CATERINA DOGLIONI - LUND UNIVERSITY

6TH LLP COMMUNITY WORKSHOP, GHENT

Long Lived Particles and Dark Matter

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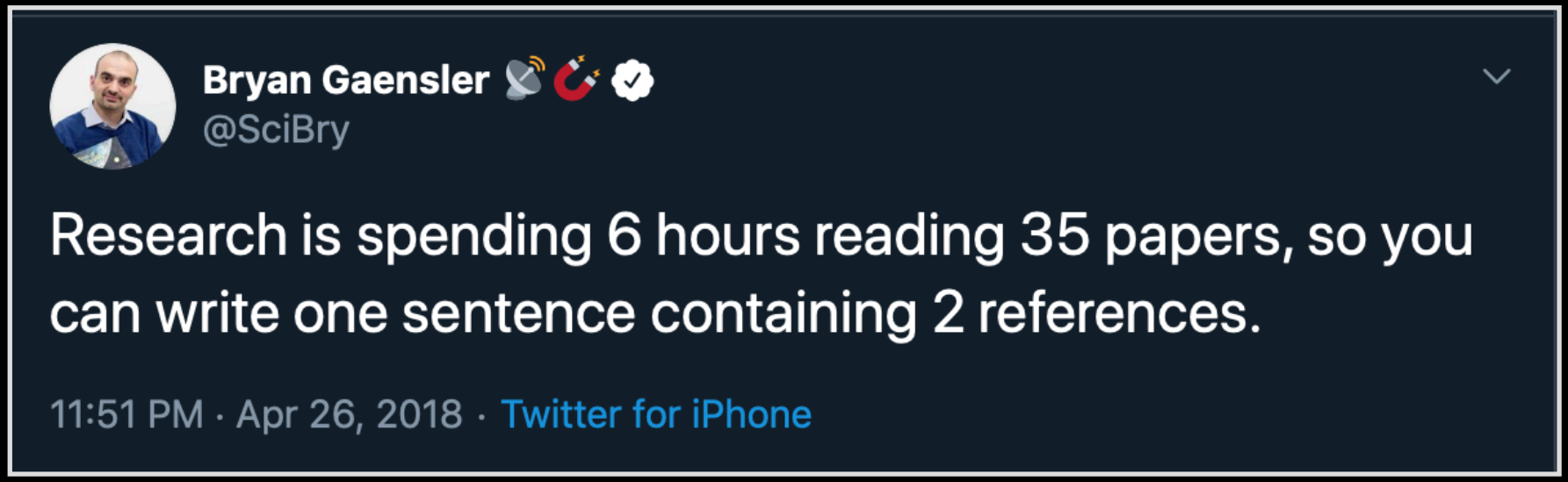
http://www.hep.lu.se/staff/doglioni/

Disclaimers: I am rather new to this community && an experimentalist
(&& it's term time && I only have 15' for this contribution)



Consequence: This is a limited, personal view of the matter, restricted to models that are themselves limited wrt the wealth of literature…
…but this discussion should continue, here and in other fora!

Outline

- **LHC DM benchmarks and searches: where we started and where to go**
  - EFTs, simplified models, more complete models
- **Interlude: when can we call a model a *dark matter* model?**
  - [personal note: we shouldn't stop searching for models w/o DM]
- **Beyond WIMPs**
  - Dark sectors as an example
  - ~~Dark~~ hidden ~~photon~~ boson models and complementarity
- **Closing remarks**

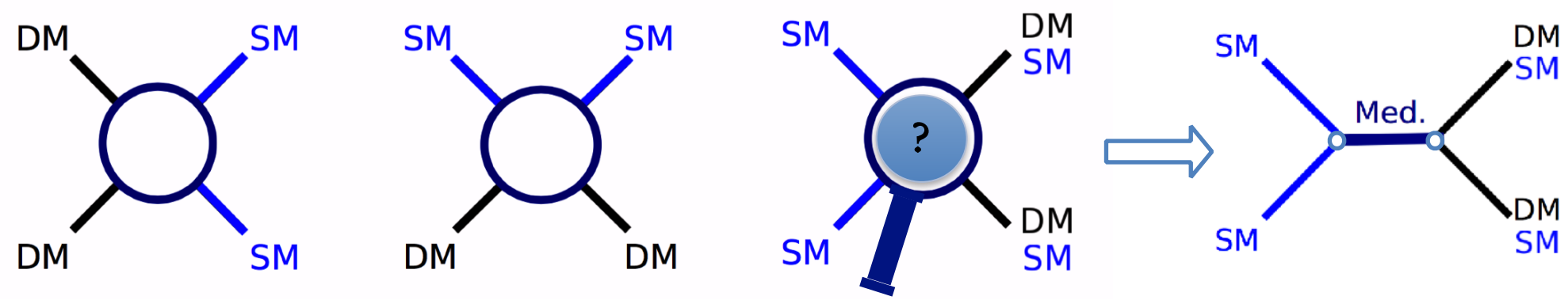
The WIMP miracle of complementarity

Complementary experiments tackling DM problem

Why we need complementarity:

DD/ID can discover DM with cosmological origin

Colliders can produce DM and probe the dark interaction



Indirect Detection | Direct Detection | Particle Colliders

Also: complementarity of colliders with direct / indirect detection needs a **theoretical framework**

(+ WIMP miracle)

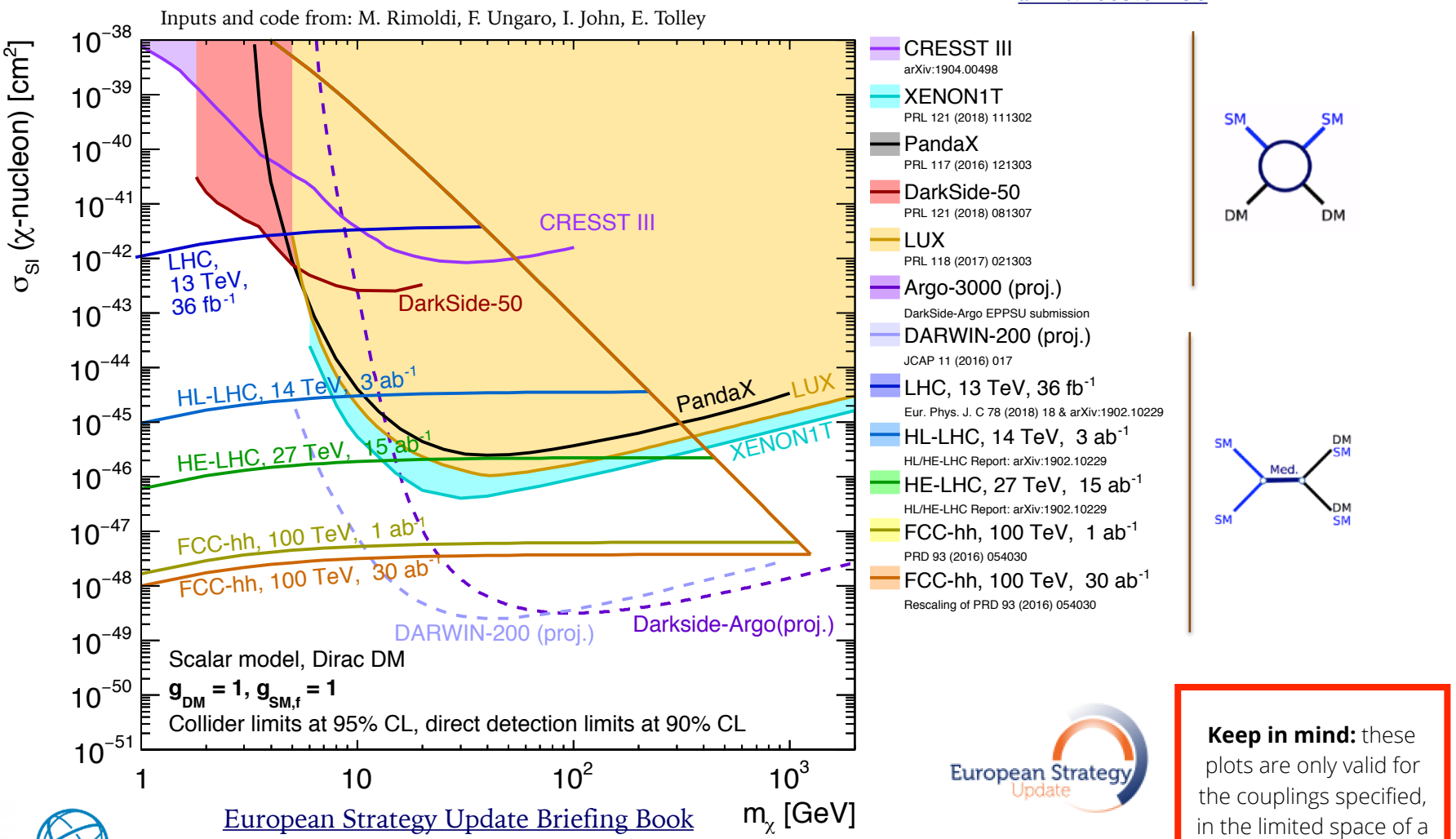
This complementarity, in context of a predictive yet simple theory facilitated wide adoption of WIMP models as LHC benchmarks

Complementarity example

- **Collider constraints** on simple models of DM can be compared to **direct detection** ones

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\,{\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2 .$$

arXiv:1603.04156

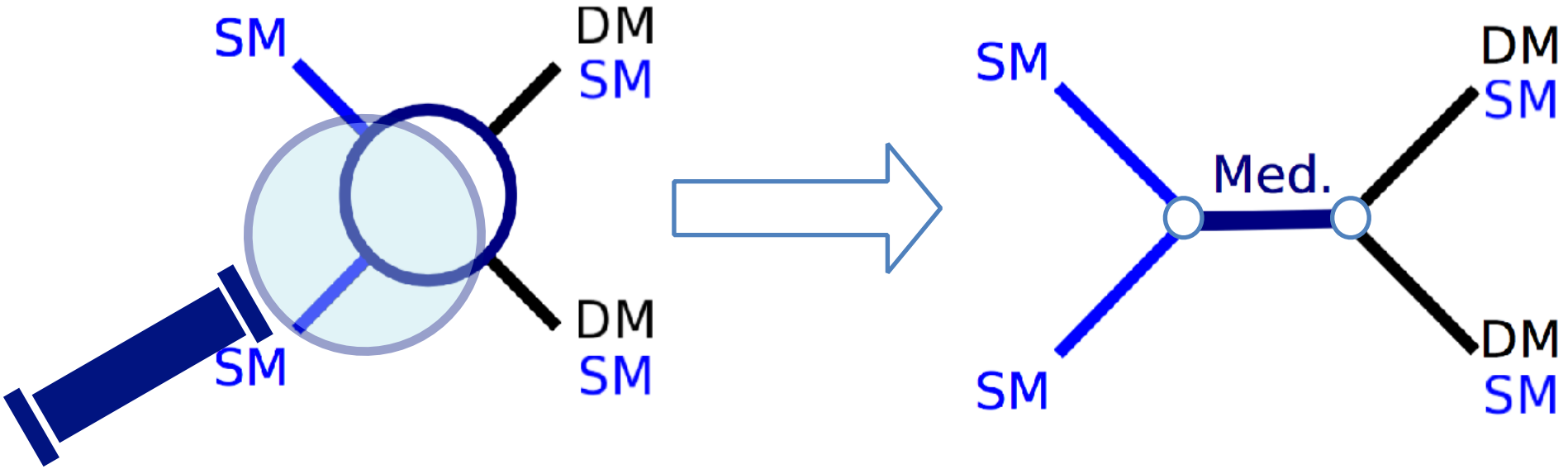


European Strategy Update Briefing Book

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

LHC experiment can probe Dark Matter mediators

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

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)**
(hep-ph)
Cite as: arXiv:1507.00966 [hep-ex]
(or arXiv:1507.00966v1 [hep-ex] for this ve

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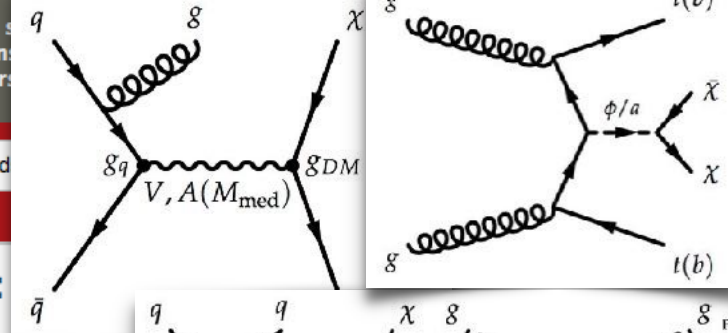
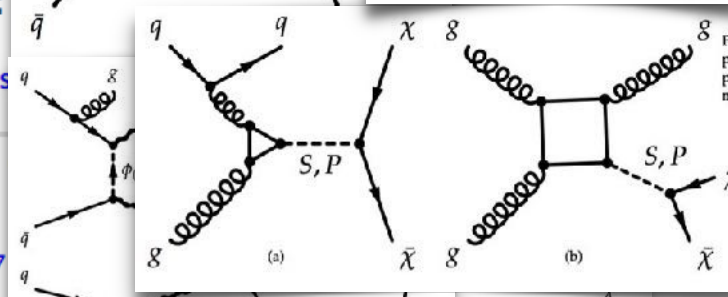
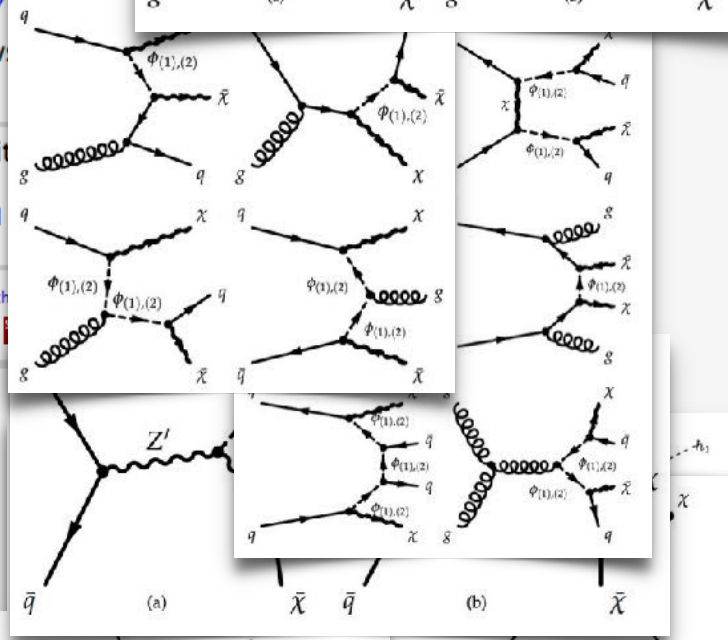
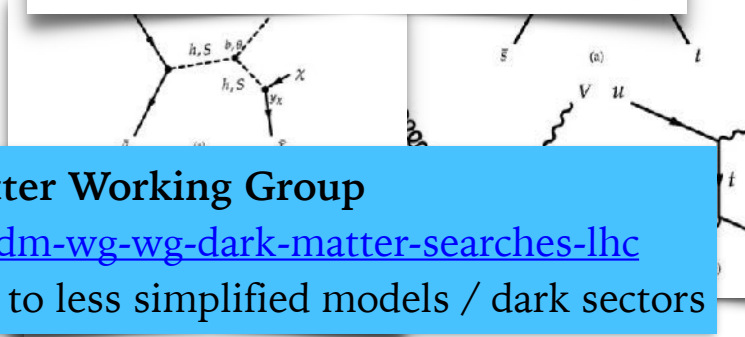




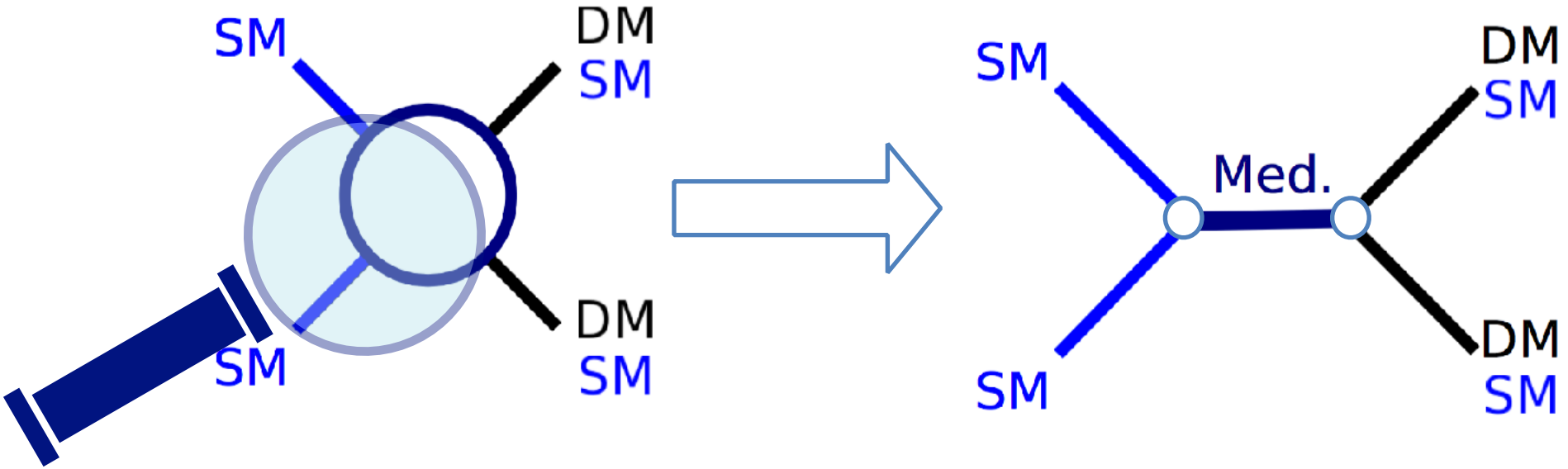




Now: **LHC Dark Matter Working Group**
http://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc
extending the menu of LHC benchmarks to less simplified models / dark sectors

