


Horizon 2020
European Union funding
for Research & Innovation

Searches for Dark Matter mediators with DARKJETS

or: how to make the most of LHC data

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 679305)

Caterina Doglioni - Lund University

06/04/2016 - ATP Talk

What do we know about dark matter?

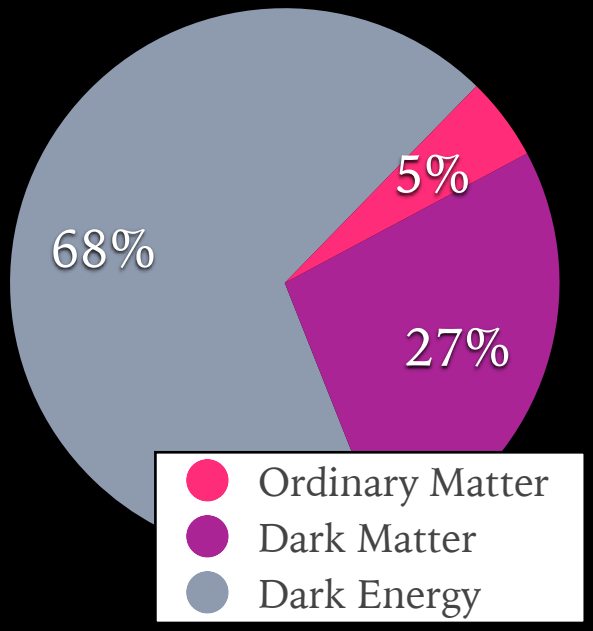
it is dark

it is dark

it has mass

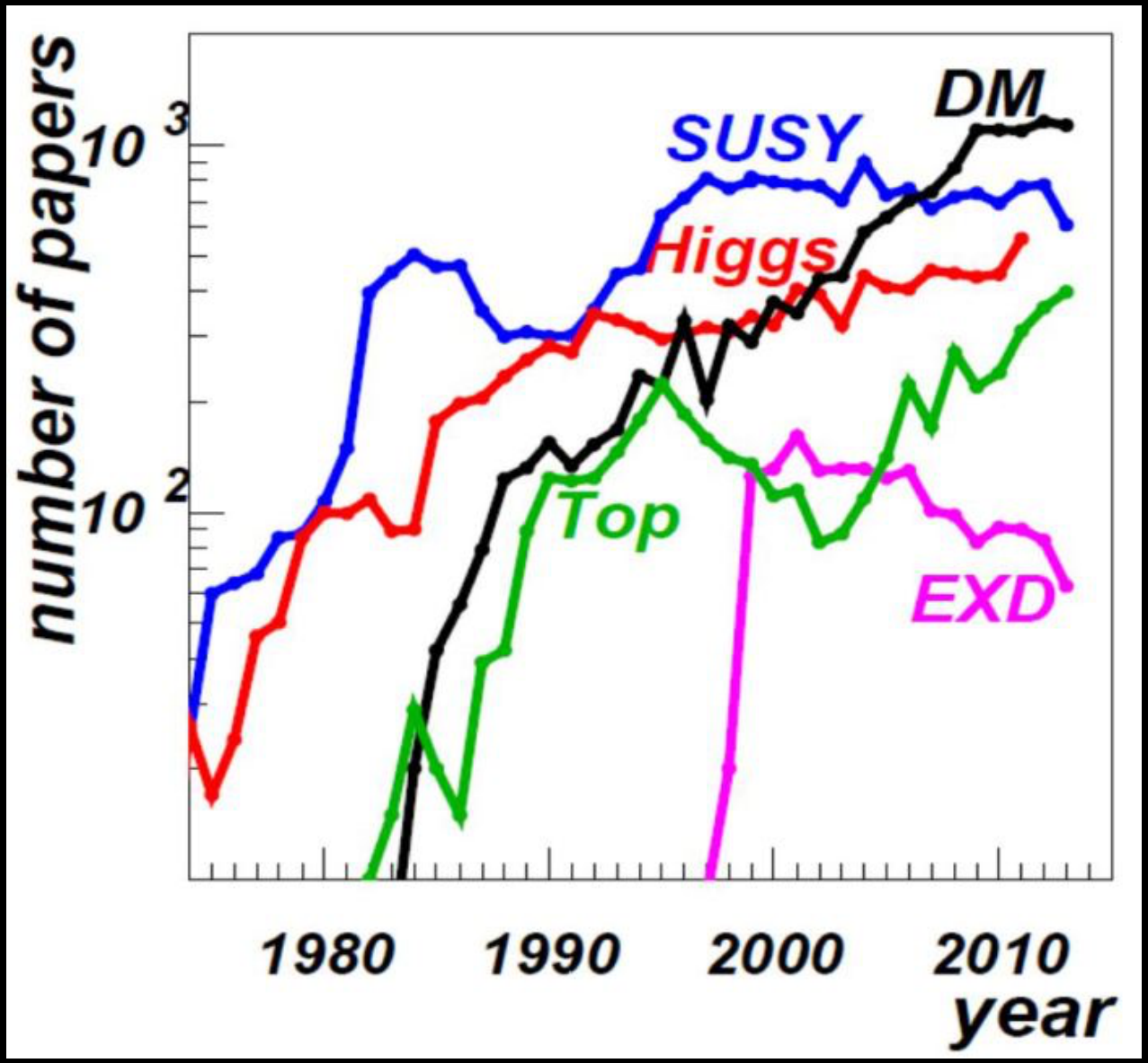
it is dark

it has mass

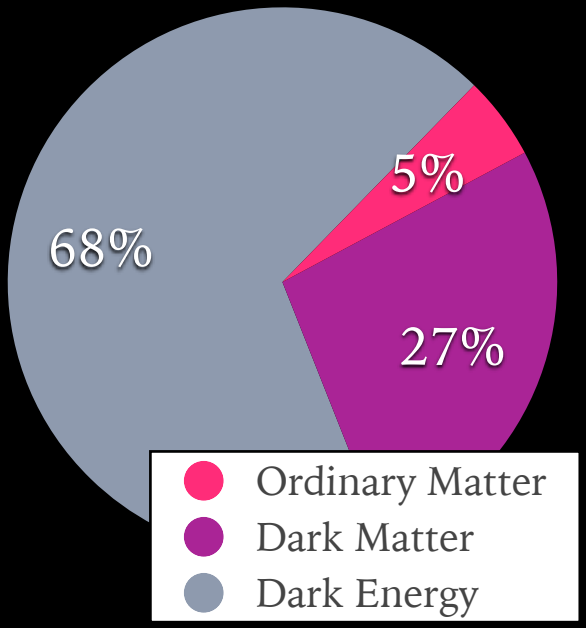


it constitutes
most of the matter
in the universe

many physicists are talking about it



A. Belyaev



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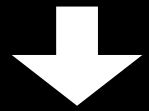


relic density

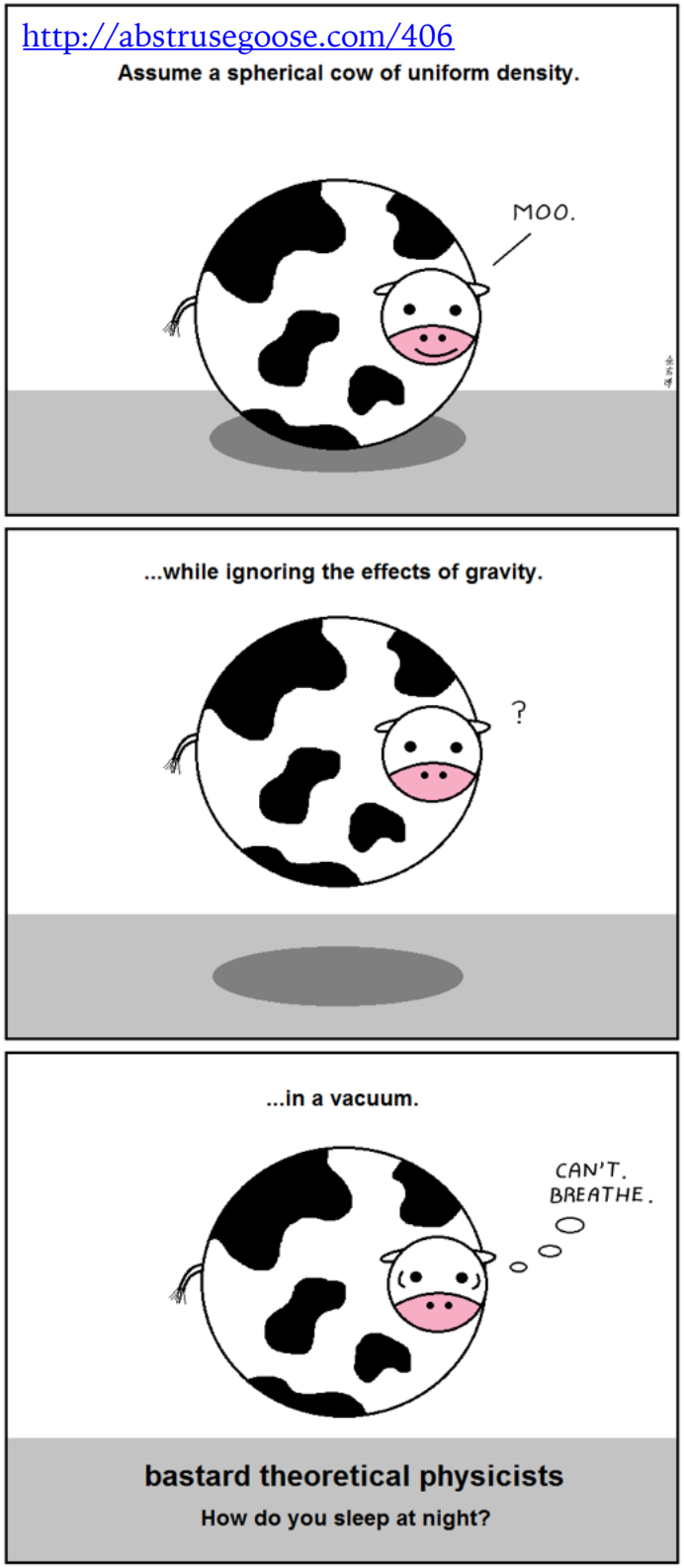
This relic density can be explained with

a new particle

- that interacts only weakly with known matter
- with mass in the range of current experiments

(WIMP)

Under these assumptions…

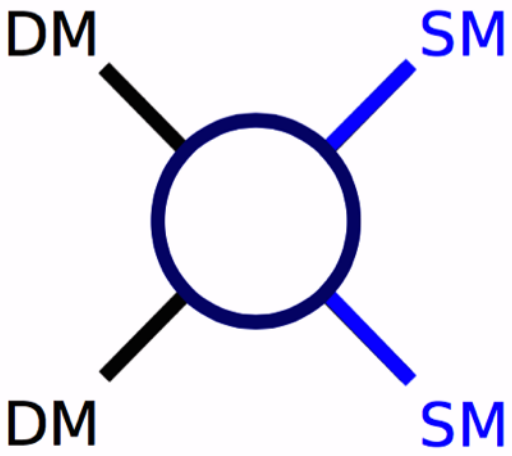


…we could discover Dark Matter!

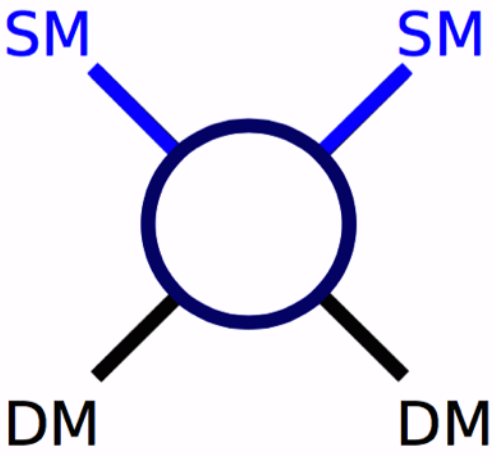
How to discover Dark Matter

Dark Matter

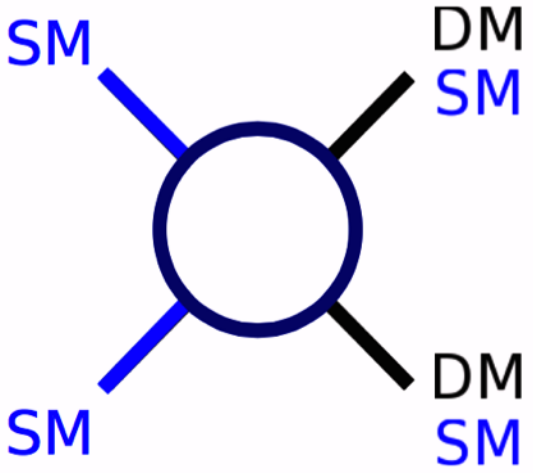
Ordinary particles



Indirect Detection



Direct Detection

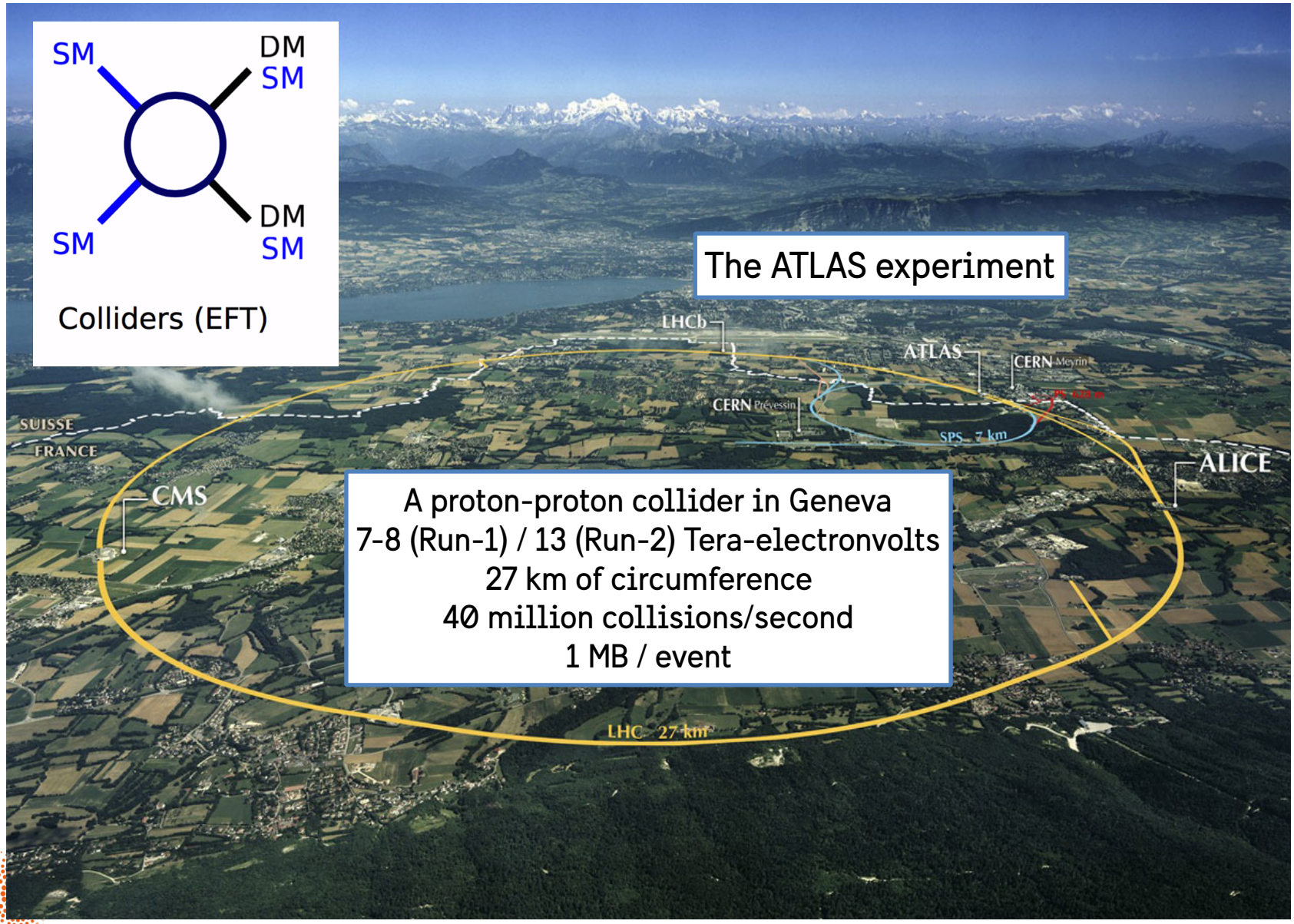


Particle Colliders

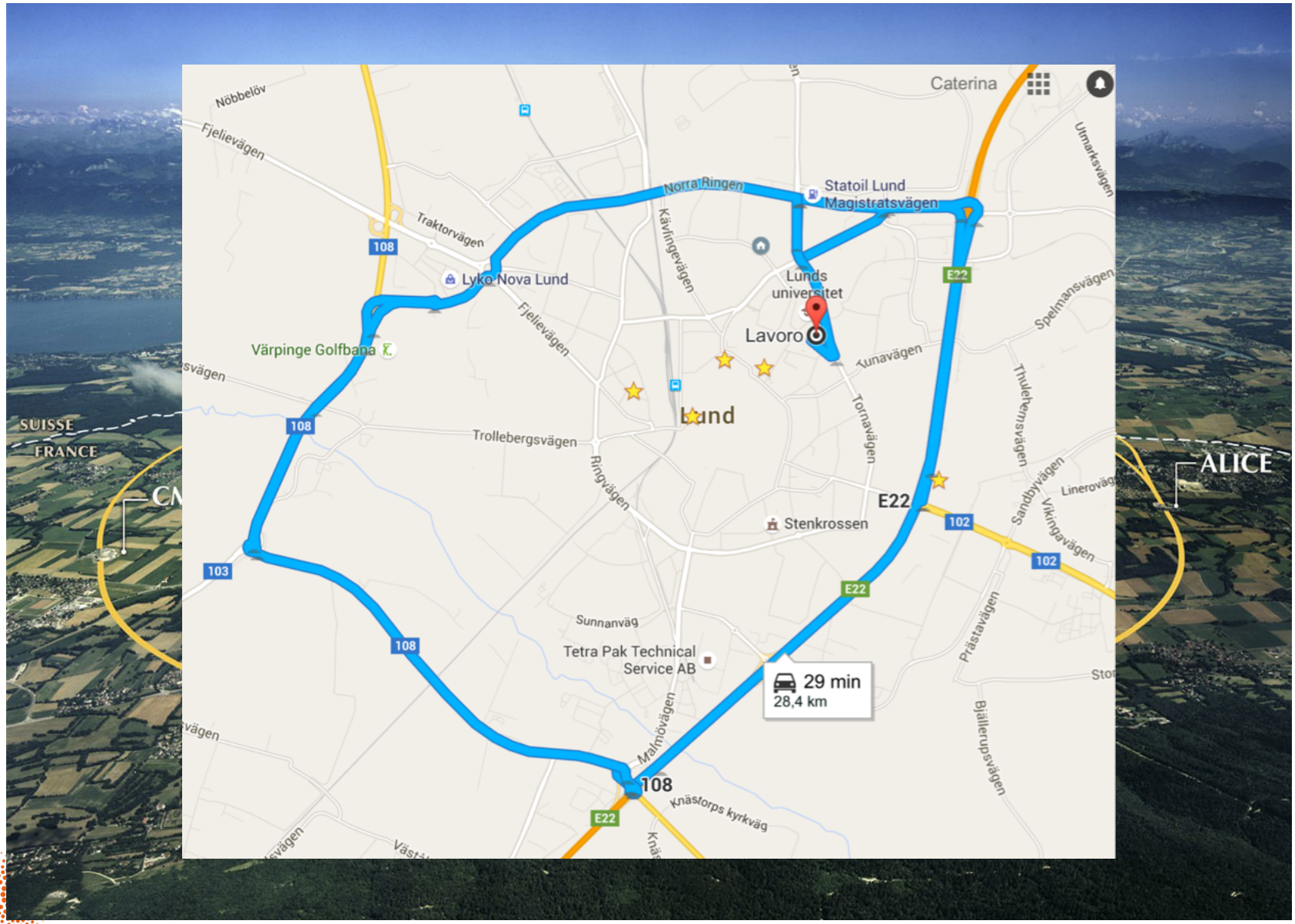
Complementary experimental strategies

Looking for **small signals** over **large backgrounds**

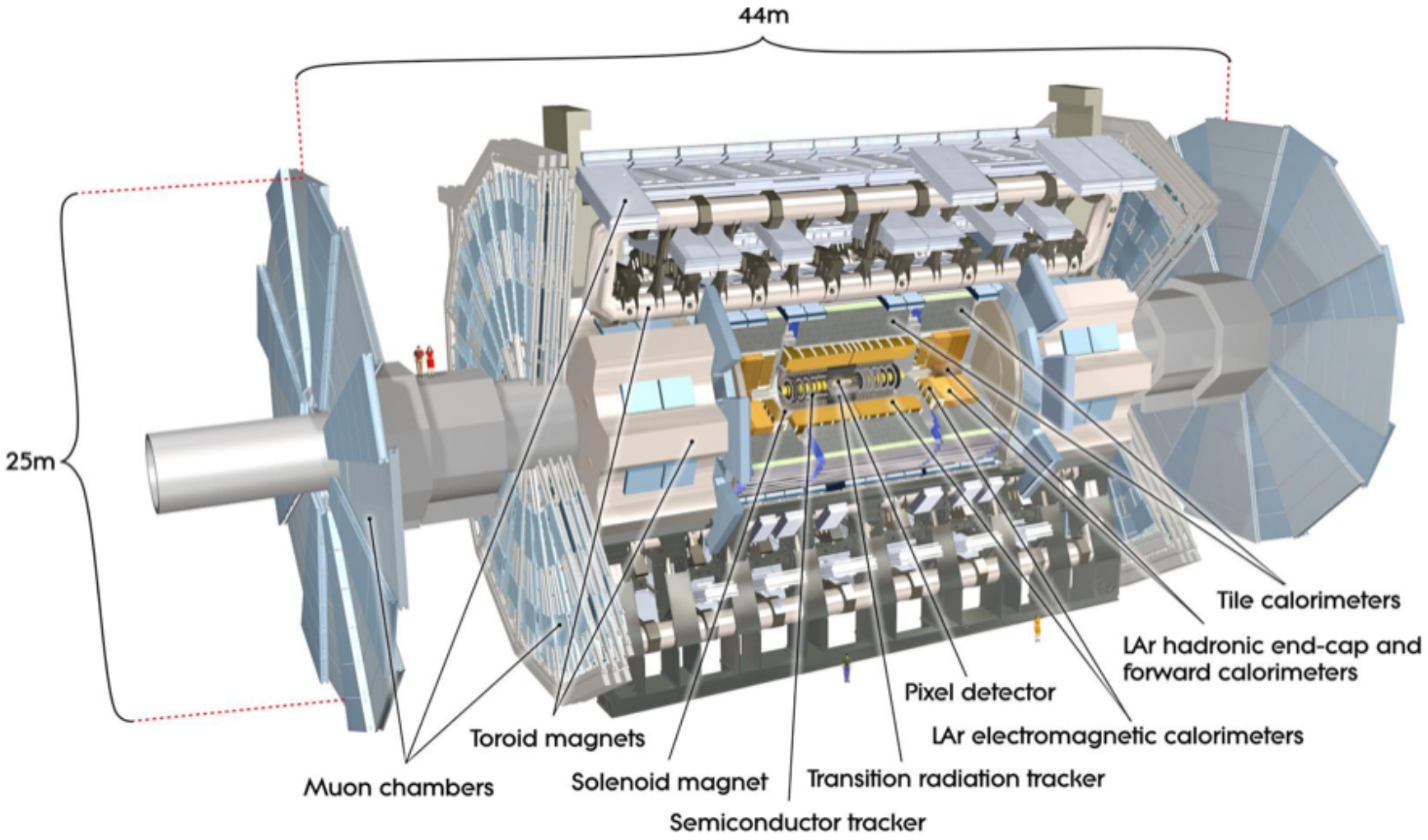
LHC: the biggest man-made discovery machine



