CATERINA DOGLIONI - LUND UNIVERSITY

TEVPA 2018, BERLIN

Dark Matter searches at ATLAS and CMS

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

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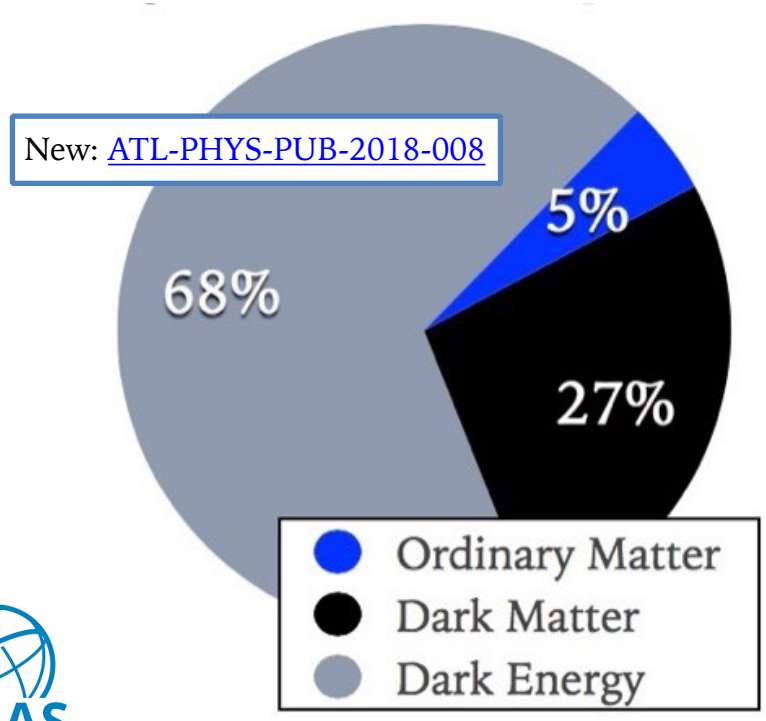
Where ~~do~~ did we go from ~~here~~ the LHC Run-1?

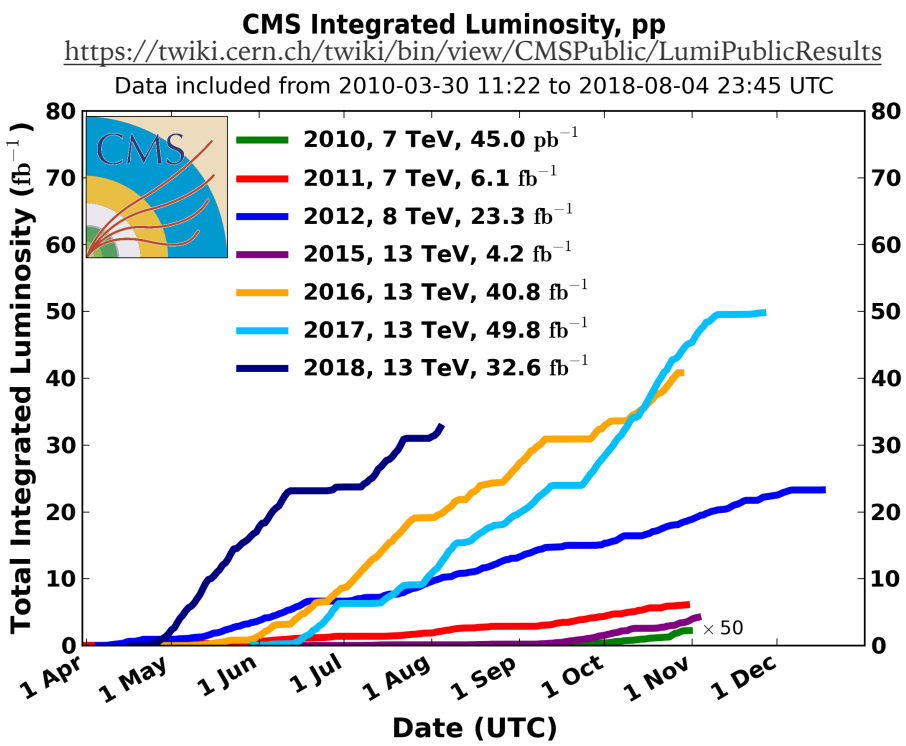
(Some) outstanding questions of the Standard Model:

- How do **particles get mass**?
  - Higgs mechanism ✓

- Is **dark matter a particle** that interacts with the SM?



(see B. Heinemann' talk today)



LHC operating beyond its design luminosity

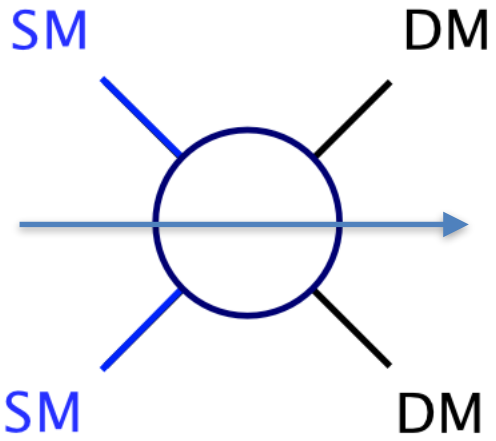
With LHC Run-2 data we can:
- detect rare processes
- use the Higgs as a discovery tool

ion funding
& Innovation

Looking for invisible particles at the LHC

If dark matter particles interact with ordinary particles, the **LHC** can **produce** them

proton-proton collision

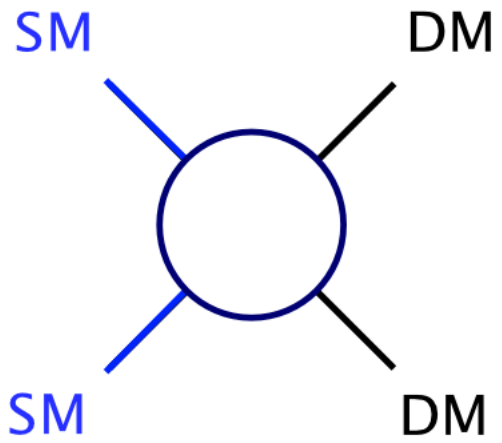


production of DM particles

Caveat: very simplified diagram

Looking for invisible particles at the LHC

If dark matter particles interact with ordinary particles, the **LHC** can **produce** them



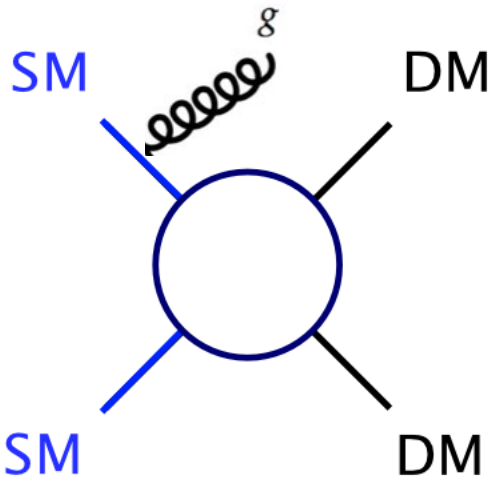
Caveat: very simplified diagram

however, ***dark*** ↔ ***invisible*** to the detectors

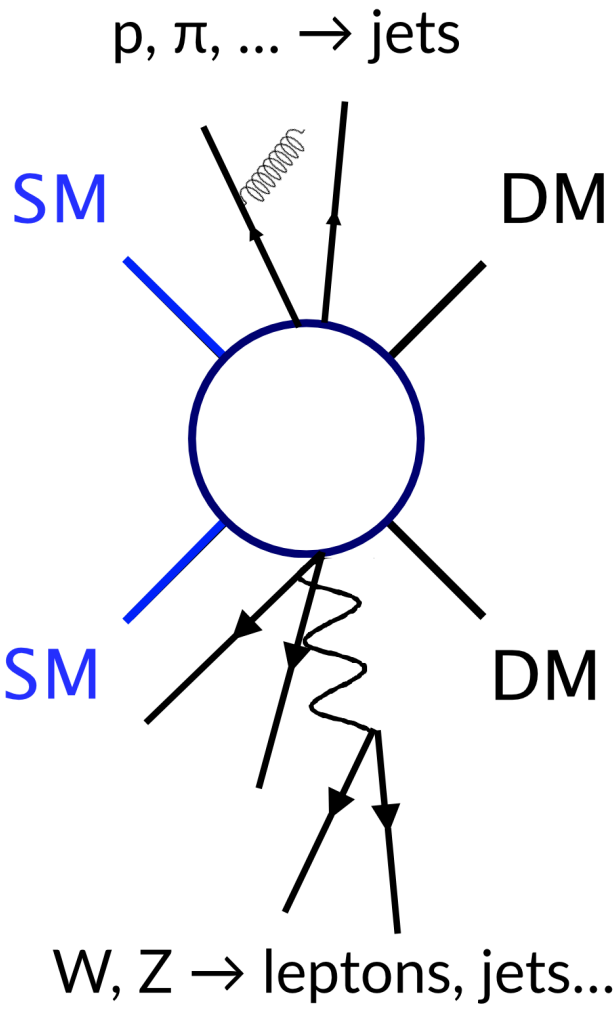
Looking for ~~in~~visible particles at the LHC

Rely on **visible particles** to detect invisible particles

"Mono-X" searches



"Multi-object" searches



Not pictured here but necessary to cover all ground for DM @ LHC:
Long-lived particle searches
(see Todd Adams' talk today)

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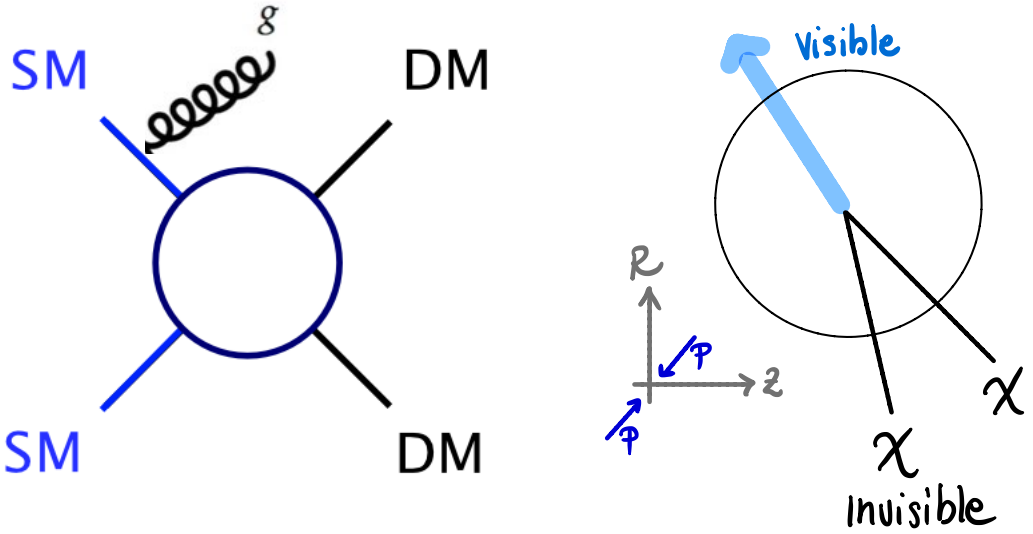
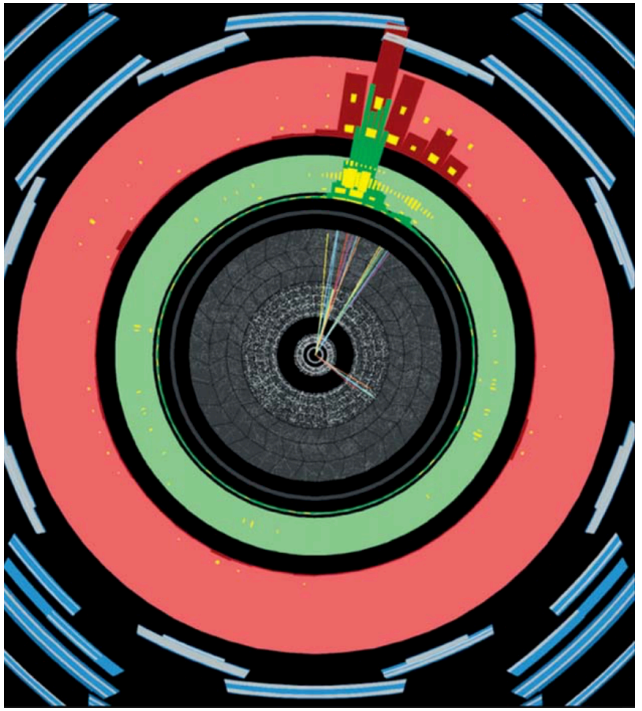
C.

