IFAE Colloquium, 28 April 2026

# The ATLAS Exotics programme

## How we are organising the search for new physics for Run 3 and beyond

Louie Corpe (Clermont-Ferrand)

ATLAS
CLERMONT-FERRAND

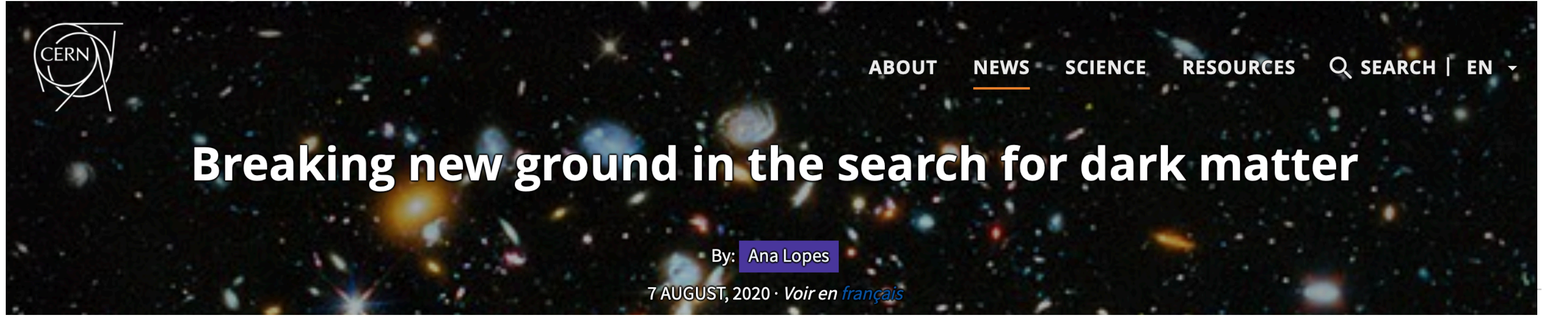


ATLAS
EXOTICS GROUP

# About this talk

- I will **not** use this time to make a laundry list of our recent results.
  - You can see great summaries from EPS, Lepton-Photon and SEARCH 2025, and Moriond EW/QCD 2026.
  - (I will however show a couple of recent examples of our searches)
- I thought I would instead try to make this talk different from what you usually get at conferences...
- ....instead give you a **flavour of our thinking in ATLAS** as we organise our Run-3 (and beyond) search programme.
- Many opinions expressed which represent my own views, and not necessarily those of the ATLAS collaboration (ie Aurelio may disagree with me ;) )

# What is the ATLAS plan for searches for the rest of the LHC lifetime?




“We will leave no stone unturned, no matter how big or small and how long it will take us,” says Pani. ”

# What is the ATLAS plan for searches for the rest of the LHC lifetime?

## Leave no stone unturned

- Run-2 searches starting to converge, early analyses with full data:
  - dijets, dileptons, lepton+MET, di-bosons, di-Higgs, multileptons…
- Many others will follow soon

## What can we do with the LHC data?

*probe the Standard Model - and search for new phenomena beyond it!*

- Why should we search for new physics beyond the Standard Model?
  - we *must* leave no stone unturned in data
  - … and we have good motivations to think that new physics exists
    - mass hierarchy of the fermions
    - matter/anti-matter asymmetry
    - dark matter
    - …

## No Stone Unturned: A Comprehensive Approach to New Physics Searches at Colliders

## Why Search for Long-Lived Exotica?

**Why not?**

- No sign of new physics yet! → **We should leave no stone unturned**
- A new massive, long-lived particle would be a clear sign of new physics
- **But challenging (exciting)!** We need to push our detectors, triggers, reconstruction, and analysis techniques to the limit

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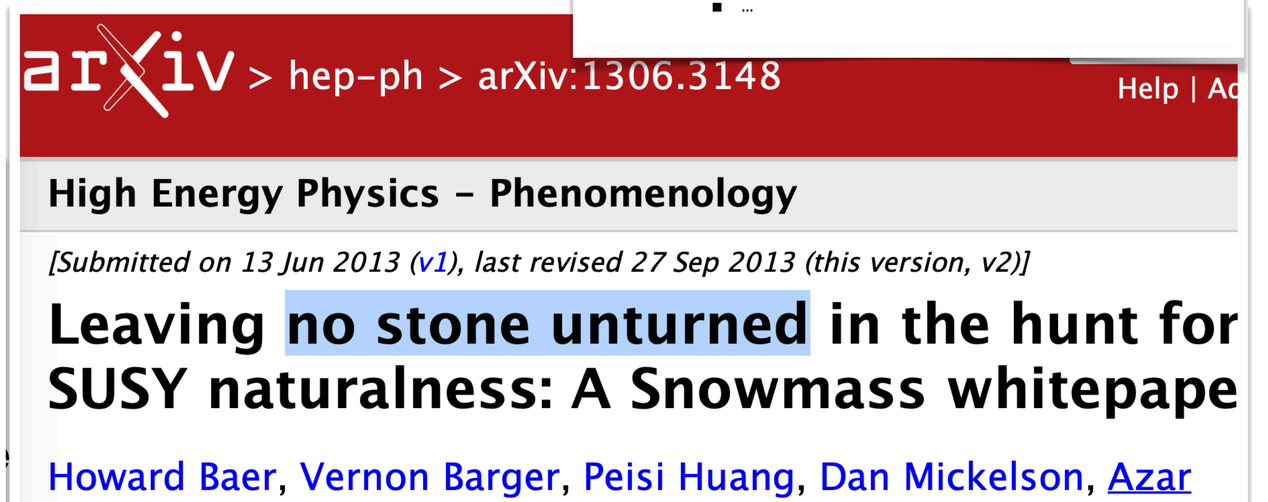


# What is the ATLAS plan for searches for the rest of the LHC lifetime?

- Just saying "Leave no stone unturned" is **not good enough**
  - Intellectually light-weight
  - Impossible: ~infinitely many models and final states
- What we need is a **planned**, and well thought-out **strategy**
- It's a focus of the current BSM search convenership in ATLAS to make this strategy a concrete reality more than just vague ideas.

# What is the ATLAS plan for searches for the rest of the LHC lifetime?

# It's time to plan the Endgame of the LHC

In chess, the **endgame** refers to the **final phase** of the game, when most of the pieces have been used up (**limited resources and time** remaining), and one player must eventually win.

Having a **clear endgame strategy** is essential.

So let's take stock of the state of the board

# Let's take stock of the board

# Boundary conditions for a search programme

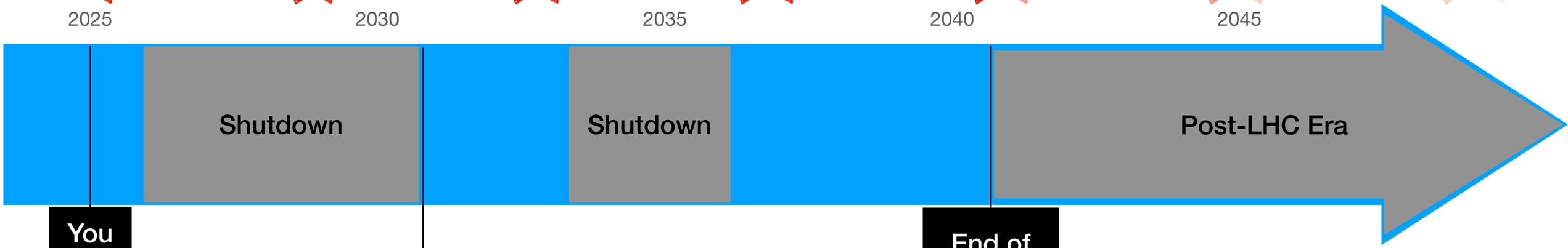
| Time | Resources | Objectives |
| --- | --- | --- |
| | | |

# Time: the LHC will not last forever

Typical time for a search analysis kickoff-> publication

We have time for at most 5 consecutive analyses on any given topic...

Analyses will continue after end of data taking but with decreasing resources




You are here

40% of ATLAS replaced. New detector and new conditions which will take several years to fully understand

End of HL-LHC data collection

# Boundary conditions for a search programme

**Time: the LHC will not last forever**

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- 1/3 of time during **shutdowns periods**
- 1/3 of time with a **new detector and conditions** we don't fully understand
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**We need to plan the endgame of the LHC today!**

**Resources: People and Tools**

**Objectives:**

# Resources: People

**Population:**
550 + 450 - overlap ~ O(900) active analysts

**Capacity:**
70+60 = O(130) active analyses

**Throughput:**
2x ~18 = O(35) search papers / year

**Inter-operability:**
last year:
35% of analysts participated in upgrade
1/3 of operations tasks by Search analysts



**HMBS**
Higgs, Multi-Boson and SUSY searches

**HLRS**
Higgs & Light Resonances

**EWK SUSY**
Electroweak SUSY production

**HBSM**
Beyond the SM Higgs

**Strong SUSY**
Strong SUSY production

**MBL**
Multi-Boson Lab

**CMBF**
Central Methods & Background Forum

*previously HDBS*

**EXOTICS**
New Physics Beyond the SM signature-based searches

**LPX**
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Long-Lived & Unconventional

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Heavy Quarks & Top

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Combinations, Cross-talk & Summaries

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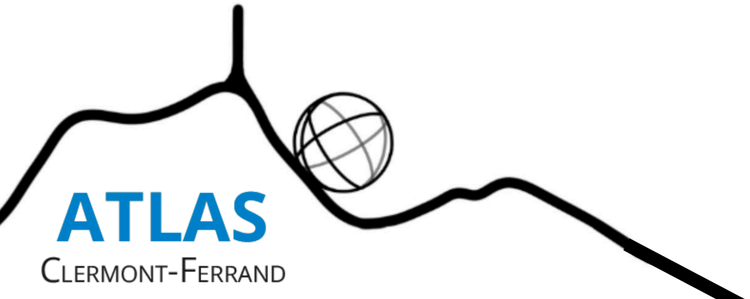
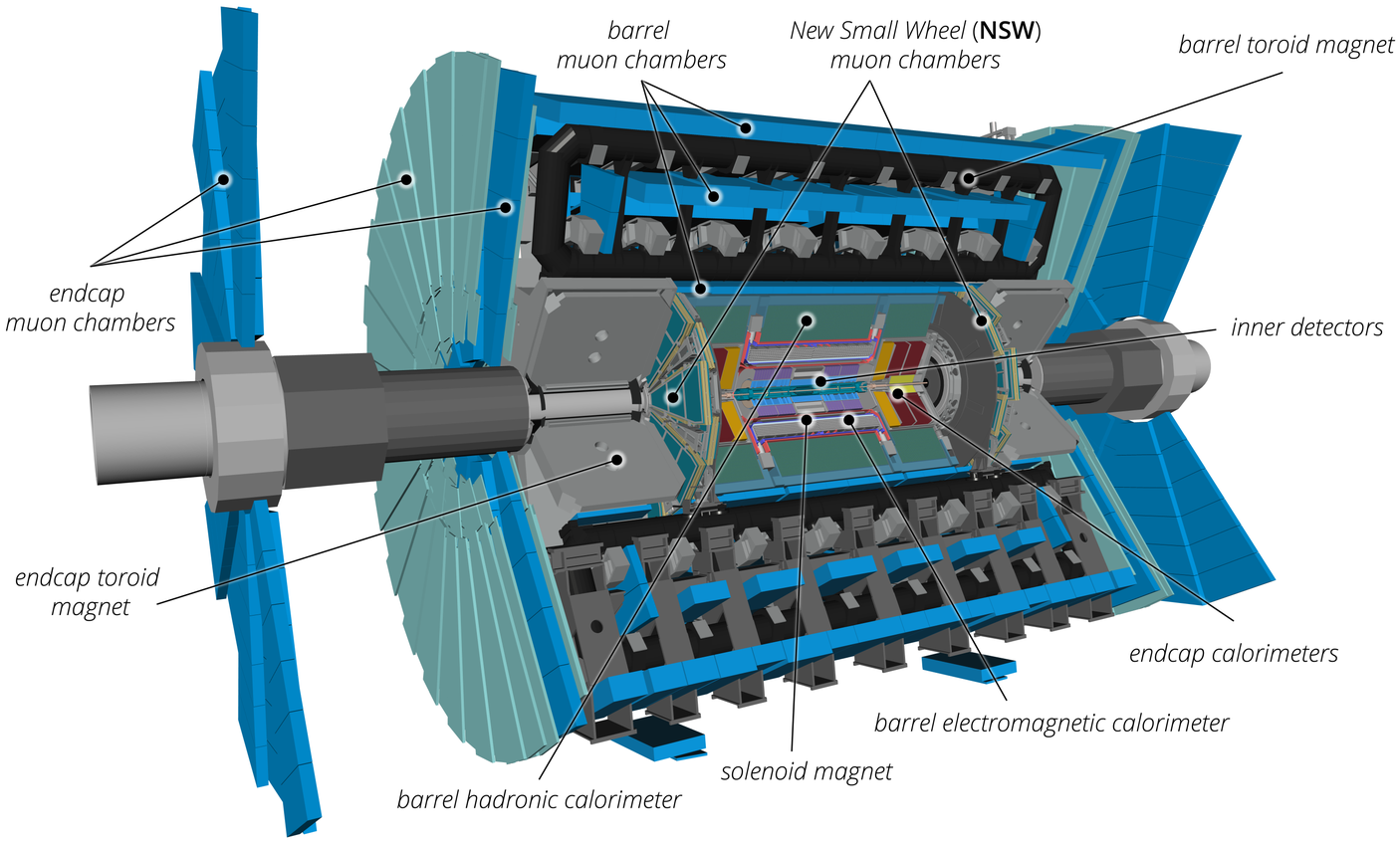




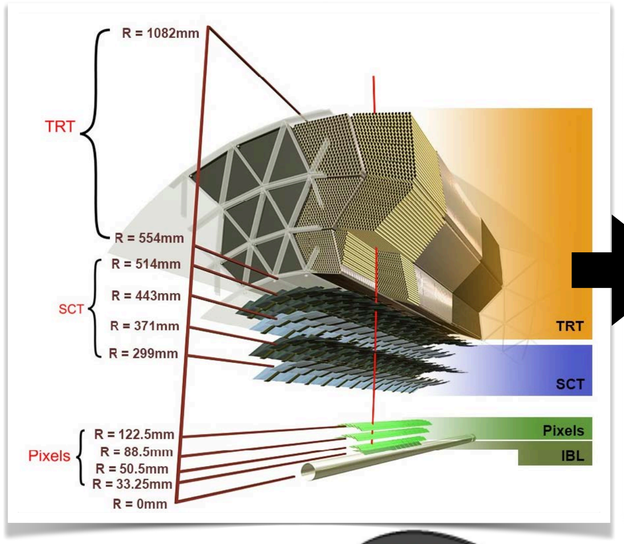

# Resources: Phase 1 Detector

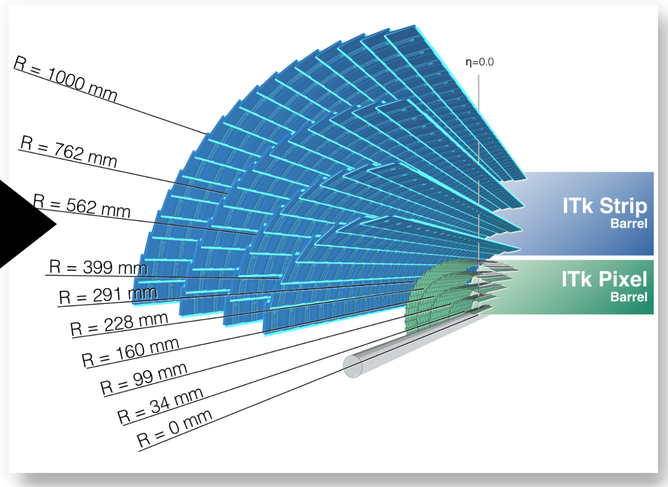
- Will have nearly **0.5/ab of data collected by Run2+3 detector**
- Likely the **best-understood dataset** until mid 2030s!
- Half an attobarn is a ***lot*** of data, (more than we were expecting due to 2026 running extension)
- **Revisit out priors** in terms of analyses are scientifically interesting with Phase 1 data

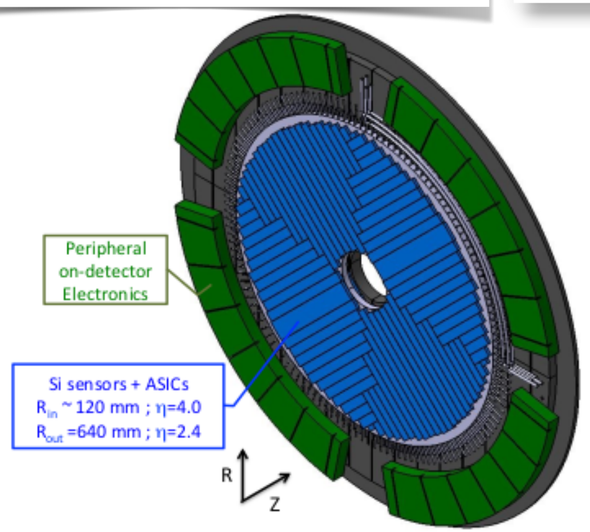


# Resources: Phase 2 Detector

- ITk + HGTD: **existential challenge** for ATLAS community.
- Challenge = opportunity:
  - Silicon tracking to radii of 1m
  - Tracking **+** timing from 2.5 <|η| < 4
  - Exciting possibilities for searches !!!
- To exploit upgrades, search analysts must **be at forefront** of assembly, installation + commissioning




- Distinguish beam induced backgrounds
- Large Radius Tracking
- Unprecedented resolution

# Boundary conditions for a search programme

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**We need to plan the endgame of the LHC today!**

**Resources: people and tools**

- Two **search groups**, O(1000) people capable of producing 35 papers / year
- Search community heavily **invested in Upgrade and Operations**
- **0.5/ab with our best-understood detector**, exploitable for next decade.
- Then **unprecedented dataset** w/ new detector, opening new opportunities.
- Harness detector expertise, new techniques+ideas to support and drive our programme

**We have plenty of people, need to make sure to organise efforts efficiently**

**Objectives:**

# Objective: What do we want to achieve with the LHC?

- Primary objective, by the end of the LHC programme:

**Discover a new particle or interactions**

OR

**Be 95% confident there was no discovery to make**
(at accessible energy and coupling scales)

# Objective: What do we want to achieve with the LHC?

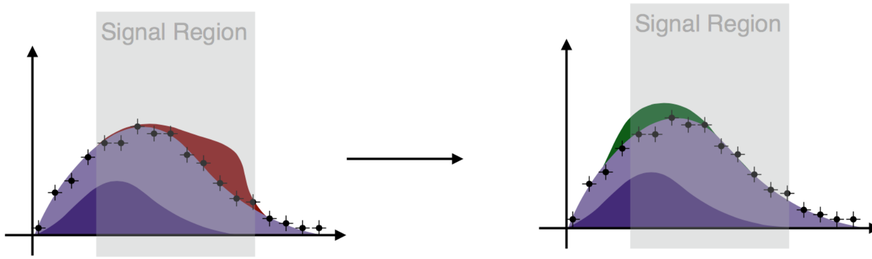
- **Game theory:** what is the most efficient way to achieve this objective with the constraint of limited resources.
  - **Not the answer:** randomly sampling model space with no plan.
  - **Also not the answer:** Blindly turning handle on same analyses with more data.
  - **DEFINITELY NOT THE ANSWER:** forcing people to work on things they don't want to work on.

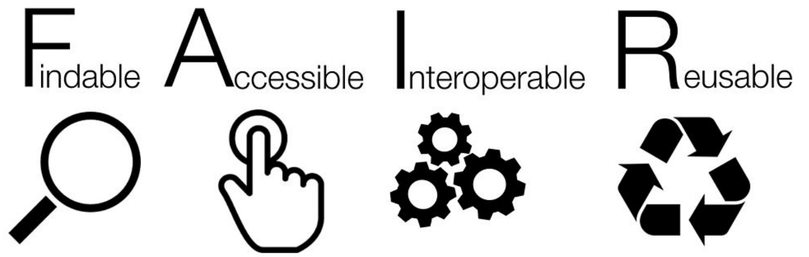
# Objective: What do we want to achieve with the LHC?

- **Maybe the answer:**
  - Exploiting the **strengths** of our **people** to
  - ensure **deep but focused** coverage of **well-motivated models**,
  - and also **broad but shallow** coverage for more **speculative models**,
  - **scheduled in time** according to **potential gains** and with **critical mass** to converge,
  - from **extra data** and **instrumental/tools/method** developments,
  - and designed for **long-term impact** and **avoiding repetition** of work

# Objective: Multi-use results and a long-lasting legacy

- All searches should be **re-exploitable:**
  - Able to constrain another model in a similar signature. **Repeating searches** because we didn't correctly preserve/ present past results **is inefficient and unacceptable**.
- Serious focus on **analysis preservation** and **re-interpretability.** Results should still **be re-useable** until next hadron collider comes online in **half a century**.
- On some topics, the Run2+3 searches will be the last word. We need to get this right **NOW**.
- On a human level, knowing one is working on a long-impact publication is more motivating




**ATLAS Exotics has 100% HEPData coverage for its 2025 papers**

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**We have plenty of people, need to make sure to organise efforts efficiently**

**Objectives:**

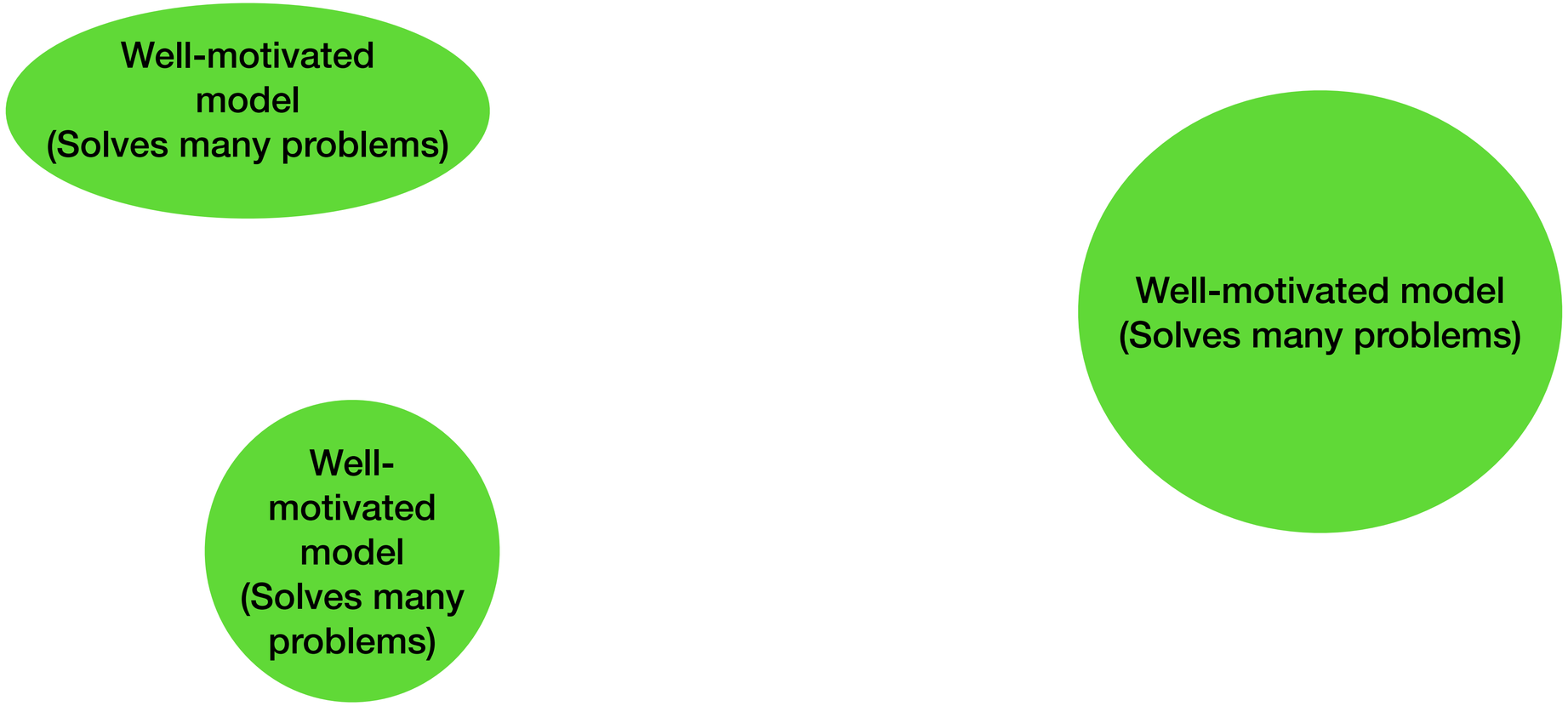
- **Discover** new particles or interactions
- Or be certain that there was nothing there to find in all reasonably-accessible parts of model space.
- Analyses with **long scientific legacy**
- Game theory:
  - How to achieve one of these **outcomes** in the **most efficiently** , given time+resource **constraints** ?

