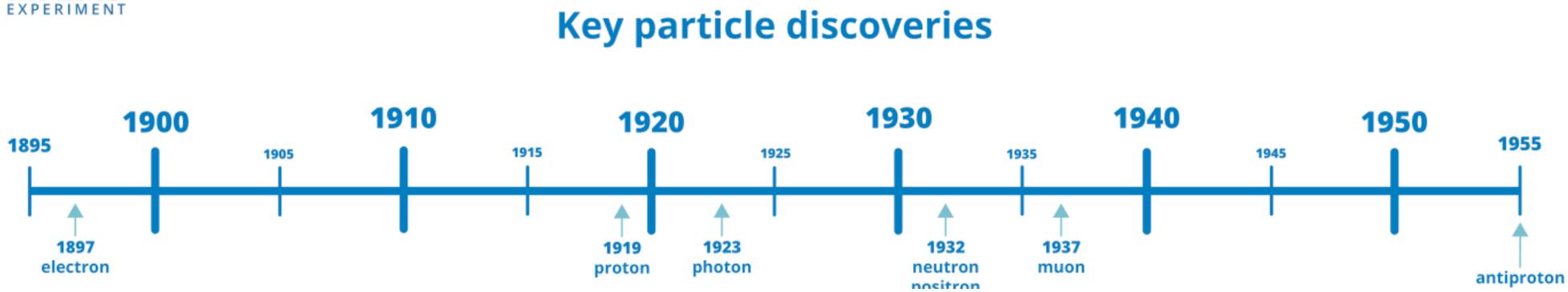
https://abstrusegoose.com/406

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

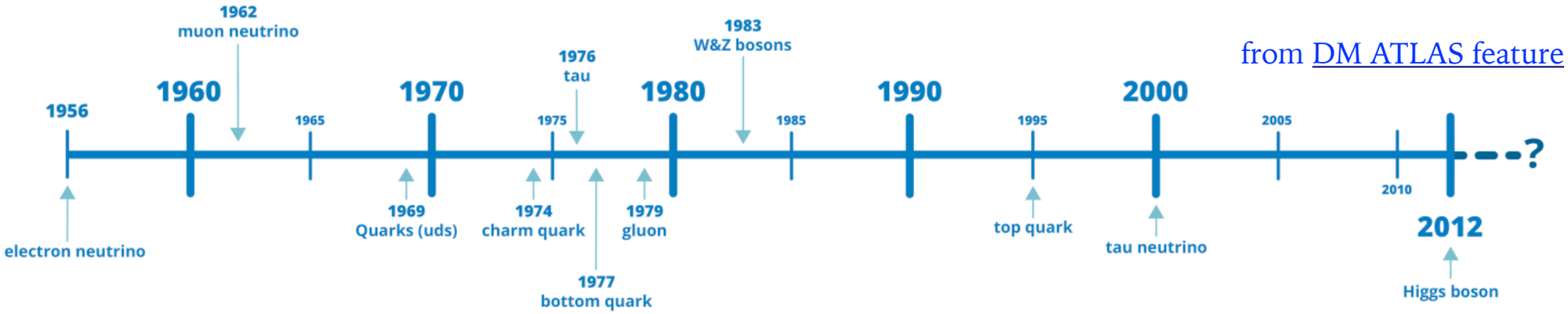
"Do we think DM is all made of a single WIMP model?"

(not really…see dark sectors!)