LHC: the biggest man-made discovery machine



The ATLAS detector

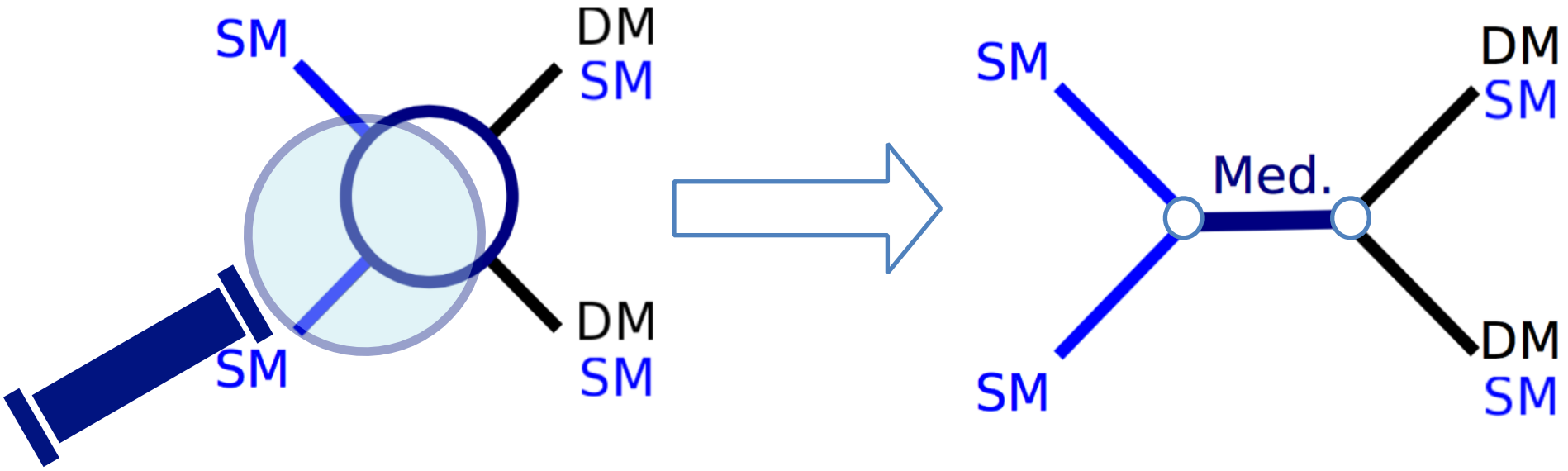


>96% working channels (pixels, cells…) in each sub-detector

[ATLAS detector status]

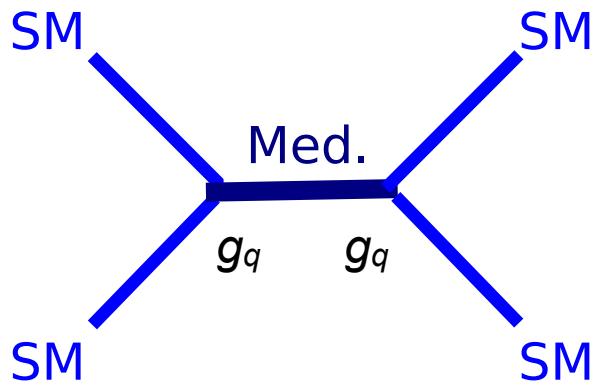
Dark Matter mediators at the LHC

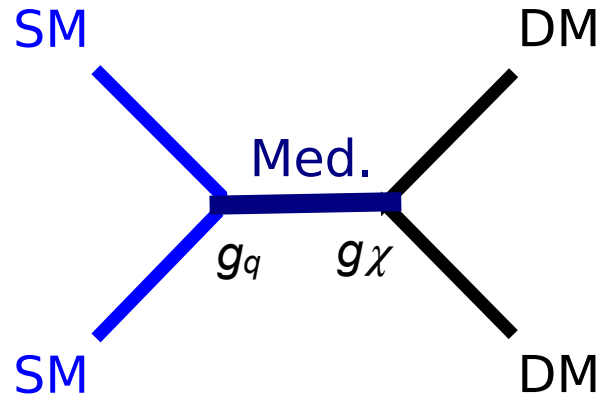
These new particles are what we look for with DARKJETS

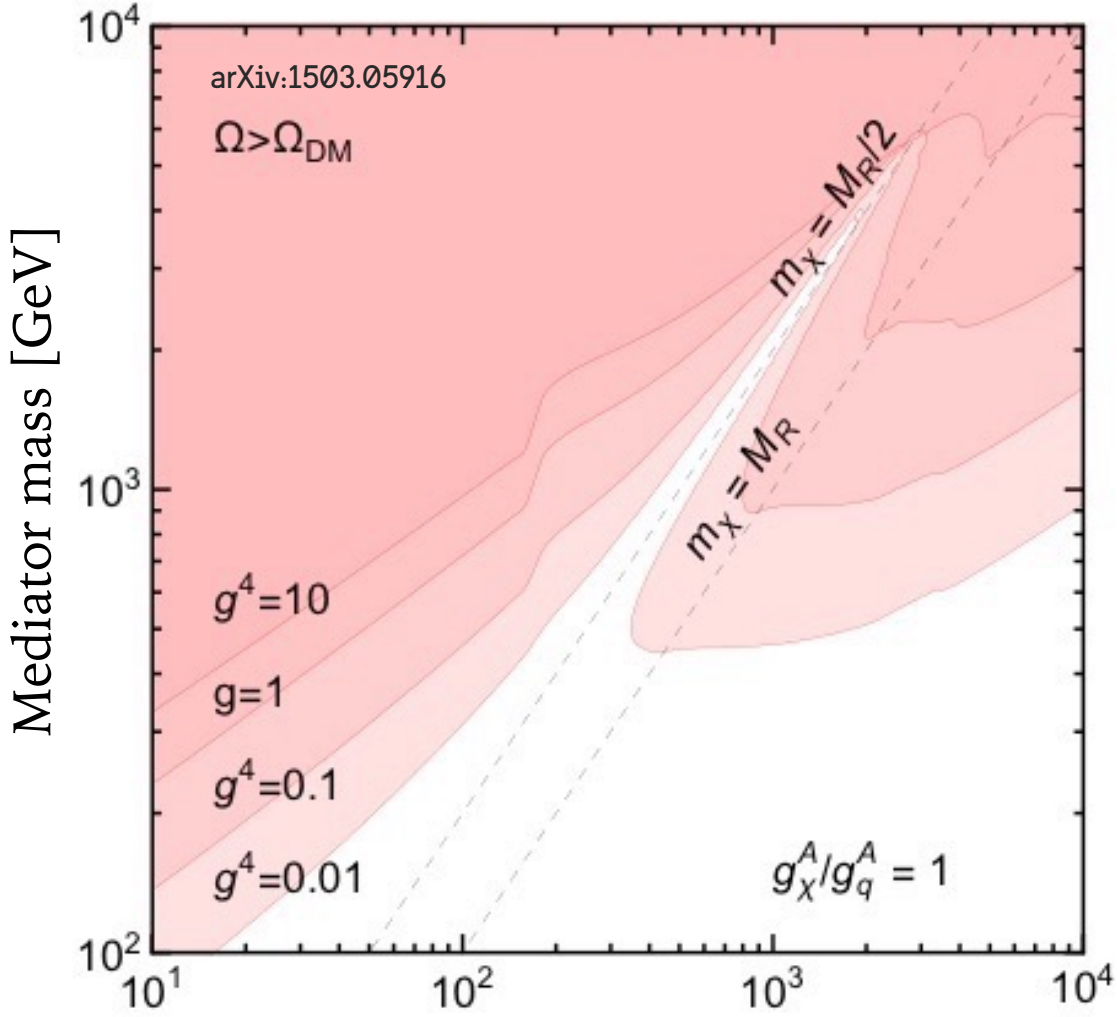


To make up for relic density:
mediators should have **low masses**

Dark Matter mediators: decays

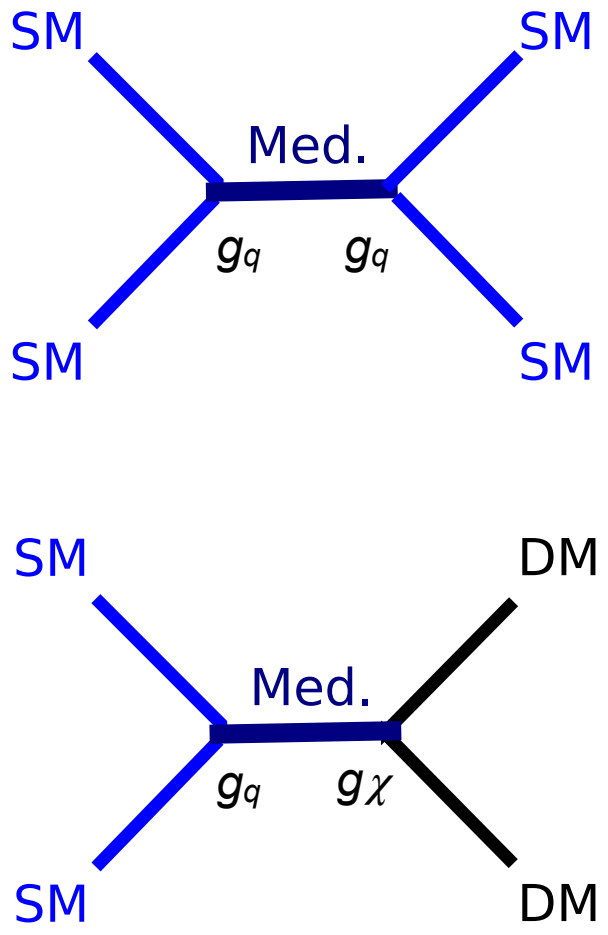


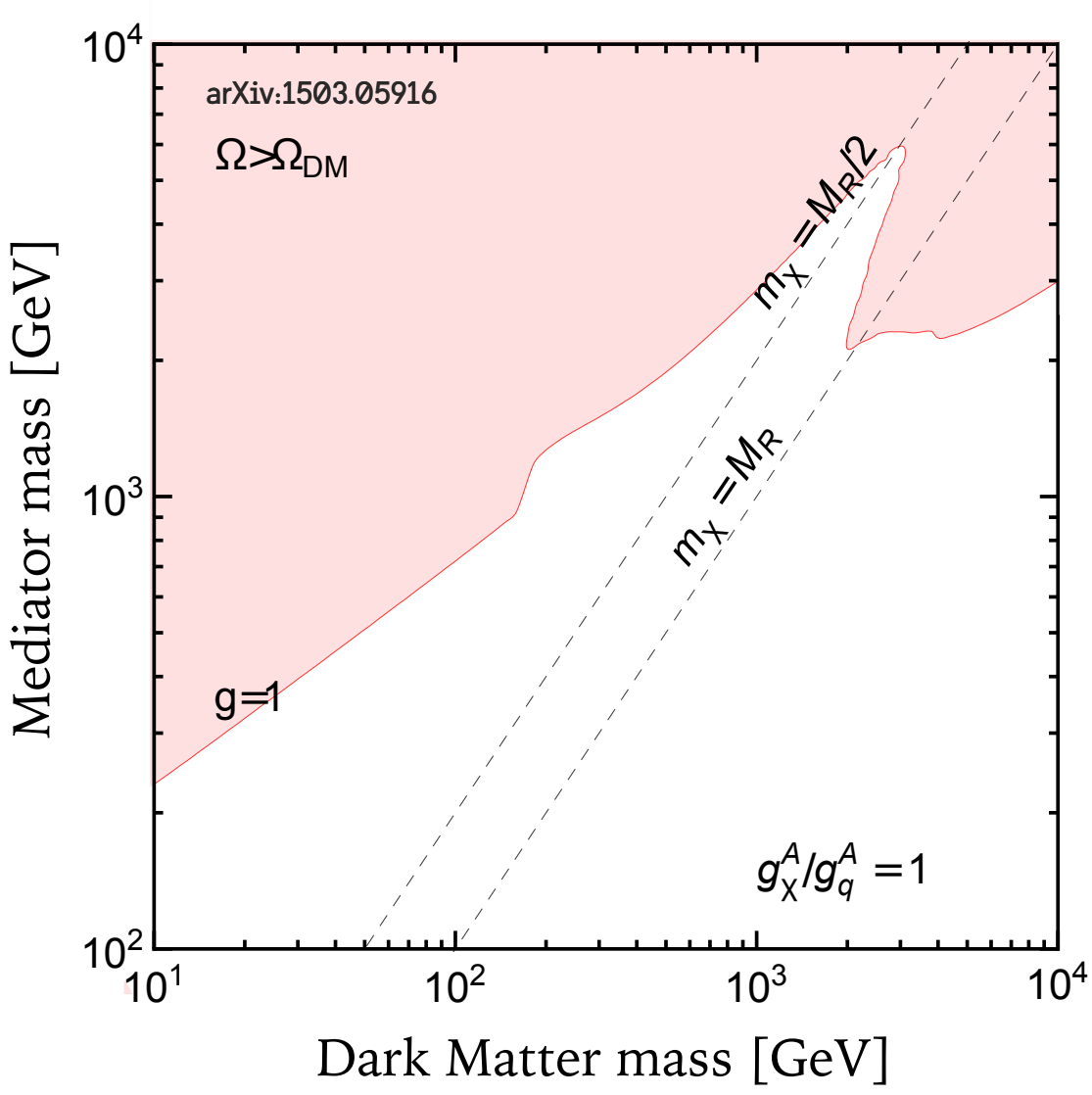




$$g \equiv (g_q^A \, g_\chi^A)^{1/2}$$

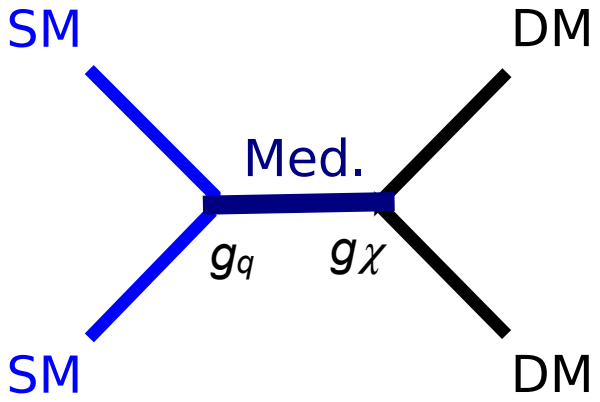
Dark Matter mediators: decays





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

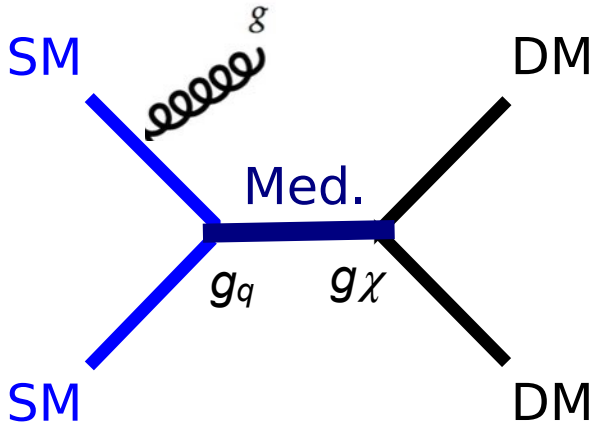
Looking for Dark Matter at the LHC



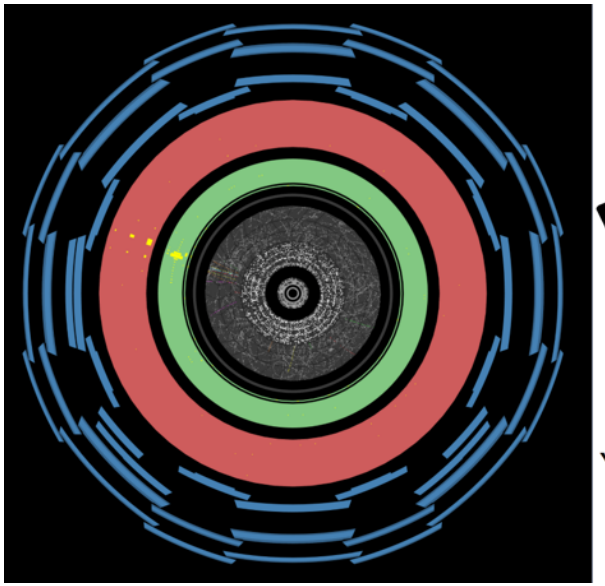
A WIMP is invisible to detectors!

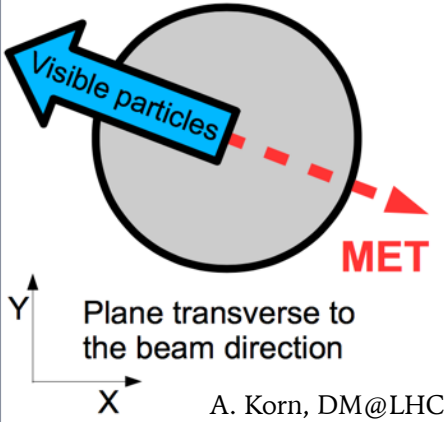
Looking for Dark Matter at the LHC

Signature: **missing transverse momentum**

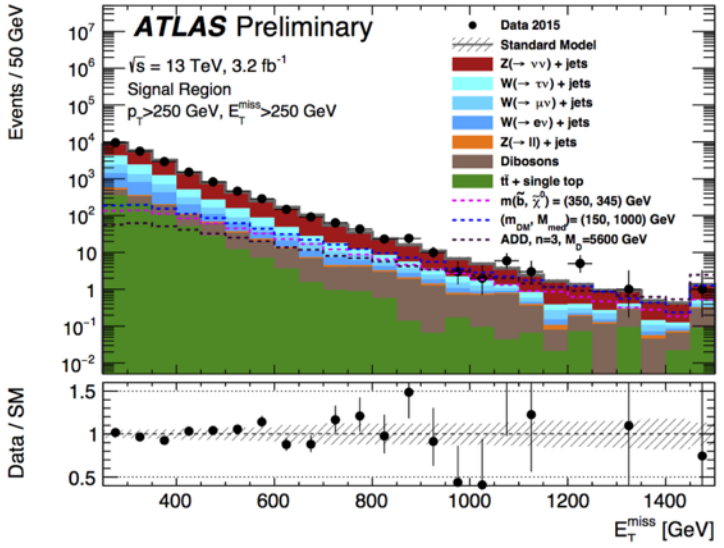


A WIMP is invisible to detectors!
Initial state radiation makes it visible





A. Korn, DM@LHC



The ATLAS/CMS Dark Matter Forum

Determined **Benchmark models** for LHC searches:

- emphasis on **mediators**
- mediators can be **produced** and **discovered** at the **LHC**!

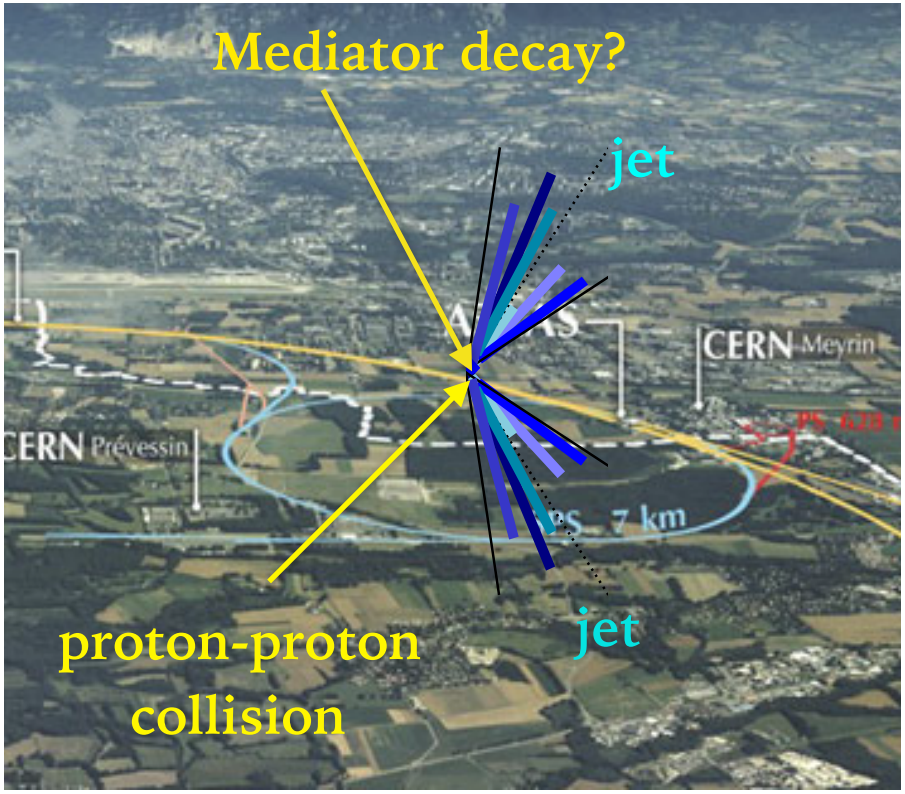
Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

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



The ATLAS/CMS Dark Matter Forum

Determined **Benchmark models** for LHC searches:

