LHC Physics - BSM searches & beyond

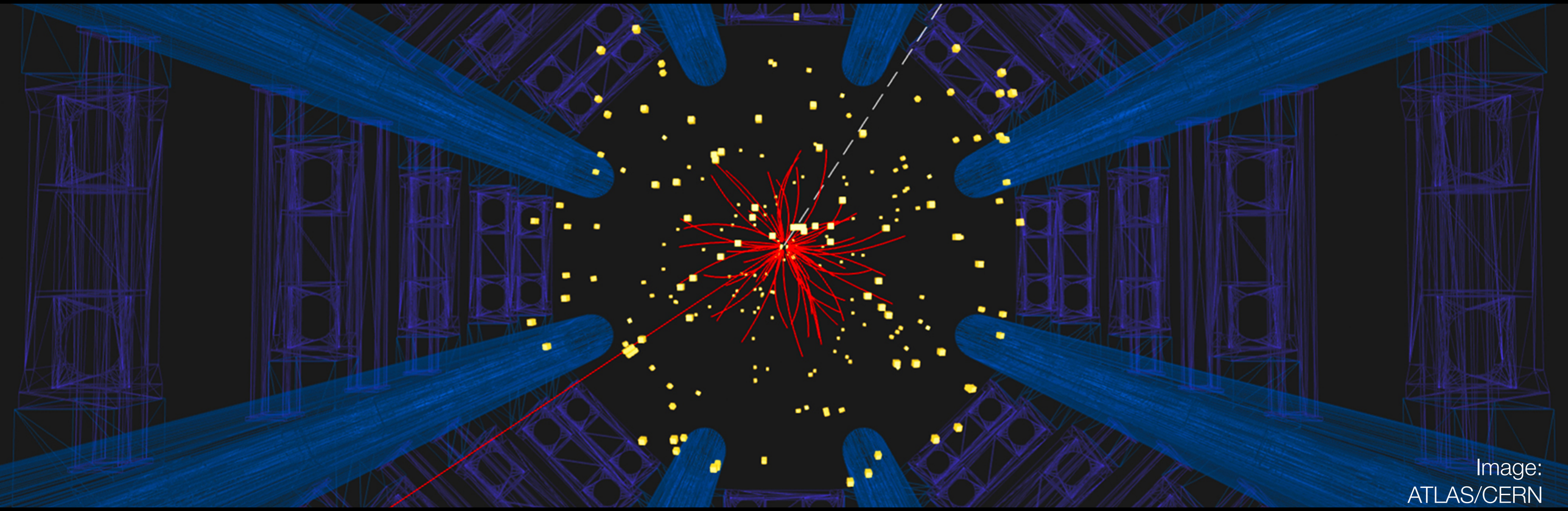


Image:
ATLAS/CERN

Lydia Beresford

DESY Summer Student Lectures

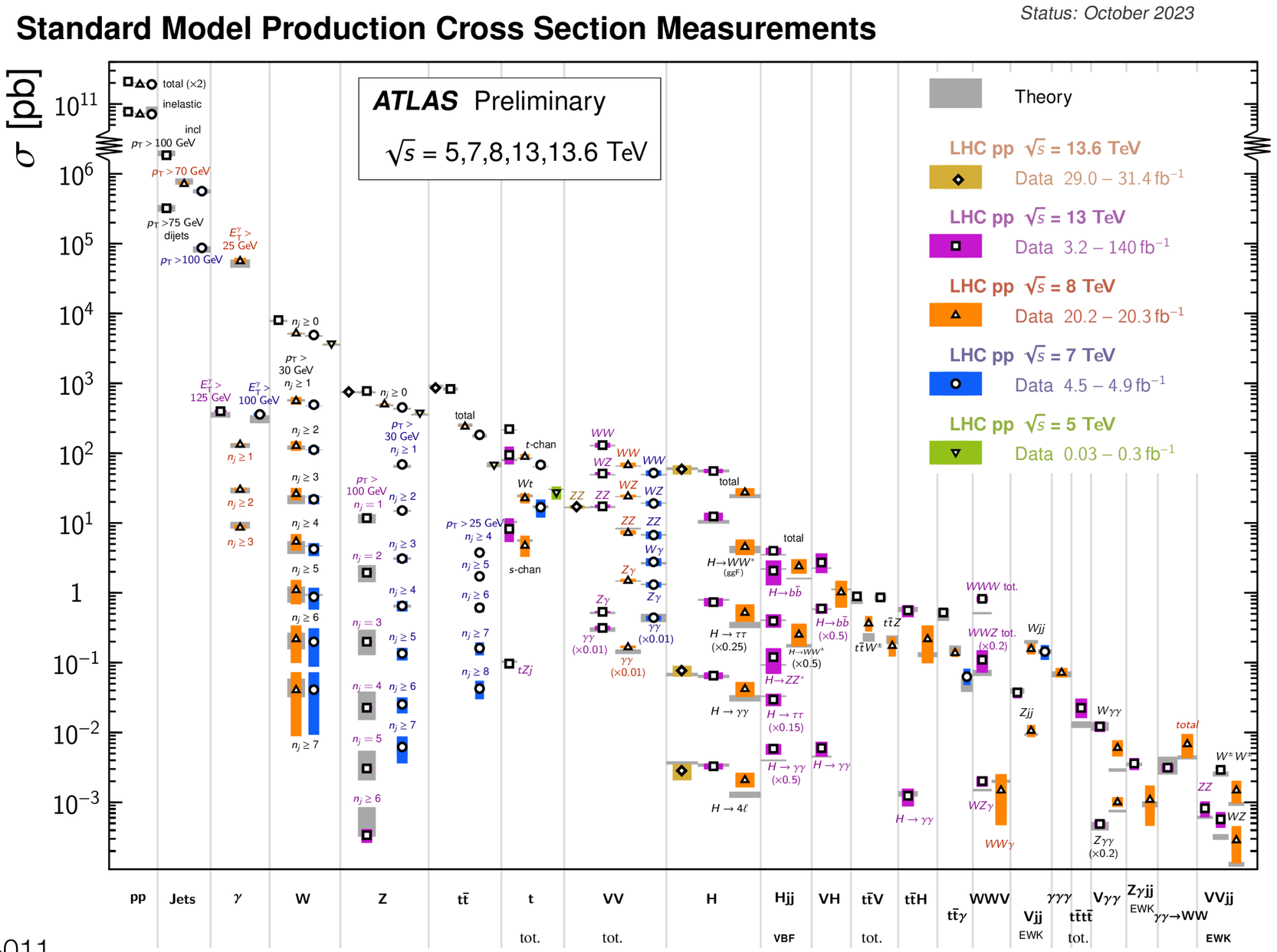
05.08.25

Physics Goals of the LHC

wikimedia

Search for
New Physics

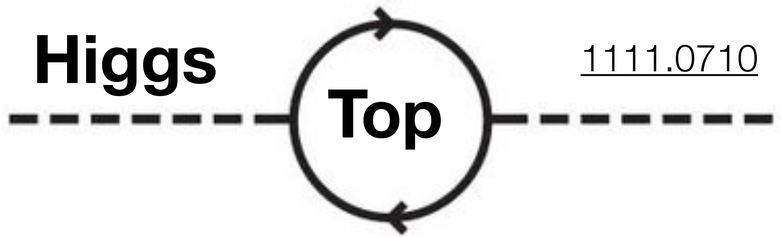
Standard Model success



ATL-PHYS-PUB-2024-011

Shortcomings of the Standard Model

- No explanation for **Dark Matter** or **Dark Energy**
- **Gravity** is not included in the Standard Model
- Doesn't explain why the **Higgs is so light** (hierarchy problem)



- Does not explain **matter-antimatter asymmetry** in the universe

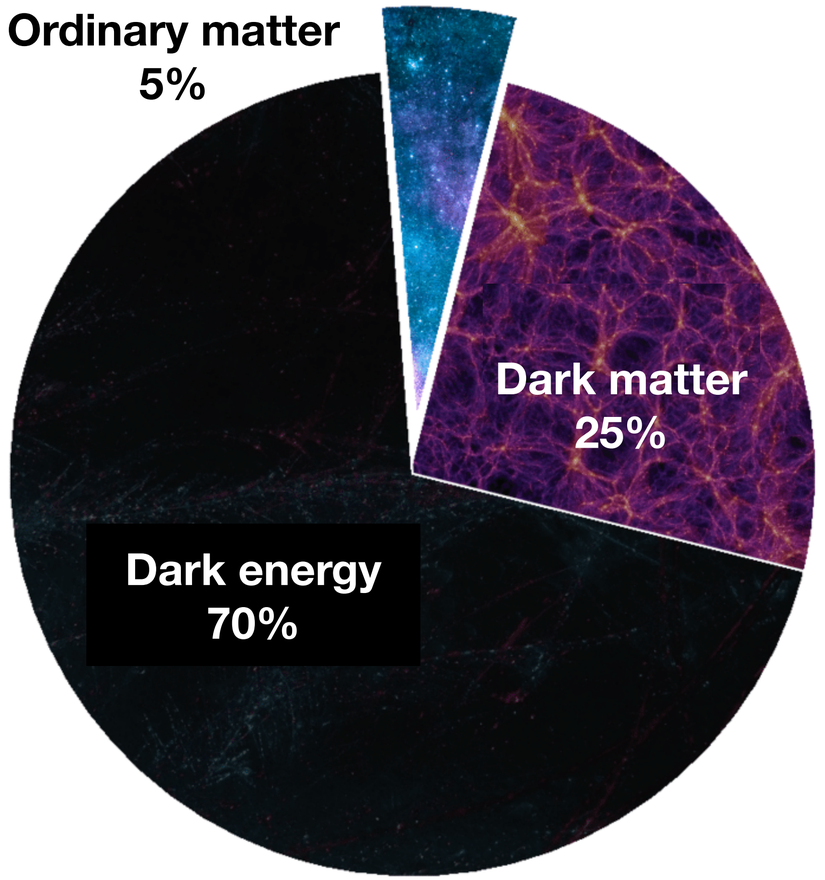
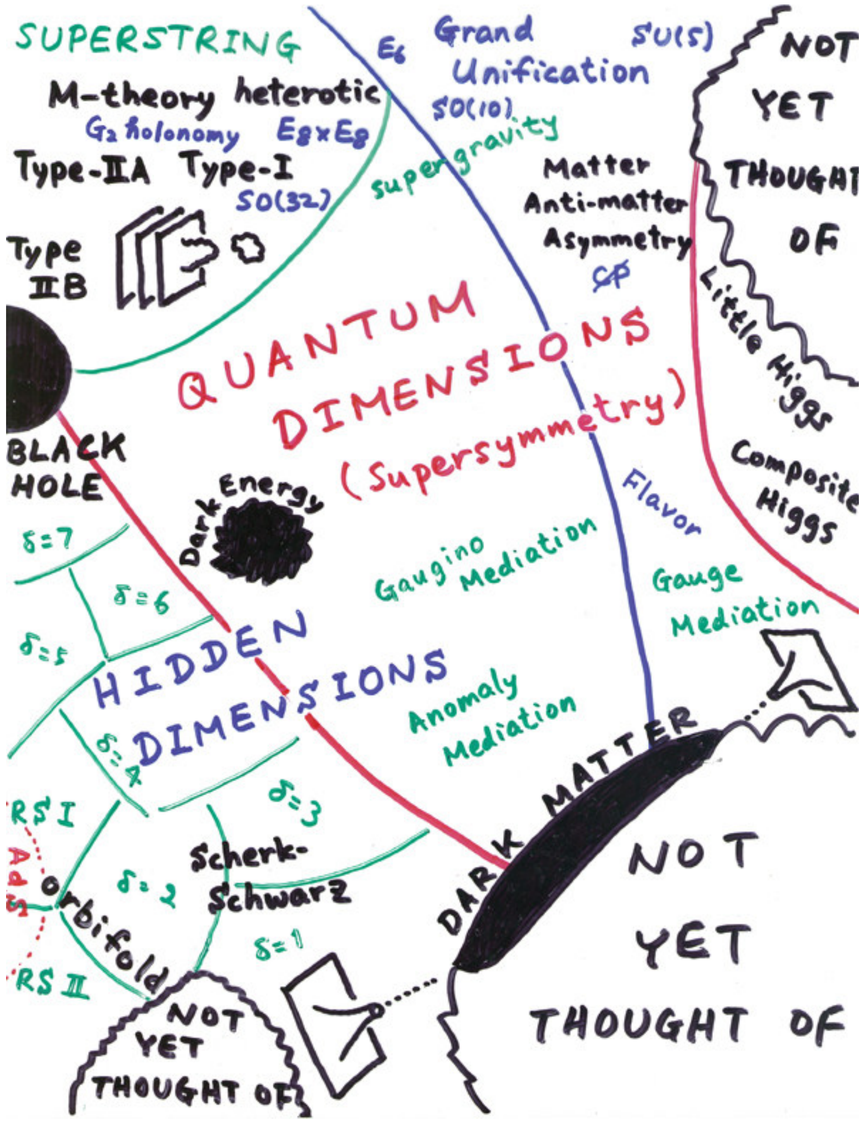


Image: adapted from Florian Wolz

Energy density of the universe

Landscape of proposed New Physics scenarios is vast!



Two ways of approaching this

- **Model driven**

  Start from a specific theory prediction
  → design and optimise for that specific signal

- **Signature driven**

  Look for deviation from the SM anywhere
  → look at specific final states (dijet, high MET)

Both strategies are followed at the LHC

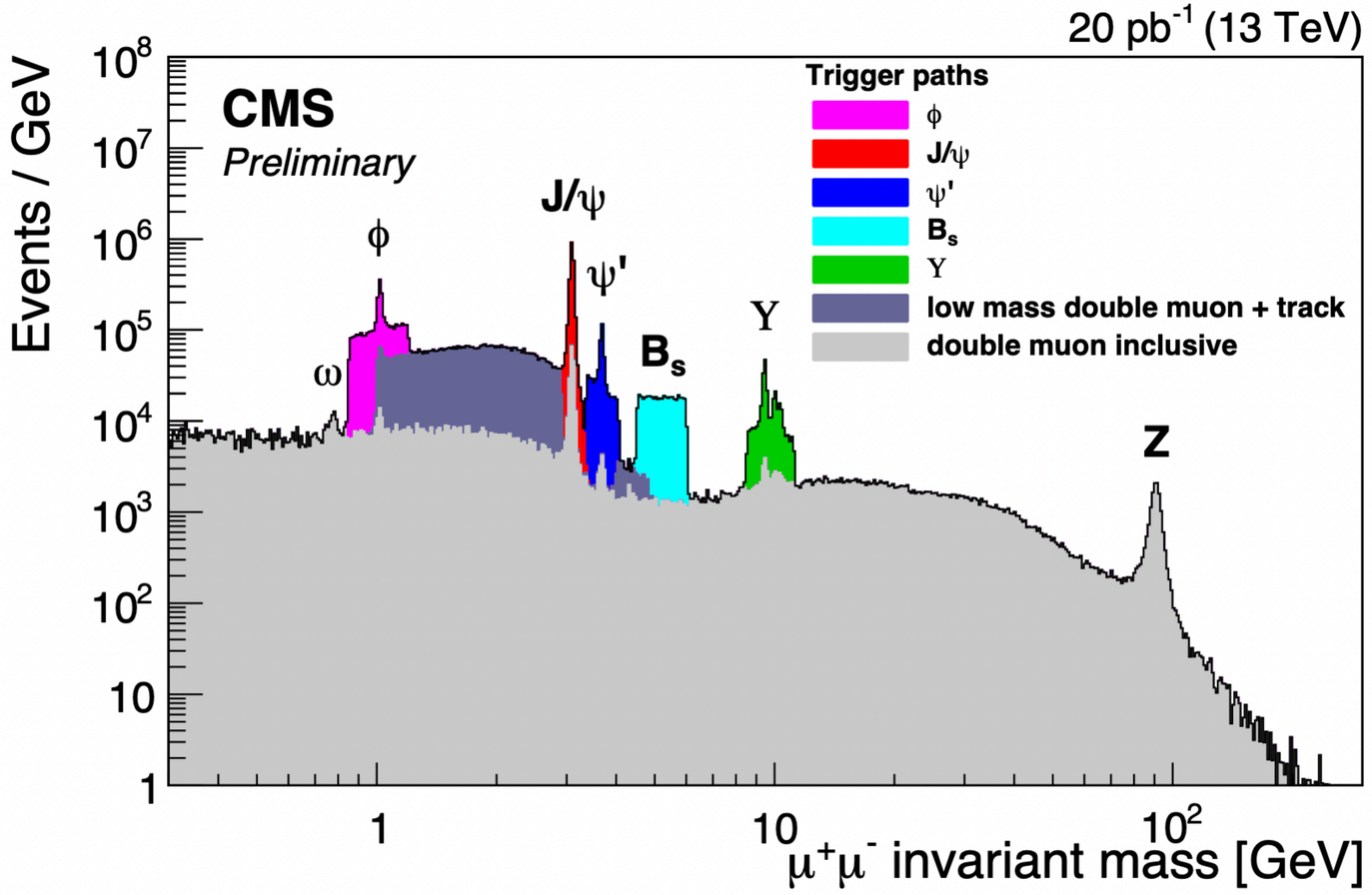
Crucial: excellent understanding of Standard Model backgrounds is needed!

http://newsline.linearcollider.org/images/2010/20100401_dc_2.jpg

Resonance searches

Many models predict the existence of additional, so-far undiscovered particles

→ Would likely find them through their decay products

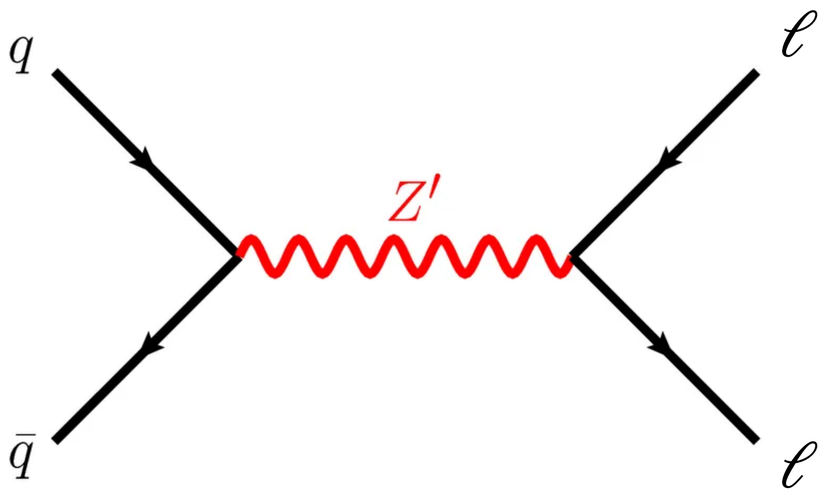


https://cds.cern.ch/record/2037379

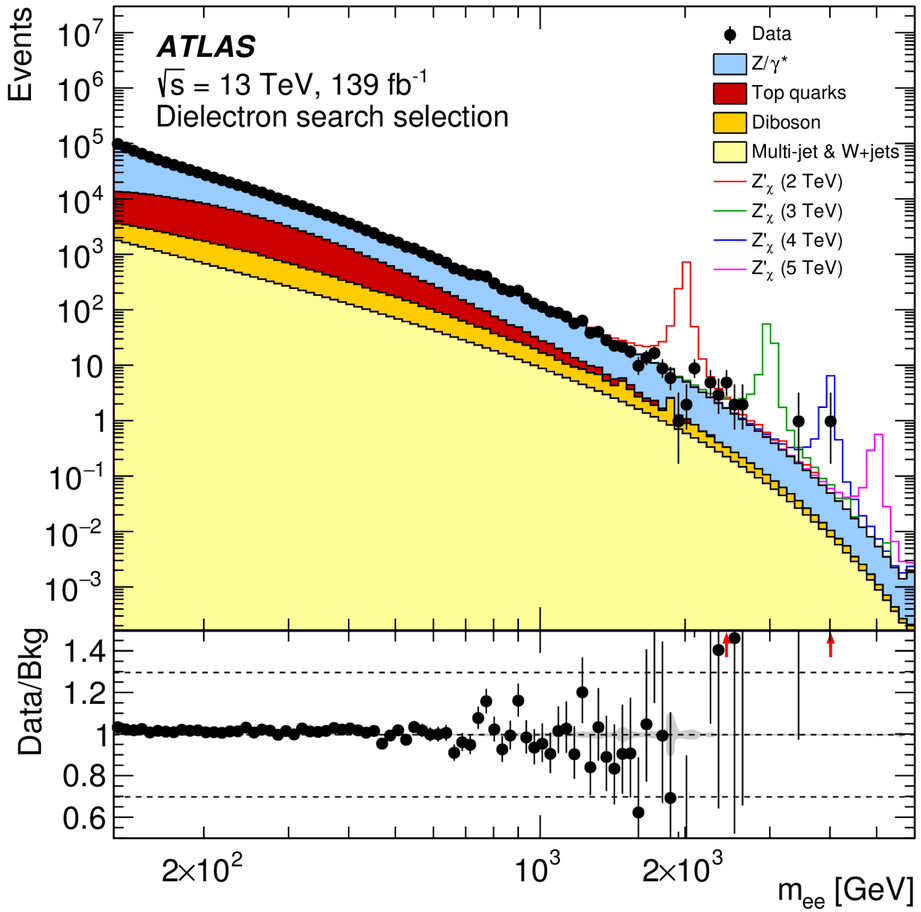
Dilepton resonances

Heavy partners of the known bosons e.g. $Z' \to \ell\ell$

Occur in e.g. grand unified theories (GUT)



Phys. Lett. B 796 (2019) 68



Now probing masses up to 4 TeV

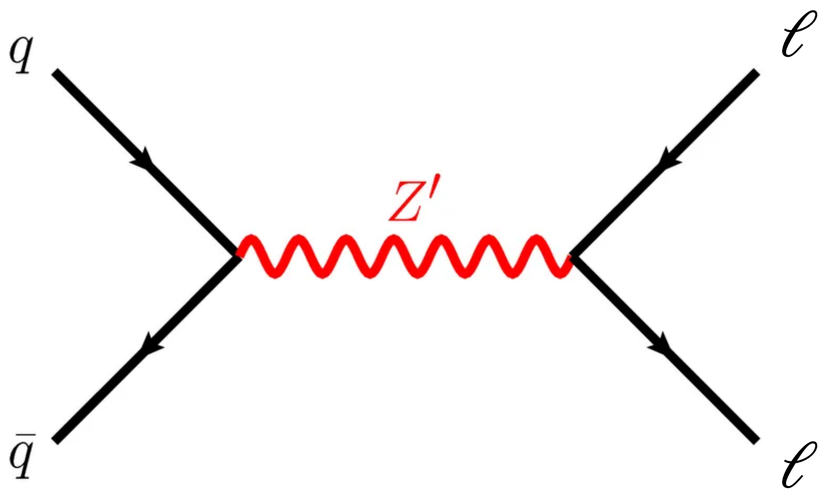
LHC strength: high CM energy → sensitivity to so far un-probed high masses!

