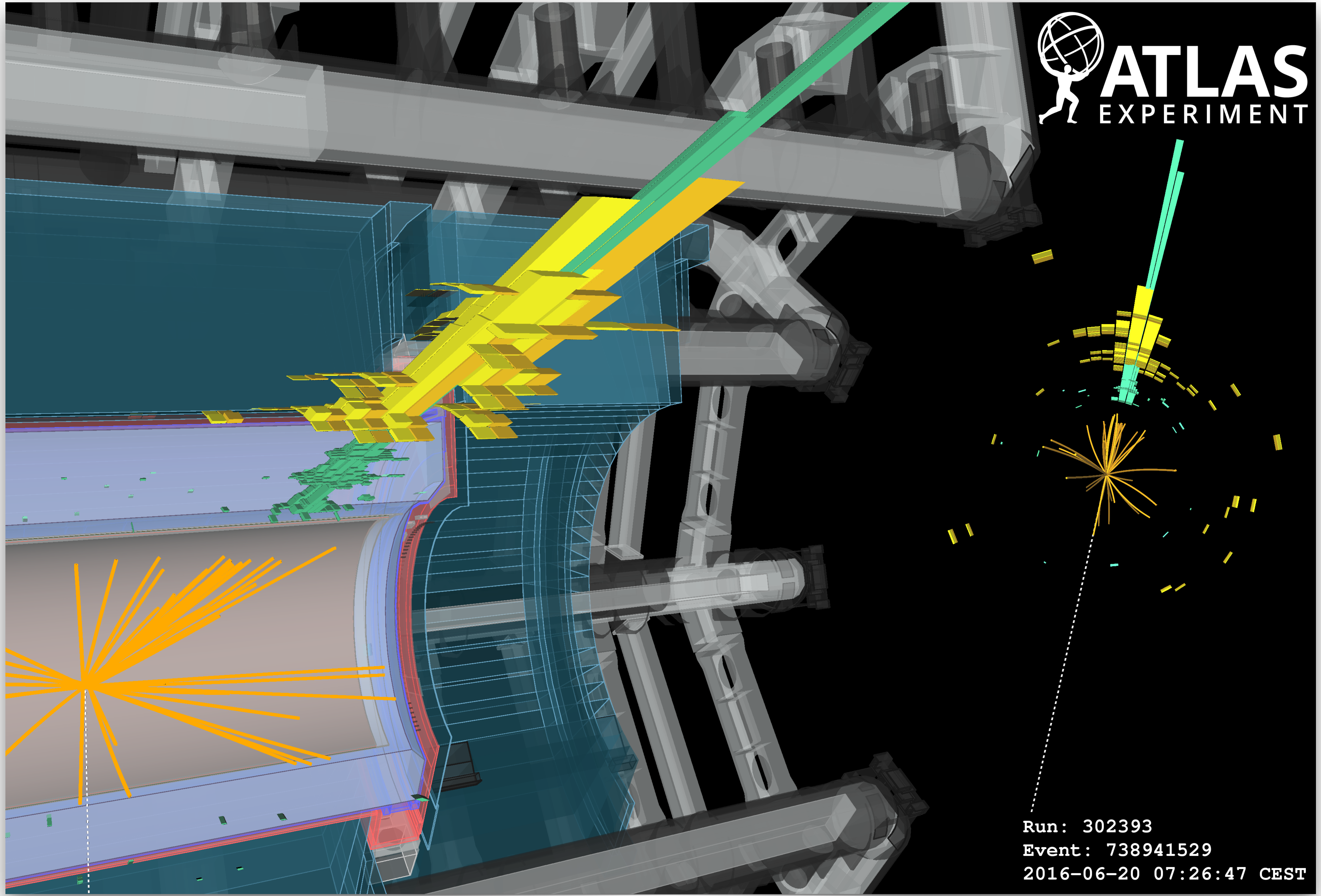
Experimental Physics at Hadron Collider



Lecture 4

Searches for New Physics

Conclusions and Outlook

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Sapienza, Roma and LAL, Orsay

CERN Summer Students Lectures

July 22-25, 2019

ATLAS mono-jet event

Outline

***Lecture 1**: Basic concepts, cross sections and QCD results*

- Preamble
- Context and mission of the LHC
- Fundamentals of hadron collisions
- Luminosity and total cross section
- Cross sections measurements
- Jet production measurements
- Measurement of the strong coupling constant

***Lecture 2**: SM Measurements*

- The electroweak sector in a tiny nutshell
- Measurement of the weak mixing angle
- W mass measurement
- Top mass measurement
- Diboson production
- Global fit of the Standard Model

***Lecture 3**: Higgs physics*

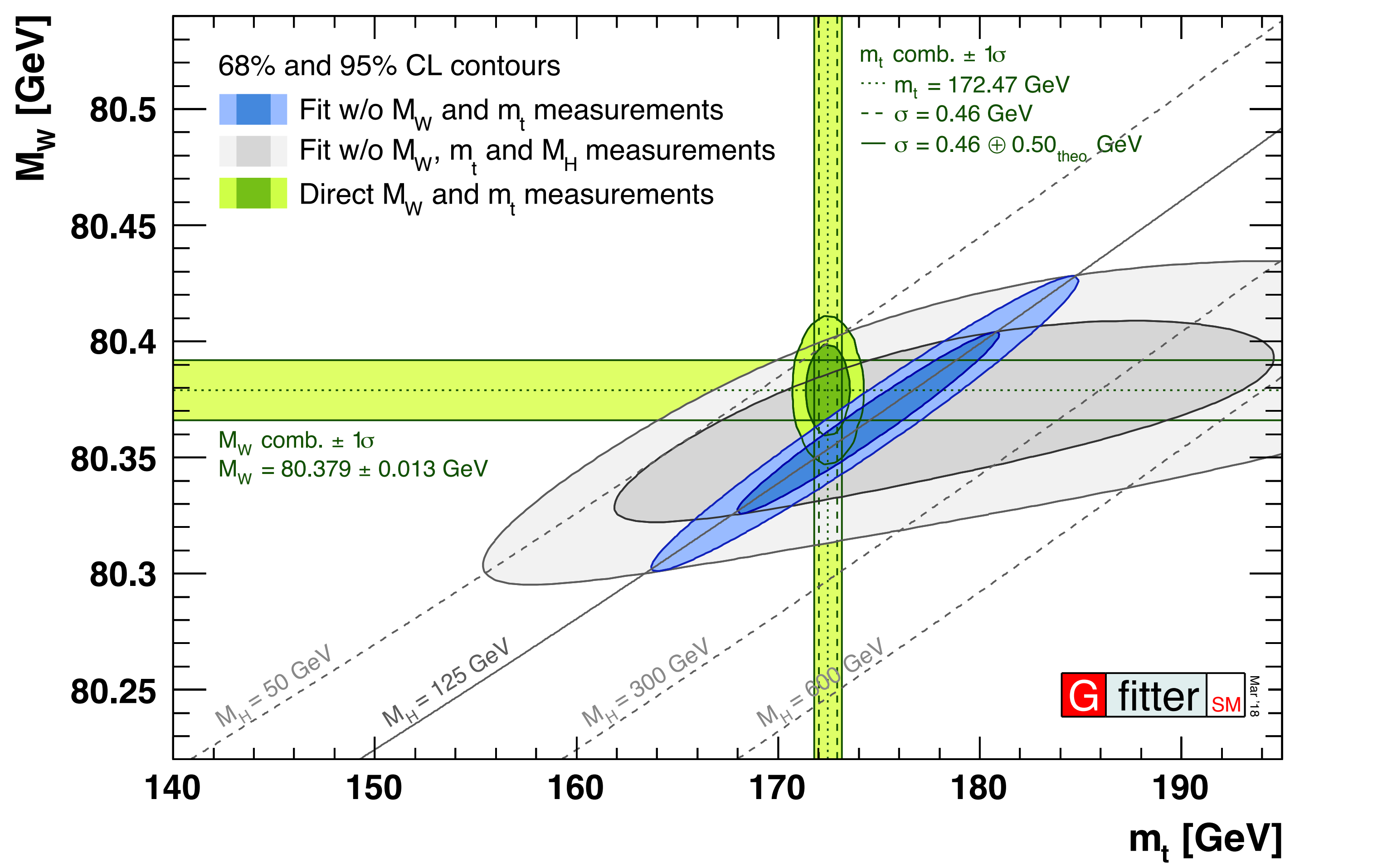
- The Higgs mechanism and Higgs production
- The discovery of the Higgs boson
- Precision Higgs physics with diboson channels
- Measuring the Yukawa couplings
- Measurement of Higgs properties
- Rare production and decays
- Global fit of the Standard Model (revisited)

***Lecture 4**: Searching for new physics BSM*

- Introduction
- Searches for supersymmetry and Dark Matter
- Searches in non SUSY theories
- Following up on anomalies
- Searches for unconventional signatures
- EFT and high energy observables
- Conclusions and outlook

Direct Searches for New Physics

From Lectures 2 and 3:

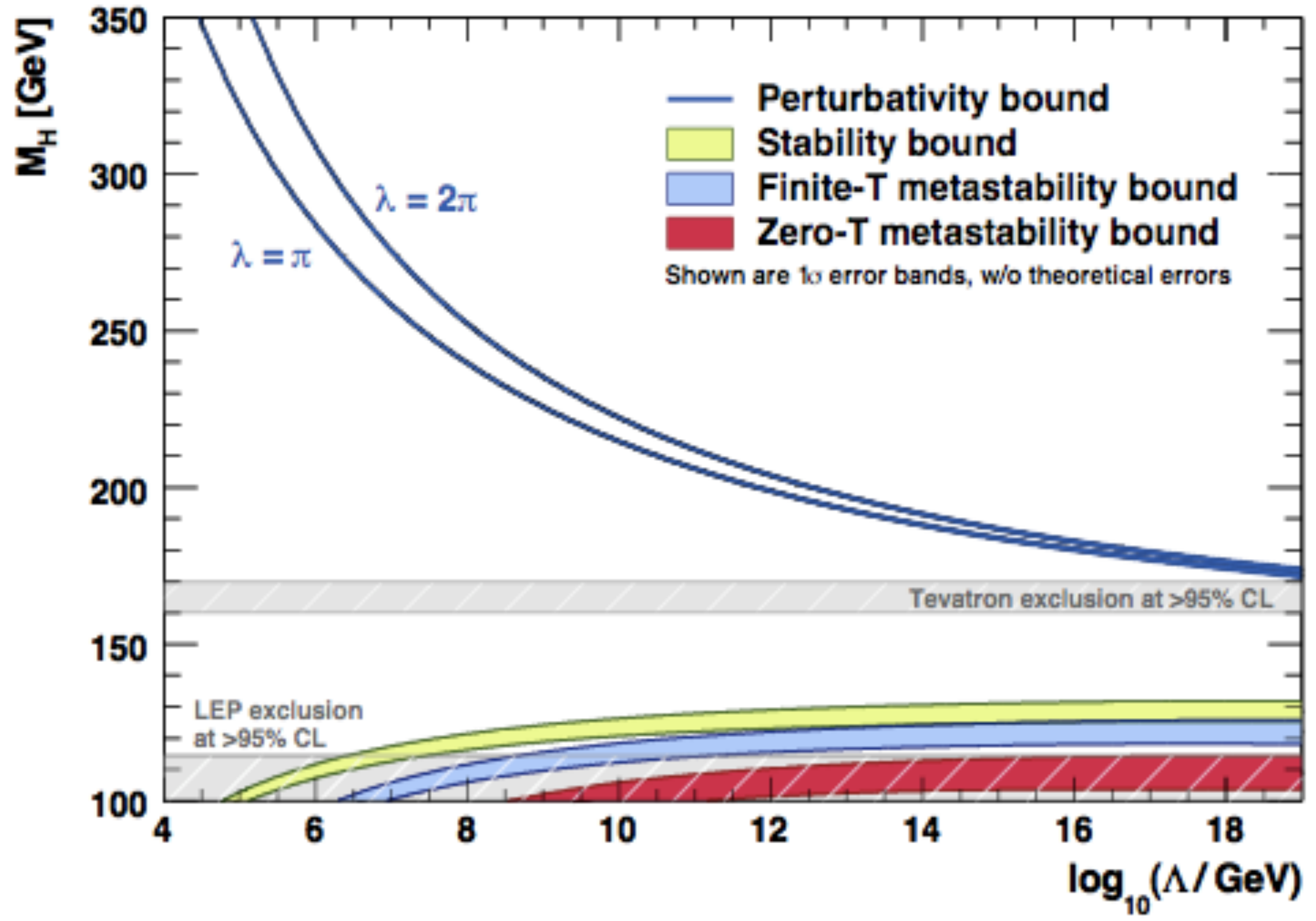


Global fit of the Standard Model: fully consistent!

In lectures 2 and 3 we have discussed how important it is to probe new physics through precision measurements of Standard Model parameters.

Within the current precision all measurements are consistent with the Standard Model

To further probe the Standard Model it is also extremely important to search directly for new phenomena which would yield different predictions than the Standard Model.



No indication of new physics scale.

With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

Finite-T metastability: The electroweak vacuum can become unstable against collapse because of thermal tunneling during the evolution of the universe)

Zero-T metastability: …or through 0-temperature quantum tunnelling

The *Unsatisfactory* Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

The elegant gauge sector (tree parameters for EWK and one parameter for QCD)

$$\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu} \qquad \theta < 10^{-10}$$

From neutron electric dipole moment measurements

The strong CP problem

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

The less elegant Higgs sector:

- Carries the largest number of parameters of the theory
- Not governed by symmetries
- Gauge Hierarchy (and Naturalness)
- Flavour hierarchy (includes neutrino masses)

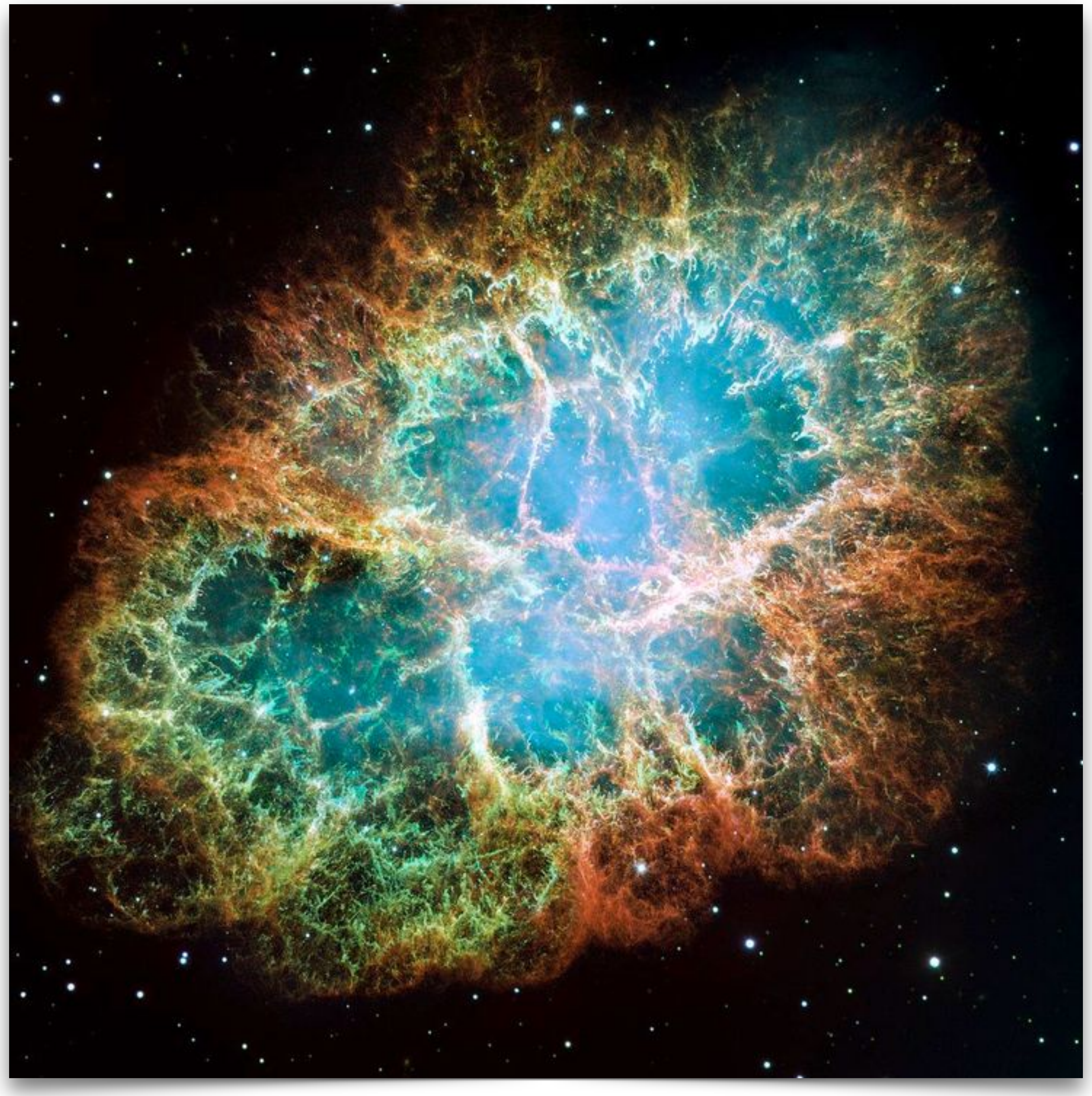
More fundamental questions (not explained by the SM):

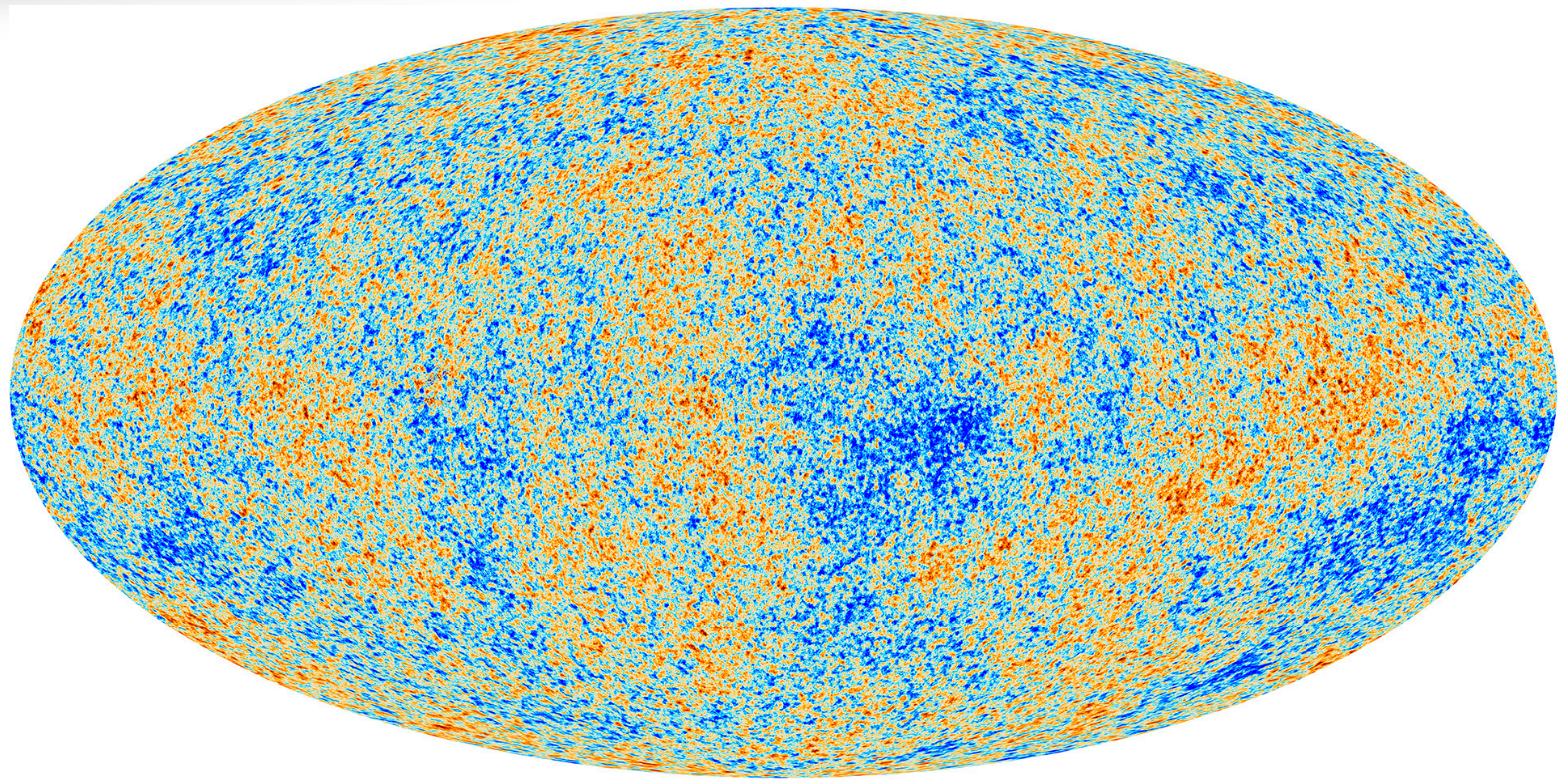
- Description of gravity at small distant scales?
- Why is the mu parameter in the Higgs potential negative? Is the Higgs composite?
- Why is the charge quantised and the charge of the electron equal that of the proton (grand unification)?
- … and many more!

Experimental anomalies and observations:

- Anomalous magnetic moment of the muon (recently confirmed by FERMILAB)
- B Lepton Flavor anomalies (see secures by Mark)
- and of course…

Unexplained Observed Phenomena





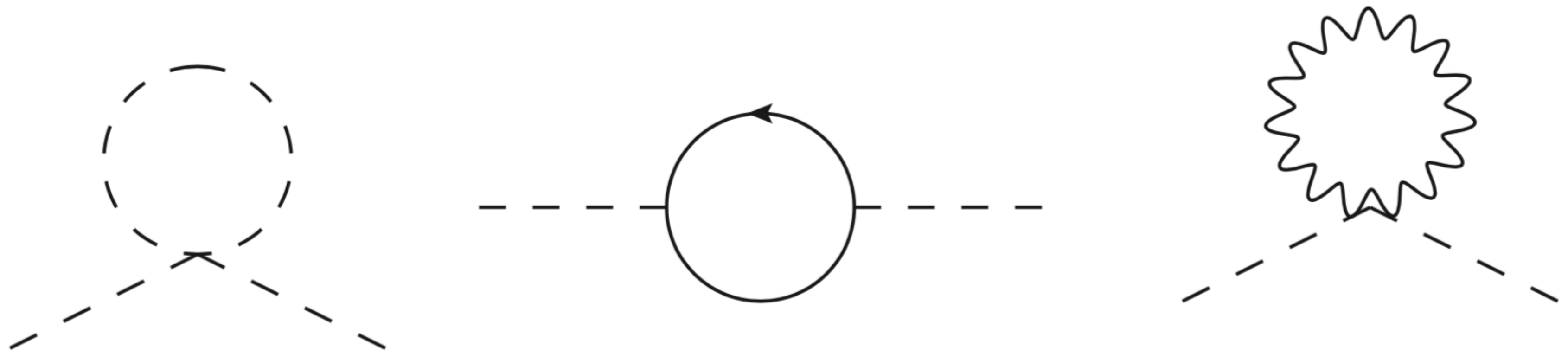
Astrophysical and cosmological observations:

- The mere existence of the universe and the matter/anti-matter balance?
- The nature of Dark Matter?
- The nature of Dark Energy?

Why is the Hierarchy an Issue?

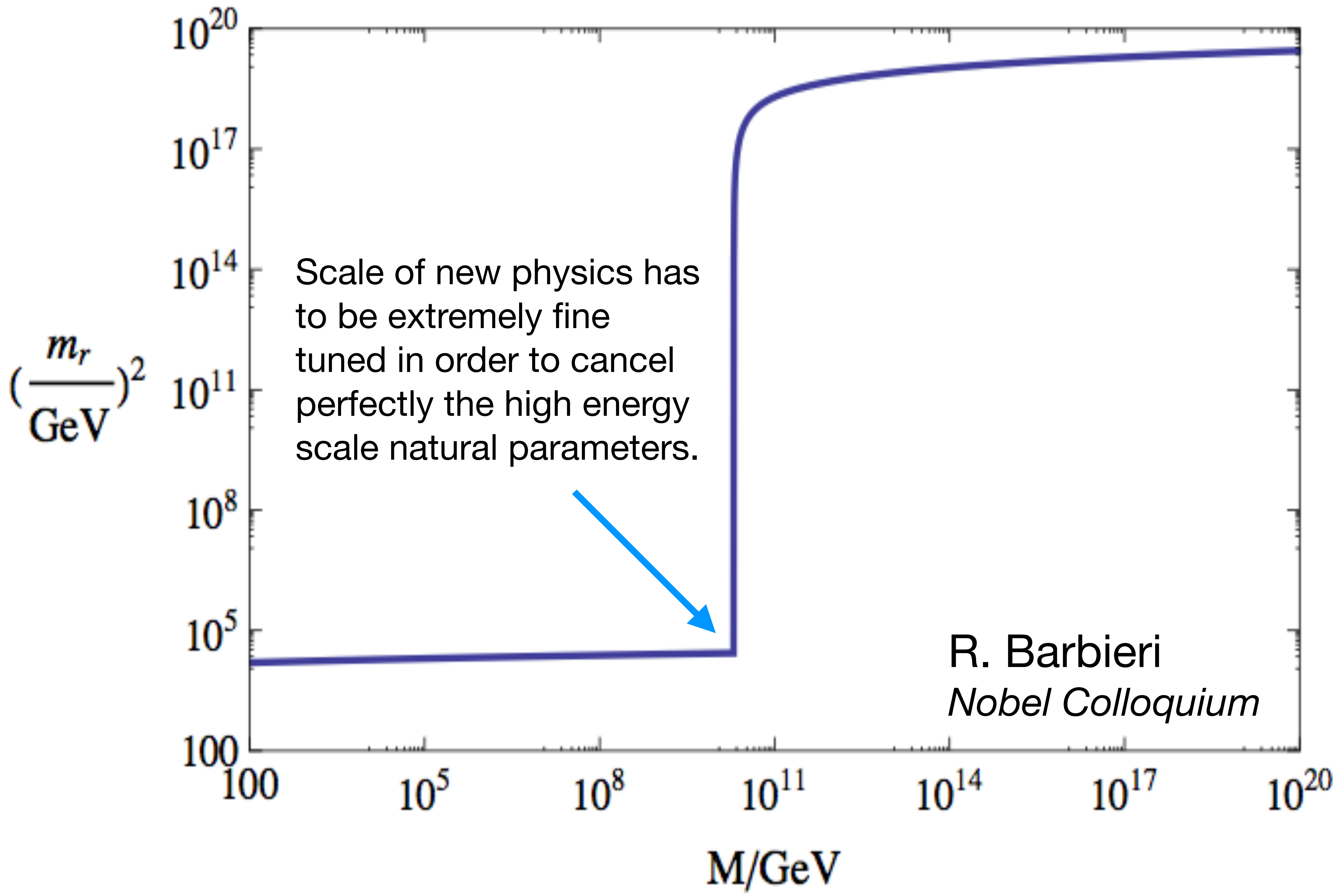
Naturalness

If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent:



$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi}$$

The Standard Model is a renormalisable theory quadratic divergences are not a problem per se, but if we look at the running of the Higgs boson mass:



Solutions:

- **Weakly coupled**: introduce fields in the theory that can cancel the quadratic divergence and alleviate the fine tuning (e.g. SUSY)
- **Strongly coupled** (Composite): in this case the above does not apply. The Higgs could be either a generic bound state or a pseudo goldstone boson (similarly to the pion in Chiral perturbation theory).
- **Warped extra dimensions**: Difference between scales generated by warping.
- **Anthropic principle**: fine tuning is acceptable since it is a condition for existence of the universe as it is.

Searches for Supersymmetry

Supersymmetry

An elegant, simple and complete solution…

Nutshell description:

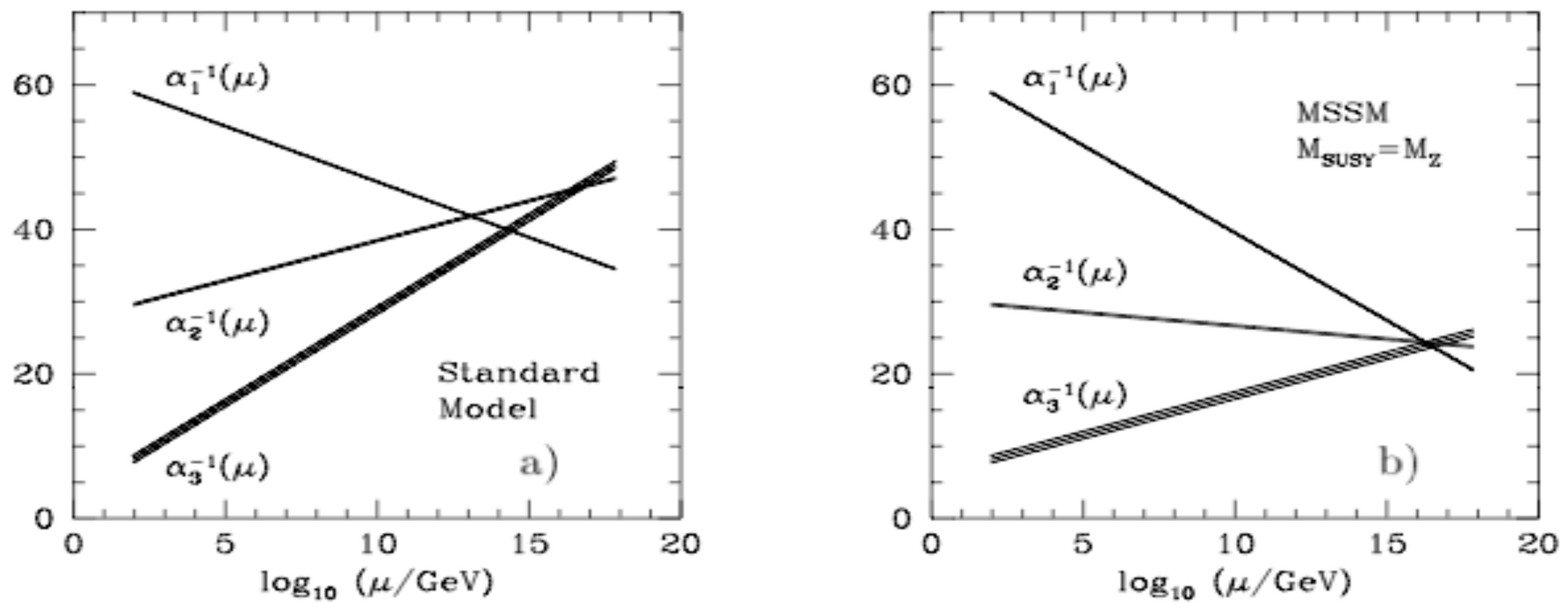
- For all fermions degree of freedom SUSY adds a boson degree of freedom
- To all bosons degree of freedom, SUSY adds a fermions

What SUSY addresses:

- It resolves the gauge hierarchy (naturalness problem)
- It allows unification of gauge couplings
- Local SUSY requires gravitino and therefore via SUSY naturally brings the graviton and is an essential ingredient in string theory
- It provides a natural candidate for dark matter

The only few (non negligible) **issues:**

- It has not been found! If it exists it has to be broken
- If the super-partners are too heavy fine tuning re-emerges and one of the main issues (naturalness) reappears).
- With a much larger number of fields come a much larger number of parameters!

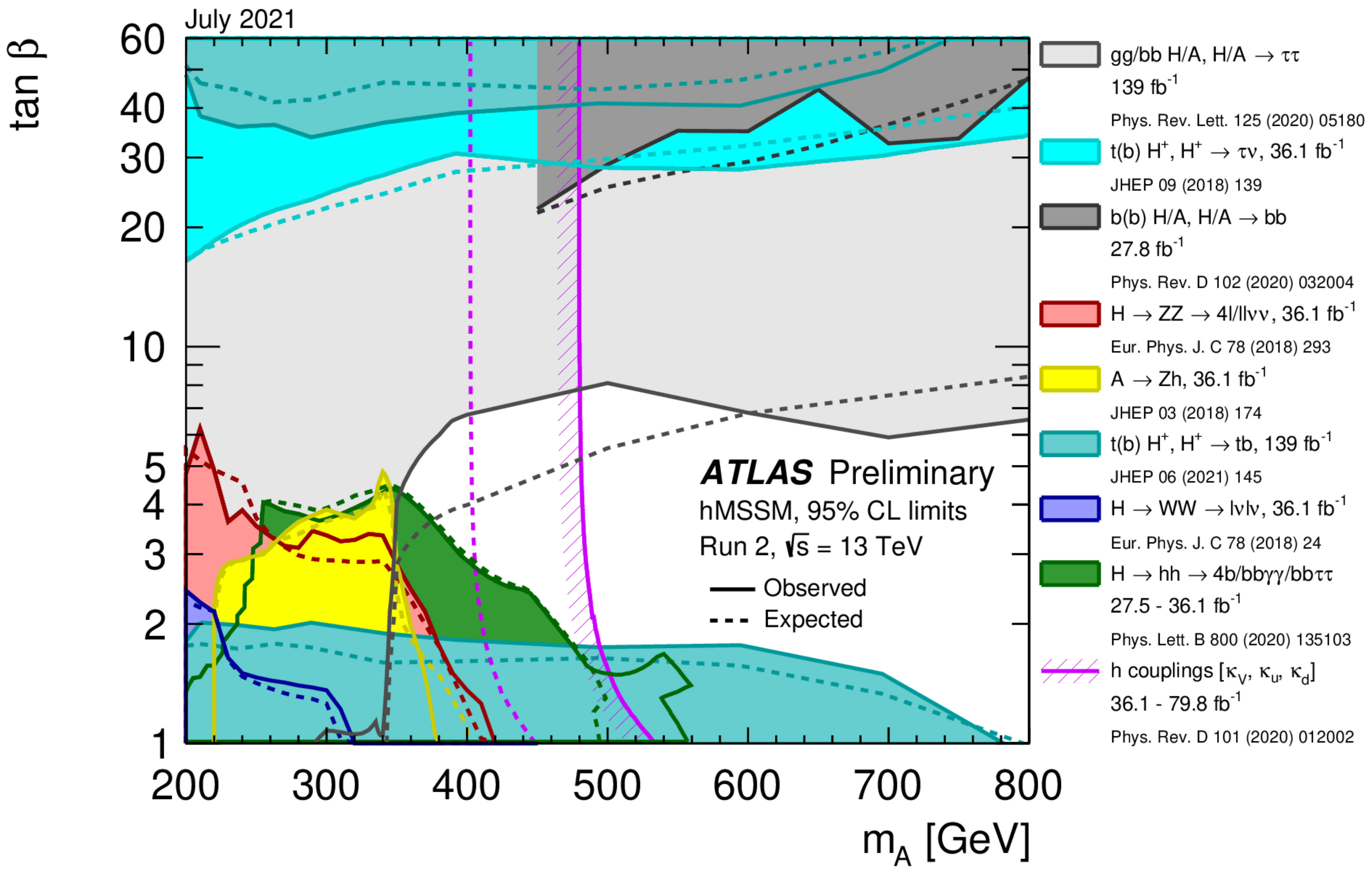


The main predictions of SUSY

- Superpartners that should be at a reachable scale!
- A candidate dark matter particle: the neutralino (typically).
- An extended Higgs sector. Its minimal realisation is the MSSM (2 Higgs doublets so 5 Higgs bosons, 3 neutral and 2 charged).

Reaching SUSY from an extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



SUSY could modify the couplings of the Higgs

From the combination of all channels presented in Lecture 3, from constraints on up versus down Yukawa and coupling to vector bosons, limits in the MSSM parameter space can be set.