Looking for ~~in~~visible particles at the LHC

Rely on **visible particles** to detect invisible particles

"Mono-X" searches (example)



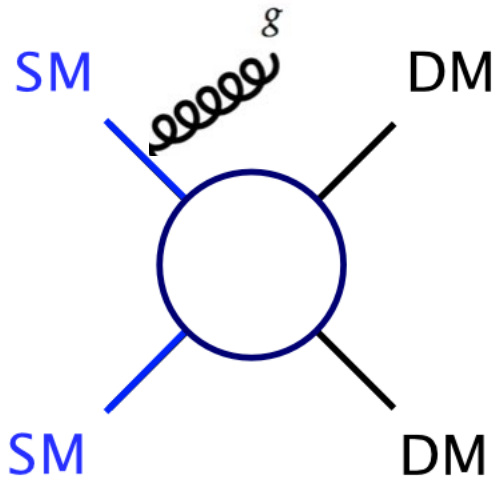


Signature of invisible particles
(like Dark Matter):
missing transverse momentum (E_T^{miss})

Broad categories of LHC searches

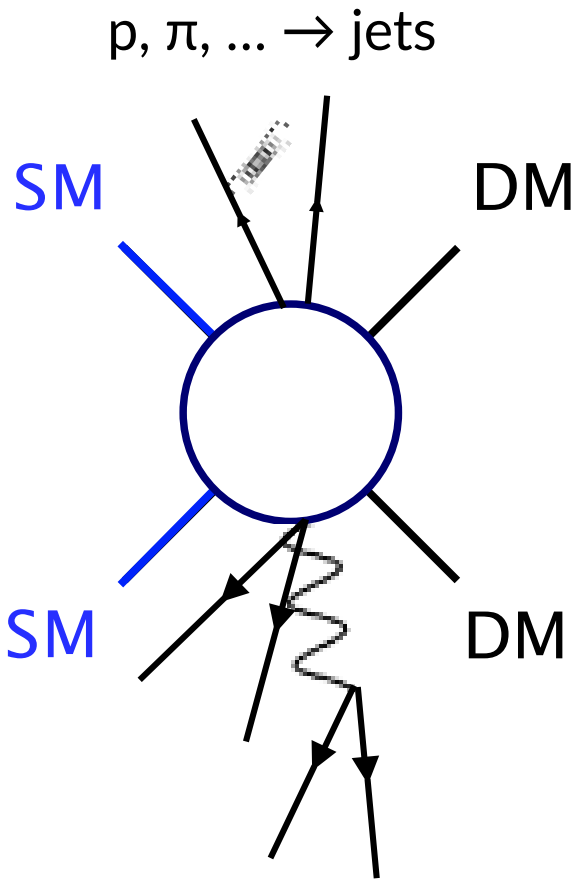
Generic searches

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



More specific searches

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

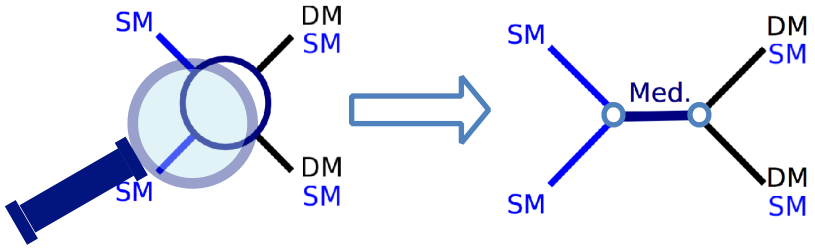


This talk:
only a **very small selection** of LHC DM searches
for more results see here: ATLAS and CMS
and Beate Heinemann's talk today

Benchmarks for LHC DM searches

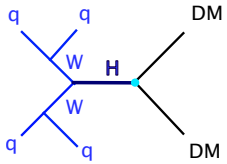
Simple models — More complex/complete models

Simple DM mediation



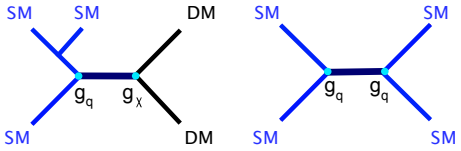
SM mediator

- **Z/Higgs** portals

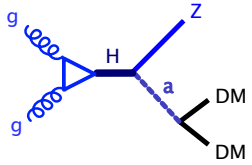


Beyond-SM mediator

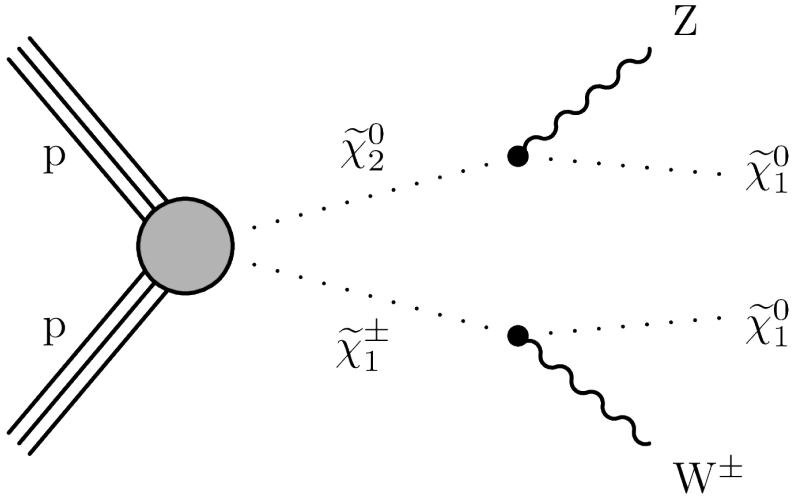
- **Vector-like** mediator



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



Supersymmetry



(*Simplified model* diagram)

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Not pictured here but very relevant for LHC DM searches: **dark sectors** (see e.g. JiJi Fan's talk)

Current focus of LHC Dark Matter Working Group

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High Energy Physics - Experiment

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

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

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

Subjects: **High Energy Physics - Experiment (hep-ex)**; Hig
(hep-ph)
Cite as: **arXiv:1507.00966 [hep-ex]**
(or **arXiv:1507.00966v1 [hep-ex]** for this version)

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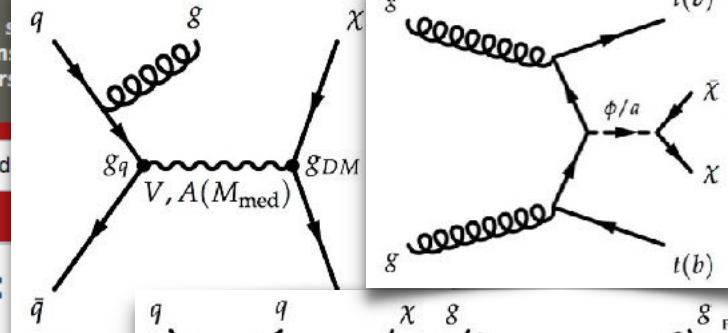

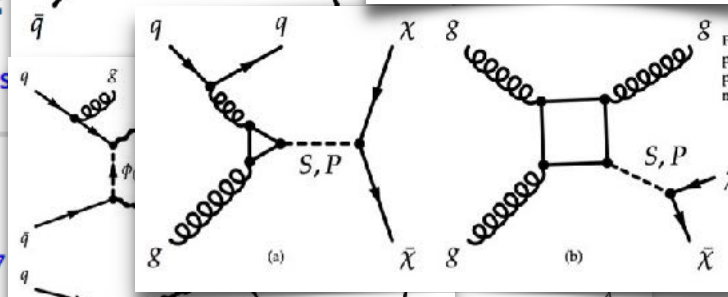

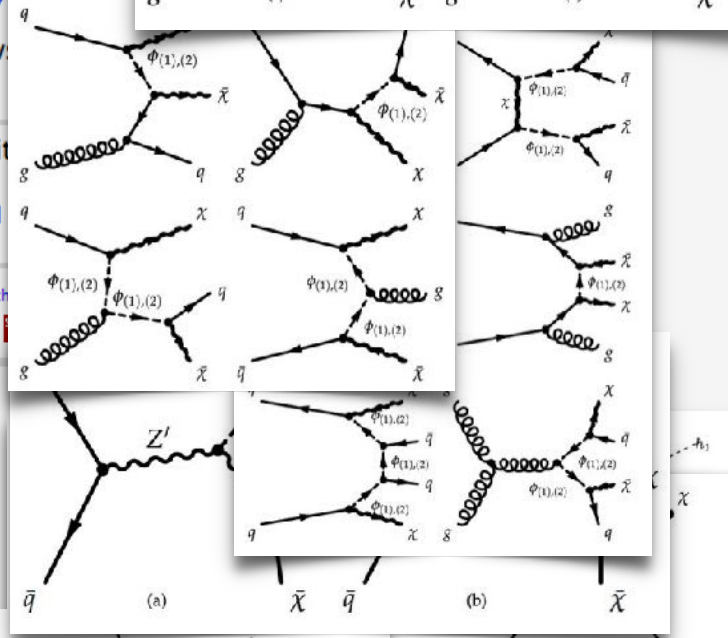

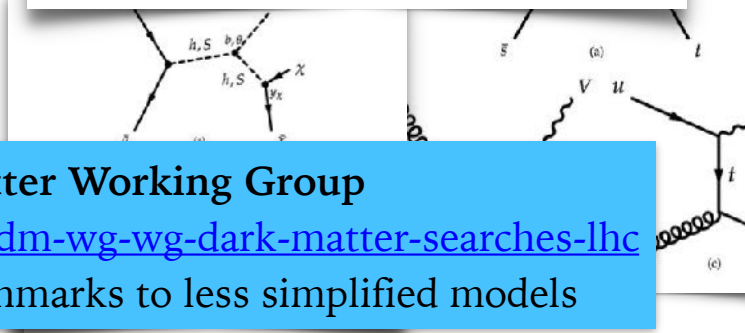

Now: **LHC Dark Matter Working Group**
http://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc
extending the menu of LHC benchmarks to less simplified models

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Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara A
Azuelos, Patrizi
Beacham, Alexa
Buchmueller, M
Cacciapaglia, R
Gomez Ceballo
Cowden, France
Roeck, Andrea
Caterina Doglio
Fischer, Hennin

(Submitted on 3 Ju

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report also ad
searches and present the results of such interpretations.

Subjects: **High Energy Physics – Experiment (hep-ex)**; High Energy Physics – Phenomenology (hep-ph)
Cite as: arXiv:1507.00966 [hep-ex]
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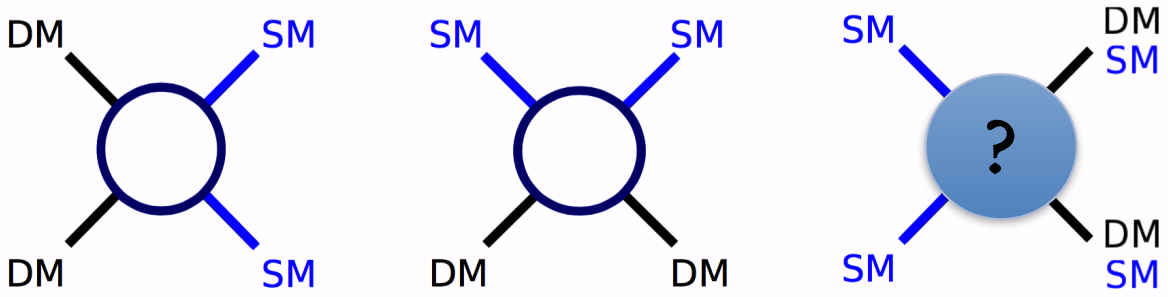
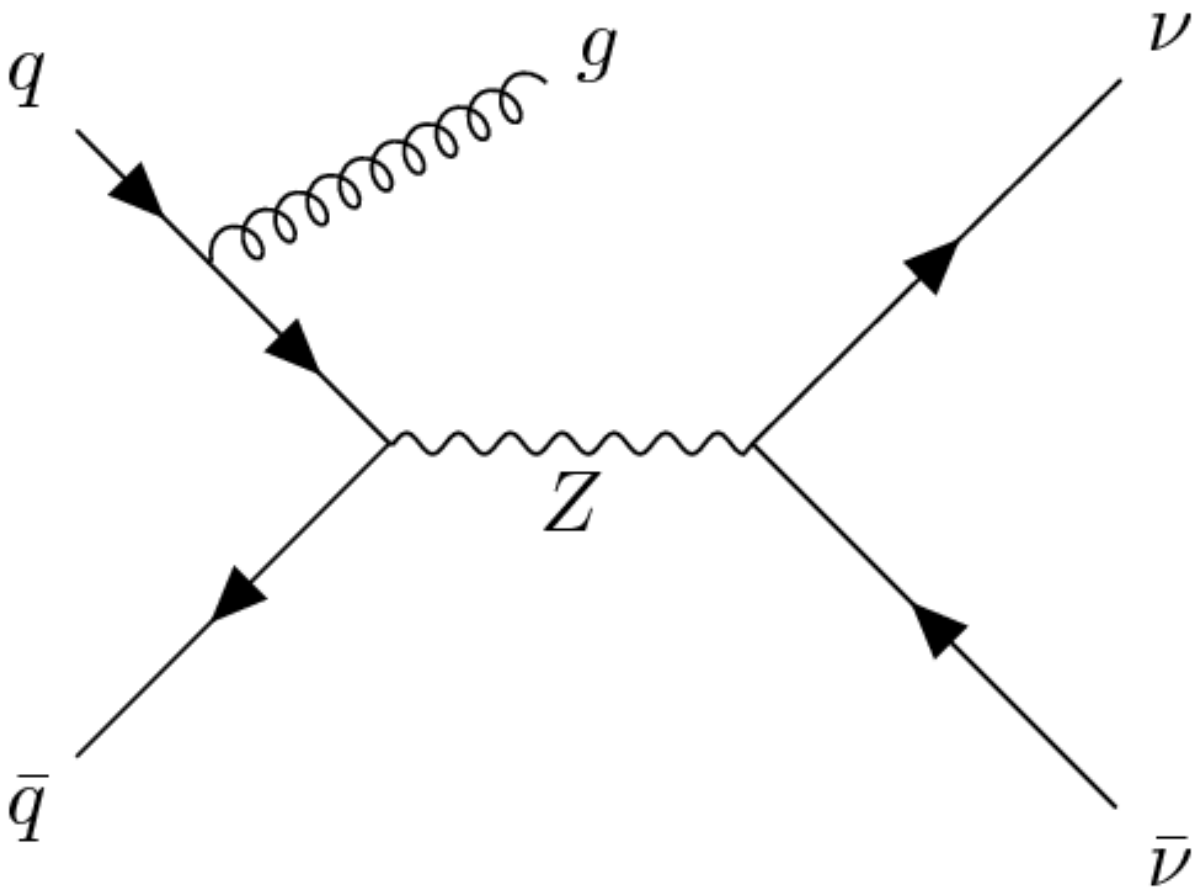


Indirect Detection | Direct Detection | Particle Colliders

Collider complementarity with direct / indirect detection needs a **theoretical framework**