Dilepton resonances

Quiz: what is a grand unified theory?

Heavy partners of the known bosons e.g. $Z' \to \ell\ell$

Occur in e.g. grand unified theories (GUT)



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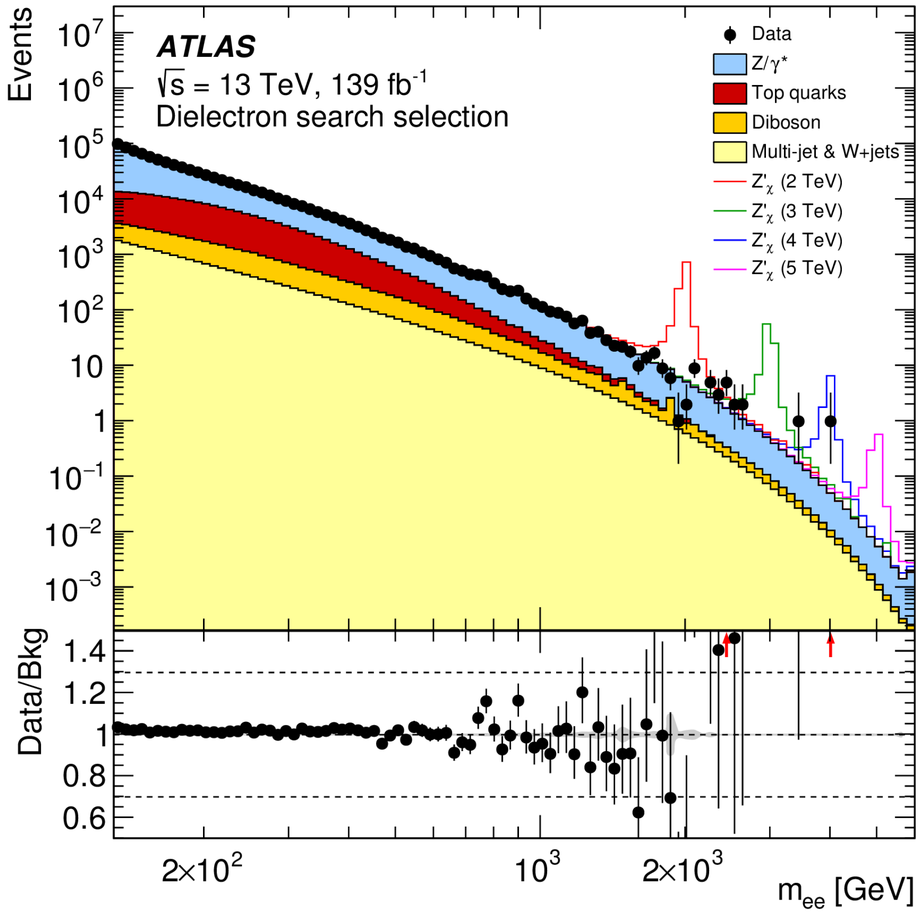
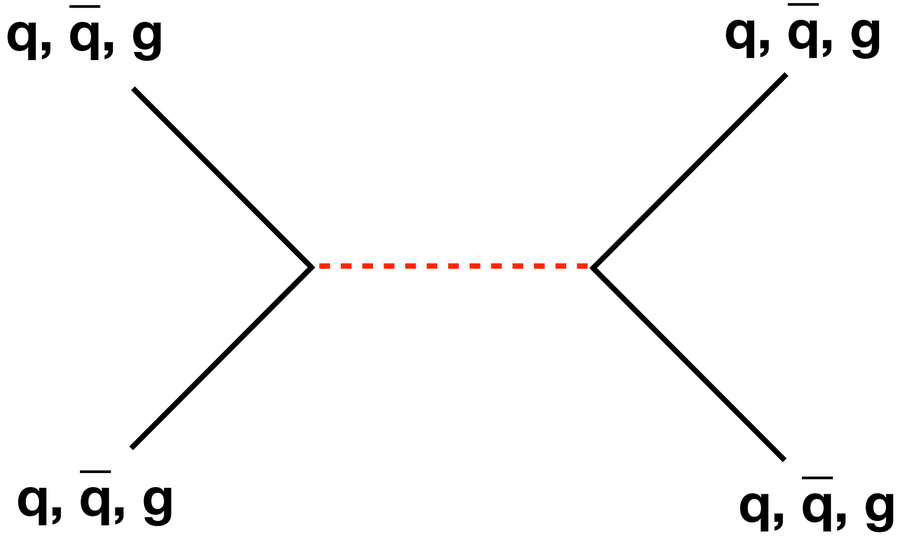


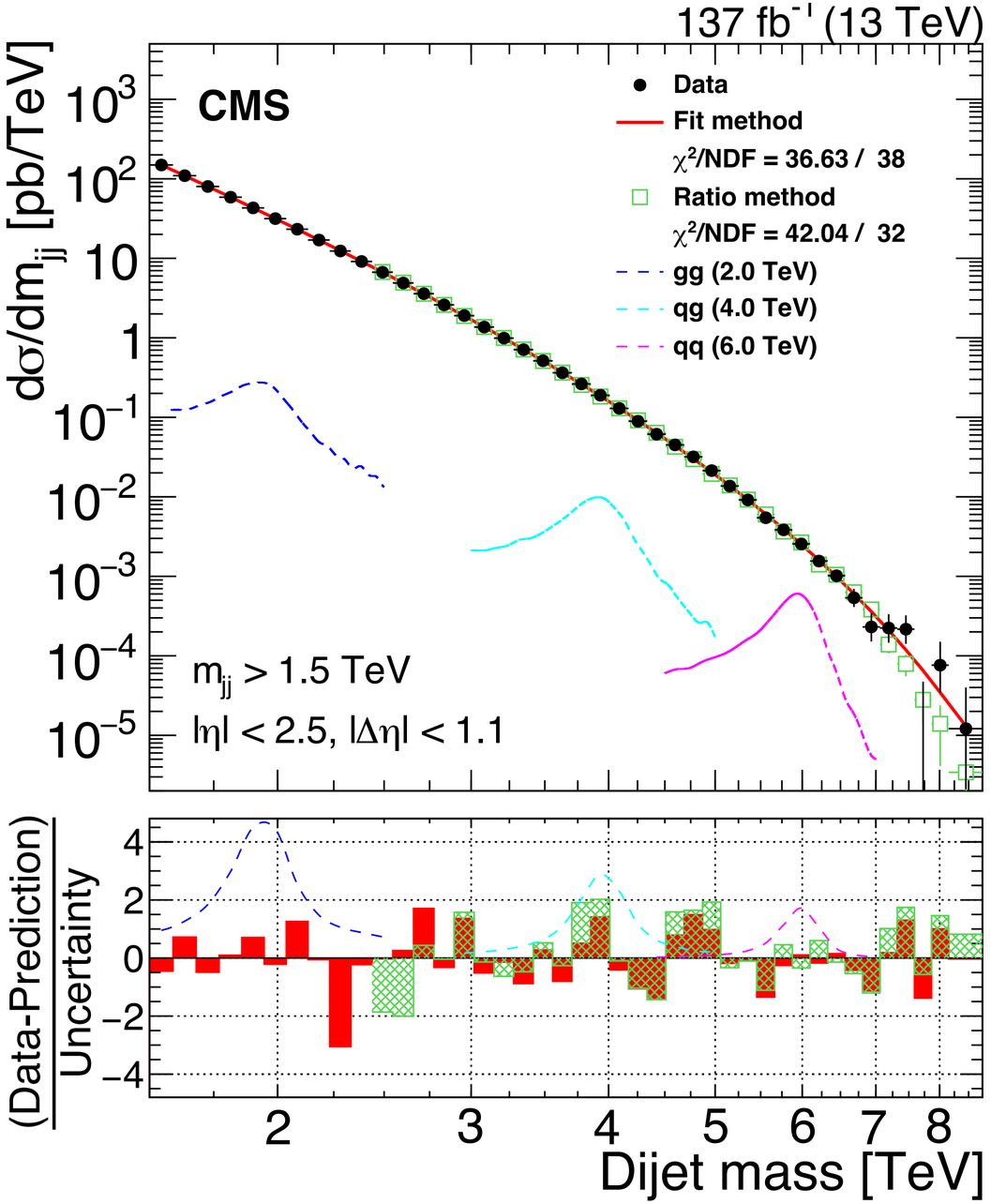
Now probing masses up to 4 TeV

LHC strength: high CM energy → sensitivity to so far un-probed high masses!

Dijet resonances

Several new physics models predict heavy resonances that decay into dijets (qq, qg or gg)





JHEP 2005 (2020) 033

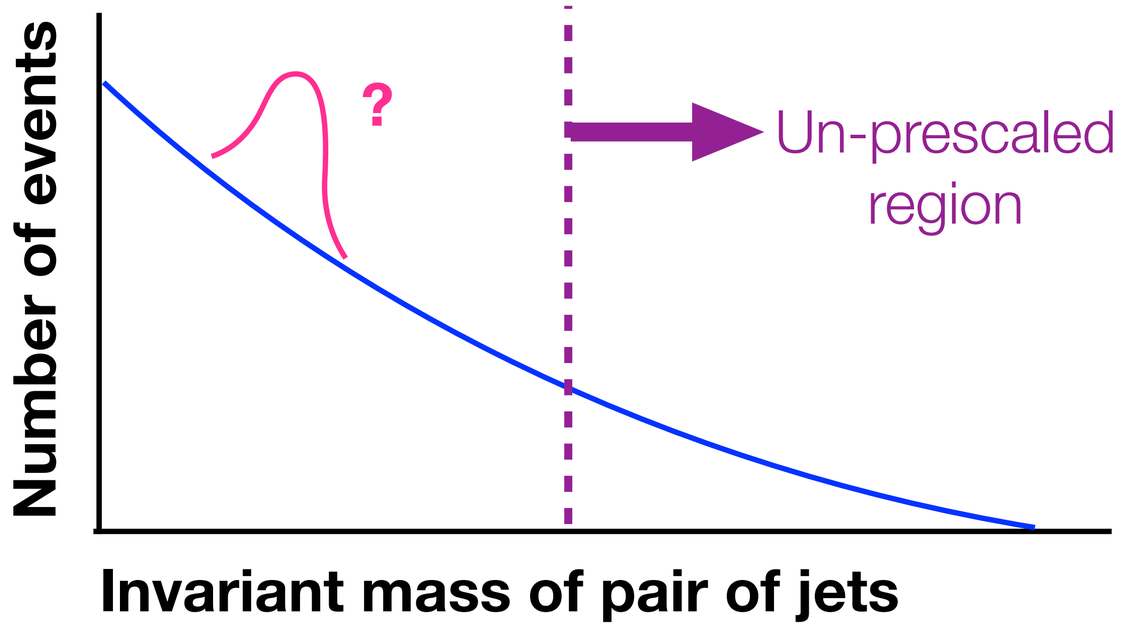
What about lower masses?

Experimental Challenge

LHC produces huge amount of jet events at low mass

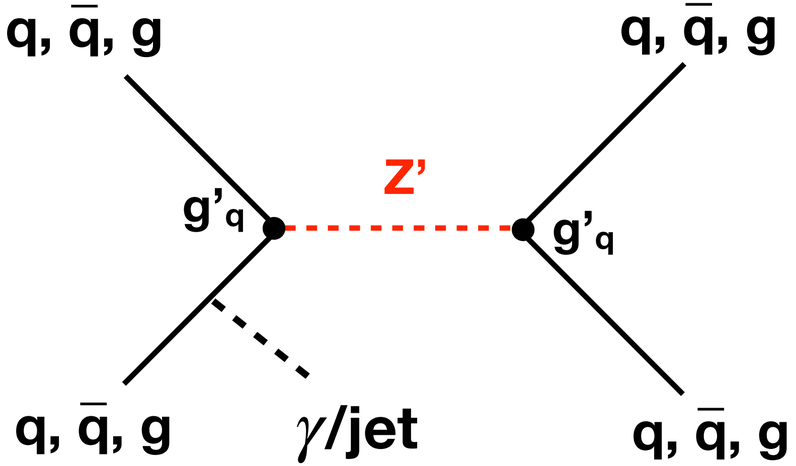
→ Single jet triggers highly prescaled at low masses

→ **New techniques needed**

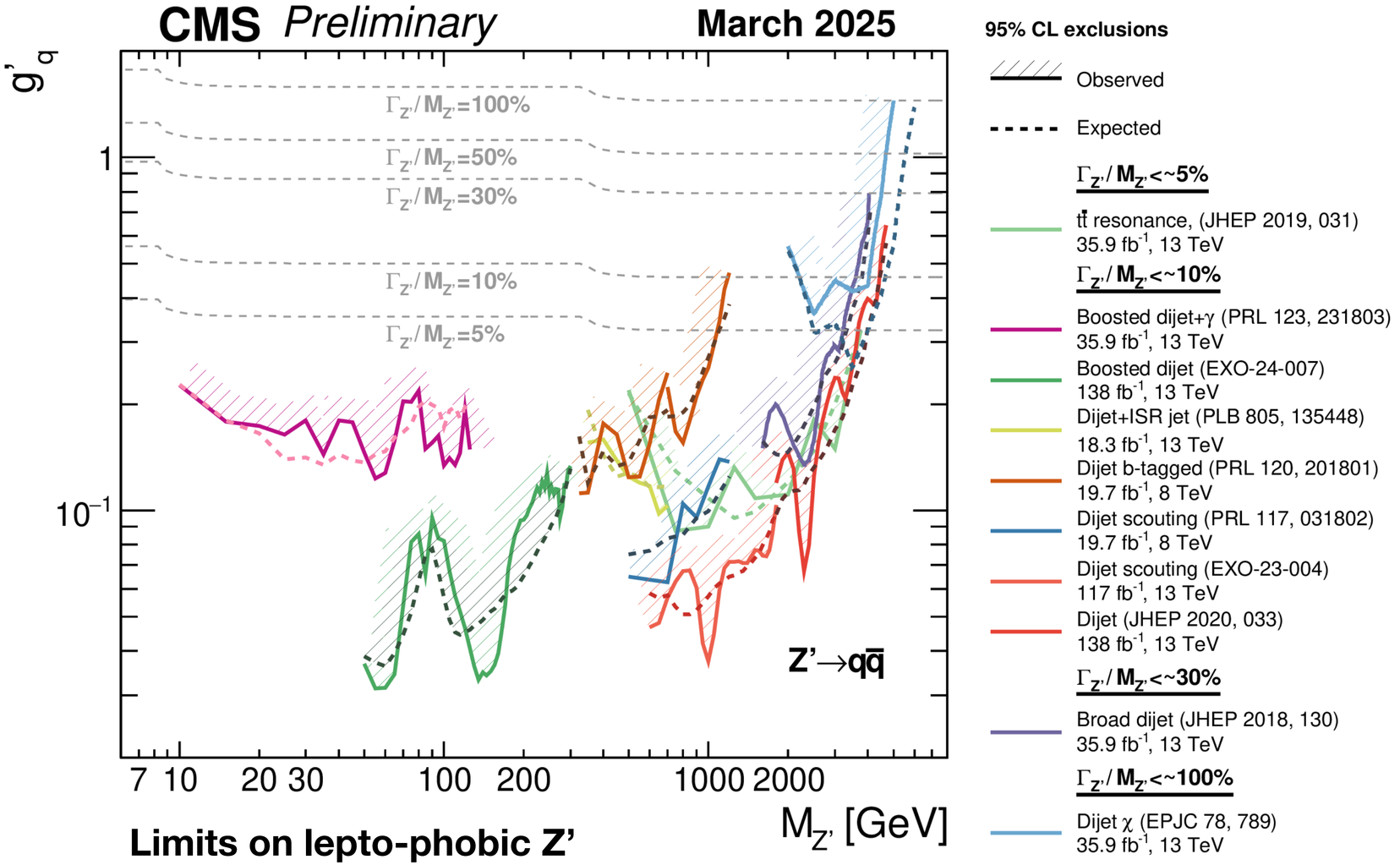


What about lower masses?

Trigger on radiated photon or jet



Reconstruct resonance as a single large radius jet & use sub-structure

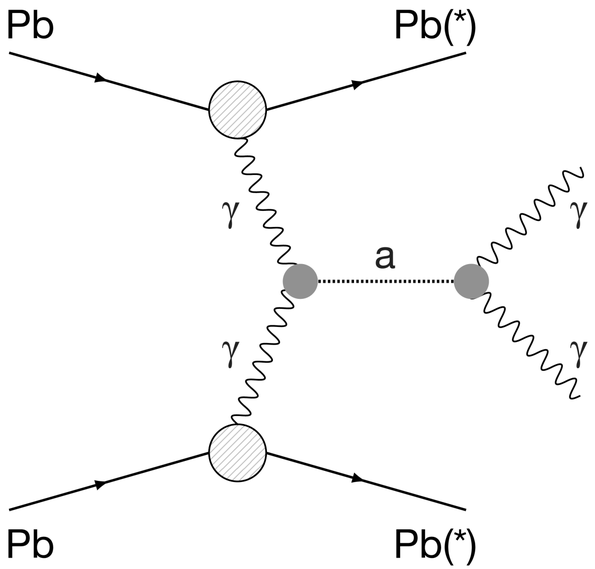


Limits on lepto-phobic Z'

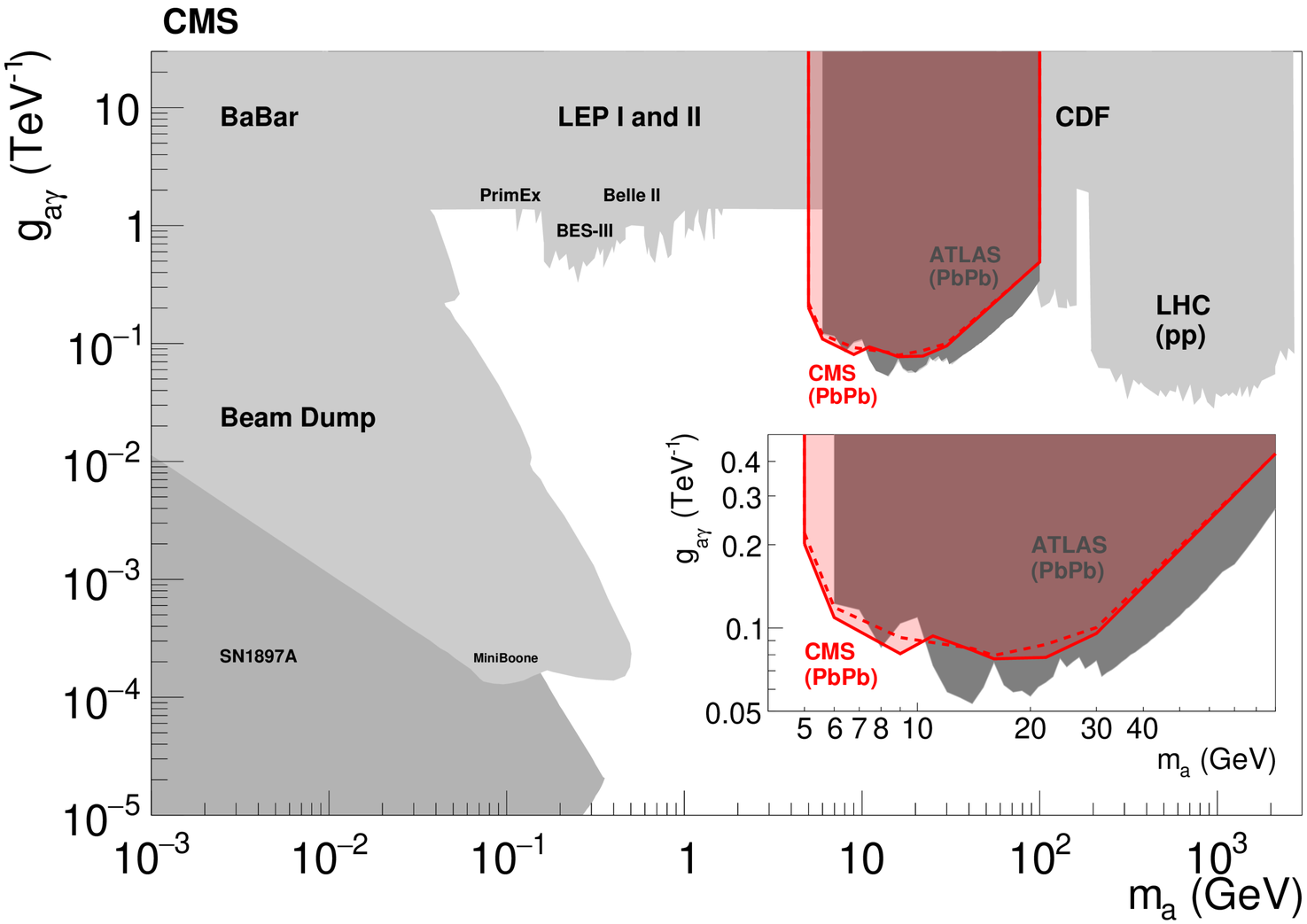
CMS summary plot

What if the new resonance only couples to photons?