Dark Matter mediators at the LHC

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

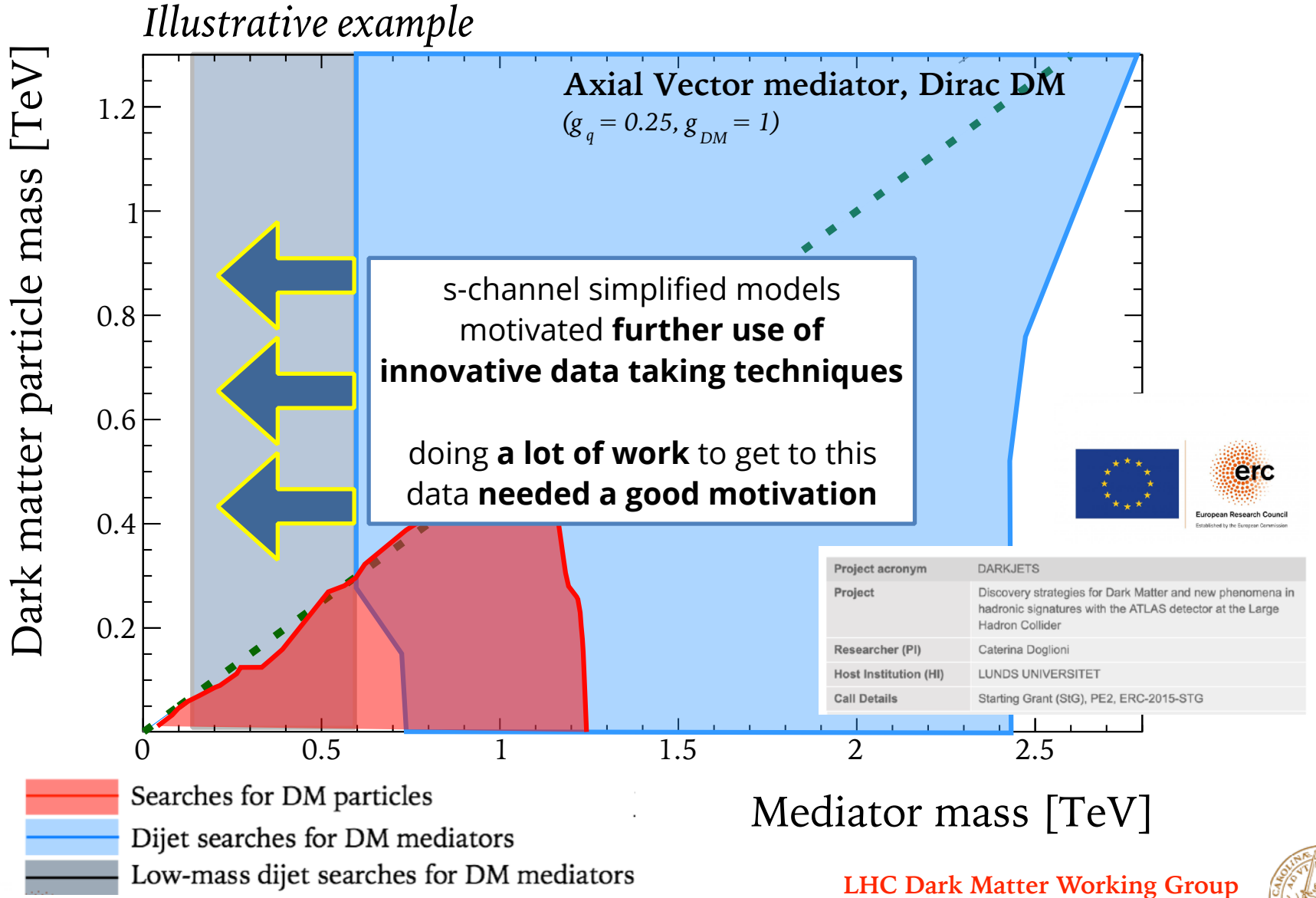


Can **probe the dark interaction** even if DM is inaccessible
Can look for both **invisible and visible decays** of the mediator

Look for an inevitable LHC physics process:
di-jet (and di-X) resonances

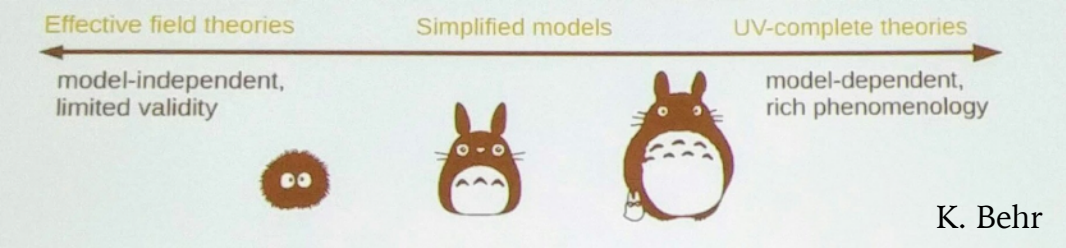
See W. Kalderon's talk

A motivational slide

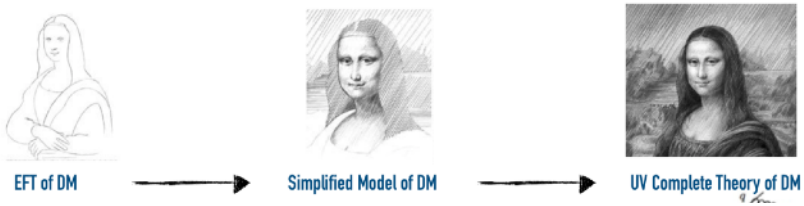


LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

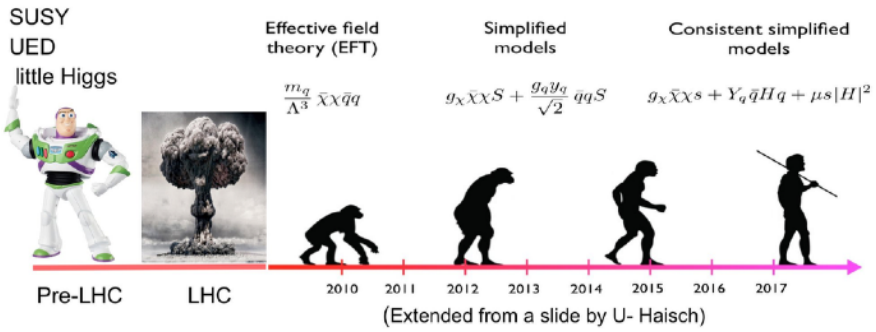
Tired of WIMPs? Go forth and UV-complete, or…



K. Behr



S. Sevova



G. Polesello

Winner of the Twitter competition at DM@LHC 2018, Heidelberg

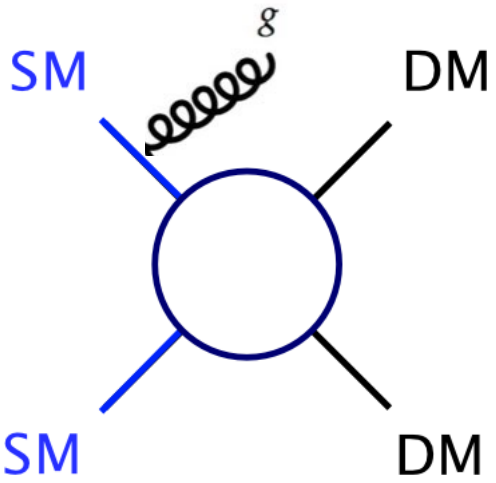
Credits to K. Hoberg for spotting the picture

...go look for DM motivations in other models!

Generic searches ⟷ More specific searches

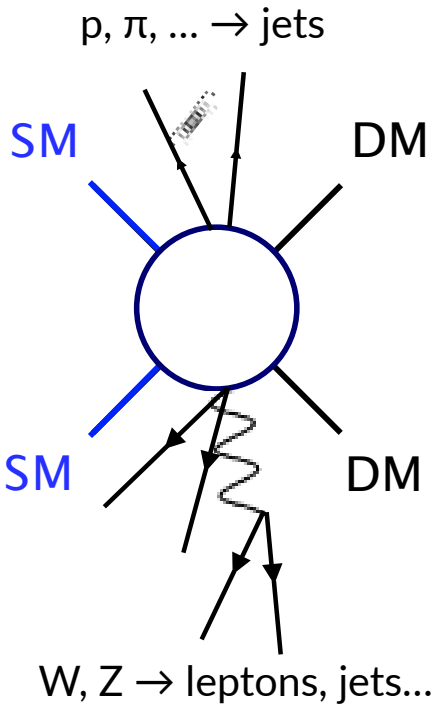
- Good for **simple models** with **sizable cross-sections**
- **Fewer assumptions** on specific model characteristics

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



where do LLP stand?

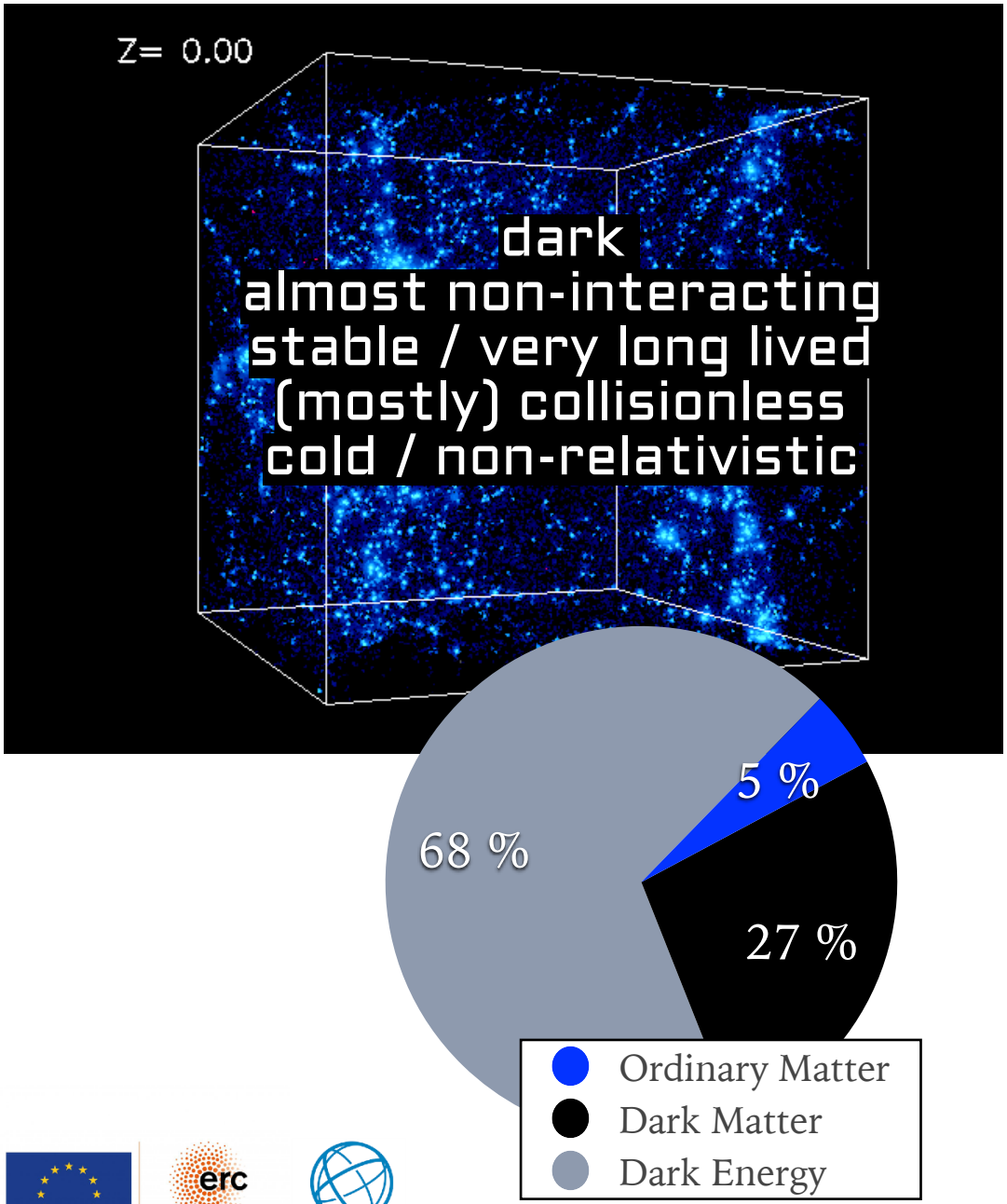
some answers in e.g.
arXiv:1810.12602
arXiv:1903.04497



→ the way we think of benchmark models **influences collider searches**

Simple models ⟷ More complex/complete models

How does (particle) dark matter look like?



Do we need a particle like this in our LLP models?

- It would be nice…
- …but it is not needed to justify searching for the model, especially in broad-range searches
  - T. Sjöstrand: ”[Hidden Valley] models don’t have a direct connection to cosmology, they just ”could happen” *@ Lund Dark Sector mini-workshop, last week*

Do we need to make up *all* the DM relic density with this particle?

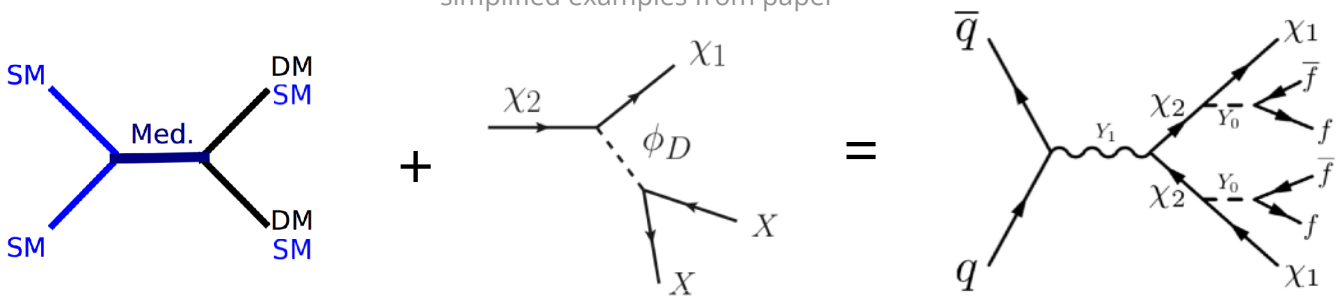
- Some like Occam’s razors…
- This has never been a strict requirement in WIMP models
  - Some reasons: see this talk
- Also: different ways to get at the relic (freeze in/out/…) lead to different (interesting) properties
  - see e.g. asymmetric DM arXiv: 1308.0338

Another approach: take one small step further…

~~Take a 2HDM, add a pseudoscalar particle mediating DM~~

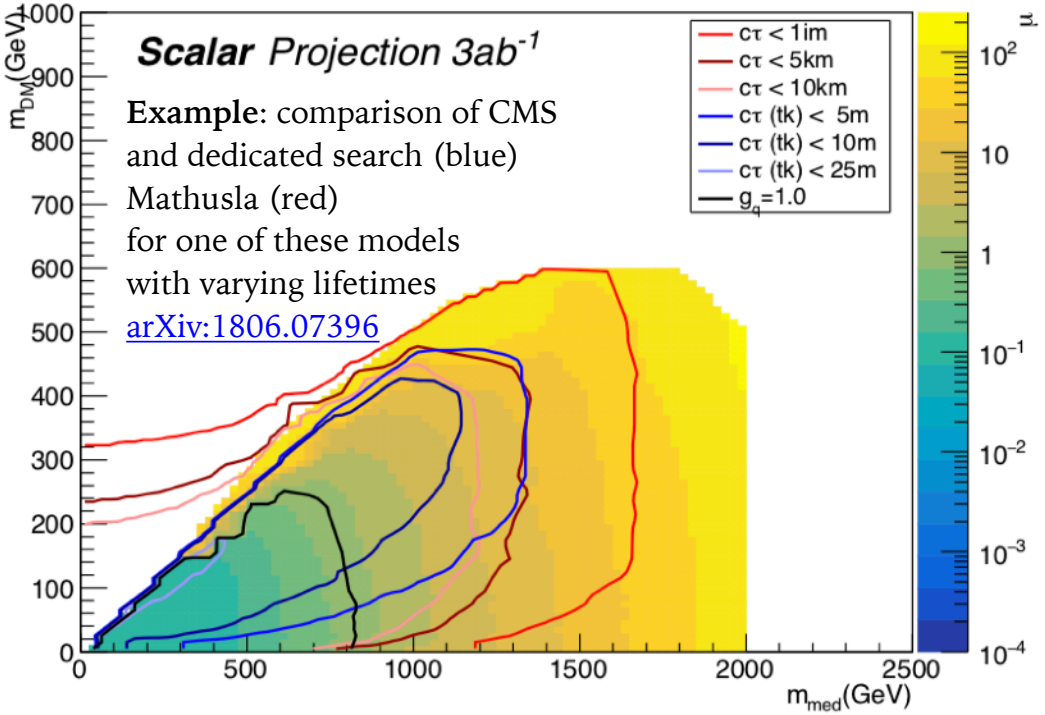
Take WIMP simplified models for production, add LLP in decay

simplified examples from paper



Simplified DM Models		
Variables	DM candidate	Interaction
m_ϕ	Dirac	Vector
m_1	Majorana	Axial-Vector
g_χ	Scalar-real	Scalar
g_ϕ	Scalar-complex	Pseudoscalar
Displaced Signature Extension		
τ , m_2	Decay of $\chi_2 \to \chi_1 X$	

- Start with WIMP simplified models (including DM candidate), add LLP in final state
  - Adds displaced vertex signature
  - Need to keep limitations in mind!
- Reasoning behind this approach:
  - Can be used systematically
  - Can map to more complete/ realistic models
- Question (to CMS?): which searches use such an approach?