LHC production of invisible particles

Production of invisible particles can be common in the SM



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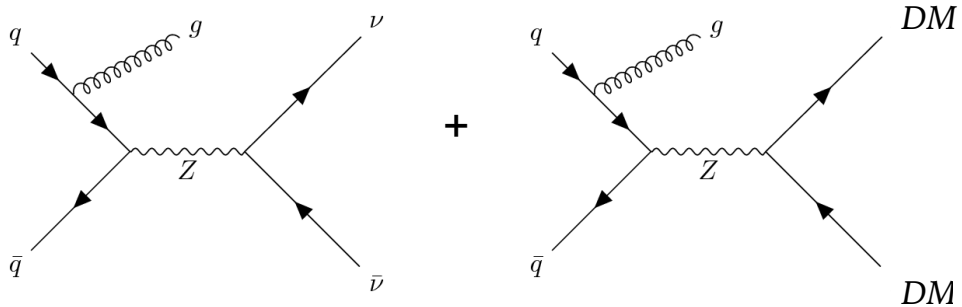
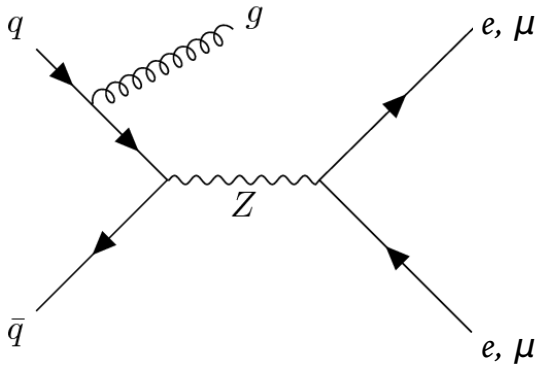
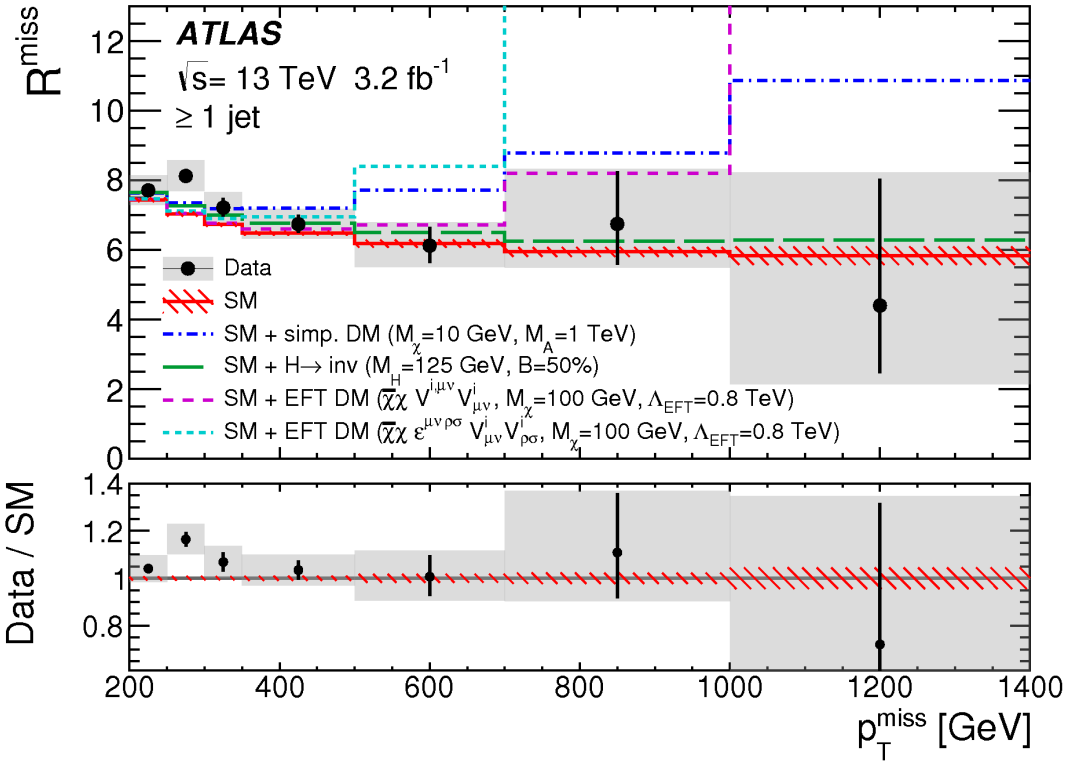
LHC production of **new** invisible particles

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





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



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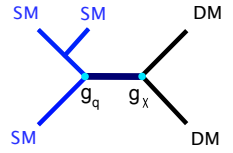
Generic searches for DM: "X+MET"



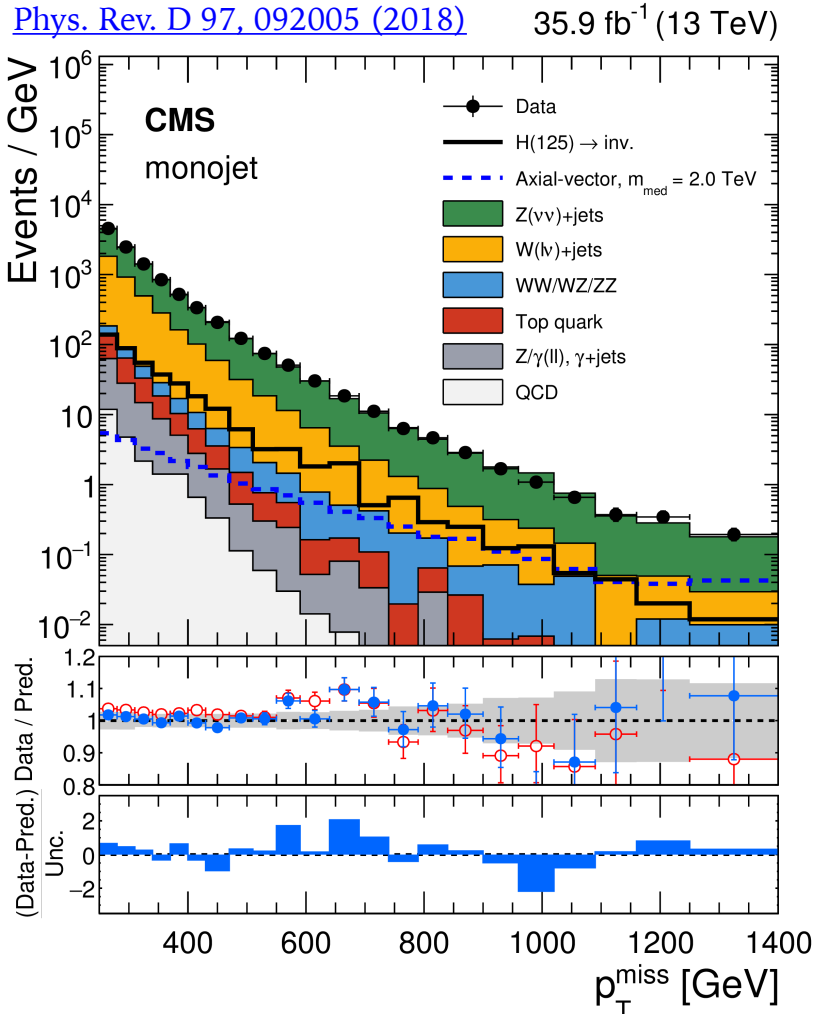
ISR (jet, photon, V boson…) + MET signature

Background normalized using data

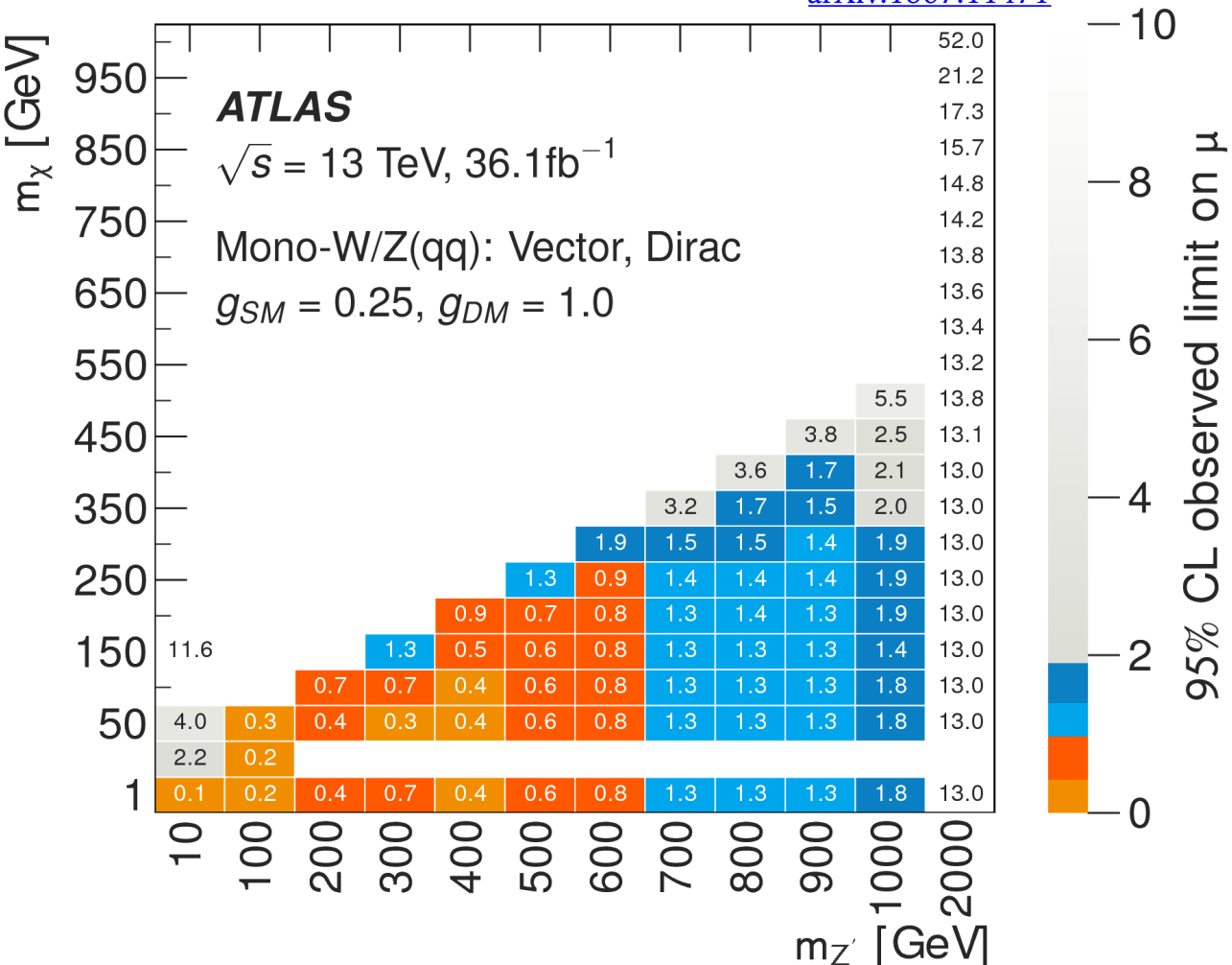
Background shapes need precise theory predictions [EPJC 2017 77:829]

Results interpreted in a variety of models

[Phys. Rev. D 97, 092005 (2018)]

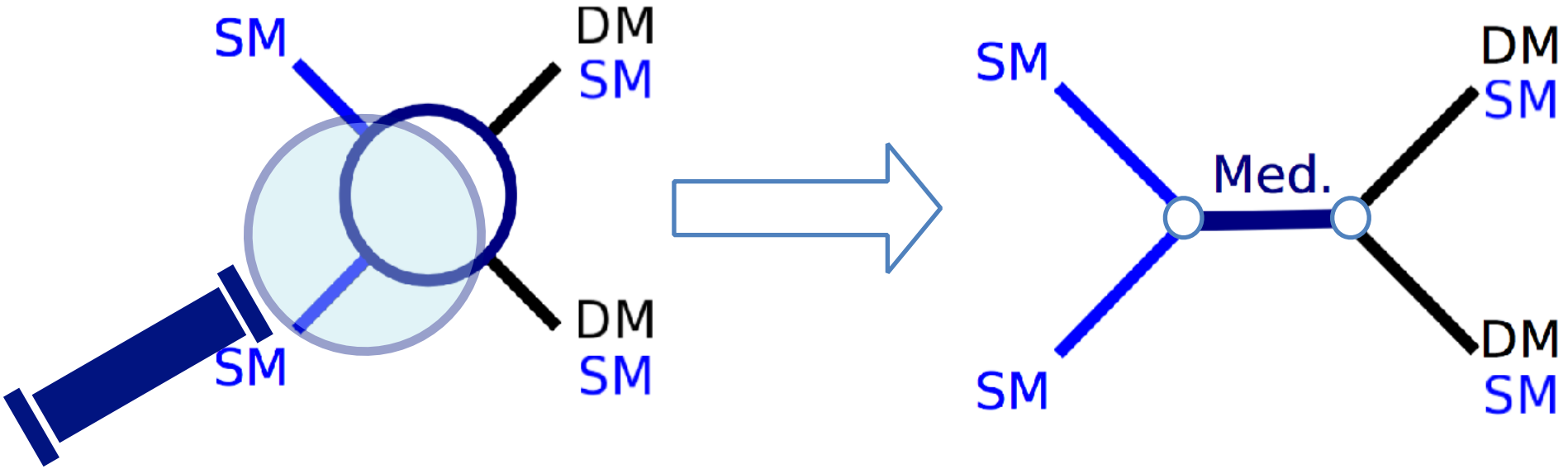


[arXiv:1807.11471]



Dark Matter mediators at the LHC

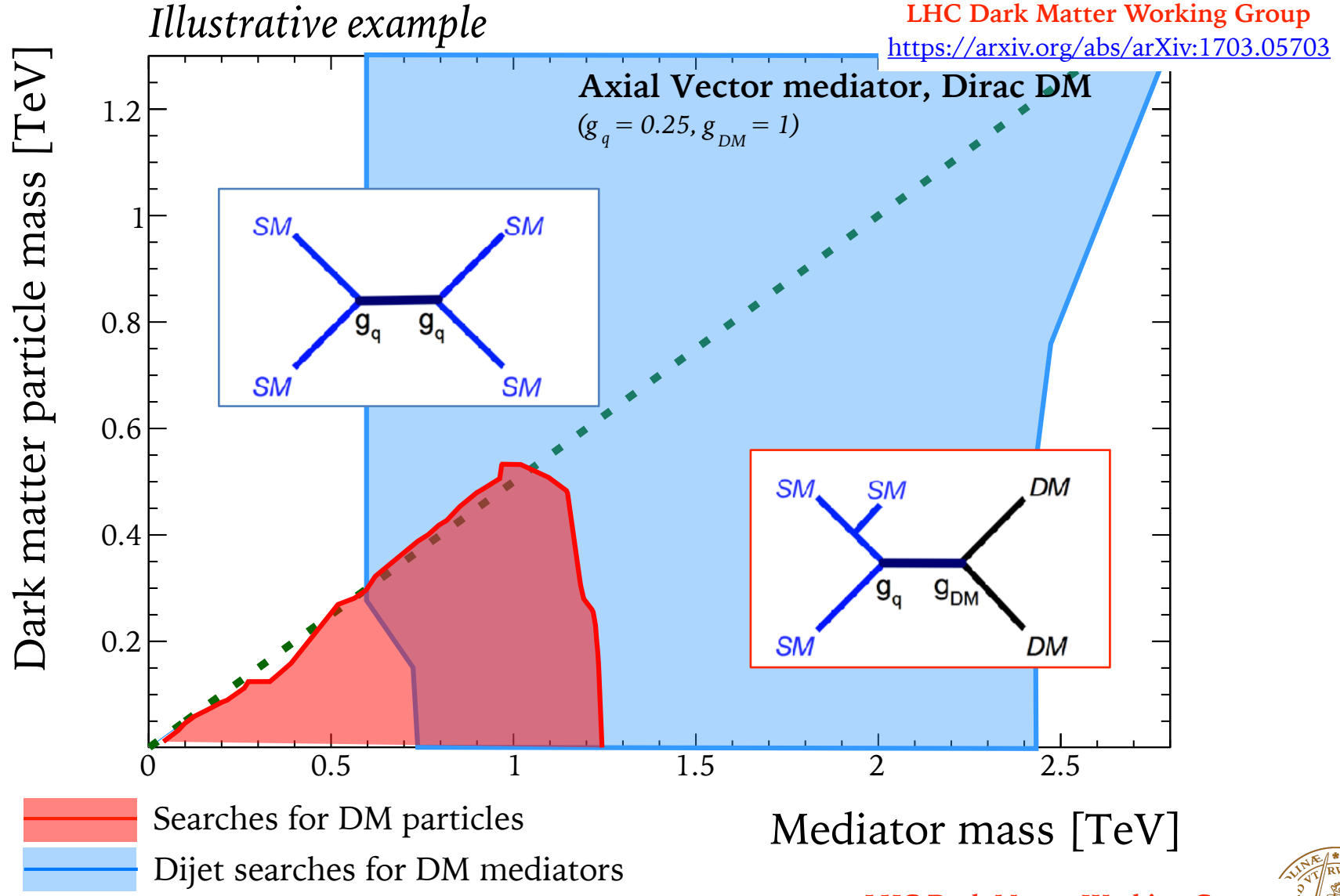
If there's a force there's a mediator:



Can **probe the dark interaction** even if DM is inaccessible
Can look for both **invisible and visible decays** of the mediator

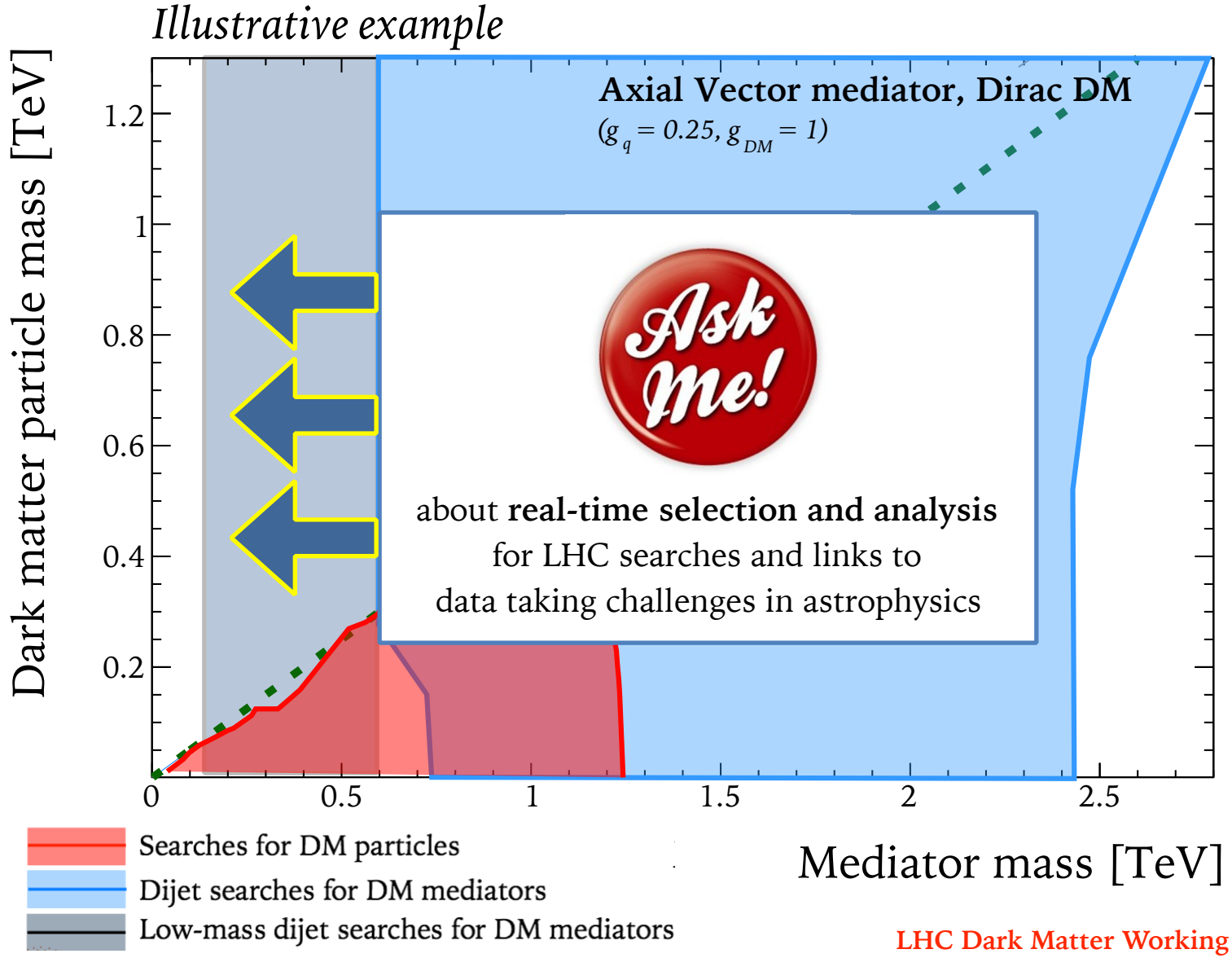
Look for an inevitable LHC physics process:
di-jet (and di-X) resonances - see S. D'Auria's talk

Visible/invisible DM LHC searches



Collider strength for these models: searches for visible mediator decays

Visible/invisible DM LHC searches



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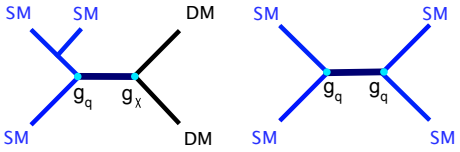
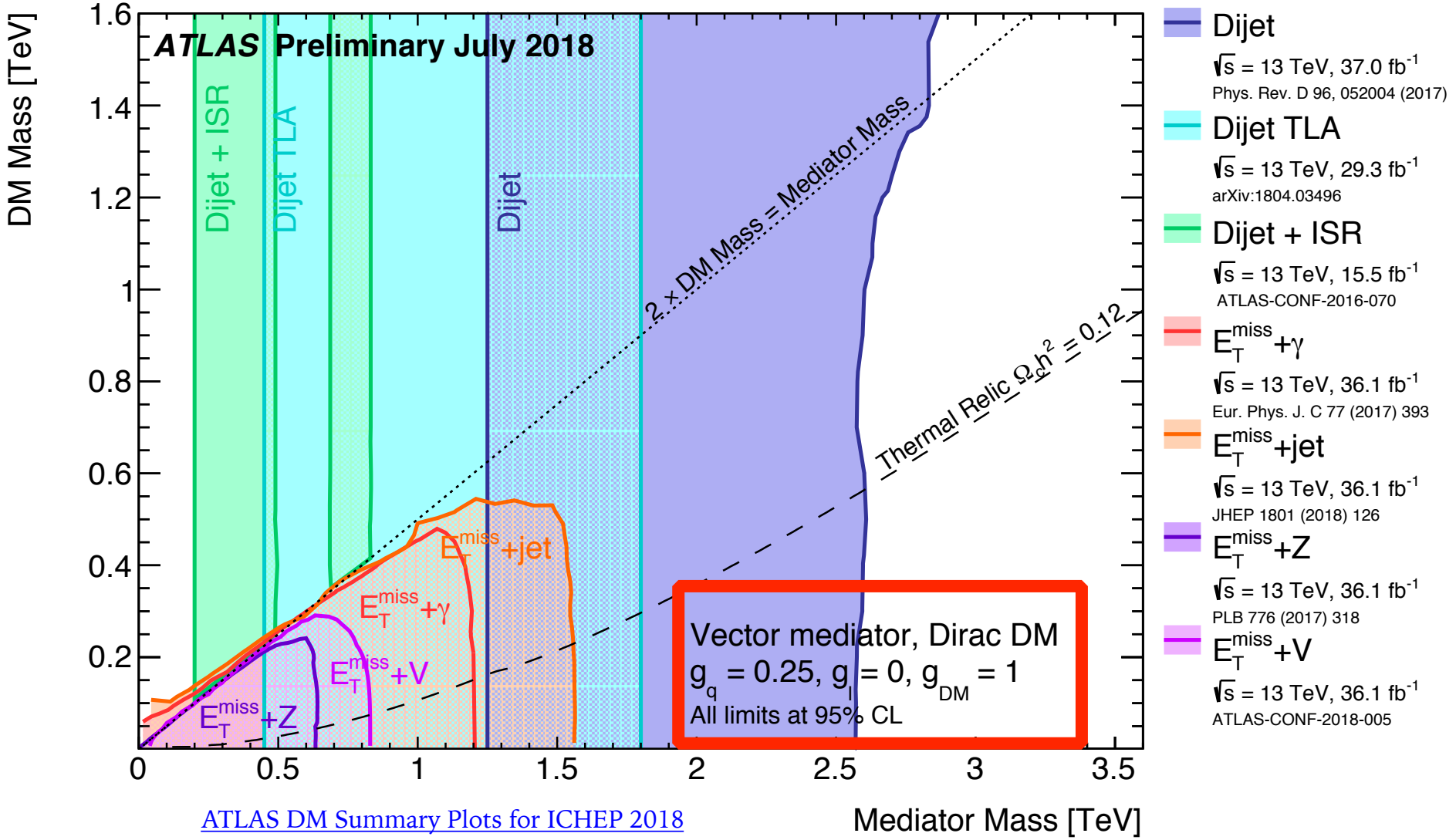
https://arxiv.org/abs/arXiv:1703.05703

Collider strength for these models: searches for visible mediator decays

Visible/invisible DM searches



(only valid for these specific parameters of leptophobic vector mediators)



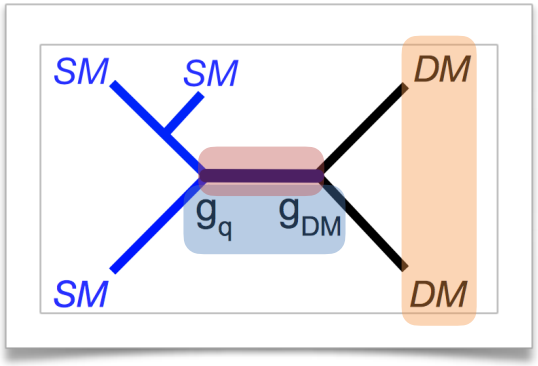
ATLAS DM Summary Plots for ICHEP 2018

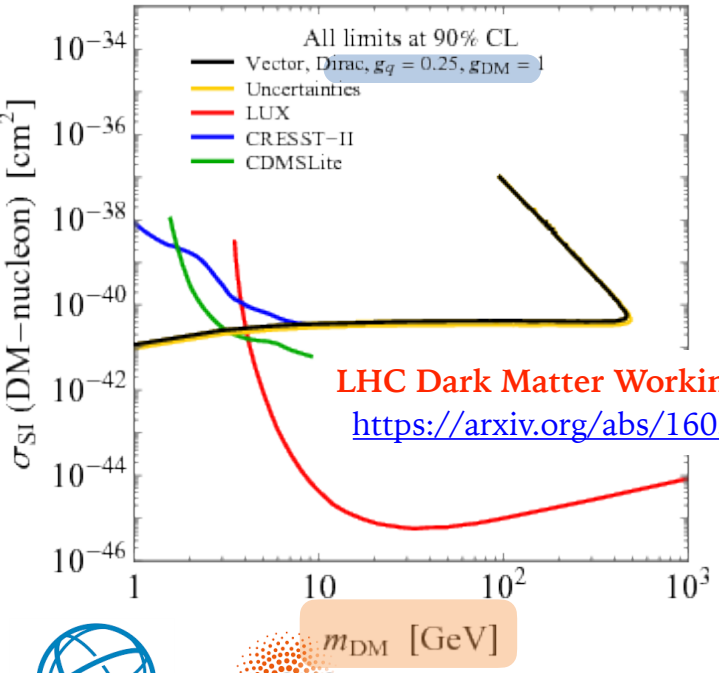
Complementarity of DM experiments

Comparisons are possible only in the context of a benchmark

Essential to **fully specify model/parameters**

and **be aware of limitations**





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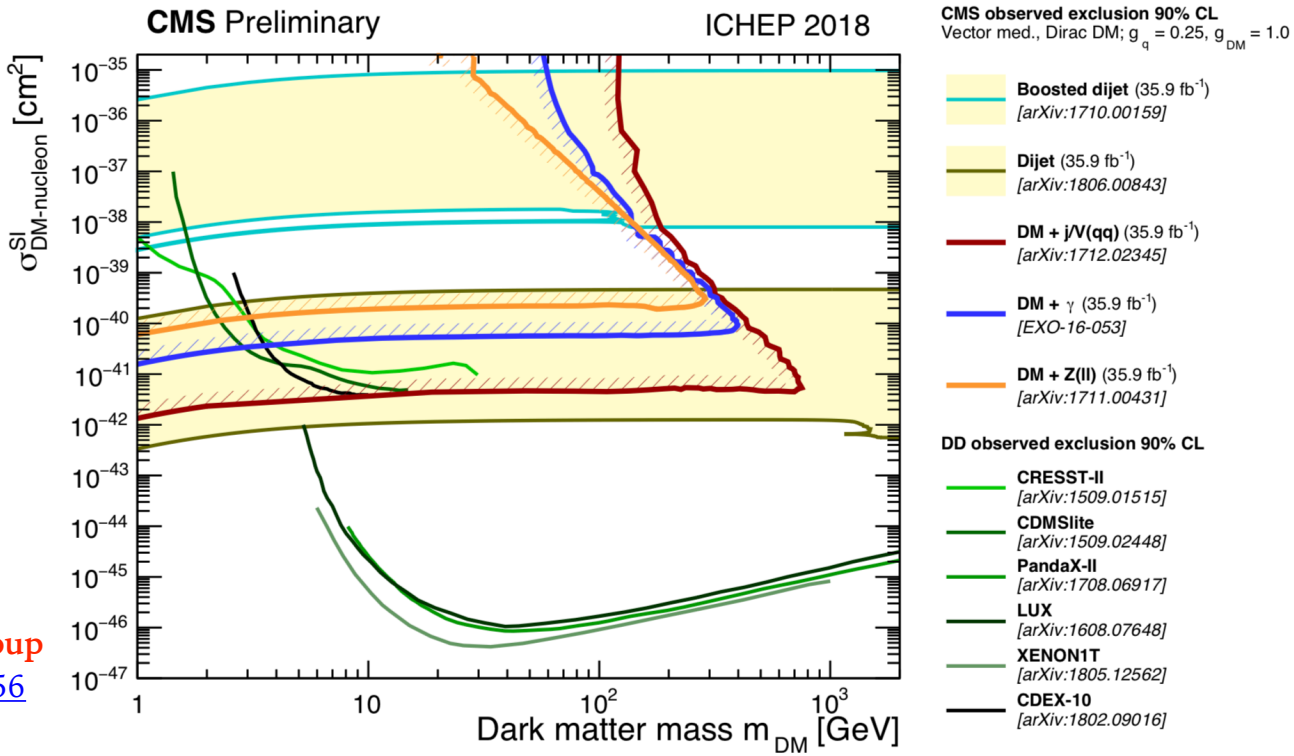
https://arxiv.org/abs/1603.04156