Axion-Like-Particle (ALP)



Look for narrow resonance in $m_{\gamma\gamma}$

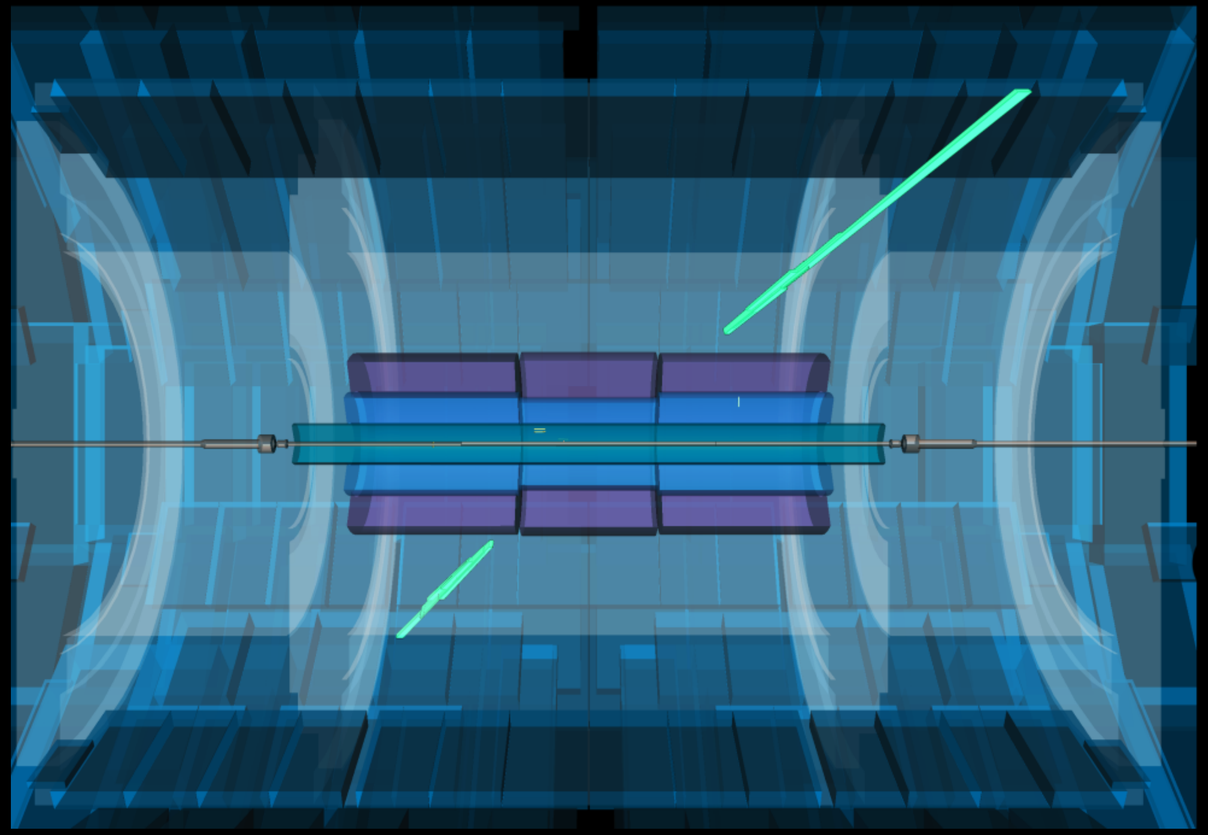


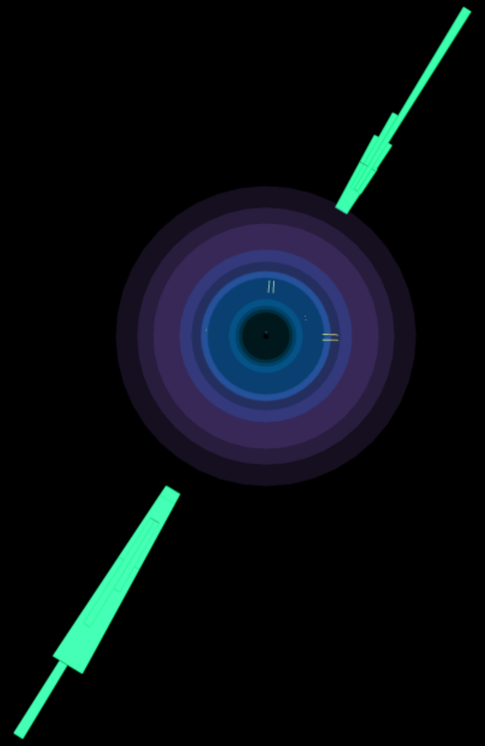
HIN-21-015

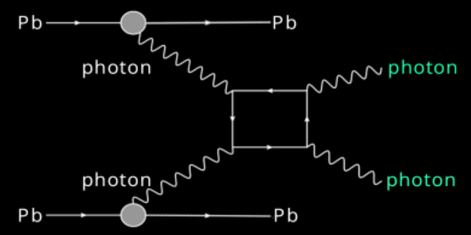
Pb+Pb Light-by-light scattering candidate event

ATLAS EXPERIMENT

Candidate Event:
Light-by-Light Scattering
Run: 366994 Event: 453765663
2018-11-26 18:32:03 CEST







PLB 816 (2021) 136190

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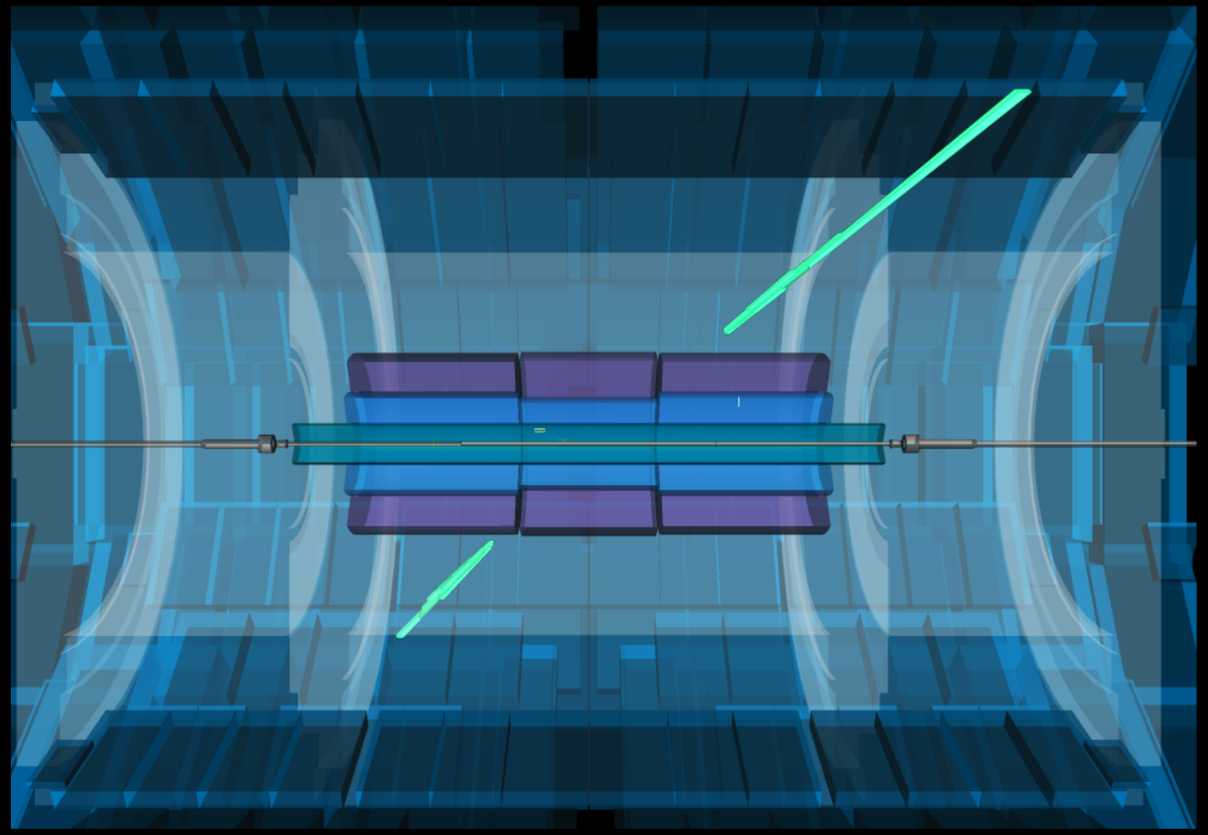
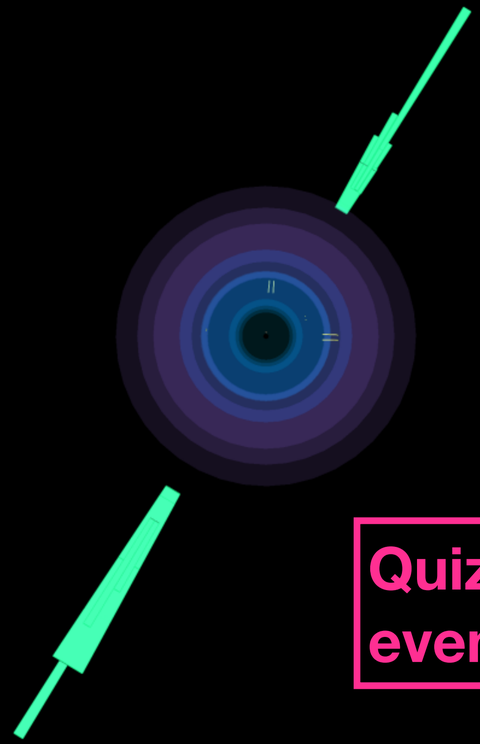
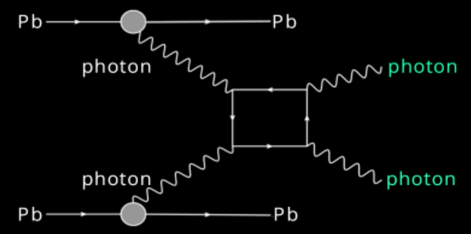




Quiz: why is this event so clean?



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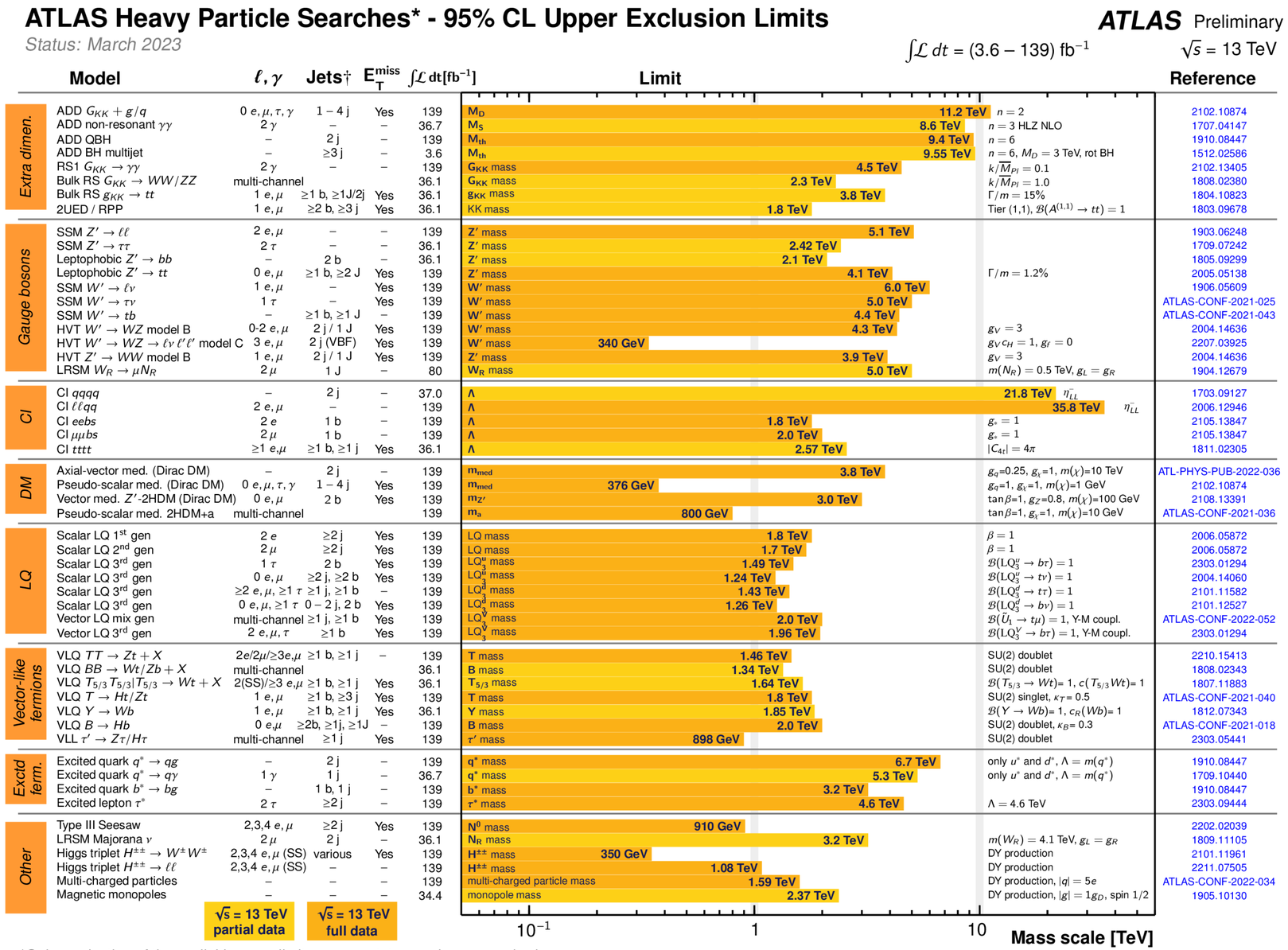
Exotics search summary plot - a subset



*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

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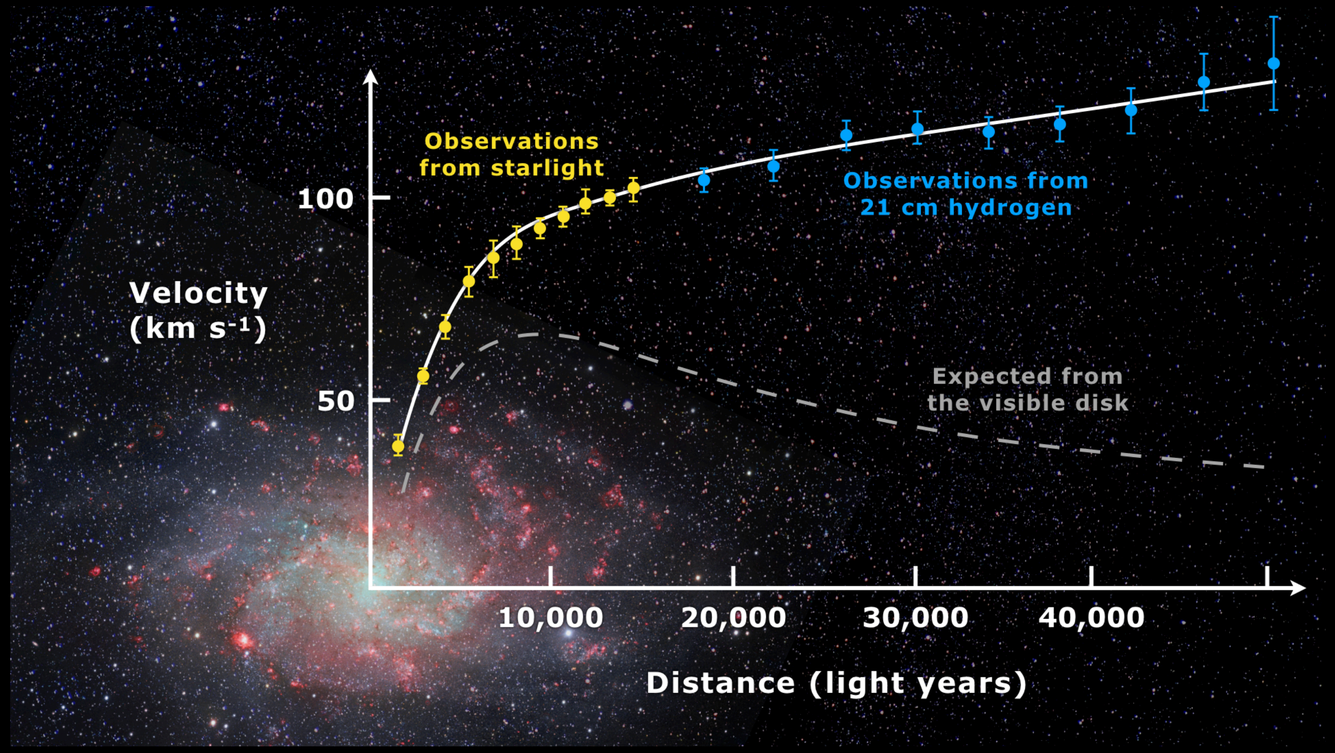
Dark Matter

Astrophysical observations give strong evidence for a new kind of matter that interacts gravitationally

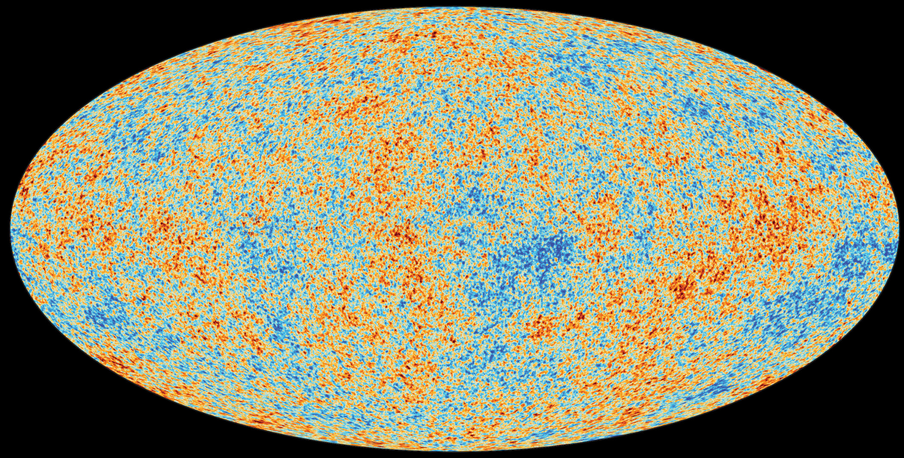


Rotational curves of galaxies

wikipedia

wikipedia

Gravitational lensing

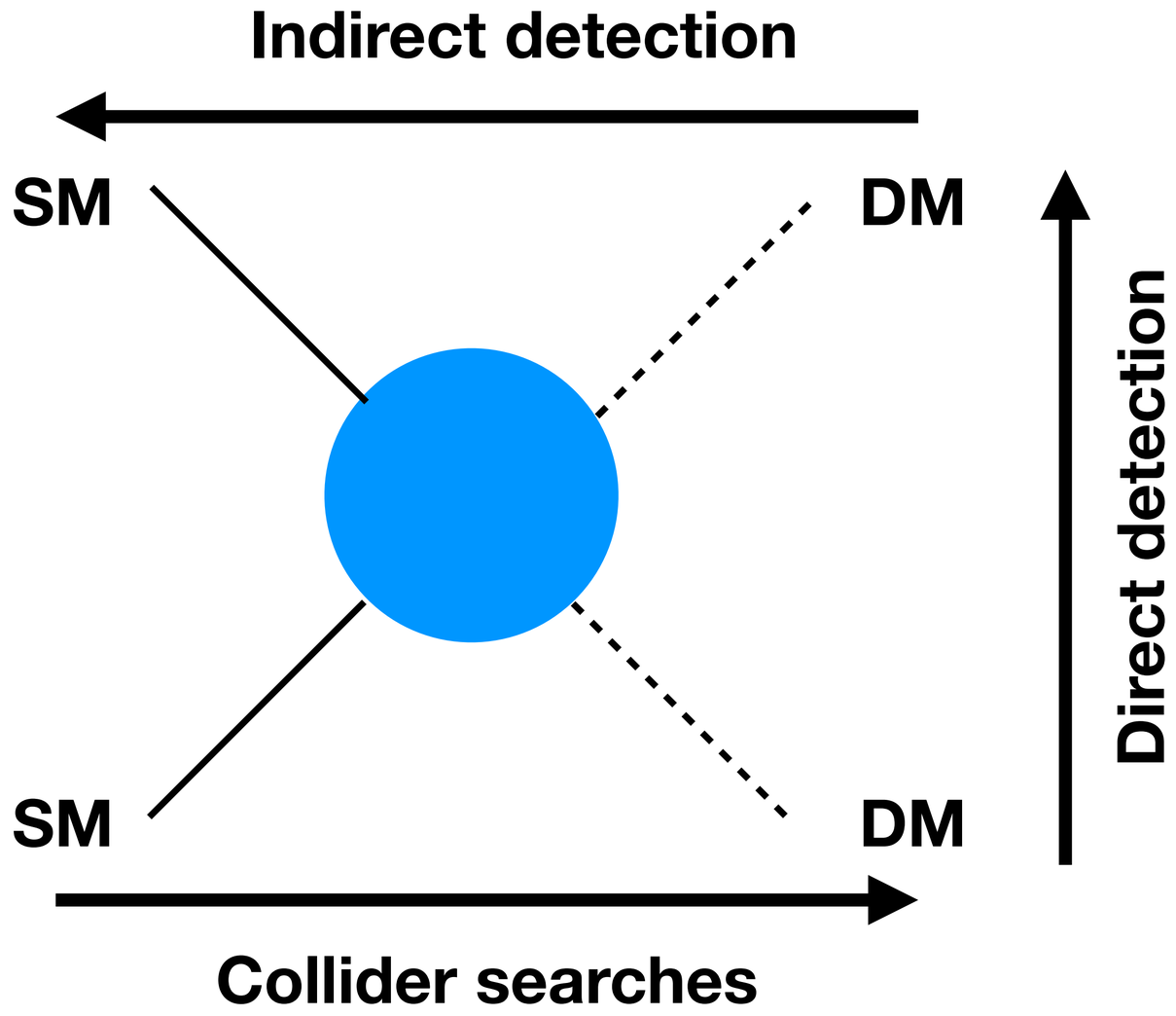


Cosmic microwave background

ESA

Searching for Dark Matter

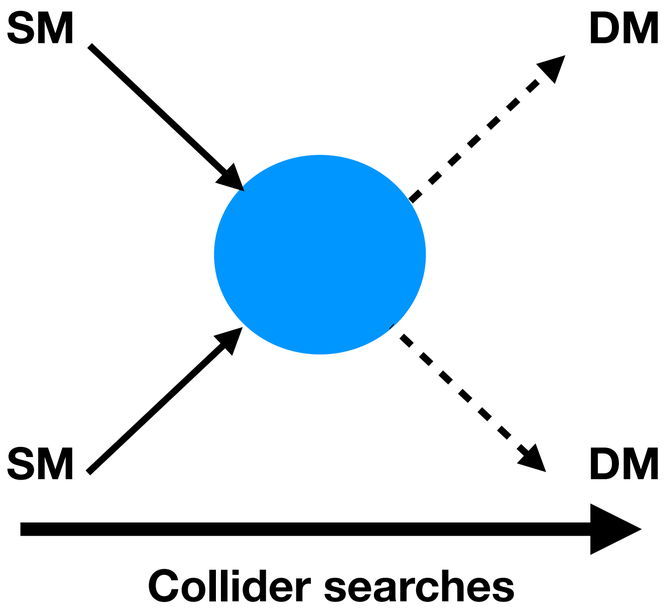
See lectures by Axel Lindner and Aaron Dean Spector for more on Dark Matter