**We need to plan the endgame of the LHC today!**

Now that we know
The **time** available
What **resources** are at our disposal
And what we want to **achieve**..

# Let's make a plan

# Many models


Well-motivated model (Solves many problems)
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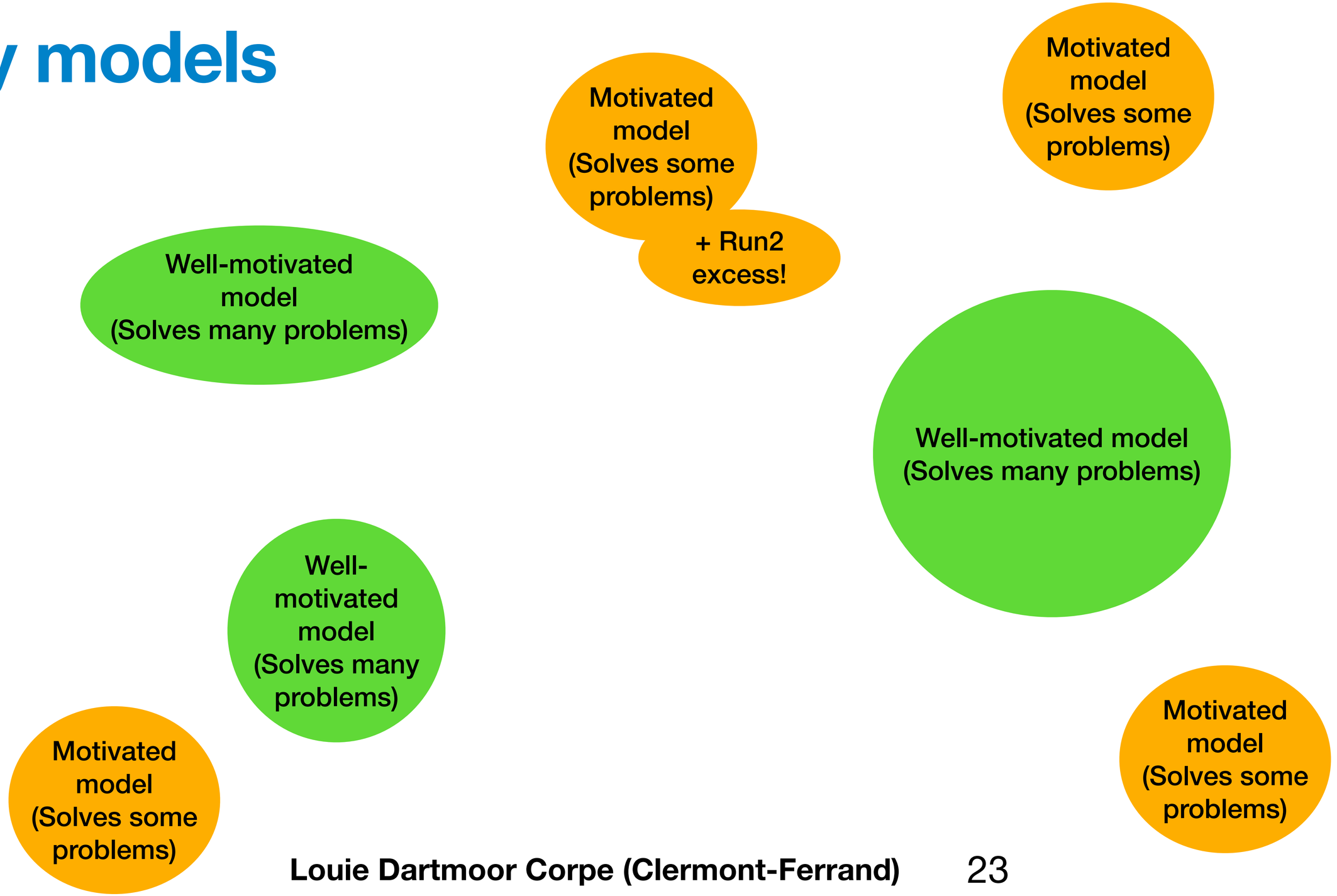
# Many models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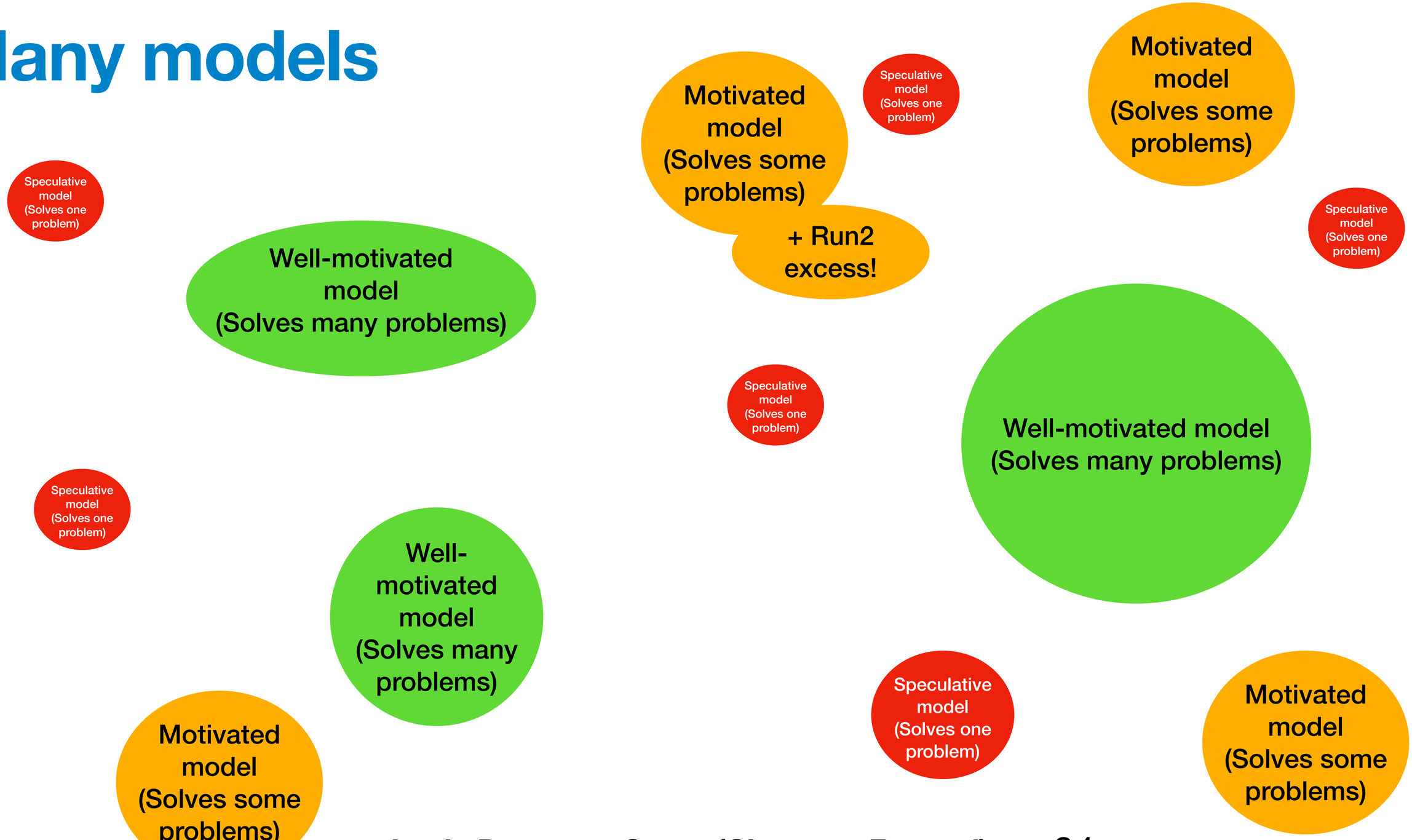
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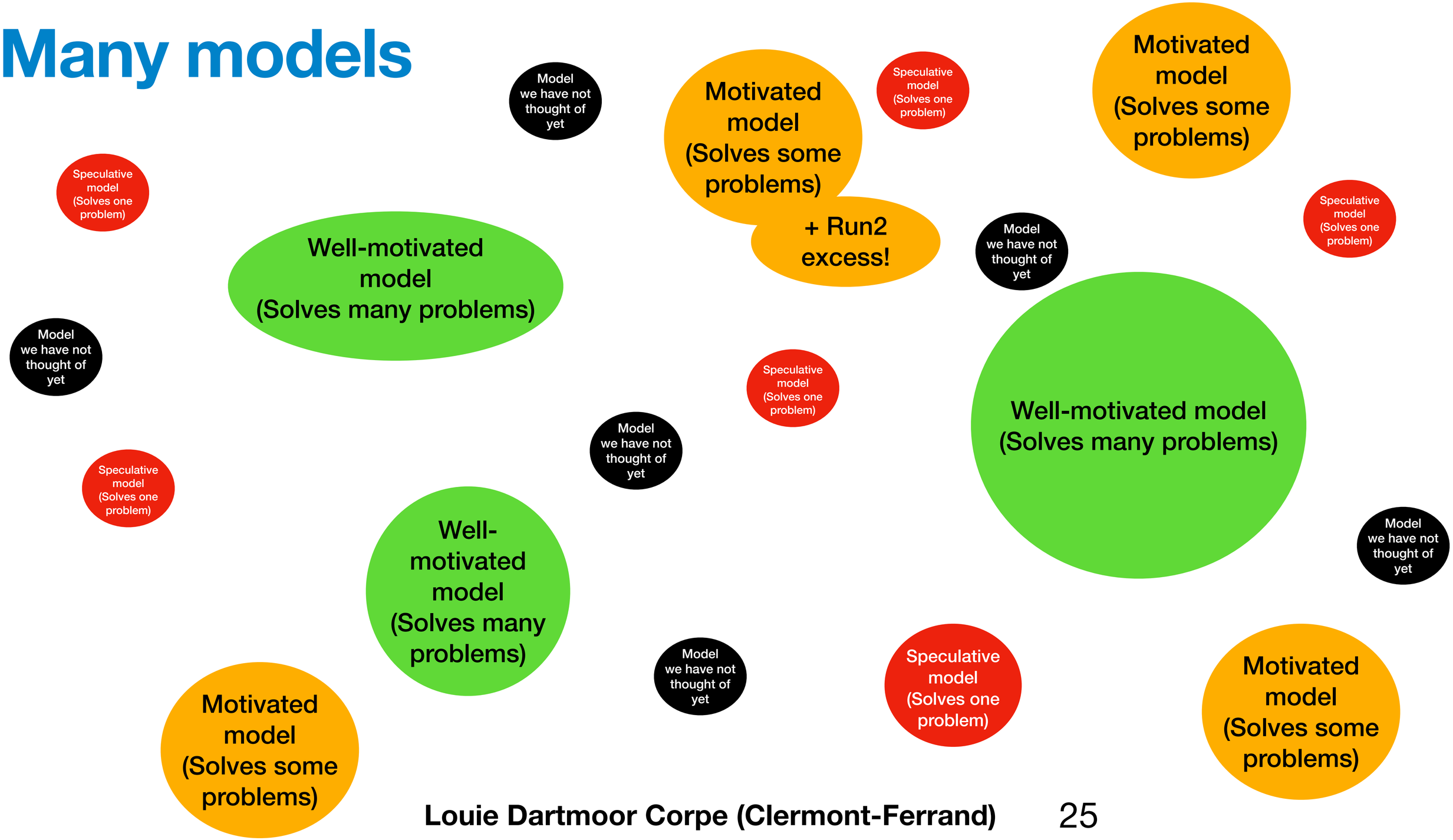
Model we have not thought of yet
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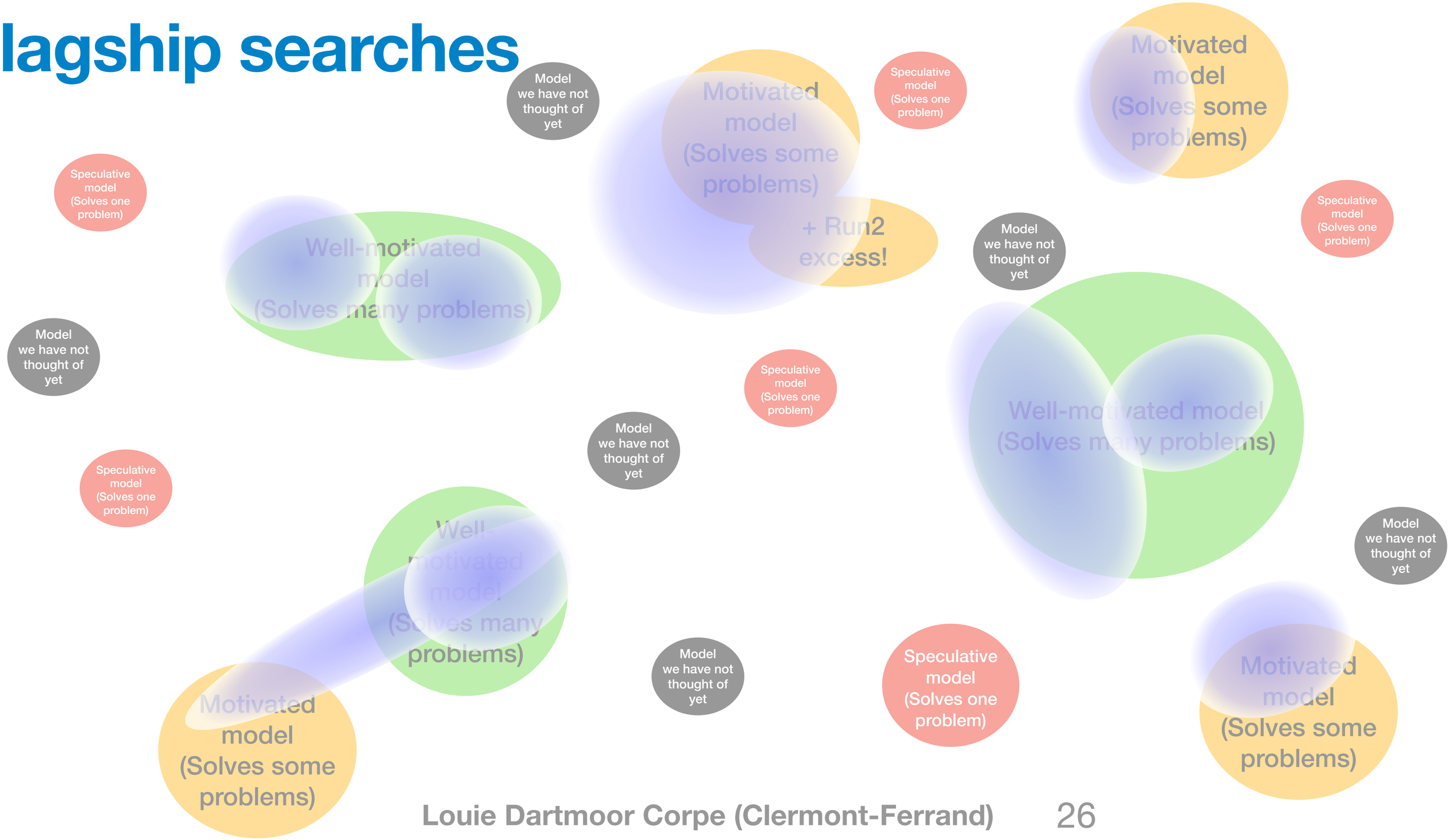
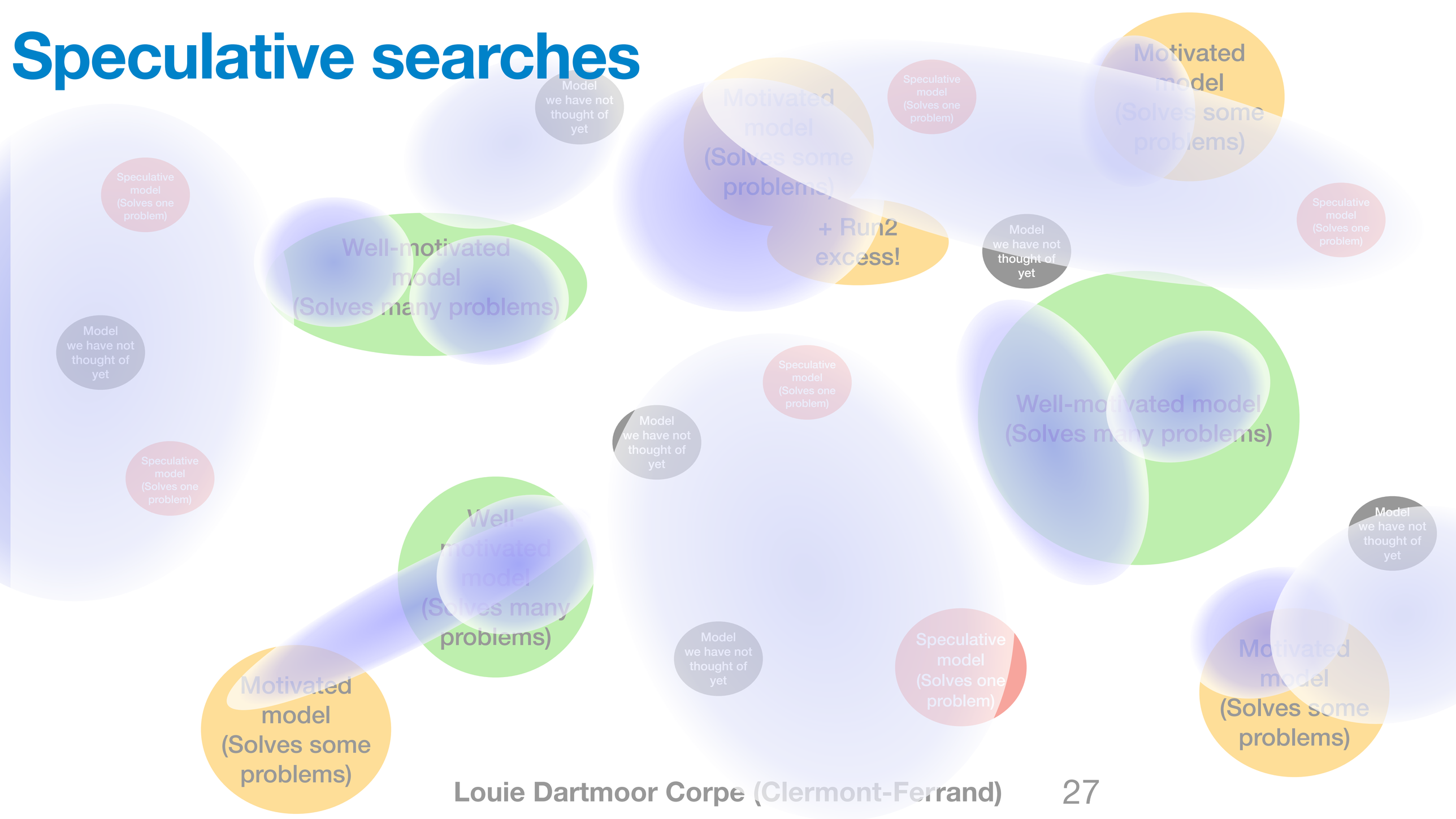
# Flagship searches



# Speculative searches



# The Flagship programme

**flagship** noun

flag·ship ˈflag-ˌship

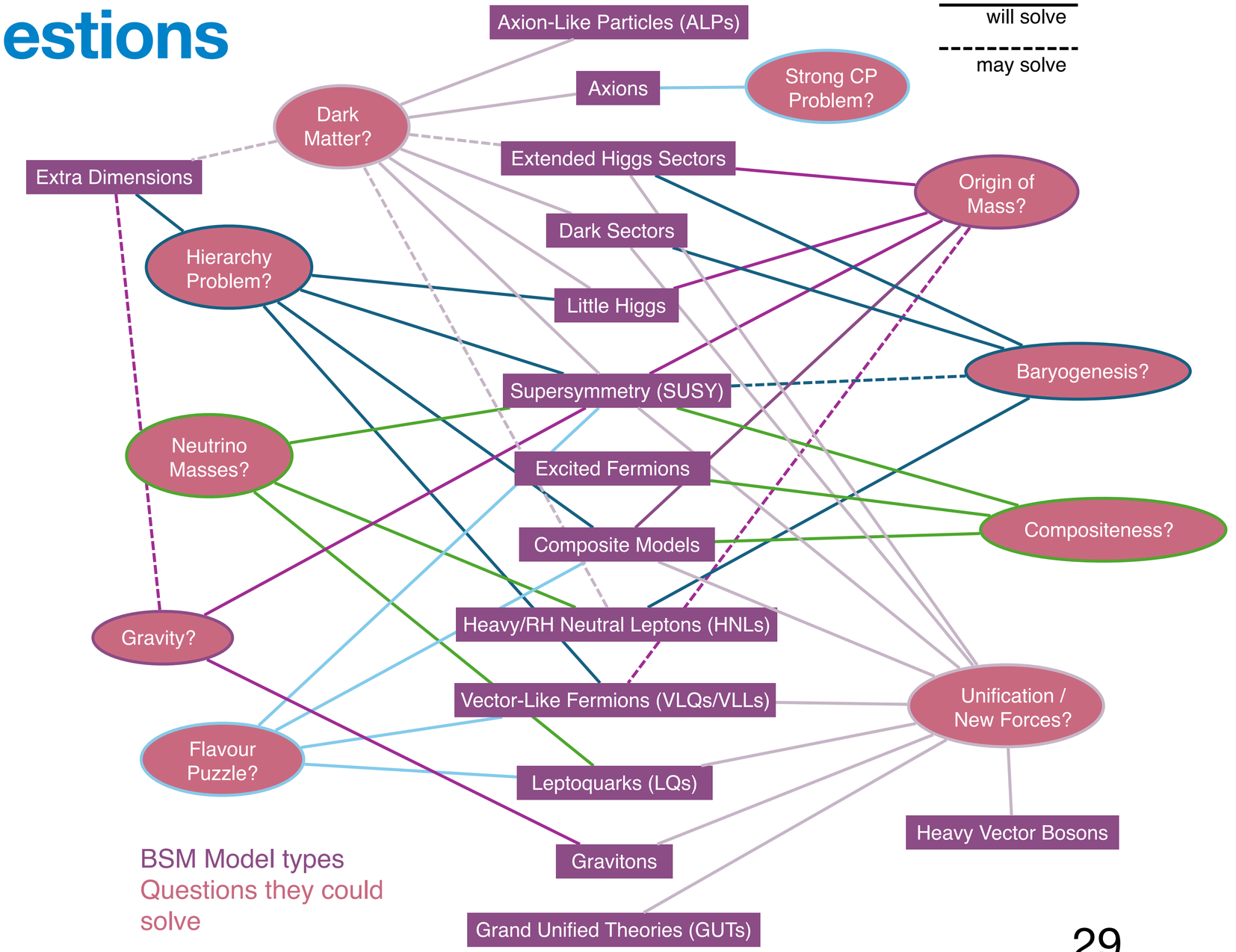
Synonyms of *flagship* ›

1 : the ship that carries the commander of a fleet or subdivision of a fleet and flies the commander's flag