- emphasis on **mediators**
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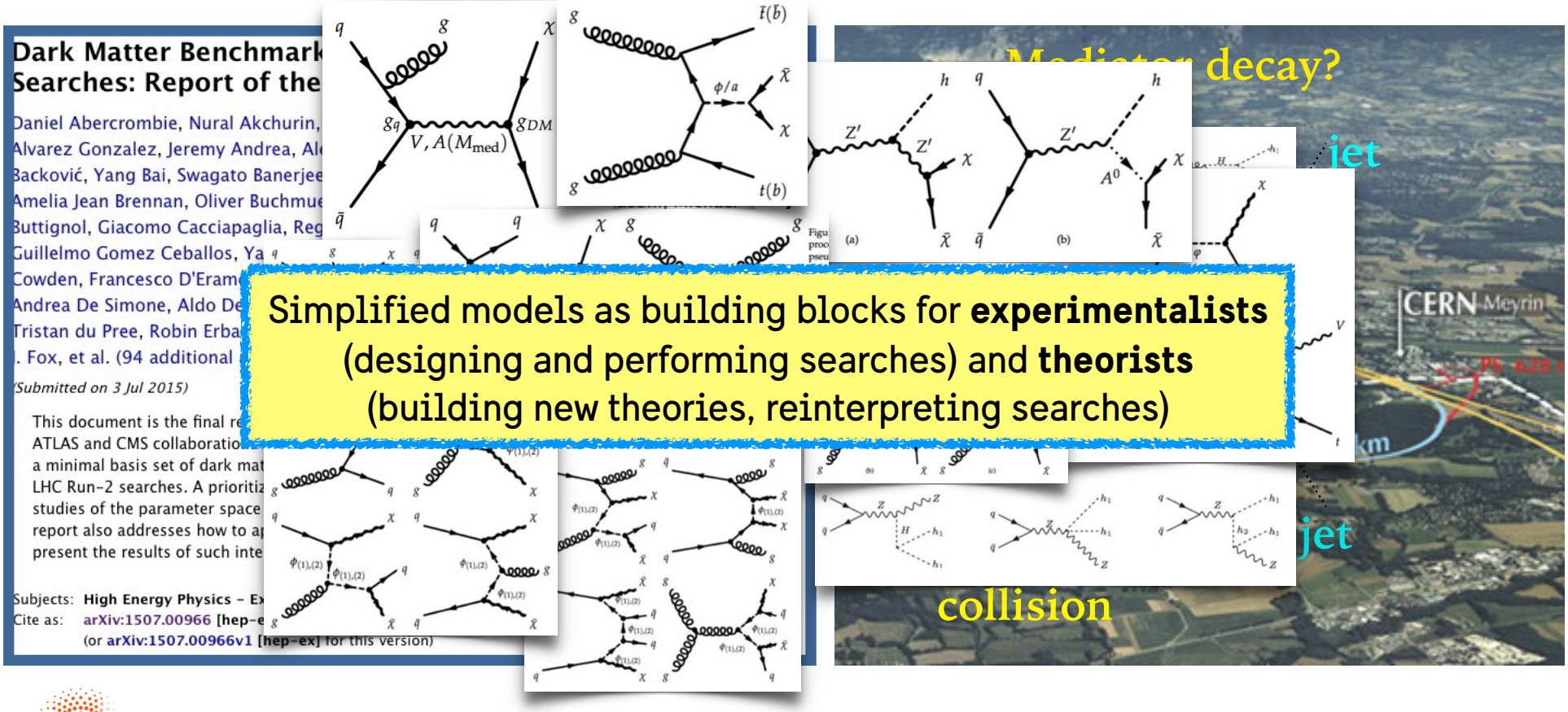
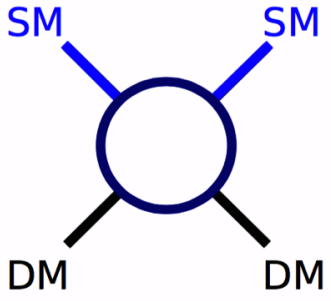
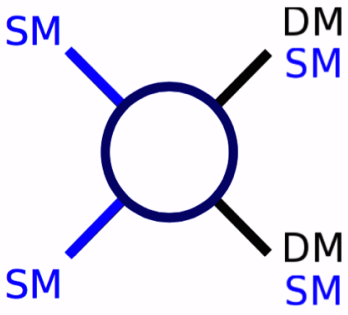


The LHC Dark Matter Working Group

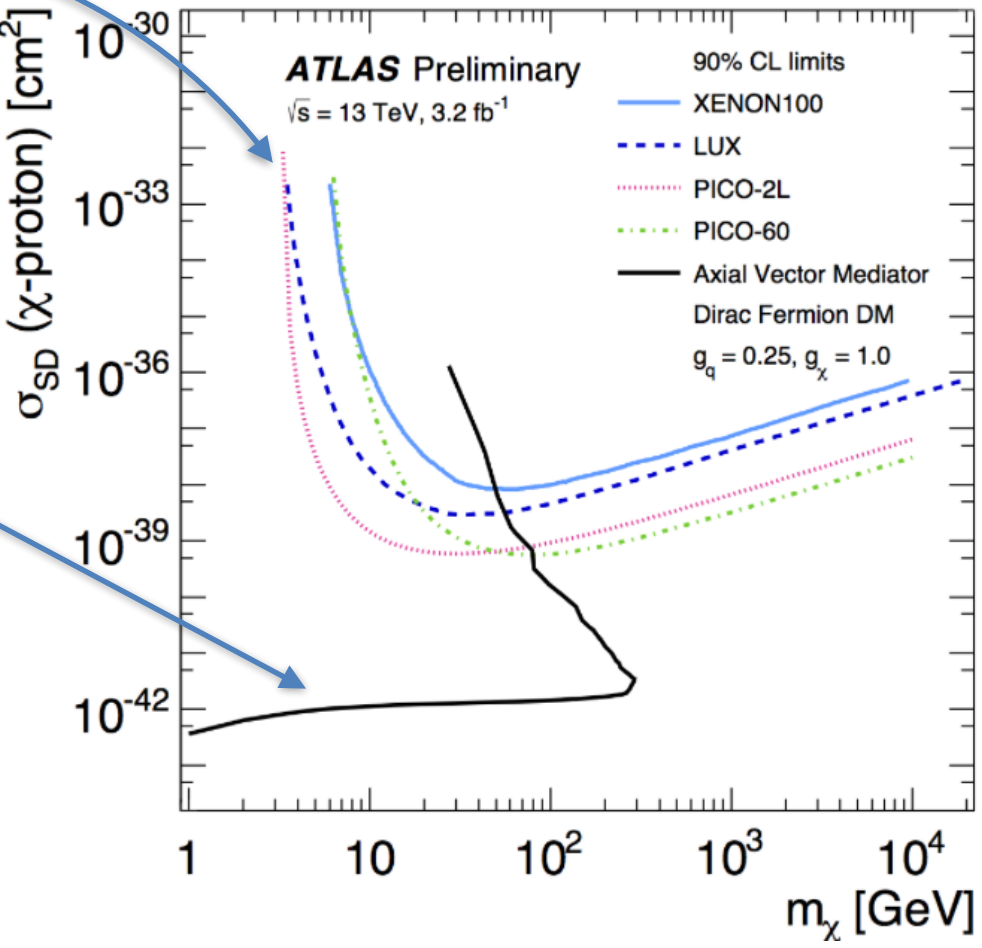
Complementarity between Dark Matter experiments:
highlighted in agreement on presentation of results arXiv:hep-ex/1603.04156



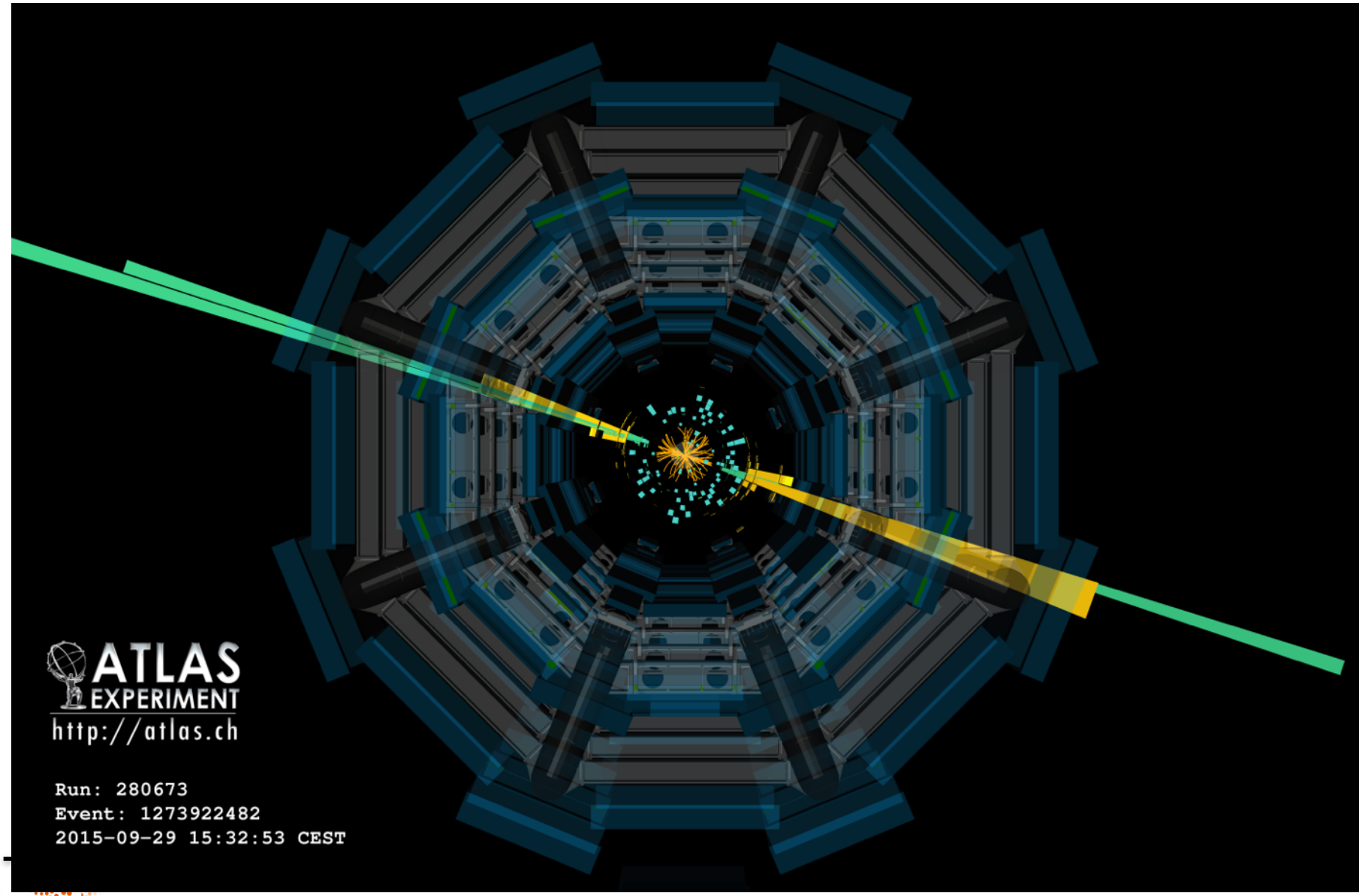
Direct Detection



Particle Colliders

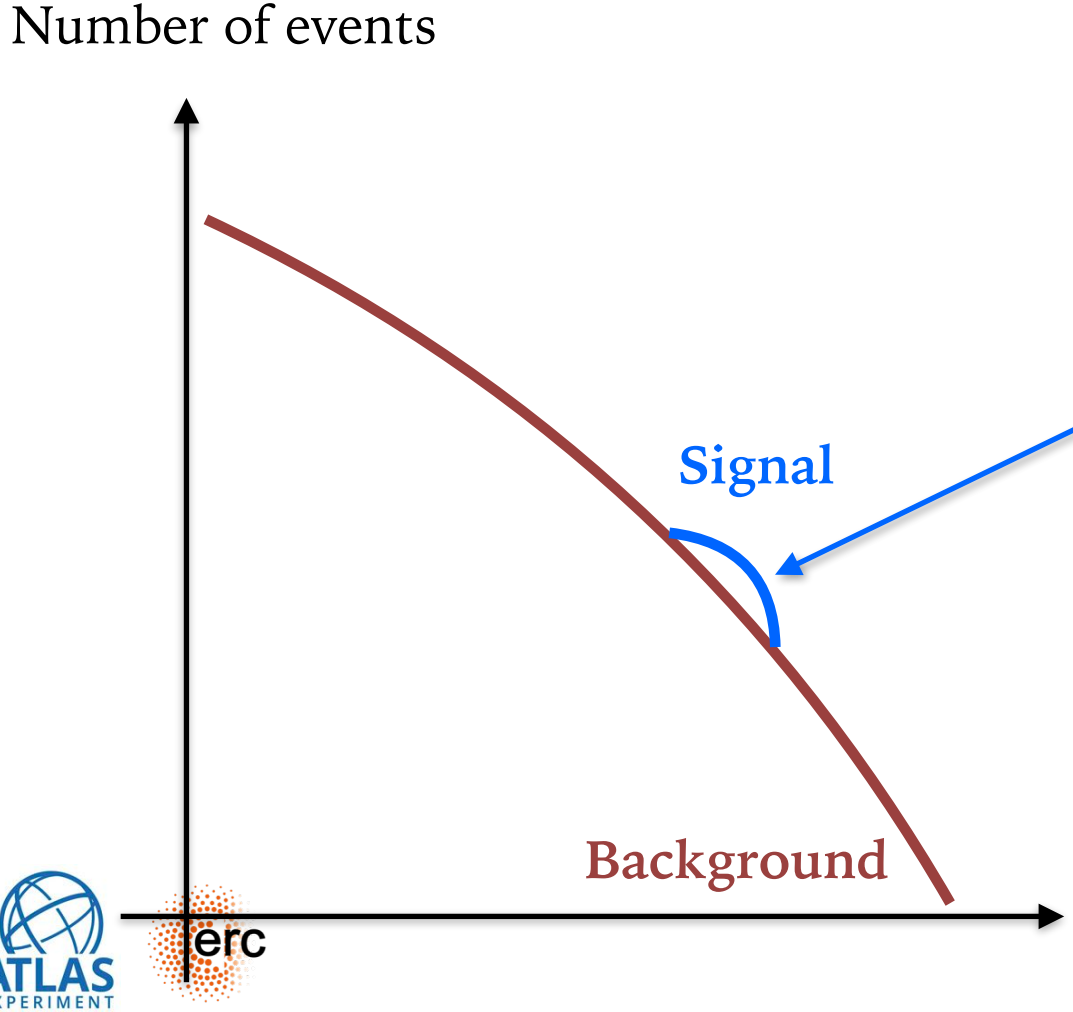


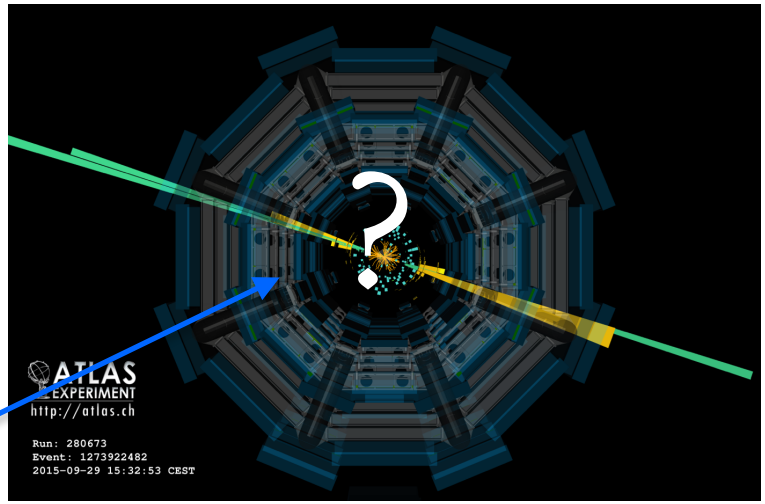
DM mediators: how they would look like



DM mediators: how they would look like

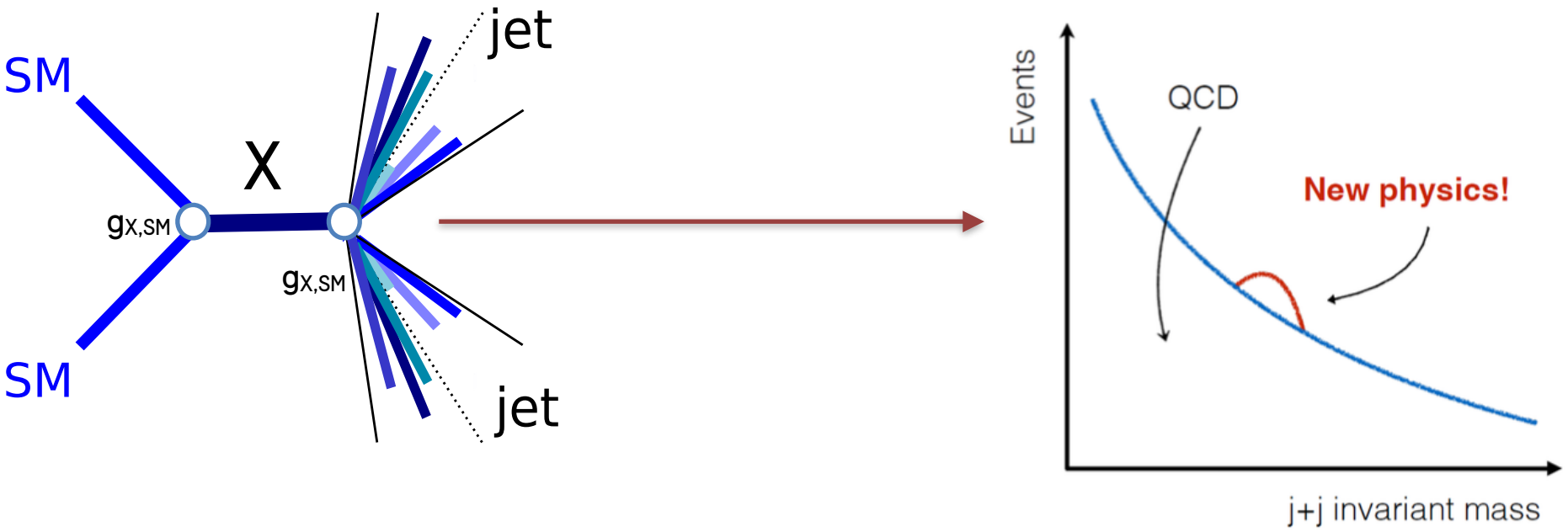
New particles: resonant excess (bump) over known particle background





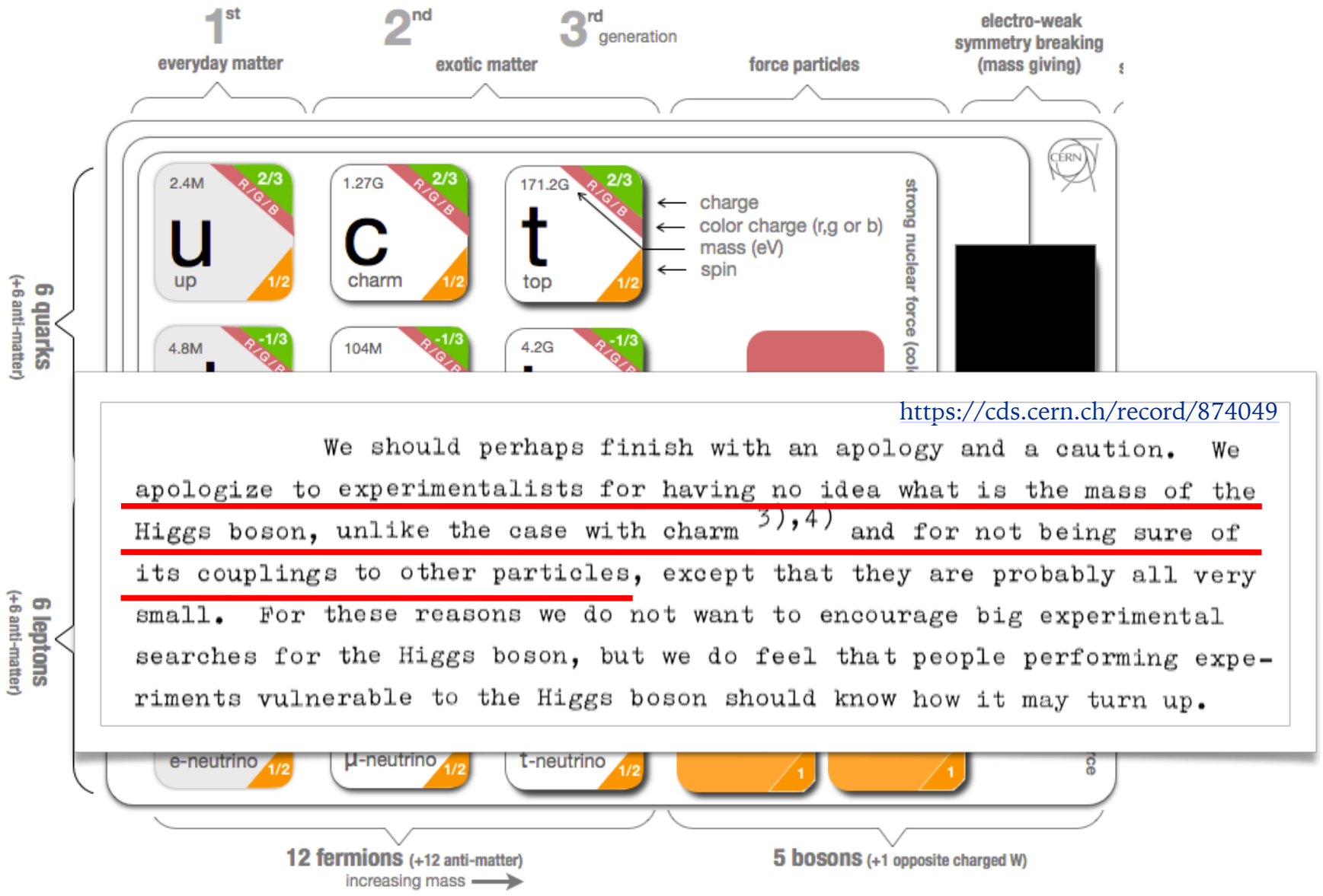
Resonant phenomena producing jets

Look for new particles decaying to quarks and gluons (→jets) appearing as "bump" over QCD background



Many models fit the bill: excited quarks, heavy boson partners…

More motivation to look into the heart of the matter



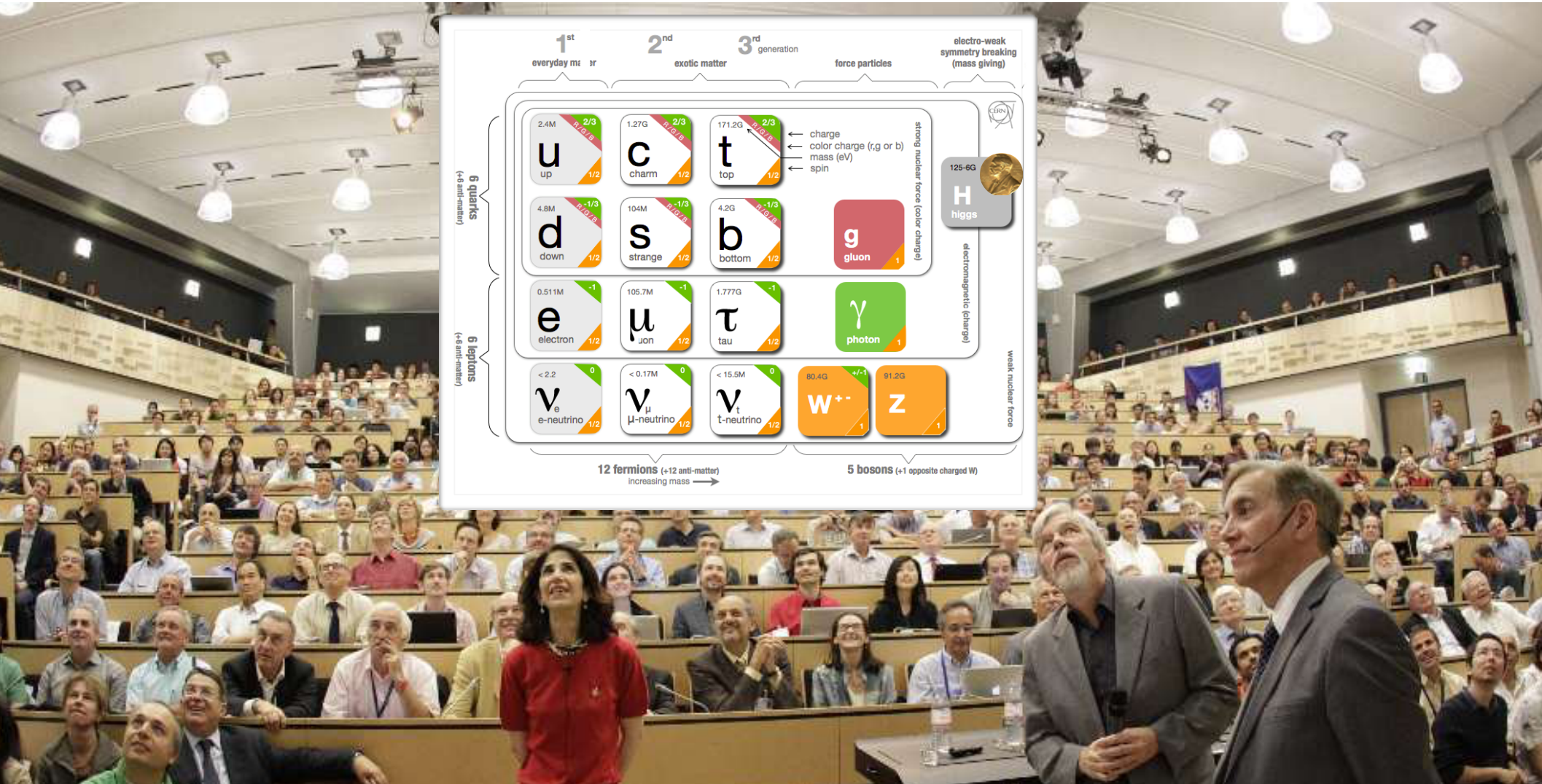
https://cds.cern.ch/record/874049

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Searches (and discoveries) at the LHC Run 1