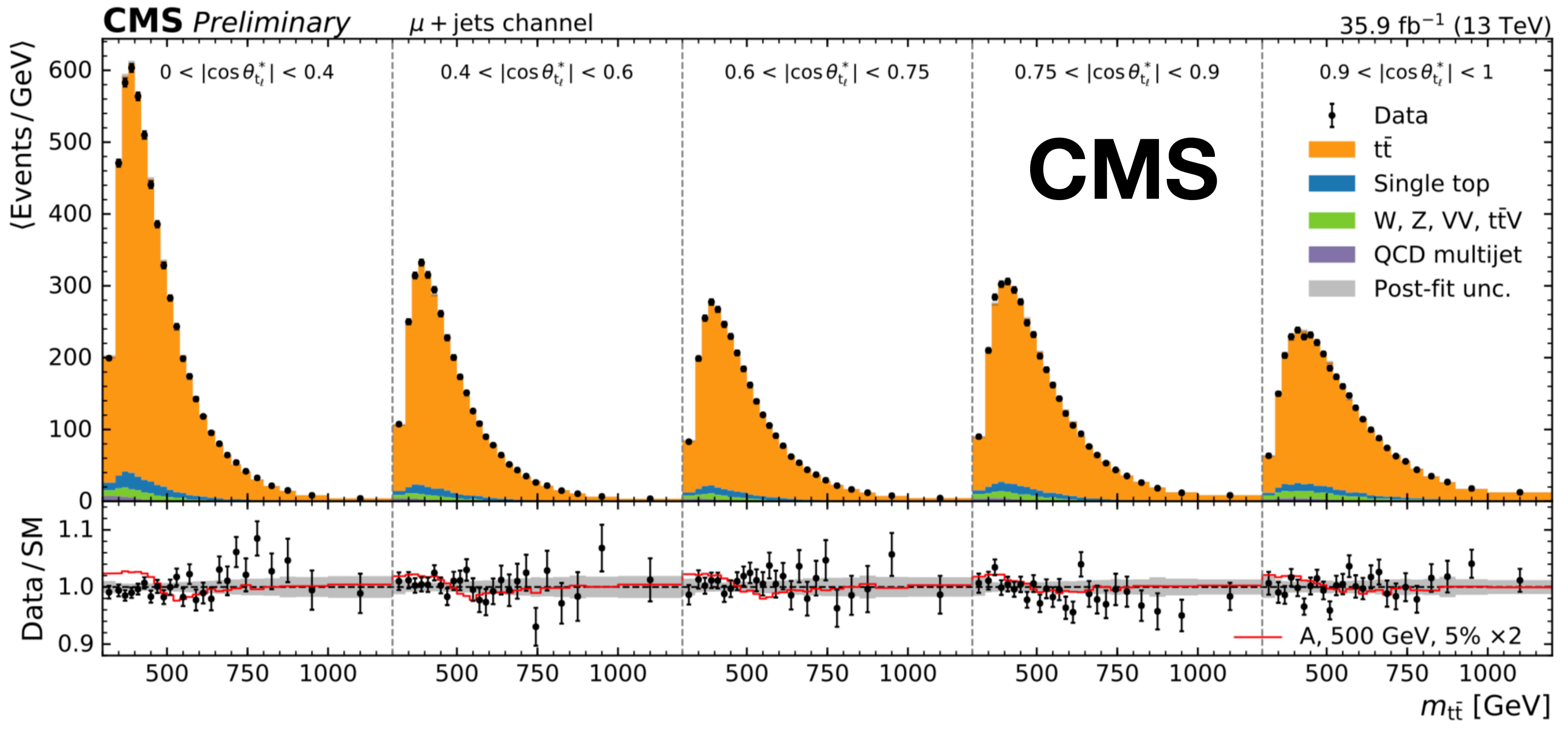
Direct searches for additional Higgs bosons (neutral and charged) have been performed:

- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb
- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH

Search for Higgs to top pair

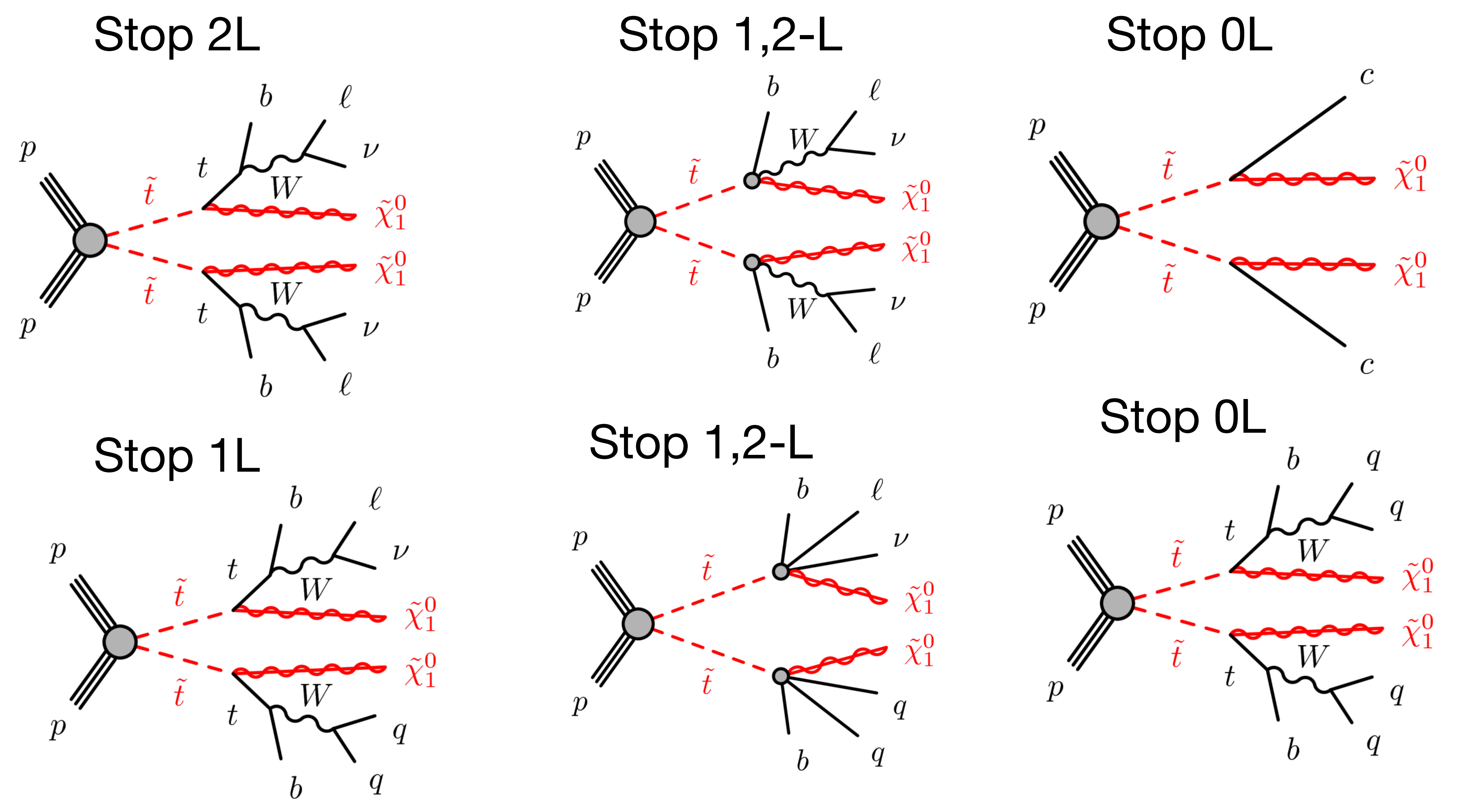
μ -jets channel

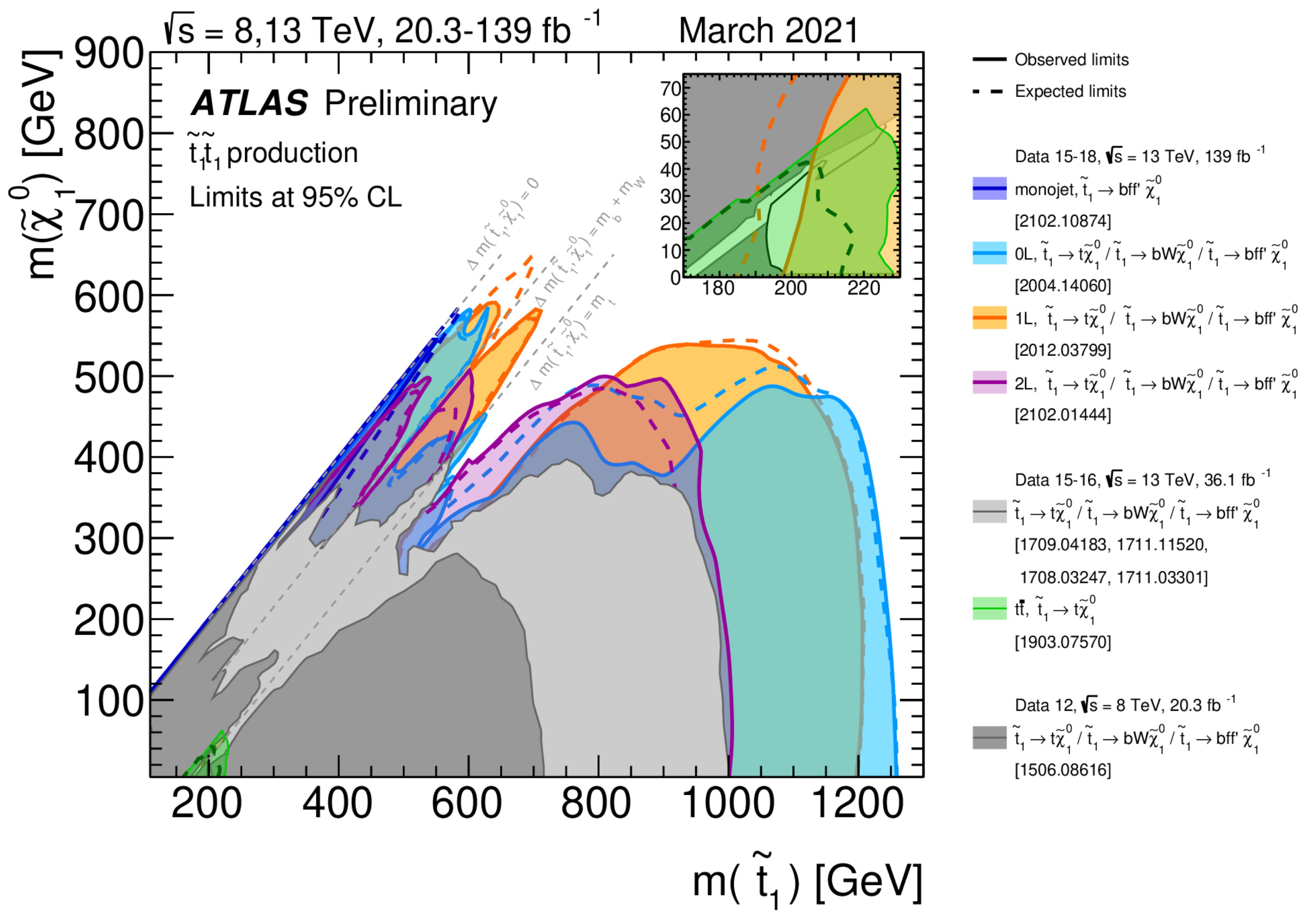
Intricate search for a non trivial interference pattern in ttbar mass.

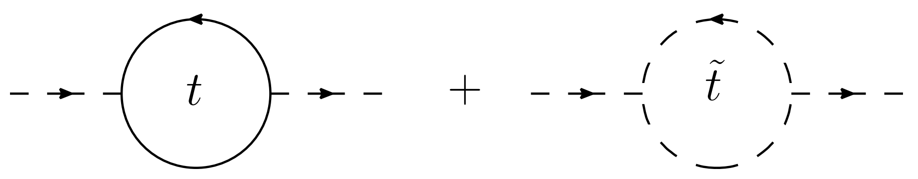


Searches for Natural and Strongly Produced SUSY

Stop

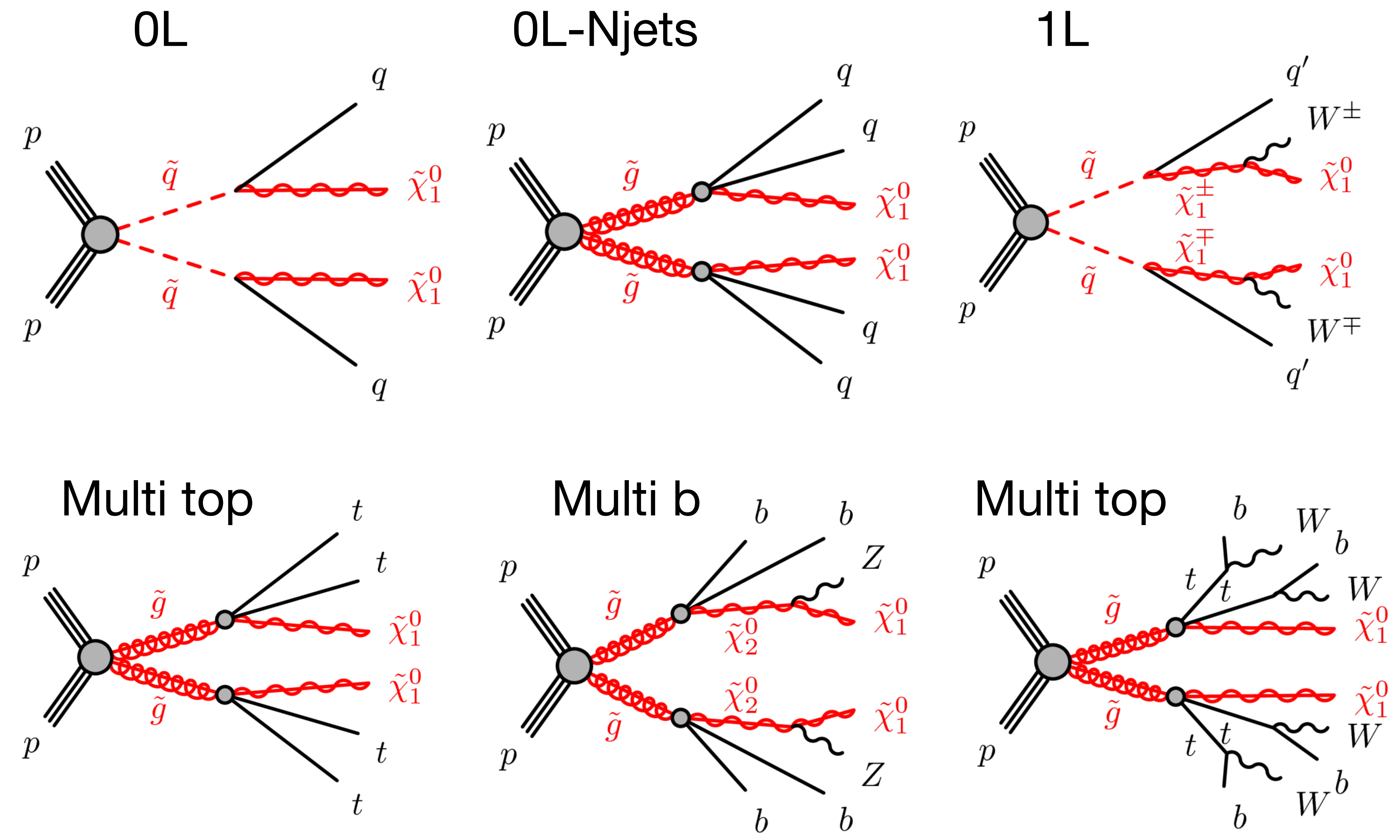


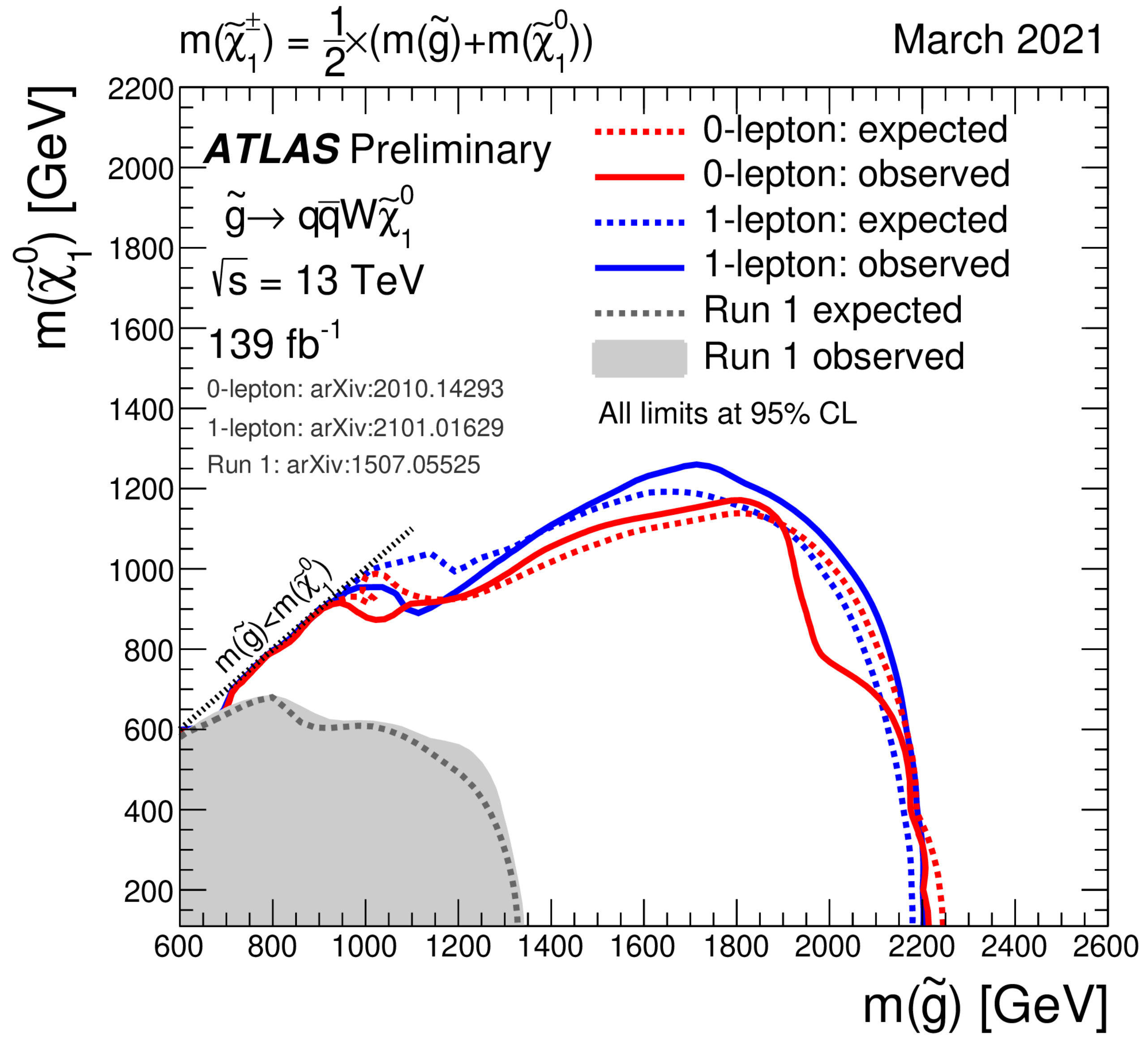


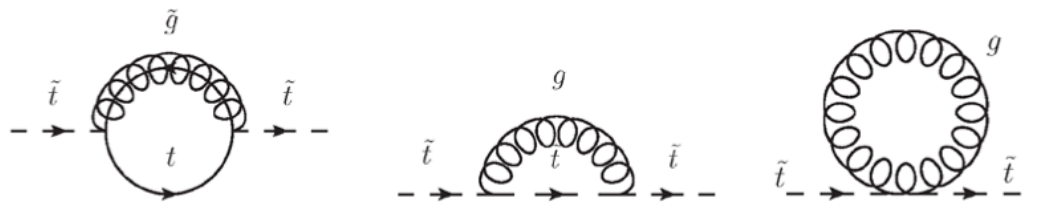


Not so natural SUSY:
Stops > 1 TeV ~Tuning of factor **20**, but these exclusions are under specific conditions, and there are unexcluded corridors.

Squarks and gluinos



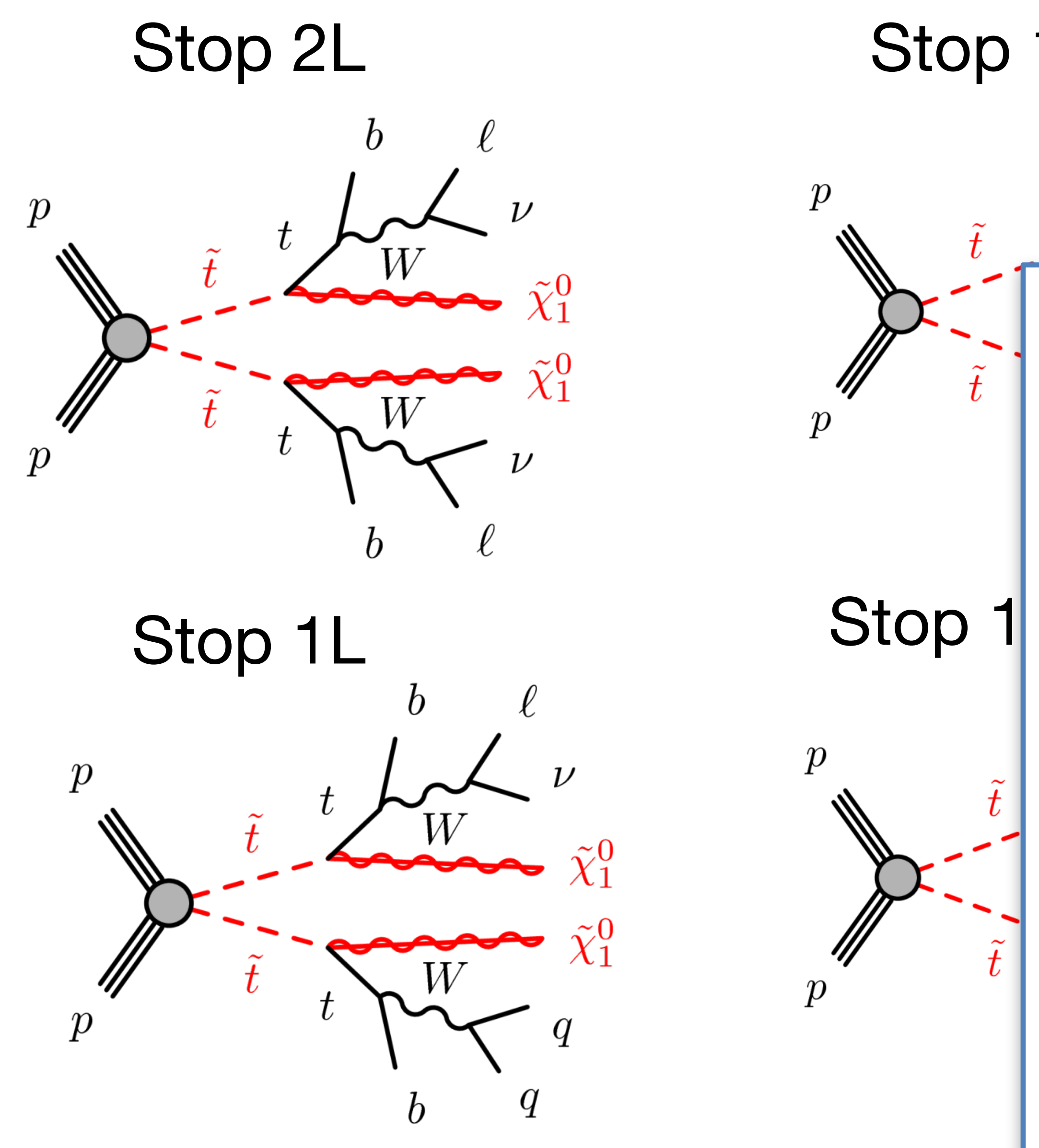




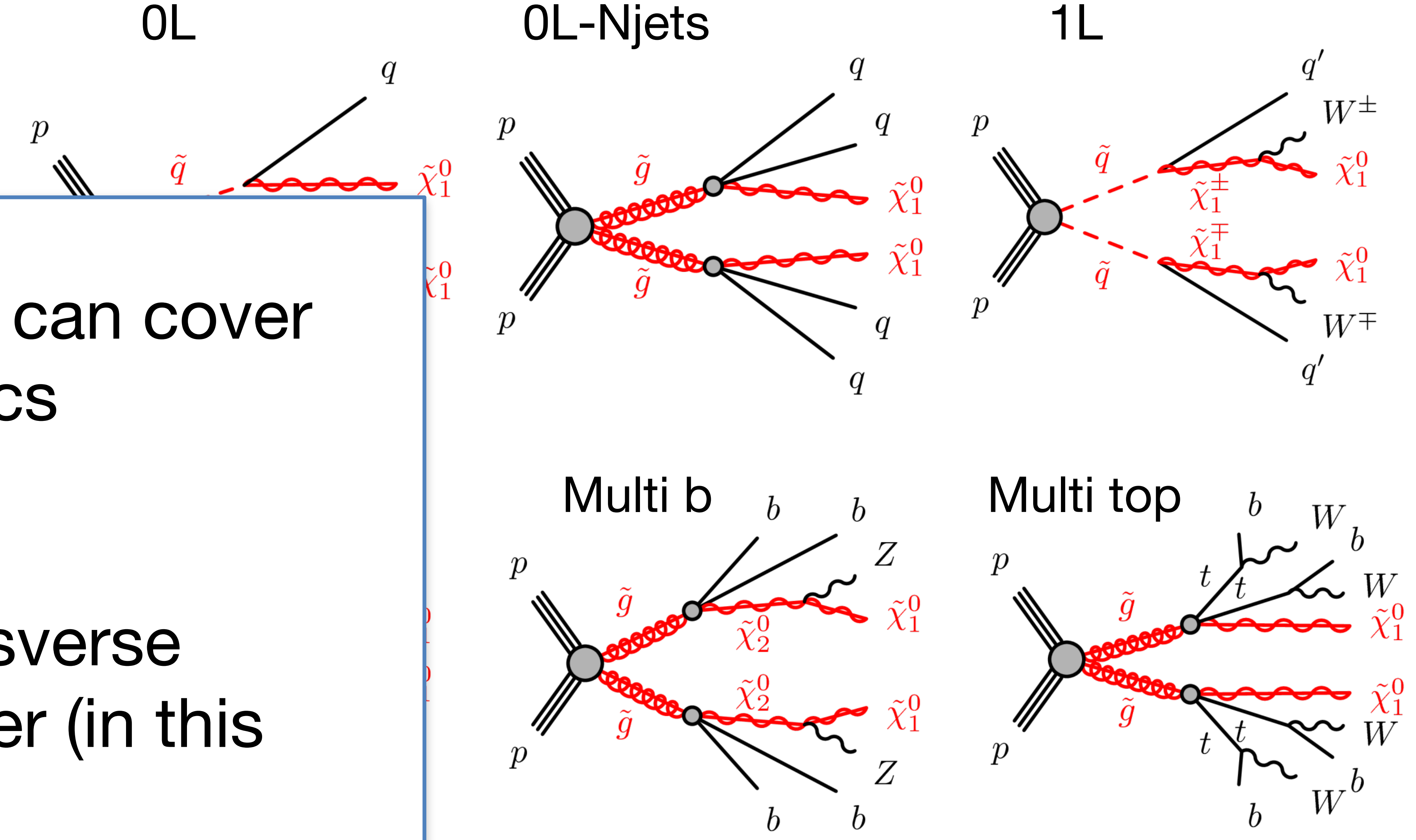
Stop also a scalar requires light gluinos to be light enough: for gluinos > 2 TeV ~tuning of Factor of **30**

Searches for Natural and Strongly Produced SUSY

Stop

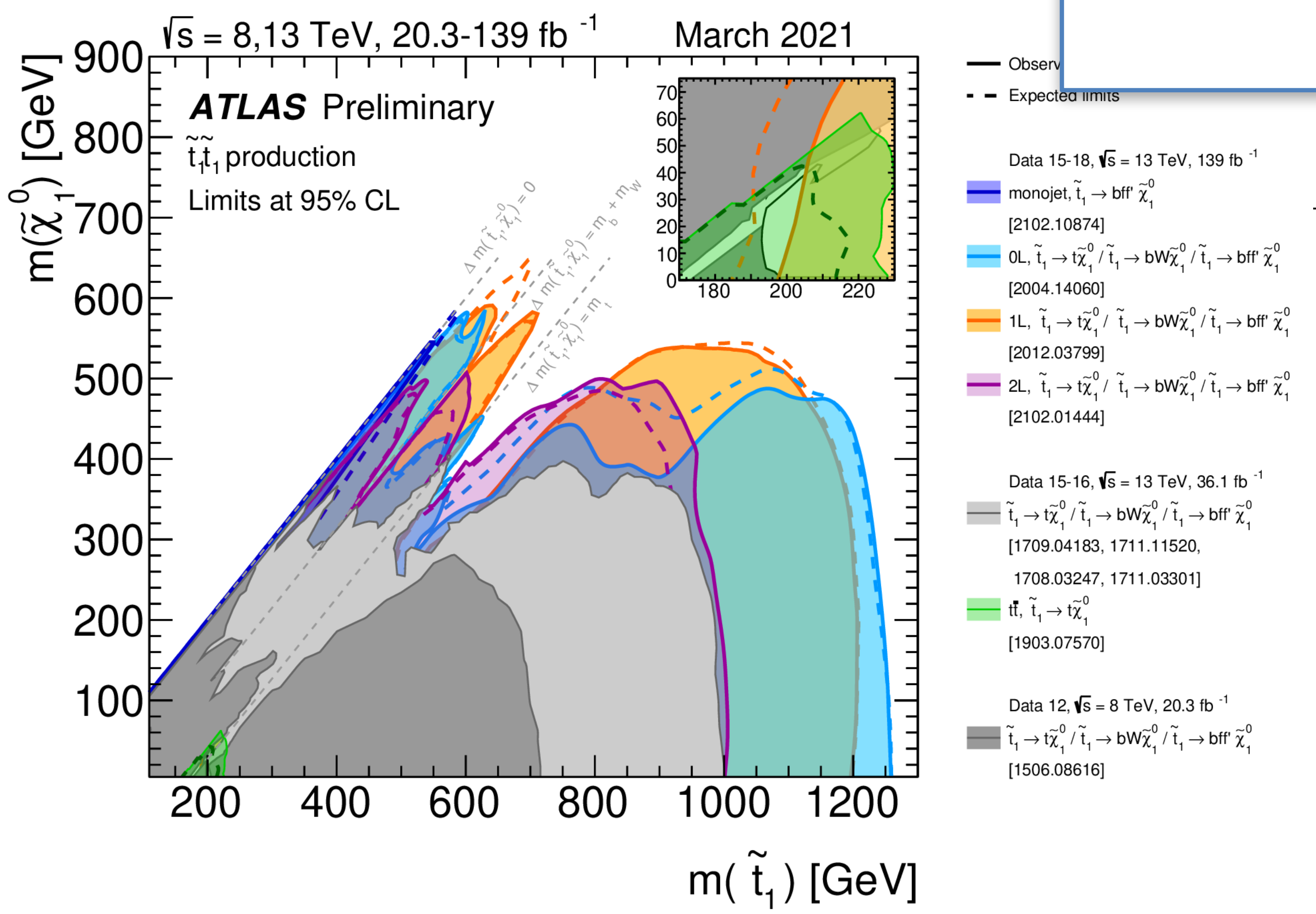


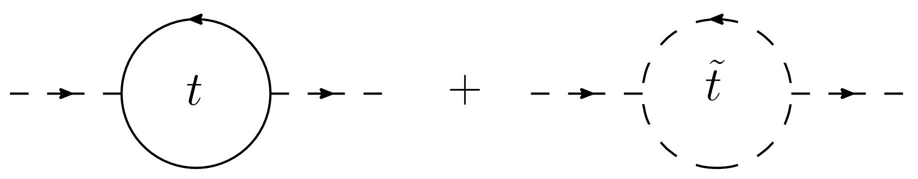
Squarks and gluinos



Large number of topologies which can cover different SUSY or other new physics scenarios

All signatures feature missing transverse energy are searches for Dark Matter (in this case the lightest SUSY particle)!





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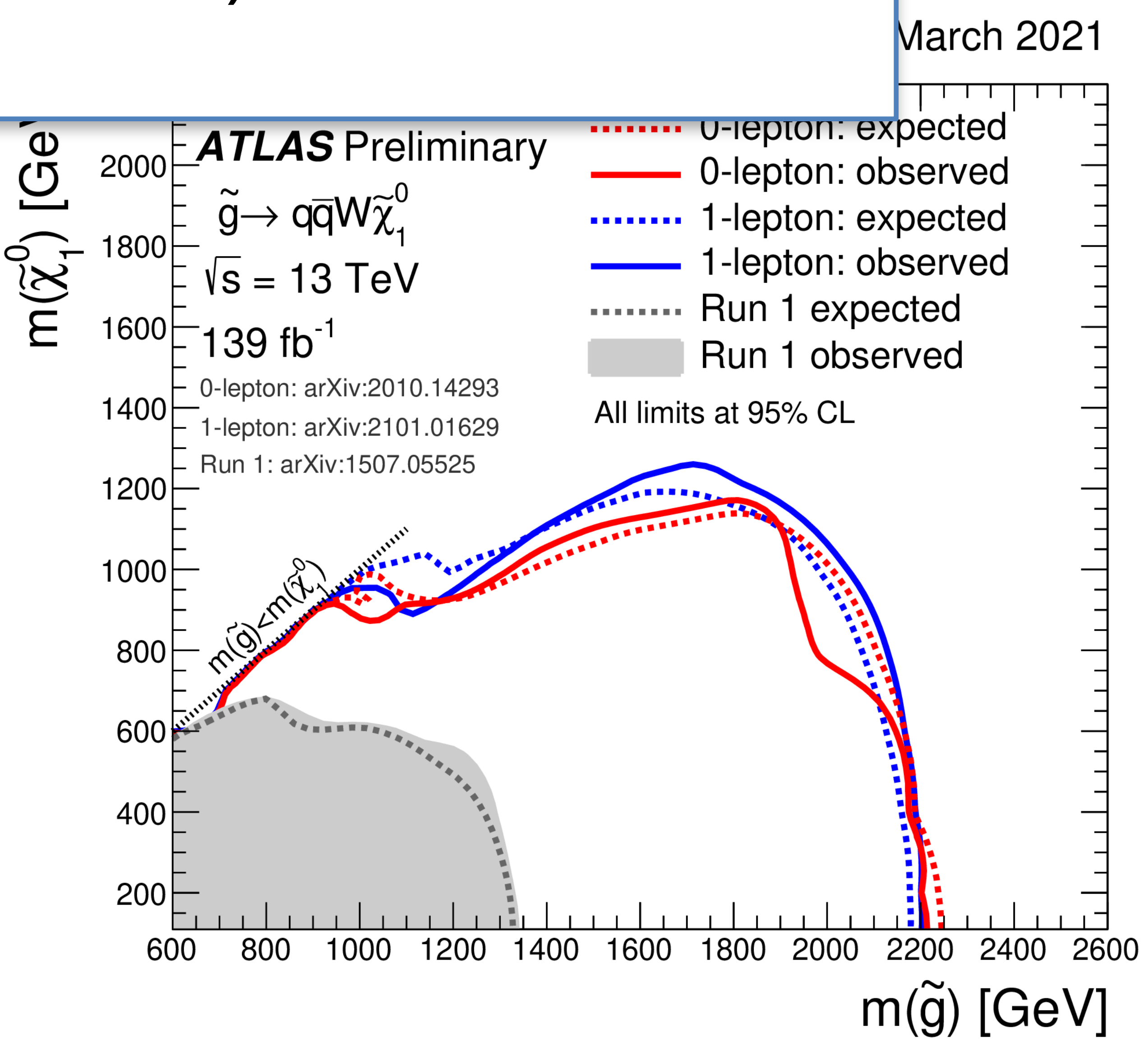
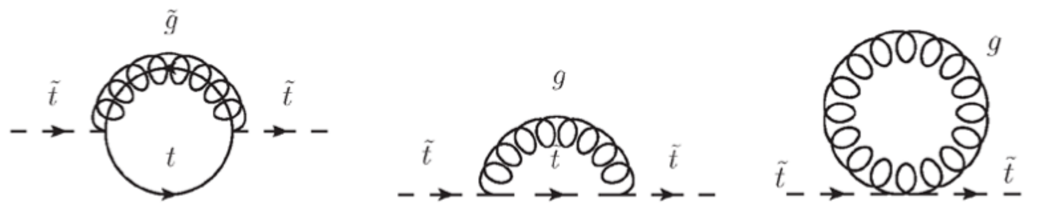
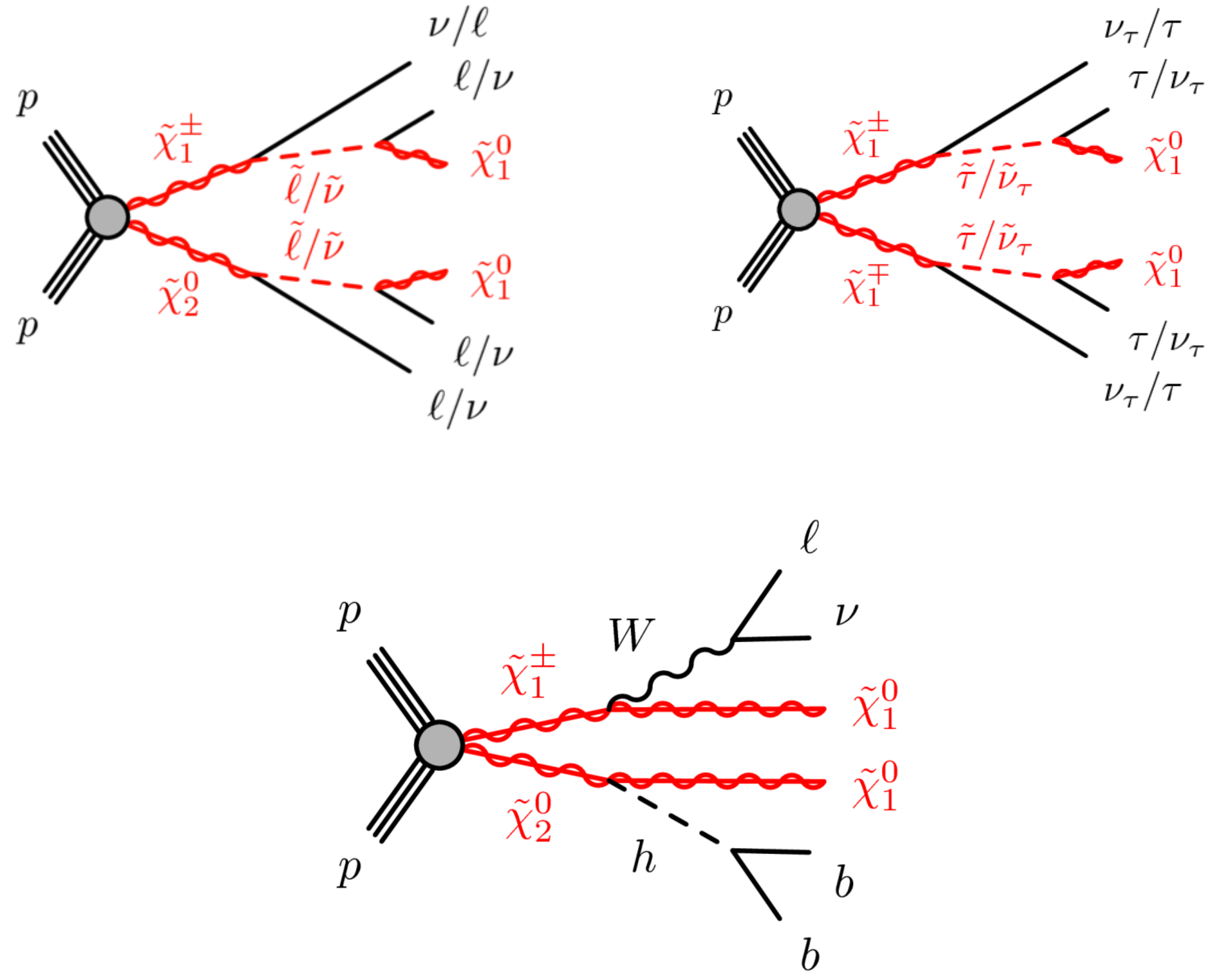




Stop also a scalar requires light gluinos to be light enough: for gluinos > 2 TeV ~tuning of Factor of **30**

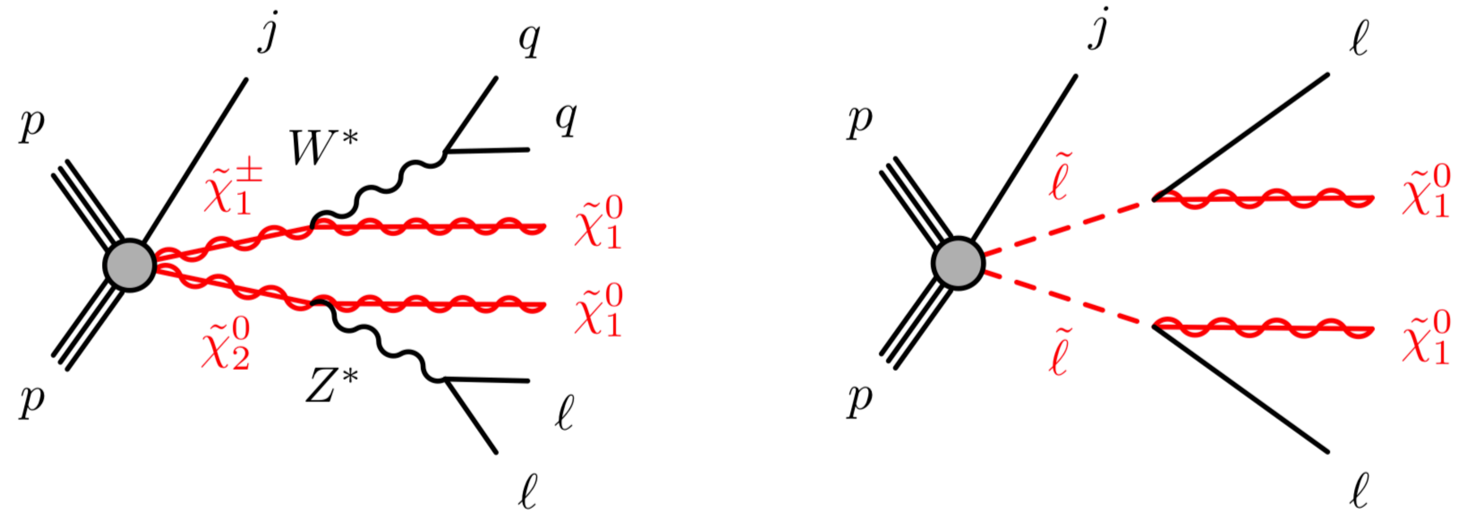
More intricate scenarios

Weak production of charginos, neutralinos and sleptons



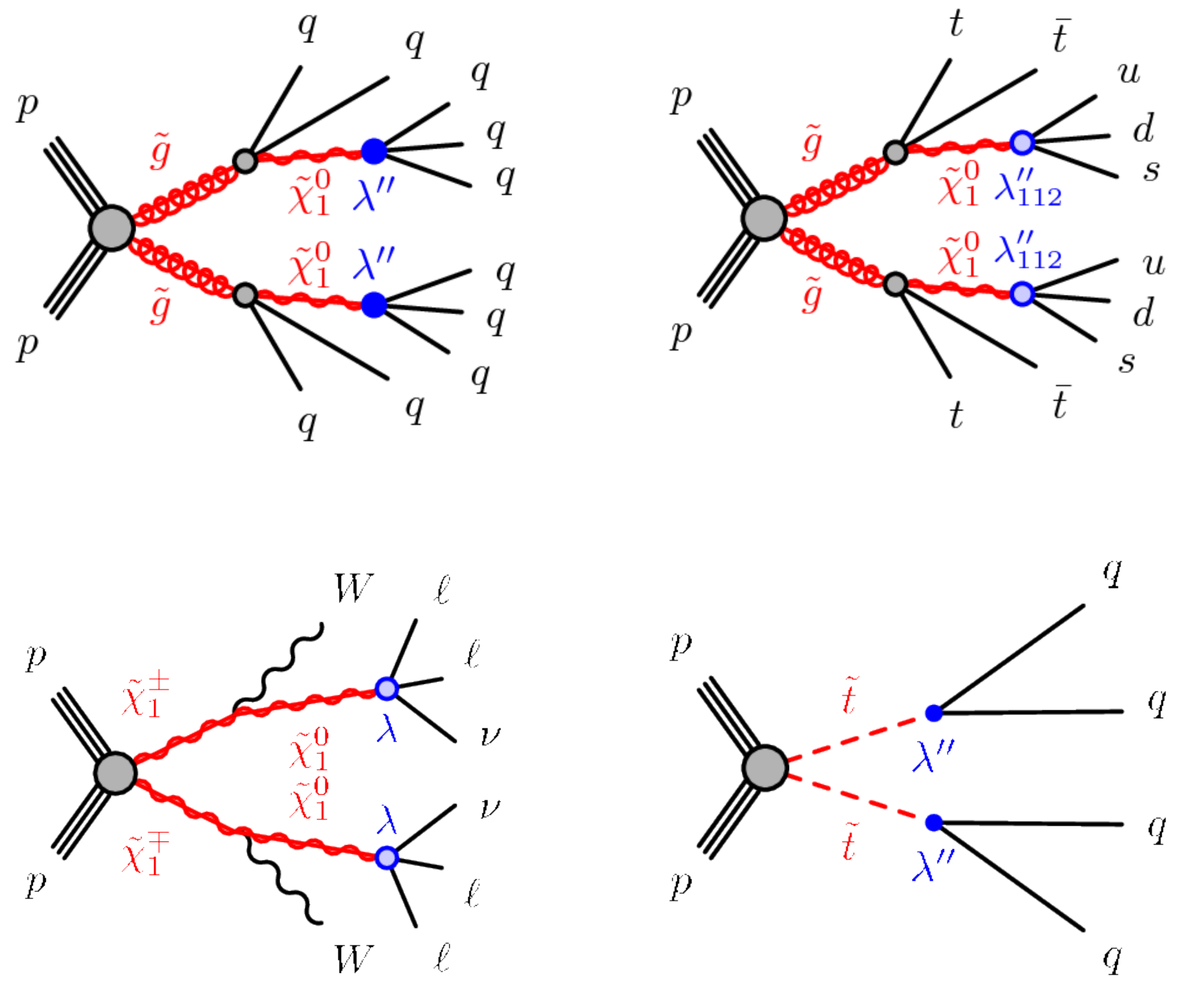
1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.