2 : the finest, largest, or most important one of a group of things (such as products, stores, etc.) → often used before another noun

The mantra is:
"Narrow but deep sensitivity"

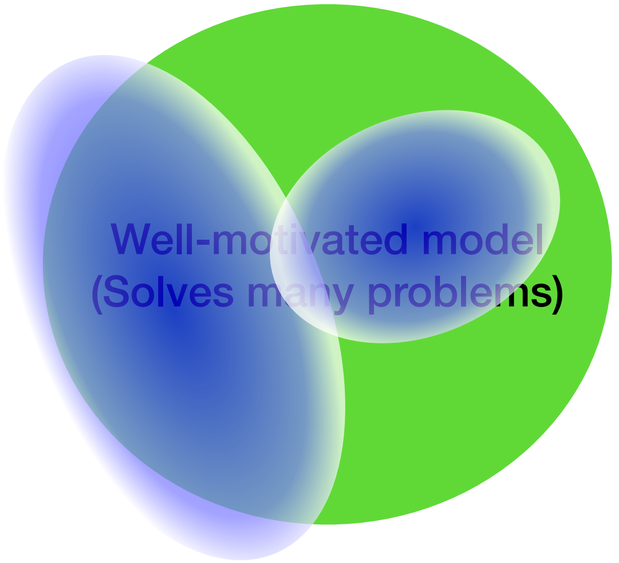
# Tentative answers to big questions




By Holly Pacey

# The ATLAS search flagship programme

- Probe most **promising models** with **focused sensitivity**.
- Dedicated searches and techniques, **optimised for target model**(s)
- **Summary plots to gauge our progress** against each other + the rest of the field.
  - Important to use **comparable benchmarks** with CMS and non-collider
- **Timing of searches** will depend on **data collection**:
  - Each new wave only when **enough data** to make **significant impact**
  - Calls for a **5-year plan** / timeline
  - Set objectives for HL-LHC programme for each model family



# Subgroups organised around the flagships

- What are the best-motivated parts of model/signature space?
- Still the ***same models as the start of the LHC***:
  - SUSY
  - Exotic Higgs
  - Leptoquarks
  - Axions and Axion-like particles
  - Vector-like quarks and vector-like leptons
  - Direct DM production
  - Heavy Neutral Leptons
  - Unusual signatures and LLPs
  - GUT/Extra Dimensions (Z' / W')

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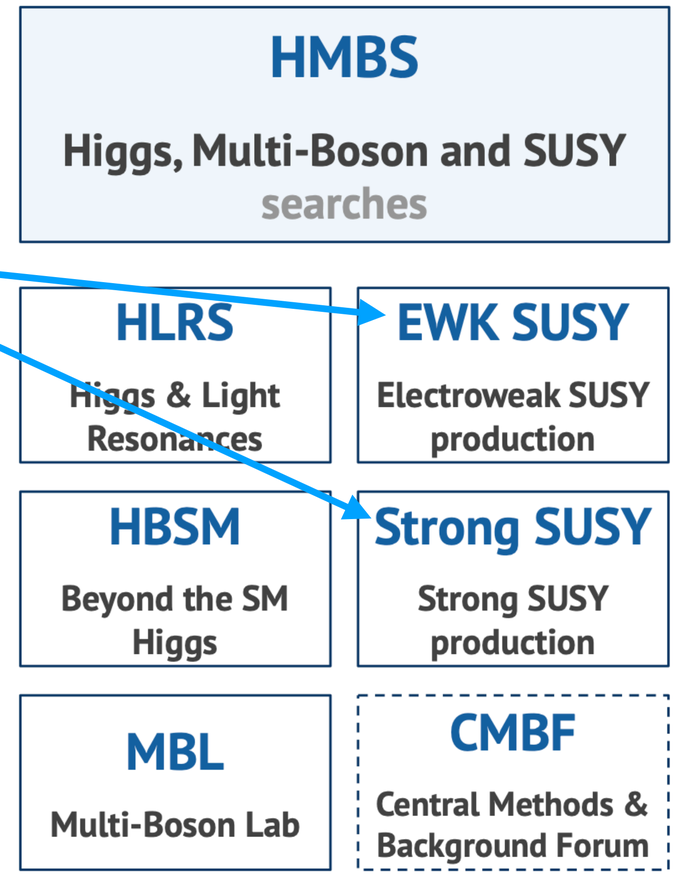

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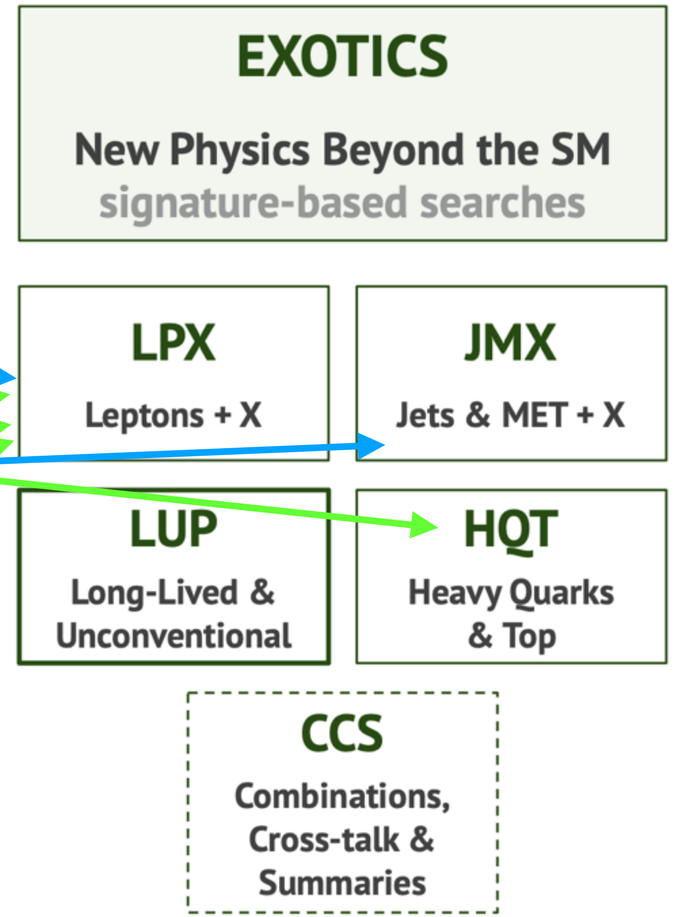
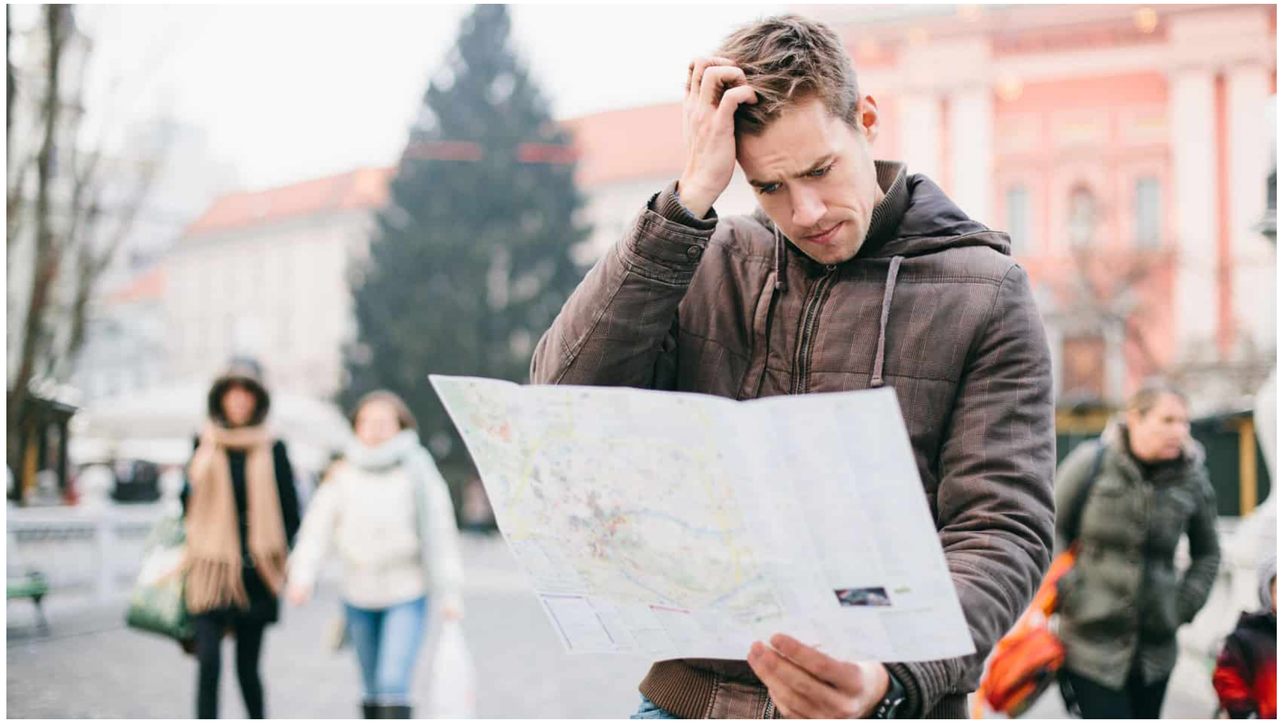


# Check your map regularly



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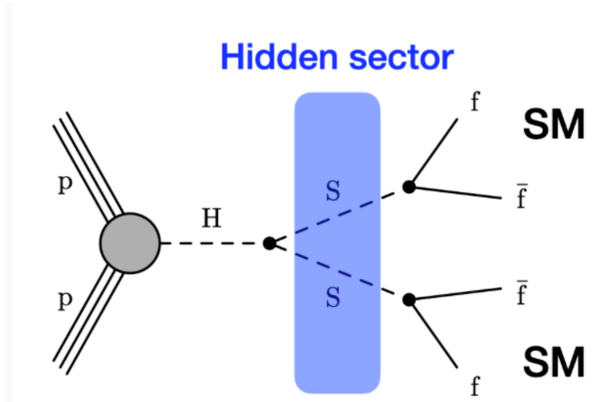
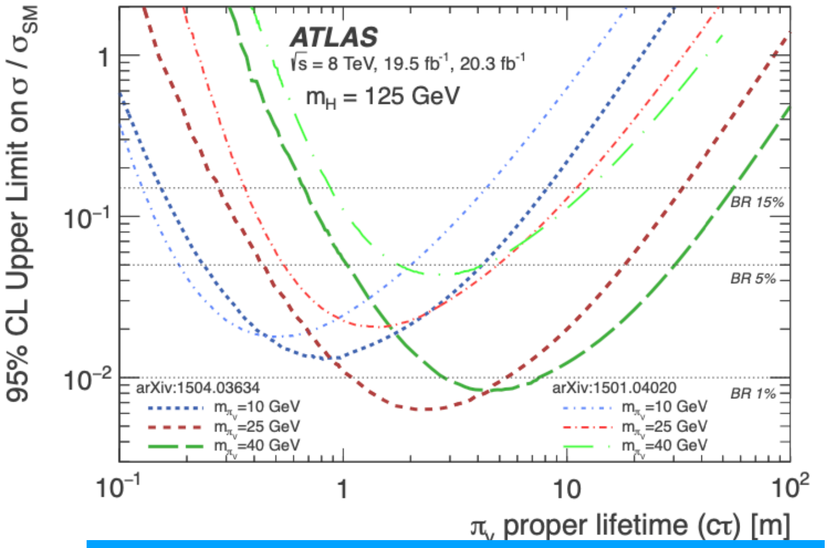
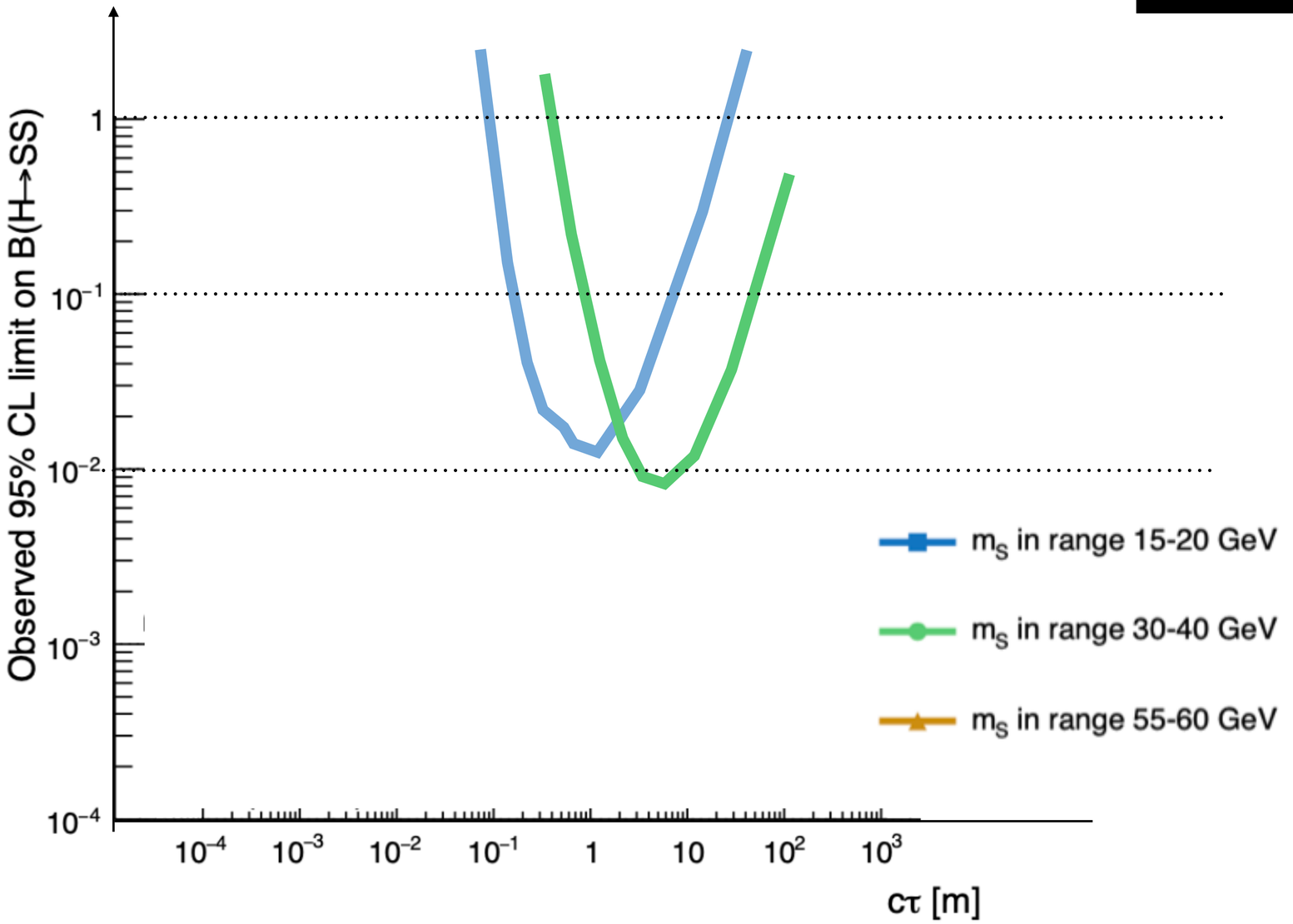
# Run 1 first Long-lived Hidden Sector searches

2015



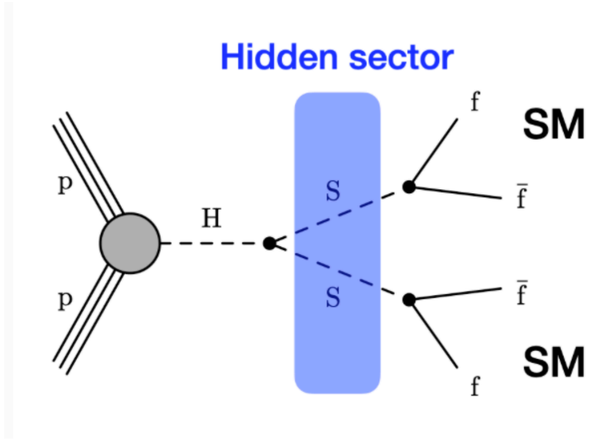



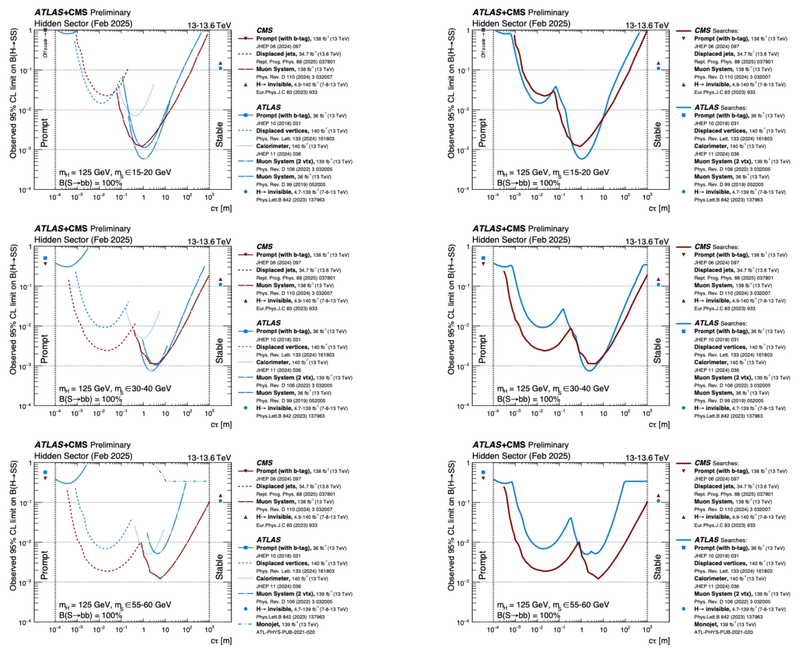

Phys. Rev. D 92 (2015) 012010,
arXiv: 1504.03634 [hep-ex]