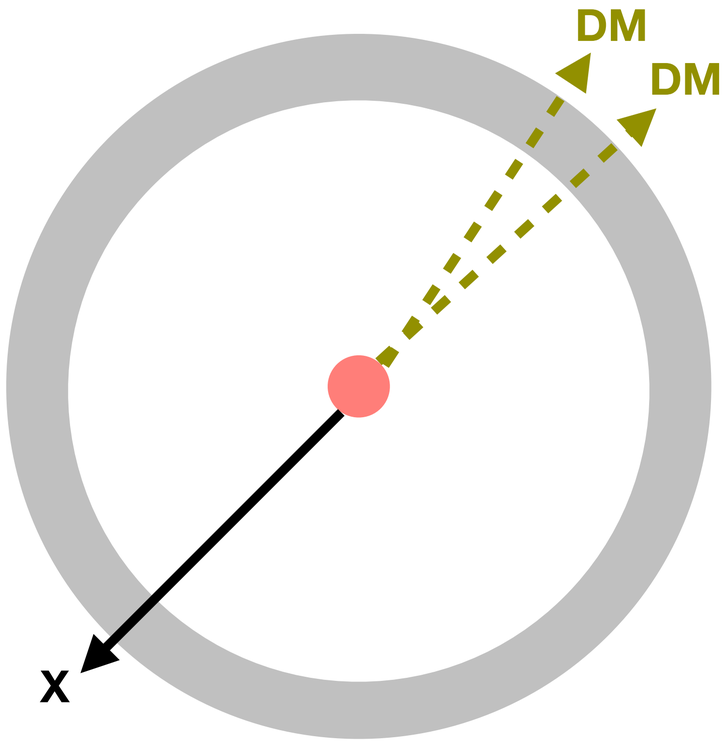


Dark Matter searches at colliders

DM could be produced in proton-proton collisions

- DM does not interact with the detector
- Infer due to momentum imbalance when produced in association with particle “X”
  → mono-X (can also be several particles)



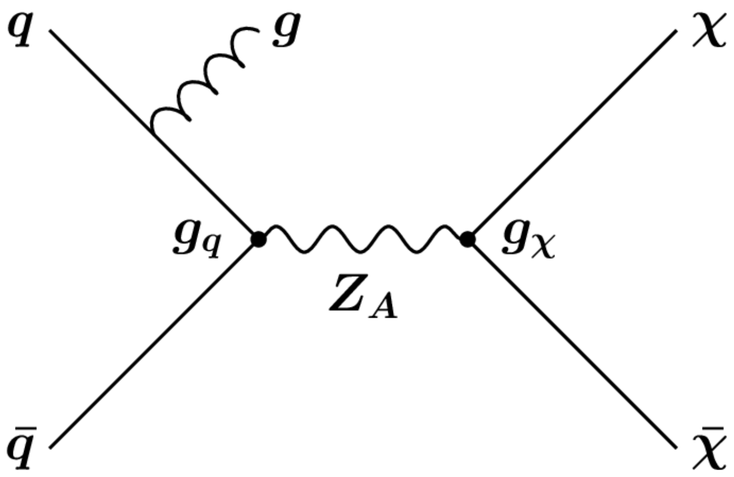


Mono-X signature

ATLAS and CMS cannot detect what they cannot see

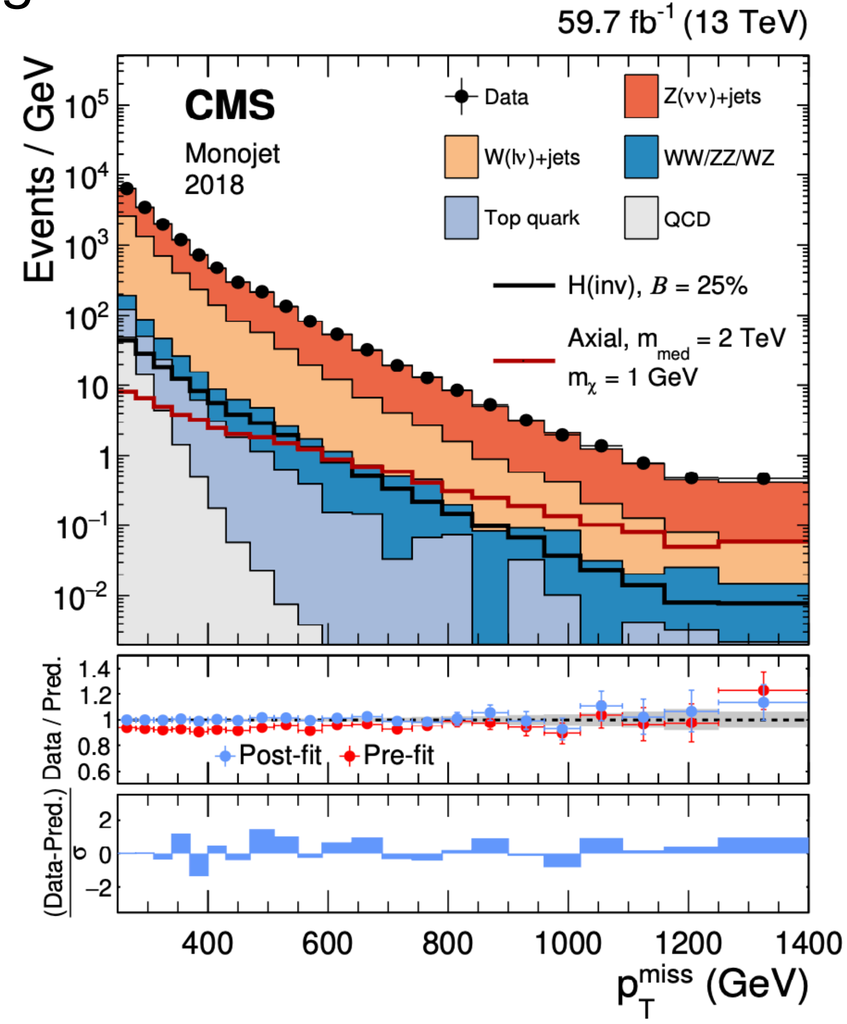
→ If DM is produced at the LHC need some X to trigger on

Simplified model



ISR jet with axial-vector Z (spin 1, parity even)

Could also be: photon, W, Z



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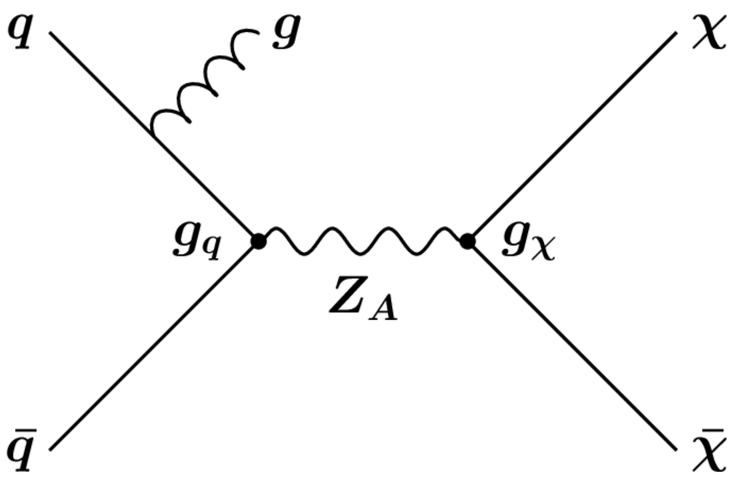

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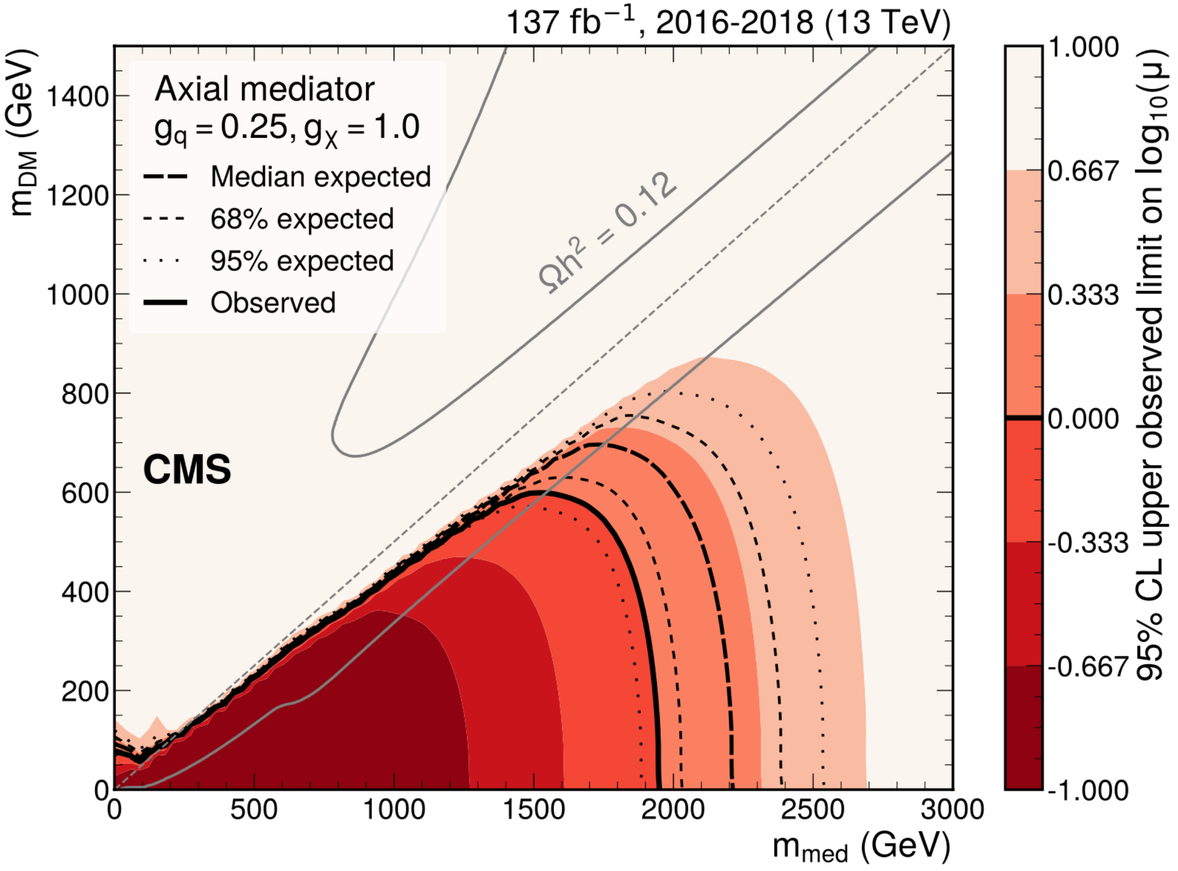

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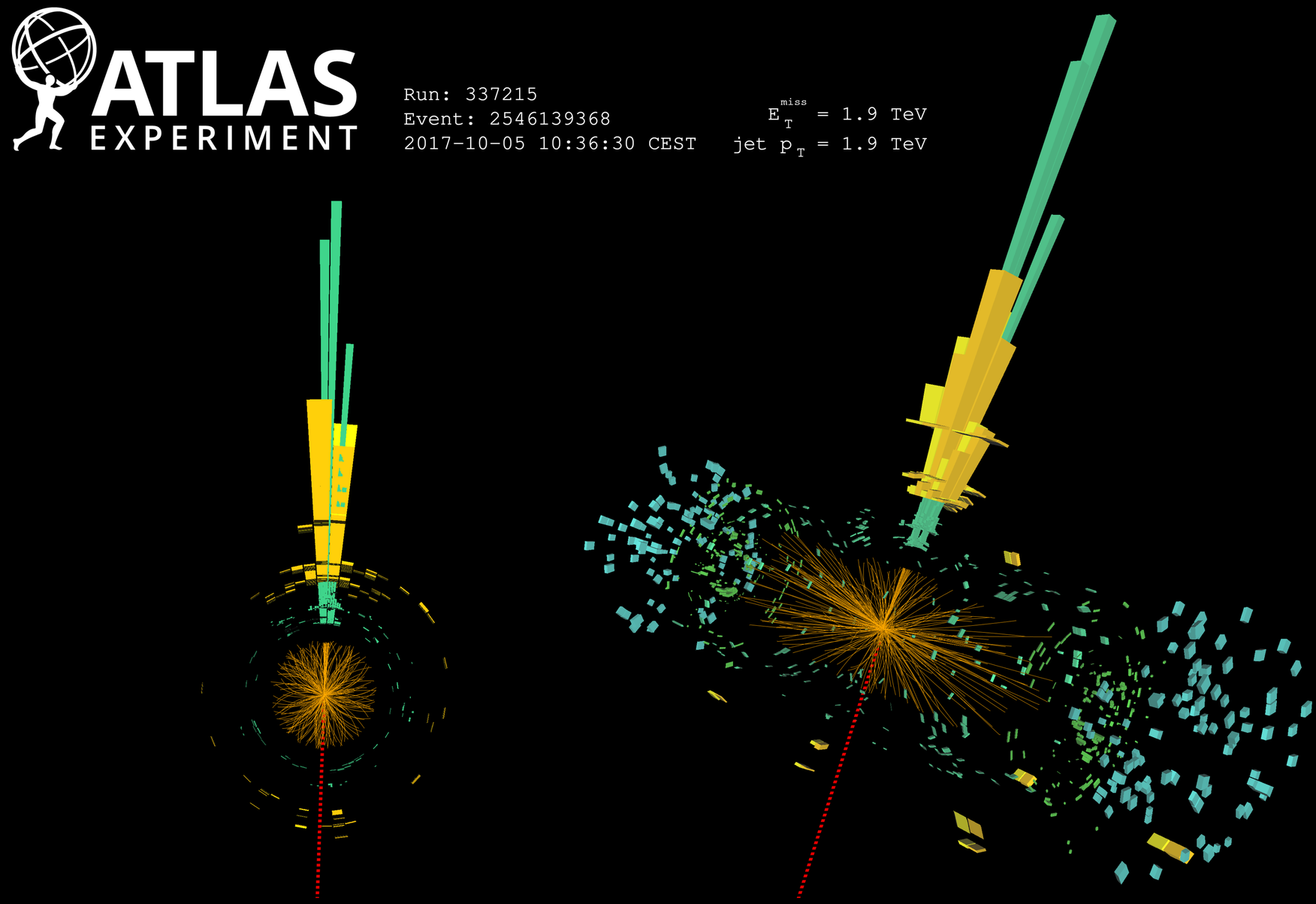
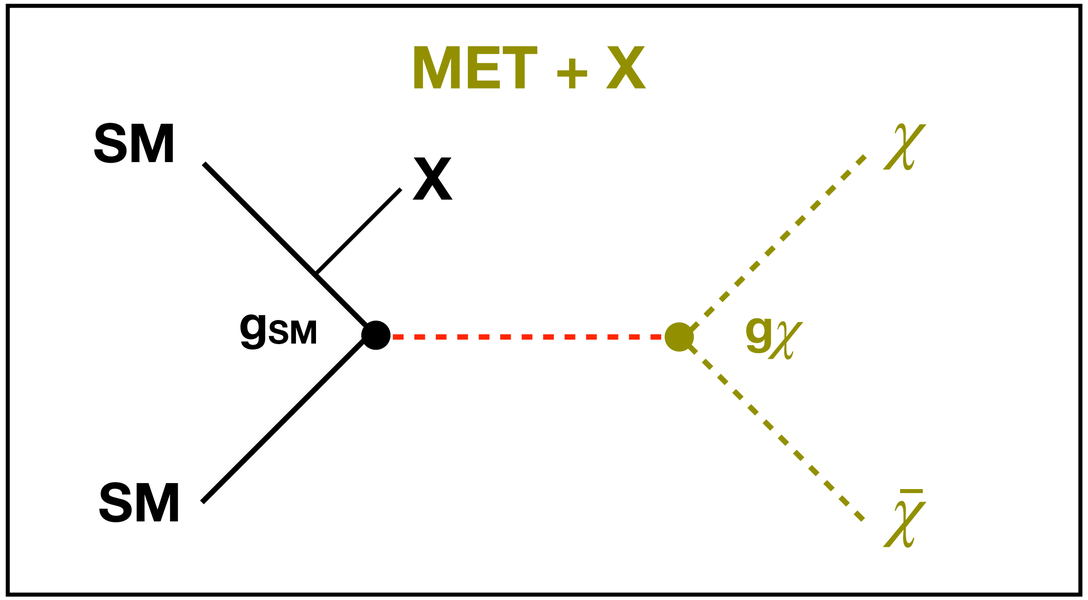
A spectacular mono-jet event

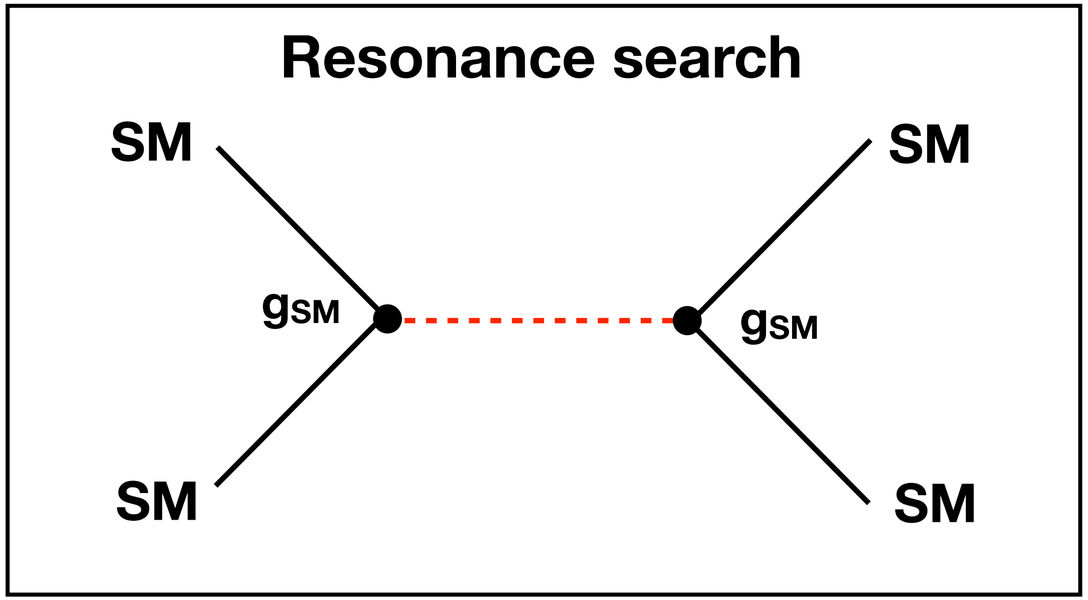


Phys. Rev. D 103 (2021) 112006

Searching for the mediator

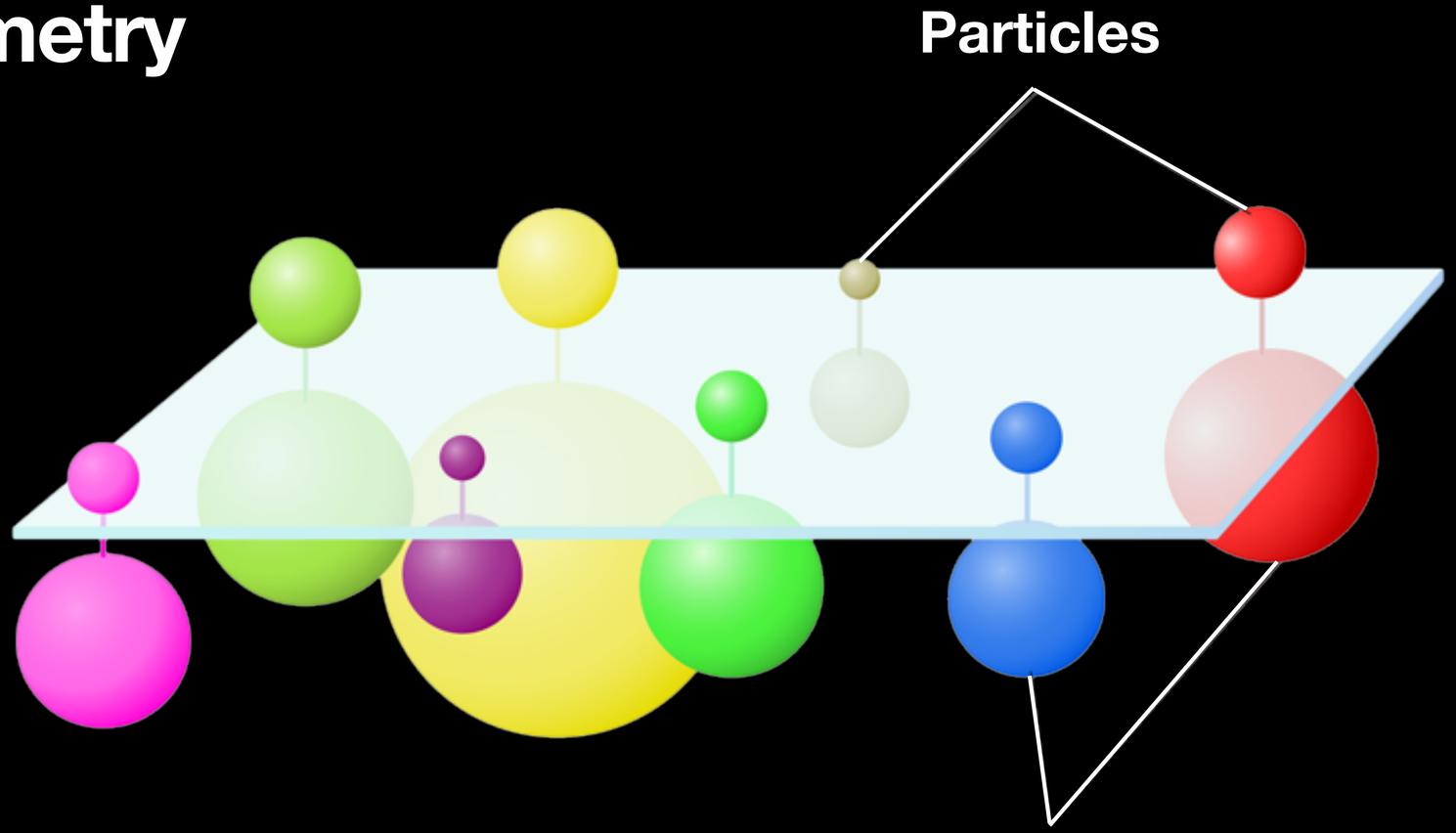
Can also look for dark matter mediators at the LHC!