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

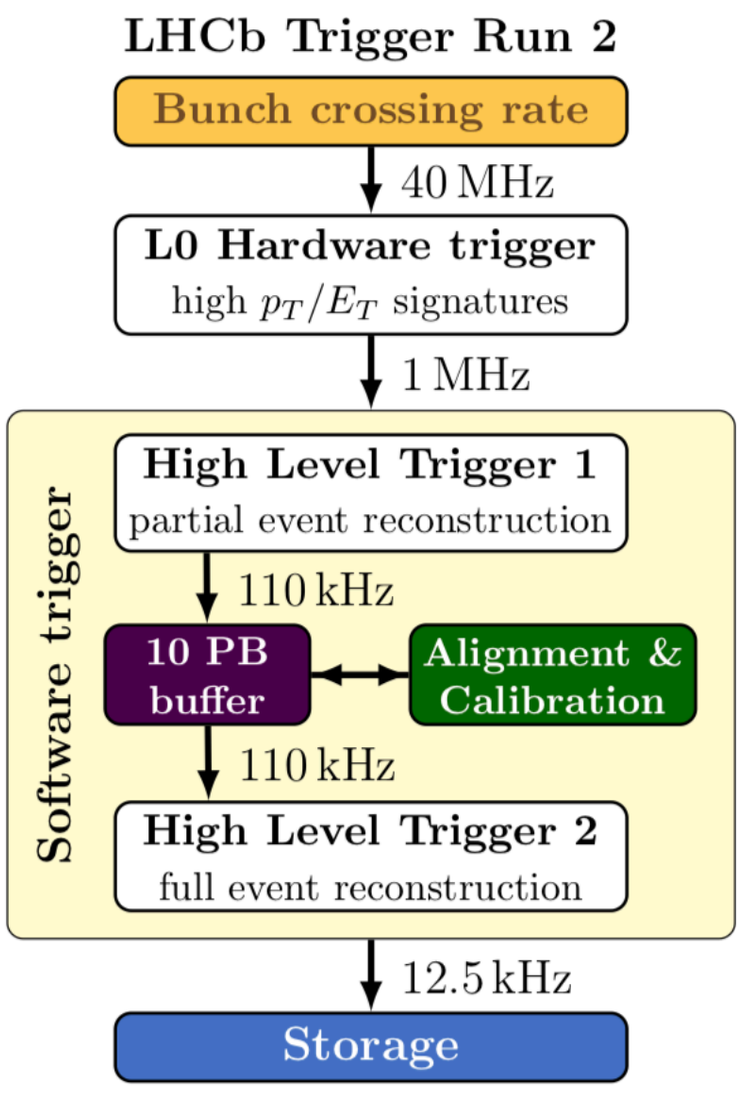


from DM ATLAS feature

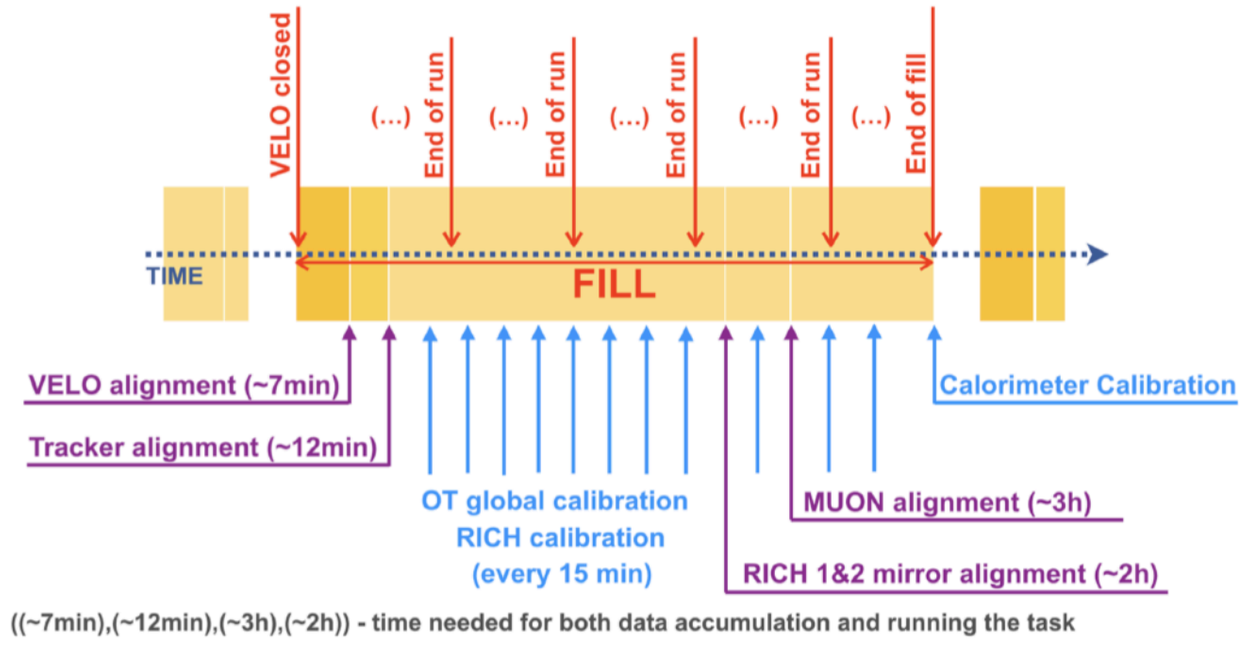
- Even simple models can encapsulate **relevant experimental characteristics** representing wider classes of theories