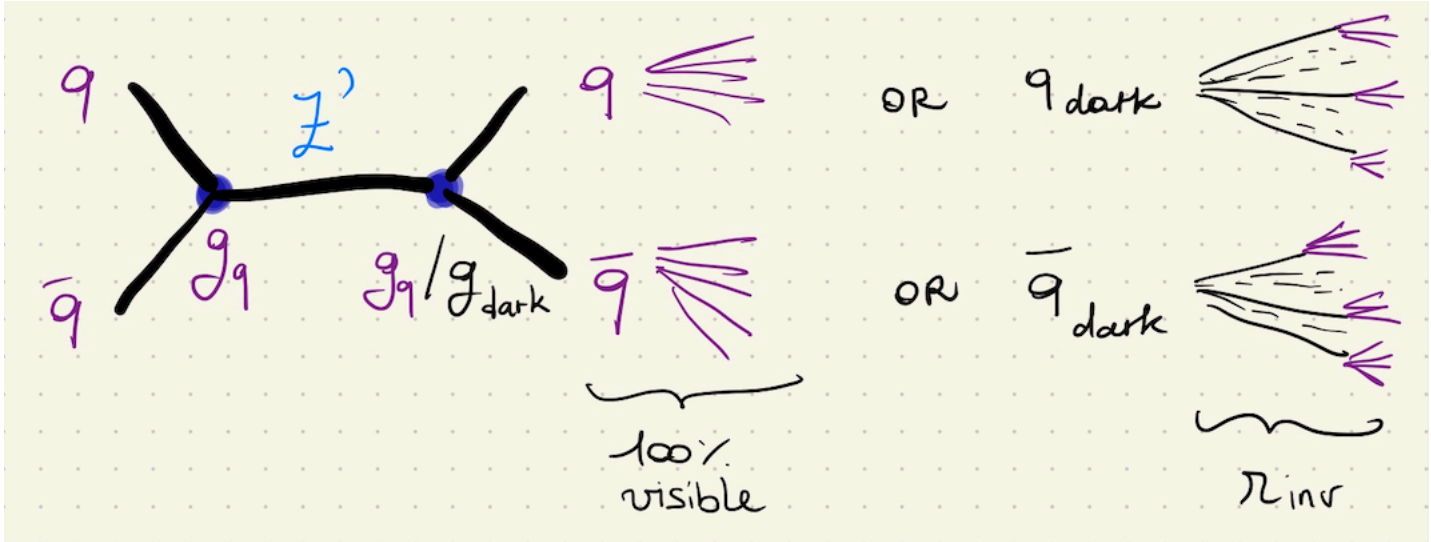


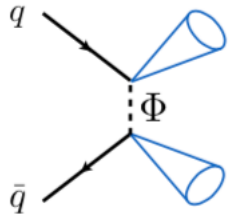
Dark sectors: semi-visible jets

arXiv:1707.05326
arXiv:1503.00009

~~Take WIMP simplified models, add a LLP~~

Take WIMP simplified models, add a dark sector

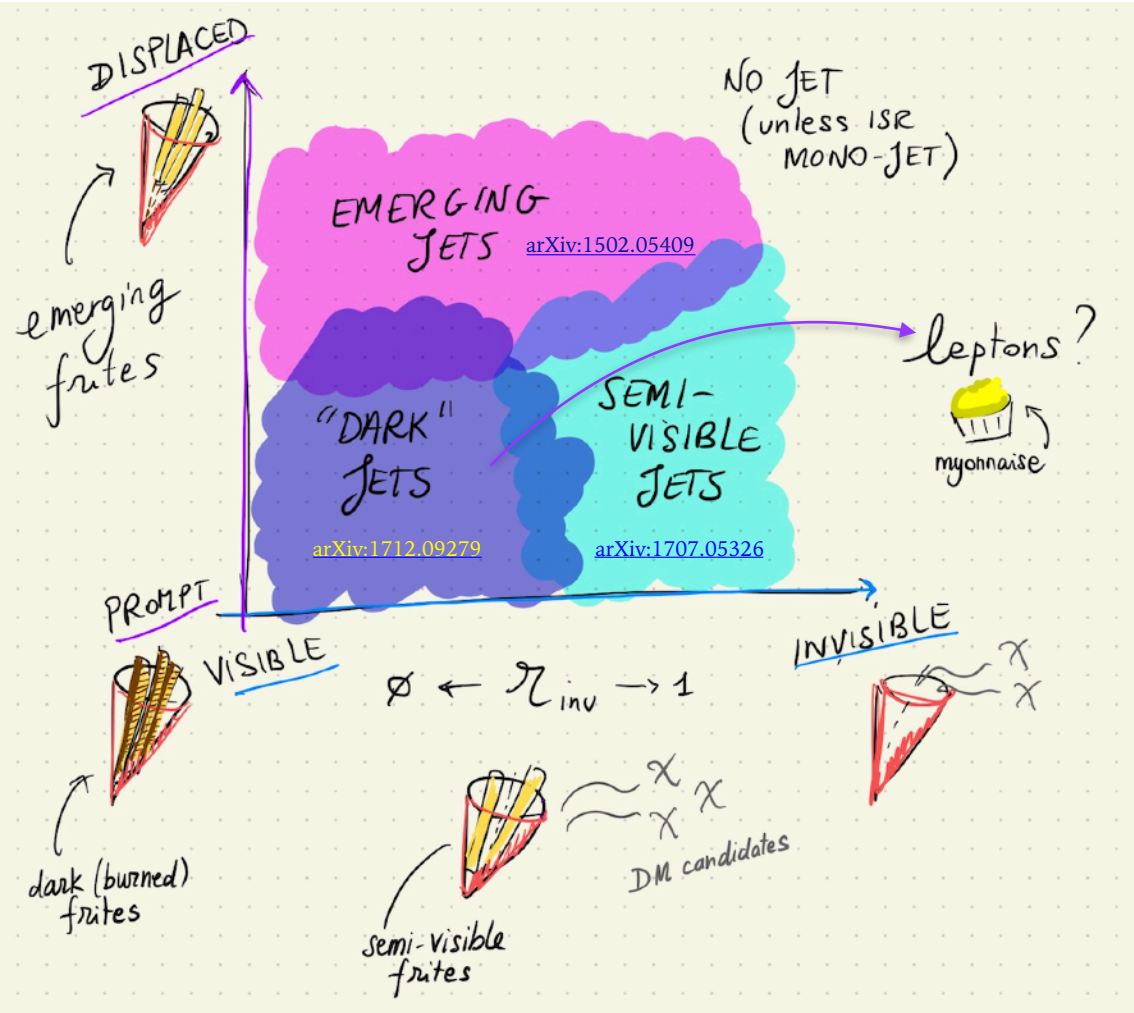




both s- and t-channel models studied

- **Reasoning:** DM is part of a more complex dark sector with strong couplings
  - we may have missed it so far because:
    - it could look *QCD-like*: dark fragmentation (may have different substructure)
    - it could look *QCD-background-like* (to MET searches): MET behind jet
  - solution: design searches targeting benchmarks on the r_{inv} spectrum
    - some signal caught by monojet and dijet, but **not optimized**

Dark sectors: semi-visible jets & co



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

A family of signatures, with DM particles (& more) in the dark shower

Generate using Madgraph WIMP simplified models + Pythia Hidden Valley

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

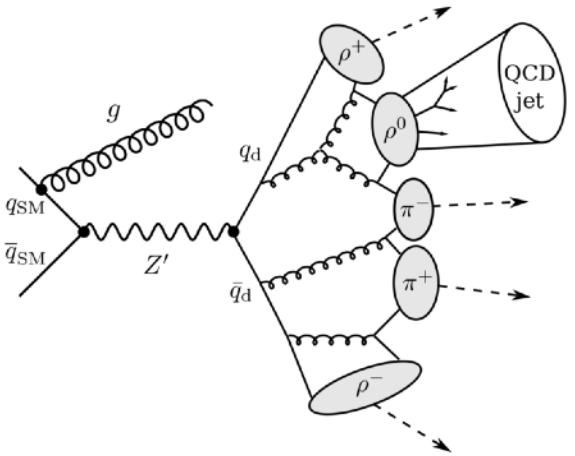
Dark sectors: thermal relic in semi-visible jets

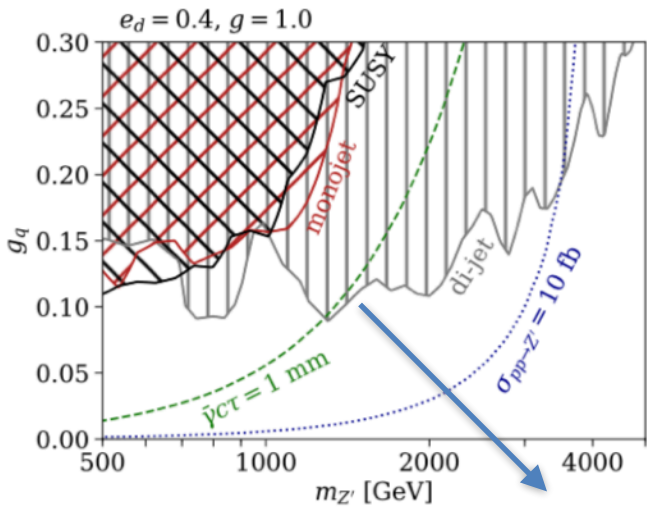
~~Take WIMP simplified models, add a LLP~~

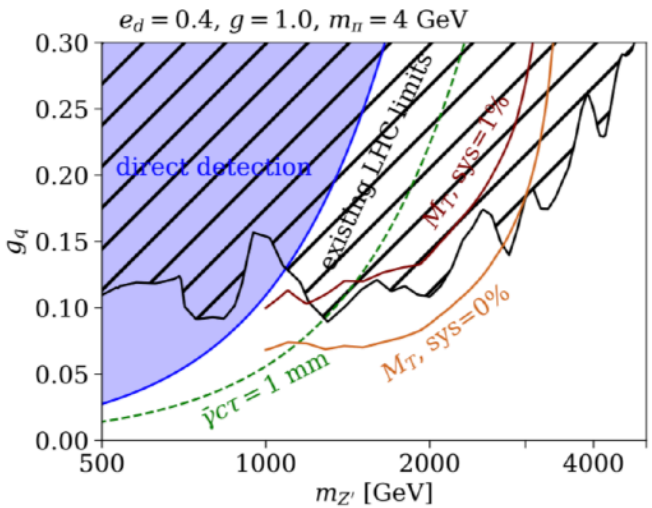
Take WIMP simplified models, add a dark sector with a thermal relic

- **Reasoning**: let's build a model with a suitable DM candidate, avoiding too much dependence on the model
  - Ingredients:
    - A dark QCD with 2 flavors:
      - Stable pions (for DM candidate), unstable rhos (for thermal relic)
    - A TeV-scale Z' coupling to regular and dark quarks
- Still plenty of parameter space for dedicated LHC searches

Signature: semi-visible jets



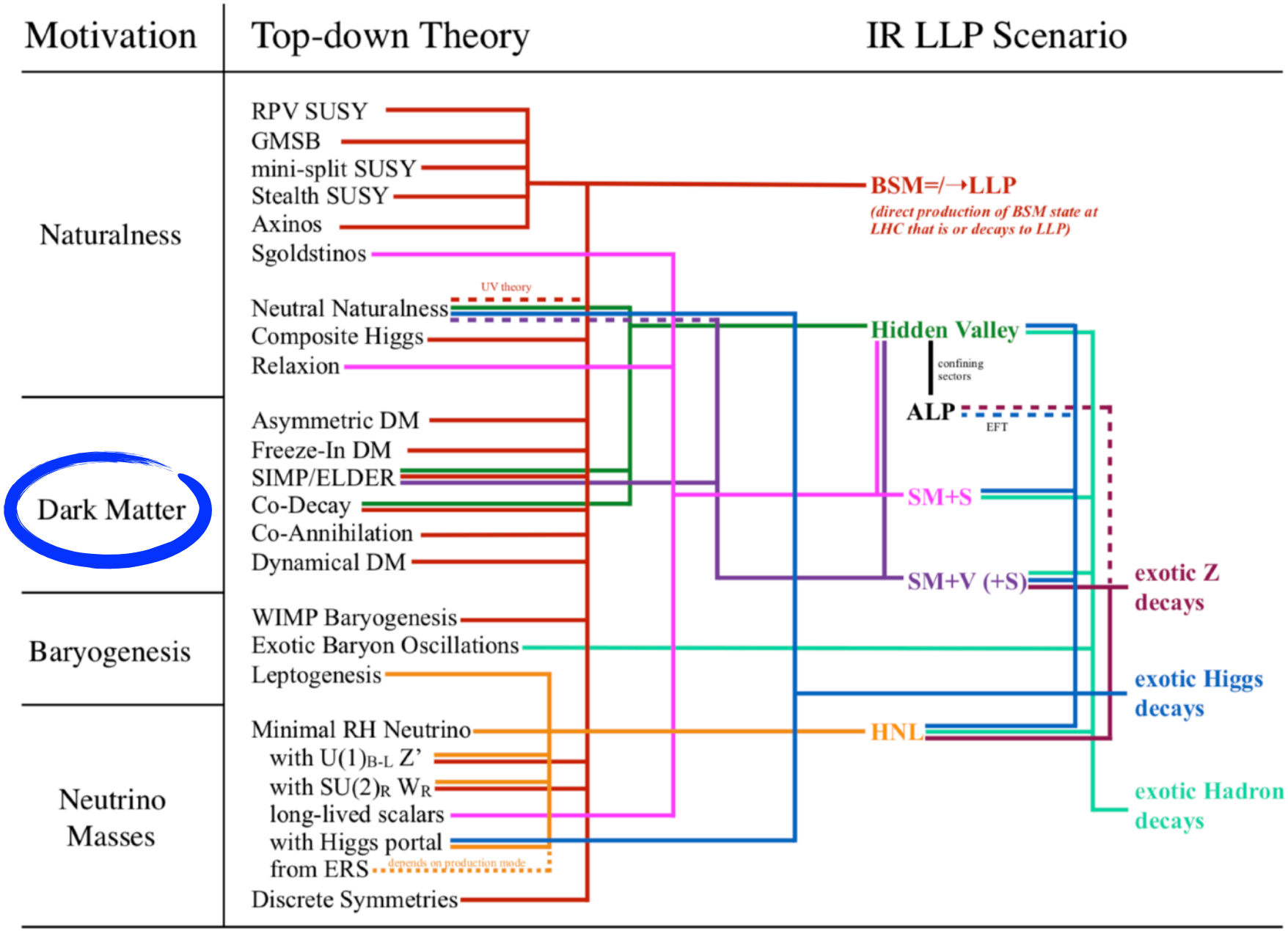




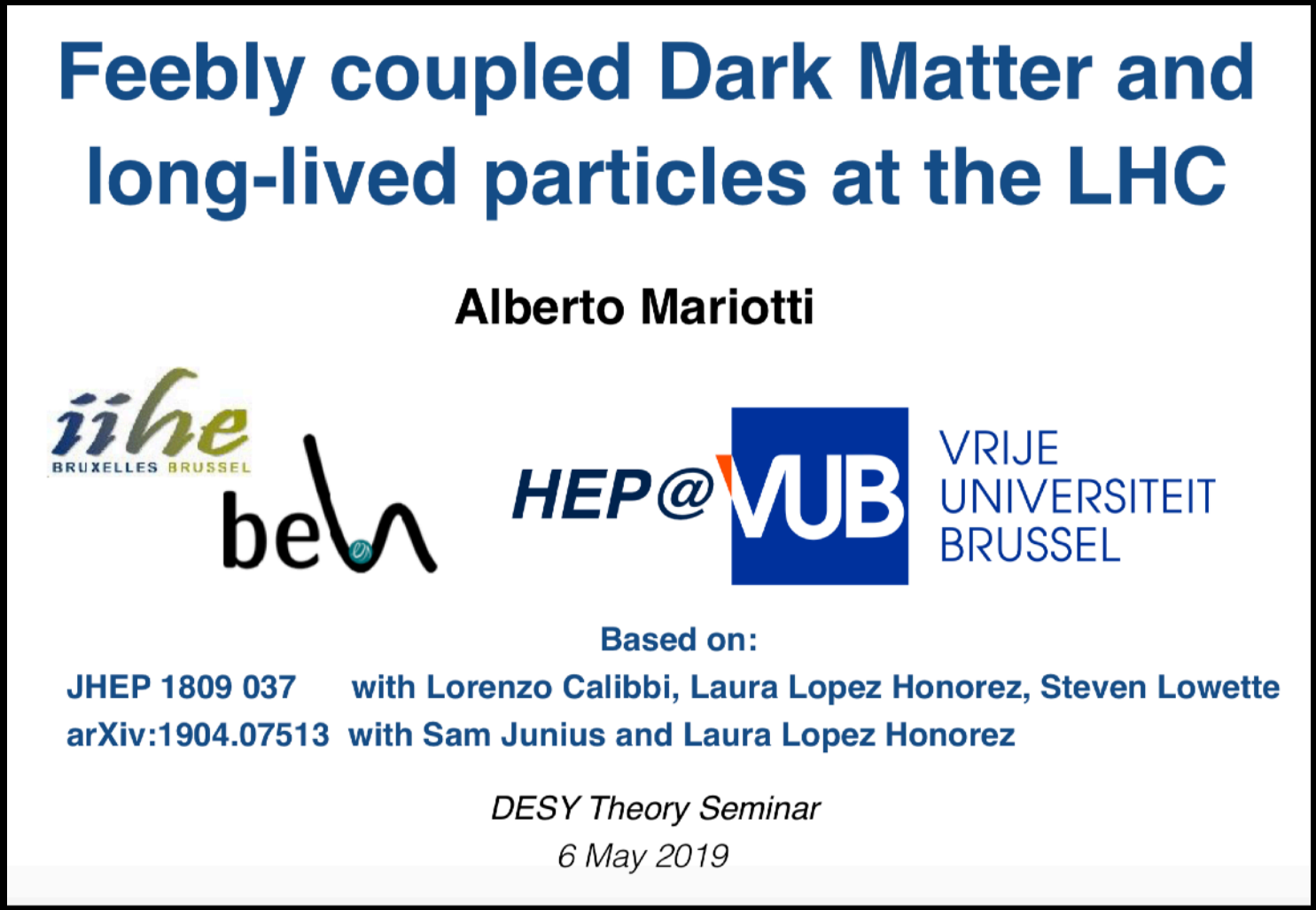
potential for dedicated LLP searches

Many other theory possibilities…

arXiv:1806.07396



For more insight: go local!



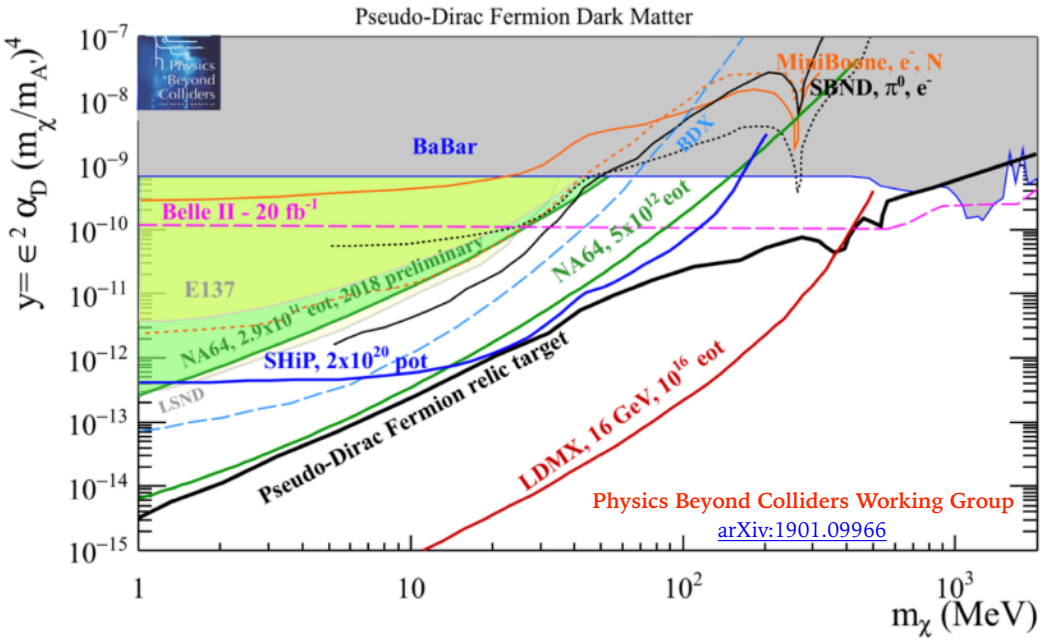
https://indico.desy.de/indico/event/22458/material/slides/0.pdf

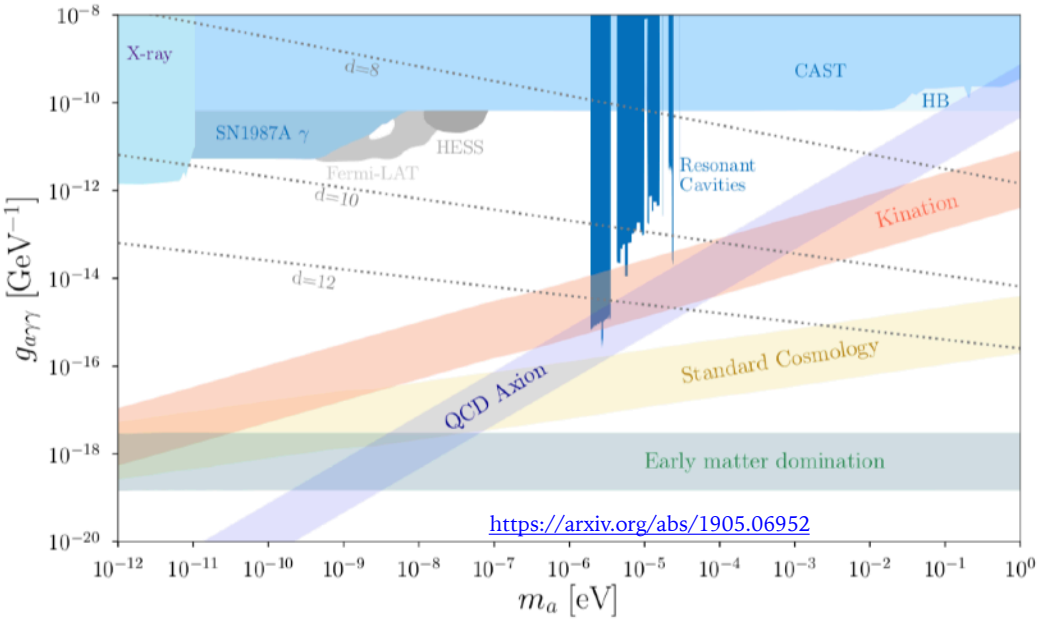
LLP complementarity is behind the corner!