Need a model to combine the searches which increases sensitivity

Supersymmetry



Every SM particle has a SUSY partner (sparticles)
with spin difference of 1/2 i.e. Fermions ↔ Bosons
Broken symmetry → different masses

Supersymmetry

R-parity: **(B=baryon number, L=lepton number, s=spin)**

$$R = (-1)^{(2s+3B+L)} = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for SUSY particles} \end{cases}$$

R-parity conservation (RPC)

originally introduced for proton stability

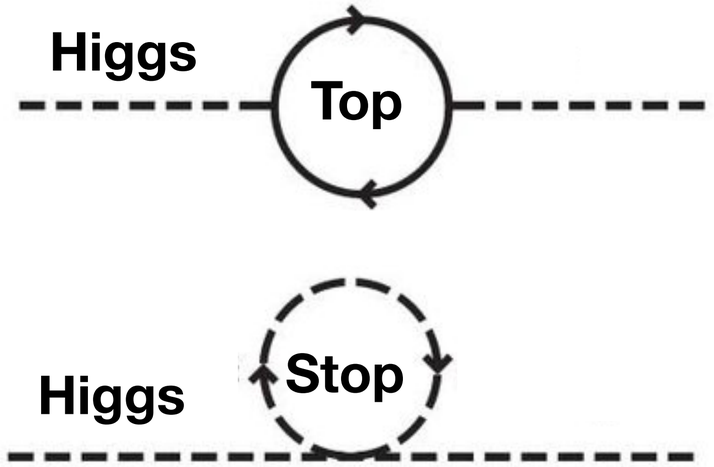
- Always pairs of sparticles
- Lightest supersymmetric particle (**LSP**) is stable and escapes detection
- Final state decay has at least one LSP

R-parity violation (RPV)

- Either lepton or baryon number violation
- Sparticles can decay exclusively to SM particles
- Low missing energy in the final state

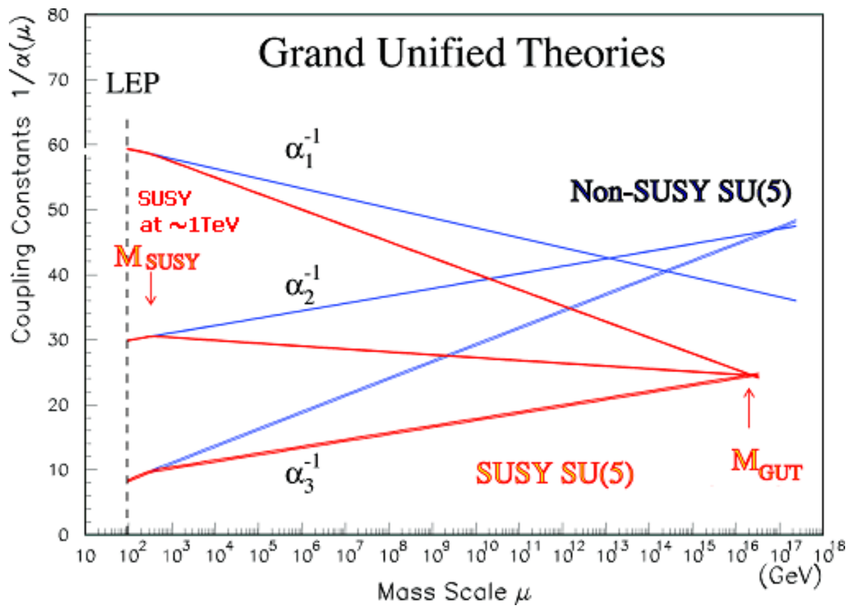
Supersymmetry

1111.0710



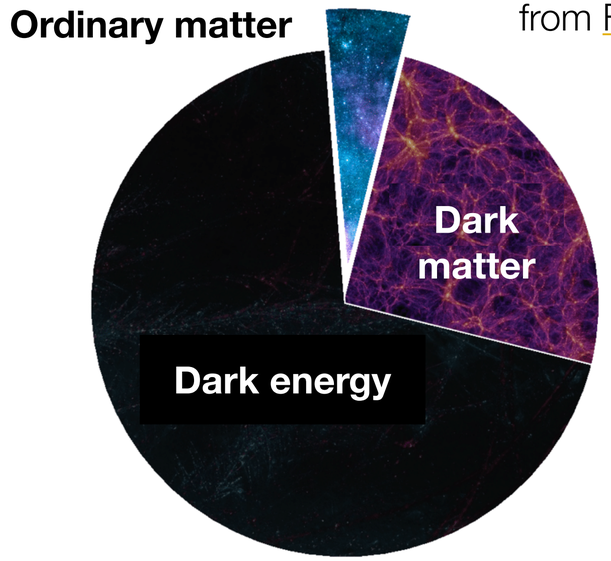
Sparticle loops cancel corrections to Higgs mass

icepp.s.u-tokyo



Possible unification of the gauge couplings at GUT scale

Image: adapted from Florian Wolz



R-parity conservation

→ Existence of stable LSP as a dark matter candidate

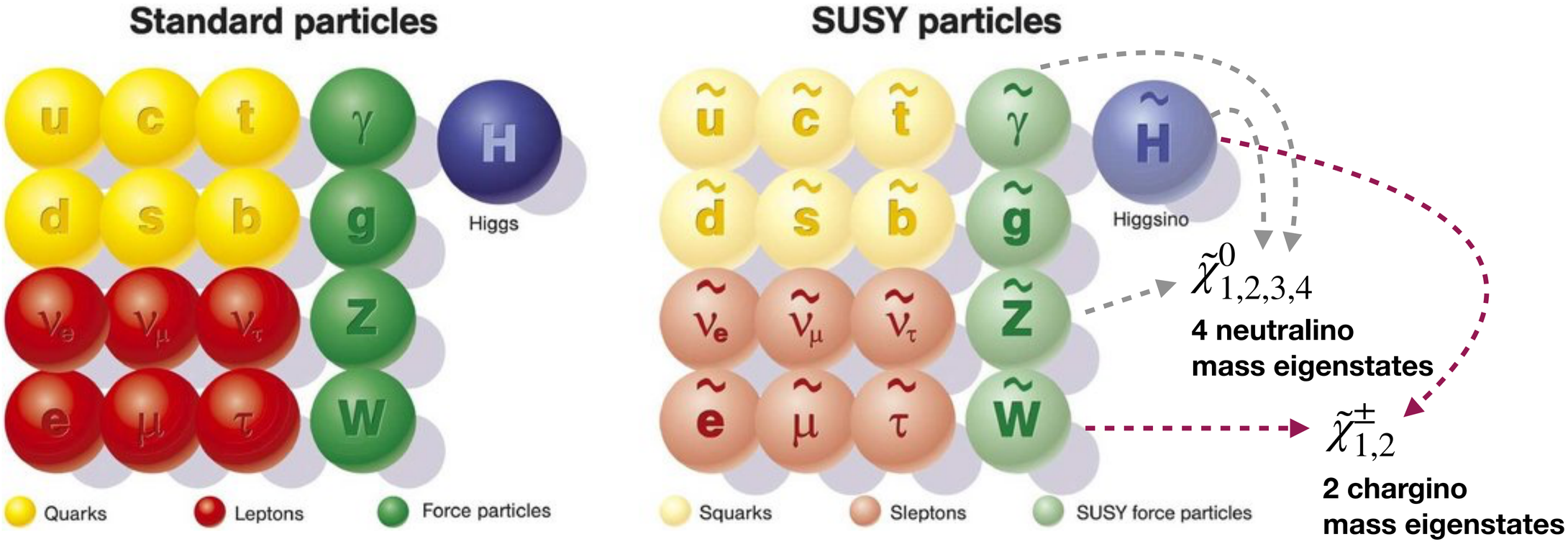
Naturalness and fine tuning

Supersymmetry

SUSY predicts a plethora of new particles

Potential parameter space is huge

e.g. MSSM: ~100, pMSSM: 19



MSSM = Minimal Supersymmetric Standard Model

Image credit: DESY

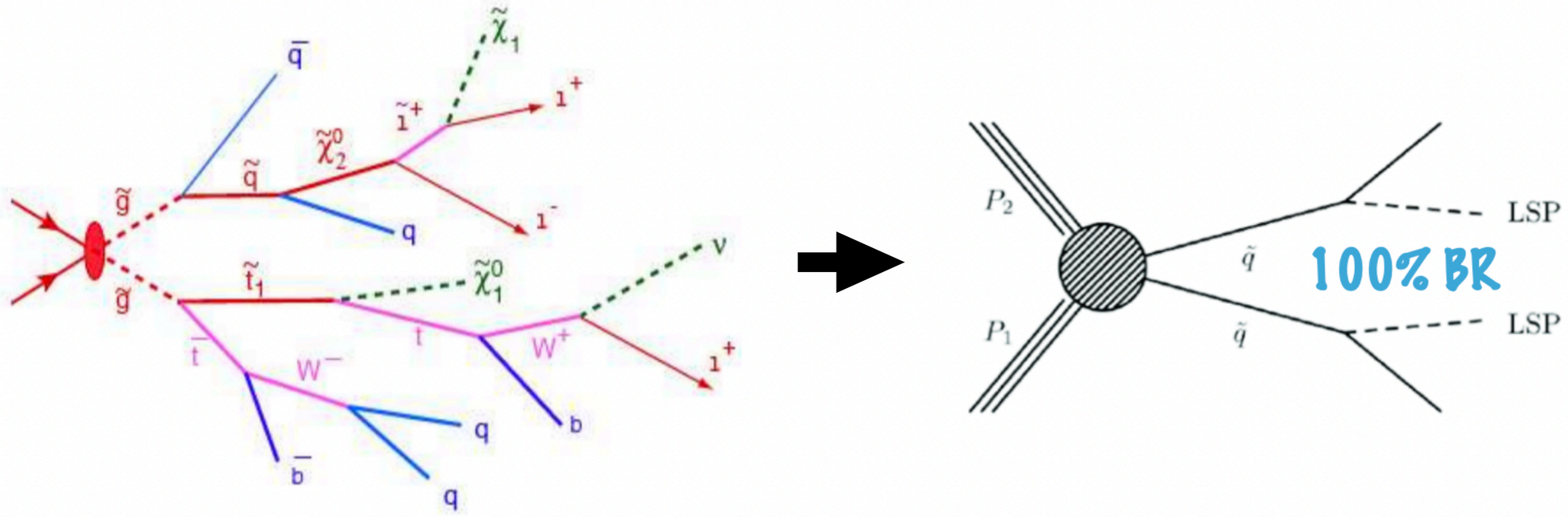
Simplified models in SUSY searches

Often we simplify further e.g.

Assume masses of most SUSY particles are so high they do not affect the decay chains

Make assumptions about mass degeneracy

Be careful when interpreting limits, always check assumptions

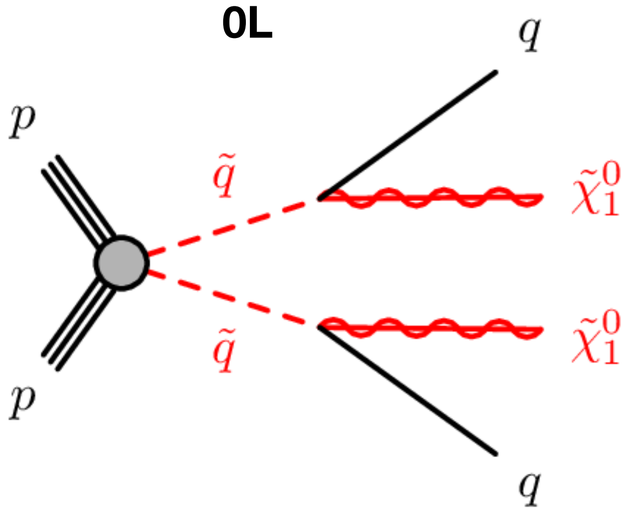


Squark and Gluino searches

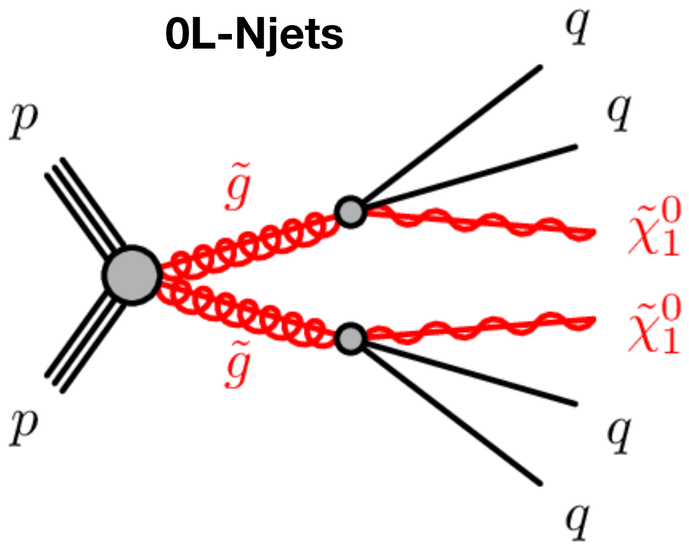
Assuming pair production of squarks and gluinos, decays to LSP + various SM quarks (light and heavy flavour) → Highest production cross sections

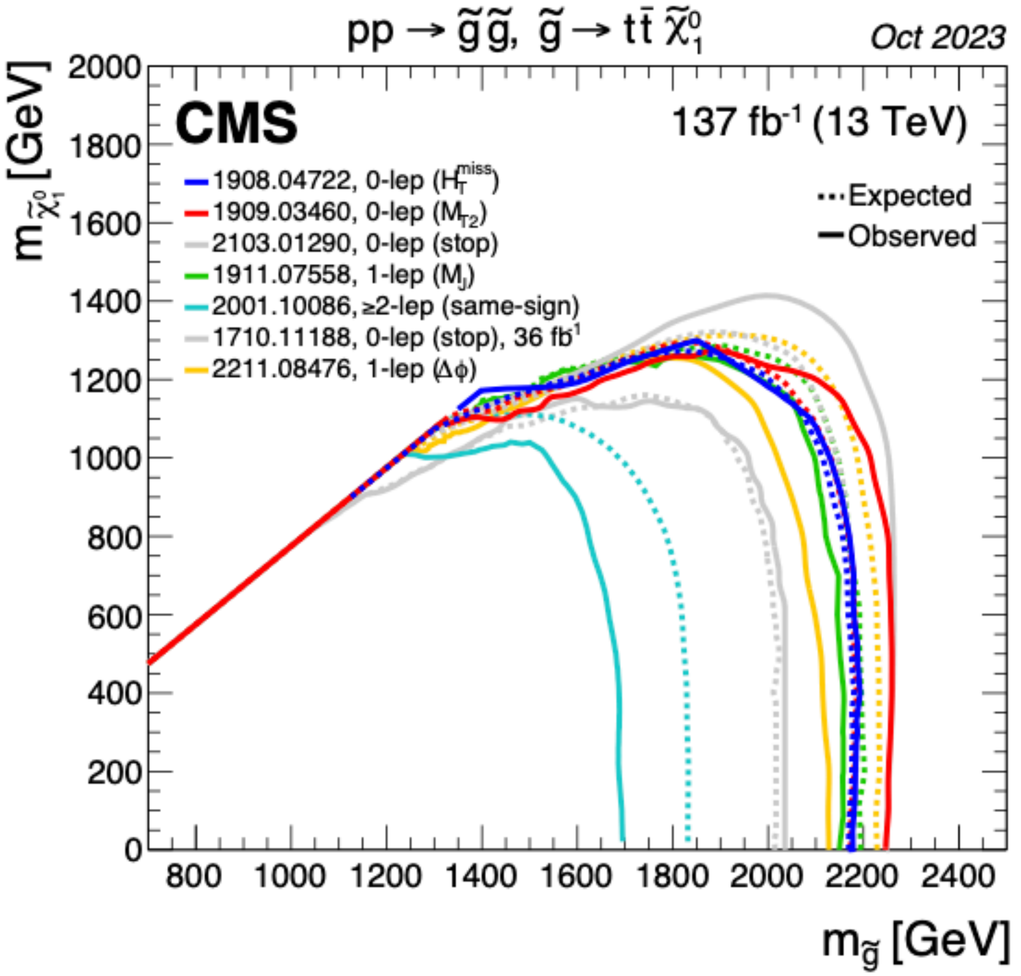
Examples:

0L



0L-Njets





Limits on Gluino mass pushing 2200 GeV in simplified models

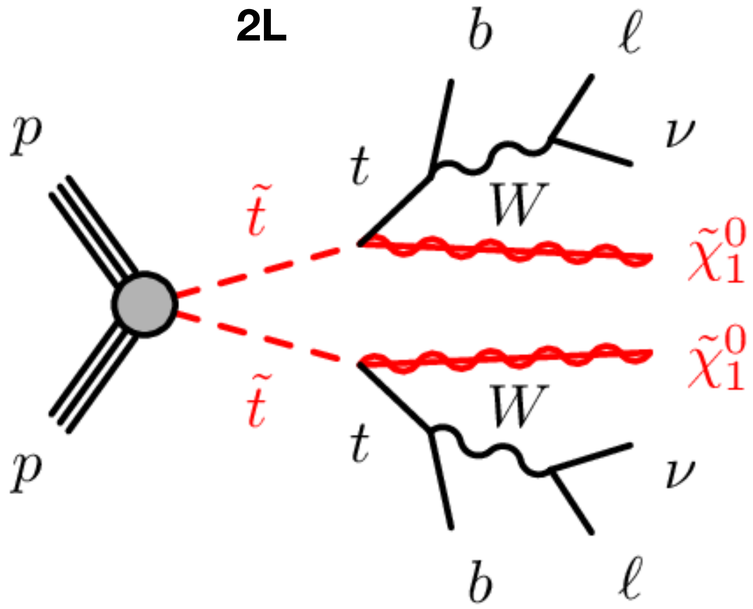
ATL-PHYS-PUB-2023-025

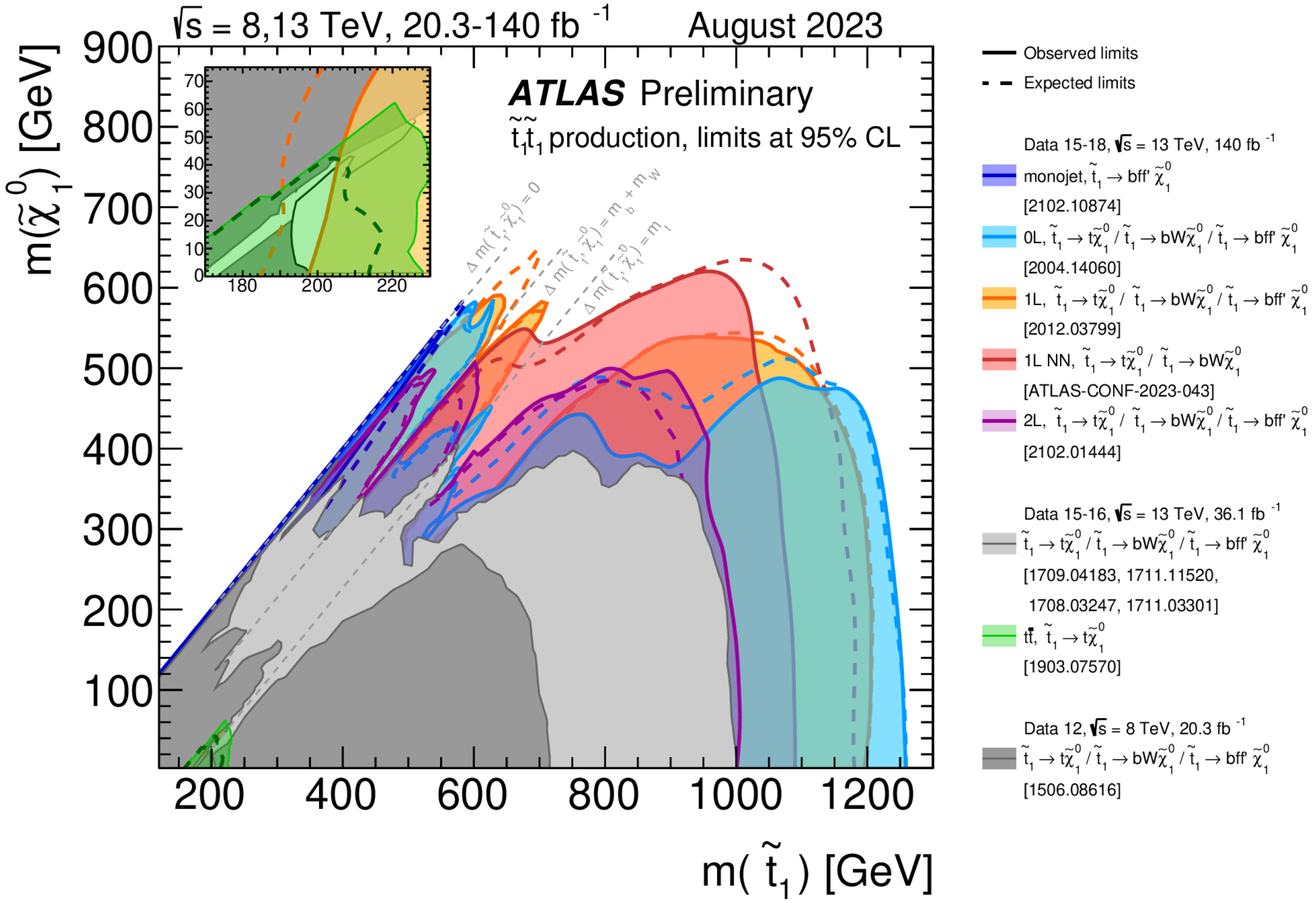
Stop searches

Stops plan important role in stabilising the Higgs mass (cancel top contribution)

0, 1 and 2 lepton channels → remember $t\bar{t}$ decay modes + extra MET

Example:





Limits on Stop quark mass pushing 1200 GeV in simplified models

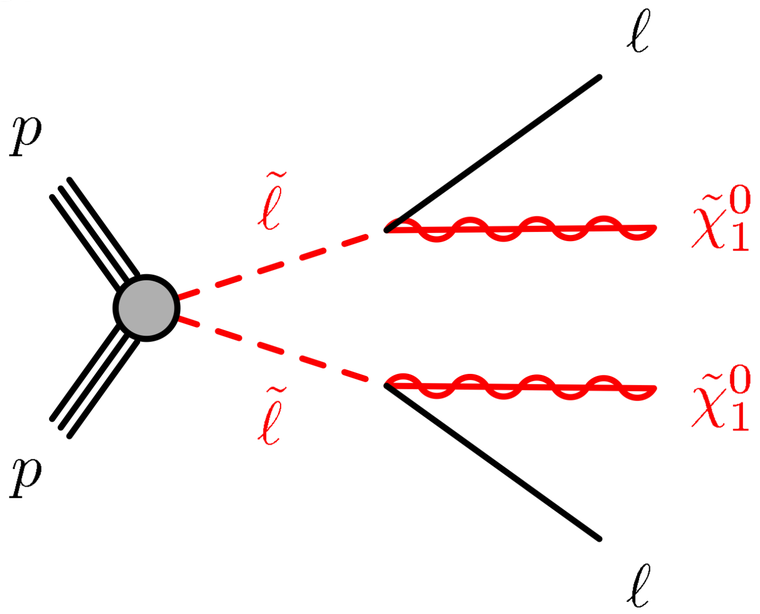
ATL-PHYS-PUB-2023-025

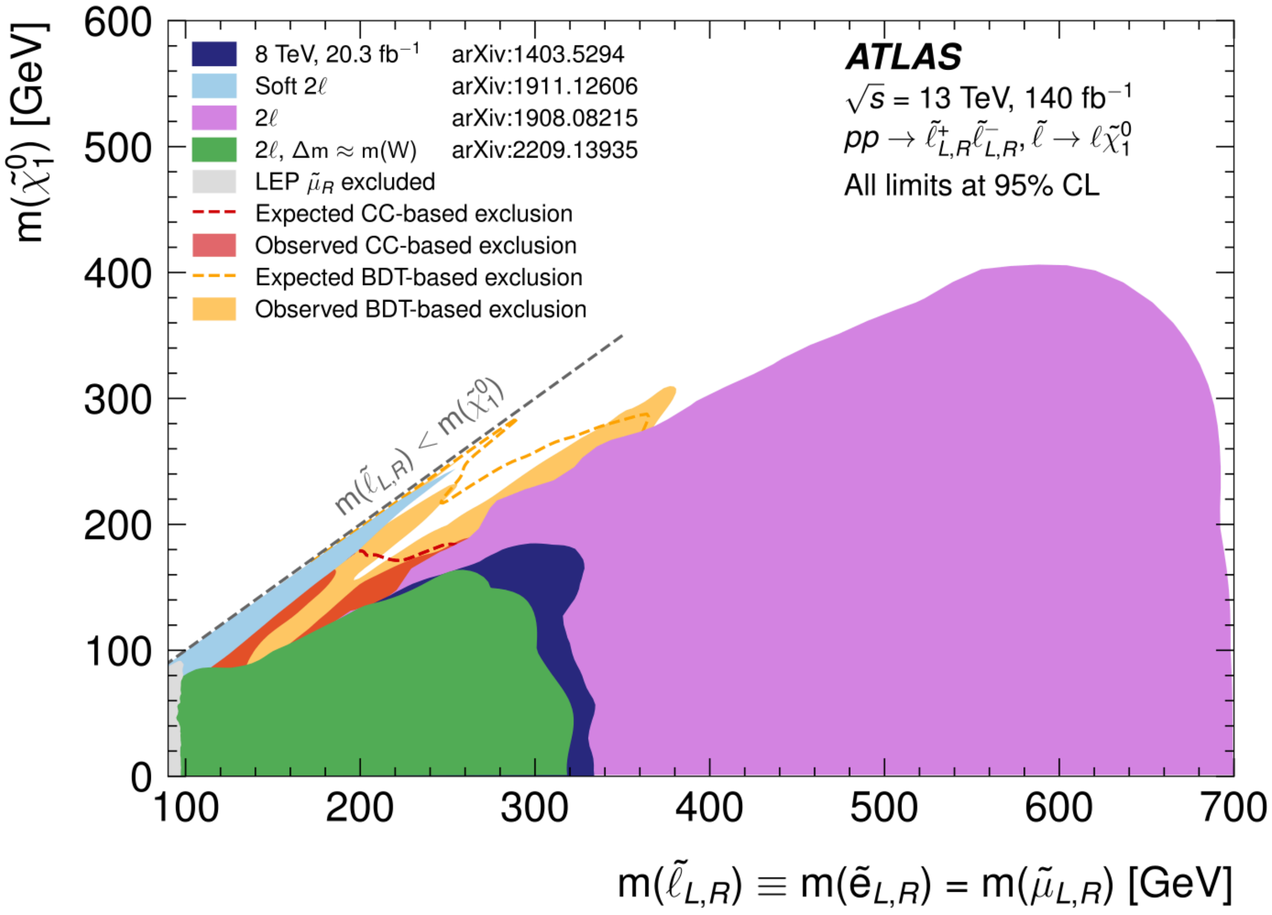
Electroweak searches

Coloured sparticles could be heavier than EW sparticles

Production cross section much lower for charginos & sleptons than squarks & gluino

Example:





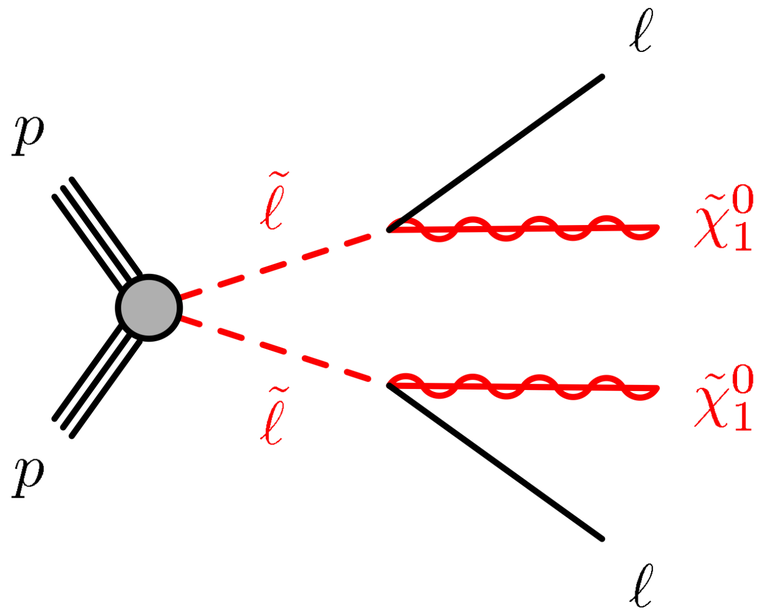
2503.17186

Slepton limits pushing 700 GeV in simplified models but gaps remain

From low to high-hanging fruits

- Strong
- Electroweak
- Compressed → Small mass differences
- R-parity violating (low MET)
- Unconventional signatures

Difficulty

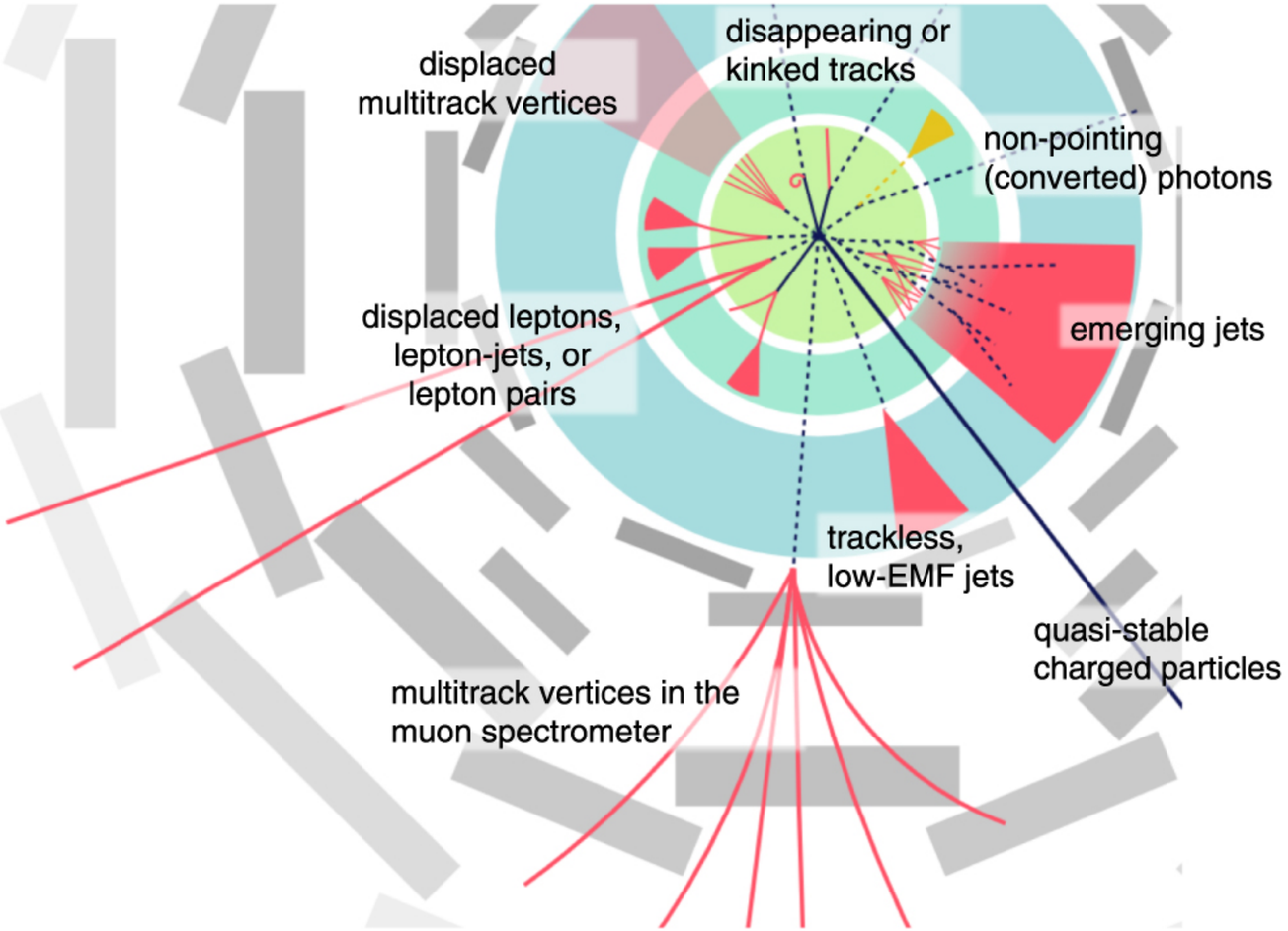


Unconventional signatures

So far the models were BSM but the signatures contained “known” SM particles

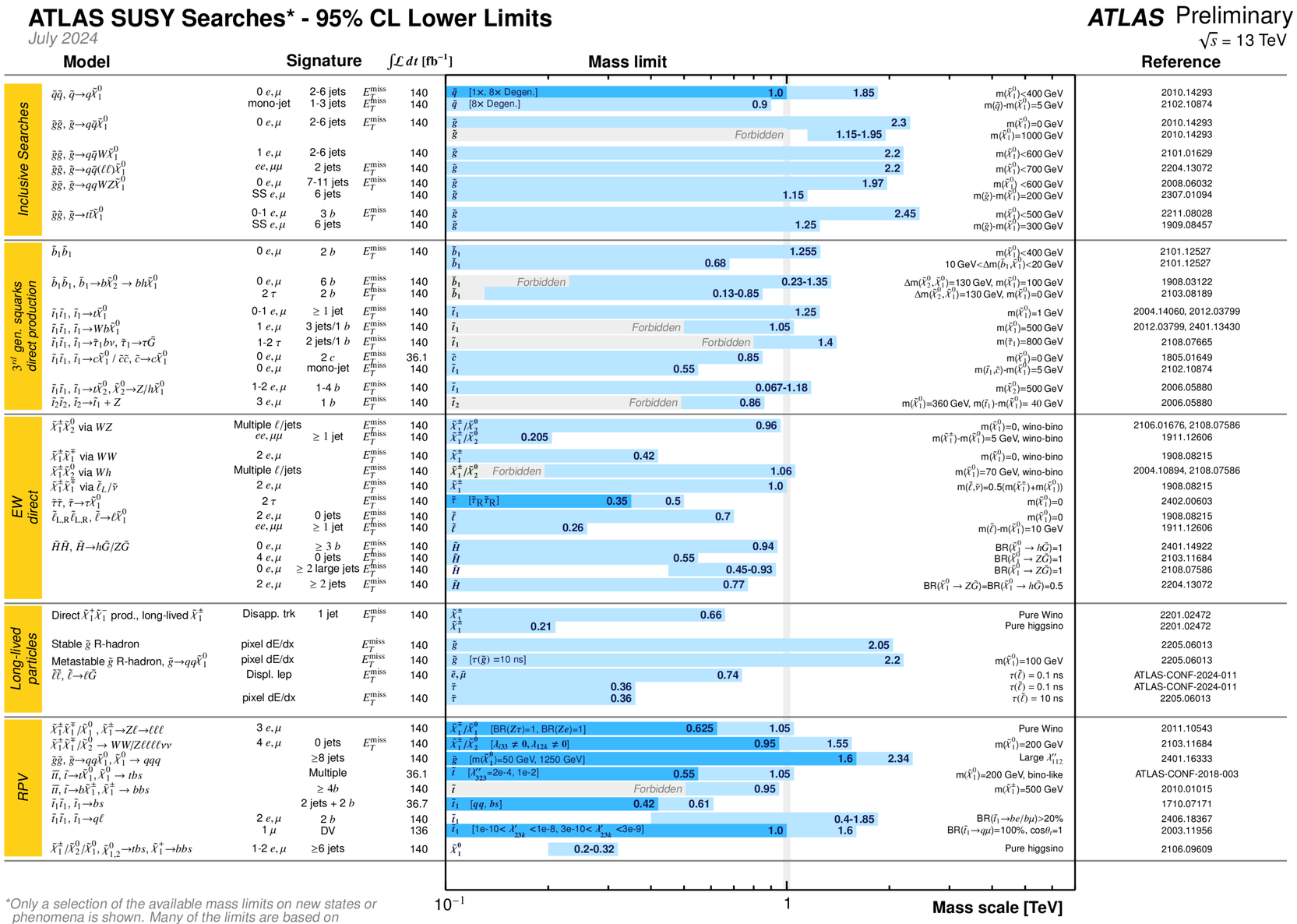
→ What if the decay products are “BSM”?

- Often “long lived” new particles
- Bkgs very different from other searches
  - Data driven approaches to estimate them
- Often dedicated data reconstruction algorithms needed



https://indico.cern.ch/event/607314

Where do we stand after Run 2?



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Remember simplified models are only part of the story

Always check assumptions in the model and how it fits with the bigger picture

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Searches for new physics at the LHC

So far no smoking gun for signs of new physics

Here and there local 2-3 sigma excesses → Important to follow up

However, luminosity will now double only every couple of years

New Ideas?

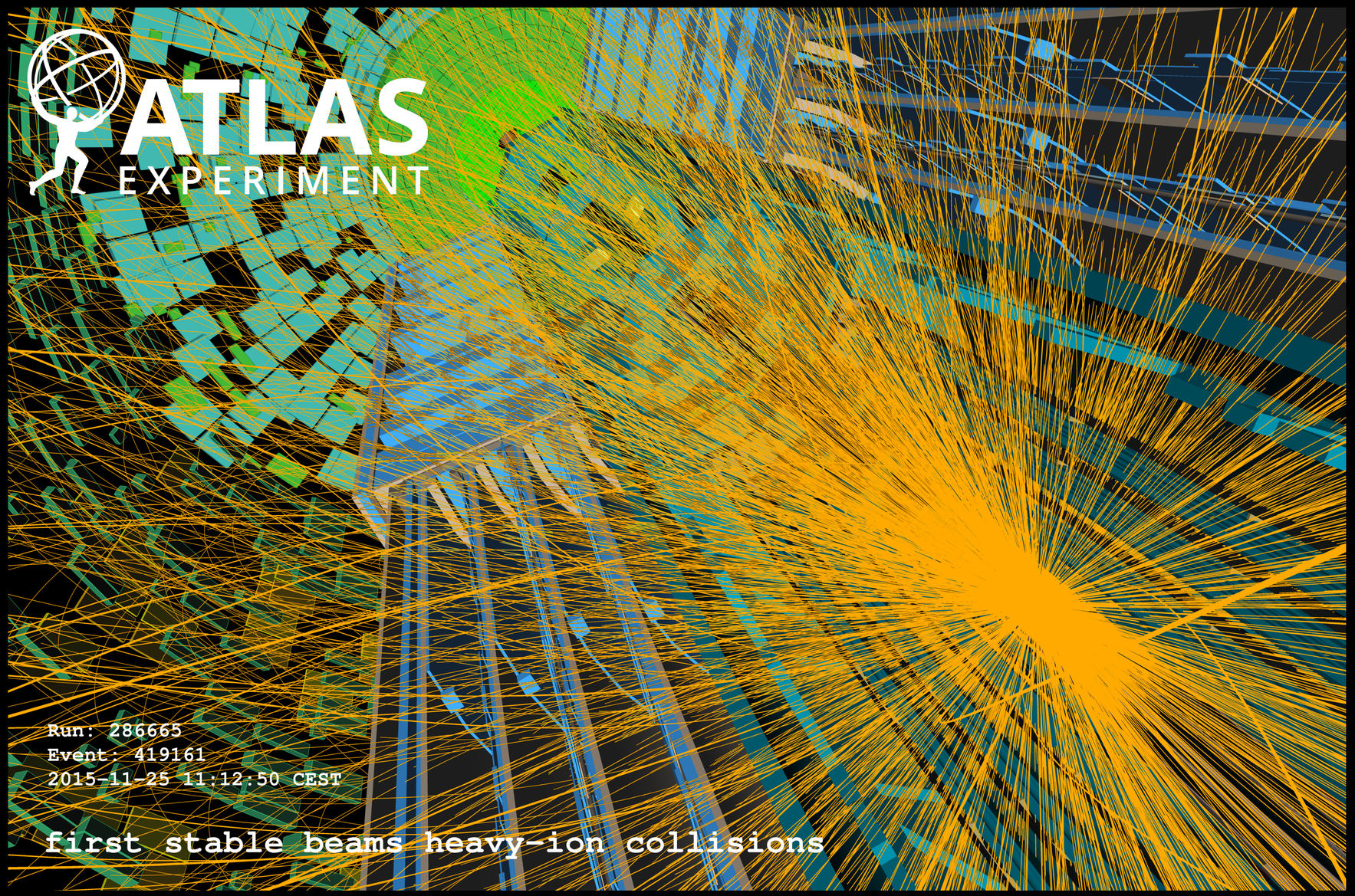
- Make sure we didn’t miss something → what we didn’t trigger on is lost forever
- Maybe something super long lived is produced in ATLAS/CMS but can only be detected with other experiments → e.g. FASER?

Physics Goals of the LHC

wikimedia

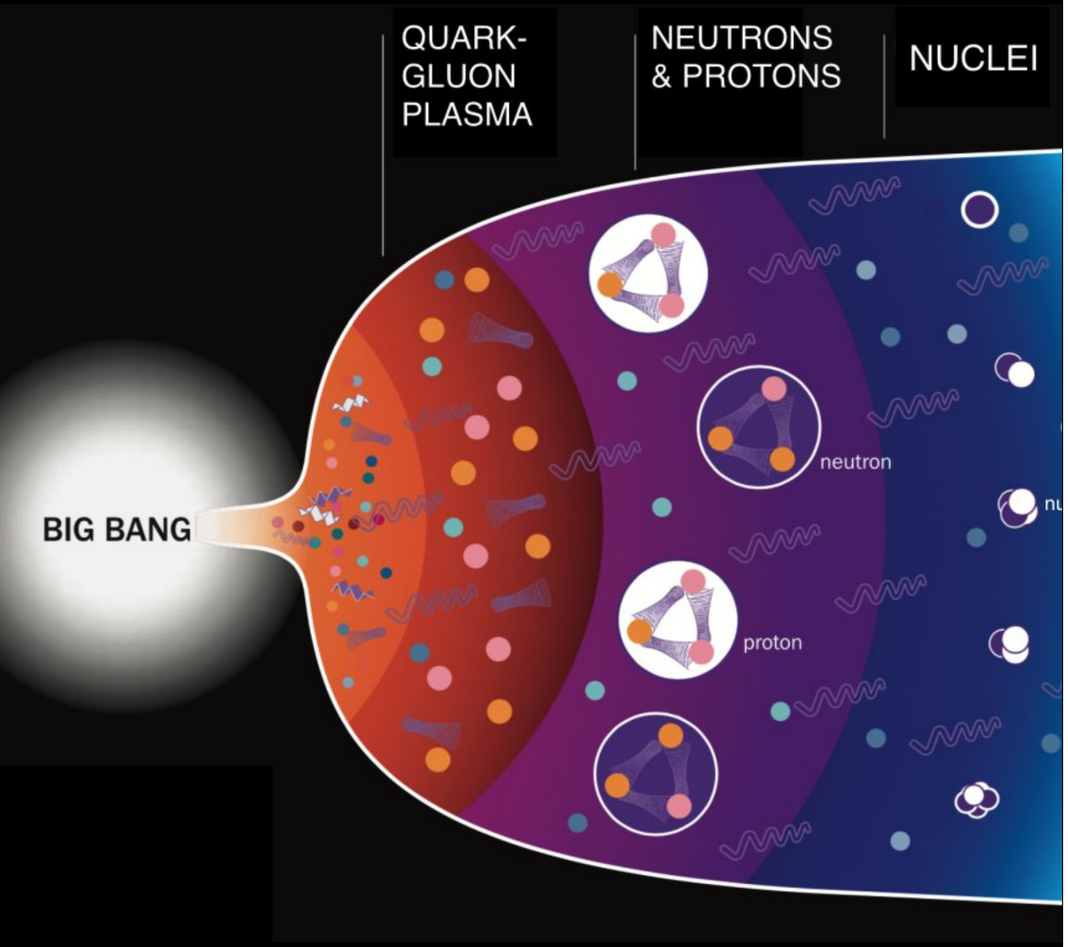
Study the Quark-Gluon Plasma

LHC Pb+Pb collision



ATLAS heavy ion event display

Quark Gluon Plasma (QGP)



https://twitter.com/QM2018

Our early universe was too hot & dense for the strong force to bind quarks and gluons together

→ **Quark Gluon Plasma (QGP)**
Hot dense medium with free colour charges

We can create it in the lab in LHC heavy ion collisions

We study how high momentum partons strongly interact in QGP & lose energy before hadronising

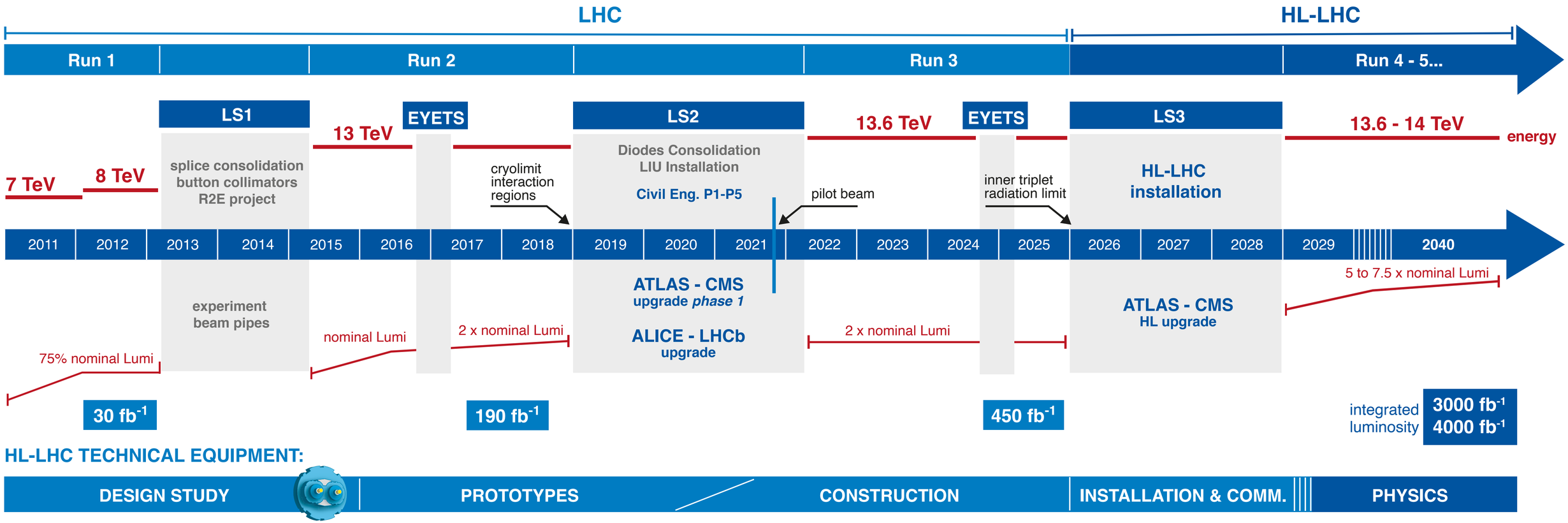
→ **Jet quenching**

Binding potential of quarkonia e.g. $\Upsilon(b\bar{b})$ can be modified in QGP (colour screening by QGP constituents)

→ **Suppression of Quarkonia**

Where do we go next?