CMS Dark Matter Summary Plots for ICHEP 2018

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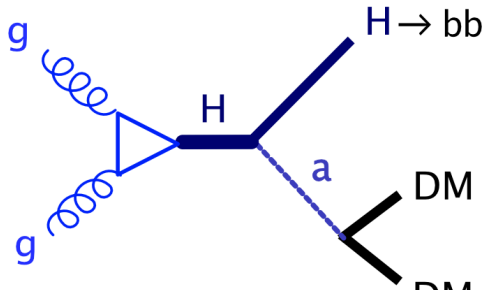
More complex models: pseudo/scalars

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

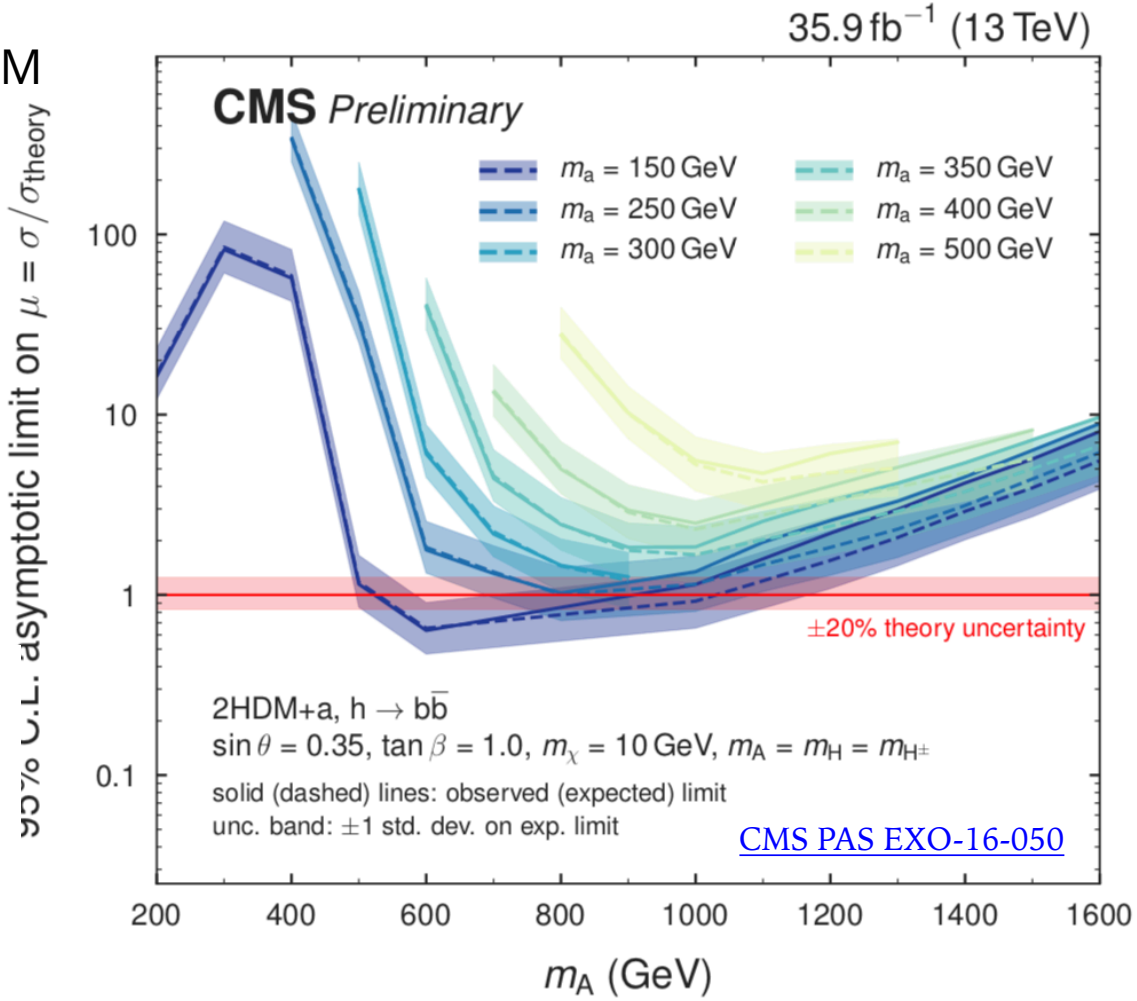
Example: pseudoscalar interacting with DM in a Two (2)-Higgs Doublet Model



LHC Dark Matter Working Group
Whitepaper in preparation

Search for MET + two b-quarks
ATLAS / CMS
No excess observed yet

LHC dataset sufficient to start being sensitive to this kind of processes



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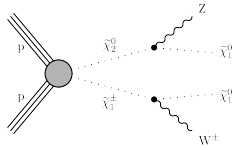
Highlights of SUSY EW searches



Among other desirable features, SUSY provides a dark matter candidate:
the **stable, lightest supersymmetric particle**

Many SUSY production modes: examples of
low cross-sections from **electroweak production** that can be probed with LHC data
and **3rd generation squarks** in models yielding **relic density**

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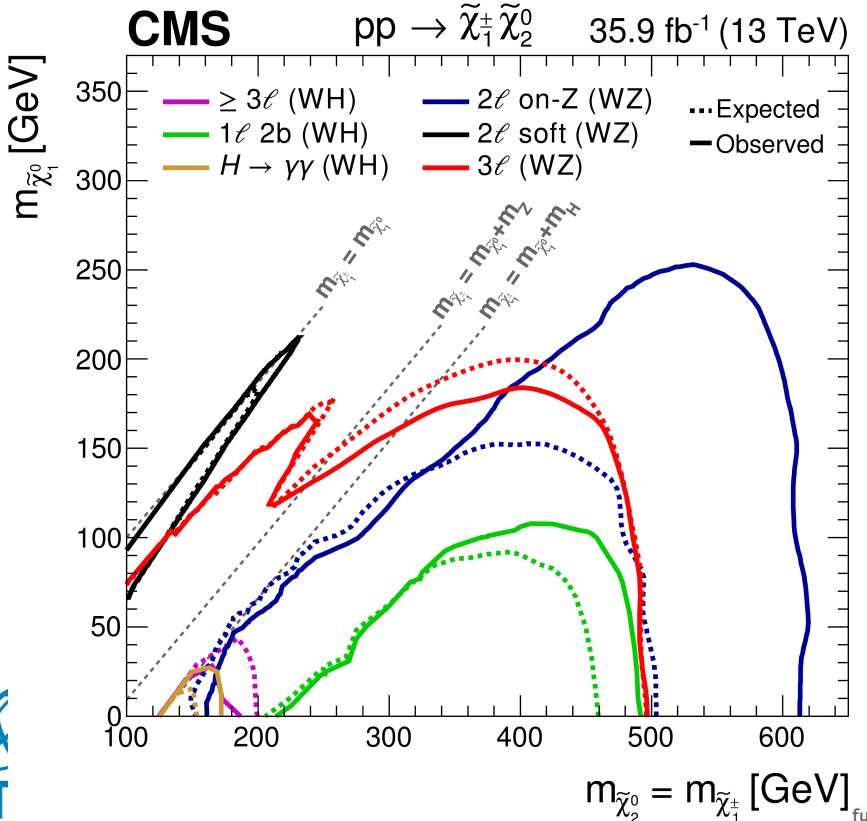
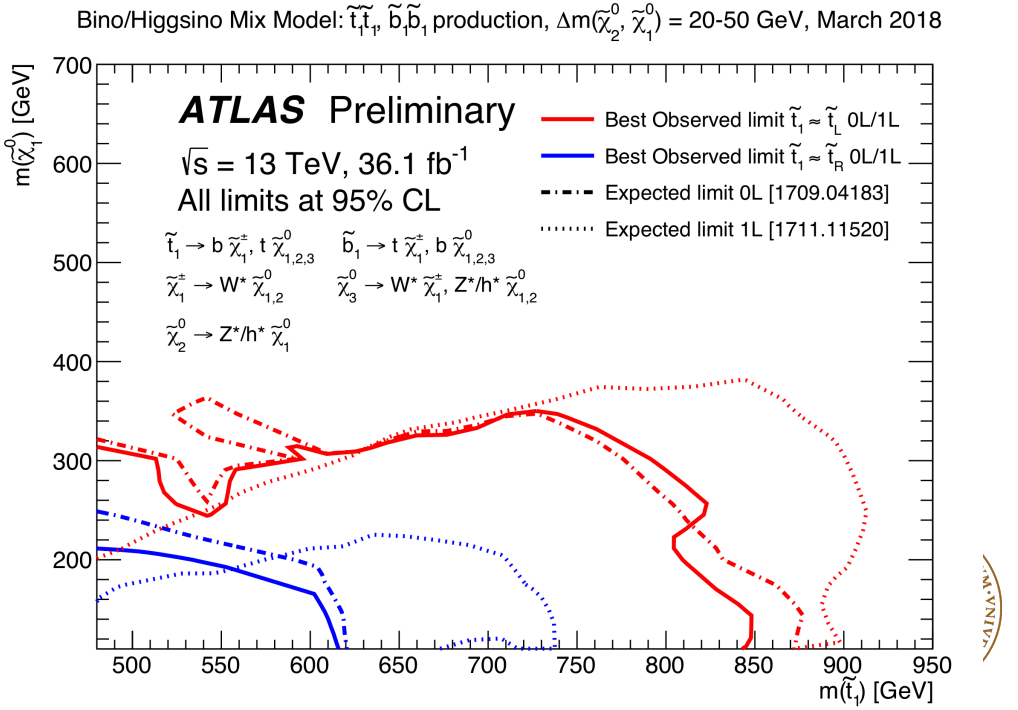


ATLAS SUSY Public Results



Conclusions

- If DM interacts with SM particles,
  it can be **produced and detected** at the LHC

- **No excesses** in ATLAS/CMS analyzed data so far
  - Constraints on a variety of benchmarks

- **Outlook for** LHC DM community (DM Working Group):
  expanding **beyond WIMP simplified models:**
  - less simplified models (e.g. 2HDM)
  - dark sectors

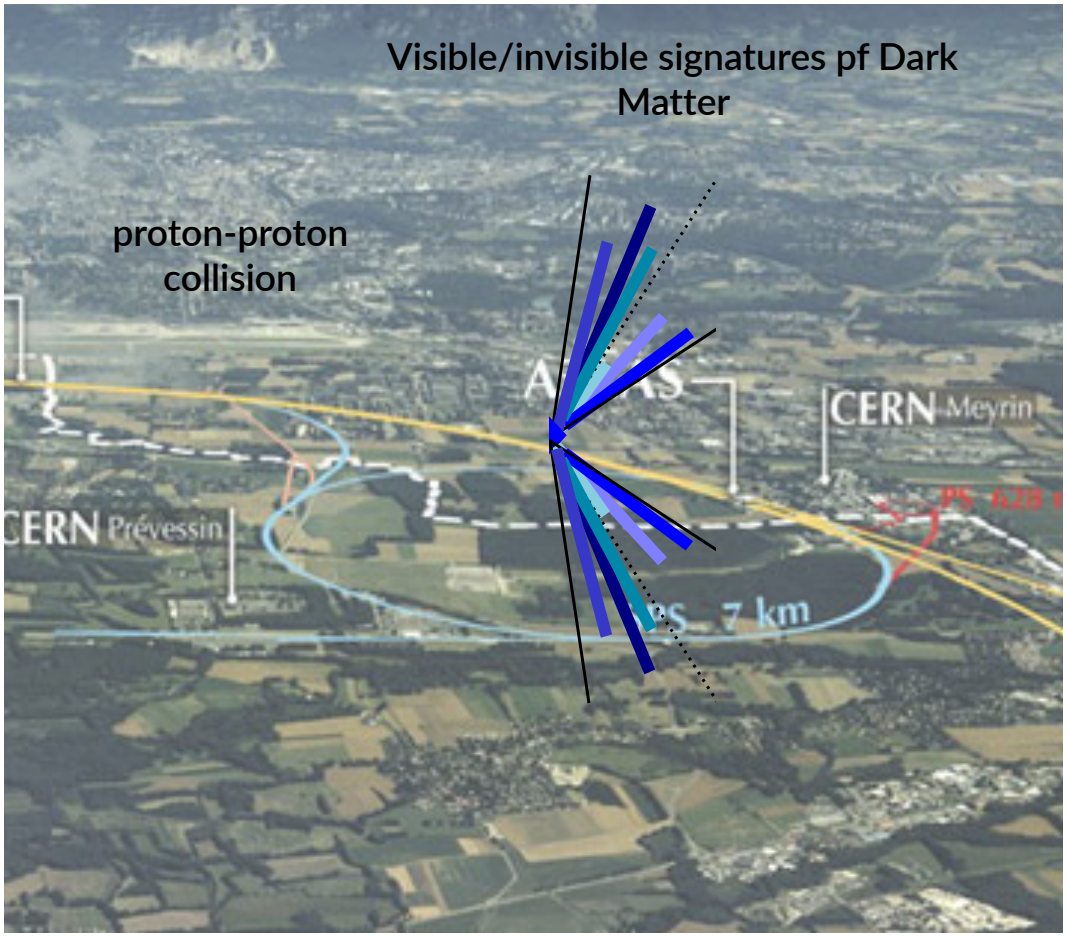
- Only **1% of full LHC dataset** analyzed so far
  - Current dataset will be tripled next year
  - Great chance to probe SM-DM interactions and rare processes

Backup slides

Dark Matter Working Group

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

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



Dark Matter Working Group

Summer 2015
https://arxiv.org/abs/1507.00966

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

Winter 2015
https://arxiv.org/abs/1603.04156

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

Winter 2016
http://arxiv.org/abs/1703.05703

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

Spring 2017
https://arxiv.org/abs/1705.04664

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

Spring 2018
In preparation

Develop scalar sector and colored scalar benchmark models

Current topics

Connect dark boson models to existing benchmarks and cosmology

?