- Physics Beyond Colliders (&& LLP community): non-WIMP benchmark models for **dark sector** searches with dark matter interpretation:
  - e.g. Dark photon, Axion(-like particles)

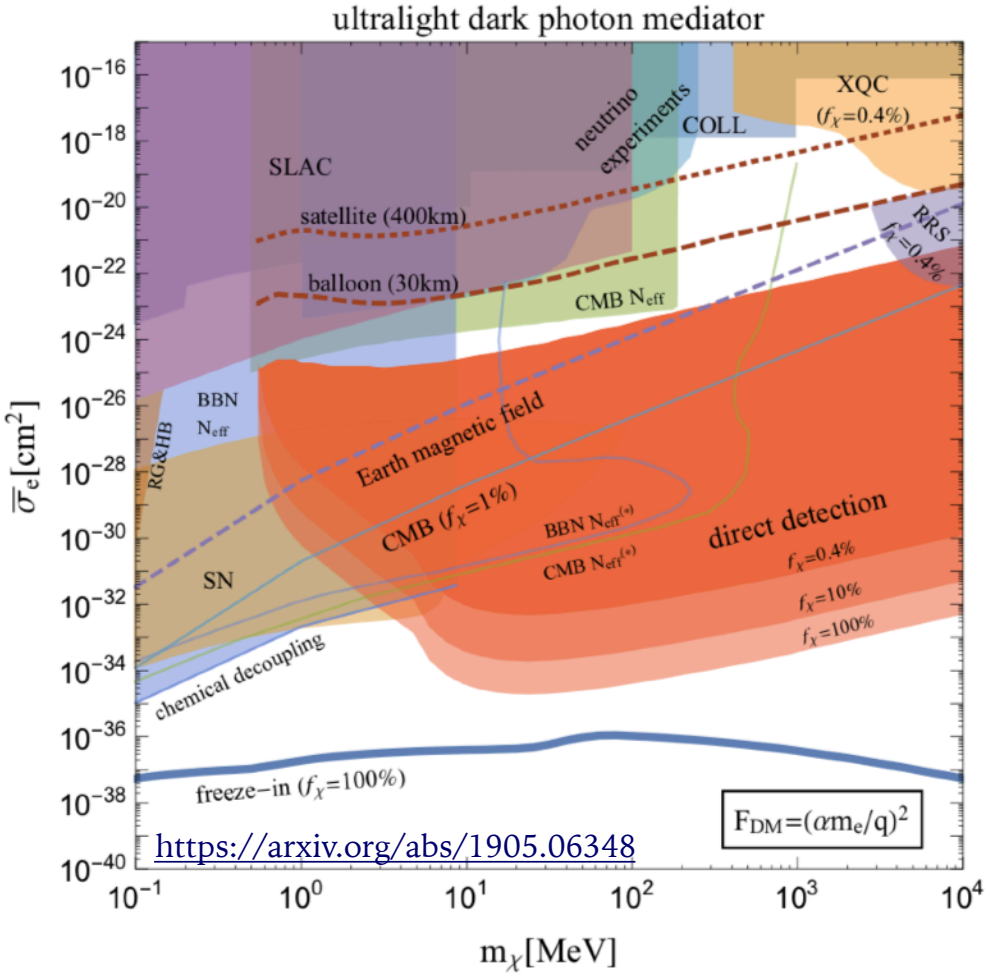
- Benchmark with thermal dark matter interpretation: dark photon → **complementarity of collider, non-collider and astrophysics**

- Axions/Axion-Like Particles (ALPs): inter-field connections, solve more than the DM problem
  - haloscopes starting to become **sensitive to QCD axion / DM regime**!





LLP complementarity, from above



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

very low-mass but "**strongly interacting**" DM particles will:

- interact with **detectors**
  - need to take this into account for collider searches (WIMP and not)
- interact with **atmosphere & earth**
  - use/send detectors higher up!
- be detectable using **astrophysical signals**
  - Supernova, BBN, CMB...

Note also: "Looking up" is a necessary consequence of "looking at low mass DM"

Conclusions

Take-home points/conclusions

- **Why connecting DM and LLP? The big picture is important:**
  - good to look everywhere and leave no stone unturned…
  - …but models & big picture (e.g. complementarity) inevitably influence motivation for searches
    → use model dependence (in moderation) to our advantage

- **Much work to be done, in synergy with DM community**
  - one possible approach: build from current simplified models
    - …without forgetting their limitations!
  - always work alongside signature-based LLP community
    - can use LLPs as an extra handle to uncover/characterize DM

- **Complementarity**: many upcoming *beyond colliders* experiments!

Thank you for your attention!
…and to Oleg Brandt, Eva Brottmann, Deepak Kar, Suchita Kulkarni, Jannik Geisen, Gaia Lanfranchi, Christian Ohm, Sukanya Sinha, the Lund University Theory division for input&discussions

Do we have time
for one more discussion point?

Putting different benchmarks on the same plot

…it is possible, but there may be disagreements

Comparing apples and oranges: a randomised prospective study

James E Barone

For many years the comparison of apples and oranges was thought to be impossible. Many authors use the analogy of the putative inability to compare apples and oranges as a means of scornfully reviewing the work of others. The titles of some recent publications[1 2] suggest an actual comparison of apples and oranges, but the authors do not, in fact, compare these two fruits. Our laboratory has been interested in this problem for many years. We attempted numerous pilot studies (unpublished data) but had not accomplished a true comparison until now. At last, successful comparison of apples and oranges has been achieved and is the subject of this report.

Table 1 Non-parametric background fructological information

	Apples	Oranges
Grown in orchards	Yes	Yes
Flowering trees	Yes	Yes
Considered a fruit	Yes	Yes
May be eaten	Yes	Yes
May be made into juice	Yes	Yes
Subject to damage by disease	Yes	Yes
Subject to damage by insects	Yes	Yes
Involvement of Johnny Appleseed*	Yes	No

*P<0.01.

Stamford Hospital, Stamford, CT 06904, USA

James E Barone
surgeon in chief

drjbarone@stamhosp.chime.org

BMJ 2000;321:1569–70

https://www.bmj.com/content/bmj/321/7276/1569.full.pdf

A point for discussion (brought up by Gaia Lanfranchi)

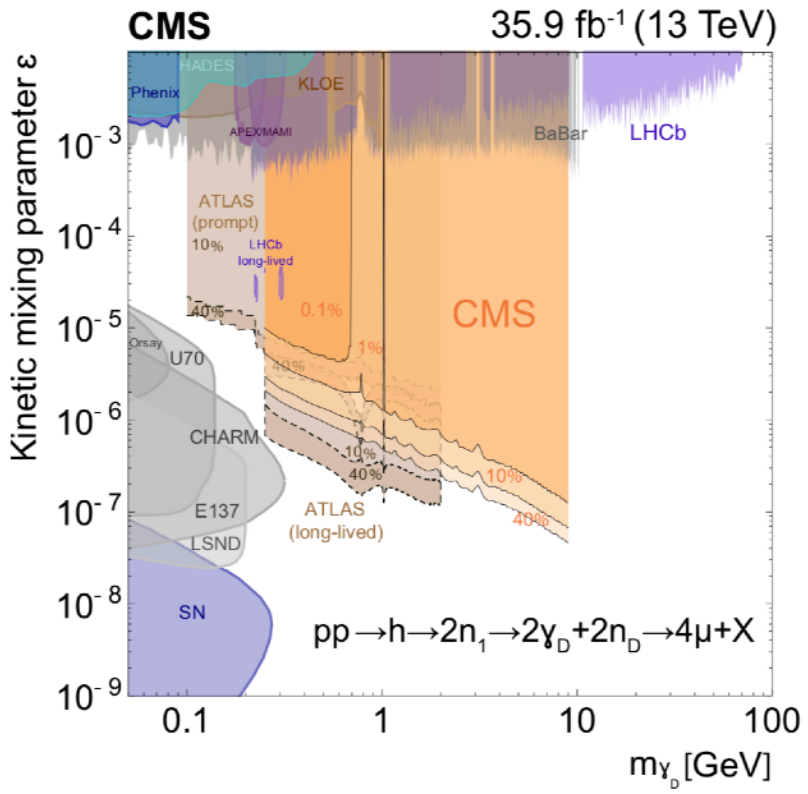
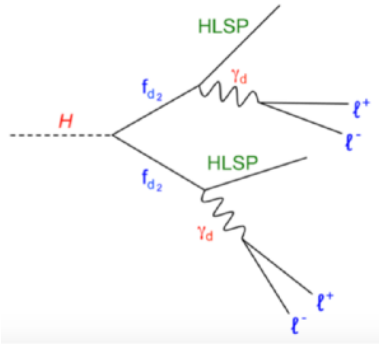


Figure 3.2: Comparison of the lepton-jet searches at ATLAS [265] and CMS [264] with respect to a dark photon scenario [148] vis-a-vis dark photon limits coming from low-energy experiments. Figure taken from Ref. [264].

Potential issue: putting visible decays of **minimal** and **non-minimal** dark photon on the same plot

ATLAS and CMS



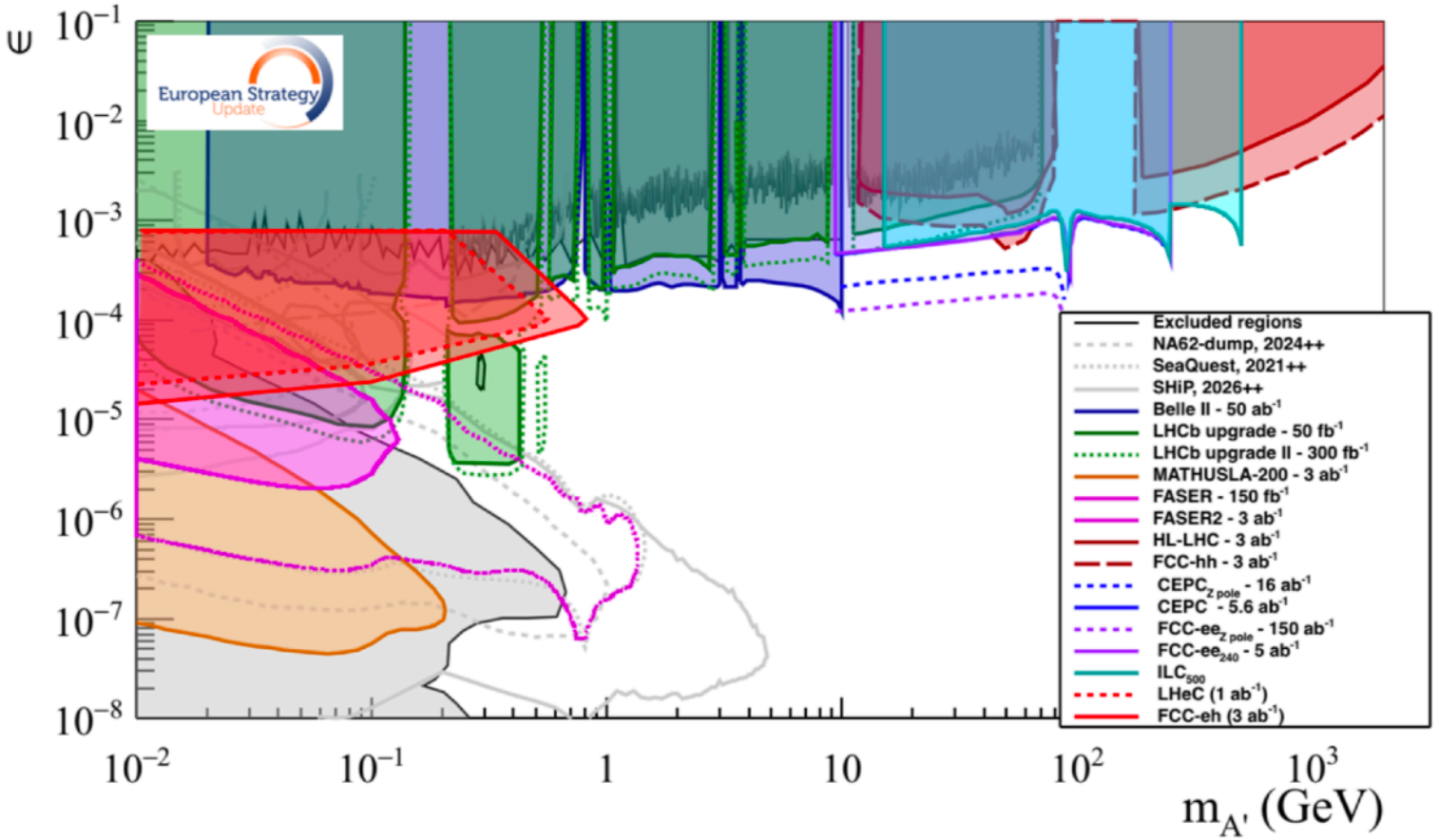
Other experiments

- cannot produce a Higgs not at colliders
- the Lagrangian of e.g. LHCb results does not have the extra terms for Higgs couplings

Suggestion: coherently with e.g. WIMP simplified models, use only minimal dark photon model, or perform specific reinterpretation

Physics Beyond Colliders visible dark photon

Visible dark photon decays



All experiments

Note: HL-LHC and FCC projections assume 8 TeV trigger thresholds...essential to think of future collider detectors, trigger & DAQ together with physics (and do Turbo/Scouting/trigger-Level Analysis!)

Backup slides

Where do we go from here? Up to everyone

Dark Matter Working Group within LHC Physics Centre (LPCC) including ATLAS, CMS, LHCb and theory

Organizers:
Oleg Brandt, Francesca Ungaro (ATLAS)
Phil Harris (CMS)
Xabier Cid Vidal (LHCb)
Tim Tait, Uli Haisch (theory)

- **Mandate:**
  - **D**efine 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

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

Dark Matter Working Group

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

2016
https://arxiv.org/abs/1603.04156

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

2017
http://arxiv.org/abs/1703.05703

Agree on how to **present searches for mediators** of DM interactions in visible decays together with searches for invisible DM particles

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

Provide a procedure for **estimation of theory uncertainties** for precision backgrounds of mono-jet DM search at colliders

2018
https://arxiv.org/abs/1810.09420

Develop **scalar sector** and **colored scalar** benchmark models: **2HDM+a**

Current topics

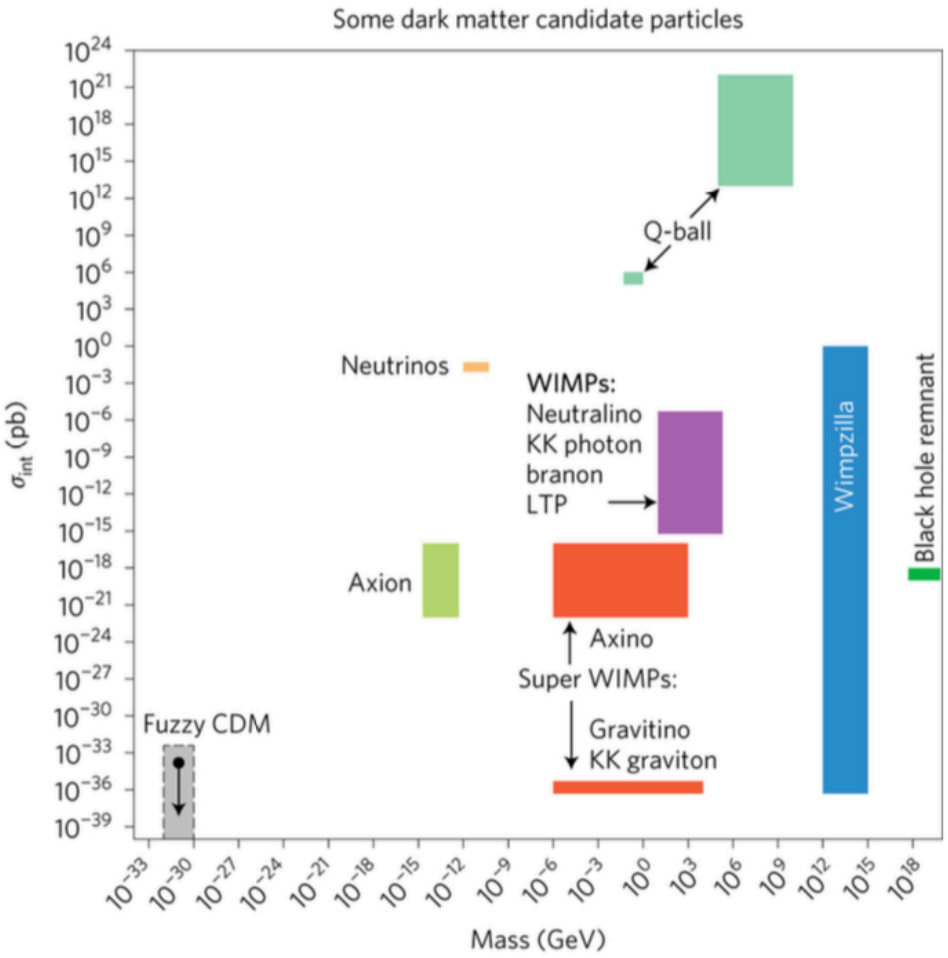
Define recommendations for **t-channel models**

? your ideas here!

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

The dark matter landscape

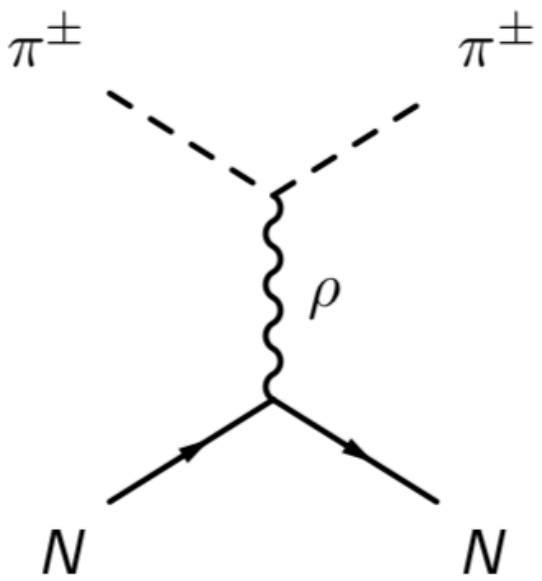
10^{-22} eV — 10^{-2} eV — 1 GeV 1 TeV — 10^{19} GeV (10^{-5} g) — 10^{57} GeV (10^{33} g)



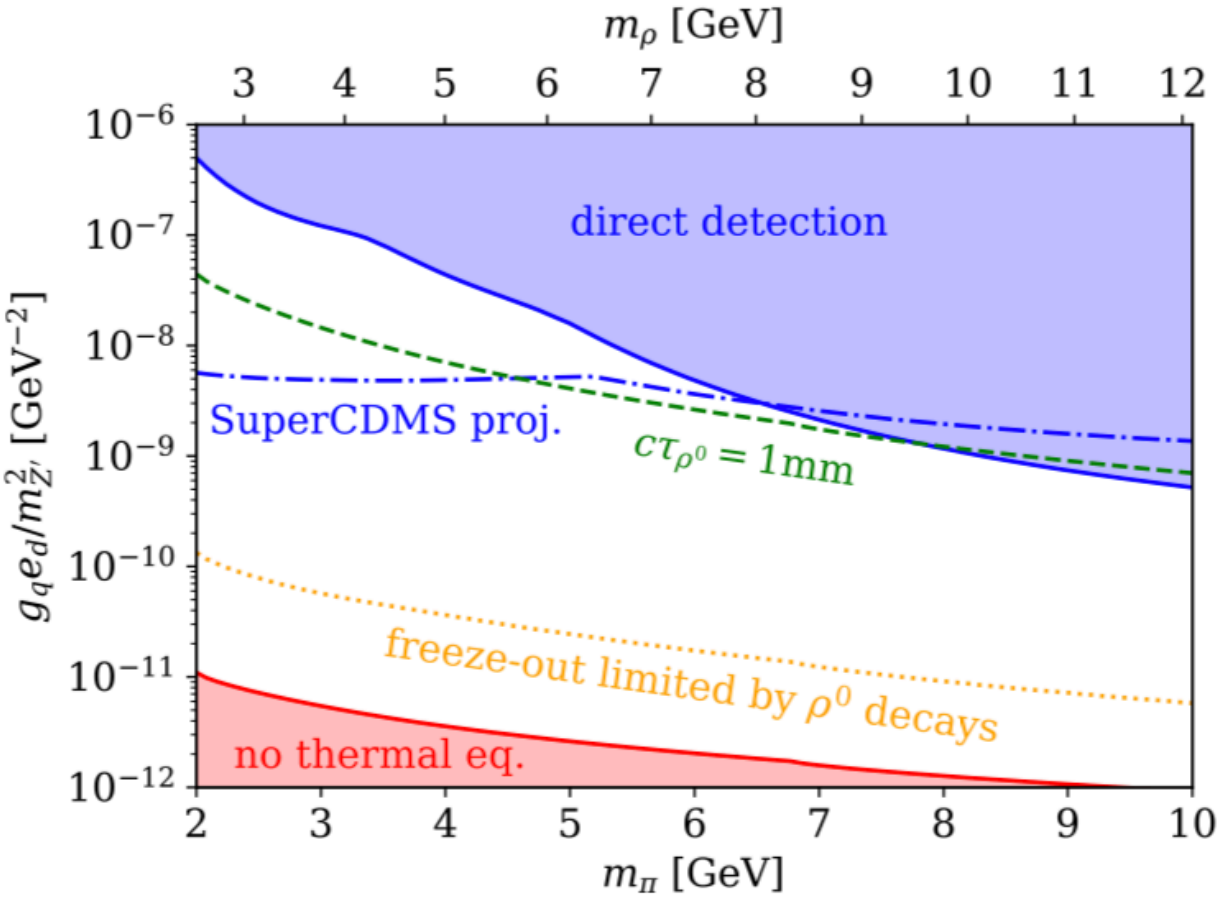
- Identification strategies are necessarily (more or less) model dependent
- The **theoretical prejudice in dark matter searches** is also set by what we can probe with available data
- You always need some sort of signature of your model!