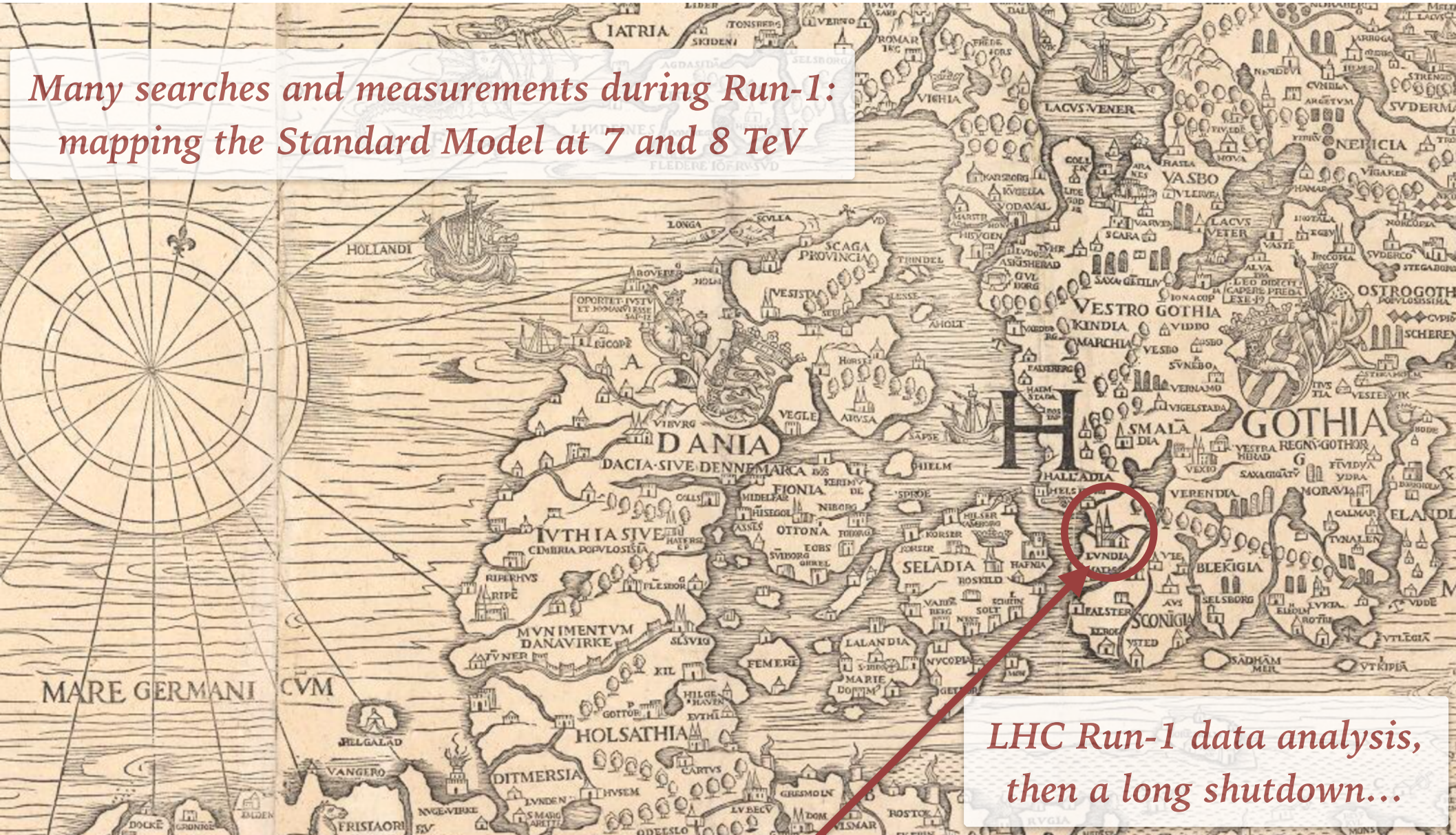
Discovery of the Higgs boson:

guided by **clues** from the **Standard Model** of particle physics



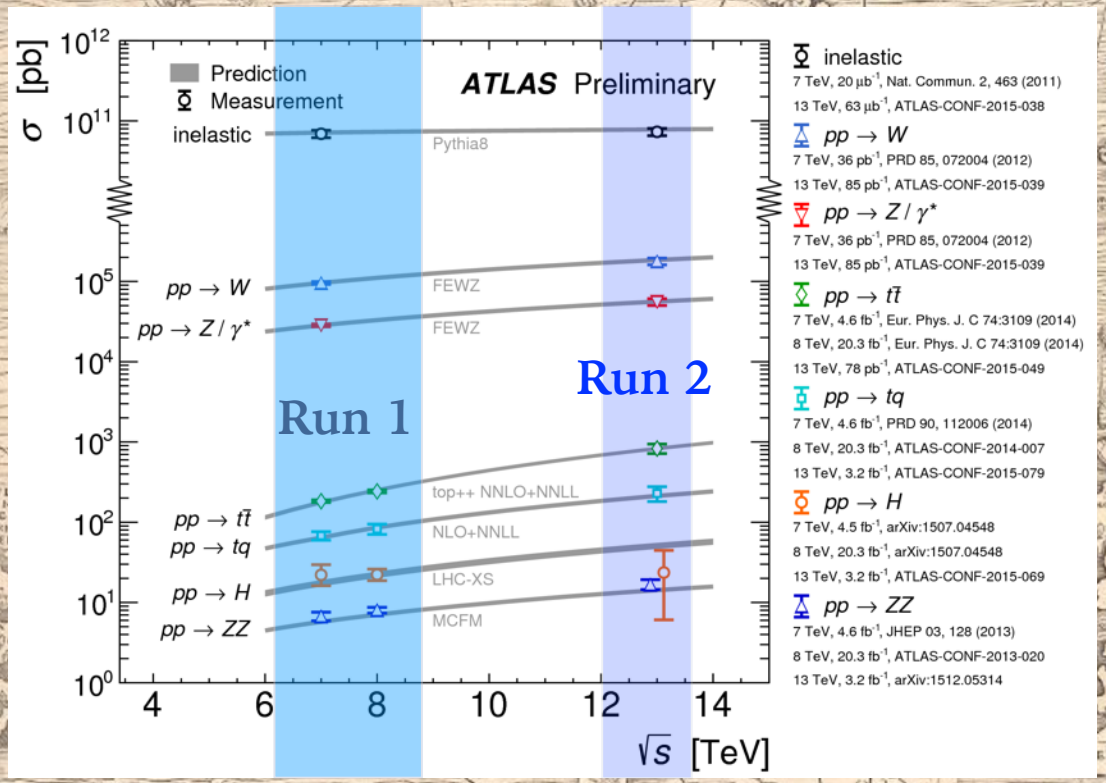
A chart of LHC searches (and discoveries)

Image from University of Uppsala



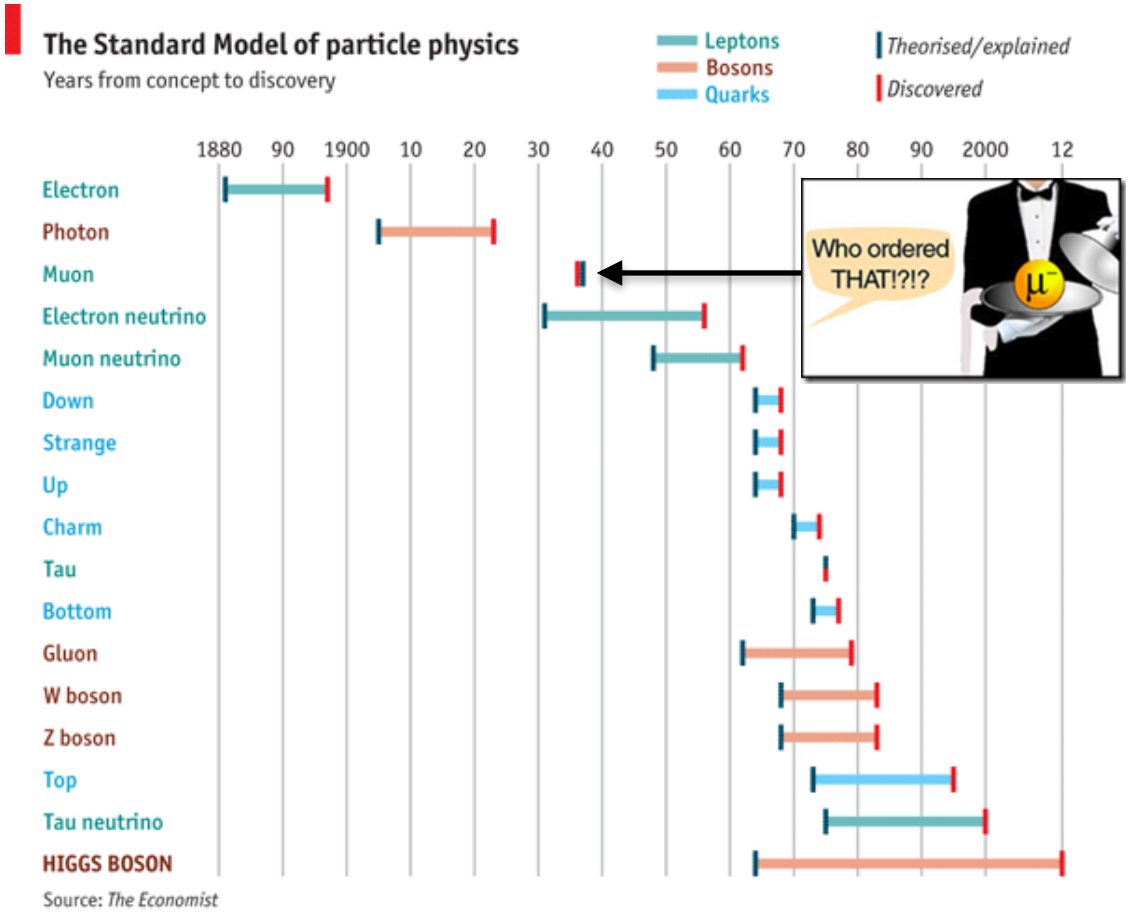
Re-charting known territories in Run 2

Image from University of Uppsala



Run-2: Rediscovering and measuring standard candles with high precision

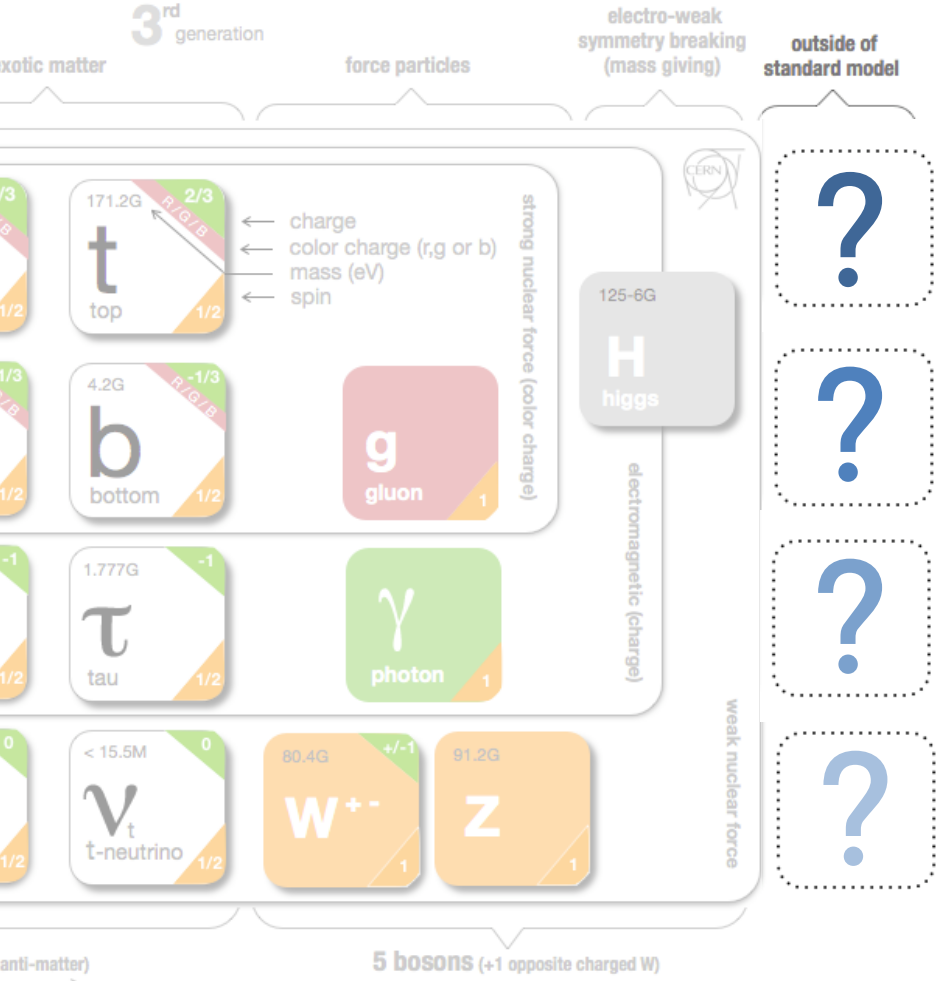
Where to look for new particles?



Everywhere!

design **model-independent searches** for new phenomena

Uncharted discoveries in Run 2

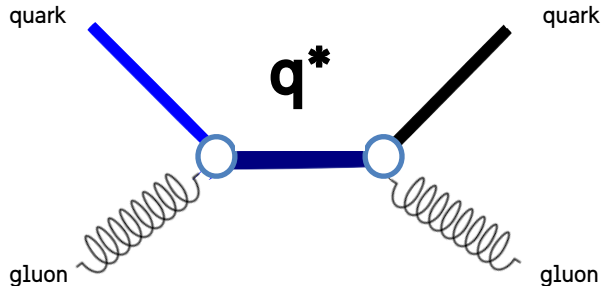


Where to look for new physics?

Everywhere, starting with high masses

Increase of LHC energy

Increase of reach for new phenomena



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

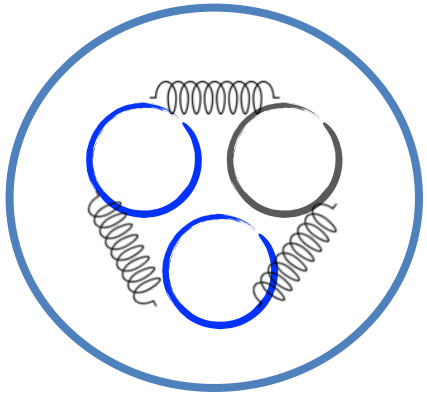
Uncharted energies in Run 2

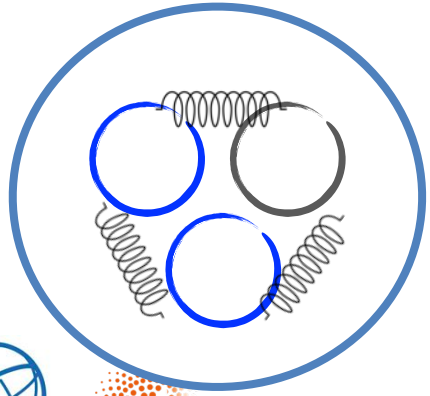
Image from University of Uppsala

From the jets in DARKJETS!

