CATERINA DOGLIONI - LUND UNIVERSITY

DAWN OF DISCOVERY WORKSHOP, HEIDELBERG

Innovating ideas, searches at the LHC

(a story based on a personal view)

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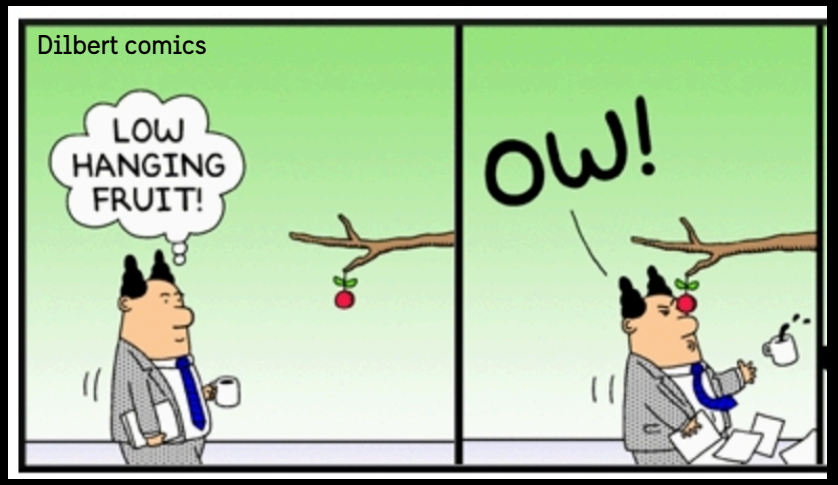
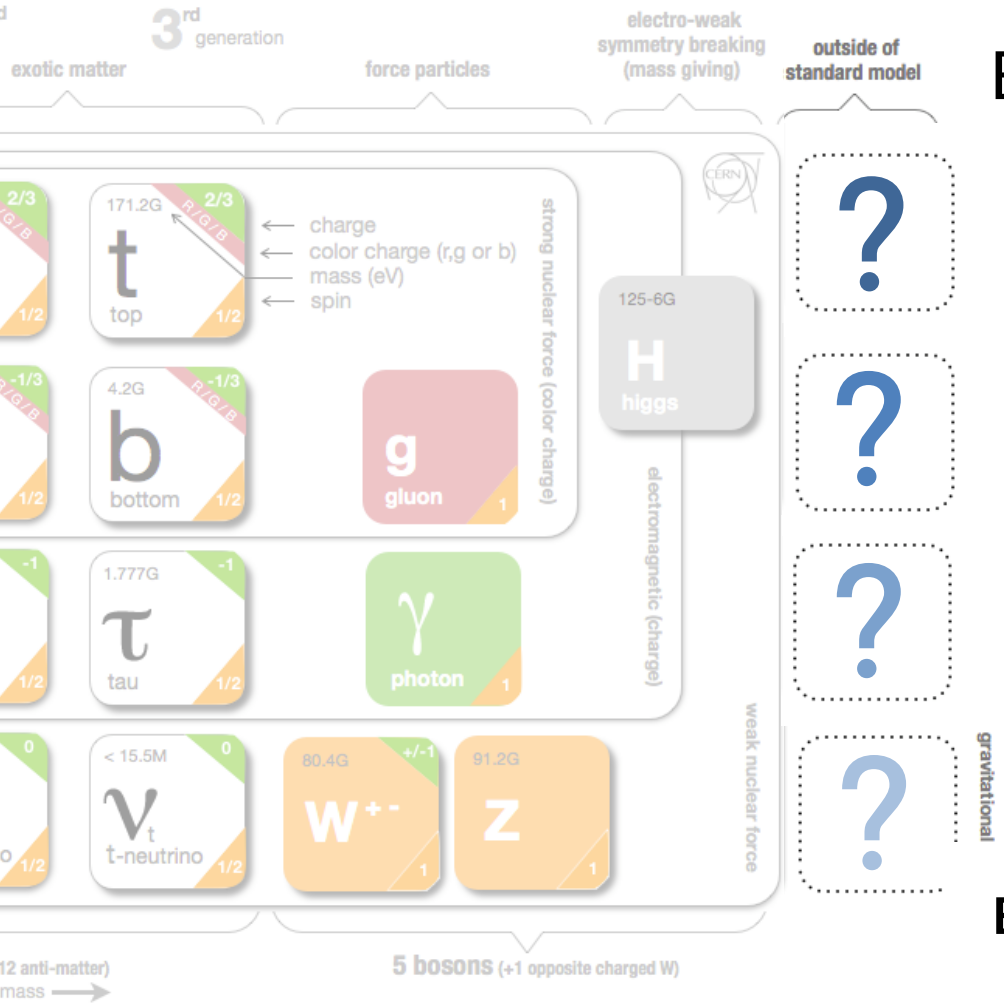
Outline

1. *"Low-hanging fruit for DM @ LHC has been picked"*
   - From MET+X searches to di-X searches
2. Searches for (visible) light DM mediators at the trigger level



The road to discovery in Run 2

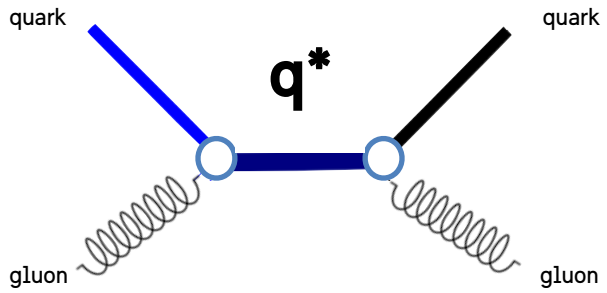


Where to look for new physics?

Everywhere, starting with high masses

Increase of LHC energy

Increase of reach for new phenomena



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

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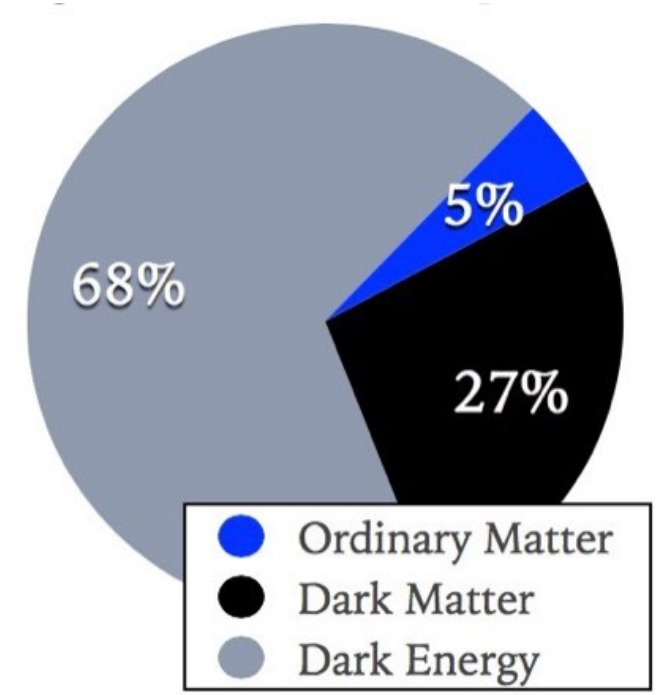
Where ~~do~~ did we go from ~~here~~ the LHC Run-1?

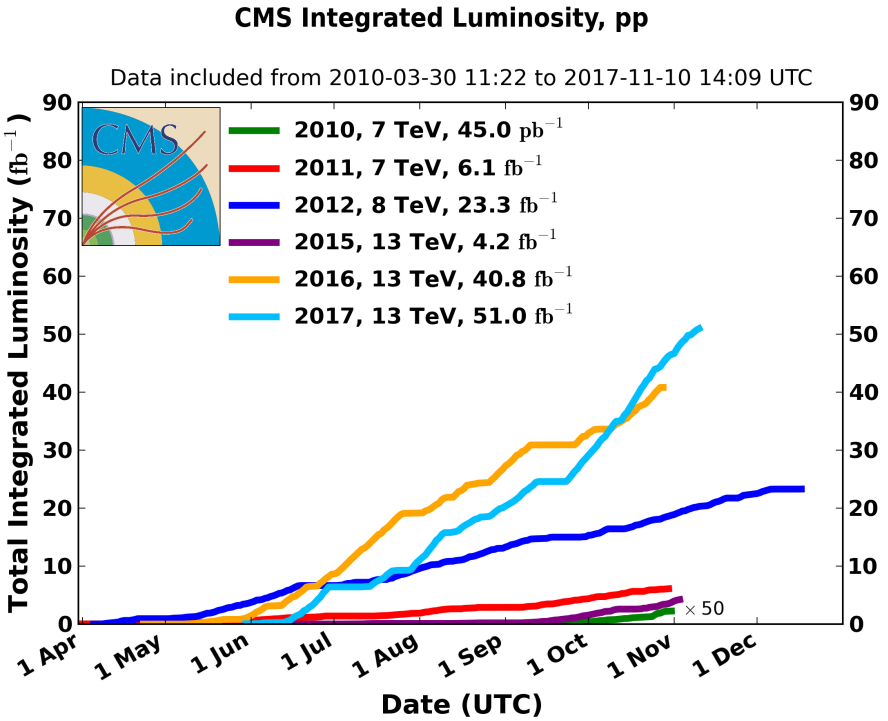
(Some) outstanding questions of the Standard Model:

- How do particles get mass?
  - Higgs mechanism ✓

- What is the nature of dark matter?



https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

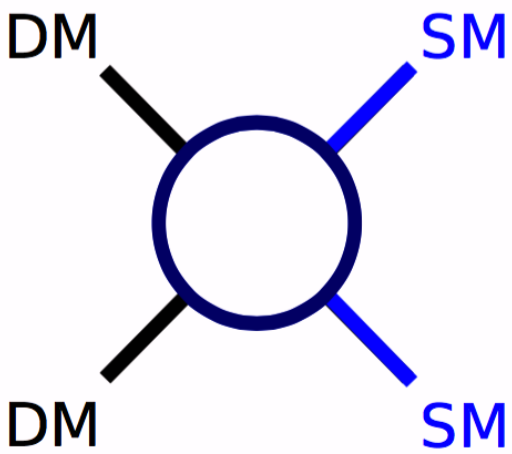


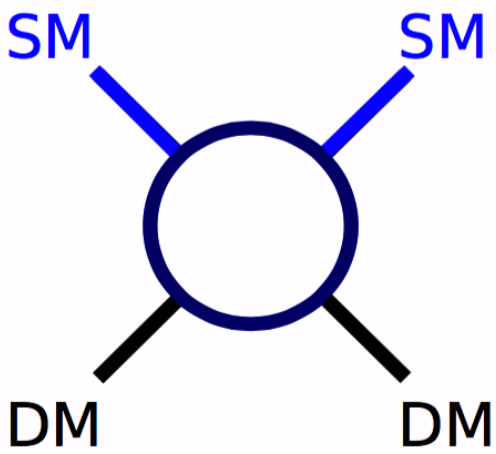
LHC operating beyond its design luminosity!

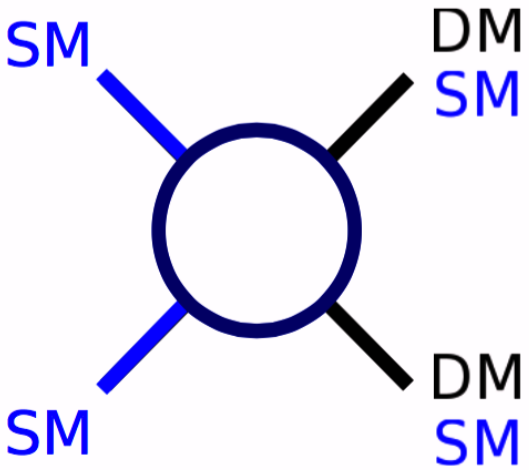
We have the chance to answer these questions with LHC Run-2 data

WIMP DM in different production modes

Dark Matter — Ordinary particles







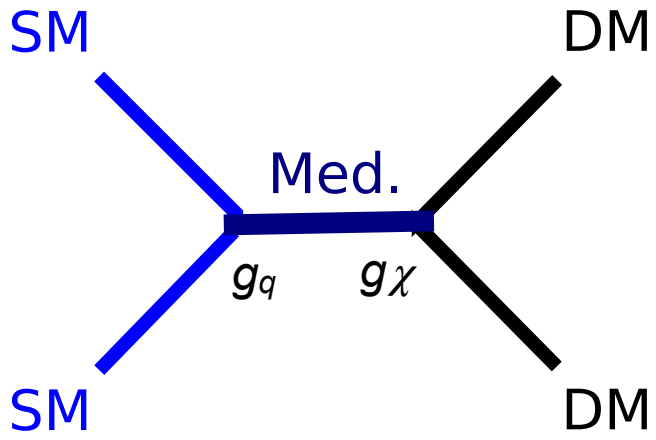
Many resident experts here!

Indirect Detection | Direct Detection | Particle Colliders

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

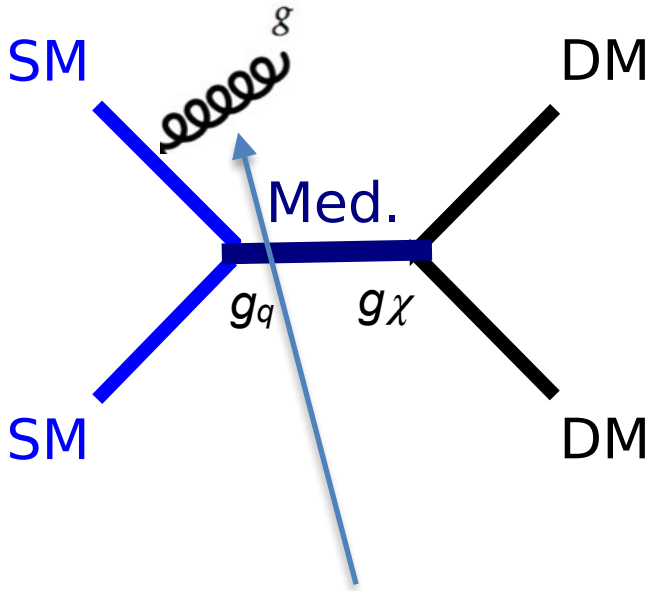
Looking for Dark Matter at the LHC

WIMPs are invisible to detectors

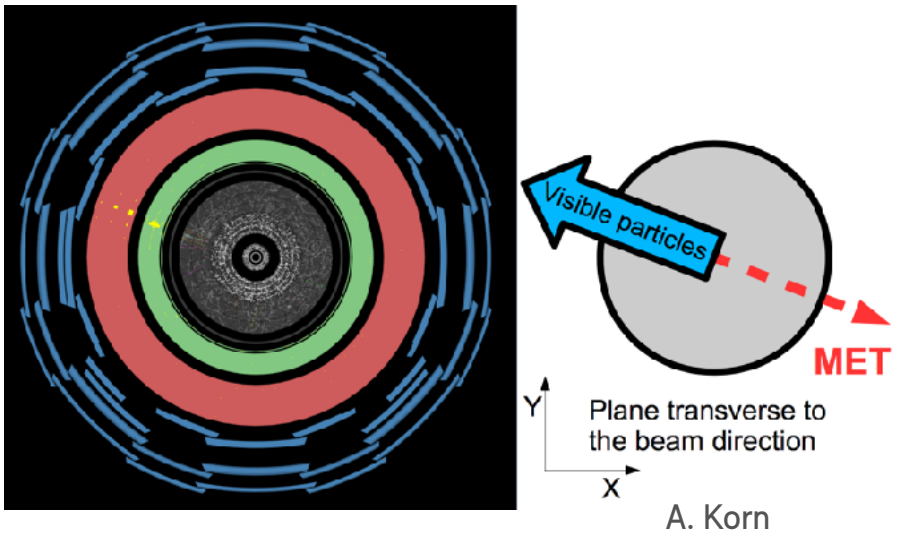


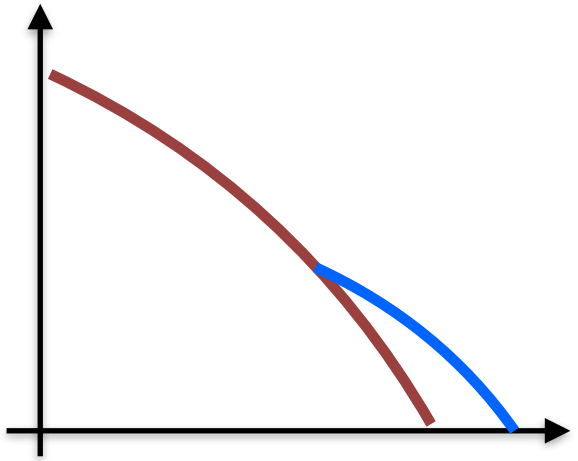
Looking for invisible particles at the LHC