Conrad & Reimer, Nature Physics 13 (2017) 224-231

Direct detection



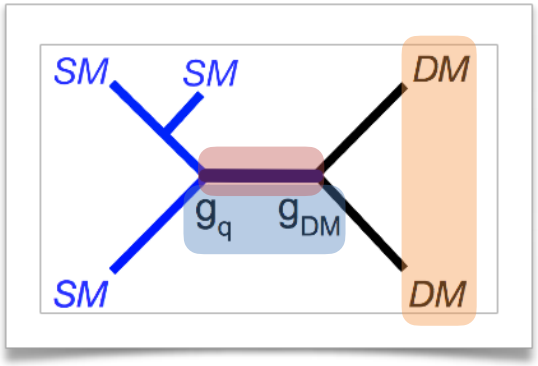
$$\sigma^{\mathrm{SI}} \propto \frac{e_d^2 g_q^2}{m_{Z'}^4}$$

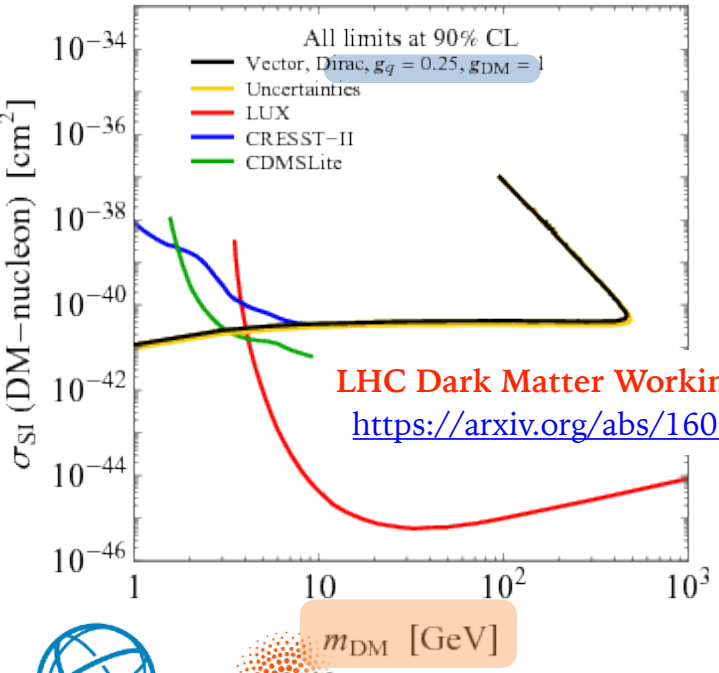


Combination of CRESST-III, CDMSLite, PICO-60, PandaX and XENON1T

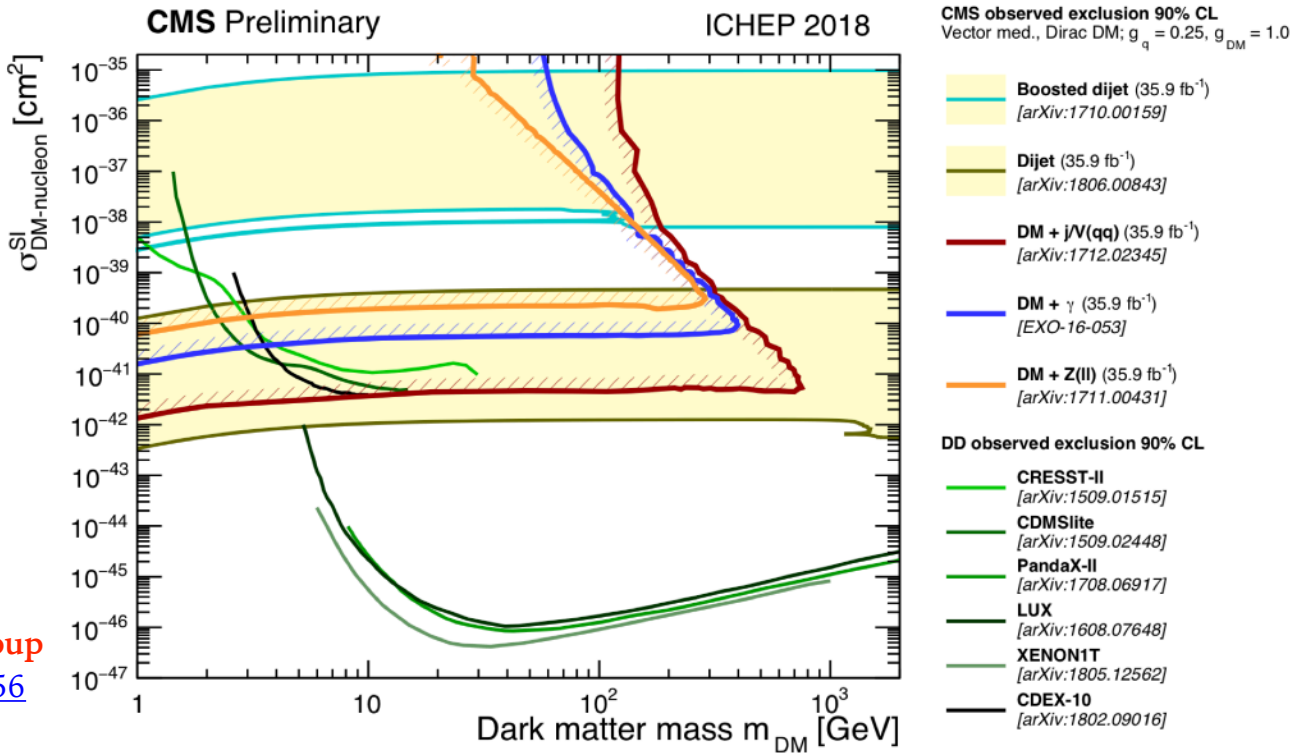
Complementarity of DM experiments

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



CMS Dark Matter Summary Plots for ICHEP 2018

For more thought on upper bounds to collider sensitivity:
G. Landsberg's contribution, DMWG meeting June 2017
https://arxiv.org/abs/1810.07705

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European Research Council
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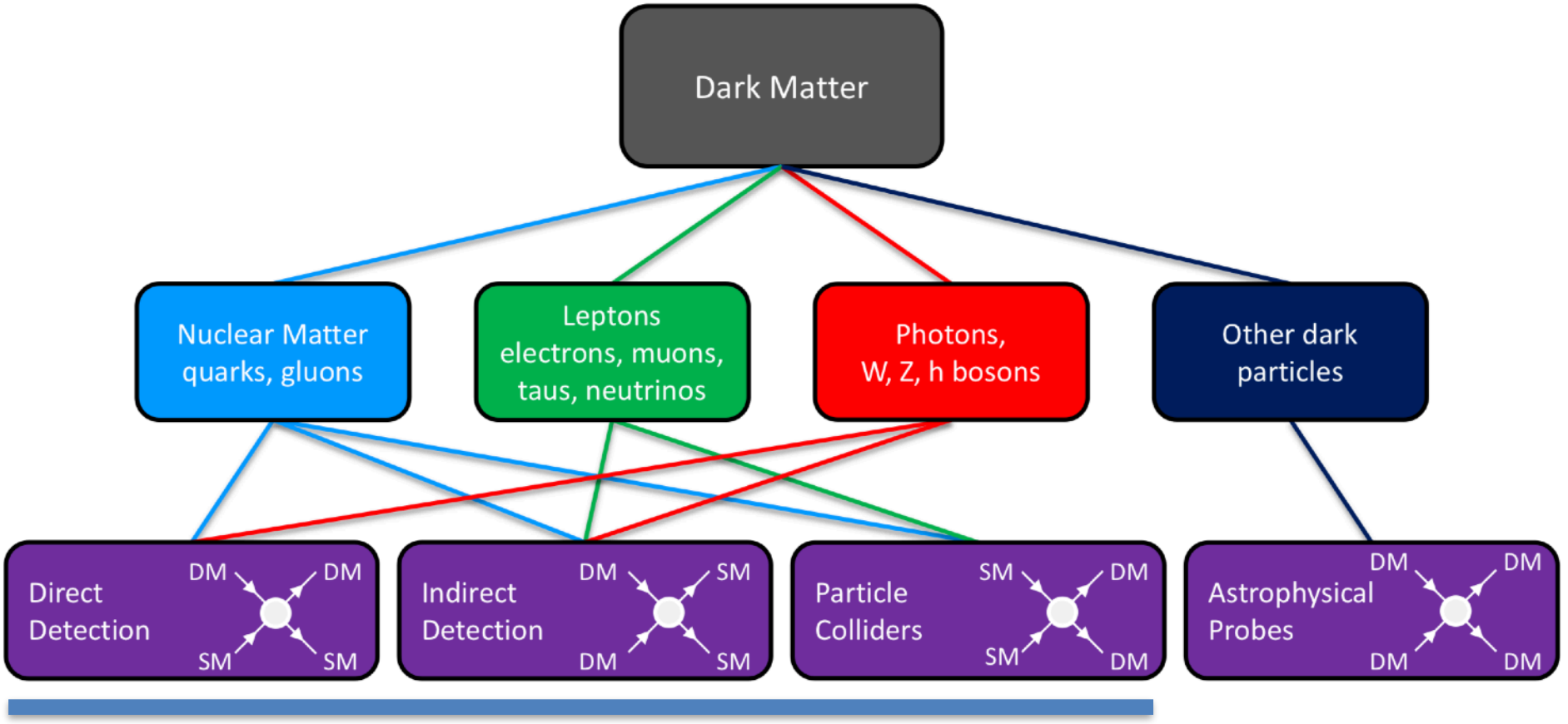
Horizon 2020 European Union funding for Research & Innovation

What about complementarity with astrophysics?

Dark Matter in the Coming Decade: Complementary Paths to Discovery and Beyond + many more



Complementarity focus so far

Possible inputs to LHC DM searches: constraints on DM particle candidates from impact on astrophysical observables

Aside: the importance of triggering

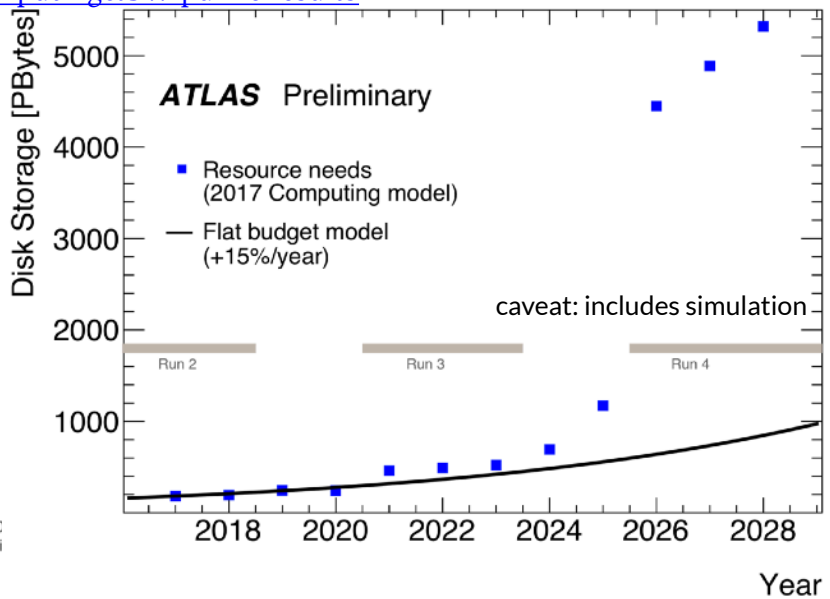
Many different theories can explain DM, none favored by data yet
Very different detector signatures
- signals can be buried in high-rate backgrounds or rare but unusual

***Look everywhere effect*:** we need to make sure we record the events first
→ software/hardware **innovations needed**

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**

Computing&SW public results



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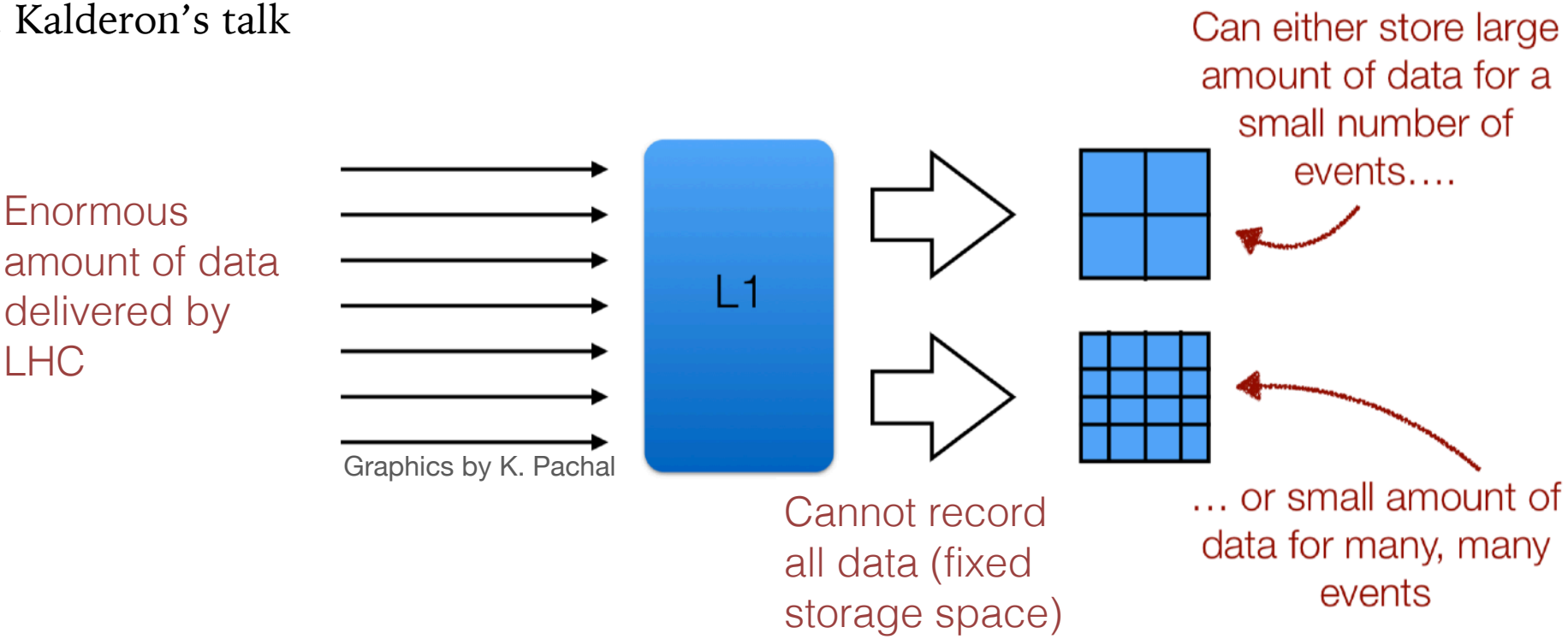
*Real-time** analysis across the ring

W. Kalderon's talk

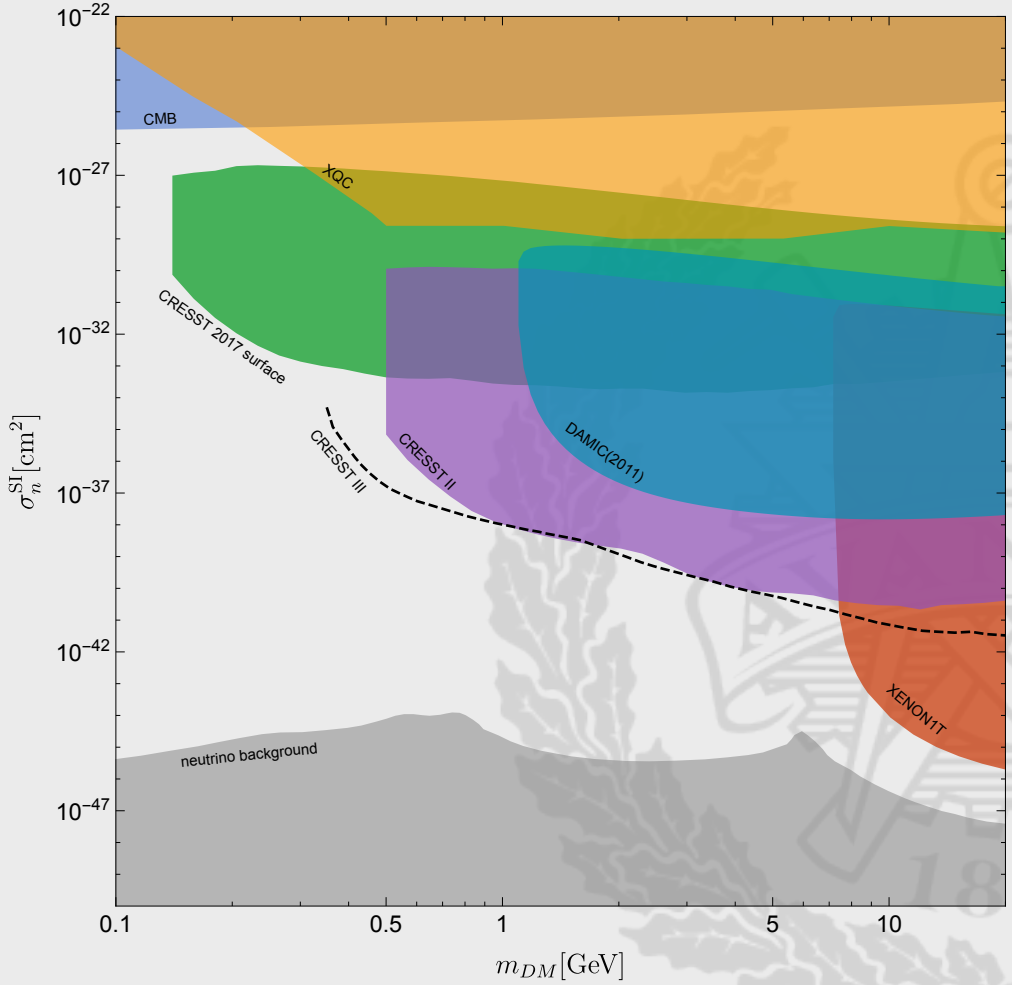


- Current paradigm: first record data, then analyze it
- Data Scouting (CMS) / Turbo Stream (LHCb) / Trigger-Level Analysis (ATLAS): do **object reconstruction in real-time** (* definitions vary)
  - Only save **refined information**
  - **much** smaller in size than full information → can record more