Weak production in **compressed scenarios**



Scenarios where the charginos, neutralinos or sleptons are close to mass degenerate with the lightest SUSY particle (LSP).

R-Parity violating SUSY



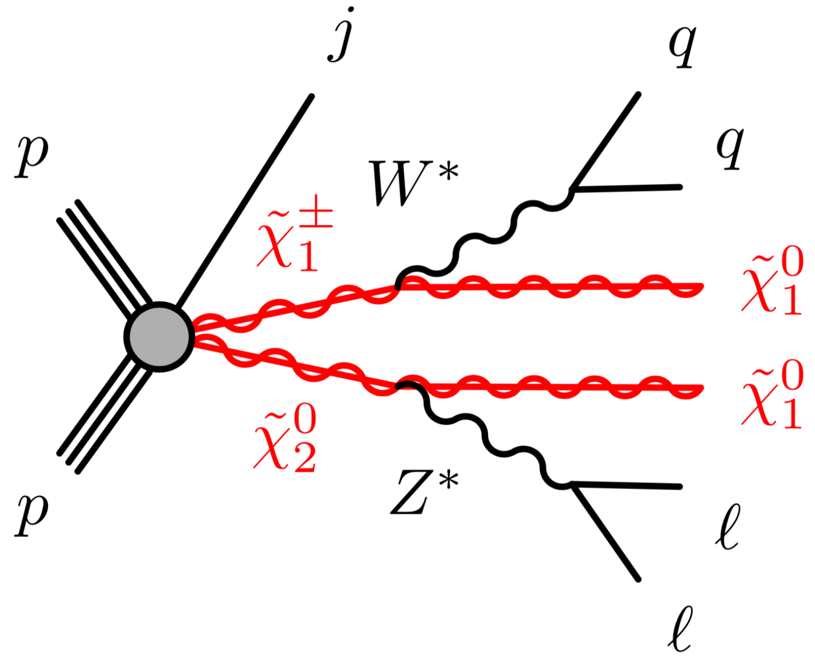
Resulting in topologies without LSP in the final state and therefore no MET.

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

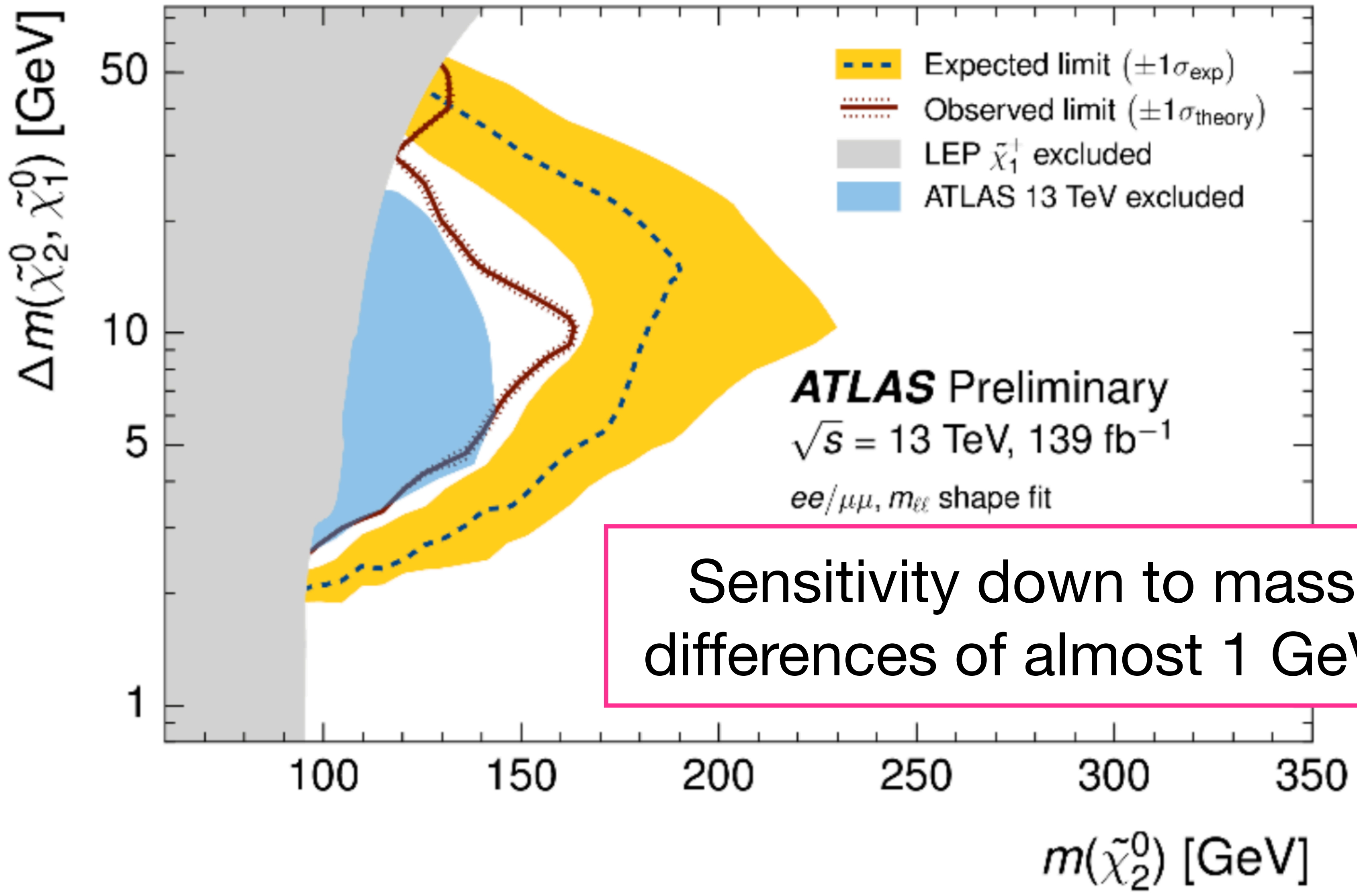
RPV components of superpotential

Searches for Charginos and Neutralinos (Examples)

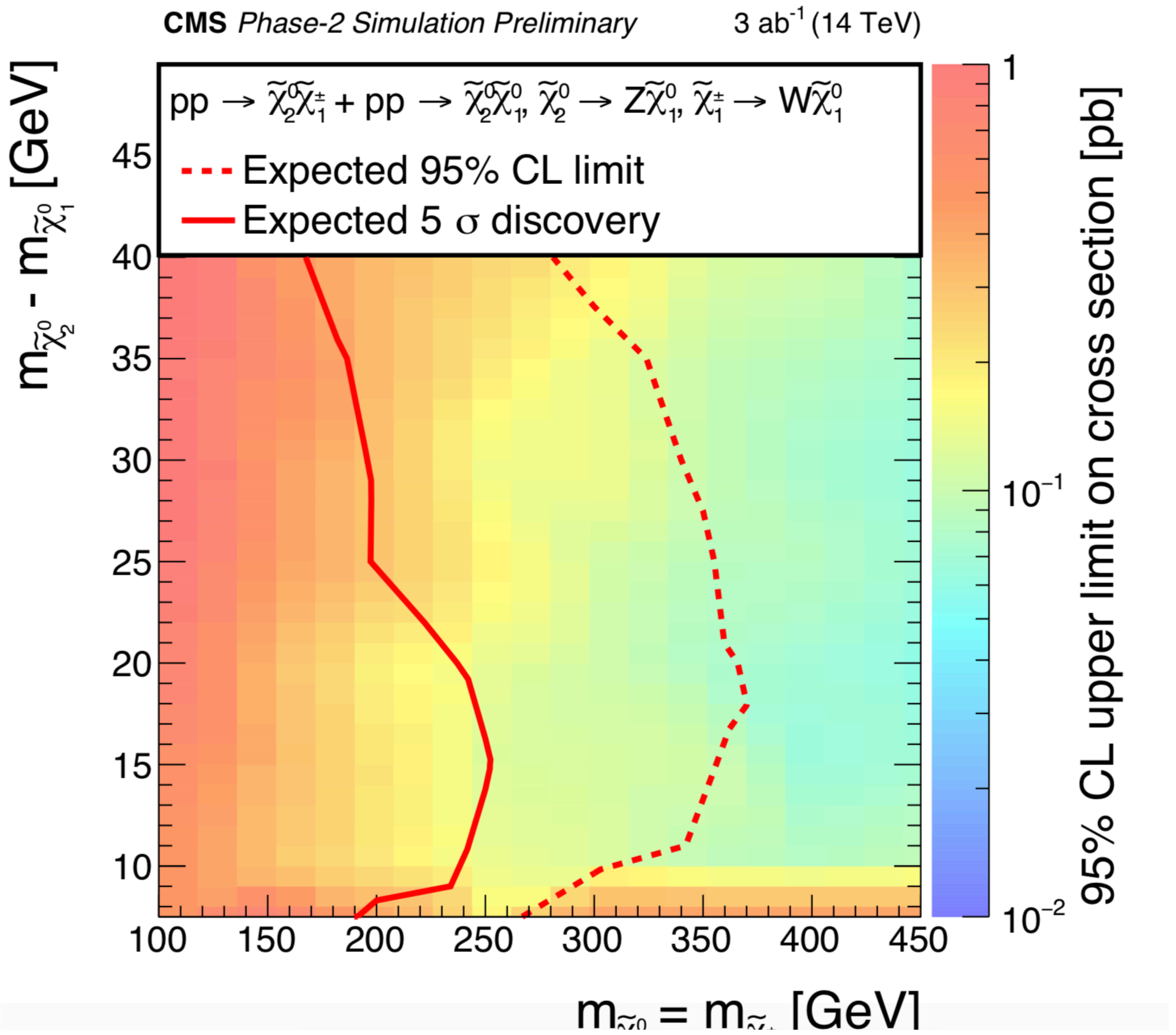
Weak production of charginos and neutralinos



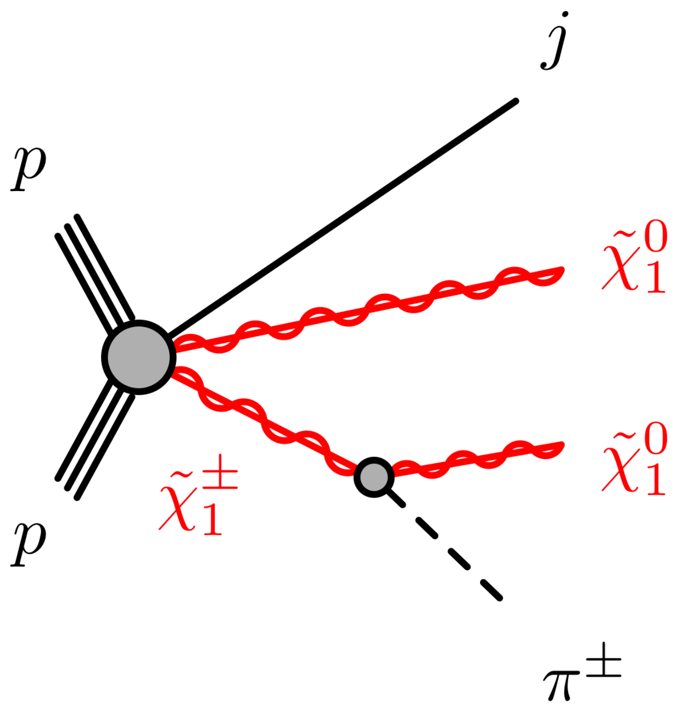
Example of boosting to find small mass differences.



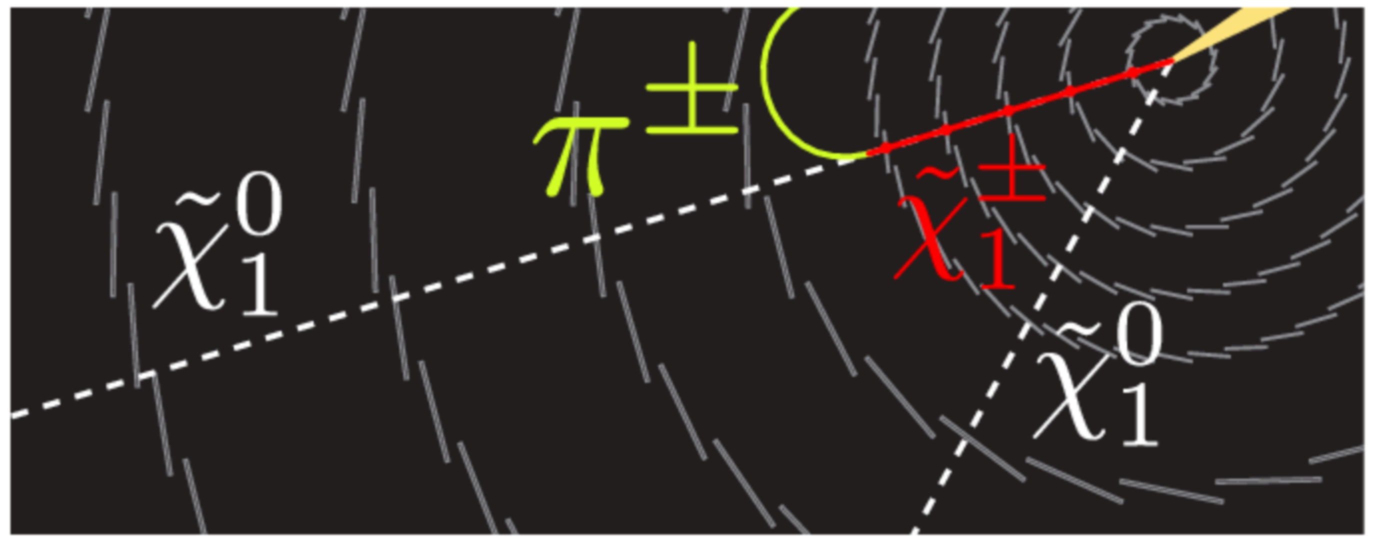
Sensitivity down to mass differences of almost 1 GeV!



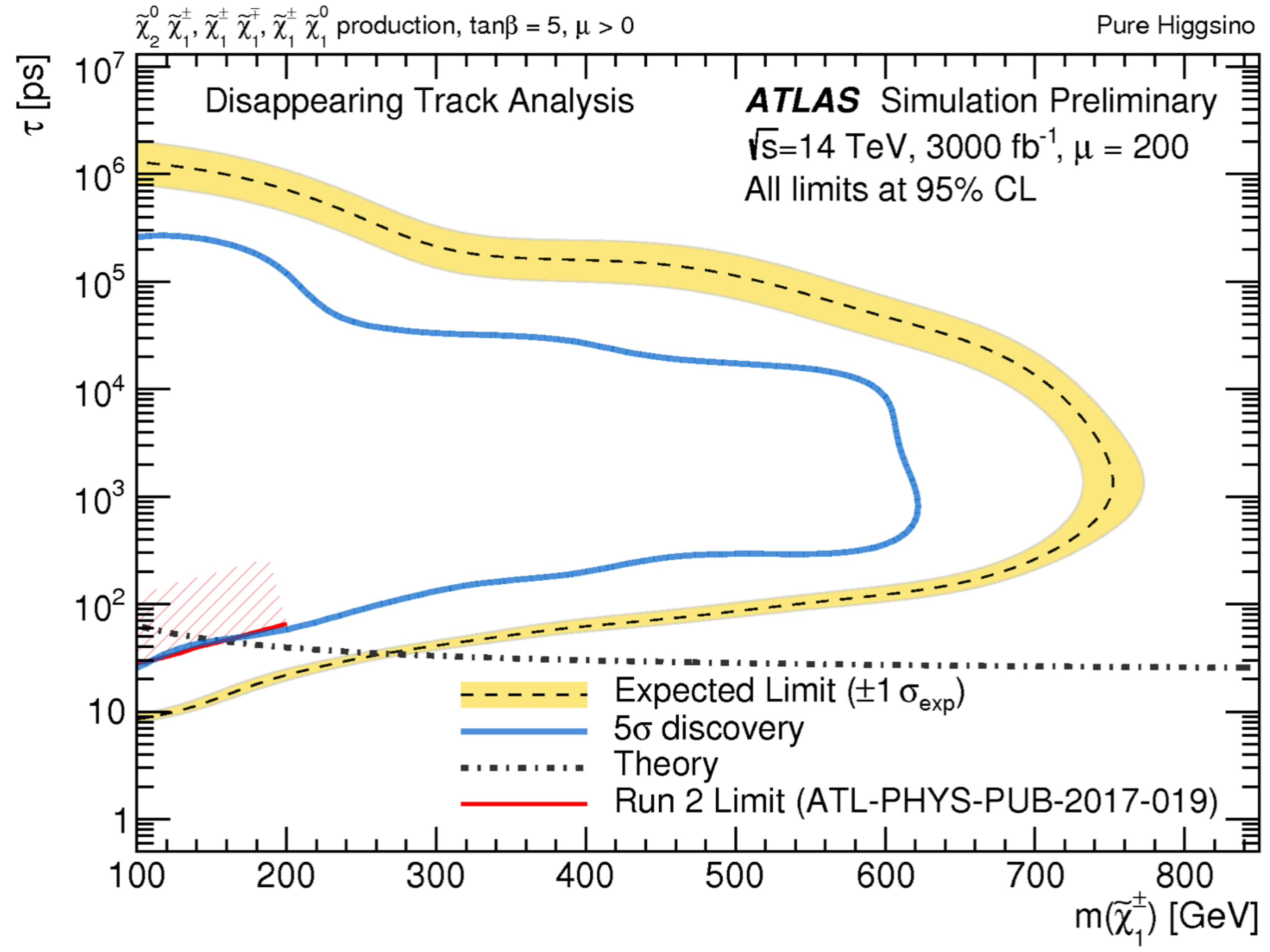
SUSY in highly compressed scenarios



Disappearing tracks topologies
(Uses MET Trigger - requires ISR jet)

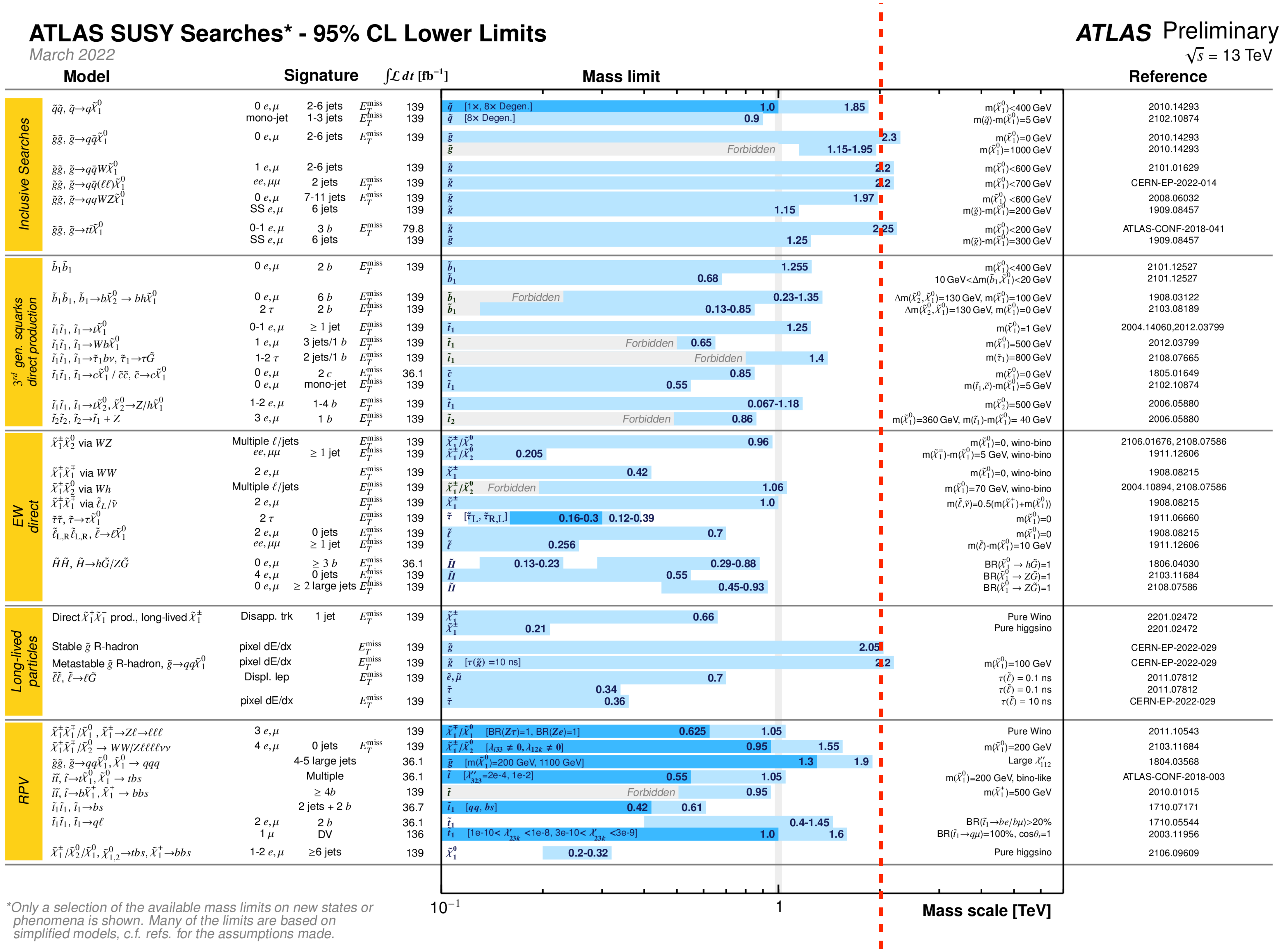


Scenario where the charginos and neutralinos are almost degenerate (chargino has significant lifetime and is seen in the first layers of the ID).

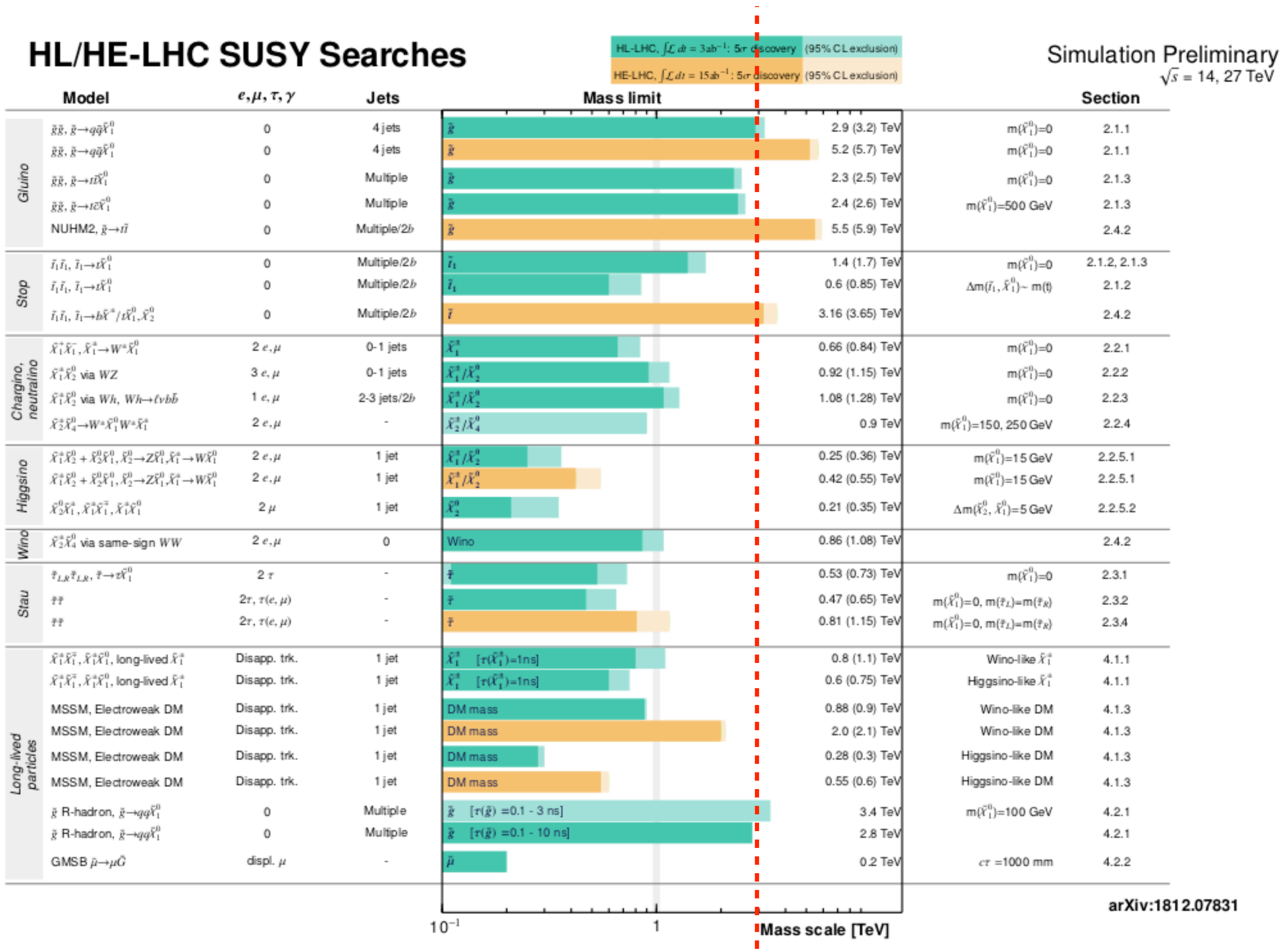


Very Large Number of SUSY Searches

(in large variety of topologies and models)



2 TeV



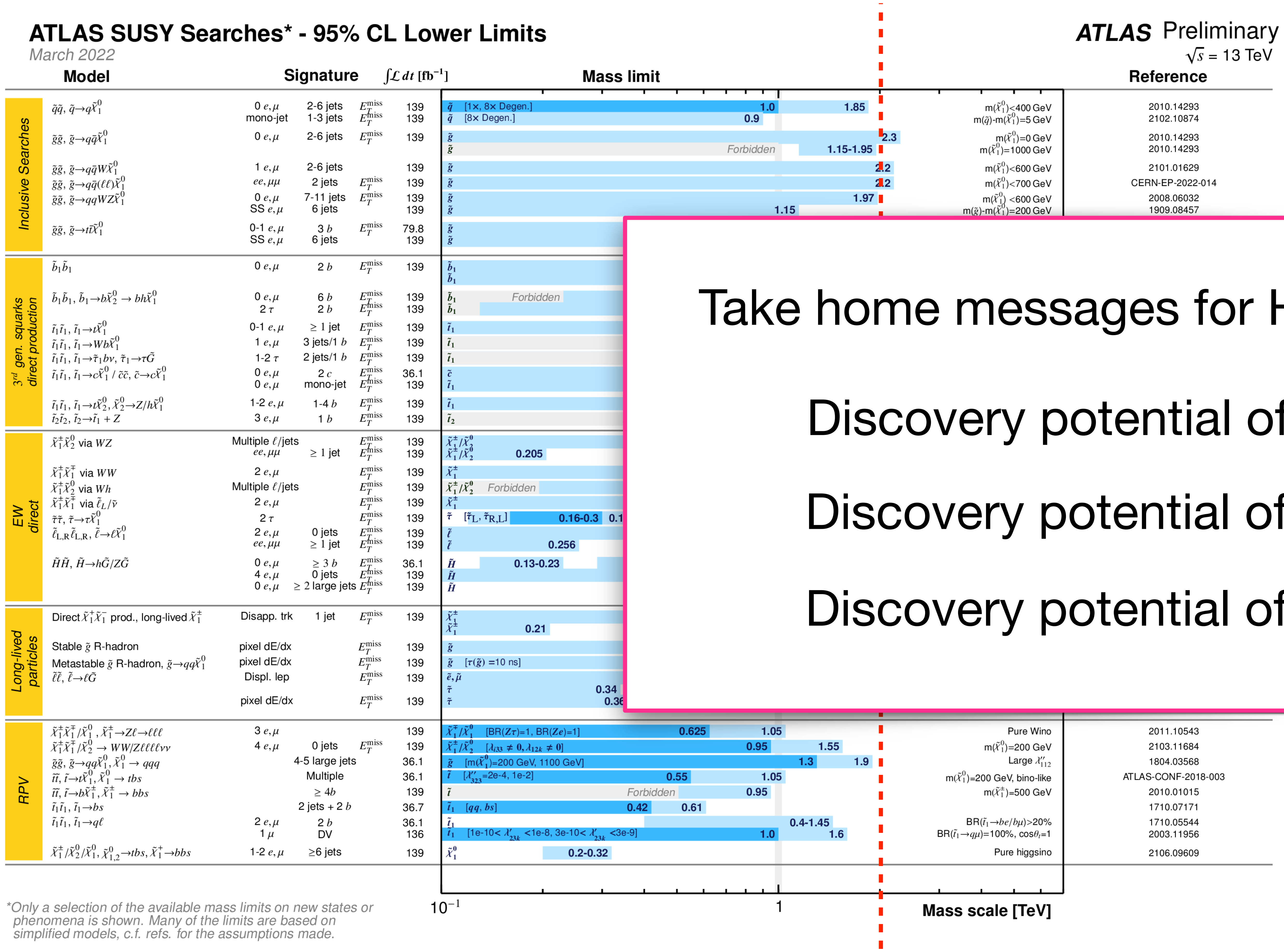
3 TeV

Example from ATLAS (**same for CMS**)

HL-LHC YR
1812.07831

Very Large Number of SUSY Searches

(in large variety of topologies and models)

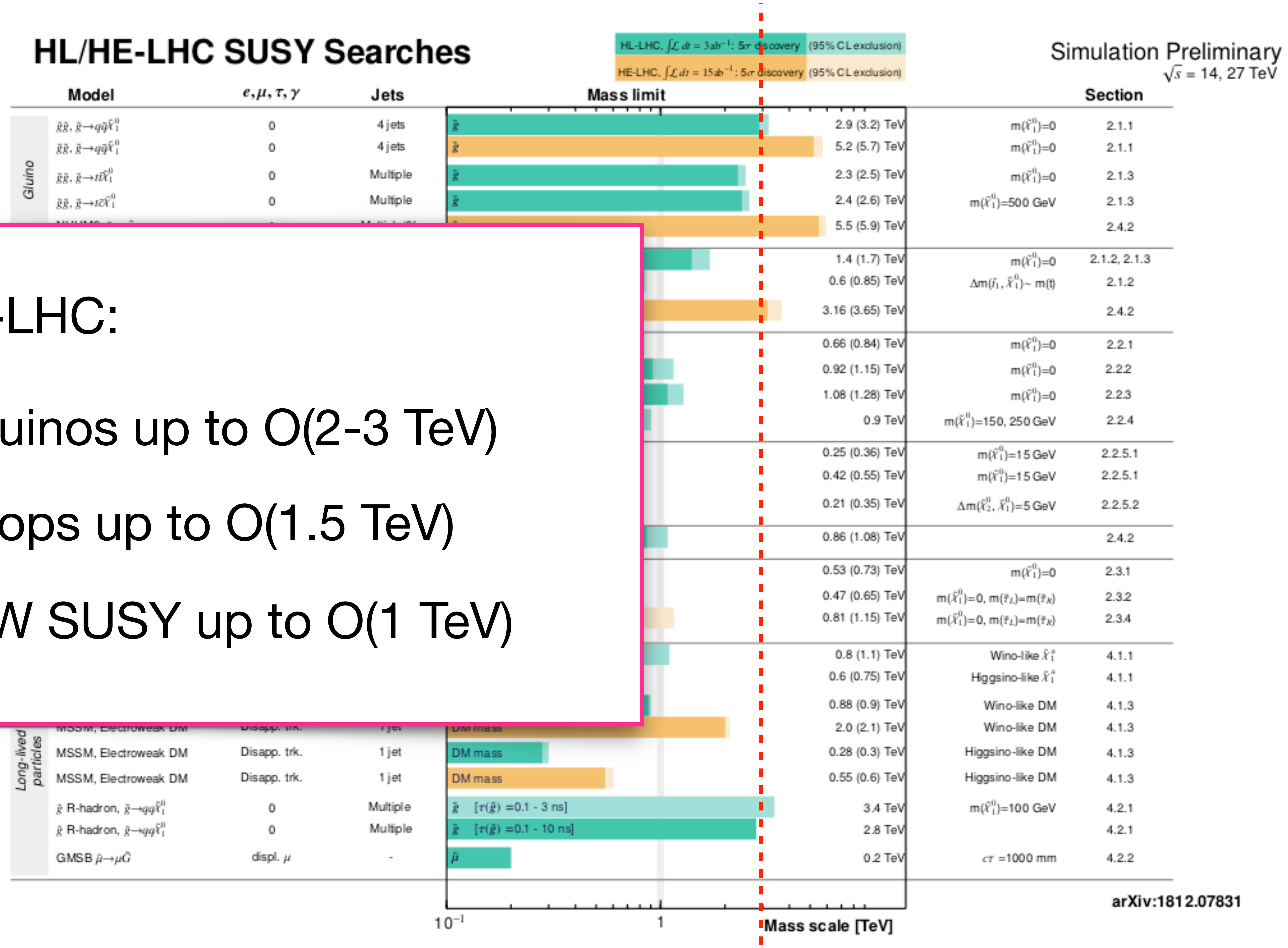


Take home messages for HL-LHC:

Discovery potential of gluinos up to O(2-3 TeV)

Discovery potential of stops up to O(1.5 TeV)

Discovery potential of EW SUSY up to O(1 TeV)



2 TeV

3 TeV

Example from ATLAS (**same for CMS**)

HL-LHC YR 1812.07831

Broad searches for new Physics beyond the Standard Model

Panorama of Searches for Conventional Signatures

Searches for Vector Like Fermions

Simple additional chiral fermions are essentially ruled out by Higgs data.