Signature of invisible particles (like Dark Matter):
missing transverse momentum



Invisible WIMPs:
Initial state radiation
makes them visible

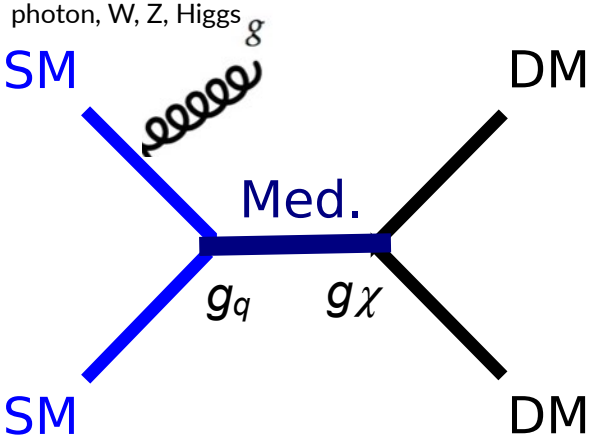




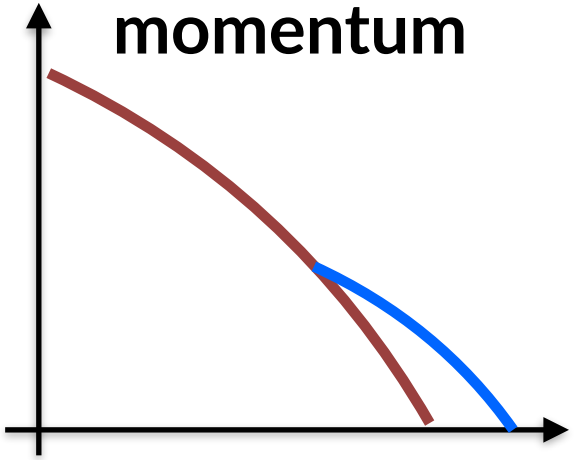
Excess of missing transverse momentum

A sample "monojet" result

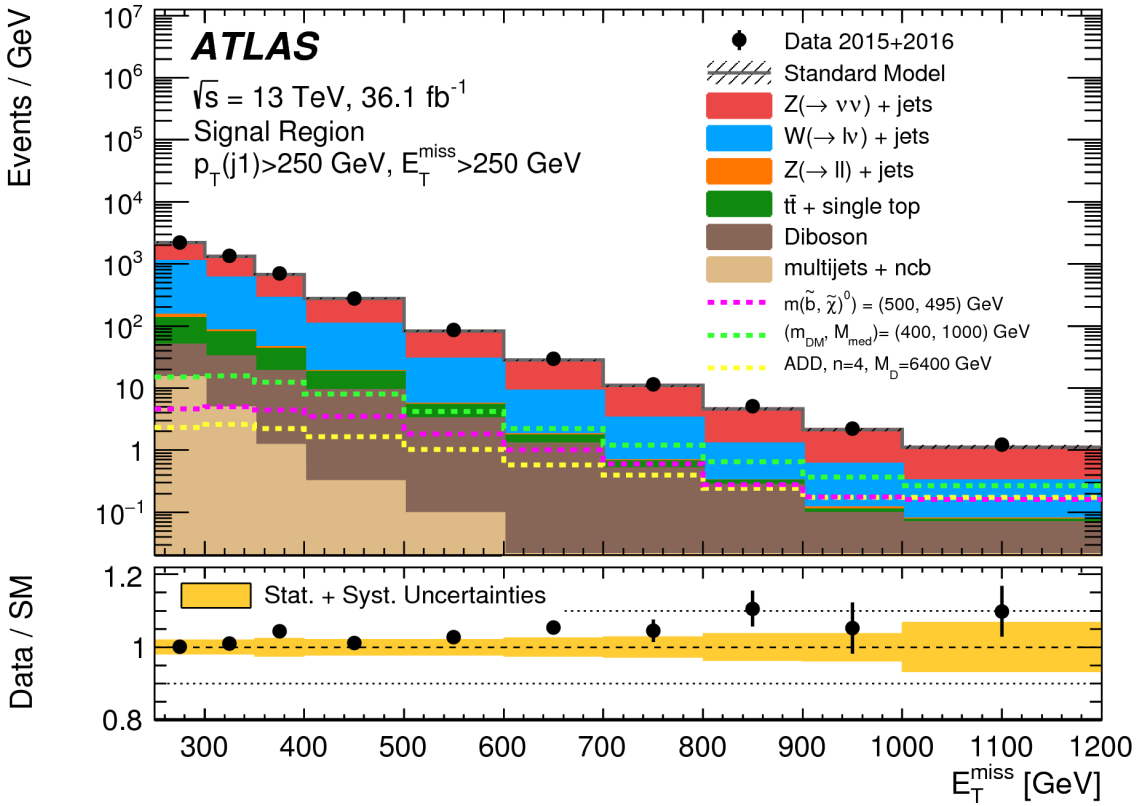
Can also use other associated objects:
photon, W, Z, Higgs



Simplest signature of Dark Matter: **missing transverse momentum**



JHEP 01 (2018) 126



How to interpret
the absence of excesses?

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Cornell University Library

Dark Matter Forum

We gratefully acknowledge support from the Simons Foundation and member institutions

High Energy Physics – Experiment

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

Danie
Allen
Azuel
Beach
Buchr
Cacci
Gome
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Cater
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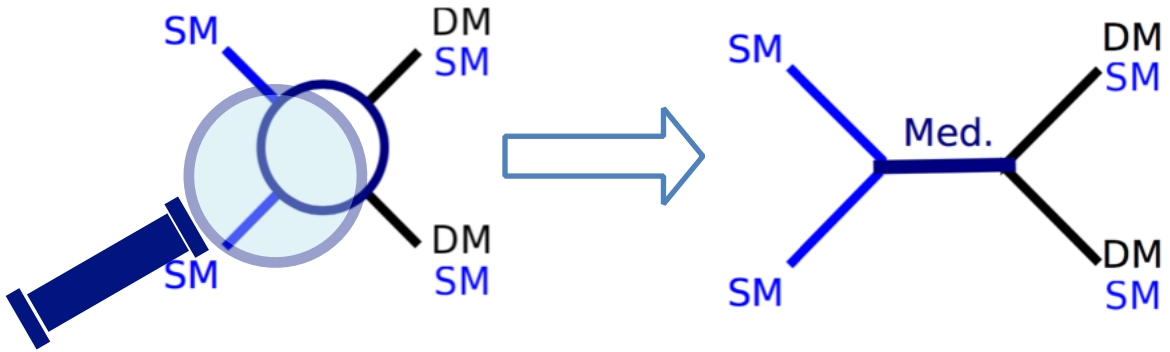
Simplified models as building blocks for **experimentalists** (designing and performing searches) and **theorists** (building new theories, reinterpreting searches) and as common framework for reinterpretation together with **complementary experiments**

Caveat: very (too?) simple!

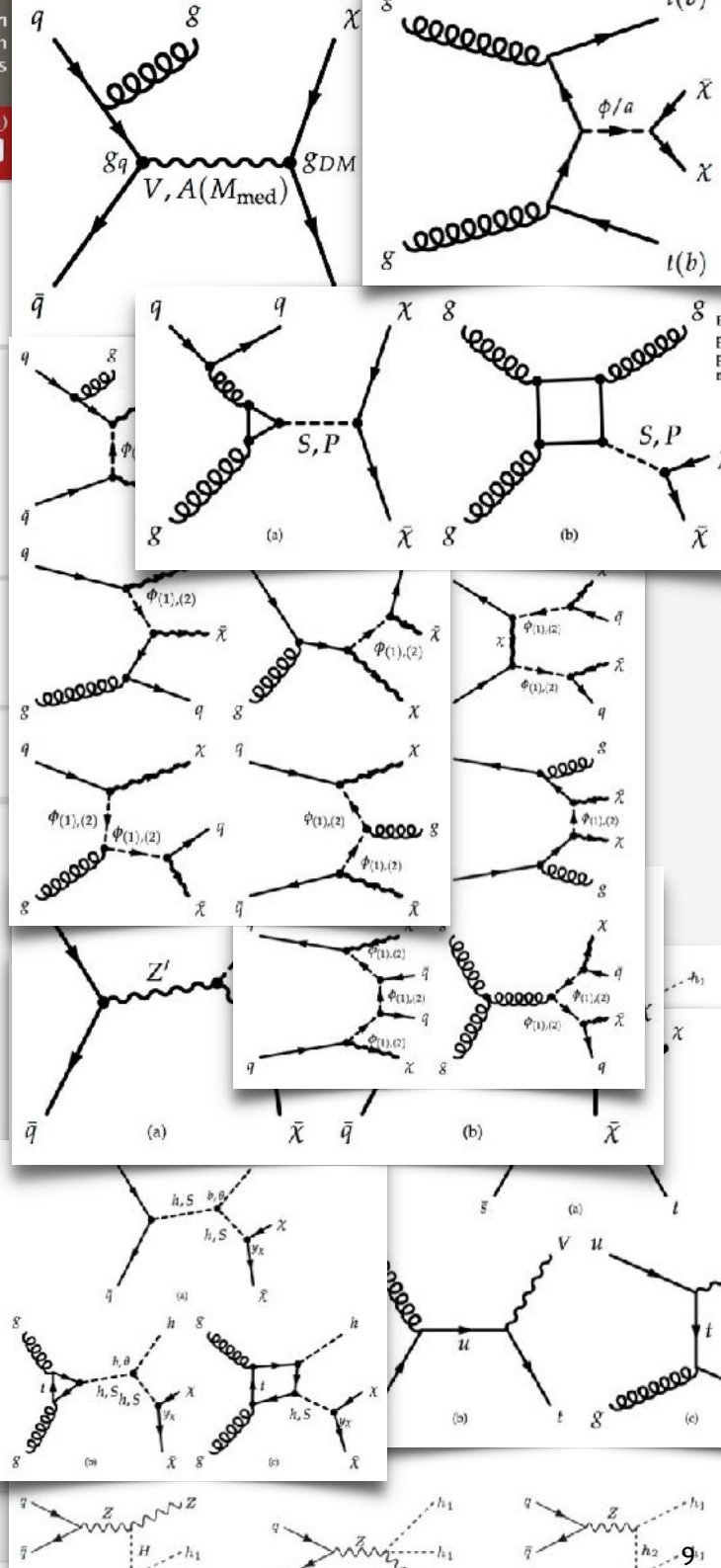
(Submitted on 3 Jul 2015)

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



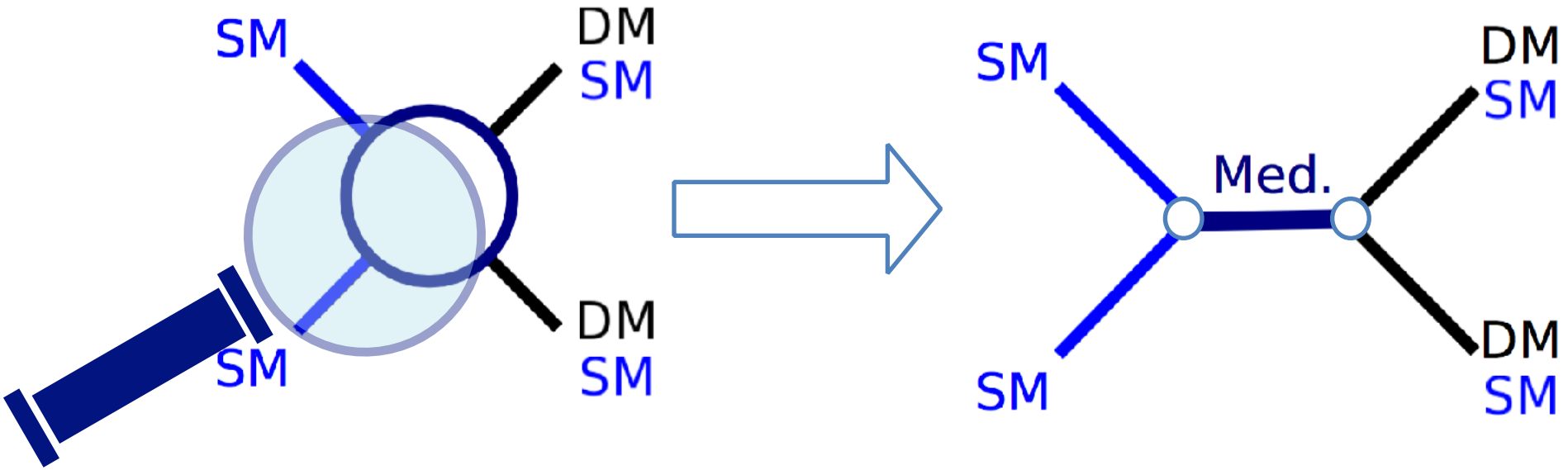
Colliders (Effective Field Theory)

Colliders (Simplified Models)



Dark Matter mediators at the LHC

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



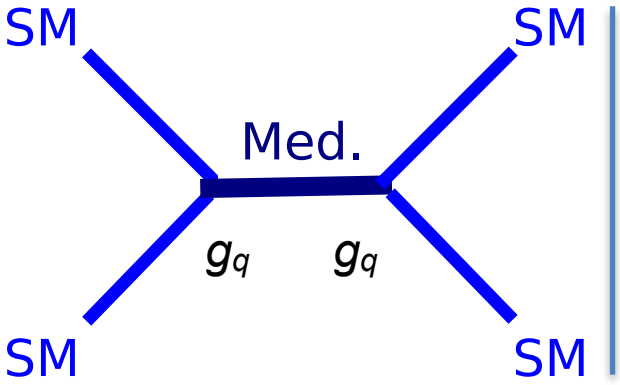
Particle Colliders

Can look for both invisible and visible decays of the mediator

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

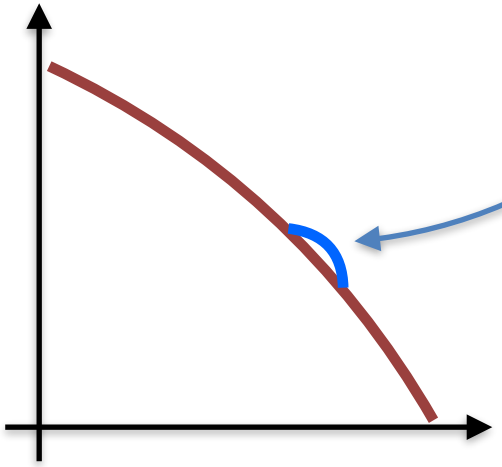
Look for an inevitable LHC physics process: **di-jet resonances**

Anatomy of a *bump-hunt*



invariant mass

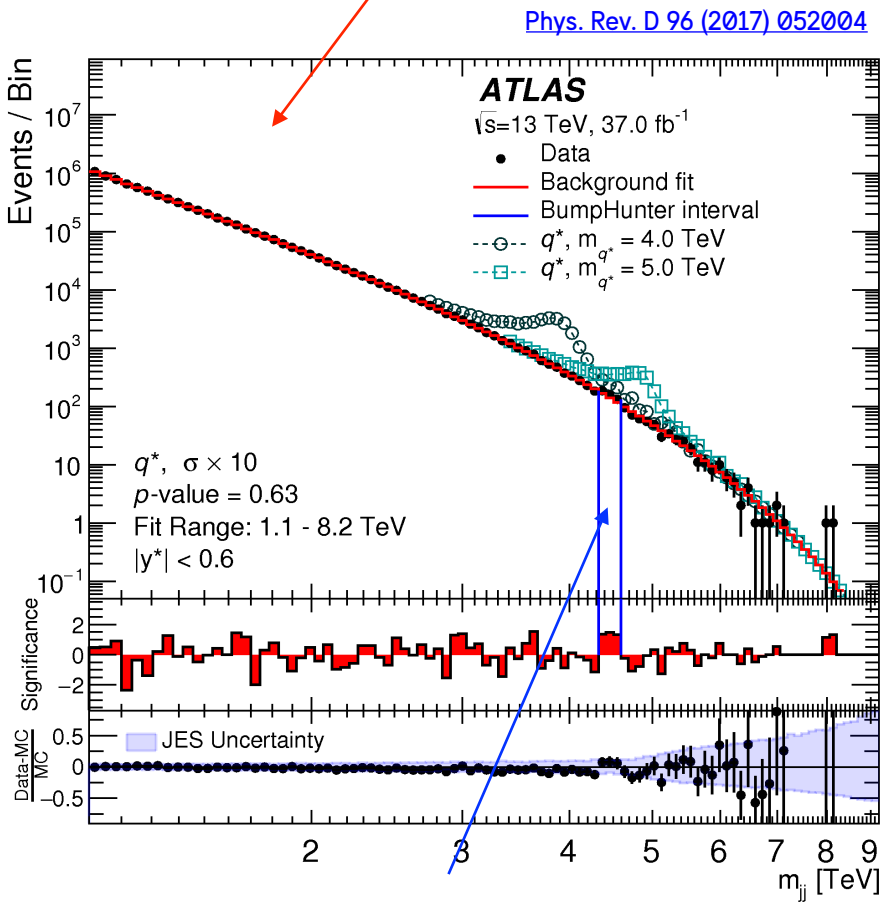
number of events



invariant mass

Data-driven background fit

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



Most discrepant region

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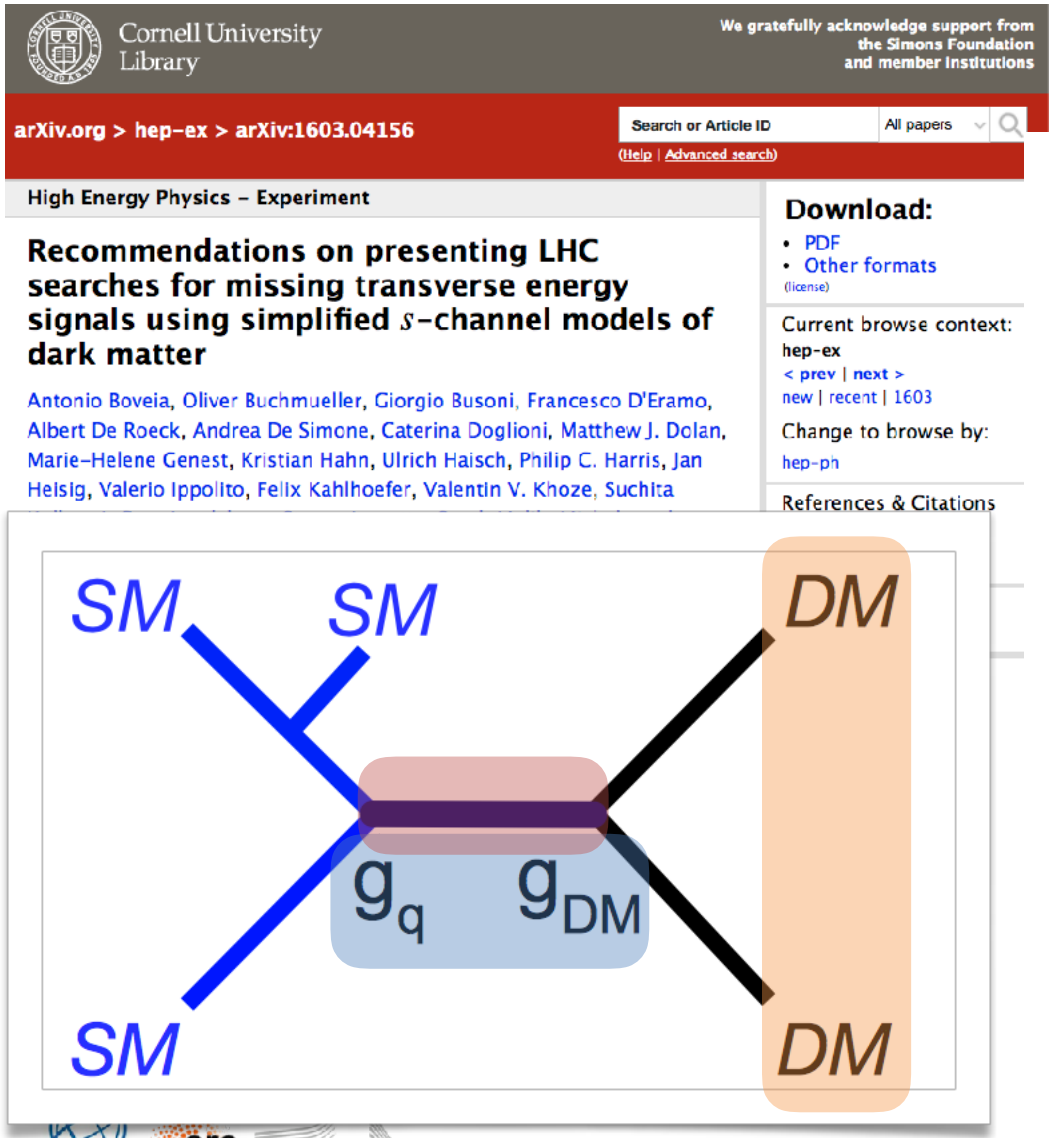
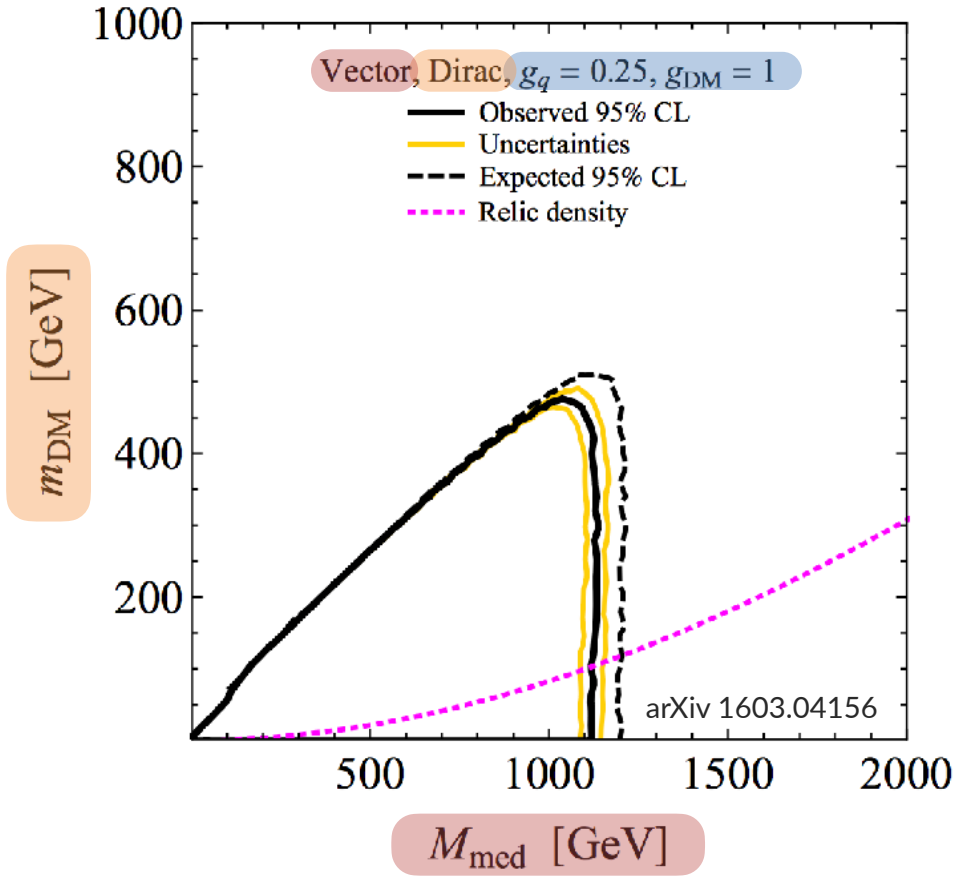
Visible/invisible DM LHC searches