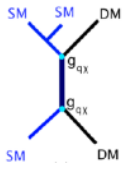
See W. Kalderon's talk

Timon Emken's talk

Constraints on the DM-nucleon scattering cross-section

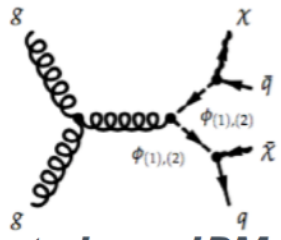


Colored scalar (t-channel) models

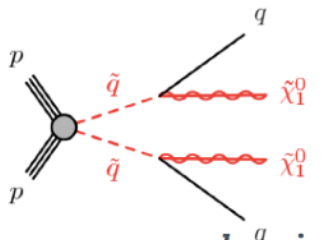


Colored scalar mediators: **less popular yet viable** simplified models

No dijet resonance signatures, sensitivity to jet+MET searches



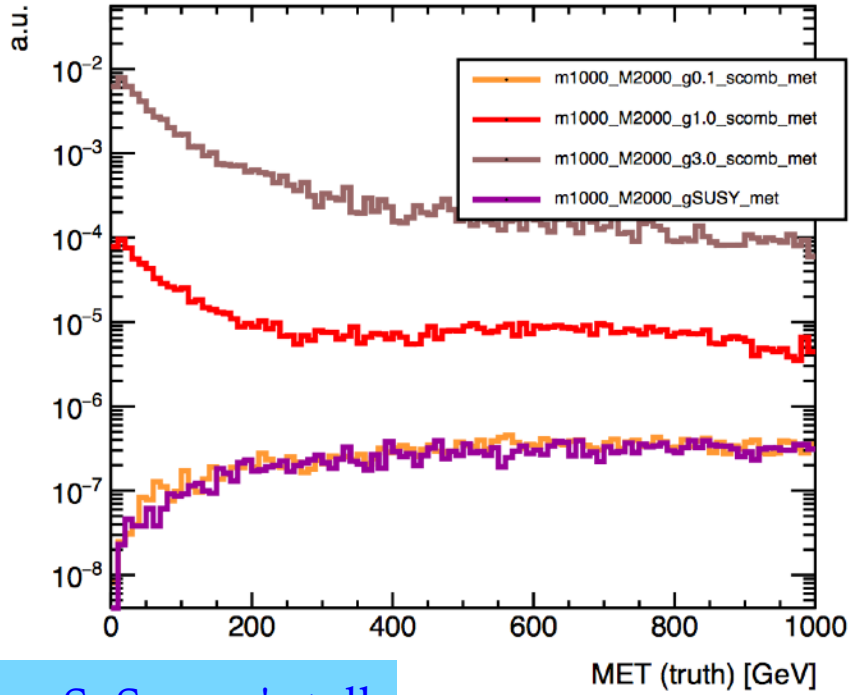
t-channel DM production

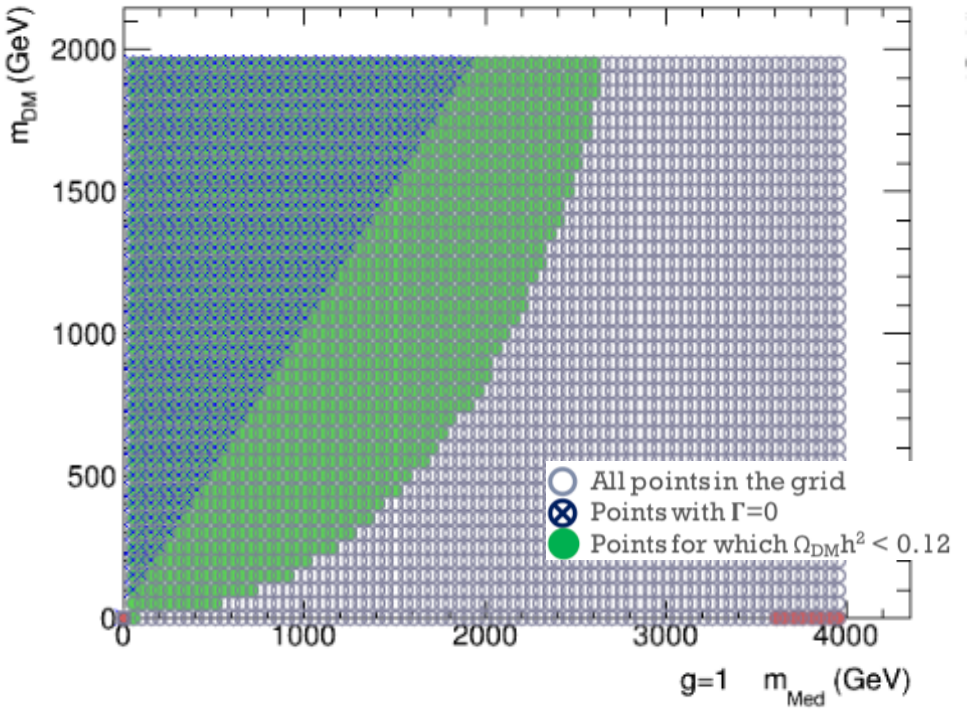


mssm squark pair production

Relic density:

- "Compatible" region depends on coupling/mass of DM mediator, but still viable in many parameter scenarios





M. G. Ratti, M. McDonald, DMWG meeting June 2016

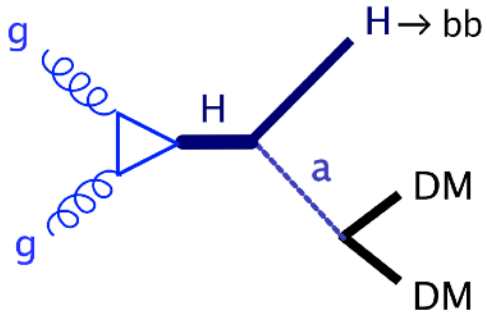
See also references from A. DiFranzo's talk in DMWG meeting Sep 2016

See S. Sevova's talk

More complex models: pseudo/scalars

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

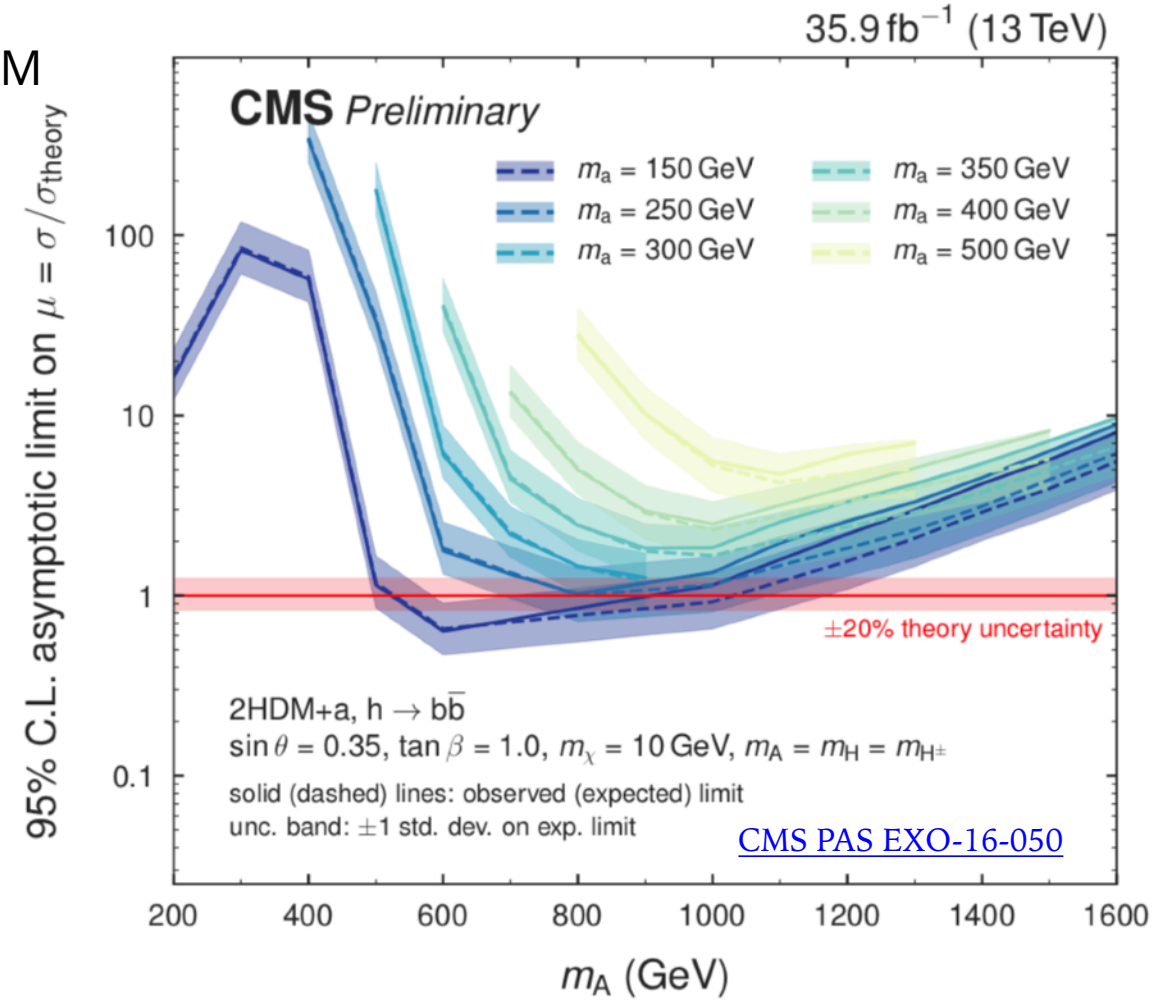
Example: pseudoscalar interacting with DM in a Two (2)-Higgs Doublet Model



Dark Matter Working Group
https://arxiv.org/abs/1810.09420

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

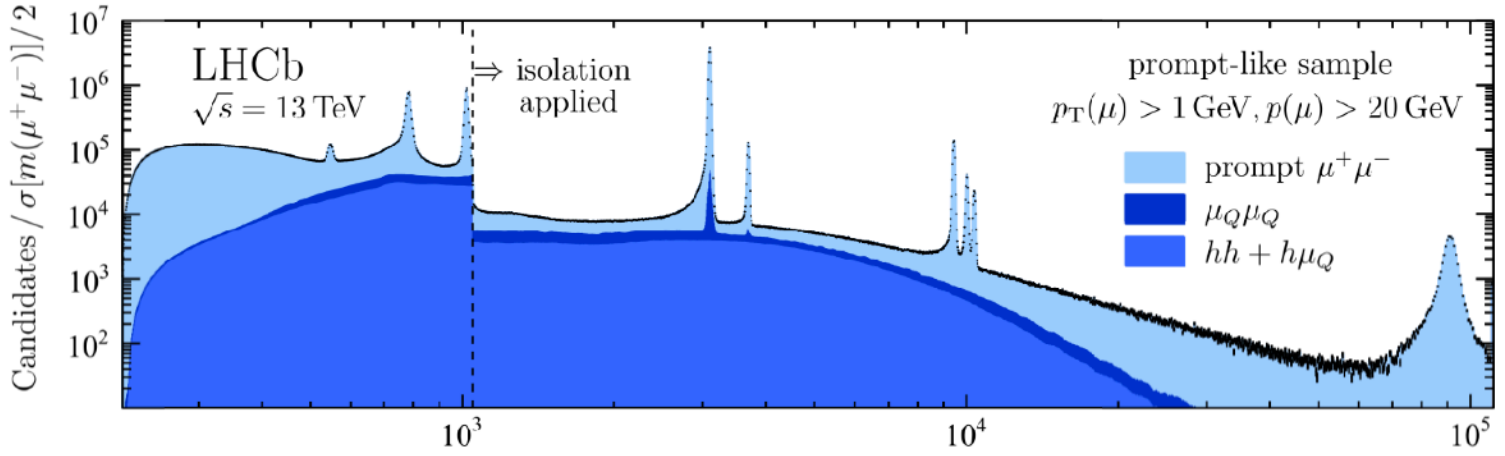
LHC dataset starting to be sensitive to this class of processes