Fermions that are not Chiral

- The L and R components transform the same way under SM symmetries.
- Interact with SM through mixing with SM quarks.
- Present in models where the Higgs is a pseudo Goldstone boson (e.g. in Composite Higgs and little Higgs models).
- Present in Warped Extra dimension models.

Large variety of possible states and complex channels

- Heavy quark partners with charges -1/3, 2/3, 4/3 and 5/3.
- Complex channels looking for T(2/3), B(1/3): Ht+X, Wt+X, Wb+X, Zb+X, Zt+X (Performed at Run 2) so far and T(5/3) 4tops final state.

And still many more !!

Searches for W'and Z'

High mass states motivated in many theories e.g. Grand Unified and additional gauge symmetries.

- electrons, muons, taus, jets, b-jets and tops.
- di-bosons including vector bosons and Higgs bosons

Searches for high mass states of spin 0 and 2

Motivated in Randall Sundrum models (Graviton and radion)

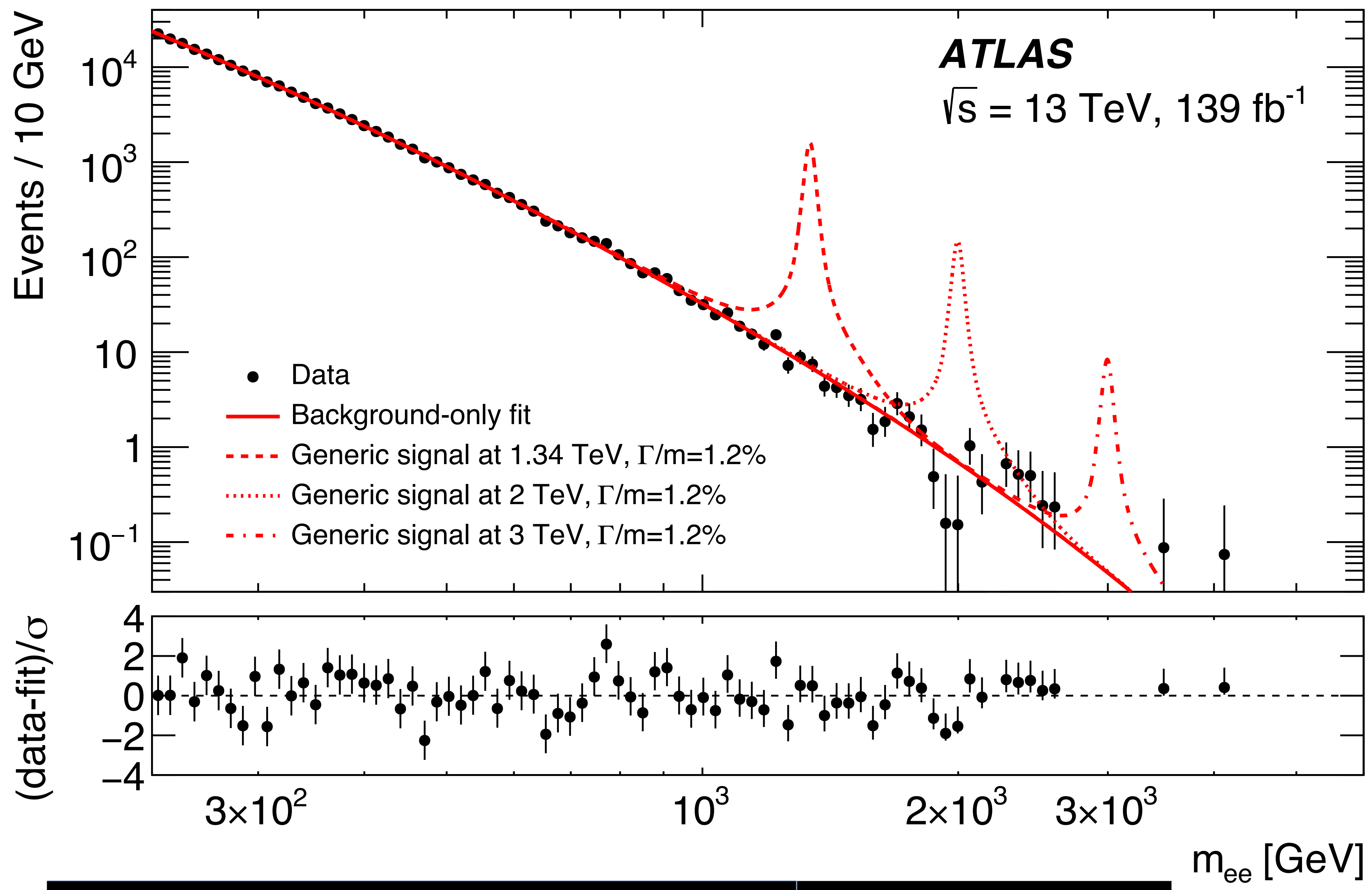
Searches in various channels dijet, diphoton and di-leptons

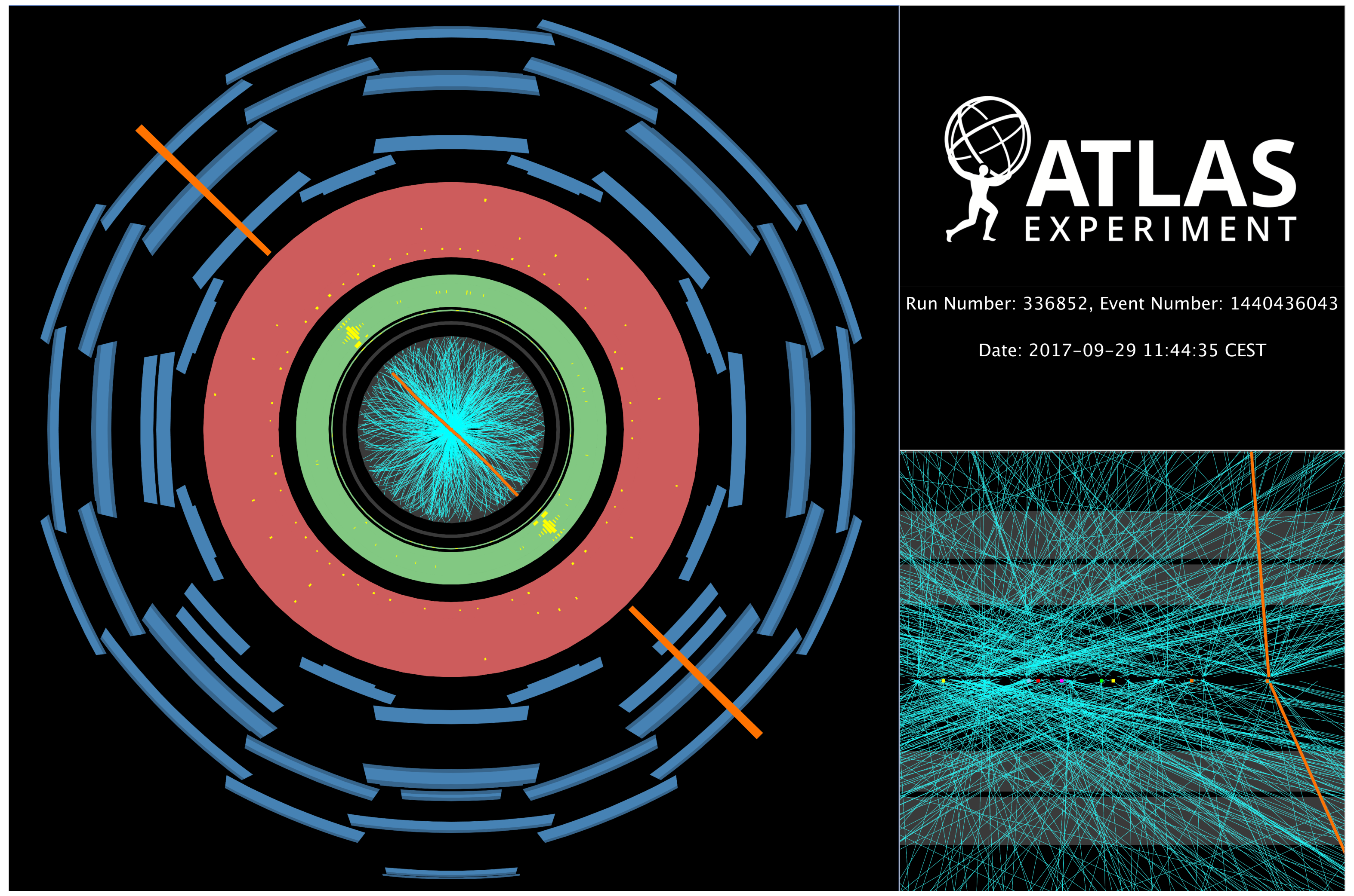
Any many more

- **Quark compositness**
- **Leptoquarks**: predicted in grand unified theories and interest raised by lepton flavor universality anomalies
- **Heavy neutrinos**: produced in theories for neutrino masses (e.g. Seesaw)
- **High mass and high activity events**: strong gravity (from extra dimension theories), mini black holes, quantum black holes…
- **Searches for low mass states.**

Searches for High Mass Resonances

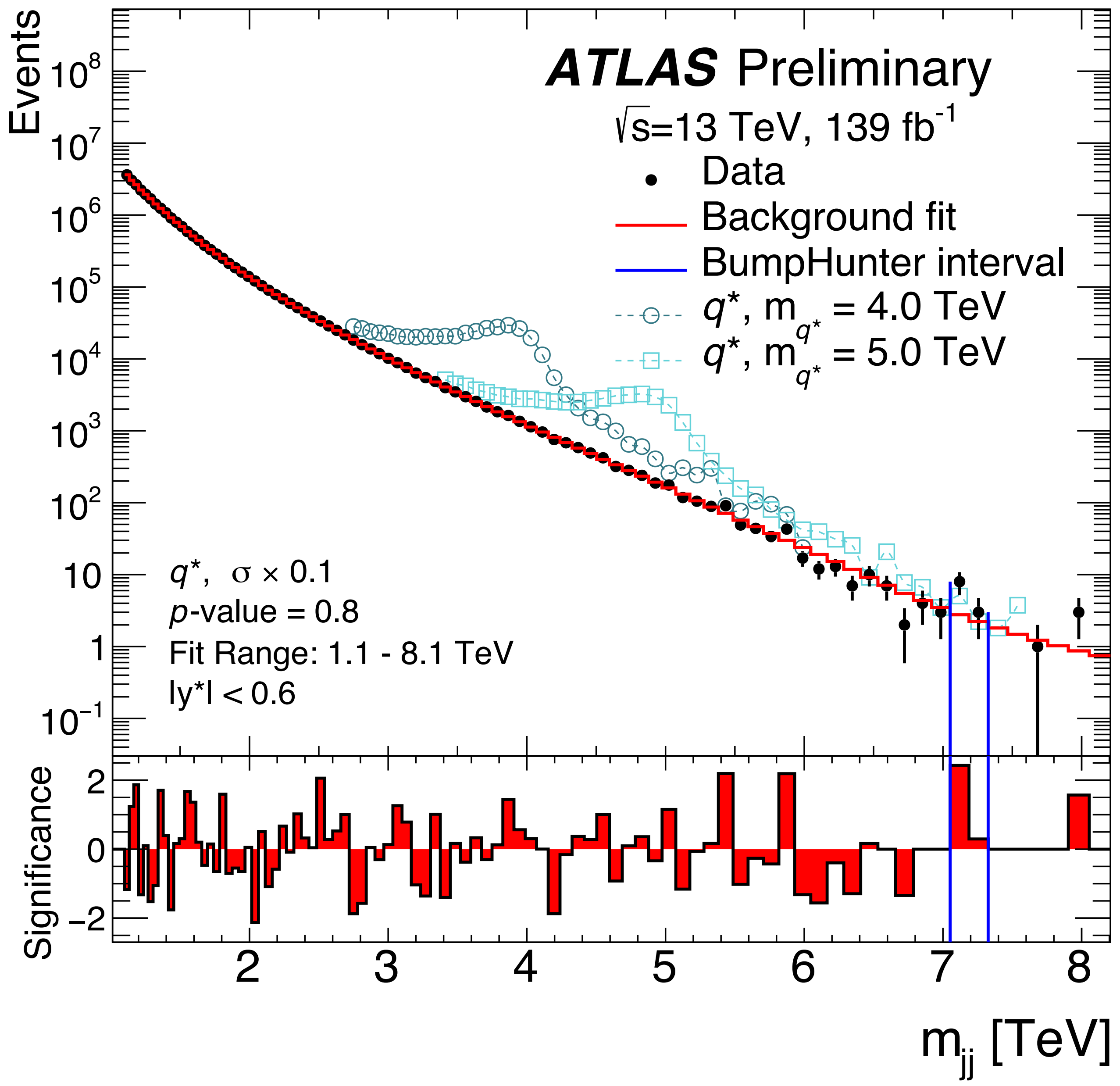
ATLAS Dilepton search ATLAS 1903.06248





Exclusions up to ~5 TeV

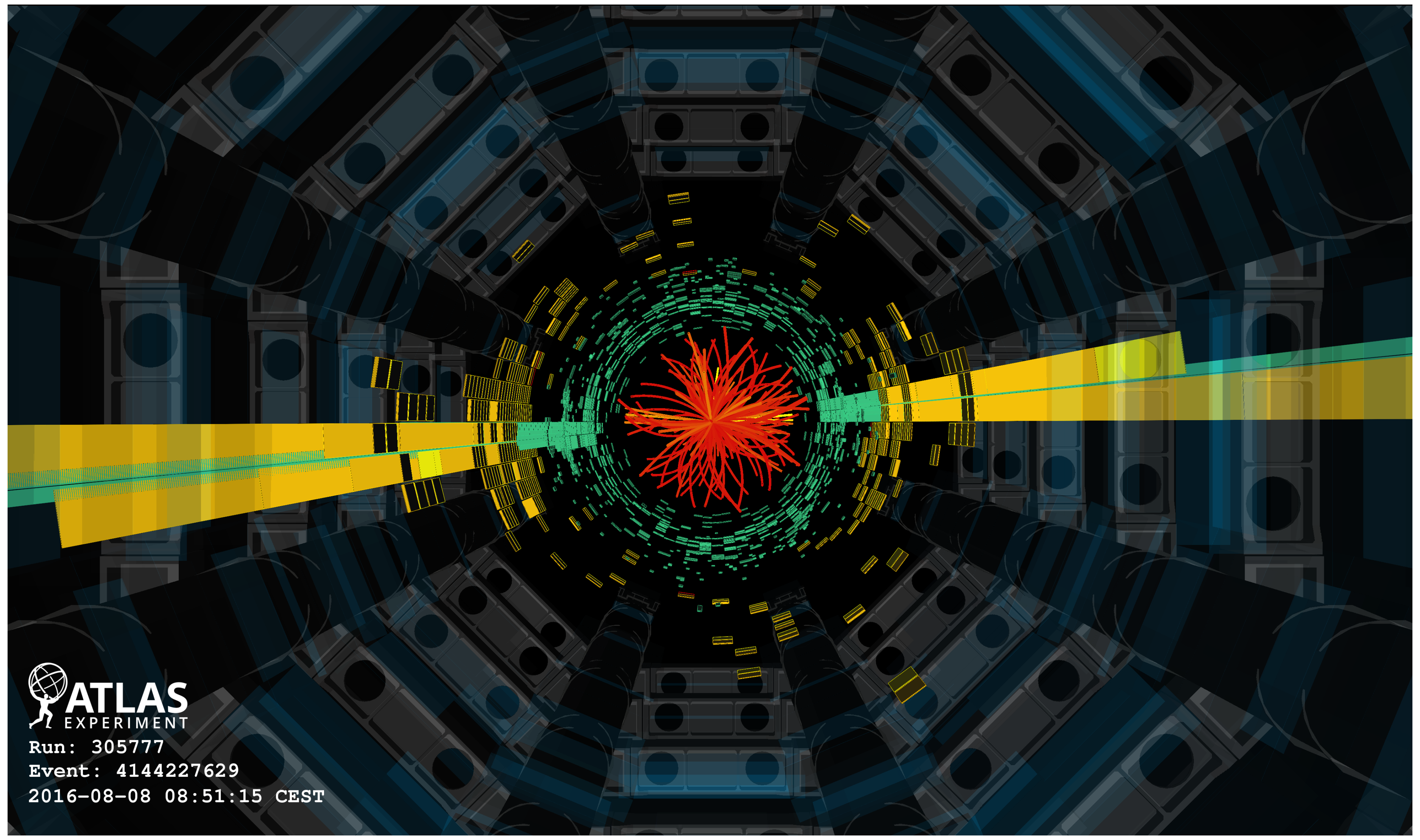
Highest mass di-electron event ~4 TeV



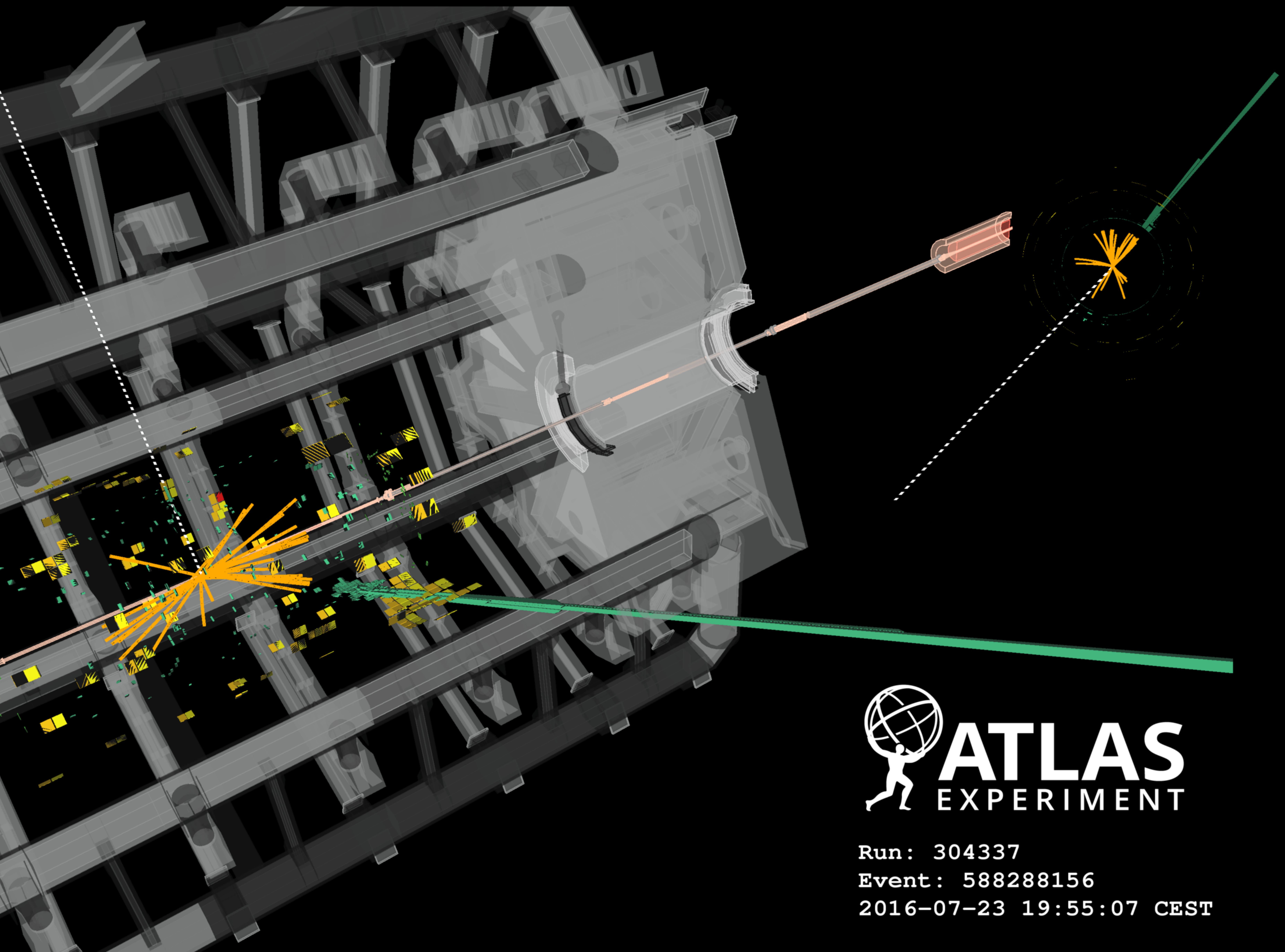
ATLAS Dijet search

ATLAS-CONF-2019-007

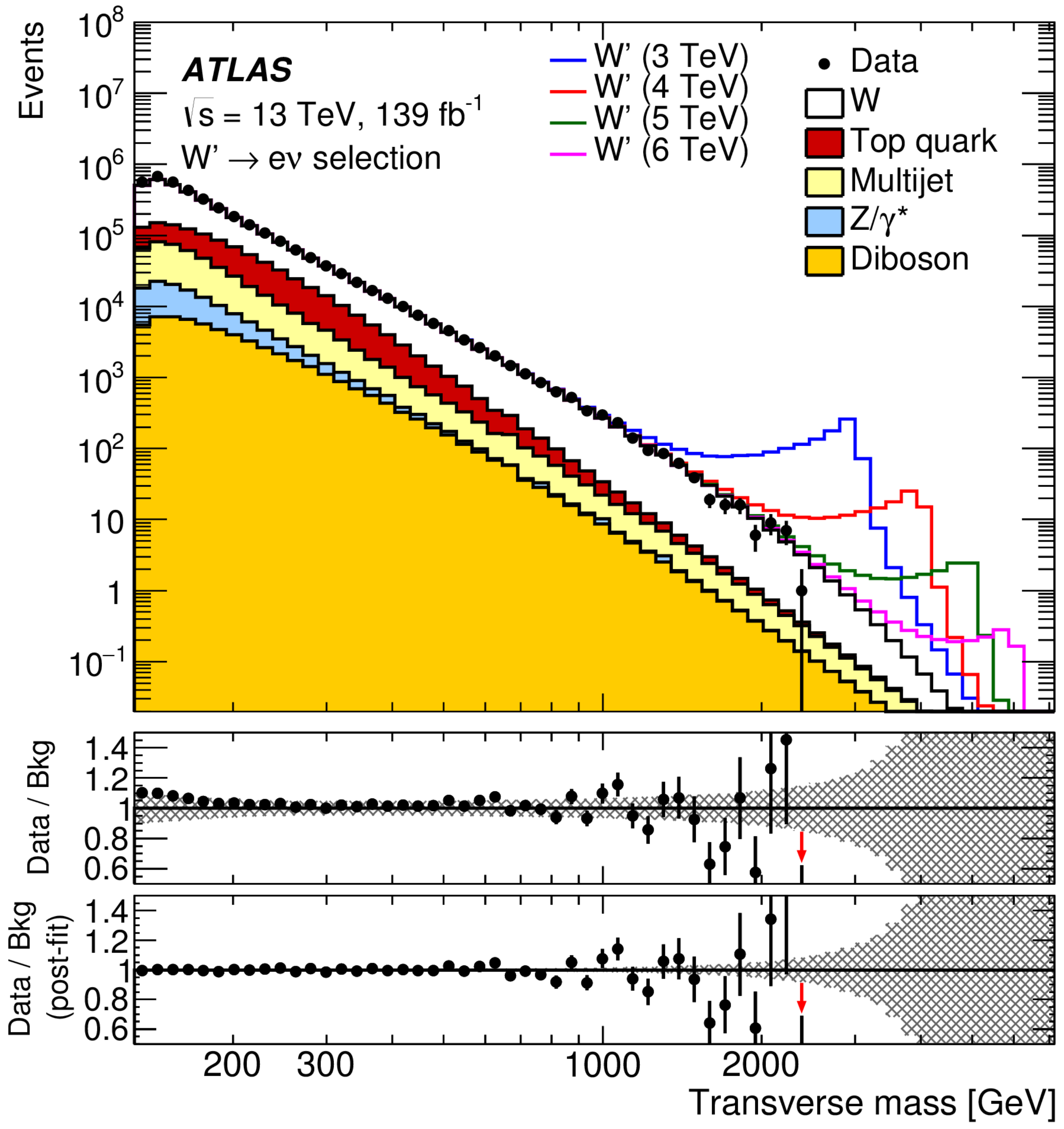
Limits on excited quarks at 6.7 TeV



Highest mass (central) dijet event ~8 TeV



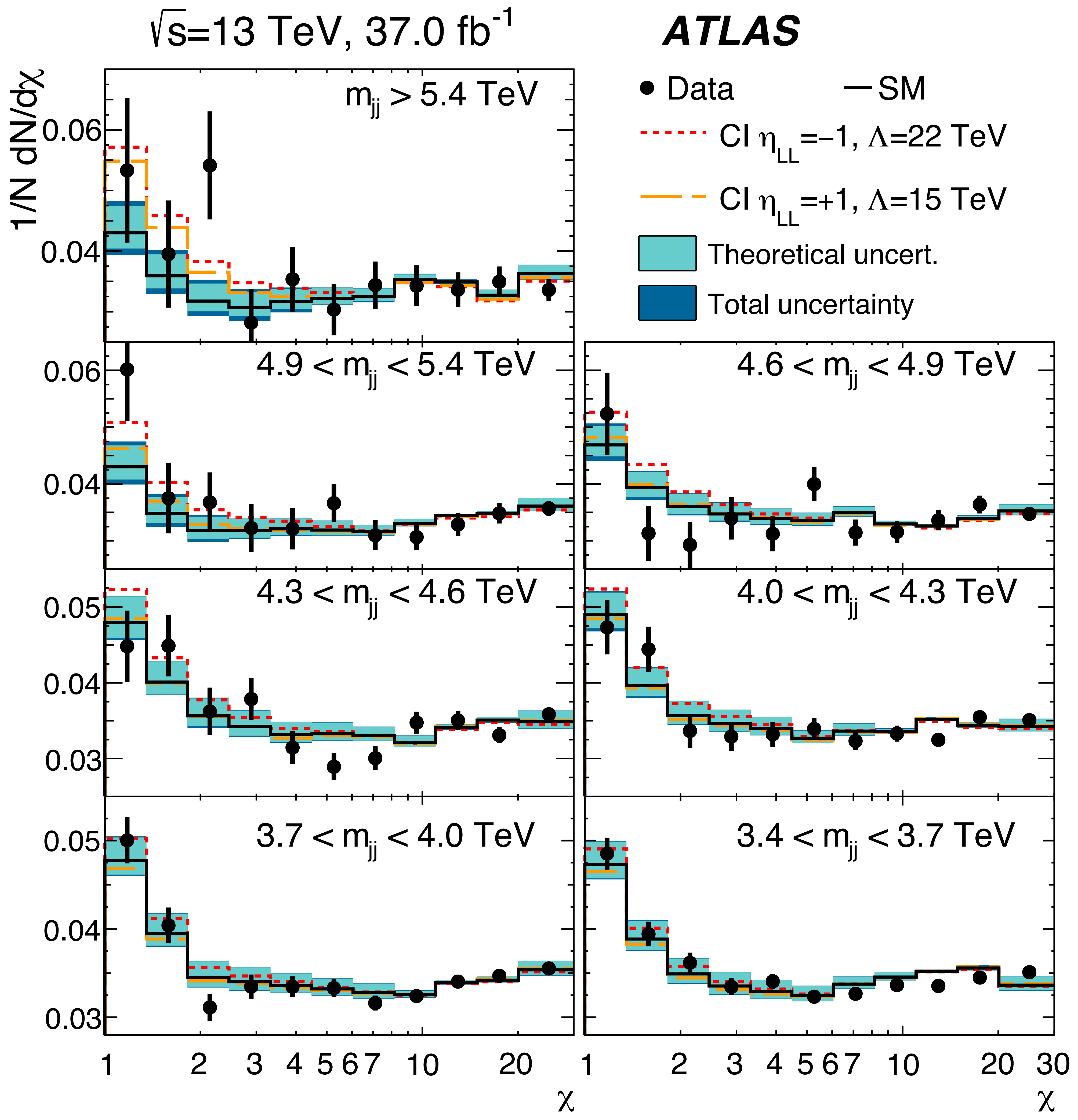
Transverse mass (in lepton-MET search)



Drell Yan (and other processes) predictions and lepton calibration in the TeV energy range.

Electron pT = 1.1 TeV
MET = 1.16 TeV

More Searches…



Searches for non-resonant features at high mass

Any deviation in the measurements with a special attention to the high energy regime can be the manifestation of new higher energy domain new physics.

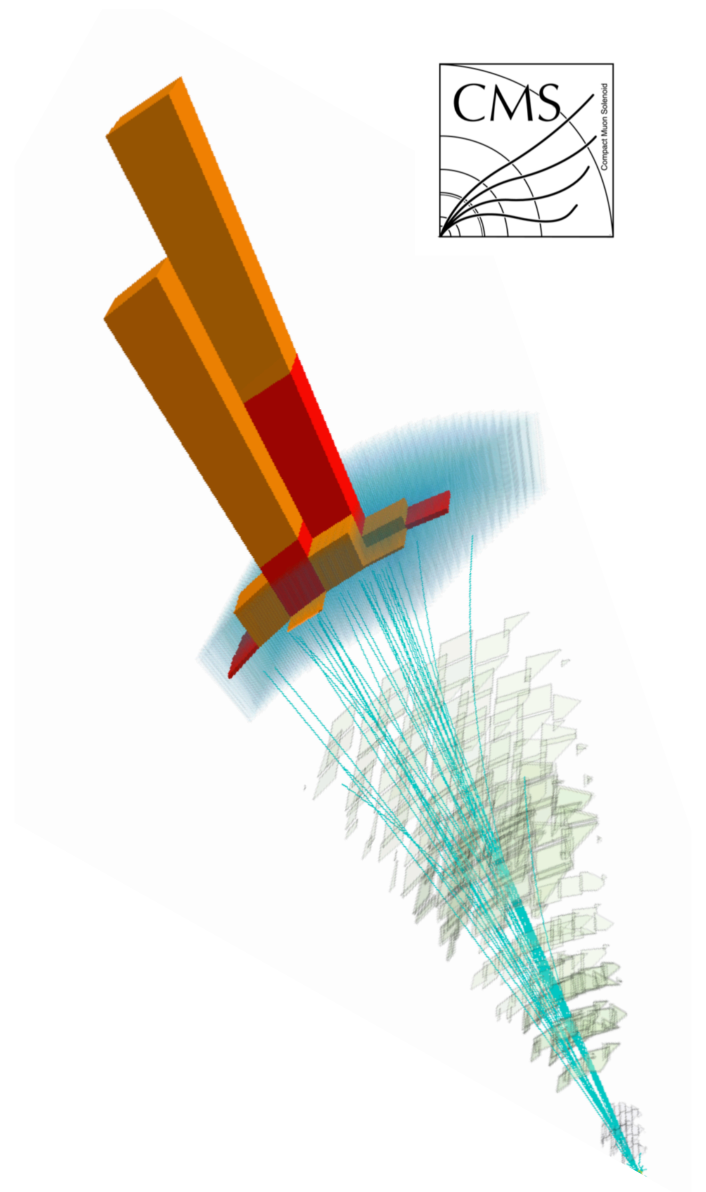
Key aspects: Jet cross sections predictions and jet calibration with multi TeV jets

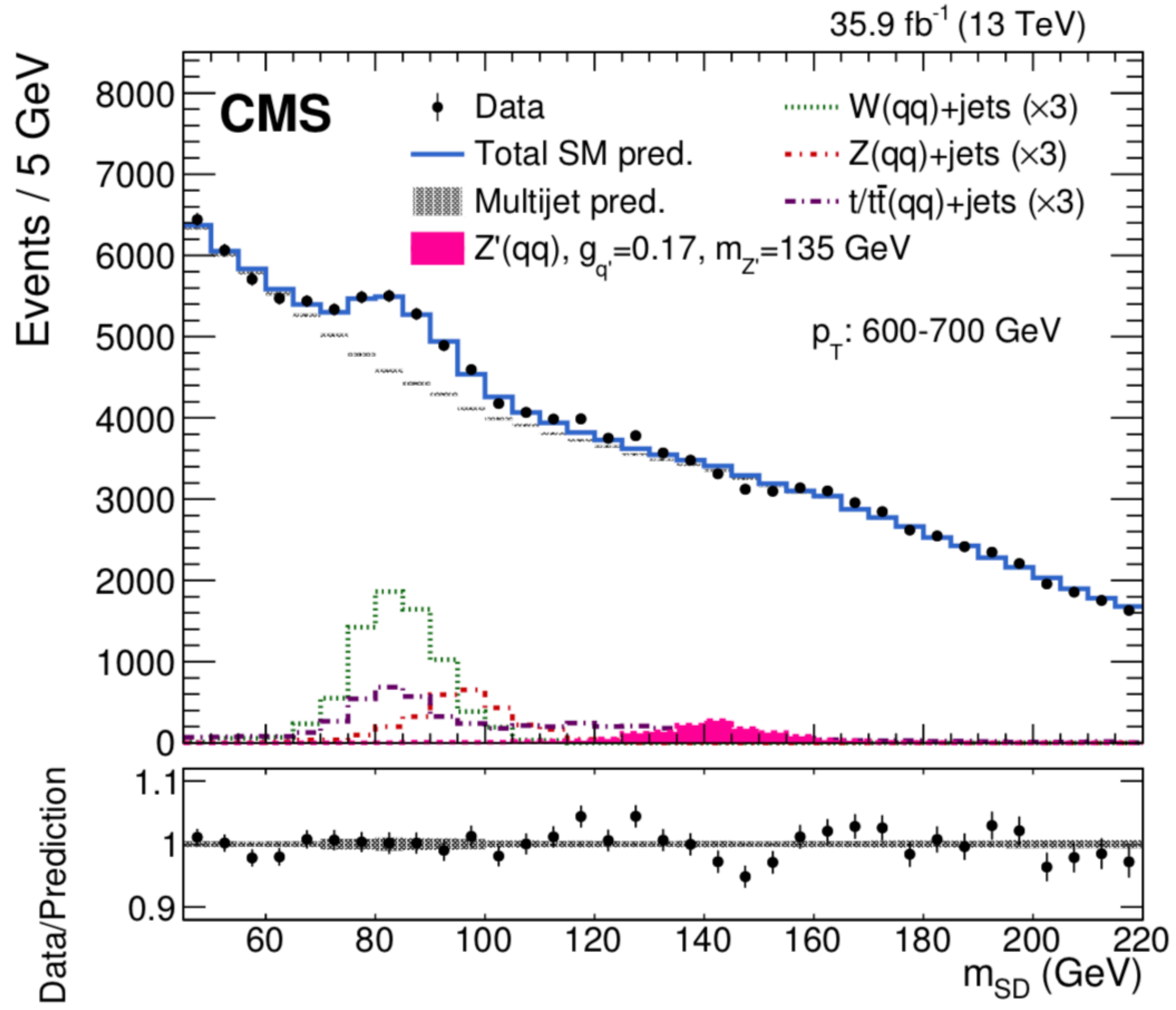
Angular distribution

$$\chi \equiv \exp(|y_1 - y_2|)$$

Improving Reconstruction Techniques

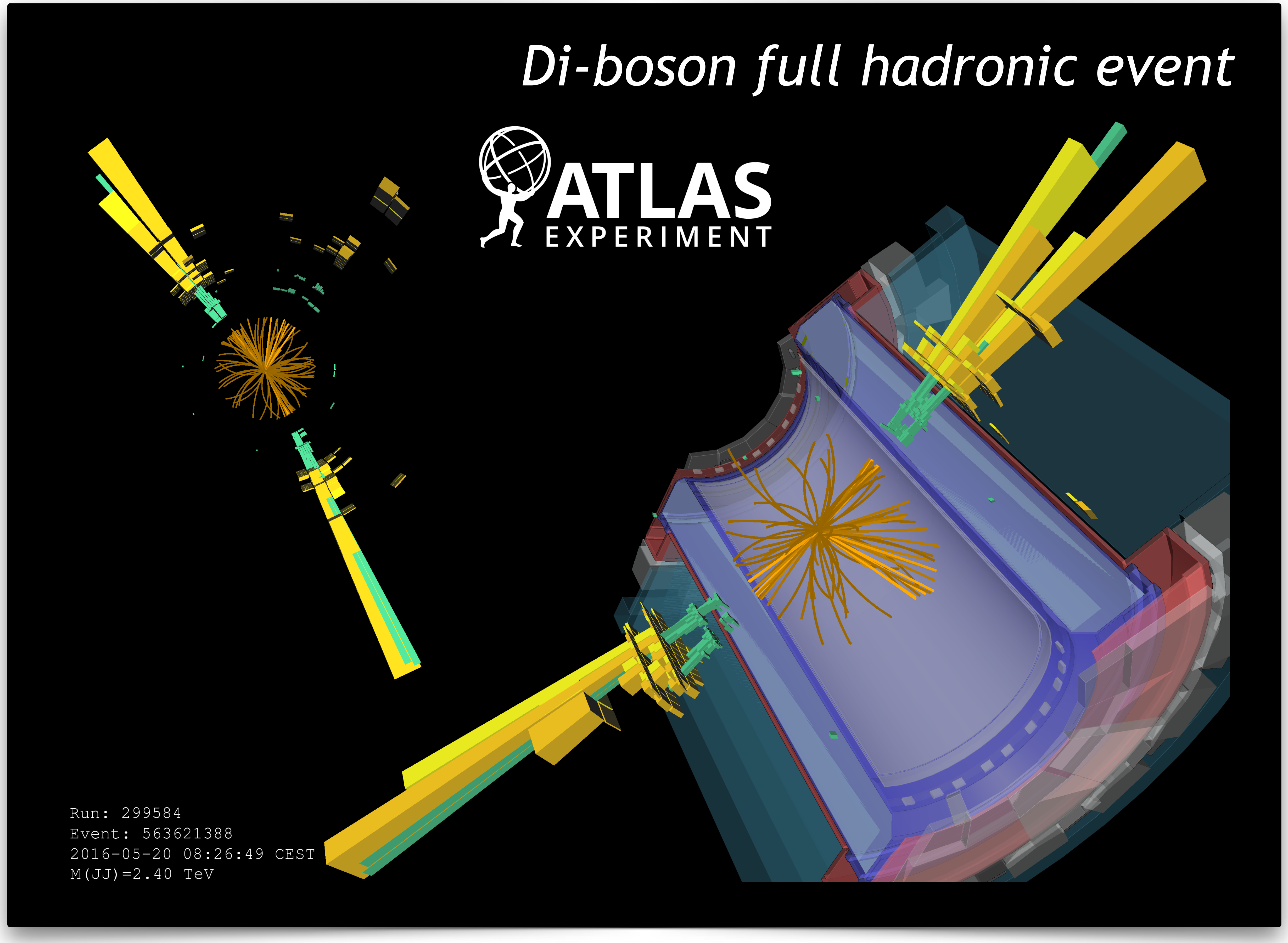
Jet substructure reconstruction improvements reconstructing a vector boson, a Higgs boson or a top quark.