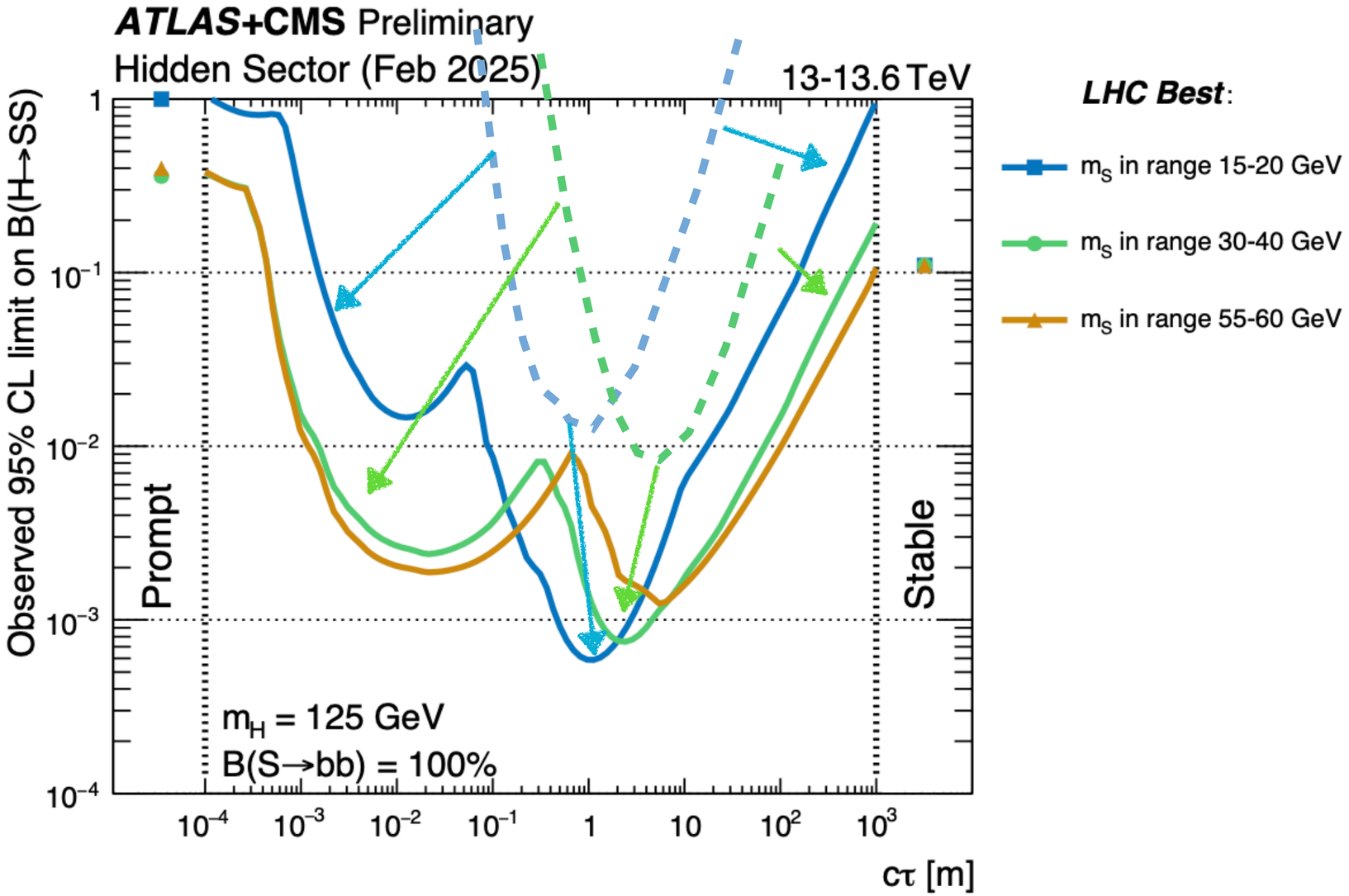


# The difference a decade makes

2025



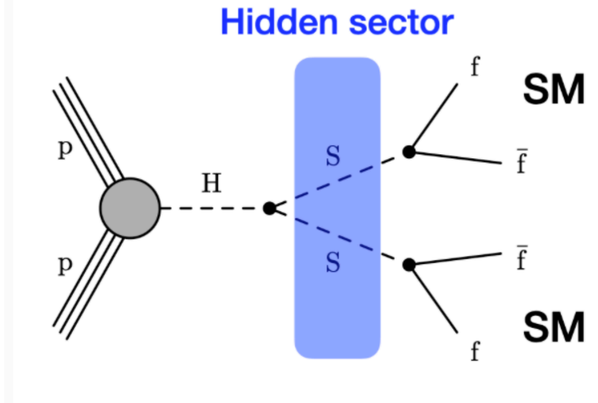



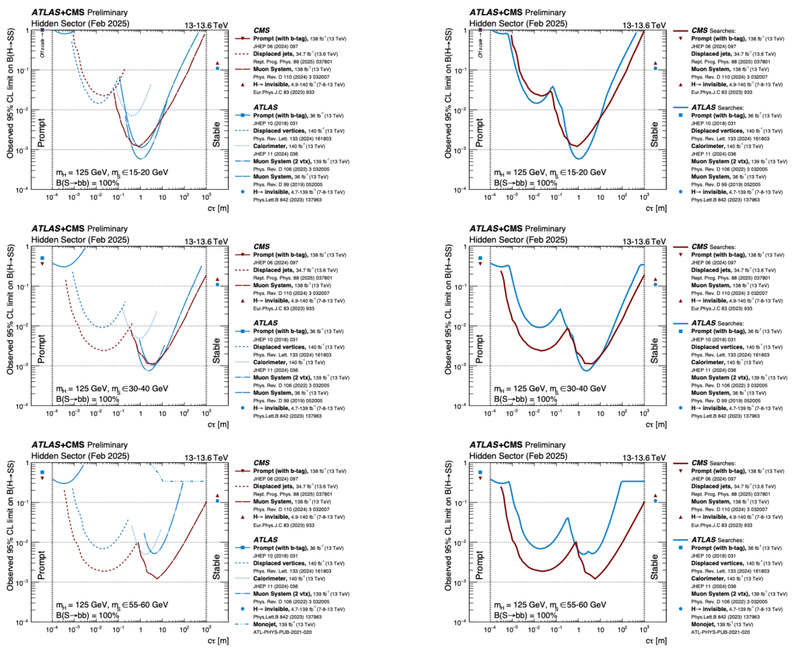



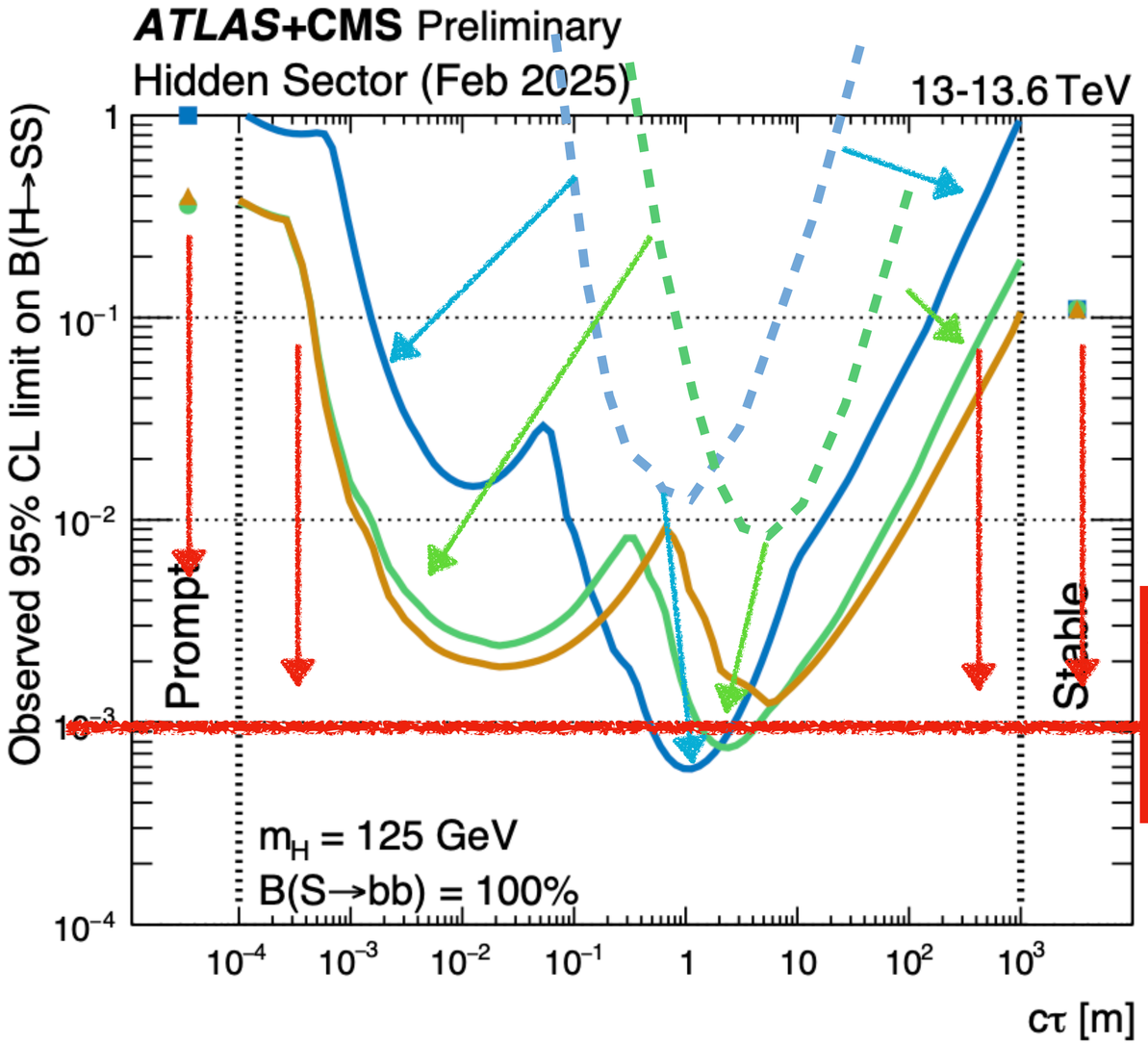

ATL-PHYS-PUB-2025-002
https://cds.cern.ch/record/2924617

# What is a reasonable target for HL-LHC?

2025




***LHC Best***:

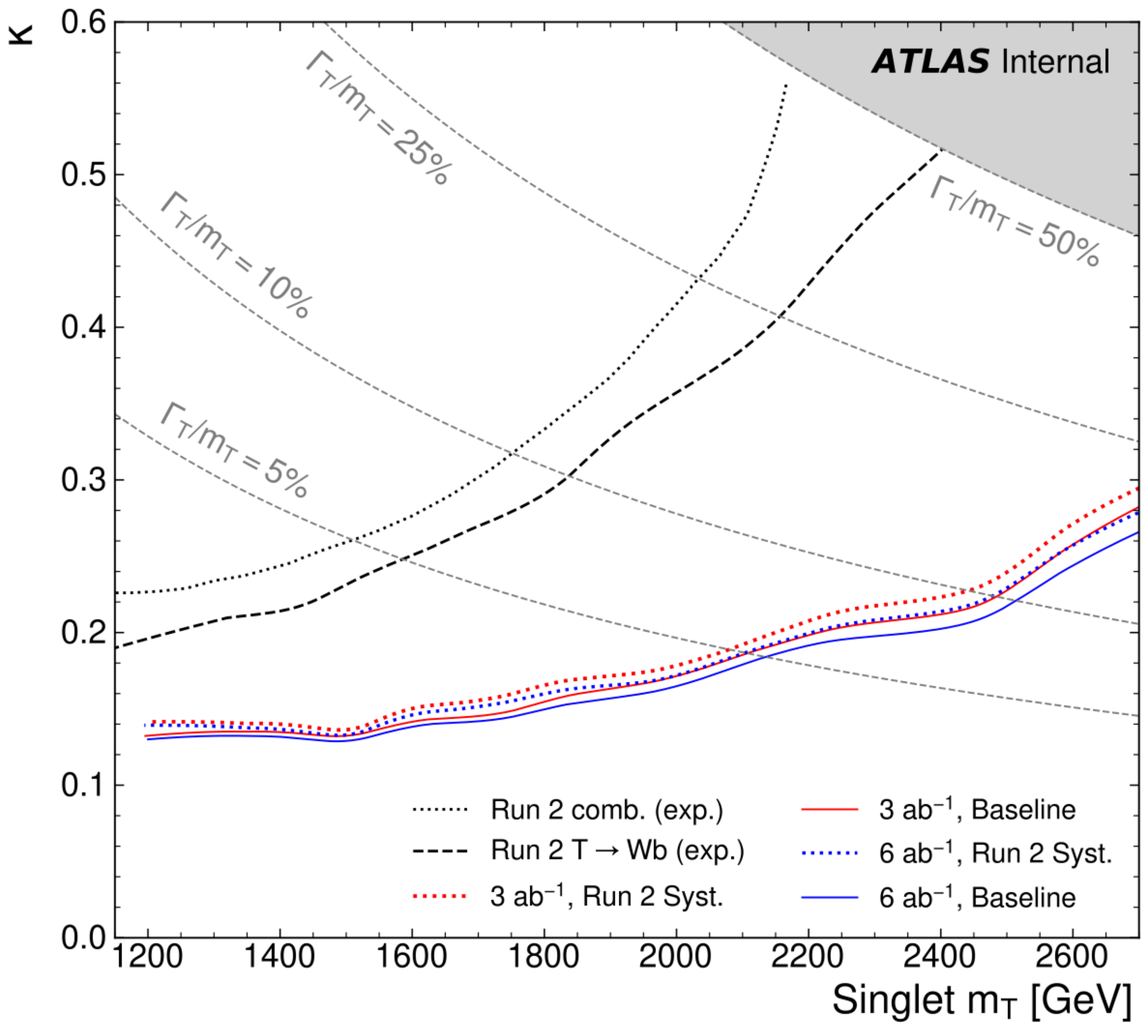
- $m_S$ in range 15-20 GeV
- $m_S$ in range 30-40 GeV
- $m_S$ in range 55-60 GeV

Approx H->ZZ*->vvvv BR
Our own "neutrino floor" ?

ATL-PHYS-PUB-2025-002
https://cds.cern.ch/record/2924617

# Project to plan

- Systematically project our flagship results to understand when it's time to repeat them
- do need more data ? Wait for theory improvements ? Work on systematics ?
- When can we make a big impact on limits ? When could we make a discovery ?
- Use this to inform our 5-year plan

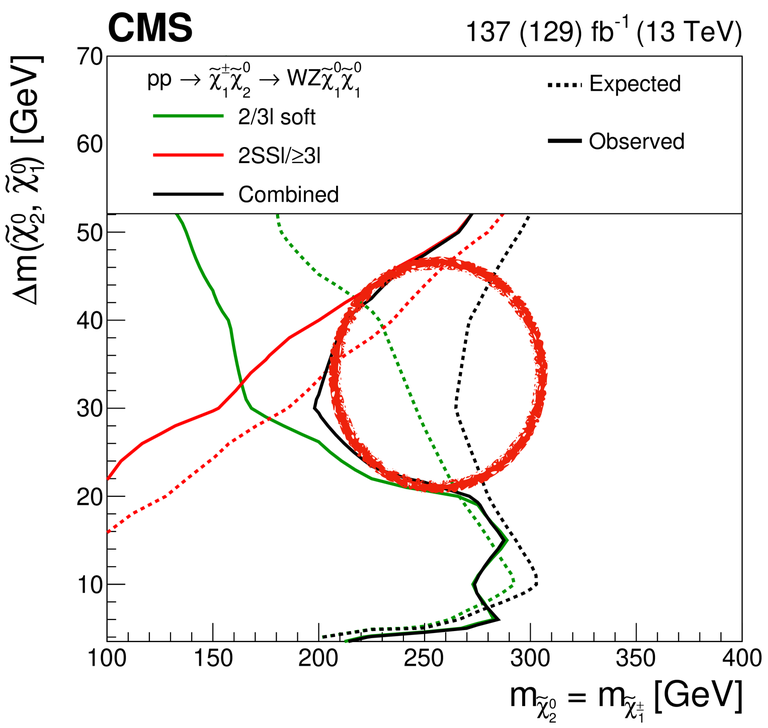



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2025-040/

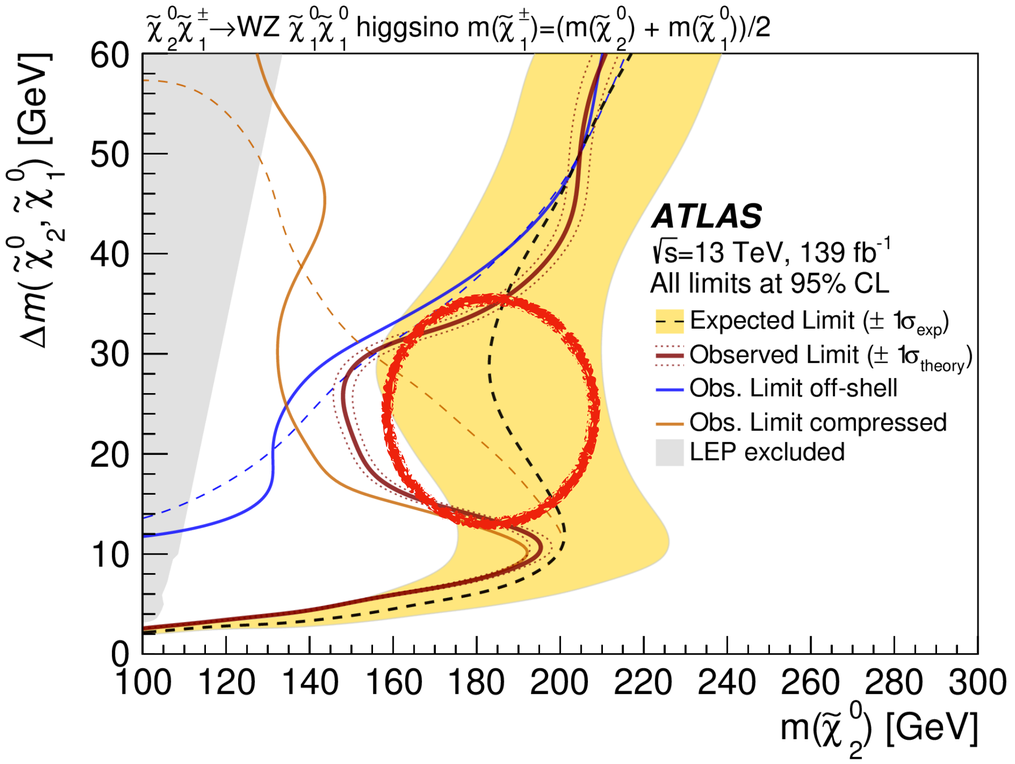
# Follow up on excesses

- Don't forget our main objective : a discovery could still be in store for us!
- Should invest huge resources in following up excesses, eg: compressed SUSY

CMS-SUS-21-008




SUSY-2019-09




**ATLAS Excesses**:
[Soft 2L], [3L],
[Sleptons 2L],
[SBH 3L]

**CMS Excesses:**
[Soft 2/3L]

# Follow up on excesses

https://lhc-bsm-wg.docs.cern.ch/excesses/

Thanks Tamara!

## List of Excesses at the LHC

The LHC BSM WG steering committee thanks the physics group conveners from the LHC experiments who helped us p
together the following lists.

**Note: this list is still work in progress. This page is only editable by the LHC BSM WG steering committee. Please cor
case a relevant LHC excess (local significance > 2.4 standard deviations) from a search for new physics is missing fr**

### ATLAS

| Physics Group | Final state | Nature of excess | Local (global) significance [standard deviations] | Dataset | Reference | Do other experiments see it? |
|---|---|---|---|---|---|---|
| HMBS | Compressed sleptons \(\to\) 2L | m(\(\mu\mu\)) 5-10 GeV 2.0 (SR2-BDTmm5+10) | 2.4 | Run 2 | HMBS-2024-64 | |
| HMBS | Compressed EWKinos \(\to\) 2L | mll ~ 20GeV (SR-E) | 2.7 | Run 2 | SUSY-2018-16 | |
| HMBS | EWKinos \(\to\) multib | 2017 in SR with MET>200 Meff>860 | 2.6 | Run 2 | SUSY-2020-16 | |
| HMBS | VBF Charged Higgs \(\to\) 2-3L | mH = 375GeV | 3.3 (2.5) | Run 2 | HDBS-2023-19 | |
| HMBS | Charged Higgs \(\to\) cb | mH+ = 130 GeV | 3 | Run 2 | HDBS-2019-24 | |
| HMBS | VBF Diboson \(\to\) 1L2j | mT ~ 1.5TeV | 2.8 | Run 2 | HDBS-2018-10 | |
| EXO | dE/dX | | 3.6 | Run 2 | SUSY-2018-42 | |
| EXO | displaced HNLs | mN of 5 GeV in the 2QDH model | 3.1 | Run 2 | EXOT-2022-12 | |

### CMS

| Physics Group | Final state | Nature of excess | Local (global) significance [standard deviations] | Dataset | Reference |
|---|---|---|---|---|---|
| B2G | V' \(\to\) V(V/H) \(\to\) jets | 2.1 and 2.9 TeV | 3.6 (2.3) | Run 2 | B2G-20-009 |
| HIG | X \(\to\) YH \(\to\) 4b resolved | (mX, mY) = (700 GeV, 400 GeV) | 4.1 (2.8) | Run 2 | HIG-20-012 |
| B2G | X \(\to\) YH \(\to\) 4b boosted | (mX, mY) = (1.6 TeV, 90 GeV) | 3.1 (0.7) | Run 2 | B2G-21-003 |
| HIG | X \(\to\) YH \(\to\) (bb)(\(\gamma\gamma\)) | (mX, mY) = (650 GeV, 95 GeV) | 3.8 (2.8) | Run 2 | HIG-21-011 |
| B2G | X \(\to\) YH \(\to\) (\(\gamma\gamma\)) (bb) | (mX, mY) = (300 GeV, 77 GeV) | 3.3 (0.7) | Run 2 | B2G-24-001 |
| B2G | X \(\to\) YH \(\to\) (VV \(\to\) 4q)(bb) | (mX, mY) = (900 GeV, 80 GeV) | 3.3 (< 1) | Run 2 | B2G-23-007 |

# Example of a recent 'flagship' result: Quantum Black Holes

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

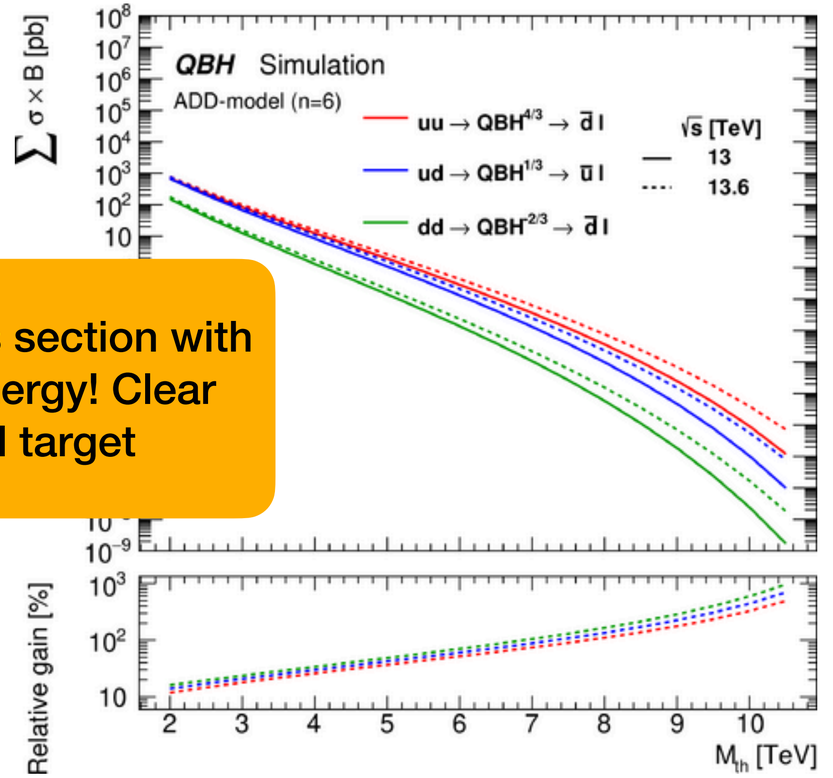
CERN

Submitted to: PLB

22nd April 2026

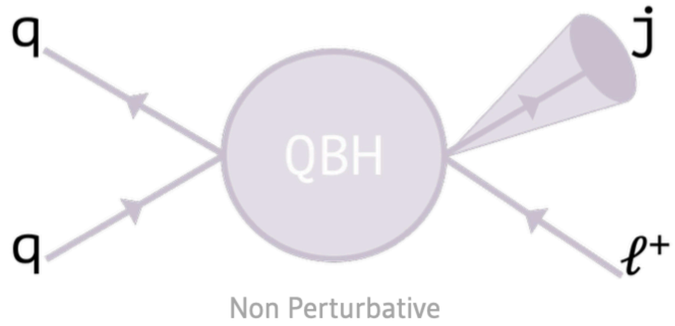
**Search for quantum black holes in lepton+jet final states using proton–proton collisions at $\sqrt{s}$ = 13.6 TeV with the ATLAS detector**

The ATLAS Collaboration



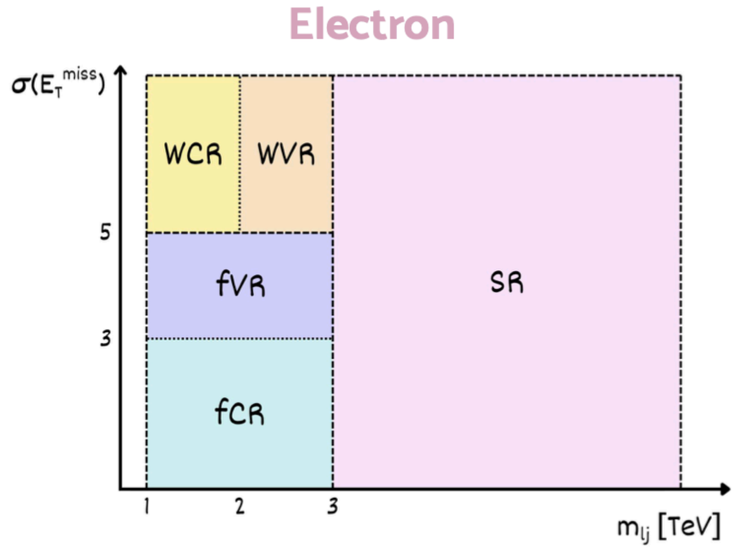

Huge gain in cross section with CoM collision energy! Clear experimental target

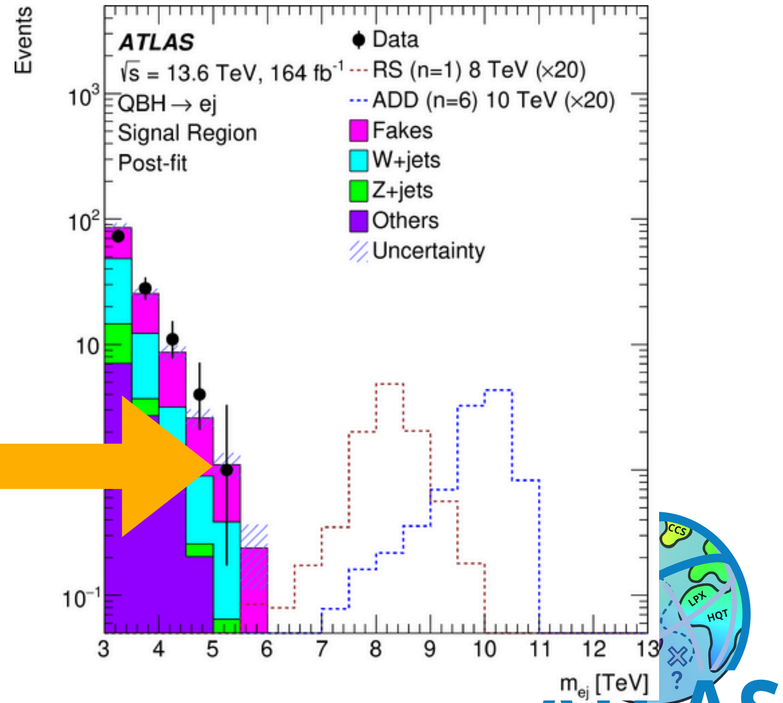
- Quantum Black Holes are well motivated: help solve gauge hierarchy problem (why is Planck scale so far from EW scale?)