Proton-proton collisions at the LHC

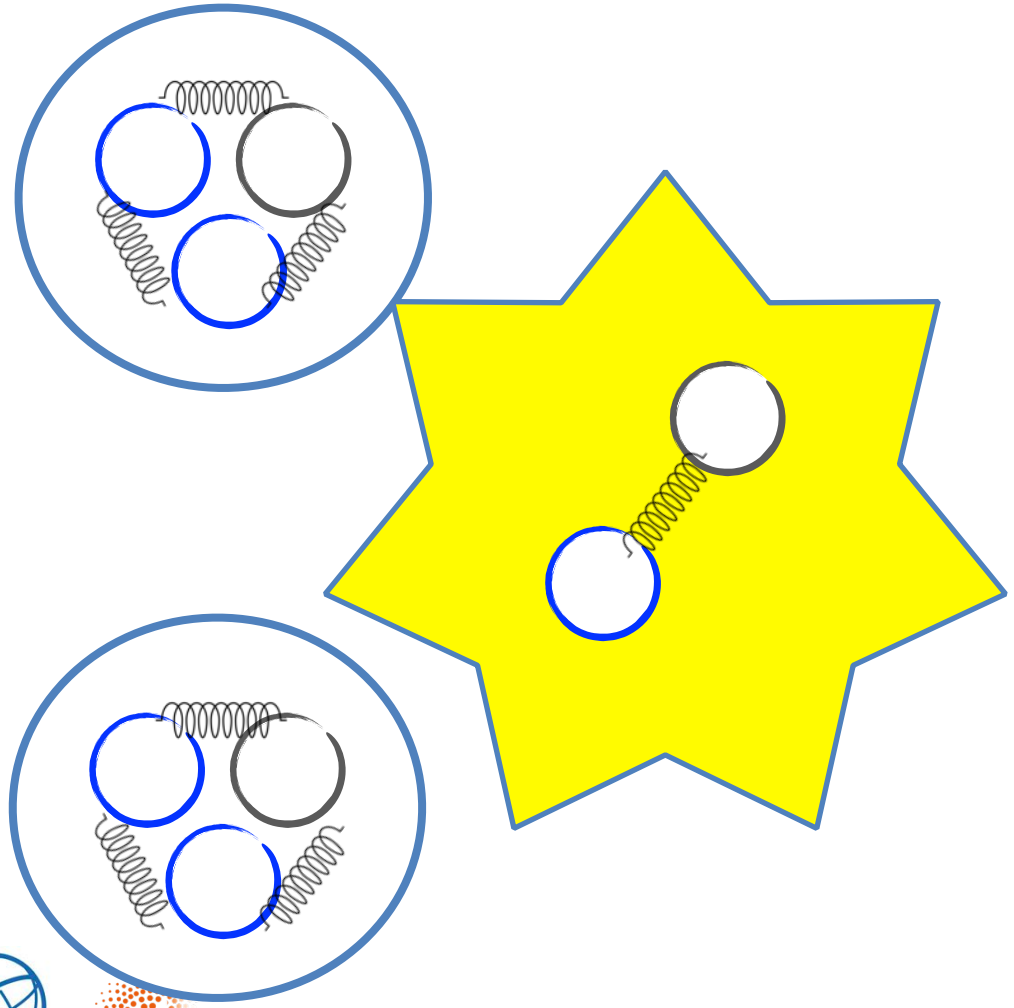
Protons are made of quarks and gluons





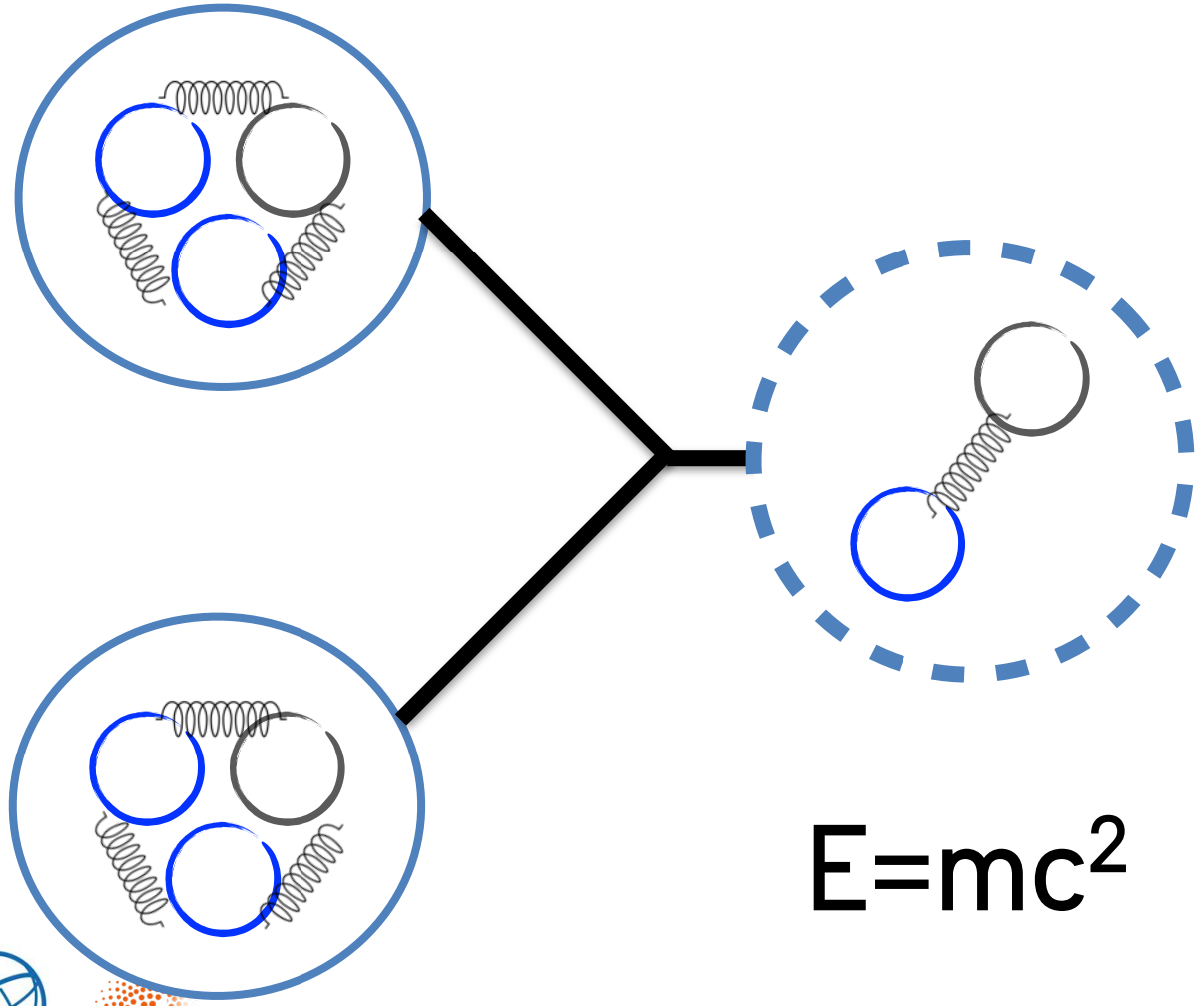
Proton-proton collisions at the LHC

…so it's the quarks and gluons that collide at the LHC…



New particles created at the LHC

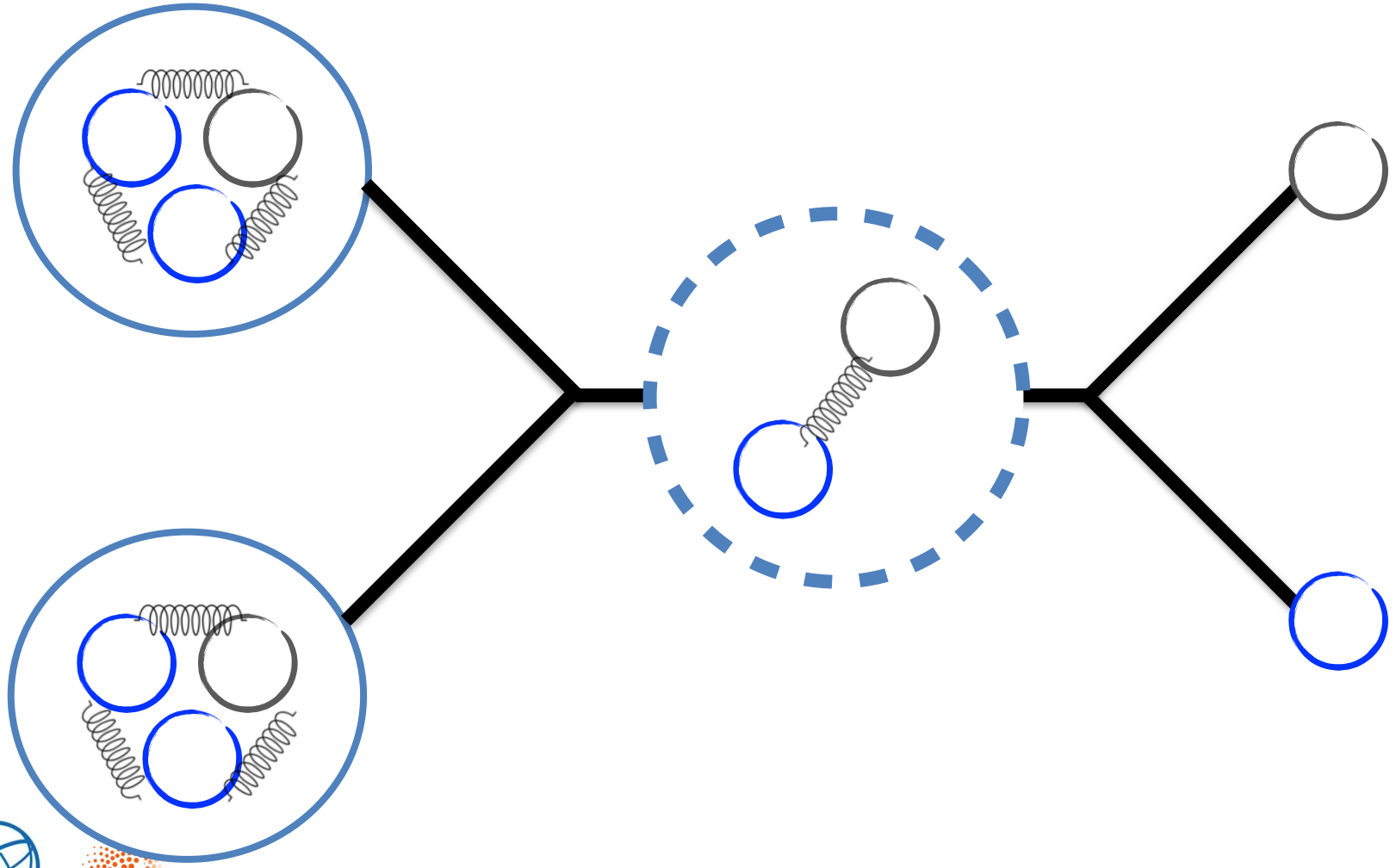
…and could create new particles…



$E=mc^2$

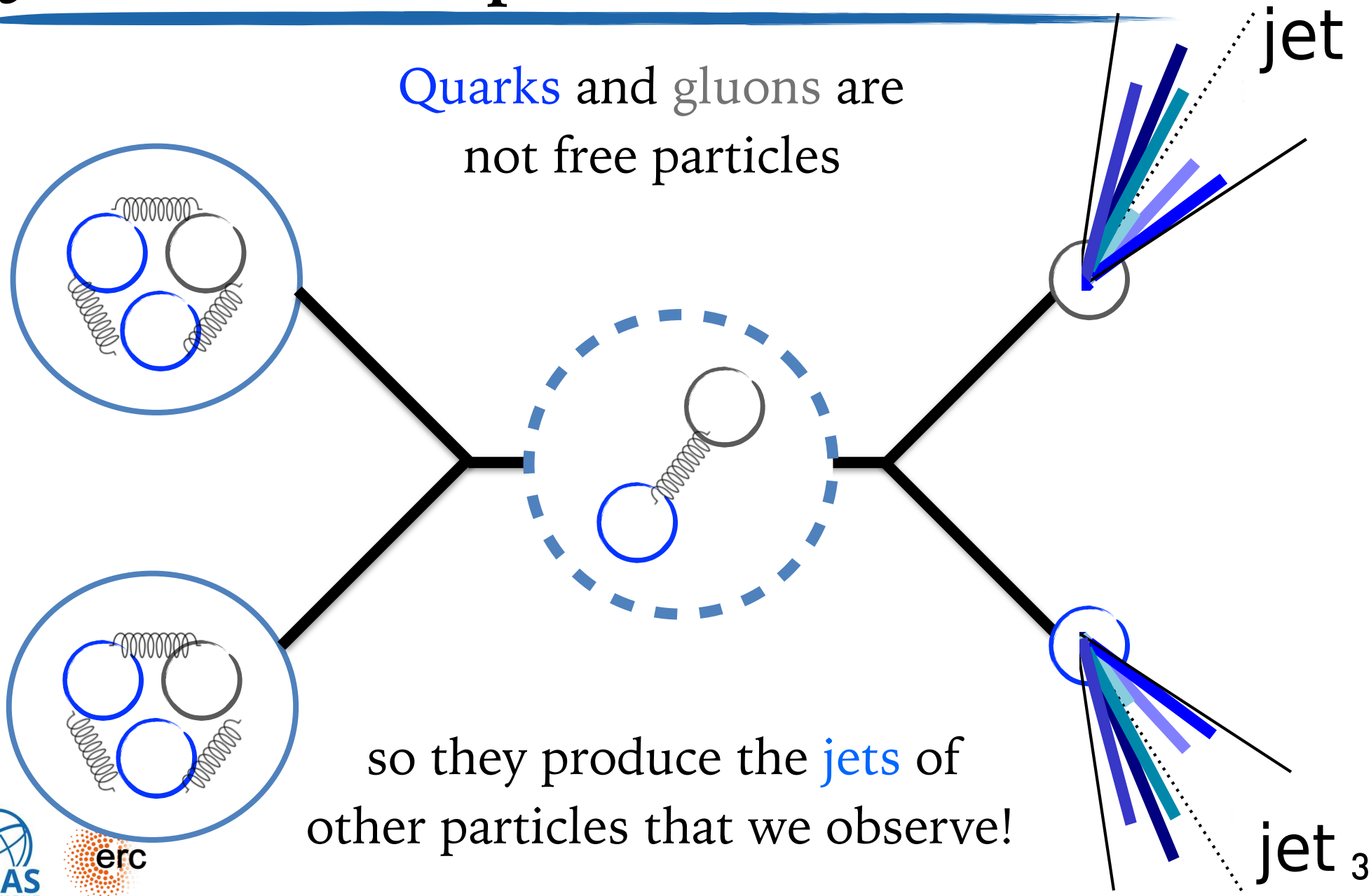
New particles created at the LHC

…which are unstable and decay again into quarks and gluons



Jets from new particles at the LHC

Quarks and gluons are not free particles



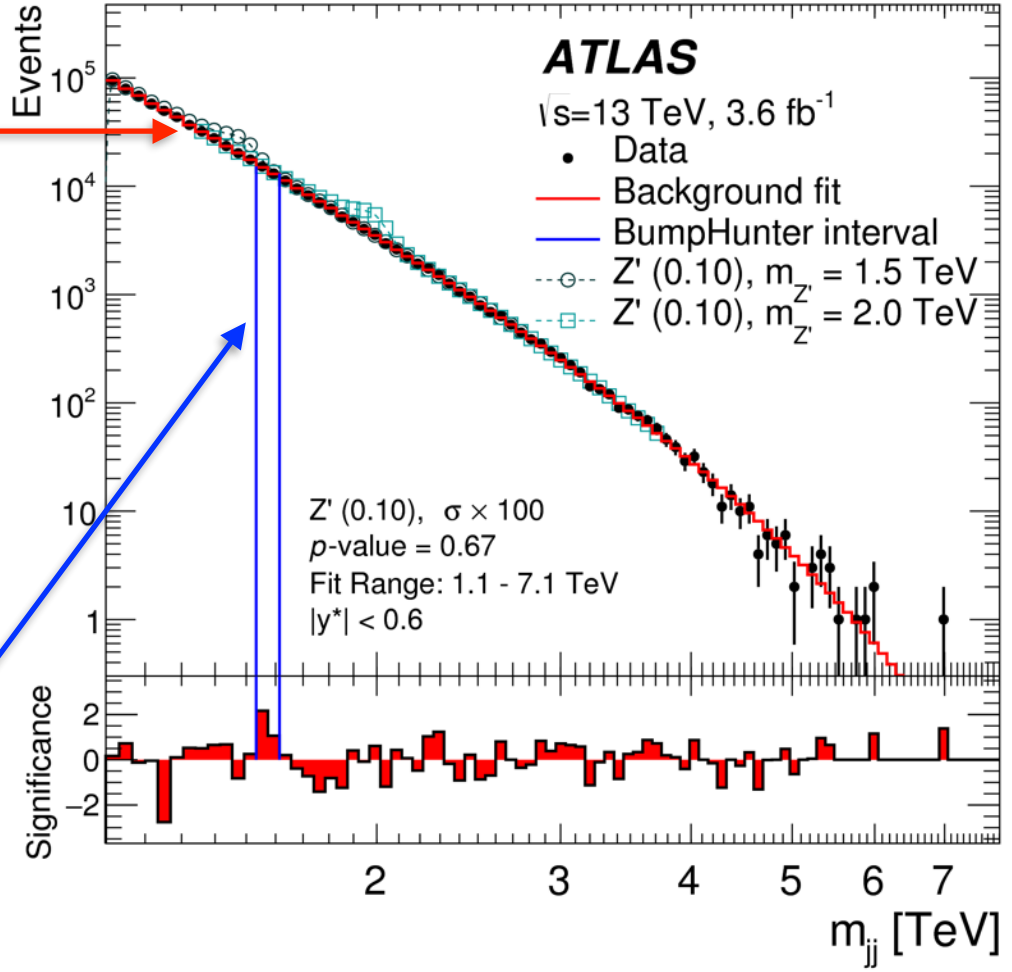
so they produce the jets of other particles that we observe!

A new search for new particles

Compare **data** with **smooth fit**:

$$f(z) = p_1(1-z)^{p_2} z^{p_3}$$

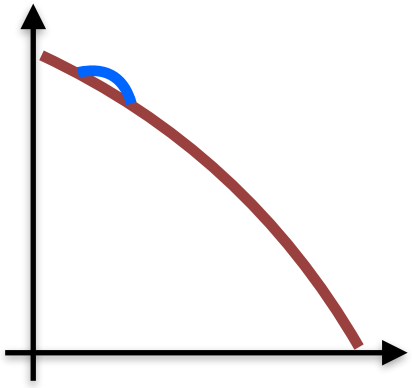
doi:10.1016/j.physletb.2016.01.032

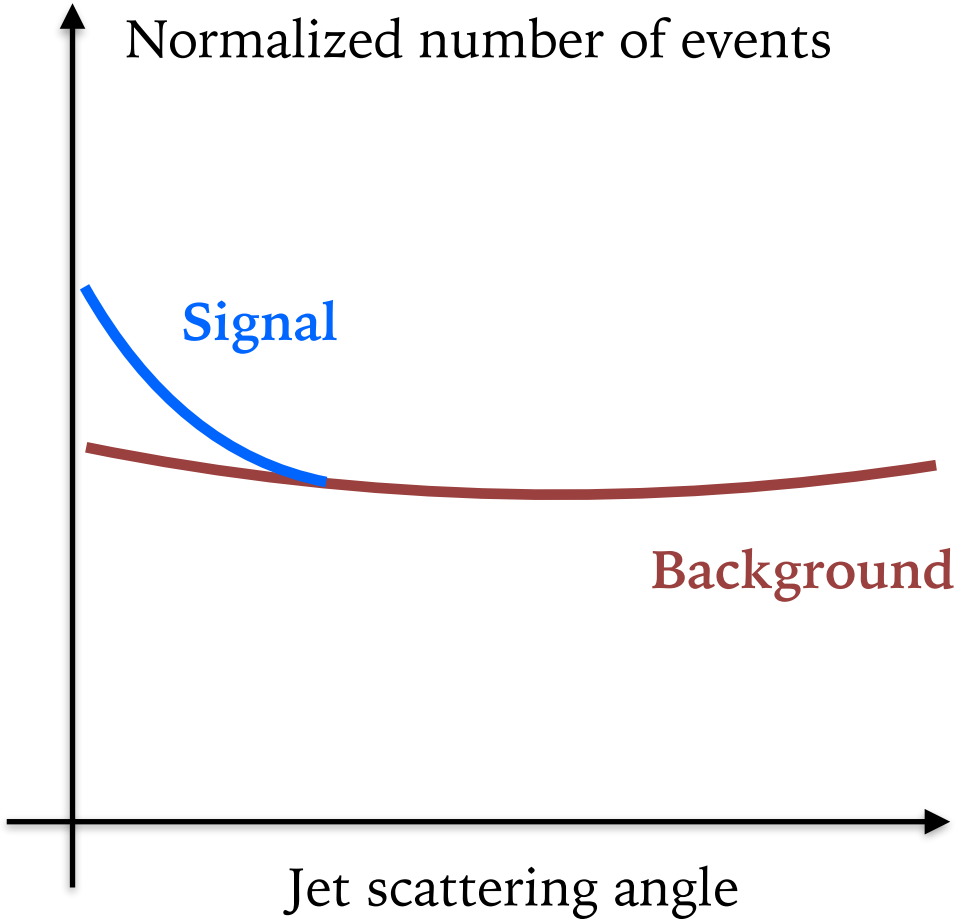


Run **BumpHunter** algorithm to find most significant **excess**
(not significant)

How could new phenomena manifest?

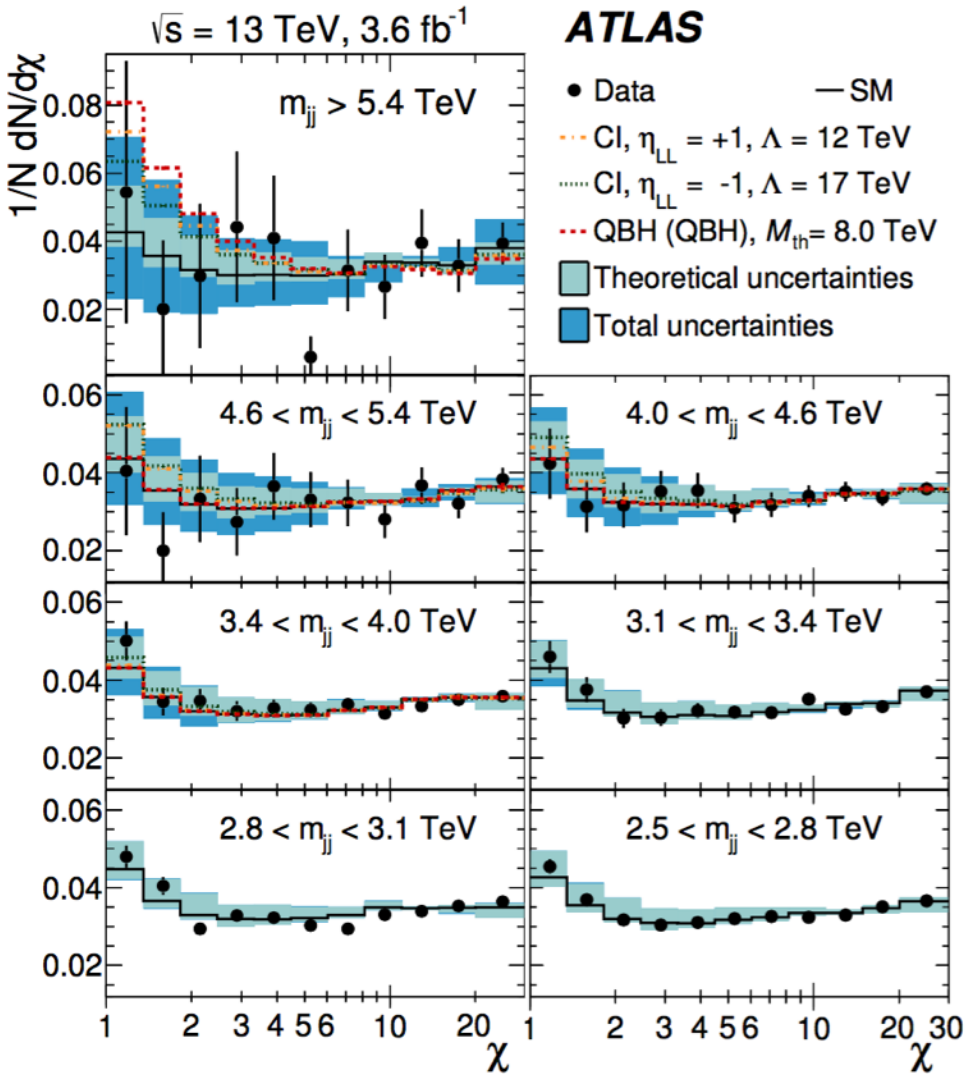
New interactions: more central production with respect to backgrounds





more central events more forward events

A new search for new particles



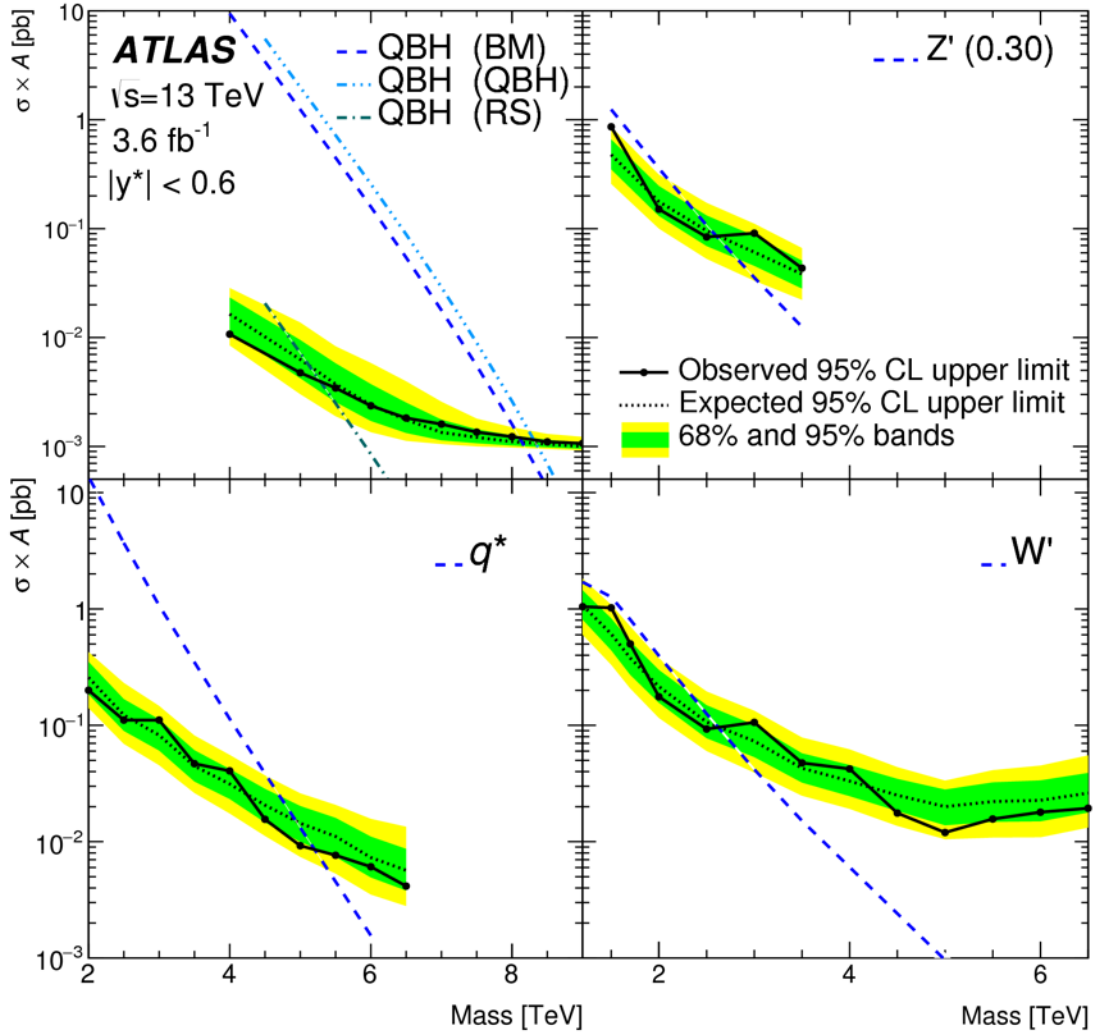
doi:10.1016/j.physletb.2016.01.032

Compare **data** with **NLO-corrected QCD** from simulation

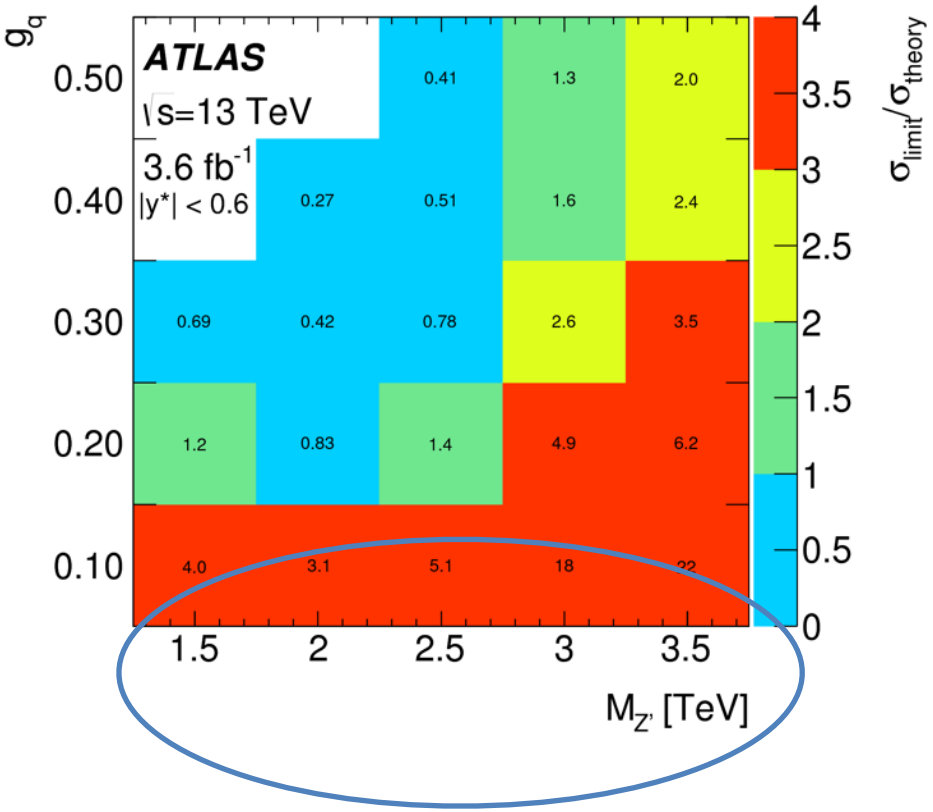
Find **compatibility** between signal and background (compatible)