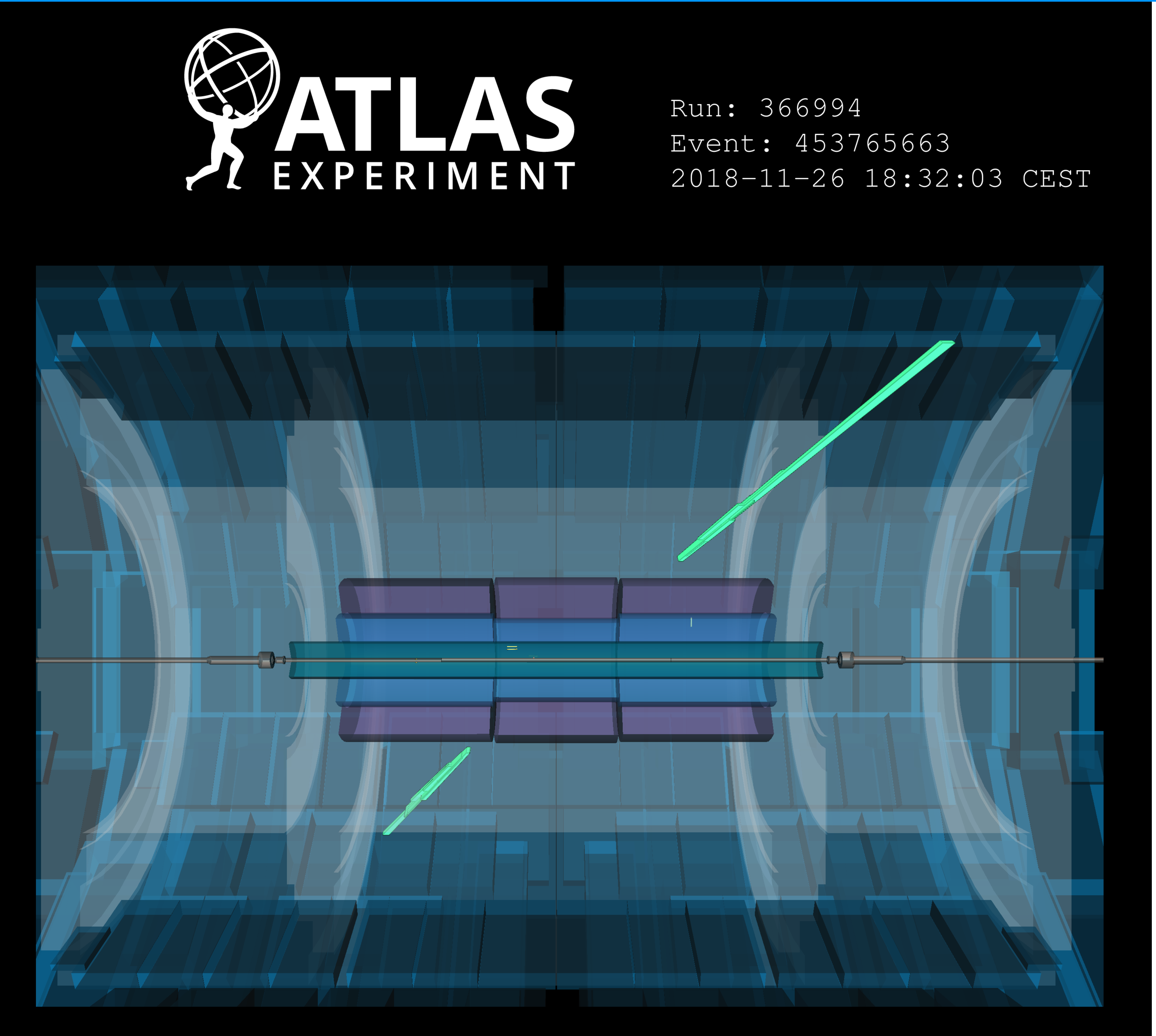
Search for intermediate mass resonance as a single jet investigating its substructure.

Searches for diboson in two boosted jets signatures

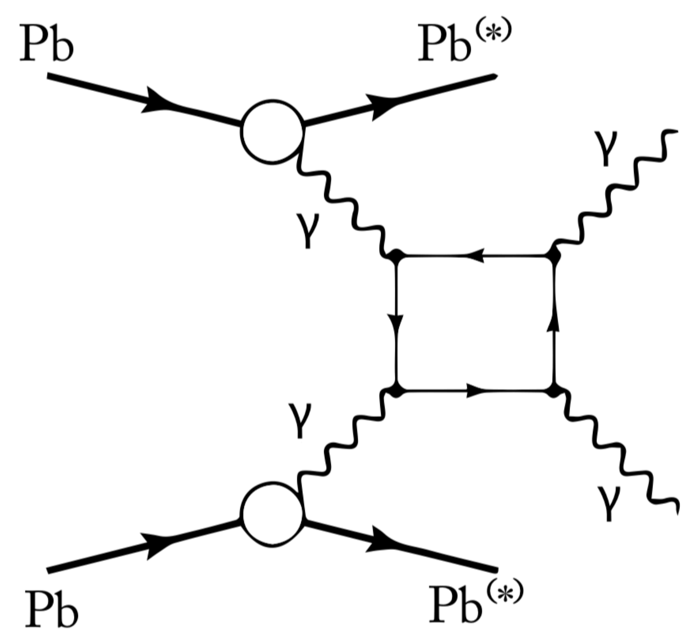


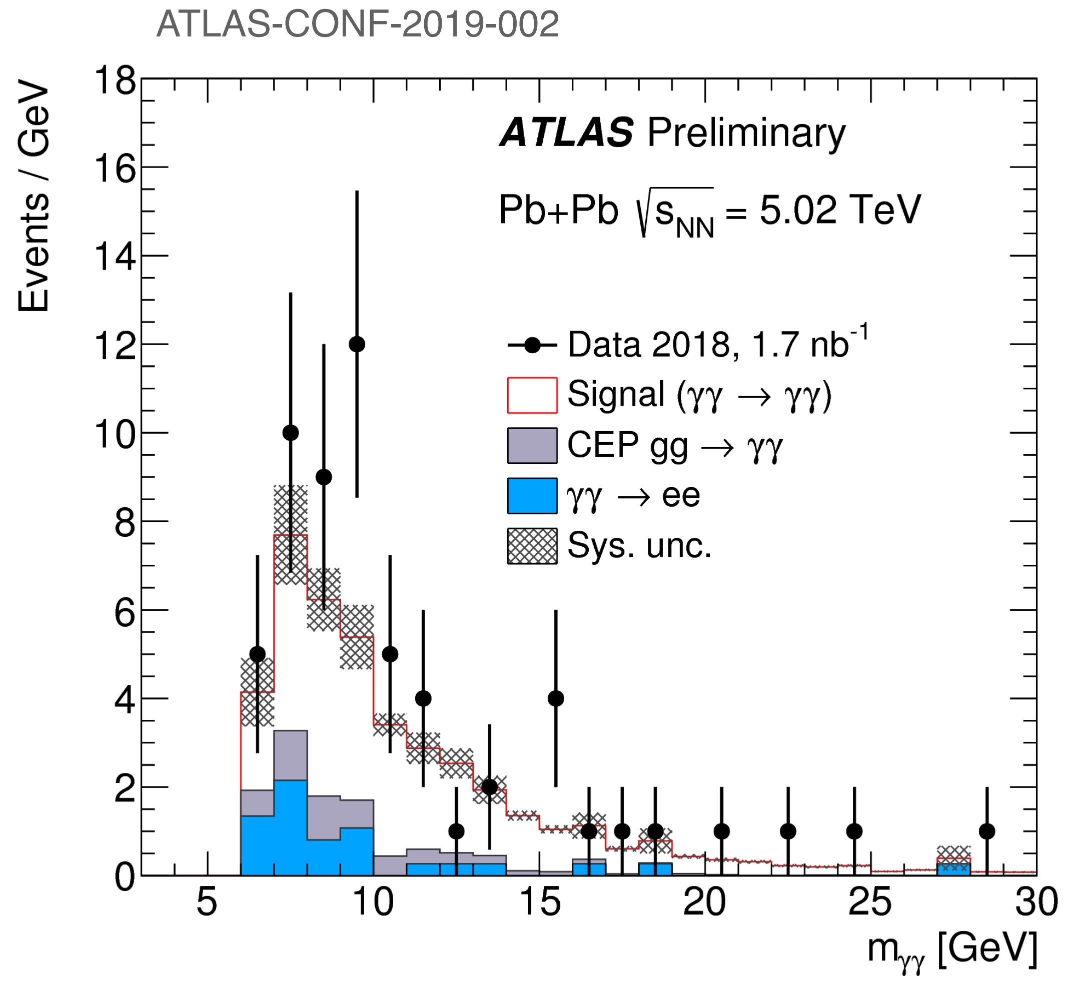
Di boson candidate event in a fully hadronic search, each jet has a mass compatible with a vector boson (W or Z).

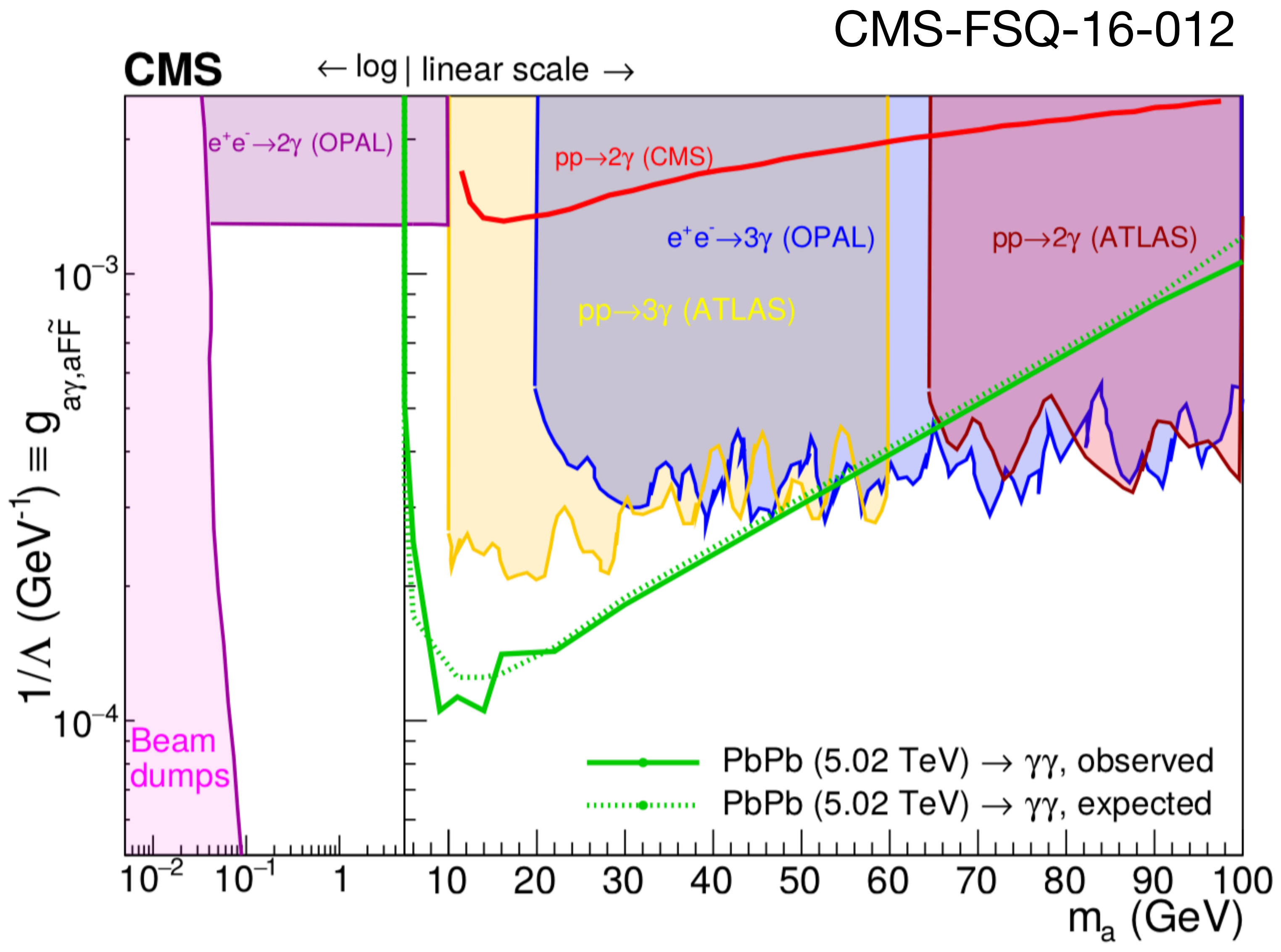
A Spectacular Heavy Ion Event



Observation of **Light-by-light scattering** (Central Exclusive Production)





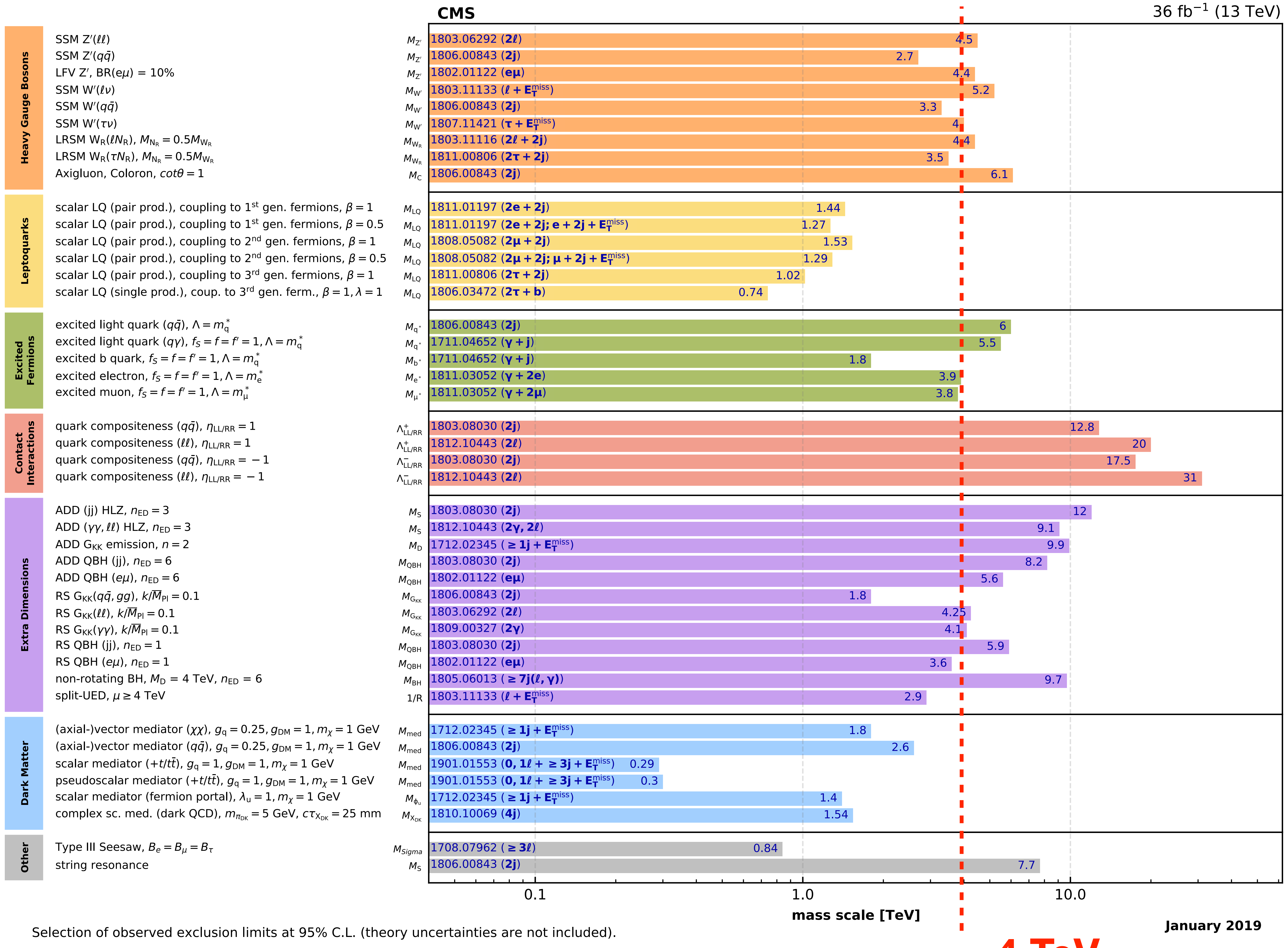


Constraints on ALP (Axion Like Particles) assuming sole coupling to photons.

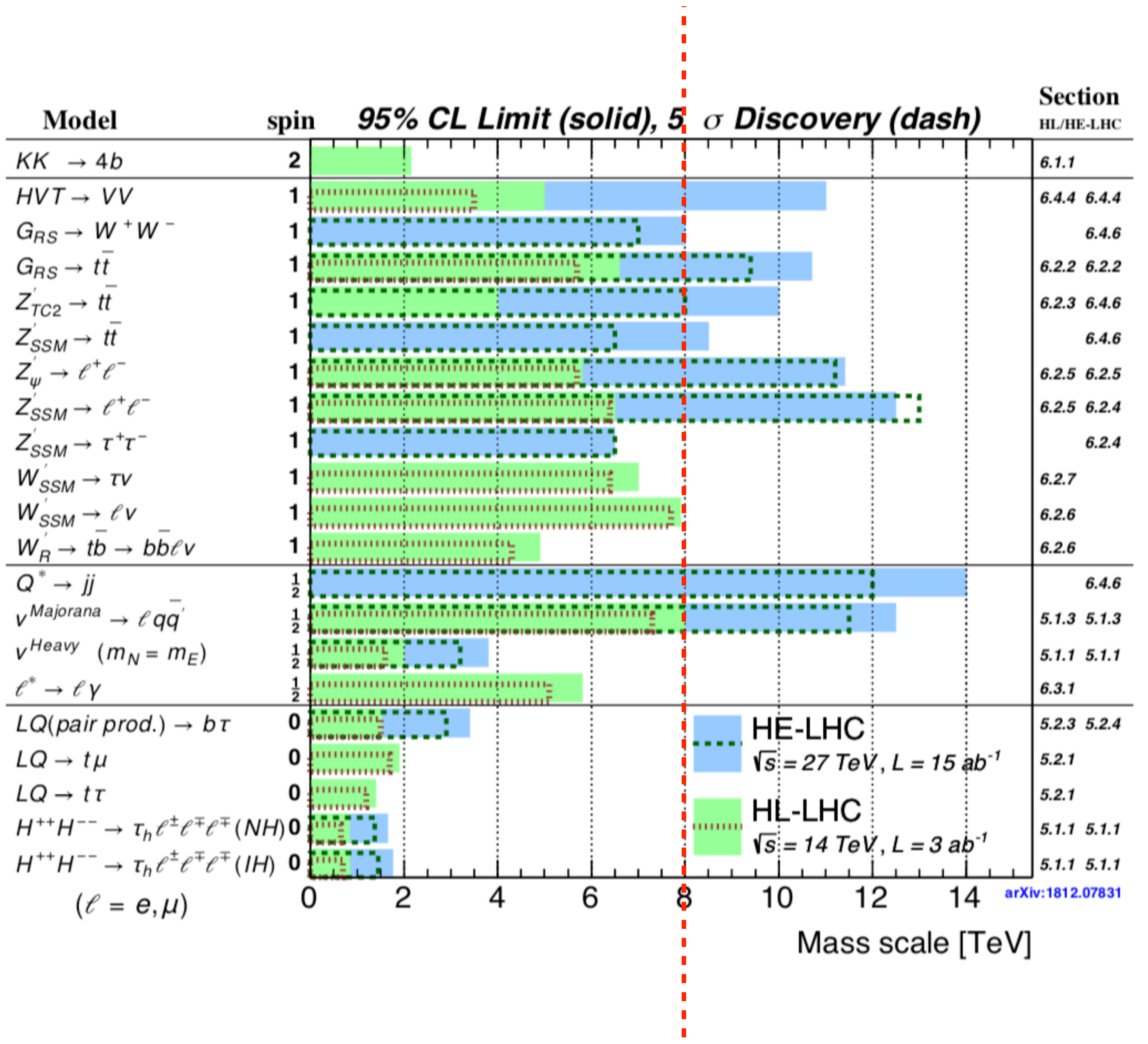
Very Large Number of Searches

(in large variety of topologies and models)

Overview of CMS EXO results



4 TeV



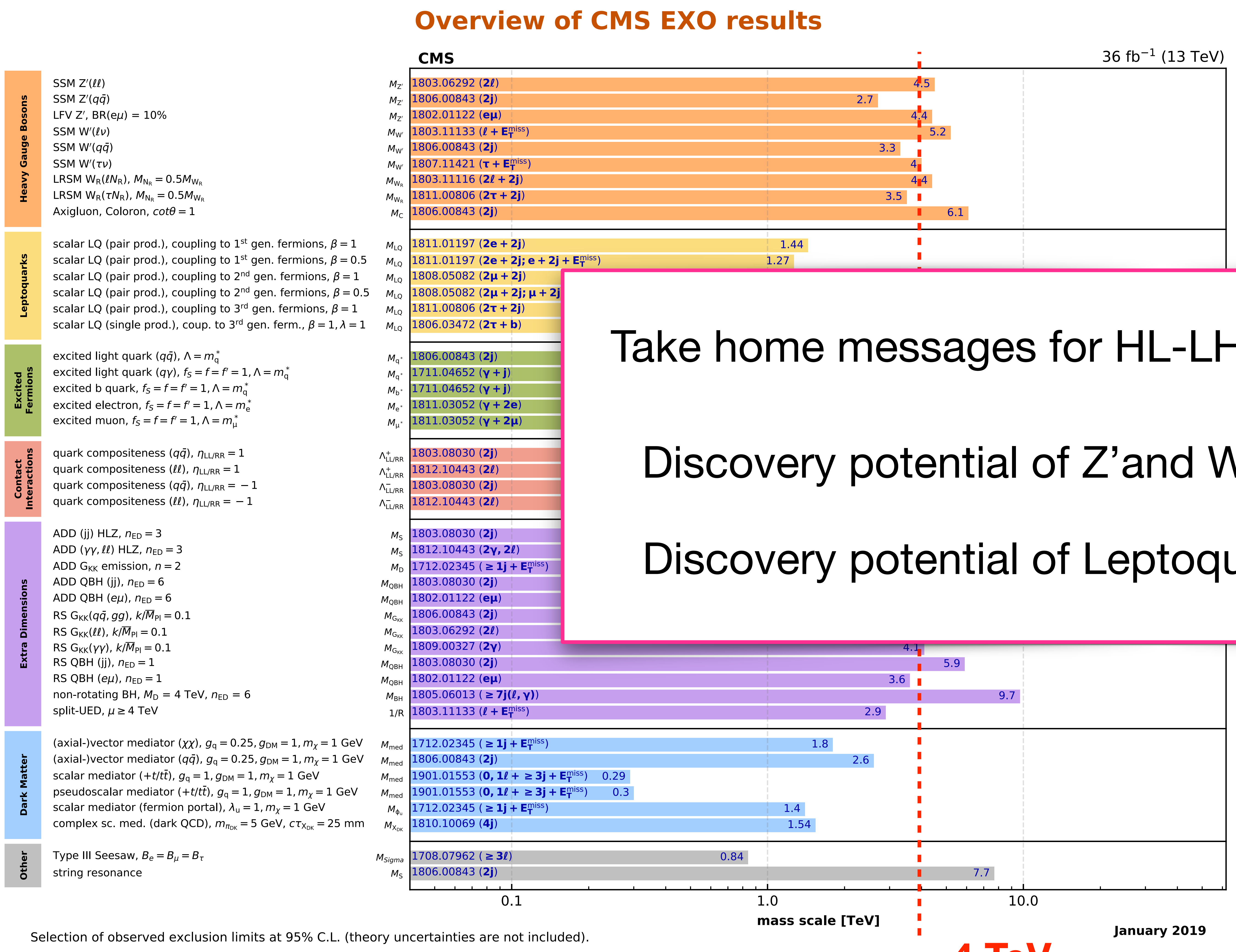
8 TeV

HL-LHC YR
1812.07831

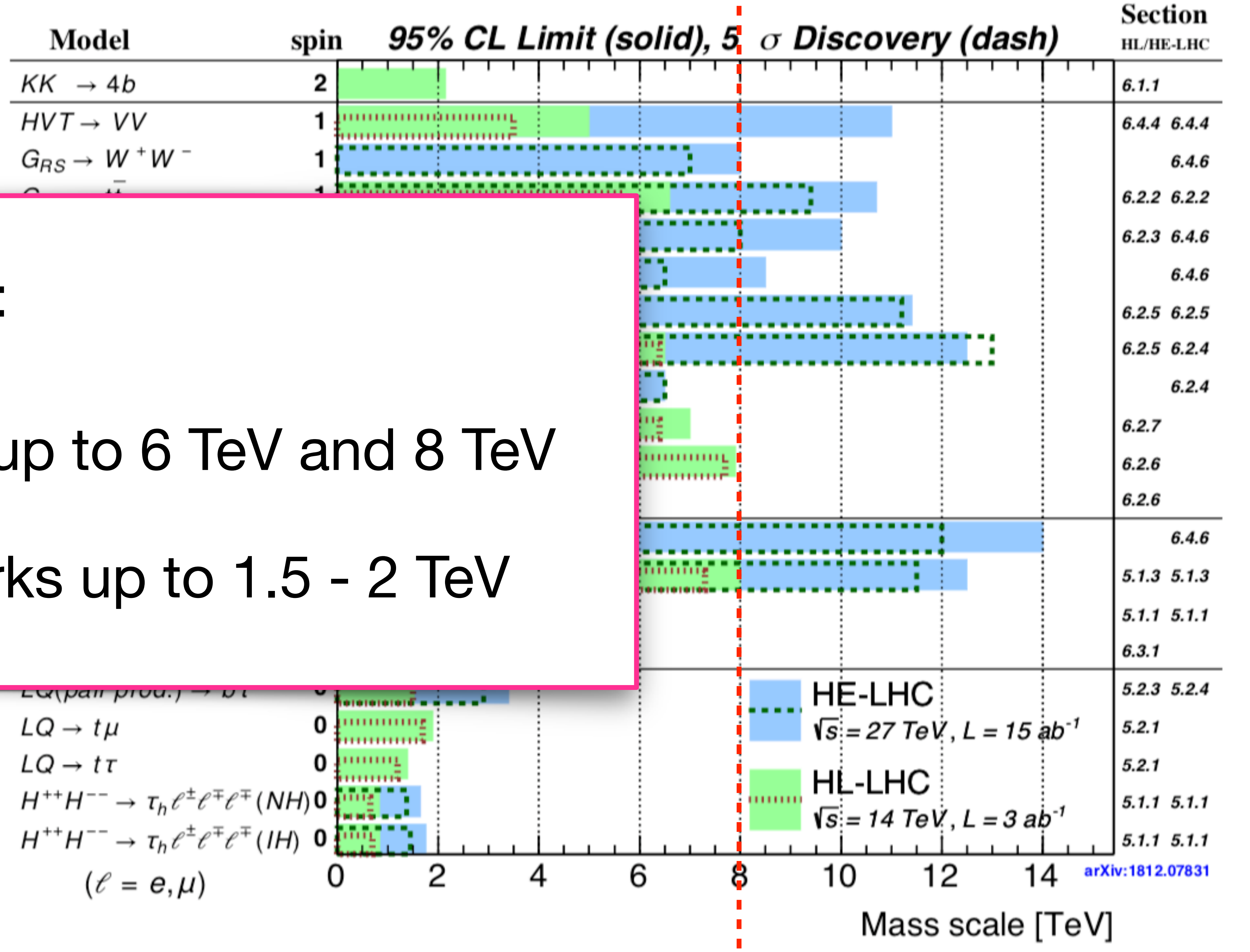
Example from CMS (similar for ATLAS) - latest plot in the backup!

Very Large Number of Searches

(in large variety of topologies and models)



4 TeV



8 TeV

Take home messages for HL-LHC:

Discovery potential of Z’and W’ up to 6 TeV and 8 TeV

Discovery potential of Leptoquarks up to 1.5 - 2 TeV

Example from CMS (similar for ATLAS)

HL-LHC YR 1812.07831

Unconventional Signatures

Many extensions of the Standard Model predict new particles that are long lived heavy (neutral and charged) and can decay after several cm or even meters.

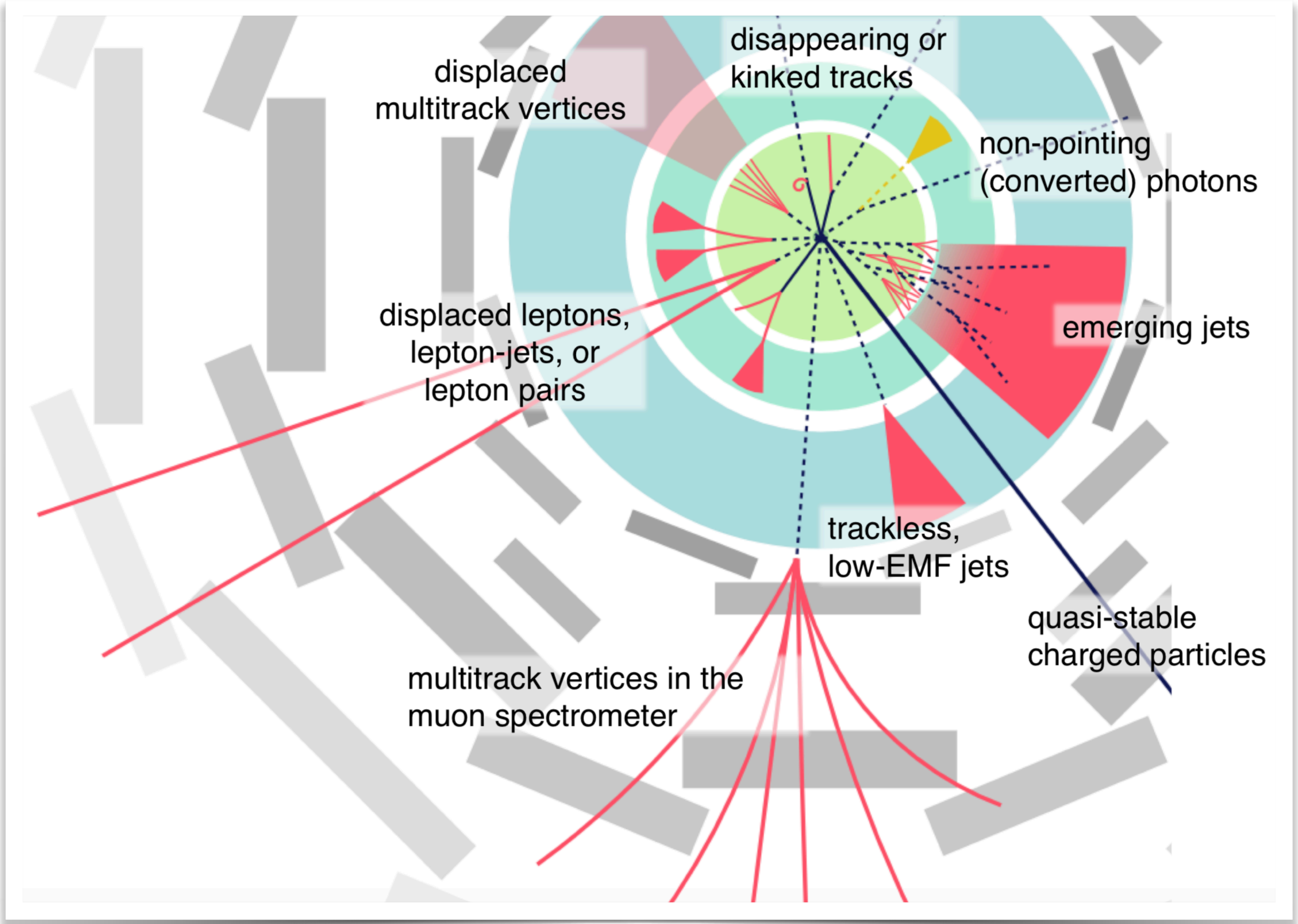
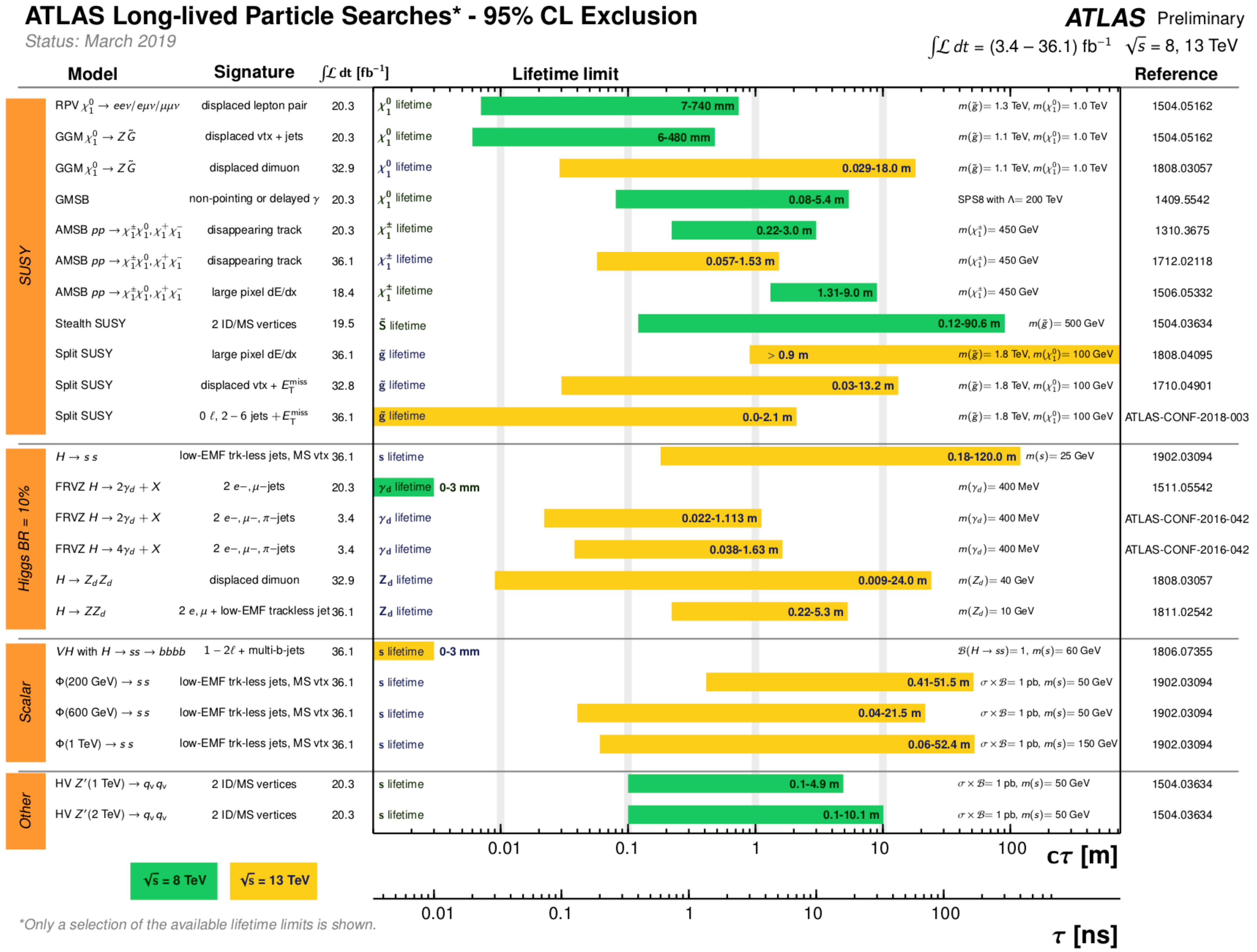


Image from H. Russel



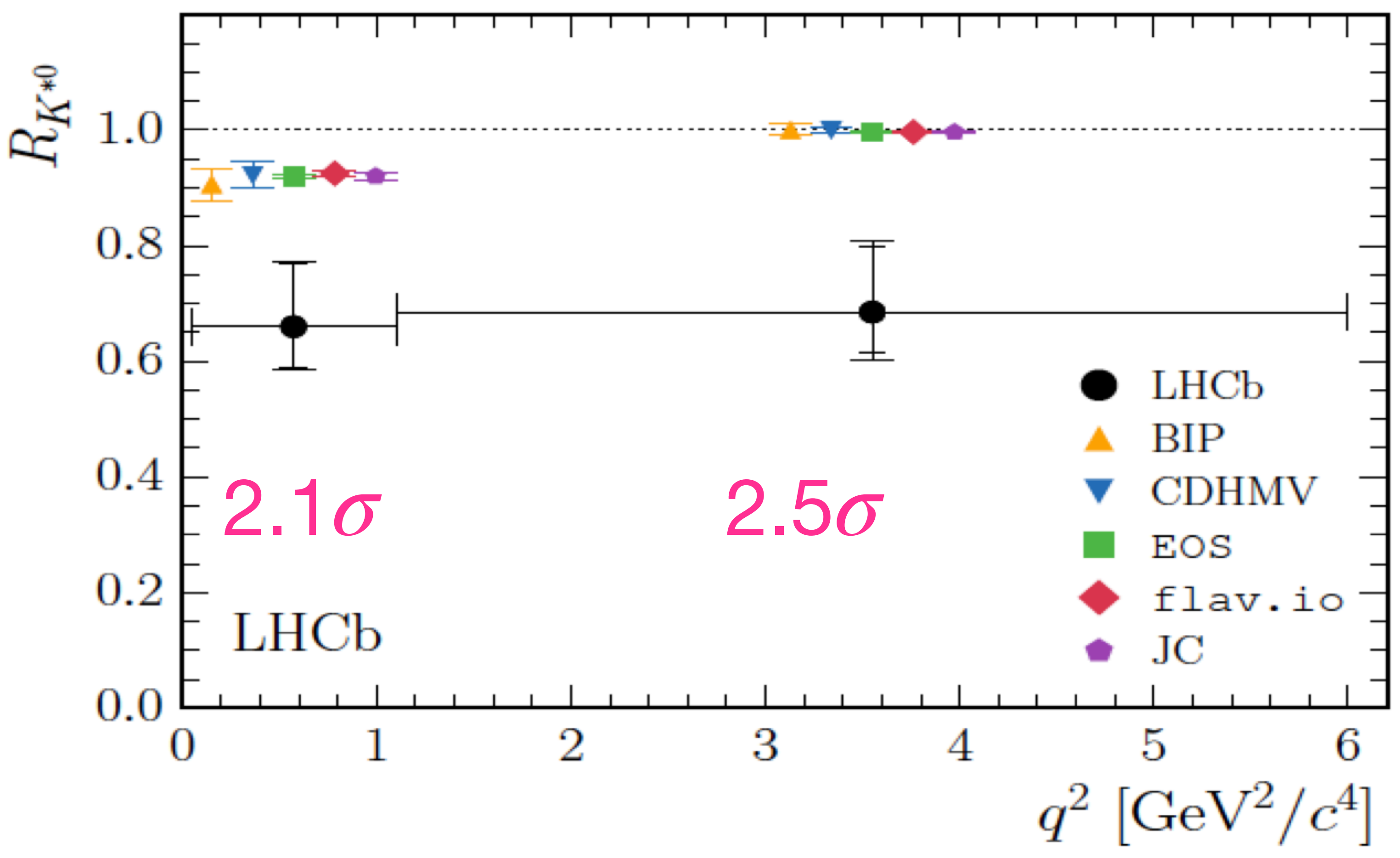
Sample for ATLAS (same for CMS)

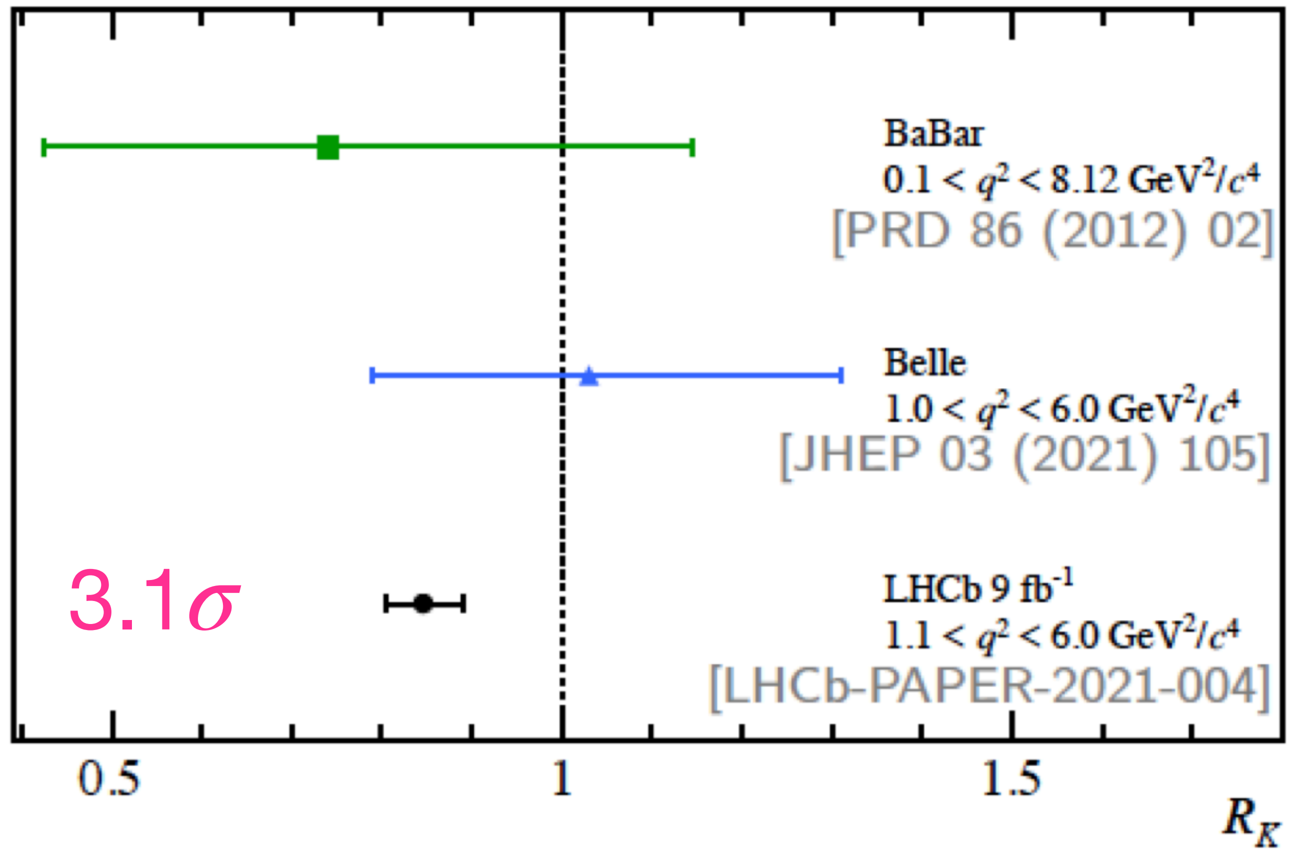
Difficult signatures requiring specific complex reconstruction and trigger!