LHC / HL-LHC Plan



https://hilumilhc.web.cern.ch

HL-LHC

Major detector upgrades underway

- Expected pile-up of ~200 poses immense challenge

Precision measurements of the Higgs boson

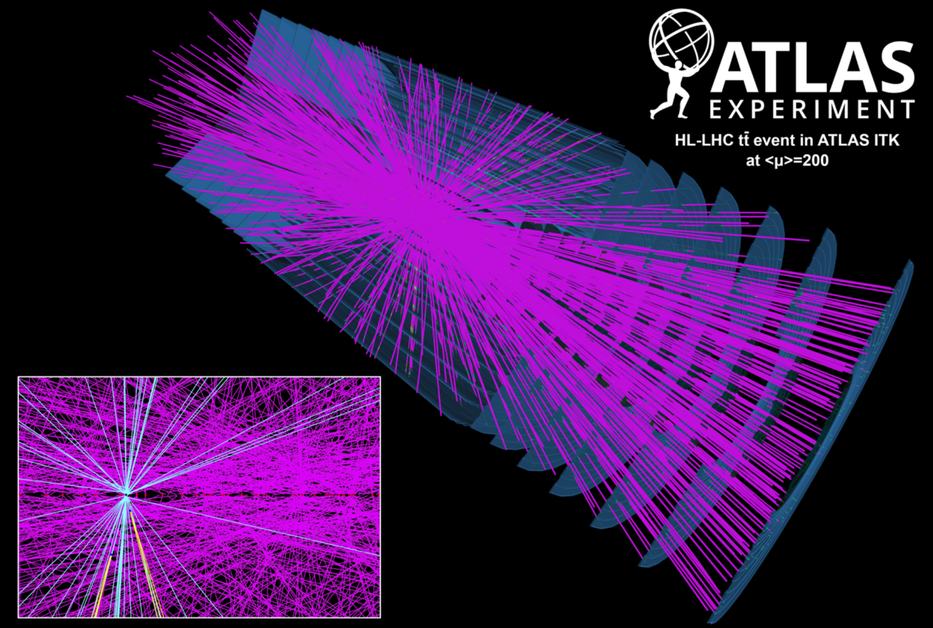
- Establish Higgs self-coupling at the 5σ level

Push the boundaries of SM precision measurements

- Could find deviations that could hint at new physics

Pursue dedicated searches for new physics

- Your new idea!



https://cds.cern.ch/record/2674770

Physics Goals of the LHC

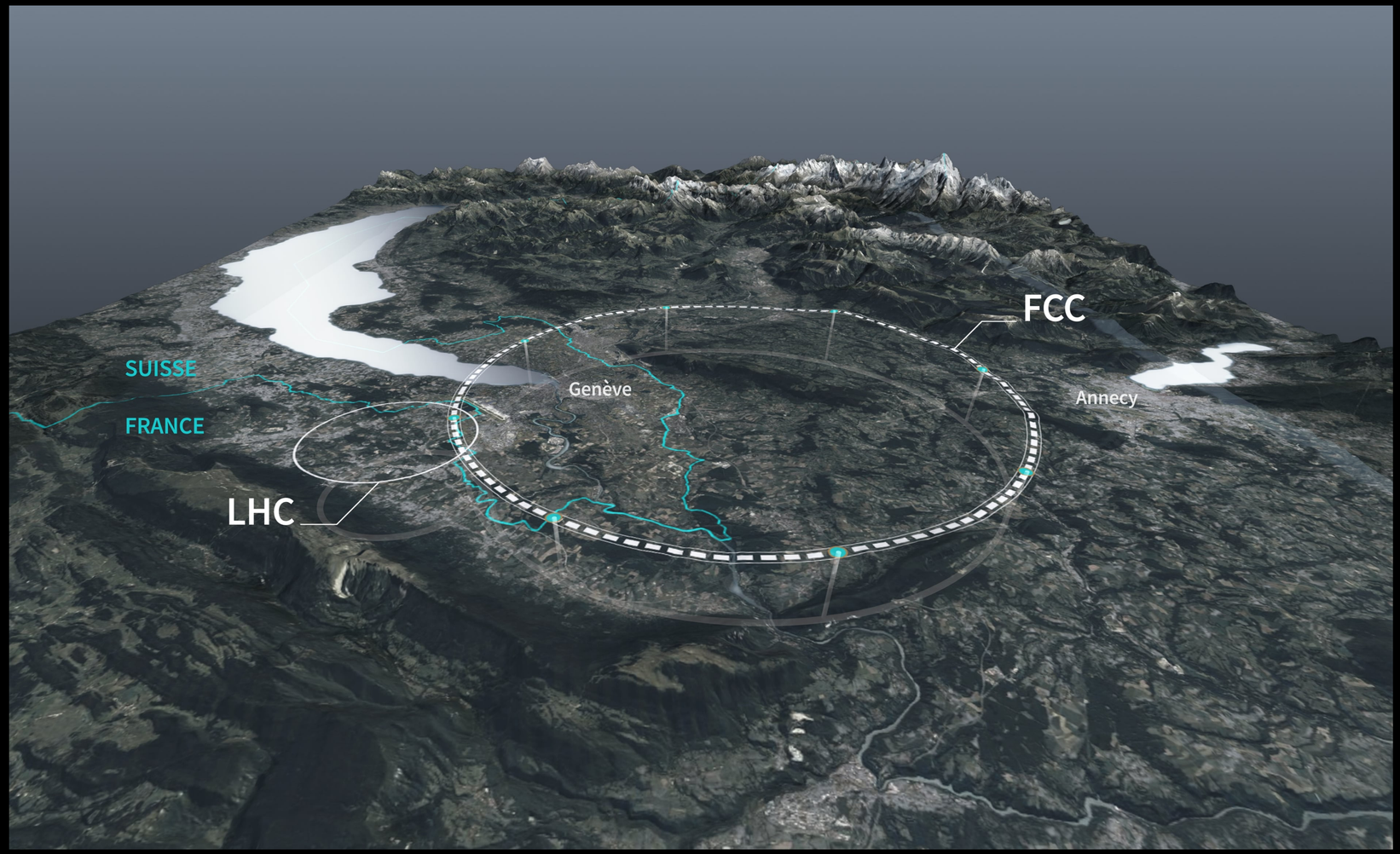
Measure the Standard Model

Search for the Higgs Boson

Search for New Physics

Study the Quark-Gluon Plasma

Outlook

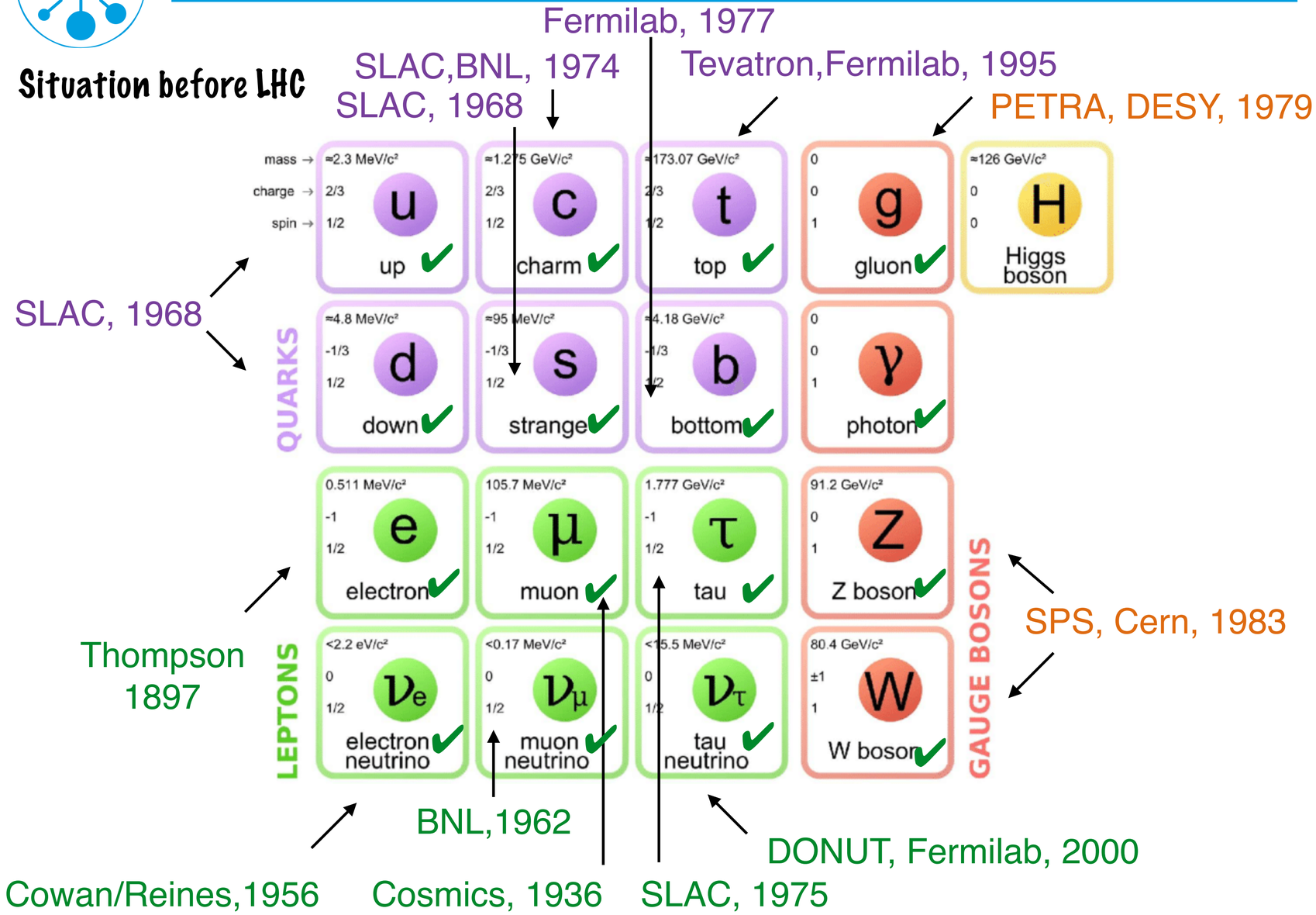


See lectures by Karsten Buesser for more on Future Colliders

https://fcc.web.cern.ch

The Standard Model - fundamental particles

Situation before LHC



Eur. Phys. J. C. 84 (2024) 1102

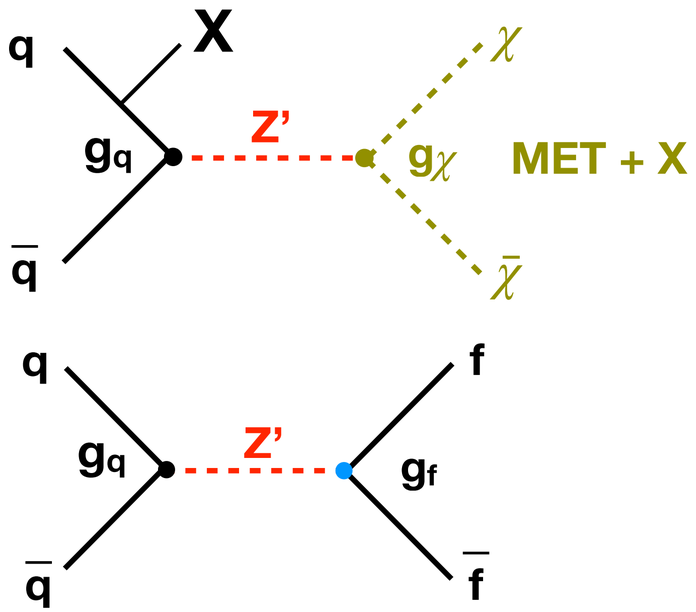
Comparing LHC results with direct detection

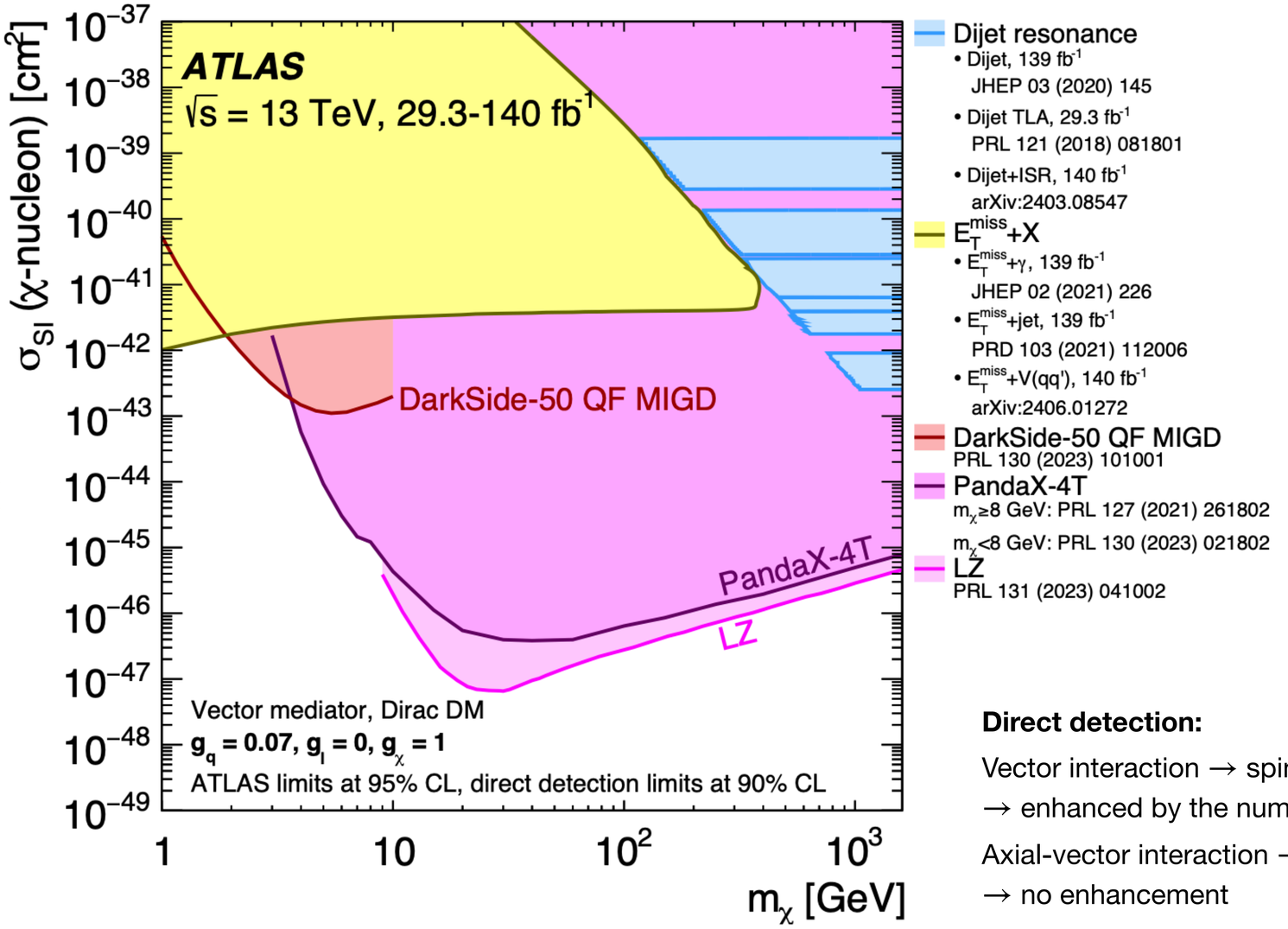
Vector mediator

DM coupling $g_\chi = 1$

Quark coupling $g_q = 0.07$

Lepton coupling $g_\ell = 0$





Direct detection:

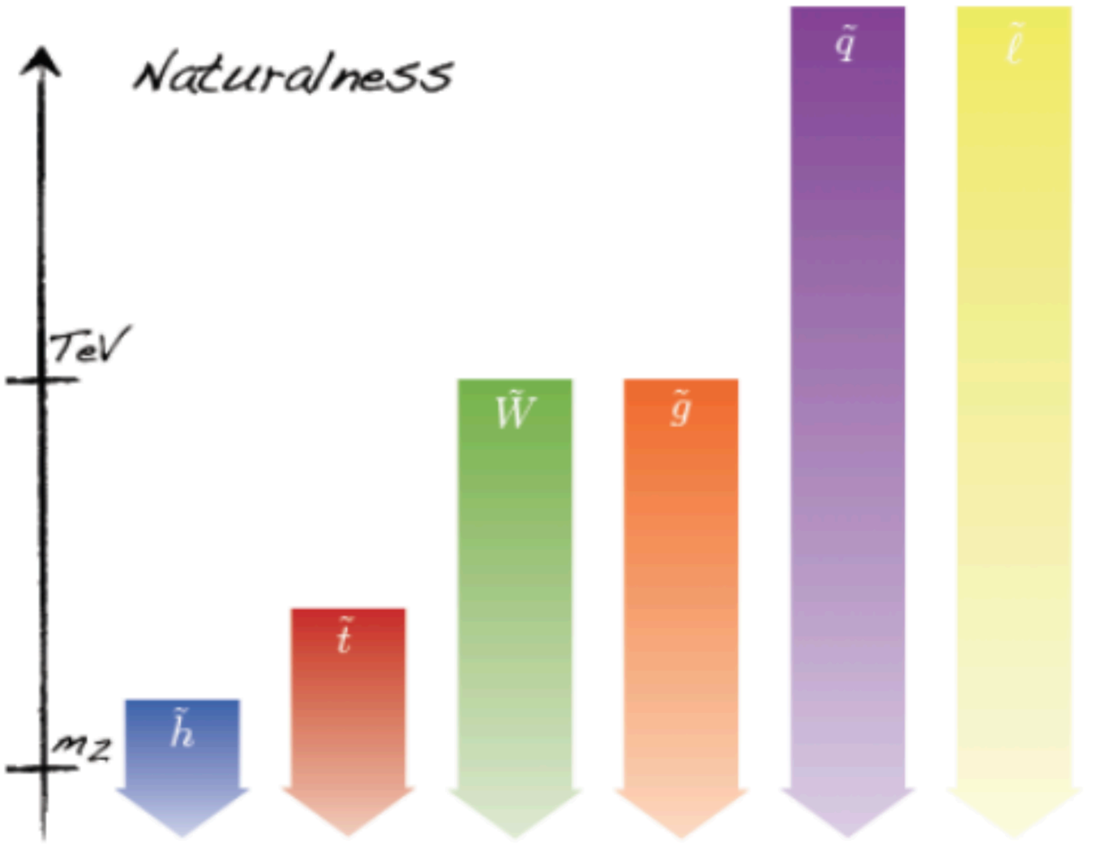
Vector interaction → spin-independent

→ enhanced by the number of nucleons

Axial-vector interaction → spin-dependent

→ no enhancement

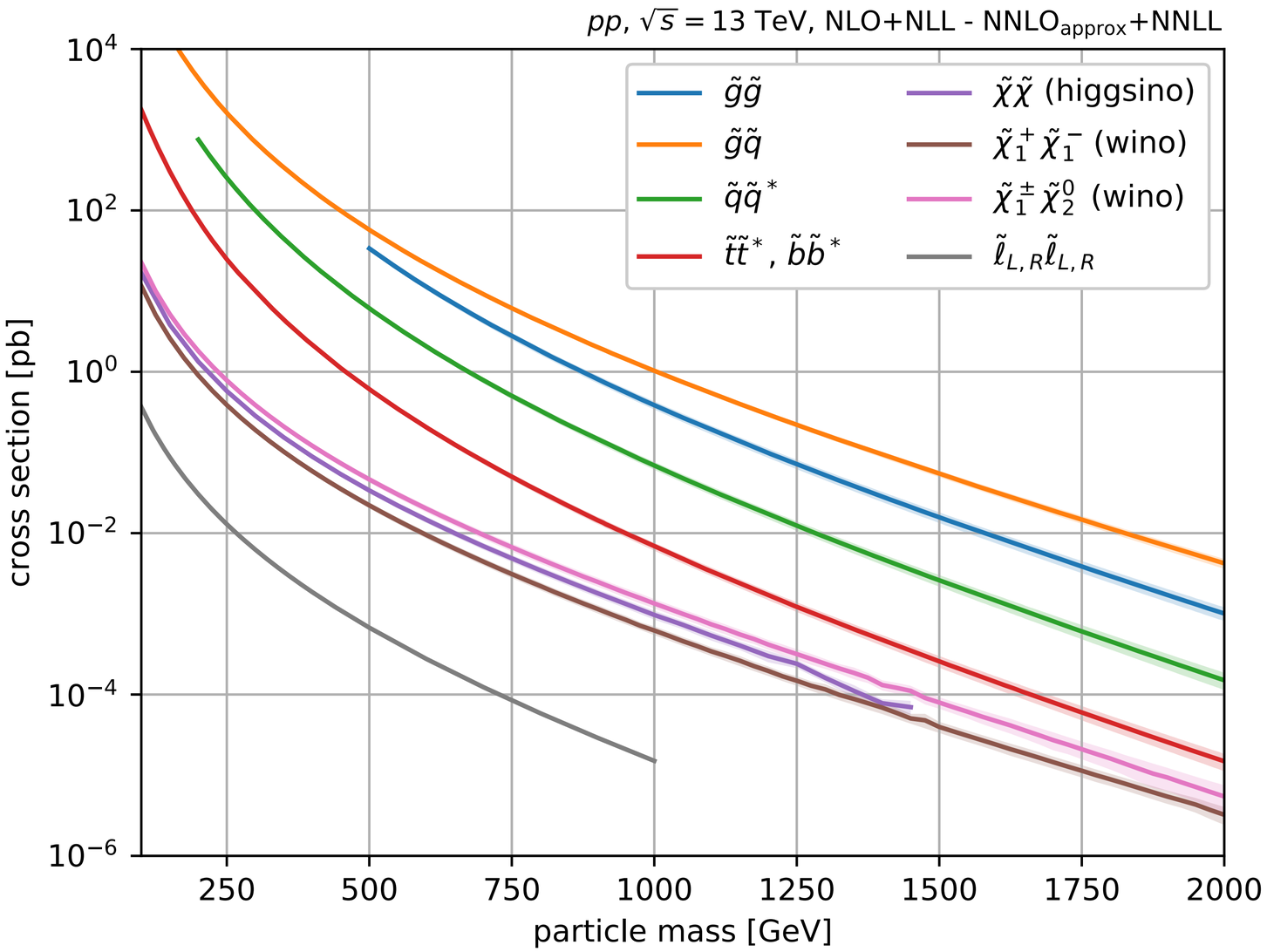
Can only compare results for a given model and set of parameters