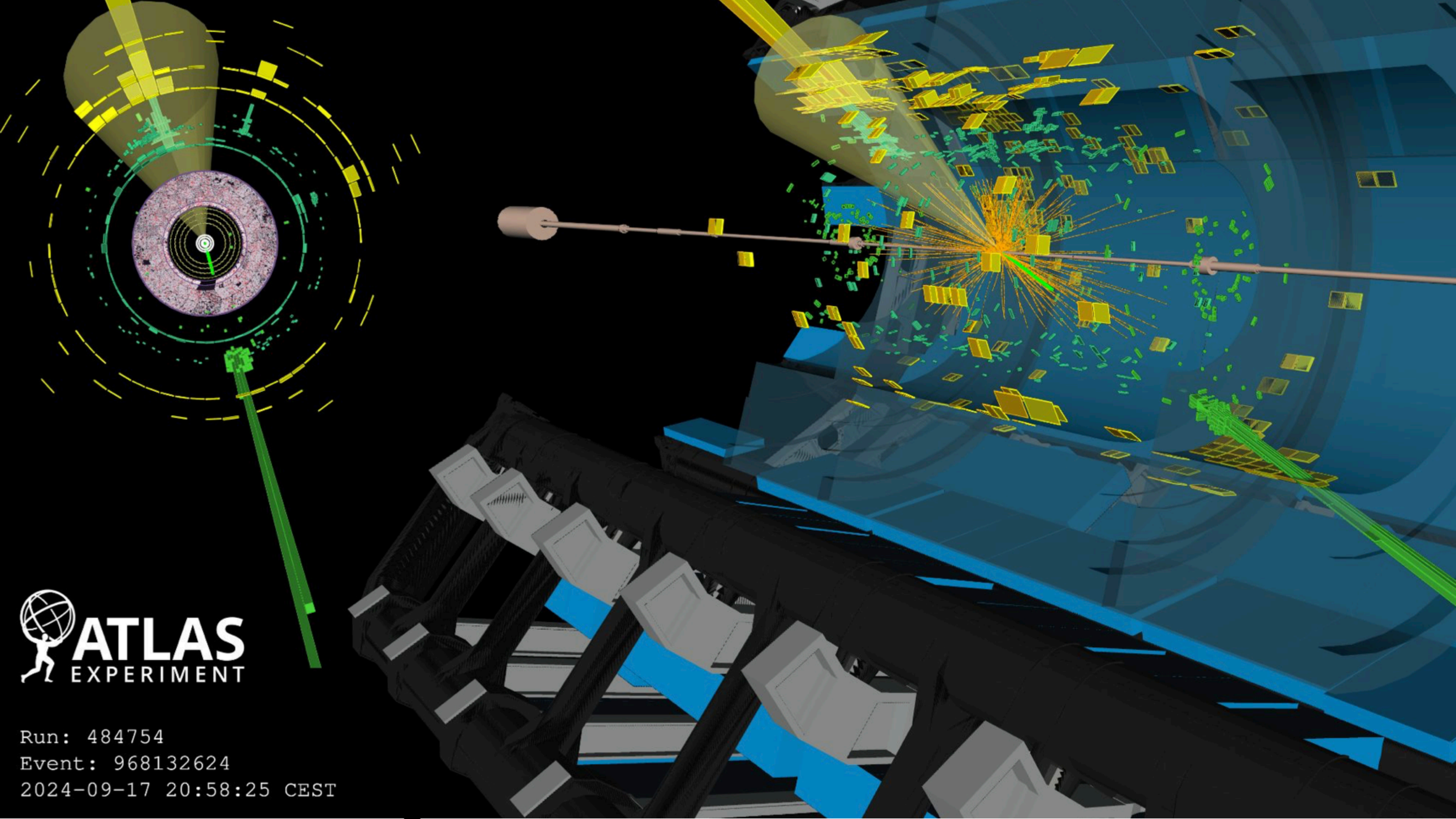
# Quantum Black Holes

- Simple analysis strategy:
  - Require lepton + jet, both very high pT (> 130 GeV)
  - Angular selections to reduce background, low missing energy
  - Most backgrounds from Monte Carlo Simulation, with normalisation from dedicated regions
  - Fakes electrons from data-driven method
  - Check for excess in $m_{lj}$ invariant mass distribution

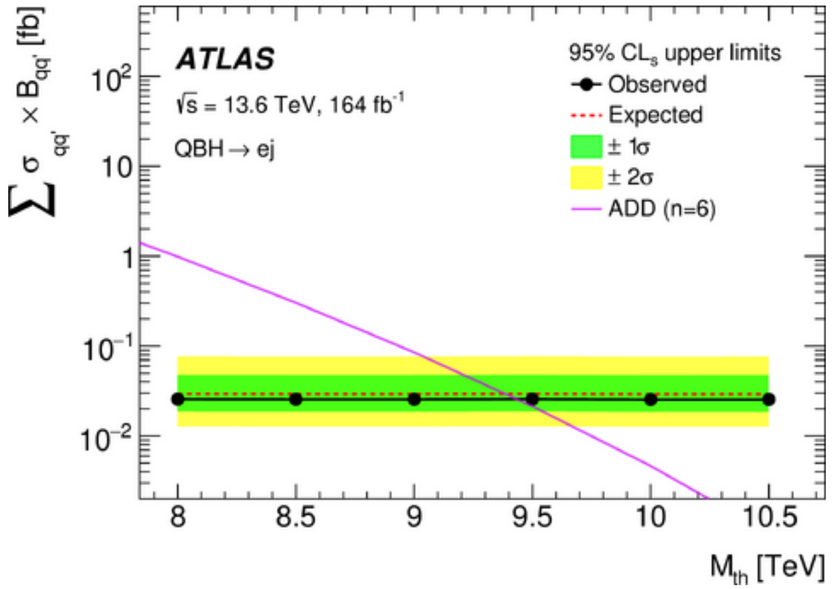


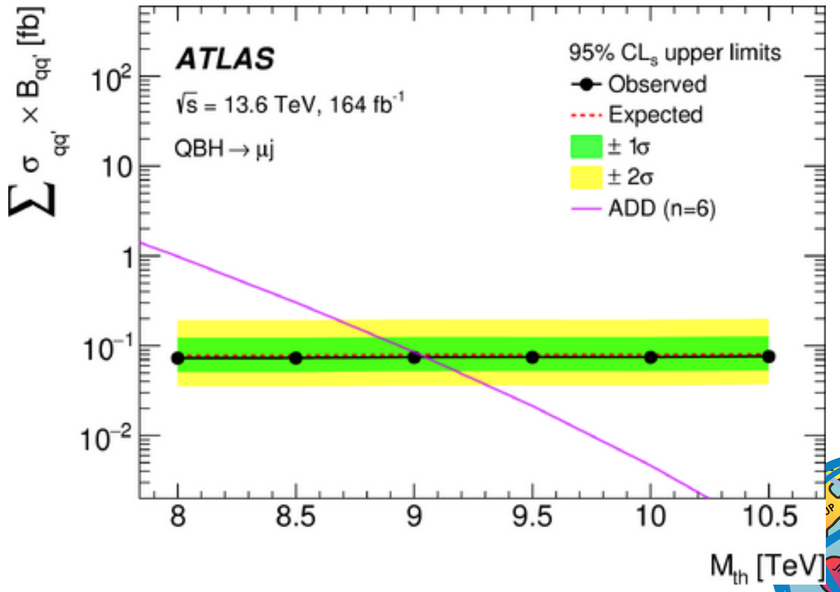

**Highest event, 5.3 TeV invariant mass!**


ATLAS
EXPERIMENT
Run: 484754
Event: 968132624
2024-09-17 20:58:25 CEST

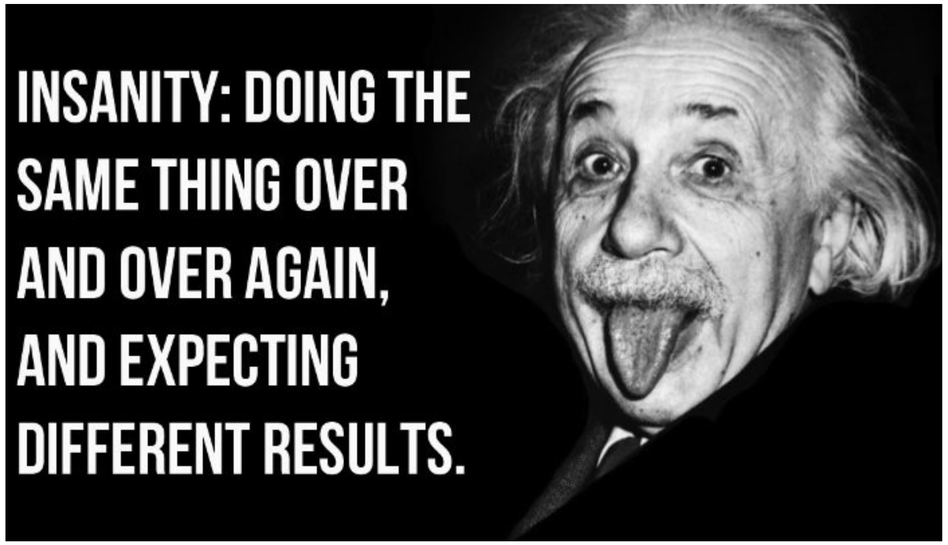
# Quantum Black Holes




- No excess seen, but we are probing scales up to 9.5 TeV depending on the model and channel!

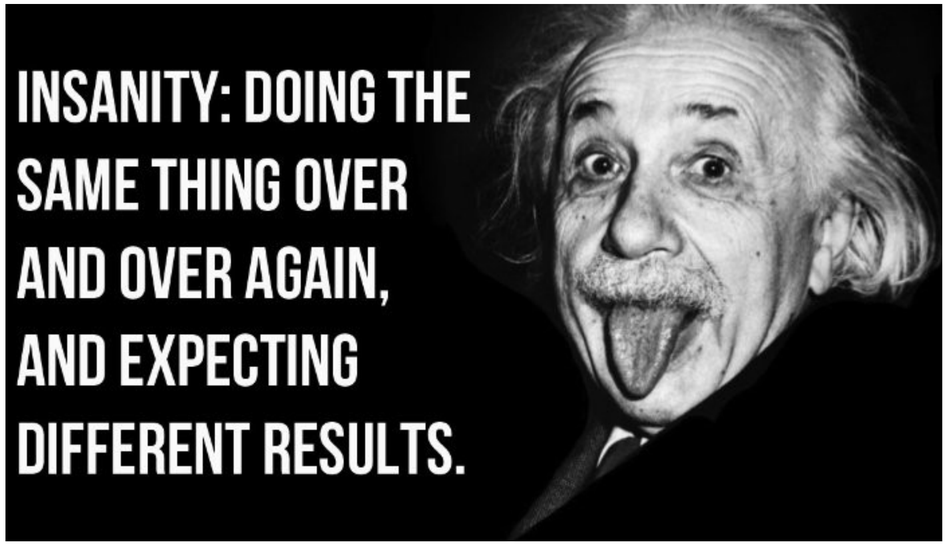


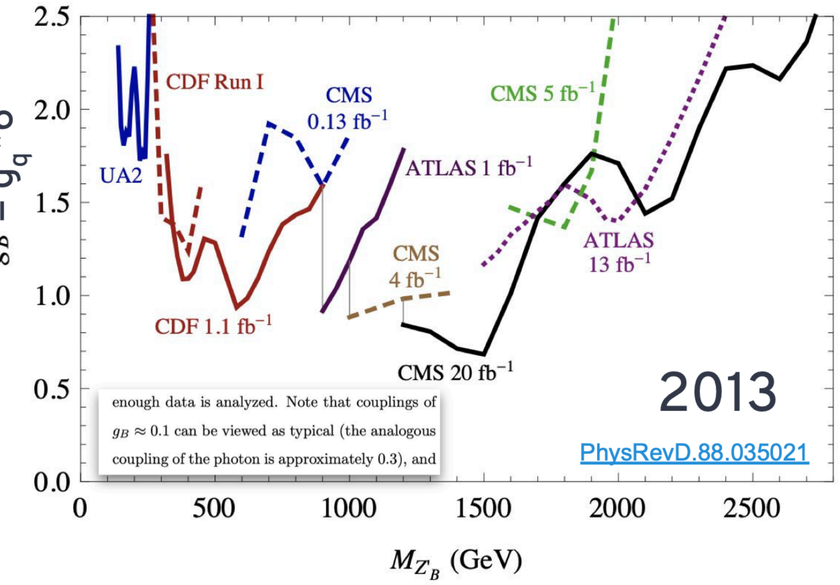
# Why keep digging ?



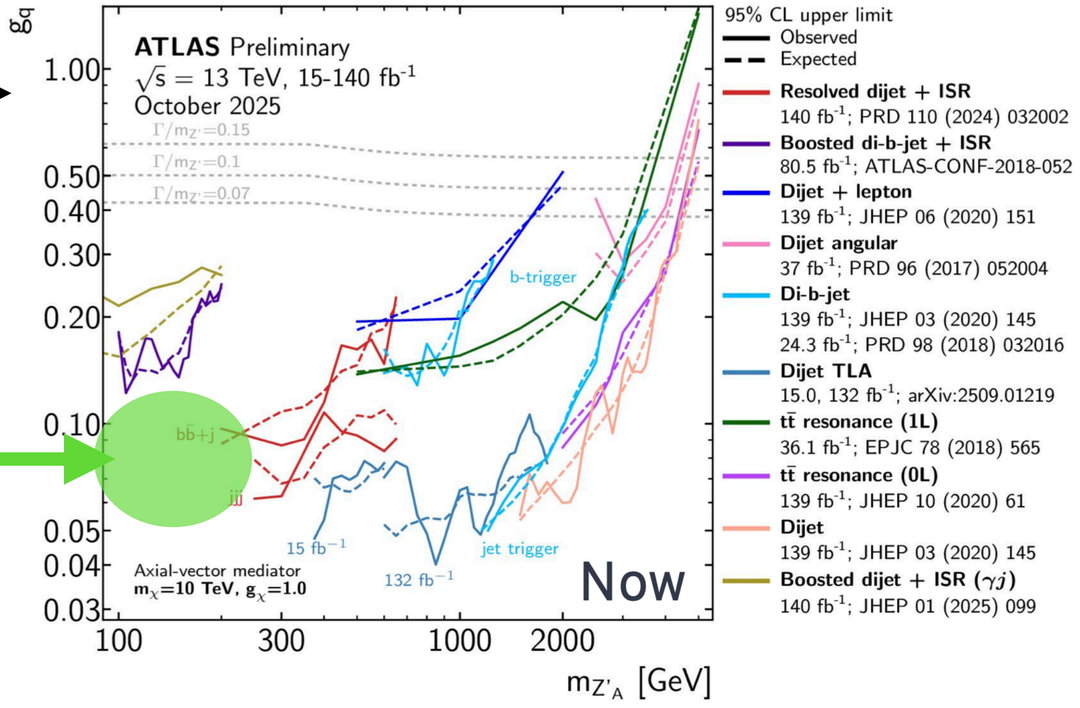
# Why keep digging ?

BUT... we are only now beginning to probe some areas which are *actually* well motivated...
(Eg dijet resonances!)




13 years




enough data is analyzed. Note that couplings of $g_B \approx 0.1$ can be viewed as typical (the analogous coupling of the photon is approximately 0.3), and

# Speculative searches

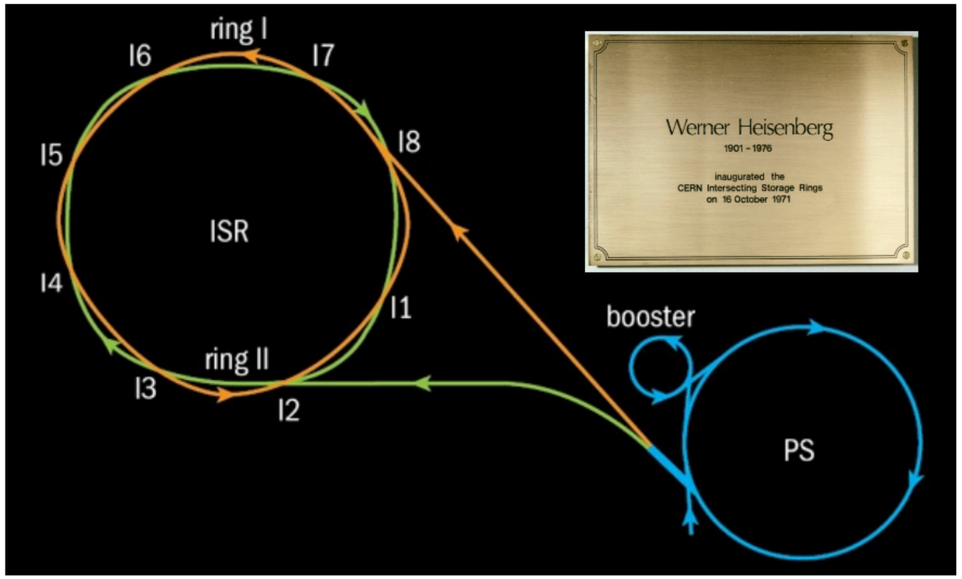
noun

Definition : Investment in stocks, property, or other ventures in the hope of gain but with the risk of loss.

The mantra is:
"Broad but shallow sensitivity"

# First ... a warning from history

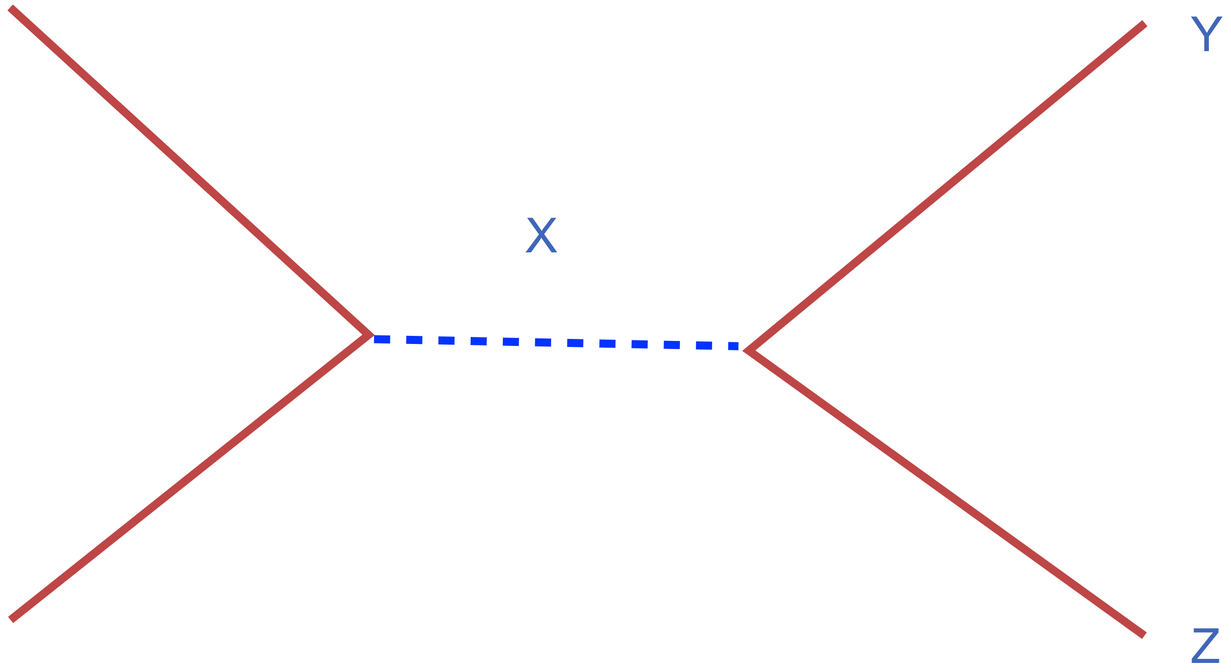
- 1971: **Intersecting Storage Rings (ISR)** at CERN marked **birth of hadron colliders**
- **√s = 30 GeV**: enough for bound states of ***c-* and *b-quarks (at time undiscovered!!)***
- ...but theoretical bias suggested "new physics" to manifest in forward direction **Transverse direction not instrumented !!**
- **ISR could have discovered J/Ψ and ϒ**... but **did not** : instrumentation in wrong place. **CERN/Europe left as a bystander** during November revolution in US.




2026: similar situation, with **theoretical bias for new physics to be prompt** preventing a discovery?

Disaster scenario: fundamental physics **breakthrough possible at LHC, but missed**.

# Remember Resonances




Strategy:

Look in $m_{YZ}$ invariant mass distribution, and search for a peak at $m_X$

# Question for the audience

- Consider this list of basic ATLAS objects: $e^+$, $e^-$, $\mu^+$, $\mu^-$, light jets, b-jets, ETMiss

**What fraction of 2-body invariant mass spectra involving any of these objects have *ever* been probed for resonances by ATLAS ?**

85%? 70%? 50%? 30%? 15%?

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- Consider this list of basic ATLAS objects: $e^+$, $e^-$, $\mu^+$, $\mu^-$, light jets, b-jets, ETMiss

**What fraction of 2-body invariant mass spectra involving any of these objects have *ever* been probed for resonances by ATLAS ?**

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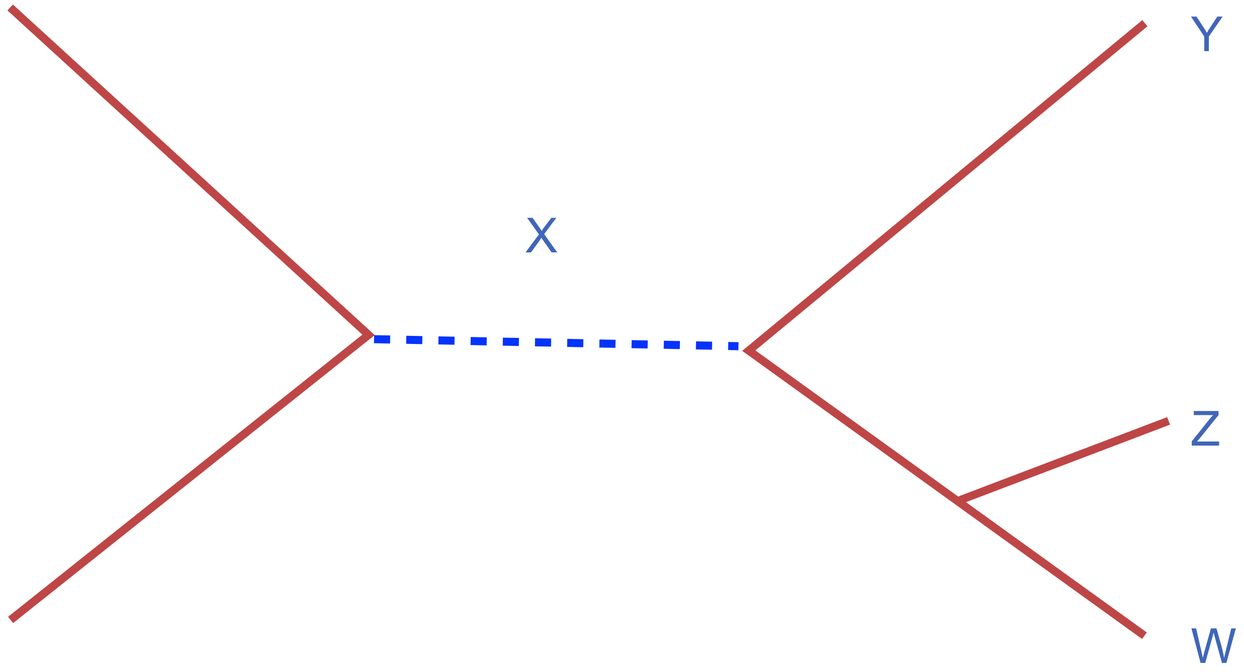
# Remember Resonances




Strategy:

Look in $m_{YZW}$ invariant mass distribution, and search for a peak at $m_X$

# Question for the audience

- Consider this list of basic ATLAS objects: $e^+$, $e^-$, $\mu^+$, $\mu^-$, light jets, b-jets, ETMiss

**What fraction of 3-body invariant mass spectra involving any of these objects have *ever* been probed for resonances by ATLAS ?**

85%? 70%? 50%? 30%? 15%?