A new search for no new particles

Various New Physics benchmarks:



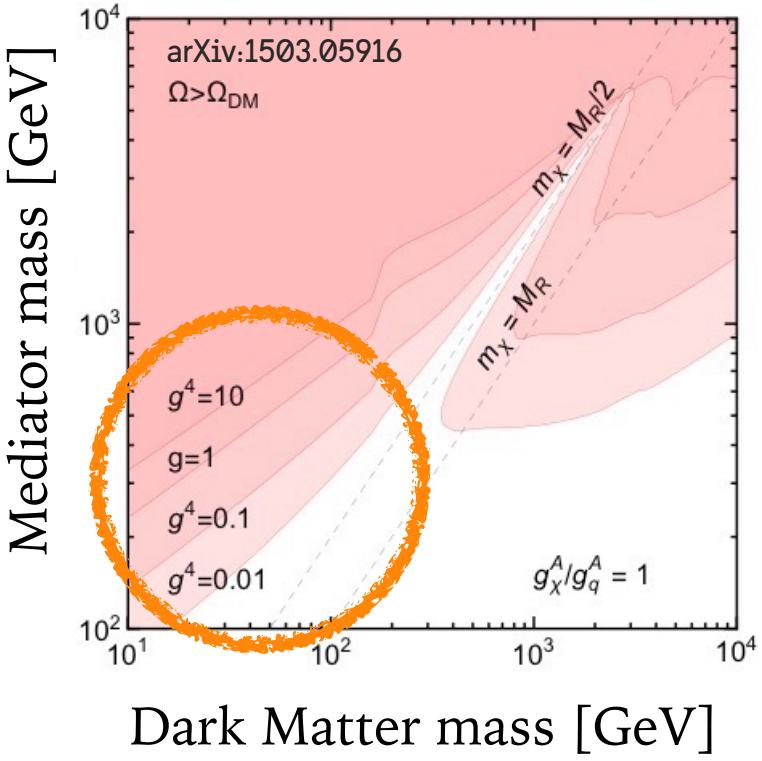
Dark Matter Mediators:



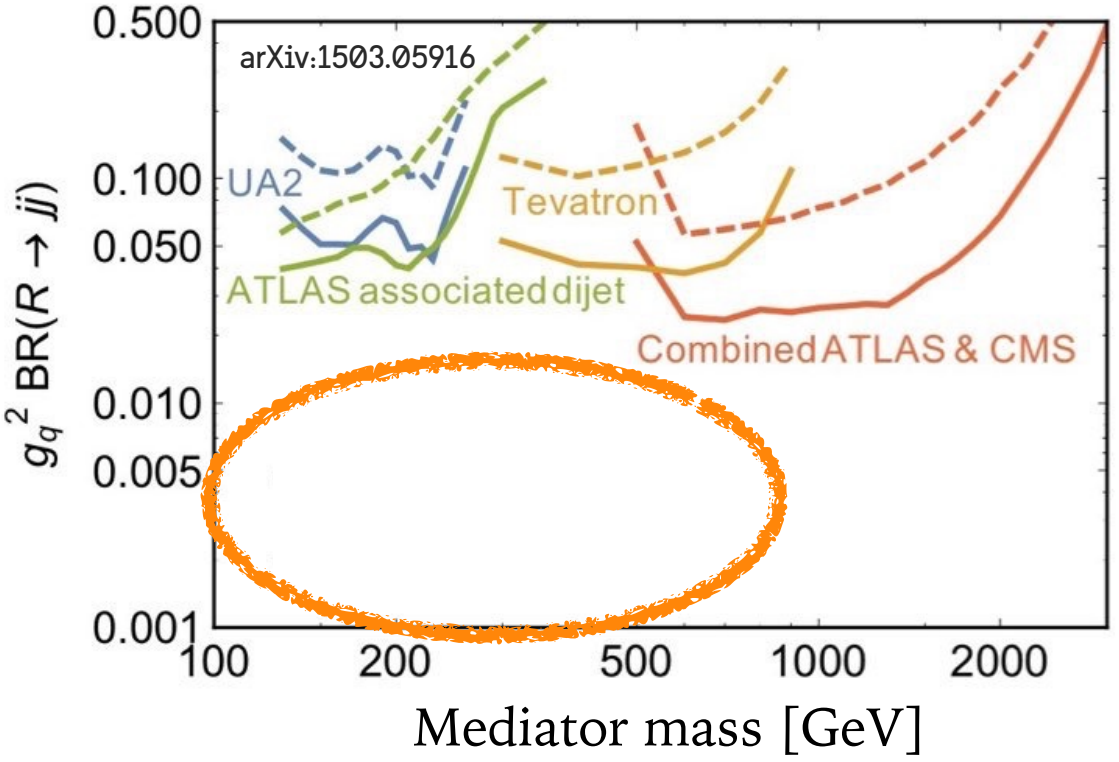
Very high particle masses!

Dark Matter Mediators decays to jets

Most interesting region:
low mediator masses



Least constrained region:
low mediator masses

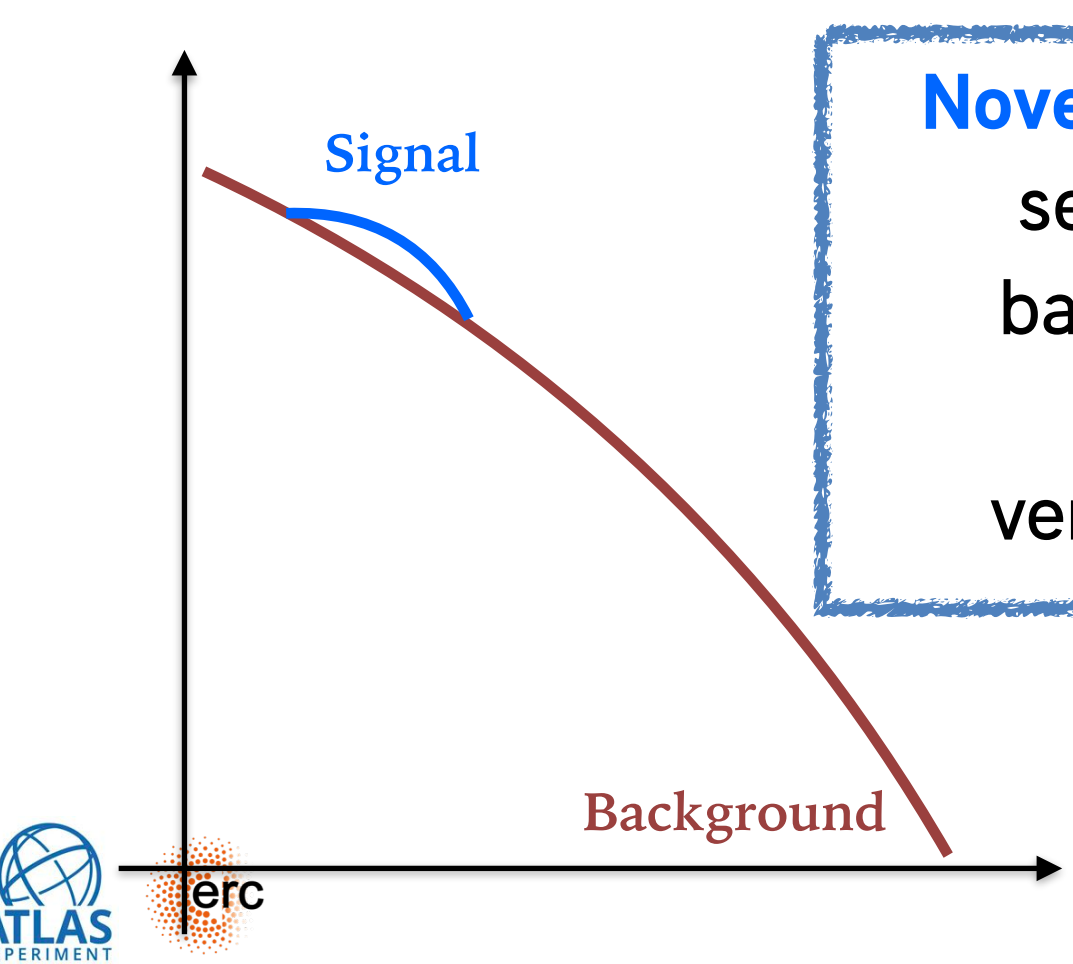


Reason: compatibility with relic density

Reasons: large backgrounds difficult to record all events

DM mediators: how they would look like

New particles: resonant excess (bump) over known particle background

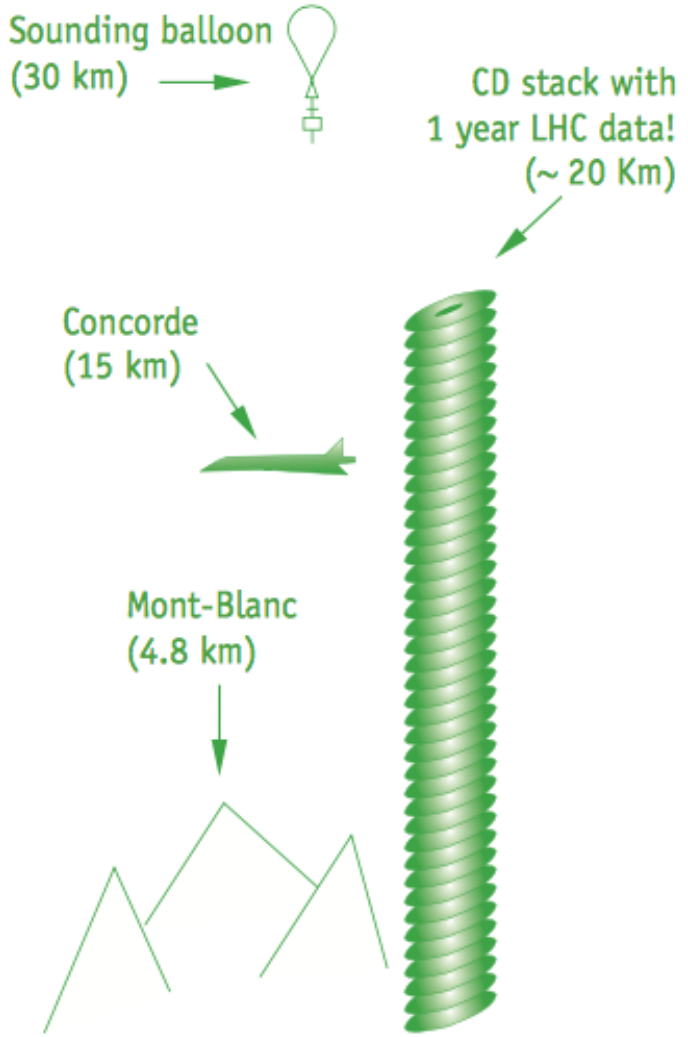


Novel aspect of DARKJETS:
search in region where backgrounds are **higher** and deal with very large **data volumes**

Data volumes at the LHC

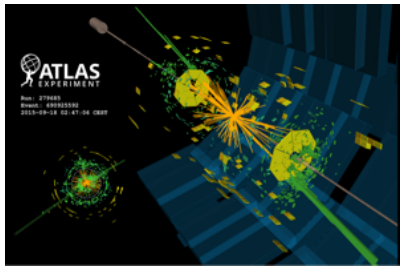
- LHC: if everything was recorded…
  - up to 40 million collisions/second (MHz)
  - 1-1.5 MB/data per collision
  - 40 MHz * 1 MB = 40 TB/s
  - 40 TB/s * 10e+6 s/year = 0.05 ZB/year
- Facebook:
  - 600 TB/day ~ 200 PB/year [Facebook]

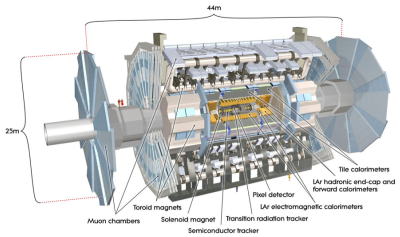
LHC experiments need to:
1. **process** all data, fast
2. **select** only interesting events



(**after** selecting interesting events)

Data taking and computing





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

Computing resources (CERN/Grid) are essential for the full data taking chain

Trigger and data acquisition: select interesting events

First step: **fast hardware selection (Level 1)**
Run-1 data taking rate: 75000 events/second (75 kHz)
Run-2 data taking rate: 100 kHz

Second step: **computer farm (High-Level Trigger)**
Run-1 data taking rate: 400 Hz
Run-2 data taking rate: 1000 Hz

Limitations to recording all data

Limited by:

fast **read-out** of o(100M) detector channels

computing resources (reconstruction)

disk **storage** (saving for further processing)

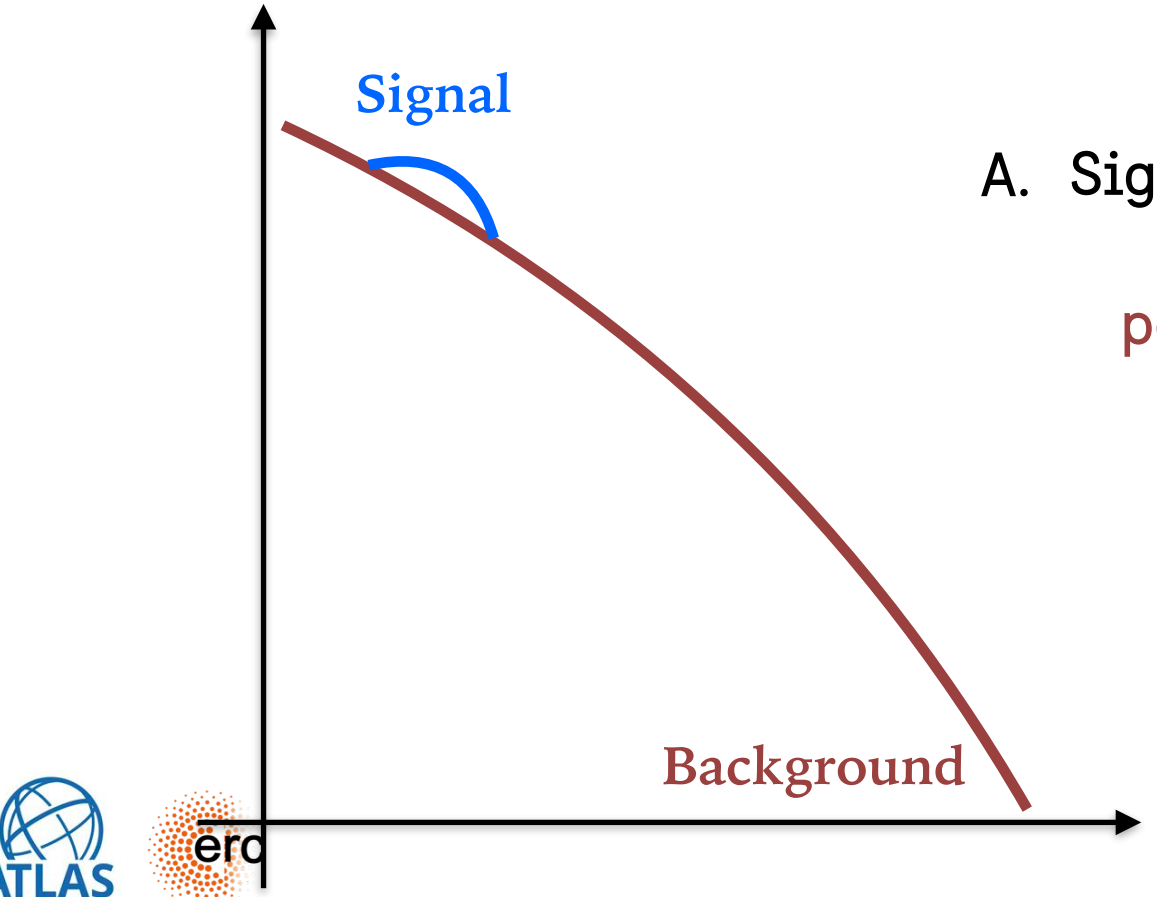
everyone else's favourite **physics** channel

Bandwidth = Event rate x Event size

LHC: 40 MHz	(Reconstructed)
ATLAS: 1 kHz	ATLAS: o(MB)
LHCb: 12.5 kHz	LHCb: ~100 kB
CMS: 1 kHz	CMS: o(MB)

Signals and backgrounds with jets

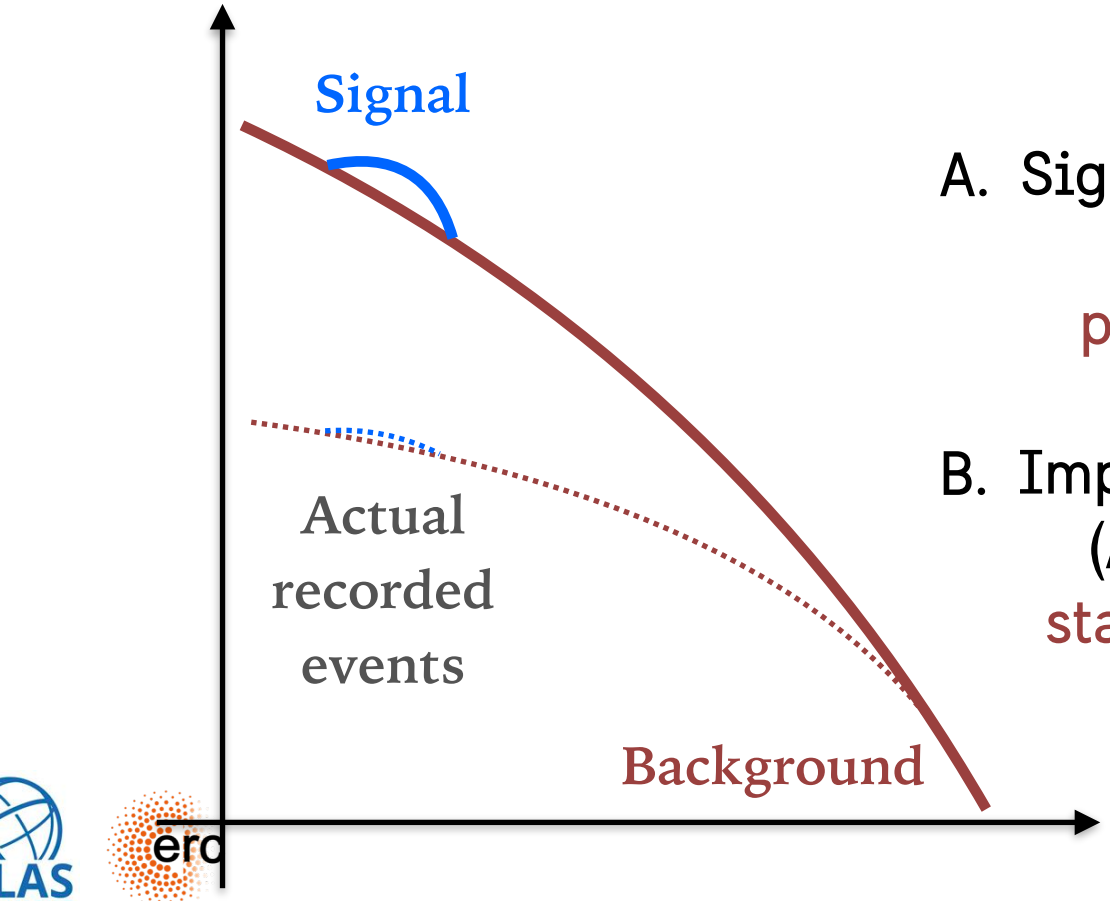
Main challenge for jet searches: large backgrounds



A. Signal overwhelmed by background if no discriminating power
poor sensitivity to new physics!

Signals and backgrounds with jets

Main challenge for jet searches: large backgrounds



A. Signal overwhelmed by background:
if no discriminating power
poor sensitivity to new physics!

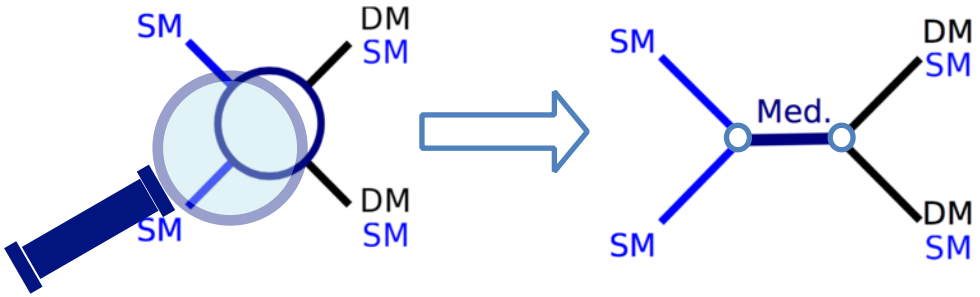
B. Impossible to record all events fully:
(ATLAS **trigger system** needed)
statistical error harms sensitivity!

Dark Matter mediators

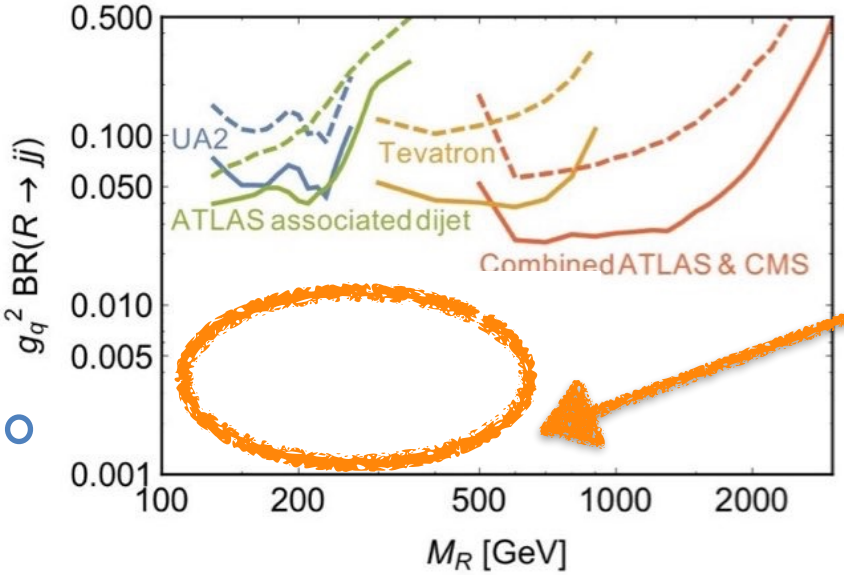
Where to look for new physics?