Following Up on Anomalies

LFU Anomalies in B decays

Part of the ''Footprints''* of rare B decays anomalies



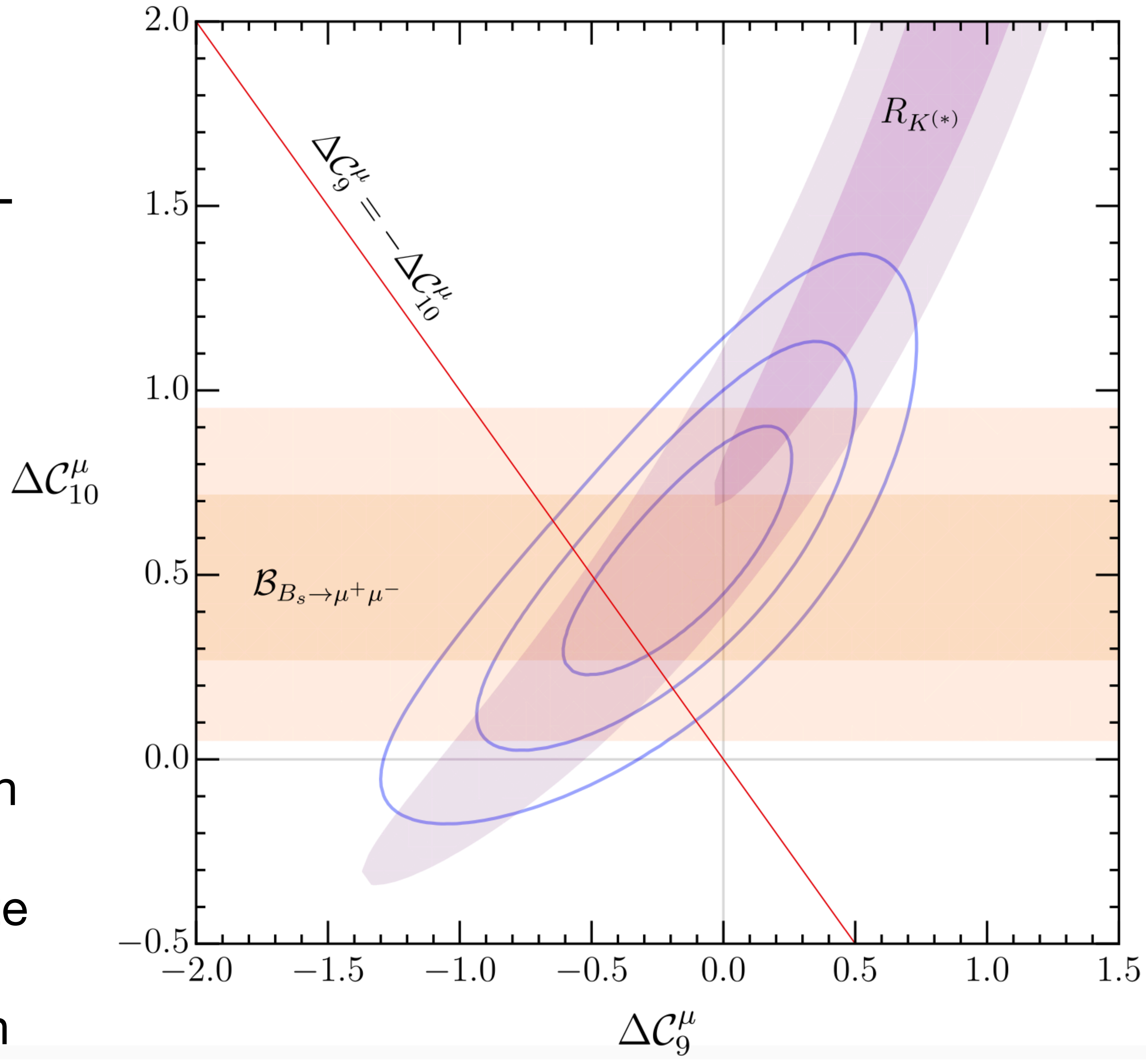


Combining through SM-EFT Dim.-6 FCNC operators:

$$\mathcal{O}_{10}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_{9}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

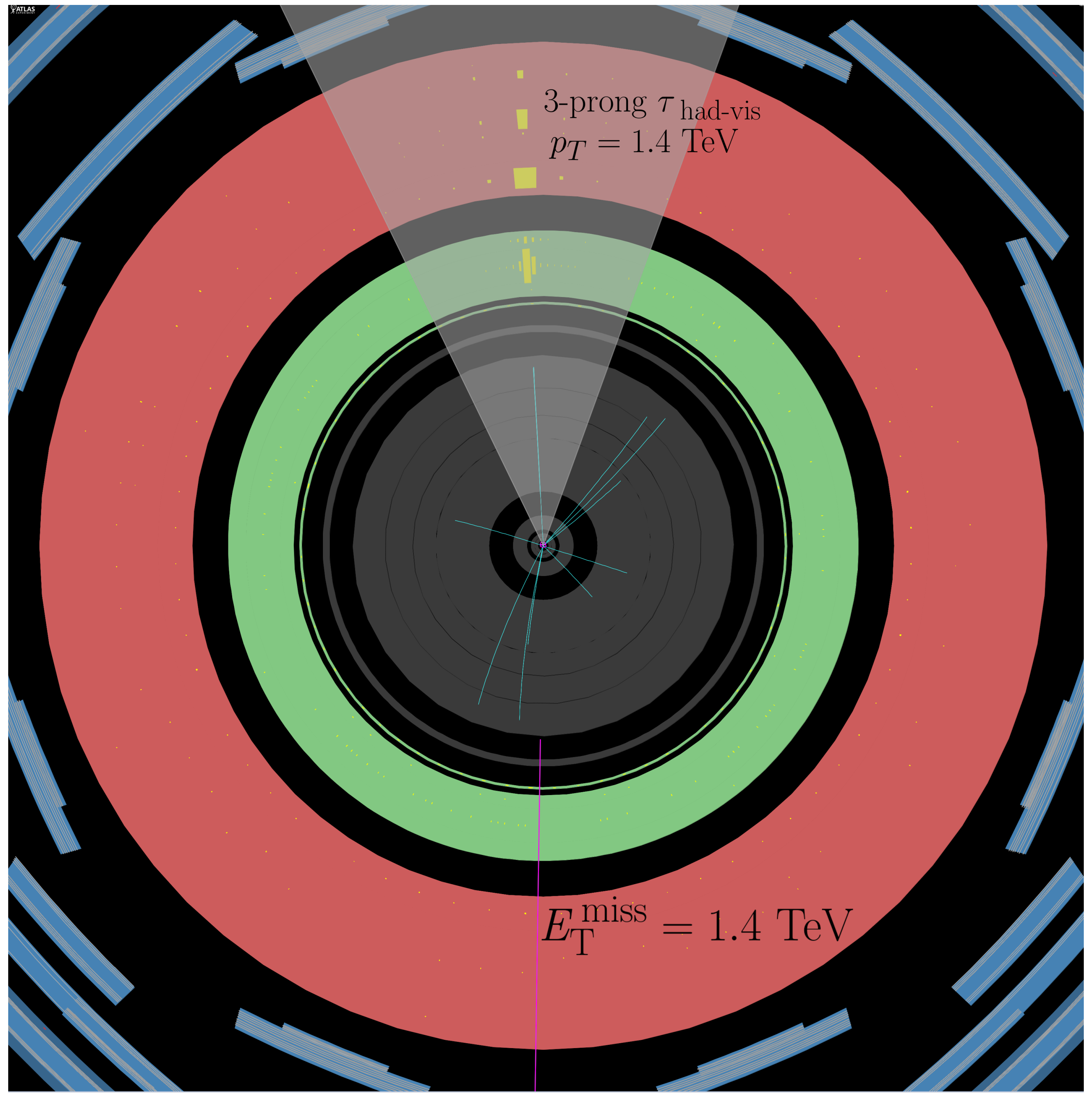
These anomalies could be a sign of **non trivial flavour dynamics at the TeV scale** further motivate direct searches of **leptoquarks** (both scalar and vector) and non universal **heavy vector boson**.

*C. Cornella et al. 2021



Combined with the RK* anomaly leads to a **4.6σ** tension

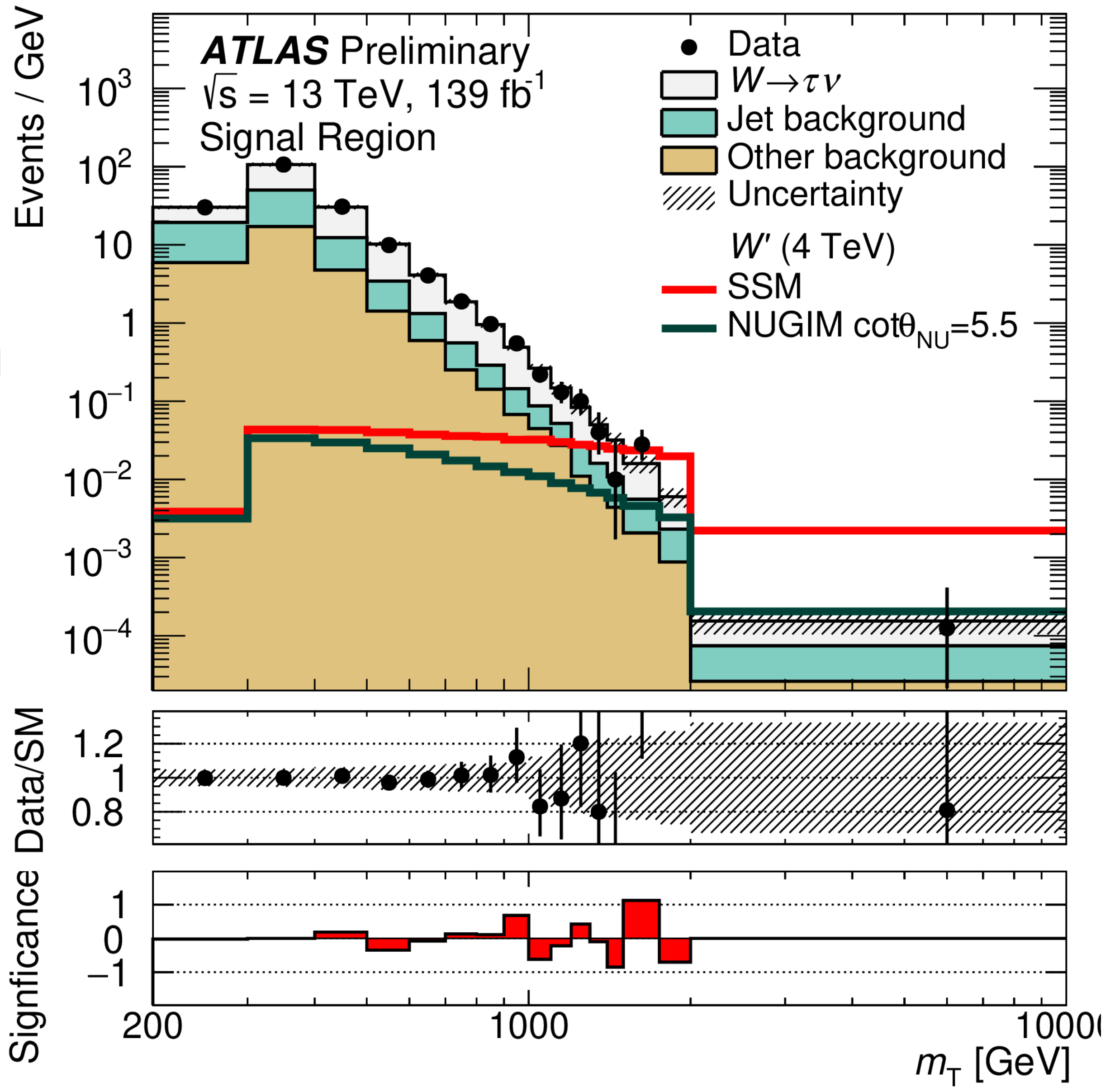
High energy phenomena with taus and b's

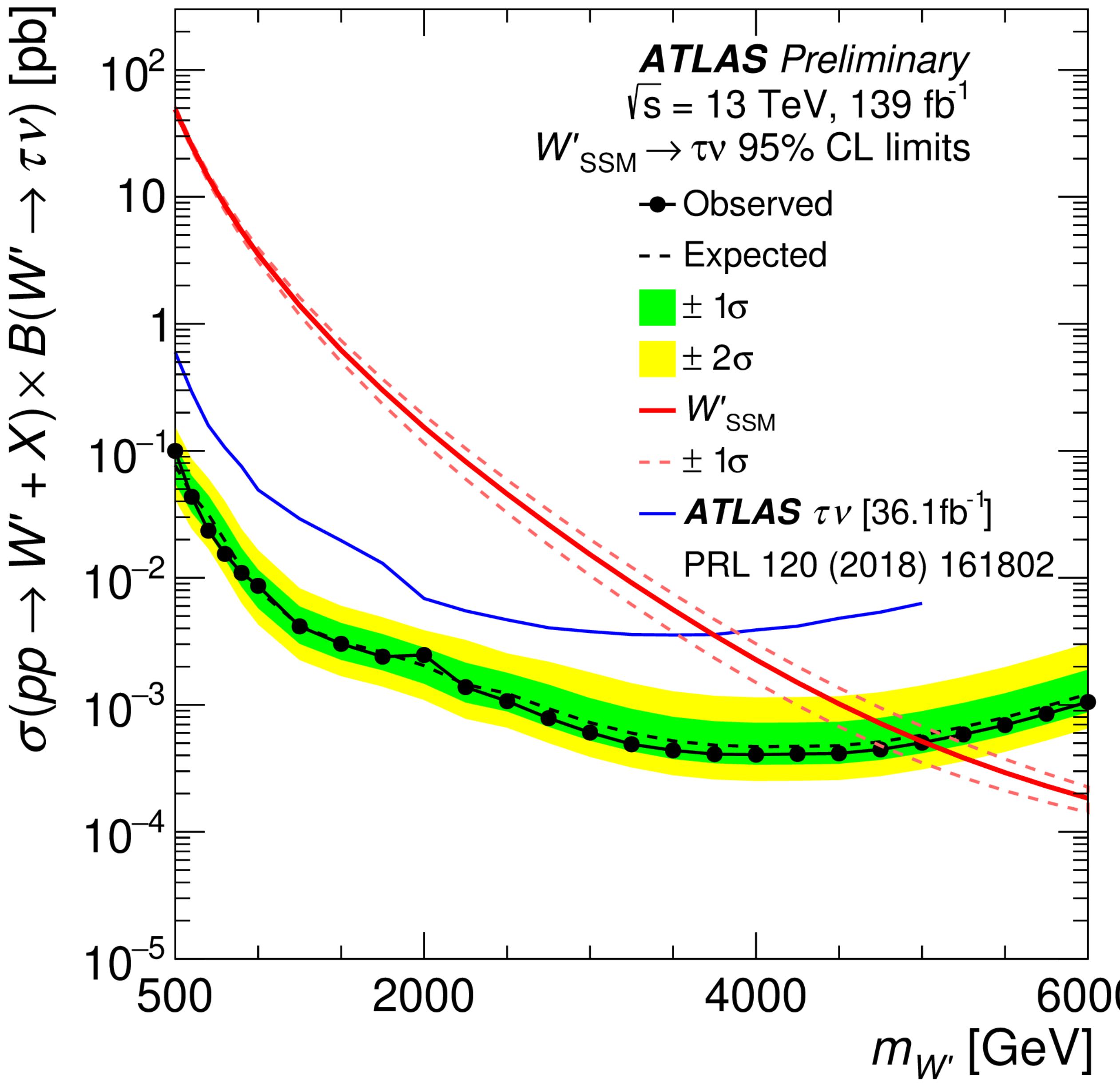


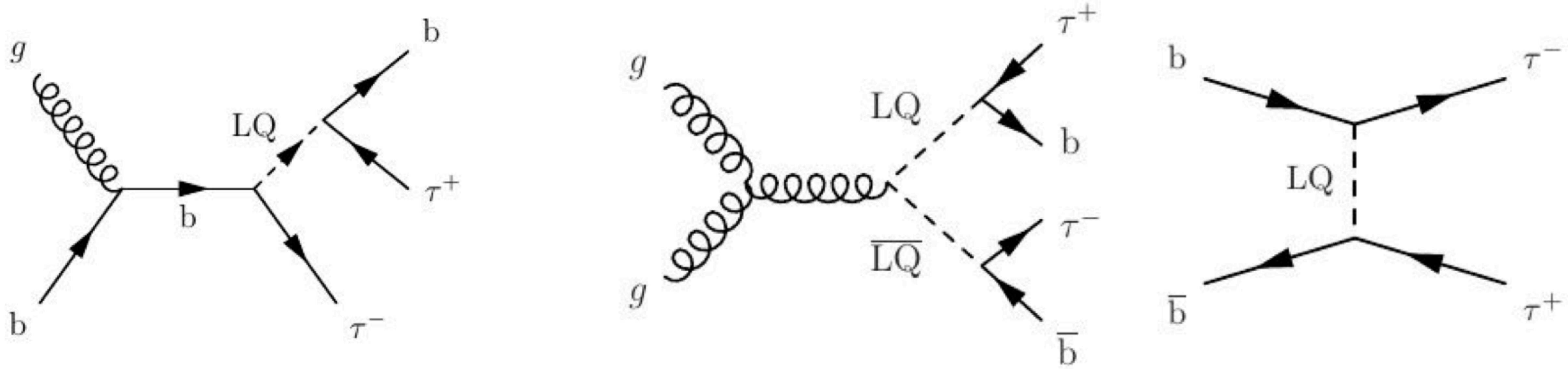
Search for $W' \to \tau\nu$

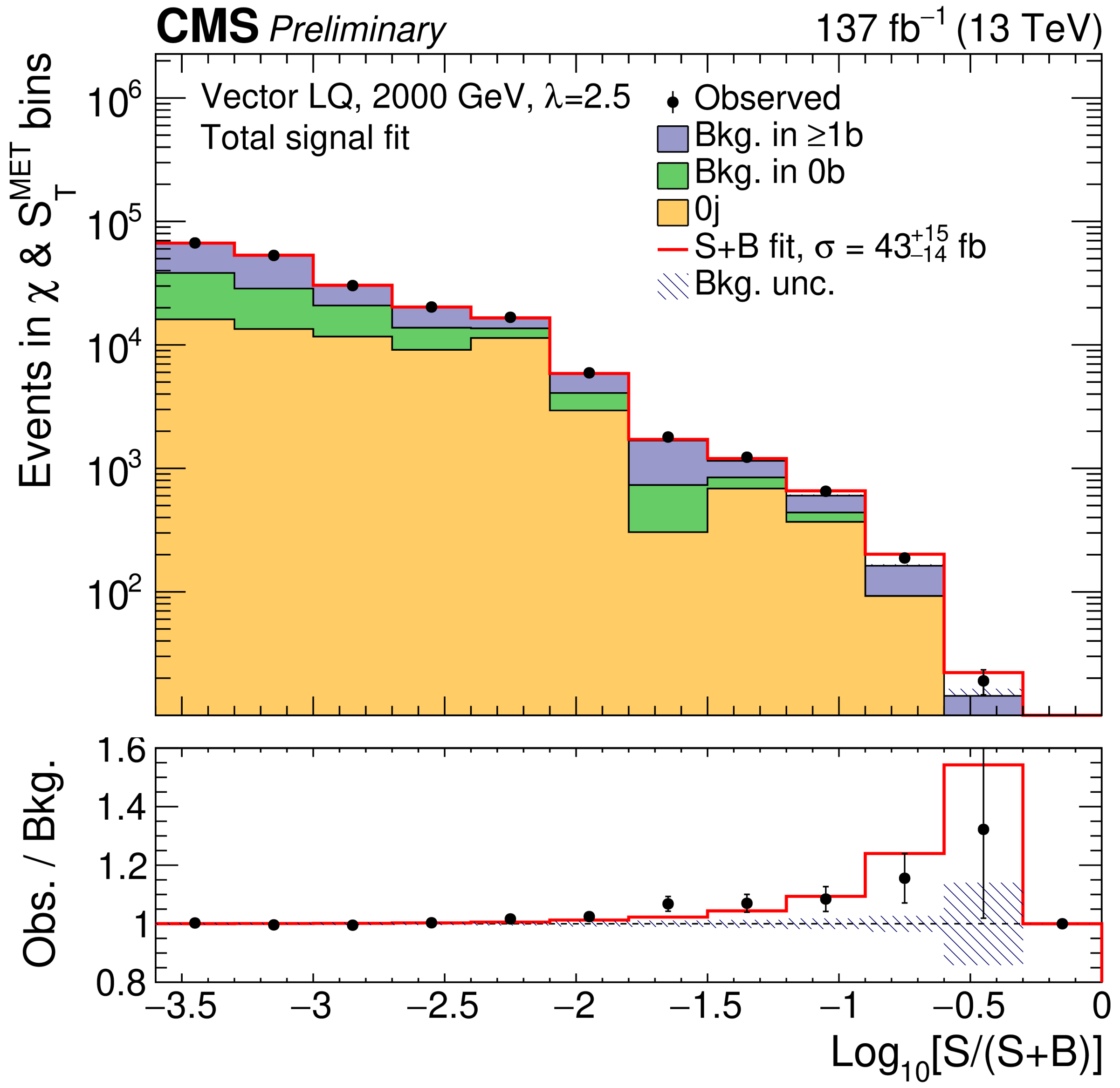
Excellent agreement between data and MC predictions!

Highest transverse mass candidate (see above event display is at **mT ~2.8 TeV**)





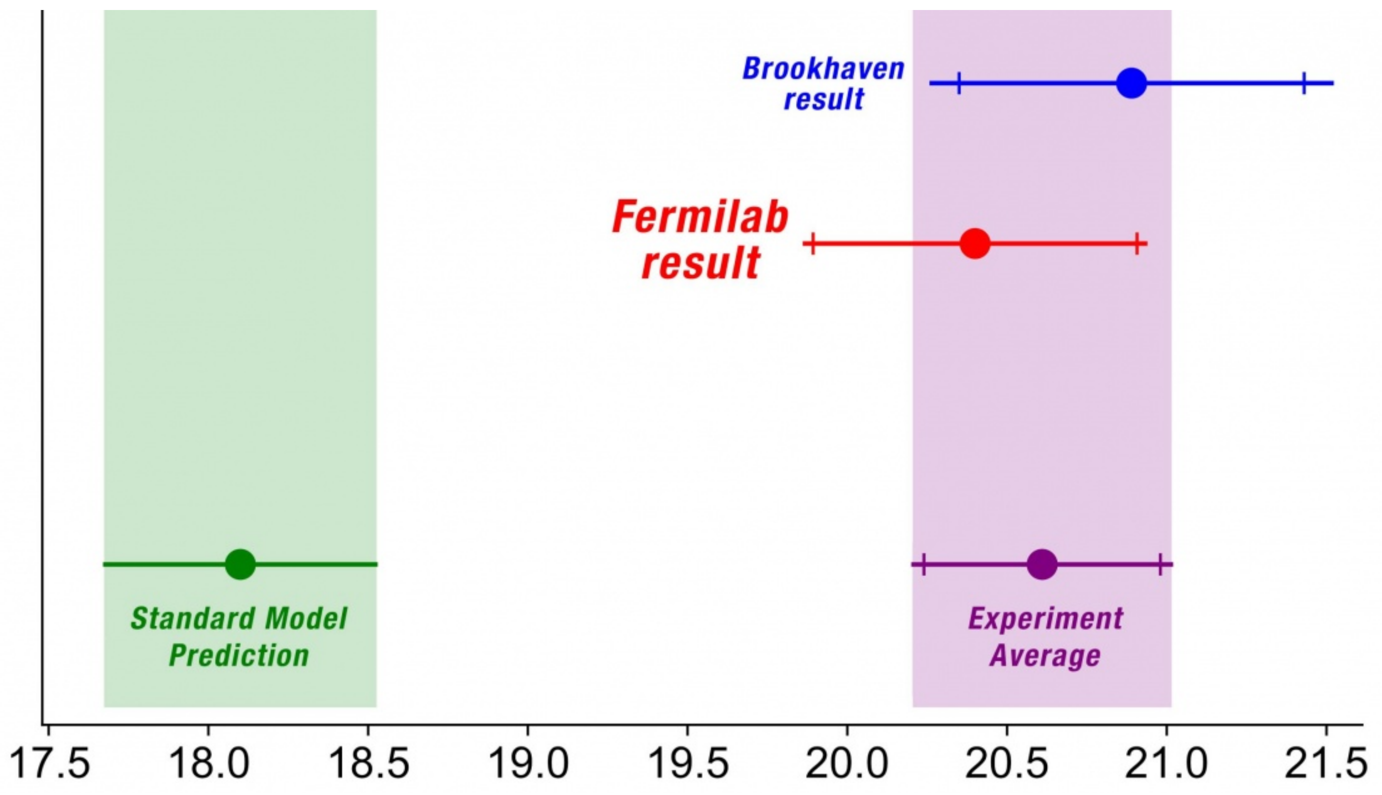




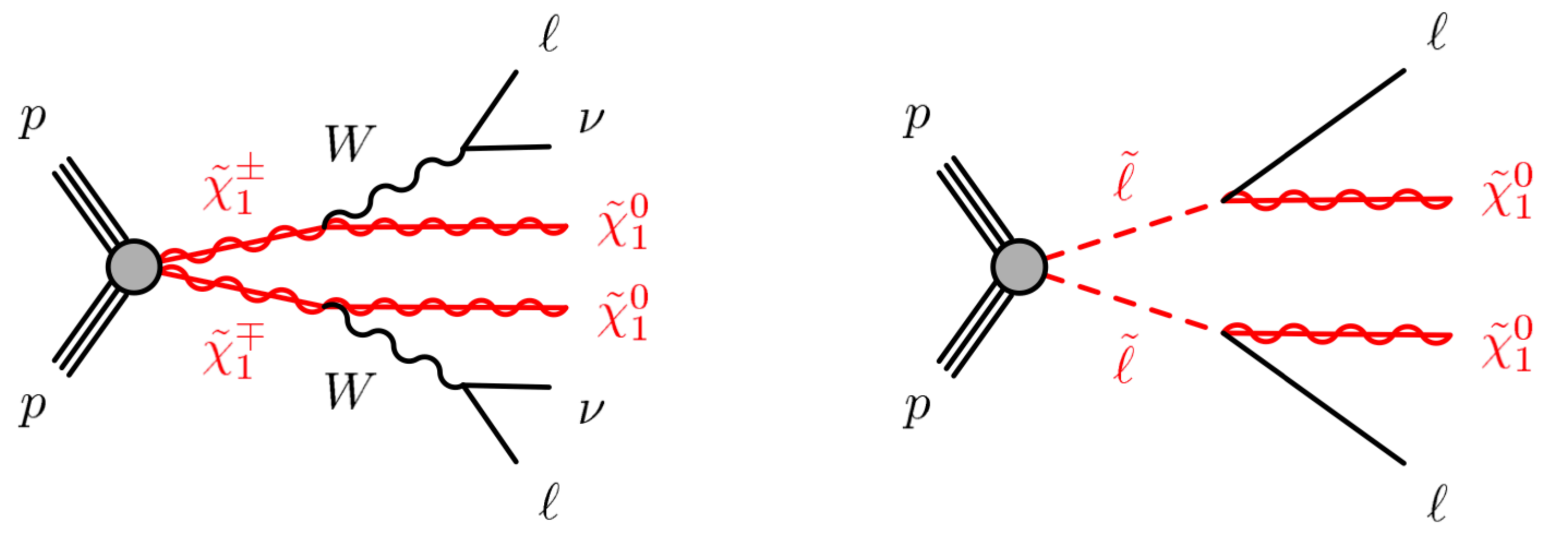
Search for third generation leptoquarks (LQ) in events with taus and bs…

Probing (g-2) and flavour Anomalies at High energy

Eur. Phys. J. C 80 (2020) 123



Recent muon (g-2) result from Fermilab reinforces the long standing tension with SM prediction

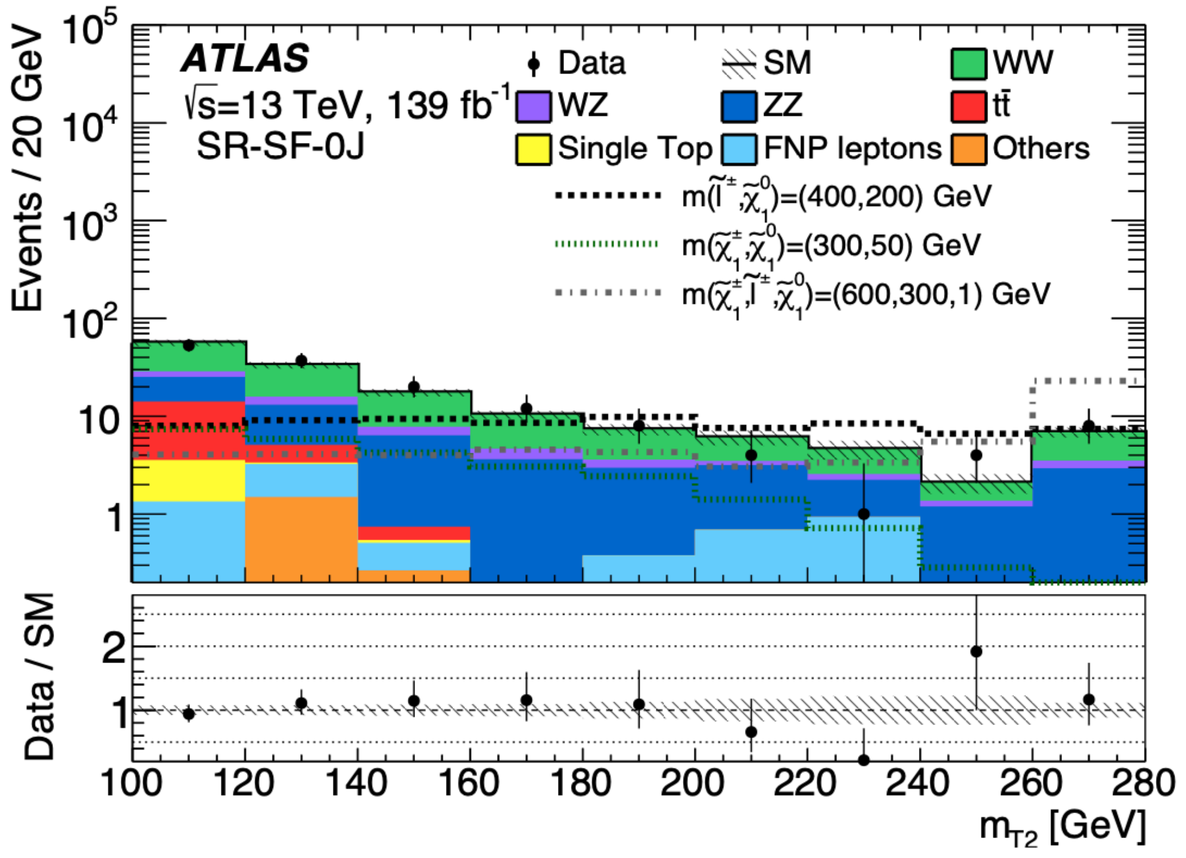


Search in scenarios with two leptons and MET

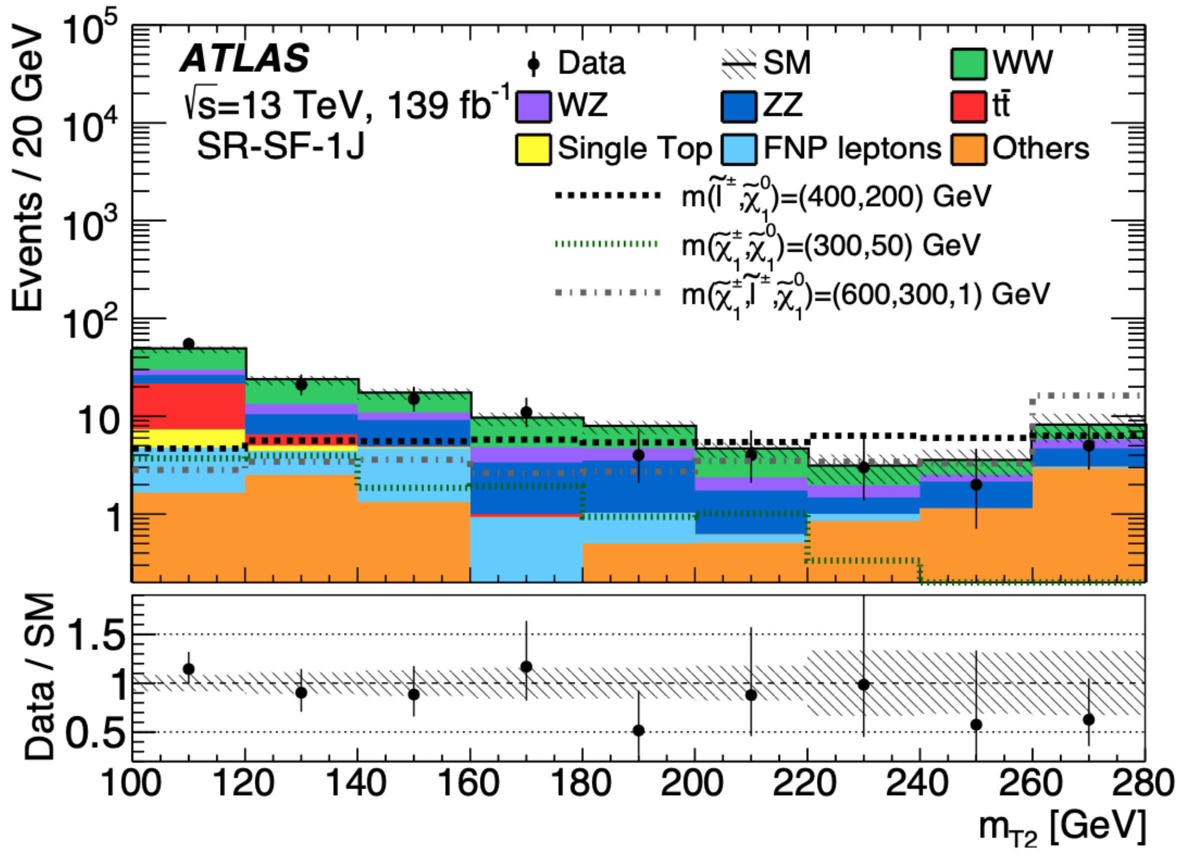
Muon (g-2) anomaly motivates searches for **smuons**