# Question for the audience

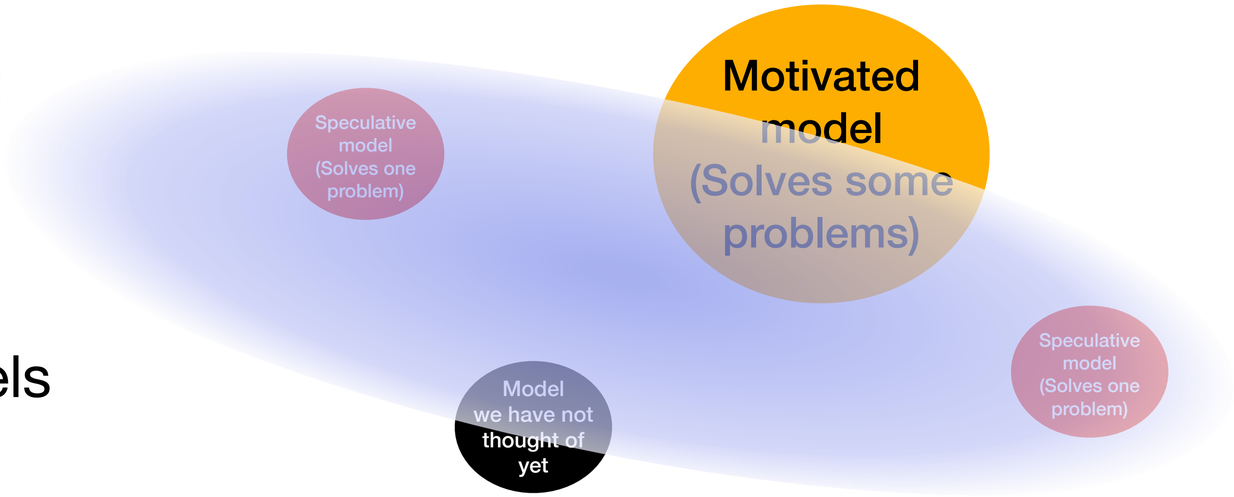
- Consider this list of basic ATLAS objects: $e^+$, $e^-$, $\mu^+$, $\mu^-$, light jets, b-jets, ETMiss

**What fraction of 3-body invariant mass spectra involving any of these objects have *ever* been probed for resonances by ATLAS ?**

85%? 70%? 50%? 30%? **15%?**

# Shallow but broad coverage: the speculative programme

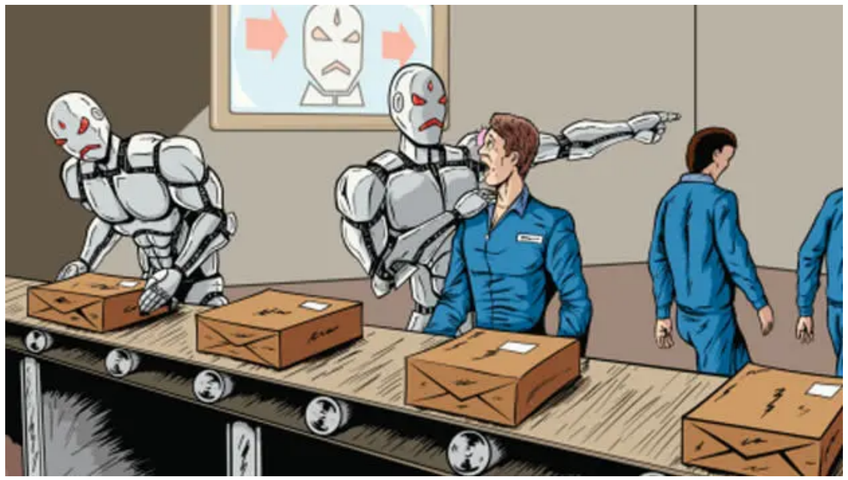
- Flagship models don't cover whole signature space
- Cannot accept to miss discovery by theory bias
- Hence: need to think outside the box. Can't afford to look only in well-motivated places!
- New paradigm, next techniques:
  - Dedicated searches for speculative models where discovery potential is proven
- General searches and anomaly detection: allow us to cover a very large part of parameter space. One paper instead of 10 : more efficient use of resources.



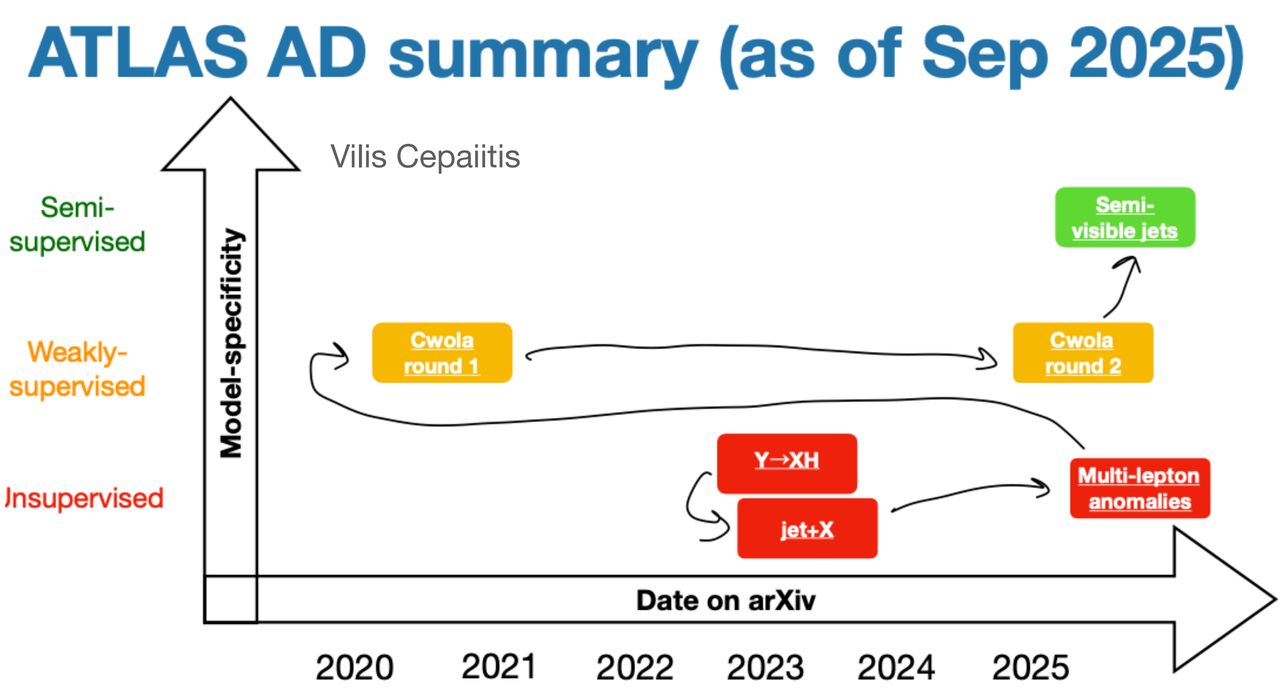



ATLAS EXOTICS GROUP

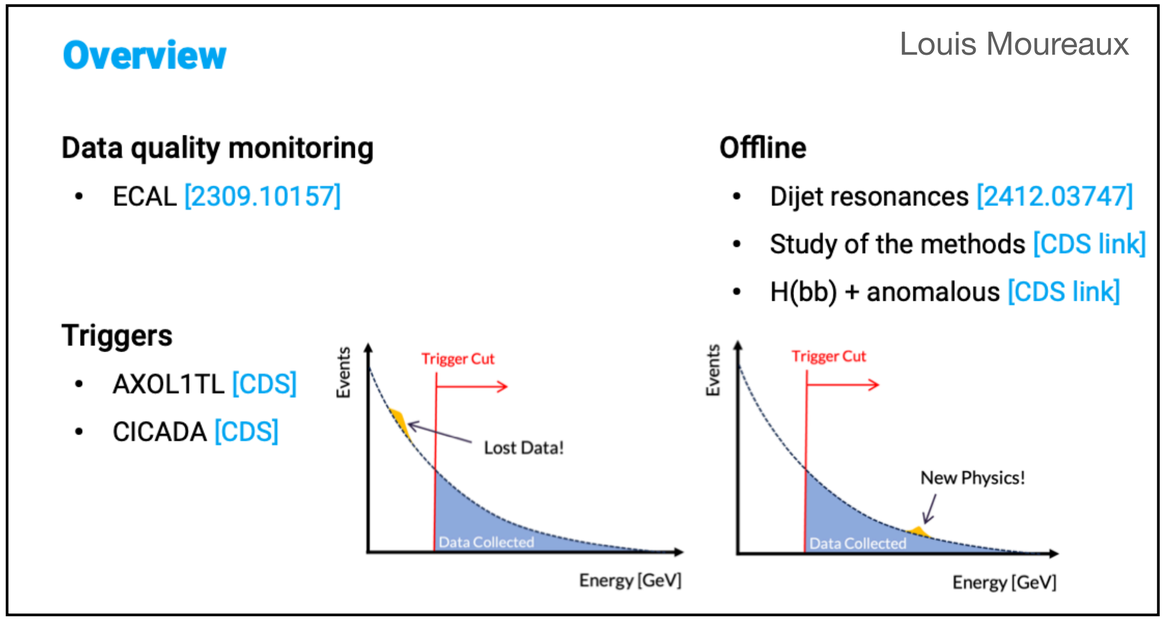
# The machines are coming to steal out jobs *(kidding, but let's use them properly)*



# The ATLAS and CMS Anomaly Detection Papers




https://indico.cern.ch/event/1578072/contributions/6648740/attachments/3136423/5565386/ADTopicalMeetingATLAS.pdf



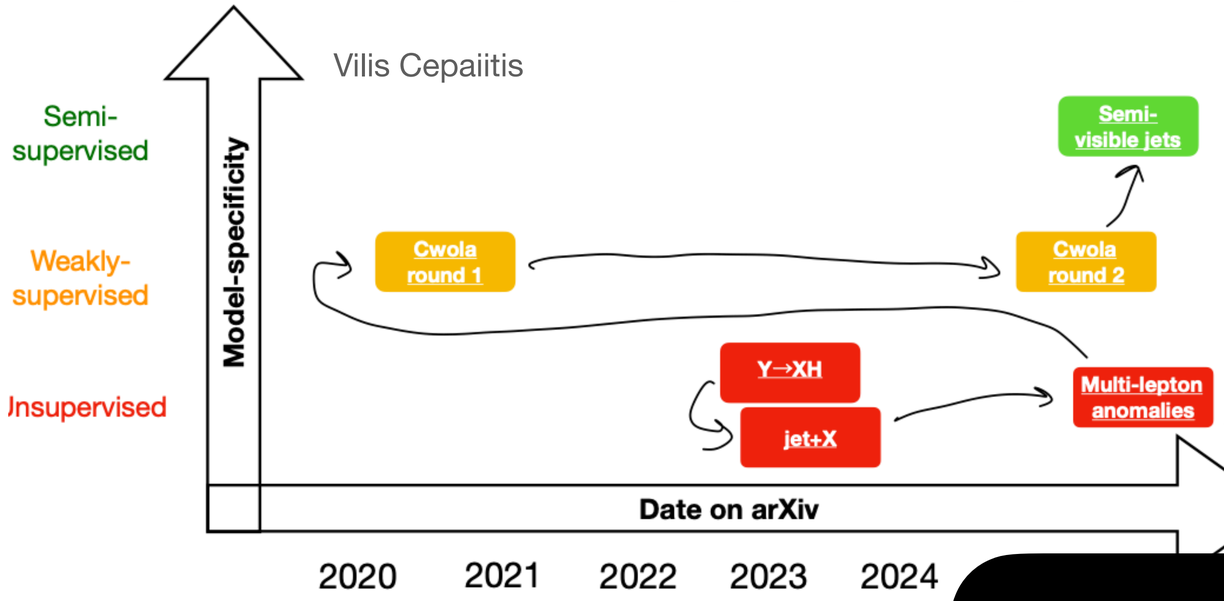

https://indico.cern.ch/event/1578072/contributions/6648741/attachments/3136689/5565917/CMS_Anomalies.pdf

- CMS and ATLAS have together published only a handful of AD searches, mostly on hadronic final states...
- But now we are breaking into leptonic final states!

# The ATLAS and CMS Anomaly Detection Papers

## ATLAS AD summary (as of Sep 2025)

Vilis Cepaiitis




https://indico.cern.ch/event/1578072/contributions/66
attachments/3136423/5565386/ADTopicalMeetingATL

## Overview

Louis Moureaux

**Data quality monitoring**

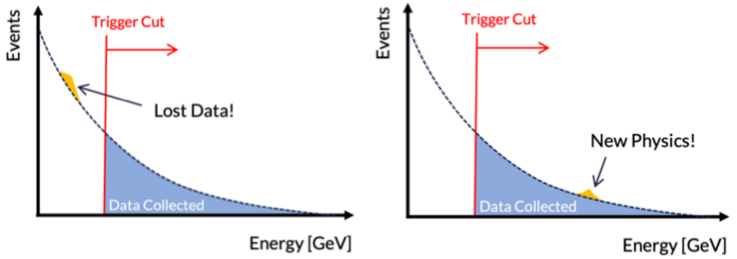
- ECAL [2309.10157]

**Offline**

- Dijet resonances [2412.03747]
- Study of the methods [CDS link]
- H(bb) + anomalous [CDS link]

**Triggers**

- AXOL1TL [CDS]
- CICADA [CDS]




/1578072/contributions/
3136689/5565917/
alies.pdf

Jack's thesis is an excellent example of this type of search, so I will direct you to his defence tomorrow for more details :)

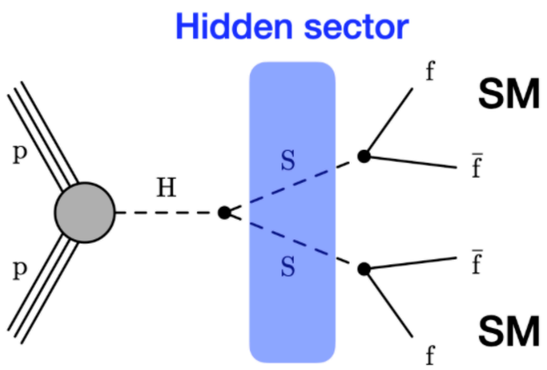
- CMS and ATLAS have togeth searches, mostly on hadronic final states...
- But now we are breaking into

# Re-interpretation and Analysis Preservation: Why it matters, why we are not currently successful, and how we can be.

# An example LLP search

**Search for neutral long-lived particles in $pp$ collisions at $\sqrt{s}$ = 13 TeV that decay into displaced hadronic jets in the ATLAS calorimeter**

https://arxiv.org/pdf/2203.01009




LHC Collisions

CalRatio Triggers — Low-$E_T$ & High-$E_T$ separately

Preselection
*On jet and event variables*

Per-Event BDT
*Separates signal & background events* — Low-$E_T$ & High-$E_T$ separately

Per-Jet NN
*Separates signal, QCD & BIB jets* — Low-$E_T$ & High-$E_T$ separately

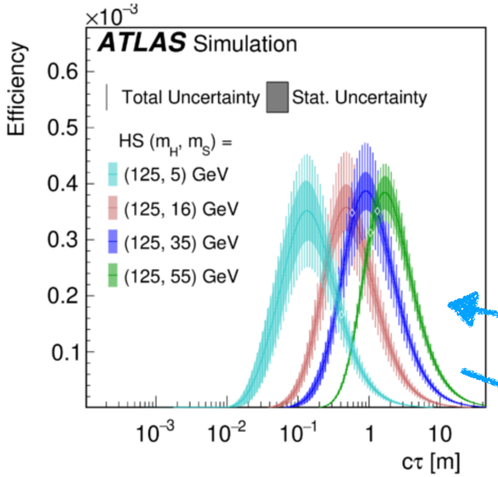
\+ event variables

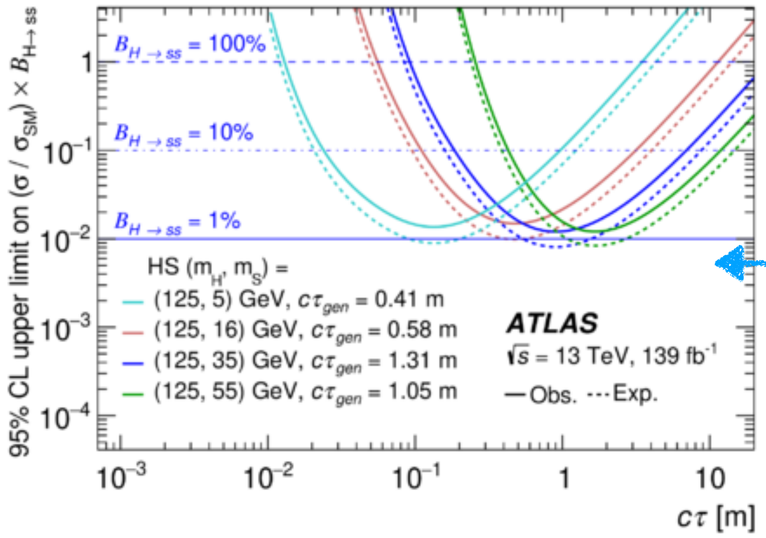
Event Cleaning & Final Selections — Low-$E_T$ & High-$E_T$ separately

ABCD Method
*Data-driven background estimation* — Low-$E_T$ & High-$E_T$ separately

Signal Significance & Limit-setting if applicable
*Includes lifetime extrapolation*

Key: Filtering; Calculation

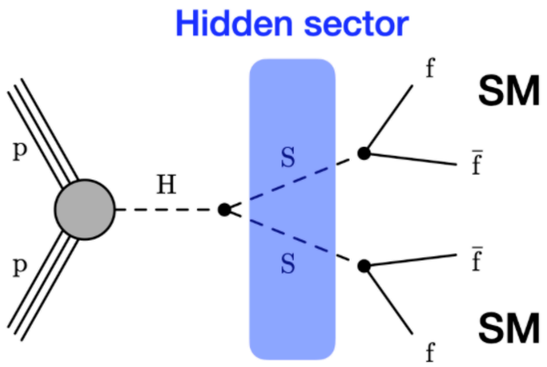


# Different lifetime?

**Search for neutral long-lived particles in $pp$ collisions at $\sqrt{s}$ = 13 TeV that decay into displaced hadronic jets in the ATLAS calorimeter**

https://arxiv.org/pdf/2203.01009




LHC Collisions

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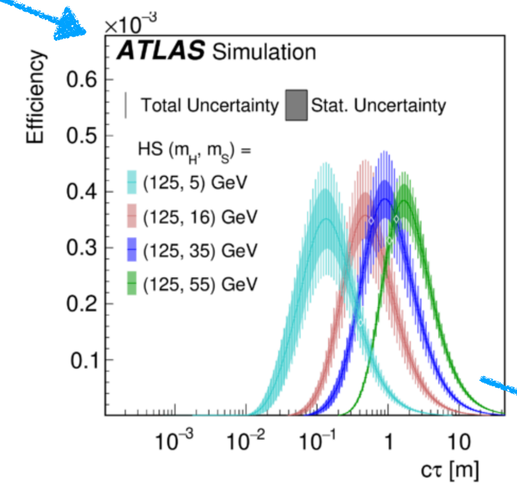


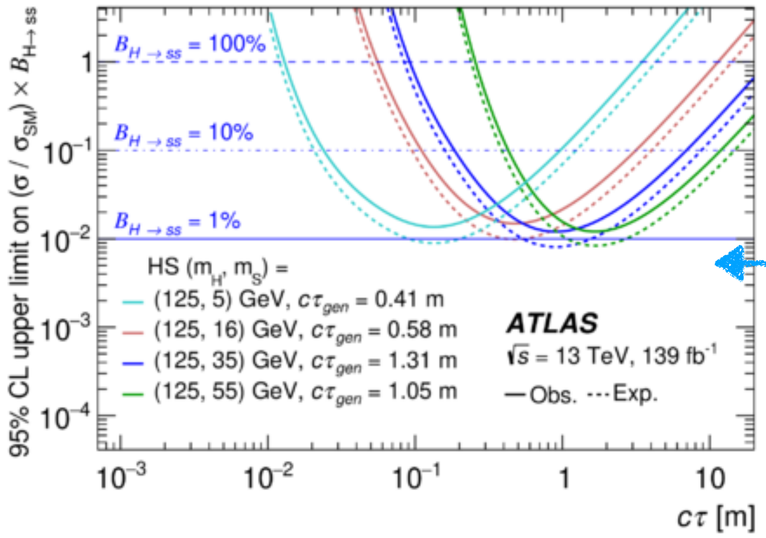

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**Search for neutral long-lived particles in $pp$ collisions at $\sqrt{s}$ = 13 TeV that decay into displaced hadronic jets in the ATLAS calorimeter**

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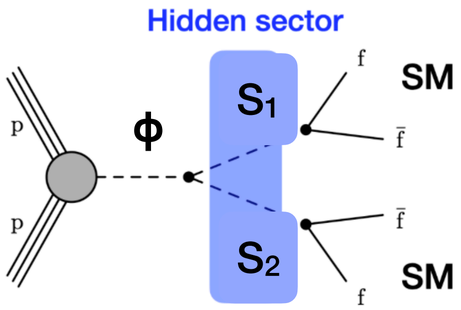


LHC Collisions

???

No way to re-interpret this search with published efficiencies ?

CalRatio Triggers — Low-$E_T$ & High-$E_T$ separately

Preselection
*On jet and event variables*

Per-Event BDT
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???

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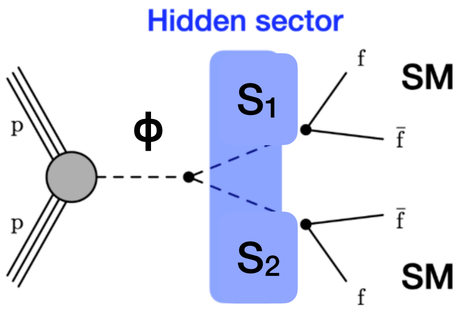



LHC Collisions

???

No way to re-interpret this search with published efficiencies ?

CalRatio Triggers — Low-$E_T$ & High-$E_T$ separately

Preselection
*On jet and event variables*

Low-$E_T$ & High-$E_T$ separately

Per-Event BDT
*Separates signal & background events*

Low-$E_T$ & High-$E_T$ separately

+ event variables

Per-Jet NN
*Separates signal, QCD & BIB jets*

Event Cleaning & Final Selections — Low-$E_T$ & High-$E_T$ separately

Inaccessible to theorists

ABCD Method
*Data-driven background estimation*

Low-$E_T$ & High-$E_T$ separately

Signal Significance & Limit-setting if applicable
*Includes lifetime extrapolation*

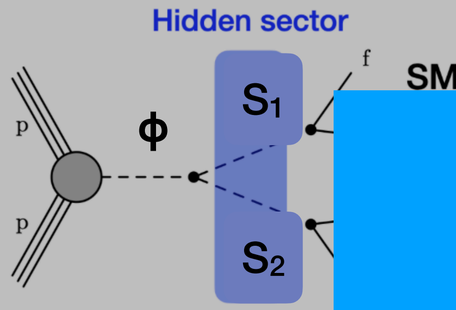
Key: Filtering; Calculation

???