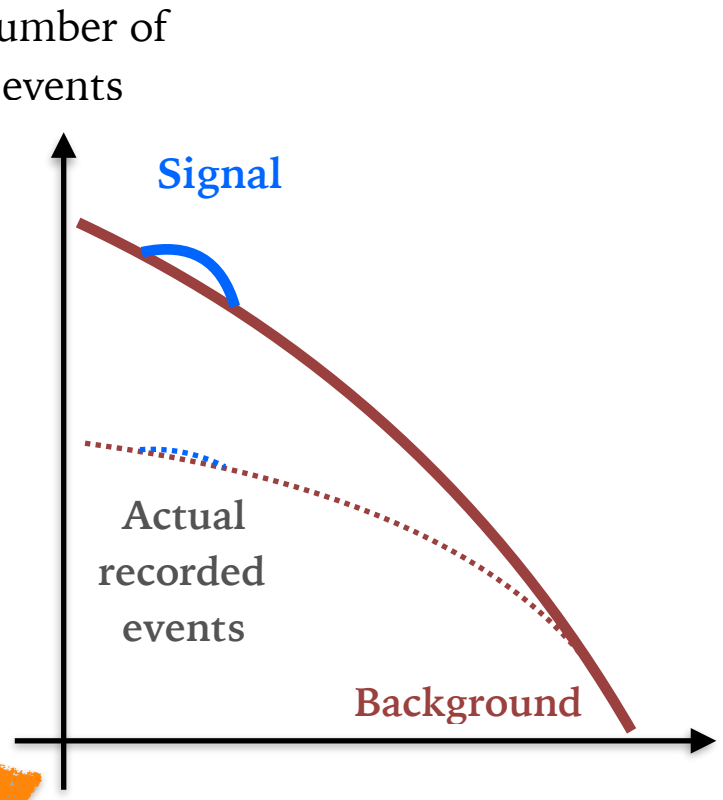
Keep looking, also at **low masses**

DARKJETS erc



arXiv:1503.05916





Reason: cannot record all events due to limited bandwidth/storage

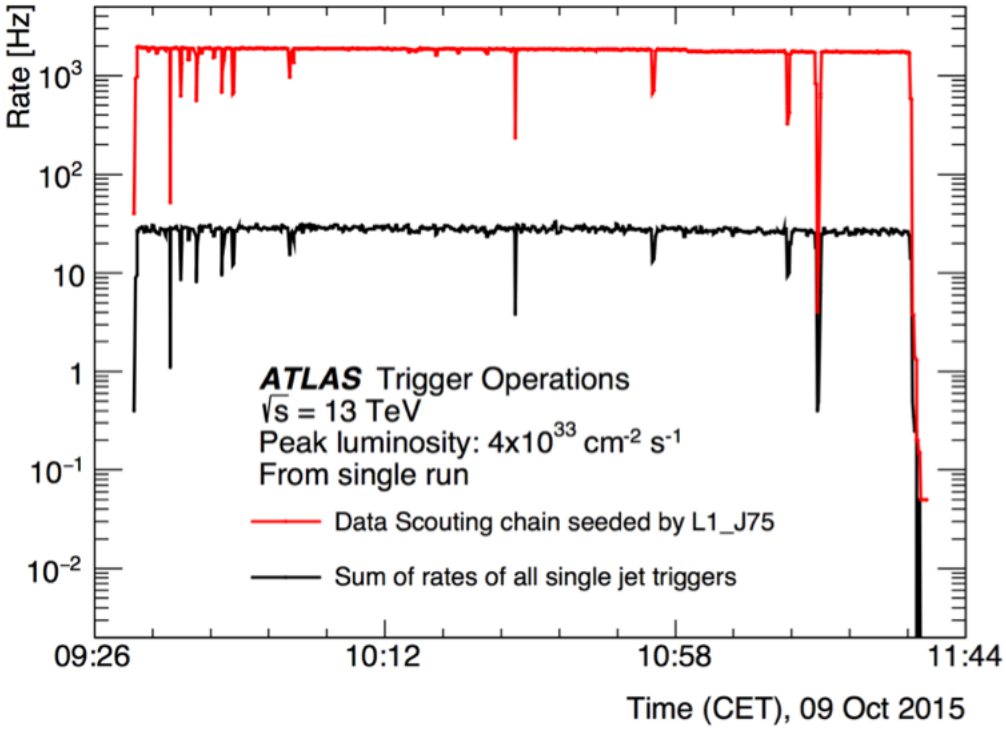
(One of the) DARKJETS idea(s)

Bandwidth = **Event rate** x Event size

Event rate can be increased if **event size** is smaller!

do the analysis at the trigger level
Trigger-Level Analysis (TLA)

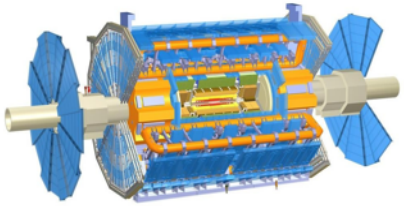
(…requires **online** detector calibration and reconstruction)



Rate of events recorded ∝ events available for analysis

A TLA Analysis workflow

See also: https://en.wikipedia.org/wiki/Three-letter_acronym
https://en.wikipedia.org/wiki/RAS_syndrome



Other L1/HLT event reconstruction

Calorimeter event reconstruction

HLT Trigger decision

if passed trigger

Full event reconstruction

physics_Main stream

Standard data analysis

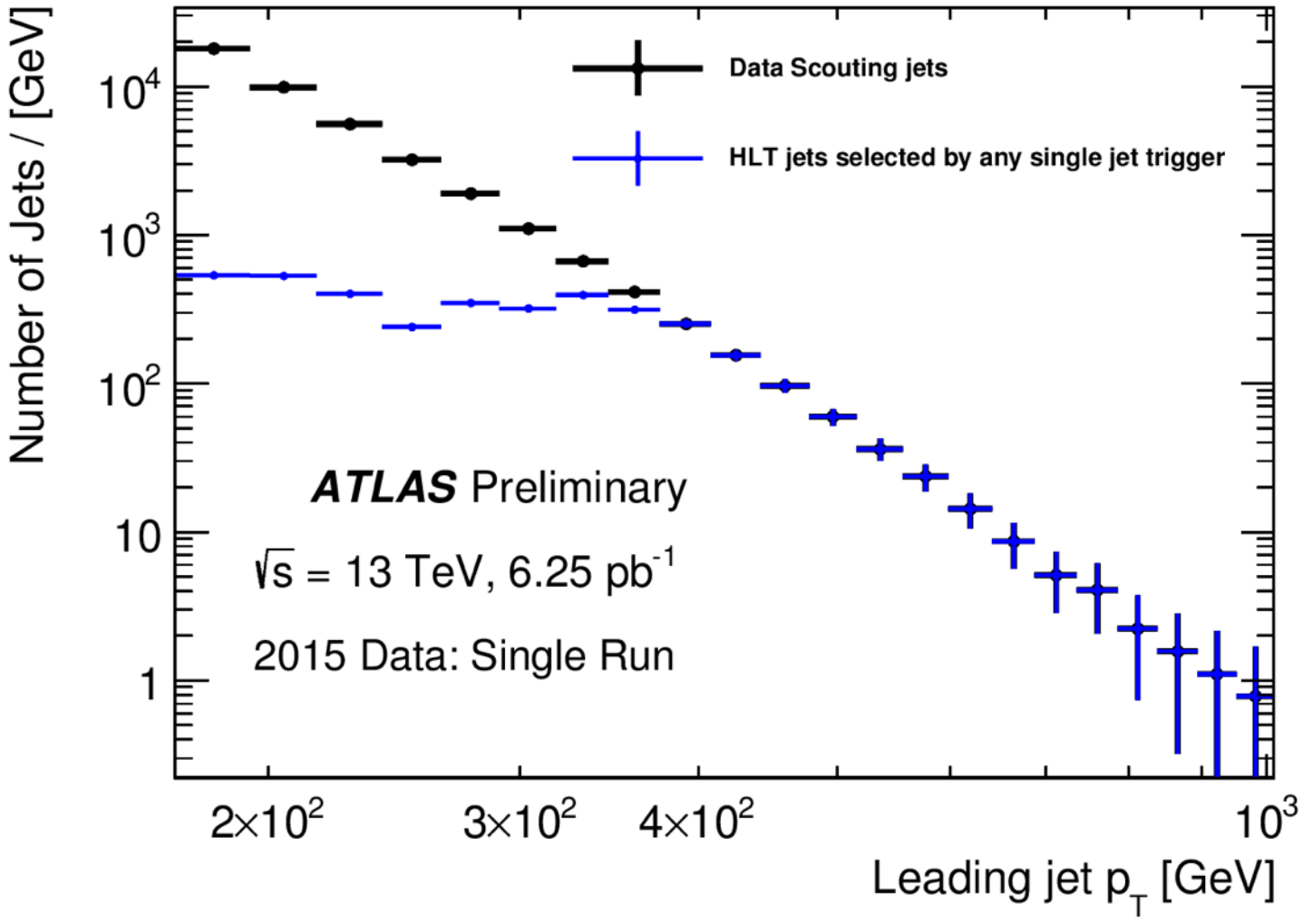
In any case

Partial (HLT-jet-only) event reconstruction

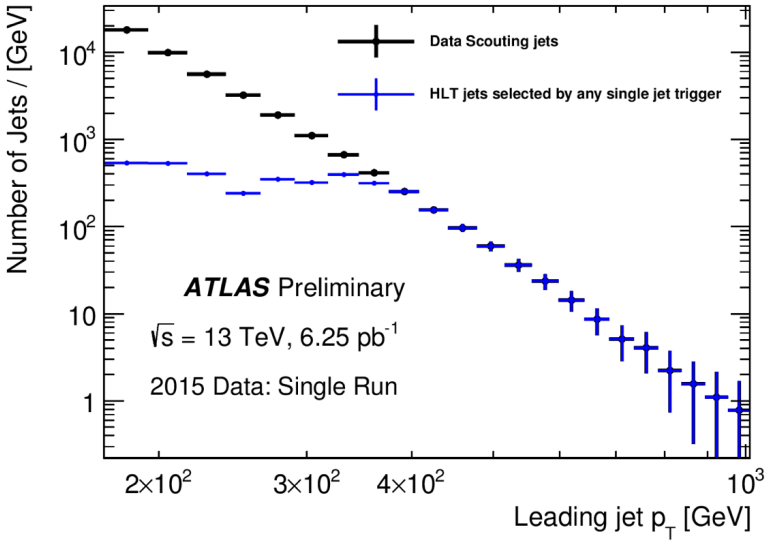
Data scouting stream

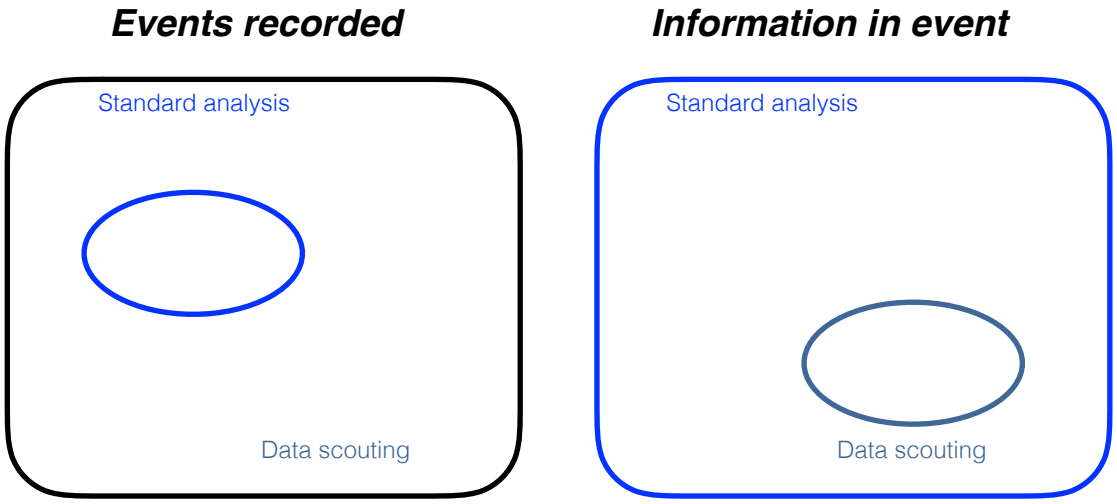
Trigger-Level Analysis

A TLA with real data



A TLA with real data





Challenge: ensure same performance of partial and full event reconstruction

Advantages:

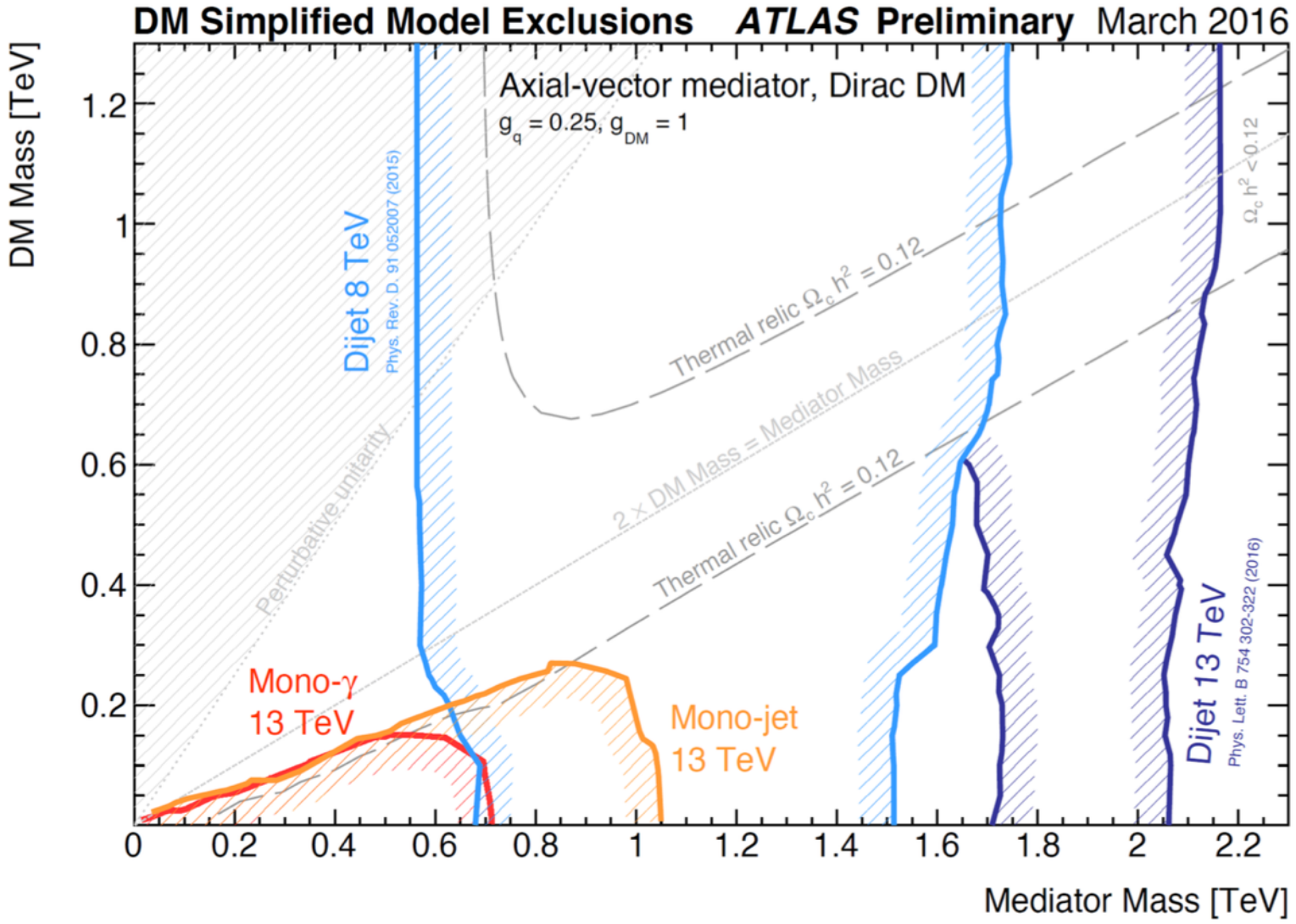
1) data format is much smaller and simpler (-> can record more of it)

2) strike a balance between data complexity and precision

3) pave the way for self-calibrating, self-learning detectors

4) automate as much as possible

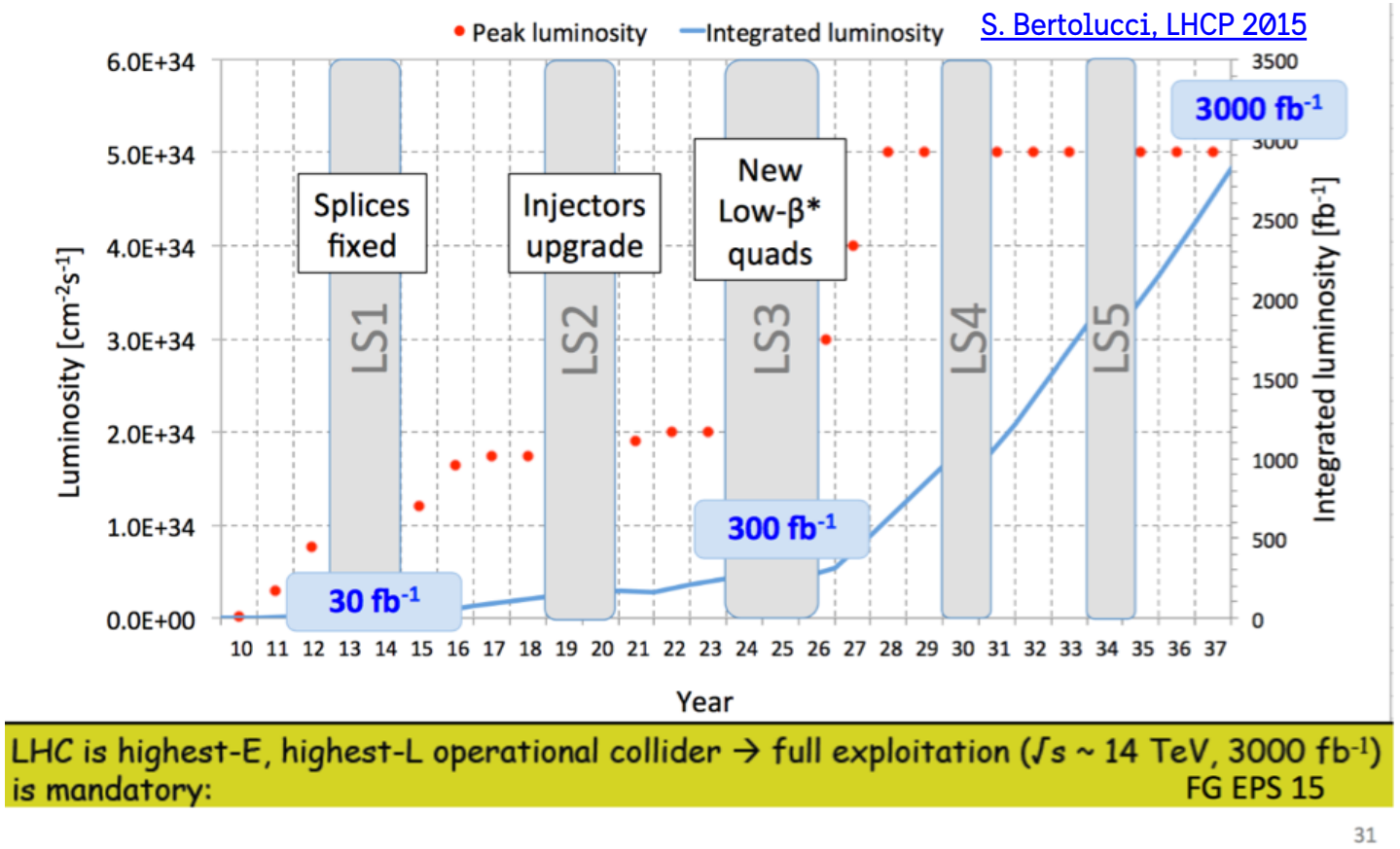
TLA in the near future of the LHC



Demonstration that searching for the mediator is effective!

TLA in the future of the LHC

LHC upgrades: keep the energy fixed, increase the amount of data collected



Techniques like real-time analyses and Trigger Level Analyses needed!