Using the s-transverse mass (estimated varying hypotheses of individual MET components)

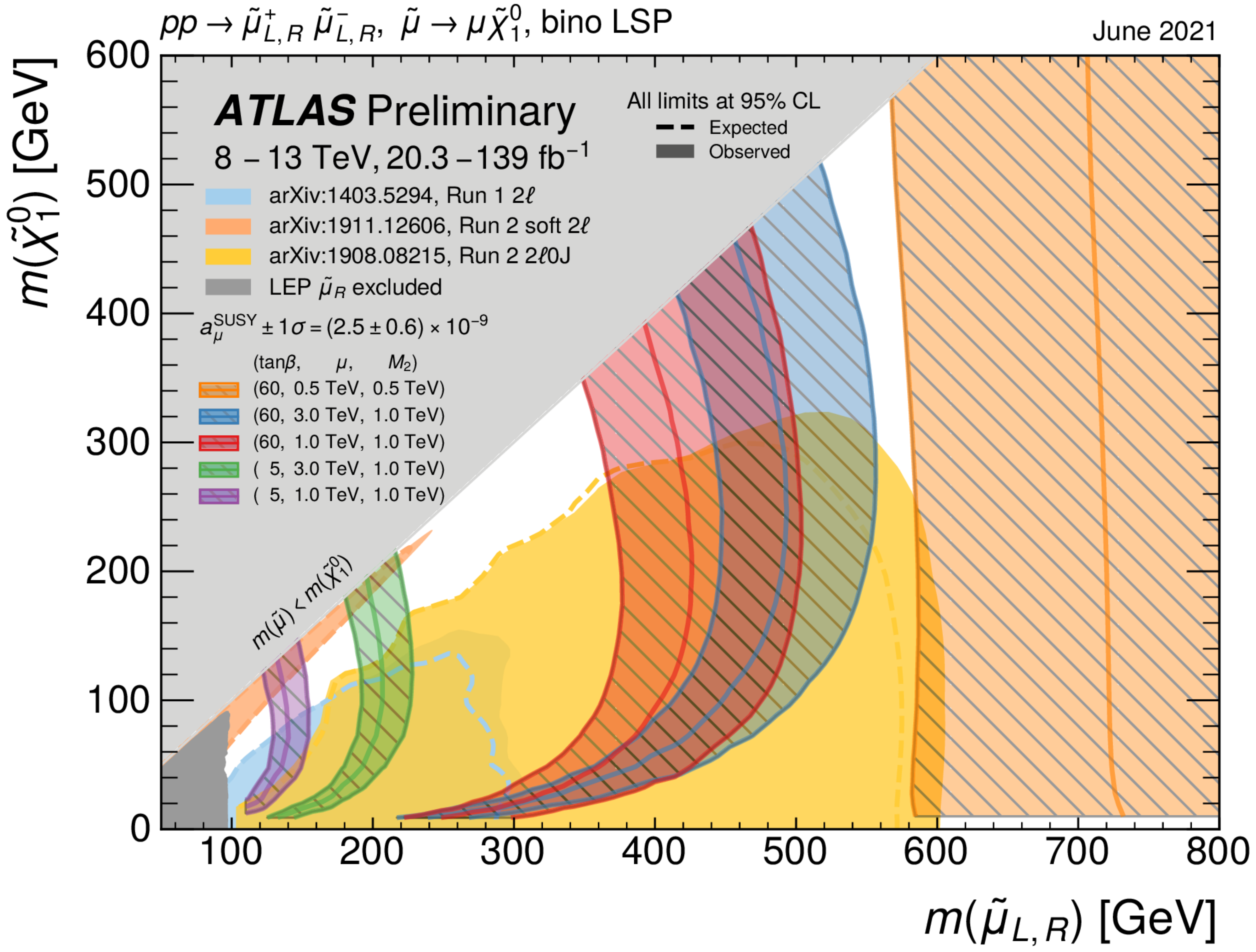
$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{p}_T^{miss}} \{\max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2})\,]\}$$



m_{T2} distribution in SR-SF-0J

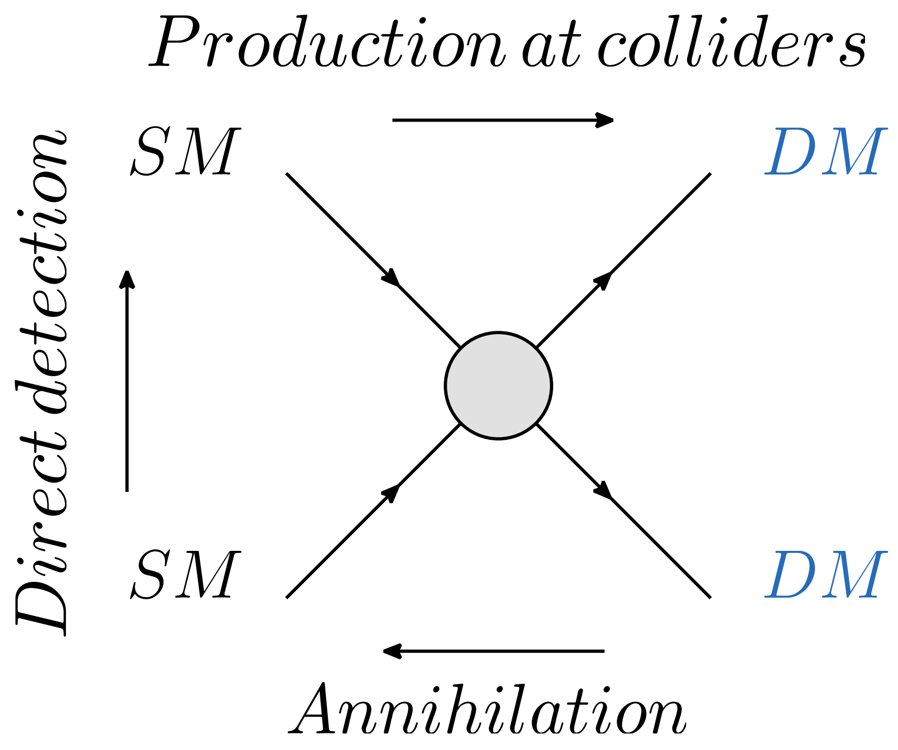


m_{T2} distribution in SR-SF-1J

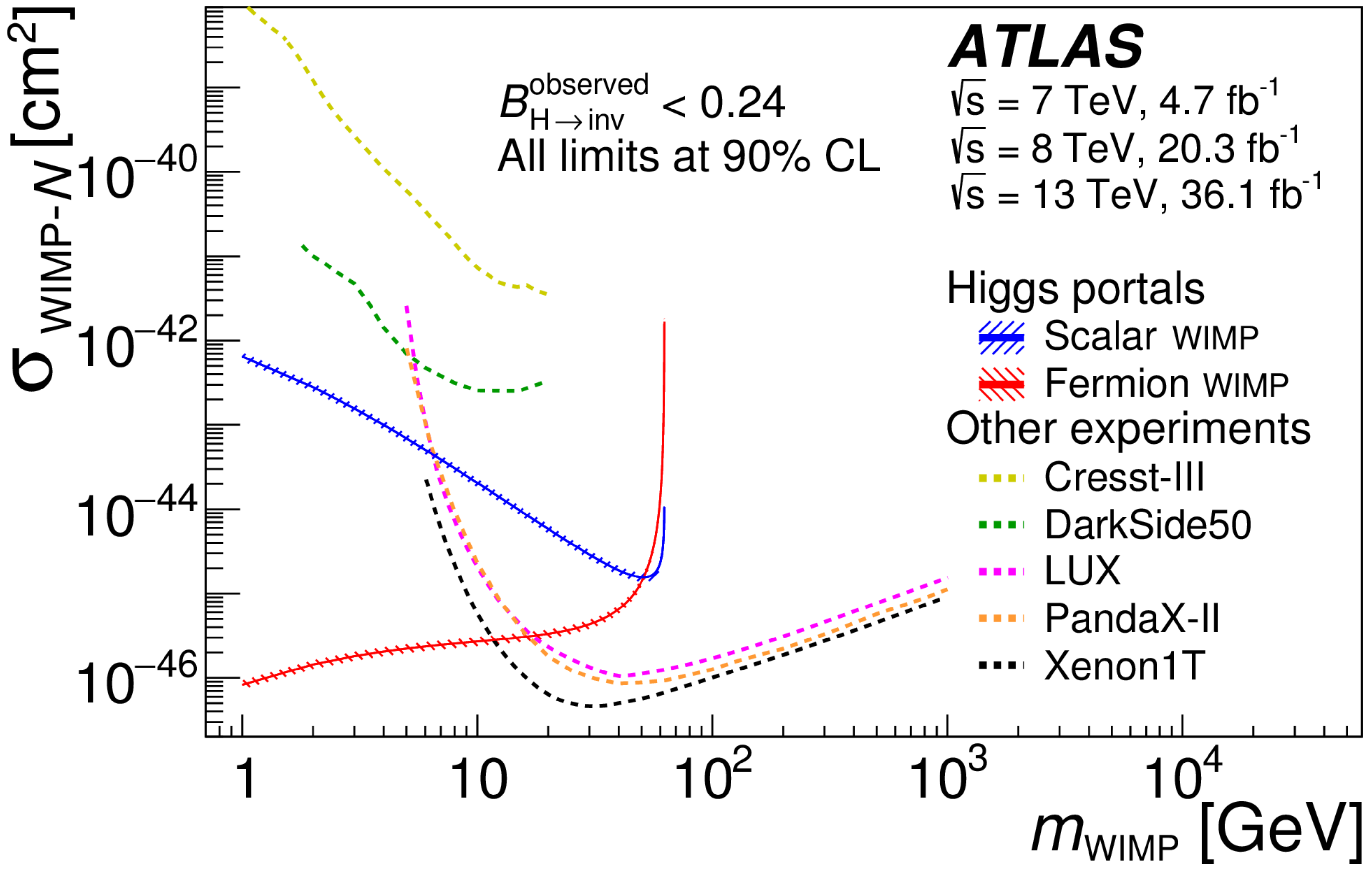


Generic Searches for Dark Matter

Generic Searches for Dark Matter



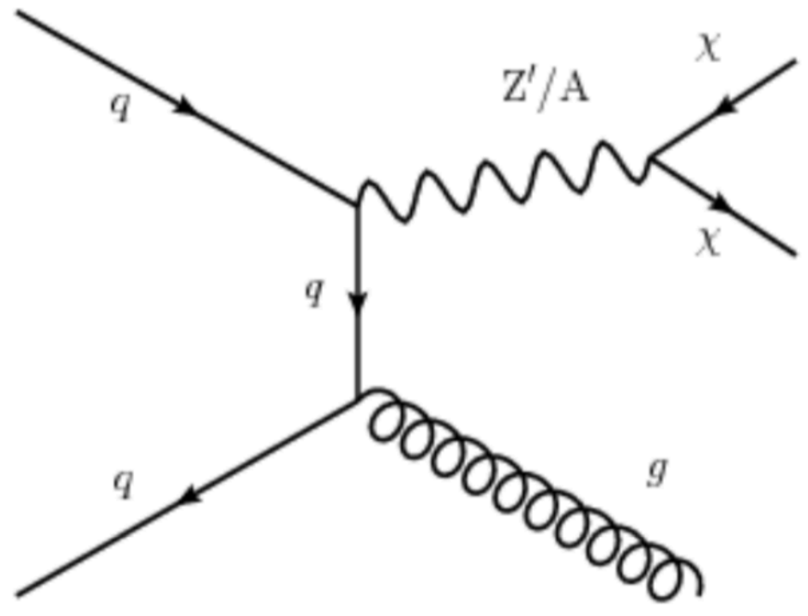
Complementarity of searches at colliders, direct and indirect searches!



Searches for Dark Matter at the LHC

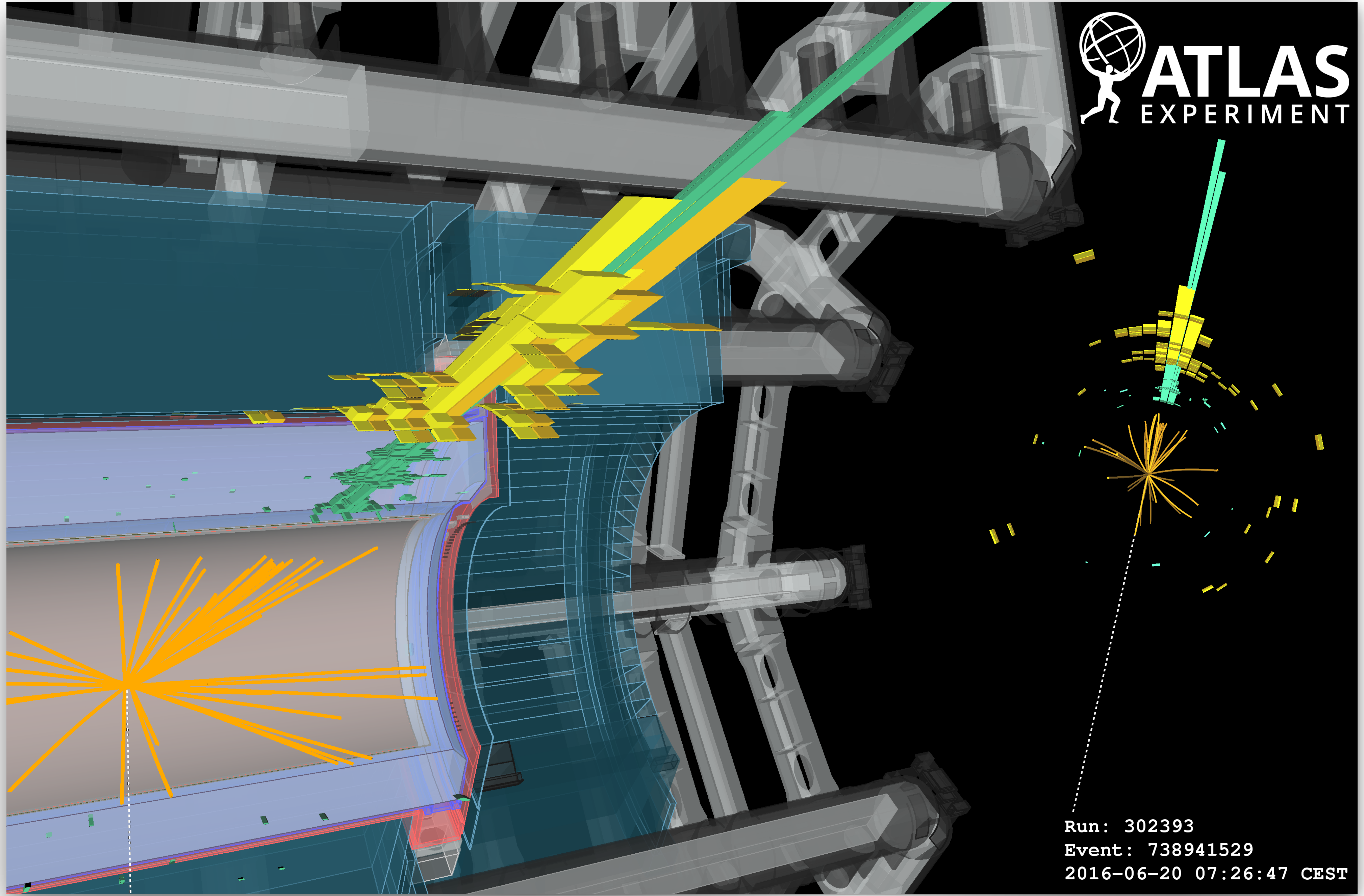
- Invisible Higgs searches (Lecture 3).

- In order to be observed invisible final states need additional objects to be associated with. Mono-anything searches: Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top.



Monojet signature! One of the most sensitive channels!

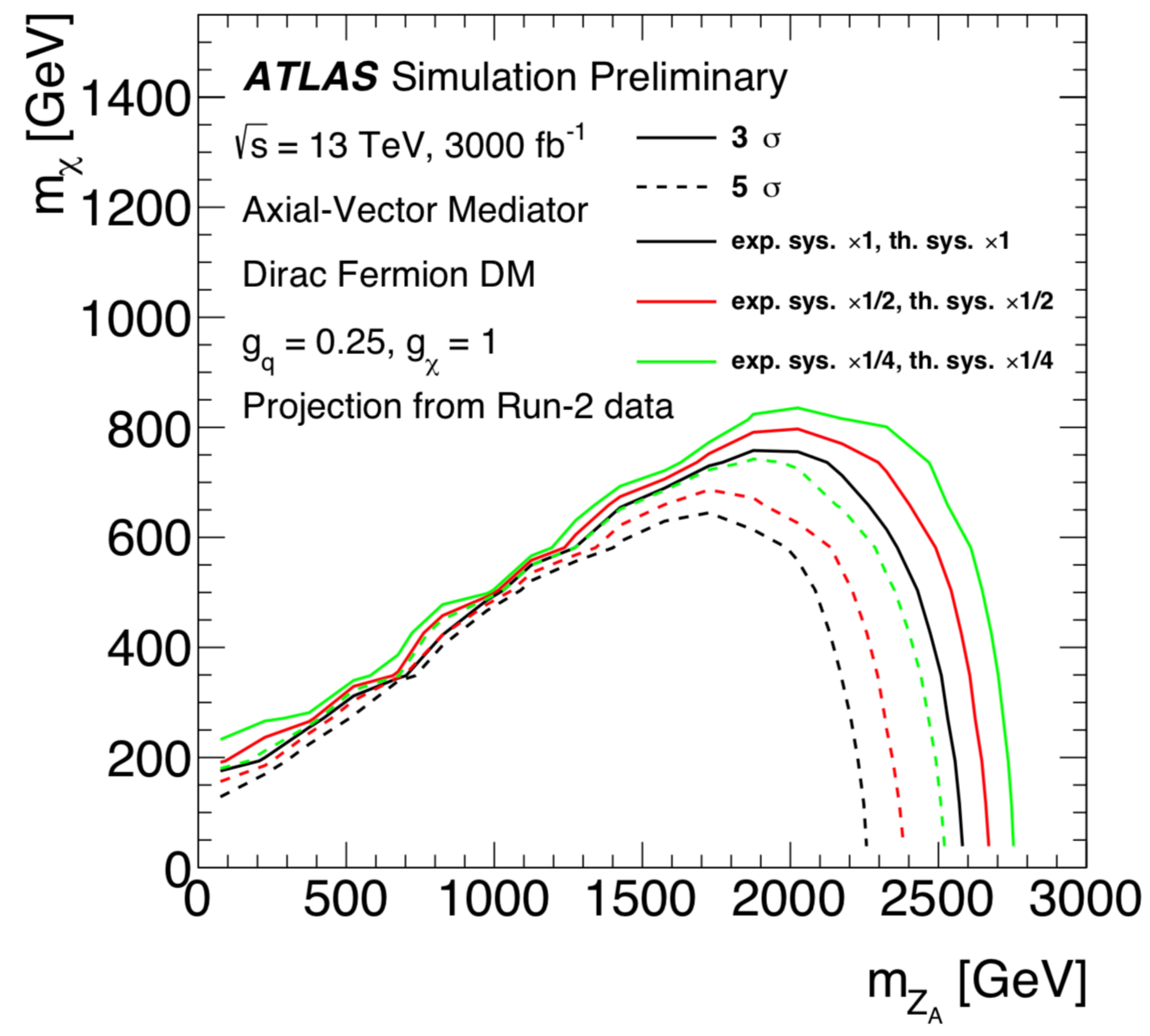
Generic Searches for Dark Matter



A jet with pT of 1707 GeV. The ETmiss of 1735 GeV is shown as the white dashed line. No additional jets with pT above 30 GeV is found.

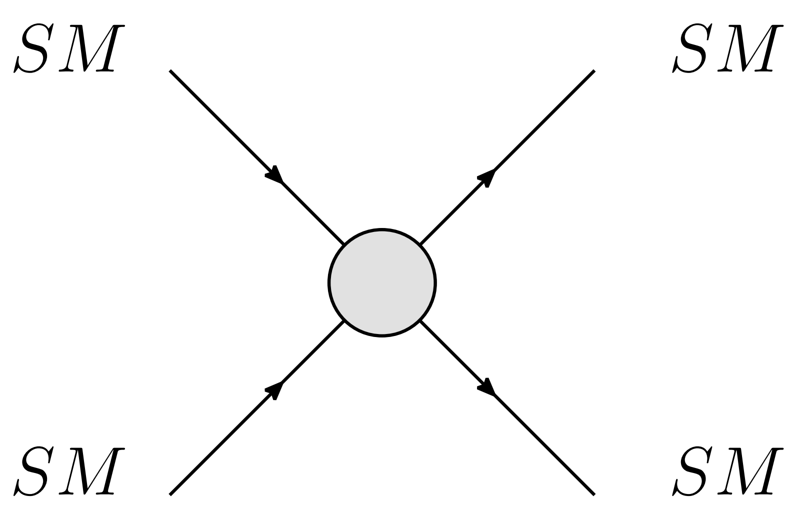
Mono jet search prospects

Reach close to TeV range at HL-LHC (model dependent)



Generic Searches for Dark Matter

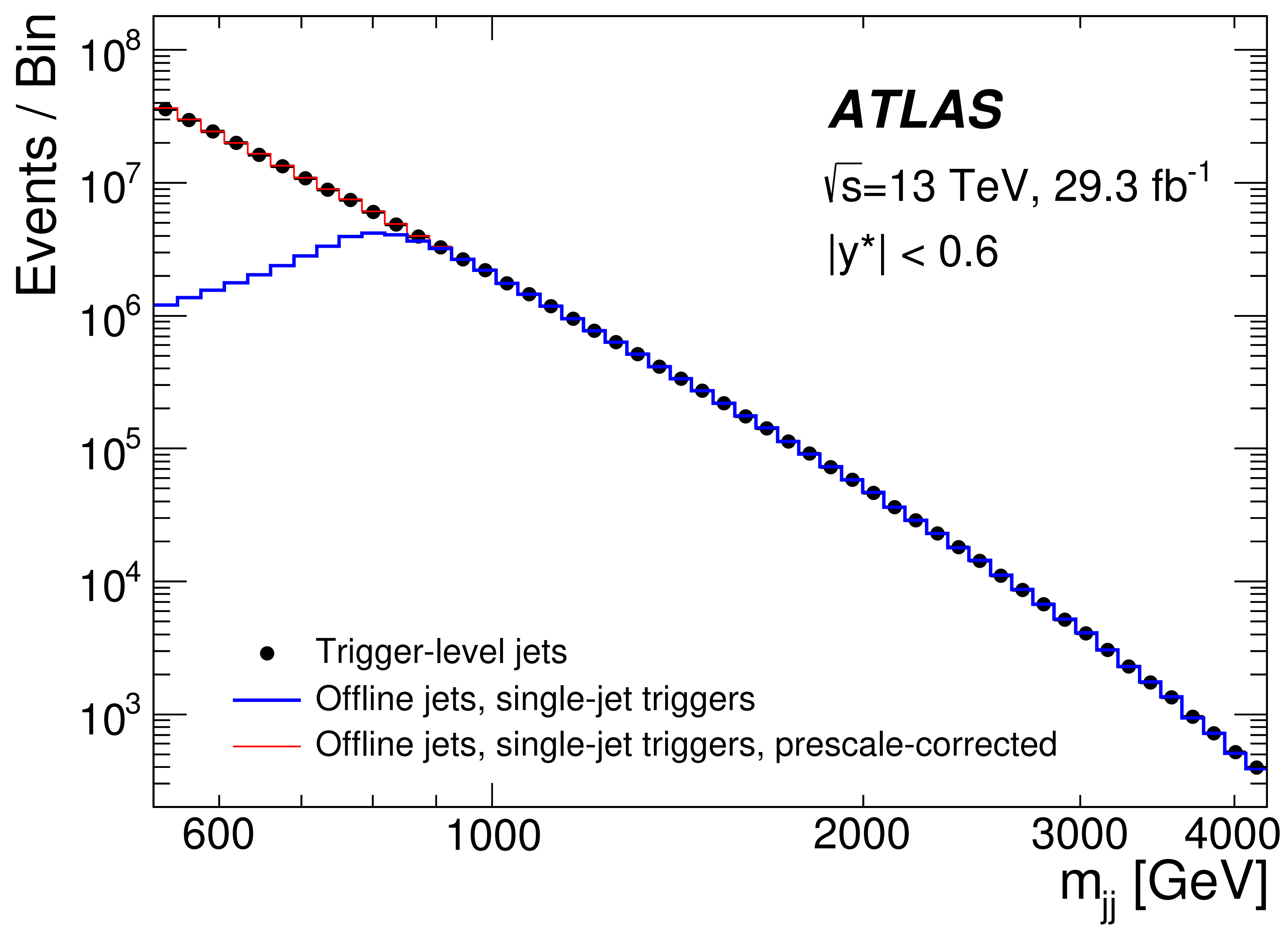
Searches for the dark matter mediator
in e.g. in dijet events extending at low masses

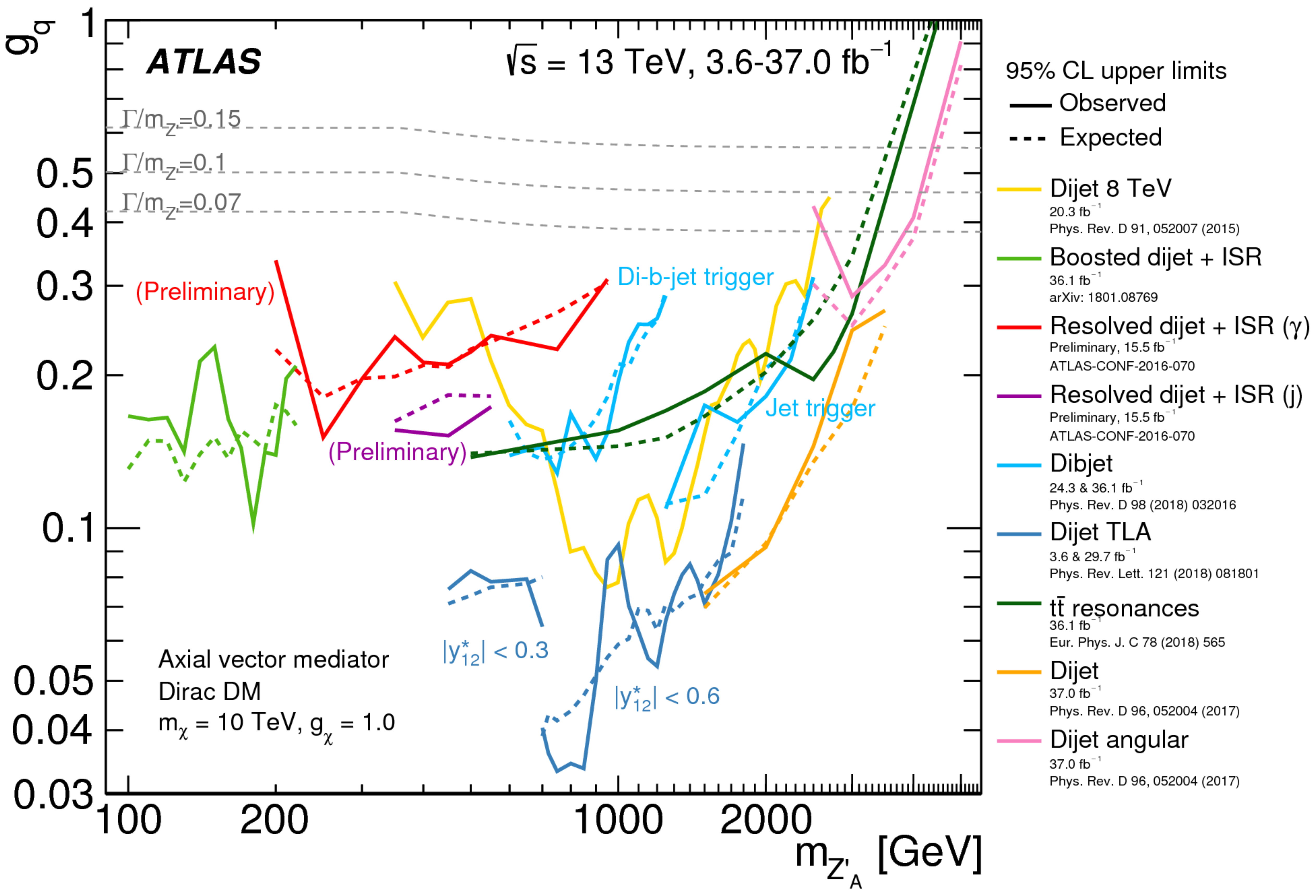


Numerous strategies to also cover lower masses e.g.:

- boosting (ISR photon/jet)
- Trigger level analyses

Dijet Trigger level analysis





Outlook and Conclusions

Searching with Precision and High energy Phenomena

Measurement of SM processes in the high energy domain

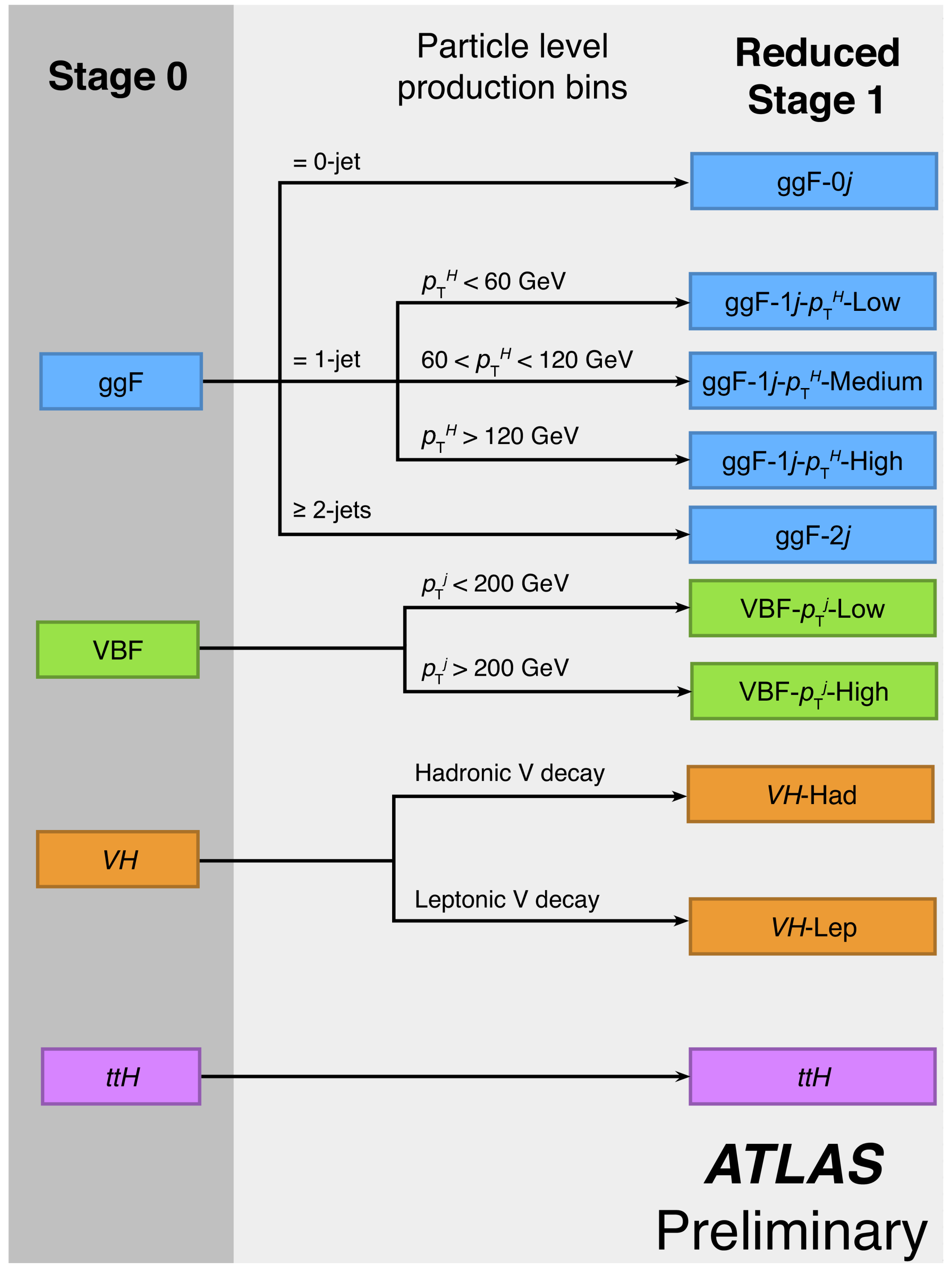
Effective field theory and measurements of non resonant processes at higher energy

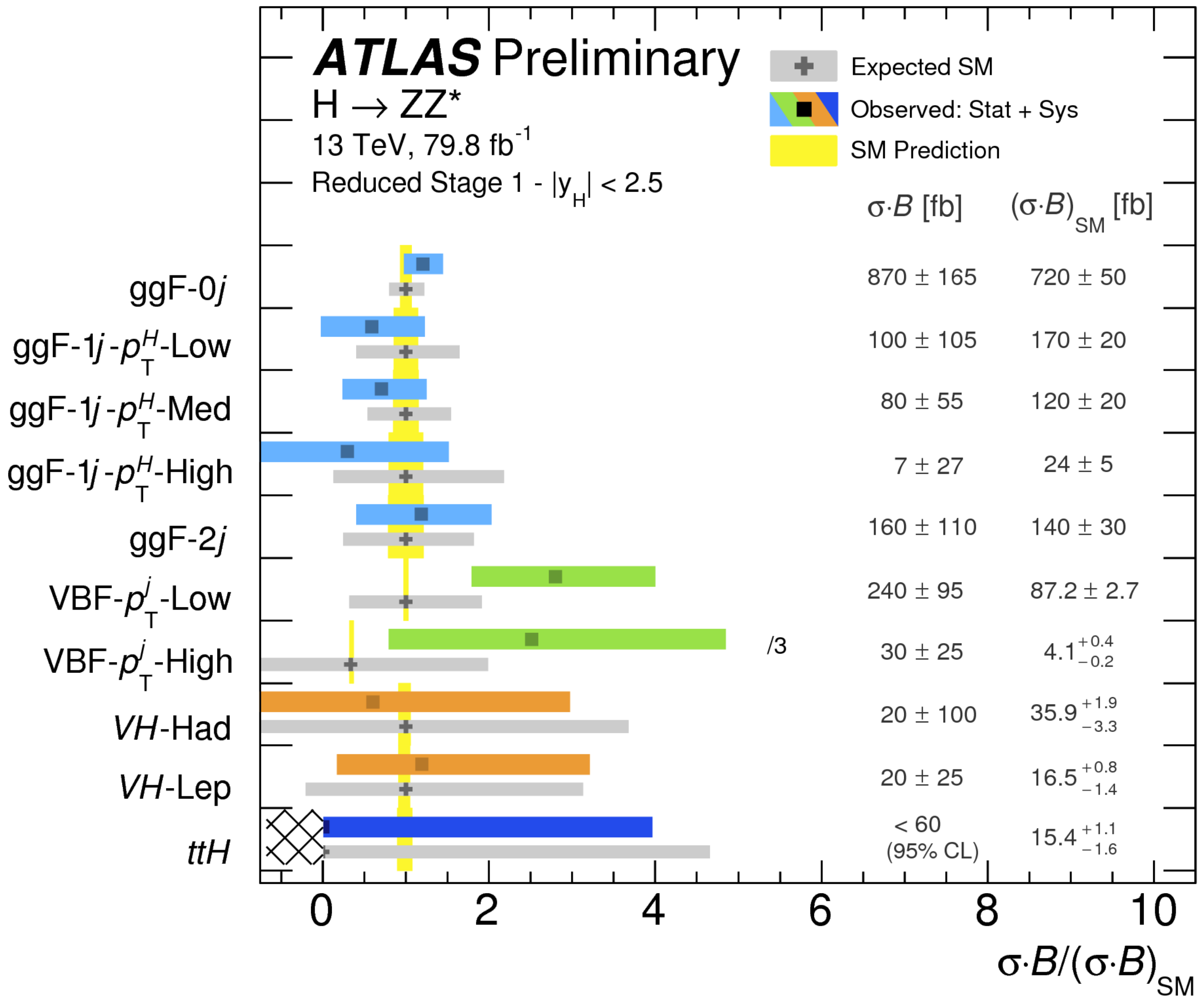
Higgs couplings at low energies

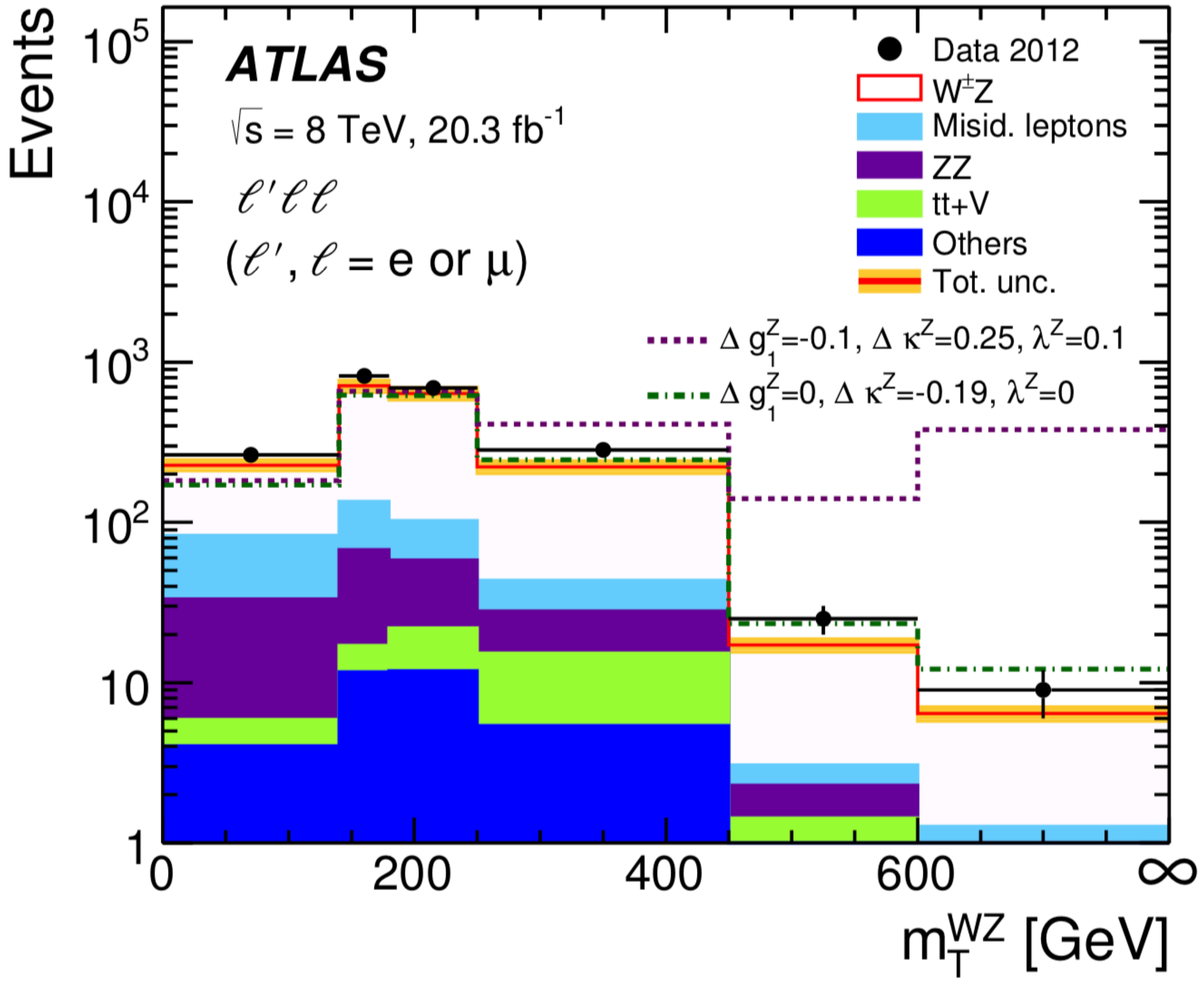
$$\frac{\delta c}{c} \sim \frac{g_*^2}{g_{SM}^2}\frac{m_h^2}{\Lambda^2}$$