SUSY mass scales motivated by electroweak naturalness

N. Craigh, arXiv:1309.0528

SUSY cross sections

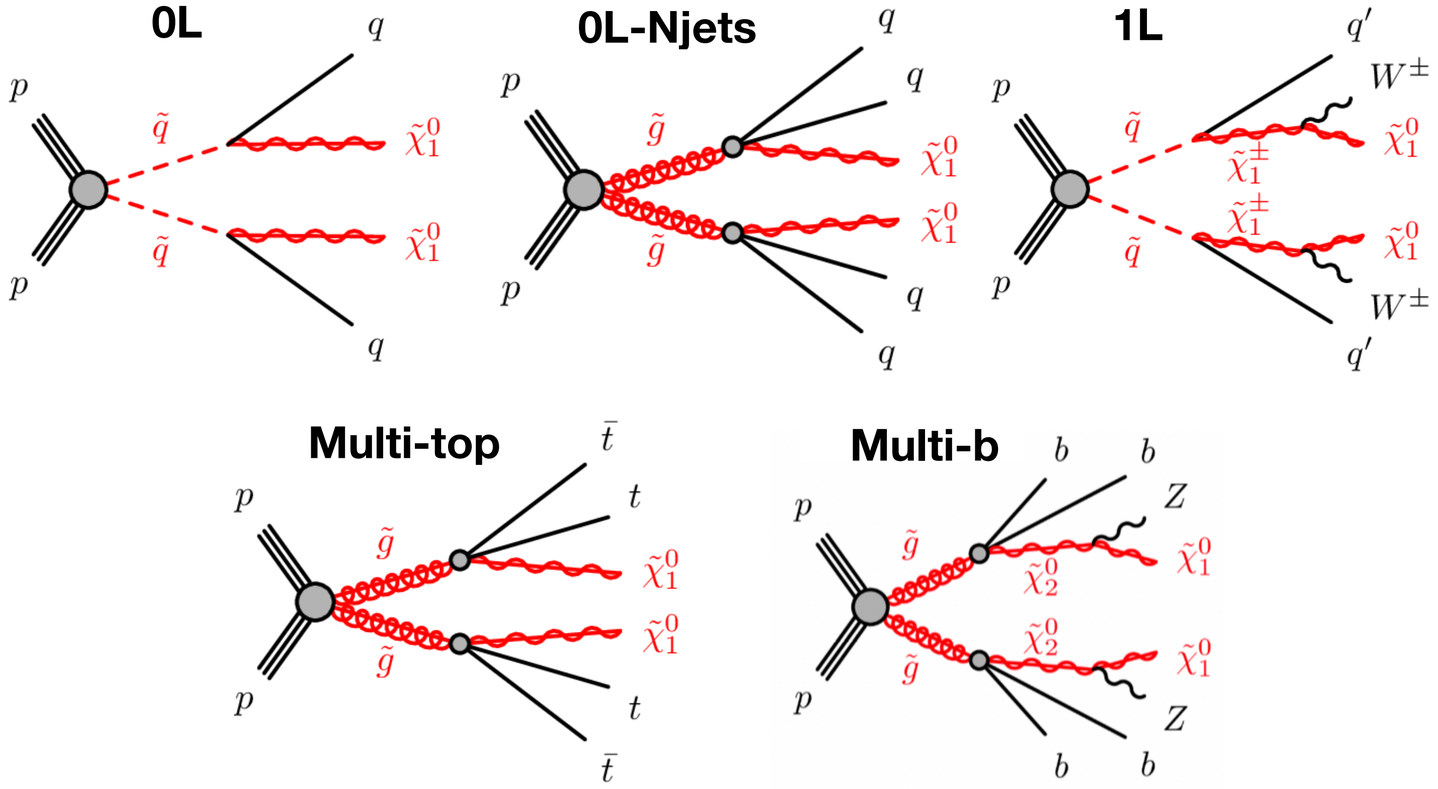


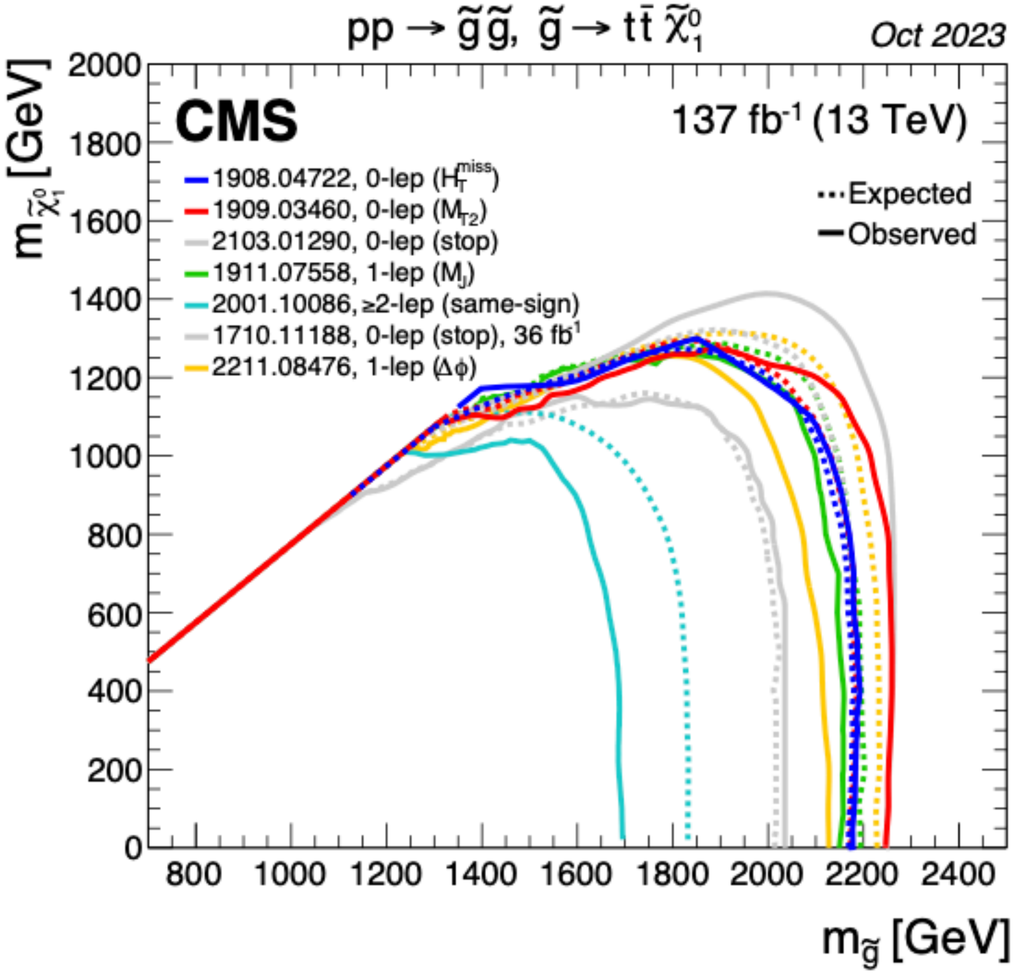
LHC SUSY Cross Sections

Squark and Gluino searches

Assuming pair production of squarks and gluinos, decays to LSP + various SM quarks (light and heavy flavour) → Highest production cross sections

Examples:





Limits on Gluino mass pushing 2200 GeV in simplified models

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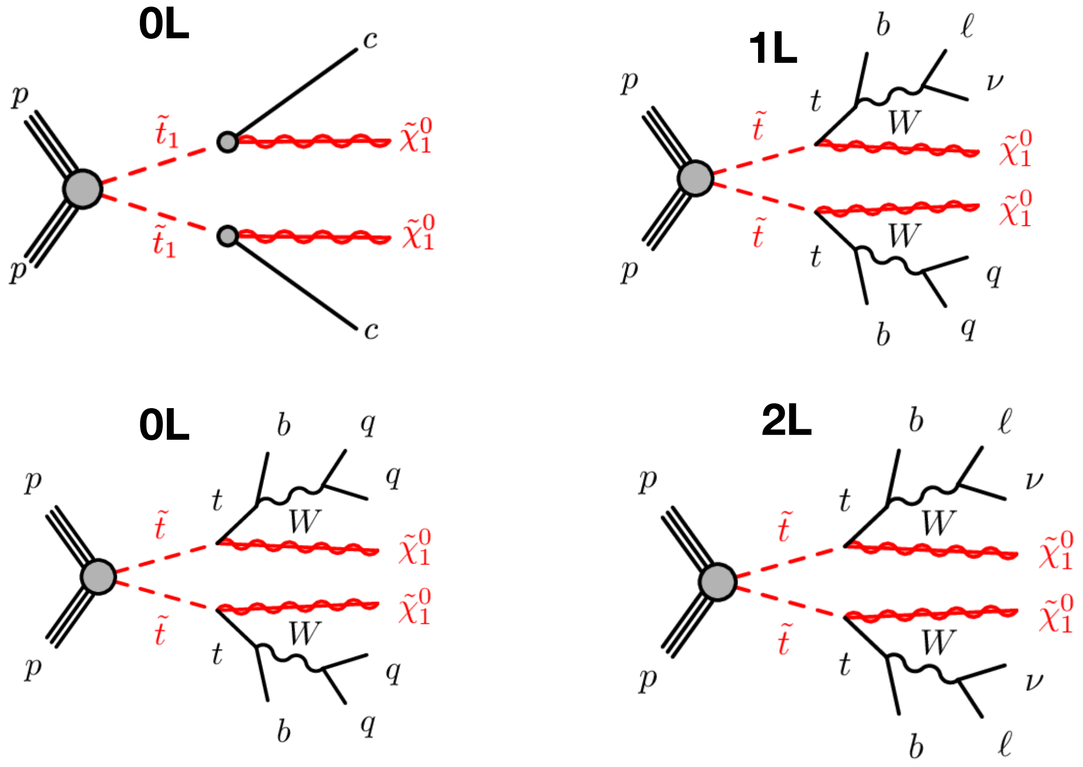
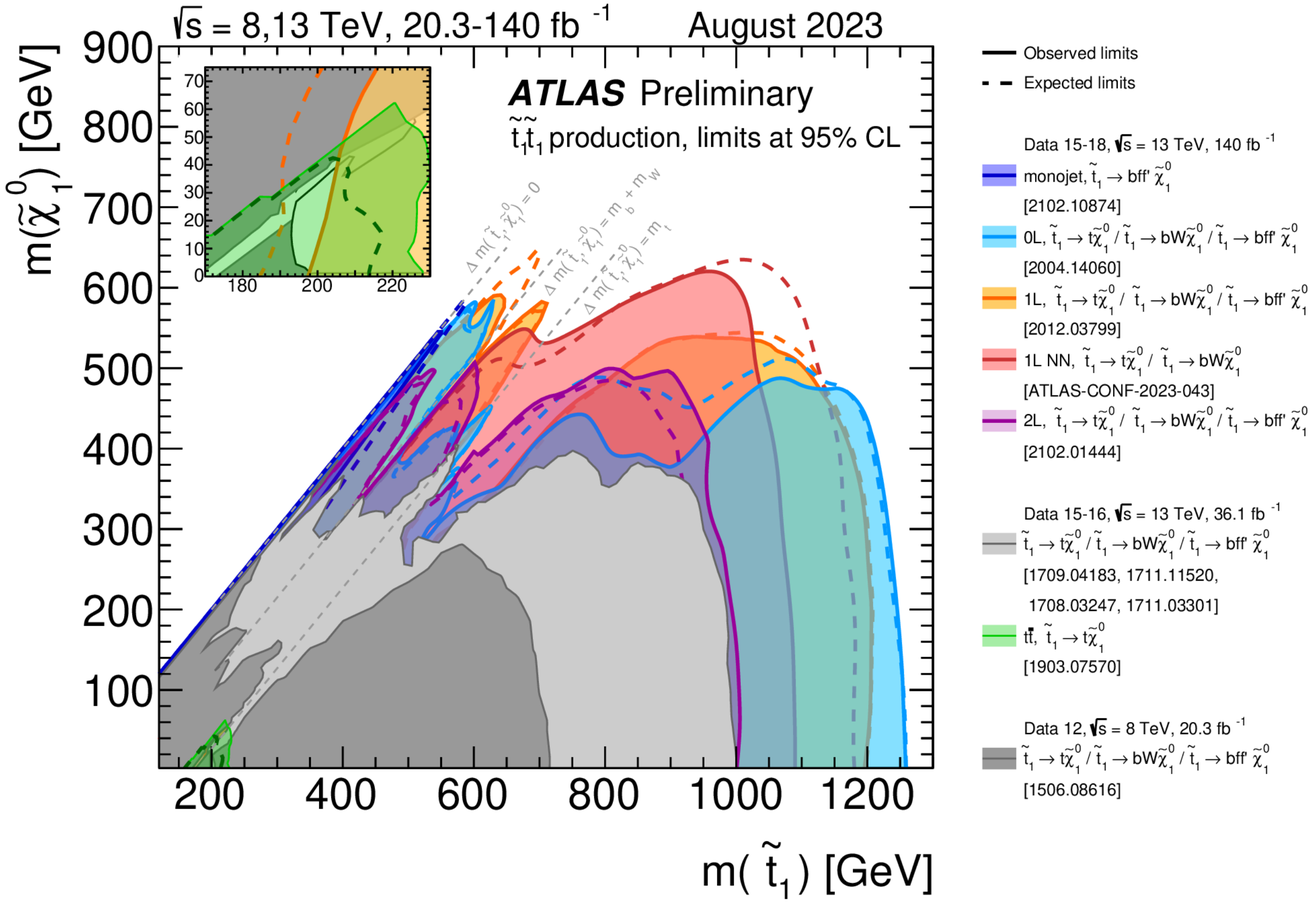
Stop searches

Stops plan important role in stabilising the Higgs mass (cancel top contribution)

0, 1 and 2 lepton channels → remember $t\bar{t}$ decay modes + extra MET

Examples:





Limits on Stop quark mass pushing 1200 GeV in simplified models

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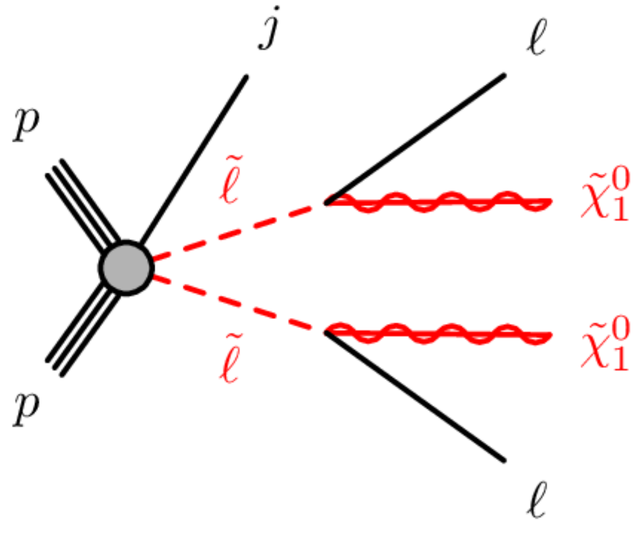
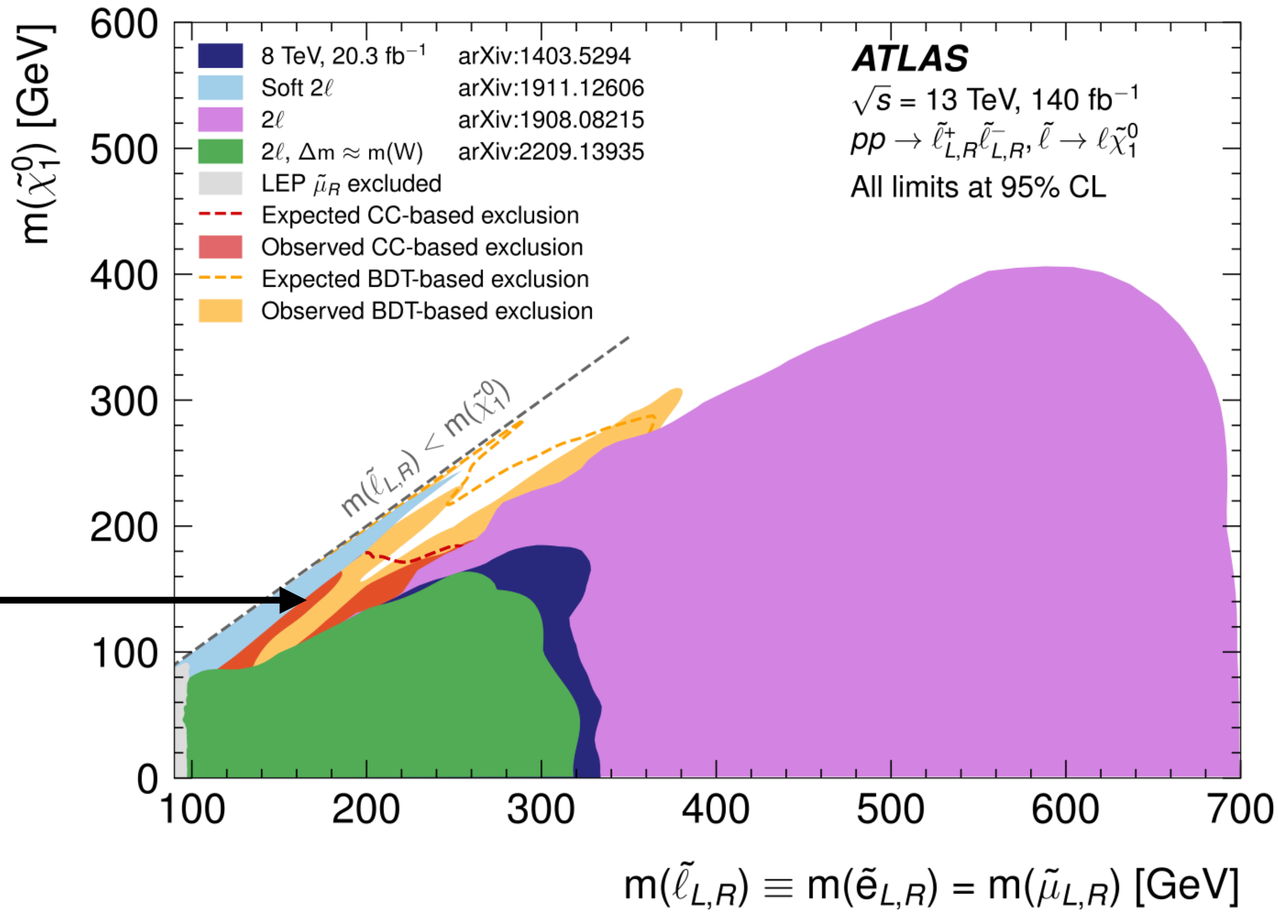
Electroweak searches

Radiated jet used here to boost the system

→ Increases MET to trigger on





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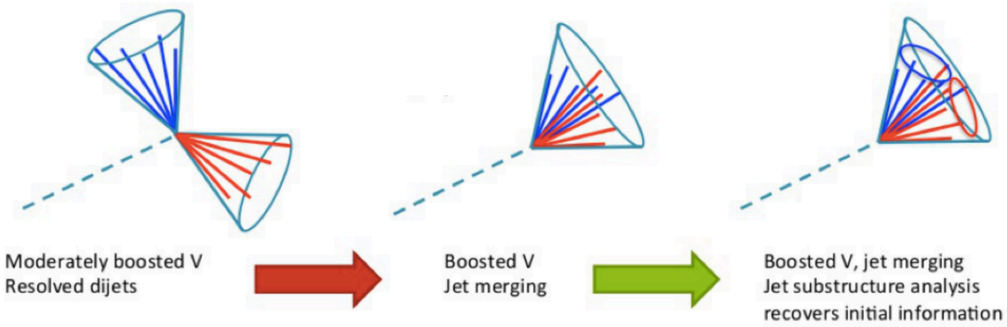
Slepton limits pushing 700 GeV in simplified models but gaps remain

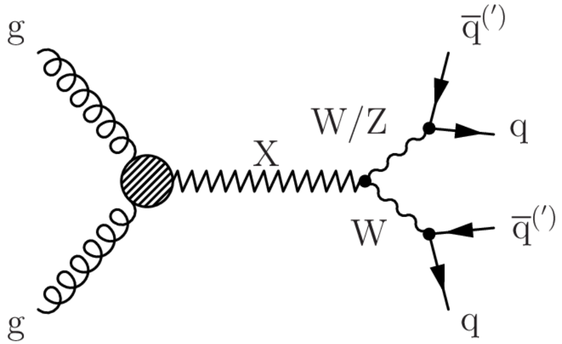
Advanced jet reconstruction - substructure

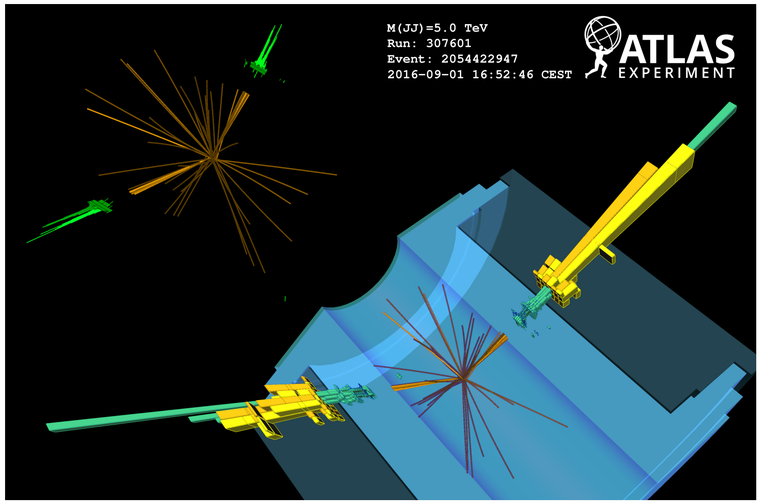
At very high momenta, jets (p.ex. from boson decays) can merge to form one big jet

- analyzing the jet substructure allows to reduce background

- example: high mass resonance search with diboson final state







Diboson candidate event

WIMP miracle

In the early universe dark matter and SM particles were in thermal equilibrium

- Constant production and annihilation of dark matter $\chi\chi \leftrightarrows ff$
- Freeze out
  - Universe cools
  - WIMP mass too high for production $\chi\chi \rightarrow ff$
  - Universe expands, particles don't meet anymore
- Can obtain relic density from Boltzmann equation
- Compare with observation (CMB)

Corresponds to ~100 GeV particle interacting with the weak force