How to display interpretation of collider search using simplified models



Dark Matter Working Group



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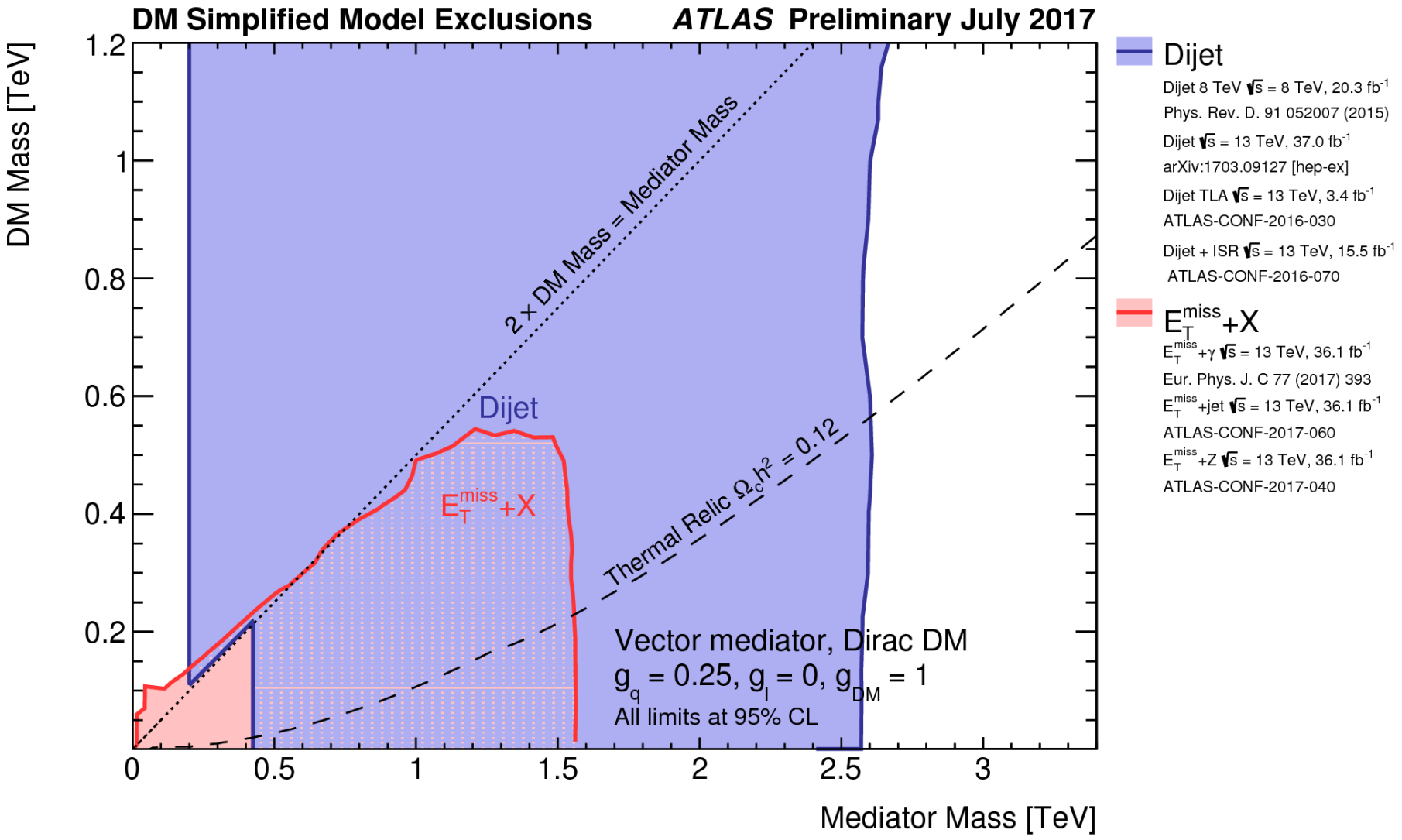
Visible/invisible DM LHC searches



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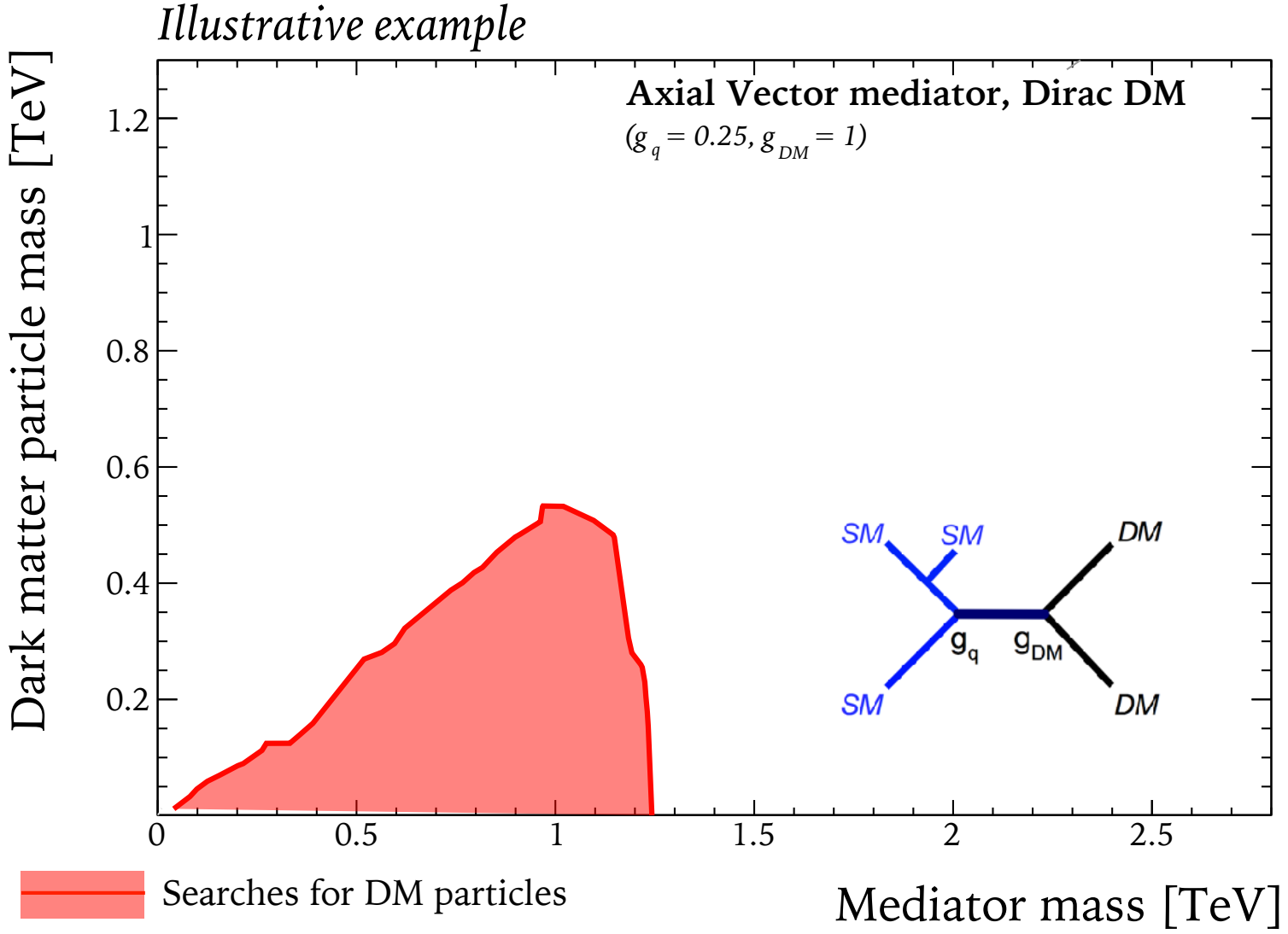
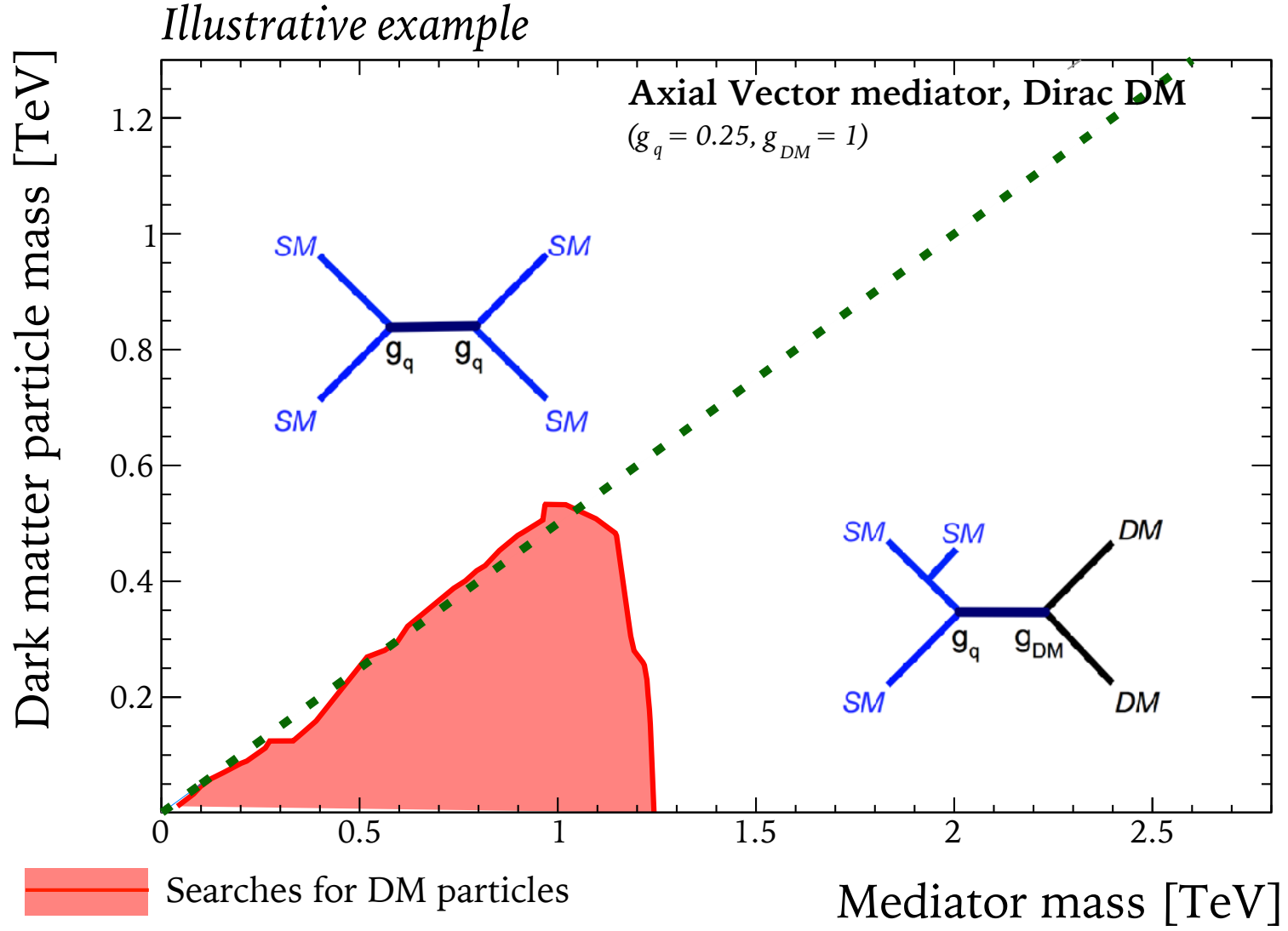
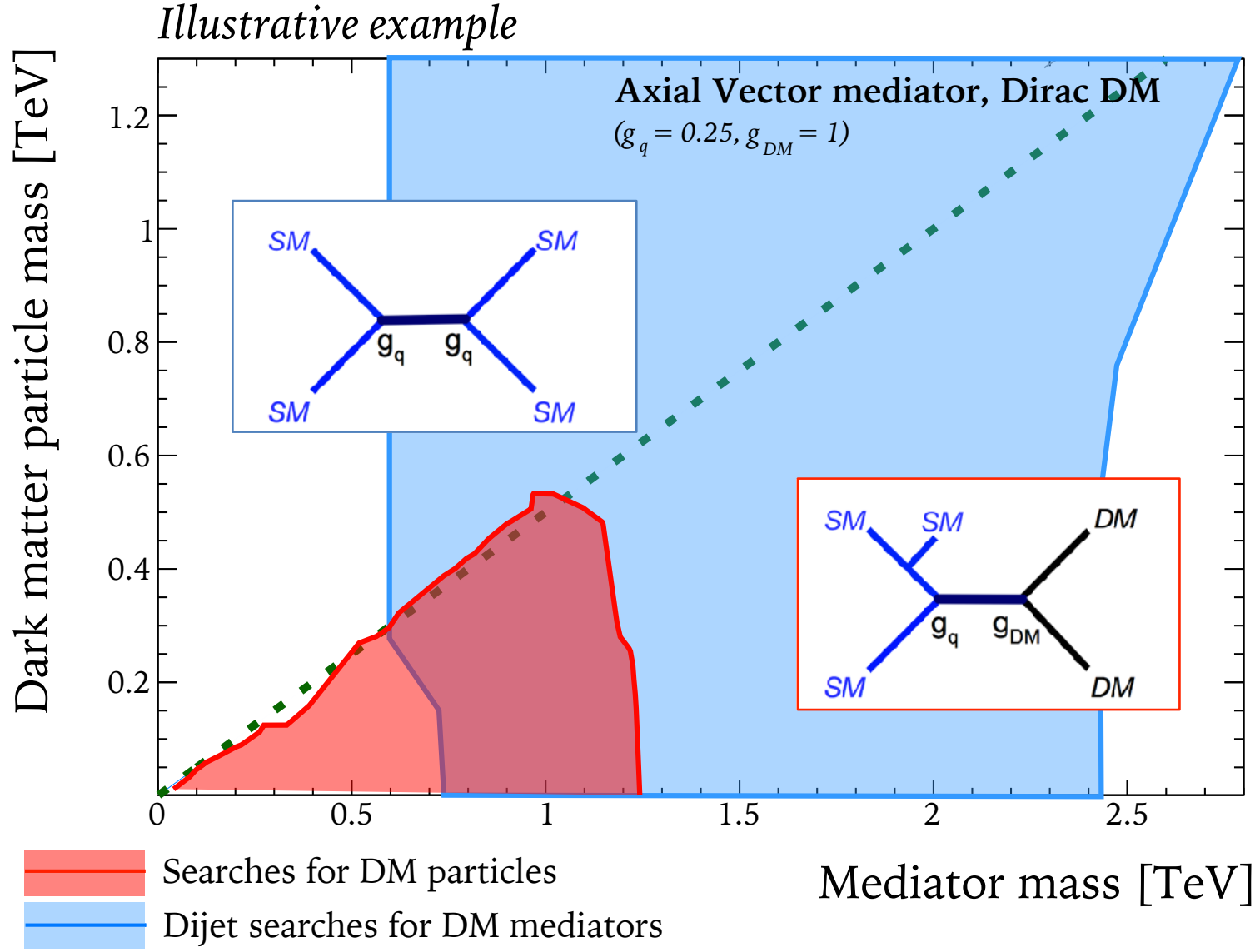
Visible/invisible DM LHC searches