Higher energy phenomena
(e.g. VV scattering)

$$\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \frac{g_*^2}{g_{SM}^2}\frac{E^2}{\Lambda^2}$$





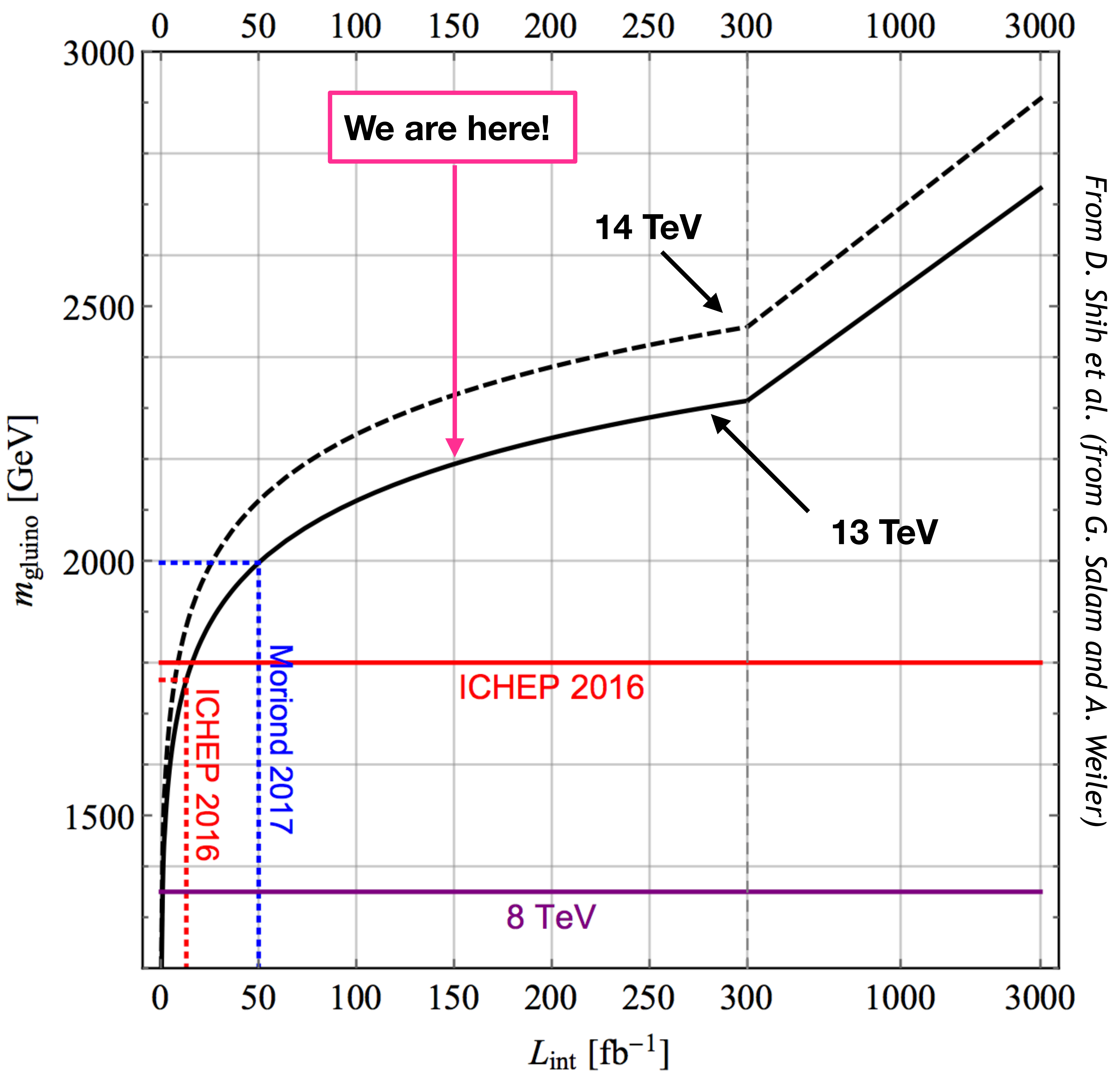


Measurement of Higgs production cross sections in high transverse momentum regime

Measurement of di-boson in the high mass regime

Towards HL-LHC and Precision Physics at LHC

Evolution of **exclusion** search sensitivity for generic strongly interacting particle (e.g. **gluino**)



http://collider-reach.web.cern.ch/collider-reach/

Towards HL-LHC still a **factor of 20** in luminosity:

- Still **room for discoveries!**
- Given that the **doubling time of the luminosity** is now counted in **several years**: discoveries will take time, and times for spectacular discoveries (in the sense of immediate) are over.
- Low hanging fruits typically have been (or are being) harvested! Immense amount of work in trying to expand search reach beyond the root-L:
  - With new ideas and developments at all levels.
  - **Improving precision (theoretical and experimental) will be key!**

Also: Increase in centre-of-mass energy from 13 TeV to 14 TeV gives an increase in high energy phenomena such as (q* or QBH) production of **2-5**!

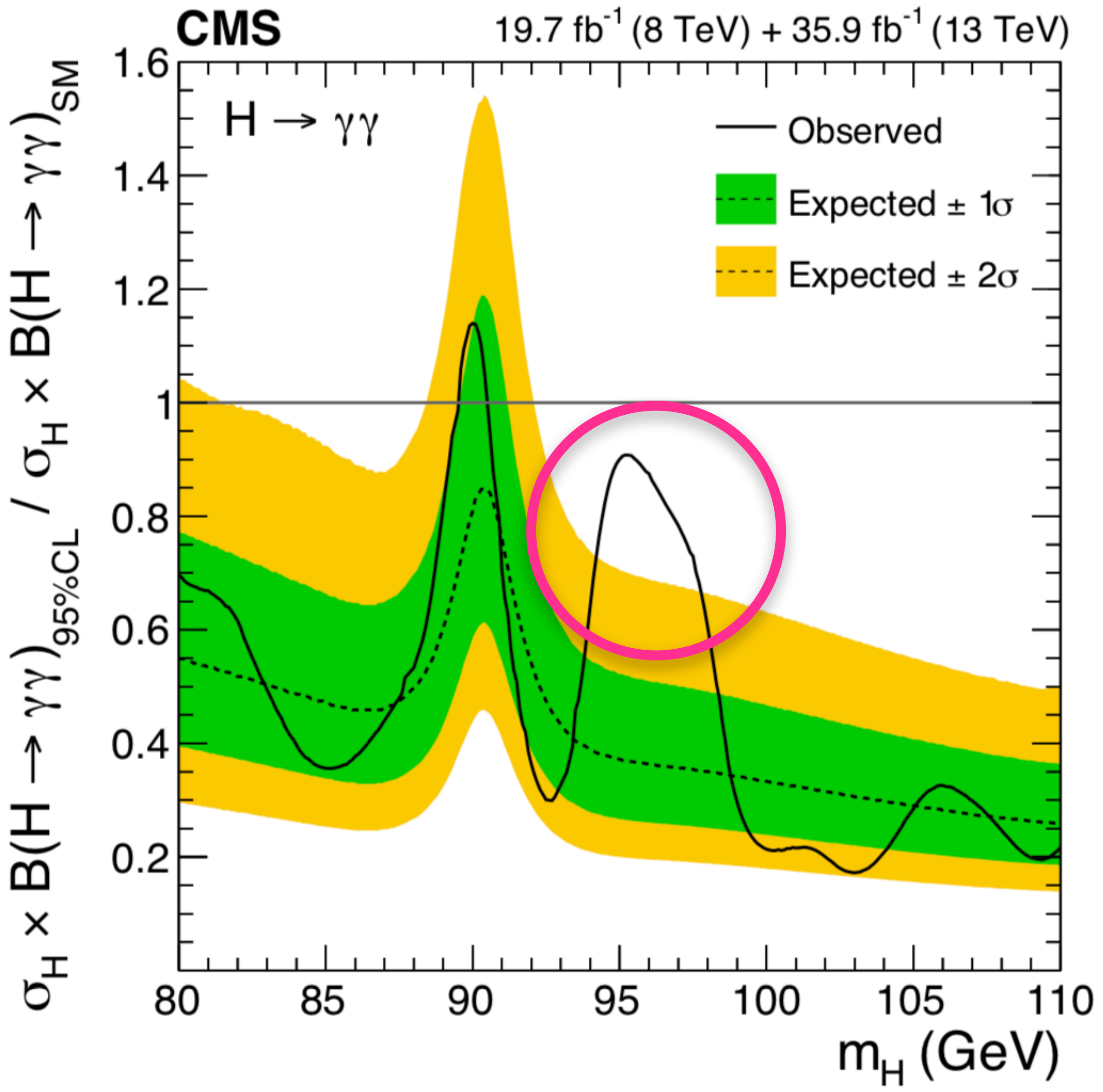
Anomalies in the Searches done so far?

Several ~3σ (local) excesses

A few examples…

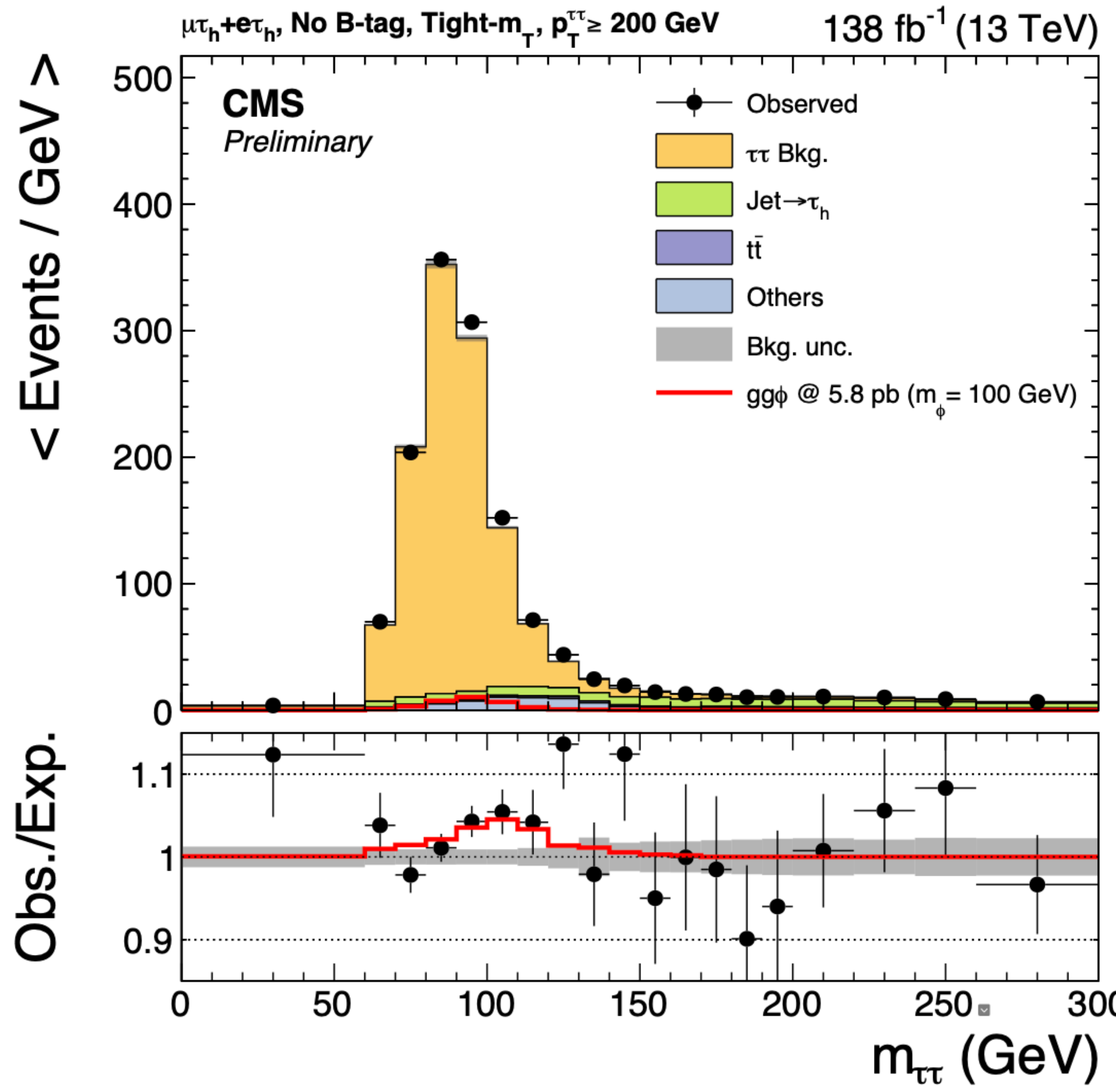
$$a \to \gamma\gamma$$

Local (global) significance at 95.3 GeV : 2.9σ (**1.5σ**)

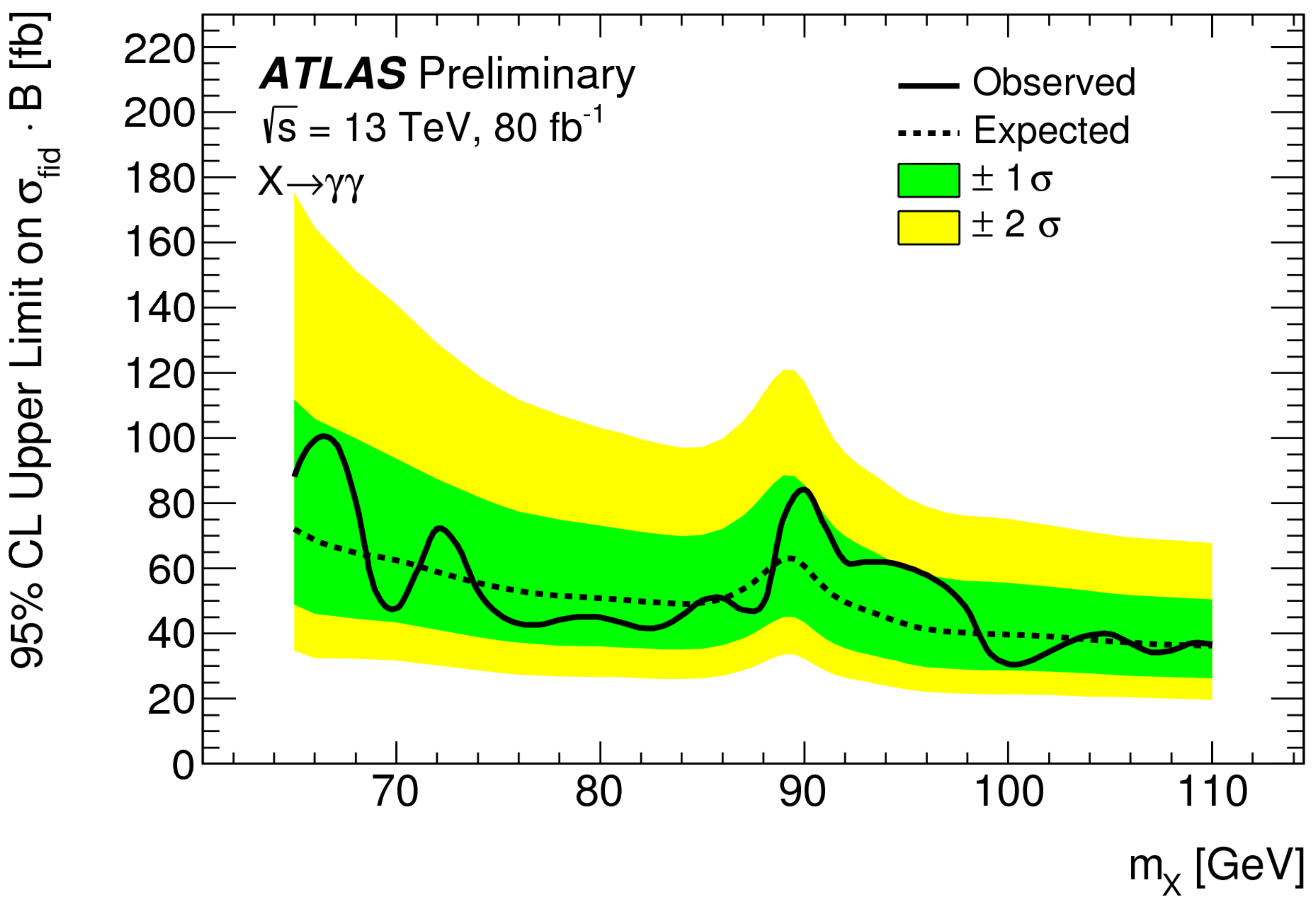


$$\phi \to \tau^+\tau^-$$

Local (global) significance at 95 TeV : 3.1σ (**2.7σ**)



ATLAS-CONF-2018-025



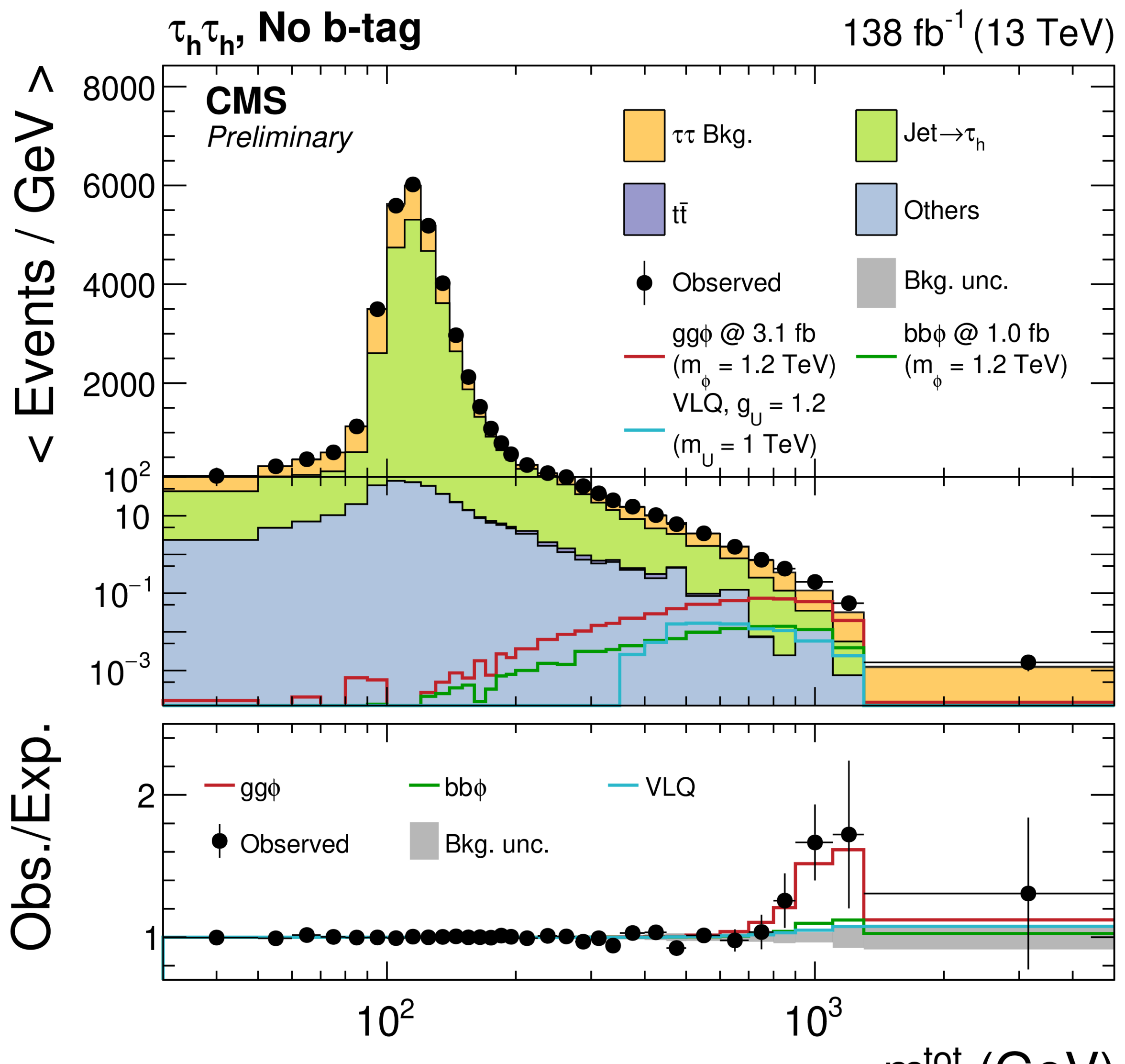
Acceptance ~50%

Limit on σxBR~120 fb

Not confirmed (but not conclusively excluded)

$$\phi \to \tau^+\tau^-$$

Local (global) significance at 1.2 TeV : 2.8σ (**2.4σ**)



But careful, with such large number of searches anomalies are expected and there could be systematic effects!

Conclusions

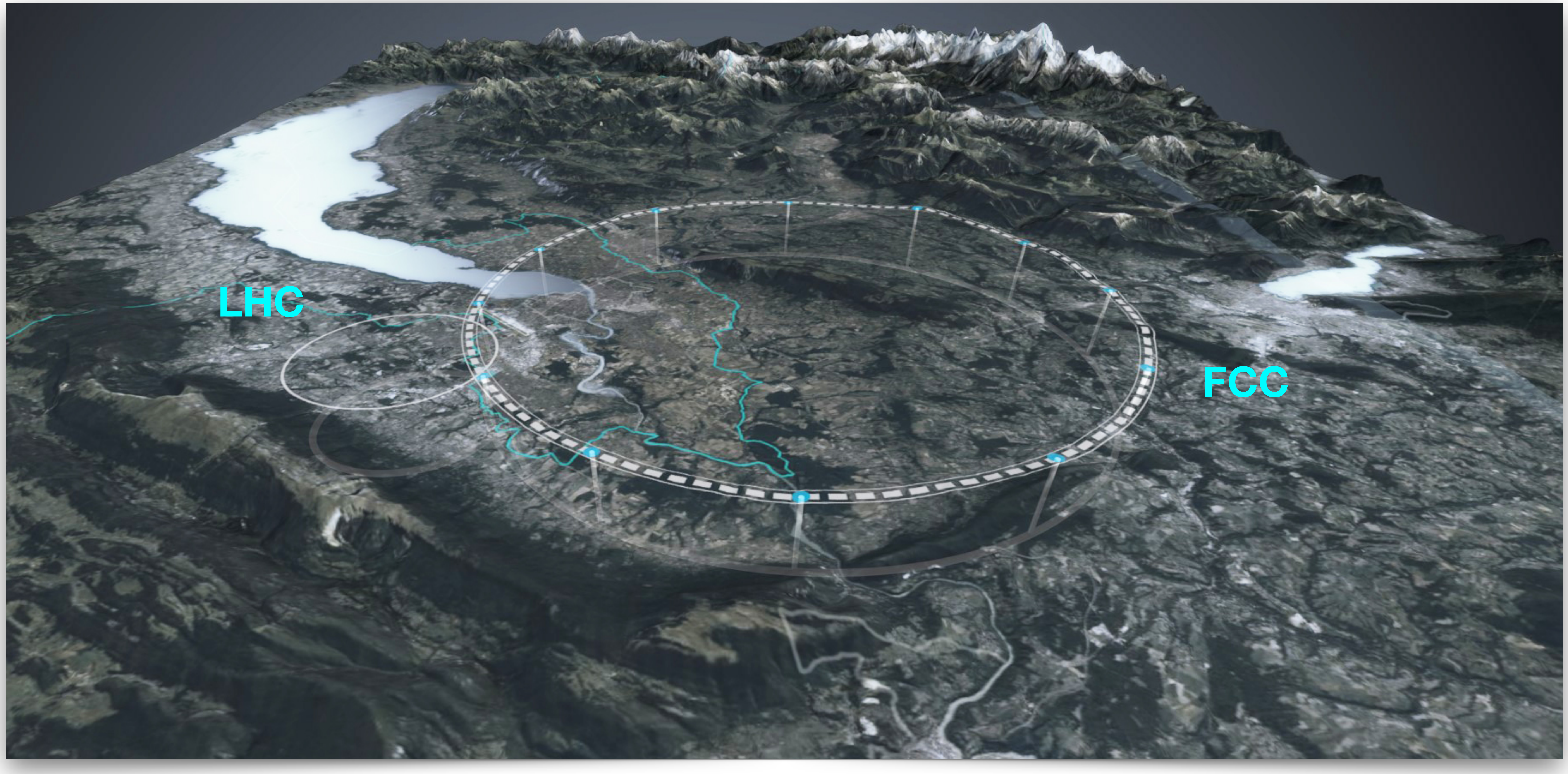
The first 10 years of the LHC running with the immense progress in theoretical predictions have been an immense success with major landmark results:

- The LHC has proved not to be only a discovery machine with a vast potential in direct searches, but also a broad range of precision measurements machine!
- The discovery of the Higgs boson, and the measurement of its properties all compatible with the Standard Model Higgs boson.
- A vast campaign of searches at the energy frontier leaving no stones unturned, which have so far revealed no signal of physics beyond the Standard Model.

This has completely changed the field and opened new opportunities!

The LHC physics program is broad, diverse and exciting with great opportunities for you!!

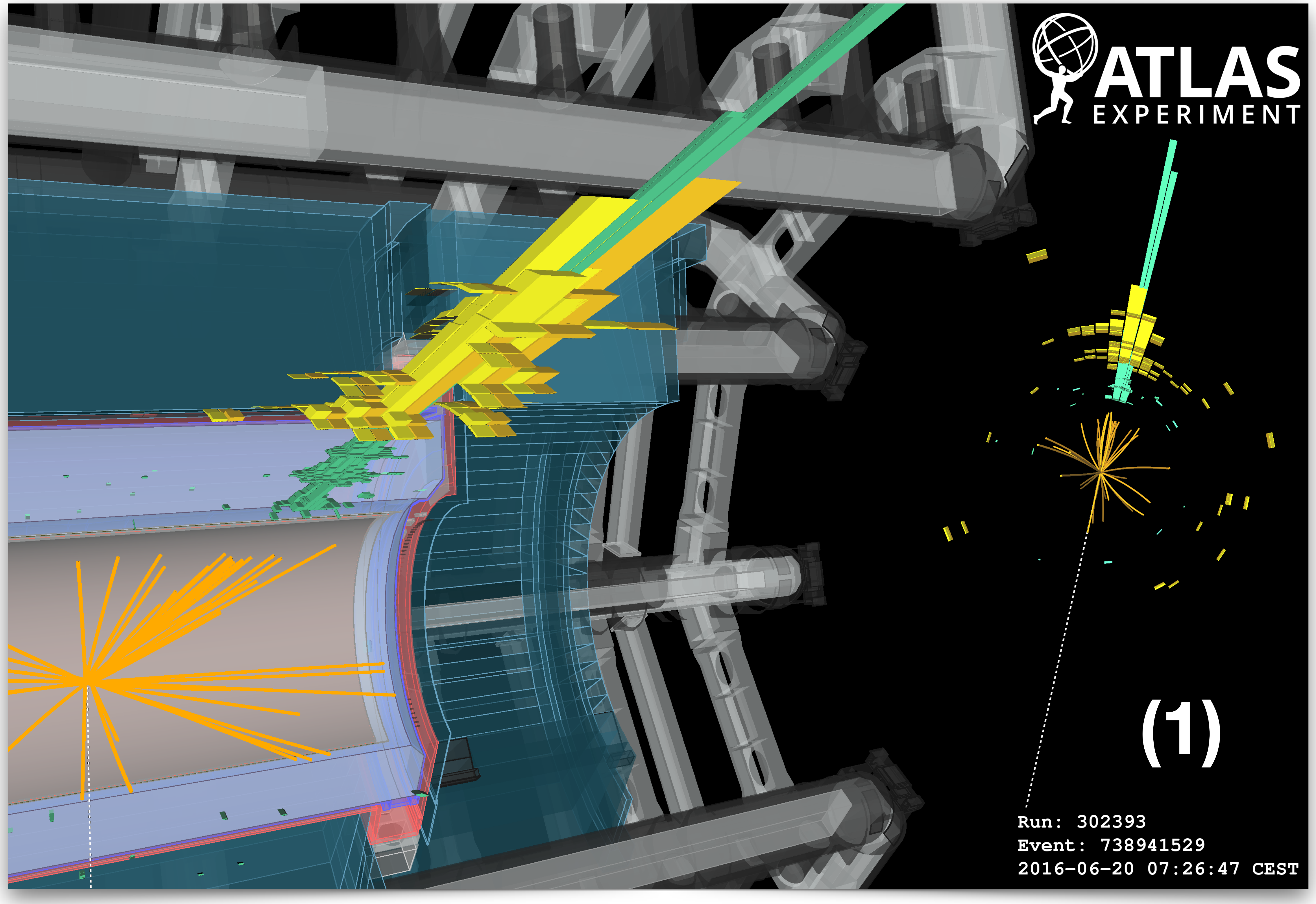
Outlook

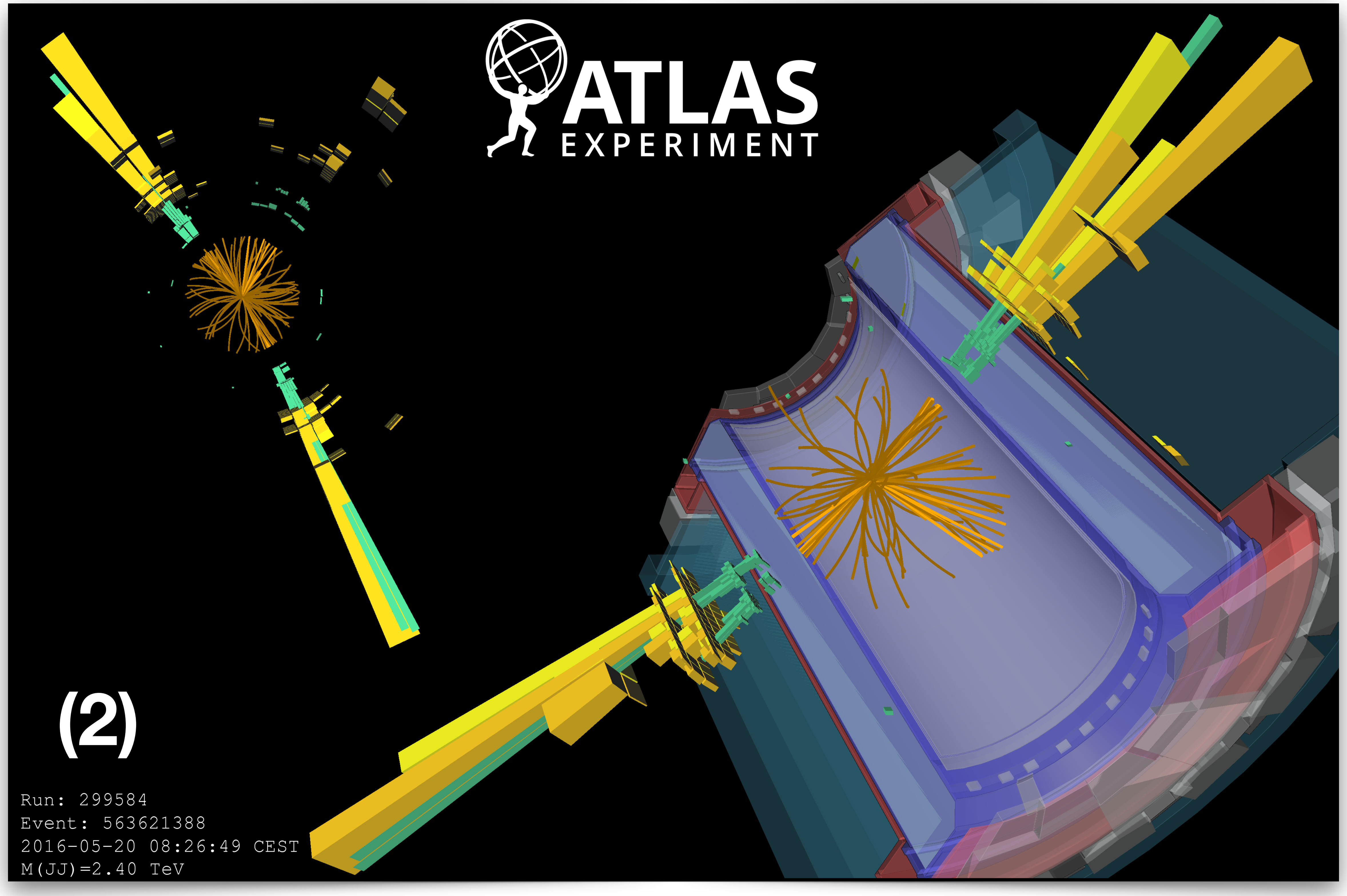


See lectures by Frank Simon and Barbara Dalena

Quiz

Quick Mini Quiz





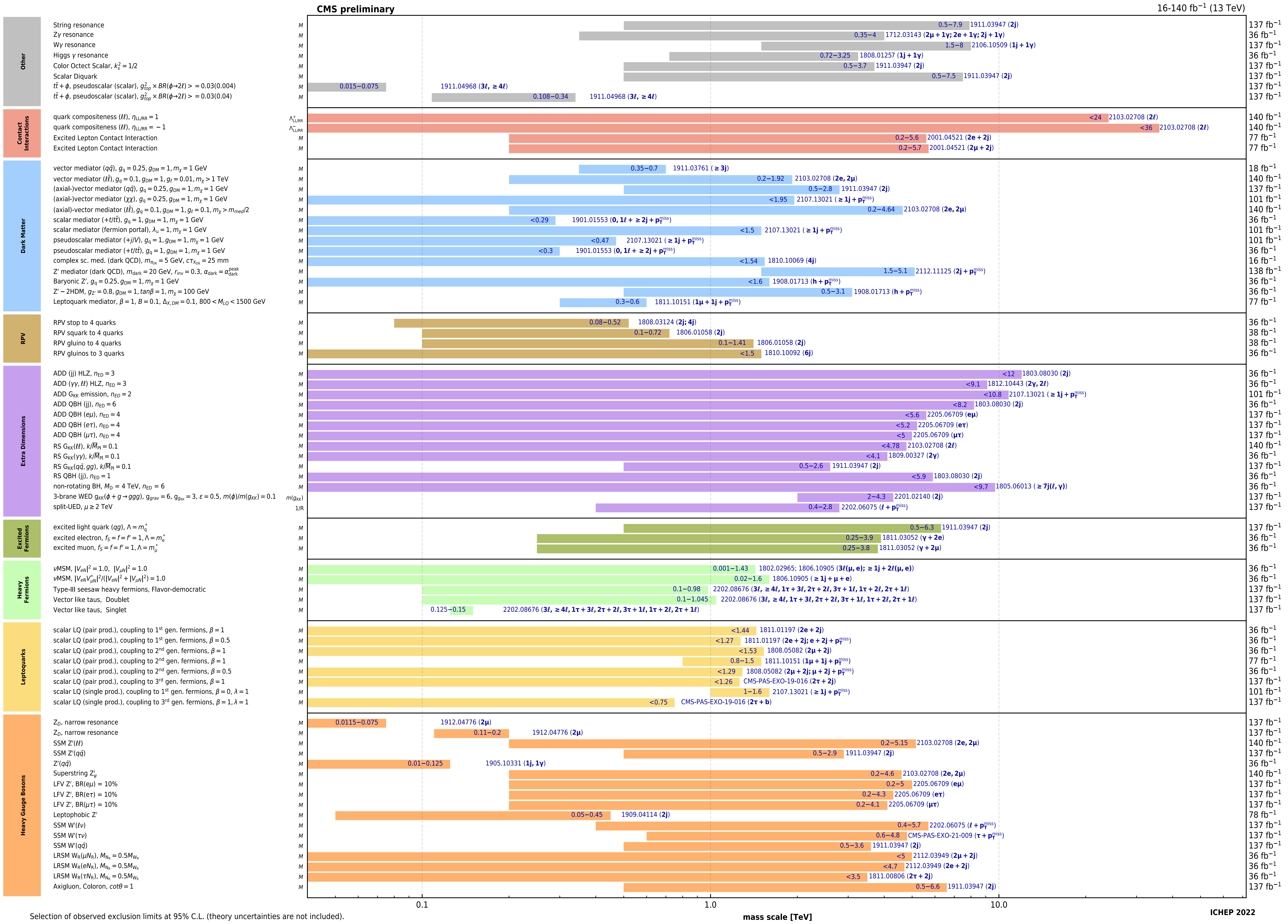
1.- If not the production of Dark Matter what process is this event likely due to in the Standard Model?

2.- What is the most likely interpretation of this event with two large-R jets with masses compatible with the W or Z boson?

3.- Can the Higgs Boson decay to neutrinos?

Further Reading

CMS Exotics Searches summary



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).