# Different kinematics?

**Search for neutral long-lived particles in $pp$ collisions at $\sqrt{s} = 13$ TeV that decay into displaced hadronic jets in the ATLAS calorimeter**

https://arxiv.org/pdf/2203.01009




LHC Collisions

Same issue arises with basically ANY BSM search which uses machine learning.
(Most of them these days).

Should we now accept that none of our searches are never going to be re-used?

Or can we do better?

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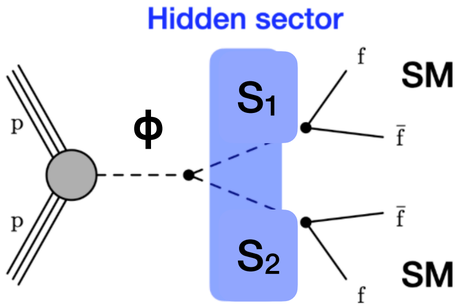
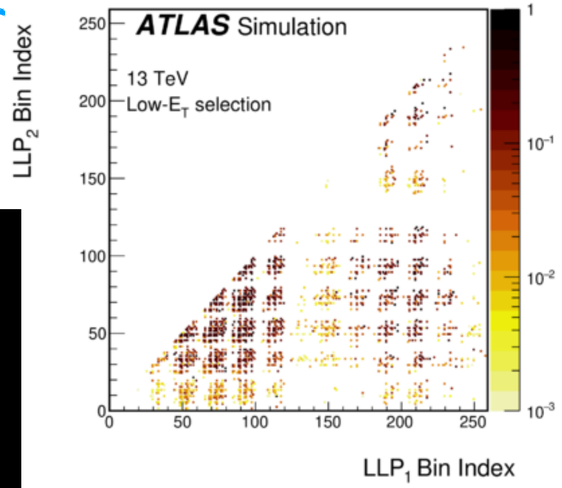



LHC Collisions




Six-dimensional efficiency map binned in LLP truth kinematics, decay position and decay mode

CalRatio Triggers — Low-$E_T$ & High-$E_T$ separately

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New limits

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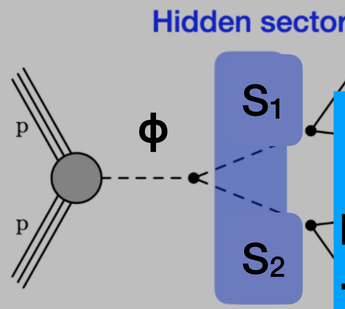



LHC Collisions

Nice advance, but hard to use:
- complicated rolling up of 8-dimensional map to 2-dimensions
- Slow and difficult to query
- Hard to get binning right
- Unfamiliar to theorists and fiddly to use.

Thus the idea to pass to a Boosted Decision Tree, which is the natural generalisation of a multi-dimensional map:
- No need for the "rolling" of dimensions, provide the inputs directly
- Fast to train and query (using eg Python SciKitLearn)
- Effectively automates binning choices
- Well-known format, can export as industry-standard ONNX, easy to integrate in downstream tools

-> Has come to be known as the "Surrogate Model" (SuMo) method

Low-$E_T$ & High-$E_T$ separately

t NN

QCD & BIB jets

ey

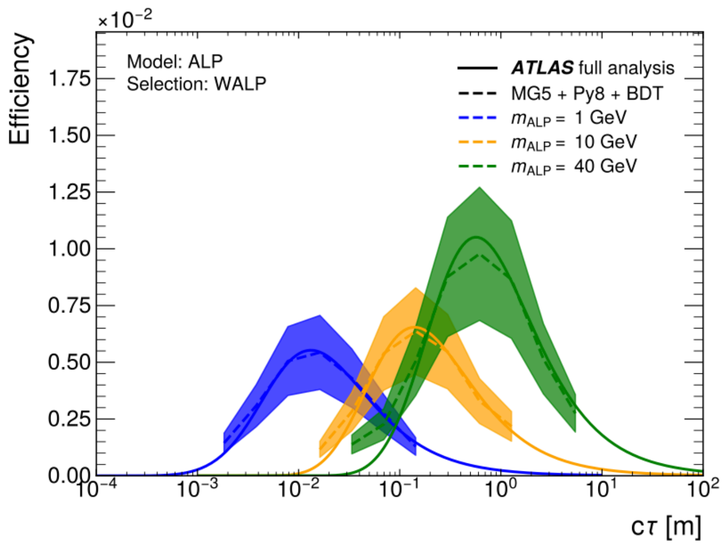
ering

ulation

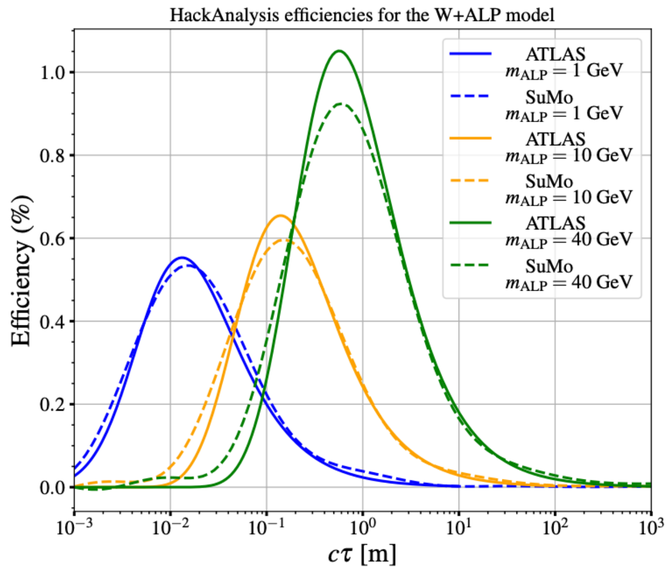
# A SuMo for the displaced jets search

- SkiKitLearn RandomForest classifier (BDT).Trained on analysis signal samples using truth-level inputs (both LLP kinematics, decay positions, daughter PDG id).
- Validated using independently generated samples.
- Available as ONNX file on analysis HEPData, already integrated in HackANalysis re-interpretation tool

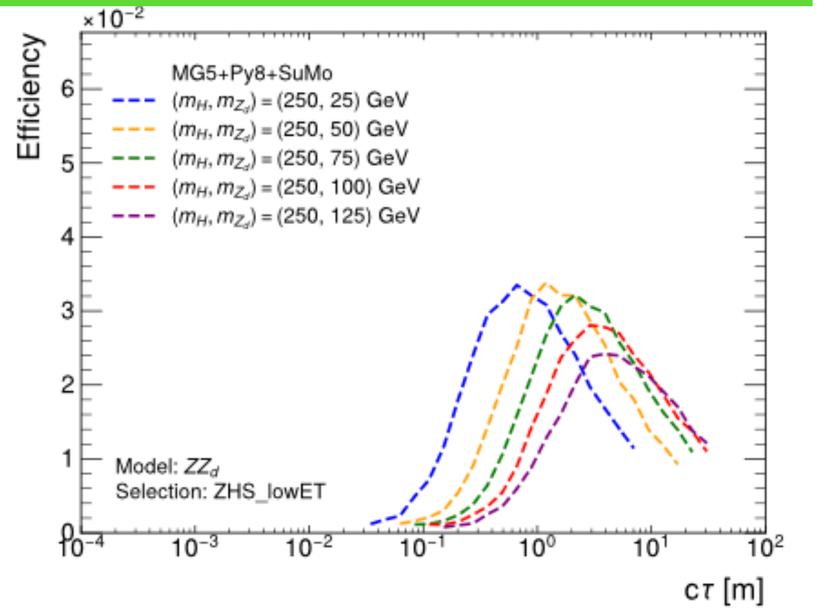
**Reproduce published results with high accuracy...**




**Easily port ONNX files to new frameworks (eg HackAnalysis)**




**Interpolate between mass points... Or new models with different kinematics !**

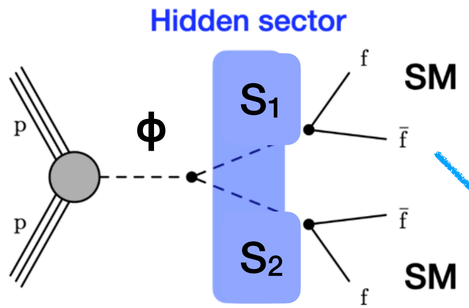



https://arxiv.org/abs/2502.10231

# Different kinematics?

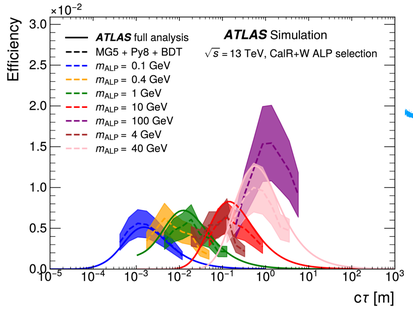
**Search for neutral long-lived particles that decay into displaced jets in the ATLAS calorimeter in association with leptons or jets using $pp$ collisions at $\sqrt{s} = 13$ TeV**

https://arxiv.org/pdf/2407.09183

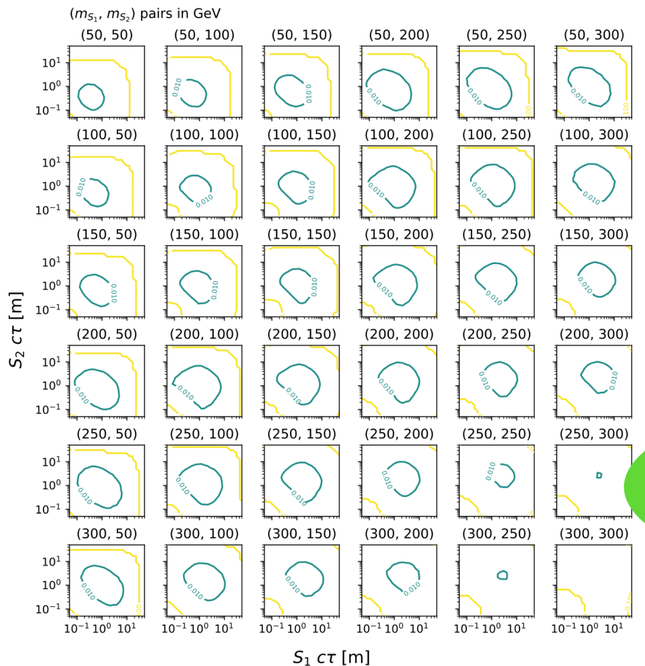



LHC Collisions

Surogate Model




https://arxiv.org/abs/2502.18021




- CalRatio Triggers — Low-$E_T$ & High-$E_T$ separately
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Key: Filtering, Calculation

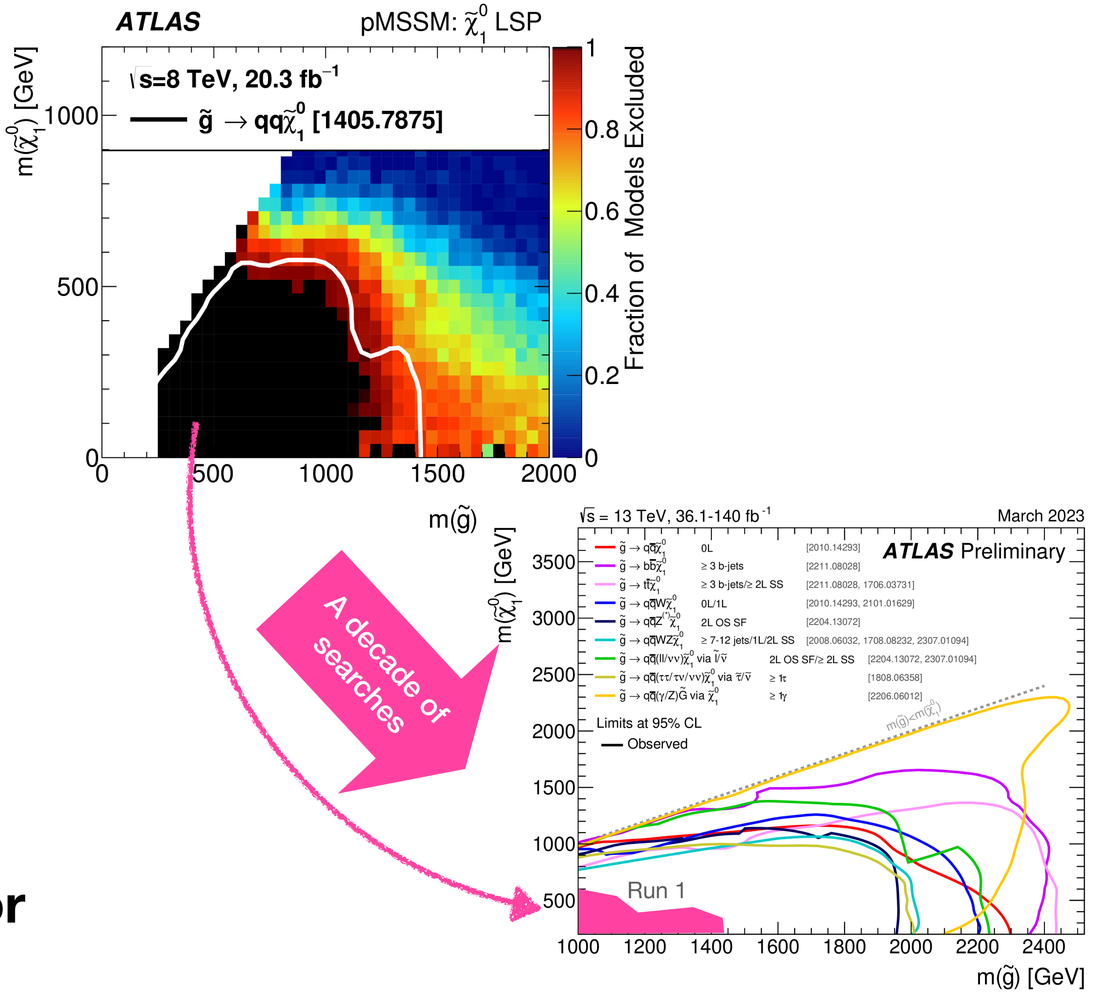
New limits on previously unprobed model

# A solution to the wider re-interpretation problem

- "LLP re-interpretation problem" is an almost maximally-difficult case.
- The Surrogate Model method appears to work well, even with a "simple" BDT trained on a local machine with only 10 trees, and without any calibration.
- More complex ML methods may do even better!
- Allows theorists to input truth-level information to evaluate full analysis selection probability for each event.
- Caveats: how to define uncertainties, bounds of applicability, safety checks, etc?
- Nevertheless, systemically training surrogate models could provide a route to mass re-interpretability of *all* LHC search results, which could then be included in downstream recasting tools (eg Rivet, MadAnalysis...)

# To finish: what have we achieved with Run 1+2 ?

- After 15 years of LHC operation...
  **we have not discovered any BSM particles or processes.**
- ...but **lack of discovery ≠ null result.**
- Before LHC turned on, theory community convinced SUSY was "just around the corner".
  - Today, SUSY at EW scale **pushed back** to more **remote corners** of parameter space.
  - Still a great candidate for BSM, but not in its most obvious realisations (compressed spectra?)
- **The LHC has already revolutionised our best guess for the underlying nature of fundamental physics.**
- Similarly, simple DM models are also largely excluded at TeV scale. These are **big achievements!**



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# Final thought :

# Surprises can still happen !

# Surprises can still happen

https://arxiv.org/pdf/2503.22382

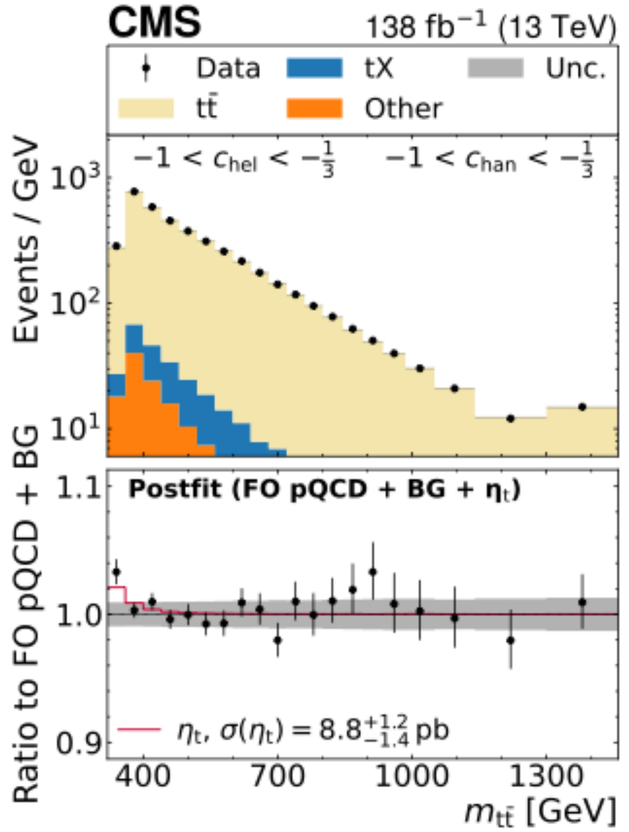
Observation of a pseudoscalar excess at the top quark pair production threshold

The CMS Collaboration*

https://cds.cern.ch/record/2937636

**Observation of a cross-section enhancement near the $t\bar{t}$ production threshold in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector**

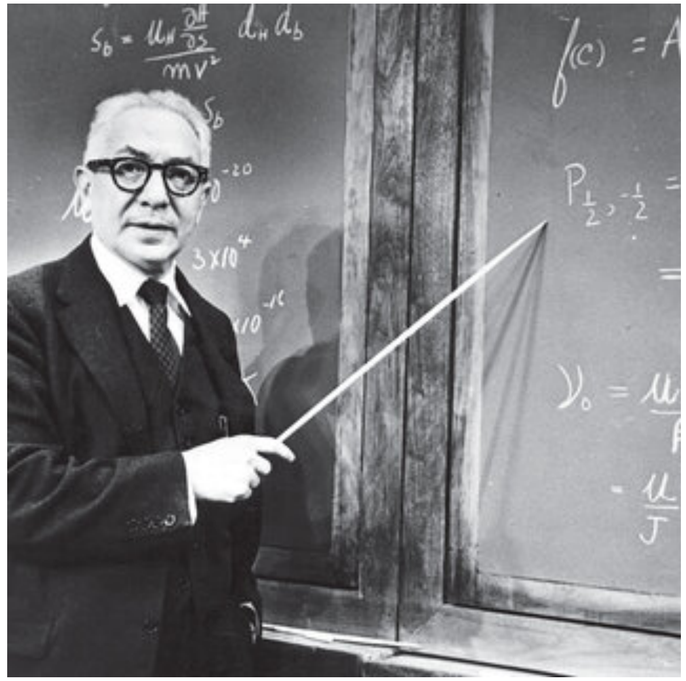
The ATLAS Collaboration




A deviation from the background prediction, modeled only using pQCD, is observed. It is located close to the $t\bar{t}$ production threshold, similar to the moderate deviation observed in a previous CMS search based on a data sample corresponding to an integrated luminosity of 35.9 fb$^{-1}$ [24]. This deviation significantly favors the pseudoscalar signal hypothesis over the scalar hypothesis. It is compatible with the production of a $^1S_0^{[1]}$ $t\bar{t}$ bound state $\eta_t$, as predicted by a simplified model of nonrelativistic QCD. The cross section of this contribution is found to be $\sigma(\eta_t) = 7.1$ pb, with an uncertainty of 11%. The excess has a significance of above five standard deviations. Further investigations by both the experimental and theoretical communities are necessary to elucidate the nature of this excess.

Could have been a BSM resonance ... dress rehearsal for unexpected discovery ?

# Surprises can still happen

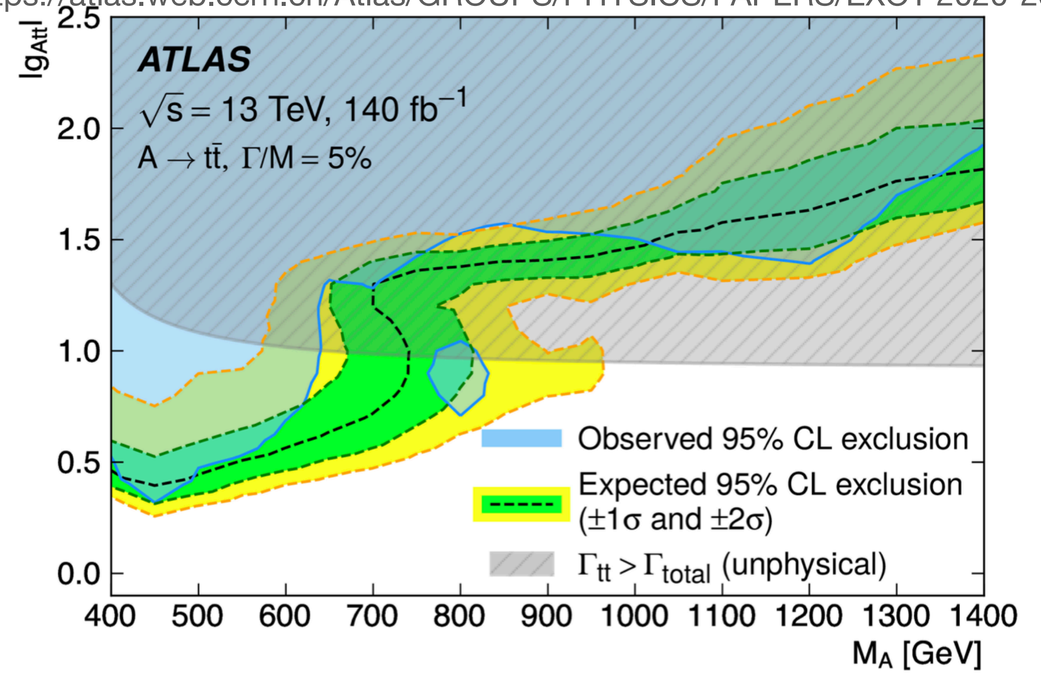


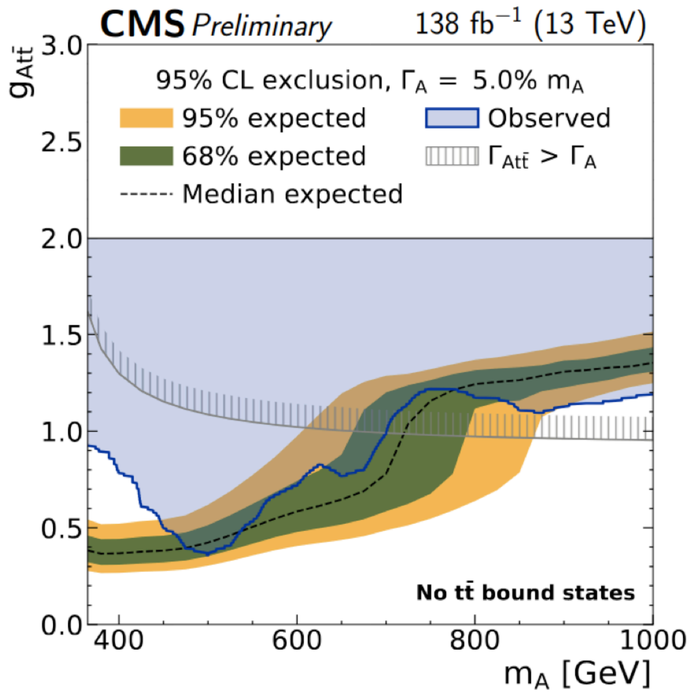
*“ Who ordered that ? ”*

I. Rabi on the discovery of the muon.... Also applies to "toponium"

# But a few months earlier...

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2020-25




- ATLAS seemingly excluded (at 95%CL) the same discovery they confirmed a few months later... We need to be careful about this!
- Treatment of theory systematics, different signal model... and plain old confirmation bias ?
- Is there a risk that a BSM discovery could similarly be disregarded ?