Visible/invisible DM LHC searches

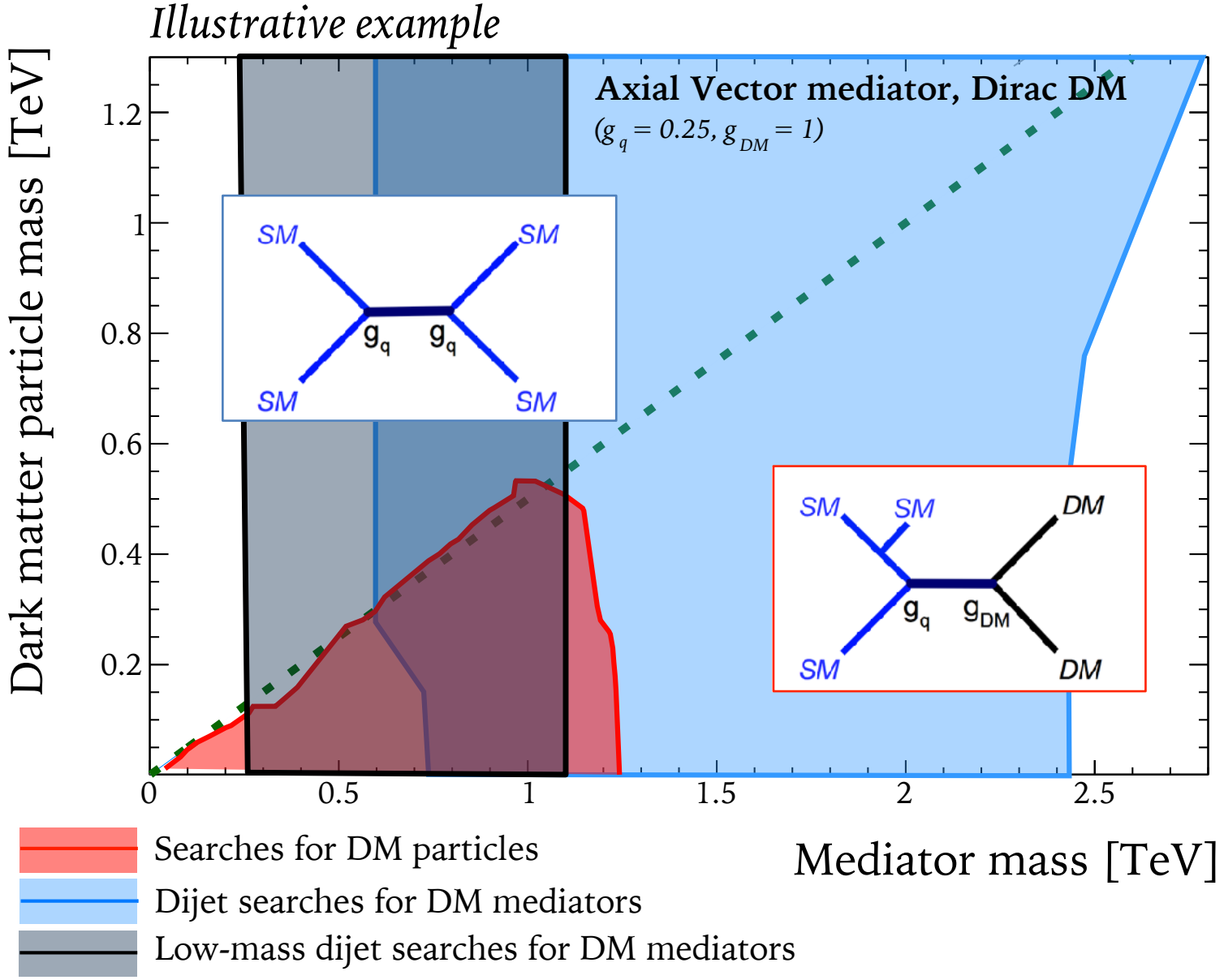


Visible/invisible DM LHC searches



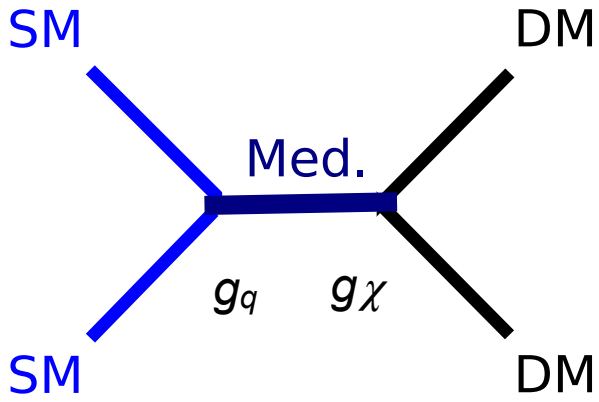
Collider strength: searches for visible mediator decays

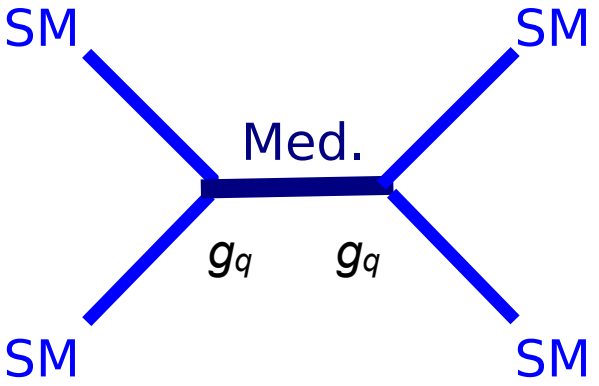
Visible/invisible DM LHC searches



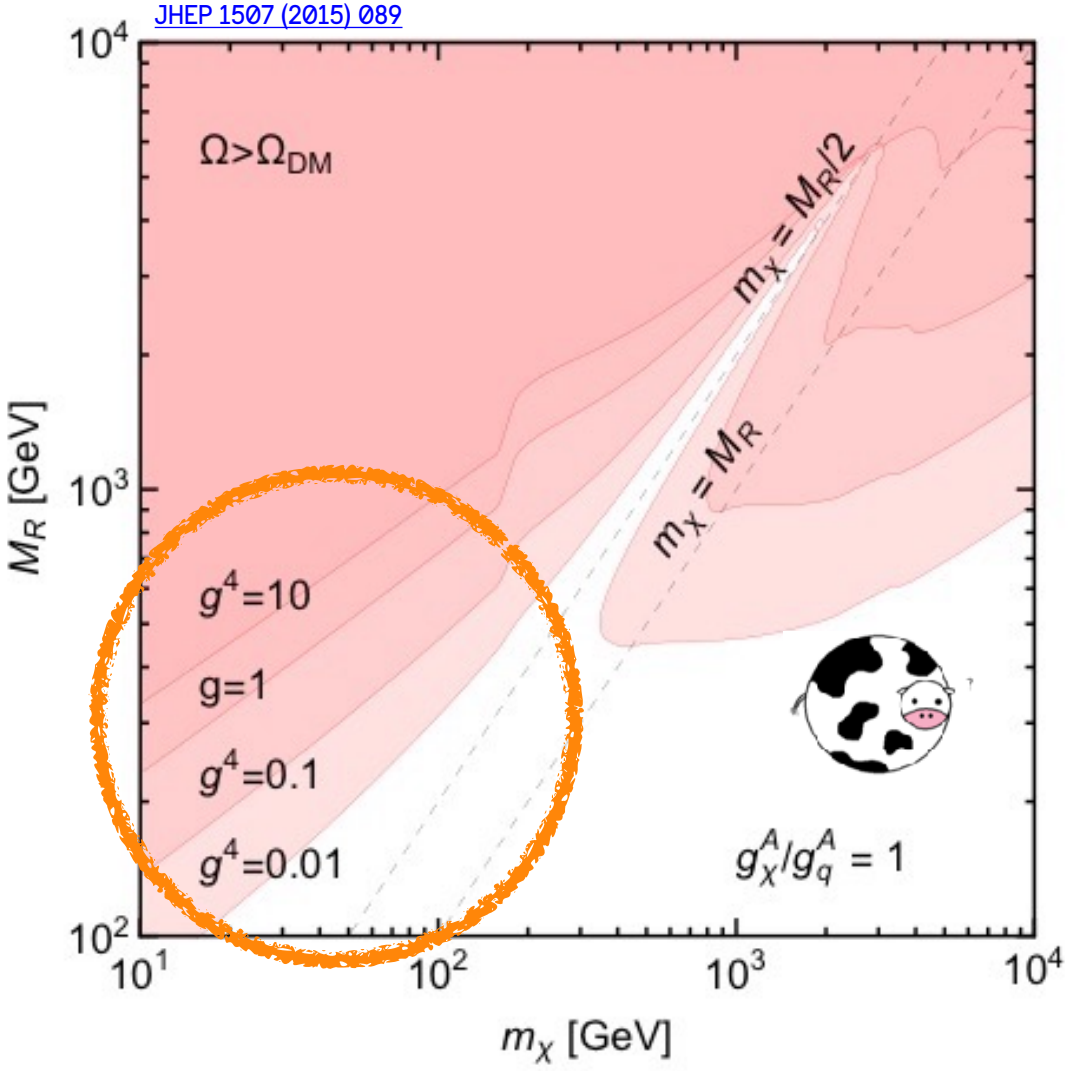
Motivating new searches for visible mediator decays

Visible low mass DM mediators: interesting!





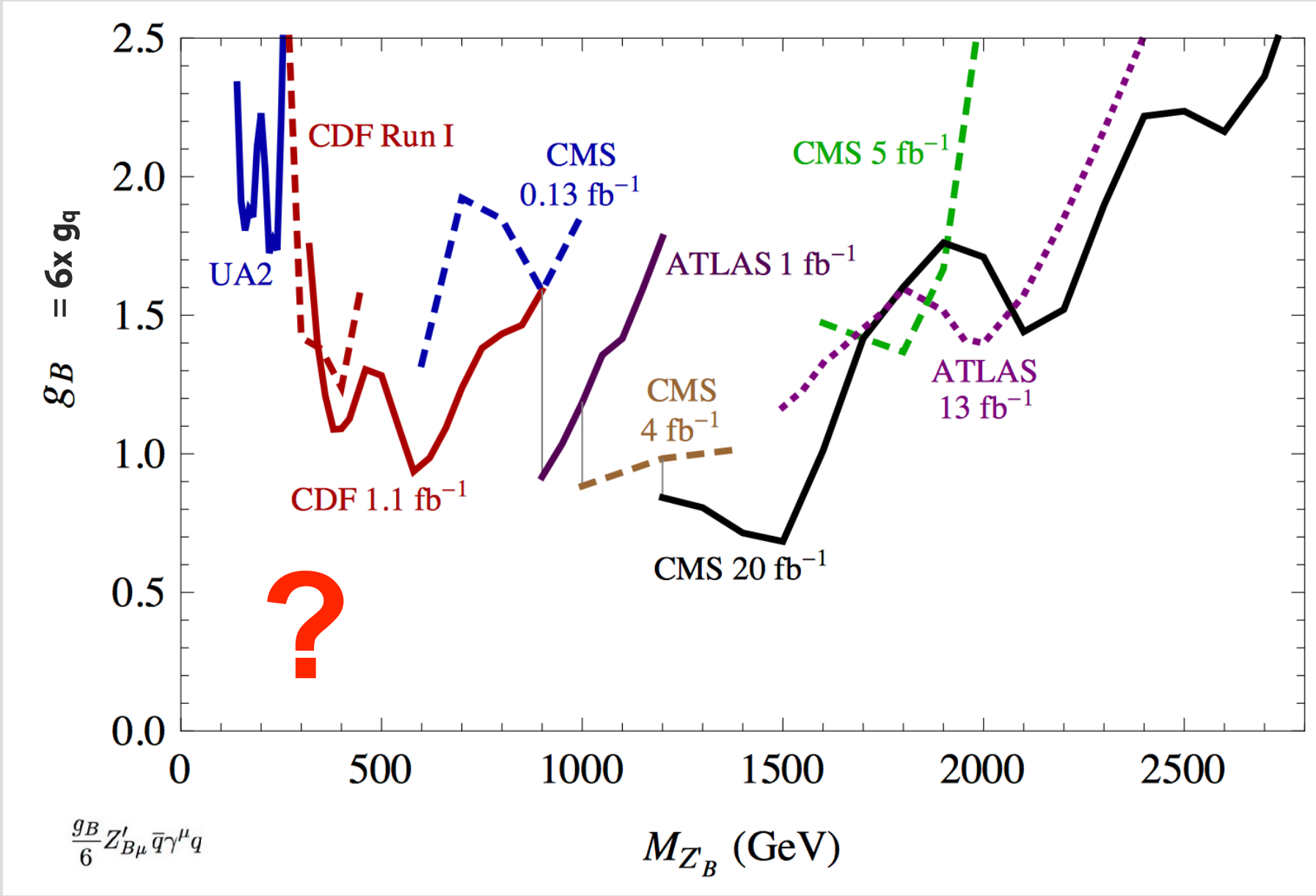
$$g \equiv (g_q^A \, g_\chi^A)^{1/2}$$



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

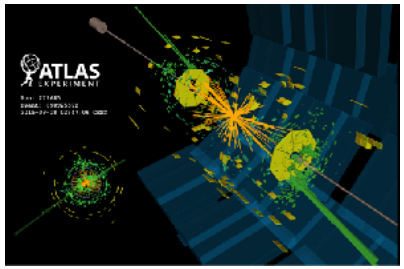
A. Boveia, LBL workshop

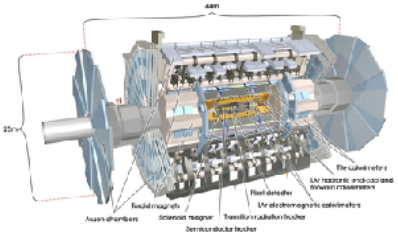
Dobrescu, Yu Phys Rev D 88 035021 (**2013**)



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

Data taking in ATLAS





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

Computing resources are essential for the full data taking chain

Trigger and data acquisition: select interesting events

LHC delivers data at 40 MHz (events/second)
First step: **fast hardware selection (Level 1)**
data taking rate: 100 kHz
Second step: **computer farm (High-Level Trigger)**
data taking rate: 1000 Hz

C. Fitzpatrick's talks on LHCb trigger

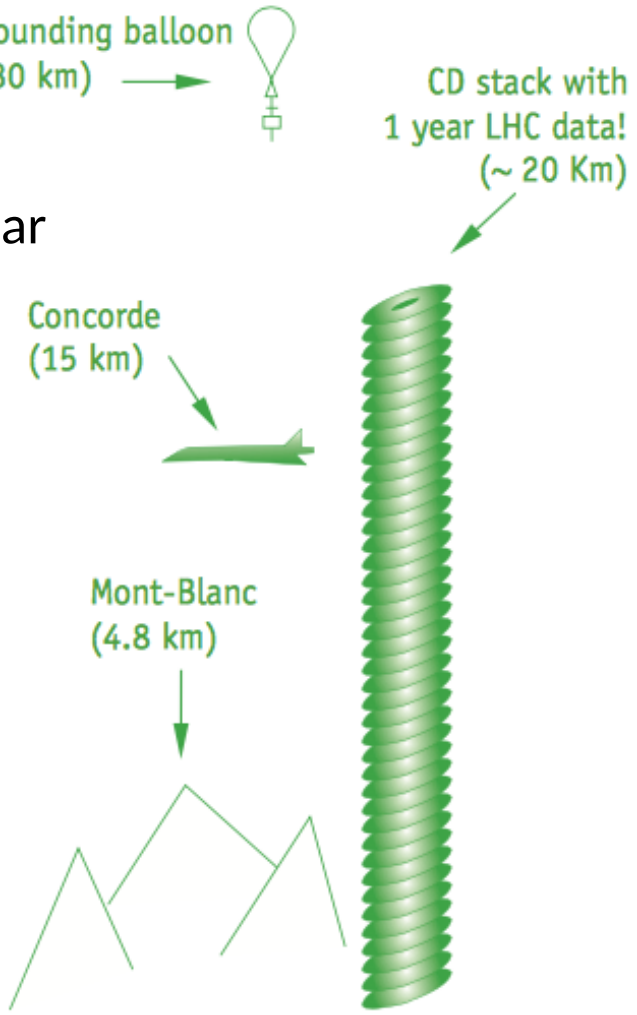
Why do LHC experiments *trigger*?

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

- Facebook:
  - 600 TB/day ~ 200 PB/year [Facebook 2014]
  - "There's always a bigger fish"

  [C. Tull's talk @ siRTDM18]

LHC experiments need to:
1. frequently **process** all data, fast
(this includes calibrating
and aligning the detectors!)
2. **select** only interesting events
(problem: we don't yet know what
interesting means)



(**after** selecting interesting events)

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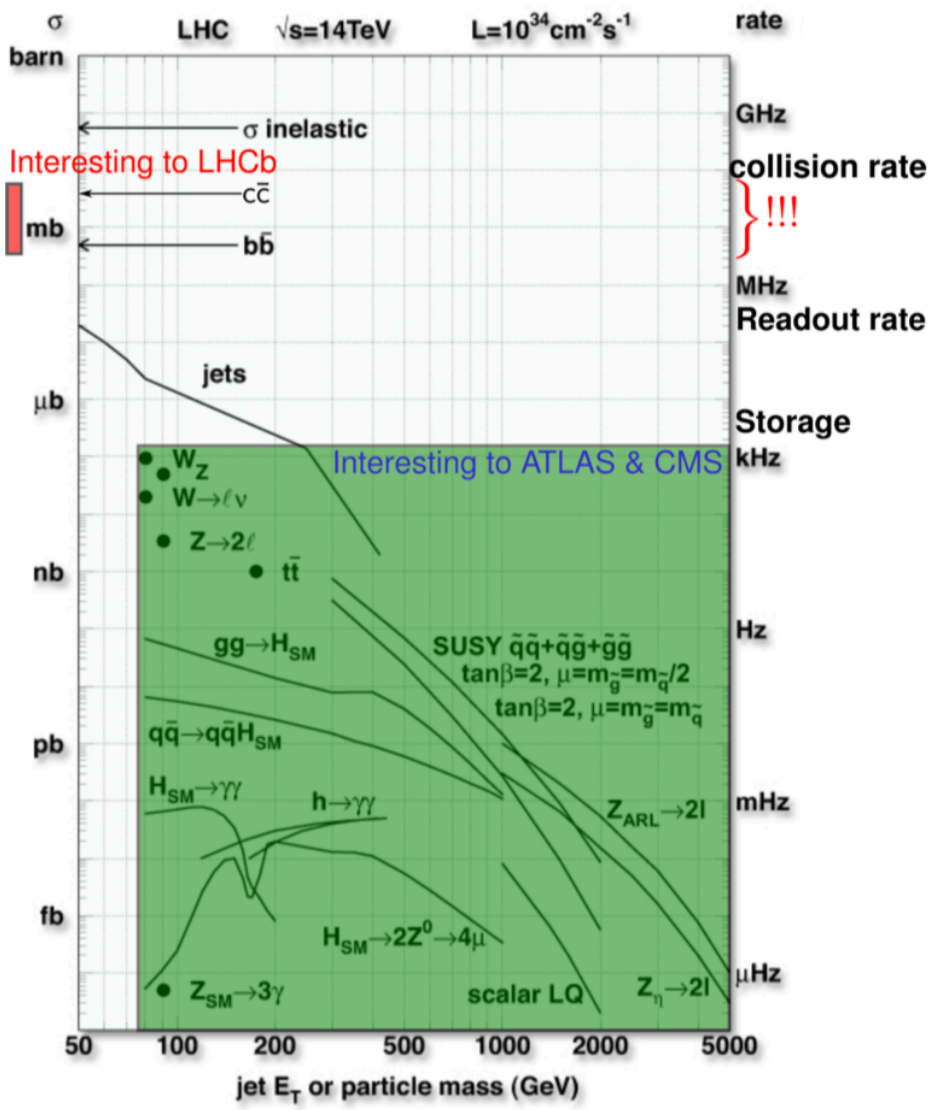
What is interesting?