You're welcome to join and help define DM searches at the LHC!
http://lpcc.web.cern.ch/lpcc/index.php?page=dm_wg
mailing lists lhc-dmwg@cern.ch / lhc-dmwg-contributors@cern.ch at https://e-groups.cern.ch

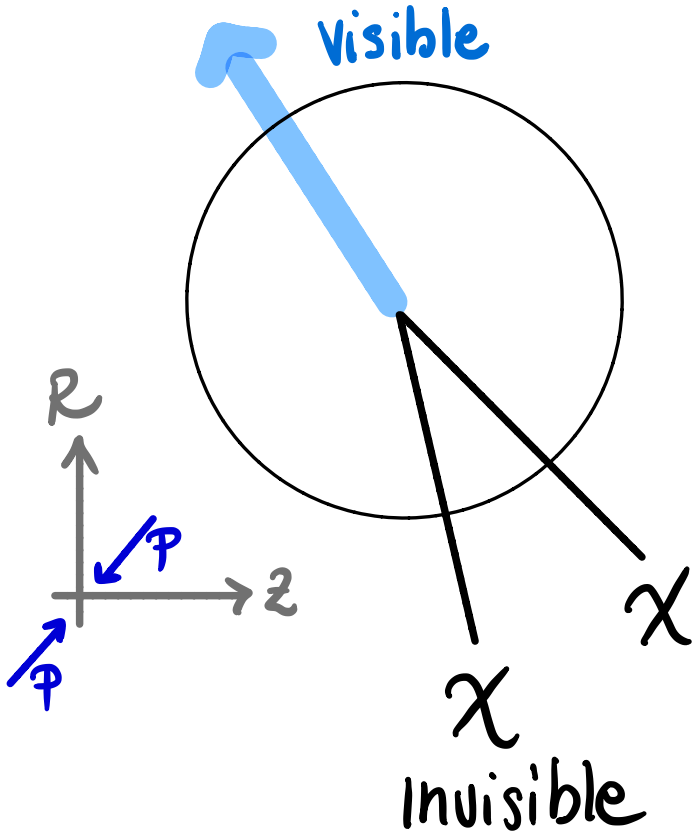
ATLAS EXPERIMENT erc European Commission Horizon 2020 European Union funding for Research & Innovation

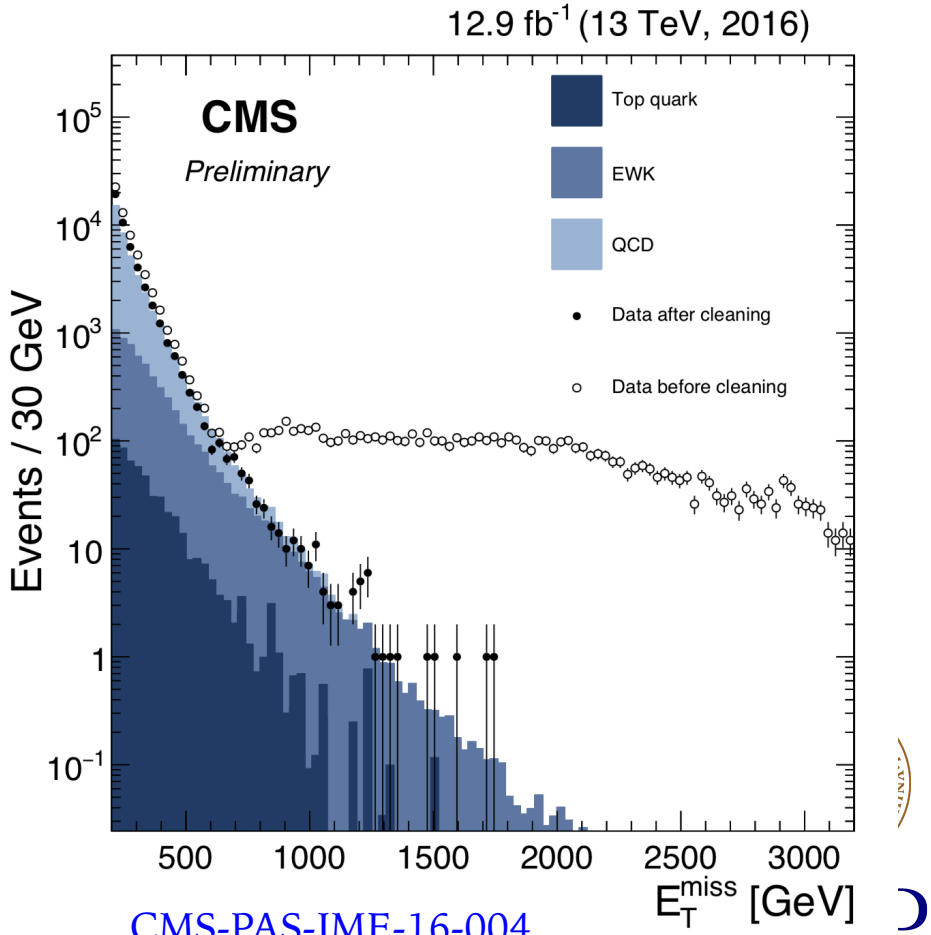
Looking for invisible particles at the LHC

Signature of invisible particles (like Dark Matter):

missing transverse momentum (E_T^{miss})

Good performance of missing transverse momentum crucial for DM searches
e.g. reject fake E_T^{miss}

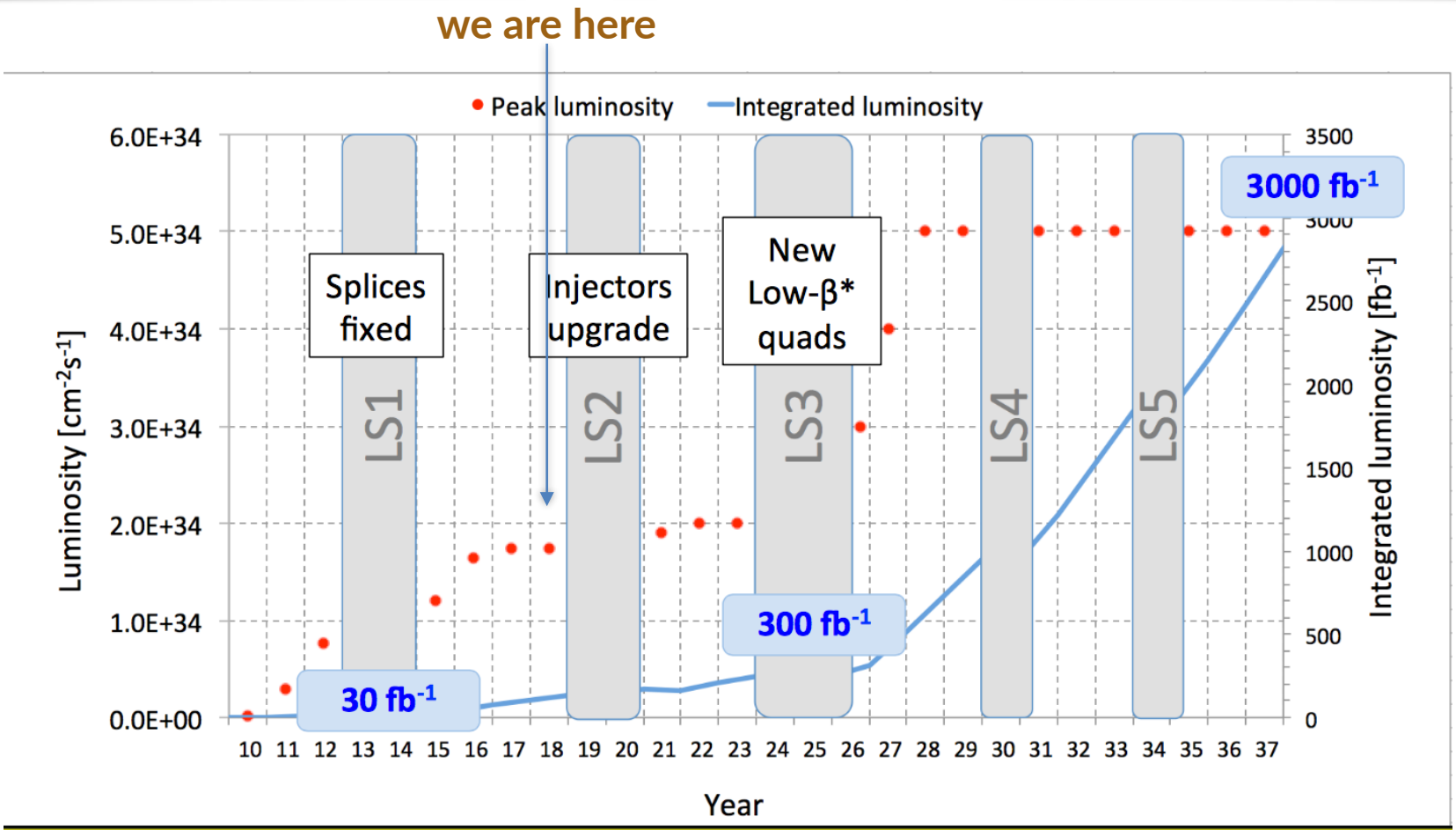




CMS-PAS-JME-16-004

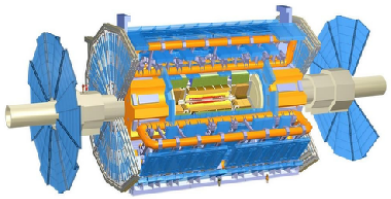
The future of the LHC

The exploration of the energy frontier has just started



LHC is highest-E, highest-L operational collider → full exploitation ($\sqrt{s}$ ~ 14 TeV, 3000 fb^{-1}) is mandatory: FG EPS 15

Triggering in LHC experiments



Trigger event reconstruction

Trigger Decision **Keep the event?**

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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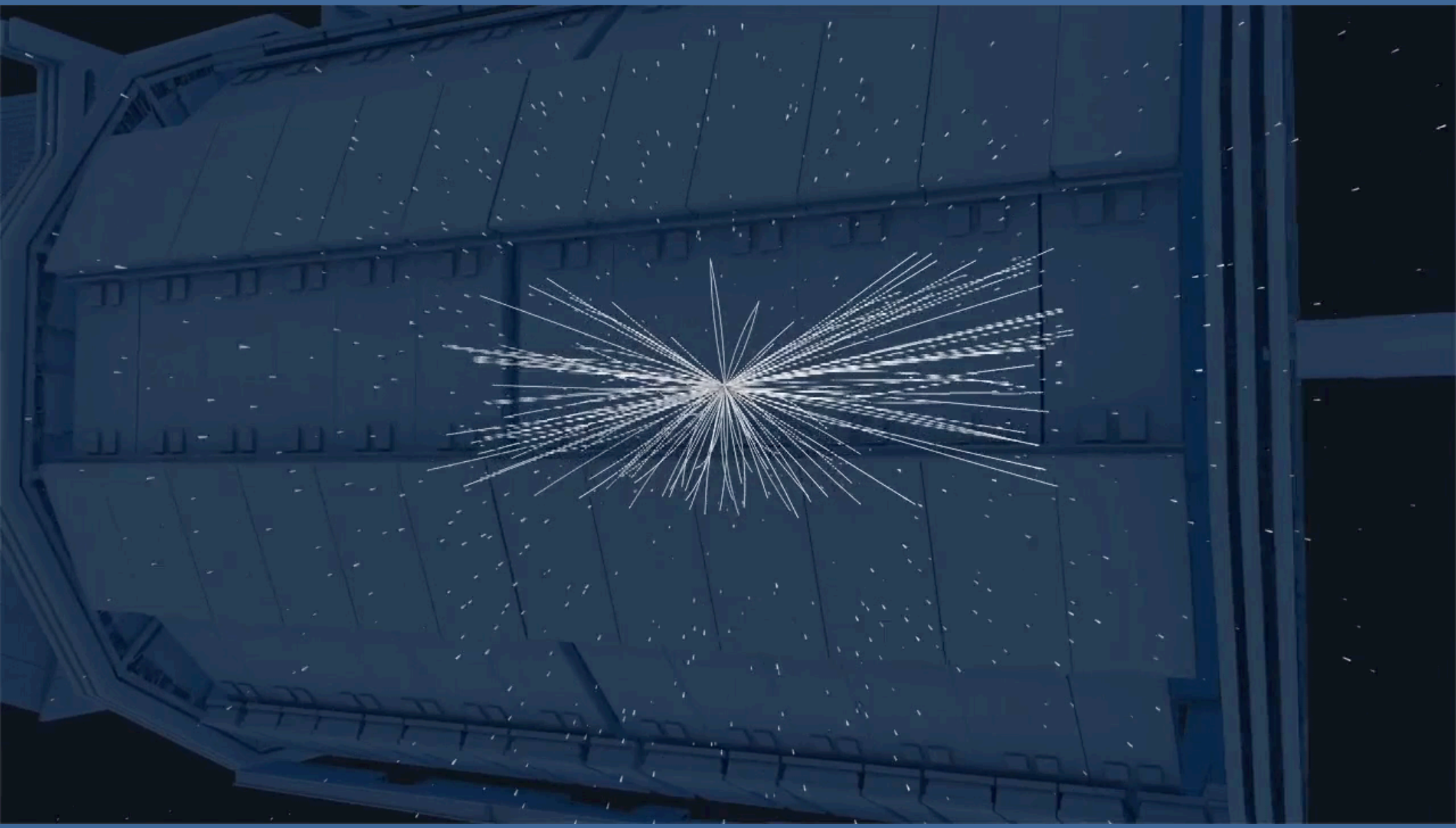
Video: triggering and processing data

CERN-MOVIE-2013-041-001



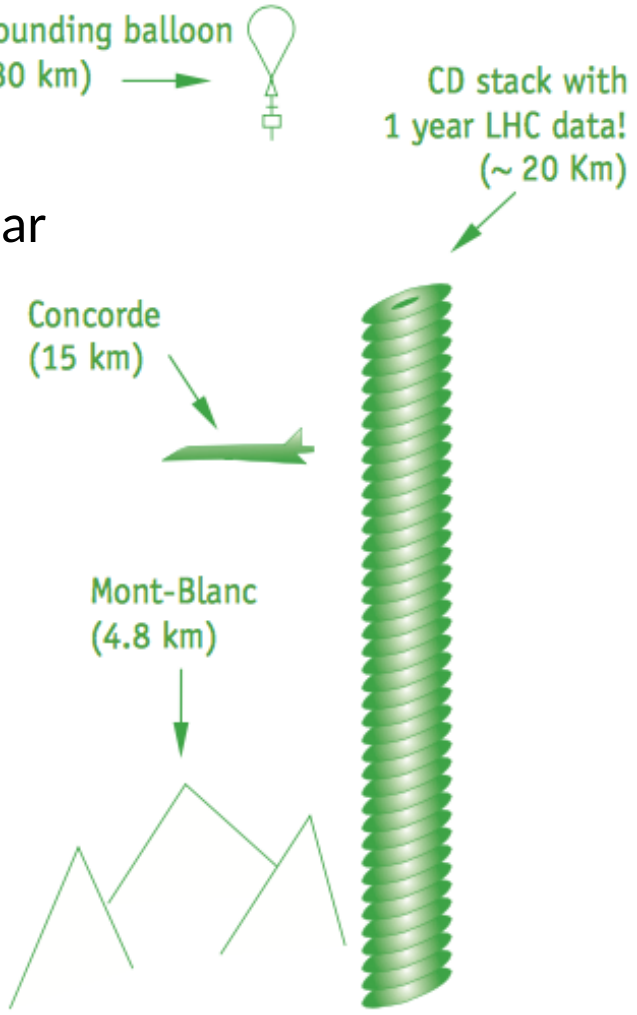
Why do LHC experiments *trigger*?