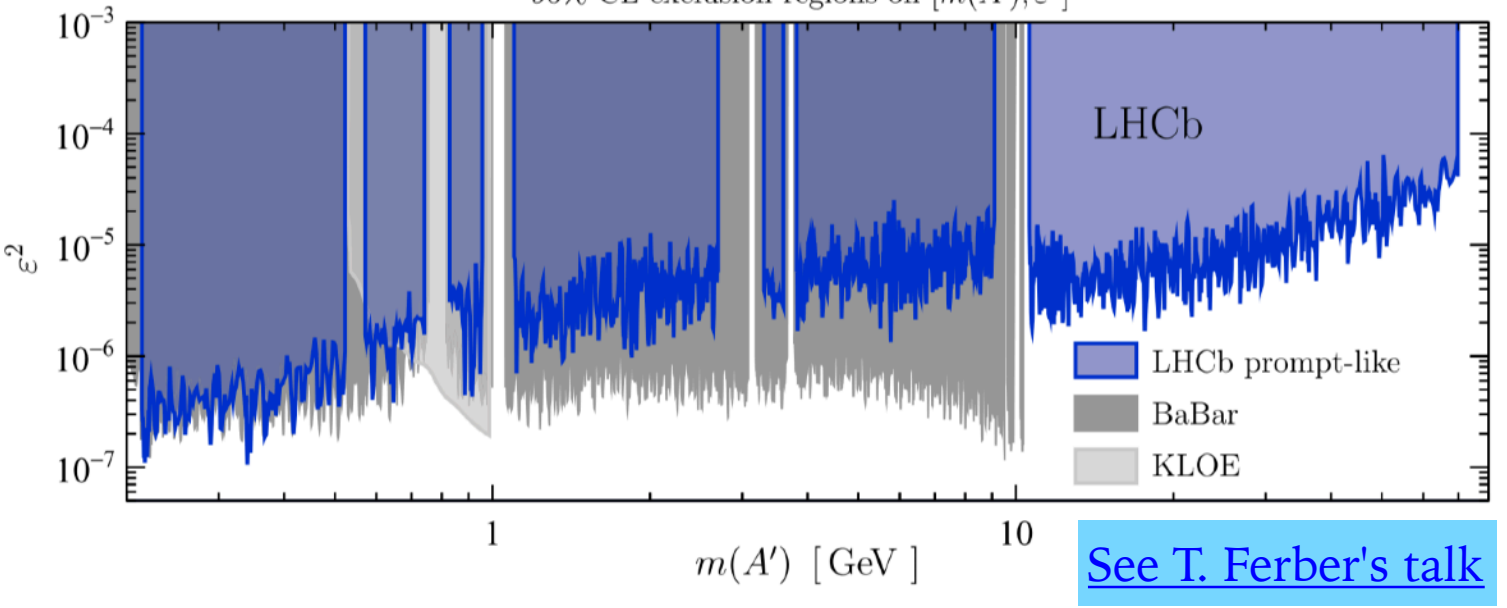


See A. Cortes Gonzalez's talk

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





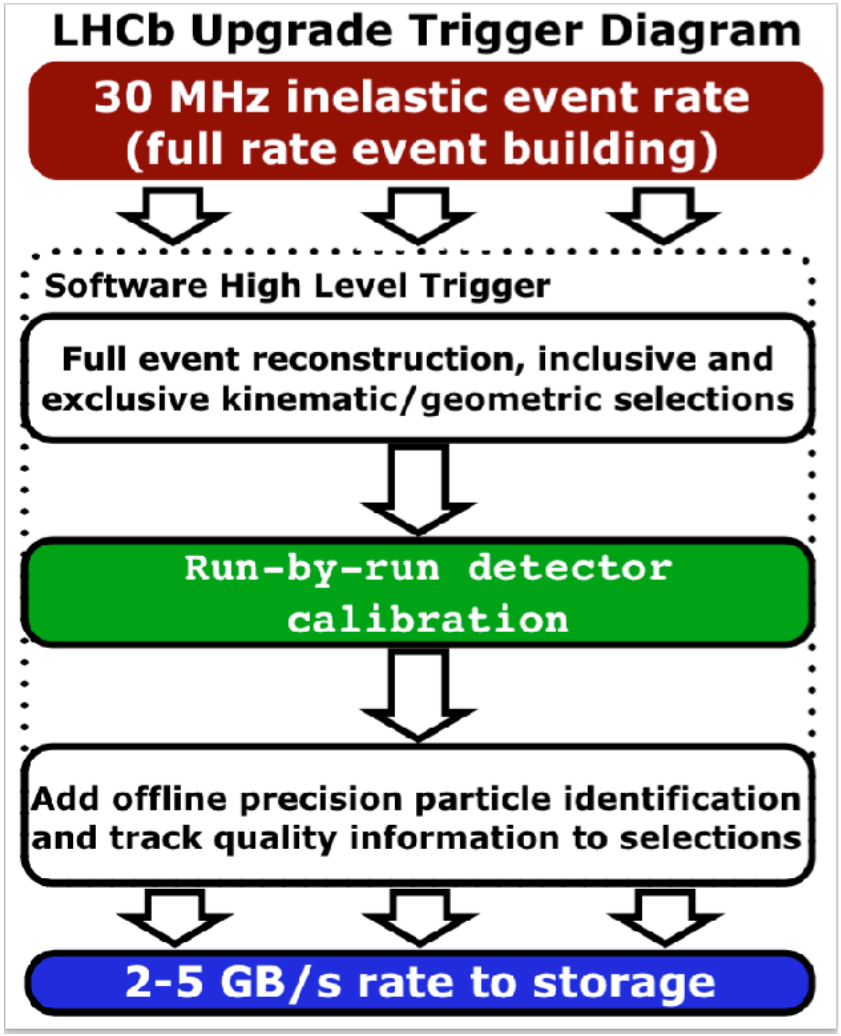
lower rate of events

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

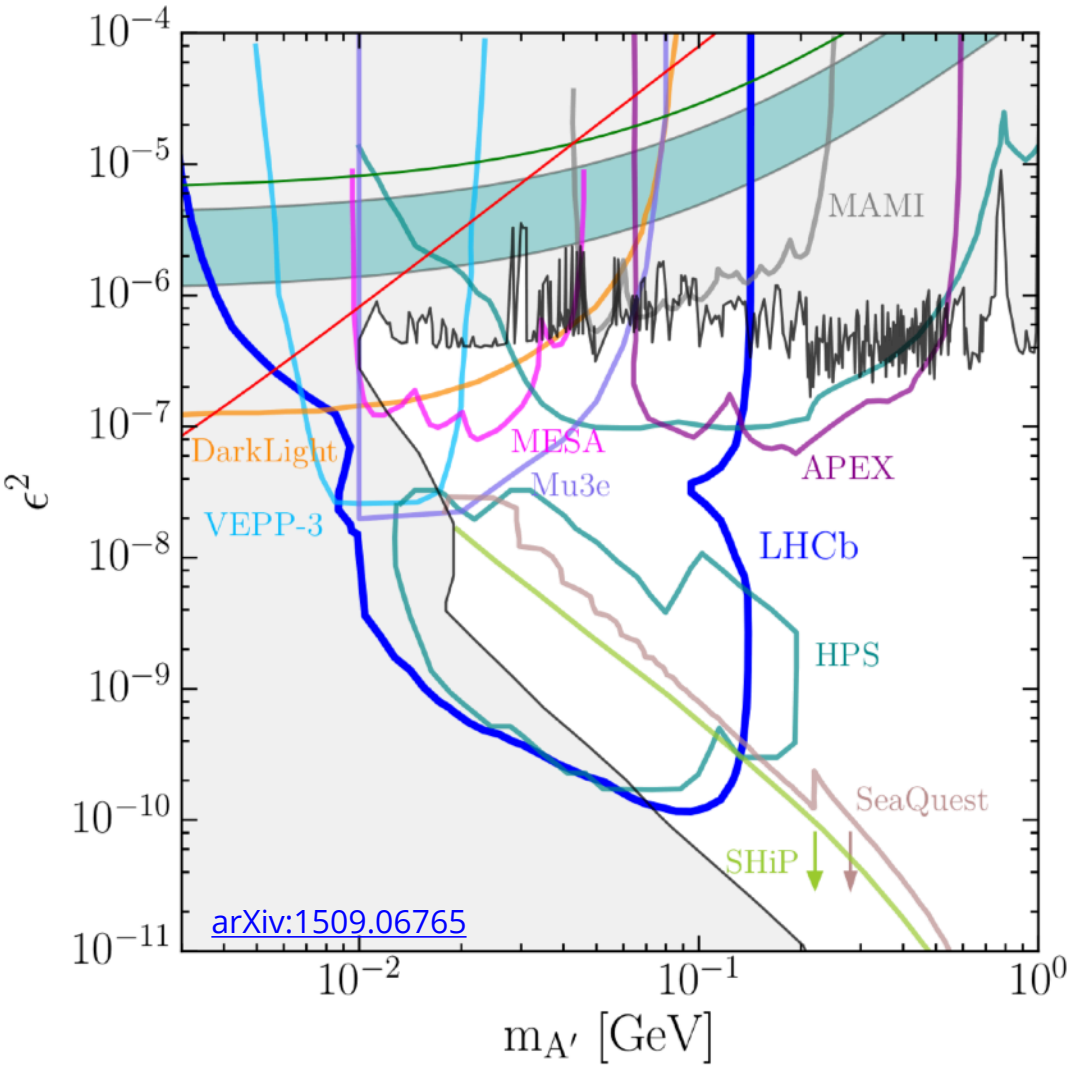
[See T. Ferber's talk]

LHCb in the future (Run-3)

"Triggerless" readout



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



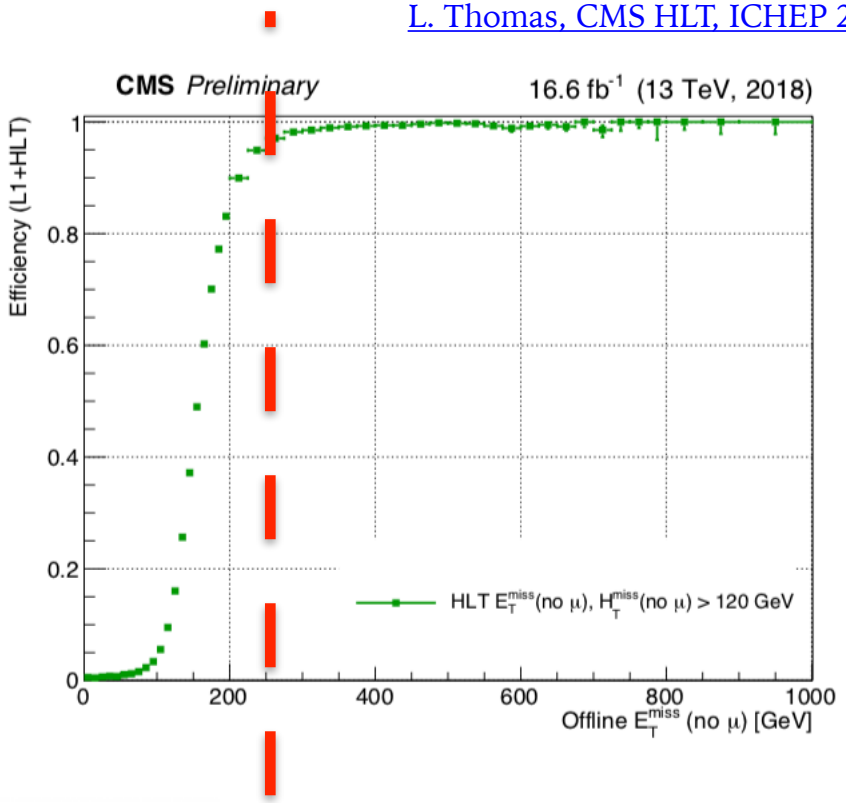
See T. Ferber's talk

Colliders can still do more (with Run-2 data)

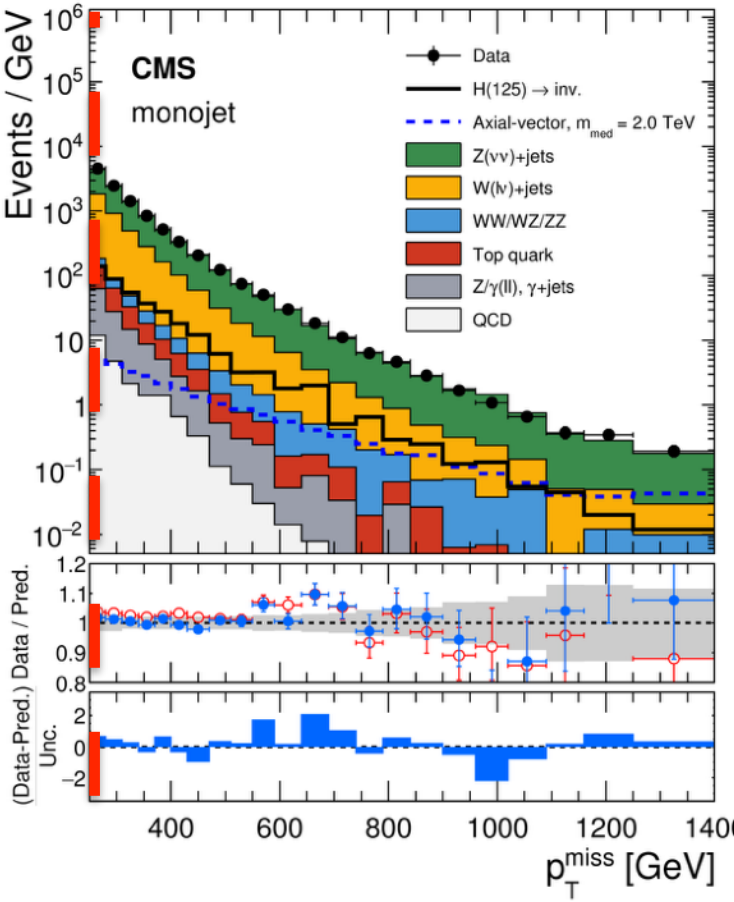
Take advantage of a (relatively) low pile-up dataset

- Number of simultaneous p-p interactions will only increase in the future
  - So will trigger thresholds for recording events
  - Many interesting models have low pT/MET -> **will we lose sensitivity?**

L. Thomas, CMS HLT, ICHEP 2018



Phys. Rev. D 97 (2018) 092005 35.9 fb^{-1} (13 TeV)



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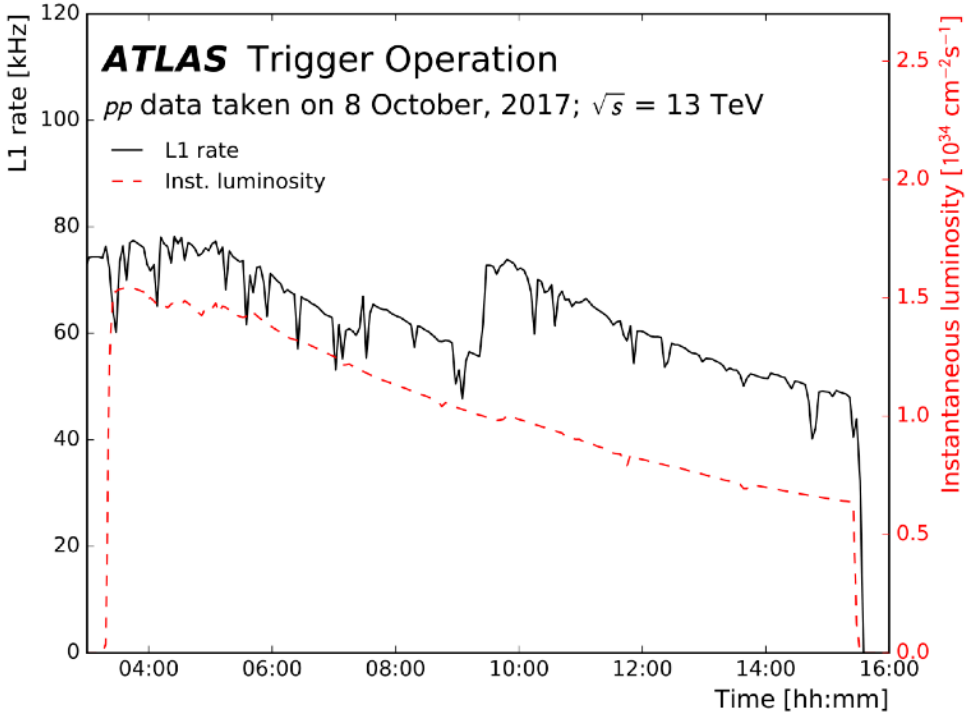
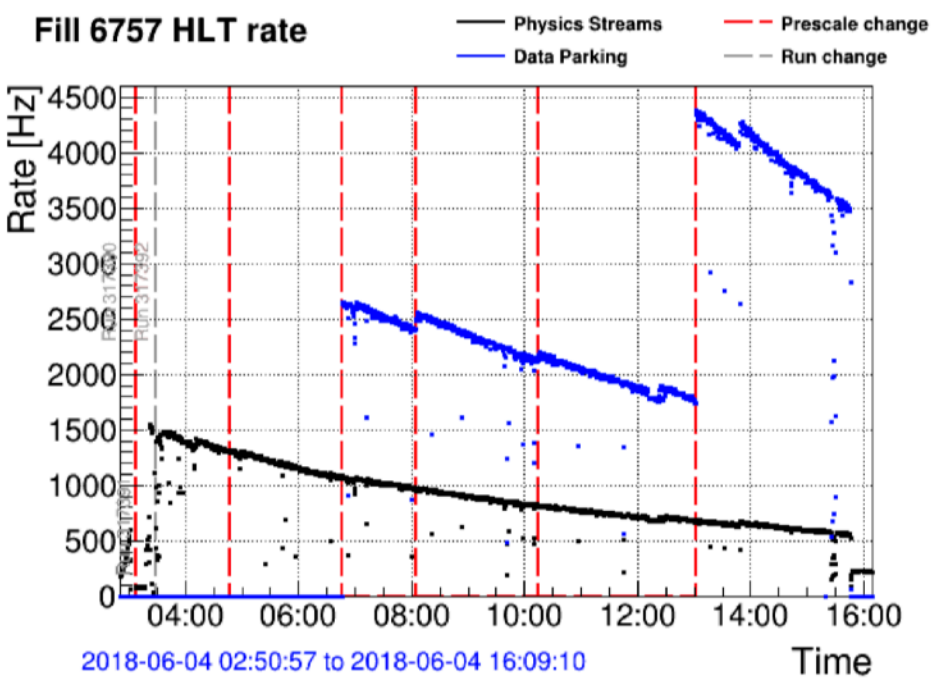
- 1) In addition to searches in VBF, object + (other) ISR, **make the most of current data**
  - e.g. trigger-level-type analysis (trigger objects used for analysis)
  - new physics could still be buried in **delayed / parked streams** (not processed promptly)

ATLAS Trigger Operation Public Results



L. Thomas, CMS HLT, ICHEP 2018



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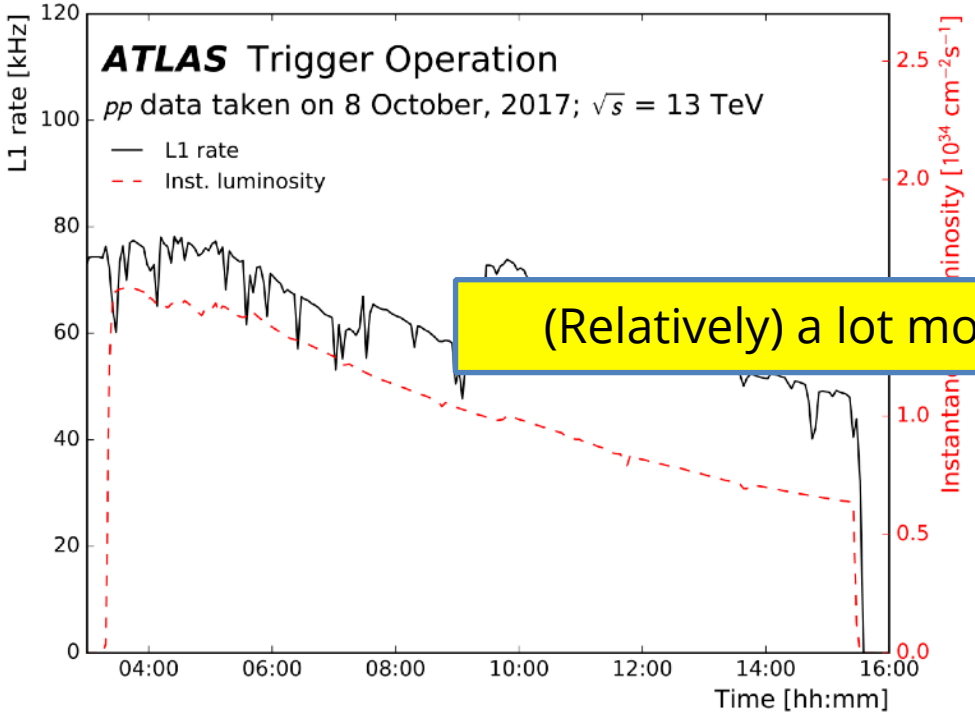
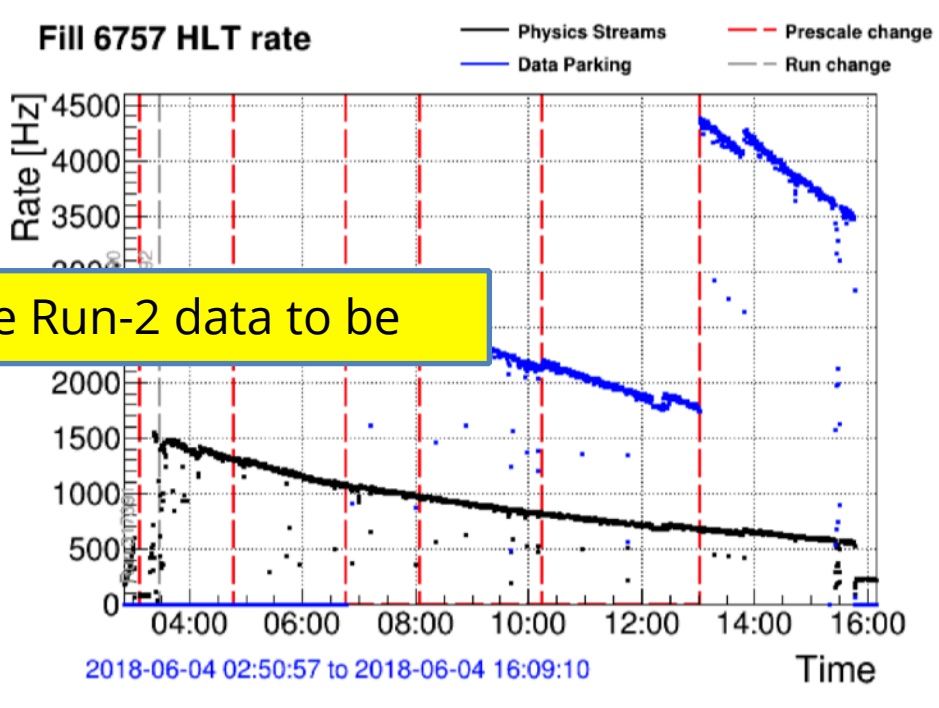


L. Thomas, CMS HLT, ICHEP 2018



(Relatively) a lot more Run-2 data to be

Colliders can still do more (with Run-2 data)

Take advantage of a (relatively) low pile-up dataset

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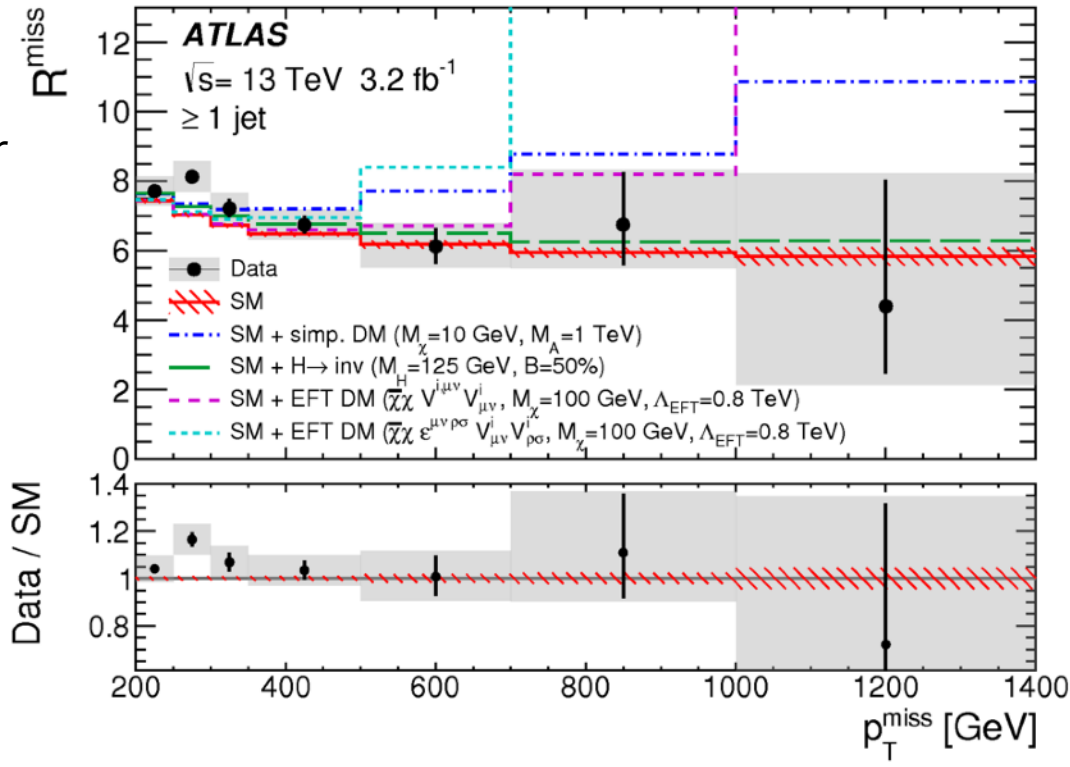
  - e.g. trigger-level-type analysis (trigger objects used for analysis)
  - new physics could still be buried in **delayed / parked streams** (not processed promptly)