J. Stirling / C. Fitzpatrick



Number of expected events
= luminosity * cross-section

Problem (to be discussed later):
what if we aim to discover
a new rare process
that looks like one of those
high-rate backgrounds?

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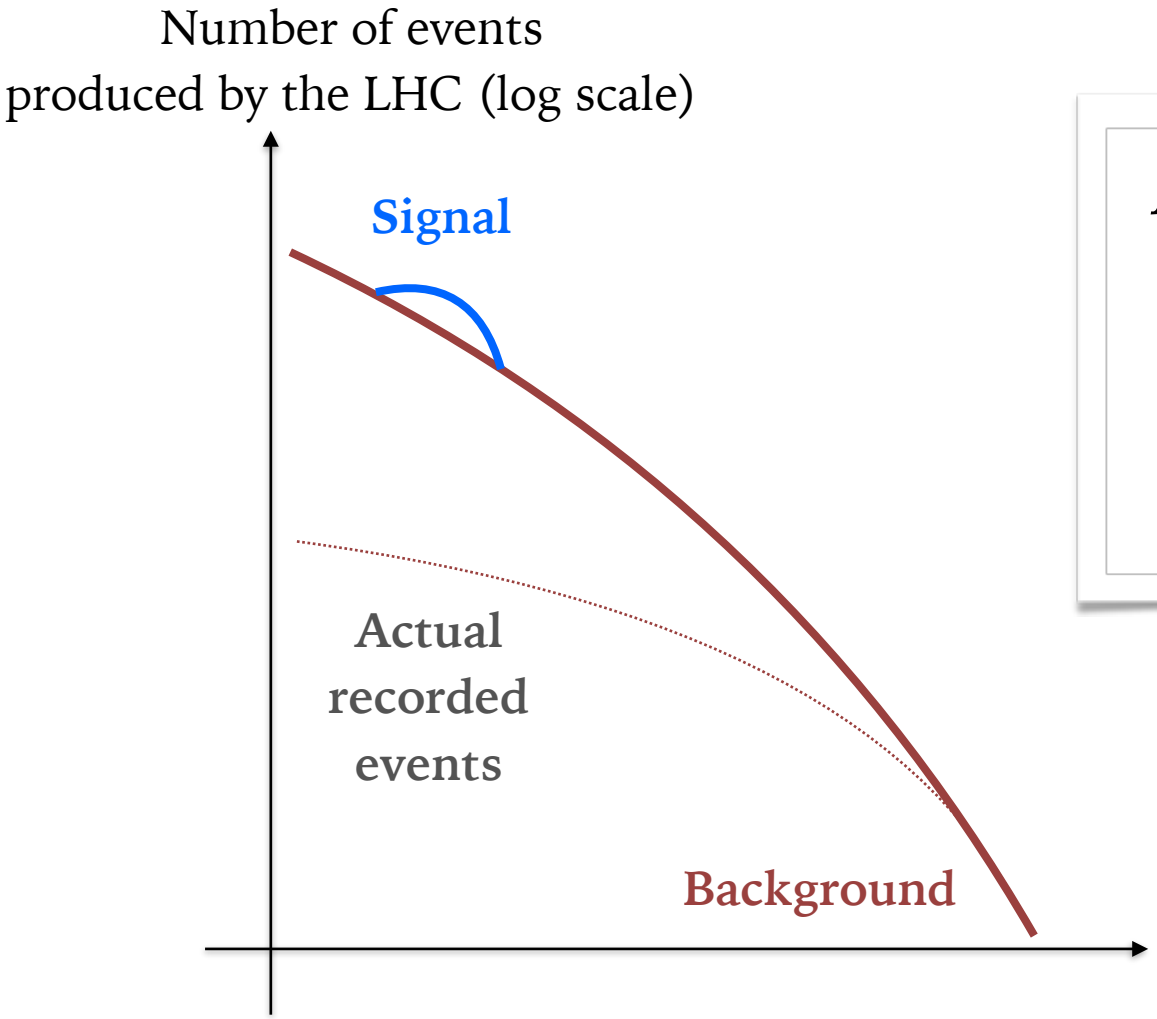
Signals vs backgrounds

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



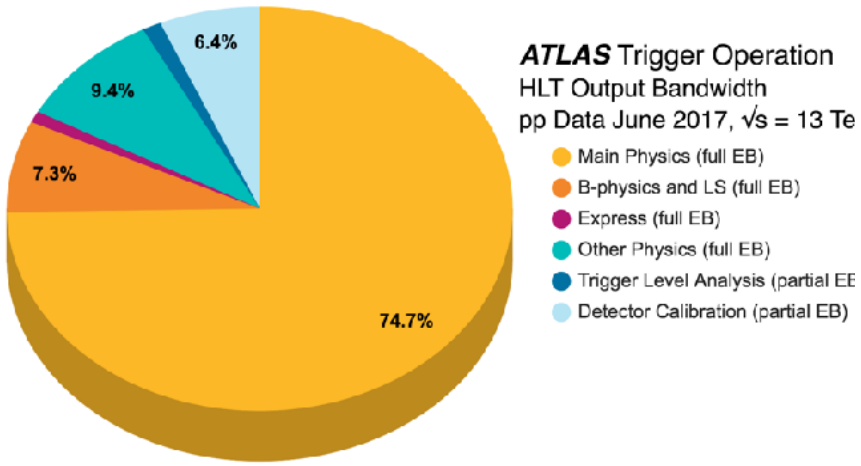
Impossible to record all events in full
→statistical error harms sensitivity!

Trigger Level Analysis technique (TLA)

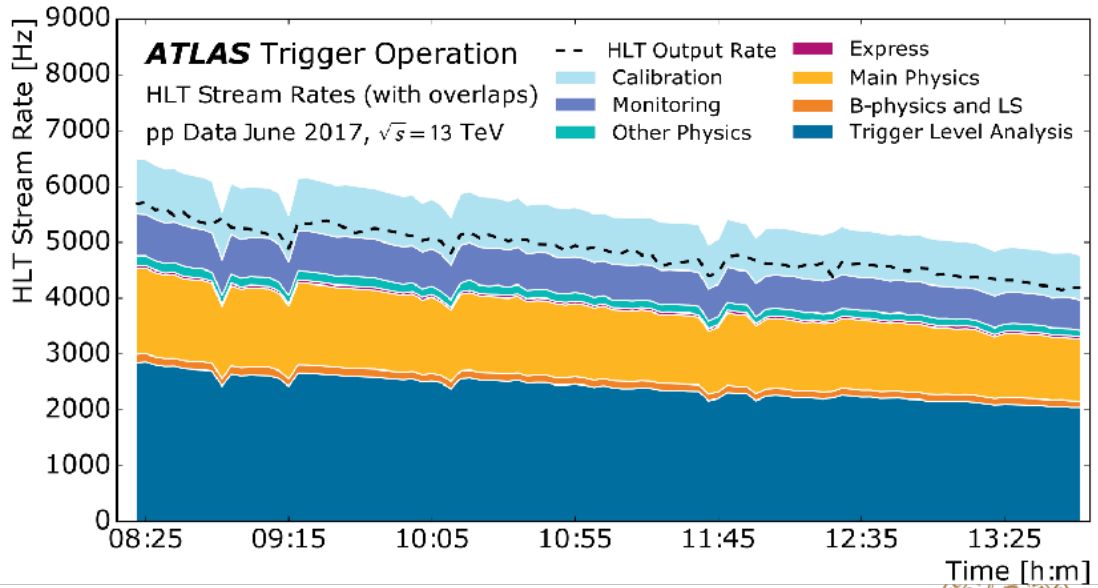
(LHCb: Turbo Stream, CMS: Data Scouting)

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

Event size reduced to <<5%
of fully recorded event



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



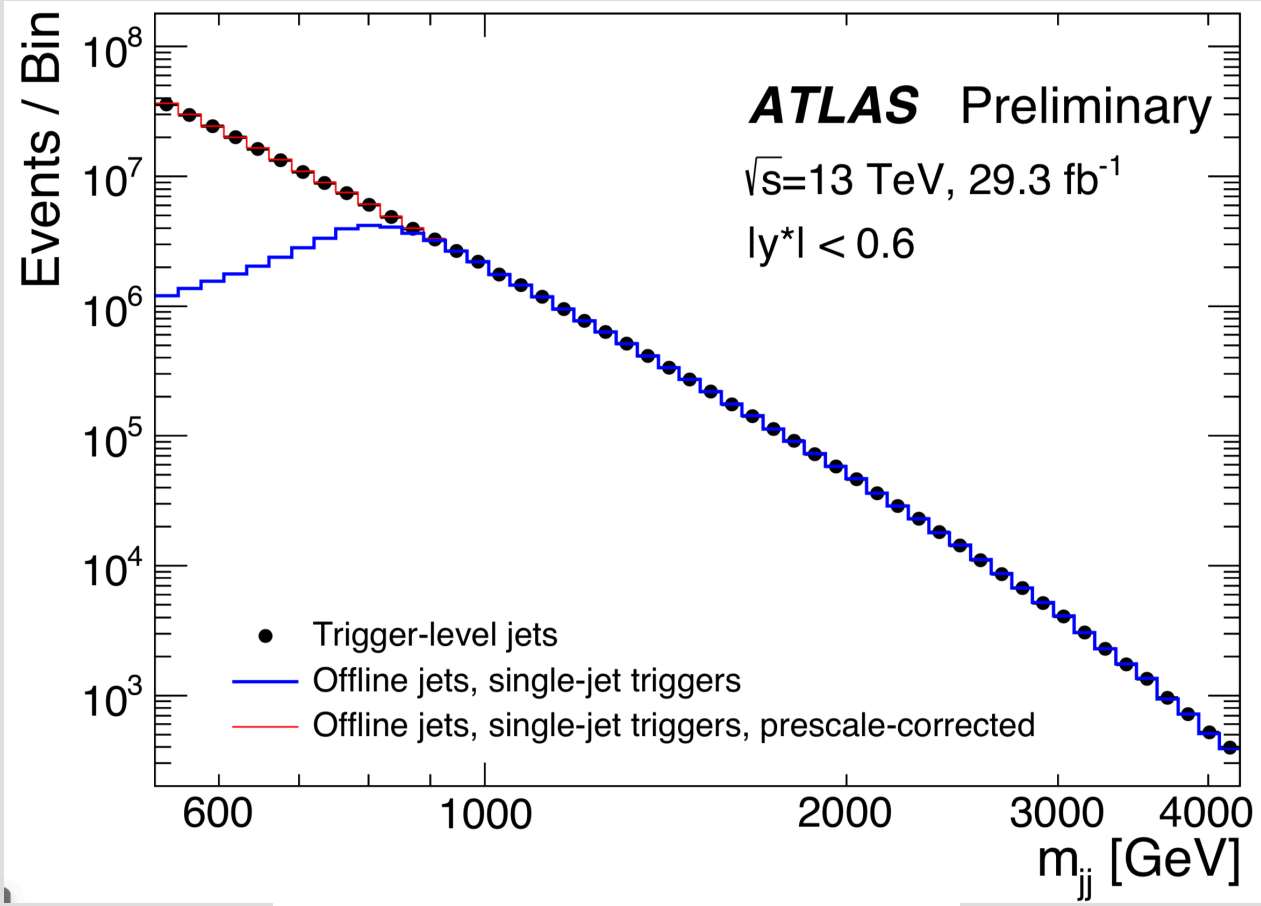
Other ways to get to low masses (beyond +ISR, +VBF):
prescaled triggers/data parking/delayed stream

Statistics increase from Trigger-Level Analysis technique: dijet invariant mass

update from A. Boveia, LBL workshop

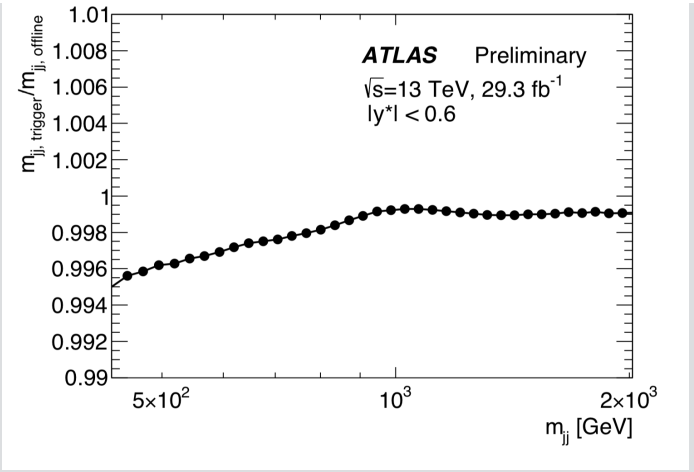
Upcoming EXOT-2016-20

Statistics increase



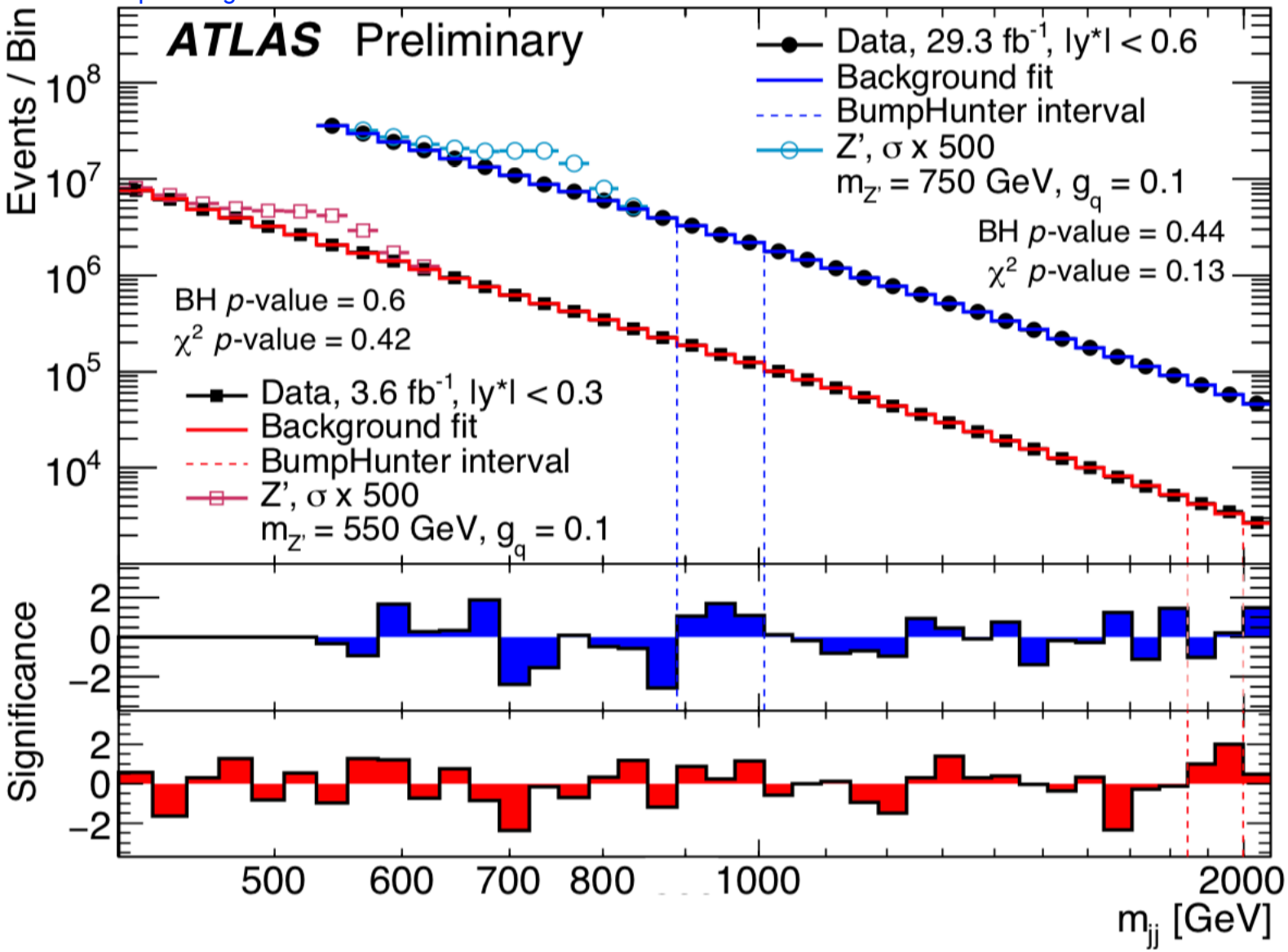
Performance comparison:

trigger/fully reconstructed response ~= unity



Search results: no excess over background

Upcoming EXOT-2016-20



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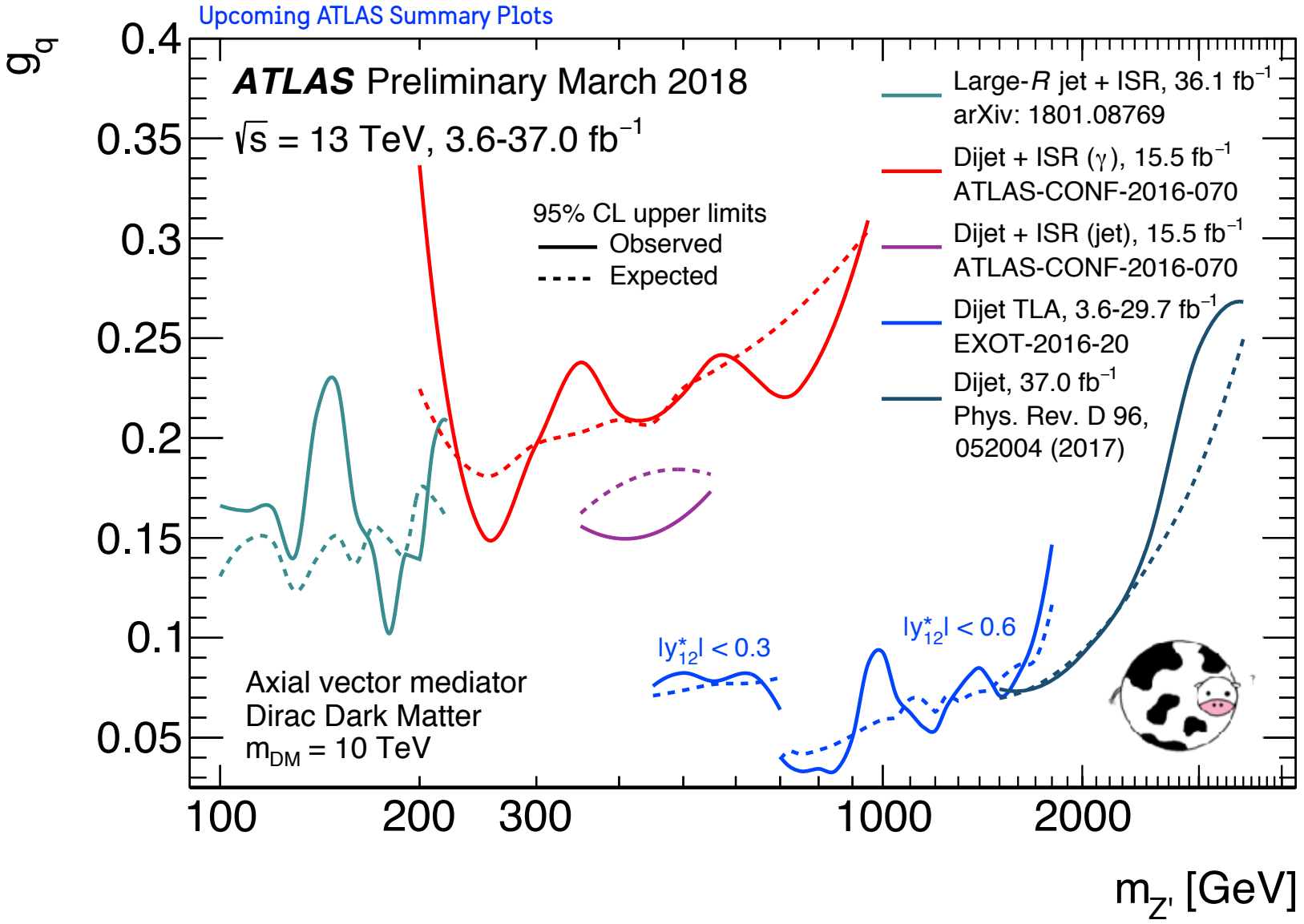
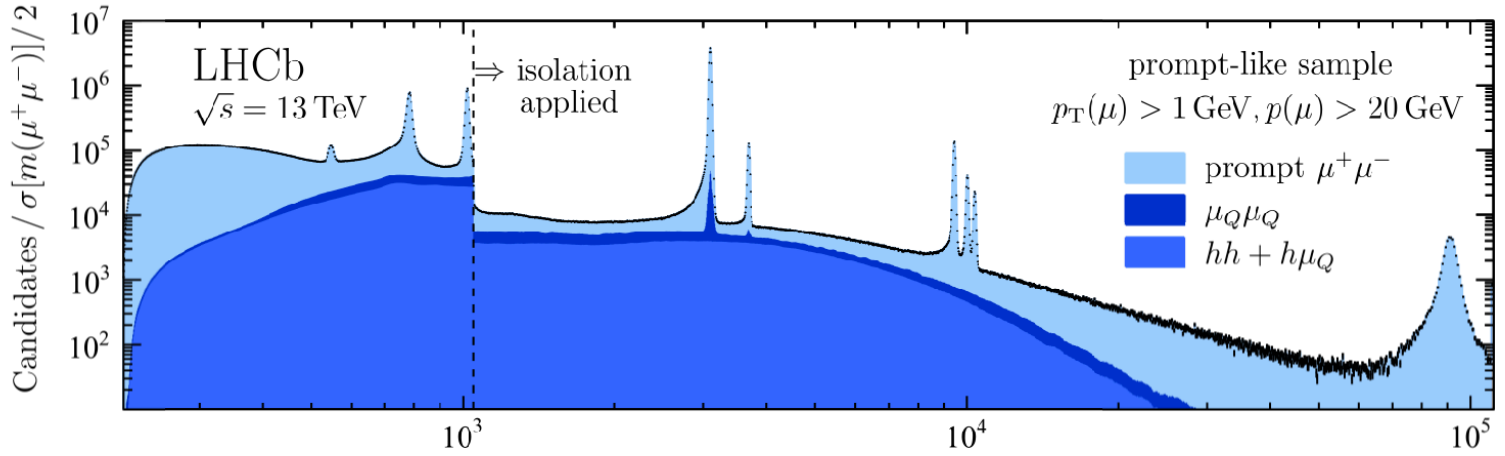
The full picture for hadronic resonances

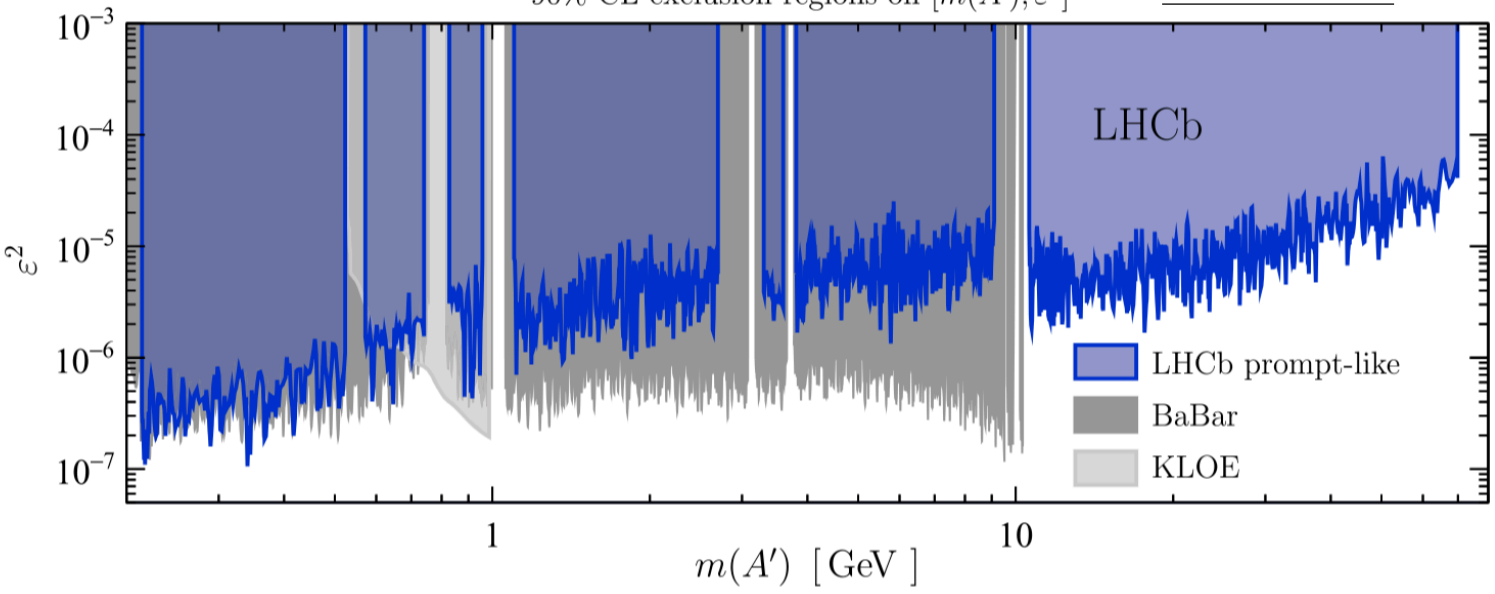


LHCb turbo stream: dark boson search

Dark bosons decaying to dimuons: same principle as dijets
very large background but good mass resolution online
→ use trigger objects to discover new resonances with large SM backgrounds



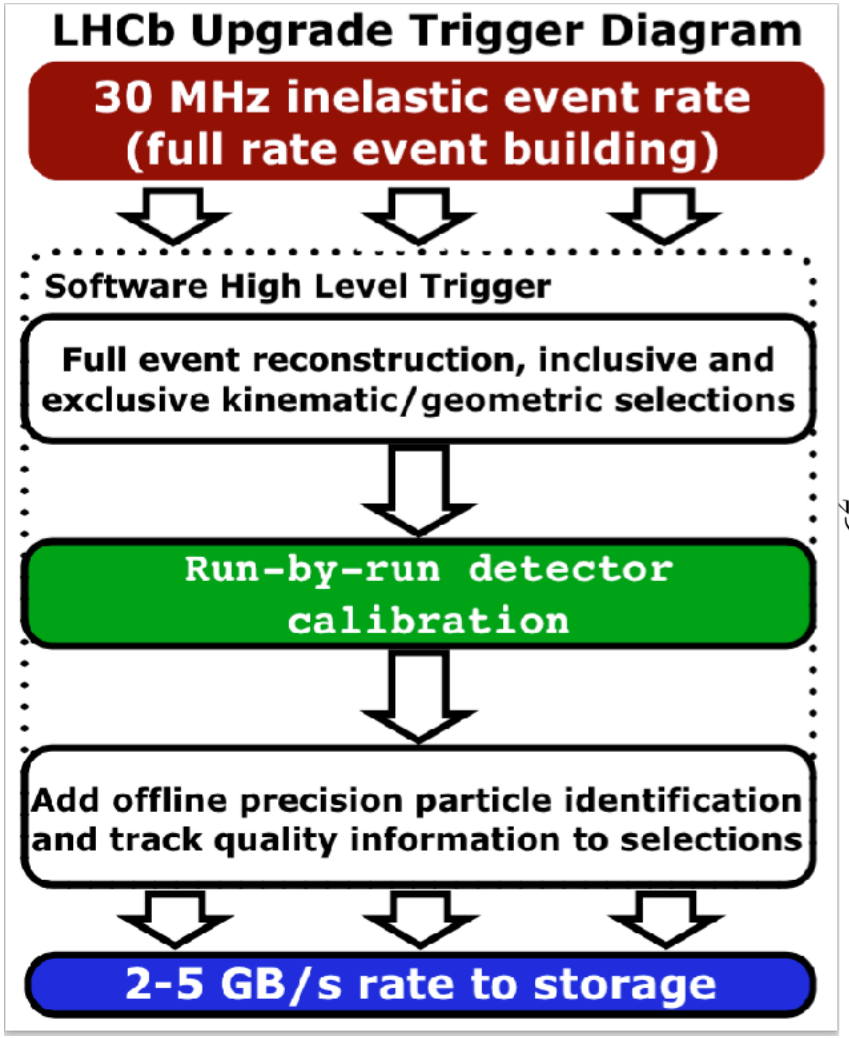
90% CL exclusion regions on $[m(A'), \varepsilon^2]$ arXiv:1710.02867



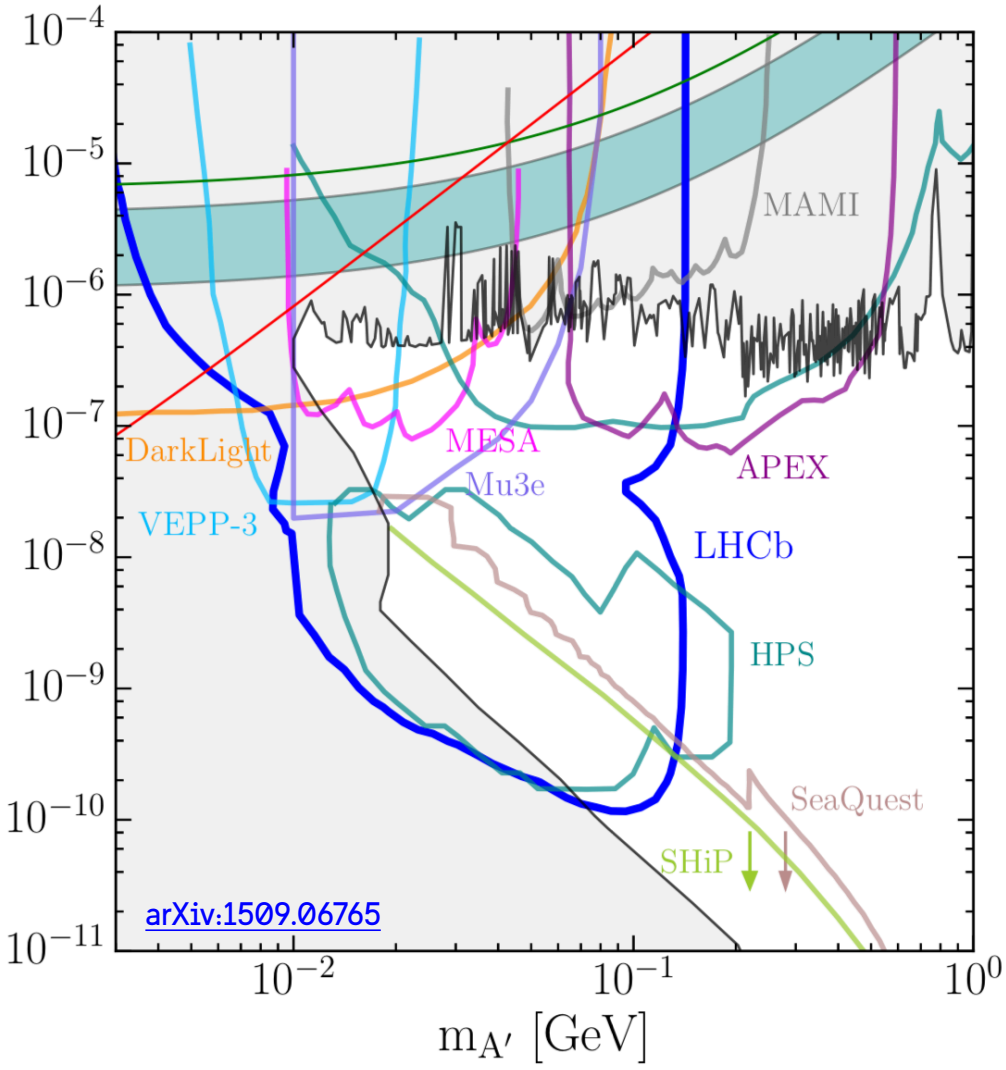
lower rate of events

LHCb in the future (Run-3)

"Triggerless" readout



$D^{*0} \to D^0 A', \quad A' \to e^+e^-$



A paradigm change

Asynchronous data analysis
(all raw data recorded, then analyzed)

- ❌output: large (all detector information)
- ❌current "interesting" thresholds not sustainable at high luminosities
- ✅allows for offline analysis as refined as possibl

"keep only the science content"
LCLS-II data flow, talk by A. Perazzo

"Real-time" data analysis
(data is reconstructed/analyzed right after being recorded, so that only final-state objects can be stored, if needed)

- ✅output: small (only high-level objects)
- ✅collects more data using less storage
- ❌requires more "online" computing power
- ❌can't go back and re-reconstruct (no info)

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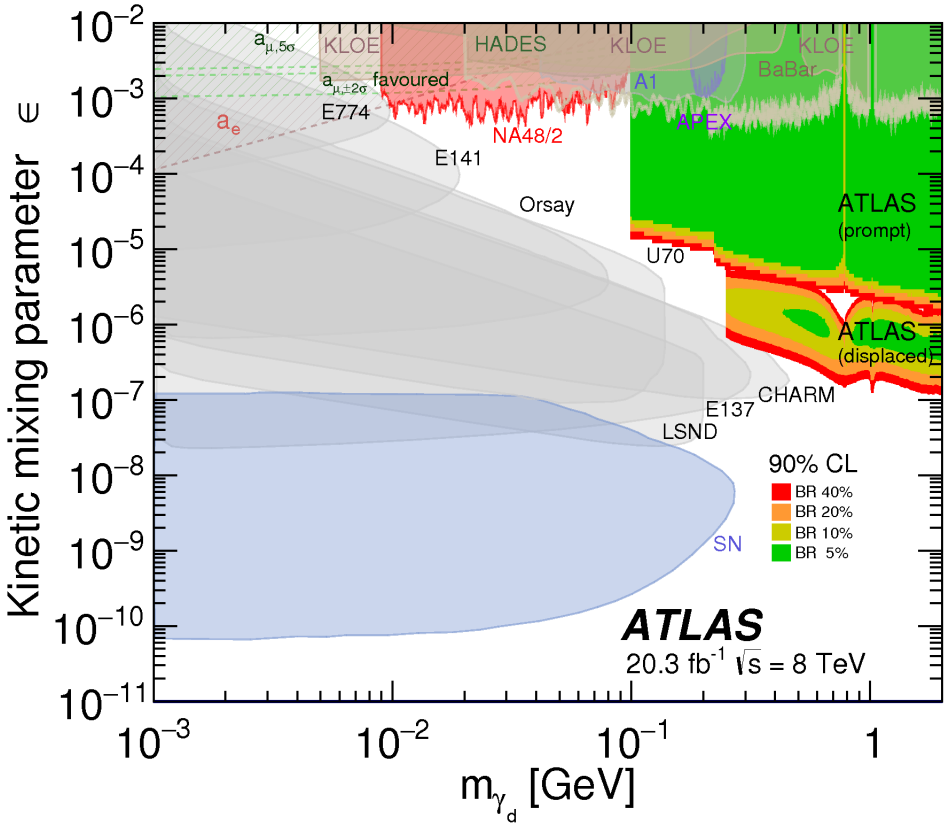
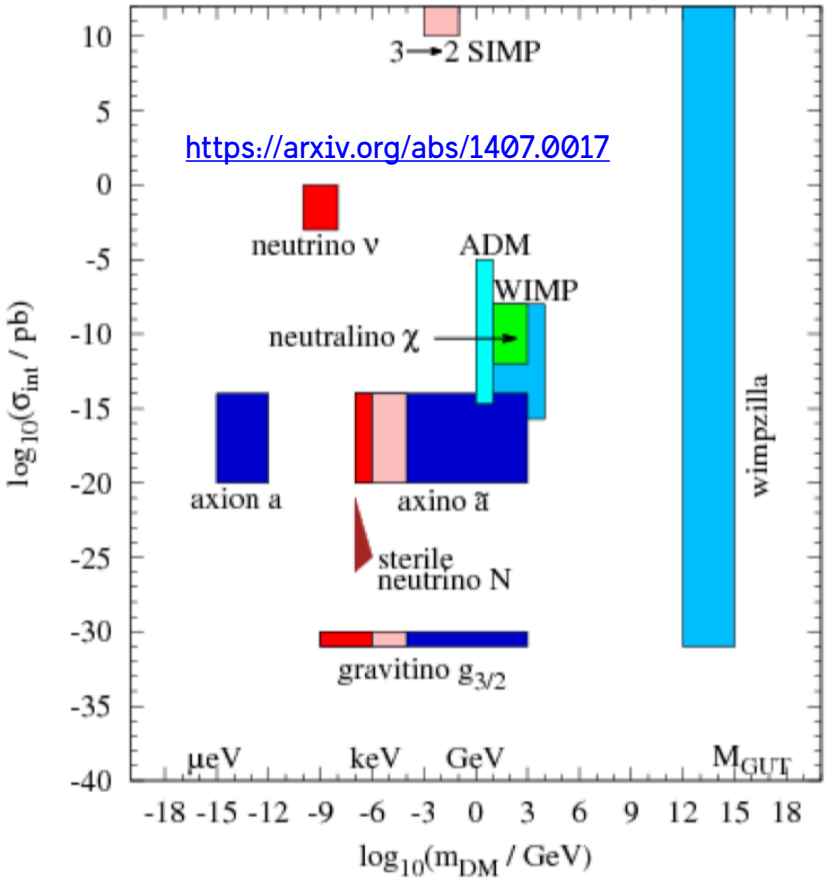
Parameter space for light DM/mediators