- 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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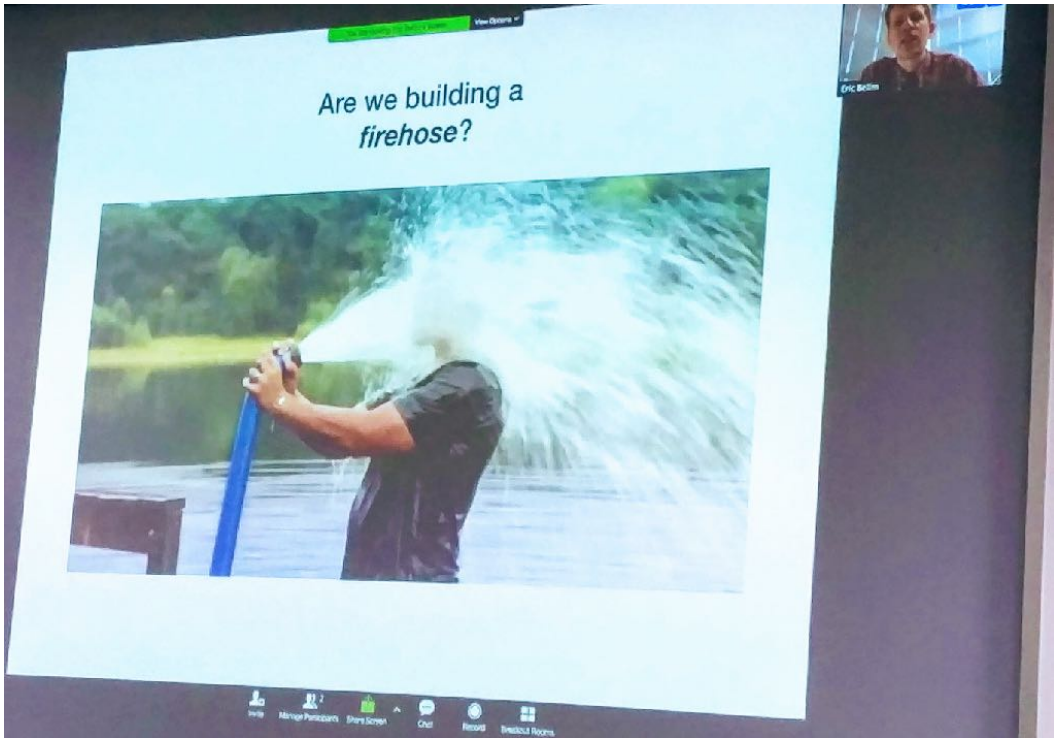
Parallels with astrophysics - I

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 - II

LSST/IceCube/AMON… 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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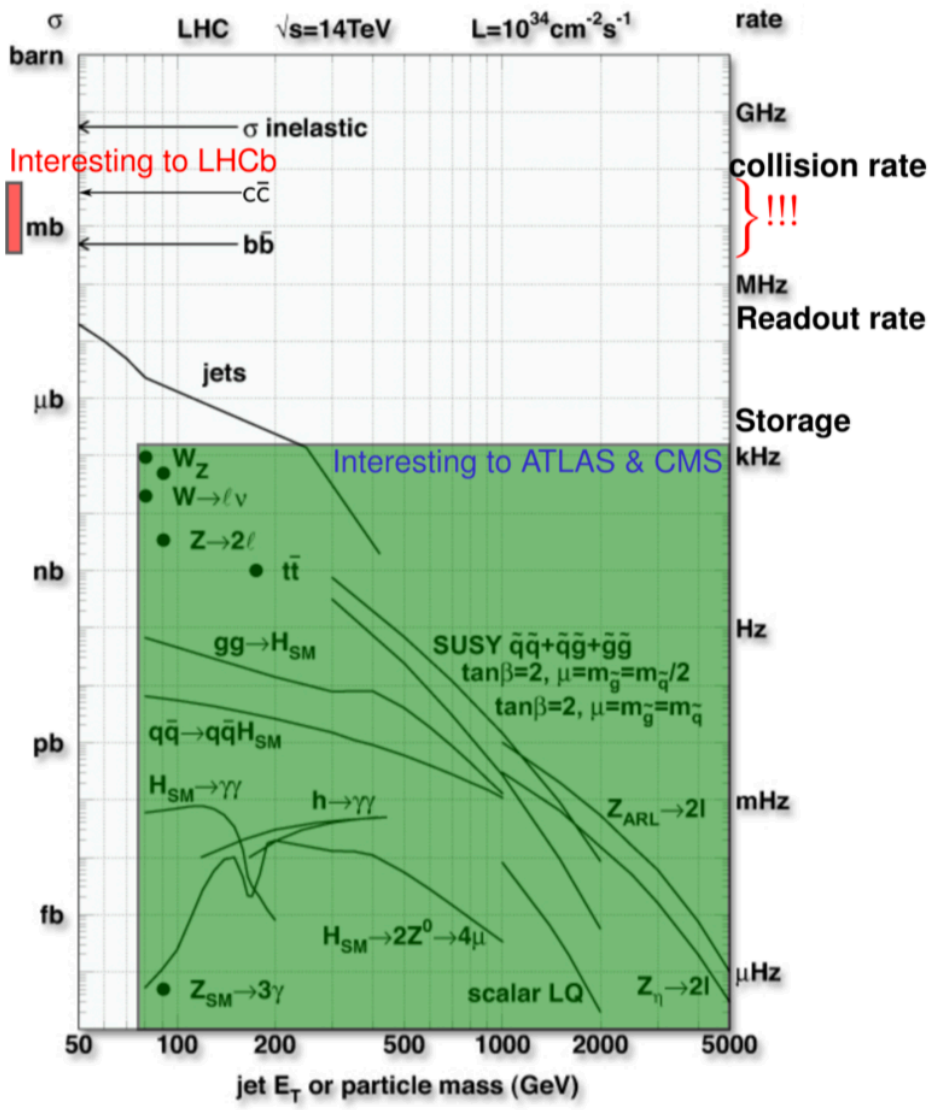
What is interesting?

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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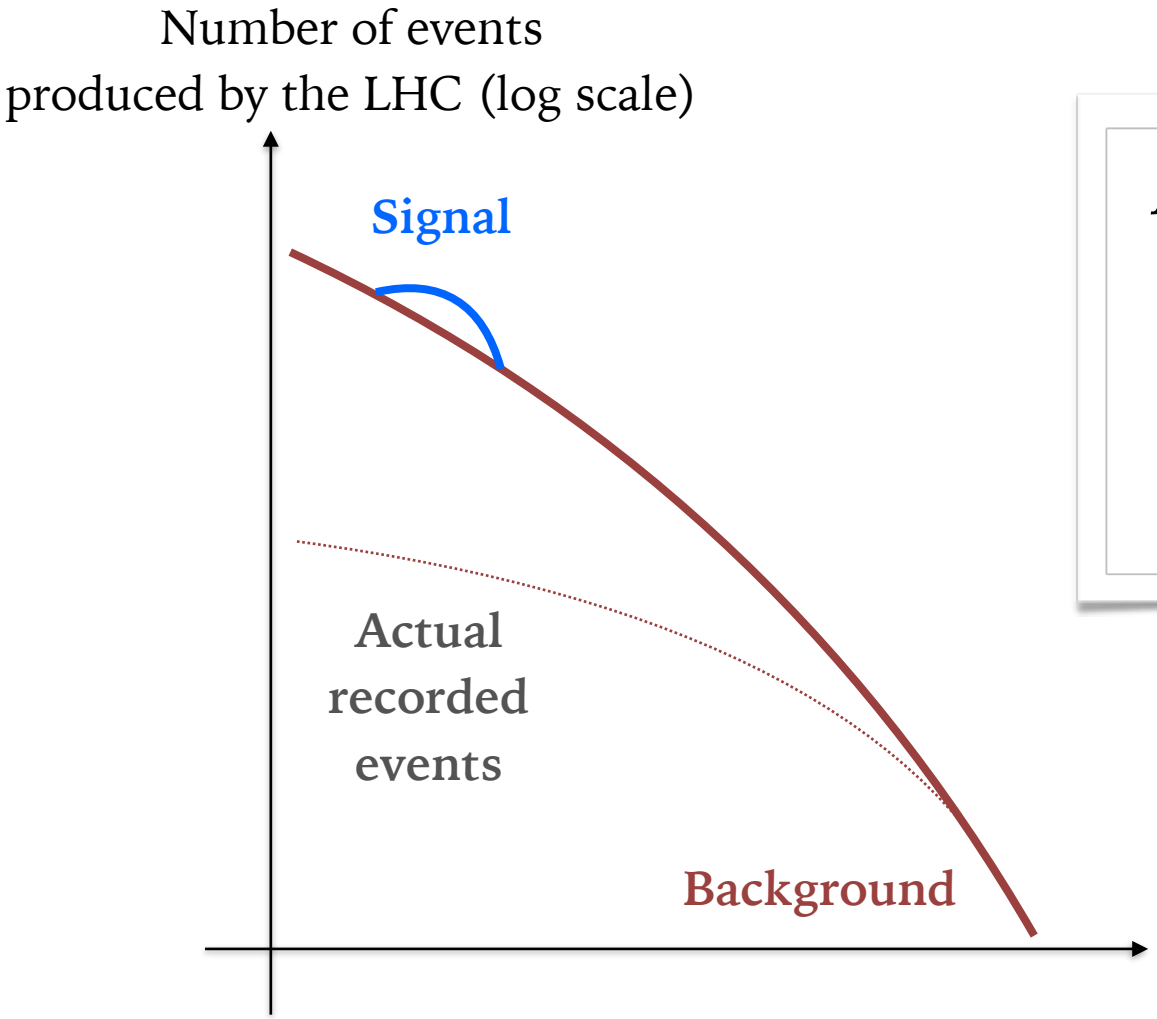
Signals vs backgrounds

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!

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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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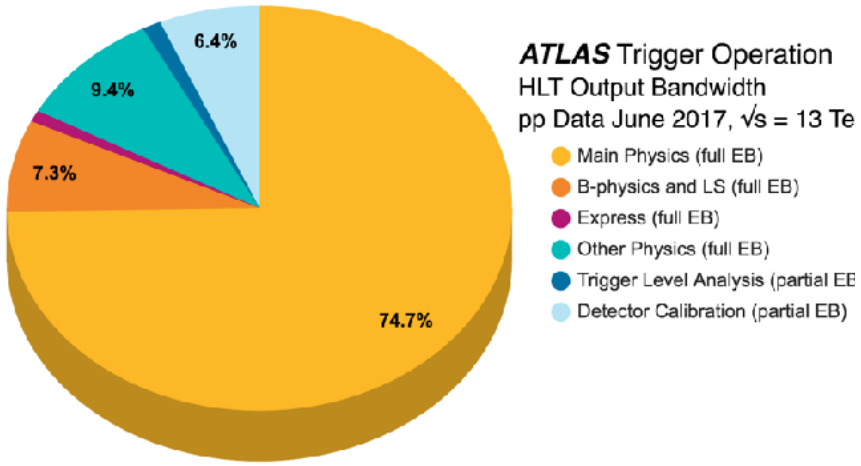
How to record more data for less

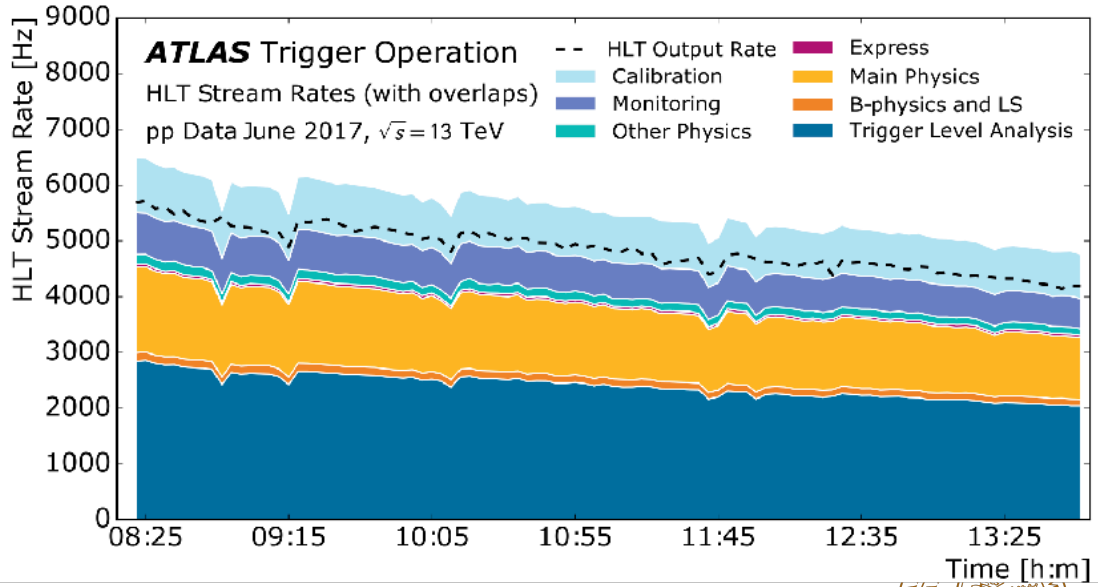
(LHCb: Turbo Stream, CMS: Data Scouting, ATLAS: Trigger-Level Analysis (TLA))