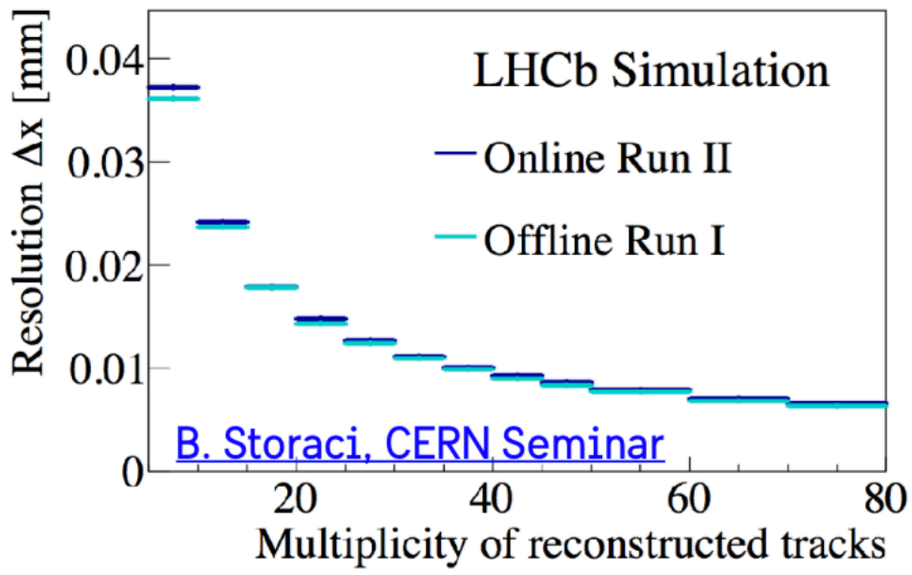
as long as we are aware that they can be more rare than what we choose as example

LHCb online vs offline reconstruction



arXiv:1812.10790





Real-time data analysis requires real-time detector alignment and calibration, in computing farm

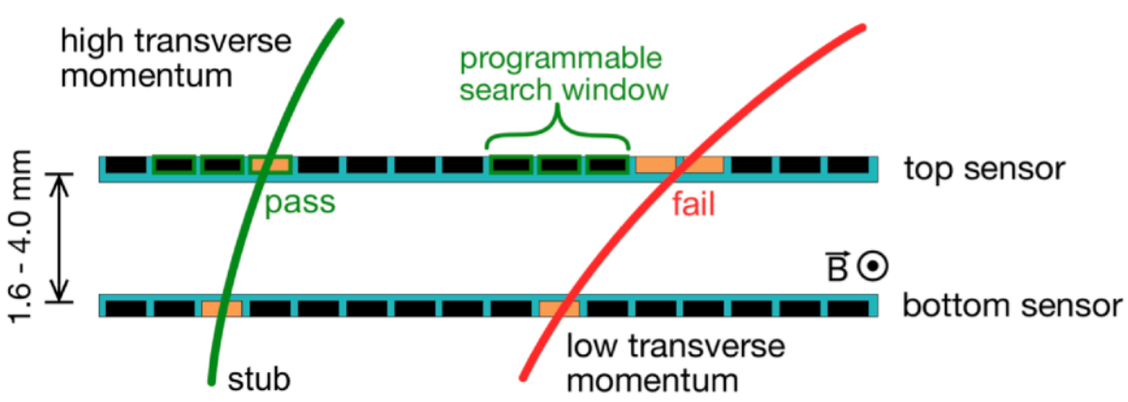
This is also done in ATLAS and CMS

CMS track trigger for LHC upgrade

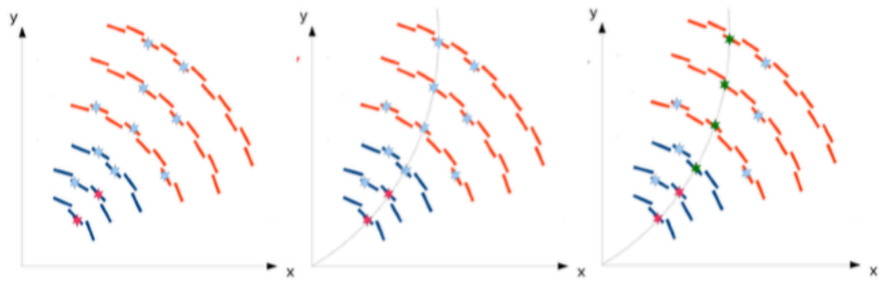
LHC upgrade (**HL-LHC**): CMS detector can be read out at ~1000 kHz (100 today)

- **Particle tracks** necessary to distinguish multiple interactions (**pile-up**)
- Software-based particle tracking information too expensive to be available at L1 for each track
- Need **hardware tracking**

On-detector data reduction:
decide what "stubs" to pass on to pattern recognition based on track expectations for particles above thresholds



Implementation of **real-time pattern recognition** in hardware (FPGA and/or ASICs)



More details: talk by Imma Riu, CHEP 2018, talk by T. Eichorn