Searches for Dark Sector particles (example)

10.1007/JHEP02(2016)062



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



Many other interesting and compelling DM candidates need **innovation** to record these events (e.g. long-lifetime) - not covered here

LLP community effort: benchmark models and experimental signatures
LHC DMWG effort: connecting LHC dark boson benchmarks to cosmology and other LHC searches

Conclusions & outlook

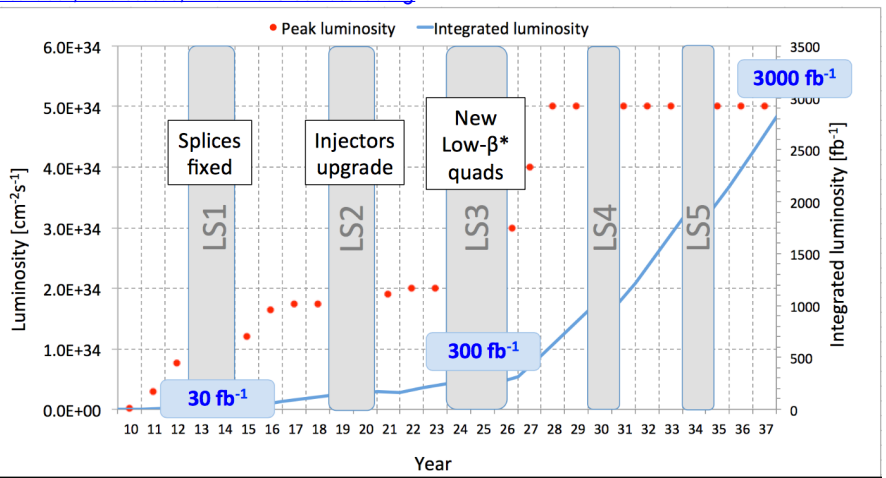
Many different theories can explain DM, none favored by data yet
Very different detector signatures
- signals can be buried in high-rate backgrounds or rare but unusual

***Look everywhere effect*:** we need to make sure we record the events first
See backup slides for present/upcoming **hardware innovations**

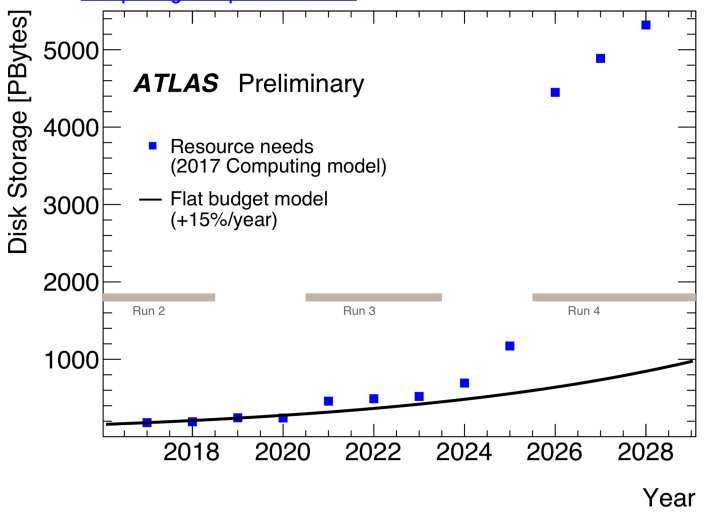
Making the most of LHC data: enabling discoveries
by ensuring events are selected and recorded in the most efficient way

Crucial at HL-LHC: full exploitation of dataset will require innovation

S.Bertolucci, LHC status, LHCP 2015 St Petersburg



Computing&SW public results caveat: includes simulation



Discussion points

For further discussion (related)

1. **How far should we go in terms of couplings for visible resonance (mediator) searches**
   - Trade-off between work needed and scientific output
   - Could DM models have arbitrarily low couplings?
2. **Are there any other DD/ID experiments with the same issue (excess of data)?**
   - Example of LSST, see backup slides
   - Inter-experiment connections are always interesting
   - See HEP Software Foundation whitepaper (roadmap to 2020), trigger chapter, executive summary

For further discussion (unrelated)

1. **Where do we go from here?**
   - Are we missing something?
   - *Pro domo mea*: LHC Dark Matter Working Group
   - Long-Lived Particle Working Group
2. **What makes the interpretation of a search "DM"?**
   - How seriously should we take relic density (many ramifications)?
3. **Connections with astrophysics**
   - See next slide

Further complementarity: astro/cosmo?

Relic density

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

Galaxy formation

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

Nature of DM

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

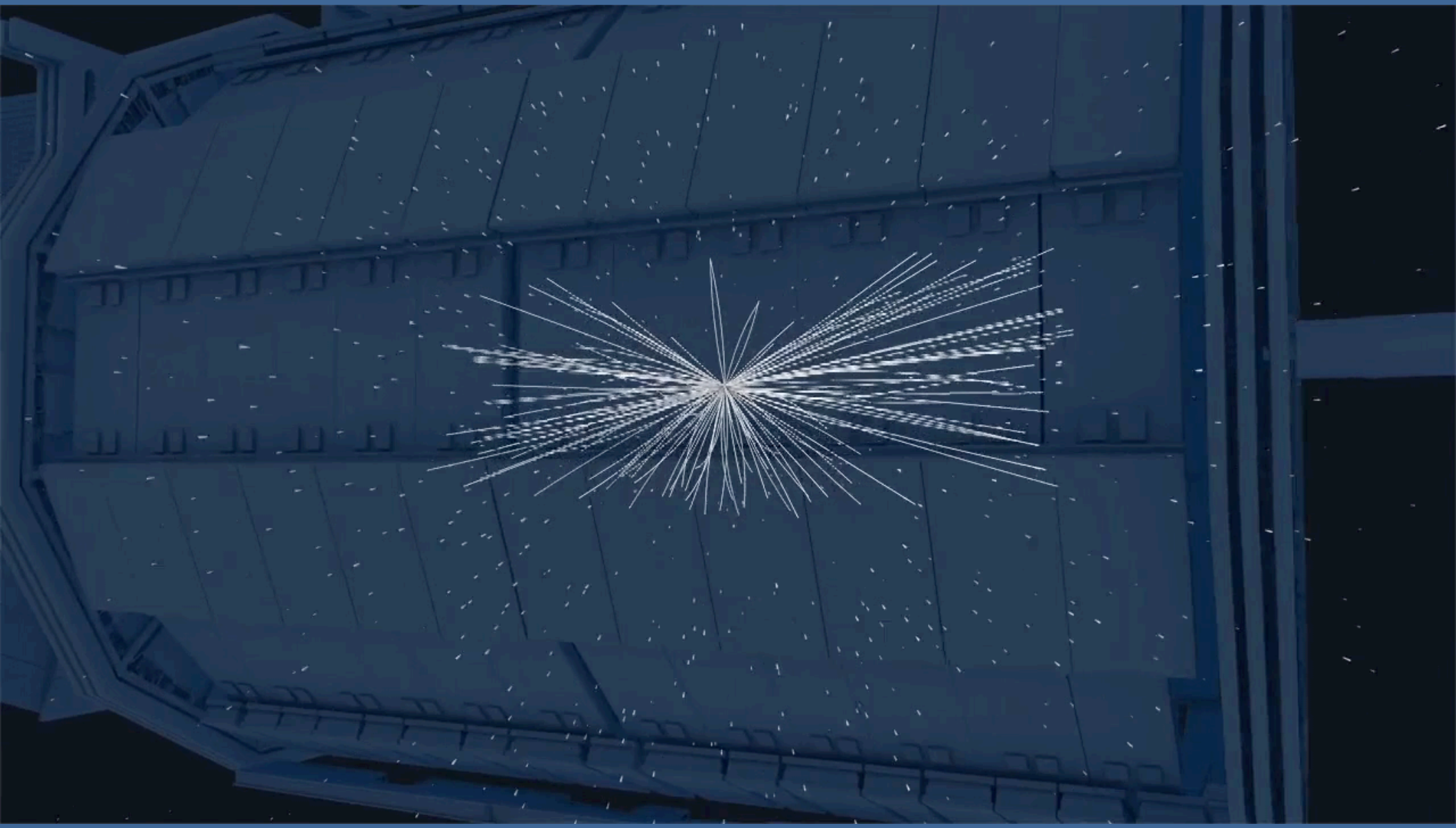
Role of the Higgs

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

Backup slides

Video: triggering and processing data

CERN-MOVIE-2013-041-001



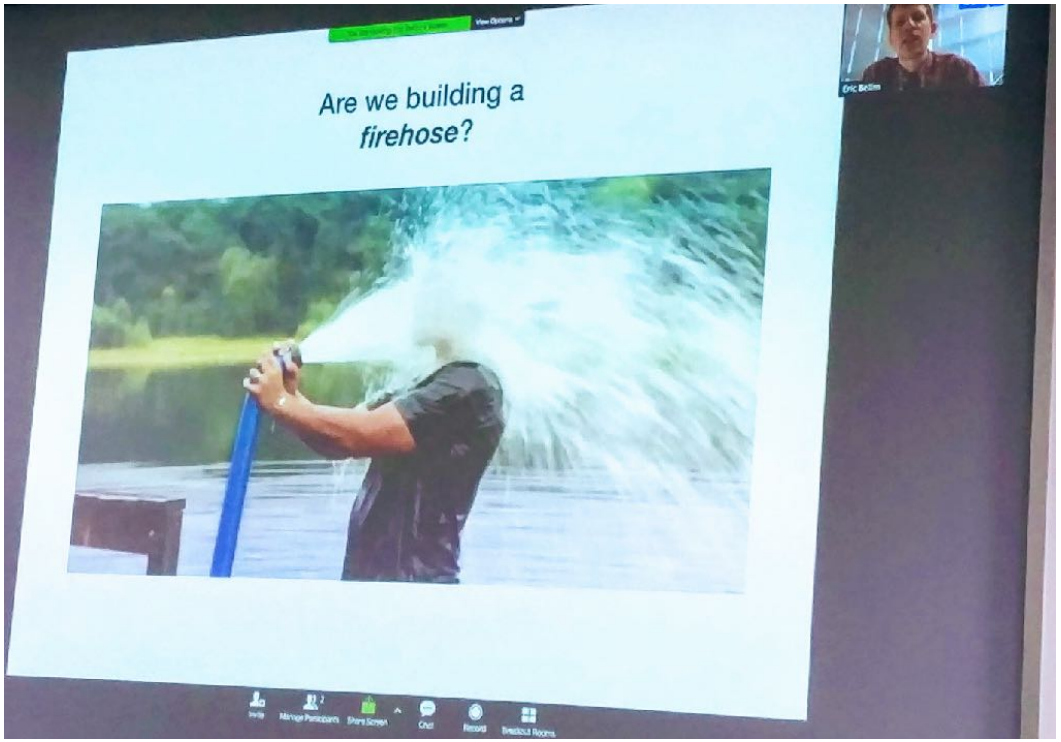
Parallels with astrophysics

C. Fitzpatrick

The trigger

...or how to drink from a firehose

E. Bellm - LSST talk at siRTDM18



The LHC is also a data firehose!

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Parallels with astrophysics observations

LSST [data broker] 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

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Detail #1: ATLAS Fast TracKer

A. Boveia

Many collisions happen simultaneously (pile-up)

Precisely measure each particle trajectory (track) → associate a particle with a particular collision amongst noise of many collisions

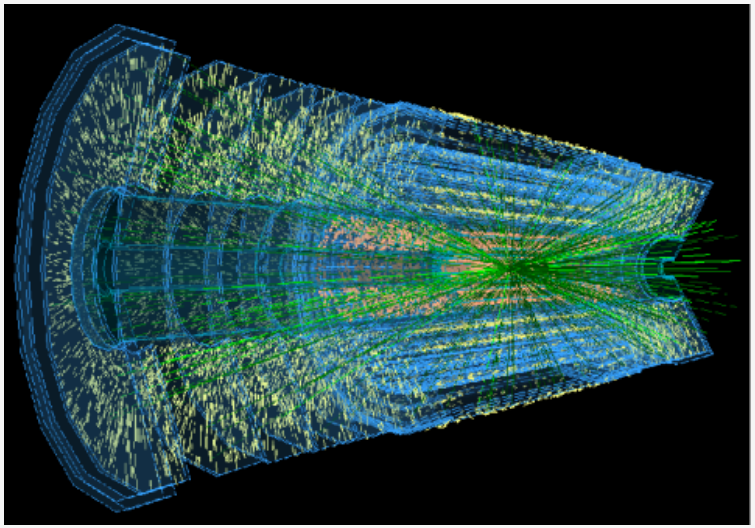
- Pattern recognition problem (connect the right dots amongst ~10^5) and helix fitting (particle momentum, vertex)
- On analysis farms, this is done by brute-forcing many possible combinations in series (tracking); can take 10's of sec.

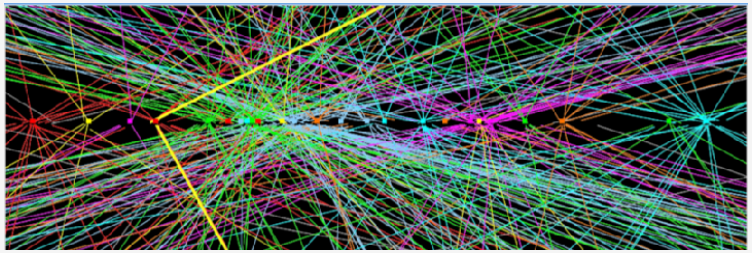
Tracking is very useful to make real-time decisions about which events to keep

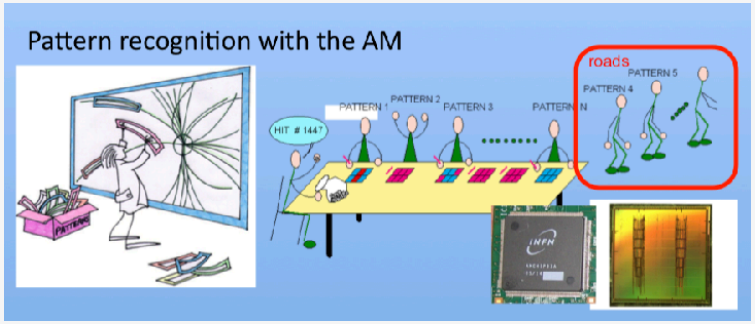
- Must reduce event rate from 100 kHz to 1 kHz by real-time analysis
- <1 ms to make decision

ATLAS FTK (coming online this year) solves the tracking problem in custom-built hardware

- Content-addressable "Associative Memory" chips to match data to >10^9 pre-computed hit patterns, massively parallel
- Linearized helix fits in Altera Arria V FPGAs at 1 fit/ns



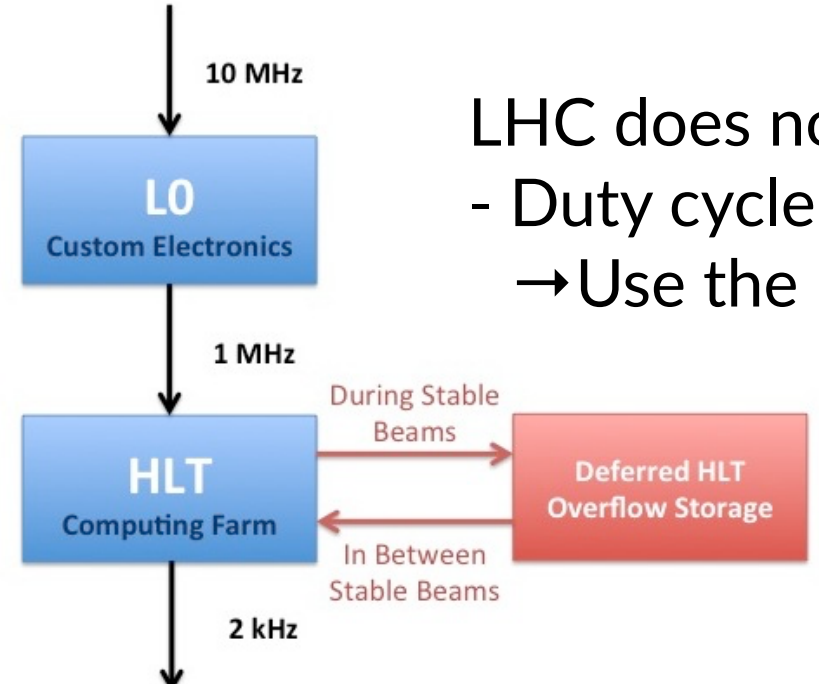




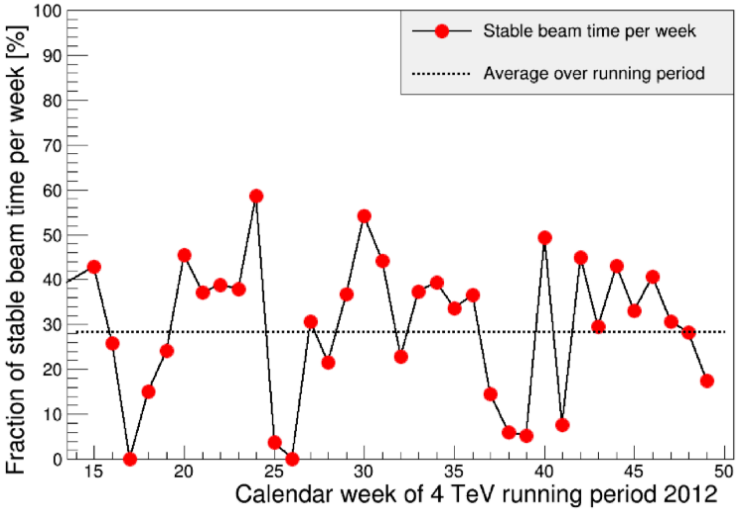
See I. Shapoval's talk yesterday

Detail #2: LHCb buffering

A. Phan, Quantum Diaries

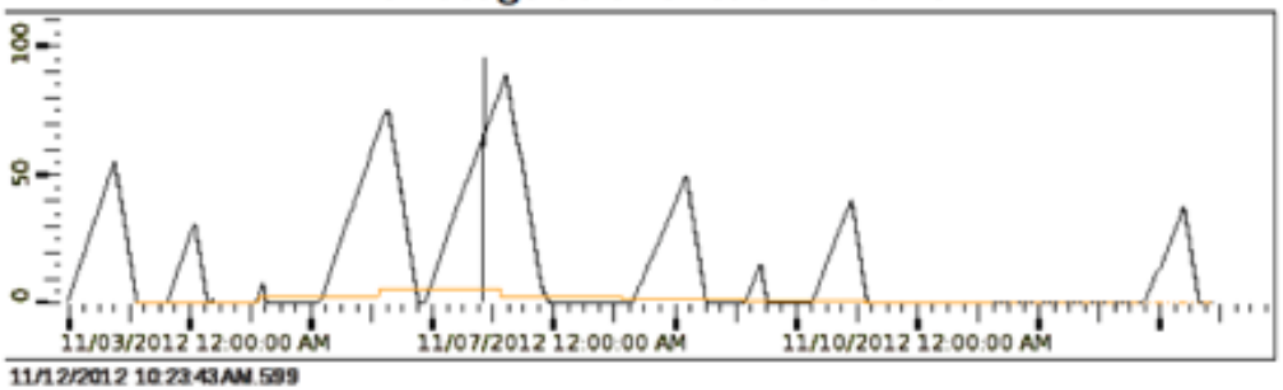


LHC does not operate 100% of the time
- Duty cycle in Run-1: 30% of the time
  →Use the rest of the time to **process more data**