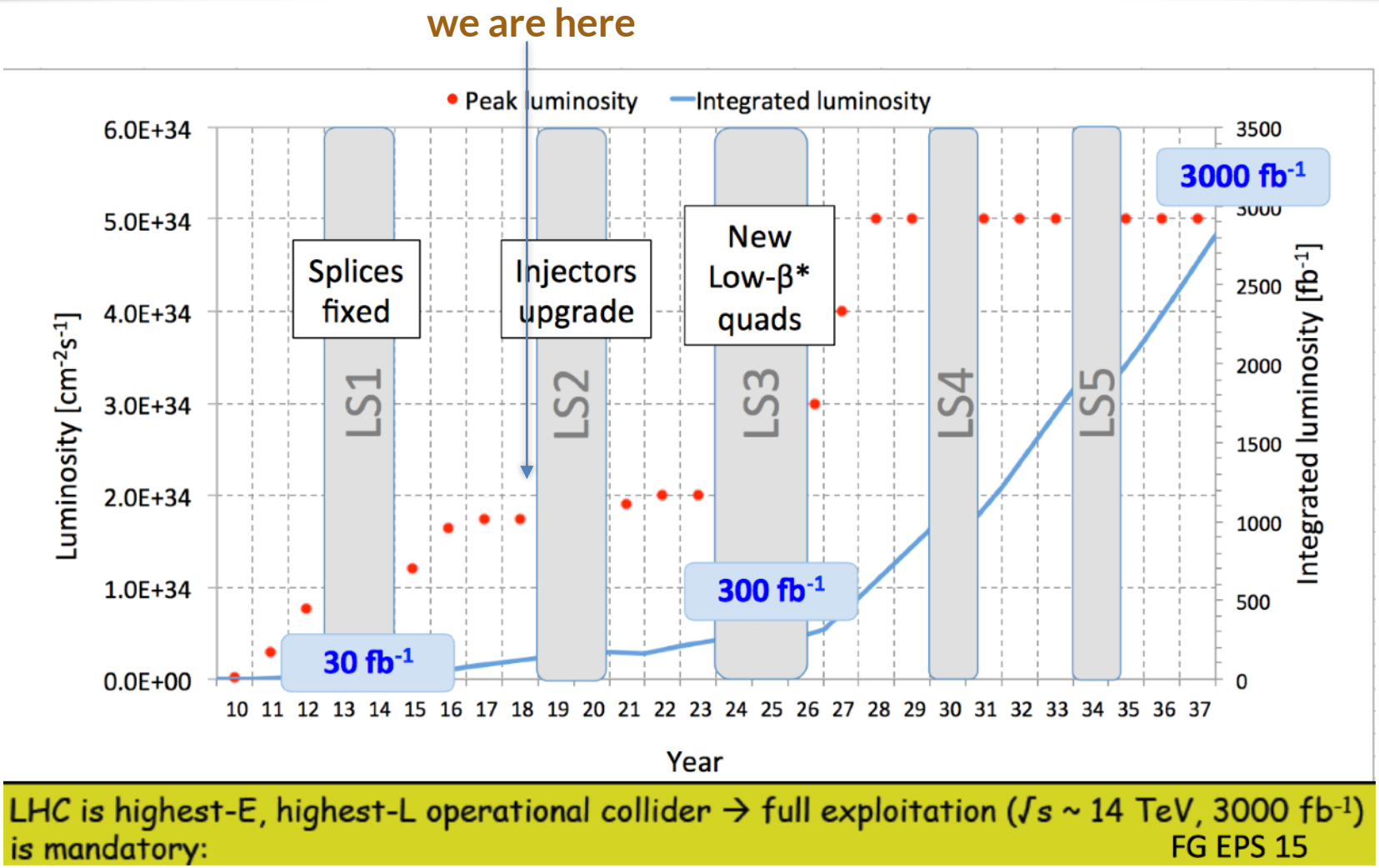
- 2) Make **analyses reproducible** and easy to run so lower-pileup-datasets can be used later
  - Effort on **containerization** (e.g. Docker)
  - Use **standard candles** (Z boson) to search for non-SM production, **unfold** detector effects

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



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

S.Bertolucci, LHC status, LHCP 2015 St Petersburg[31]

Collider experiments with upgraded hardware

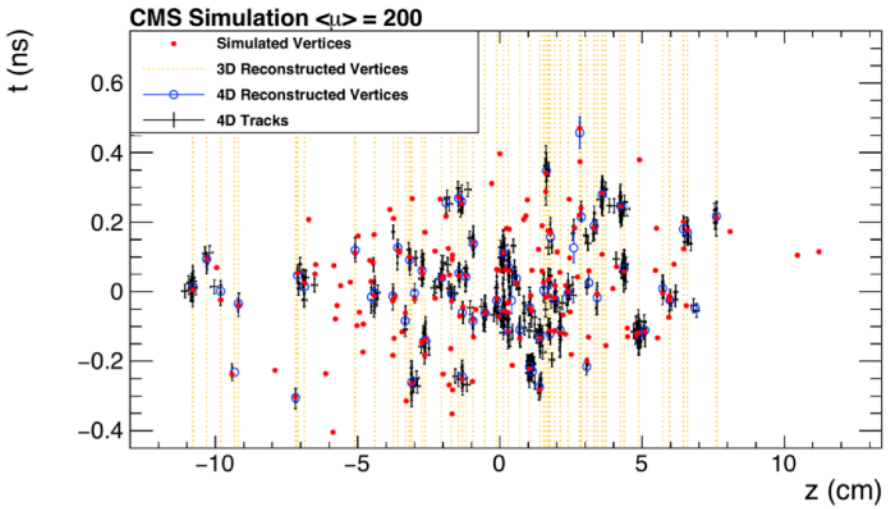
Examples of upgrades expected for Run-3

- ATLAS: Fast TracKer (FTK)
- LHCb: 40 MHz data taking (new tracking) + software trigger

Run-4 (HL-LHC) will bring new, more performant detector components (to sustain performance in high pile-up), as well as 10x recording rates.

- New tracking detectors for ATLAS, CMS
- Hardware track triggers for ATLAS, CMS
- **Timing detectors**
  - CMS: full barrel, ATLAS: endcap
  - Examples of improvements in the following slides

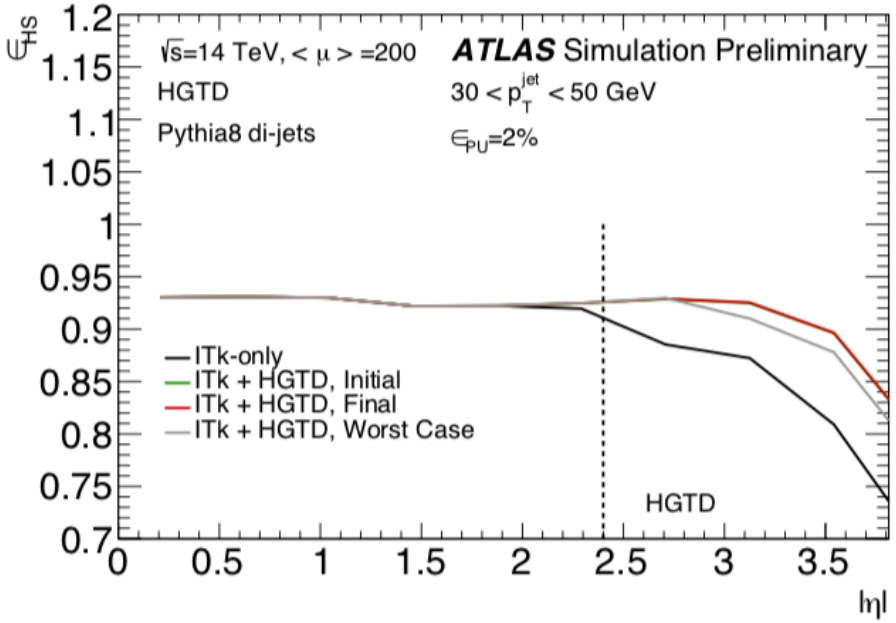
CMS Timing Detector (MTD) technical proposal



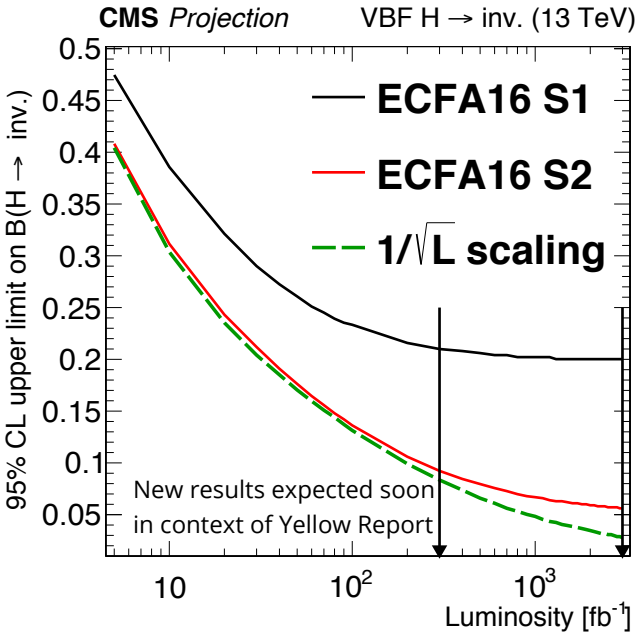
Example of improvements with timing upgrades

Improvements to hard scatter efficiency in forward region:

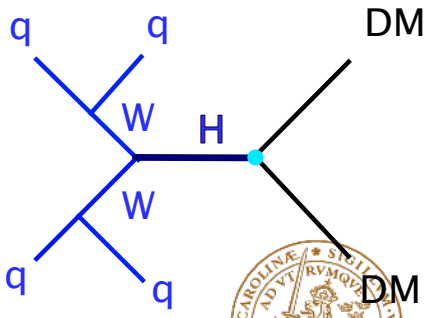
ATLAS HGTD Technical Proposal



CMS-PAS-FTR-16-002



Relevant for **VBF Higgs to invisible searches**



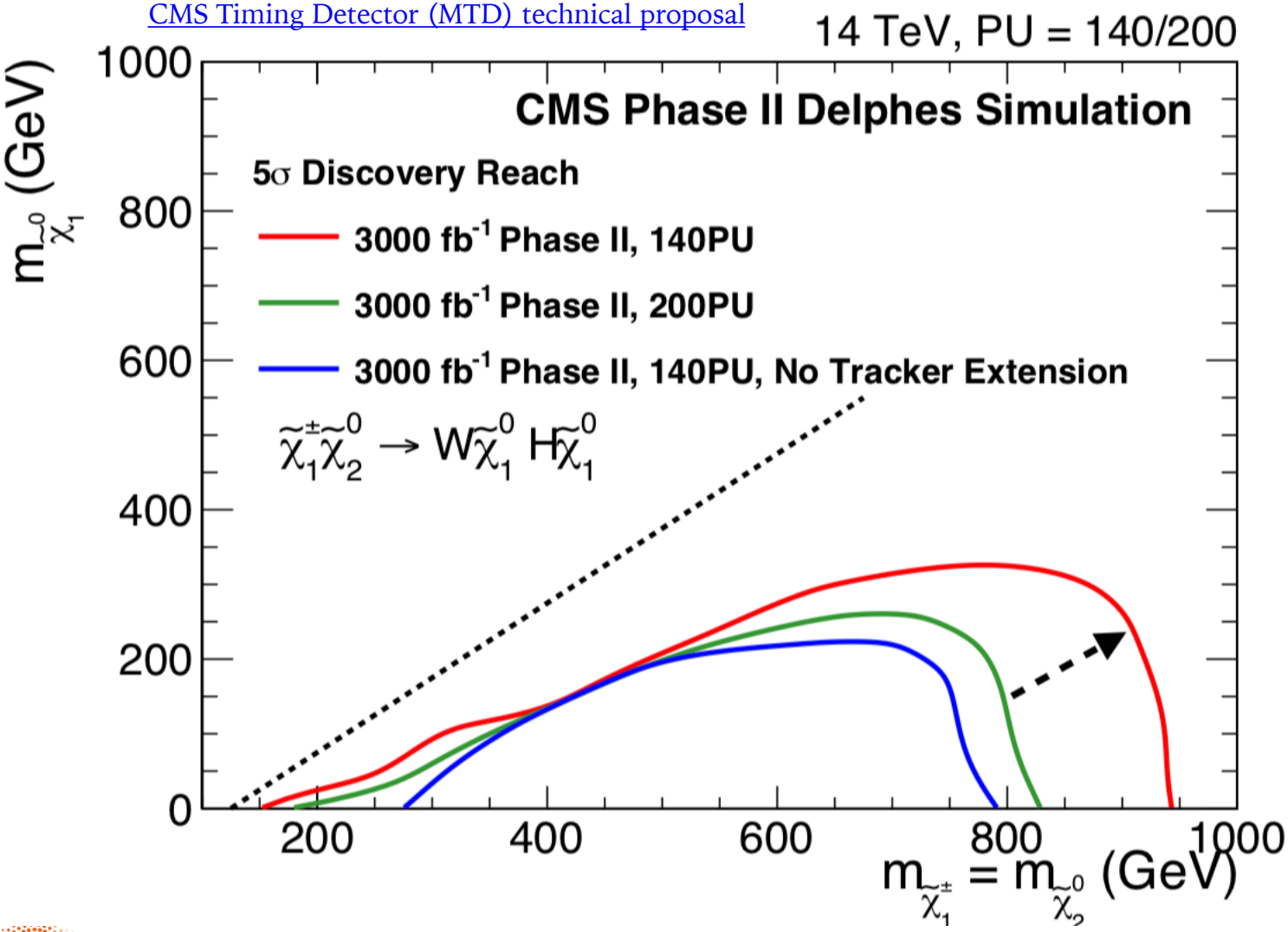
Additionally: HGTD can be used as a luminometer

Luminosity uncertainty mostly relevant for measurements,
but also not negligible for searches

Prospects for SUSY EW searches

Barrel timing information restores sensitivity equivalent to 140 PU

CMS Timing Detector (MTD) technical proposal



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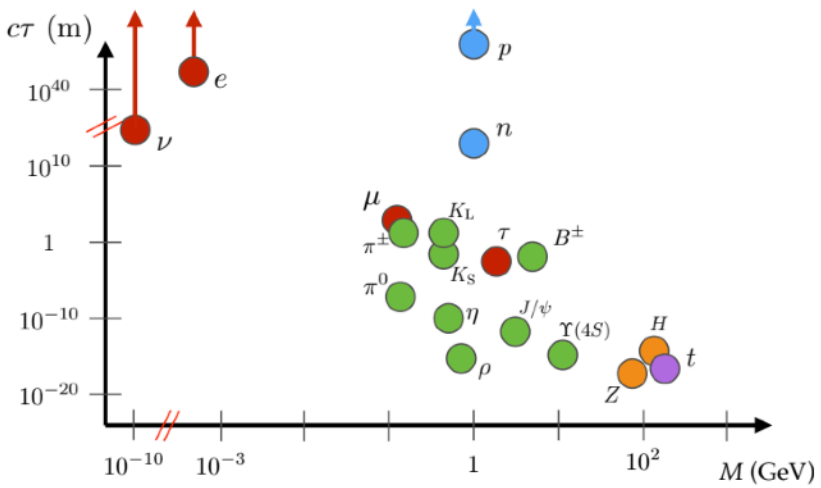
What can be done with timing detector (barrel)

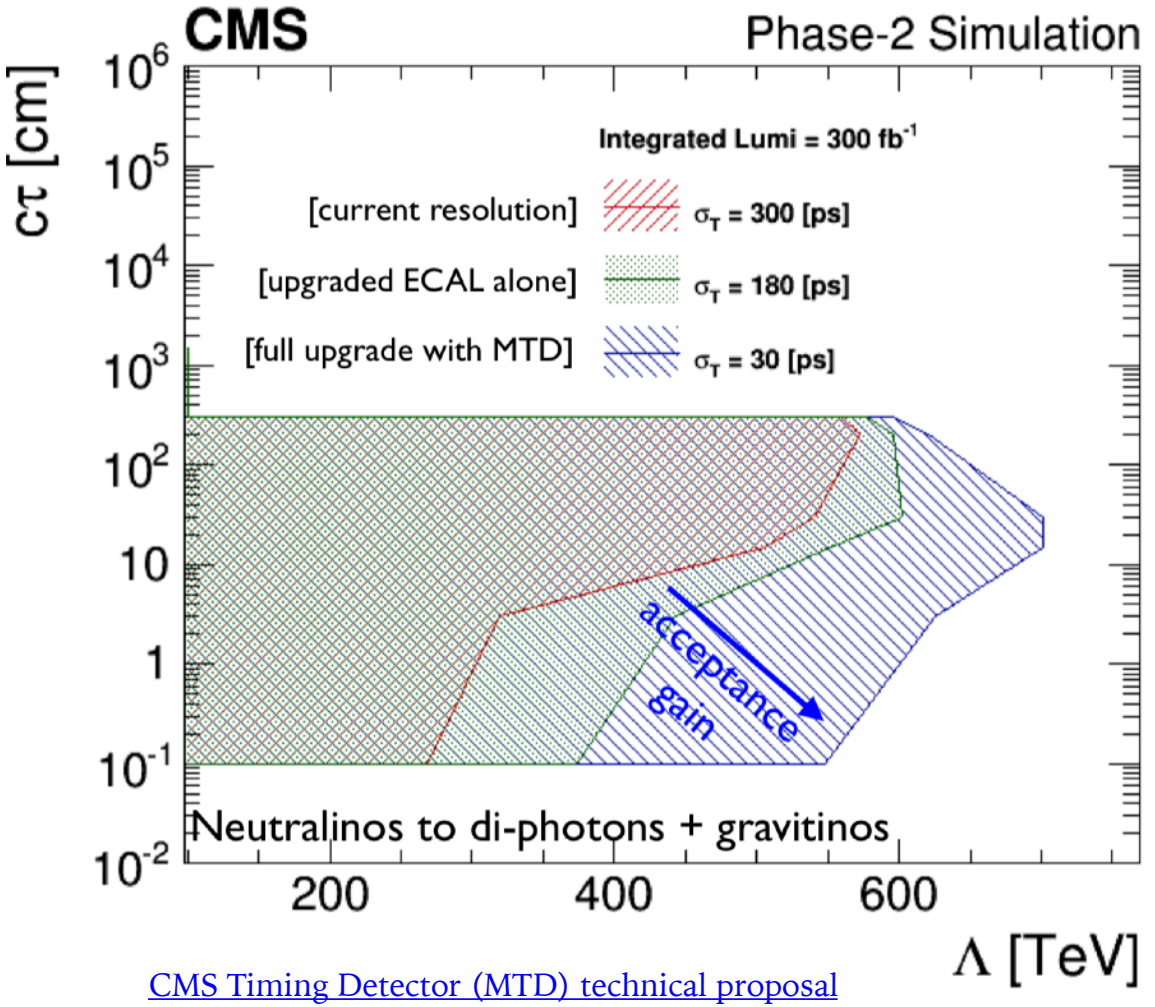
Measurement of **decay time** becomes possible

More LLP acceptance can translate into sensitivity to different models

Known example: range of masses and lifetimes of SM particles



The LHC LLP Community,
Searches for long-lived particles beyond the Standard Model at the Large Hadron Collider



CMS Timing Detector (MTD) technical proposal

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