DARKJETS in ATLAS and in Lund

The ATLAS Collaboration

Only < 1/10 of the ATLAS collaboration shown here
(find me, and maybe Waldo too)

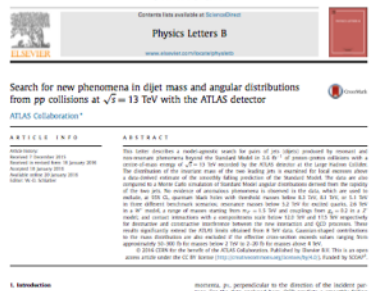
>500 papers as of today

28 public results with **full 2015 dataset** released within 5 weeks after end of p-p data taking

If you're curious about diphotons…
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/December2015-13TeV

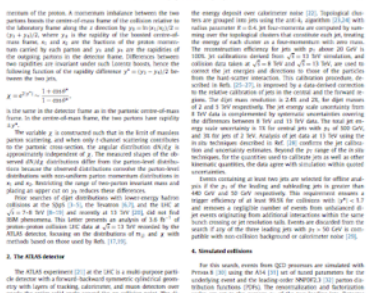
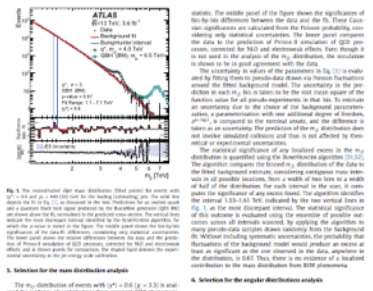
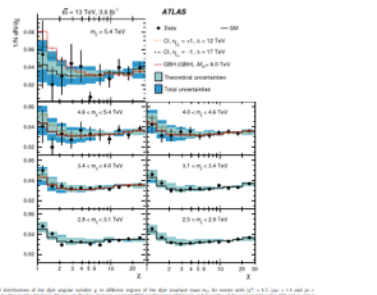
38 countries, ~180 universities,
>1000 students

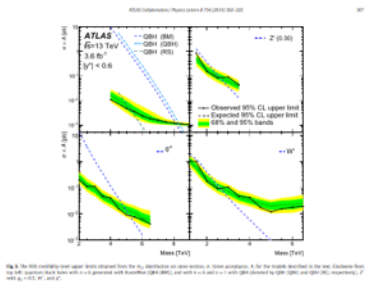
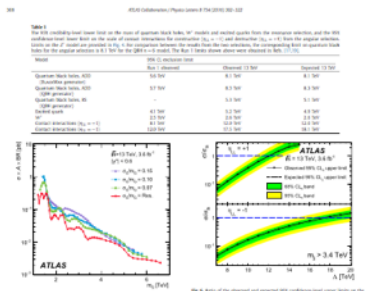
An ATLAS scientific paper (made in Lund)


Physics Letters B

Search for new phenomena in dijet mass and angular distributions from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration *

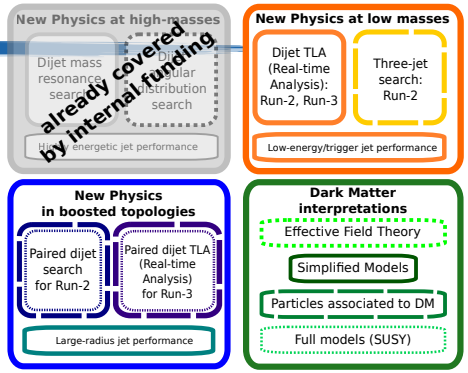

The author-list of an ATLAS paper

The DARKJETS team

Lund ATLAS group

7 senior members, PhD students,
Master's students, engineers

New physics searches with jets and leptons



2016	2017	2018	2019	2020	2021

CD, Principal Investigator

Post-doctoral researcher

Post-doctoral researcher

PhD student

PhD student

Lund ALICE group

Heavy ions and jet physics

Lund theory group

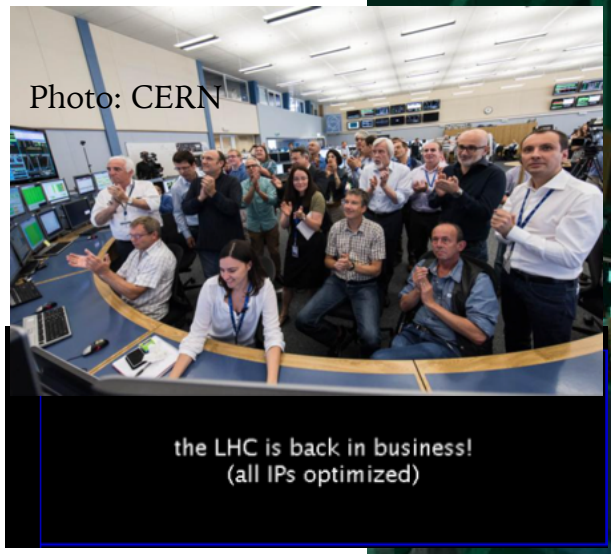
LHC and QCD phenomenology

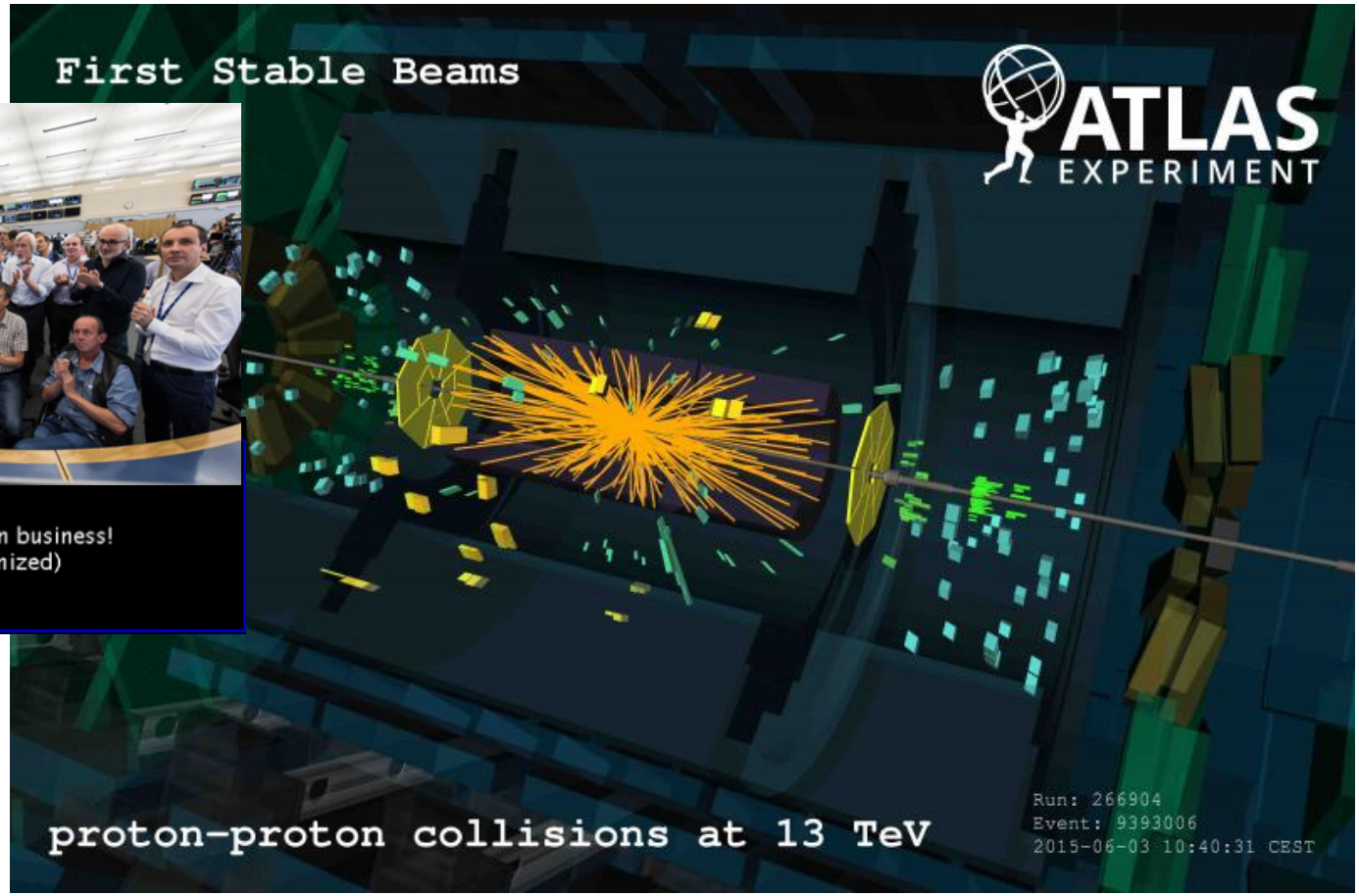
Collaboration and network within ATLAS

Physicist from different institutes
with complementary expertise

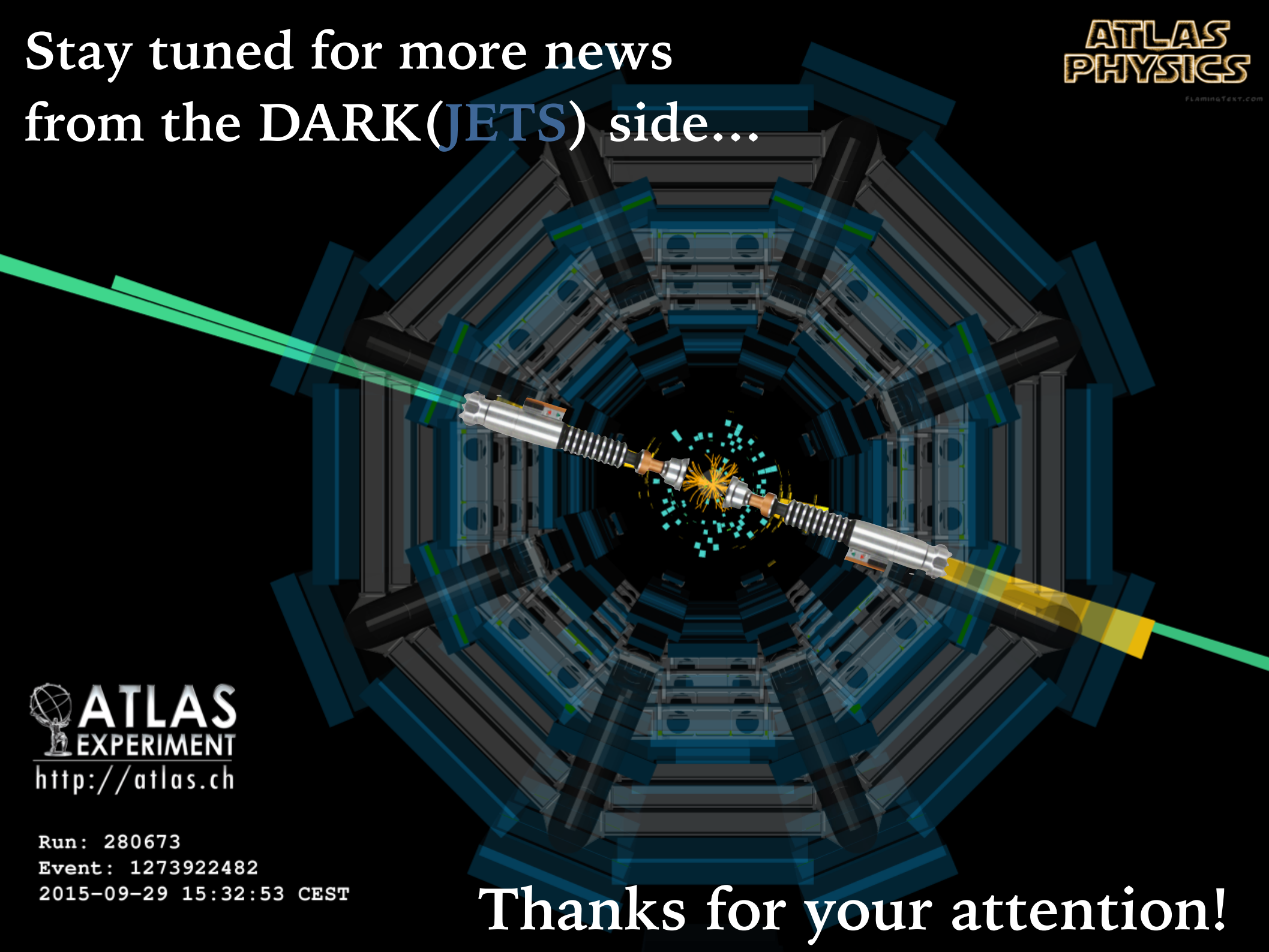
LHC Run 2 has started!

LHC proton-proton collisions
restarted in June 2015 at **13 Tera-electronVolt**





Stay tuned for more news
from the DARK(JETS) side...



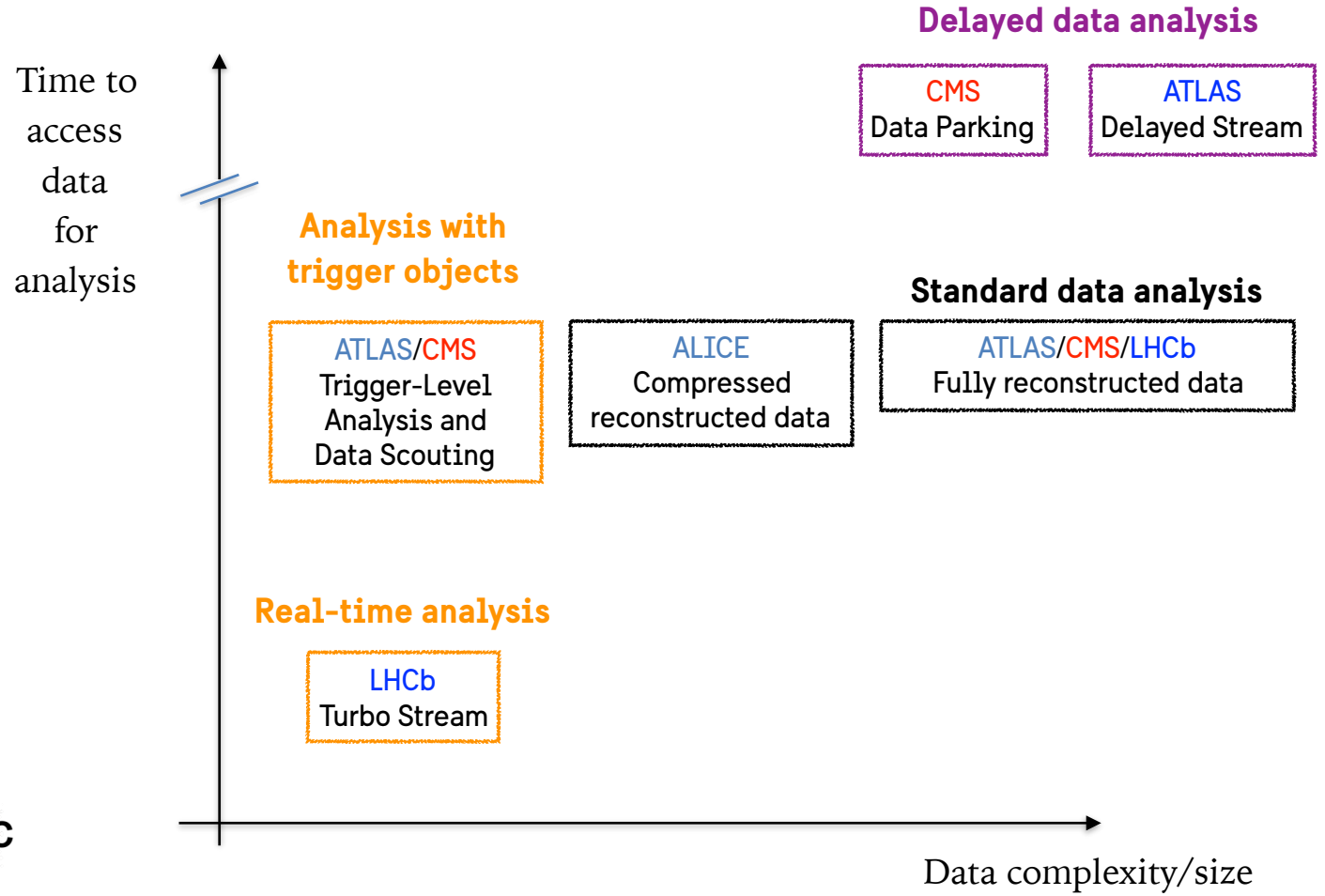
Thanks for your attention!

Trigger-level and real-time LHC analysis

Key concept: since storage is limited, reduce data size/complexity to increase rate of recorded data

(One step further: do not keep data, analyse it directly online)

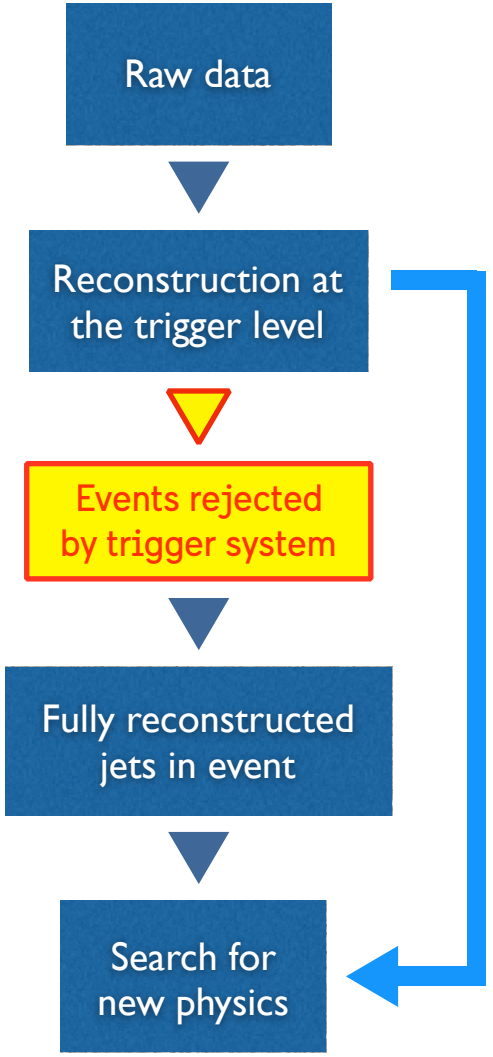
All four LHC experiments use Data Scouting/Trigger-Level Analysis techniques to make the most of LHC data

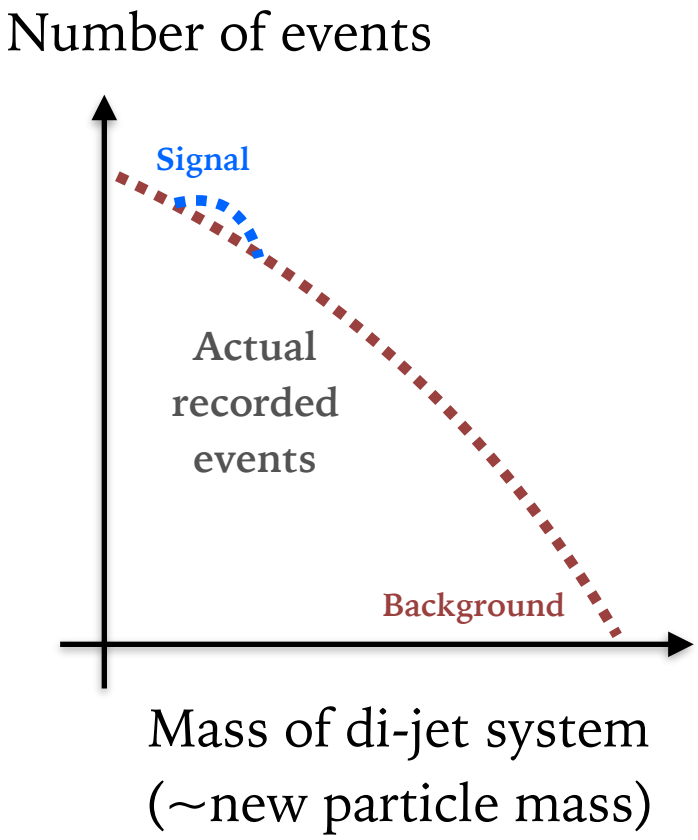


Signals and backgrounds with jets

My solutions to overcome backgrounds within DARKJETS:

1. Make it possible to analyse all events:
   Use jet-only events with trigger-level analysis that I introduced in ATLAS

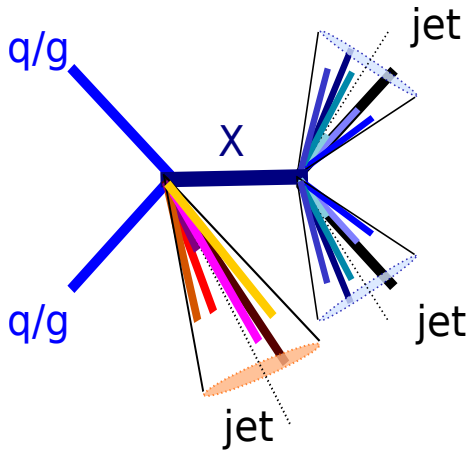


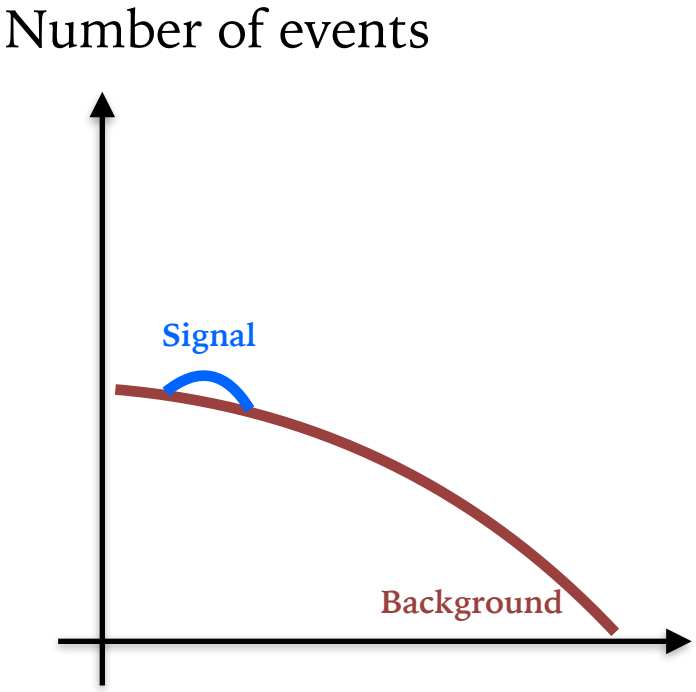


Signals and backgrounds with jets

My solutions to overcome backgrounds within DARKJETS:

2. Use decay topologies with less backgrounds
   dijet + energetic object from radiation

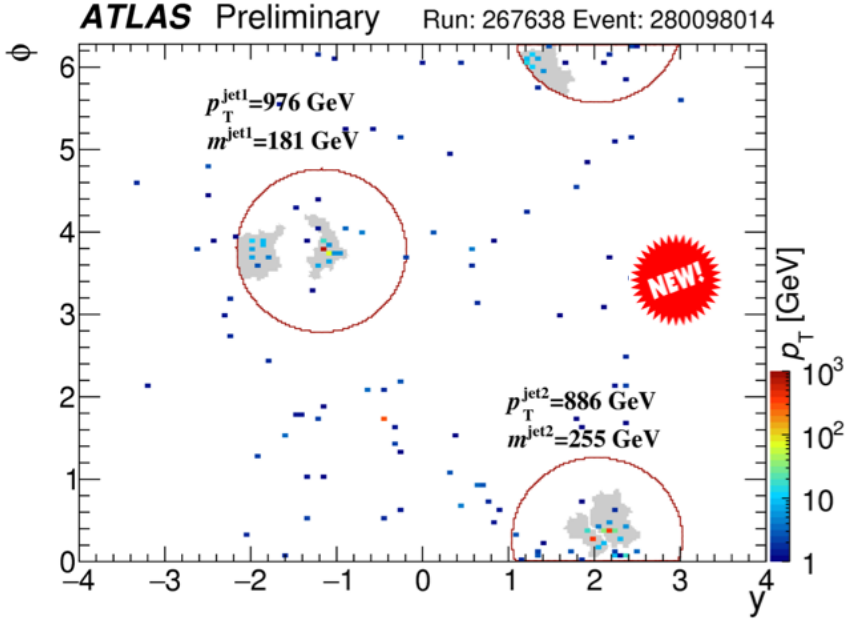


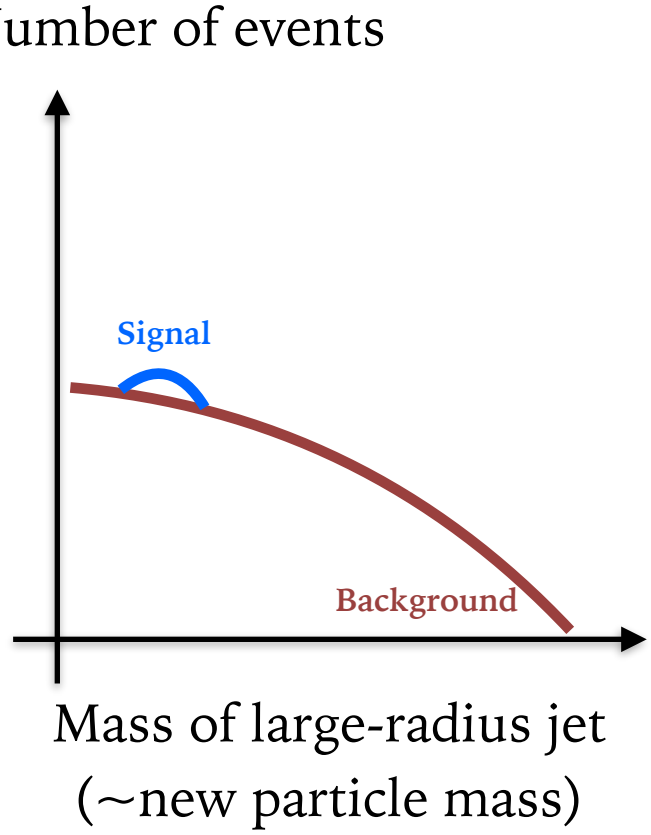


Signals and backgrounds with jets

My solutions to overcome backgrounds within DARKJETS:

3. Discriminate and reject background **mediator pair-production: jet substructure**





Potential DARKJETS reach

1. Make it possible to analyse all events:
   Use jet-only events with **trigger-level analysis**

2. Use decay topologies with less backgrounds
   dijet + energetic object from radiation

3. Discriminate and reject background
   mediator pair-production: jet substructure