LHCb-TALK-2015-066

Disk usage as a function of time



See also: ALICE

Detail #3: LHCb software-only upgraded trigger

arXiv:1410.5012

Rates for Run-1

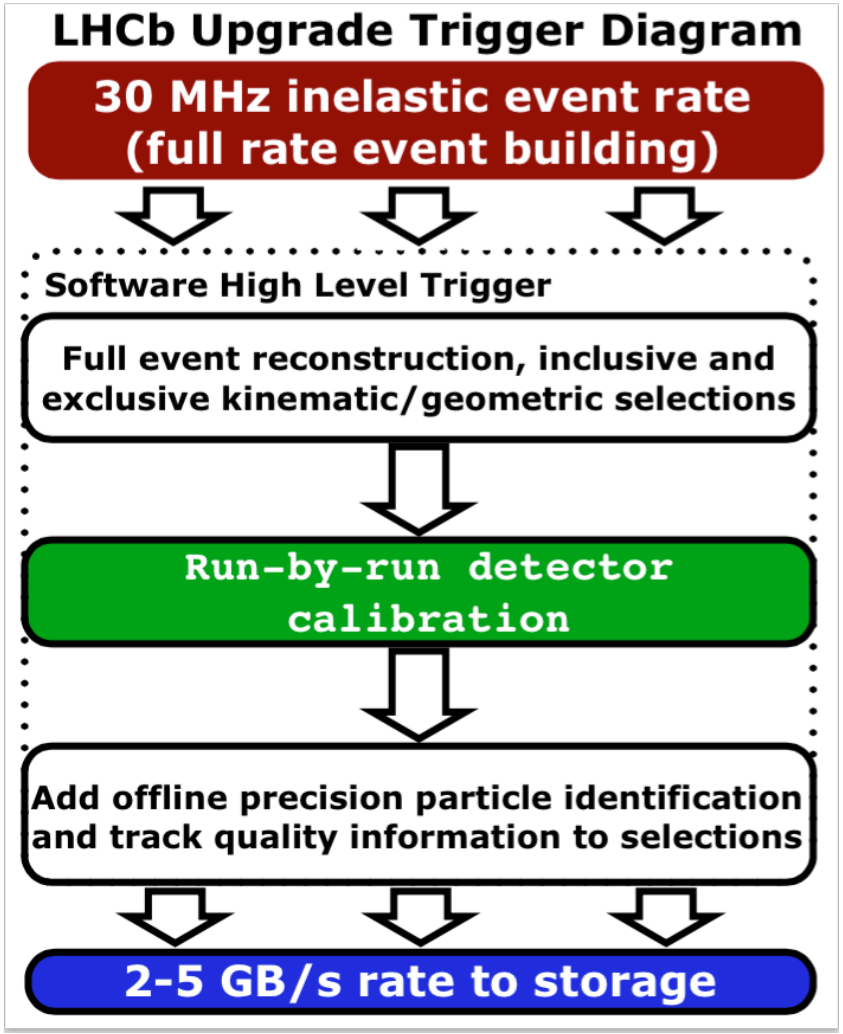
	b-hadrons	c-hadrons	light, long-lived hadrons
Output rate	17.3 kHz	66.9 kHz	22.8 kHz

Rates for Run-3, 2021

	b-hadrons	c-hadrons	light, long-lived hadrons
Output rate	270 kHz	800 kHz	264 kHz

Every event is signal!

- move analysis to trigger
- increase capability of HLT farm
  - expecting:
    - 27 GB/s for b-hadrons
    - 80 GB/s for c-hadrons
    - 26 GB/s for long-lived hadrons



If every event is interesting, move towards trigger-less readout

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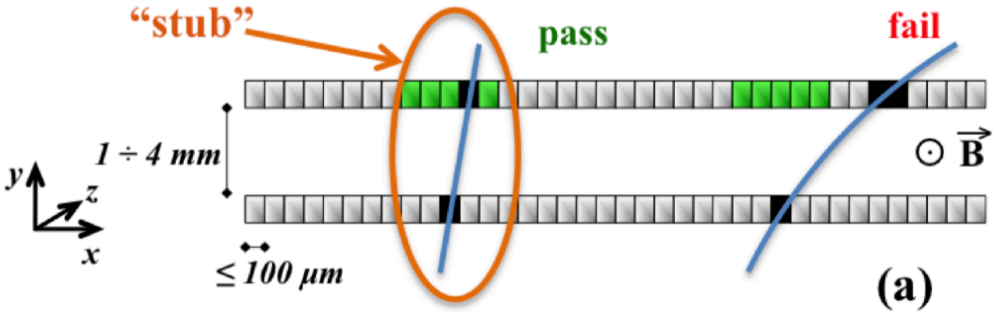
LHCb-PUB-2014-027

Detail #4: CMS upgrade track trigger

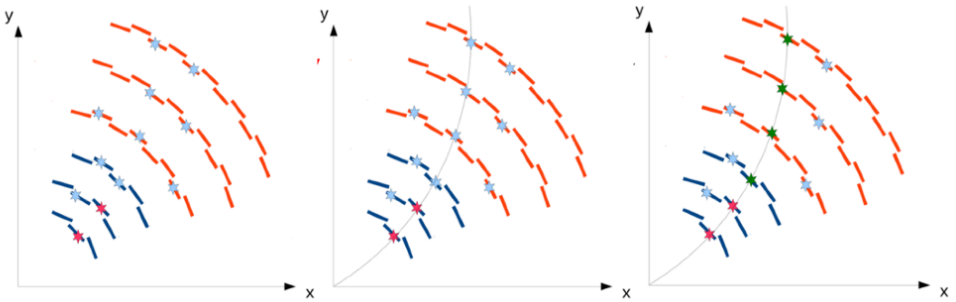
Full particle tracking information too expensive to be available at L1
At HL-LHC, tracks necessary to reject rate due to pile-up

ATLAS / CMS plan to provide tracks to L1 (CMS example: @ 40 MHz) with a latency of 5 μs

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)



CMS upgrade TDR

F. Palla et al 2016 JINST 11 C03011

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"Real-time analysis" at LHC experiments?

A rather personal (debatable?) definition

First-pass data analysis
done on short timescales
and/or with limited information
that influences further data-taking

Data analysis: done within the **trigger** system
Decision taken: **whether to record the data**
Timescales involved: **microseconds**

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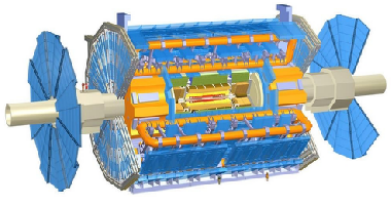
Turbo/Data scouting/TLA path



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

LHCb/ATLAS/CMS:
~same reconstruction **software and inputs** online and offline
(ALICE: planned upgrade)

LHCb: **buffering** data on disk allows for precise detector alignment and calibration

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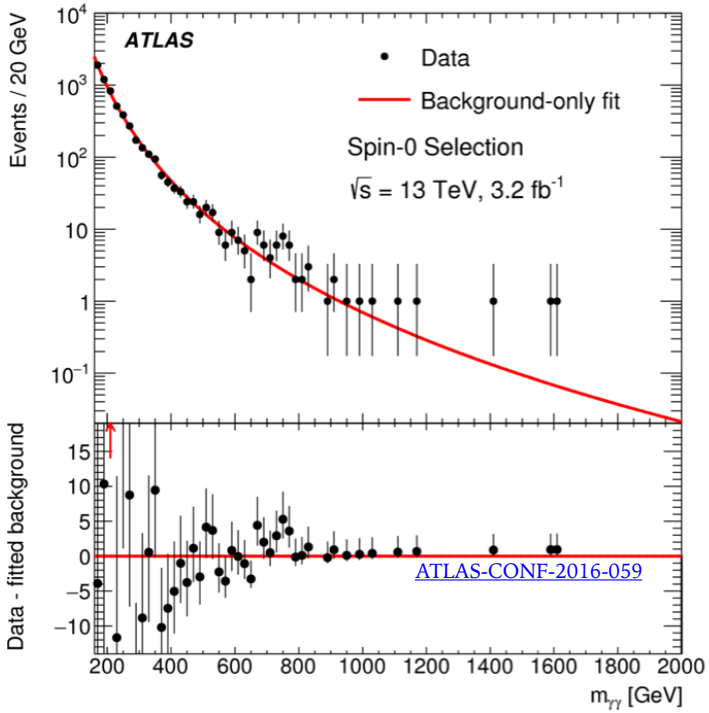
Better-than-real-time data interpretation?

Di-photon, December 2015:
(small) overall excess over background,
not confirmed with more data

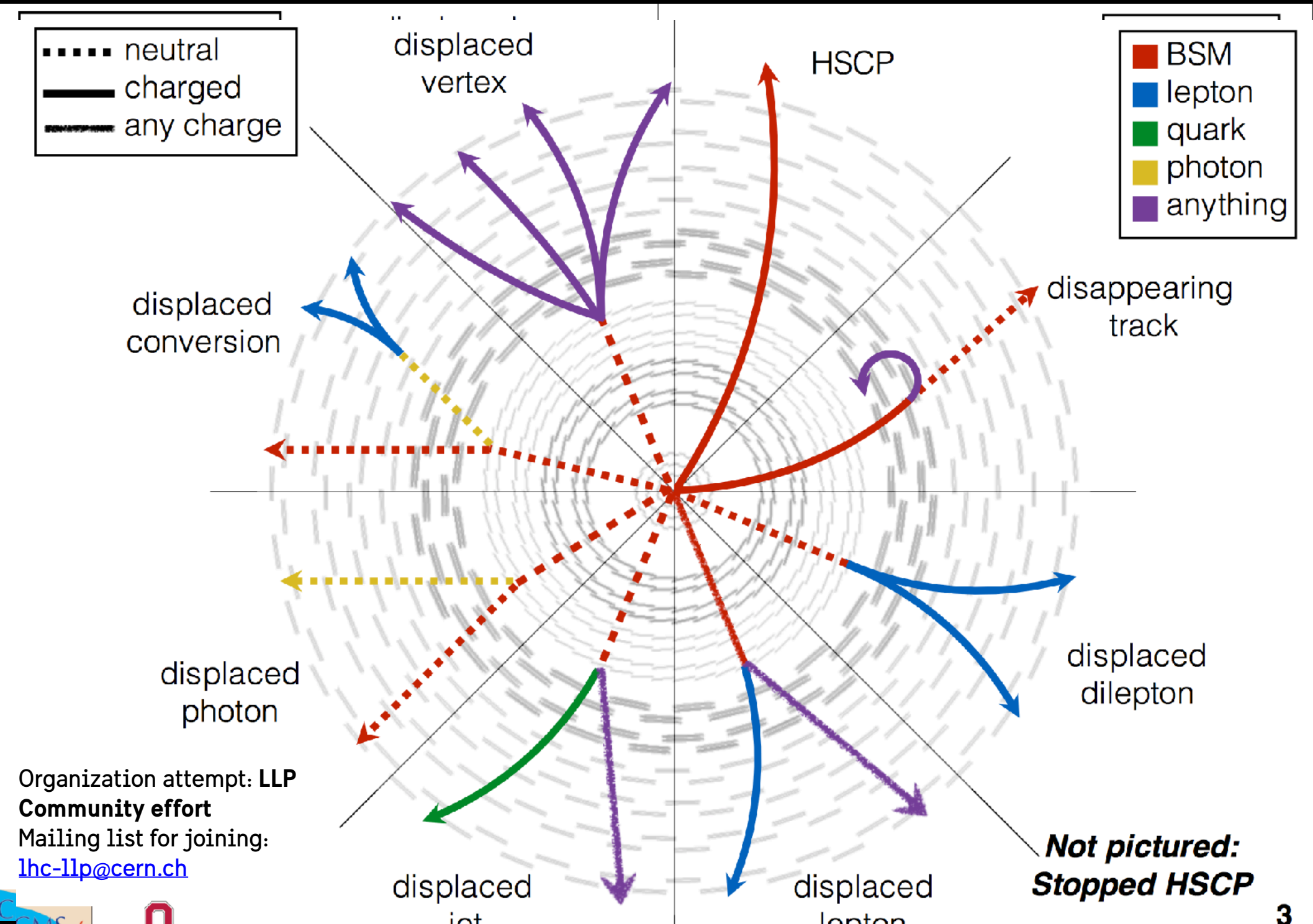


The key to many LHC analysis is to collect sufficient data to make "significant" statements

December 2015: the Gold Rush			
0	ATLAS and CMS	seminar	15 Dec 2015 14-16
1	K. Harigaya, Y. Nomura, 7 pages	1512.04850	v1: 15 Dec 2015 16:47:58 v2: 16 Dec 2015 08:19:11
2	Y. Mambrini, G. Arcadi, A. Djouadi, 9 pages	1512.04913	15 Dec 2015 20:05:04
3	M. Backovic, A. Mariotti, D. Redigolo, 17 pages	1512.04917	15 Dec 2015 20:26:16
4	A. Angelescu, A. Djouadi, G. Moreau, 15 pages	1512.04921	15 Dec 2015 20:32:58
5	Y. Nakai, R. Sato, K. Tobioka, 6 pages	1512.04924	15 Dec 2015 20:39:32
6	S. Knapen, T. Melia, M. Papucci, K. Zurek, 20 pages	1512.04928	15 Dec 2015 20:44:08
7	D. Buttazzo, A. Greljo, D. Marzocca, 16 pages	1512.04929	15 Dec 2015 20:49:36
8	A. Pilaftsis, 6 pages	1512.04931	15 Dec 2015 20:50:27
9	R. Franceschini, G. Giudice, J.F. Kamenik, M. McCullough, A. Pomarol, R Rattazzi, M. Redi, F. Riva, A. Strumia, R. Torre, 32 pages	1512.04933	15 Dec 2015 20:53:14

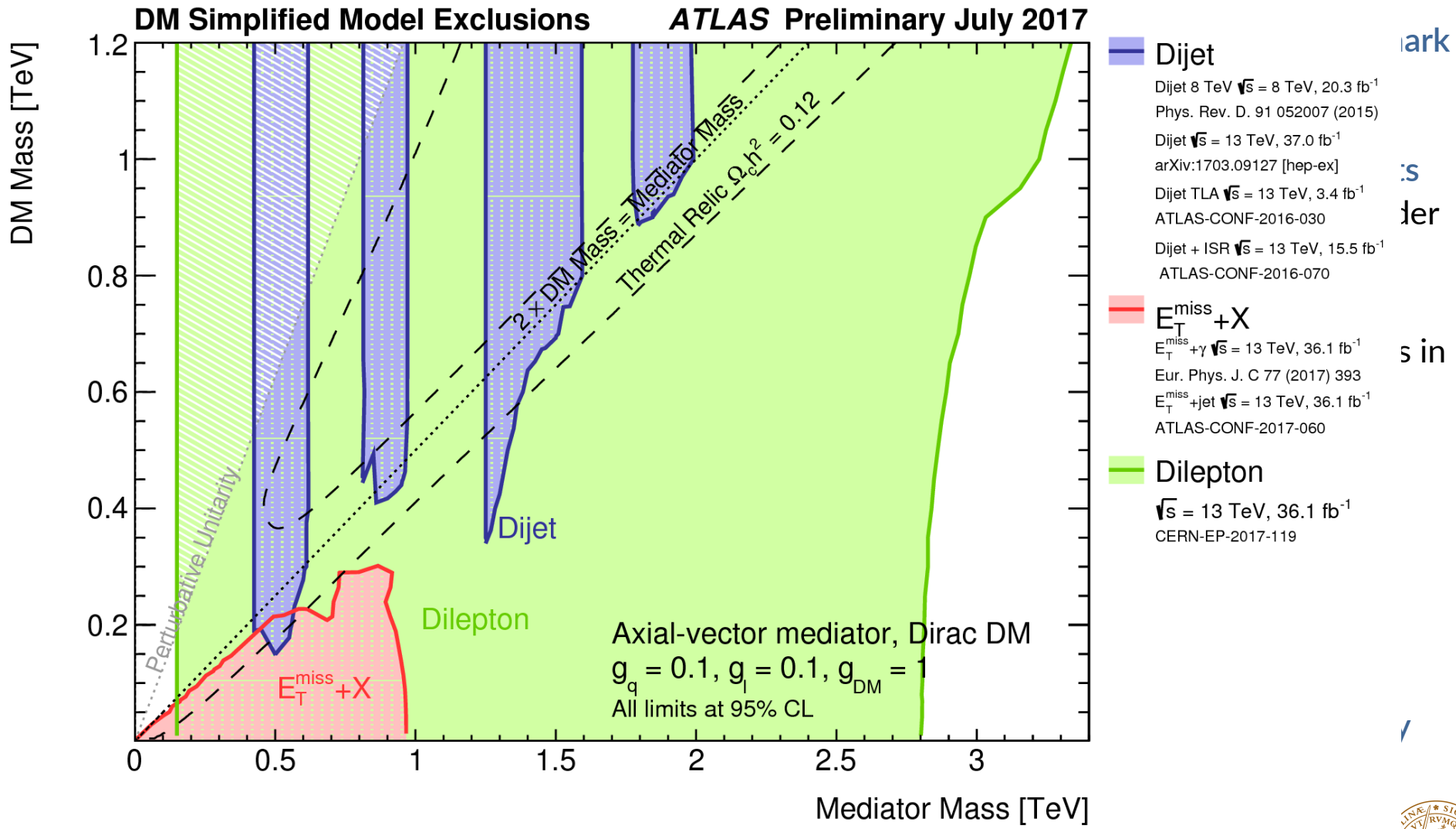
http://astrumia.web.cern.ch/astrumia/instantPaper.html

B. Francis' TeVPA talk, Original drawing by Jamie Antonelli



Organization attempt: **LLP Community effort**
Mailing list for joining:
lhc-llp@cern.ch

Dark Matter Working Group



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subscribe to/view archive of lhc-dmwg@cern.ch at https://e-groups.cern.ch