# In conclusion

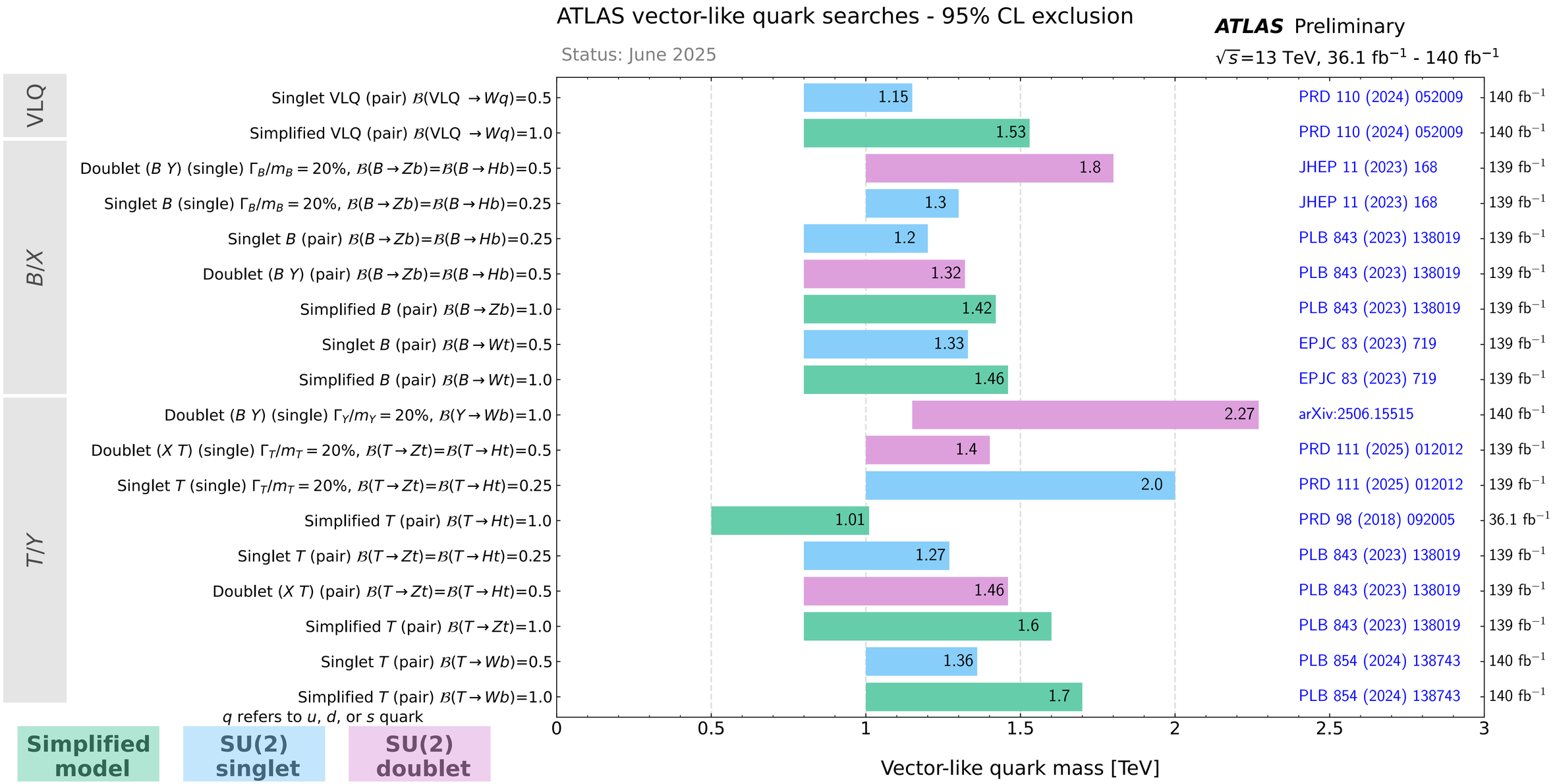
- I have tried to use this talk to give you an idea of the thinking on the ATLAS side of the Ring for Exotics
- The **search for new particles** or interactions is one of the **key deliverables of the LHC** programme (there is more to life than Higgs self-coupling)
- Task is not easy to define, but with some thought can create a **strategy which maximises our chances** to reach our objective
- In short: **dig deep for well motivated "flagship" models**, **dig widely for things we don't expect.**
  - **Plan our papers** such that we get maximum impact from extra data and developments, and plan for long-term legacy
  - **Every single search should be exciting**.
  - Every single unblinding **teaches something new** about nature.
- We are pulling our weight: the **search community is heavily invested in the detector** operation and upgrade.
- We're in the **endgame** of the LHC. **We have a plan**.

# Backup

# What are VLQs



# VLQs




**Simplified model** | **SU(2) singlet** | **SU(2) doublet**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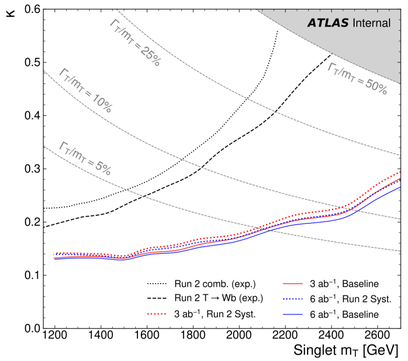
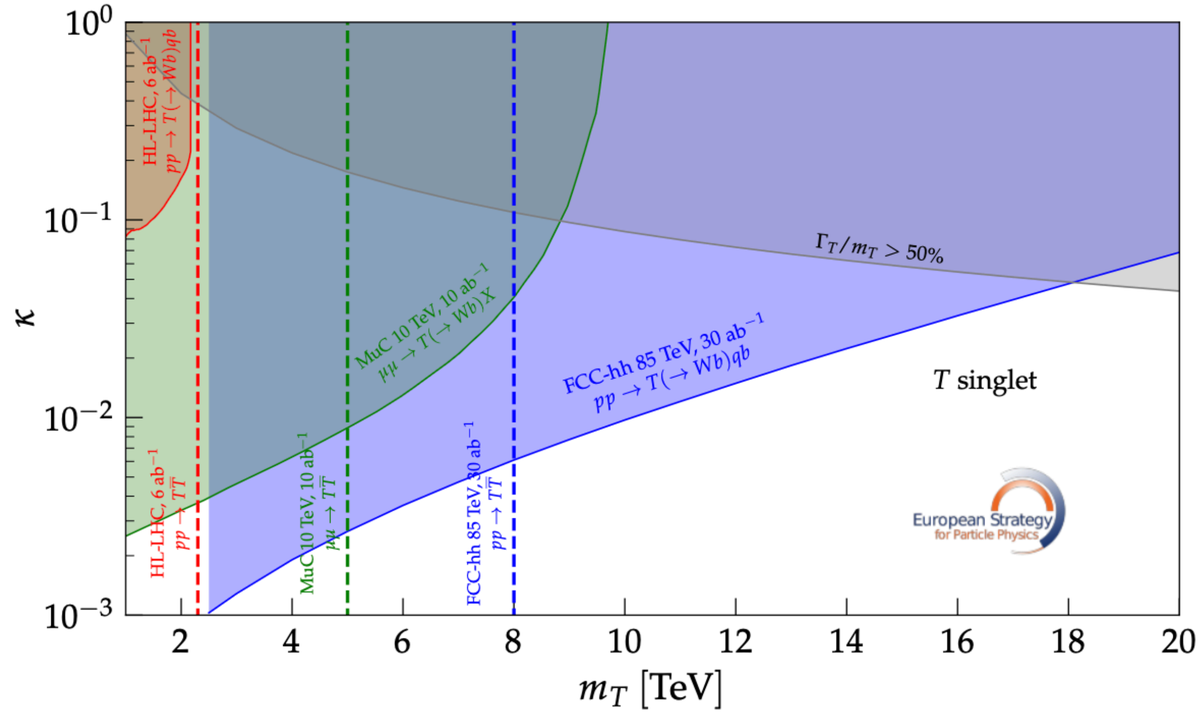
# VLQs - the long view

Run 2 comb beaten but this single quark - better to invest

EPPSU briefing book




t some stage we become syst limited and not stat limited



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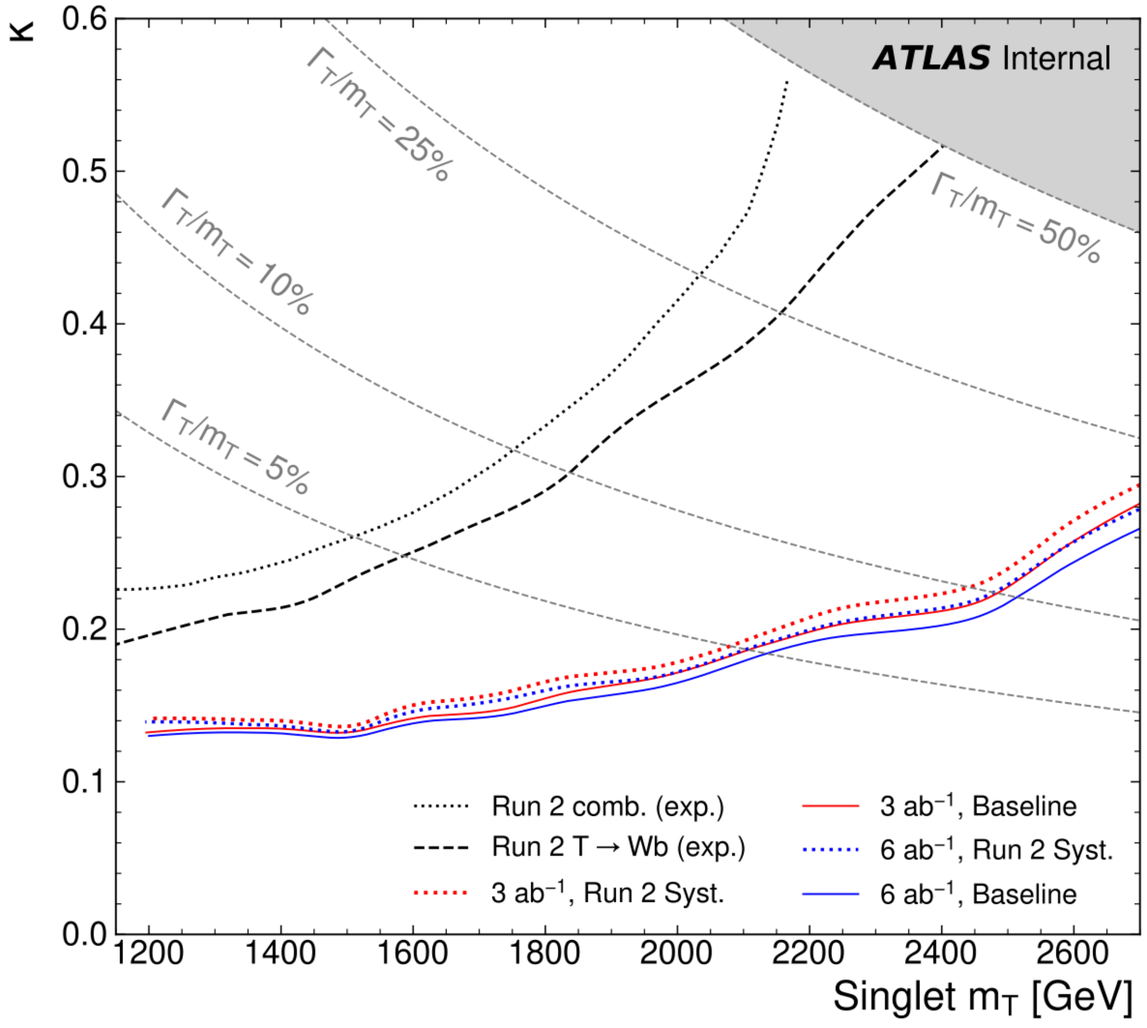
ATLAS Internal
K
0.6
0.5
0.4
0.3
0.2
0.1
0.0
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1600
1800
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2200
2400
2600
Singlet m_T [GeV]
Γ_T/m_T = 25%
Γ_T/m_T = 10%
Γ_T/m_T = 5%
Γ_T/m_T = 50%
Run 2 comb. (exp.)
Run 2 T → Wb (exp.)
3 ab⁻¹, Run 2 Syst.
3 ab⁻¹, Baseline
6 ab⁻¹, Run 2 Syst.
6 ab⁻¹, Baseline

# Resources: Tools

- **New technologies** can change the way we do searches. Examples:

# Resources: Tools

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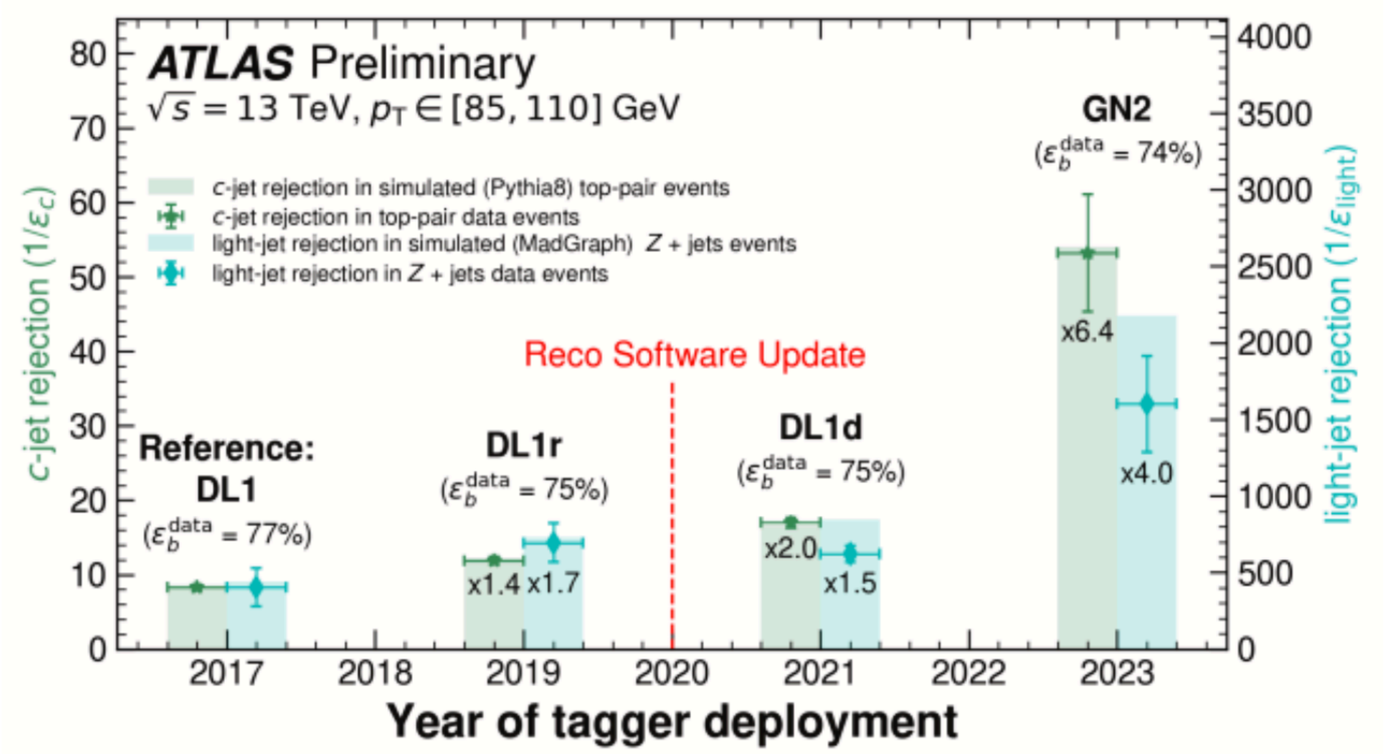
  - **Machine learning**: eg Graph Neural Networks unlocked c-tagging, and access to new parameter space

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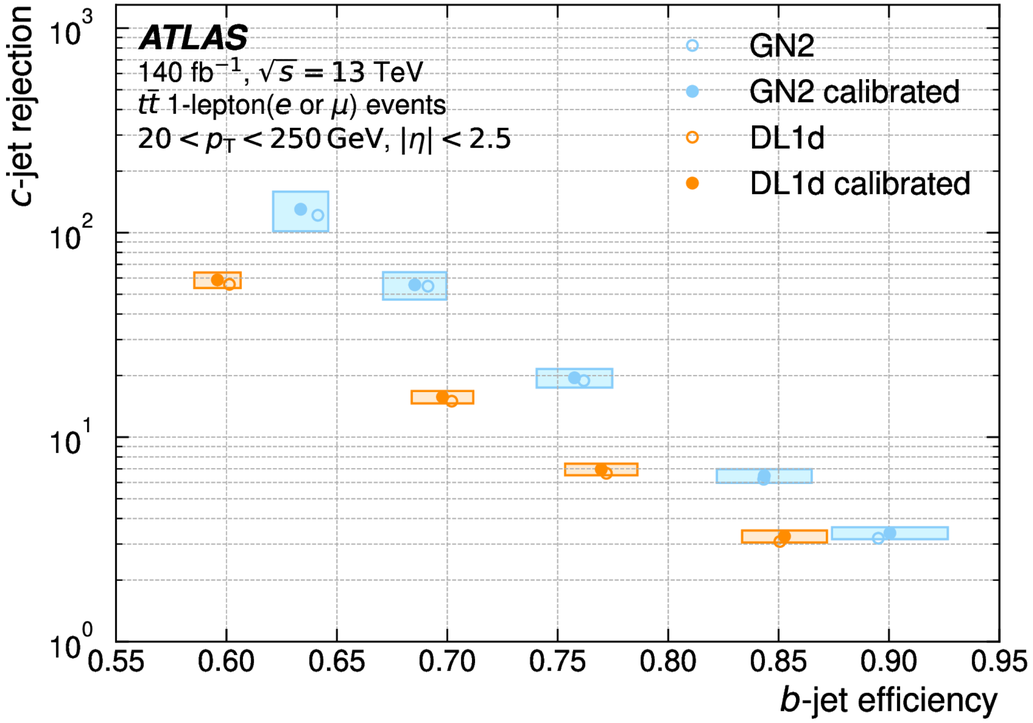
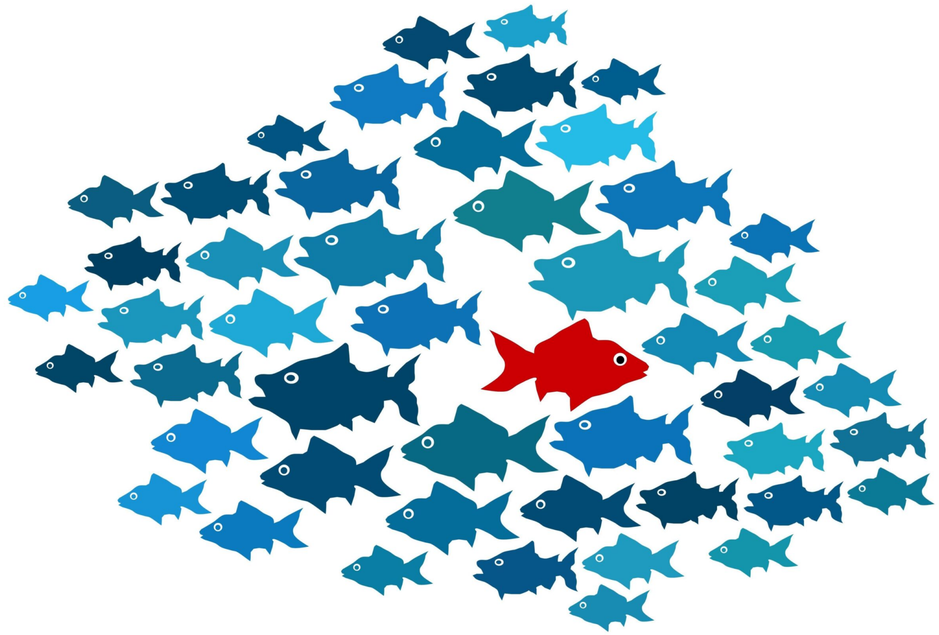



Nature Commun. 17 (2026) 541

https://arxiv.org/abs/2505.19689

# Resources: Tools

- **New technologies** can change the way we do searches. Examples:
  - **Machine learning**: eg Graph Neural Networks unlocked c-tagging, and access to new parameter space
  - **Anomaly detection:** cover large parts of model space quickly but with reduced sensitivity
    - **More about this later!**



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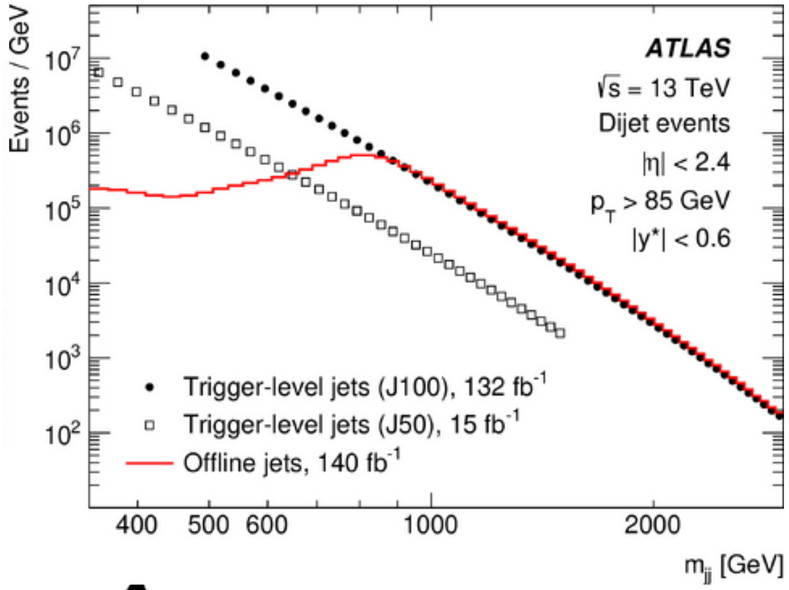
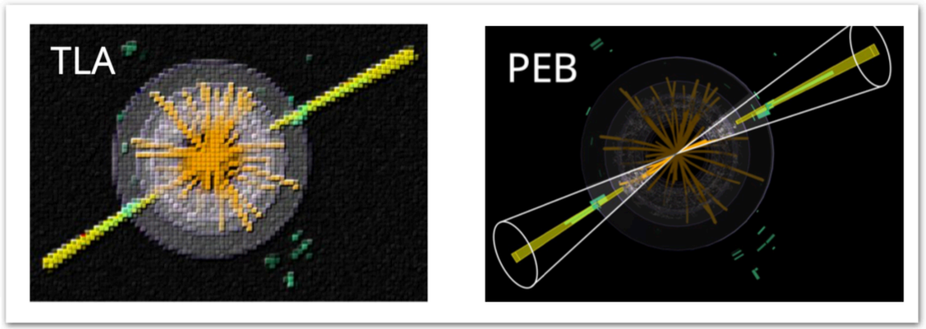
  - **Machine learning**: eg Graph Neural Networks unlocked c-tagging, and access to new parameter space
  - **Anomaly detection:** cover large parts of model space quickly but with reduced sensitivity
  - Extensive **Trigger-level Analysis/Partial Event Building** programme to explore trigger-limited regions




- Single and Multi-Jets
- Flavour Tagging
- Photons
- Partial-Event Building

**Bandwidth = Rate x Event Size**

≈ = ↑↑ x ↓↓




A. Salvador