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

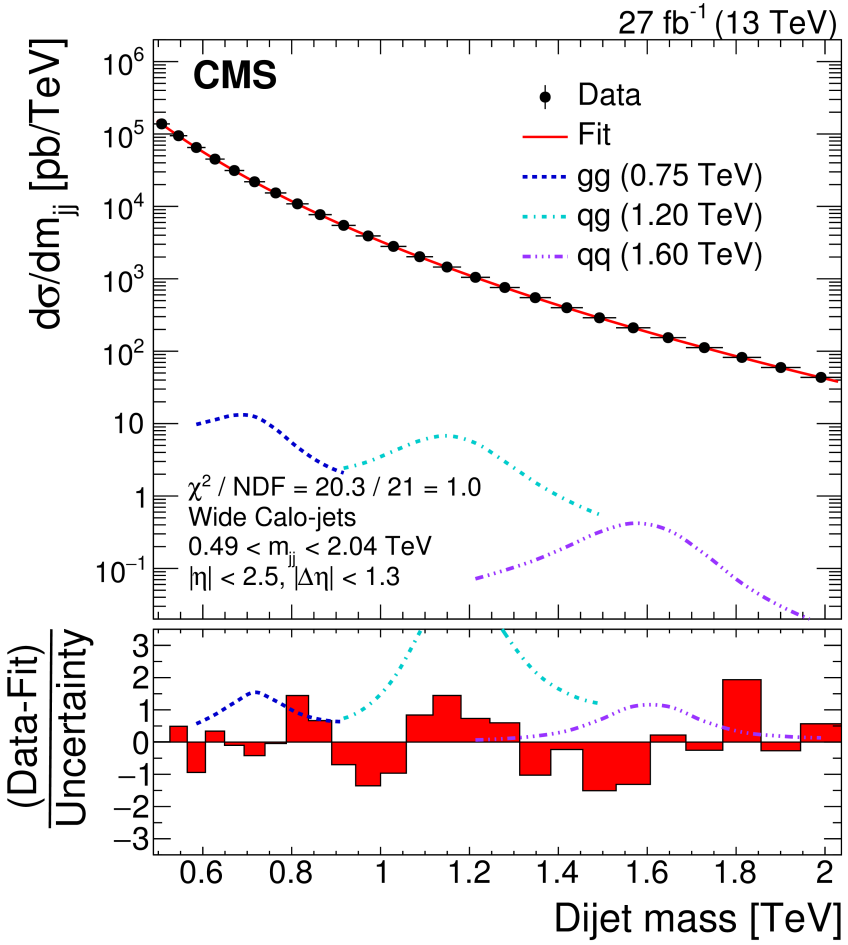


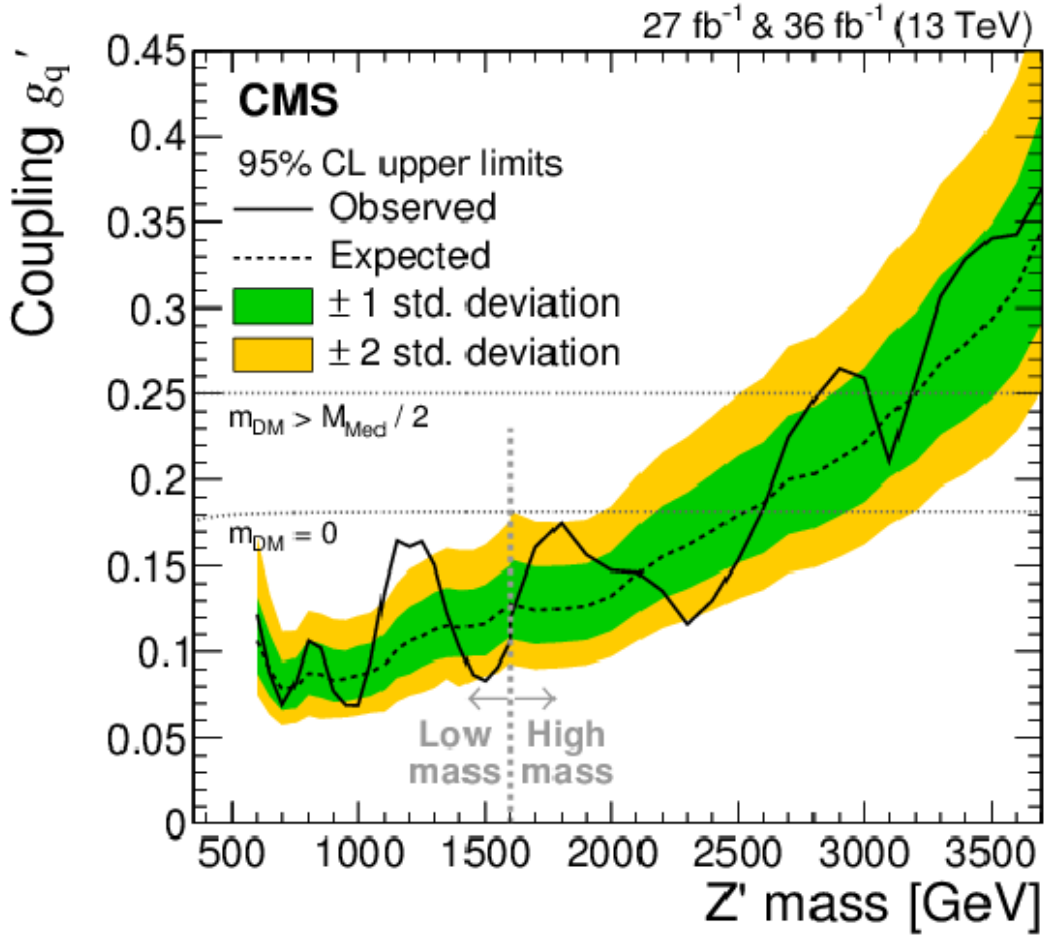
Other ways to get to low masses (beyond +ISR, +VBF):
prescaled triggers/data parking/delayed stream

CMS Data Scouting: low-mass resonances

Dark matter leptophobic mediators decaying to dijets:
very large background, cannot record all data
→ use trigger objects to discover new resonances with large SM backgrounds

https://arxiv.org/abs/1806.00843

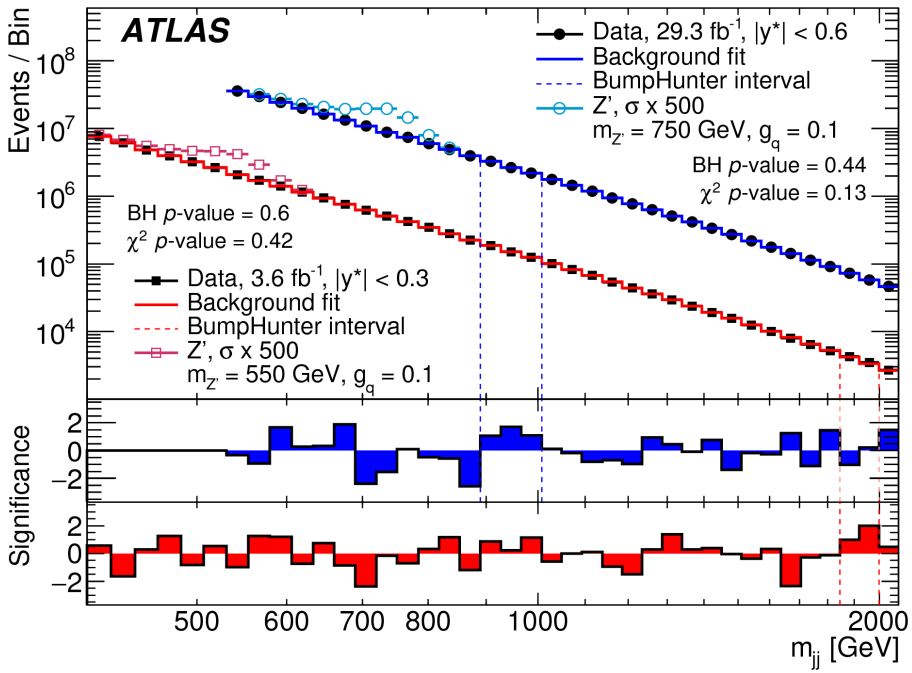


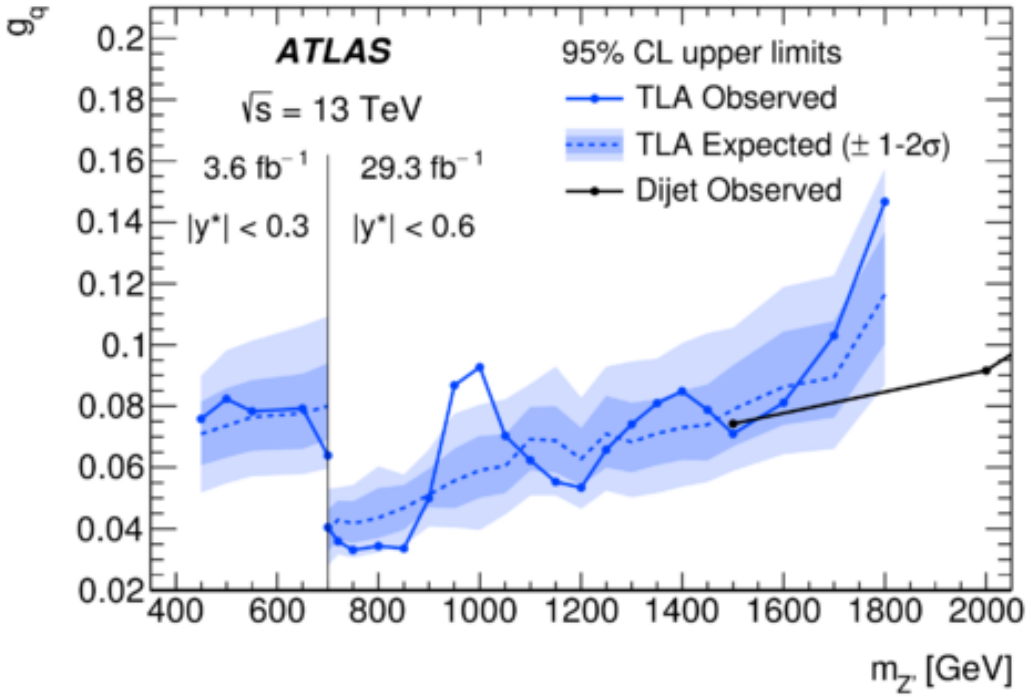


ATLAS TLA: low-mass resonances

Dark matter leptophobic mediators decaying to dijets:
very large background, cannot record all data
→ use trigger objects to discover new resonances with large SM backgrounds

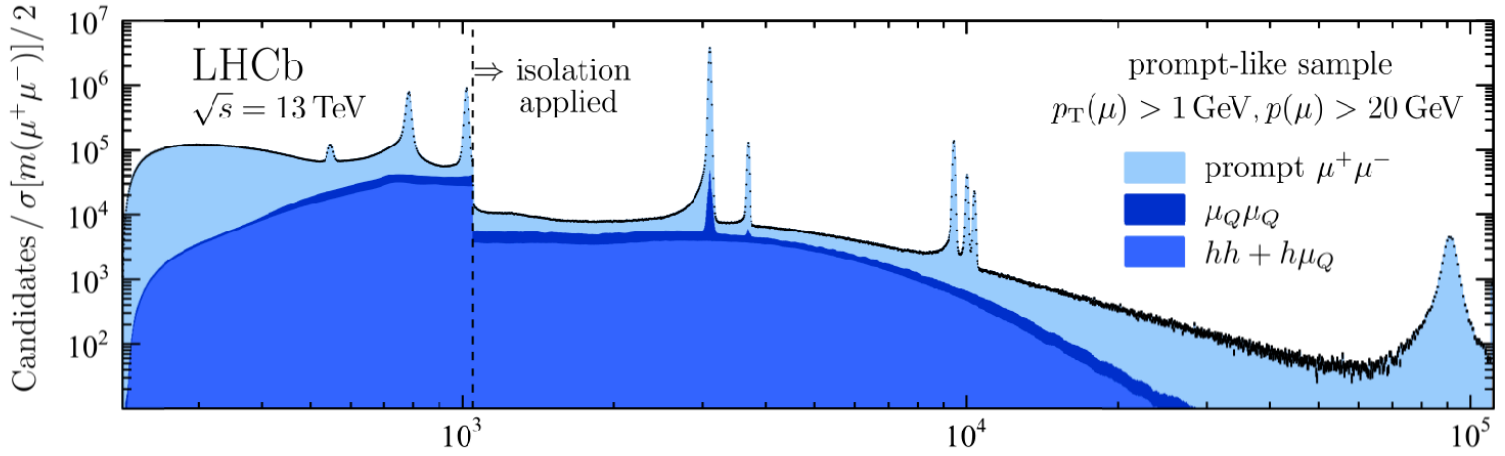
Phys. Rev. Lett. 121 (2018) 081801





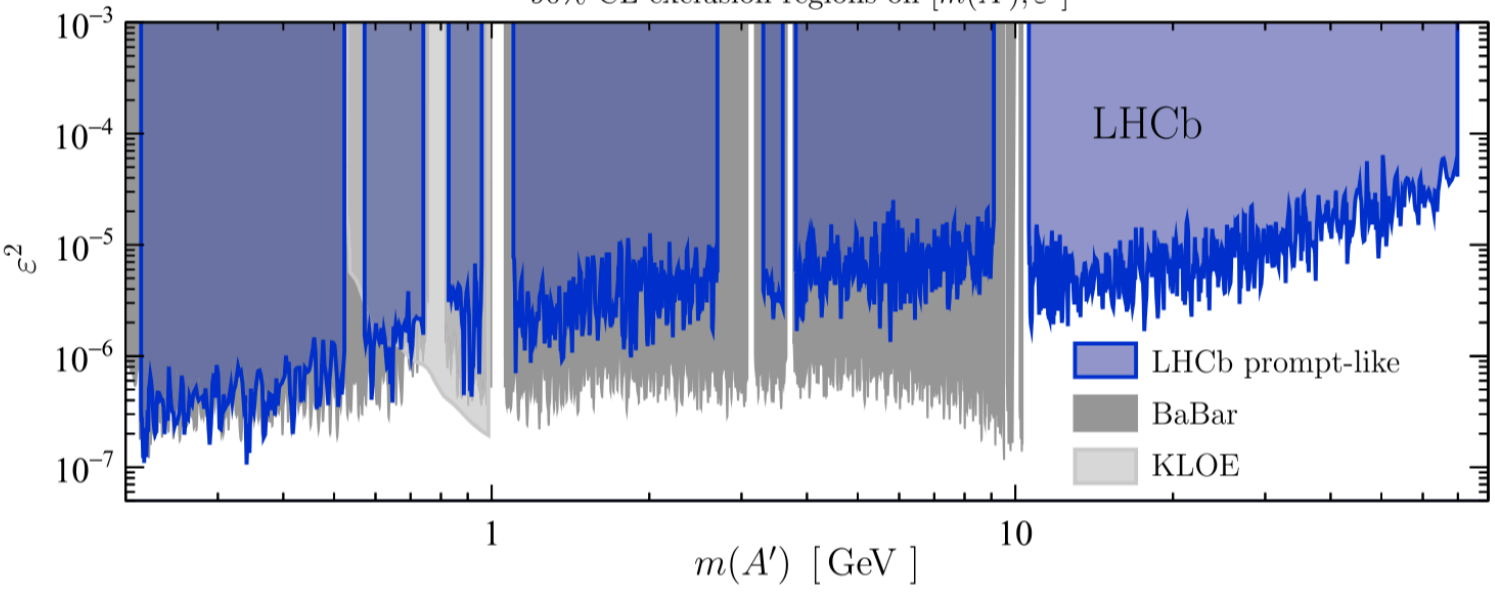
LHCb turbo stream: dark boson search

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 $[m(A'), \varepsilon^2]$

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



lower rate of events